

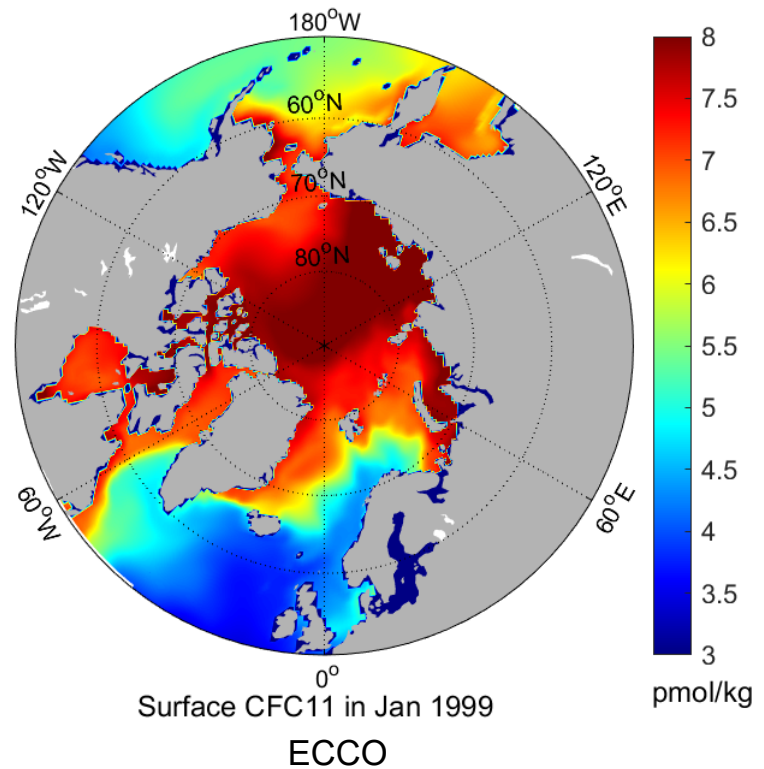
# CFC-11 added to ECCO as an abiotic tracer that highlights the role of biology

**Yavor Kostov**

British Antarctic Survey

A collaboration dating back to my previous postdoc with

Marie-José Messias at Exeter and Herlé Mercier at IFREMER



Motivation

## Climate Change 2007: Working Group I: The Physical Science Basis

[Back to report](#)

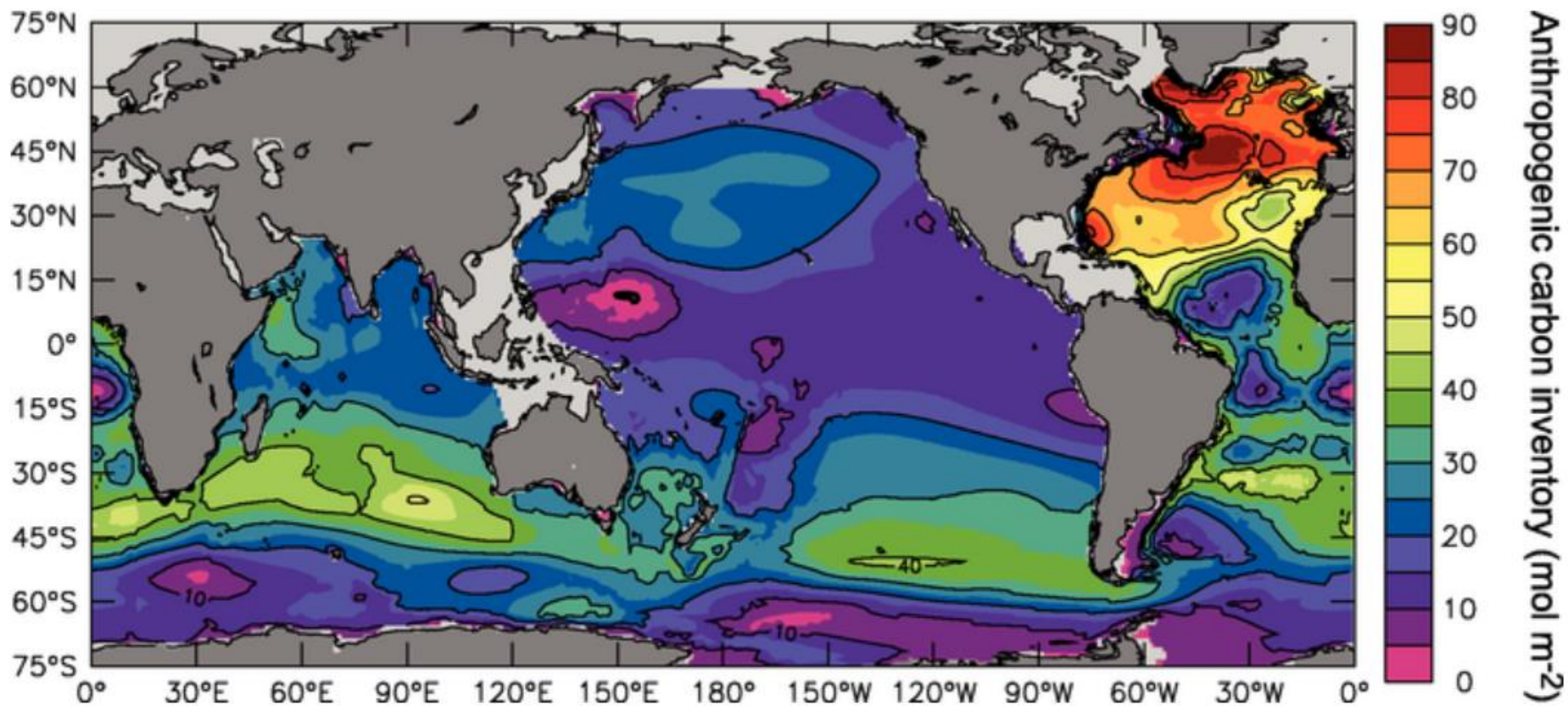
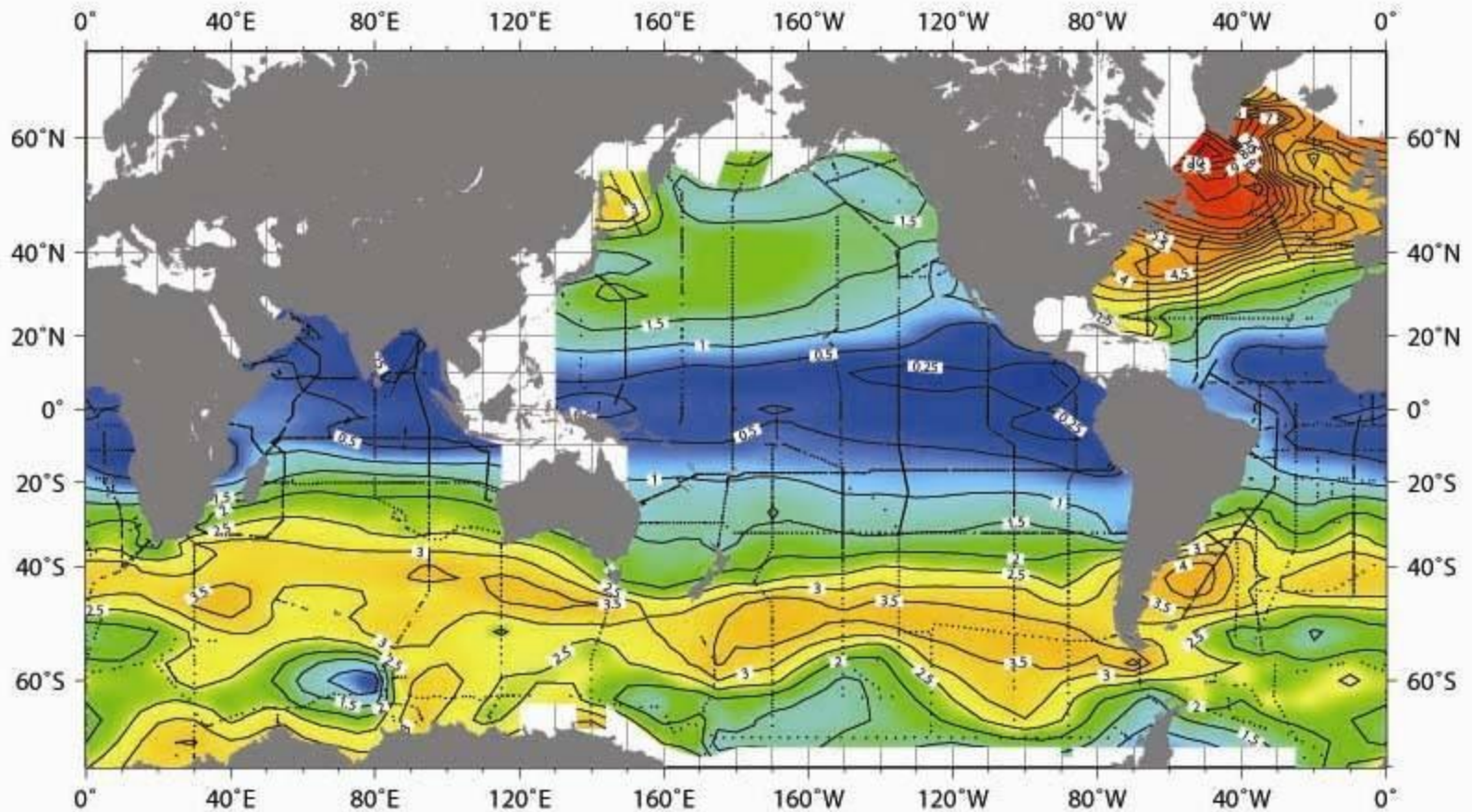


Figure 5.10. Column inventory of anthropogenic carbon (mol m<sup>-2</sup>) as of 1994 from Sabine et al. (2004b).

# Distinguishing biological and physical effects

- In a forward model simulation, you can have a counterfactual tracer without active biology.
- Or in the adjoint you can choose not to differentiate the biology, taking advantage of the flow directive capability. Otherwise, say, the sensitivity to heat fluxes and carbon fluxes effects may overlap. In previous studies, I have used the adjoint **flow directive capability** when computing sensitivity maps. I have selectively not differentiated parts of the model code to isolate contributions of different processes.  
**Mathematically clean, difficult to communicate (Linear)**
- Alternatively, for a more indirect comparison with CO<sub>2</sub> but a more direct and intuitive comparison with the real world, you can consider CFCs as purely abiotic tracers.

PMEL NOAA  
CFC-11 Inventory (moles/km<sup>2</sup>)



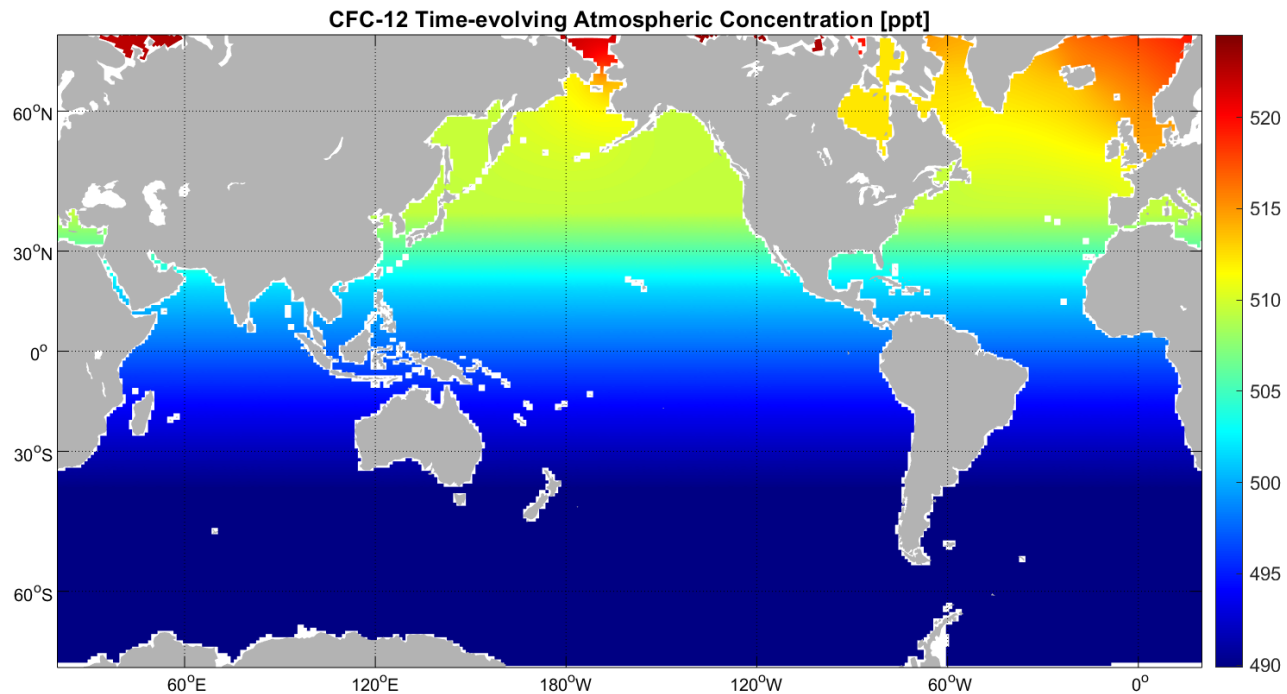
**CFCs are an abiotic analogue to anthropogenic carbon in the ocean highlighting the North Atlantic subpolar gyre**

Setup

# CFCs in ECCO

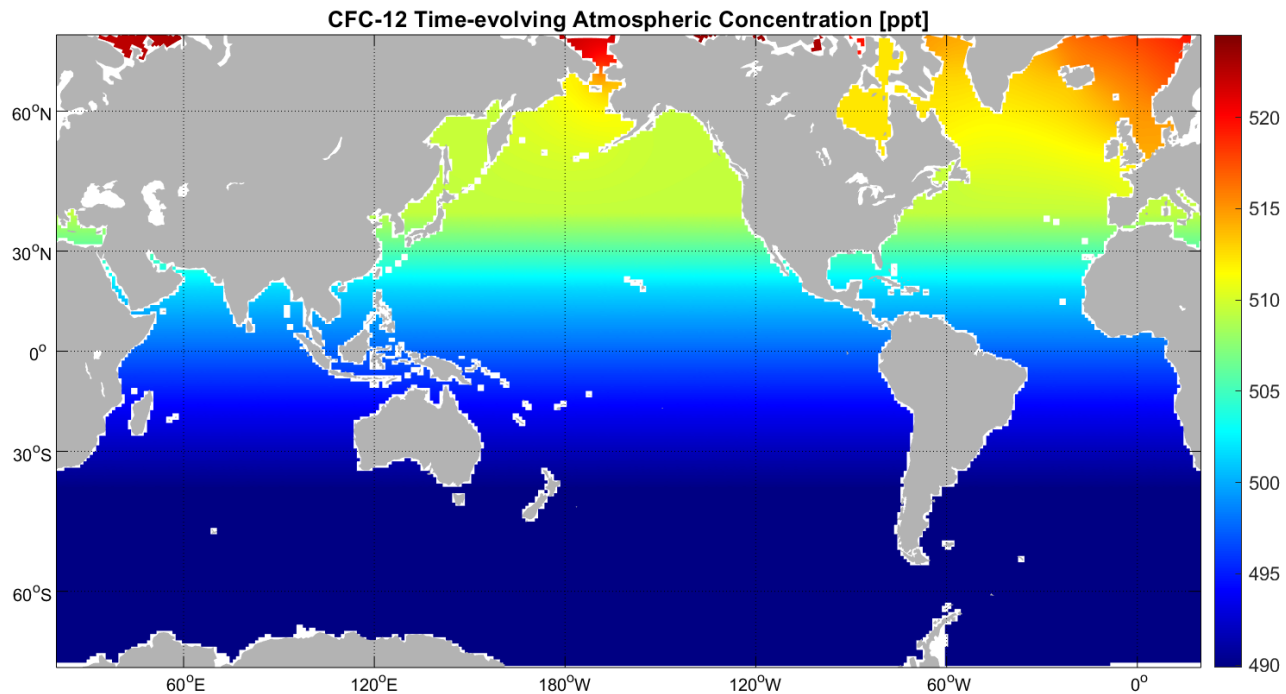
- ❖ Initialization with GLODAP
- ❖ Inclusion of historical time-evolving and latitude-dependent atmospheric CFCs in ECCO.
- ❖ Parametrization of gas transfer (piston) velocity.
- ❖ Comparison of CFCs (abiotic analogue to anthrop. carbon) against PV (abiotic analogue to oxygen).

# Time-evolving, zonally varying atmospheric concentration



Jan. 1992

# Time-evolving, zonally varying atmospheric concentration



Jan. 1992

I included both CFC-11 and CFC-12, but still  
have to verify CFC-12

**Time-evolving monthly-averaged zonally-dependent atmospheric concentration datasets from NOAA, re-gridded on the ECCOv4 native coordinates and converted to binary files**

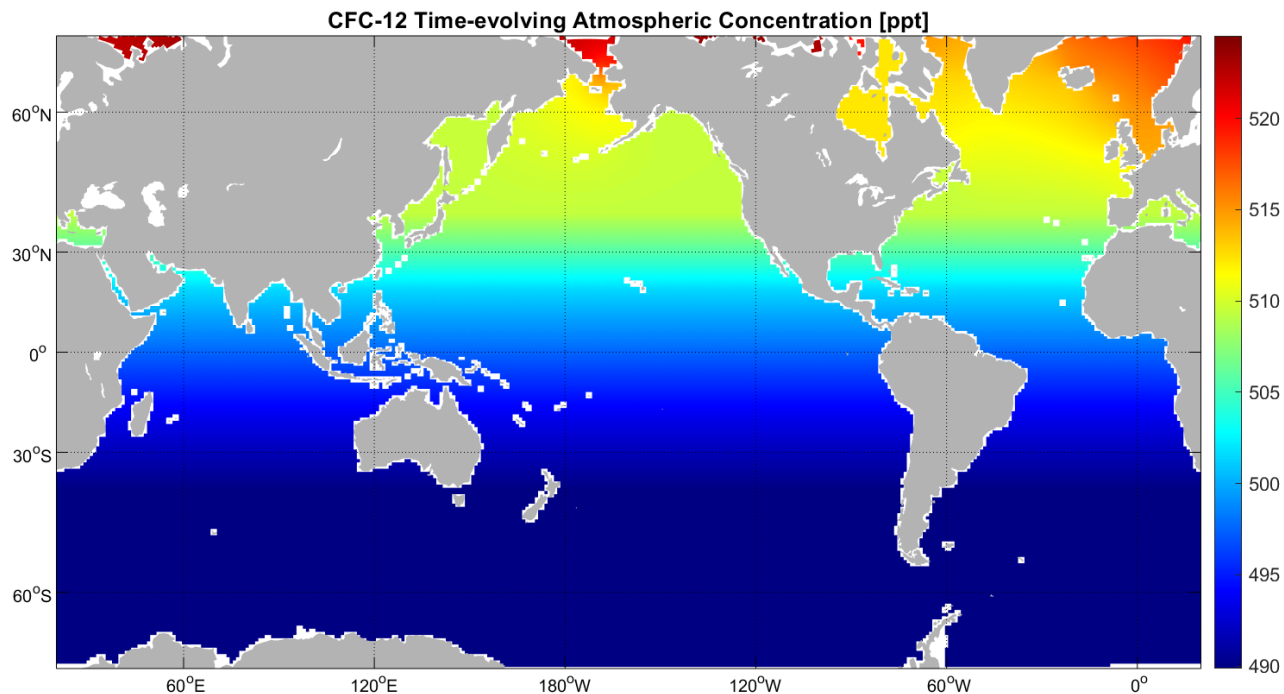
# **Time-evolving monthly-averaged zonally-dependent atmospheric concentration datasets from NOAA, re-gridded on the ECCOv4 native coordinates and converted to binary files**

Dutton, G.S., B.D. Hall, S.A. Montzka, J.D. Nance, S.D. Clingan, K.M. Petersen (2025), Combined Atmospheric Chlorofluorocarbon-11 Dry Air Mole Fractions from the NOAA GML Halocarbons Sampling Network, 1977-2025, Version: 2025-05-12, <https://doi.org/10.15138/BVQ6-2S69>

Dutton, G.S., B.D. Hall, S.A. Montzka, J.D. Nance, S.D. Clingan, K.M. Petersen (2025), Combined Atmospheric Chlorofluorocarbon-12 Dry Air Mole Fractions from the NOAA GML Halocarbons Sampling Network, 1977-2025, Version: 2025-05-12, <https://doi.org/10.15138/PJ63-H440>

Dutton, G.S., B.D. Hall, E.J. Dlugokencky, X. Lan, M. Madronich, J.D. Nance, K.M. Petersen (2025), Combined Atmospheric Sulfur hexafluoride Dry Air Mole Fractions from the NOAA GML Halocarbons Sampling Network, 1995-2025, Version: 2025-05-12, <https://doi.org/10.15138/TQ02-ZX42>

# Time-evolving, zonally varying atmospheric concentration



Jan. 1992

Based on the Dutton et al. dataset from NOAA  
Re-gridded on the ECCOV4 native coordinates

# Air-sea fluxes of CFC

$$F = k(C_w - \alpha C_a)$$

Gas transfer velocity depends on **sea-ice cover** and on **surface winds**;

Solubility depends on **temperature and salinity**.

Also depends on **mixing** near the ocean skin layer.

Schmidt numbers (mixing param.) dependent on gas species;

e.g., Wanninkof et al. (2009)  
in *Annu. Rev. Marine Sci.*

```

C calculate SCHMIDT NO. for CFC12
    SchmidtNocfc12(i,j) =
    &         sca_12_1
    &         + sca_12_2 * thetaTOP(i,j,bi,bj)
    &         + sca_12_3 * thetaTOP(i,j,bi,bj)*thetaTOP(i,j,bi,bj)
    &         + sca_12_4 * thetaTOP(i,j,bi,bj)*thetaTOP(i,j,bi,bj)
    &         *thetaTOP(i,j,bi,bj)
c calculate solubility for CFC12
    ttemp2=( B3_12 * ttemp + B2_12 )*ttemp + B1_12
    SolCFC12(i,j) =
    &         EXP ( A1_12
    &         + A2_12 / ttemp(i,j,bi,bj)
    &         + A3_12 * log( ttemp(i,j,bi,bj) )
    &         + A4_12 * ttemp(i,j,bi,bj) * ttemp(i,j,bi,bj)
    &         + saltTOP(i,j,bi,bj)* ttemp2(i,j,bi,bj) )
c conversion from mol/(1 * atm) to mol/(m^3 * atm)
    SolCFC12(i,j) = 1000. _d 0 * SolCFC12(i,j)
c conversion from mol/(m^3 * atm) to mol/(m3 * pptv)
    SolCFC12(i,j) = 1. _d -12 * SolCFC12(i,j)
C Determine surface flux (Fcf12)
    Csat(i,j) = SolCFC12(i,j)*AtmPress
    &         *AtmHist2(i,j,month_count,bi,bj)
    rec_tauRlx=rbcsvanishingFac
    &         *AREAopen(i,j,bi,bj)
    &         * pisVel(i,j,bi,bj)
    &         / SQRT(SchmidtNoCFC12(i,j)/660. _d 0)
    &         /(drF(1)*hFacC(i,j,1,bi,bj))
    ENDIF
    gTendency(i,j) = gTendency(i,j)
    &         - RBC_mask(i,j,k,bi,bj,irbc)*rec_tauRlx
    &         *( pTracer(i,j,k,bi,bj,iTracer)
    &         - Csat(i,j) )
C    &         RBC_ptracers(i,j,k,bi,bj,iTracer)

```

# Old CFC Package

incompatible with ECCO

- No initial condition – always spun-up from the end of the pre-CFC era.
- The only possibility is to prescribe exactly 100 years of annually-averaged forcing. No monthly variability.
- One value for each hemisphere, no other zonal variability.
- **No** adjoint sensitivity to an initial condition.  
Unclear compatibility when it comes to surface flux sensitivity or storing the background state.
- **Not** compatible with the ECCOv4, ASTE, or BLING grids.

<https://github.com/MITgcm/MITgcm/tree/master/pkg/cfc>

[https://github.com/MITgcm/MITgcm/tree/master/verification/tutorial\\_cfc\\_offline](https://github.com/MITgcm/MITgcm/tree/master/verification/tutorial_cfc_offline)

**NEW:**

**Concentrations and fluxes on the ECCO grid;**

**Initialization with GLODAP;**

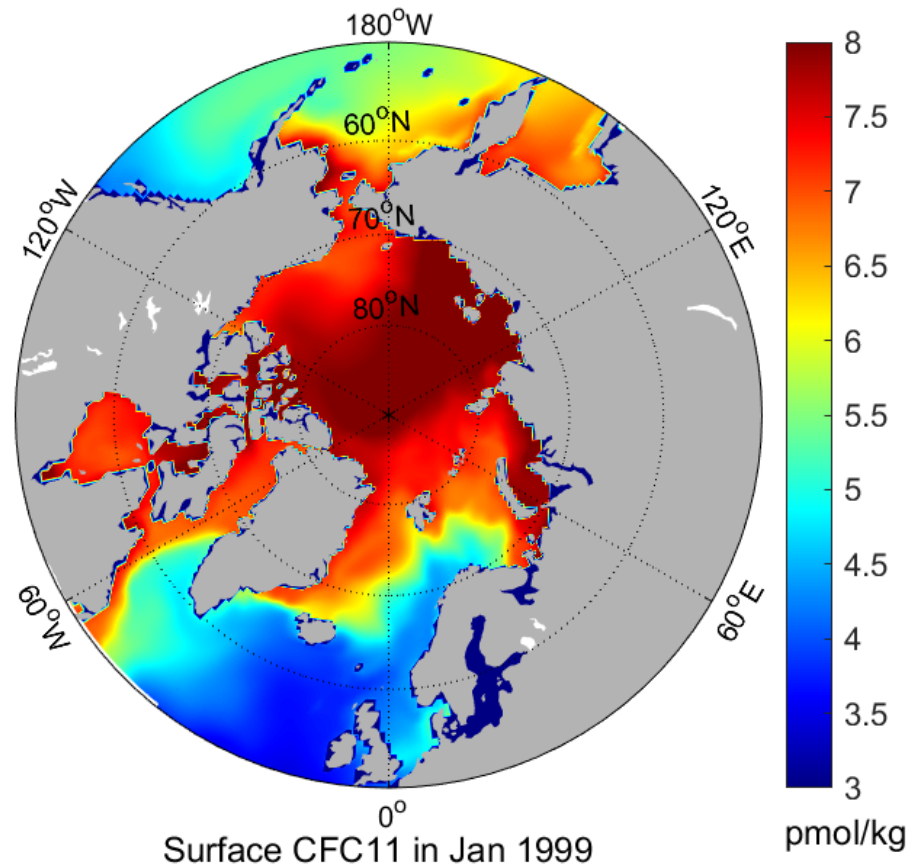
**Time-evolving monthly-averaged zonally-dependent atmospheric concentrations**

**Use of the differentiable relaxation package.**

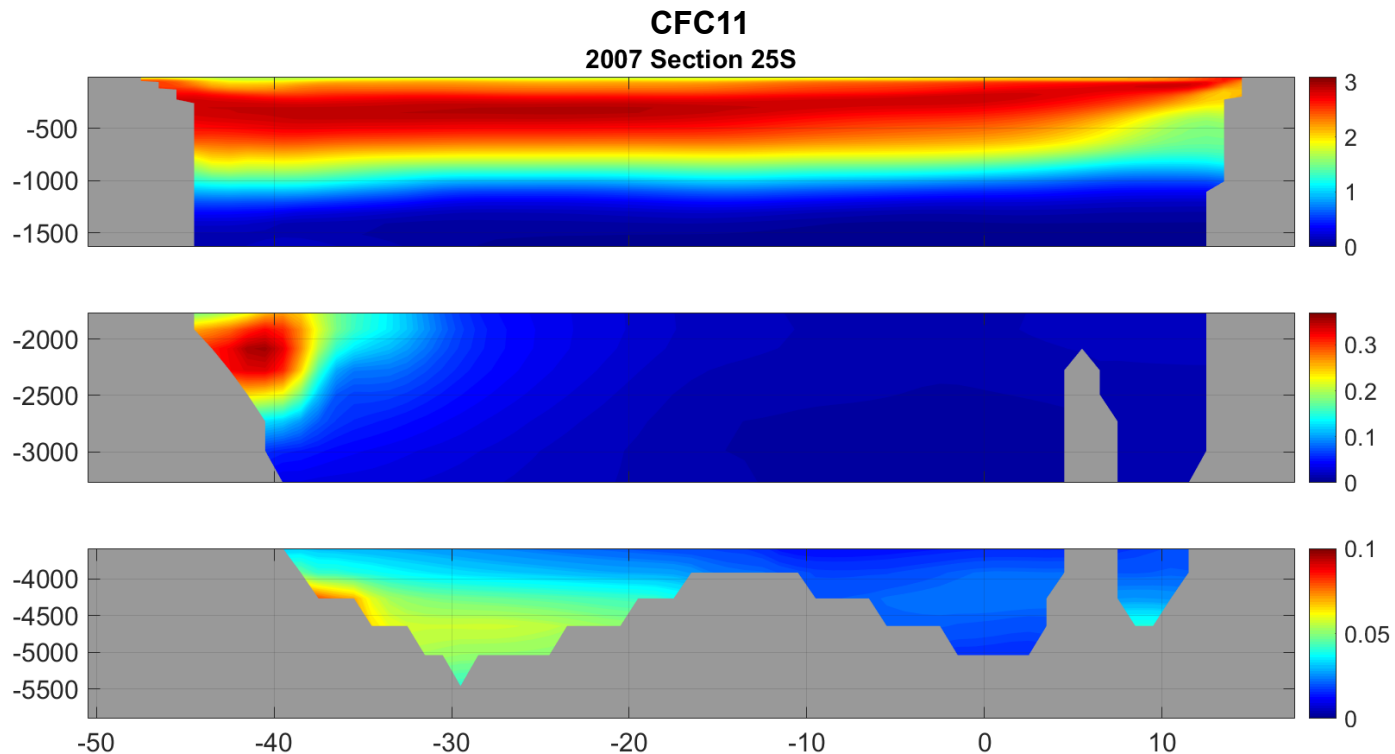
**Possibility to further breakdown the surface flux sensitivity offline.**

# Results

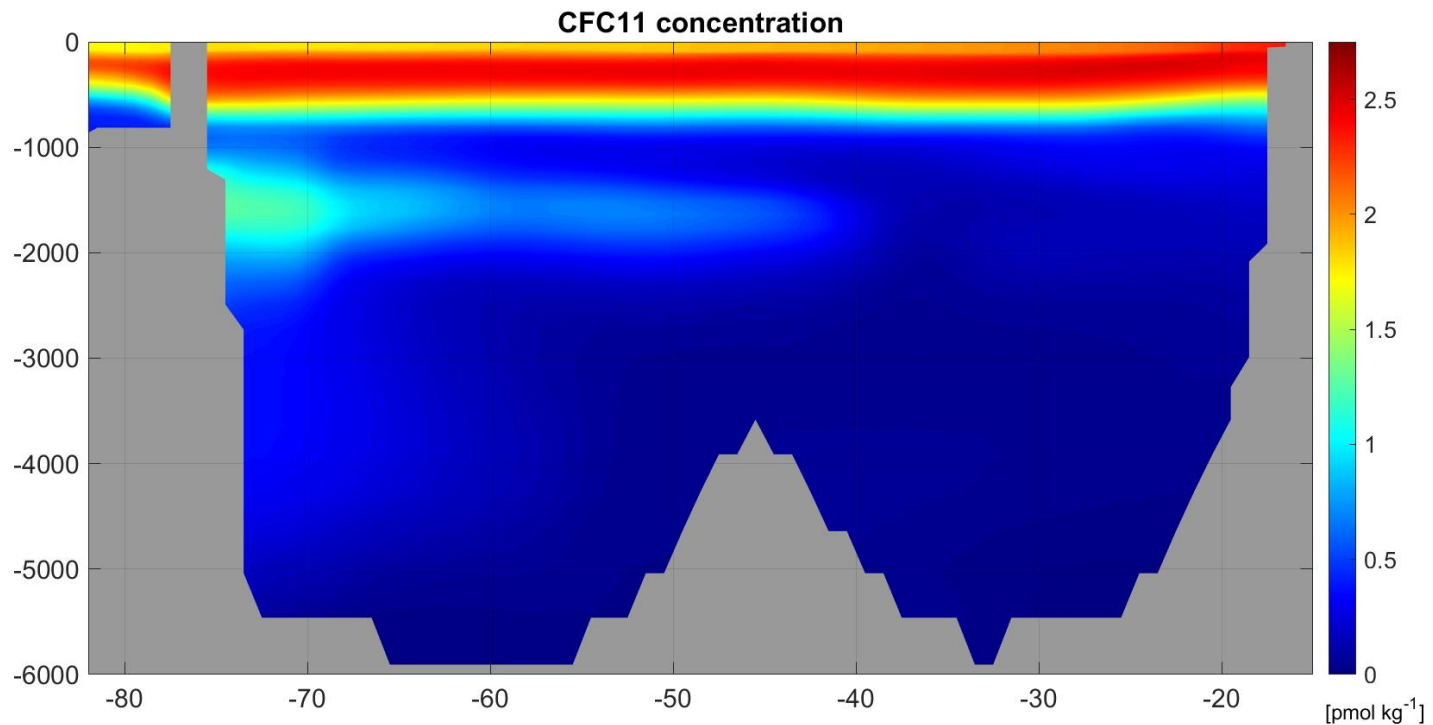
# A large advective signal in the marginal ice zone



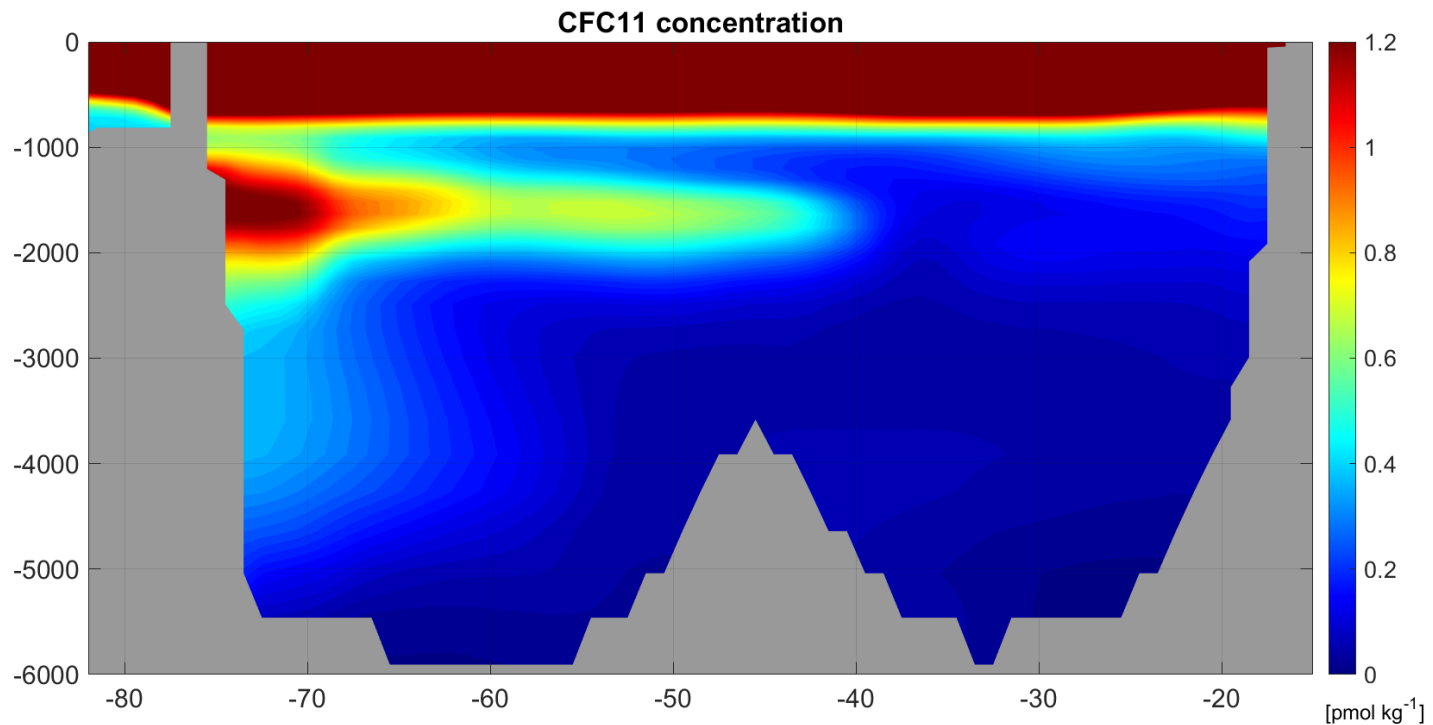
# CFCs are useful for illustrating the ventilation of water masses



# Large CFC signal in the DWBC along 24N

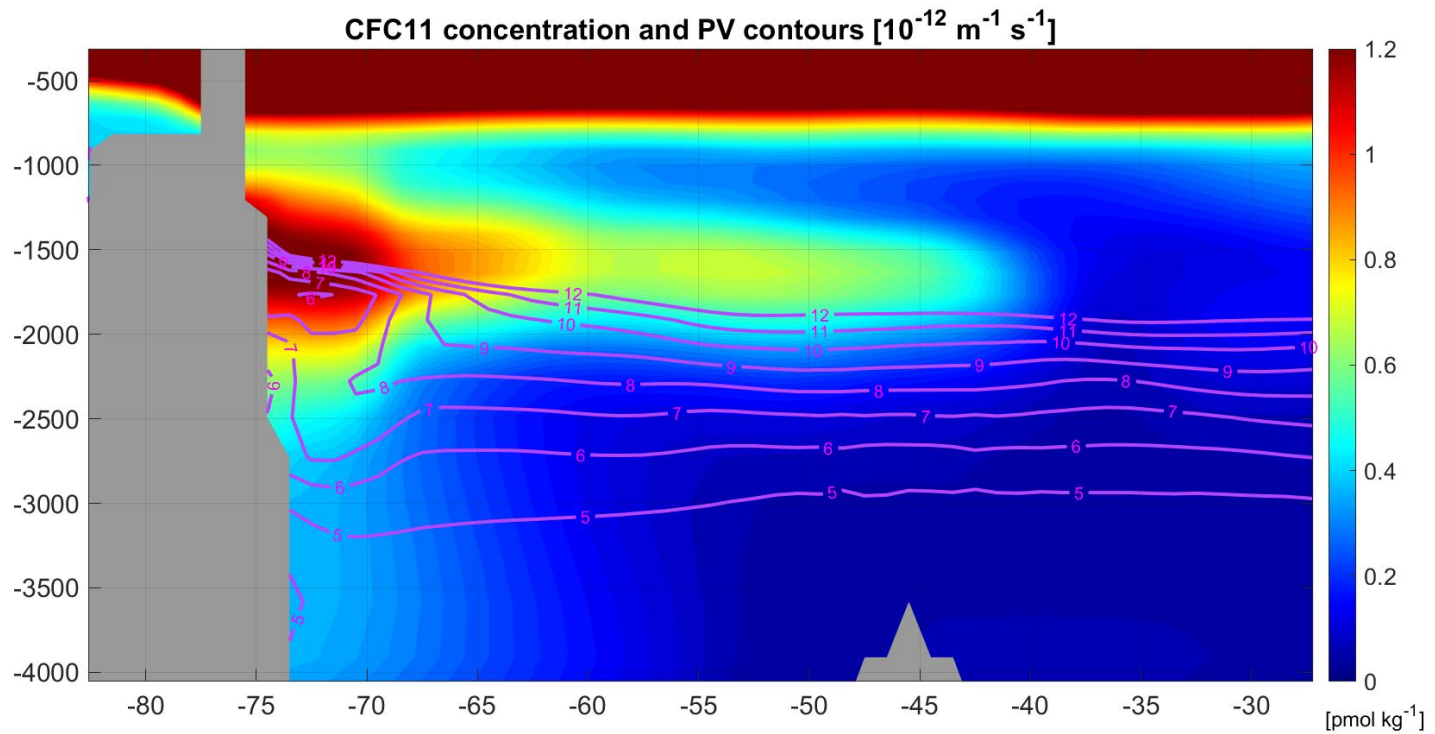


# Large CFC signal in the DWBC along 24N

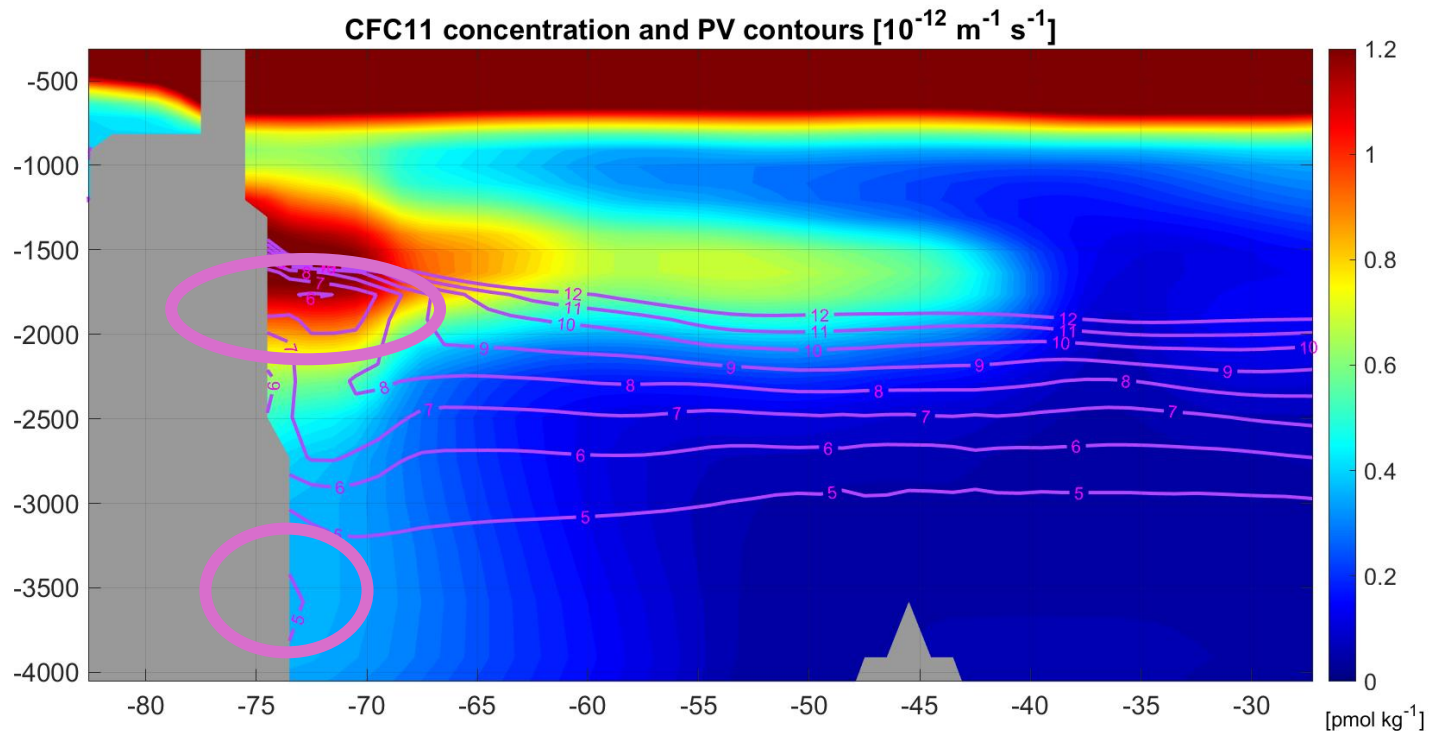




# Large CFC signal in the DWBC

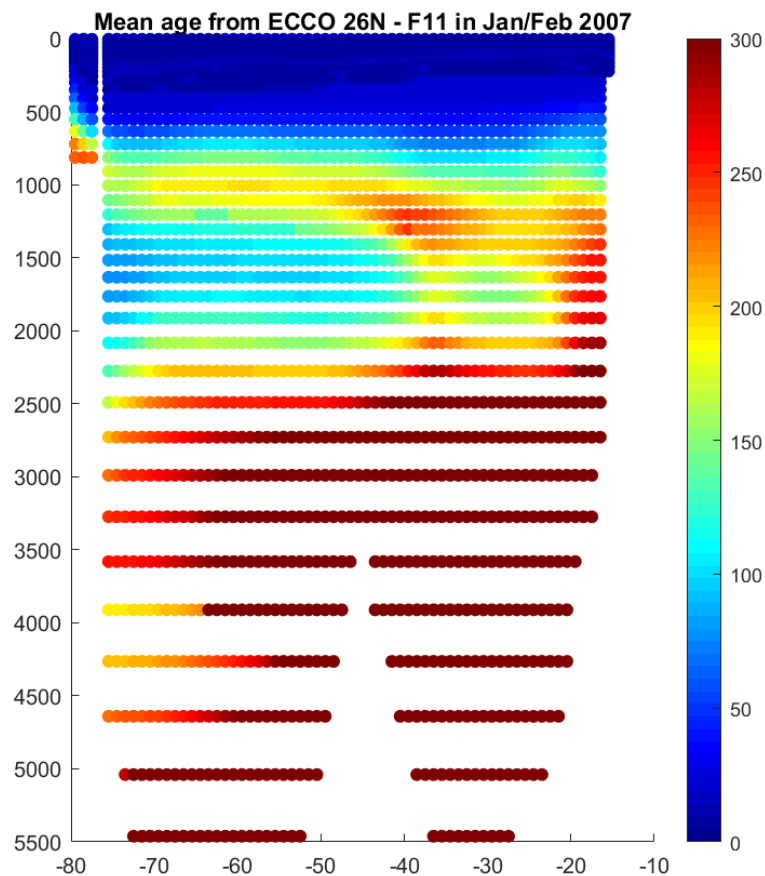


# The **CFC “core”** is above the PV minimum/minima

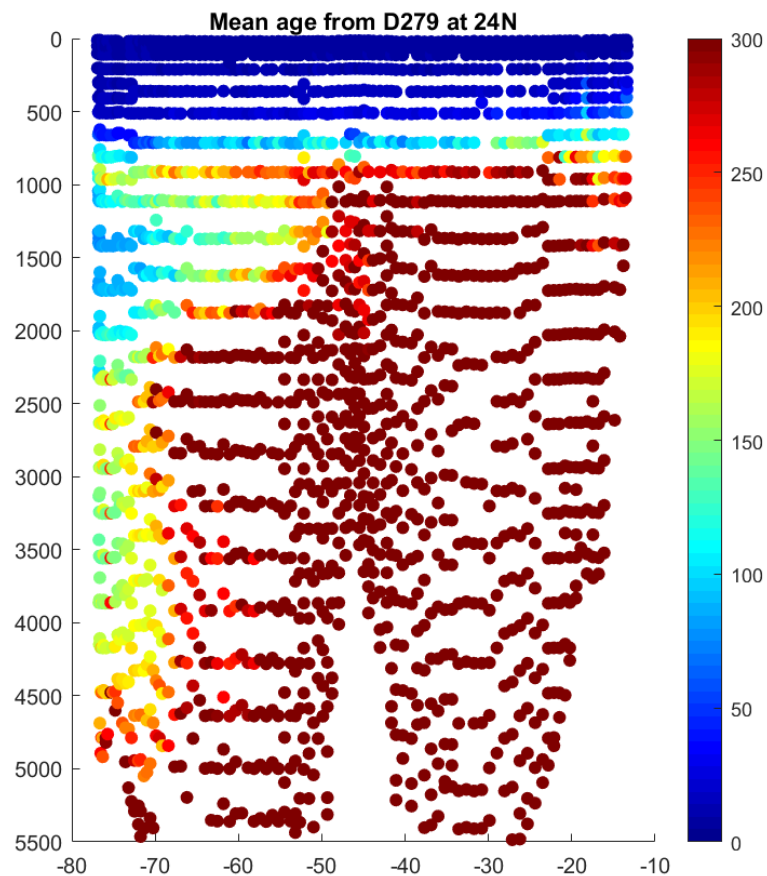


**Not a transient aberration and not peculiar to ECCO only**

# Using CFC11 to invert for water mass age along $\gamma^n$ surfaces, assuming an inverse Gaussian advective-diffusive solution

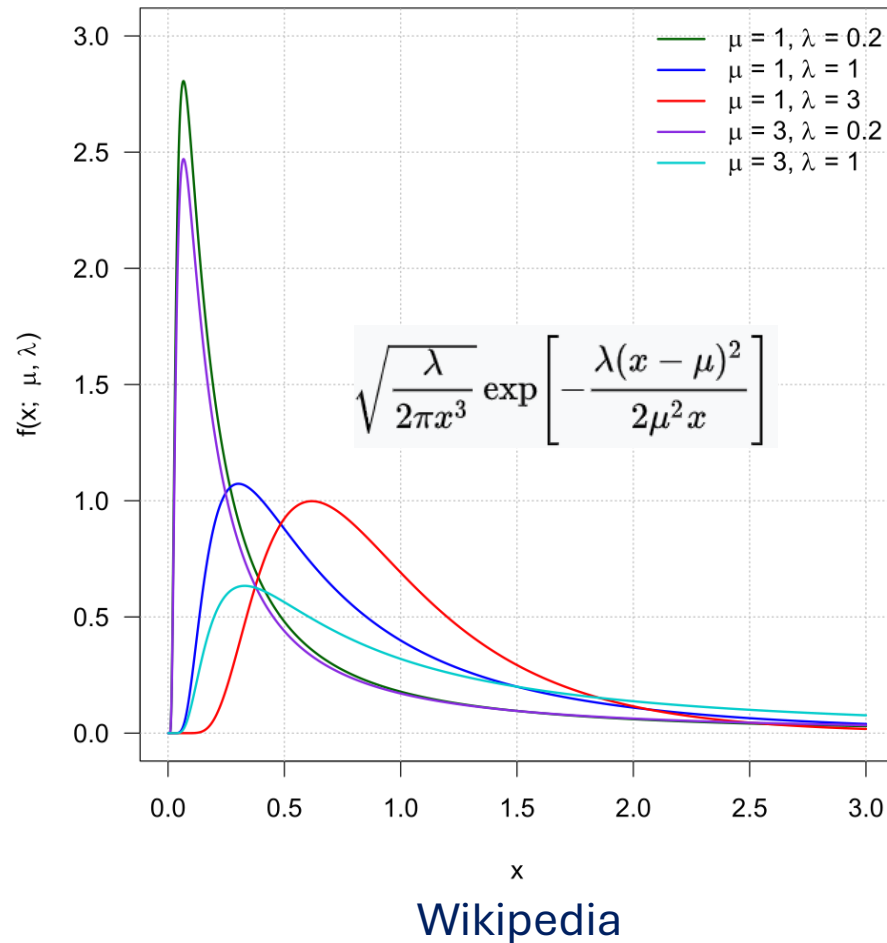


ECCO



Bottle data from cruise D279

# Inverse Gaussian with mean $\mu$ and variance $\mu^3 / \lambda$



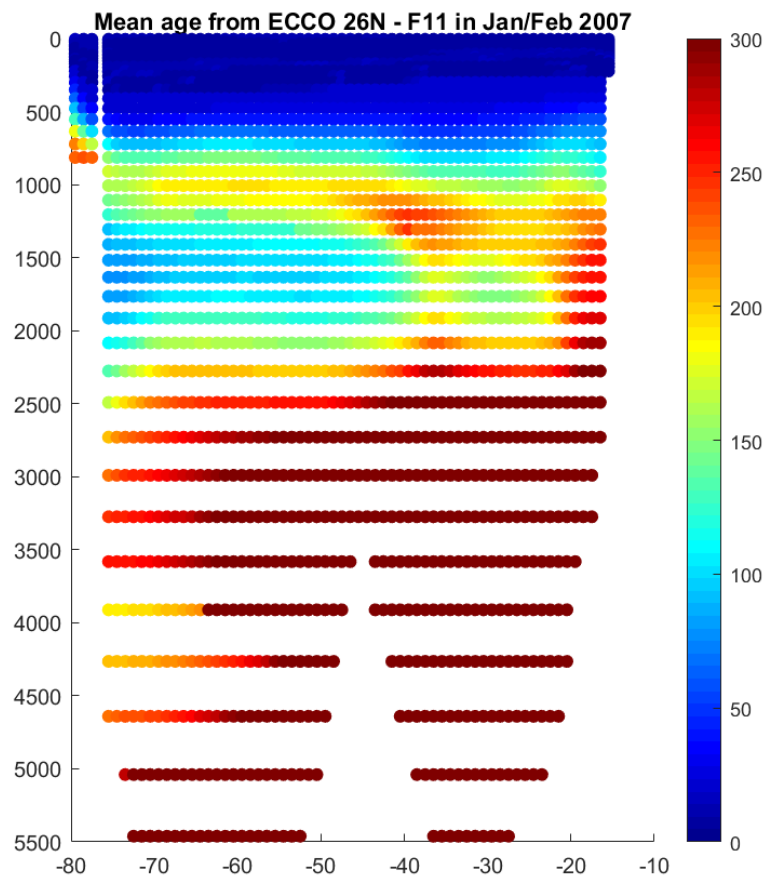
Using CFC11 to invert for water mass age  
along  $\gamma^n$  surfaces,  
assuming an inverse Gaussian advective-diffusive solution

Methodology:

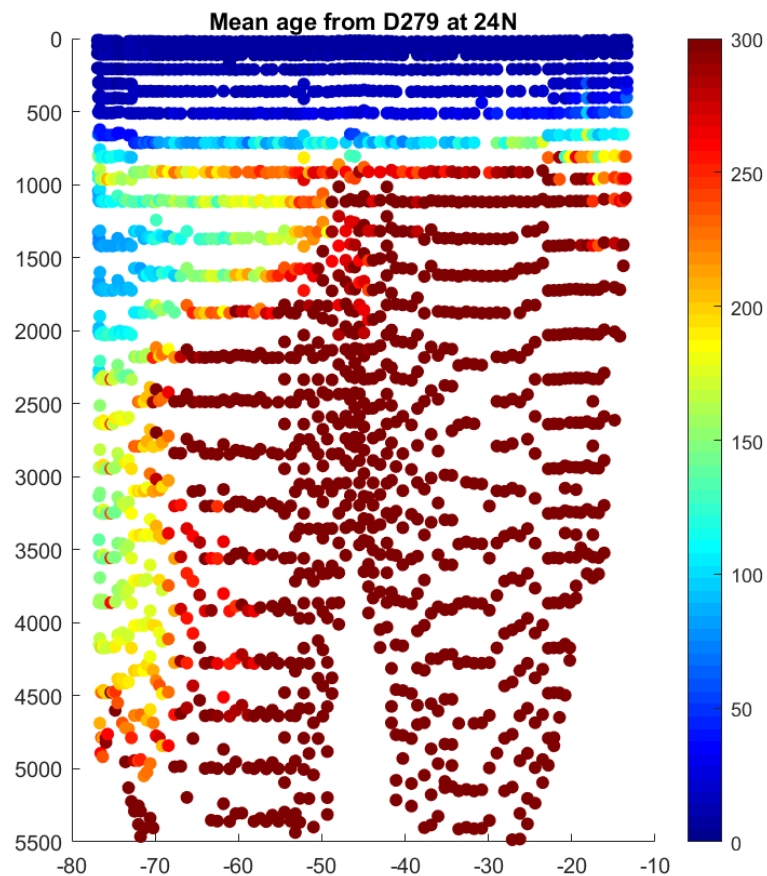
Messias, MJ., Mercier, H. The redistribution of anthropogenic excess heat is a key driver of warming in the North Atlantic. *Commun Earth Environ* **3**, 118 (2022). <https://doi.org/10.1038/s43247-022-00443-4>

Holzer, M. & Hall, T. M. Transit-time and tracer-age distributions in geophysical flows. *J. Atmos. Sci.* **57**, 3539–3558 (2000). [https://doi.org/10.1175/1520-0469\(2000\)057<3539:TTATAD>2.0.CO;2](https://doi.org/10.1175/1520-0469(2000)057<3539:TTATAD>2.0.CO;2)

# Using CFC11 to invert for water mass age along $\gamma^n$ surfaces, assuming an inverse Gaussian advective-diffusive solution



ECCO



Bottle data from cruise D279

Application:

CFC-11 as an abiotic analogue  
to biologically active tracers

Case 1:  
Labrador Sea

# Seasonal cycle of tracer surface concentration in the Labrador Sea

- Williams et al. (2026) consider the annual surface flux of CO<sub>2</sub> as decomposed into thermal and biophysical contributions
- Seasonality (winter to summer contrasts) play an important role in the biophysical contribution

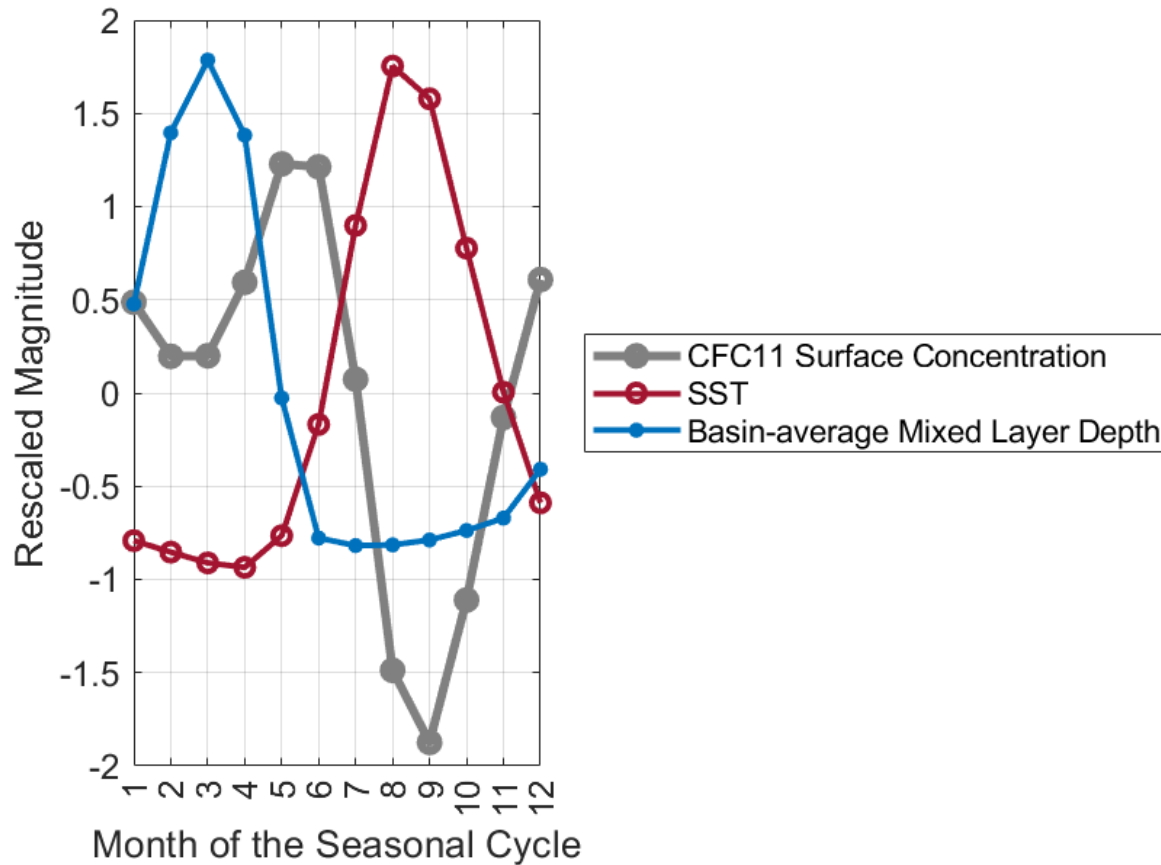
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- The biophysics capture an interplay between physics and biology. Could this be disentangled further?

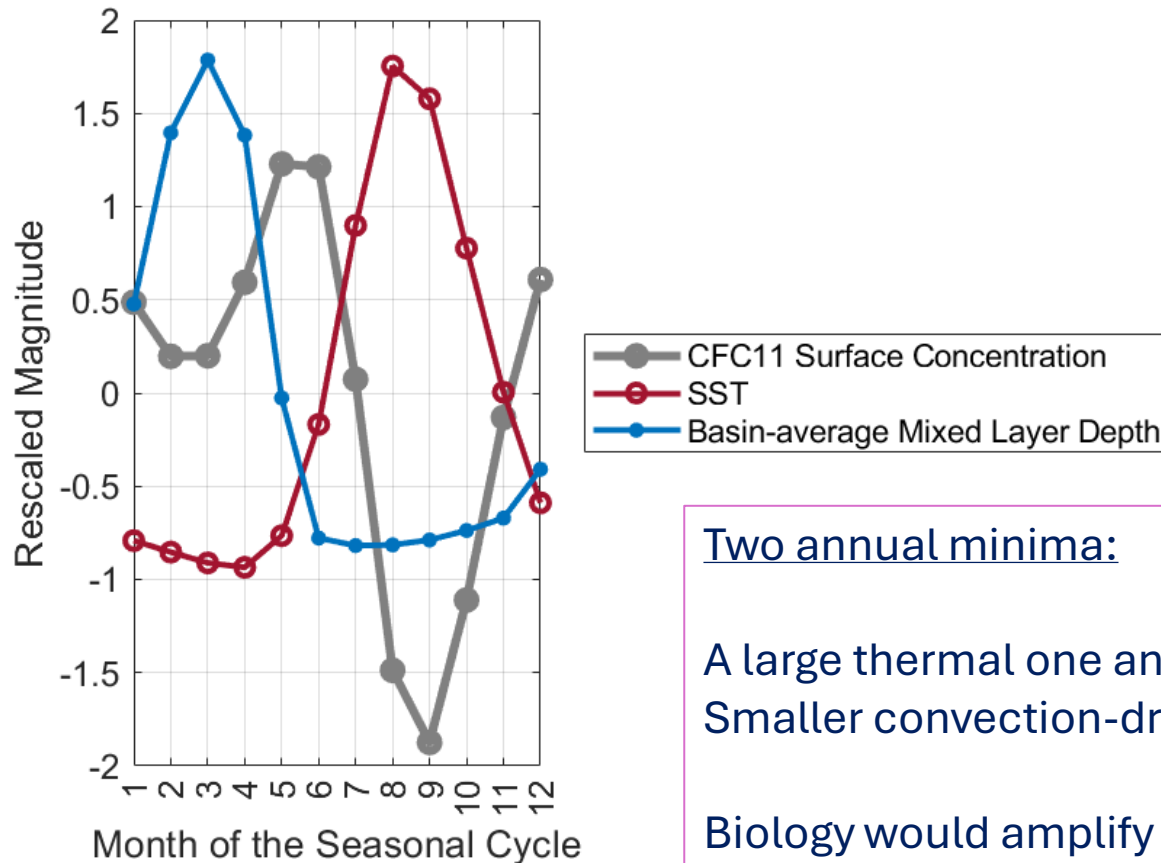
# Seasonal cycle of tracer surface concentration in the Labrador Sea

- Williams et al. (2026) consider the annual surface flux of CO<sub>2</sub> as decomposed into thermal and biophysical contributions
  - Seasonality (winter to summer contrasts) play an important role in the biophysical contribution
  - The biophysics capture an interplay between physics and biology. Could this be disentangled further?
- You can consider CFCs as purely abiotic tracers.

# Seasonal cycle of tracer surface concentration in the Labrador Sea



# Seasonal cycle of tracer surface concentration in the Labrador Sea



Two annual minima:

A large thermal one and a  
Smaller convection-driven dip

Biology would amplify the seasonal  
effects for CO<sub>2</sub> relative to CFC-11

# Textbook cases

A subsurface minimum in stratification  
(minimum in PV magnitude) matches:

- ❖ A local maximum in dissolved oxygen;
- ❖ A local maximum in the CFC concentration.

All because of ventilation.

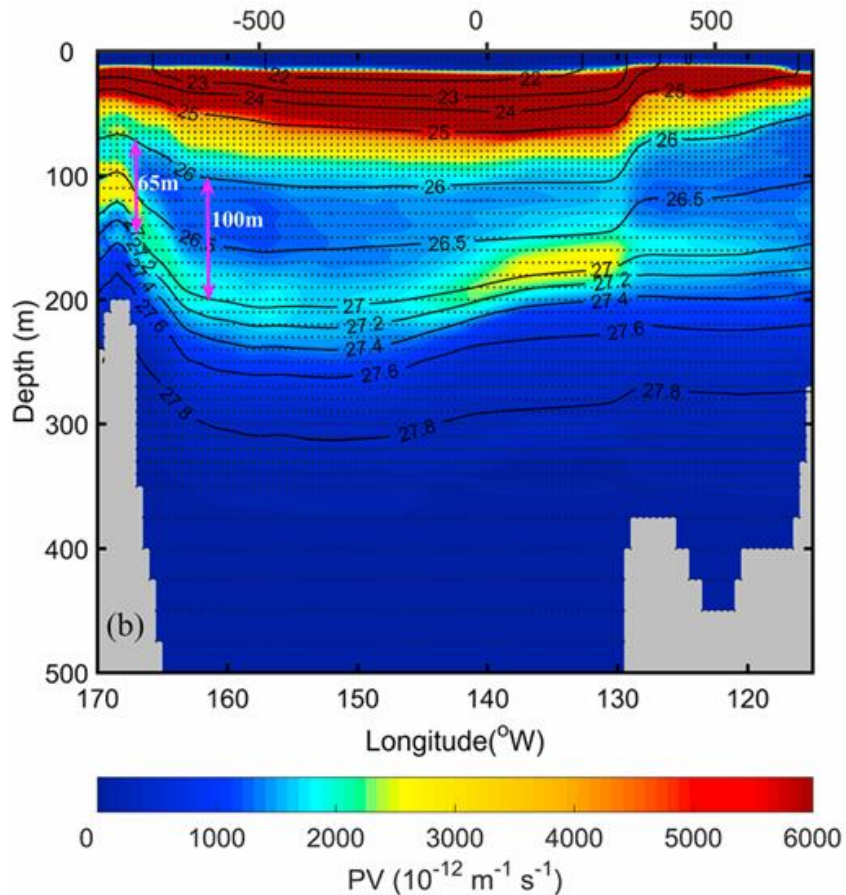
Exception:

Pacific Winter Water in the Arctic  
because of biology and sea-ice

Case 2:

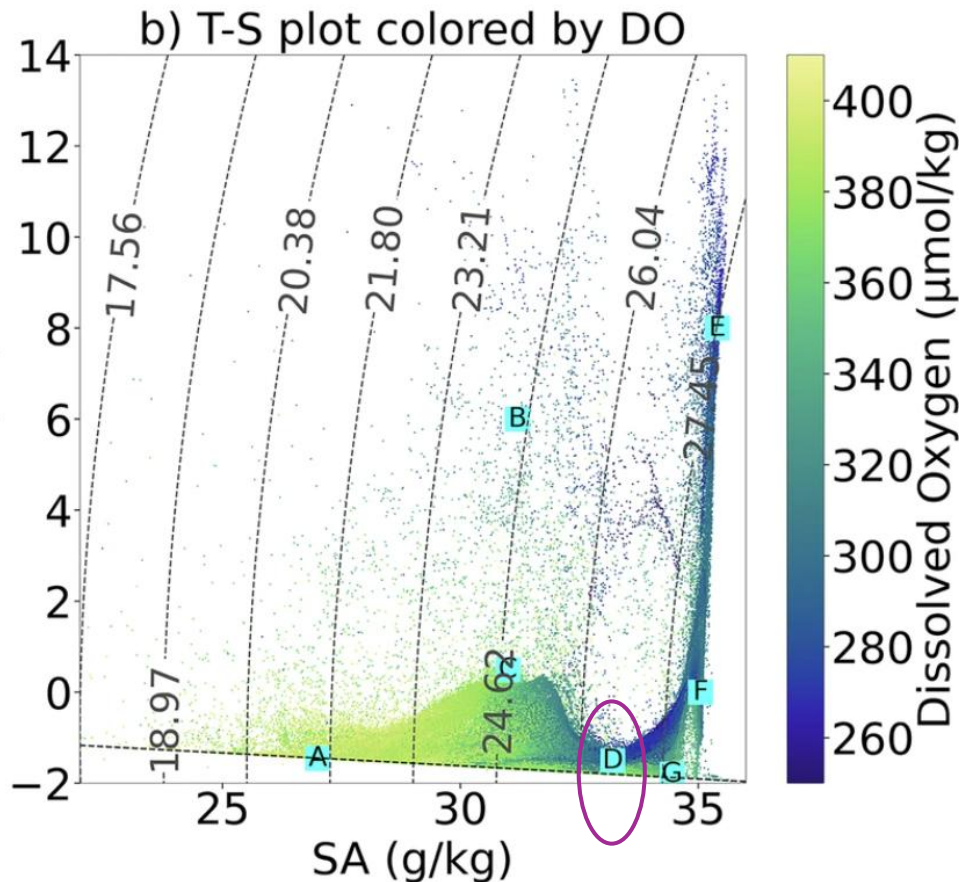
Pacific Winter Water in the Arctic

# Pacific Winter Water is a PV minimum



Zhong, W., Steele, M., Zhang, J., & Cole, S. T. (2019). Circulation of Pacific Winter Water in the western Arctic Ocean. *Journal of Geophysical Research: Oceans*, 124, 863–881. <https://doi.org/10.1029/2018JC014604>

# Pacific Winter Water is an oxygen minimum!



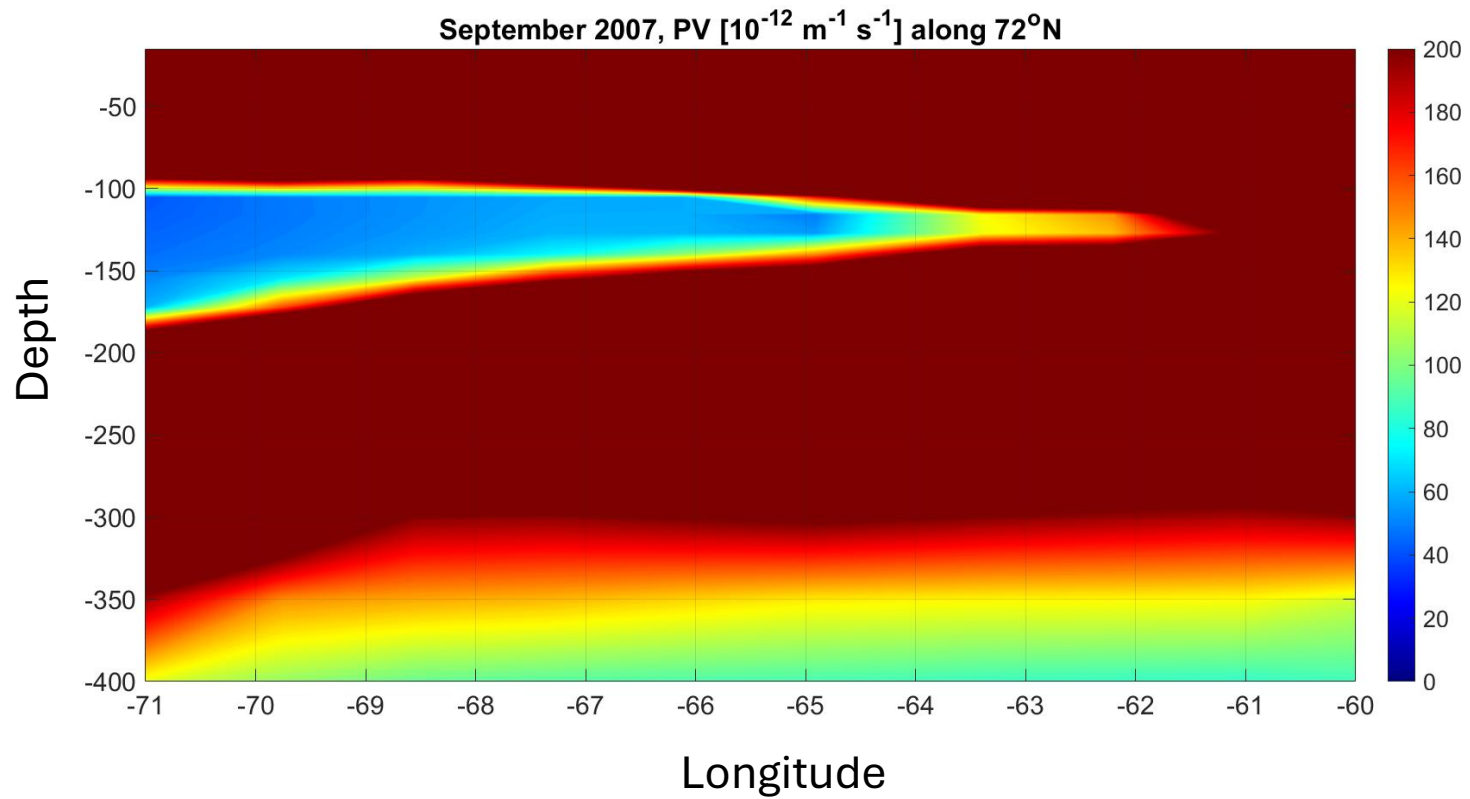
D - winter Pacific Water (sPW)

Oglethorpe, K., Lanham, J., Reiss, R.S. *et al.* Water Masses of the Arctic from 40 Years of Hydrographic Observations. *Sci Data* **13**, 456 (2026).

<https://doi.org/10.1038/s41597-026-06749-8>

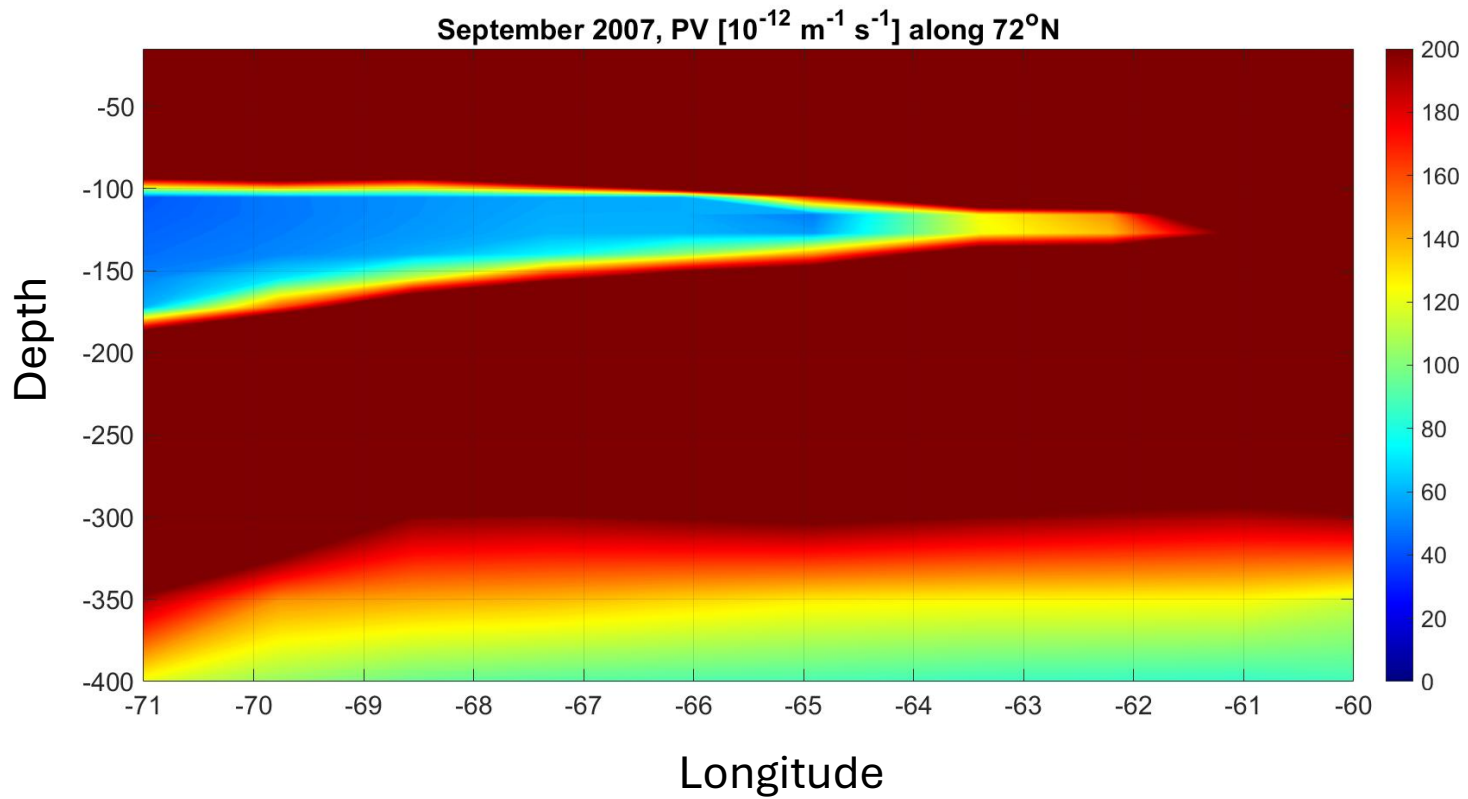
**Oxygen minimum due to respiration in the Chukchi Sea**

# Subsurface PV Minimum in PWW



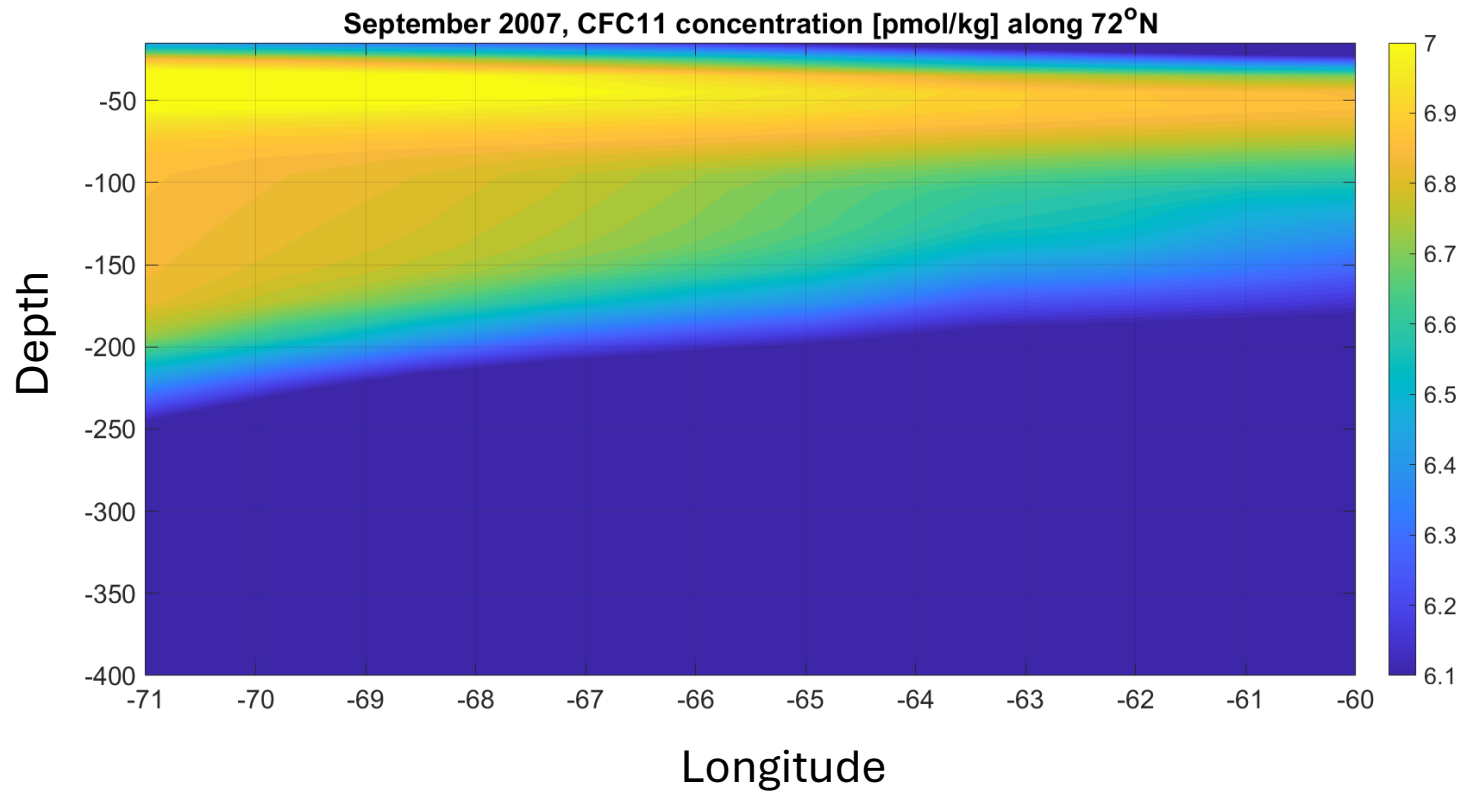
# Subsurface PV Minimum in PWW

Might we expect a matching subsurface CFC-11 maximum?



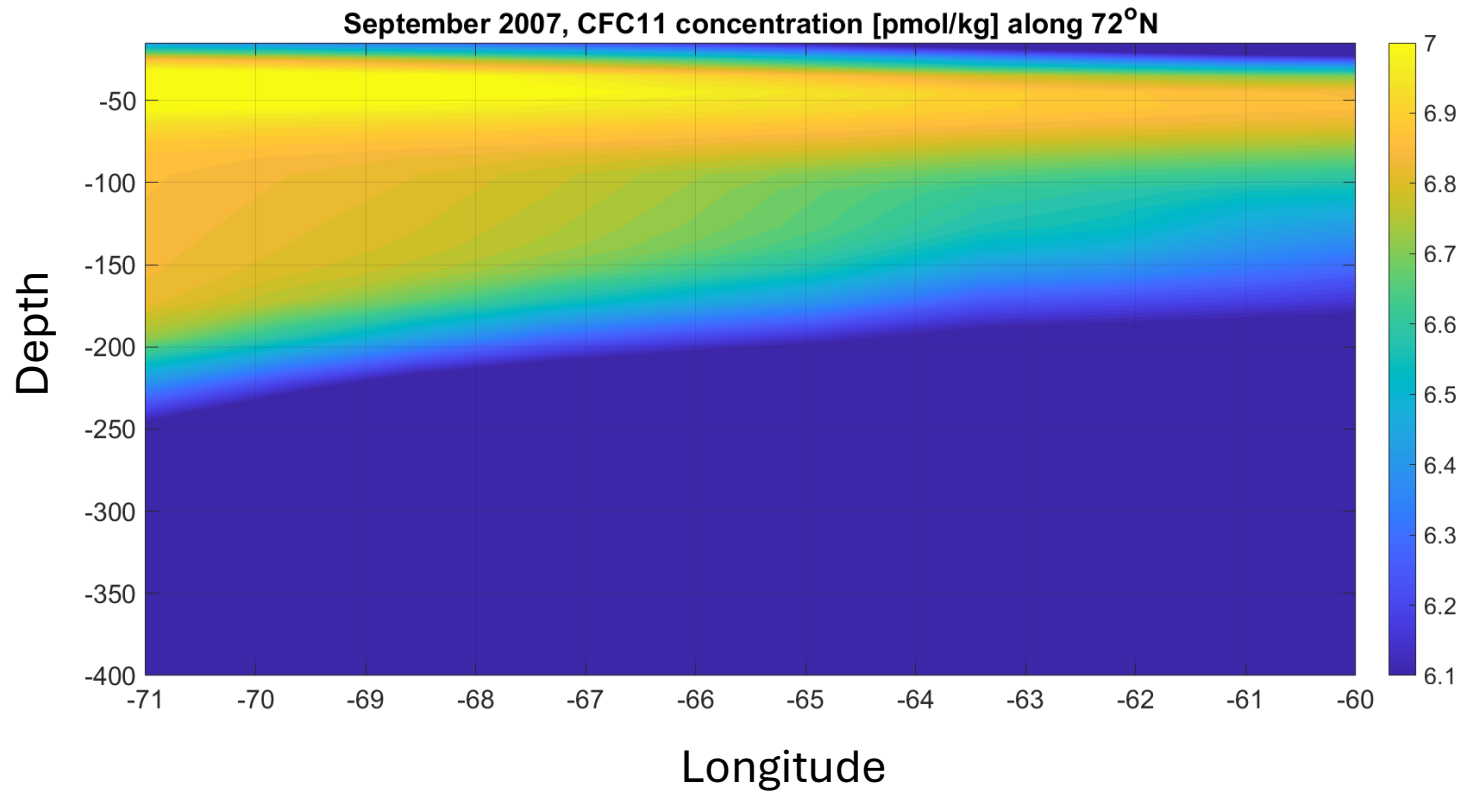
Not matched by a subsurface max. in CFC11  
(gradual decline in concentration with depth)

Contrast with PV: most likely a sea-ice effect

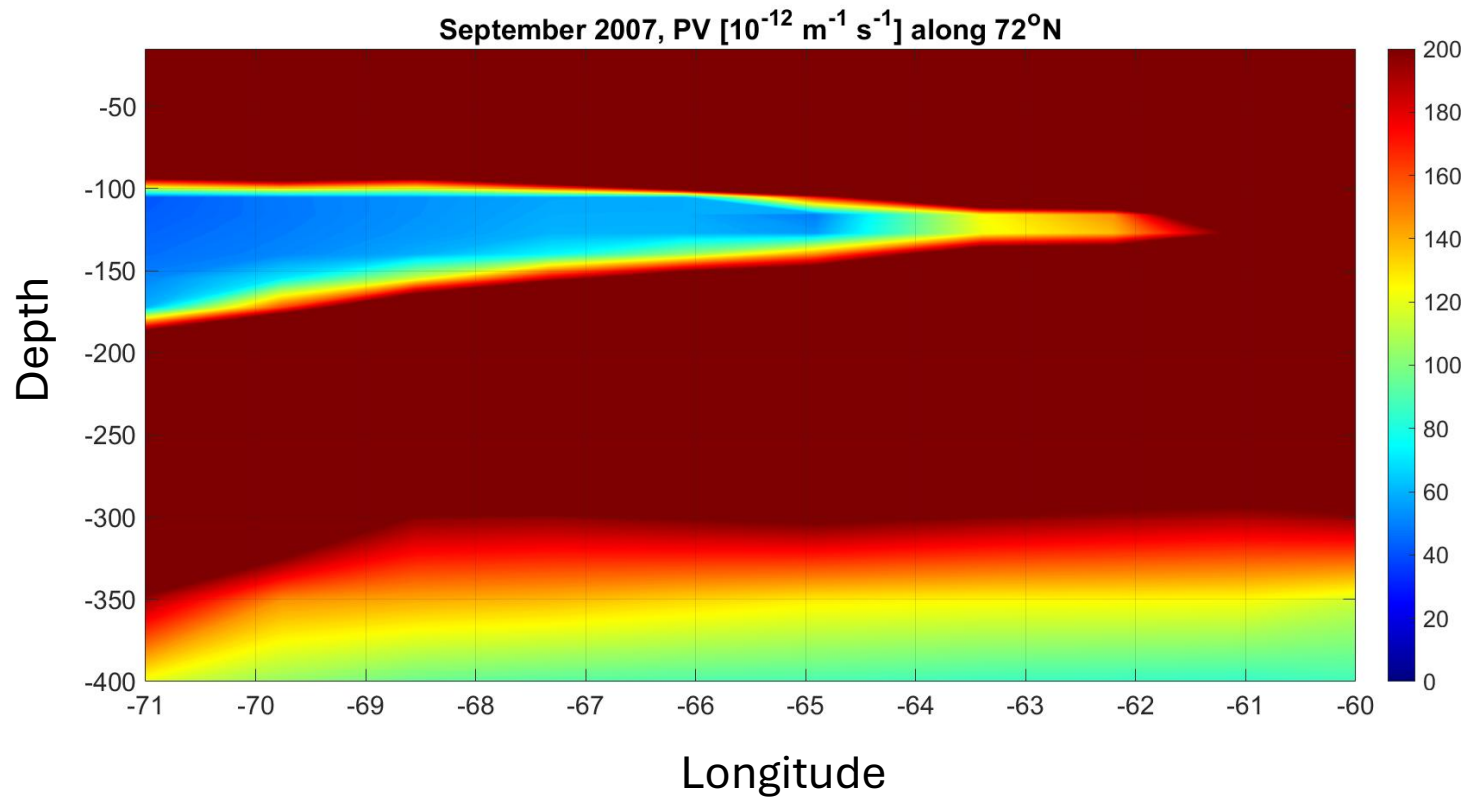


Not matched by a subsurface max. in CFC11  
(gradual decline in concentration with depth)

**Sea-ice formation: brine rejection but surface insulation**



# Subsurface PV Minimum in PWW



# Key points:

- ❖ Pacific Winter Water represents a subsurface local PV minimum because the minimum forms as a result of sea-ice growth, brine rejection, and convection.
- ❖ One might expect a matching CFC-11 subsurface local maximum because of ventilation. However, sea-ice growth isolates the ocean from the atmosphere. As a result, CFC-11 has no subsurface maximum formed during periods of brine rejection. CFC-11 concentration decreases with depth.
- ❖ Oxygen does not just decrease with depth but has a local subsurface minimum due to respiration in the Chukchi sea (not modelled). So, respiration (not modelled) is superimposed on the above sea-ice and convection effects. **To isolate the effect of respiration, we need to account for the above**



# Summary

# CFCs and PV as abiotic analogues of carbon and oxygen in the ocean

- Historical CFCs and PV in ECCO, initialized and forced with observations;
- Possibility to differentiate, invert offline;
- Interesting mismatches between CFC concentration and PV extrema;
- To isolate the biological impacts on biologically active tracers, we can – at least qualitatively – subtract the physical effects that govern abiotic tracers like CFC;
- The observational community can relate to CFC concentrations more intuitively than to counterfactual CO<sub>2</sub> with switched-off biology or adjoint flow directives that block the differentiation of biology.

# Other developments

- ❖ Wang et al. (Dec. 2025) also added CFC-11 to ECCO

Wang, P., Solomon, S., Scott, J. R., Yvon-Lewis, S. A., Wennberg, P. O., Weiss, R. F., et al. (2025). Ocean outgassing of methyl chloroform as an underestimated source of emission. *Geophysical Research Letters*, 52, e2025GL118618. <https://doi.org/10.1029/2025GL118618>

- ❖ I suggest looking at the mixing of CFC-11 alongside the biologically active and dynamically active tracers in the Bellingshausen Sea, as well as circumpolarly around Antarctica (but in NEMO)

# CFC-11 added to ECCO as an abiotic tracer that highlights the role of biology

**Yavor Kostov**

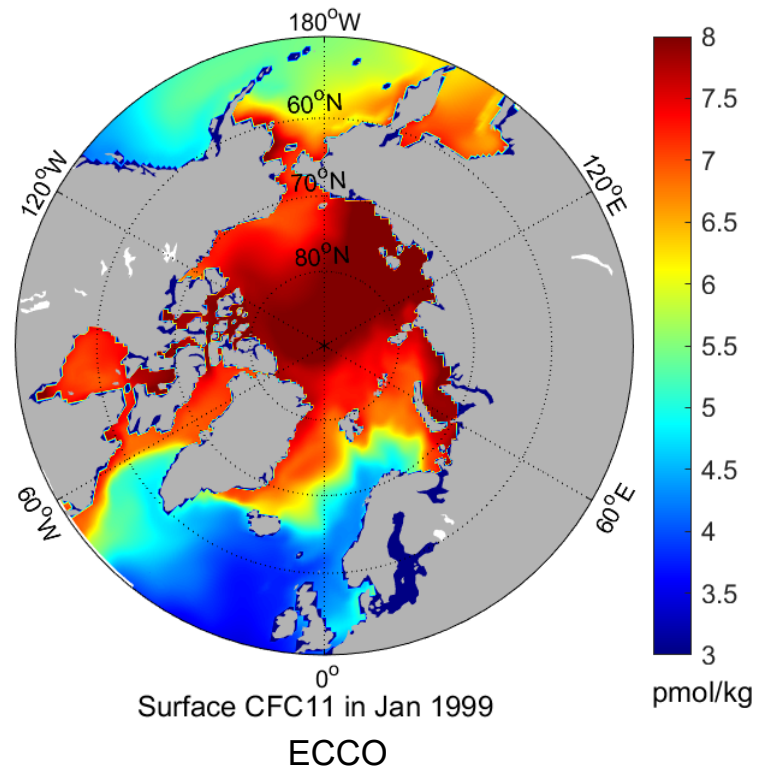
British Antarctic Survey

A collaboration dating back

to my previous postdoc with

Marie -José Messias at Exeter and

Herlé Mercier at IFREMER



***Thank you for your attention!***