Observing and understanding the Atlantic Meridional Overturning Circulation
Conference LEFE-IMAGO (Brest, France, 3-5 May 2017)

AMOC-driven nutrient flux variability across the RAPID-26.5ºN section

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NOAA (US): M. Baringer
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Postdoctoral Project: CAVINA
(CArbon Variability In the North Atlantic)

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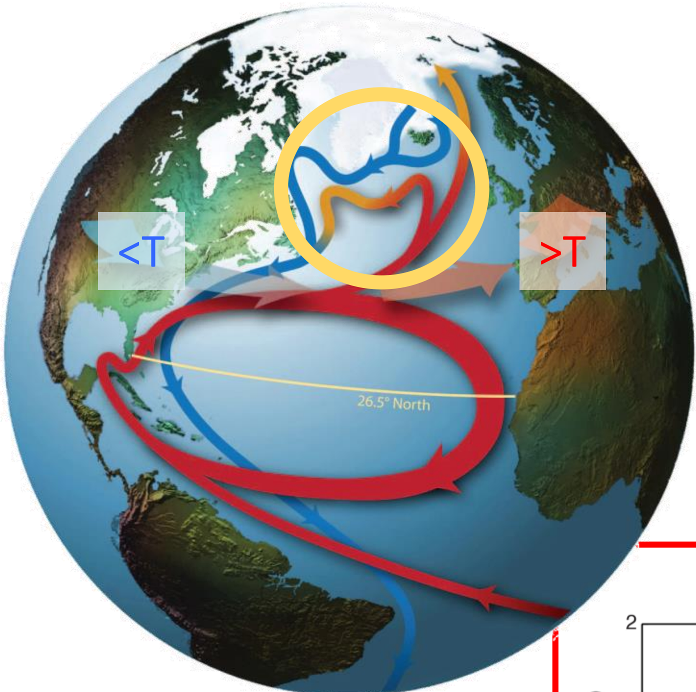
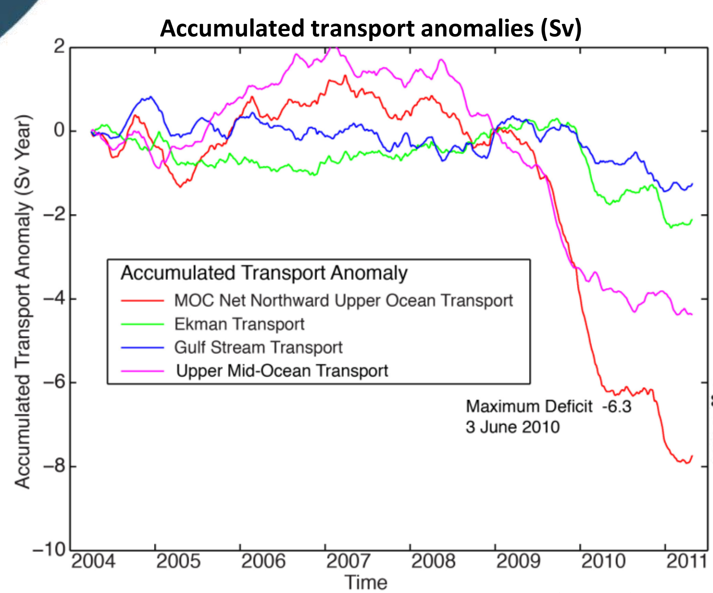
Framework Project: Atlantic BiogeoChemical Fluxes

Why is the AMOC important?

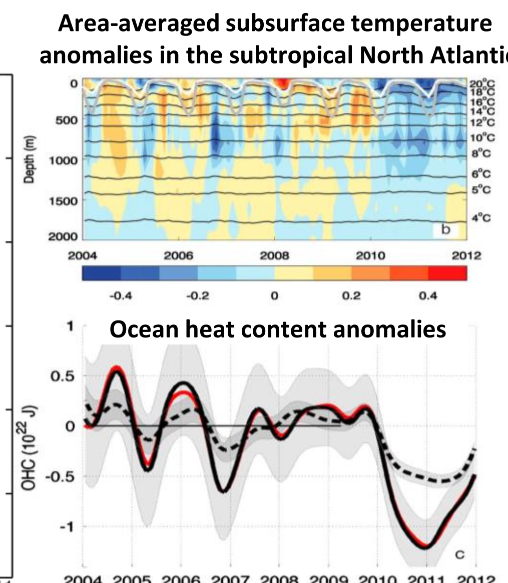


Source: Srokosz and Bryden (2015)

- ✓ Ventilation of the deep ocean interior
- ✓ Heat & AMOC:
  - AMOC responsible for the meridional redistribution of heat
  - N-transport of heat throughout the Atlantic (max. 1.3 PW at 24.5°N, 25% of the global heat flux)
  - Changes in AMOC strength:
    - change the heat content (Cunningham et al. 2013; Bryden et al. 2014)
    - drives SST anomalies that affect NAO (Buchan et al. 2013)

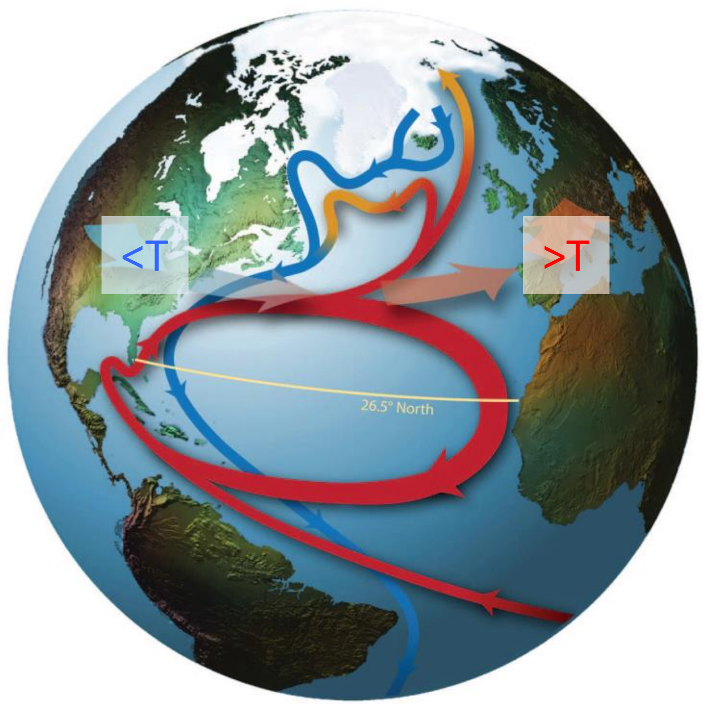


Source: Bryden et al. (2014)



Source: Cunningham et al. (2013)

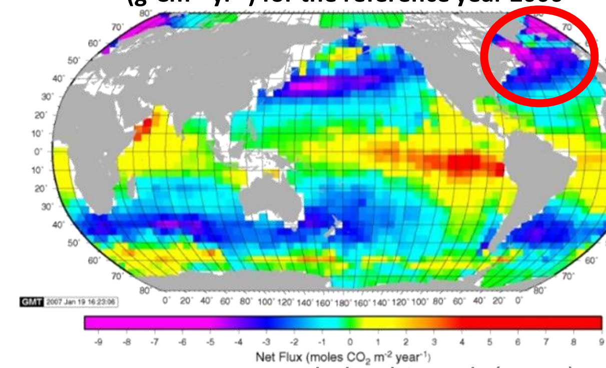
Why is the AMOC important?



Source: Srokosz and Bryden (2015)

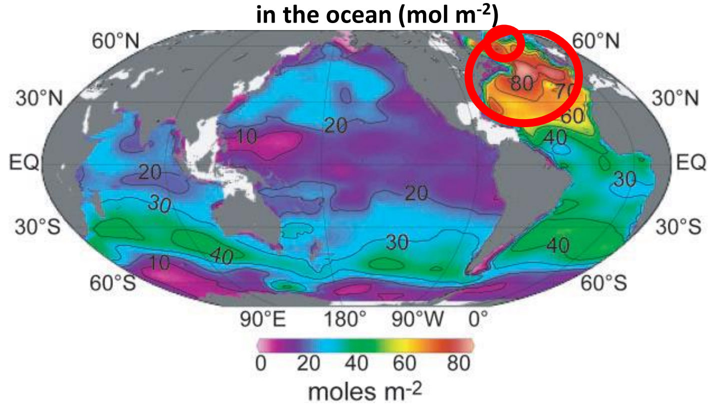
- ✓ CO_2 & AMOC:
  - Highest CO_2 air-sea uptake
  - Highest C_{ant} inventory
  - High acidification rates

Climatological mean annual NCEP sea–air CO_2 flux ($g\text{-}Cm^{-2}\ yr^{-1}$) for the reference year 2000



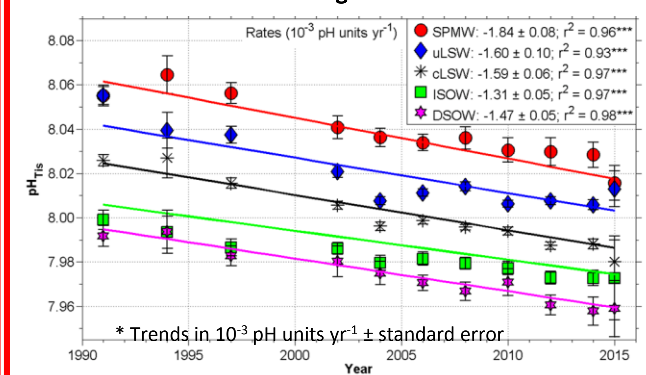
Source: Takahashi et al. (2009)

Column inventory of anthropogenic CO_2 in the ocean ($mol\ m^{-2}$)



Source: Sabine et al. (2004)

Temporal evolution of average pH in the Irminger Basin



Source: García-Ibáñez et al. (2016)

Monitoring AMOC: The RAPID 26.5N section

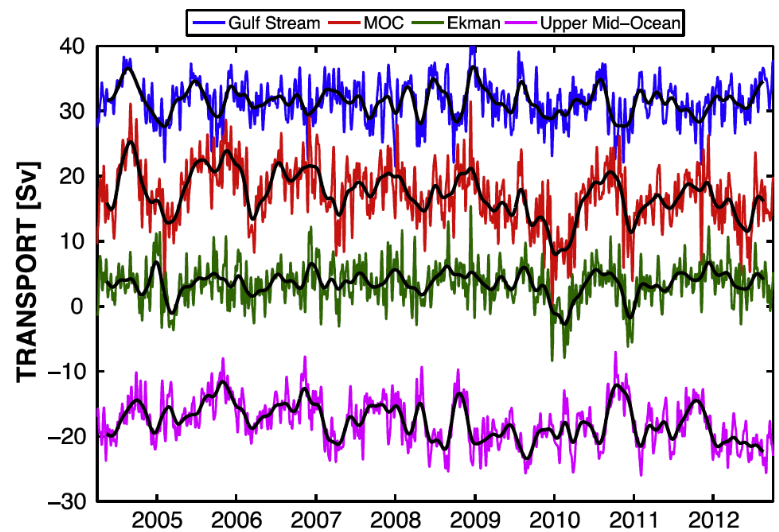
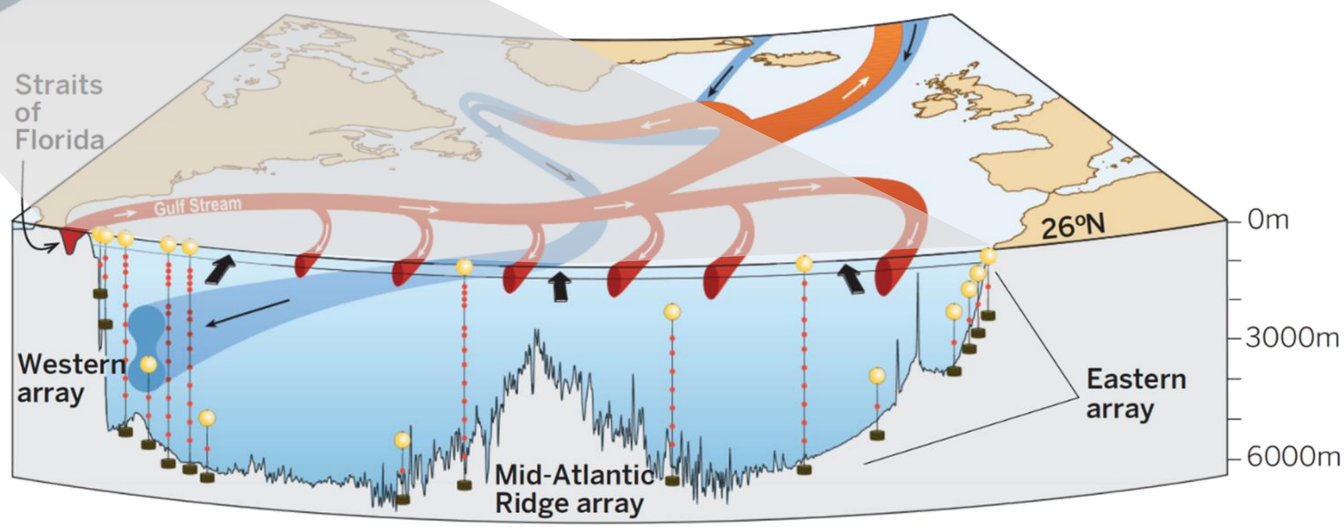


Figure from McCarthy et al. (2014)

17.2 Sv

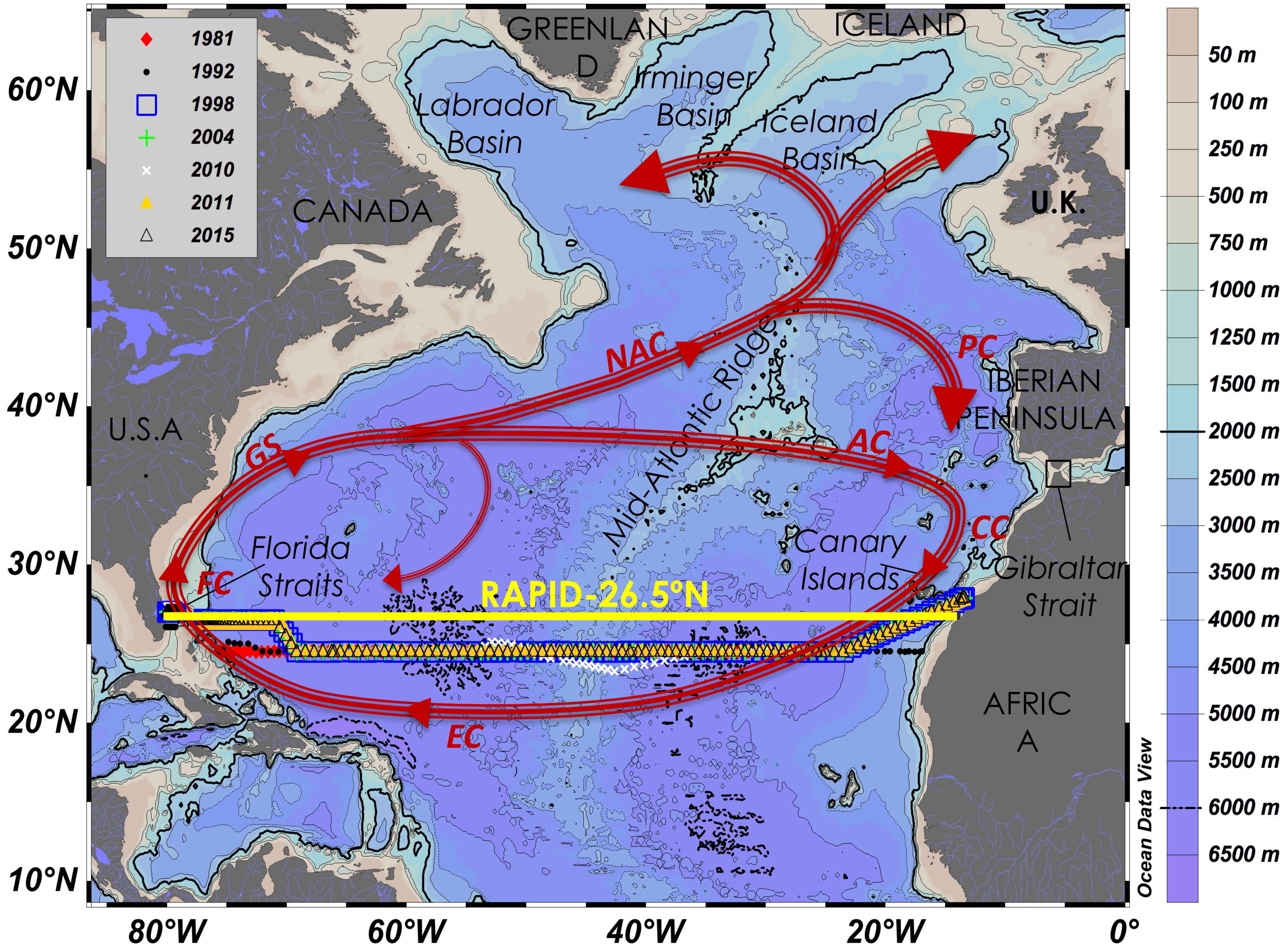
$$MOC(t) = GS(t) + EK(t) + UMO(t)$$

(Mc Carthy et al. 2012; Smeed et al. 2013)

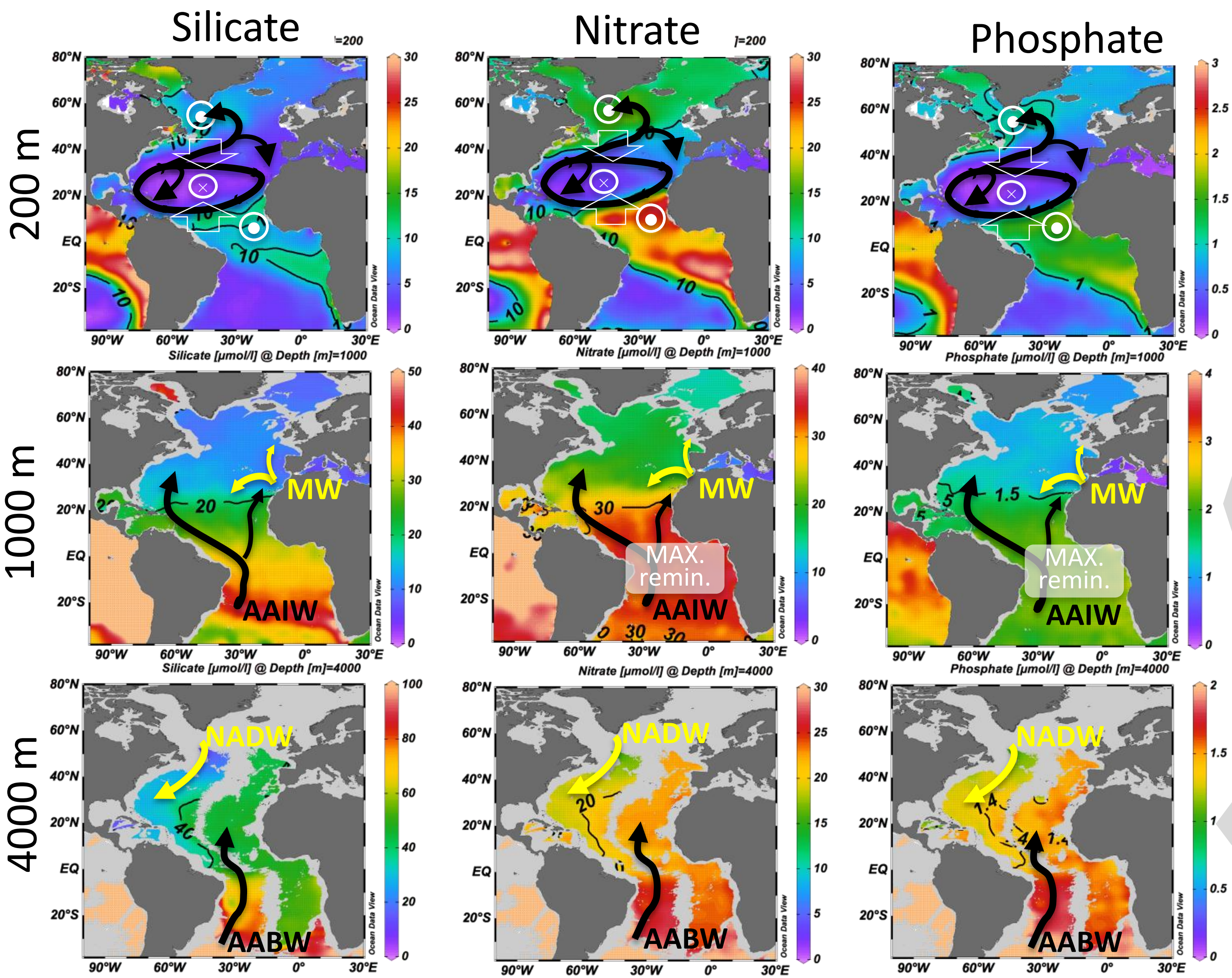


Figures from Srokosz and Bryden (2015)

Region of study:



What is the nutrient distribution in the NA?



- Wind-driven distribution pattern

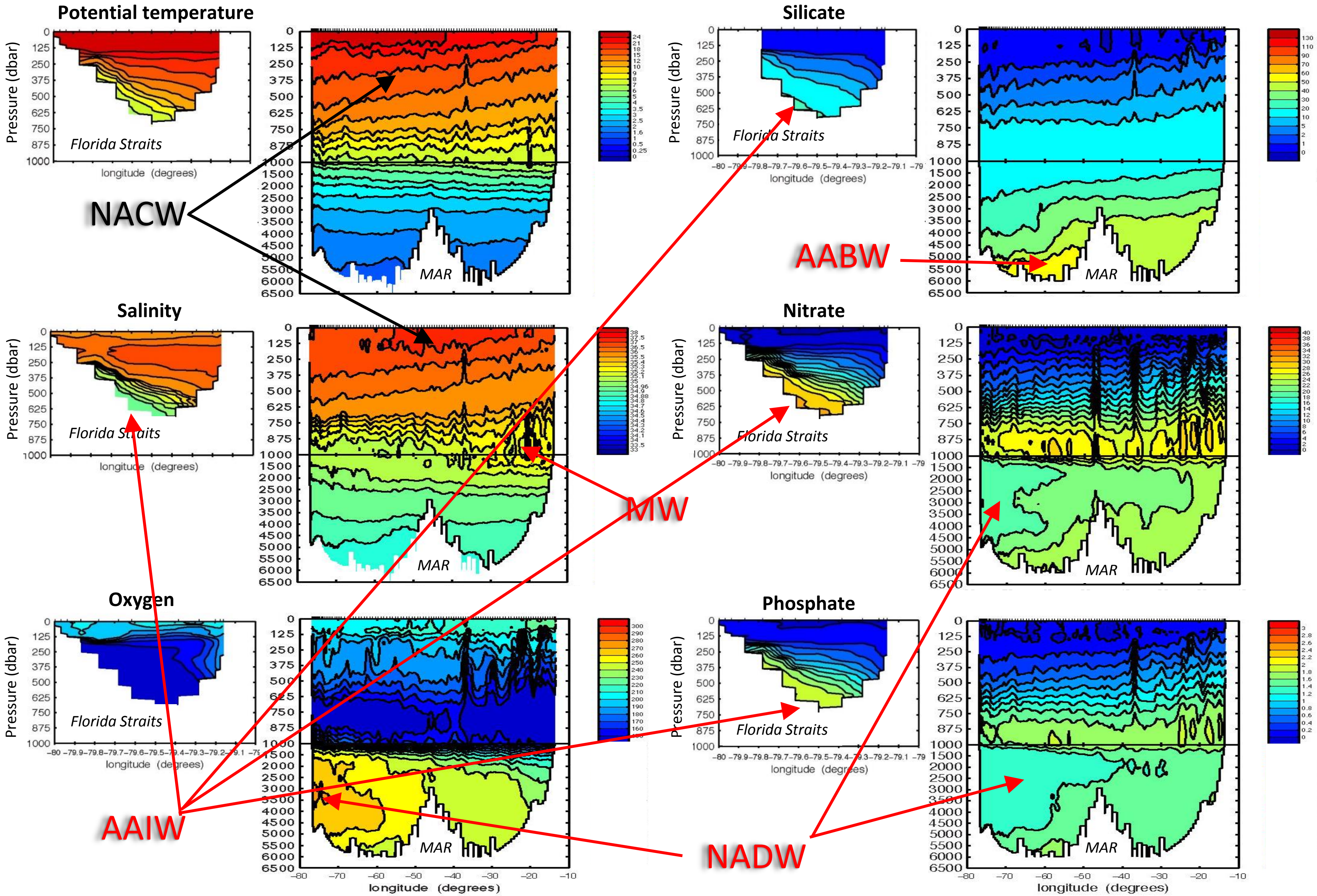
- Max. remineralization ~800-1000 dbar.

- **MW** vs. **AAIW** advection

- **NEADW** vs. **AABW** advection

Plotted in ODV from WOA13 database

Θ, S, O_2 and nutrients distribution across 24.5°N section:



DY040 CRUISE property sections. Images Courtesy of B. King

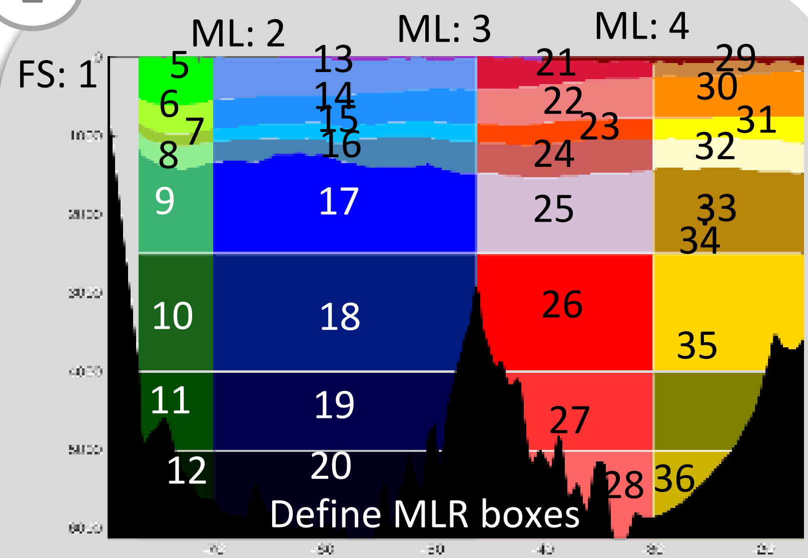
What is the methodology?

1

19202 hydro data: 1981, 1992, 1998, 2004, 2010, 2015 24°N, GOMMEC 2007, 2012

input data →

2



- ➢ <u>LONGITUDINAL LIMITS (ºE):</u>
  FS: -81, -79
  ATL-ML: -79, -64, -40, -10
  ATL: -78, -70, -46, -30, -10

- ➢ <u>VERTICAL LEVELS:</u>
  γ= 26.0 kg m^{-3}; γ =26.7 kg m^{-3}; γ=27.4 kg m^{-3}; γ= 27.65 kg m^{-3}; γ= 27.85 kg m^{-3}; P= 2500dbar; P= 4000dbar; P= 5000dbar

create mlr for each box

3

Create linear regression model (*stepwise MLR*). The MLR equation:

$$N = \textbf{ct.} + \textbf{coef}_1 {*}\theta + \textbf{coef}_2 {*}S + \textbf{coef}_3 {*}O_2 + \ldots + \textbf{coef}_4 {*}P + \textbf{coef}_5 {*}lon + \textbf{coef}_6 {*}time$$

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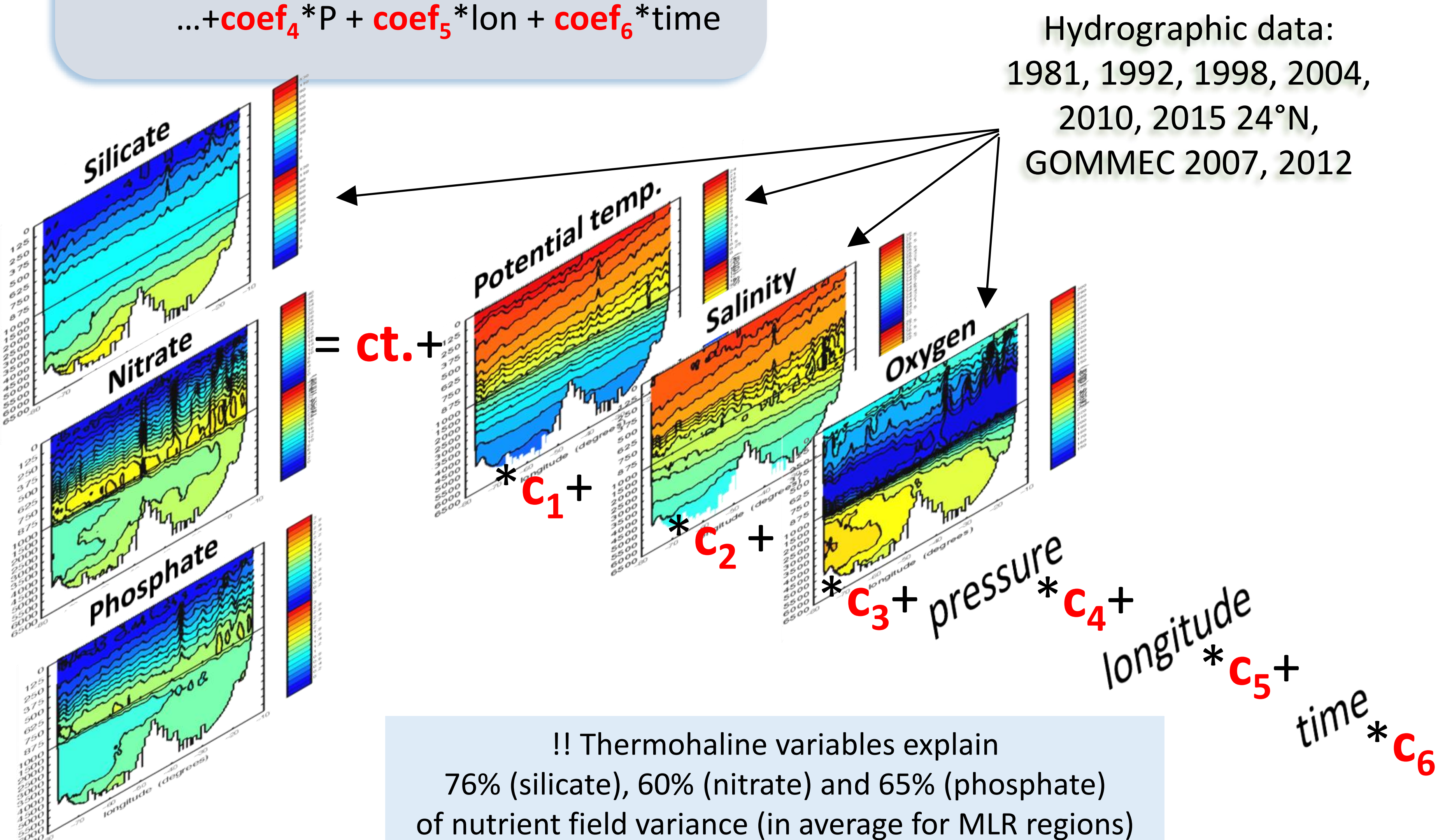
Create linear regression model (*stepwise MLR*). The MLR equation:

$$N = \text{ct.} + \text{coef}_1 * \theta + \text{coef}_2 * S + \text{coef}_3 * O_2 + \ldots$$
$$\ldots + \text{coef}_4 * P + \text{coef}_5 * \text{lon} + \text{coef}_6 * \text{time}$$



!! Thermohaline variables explain
76% (silicate), 60% (nitrate) and 65% (phosphate)
of nutrient field variance (in average for MLR regions)

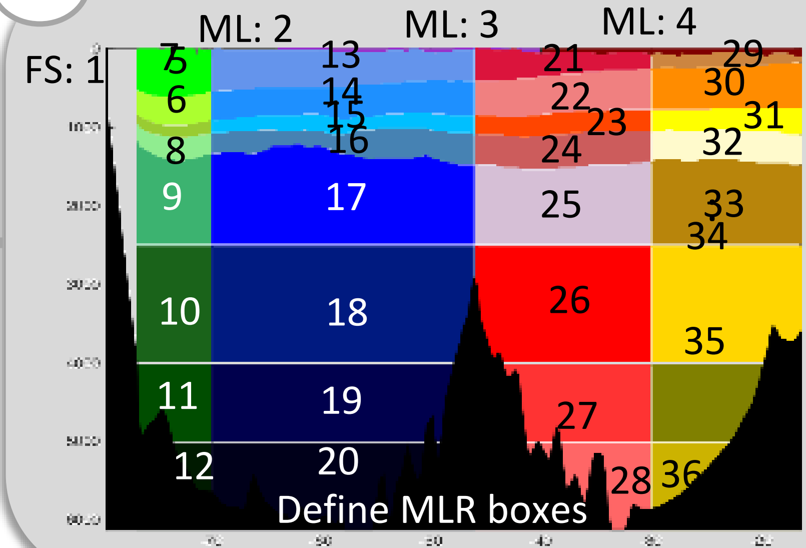
What is the methodology?

1

19202 hydro data: 1981, 1992, 1998, 2004, 2010, 2015 24°N, GOMMEC 2007, 2012

input data →

2



create mlr for each box

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Create linear regression model (*stepwise MLR*). The MLR equation:

$$N = \textbf{ct.} + \textbf{coef}_1 \cdot \theta + \textbf{coef}_2 \cdot S + \textbf{coef}_3 \cdot O_2 + \ldots$$
$$\ldots + \textbf{coef}_4 \cdot P + \textbf{coef}_5 \cdot lon + \textbf{coef}_6 \cdot time$$

4

Evaluate the statistics (RMSE, R^2, residuals)

KO? → *readjust mlr parameters and/or mlr-boxes*

OK? → *apply mlr* → *our result:* →

5

ϴ, S RAPID 10-day resolution time series

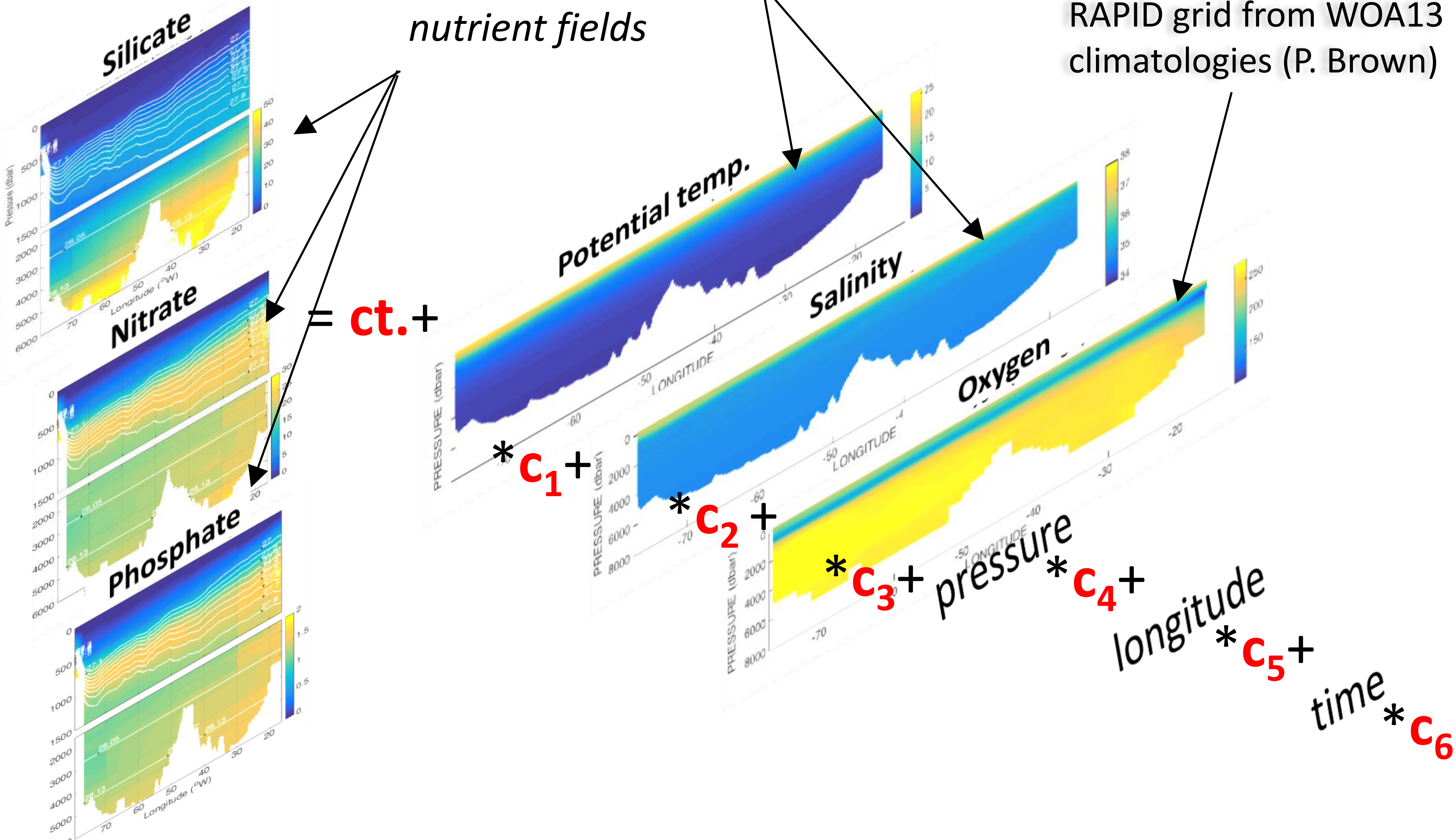
5

Θ, S RAPID 10-day resolution time series

Our result: 10-day resolution nutrient fields

Θ, S RAPID 10-day resolution time series. Source: Argo optimal interpolation (E. McDonagh)

O_2 seasonal climatology, optimally interpolated to RAPID grid from WOA13 climatologies (P. Brown)

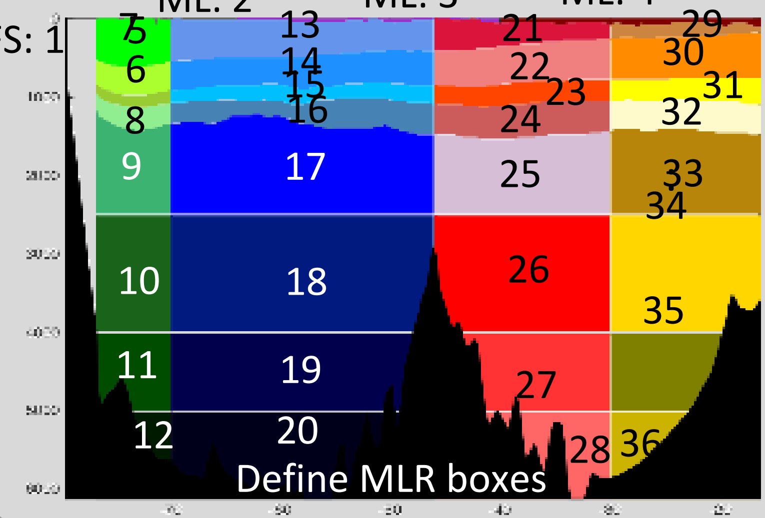


What is the methodology?

1 19202 hydro data: 1981, 1992, 1998, 2004, 2010, 2015 24°N, GOMMEC 2007, 2012

input data →

2



create mlr for each box

3 Create linear regression model (*stepwise MLR*). The MLR equation:

$$N = \text{ct.} + \text{coef}_1 \cdot \theta + \text{coef}_2 \cdot S + \text{coef}_3 \cdot O_2 + \ldots$$
$$\ldots + \text{coef}_4 \cdot P + \text{coef}_5 \cdot \text{lon} + \text{coef}_6 \cdot \text{time}$$

4 Evaluate the statistics (RMSE, R^2, residuals)

KO? → *readjust mlr parameters and/or mlr-boxes*

OK? → *apply mlr*

5 Θ, S RAPID 10-day resolution time series

our result: →

6 [Nutrients]

multiply by RAPID transports (McDonagh et al. 2015)

7 **NUTRIENT FLUXES**

$$T_{net}\, N = \int\int \rho\, \mathbf{Nutr(x,z)}\, \mathbf{v(x,z)}\, dx\, dz$$

Nitrate and phosphate: preformed vs. remineralized fractions:

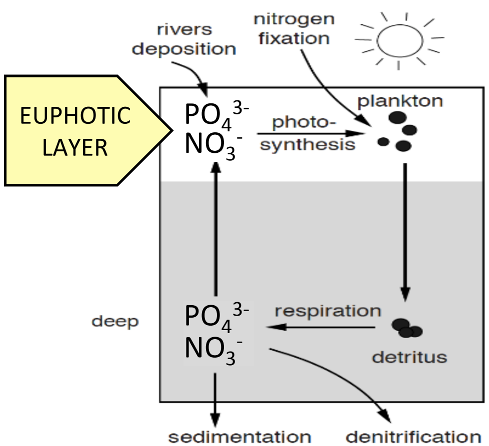
- Nitrate and phosphate are affected by biology:
  - ✓ consumed during photosynthesis (photic layer)
  - ✓ regenerated during respiration of the organic (remineralized nutrients)

- Nitrate and phosphate can be split into:

Nutr. = remin. + preform.

$[NO_3^-] = [NO_3^-]_{remin.} + [NO_3^-]^0$

$[PO_4^{3-}] = [PO_4^{3-}]_{remin.} + [PO_4^{3-}]^0$

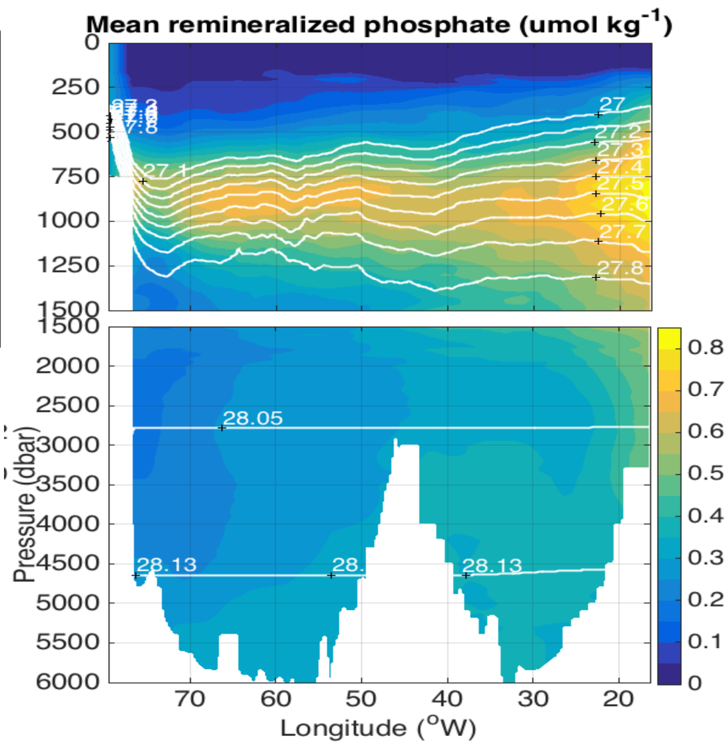


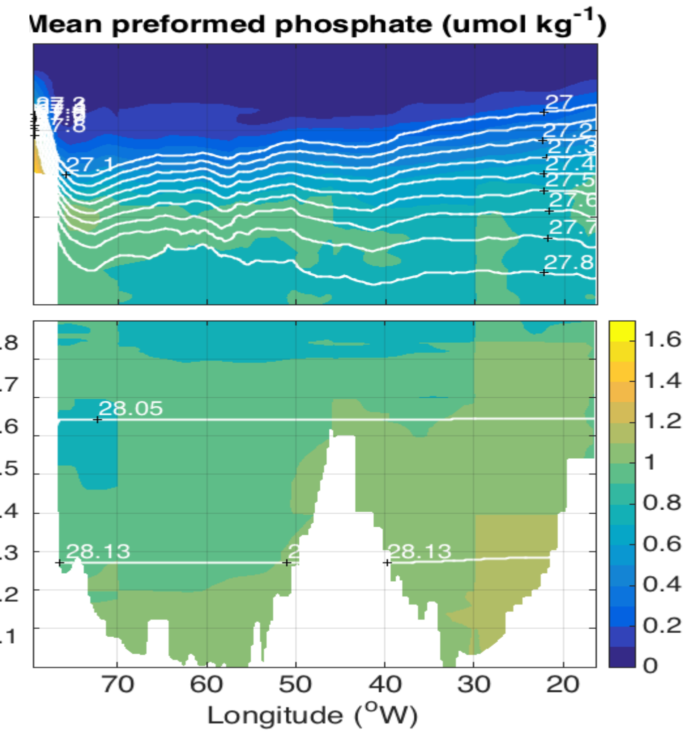
$[NO_3^-]_{remin.} = AOU/R_{O/N}$

$[PO_4^{3-}]_{remin.} = AOU/R_{O/P}$

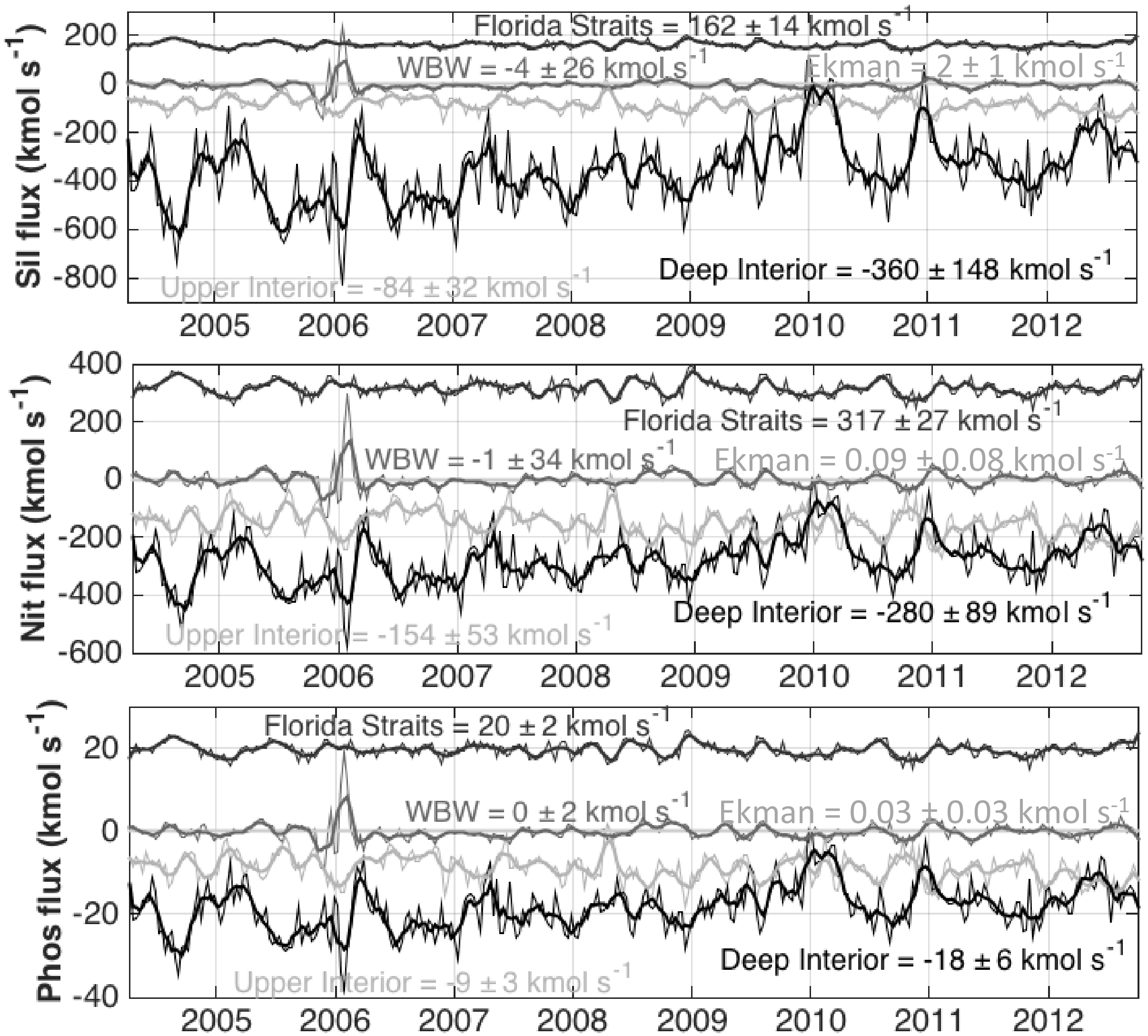
$[NO_3^-]^0 = [NO_3^-] - [NO_3^-]_{remin.}$

$[PO_4^{3-}]^0 = [PO_4^{3-}] - [PO_4^{3-}]_{remin}$





Nutrient transports by regions:



1. **Ekman wind-driven flux**
   (ERA-Interim winds)
2. **Florida Strait flux**
   (submarine cable)
3. **Western Boundary Current**
   (mooring)
4. **Upper interior flux**
   (<1760 dbar, mooring + Argo)
5. **Deep interior flux**
   (>1760 dbar, mooring + hidrography)

- Florida Current acts as a “nutrient stream” northwards (Pelegrí et al. 1996)
- Upper Interior (Atalntic basin) recirculates nutrient southwards (upper gyre recirculation)
- Main transport of nutrients by deep interior (lower AMOC branch)

Physical mechanisms driving net nutrient fluxes:

Nutrient transport decomposition:

$$v = V_0 + \langle v \rangle(z) + v'(x,z)$$

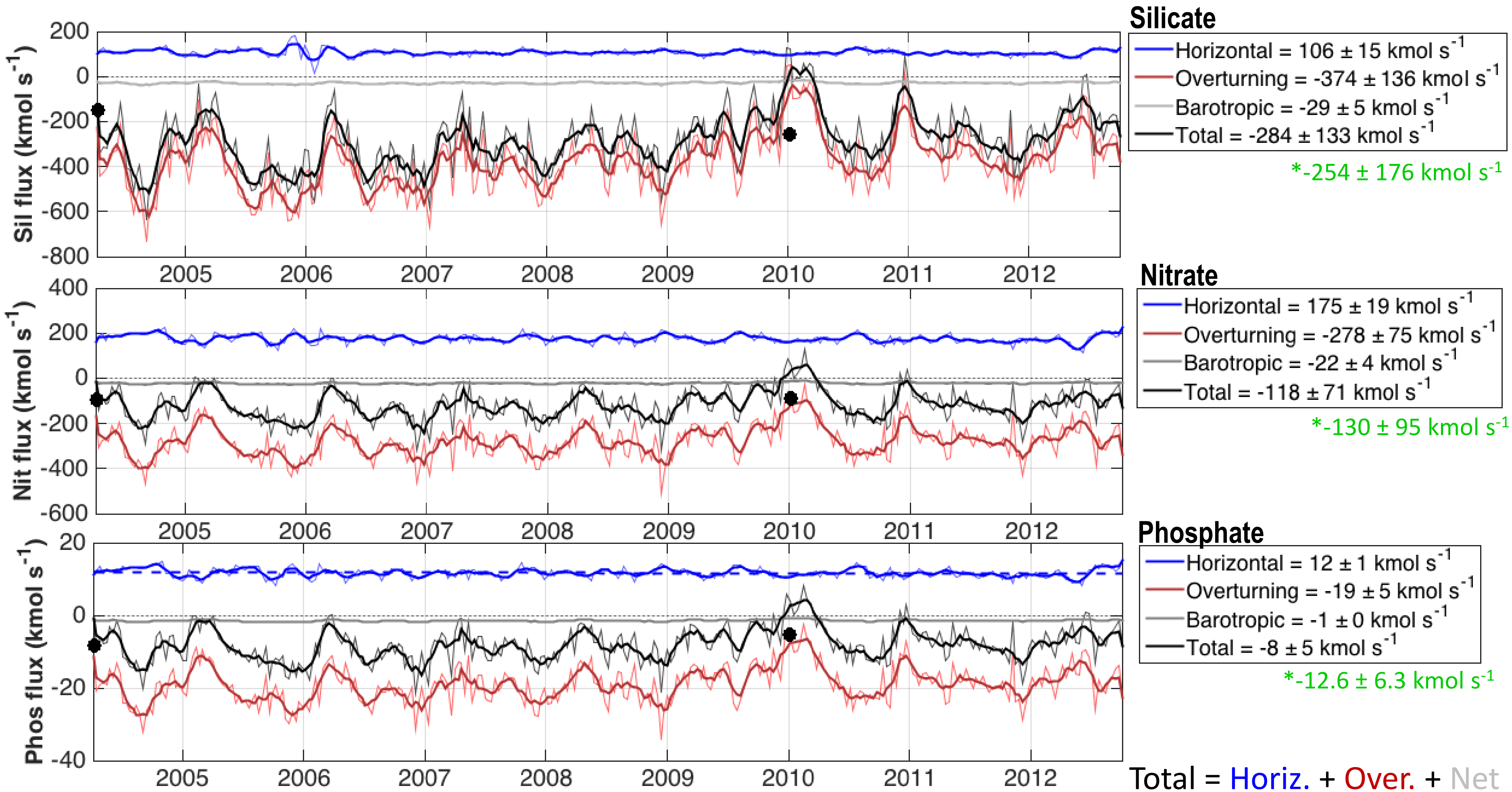
$$Nutr = \langle Nutr \rangle + \langle Nutr \rangle(z) + Nutr'(x,z)$$

1. **Net transport**......................... $T_{nutr}^{net} = \rho \, \langle Nutr \rangle \, V_0 \int L(z)\, dz$

2. **Overturning component**........ $T_{nutr}^{over} = \rho \int \langle Nutr \rangle(z) \, \langle v \rangle(z) \, L(z)\, dz$

3. **Horizontal component**............ $T_{nutr}^{horiz} = \rho \int\int Nutr'(x,z) \, v'(x,z) \, L(x,z)\, dz\, dx$

Physical mechanisms driving net nutrient fluxes (NNF):



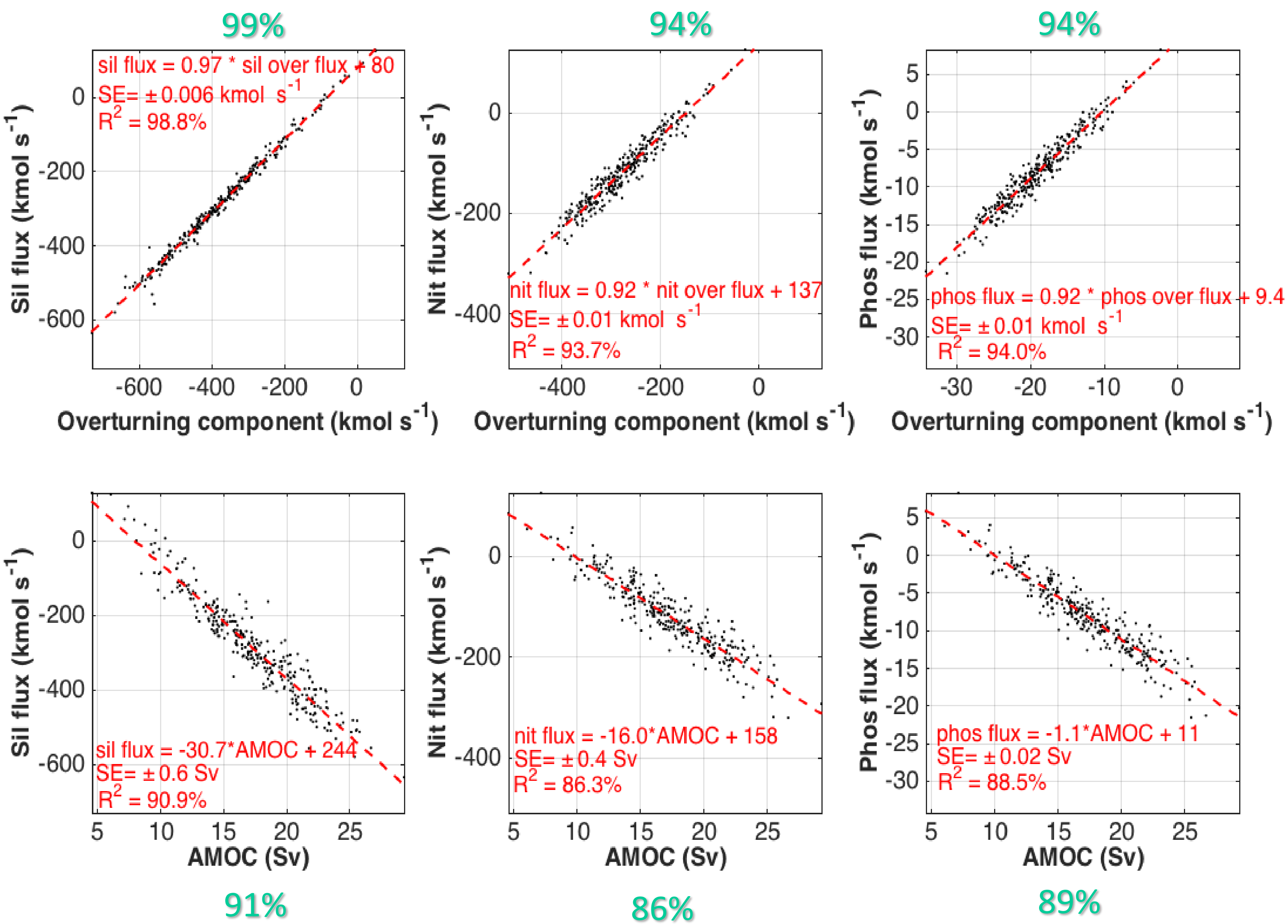
Total = Horiz. + Over. + Net

(Álvarez et al., 2005, Bryden et al., 2011)

- **VARIABILITY NNF:**
  AMOC-driven NNF explain:
  - ✓ Sil: 99% of variance
  - ✓ Nit: 94% of variance
  - ✓ Phos: 94% of variance
- **MAGNITUDE NNF:**
  AMOC-driven NNF represent:
  - ✓ Sil: 73% of magnitude
  - ✓ Nit: 58% of magnitude
  - ✓ Phos: 58% of magnitude

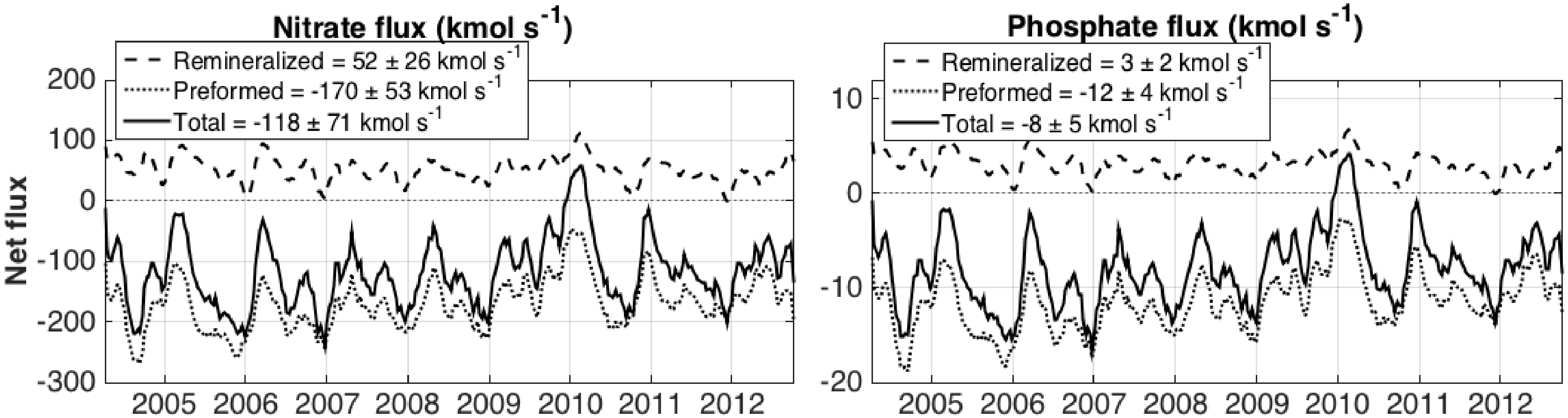
(*) 1992, 24°N cruise (Lavín et al. 2003)

Physical mechanism driving net nutrient fluxes:



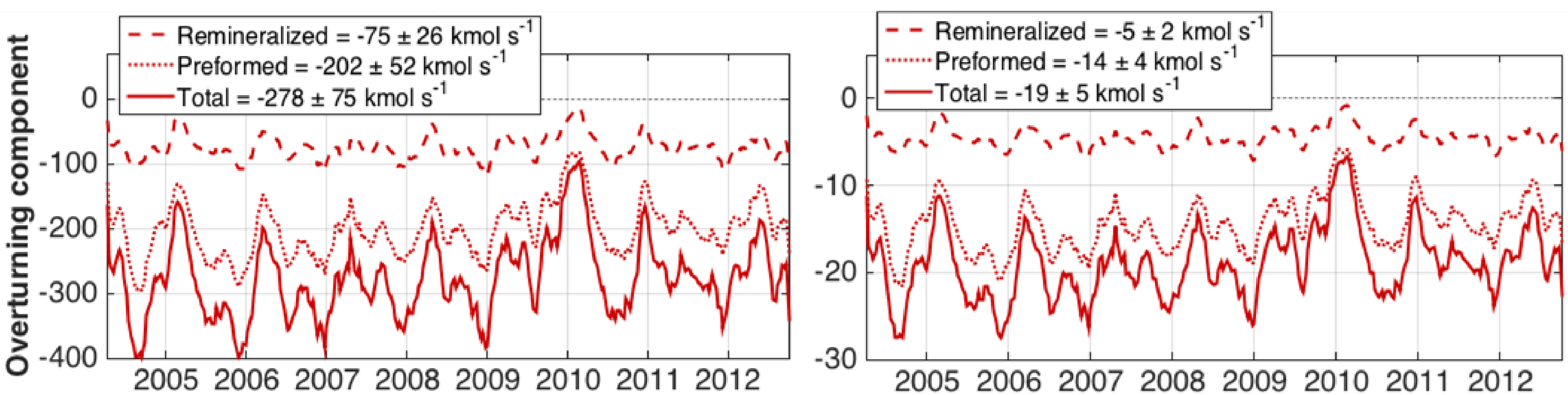
Nitrate and phosphate: preformed vs. remineralized fractions:

TOTAL TRANSPORT:



- Most nutrient transport correspond to the preformed fraction, advected southwards
- Remineralized fraction northwards

OVERTURNING COMPONENT:



- AMOC- driven net nutrient (southwards) advection: ~75% preformed, ~ 25% remineralized

Interannual Variability:

- **Vertical structure:**

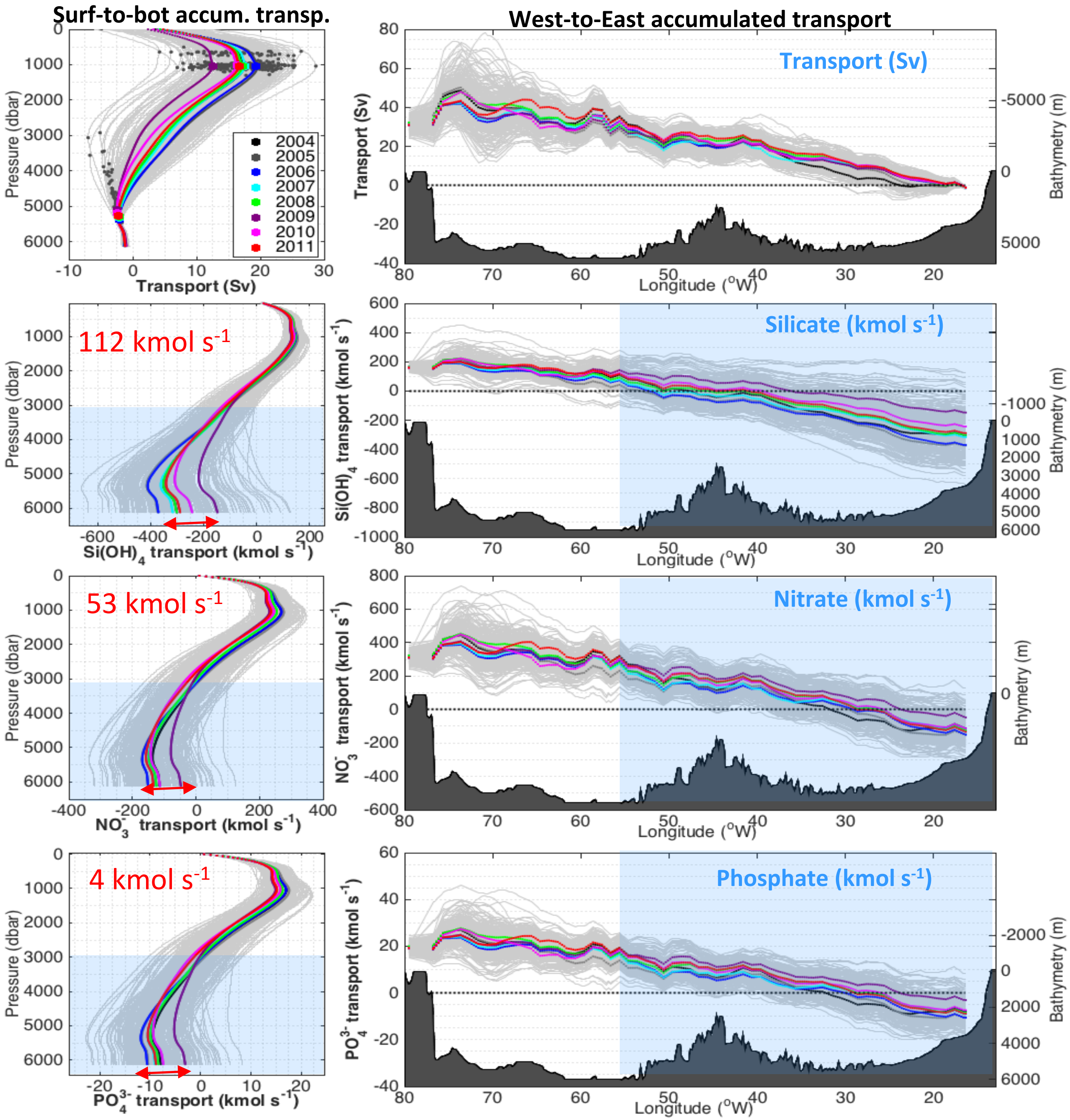
  - Interannual variability of nutrient transports occurs below 3000

  - Largest anomaly is the 2009-2010 nutrient flux decrease

- **Horizontal structure:**

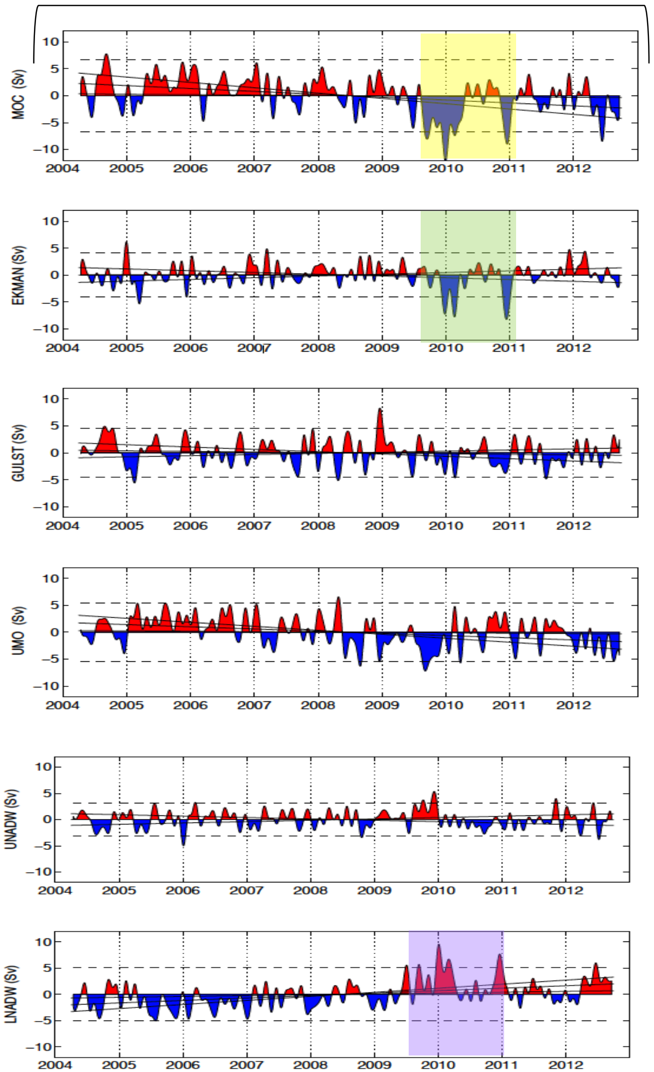
  - 2009-2010 anomaly east of 55°W

- **Amplitude of interannual variability**

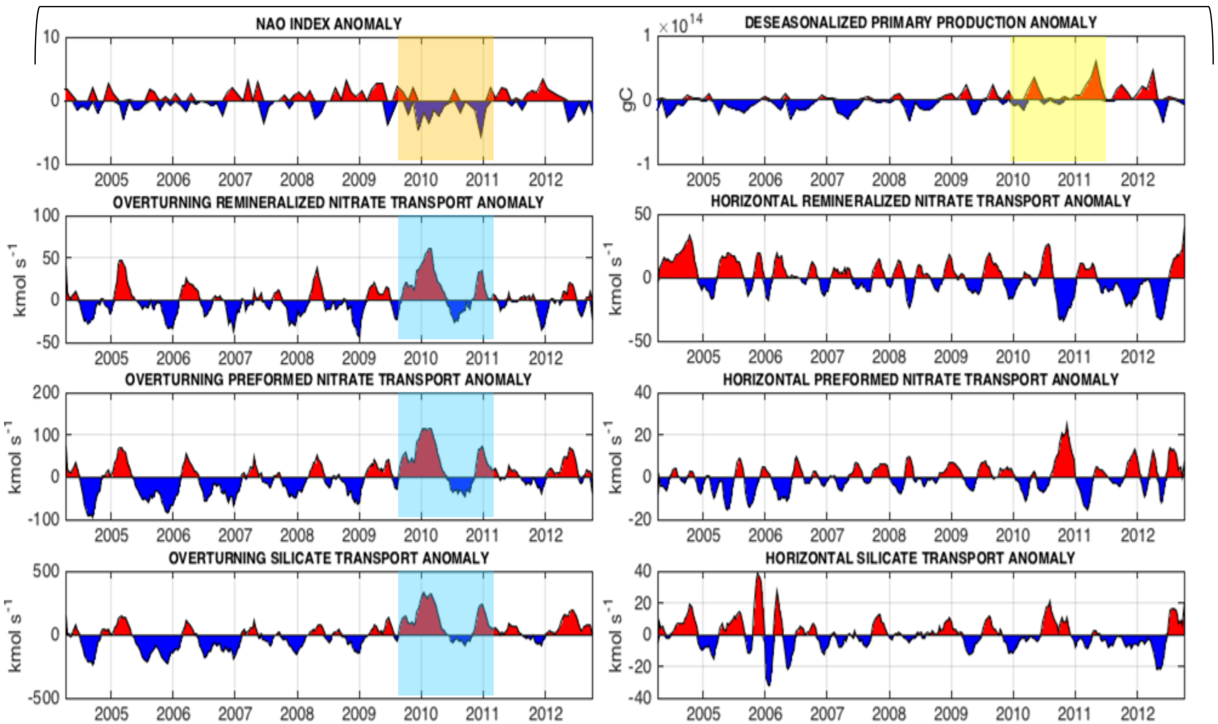


Interannual variability:

From Smeed et al. (2013):

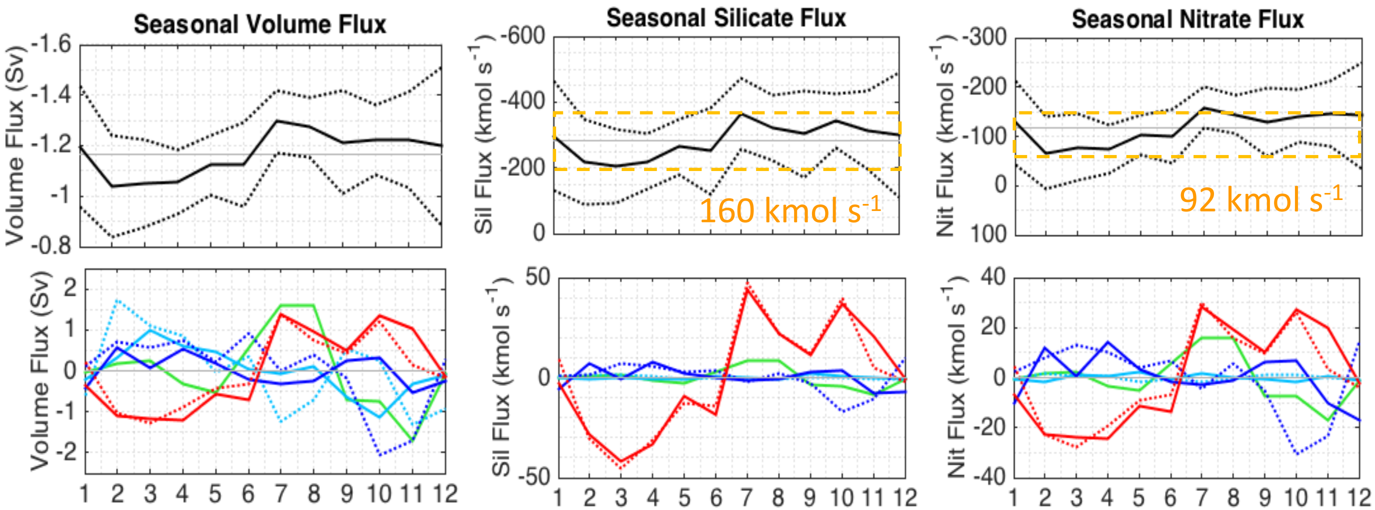


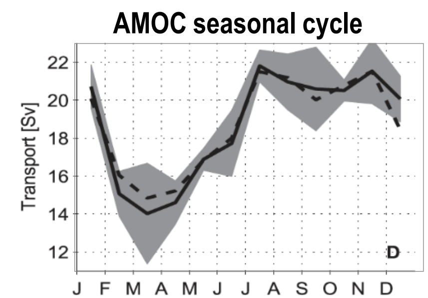
This study:



- Exceptionally low NAO Index Winter 2009-2010 (Taws et al. 2011)
- Anomalus negative Ekman transport (Smeed et al. 2013)
- Anomalous reduced S-transport by LNADW (Smeed et al. 2013)
- 2nd negative NAO peak as atmospheric response of re-emerging temperature anomalies on early 2010/11 winter (Taws et al. 2011)
- In nutrient transport 2009/2010 anomaly caused a 53%, 64%, 66% drop in the silicate, nitrate and phosphate fluxes, respectively

Seasonal variability:

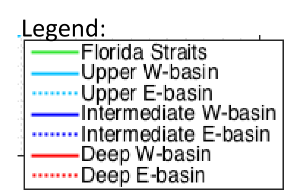




From Kanzow et. al (2010)

- Seasonal cycle of net nutrient fluxes (NNF):
  - ✓ ↓ southward nutrient transport 1st half of the year (<AMOC)
  - ✓ ↑ southward nutrient transport 2nd half of the year (>AMOC)
- Seasonal cycle of NNF driven by seasonal cycle of volume flux
- Most of the amplitude of the seasonal signal driven by deep circulation
- Seasonality is a notable source of intraaannual variability

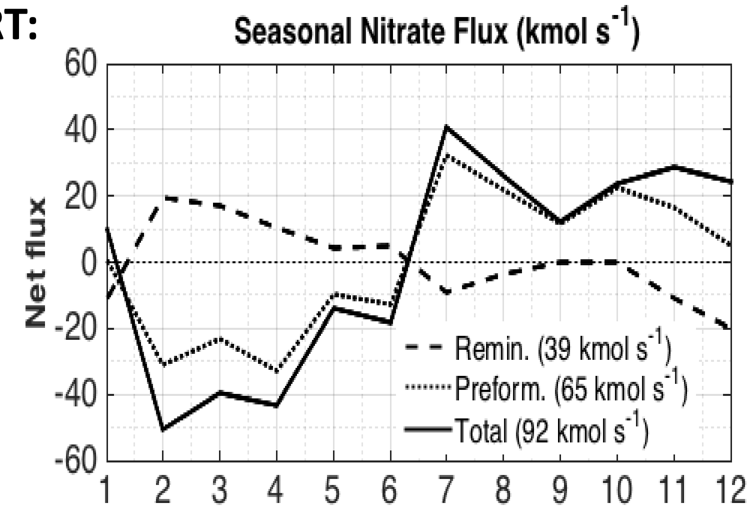
  (peak-to-peak amplitudes)

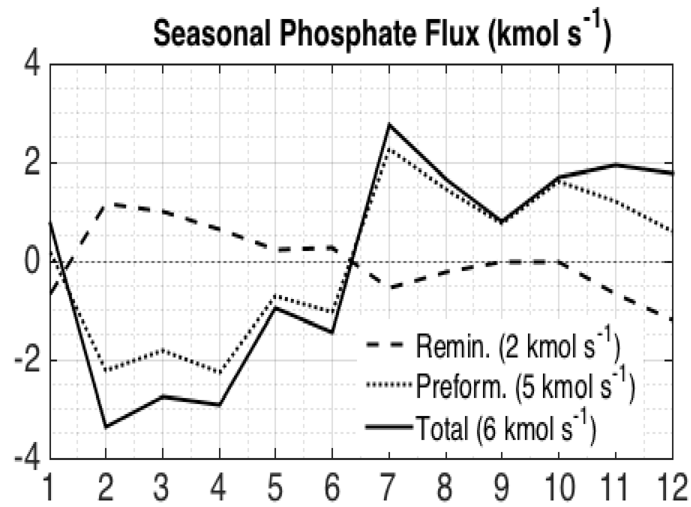


Seasonality: preformed vs. remineralized fractions

TOTAL TRANSPORT:

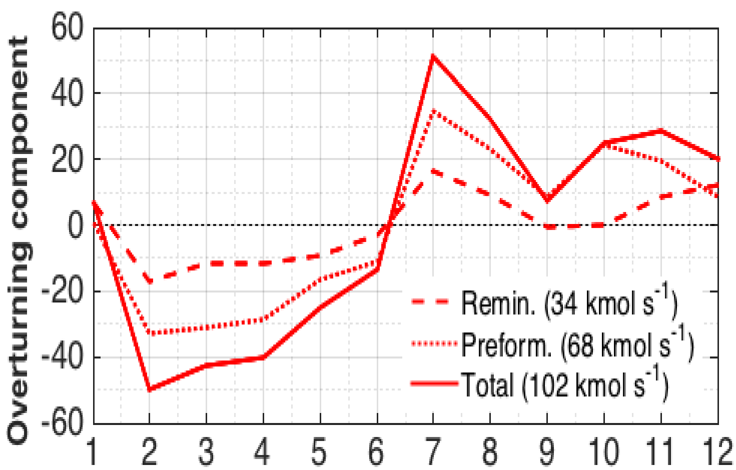
Opposed seasonal cycles for remineralized and preformed components

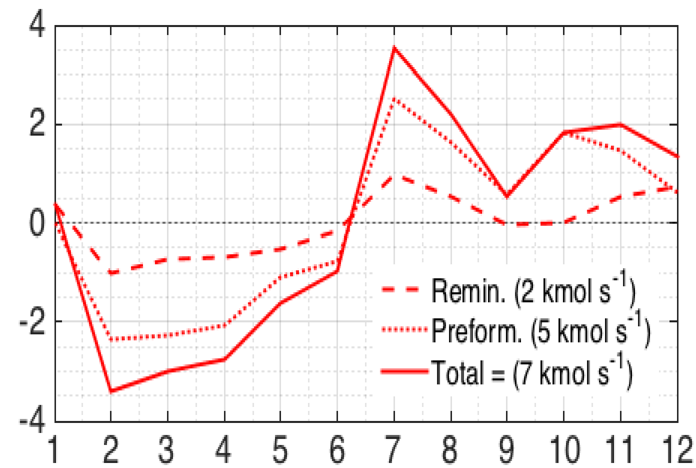




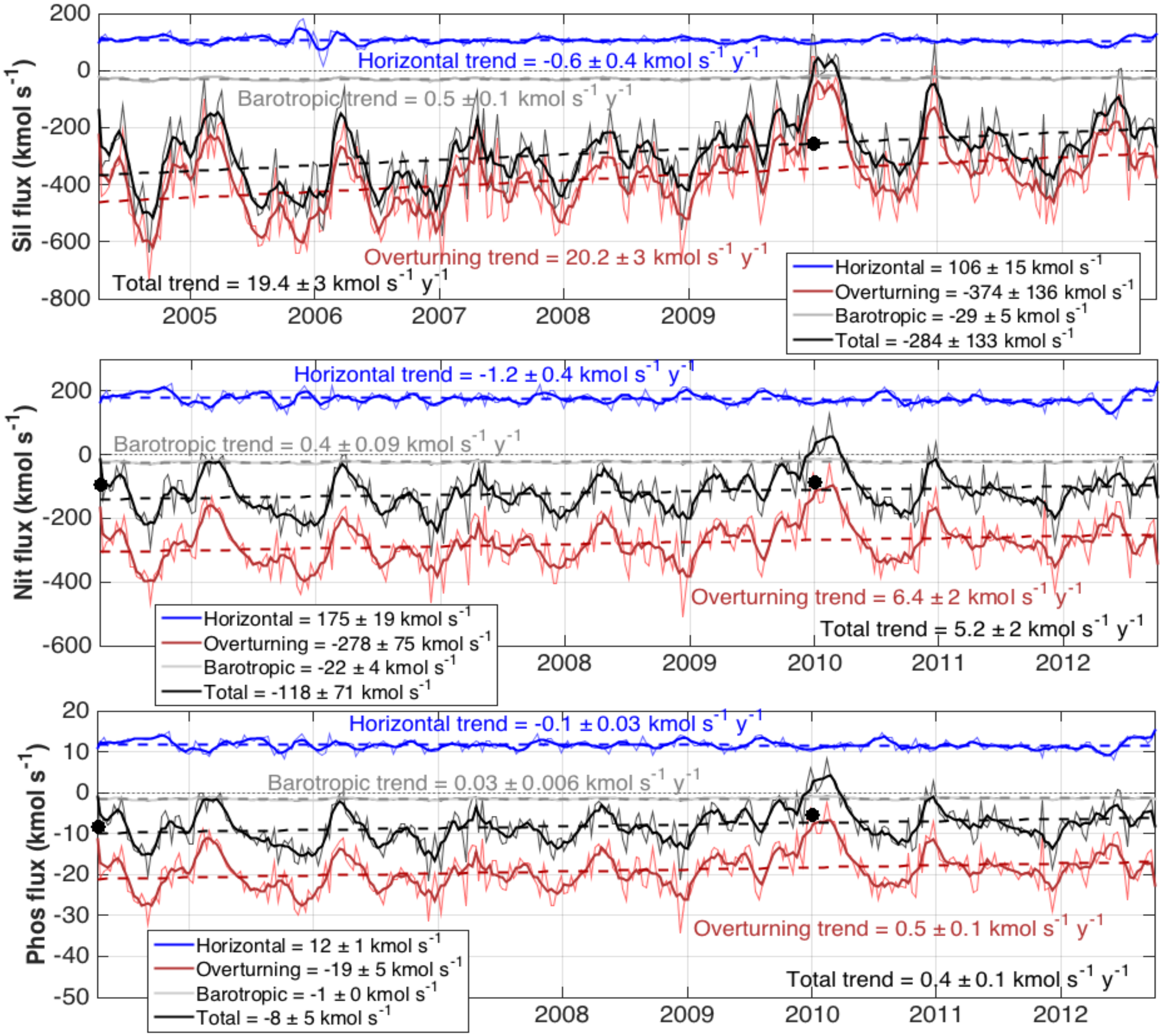
OVERTURNING COMPONENT:

AMOC drives most of the seasonal cycle





8-year trends:



8-year change (kmol s^{-1})

Silicate

	Total flux	Overturning component
Amplitude (kmol s^{-1})	-155	-162
% of change	↓45%	↓37%

82%

Nitrate

	Total flux	Overturning component
Amplitude (kmol s^{-1})	-42	-51
% of change	↓31%	↓18%

58%

Phosphate

	Total flux	Overturning component
Amplitude (kmol s^{-1})	-3	-4
% of change	↓30%	↓20%

67%

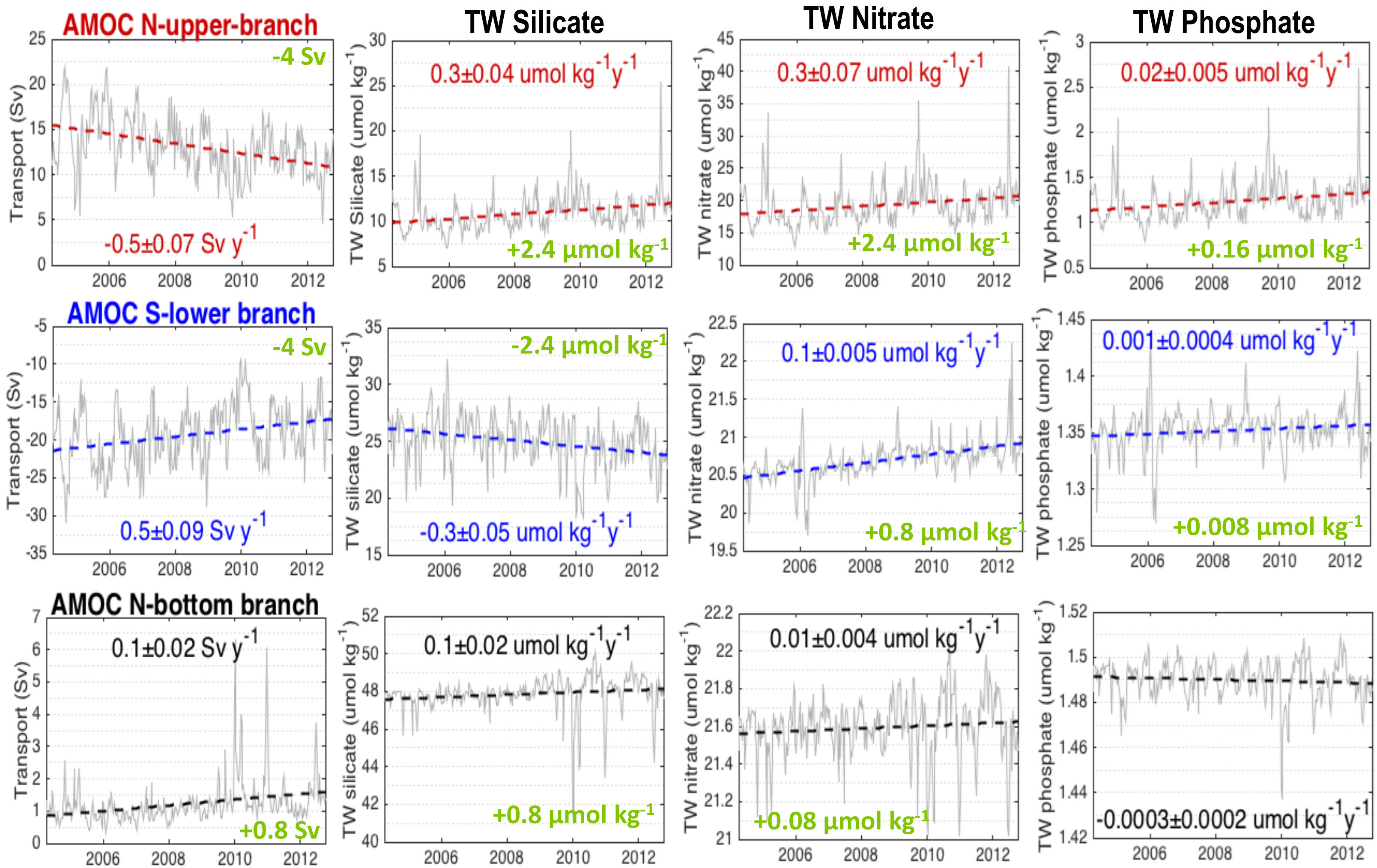
8-year changes:

8-year change by AMOC branches (kmol s^{-1})

Sil: -19
Nit: -46
Phos: -2.4

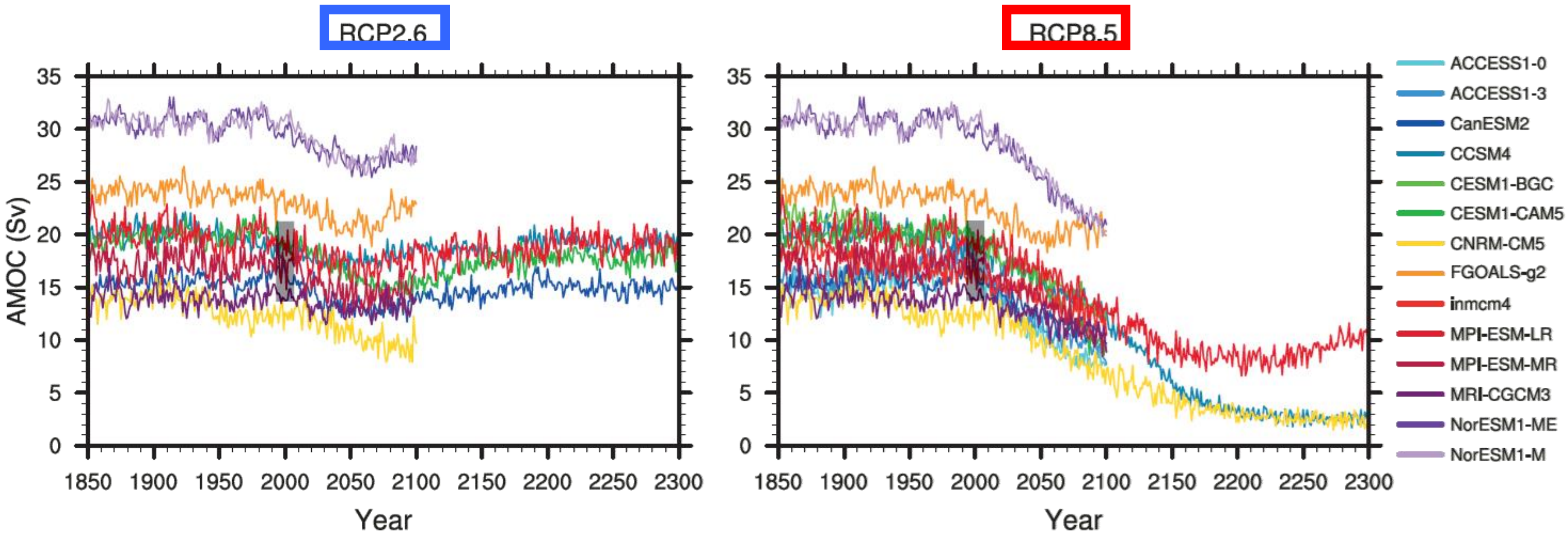
Sil: -142
Nit: -73
Phos: -4.8

Sil: +32
Nit: +16
Phos:+0.8

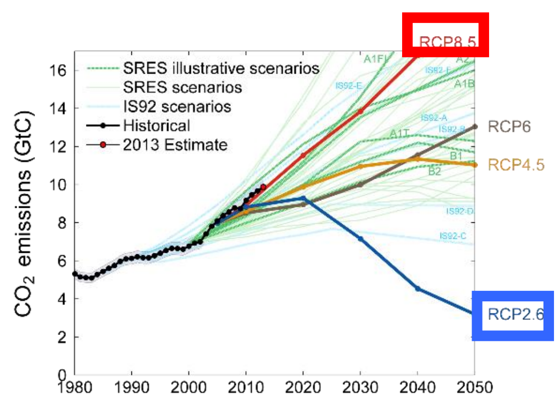


Long-term AMOC decay:

- Future projections of the AMOC strength at 30^{o}N:



- It is *very likely* AMOC will weaken over the 21st century.
- It is *very unlikely* AMOC will undergo an abrupt transition or collapse in the 21st century for the scenarios considered.



Source: IPCC Report, 2015

Summary:

- AMOC-driven nutrient fluxes explain 99% (94%) of variance of the net nutrient fluxes, and account for 73% (58%) of their magnitude.
- For nitrate and phosphate, ~75% of the AMOC-driven net southward nutrient advection corresponds to the preformed fraction, and around 25% to the remineralized fraction.
- AMOC dominates the seasonal and interannual variability of the net nutrient fluxes, as well as the long-term trends:

	Mean net fluxes	Amplitude seasonal variability		Amplitude interannual variability		Amplitude 8-year change in net fluxes	
Silicate flux	-284 (-374)	80 (83)	~25%	112 (117)	~ 30%	155 (162)	~50%
Nitrate flux	-118(-278)	46 (51)	~20%	52 (53)	~20%	42 (51)	~20%
Phosphate flux	-8 (-19)	3 (3.5)	~20%	3.5 (4)	~20%	3 (4)	~20%

- As part of the interannual variability, net nutrient southward transport can undergo substantial AMOC-driven drops, even temporal reversals (extreme event 2010).
- The long-term (2004-2012) AMOC slowdown is driving a decrease of the net (southward) nutrient transport.

Thank you!

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