C-STREAMS
The Gulf Stream control of the North Atlantic carbon sink

Ocean Sciences, Glasgow 2026
Abstracts for Presentations and Poster Sessions

Title	Presenter	Talk/Poster	Location	Day	Time
Lagrangian Changes in Anthropogenic Carbon in The Gulf Stream and Implications to Subpolar Carbon Uptake	Robyn Tuerena	Talk	Lomond Auditorium	Mon 23rd	11:20 - 11:30
Carbon in Transit: Is Shifting Ocean Circulation Reshaping the North Atlantic CO_2 Sink?	Peter Brown	Talk	Hall 1	Tues 24th	08:43 - 08:53
The Role of Sea Ice in the Import and Export of Carbon and Nutrients from the Weddell Gyre	David Munday	Poster	Hall 4 (Poster Hall)	Weds 25th	16:00 - 18:00
The Central Role of the Labrador Sea in the Ventilation of the Deep North Atlantic	Jaime Palter	Talk	Hall 3, Coral Cove	Thurs 26th	08:30 - 08:41
Residual Circulation of the North Atlantic Subtropical Gyre	Louis Clement	Talk	Hall 1	Thurs 26th	08:30 - 08:40
Global Observational Estimates of Thermohaline Transformations by Diapycnal and Isopycnal Mixing	Bieito Fernandez Castro	Poster	Hall 4 (Poster Hall)	Thurs 26th	16:00 - 18:00
Biogeochemical Variability in the Gulf Stream from Mooring Observations in the Florida Current	Rachel Bramblett	Poster	Hall 4 (Poster Hall)	Thurs 26th	16:00 - 18:00
Mesoscale Eddy Stirring and Diapycnal Mixing for the Subtropical North Atlantic and Gulf Stream	Esperanza Broullón	Poster	Hall 4 (Poster Hall)	Thurs 26th	16:00 - 18:00
Residual Circulation of the North Atlantic Subtropical Gyre	Louis Clement	Poster	Hall 4 (Poster Hall)	Thurs 26th	16:00 - 18:00
Challenges of Deploying BGC-Argo in the Florida Straits: Assessing Changes in Nitrate Along the Gulf Stream Path	Clare Johnson	Poster	Hall 4 (Poster Hall)	Thurs 26th	16:00 - 18:00
Modulations of the North Atlantic Ocean Carbon Sink Under a Warming World	Yohei Takano	Poster	Hall 4 (Poster Hall)	Thurs 26th	16:00 - 18:00

Lagrangian Changes in Anthropogenic Carbon in The Gulf Stream and Implications to Subpolar Carbon Uptake

Robyn Tuerena, *Clare Johnson, Pete Brown, Espe Broullón, Bieito Fernández Castro and Ric Williams*

Southern Ocean sourced waters are transported northward as intermediate waters underlying the oligotrophic subtropical gyres. On density surfaces of σ_0 >27 kg m^{-3}, these waters are characterised by elevated nutrient concentrations and low levels of anthropogenic carbon (C_{ant}). The Gulf Stream serves as an efficient conduit, carrying these waters undersaturated in C_{ant} into the North Atlantic subpolar gyre, driving high carbon uptake where they ventilate. As part of the C-Streams project, we have deployed two biogeochemical Argo floats in the Florida Straits to investigate the northward transport of C_{ant}, and to identify ventilation pathways. We use the φC_T^O method to calculate C_{ant} from calibrated O_2, nitrate and pH profiles and existing neural networks. We augment our measurements with the wider float network to produce a highly spatially resolved transect of C_{ant} in the Gulf Stream between 24-45°N. Relatively unmodified Antarctic Intermediate Waters have low C_{ant}(~20 uM) in the Florida Straits at 24°N which remains stable (<30 uM) until 40°N. Here, C_{ant} increases rapidly to >50 uM by 44°N as these waters are increasingly ventilated. The physical processes driving ventilation and carbon uptake are identified and discussed in the context of a fast changing climate.

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Carbon in Transit: Is Shifting Ocean Circulation Reshaping the North Atlantic CO_2 Sink?

***Peter Brown**, Elaine McDonagh, Cathy Wimart-Rousseau, David Smeed, Ben I Moat, William Johns, Denis Volkov and Leticia Barbero*

The Atlantic Meridional Overturning Circulation (AMOC) plays a pivotal role in sustaining the North Atlantic (NA) as a major atmospheric CO_2 sink—via surface cooling of poleward-advected waters prior to high-latitude subduction, and through robust biological production fuelled by northward nutrient transport. As atmospheric CO_2 concentrations have risen, the NA has disproportionately mitigated their increase, accounting for ~30% of global oceanic CO_2 uptake and 25% of the anthropogenic carbon (C_{anth}) inventory.

Given projections of a weakening AMOC, it is critical to understand how ventilation and overturning dynamics shape the NA carbon sink and govern the fate of advected carbon. Here, we extend the time series of C_{anth} transports across 26°N to 2004–2023, integrating repeat hydrography with circulation fields from the RAPID-MOCHA-WBTS mooring array, and compare these transports to regional air-sea CO_2 flux estimates over the same period.

Three distinct periods are identified; from 2004-2012, NA air-sea CO2 fluxes grew strongly but no increase in northward C_{anth} transports was observed despite concentrations rising, as they were offset by a declining overturning circulation. From 2012-2019, a recovery in AMOC strength combined with further C_{anth} level increases led to an acceleration in northward C_{anth} transports, but a downstream decrease in the magnitude of the NA carbon sink. Lastly, since 2019 a stable overturning circulation but stronger southward gyre thermocline recirculation have led to a *decrease* in northward C_{anth} transports (again despite C_{anth} concentrations continuing to rise), and a flatlining in NA CO_2 uptake.

These findings reveal a nuanced coupling between oceanic carbon transport and regional CO_2 fluxes, suggesting that circulation changes may be impacting downstream CO_2 uptake efficiency and the storage rate of carbon in the NA. They also underscore the importance of correctly accounting for dynamic carbon transport pathways in models to increase confidence in future carbon sink projections.

The Role of Sea Ice in the Import and Export of Carbon and Nutrients from the Weddell Gyre

David Munday*, Graeme MacGilchrist, Katharine Hendry, Andrew Styles, Christopher Auckland and Yohei Takano*

The physical circulation and biogeochemistry of the Southern Ocean has proved crucial to understanding the sensitivity of global climate. The ventilation of deep water, rich in carbon and nutrients throughout the subpolar Southern Ocean is usually framed in terms of the residual overturning. This places the emphasis on the up- and down-welling of different water masses. However, for the Weddell Gyre it has been proposed that casting the carbon cycle in terms of the horizontal gyre circulation may be more informative (MacGilchrist et al., 2019). This emphasises the role of remineralisation at mid-depth of organic carbon and the differential transport in/out of the Weddell Sea in the longitudinal direction.

Using MITgcm as an idealised two-basin model with a Weddell Sea at the southern boundary of the Atlantic basin, we examine the physical controls of the import/export of carbon & nutrients from the Weddell Sea. The idealised nature of the model allows us to easily change the surface forcing and bathymetry. By perturbing the idealised model's Scotia Ridge and Weddell Sea wind stress curl, we are able to influence the connection between the Weddell Gyre and the rest of the Southern Ocean. Other perturbation experiments, including the diapycnal diffusivity at depth, are used to perturb the overturning circulation. Using simple biogeochemistry and a carbon pump decomposition we are able to see how individual reservoirs are altered and the role of their transport in the overall carbon budget of the Weddell Sea. In particular, we are able to use Reynolds averaging to split the import/export of carbon & nutrients into the Weddell Gyre into components due to overturning and gyre circulations. Our experiments allow us to consider the physical aspects that control the relative strength of these components.

We find that sea ice, and its export across the mouth of the idealised Weddell Sea, plays a crucial role in the model's carbon cycle. Changes in the seasonal cycle of the sea ice are reflected in the decomposition of carbon transport into overturning and gyre components. A stronger (weaker) export of sea ice from the Weddell Sea results in a stronger (weaker) apparent carbon transport due to the need to replace the volume of freshwater 'lost' to the north with ocean influx containing a high concentration of carbon. The intricacies of the carbon transport decomposition are related to many aspects of the basin geometry and forcing.

The Central Role of the Labrador Sea in the Ventilation of the Deep North Atlantic

Jaime Palter, *Una Miller, Ellen Park, Dariia Atamanchuk, Kristen Fogaren, Yao Fu, Johannes Karstensen, Jannes Koelling, Isabela Alexander-Astiz Le Bras, Hiroki Nagao, David Nicholson, Hilary Palevsky and Meg Yoder*

For several decades, oxygen levels across most of the ocean have been declining, adding a major ecological stressor to those marine species already living at the edge of their respiratory needs. Our work quantifies the rate of oxygen supply to the deep North Atlantic and the ocean circulation features responsible for that supply. Somewhat enigmatically, the North Atlantic has *not yet* experienced persistent oxygen decline, and our work provides the key oceanographic context for the observed stability.

The timeliness of this work is tied to the fact that our team recently published the methodological innovations that made possible the accurate, long-term measurement of ocean oxygen within swift currents. Now, for the first time, our cross-basin deployment of oxygen optodes on moored platforms has been used to quantify oxygen transport, revealing an addition of oxygen in the Labrador Sea that is sufficient to support respiration throughout most of the deep North Atlantic.

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Residual Circulation of the North Atlantic Subtropical Gyre

Louis Clement*, Alberto Naveira Garabato, Bieito Fernandez Castro, Esperanza Broullón Mandado and Ric Williams*

The cross-stream circulation of subtropical gyres is believed to be primarily driven by Ekman pumping. Recent studies have highlighted the role of eddy-induced flows in opposing Ekman pumping. Despite the key role of the cross-stream circulation in sustaining biological activity and heat and carbon uptake in gyres, the extent of eddy cancellation of the Ekman transport remains uncertain. By combining climatological wind stress with estimates of both along- and across-isopycnal mixing rates, the Eulerian and cross-stream residual circulations are estimated in the North Atlantic subtropical gyre. To achieve this, both Ekman and eddy-induced transports are represented by time-mean stream functions. Overall, Eulerian subsurface eddy-induced transport prevails over Ekman transport along the Gulf Stream, leading to local upwelling of deep waters, whereas wind-driven circulation dominates south of the gyre. In cross-stream coordinates, however, the eddy-induced transport dominates on both sides of the gyre, leading to a deep diabatic upwelling of 2--5 Sv in the gyre centre. This upwelling appears consistent with the deep, high-oxygen waters found in the gyre centre. Finally, the buoyancy changes at the mixed-layer base associated with the residual stream function are compared to the air-sea and diapycnal buoyancy fluxes.

Global Observational Estimates of Thermohaline Transformations by Diapycnal and Isopycnal Mixing

Bieito Fernandez Castro, *Sjoerd Groeskamp, Louis Clement, Esperanza Broullón, Dafydd Gwyn Evans, Alberto Naveira Garabato*

Small-scale diapycnal and mesoscale isopycnal mixing redistribute heat and freshwater and other solutes in the ocean. These processes shape regional and global circulation patterns and impact the climate system. Due to the scarcity of mixing observations, appraising such critical role remains a major challenge. Here, we leverage new global, vertically-resolved maps of diapycnal and isopycnal diffusivity to infer variance dissipation rates of temperature (χ_Θ) and salinity (χ_S). We then revisit and expand a recent reformulation of the water-mass transformation framework to derive global thermohaline water-mass transformation rates from χ estimates. Global diathermal and diahaline water-mass transformations show respective double circulation cells transporting 600 TW of heat and 20 x 10^6 g kg^{-1} m^3 s^{-1} of salt to waters cooler than 20^oC and fresher than 35.1 g kg^{-1}. Diathermal transformations are dominated by diapycnal mixing, involving the formation of subtropical thermocline waters from warmer tropical waters and colder, deeper waters. Isopycnal mixing in the Southern Ocean is the main global driver of diahaline transformations, as well as diathermal transformations in cold waters (<5^oC), controlling the formation of Antarctic Intermediate Waters and Circumpolar Deep Waters and the redistribution heat and freshwater between the Southern Ocean and the rest of the Global Ocean. Comparison with direct χ observations demonstrates that even a modest number of microstructure profiles can yield robust regional estimates of water-mass transformations, advocating for a distributed fleet of autonomous turbulence floats as a promising solution to monitor the ocean's dynamical state.

Biogeochemical Variability in the Gulf Stream from Mooring Observations in the Florida Current

Rachel Bramblett, *Peter Brown, Darren Rayner, Ric Williams, Lisa M Beal, Edward Mawji, Edward Doherty and Paloma Cartwright*

The Gulf Stream plays a critical role in the carbon cycle as it provides the return flow of the Atlantic Meridional Overturning Circulation, supplying the North Atlantic with waters rich in nutrients and low in anthropogenic carbon. The effects of climate change are projected to affect ocean circulation which could potentially threaten the capacity for which these waters can serve as a sink for atmospheric carbon dioxide. The current understanding of the Gulf Stream and its role in a changing global climate is hindered by the limited availability and time resolution of in-situ measurements, especially for carbon and nutrients. As part of the joint UK-US C-Streams project, biogeochemical measurements were obtained from three moorings in the Florida Current designed to capture two main components of the Gulf Stream, the through-flow waters originating from the Southern Hemisphere and the recirculating waters from the North Atlantic Gyre. These year-long time series provide the first continuous biogeochemical measurements in the Florida Current, allowing us to determine the time scales of variability in dissolved carbon dioxide, pH, and dissolved oxygen. In addition to these in-situ measurements, both the Empirical Seawater Property Estimation Routines (ESPER) and CO2SYS routines were utilized to derive relevant parameters of the marine carbonate system, including dissolved inorganic carbon and total alkalinity. Based on the location of the moorings, we were able to observe and compare the time scale variability of these properties in both the through-flow and the recirculating waters that supply the Florida Current. The results of this work clarify our understanding of the sources of variability in the carbon system in the Gulf Stream, how it relates to other chemical and physical properties of the Florida Current, and the implications for the downstream transport of carbon to the North Atlantic subtropical gyre.

Mesoscale Eddy Stirring and Diapycnal Mixing for the Subtropical North Atlantic and Gulf Stream

Esperanza Broullón *Bieito Fernandez Castro, Alberto Naveira Garabato, Louis Clément and Ric Williams*

Lagrangian data from Argo are used to diagnose mesoscale eddy stirring and diapycnal mixing for temperature and salinity over the subtropical thermocline in the North Atlantic. On the large scale of typically 500 km over the interior of the subtropical gyre, a three-way balance is assumed between the mesoscale eddy and small-scale mixing productions of tracer variance and the dissipation of tracer variance. The dissipation of tracer variance is balanced by weak values of the small-scale mixing production over the central regions of the subtropical gyre, but the mesoscale eddy production dominates over the flanks of the gyre. On the scale of boundary flows (~100 km), the tracer variance balance is extended to include an advection of tracer variance, which can affect whether tracer eddy fluxes are down-gradient or up-gradient. This advection of tracer variance is found to be significant (~10% of the dissipation of tracer variance) in regions of high tracer variance and acts to enhance down-gradient tracer fluxes in the vicinity of the Gulf Stream. Our results show that the three-way balance of tracer variance at large scale is not maintained at smaller scales over the flanks of the subtropical gyre.

Challenges of Deploying BGC-Argo in the Florida Straits: Assessing Changes in Nitrate Along the Gulf Stream Path

Clare Johnson. *Robyn Tuerena, Ric Williams, Pete Brown, Darren Rayner*

The Gulf Stream transports high nutrient waters northwards as a subsurface ($\sigma_0 > 27$ kg m-3) nutrient stream. These waters outcrop in the subpolar North Atlantic and are one reason why the area takes up a disproportionately large amount of carbon relative to its size. Examining how the Gulf Stream nutrient stream evolves along its pathway requires a high spatial and temporal resolution lagrangian dataset such as from BGC-Argo. However, it also poses challenges, particularly with calibration, because of the shallow nature of the current. We deployed two BGC-Argo floats in the Florida Straits in summer 2023, with the first six months of the deployment (between 26-35 ˚N) in water depths between 200-800 m. As published calibration methods for BGC-Argo nitrate sensors require comparison to a reference dataset below 1000 m, we tried different methods to calibrate this part of the record. A good calibration, including identifying and correcting any sensor jumps, is essential to our aim of examining along-path nitrate changes within the Gulf Stream. Methods trialled included comparison to a reference dataset in pressure and density space, breakpoint analysis on different variables, and comparison with historical data and between floats. The calibrated data from the floats is then used to investigate how the Gulf Stream nutrient stream evolves along its pathway. As the current moves north, the subsurface nitrate peak situated at about 27.2 kg m-3 decreases from 28.1 µmol kg-1 at 26 ˚N to 25.1 µmol kg-1 at 35 ˚N. As volume transports between these latitudes increase, this suggests dilution by lower nutrient waters and/or biological consumption. Further examination of other data from the BGC-Argo float (e.g. temperature, salinity, chlorophyll) will help identify the relative importance of these two processes.

Modulations of the North Atlantic Ocean Carbon Sink Under a Warming World

Yohei Takano, *Dani Jones, Anna Katavouta, Richard G Williams, Gael Forget, Jonathan Maitland Lauderdale, David Roy Munday and Vassil M Roussenov*

The North Atlantic is one of the most effective regions in the global ocean for carbon uptake from the atmosphere and long-term carbon storage. Understanding the mechanism of the North Atlantic Ocean carbon uptake and storage under a changing climate is crucial for the study of the global carbon cycle. Here, we investigate the drivers of changes in the North Atlantic Ocean carbon sink and storage using forward and adjoint simulations from the Estimating the Circulation and Climate of the Ocean version 4 (ECCOv4) coupled with an ocean biogeochemistry model (ECCOv4-DIC). Adjoint sensitivity experiments with the ECCOv4r2-DIC reveal connections between the upstream carbon in the Gulf Streams and the downstream subpolar ocean carbon inventory on timescales of 4 to 8 years. The results highlight the key role of the Gulf Stream in transporting biogeochemical properties and regulating the capacity of carbon content in the subpolar North Atlantic Ocean. We also assess the impact of the rising atmospheric CO2 and warming through idealized 1% per year CO2 increase experiments based on the ECCOv4r2-DIC. The aim is to disentangle the effect of rising atmospheric CO2 from ocean warming. Furthermore, we examine the direct influence of increasing atmospheric CO_2 and ocean warming, as well as indirect changes resulting from warming-induced modifications of ocean circulation and transport, focusing on the Gulf Stream. The idealized experiments show that the increase in atmospheric CO_2 is the dominant driver of enhanced carbon uptake along the Gulf Stream and in the subpolar North Atlantic. However, the spatial pattern of warming can modulate carbon uptake in the subpolar region, reflecting both local and remote impacts of warming on ocean transport and mixing.