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Is the Atlantic Overturning Circulation Approaching a Tipping Point?

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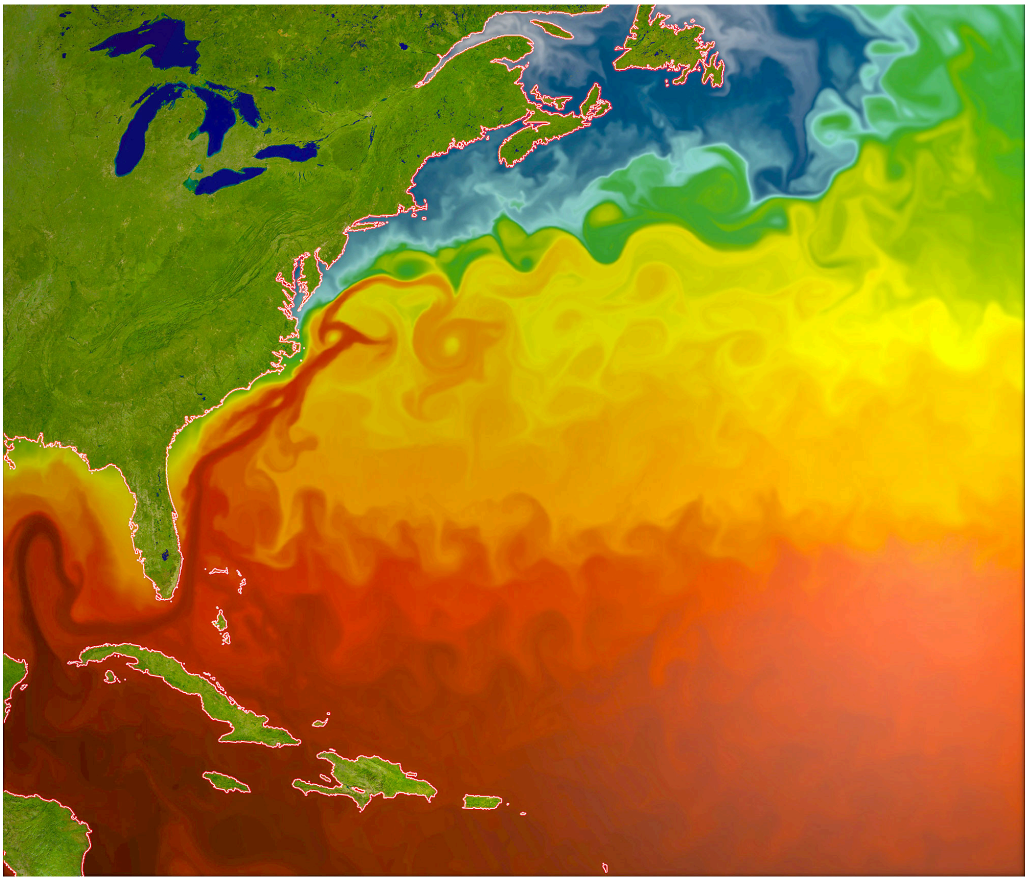
ARTICLE ABSTRACT

The Atlantic Meridional Overturning Circulation has a major impact on climate, not just in the northern Atlantic but globally. Paleoclimatic data show it has been unstable in the past, leading to some of the most dramatic and abrupt climate shifts known. These instabilities are due to two different types of tipping points, one linked to amplifying feedbacks in the large-scale salt transport and the other in the convective mixing that drives the flow. These tipping points present a major risk of abrupt ocean circulation and climate shifts as we push our planet further out of the stable Holocene climate into uncharted waters.



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Sea surface temperatures from a simulation with the CM2.6 global climate model of the Geophysical Fluid Dynamics Lab in Princeton, USA. Warm Gulf Stream waters are seen in red. > High res figure (https://tos.org/oceanography/assets/images/content/37-rahmstorf-title.jpg)

FULL TEXT

INTRODUCTION

In 1751, the captain of an English slave-trading ship made a historic discovery. While sailing at 25°N in the subtropical North Atlantic Ocean, Captain Henry Ellis lowered a "bucket sea-gauge," devised and provided to him by the British clergyman Reverend Stephen Hales, through the warm surface waters into the deep. By means of a long rope and a system of valves, water from various depths could be brought up to the deck where its temperature was read from a built-in thermometer. To his surprise, Captain Ellis found that the deep water was icy cold.

He reported his findings to Reverend Hales in a letter: "The cold increased regularly, in proportion to the depths, till it descended to 3900 feet: from whence the mercury in the thermometer came up at 53 degrees (Fahrenheit); and tho' I afterwards sunk it to the depth of 5346 feet, that is a mile and 66 feet, it came up no lower."

These were the first ever recorded temperature measurements of the deep ocean. They revealed what is now known to be a fundamental and striking physical feature of the world ocean: deep water is always cold. The warm waters of the tropics and subtropics are confined to a thin layer at the surface; the heat of the sun does not slowly warm the depths during centuries or millennia as might be expected.

Η επιστολή του Έλις προς τον Χέιλς υποδηλώνει ότι δεν είχε καμία ιδέα για τη μεγάλη σημασία της ανακάλυψής του. Έγραψε: «Αυτό το πείραμα, που στην αρχή φαινόταν απλώς τροφή για περιέργεια, έγινε στο ενδιάμεσο πολύ χρήσιμο για εμάς. Με τα μέσα του παρέχαμε το κρύο μπάνιο μας και ψύχαμε τα κρασιά ή το νερό μας με ευχαρίστηση. που είναι πολύ ευχάριστο σε εμάς σε αυτό το φλεγόμενο κλίμα» (Ellis, 1751).

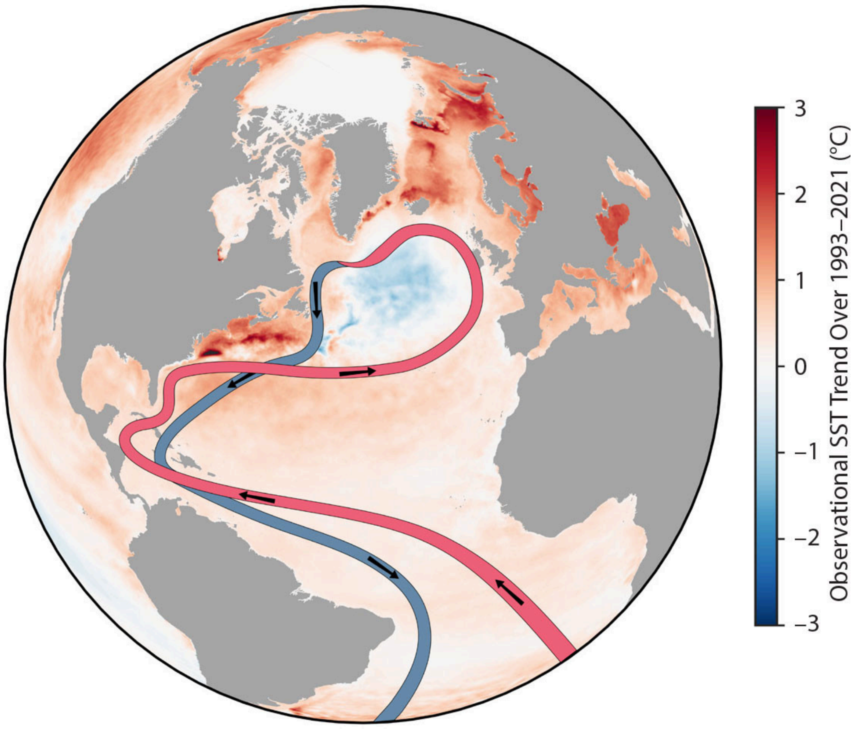
Στην πραγματικότητα, ο Έλις είχε χτυπήσει την πρώτη ένδειξη της ανατροπής της κυκλοφορίας του ωκεανού, το σύστημα των βαθιών ωκεάνιων ρευμάτων που κυκλοφορεί κρύα νερά πολικής προέλευσης σε όλο τον πλανήτη.

Αλλά μόλις μερικές δεκαετίες αργότερα, το 1797, ένας άλλος Άγγλος, ο Κόμης Ράμφορντ, δημοσίευσε μια σωστή εξήγηση για τη «χρήσιμη» ανακάλυψη του Έλις: «Φαίνεται ότι είναι εξαιρετικά δύσκολο, αν όχι εντελώς αδύνατο, να εξηγηθεί αυτός ο βαθμός ψύχους. στον πυθμένα της θάλασσας στη λυσσαλέα ζώνη, με οποιαδήποτε άλλη υπόθεση εκτός από αυτή των ψυχρών ρευμάτων από τους πόλους· και η χρησιμότητα αυτών των ρευμάτων για τον μετριασμό των υπερβολικών θερμοκρασιών αυτών των κλιμάτων είναι πολύ προφανής για να απαιτηθεί οποιαδήποτε απεικόνιση» (Thompson, 1797).

Τώρα, πάνω από 200 χρόνια αργότερα, έχουμε μια λογική κατανόηση του πολύπλοκου συστήματος της βαθιάς ωκεάνιας κυκλοφορίας και, αυτό που ο Rumford βρήκε τόσο προφανές, του ρόλου που παίζει στο κλίμα. Ωστόσο, παραμένουν κάποιοι σημαντικοί γρίφοι που μπορεί να έχουν θεμελιώδη σημασία για το μέλλον μας.

ΠΕΝΉΝΤΑ ΦΟΡΈΣ Η ΑΝΘΡΏΠΙΝΗ ΧΡΉΣΗ ΕΝΈΡΓΕΙΑΣ

Σε αυτό το άρθρο, θα συζητήσω τον κλάδο του Ατλαντικού της παγκόσμιας ανατροπής κυκλοφορίας, έναν σημαντικό παράγοντα στην προηγούμενη και πολύ πιθανή μελλοντική αλλαγή του κλίματος. Ονομάζεται AMOC (συντομογραφία του Atlantic Meridional Overturning Circulation). Η βόρεια ροή θερμών επιφανειακών υδάτων και η βαθιά κρύα ροή επιστροφής κάνει τον Νότιο Ατλαντικό μια περιέργεια: μεταφέρει θερμότητα από τα νότια μεγάλα γεωγραφικά πλάτη προς τον ισημερινό, από το κρύο στο ζεστό (**Εικόνα 1**). Όλες οι άλλες λεκάνες των ωκεανών συμπεριφέρονται «κανονικά», απομακρύνοντας την υπερβολική θερμότητα από τις τροπικές περιοχές που είναι εμποτισμένες από τον ήλιο.



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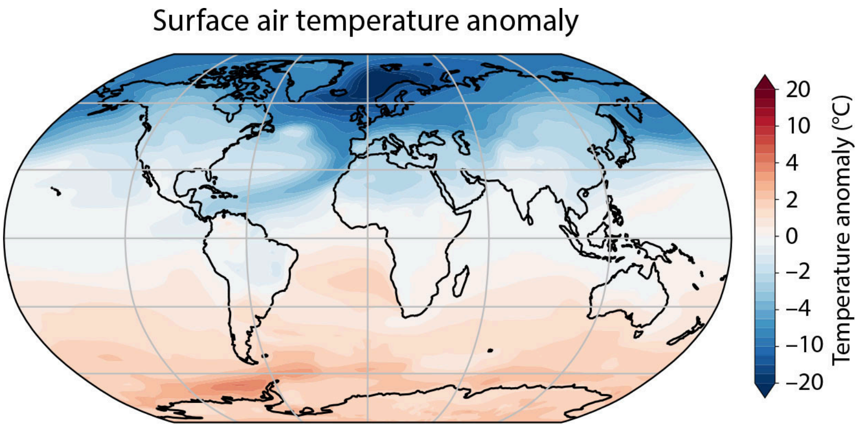
ΣΧΗΜΑ 1. Αυτό το γράφημα δείχνει μια εξαιρετικά απλοποιημένη σχηματική παράσταση της Μεσημβρινής Ανατροπής του Ατλαντικού (AMOC) με φόντο την τάση της θερμοκρασίας της επιφάνειας της θάλασσας από το 1993 από την Υπηρεσία Κλιματικής Αλλαγής Copernicus (https://climate.copernicus.eu/ (https://climate.copernicus.eu/)). *Πίστωση εικόνας: Ruijian Gou.* > Φιγούρα υψηλής ανάλυσης (https://tos.org/oceanography/assets/images/content/37-rahmstorf-f1.jpg)

Στον Βόρειο Ατλαντικό, η ανατρεπόμενη κυκλοφορία μετακινεί τη θερμότητα με ρυθμό ένα πετάβατ (10^{15} Watt, Trenberth et al., 2019), περίπου 50 φορές τη χρήση ενέργειας από όλη την ανθρωπότητα ή 3,5 φορές τον ρυθμό της παγκόσμιας πρόσληψης θερμότητας από τους ωκεανούς τις τελευταίες δεκαετίες λόγω της υπερθέρμανσης του πλανήτη που προκαλείται από τον άνθρωπο (Z. Li et al., 2023). Παρέχει θερμότητα μέχρι την περιοχή νότια της Γροιλανδίας και της Ισλανδίας, και μερικές ακόμη πιο βόρεια μετά την Ισλανδία στις Σκανδιναβικές Θάλασσες. Εκεί, δίνει γενναιόδωρα τη θερμότητά του στους ψυχρούς ανέμους από πάνω μέχρι το νερό να είναι τόσο κρύο και πυκνό που βυθίζεται στην άβυσσο, σε βάθος μεταξύ 2.000 και 3.000 μέτρων. Εκεί «ρέει ως μεγάλος ποταμός, σε όλο το μήκος του Ατλαντικού» (Broecker, 1987). Η θερμότητα που απελευθερώνεται στην ατμόσφαιρα κάνει την περιοχή του Βόρειου Ατλαντικού πολύ ζεστή για το γεωγραφικό της πλάτος, ιδιαίτερα κατά τον άνεμο του ωκεανού (**Εικόνα 2**). Είναι επίσης ο κύριος λόγος για τον οποίο το βόρειο ημισφαίριο είναι κατά μέσο όρο ~1,4°C θερμότερο από το νότιο ημισφαίριο και γιατί ο θερμικός ισημερινός, το γεωγραφικό πλάτος όπου η Γη είναι η θερμότερη, βρίσκεται σε ~10° βόρεια του γεωγραφικού ισημερινού (Feulner et al., 2013).



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ΕΙΚΟΝΑ 2. «Το κλιματικό σύστημα της Γης λειτουργεί επί του παρόντος με τρόπο ευεργετικό για τη βόρεια Ευρώπη», έγραψε ο αείμνηστος Wally Broecker (Broecker, 1987). Αυτός ο χάρτης δείχνει πώς θα ήταν ο κόσμος χωρίς το AMOC. Σχεδόν ολόκληρο το βόρειο ημισφαίριο θα ήταν πιο κρύο, ειδικά η Ισλανδία, η Σκανδιναβία και η Βρετανία. *Εικόνα του R. van Westen, προσαρμοσμένο από τους van Westen et al. (2024).* > Φιγούρα υψηλής ανάλυσης (https://tos.org/oceanography/assets/images/content/37-rahmstorf-f2.jpg)

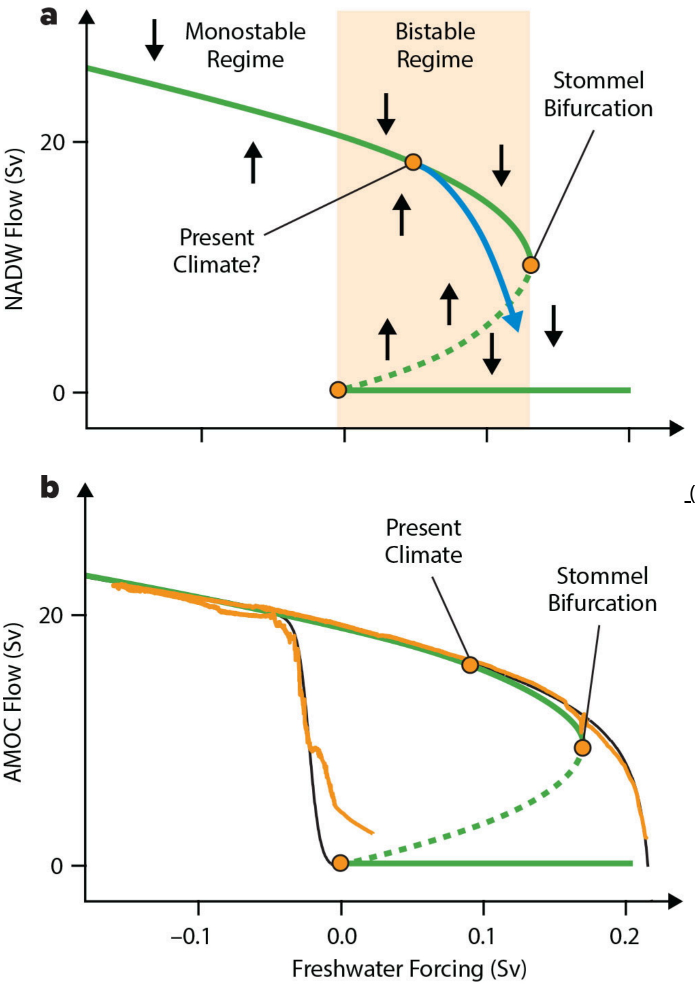
Η θερμοκρασία δεν είναι το μόνο βασικό συστατικό του AMOC — ο δεύτερος παράγοντας είναι η αλατότητα: όσο πιο αλμυρό είναι το νερό, τόσο πιο πυκνό είναι. Η αλατότητα είναι επομένως ένας σημαντικός παράγοντας για τη βύθιση που περιγράφηκε παραπάνω. Ως εκ τούτου, αυτή η ανατρεπόμενη κυκλοφορία ονομάζεται επίσης *θερμοαλονική* κυκλοφορία, που σημαίνει μια κυκλοφορία που καθοδηγείται από διαφορές θερμοκρασίας και αλατότητας, σε αντίθεση με την κυκλοφορία που οδηγείται από άνεμο και παλιρροιακά ρεύματα. Ενώ η θερμοκρασία έχει σταθεροποιητική επίδραση στο AMOC, η αλατότητα έχει τη δύναμη να το αποσταθεροποιήσει.

ΜΙΑ ΙΣΤΟΡΊΑ ΔΎΟ ΑΣΤΆΘΕΙΑΣ

Το 1961, ο αμερικανός ωκεανογράφος Henry Stommel (Stommel, 1961) αναγνώρισε πώς η αλατότητα των νερών του Ατλαντικού οδηγεί σε ένα οριακό σημείο του AMOC, ένα φαινόμενο που έγινε πρωτοσέλιδο εφημερίδων για άλλη μια φορά πέρυσι και φέτος. Το νερό βυθίζεται στον βόρειο Ατλαντικό επειδή είναι αρκετά αλμυρό (σε αντίθεση με τον Βόρειο Ειρηνικό, Warren, 1983). Το νερό είναι αλμυρό επειδή το AMOC φέρνει αλμυρό νερό από τις υποτροπικές περιοχές, μια περιοχή καθαρής εξάτμισης, στα υψηλότερα γεωγραφικά πλάτη, μια περιοχή καθαρής βροχόπτωσης. Με άλλα λόγια, το AMOC ρέει επειδή ο βόρειος Ατλαντικός είναι αλμυρός, και είναι αλμυρός επειδή ρέει το AMOC. Κοτόπουλο και αυγό, ή με πιο τεχνικούς όρους, ένα αυτοσυντηρούμενο αποτέλεσμα ανατροφοδότησης.

Αυτό λειτουργεί και αντίστροφα: Εάν ο βόρειος Ατλαντικός γίνει λιγότερο αλμυρός λόγω εισροής γλυκού νερού (βροχής ή λιωμένου νερού), το νερό γίνεται λιγότερο πυκνό και το AMOC επιβραδύνεται. Έτσι, φέρνει λιγότερο αλάτι στην περιοχή, γεγονός που επιβραδύνει περαιτέρω το AMOC. Αυτή η διαδικασία ονομάζεται ανάδραση μεταφοράς αλατιού. Πέρα από ένα κρίσιμο όριο, γίνεται ένας αυτοενισχυόμενος φαύλος κύκλος και το AMOC σταματάει. Αυτό το όριο είναι το σημείο καμπής του AMOC (που ονομάζεται Διχασμός Stommel στο **Σχήμα 3**). Όπως έγραψε ο Stommel το 1961: «Το σύστημα είναι εγγενώς γεμάτο με πιθανότητες για εικασίες σχετικά με την κλιματική αλλαγή».

Το μοντέλο του Stommel απλώς αποτελούνταν από ένα κιβώτιο υψηλού γεωγραφικού πλάτους και ένα υποτροπικό κουτί που συνδέονταν με μια ροή ανατροπής ανάλογη με τη διαφορά πυκνότητας μεταξύ τους. Το μοντέλο προέβλεψε αυτή τη ροή και τη θερμοκρασία, την αλατότητα και την πυκνότητα και στα δύο κουτιά. **Το Σχήμα 3** δείχνει την ισχύ ισορροπίας AMOC όπως υπολογίζεται από το μοντέλο κουτιού του Stommel και το σημείο καμπής που βρήκε.



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ΣΧΗΜΑ 3. (α) Διάγραμμα σταθερότητας του AMOC στο μοντέλο κουτιού του Stommel, καθώς εξαρτάται από την ποσότητα γλυκού νερού που εισέρχεται στον βόρειο Ατλαντικό. Οι συμπαγείς πράσινες γραμμές δείχνουν σταθερές καταστάσεις ισορροπίας, η διακεκομμένη πράσινη γραμμή μια ασταθή. Η μπλε καμπύλη δείχνει μια διαδρομή που φεύγει από τις γραμμές ισορροπίας κατά τη διάρκεια ταχείας κλιματικής αλλαγής. *Μετά τον Rahmstorf (2002)* (β) Εδώ, η πορτοκαλί γραμμή ανιχνεύει τις ισορροπίες AMOC σε ένα τρισδιάστατο μοντέλο παγκόσμιας ωκεάνιας κυκλοφορίας. Η μαύρη γραμμή είναι το ίδιο πείραμα ανίχνευσης που έγινε με το μοντέλο κουτιού. Οι επάνω πορτοκαλί και οι μαύρες γραμμές εντοπίζονται από αριστερά προς τα δεξιά ξεκινώντας από το AMOC "on", το κάτω από τα δεξιά προς τα αριστερά ξεκινώντας από το AMOC "off". *Μετά τον Rahmstorf (1996).* > Φιγούρα υψηλής ανάλυσης (https://tos.org/oceanography/assets/images/content/37-rahmstorf-f3.jpg)

Για μοντέλα κουτιών όπως αυτό του Stommel, οι καμπύλες ισορροπίας μπορούν να υπολογιστούν αναλυτικά - η λύση για την πράσινη καμπύλη είναι απλώς μια παραβολή. Για τον εντοπισμό των καταστάσεων ισορροπίας ενός πολύπλοκου μοντέλου, προστίθεται γλυκό νερό στον βόρειο Ατλαντικό με πολύ αργά αυξανόμενο ρυθμό (π.χ. αυξάνεται κατά 0,1 Sv σε 2.000 χρόνια, 1 Sv = 10^{6} m^{3} s^{-1}) για να παραμείνει κοντά στην ισορροπία και να δούμε πού αρχίζουν να κυριαρχούν οι εσωτερικές ανατροφοδοτήσεις στην αποδυνάμωση, η οποία συμβαίνει πέρα από το σημείο καμπής. Μια ολλανδική ερευνητική ομάδα στην Ουτρέχτη ανέπτυξε μεθόδους για τον άμεσο υπολογισμό των καταστάσεων ισορροπίας σε τρισδιάστατα μοντέλα ωκεανών (Dijkstra et al., 1995), αλλά δεν λειτουργούν σε πολύπλοκα συνδυασμένα μοντέλα ωκεανού-ατμόσφαιρας, επομένως η προσέγγιση εντοπισμού της αργής προσθήκης γλυκού νερού πρέπει να εφαρμοστεί.

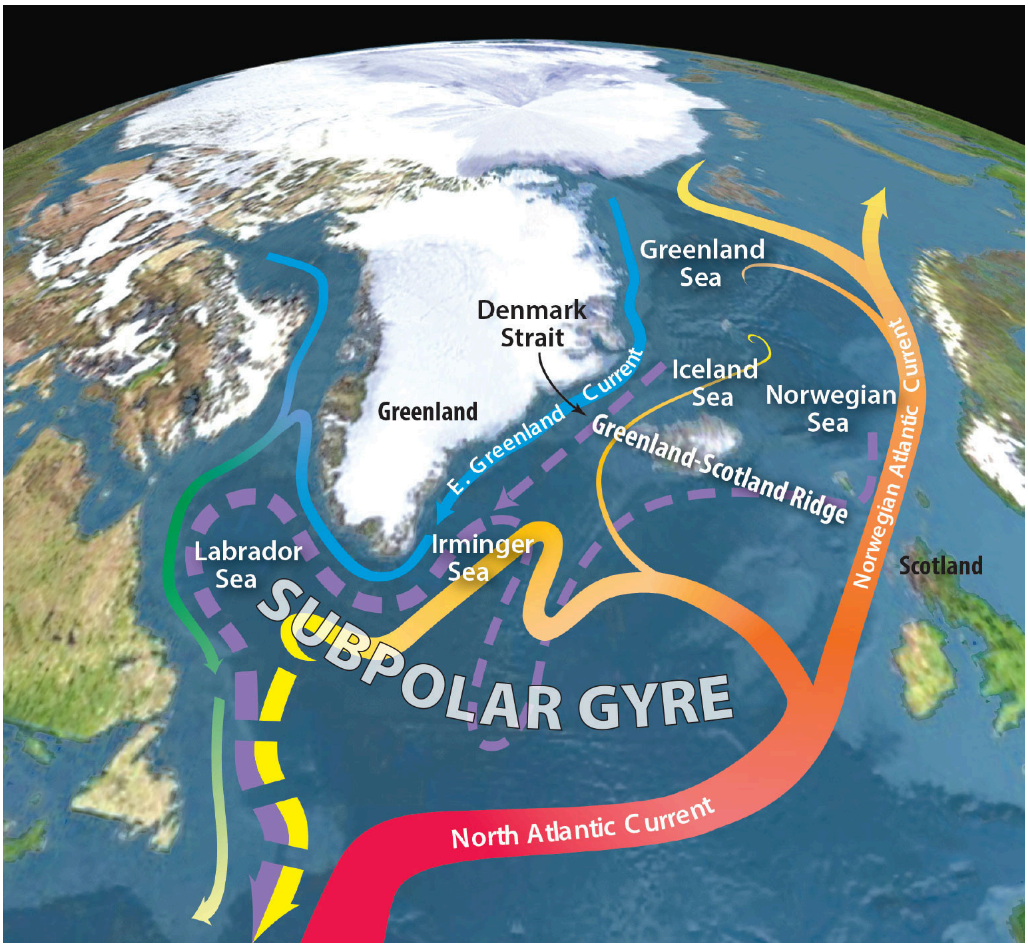
Στο μονοσταθερό καθεστώς (στα αριστερά του μηδενικού εξαναγκασμού γλυκού νερού στο **Σχήμα 3**), η διακοπή λειτουργίας του AMOC μπορεί ακόμα να εξαναγκαστεί με μια μεγάλη προσωρινή προσθήκη γλυκού νερού, αλλά το AMOC θα ανακάμψει μετά την ολοκλήρωση της επιβολής. Στο δισταθερό καθεστώς, το σύστημα μπορεί να βρίσκεται μόνιμα σε οποιαδήποτε από τις δύο σταθερές καταστάσεις, με το AMOC «ενεργό» ή «απενεργοποιημένο», ανάλογα με τις αρχικές συνθήκες. Έτσι, η ροή AMOC που τερματίζεται με προσωρινό εξαναγκασμό δεν θα ανακάμψει αλλά θα παραμείνει σε σταθερή κατάσταση "off". Πειράματα με μια τέτοια προσωρινή προσθήκη γλυκού νερού δείχνουν ότι πολλά, αν όχι τα περισσότερα, κλιματικά μοντέλα βρίσκονται στο μονοσταθερό καθεστώς και επομένως συγκριτικά μακριά από το σημείο καμπής. Αυτό δεν σημαίνει ότι δεν έχουν αυτό το οριακό σημείο ή ότι δεν έχουν ένα δισταθερό καθεστώς. δείχνει απλώς ότι δεν είναι σε αυτό για το σημερινό τους κλίμα (πιθανώς λανθασμένα, δείτε την ενότητα «Μπορούν να αξιοποιηθούν τα κλιματικά μοντέλα» παρακάτω).

Η κλιματική αλλαγή μπορεί να απομακρύνει το AMOC από τη γραμμή ισορροπίας, ακολουθώντας κάτι σαν το μπλε μονοπάτι στο **Σχήμα 3α** , επειδή η σύγχρονη υπερθέρμανση του πλανήτη προχωρά πολύ γρήγορα για να προσαρμοστεί πλήρως ο ωκεανός. Αφού διασχίσει τη διακεκομμένη γραμμή, το AMOC θα έλκεται προς την κατάσταση «off» ακόμη και χωρίς περαιτέρω ώθηση. Σημειώστε ότι το AMOC είναι όλο και πιο ευάλωτο σε πιο ταχεία εξαναγκασμό (Stocker and Schmittner, 1997). Αυτό σημαίνει ότι τα πολύ αργά πειράματα ανίχνευσης ισορροπίας που φαίνονται στο **Σχήμα 3β** υποδηλώνουν πόσο κοντά είναι το σημείο καμπής του AMOC σε μια κατάσταση ταχείας κλιματικής αλλαγής, όπως βρισκόμαστε σήμερα.

Το ότι αυτό το σημείο καμπής και το δισταθές καθεστώς είναι πραγματικό, και όχι απλώς ένα τεχνούργημα του απλού μοντέλου του Stommel, έχει επιβεβαιωθεί σε πολλά μοντέλα από ολόκληρο το φάσμα μοντέλων από την εργασία του Stommel το 1961, συμπεριλαμβανομένων εξελιγμένων τρισδιάστατων μοντέλων ωκεάνιας κυκλοφορίας, μέσης πολυπλοκότητας Γη μοντέλα συστημάτων και πλήρως ανεπτυγμένα συνδεδεμένα κλιματικά μοντέλα, για παράδειγμα, το Κοινοτικό Μοντέλο Συστήματος Γης (CESM) (van Westen et al., 2024). Μια πρώιμη σύγκριση μοντέλων βρήκε το δισταθερό καθεστώς και στα 11 συμμετέχοντα μοντέλα (Rahmstorf et al., 2005) και δεν γνωρίζω κανένα μοντέλο που έχει δοκιμαστεί και δεν είχε αυτήν την ιδιότητα. Αν και αυτό το είδος πειράματος δεν μπορεί να εκτελεστεί με μοντέλα που προσομοιώνουν ρητά τις δίνες μέσης κλίμακας στον ωκεανό, δεν αναμένω ότι αυτό θα έκανε σημαντική διαφορά, δεδομένου ότι η σχετική ανάδραση μεταφοράς αλατιού λειτουργεί σε πολύ μεγάλη κλίμακα.

Ένας δεύτερος τύπος σημείου ανατροπής μπορεί επίσης να επηρεάσει το AMOC. Ένα σημαντικό μέρος της διαδικασίας βύθισης στον βόρειο Ατλαντικό (που ονομάζεται «σχηματισμός βαθέων υδάτων») είναι η βαθιά κάθετη ανάμειξη (συναγωγή) όταν η στήλη του νερού γίνεται κατακόρυφα ασταθής, λόγω του πυκνότερου νερού που βρίσκεται πάνω από λιγότερο πυκνό νερό. Ο Σουηδός ωκεανογράφος Pierre Welander έδειξε το 1982 ότι η μεταφορά, επίσης, μπορούσε να απενεργοποιηθεί σαν διακόπτης, και πάλι λόγω της αποσταθεροποιητικής επίδρασης της αλατότητας (Welander, 1982). Σε περιοχές μεγάλου γεωγραφικού πλάτους, ο ωκεανός συνήθως κερδίζει γλυκό νερό από τη βροχή στην επιφάνεια, οπότε μόλις σταματήσει η μεταφορά για αρκετό καιρό, το γλυκό νερό μπορεί να συσσωρευτεί και να σχηματίσει ένα επιφανειακό στρώμα χαμηλής πυκνότητας. Αυτό καθιστά ολοένα και πιο δύσκολη την επανεκκίνηση της μεταφοράς και κάποια στιγμή απενεργοποιείται οριστικά. Σε μεταγενέστερη εργασία, δείξαμε πώς λειτουργεί αυτό ακόμη και αν η μεταφορά είναι διακοπτόμενη παρουσία τυχαίας μεταβλητότητας καιρού (Kuhlbrodt et al., 2001; Rahmstorf, 2001).

Υπάρχουν δύο κύριες περιοχές μεταφοράς εντός του σημερινού AMOC: μία στην υποπολική περιοχή του βόρειου Ατλαντικού (συμπεριλαμβανομένων των θαλασσών Λαμπραντόρ και Ιρμίνγκερ) και μία βορειότερα στις Σκανδιναβικές Θάλασσες. Σε πολλά πειράματα μοντέλων, η μεταφορά της Θάλασσας του Λαμπραντόρ ήταν επιρρεπής στο κλείσιμο (Weijer et al., 2019), επιβραδύνοντας όχι μόνο το AMOC αλλά και την υποπολική γύρο, μια τεράστια αριστερόστροφη περιστρεφόμενη ροή νότια της Γροιλανδίας και της Ισλανδίας (**Εικόνα 4**). Μόλις η μεταφορά (η οποία συνήθως εξάγει θερμότητα από τη στήλη του νερού αναμιγνύοντας θερμότερο νερό στην επιφάνεια, όπου η θερμότητα χάνεται στην ατμόσφαιρα) έχει περιοριστεί με αυτόν τον τρόπο, λιγότερη θερμότητα χάνεται μέσω της επιφάνειας της θάλασσας και ολόκληρη η στήλη του νερού παίρνει λιγότερο πυκνό. Αυτό επιβραδύνει το AMOC, το οποίο τελικά οδηγείται από τα κρύα, υψηλής πυκνότητας νερά που σπρώχνουν νότια από τα μεγάλα γεωγραφικά πλάτη. Έτσι, μια διακοπή λειτουργίας μεταφοράς μπορεί να βοηθήσει στην ενεργοποίηση ενός τερματισμού λειτουργίας AMOC. Και επειδή η μεταφορά είναι μια διαδικασία μικρής κλίμακας, δεν αποτυπώνεται καλά στα περισσότερα τρέχοντα μοντέλα (Jackson et al., 2023), προσθέτοντας ένα στρώμα αβεβαιότητας για το μέλλον.



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ΣΧΗΜΑ 4. Οι τρέχουσες επιφανειακές ροές (συμπαγείς γραμμές) και οι βαθιές ροές (διακεκομμένες γραμμές) παρουσιάζονται για τον βόρειο Ατλαντικό και τις Σκανδιναβικές Θάλασσες. *Το σχήμα τροποποιήθηκε από τους R. Curry και C. Mauritzen © Woods Hole Oceanographic Institution.* > Φιγούρα υψηλής ανάλυσης (https://tos.org/oceanography/assets/images/content/37-rahmstorf-f4.jpg)

ΔΡΑΣΤΙΚΈΣ ΑΛΛΑΓΈΣ ΣΤΟ ΠΑΡΕΛΘΌΝ ΣΤΟ AMOC

Με βάση αυτή την κατανόηση των μηχανισμών αστάθειας του AMOC, μπορούμε να εξετάσουμε μερικές δραματικές κλιματικές αλλαγές που έχουν συμβεί στο πρόσφατο παρελθόν — «πρόσφατες», δηλαδή από μια παλαιοκλιματική προοπτική, συγκεκριμένα τα τελευταία 100.000 χρόνια.

In 1987, Wally Broecker published a now famous article in the journal *Nature* titled “Unpleasant surprises in the greenhouse?” (Broecker, 1987). In it, he discusses data from deep-sea sediment cores and holes drilled into the Greenland ice cap, noting that these data reveal that “climate changed frequently and in great leaps” rather than smoothly and gradually. Given the regional patterns of these changes, he identified the AMOC (at the time referred to as the “Atlantic conveyor belt”) as the culprit. He warned that by releasing greenhouse gases, “we play Russian roulette with climate [and] no one knows what lies in the active chamber of the gun.”

In the decades since then, we have come to distinguish two types of abrupt climate events that repeatedly occurred during the last Ice Age, centered around the northern Atlantic but with global repercussions (Rahmstorf, 2002).

The first type is Dansgaard-Oeschger (DO) events, named for Danish ice core researcher Willy Dansgaard and his Swiss colleague Hans Oeschger. More than 20 events prominently show as abrupt warming spikes of 10°–15°C within a decade or two in Greenland ice core data (Dansgaard et al., 1982). They can be explained as sudden start-ups of ocean convection in the Nordic Seas when Ice Age convection was mostly only occurring in the open Atlantic to the south of Iceland (**Figure 5**). The warm ocean circulation configuration that reached far north was apparently not stable under Ice Age conditions: it gradually weakened, until after some hundreds of years, the convection and warm event ended again. It is thus an example of a convective flip-flop as discussed above, with the Nordic Seas convection turning on and off.

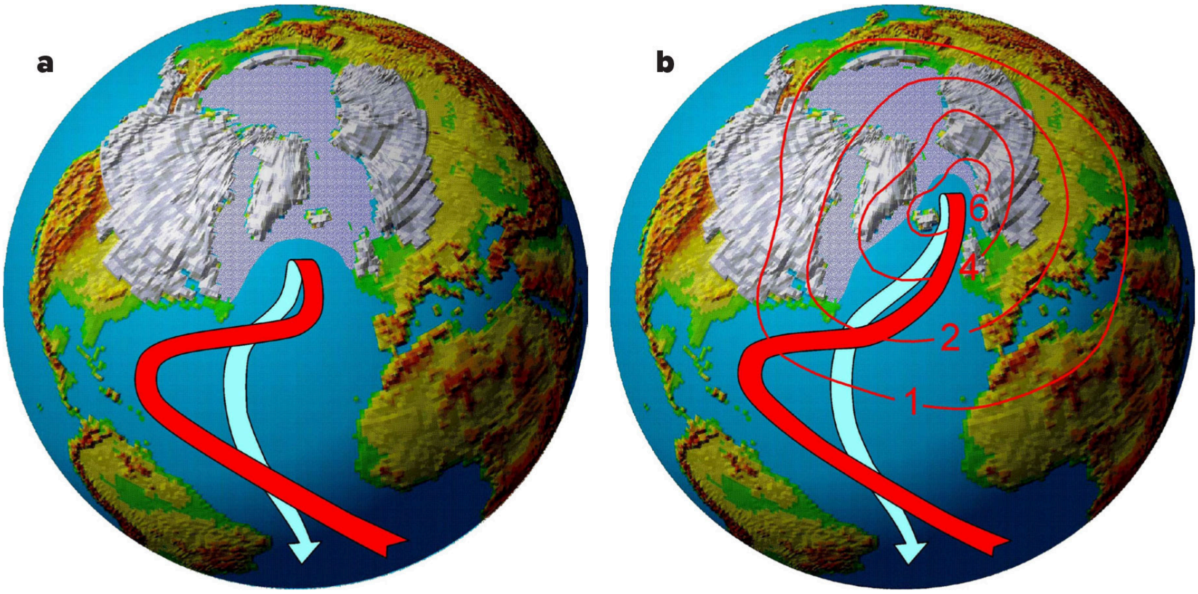

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FIGURE 5. The AMOC during the last Ice Age. (a) The prevalent cold (stadial) state. (b) The warmer (interstadial) state during Dansgaard-Oeschger events, showing the modeled temperature change from Ganopolski and Rahmstorf (2002). The very coarse resolution of that model underestimates the warming effect of Dansgaard-Oeschger events. > High res figure (https://tos.org/oceanography/assets/images/content/37-rahmstorf-f5.jpg)

The second type is Heinrich events, named for the German scientist Hartmut Heinrich (Heinrich, 1988). It involves huge masses of ice that episodically slid into the sea from the thousands of meters thick Laurentide Ice Sheet that covered northern America at that time. These iceberg armadas drifted out across the Atlantic, leaving behind telltale layers of ice-rafted debris on the ocean floor and adding fresh meltwater to the ocean surface. This led to even more dramatic climate changes, linked to a complete breakdown of the AMOC. So much ice entered the ocean that sea levels rose by several meters (Hemming, 2004). Evidence that this amount of freshwater entering the northern Atlantic shut down the AMOC is found in the fact that Antarctica warmed while the Northern Hemisphere cooled (Blunier et al., 1998), indicating that the AMOC's huge heat transport from the far south across the equator to the high north had essentially stopped.

Both the Dansgaard-Oeschger events and the Heinrich events, although strongest around the northern Atlantic, had major global climate repercussions even far from the Atlantic as they affected the tropical rainfall belts that result from the rising motion of warm air above the "thermal equator." During the warm Dansgaard-Oeschger events, these rainfall belts shifted north, leading to warm and humid conditions in the northern tropics as far as Asia. But during Heinrich events, the rainfall belts shifted south, leading to catastrophic drought in the Afro-Asian monsoon region (Stager, 2011). Could similar shifts in tropical rainfall belts be in store for us in future?

THE "COLD BLOB": AN OMINOUS SIGN OF A SLOWING AMOC?

Let us look how the AMOC is already responding to ongoing global warming, which has already pushed Earth's climate outside the envelope of the stable Holocene (Osman et al., 2021) in which *Homo sapiens* developed agriculture and started to build cities.

Unfortunately, AMOC data only go back a few decades, drawn from just a handful of cross-Atlantic cruises since the 1950s and the RAPID-AMOC array of stations that has collected continuous measurements of salinity and current velocities from the near surface to the seafloor across the Atlantic at 26°N since 2004 (Smeed et al., 2020). Therefore, we must turn to indirect evidence. Exhibit No. 1 is the "warming hole" or "cold blob" found on maps of observed global temperature change (**Figure 6**). While the entire globe has warmed, the subpolar North Atlantic has resisted and even cooled. This is exactly the region where the AMOC delivers much of its heat, and exactly the region where climate models have long predicted cooling as a result of the AMOC slowing down.

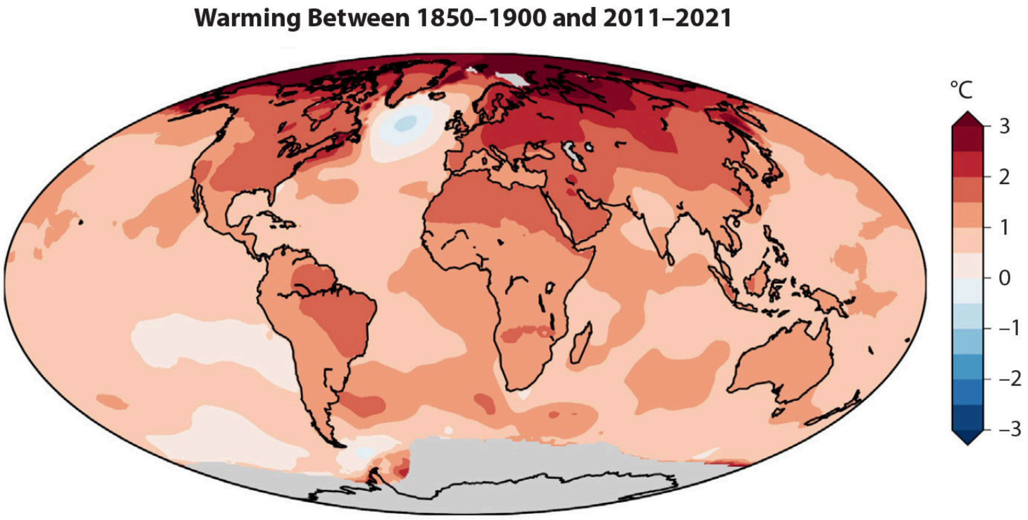

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FIGURE 6. Map of observed near-surface air temperature changes since the late nineteenth century. Gray areas indicate lack of data. *Image credit: Zeke Hausfather, Berkeley Earth.* > High res figure (https://tos.org/oceanography/assets/images/content/37-rahmstorf-f6.jpg)

A seminal study by Dima and Lohmann (2010) analyzed global patterns of sea surface temperature changes since the nineteenth century and concluded "that the global conveyor has been weakening since the late 1930s and that the North Atlantic overturning cell suffered an abrupt shift around 1970." Two years later, a Dutch group, analyzing an ensemble of model results, confirmed that an AMOC slowdown causes the northern Atlantic cooling and dubbed the feature the "warming hole" (Drijfhout et al., 2012). In 2015, I joined forces with US climate scientist Michael Mann and other colleagues in using Mann's paleoclimatic proxy reconstruction of surface temperatures to suggest that the modern AMOC slowdown is probably unique in at least the last millennium (Rahmstorf et al., 2015). The term "cold blob" originated in a quote from Mann in a *Washington Post* article on our study (Mooney, 2015), and it has since stuck.

Theoretically, the cold blob could have also arisen from an increase in net heat loss at the ocean surface (He et al., 2022). For short-term variability from year to year, weather conditions are expected to play a dominant role in changing the sea surface temperature—particularly in summer when the surface mixed layer is thin and its thermal inertia is small (thus, in later studies, we focus on the period November–May). The observations-based reanalysis data show, however, that since the mid-twentieth century, net heat loss through the ocean surface in the cold blob region has *decreased*, not increased—exactly what would be expected when the ocean is bringing less heat into that region, so less is passed on to the atmosphere (**Figure 7**). Also, analysis of climate models, in which AMOC changes are known, shows that the AMOC strength correlates closely with the cold blob temperature change (Caesar et al., 2018). This result confirms that on longer timescales, the AMOC is the dominant factor, allowing the conclusion that the cold blob so far corresponds to about 15% weakening of the AMOC.

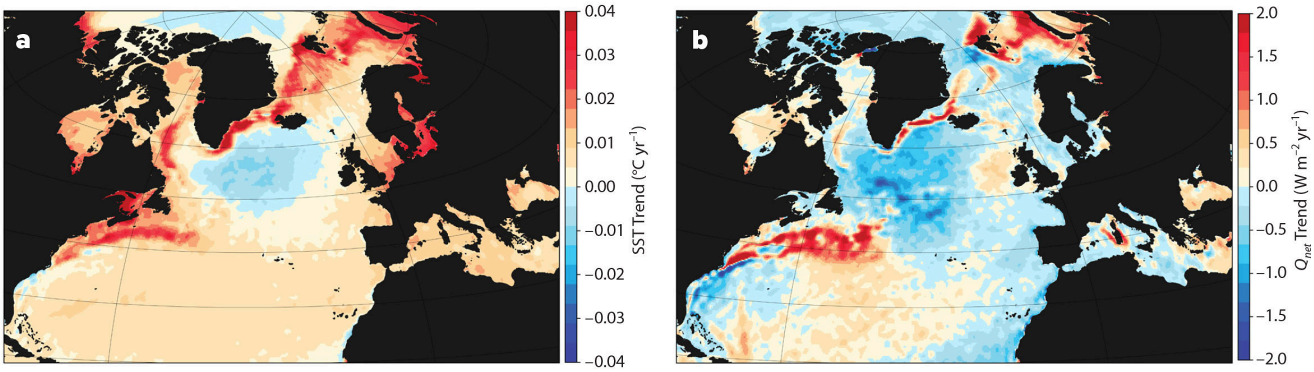

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FIGURE 7. The AMOC slowdown fingerprint in the observations-based reanalysis data from 1940 to 2022. (a) Sea surface temperature (SST) trends. (b) Trend of net heat loss from the ocean surface (sensible, latent, and radiative). The heat flux trends go in the opposite direction of being a cause of the SST trends. *From Jendrkowiak (2024).* > High res figure (https://tos.org/oceanography/assets/images/content/37-rahmstorf-f7.jpg)

The cold blob is not just a surface phenomenon; it is also clearly visible (**Figure 8**) in the trend of ocean heat content of the upper 2,000 m (Cheng et al., 2022).

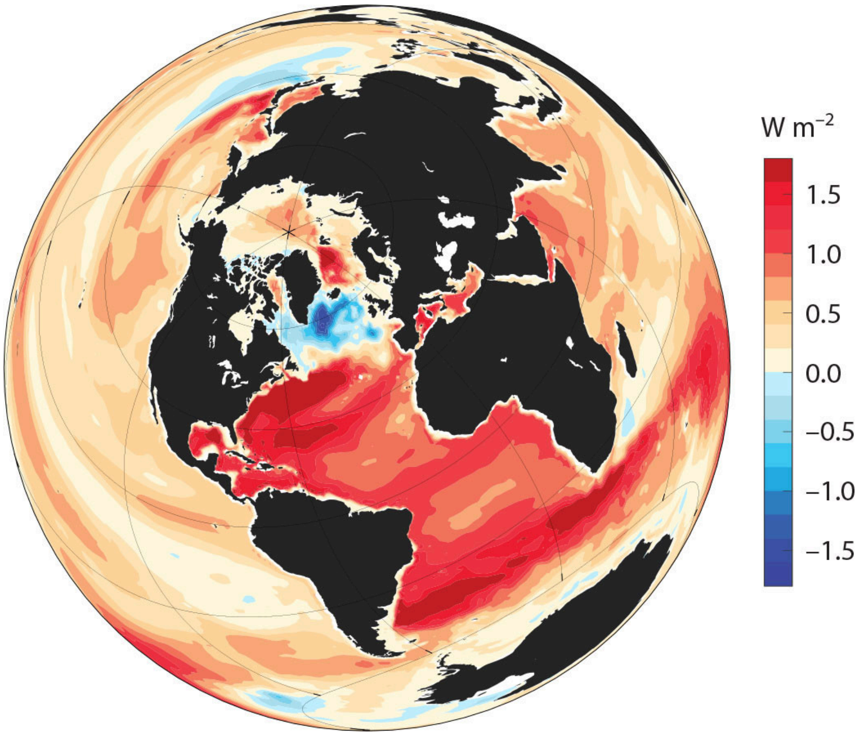

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FIGURE 8. Trend in ocean heat content of the upper 2,000 m, 1958–2023. IAP data. *Image credit: Lijing Cheng.* > High res figure (https://tos.org/oceanography/assets/images/content/37-rahmstorf-f8.jpg)

But apart from the cold blob, AMOC slowing has another telltale effect.

A SHIFTING GULF STREAM

Fluid dynamics on a rotating globe like Earth has some peculiar effects that are not intuitive. They result from the fact that the Coriolis force changes with latitude. In 2007 and 2008, two studies conducted by AMOC researcher Rong Zhang demonstrated how a basic law of physics, angular momentum conservation, acting at the point where the deep southward AMOC flow crosses under the Gulf Stream, makes the Stream shift closer to shore when the AMOC weakens (Zhang and Vallis, 2007; Zhang, 2008). Her studies describe a "fingerprint" of a weakening AMOC that not only includes the cold blob but also a sea surface temperature anomaly of opposite sign off the American Atlantic coast north of Cape Hatteras.

Caesar et al. (2018) compared this fingerprint to observed sea surface temperature changes since the late nineteenth century and found strong agreement (see **Figure 9**). The observational data are much less detailed because they rely on relatively sparse ship measurements, but more detail is in the satellite data. Although the time periods for the observed and the satellite data are different, the trends are divided by the global mean temperature change to make them roughly comparable in magnitude. Thus, for the relatively short satellite period there is much stronger random variability relative to the signal ("noise"), and the signal-to-noise ratio declines from top to bottom in the three images. Despite the differences in other variability, the fingerprint of AMOC decline is very clear in all three **Figure 9** plots.

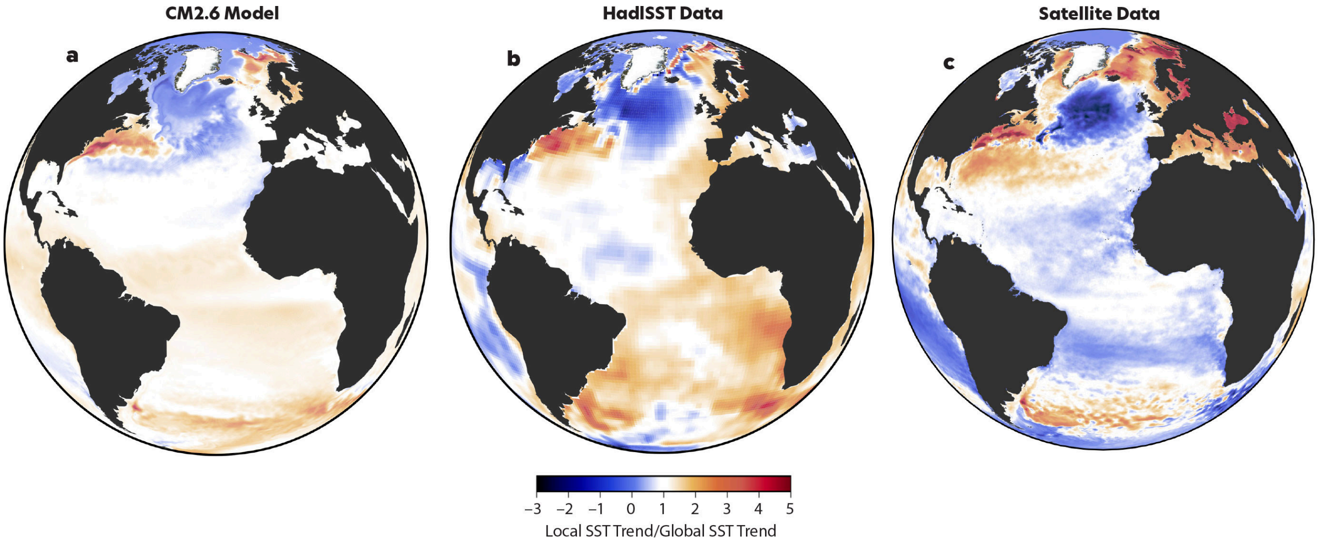

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FIGURE 9. In these maps of sea surface temperature (SST) trends divided by their global mean trend, white signifies the same trend as the global mean. (a) Result of a CO_2 doubling experiment with the CM2.6 climate model also shown on the title page of this article, (b) shows the observed trend over 1870–2016, and (c) plots data from the Copernicus satellite collected during 1993–2021. *(a) and (b) from Caesar et al. (2018). (c) Courtesy of Ruijian Gou*. > High res figure (https://tos.org/oceanography/assets/images/content/37-rahmstorf-f9.jpg)

As a side note, all three diagrams show a warming patch in the Arctic off Norway; in the model, this is due to increasing ocean heat transport from the Atlantic into the Arctic Ocean (Fiedler, 2020). This flow may be unrelated to the AMOC, or possibly anti-correlated to the AMOC and thus a third part of its fingerprint.

The strong warming off the North American Atlantic coast is again not caused by surface heat fluxes, as the reanalysis data show the surface heat flux has changed in the opposite direction, toward increasing heat loss (**Figure 7**). Also, the current generation of climate models (CMIP6) indicate a clear correlation of AMOC strength with this fingerprint pattern of sea surface temperatures, including both the cold blob and the warming part (Latif et al., 2022).

Furthermore, a recent study using the three-dimensional observational ocean data collected by Argo profiling floats (https://argo.ucsd.edu/ (https://argo.ucsd.edu/)) shows that the Gulf Stream has shifted about 10 km closer to shore since the beginning of this century (Todd and Ren, 2023). From the RAPID array we know that the AMOC has indeed weakened during this time span. In addition, there has been a "robust weakening of the Gulf Stream during the past four decades observed in the Florida Straits" (Piecuch and Beal, 2023), which, although not necessarily linked to an AMOC weakening, is at least consistent with it.

Additional evidence consistent with AMOC slowing also comes from salinity changes. The northeastern subpolar Atlantic is freshening (**Figure 10**), likely through a combination of increased freshwater input from rainfall and rivers as well as the melting of sea ice and the Greenland ice sheet, plus the effect of ocean circulation changes bringing less salty subtropical waters to the north. The Iceland Basin registers the lowest salinity in 120 years of measurements (Holliday et al., 2020).

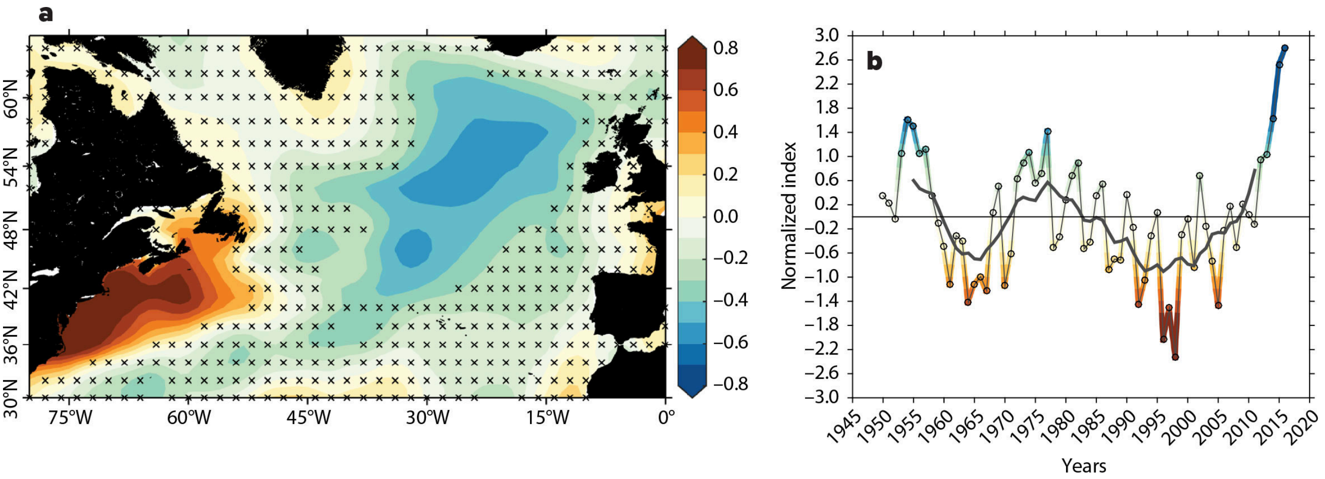

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FIGURE 10. The "fresh blob" in the northeastern North Atlantic, with a corresponding salty anomaly along the North American coast and the associated time evolution. Blue indicates anomalously low salinity and brown high salinity. Compare the sea surface temperature fingerprint in Figure 9. *Image credit: N. Penny Holliday, © National Oceanography Centre, 2020, CC-BY 4.0, https://creativecommons.org/licenses/by/4.0/* (https://creativecommons.org/licenses/by/4.0/). > High res figure (https://tos.org/oceanography/assets/images/content/37-rahmstorf-f10.jpg)

At the same time, salinity is increasing in the subtropical South Atlantic, which is considered an AMOC fingerprint less affected by short-term variations than the northern Atlantic temperature fingerprint; this suggests an acceleration of AMOC slowdown since the 1980s (Zhu et al., 2023).

Yet more evidence comes from analysis of seawater density in the upper 1,000 m in the subpolar gyre region, which correlates closely with the AMOC and shows a decline over the past 70 years. This decline implies an AMOC weakening of ~13% over this period (Chafik et al., 2022), consistent with the 15% weakening suggested by the cold blob data.

MORE LESSONS FROM PALEOCLIMATE

To understand conditions before regular temperature measurements began, we must turn to proxy data: the traces of past climate change left behind in slowly accumulating archives such as ice sheets or seafloor sediments. These proxies allow us to reconstruct past sea surface temperatures and other parameters. For example, the ratio of oxygen isotopes found in the microscopic skeletons that make up much of deep seafloor sediment provide a record of past surface water temperatures, and the sizes of sediment grains on the ocean floor reveal current speeds above it. Caesar et al. (2021) compiled a number of published reconstructions of past AMOC flow and concluded that the AMOC is currently at its weakest in the last millennium (**Figure 11**).

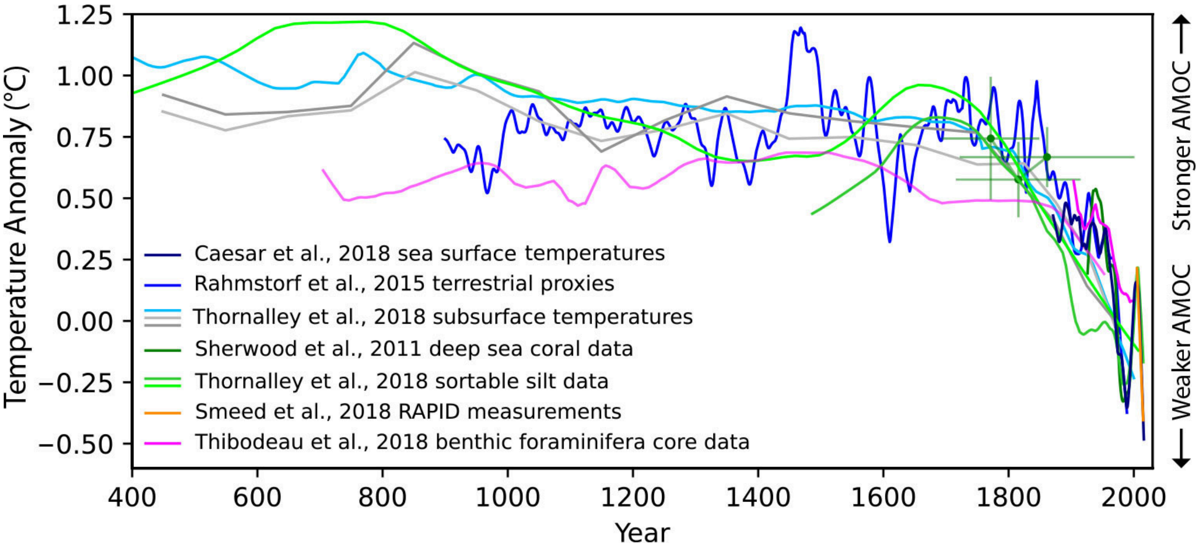

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FIGURE 11. AMOC strength for the past 1,600 years as reconstructed from different paleoclimatic data sets. *After Caesar et al. (2021)* The vertical axis shows the temperature anomaly in the "cold blob" region from Caesar et al. (2018); other data are scaled to that. > High res figure (https://tos.org/oceanography/assets/images/content/37-rahmstorf-f11.jpg)

Though the validity of proxy data can always be questioned, there is general agreement in data collected from different regions analyzed by different research teams using very different methods. For those proxy data series that extend to recent decades, the agreement between observation- and model-based AMOC reconstructions is good (Caesar et al., 2022).

Given the many independent lines of evidence, there is overwhelming evidence for a long-term weakening of the AMOC since the early or mid-twentieth century. Note that there is substantial decadal variability in the AMOC in addition to its long-term decline, which makes it essential to be clear about the exact time period when discussing AMOC changes.

Is the long-term AMOC weakening human-caused? Multiple lines of evidence point to its being a result of fossil-fuel-caused global warming. First, climate models have long predicted its decline in response to global warming, and the physics behind these predictions is understood. At least two studies analyzing state-of-the-art climate models and observations have shown "that the recent North Atlantic warming hole is of anthropogenic origin" and is caused by reduced northward oceanic heat transport related to greenhouse gas emissions (Chemke et al., 2020; Qasmi, 2023). In addition, the paleoclimatic data shown in **Figure 11** also strongly point to human activities as the cause, in that AMOC weakening coincides with the period of unprecedented modern global warming.

CAN CLIMATE MODELS BE TRUSTED?

Climate models have long predicted a significant AMOC slowdown in response to global warming, including a corresponding cold blob (see **Figure 12** for a recent version). In fact, I wrote two commentary pieces for *Nature* on that topic in the 1990s (Rahmstorf, 1997, 1999), and then as now, the amount of predicted weakening differed greatly among different models. The latest, sixth IPCC report found that, even for a low emissions scenario, the AMOC will weaken between 4% and 46% by the year 2100, depending on the model. In the high emissions scenario, the reduction ranges between 17% and 55% (IPCC, 2021). The IPCC report also concluded: "While there is medium confidence that the projected decline in the AMOC will not involve an abrupt collapse before 2100, such a collapse might be triggered by an unexpected meltwater influx from the Greenland Ice Sheet."

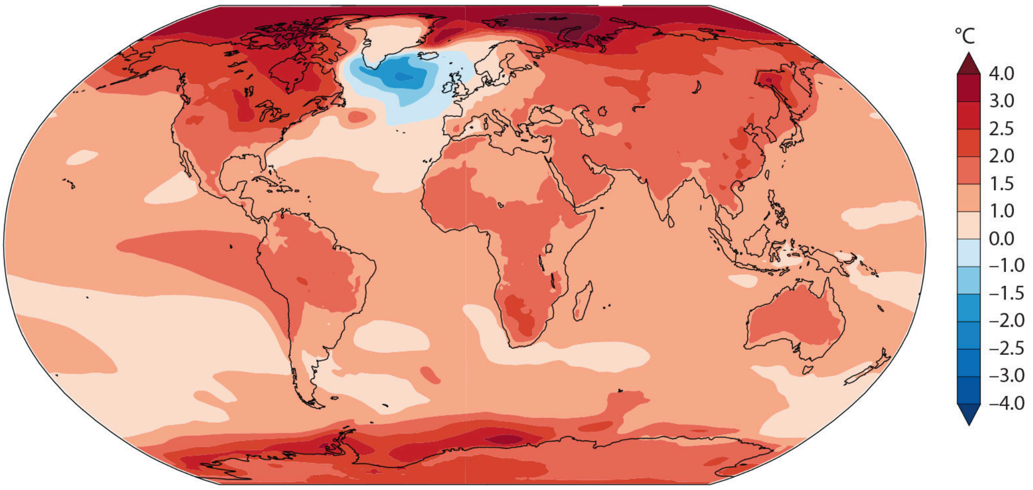

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FIGURE 12. This Intergovernmental Panel on Climate Change (IPCC) figure illustrates global temperature changes by the year 2100 for a low emissions scenario (SSP1-2.6) in high-warming models (IPCC, 2021, Figure 1 of Box TS.3). > High res figure (https://tos.org/oceanography/assets/images/content/37-rahmstorf-f12.jpg)

This brings us to an important question: Can we trust climate models on this? Generally, climate models have done a great job in predicting global mean temperatures. Even rather simple models from the 1980s predicted global warming quantitatively correctly—including the models run by Exxon (Supran et al., 2023). But that's relatively easy, as it just depends on Earth's energy balance.

Changes in thermohaline ocean circulation are far more difficult to predict, as they depend on subtle temperature and salinity differences across the ocean, in three dimensions. The models haven't done well at reproducing past AMOC changes (McCarthy and Caesar, 2023). The last IPCC report shows that current climate models on average don't even generate the observed cold blob (though many earlier models did; see **Figure 13**).

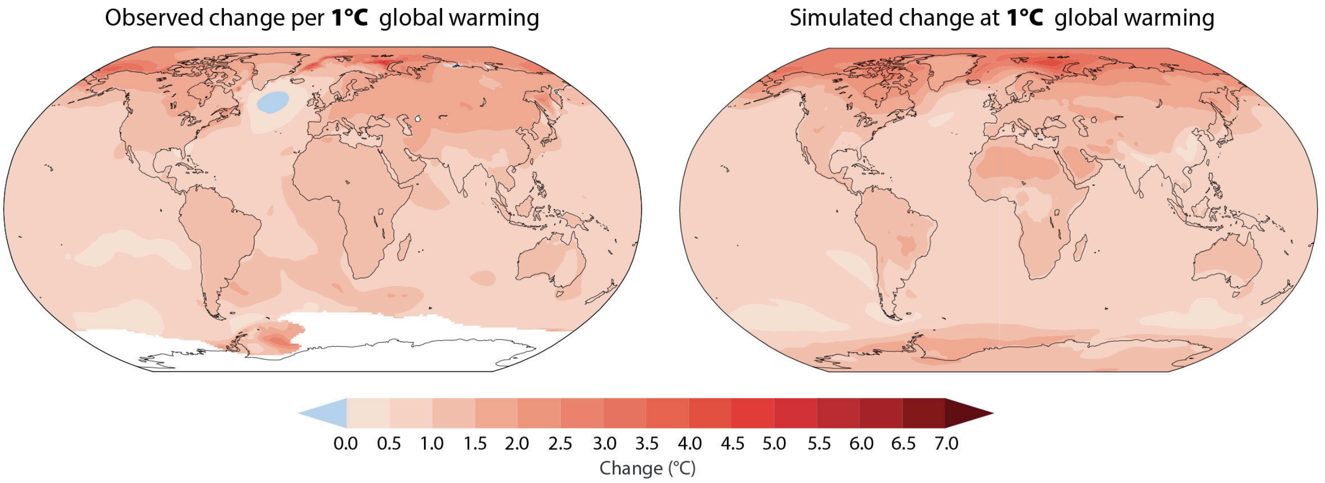

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FIGURE 13. Comparison of observed and simulated annual mean surface temperature change for 1°C global warming (IPCC, 2021, Figure SPM.5). The models on average do not reproduce the observed cold blob. > High res figure (https://tos.org/oceanography/assets/images/content/37-rahmstorf-f13.jpg)

There is in fact a substantial body of research suggesting that the AMOC is generally too stable in climate models. One reason might be what the IPCC has called "tuning towards stability." If a model has a too unstable AMOC that already collapses for the present climate, as has happened in a number of models (e.g., Manabe and Stouffer, 1988), the model will be "repaired" (i.e., improved to better reflect reality). But if the AMOC is too stable, that model will not look wrong because the present-day climate is correctly reproduced.

Another problem is even featured in the 2004 Hollywood blockbuster *The Day After Tomorrow*, where the scientist Jack Hall (Dennis Quaid) says: "No one has taken into account how much freshwater is being dumped into the ocean because of melting polar ice! I think we've hit a critical desalinization point." Until now, most climate models have not incorporated an interactive Greenland Ice Sheet (which has its own tipping point; e.g., Robinson et al., 2012) and neglect its growing meltwater input.

This "critical desalinization point" is, of course, Stommel's tipping point discussed earlier, and finding out how far we are from that point is a very hard problem indeed.

WHERE IS THAT TIPPING POINT?

One way to find the tipping point is to perform an experiment like the one shown in **Figure 3**. But this is very computationally expensive, and in models where it has been tried, the distance to the tipping point differs a lot. In 1996 I proposed that whether the AMOC transports freshwater out of or into the Atlantic at the latitude of South Africa determines whether it is in the bistable regime marked in **Figure 3**, or further away from the tipping point toward the left (Rahmstorf, 1996). Other studies have supported this idea, and observational data suggest the real AMOC is in the bistable regime, meaning relatively close to the critical point. In contrast, in most models, the AMOC is in the monostable regime, far away from the tipping point (see the review by Weijer et al., 2019). The reason is apparently subtle biases in the Atlantic salinity distribution in the models. This salinity distribution can be nudged toward more realistic, observed salinity values, rather than letting the salinity evolve freely under the influence of computed rainfall, evaporation, and ocean currents. When this was done in a climate model, the AMOC collapsed in a scenario of doubling CO_2 concentration, while it remained stable in the original unadjusted model (Liu et al., 2017).

Given the limitations of current climate models, some researchers have turned to methods borrowed from nonlinear physics to look for early warning signals of an approaching tipping point in observational data. These are based on the fact that in a "noisy" system like climate, such parameters as AMOC's strength randomly "wiggle around" a bit under the influence of stochastic (random) variations, such as the weather. But when the system is close to a tipping point, the forces that push it back to its stable equilibrium get progressively weaker—so the system takes longer to swing back. This is called "critical slowing down."

Several studies have analyzed AMOC data in that light. Boers (2021) analyzed four temperature and four salinity data series that have been linked to AMOC strength and concluded there is "strong evidence that the AMOC is indeed approaching a critical, bifurcation-induced transition." In another study, Michel et al. (2022) used 312 paleoclimatic proxy data series going back a millennium and found a "robust estimate, as it is based on sufficiently long observations, that the Atlantic multidecadal variability may now be approaching a tipping point after which the Atlantic current system might undergo a critical transition." In 2023, Danish researchers made news headlines with their "warning of a forthcoming collapse of the AMOC," starting any time between 2025 and 2095 and most likely around the middle of this century (Ditlevsen and Ditlevsen, 2023). A recent study by the Dutch group at Utrecht University—one of the world's leading research groups on AMOC stability—introduced a "new physics-based early warning signal [which] shows AMOC is on tipping course" (van Westen et al., 2024).

All of these predictions have their limitations—for example, changes in the variability might conceivably have other reasons than an approaching tipping point. But the fact that all these studies, using different methods, point in the same direction, toward a risk that is much larger and earlier than we had thought until a few years ago, is a major concern. My assessment of these early warning signal studies is that by the time they can provide a reasonably reliable warning of an impending AMOC tipping, it will be too late to prevent it. In this situation, the only responsible policy reaction is to be guided by the precautionary principle (i.e., the responsibility to protect the public from harm when scientific investigation has found a plausible risk).

To some extent, tipping may even depend on the vagaries of weather. In NASA's climate model, in 10 simulations using the same "middle-of-the-road" greenhouse warming scenario (SSP2–4.5) with under 3°C global warming, the AMOC collapses in two but recovers after significant weakening in eight; the difference is merely stochastic internal variability (Romanou et al., 2023). This is also part of the nature of tipping points.

Apart from a full shutdown of the AMOC, there is still the second type of tipping point to consider, the one where convection shuts down in one region. That happens in a surprising number of climate models, and so far hasn't gotten the public attention it deserves. The first documented case, the British Hadley Centre model, was published in 1999 (Wood et al., 1999). Of the latest model generation (CMIP6), in four out of the 35 models, subpolar gyre convection breaks down—and all four are in the group of the 11 best models in terms of reproducing the vertical density profiles in the subpolar gyre (Swingedouw et al., 2021). That's in 36% of those high-quality models. In the previous model generation (CMIP5), that number was 45%. What's more, it typically happens as soon as the year 2040 and for moderate emission scenarios—even without properly accounting for Greenland melt. Thus, a collapse of convection in the subpolar gyre, resulting in rapid AMOC weakening and abrupt regional cooling, must be considered a high risk urgently requiring attention.

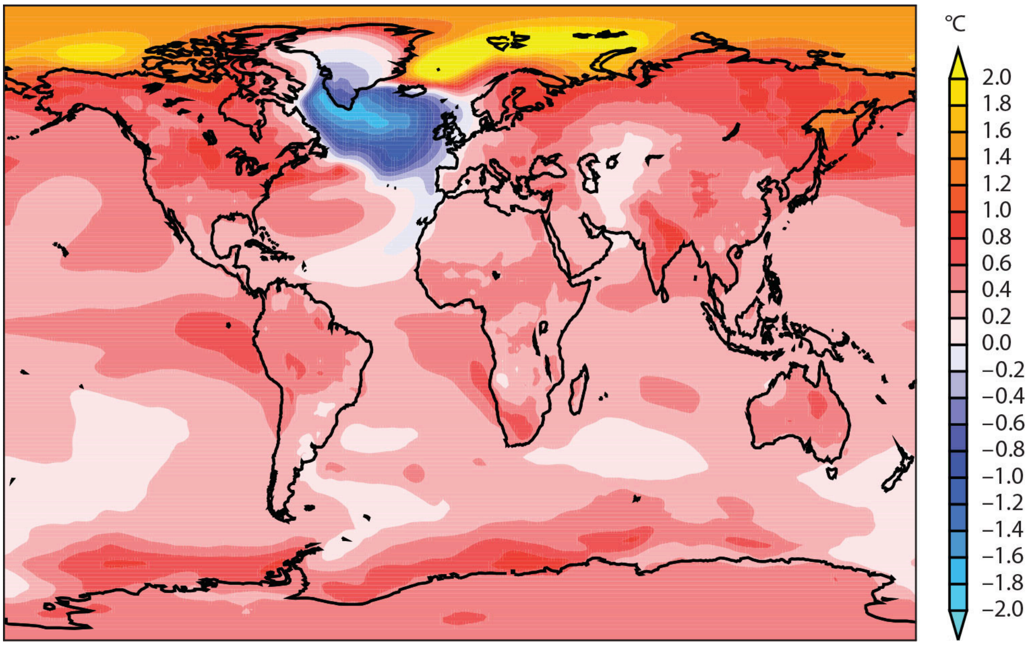
What does this mean for our future? Let's first look at the impacts of an AMOC slowdown or collapse, and then discuss the implications.

HOW BAD WOULD IT BE?

The current cold blob is already affecting our weather, though not in the way that might be expected: a cold subpolar North Atlantic correlates with summer heat in Europe (Duchez et al., 2016). The cooling of the sea surface is enough to influence the air pressure distribution in a way that encourages an influx of warm air from the south into Europe. For example, in summer 2015, the subpolar Atlantic was the coldest since records began in the nineteenth century—while Europe suffered a strong heatwave. Subsequent study has shown that heatwaves are increasing three to four times faster in Europe than in other regions of the Northern Hemisphere, related to changes in the jet stream that may well be influenced by the cold blob (Rousi et al., 2022).

Several studies show that if the AMOC weakens, sea levels on the American northeast coastline will rise more sharply (e.g., Levermann et al., 2005; Yin et al., 2010). The Coriolis force pushes moving water, in this case, in the Gulf Stream, to the right, away from the American coast. When the Gulf Stream weakens, less water is moved northward, causing water levels to rise inshore of the Gulf Stream, with models projecting a 15–20 cm rise by 2100 from this effect alone, in addition to other causes of rising seas. Coastal erosion, the frequency of nuisance flooding, and extent of storm surge damage will substantially increase.

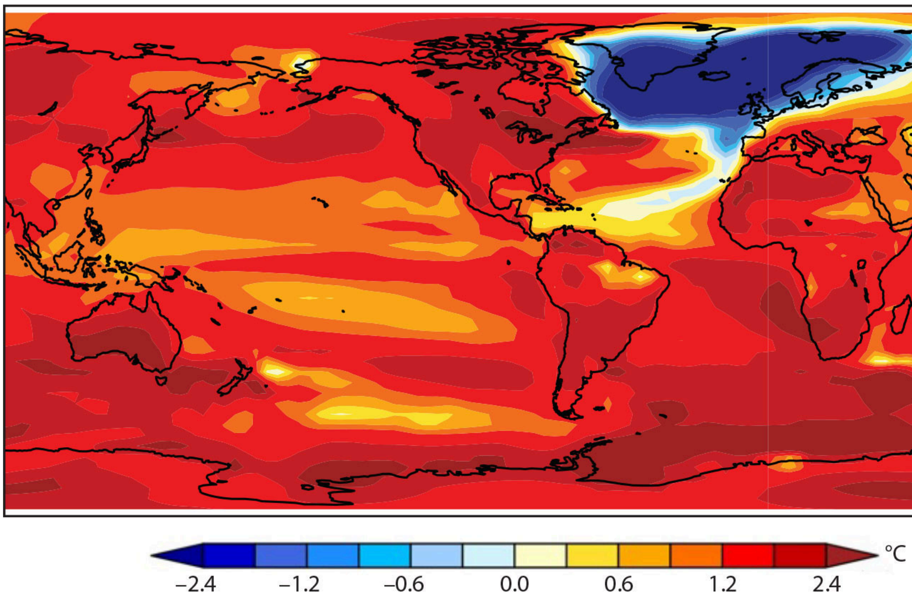
A collapse of convection in the subpolar gyre would significantly magnify these problems. **Figure 14** shows the expected temperature change in this case. It is not so much the absolute change, but the changes in temperature contrast between neighboring regions—here, the cold ocean relative to the adjacent warm land masses—that will greatly change the dynamics of the weather, as temperature gradients drive weather activity in ways we can't foresee in detail. Even this limited oceanic change will shift tropical rainfall belts, though not by as much as a full AMOC shutdown.



(https://tos.org/oceanography/assets/images/content/37-rahmstorf-f14.jpg)

FIGURE 14. Temperature changes in the model-mean before and after a collapse of convection in the subpolar gyre region are plotted here. *From Swingedouw et al. (2021).* > High res figure (https://tos.org/oceanography/assets/images/content/37-rahmstorf-f14.jpg)

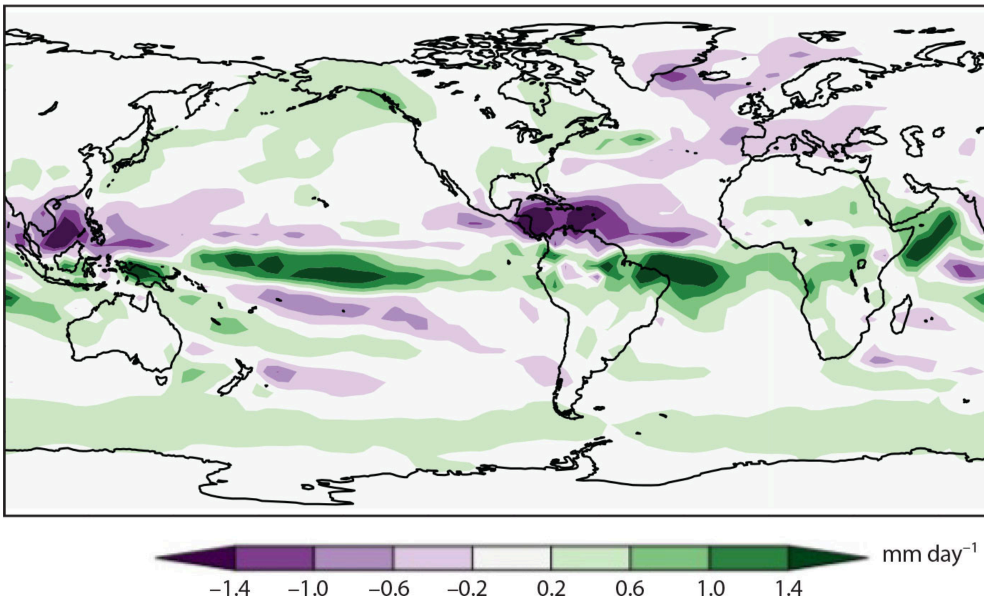
A full shutdown of the AMOC would have truly devastating consequences for humanity and many marine and land ecosystems. **Figure 15** shows the model of Liu et al. (2017) after a doubling of CO_2, with an AMOC collapse caused by this CO_2 increase. The cold air temperatures then expand to cover Iceland, Britain, and Scandinavia. The temperature contrast between northern and southern Europe increases by a massive 4°C, likely with major impact on weather, such as unprecedented storms.



(https://tos.org/oceanography/assets/images/content/37-rahmstorf-f15.jpg)

FIGURE 15. Annual-mean near-surface air temperature change resulting from a CO_2 doubling and AMOC breakdown. While Earth is much warmer, the northern Atlantic region has become colder. In winter, the cooling there is much larger still. *From Liu et al. (2017).* > High res figure (https://tos.org/oceanography/assets/images/content/37-rahmstorf-f15.jpg)

Figure 16 shows the precipitation changes in this model. As we have seen in the paleoclimate data for Heinrich events, major precipitation shifts in the tropics would likely cause drought problems in the northern tropics of America as well as Asia. Seasonal changes will be even larger than these annual mean changes. Other simulations predict a significant increase in winter storms in Europe and a “strong reduction of crop yield and pasture” there (Jackson et al., 2015).



(https://tos.org/oceanography/assets/images/content/37-rahmstorf-f16.jpg)

FIGURE 16. Annual-mean precipitation change resulting from a CO_2 doubling and AMOC breakdown. Most concerning is the southward shift in tropical rainfall belts and a generally drier Europe. *From Liu et al. (2017).* > High res figure (https://tos.org/oceanography/assets/images/content/37-rahmstorf-f16.jpg)

The IPCC summarized the impacts: “If an AMOC collapse were to occur, it would very likely cause abrupt shifts in the regional weather patterns and water cycle, such as a southward shift in the tropical rain belt, and could result in weakening of the African and Asian monsoons, strengthening of Southern Hemisphere monsoons, and drying in Europe” (IPCC, 2021, TS p. 73). Some further consequences include major additional sea level rise especially along the American Atlantic coast, reduced ocean carbon dioxide uptake, greatly reduced oxygen supply to the deep ocean, and likely ecosystem collapse in the northern Atlantic.

IMPLICATIONS: UNCERTAINTY IS NOT OUR FRIEND

The risk of a critical AMOC transition is real and very serious, even if we cannot confidently predict when and whether this will happen. We have already left behind the stable Holocene climate in which humanity has thrived (Osman et al., 2021), and the latest IPCC report warns us that beyond 1.5°C of global warming, we move into the realm of “high risk” with respect to climate tipping points (IPCC, 2023).

Also at risk is the Southern Hemisphere equivalent of the northern Atlantic deep-water formation: the Antarctic bottom-water formation. A recent study by Australian researchers concluded that the increasing meltwater inflow around Antarctica is set to dramatically slow down the Antarctic overturning circulation, with a potential collapse this century (Q. Li et al., 2023). That will slow the rate at which the ocean takes up CO_2 (hence, more will accumulate in the atmosphere), and it will reduce the oxygen supply for the deep sea.

A full AMOC collapse would be a massive, planetary-scale disaster. We *really* want to prevent this from happening.

In other words: we are talking about risk analysis and disaster prevention. This is not about being 100% or even just 50% sure that the AMOC will pass its tipping point this century; the issue is that we’d like to be 100% sure that it won’t. That the IPCC only has “medium confidence” that it will not happen this century is anything but reassuring, and the studies discussed here, which came after the 2021 IPCC report, point to a much larger risk than previously thought.

The Global Tipping Points Report 2023 was published in December 2023, a 500-page effort by 200 researchers from 90 organizations in 26 countries (Lenton et al., 2023). Its summary conclusion reads: “Harmful tipping points in the natural world pose some of the gravest threats faced by humanity. Their triggering will severely damage our planet’s life-support systems and threaten the stability of our societies.”

For the AMOC and other climate tipping points, the only action we can take to minimize the risk is to phase out fossil fuel use and stop deforestation as fast as possible. If we can reach zero emissions, further global warming will stop within years, and the sooner this happens the smaller the risk of passing devastating tipping points. It would also minimize many other losses, damages, and human suffering from “regular” global warming impacts (e.g., heatwaves, floods, droughts, harvest failures, wildfires, sea level rise), which are already happening all around us even without the passing of major climate tipping points.

As another *Climate Tipping Points* report published in December 2022 by the Organisation for Economic Co-operation and Development (OECD) concludes: “Yet, the current scientific evidence unequivocally supports unprecedented, urgent and ambitious climate action to tackle the risks of climate system tipping points” (OECD, 2022).

It would be irresponsible, even foolhardy, if policymakers, business leaders, and indeed the voting public continue to ignore those risks.

CITATION

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

REFERENCES

Blunier, T., J. Chappellaz, J. Schwander, A. Dällenbach, B. Stauffer, T.F. Stocker, D. Raynaud, J. Jouzel, H.B. Clausen, C.U. Hammer, and J.S. Johnsen. 1998. Asynchrony of Antarctic and Greenland climate change during the last glacial period. *Nature* 394:739–743, https://doi.org/10.1038/29447 (https://doi.org/10.1038/29447).

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 (https://doi.org/10.1038/s41558-021-01097-4).

Broecker, W. 1987. Unpleasant surprises in the greenhouse? *Nature* 328:123–126, https://doi.org/10.1038/328123a0 (https://doi.org/10.1038/328123a0).

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

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

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

Chafik, L., N.P. Holliday, S. Bacon, and T. Rossby. 2022. Irminger Sea is the center of action for subpolar AMOC variability. *Geophysical Research Letters* 49(17), https://doi.org/10.1029/2022GL099133 (https://doi.org/10.1029/2022GL099133).

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

Cheng, L., G. Foster, Z. Hausfather, K.E. Trenberth, and J. Abraham. 2022. Improved quantification of the rate of ocean warming. *Journal of Climate* 35(14):4,827–4,840, https://doi.org/10.1175/JCLI-D-21-0895.1 (https://doi.org/10.1175/JCLI-D-21-0895.1).

Dansgaard, W., H.B. Clausen, N. Gundestrup, C.U. Hammer, S.F. Johnsen, P.M. Kristinsdottir, and N. Reeh. 1982. A new Greenland deep ice core. *Science* 218:1,273–1,277, https://doi.org/10.1126/science.218.4579.1273 (https://doi.org/10.1126/science.218.4579.1273).

Dijkstra, H.A., M.J. Molemaker, A. Van der Ploeg, and E.F.F. Botta. 1995. An efficient code to compute non-parallel steady flows and their linear stability. *Computers and Fluids* 24:415–434, https://doi.org/10.1016/0045-7930(94)00042-W (https://doi.org/10.1016/0045-7930(94)00042-W).

Dima, M., and G. Lohmann. 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 (https://doi.org/10.1175/2009JCLI2867.1).

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

Drijfhout, S., G.J. van Oldenborgh, and A. Cimatoribus. 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):8,373–8,379, https://doi.org/10.1175/JCLI-D-12-00490.1 (https://doi.org/10.1175/JCLI-D-12-00490.1).

Duchez, A., E. Frajka-Williams, S.A. Josey, D.G. Evans, J.P. Grist, R. Marsh, G.D. McCarthy, B. Sinha, D.I. Berry, and J.J.M. Hirschi. 2016. Drivers of exceptionally cold North Atlantic Ocean temperatures and their link to the 2015 European heat wave. *Environmental Research Letters* 11(7):074004, https://doi.org/10.1088/1748-9326/11/7/074004 (https://doi.org/10.1088/1748-9326/11/7/074004).

Ellis, H. 1751. A letter to the Rev. Dr. Hales, F.R.S. from Captain Ellis, F.R.S. dated Jan. 7, 1750–51, at Cape Monte Africa, Ship Earl of Halifax. *Philosophical Transactions of the Royal Society of London* 47:211–214.

Feulner, G., S. Rahmstorf, A. Levermann, and S. Volkwardt. 2013. On the origin of the surface air temperature difference between the hemispheres in Earth's present-day climate. *Journal of Climate* 26(18):7,136–7,150, https://doi.org/10.1175/JCLI-D-12-00636.1 (https://doi.org/10.1175/JCLI-D-12-00636.1).

Fiedler, L. 2020. *Investigating the North Atlantic Heat Transport in the Global Climate Model CM2.6.* Bachelor's thesis, University of Potsdam.

Ganopolski, A., and S. Rahmstorf. 2002. Abrupt glacial climate changes due to stochastic resonance. *Physical Review Letters* 88:038501, https://doi.org/10.1103/PhysRevLett.88.038501 (https://doi.org/10.1103/PhysRevLett.88.038501).

He, C., A.C. Clement, M.A. Cane, L.N. Murphy, J.M. Klavans, and T.M. Fenske. 2022. A North Atlantic warming hole without ocean circulation. *Geophysical Research Letters* 49(19), https://doi.org/10.1029/2022GL100420 (https://doi.org/10.1029/2022GL100420).

Heinrich, H. 1988. Origin and consequences of cyclic ice rafting in the northeast Atlantic Ocean during the past 130,000 years. *Quaternary Research* 29:143–152, https://doi.org/10.1016/0033-5894(88)90057-9 (https://doi.org/10.1016/0033-5894(88)90057-9).

Hemming, S.R. 2004. Heinrich events: Massive late Pleistocene detritus layers of the North Atlantic and their global climate imprint. *Reviews of Geophysics* 42(1), https://doi.org/10.1029/2003RG000128 (https://doi.org/10.1029/2003RG000128).

Holliday, N.P., M. Bersch, B. Berx, L. Chafik, S. Cunningham, C. Florindo-Lopez, H. Hatun, W. Johns, S.A. Josey, K.M.H. Larsen, and others. 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 (https://doi.org/10.1038/s41467-020-14474-y).

IPCC (Intergovernmental Panel on Climate Change). 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*. V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, eds, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2,391 pp., https://doi.org/10.1017/9781009157896 (https://doi.org/10.1017/9781009157896).

IPCC. 2023. *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Core Writing Team, H. Lee, and J. Romero, eds, IPCC, Geneva, Switzerland, 184 pp., https://doi.org/10.59327/IPCC/AR6-9789291691647 (https://doi.org/10.59327/IPCC/AR6-9789291691647).

Jackson, L.C., R. Kahana, T. Graham, M.A. Ringer, T. Woollings, J.V. Mecking, and R.A. Wood. 2015. Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM. *Climate Dynamics* 45(11–12):3,299–3,316, https://doi.org/10.1007/s00382-015-2540-2 (https://doi.org/10.1007/s00382-015-2540-2).

Jackson, L.C., H.T. Hewitt, D. Bruciaferri, D. Calvert, T. Graham, C. Guiavarc'h, M.B. Menary, A.L. New, M. Roberts, and D. Storkey. 2023. Challenges simulating the AMOC in climate models. *Philosophical Transactions of the Royal Society A* 381(2262):20220187, https://doi.org/10.1098/rsta.2022.0187 (https://doi.org/10.1098/rsta.2022.0187).

Jendrkowiak, J. 2024. *Heat Budget Analysis over the North Atlantic*. Bachelor's thesis, Potsdam University.

Kuhlbrodt, T., S. Titz, U. Feudel, and S. Rahmstorf. 2001. A simple model of seasonal open ocean convection. Part II. Labrador Sea stability and stochastic forcing. *Ocean Dynamics* 52:36–49, https://doi.org/10.1007/s10236-001-8175-3 (https://doi.org/10.1007/s10236-001-8175-3).

Latif, M., J. Sun, M. Visbeck, and M. Hadi Bordbar. 2022. Natural variability has dominated Atlantic Meridional Overturning Circulation since 1900. *Nature Climate Change* 12:455–460, https://doi.org/10.1038/s41558-022-01342-4 (https://doi.org/10.1038/s41558-022-01342-4).

Lenton, T.M., D.I. Armstrong McKay, S. Loriani, J.F. Abrams, S.J. Lade, J.F. Donges, M. Milkoreit, T. Powell, S.R. Smith, and others, eds. 2023. *The Global Tipping Points Report 2023*. University of Exeter, Exeter, UK, 479 pp.

Levermann, A., A. Griesel, M. Hofmann, M. Montoya, and S. Rahmstorf. 2005. Dynamic sea level changes following changes in the thermohaline circulation. *Climate Dynamics* 24(4):347–354, https://doi.org/10.1007/s00382-004-0505-y (https://doi.org/10.1007/s00382-004-0505-y).

Li, Q., M.H. England, A.M. Hogg, S.R. Rintoul, and A.K. Morrison. 2023. Abyssal ocean overturning slowdown and warming driven by Antarctic meltwater. *Nature* 615(7954):841–847, https://doi.org/10.1038/s41586-023-05762-w (https://doi.org/10.1038/s41586-023-05762-w).

Li, Z., M.H. England, and S. Groeskamp. 2023. Recent acceleration in global ocean heat accumulation by mode and intermediate waters. *Nature Communications* 14(1):6888, https://doi.org/10.1038/s41467-023-42468-z (https://doi.org/10.1038/s41467-023-42468-z).

Liu, W., S.-P. Xie, Z. Liu, and J. Zhu. 2017. Overlooked possibility of a collapsed Atlantic Meridional Overturning Circulation in warming climate. *Science Advances* 3(1), https://doi.org/10.1126/sciadv.1601666 (https://doi.org/10.1126/sciadv.1601666).

Manabe, S., and R.J. Stouffer. 1988. Two stable equilibria of a coupled ocean-atmosphere model. *Journal of Climate* 1:841–866, https://doi.org/10.1175/1520-0442(1988)001<0841:TSEOAC>2.0.CO;2 (https://doi.org/10.1175/1520-0442(1988)001%3C0841:TSEOAC%3E2.0.CO;2).

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

Michel, S.L.L., D. Swingedouw, P. Ortega, G. Gastineau, J. Mignot, G. McCarthy, and M. Khodri. 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 (https://doi.org/10.1038/s41467-022-32704-3).

Mooney, C. 2015. "Why Some Scientists Are Worried about a Surprisingly Cold 'Blob' in the North Atlantic Ocean." *Washington Post*, September 4, 2015, https://www.washingtonpost.com/news/energy-environment/wp/2015/09/24/why-some-scientists-are-worried-about-a-cold-blob-in-the-north-atlantic-ocean/ (https://www.washingtonpost.com/news/energy-environment/wp/2015/09/24/why-some-scientists-are-worried-about-a-cold-blob-in-the-north-atlantic-ocean/).

OECD (Organisation for Economic Co-operation and Development). 2022. *Climate Tipping Points: Insights for Effective Policy Action*. Paris, 89 pp, https://doi.org/10.1787/abc5a69e-en (https://doi.org/10.1787/abc5a69e-en).

Osman, M.B., J.E. Tierney, J. Zhu, R. Tardif, G.J. Hakim, J. King, and C.J. Poulsen. 2021. Globally resolved surface temperatures since the Last Glacial Maximum. *Nature* 599(7884):239–244, https://doi.org/10.1038/s41586-021-03984-4 (https://doi.org/10.1038/s41586-021-03984-4).

Piecuch, C.G., and L.M. Beal. 2023. Robust weakening of the Gulf Stream during the past four decades observed in the Florida Straits. *Geophysical Research Letters* 50(18), https://doi.org/10.1029/2023GL105170 (https://doi.org/10.1029/2023GL105170).

Qasmi, S. 2023. Past and future response of the North Atlantic warming hole to anthropogenic forcing. *Earth System Dynamics* 14(3):685–695, https://doi.org/10.5194/esd-14-685-2023 (https://doi.org/10.5194/esd-14-685-2023).

Rahmstorf, S. 1996. On the freshwater forcing and transport of the Atlantic thermohaline circulation. *Climate Dynamics* 12(12):799–811, https://doi.org/10.1007/s003820050144 (https://doi.org/10.1007/s003820050144).

Rahmstorf, S. 1997. Risk of sea-change in the Atlantic. *Nature* 388(6645):825–826, https://doi.org/10.1038/42127 (https://doi.org/10.1038/42127).

Rahmstorf, S. 1999. Shifting seas in the greenhouse? *Nature* 399(6736):523–524, https://doi.org/10.1038/21066 (https://doi.org/10.1038/21066).

Rahmstorf, S. 2001. A simple analytical model of seasonal open-ocean convection: Part I. Theory. *Ocean Dynamics* 52:26–35, https://doi.org/10.1007/s10236-001-8174-4 (https://doi.org/10.1007/s10236-001-8174-4).

Rahmstorf, S. 2002. Ocean circulation and climate during the past 120,000 years. *Nature* 419(6903):207–214, https://doi.org/10.1038/nature01090 (https://doi.org/10.1038/nature01090).

Rahmstorf, S., M. Crucifix, A. Ganopolski, H. Goosse, I.V. Kamenkovich, R. Knutti, G. Lohmann, R. Marsh, L.A. Mysak, Z. Wang, and A.J. Weaver. 2005. Thermohaline circulation hysteresis: A model intercomparison. *Geophysical Research Letters* 32(23), https://doi.org/10.1029/2005GL023655 (https://doi.org/10.1029/2005GL023655).

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

Robinson, A., R. Calov, and A. Ganopolski. 2012. Multistability and critical thresholds of the Greenland ice sheet. *Nature Climate Change* 2(6):429–432, https://doi.org/10.1038/nclimate1449 (https://doi.org/10.1038/nclimate1449).

Romanou, A., D. Rind, J. Jonas, R. Miller, M. Kelley, G. Russell, C. Orbe, L. Nazarenko, R. Latto, and G.A. Schmidt. 2023. Stochastic bifurcation of the North Atlantic circulation under a midrange future climate scenario with the NASA-GISS ModelE. *Journal of Climate* 36(18):6,141–6,161, https://doi.org/10.1175/JCLI-D-22-0536.1 (https://doi.org/10.1175/JCLI-D-22-0536.1).

Rousi, E., K. Kornhuber, G. Beobide-Arsuaga, F. Luo, and D. Coumou. 2022. Accelerated western European heatwave trends linked to more-persistent double jets over Eurasia. *Nature Communications* 13(1):3851, https://doi.org/10.1038/s41467-022-31432-y (https://doi.org/10.1038/s41467-022-31432-y).

Smeed, D.A., B.I. Moat, E.L. McDonagh, G. McCarthy, B.A. King, W.E. Johns, and H.L. Bryden. 2020. Reduction in ocean heat transport at 26°N since 2008 cools the eastern Subpolar Gyre of the North Atlantic Ocean. *Journal of Climate* 33(5):1,677–1,689, https://doi.org/10.1175/JCLI-D-19-0323.1 (https://doi.org/10.1175/JCLI-D-19-0323.1).

Stager, J.C., D.B. Ryves, B.M. Chase, and F.S. Pausata. 2011. Catastrophic drought in the Afro-Asian monsoon region during Heinrich Event 1. *Science* 331(6022):1,299–1,302, https://doi.org/10.1126/science.1198322 (https://doi.org/10.1126/science.1198322).

Stocker, T., and A. Schmittner. 1997. Influence of CO_2 emission rates on the stability of the thermohaline circulation. *Nature* 388:862–865, https://doi.org/10.1038/42224 (https://doi.org/10.1038/42224).

Stommel, H. 1961. Thermohaline convection with two stable regimes of flow. *Tellus* 13:224–230, https://doi.org/10.3402/tellusa.v13i2.9491 (https://doi.org/10.3402/tellusa.v13i2.9491).

Supran, G., S. Rahmstorf, and N. Oreskes. 2023. Assessing ExxonMobil's global warming projections. *Science* 379(6628):eabk0063, https://doi.org/10.1126/science.abk0063 (https://doi.org/10.1126/science.abk0063).

Swingedouw, D., A. Bily, C. Esquerdo, L.F. Borchert, G. Sgubin, J. Mignot, and M. Menary. 2021. On the risk of abrupt changes in the North Atlantic subpolar gyre in CMIP6 models. *Annals of the New York Academy of Sciences* 1504(1):187–201, https://doi.org/10.1111/nyas.14659 (https://doi.org/10.1111/nyas.14659).

Thompson, B. 1797. The complete works of Count Rumford (1870). *Boston, American Academy of Sciences* 1:237–400.

Todd, R.E., and A.S. Ren. 2023. Warming and lateral shift of the Gulf Stream from in situ observations since 2001. *Nature Climate Change* 13:1,348–1,352, https://doi.org/10.1038/s41558-023-01835-w (https://doi.org/10.1038/s41558-023-01835-w).

Trenberth, K.E., Y. Zhang, J.T. Fasullo, and L. Cheng. 2019. Observation-based estimates of global and basin ocean meridional heat transport time series. *Journal of Climate* 32(14):4,567–4,583, https://doi.org/10.1175/JCLI-D-18-0872.1 (https://doi.org/10.1175/JCLI-D-18-0872.1).

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

Warren, B.A. 1983. Why is no deep water formed in the North Pacific? *Journal of Marine Research* 41:327–347.

Weijer, W., W. Cheng, S.S. Drijfhout, A.V. Fedorov, A. Hu, L.C. Jackson, W. Liu, E.L. McDonagh, J.V. Mecking, and J. Zhang. 2019. Stability of the Atlantic Meridional Overturning Circulation: A review and synthesis. *Journal of Geophysical Research: Oceans* 124(8):5,336–5,375, https://doi.org/10.1029/2019JC015083 (https://doi.org/10.1029/2019JC015083).

Welander, P. 1982. A simple heat-salt oscillator. *Dynamics of Atmospheres and Oceans* 6:233–242, https://doi.org/10.1016/0377-0265(82)90030-6 (https://doi.org/10.1016/0377-0265(82)90030-6).

Wood, R.A., A.B. Keen, J.F.B. Mitchell, and J.M. Gregory. 1999. Changing spatial structure of the thermohaline circulation in response to atmospheric CO_2 forcing in a climate model. *Nature* 399:572–575, https://doi.org/10.1038/21170 (https://doi.org/10.1038/21170).

Yin, J., S.M. Griffies, and R.J. Stouffer. 2010. Spatial variability of sea level rise in twenty-first century projections. *Journal of Climate* 23(17):4,585–4,607, https://doi.org/10.1175/2010JCLI3533.1 (https://doi.org/10.1175/2010JCLI3533.1).

Zhang, R., and G.K. Vallis. 2007. The role of bottom vortex stretching on the path of the North Atlantic western boundary current and on the northern recirculation gyre. *Journal of Physical Oceanography* 37(8):2,053–2,080, https://doi.org/10.1175/JPO3102.1 (https://doi.org/10.1175/JPO3102.1).

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

Zhu, C., Z. Liu, S. Zhang, and L. Wu. 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 (https://doi.org/10.1038/s41467-023-36288-4).

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