Transports and pathways of the tropical AMOC return flow from Argo data and shipboard velocity measurements

Franz Philip Tuchen, Peter Brandt, Joke F. Lübbecke, Rebecca Hummels

Tropical segment of the AMOC

Bower et al. (2019)

Tropical Atlantic:
- Both AMOC branches concentrated at the western boundary
- Western boundary circulation consists of:
  - Thermohaline Circulation (THC)
  - Wind-driven Circulation
    - Subtropical Cells (STCs)
    - Sverdrup compensation transport
Tropical segment of the AMOC

- Tropical Atlantic:
  - Both AMOC branches concentrated at the western boundary
  - Western boundary circulation consists of:
    - Thermohaline Circulation (THC)
    - Wind-driven Circulation
      - Subtropical Cells (STCs)
      - Sverdrup compensation transport

Bower et al. (2019)
Surface layer

STC/thermocline layer
Surface layer → Ekman transport → STC/thermocline layer → Ekman transport → Eq.
Tuchen et al. (2022)

Ekman transport

Surface layer

STC/thermocline layer

Subduction

S

Eq.

N

Subduction
Surface layer

Ekman transport

Geostrophic transport

STC/thermocline layer

Subduction

Upwelling

Geostrophic transport

Subduction
Tuchen et al. (2022)

Surface layer

Ekman transport

Subduction

Geostrophic transport

STC/thermocline layer

Upwelling

Subduction

Ekman transport

Geostrophic transport

S

Eq.

N
Tuchen et al. (2022)

![Diagram showing ocean circulation processes]

- **Ekman transport**
- **Subduction**
- **Upwelling**
- **Geostrophic transport**
- **STC/thermocline layer**

**Equations:**
- THC

**Orientation:**
- S (South) to Eq. (Equator) to N (North)
Roemmich (1983): "The calculation shows 6 Sv of layer 2 water from the Southern Hemisphere being upwelled, converted to layer 1 water, and then swept northward."
Argo and ship section mean

- Revisiting and quantifying the diapycnal transport within the tropics into the STC layer from below
  - High-resolution (1/6°) Argo mean (Roemmich & Gilson, 2009)
  - Validation against repeated ship section along 11°S (Schott et al. 2005, Hummels et al. 2015)
Argo and ship section mean

- Revisiting and quantifying the diapycnal transport within the tropics into the STC layer from below
  - High-resolution (1/6°) Argo mean (Roemmich & Gilson, 2009)
  - Validation against repeated ship section along 11°S (Schott et al. 2005, Hummels et al. 2015)
Argo and ship section mean

- Revisiting and quantifying the diapycnal transport within the tropics into the STC layer from below
- High-resolution (1/6°) Argo mean (Roemmich & Gilson, 2009)
- Validation against repeated ship section along 11°S (Schott et al. 2005, Hummels et al. 2015)

<table>
<thead>
<tr>
<th>Water Mass Layer</th>
<th>Vertical Boundaries ($\gamma_n$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Layer</td>
<td>Surface to Ekman depth</td>
</tr>
<tr>
<td>STC/thermocline Layer</td>
<td>Ekman depth to 26.3</td>
</tr>
<tr>
<td>Lower CW</td>
<td>26.3 to 26.8</td>
</tr>
<tr>
<td>AAIW</td>
<td>26.8 to 27.7</td>
</tr>
<tr>
<td>NADW</td>
<td>27.7 to 28.135</td>
</tr>
<tr>
<td>AABW</td>
<td>28.135 to bottom</td>
</tr>
</tbody>
</table>

Transports and pathways of the tropical AMOC return flow from observations | Franz Philip Tuchen | US AMOC Science Team Meeting (Apr 25, 2022)
Argo data validation at 11°S

- Very good agreement between high-resolution Argo data and ship section data
- Substantial underestimation by lower-resolved (1°x1°) data
- Similar at 10°N, but no comparable reference
Argo data validation at 11°S

- Very good agreement between high-resolution Argo data and ship section data
- Substantial underestimation by lower-resolved (1°x1°) data
- Similar at 10°N, but no comparable reference
Argo data validation at 11°S

- Very good agreement between high-resolution Argo data and ship section data
- Substantial underestimation by lower-resolved (1°x1°) data
- Similar at 10°N, but no comparable reference

Very good agreement between differently resolved Argo products

Resolution more crucial at the western boundary
Western boundary transports

Transports and pathways of the tropical AMOC return flow from observations | Franz Philip Tuchen | US AMOC Science Team Meeting (Apr 25, 2022)
Now including Ekman transports in the surface layer.
Western boundary transports

- Now including Ekman transports in the surface layer
- South Atlantic Water entering at all layers

Transports and pathways of the tropical AMOC return flow from observations | Franz Philip Tuchen | US AMOC Science Team Meeting (Apr 25, 2022)
Western boundary transports

- Now including Ekman transports in the surface layer
- South Atlantic Water entering at all layers
- Very good agreement between ARGO-HR and ship section data
Western boundary transports

- Now including Ekman transports in the surface layer
- South Atlantic Water entering at all layers
- Very good agreement between ARGO-HR and ship section data

**Graphs:***

**a)**
- 11°S
- **Surface**
- **STC**
- **Lower CW**
- **AAIW**
- **NET**
- **Ekman**
- **ARGO-LR**
- **ARGO-HR**
- **Ship section**

**b)**
- 10°N
- **Surface**
- **STC**
- **Lower CW**
- **AAIW**
- **NET**

**Values:**

**11°S**
- **Surface**: -1.4 ±0.1
- **STC**: 3.0 ±0.3
- **Lower CW**: 7.3
- **AAIW**: 3.6 ±0.6
- **NET**: 0.5 ±0.3

**10°N**
- **Surface**: -1.3 ±0.1
- **STC**: 0.0
- **Lower CW**: 0.3
- **AAIW**: 8.7
- **NET**: 4.0 ±0.3
Western boundary transports

- Now including Ekman transports in the surface layer
- South Atlantic Water entering at all layers
- Very good agreement between ARGO-HR and ship section data

Absence of STC and CW water?
Diapycnal transports between 10N/S

Volume Balance:

Transports and pathways of the tropical AMOC return flow from observations | Franz Philip Tuchen | US AMOC Science Team Meeting (Apr 25, 2022)
Diapycnal transports between 10N/S

Transports and pathways of the tropical AMOC return flow from observations | Franz Philip Tuchen | US AMOC Science Team Meeting (Apr 25, 2022)
Diapycnal transports between 10N/S

Transports and pathways of the tropical AMOC return flow from observations | Franz Philip Tuchen | US AMOC Science Team Meeting (Apr 25, 2022)
Diapycnal transports between 10N/S

Volume Balance:

11°S

Surface
-11.0 ±0.2

STC
5.0 ±0.1
6.7

Lower CW
0.2 ±0.1
4.8

AAIW
0.0 ±0.2
6.1

NET
-0.1
16.4

10°N

Surface
-3.1 ±0.1
-1.8

STC
-0.4 ±0.1
0.2

Lower CW
0.9 ±0.1
1.4

AAIW
3.3 ±0.5
7.7

NET
10.0
16.8

Volume Balance:

0.3

11.5

Ekman

ARGO-LR

ARGO-HR

Diapycnal transports between 10N/S

Transports and pathways of the tropical AMOC return flow from observations | Franz Philip Tuchen | US AMOC Science Team Meeting (Apr 25, 2022)
Diapycnal transports between 10N/S

Transports and pathways of the tropical AMOC return flow from observations | Franz Philip Tuchen | US AMOC Science Team Meeting (Apr 25, 2022)
Diapycnal transports between 10N/S

Volume Balance:

Meridional Transport [Sv]

11°S

Surface: -11.0 ±0.2
STC: 5.0 ±0.1
Lower CW: 0.2 ±0.1
AAIW: 0.0 ±0.2
NET: -0.1

10°N

Surface: -11.8
STC: 9.6
Lower CW: -0.4 ±0.1
AAIW: 0.9 ±0.1
NET: 3.3 ±0.5

Volume Balance: 0.3

Transports and pathways of the tropical AMOC return flow from observations | Franz Philip Tuchen | US AMOC Science Team Meeting (Apr 25, 2022)
Diapycnal transports between 10N/S
Diapycnal transports between 10N/S

Transports and pathways of the tropical AMOC return flow from observations | Franz Philip Tuchen | US AMOC Science Team Meeting (Apr 25, 2022)
Especially, close to the equator we rely on shipboard measurements (geostrophic balance does not hold)
AMOC return flow: Summary

Transports and pathways of the tropical AMOC return flow from observations | Franz Philip Tuchen | US AMOC Science Team Meeting (Apr 25, 2022)
Key Points

- Observed Atlantic western boundary mean transport of the upper 1,200 m at 11°S is realistically reproduced from high-resolution Argo data and satellite wind stress data (so far Argo products were struggling to reproduce the western boundary circulation)
Key Points

• Observed Atlantic western boundary mean transport of the upper 1,200 m at 11°S is realistically reproduced from high-resolution Argo data and satellite wind stress data (so far Argo products were struggling to reproduce the western boundary circulation)

• Diapycnal transport estimates from high-resolution Argo data show upwelling of 2 Sv into the tropical Atlantic thermocline layer (about a third of previous estimates) (important term in STC estimates to close the transport budget and to address other uncertainties)

![Diagram showing transports and pathways of the tropical AMOC return flow from observations](image)
Key Points

• Observed Atlantic western boundary mean transport of the upper 1,200 m at 11°S is realistically reproduced from high-resolution Argo data and satellite wind stress data (so far Argo products were struggling to reproduce the western boundary circulation)

• Diapycnal transport estimates from high-resolution Argo data show upwelling of 2 Sv into the tropical Atlantic thermocline layer (about a third of previous estimates) (important term in STC estimates to close the transport budget and to address other uncertainties)

• Combining shipboard measurements with Argo data, an overview of the observed transports and pathways of the AMOC return flow is provided (so far this has been limited to (Lagrangian) model studies or drifter data at the surface)
Thank you for your attention

- Thanks to all the scientists and technicians who collected the shipboard current velocity measurements along the four sections
- Thanks to the Argo program for providing the fundamental base for such studies

Questions:
franz.philip.tuchen@noaa.gov
Supplemental figures and information
Transports and pathways

(a) Upper layers (Surface – 26.8 $\gamma_n$)

Argo data
Ship section data
Coastal boundary
Transports and pathways

(b) AAIW layer (26.8 $\gamma_n$ – 27.7 $\gamma_n$)

Water Mass Layer
- Surface Layer
- STC/thermocline Layer
- Lower CW
- AAIW
- NADW
- AABW

Argo data
Ship section data
Coastal boundary
Diapycnal upwelling into the STC layer

**Table 1. Hydrographic sections used for the calculations.**

<table>
<thead>
<tr>
<th>Latitude</th>
<th>Ship</th>
<th>Stations</th>
<th>Year</th>
<th>Month</th>
</tr>
</thead>
<tbody>
<tr>
<td>24°15'S</td>
<td>Crawford</td>
<td>416-458</td>
<td>1958</td>
<td>October</td>
</tr>
<tr>
<td>8°15'S</td>
<td>Crawford</td>
<td>86-92, 94-120</td>
<td>1957</td>
<td>March</td>
</tr>
<tr>
<td>8°15'N</td>
<td>Crawford</td>
<td>134-184</td>
<td>1957</td>
<td>May</td>
</tr>
<tr>
<td>24°30'N</td>
<td>Discovery II</td>
<td>3587-3624</td>
<td>1957</td>
<td>October</td>
</tr>
<tr>
<td>27°23'N</td>
<td>Atlantis</td>
<td>5334-5343</td>
<td>1955</td>
<td>June</td>
</tr>
</tbody>
</table>

**Table 2. Water masses, their isopycnal boundaries and the average depth of the isopycnals.**

<table>
<thead>
<tr>
<th>Layer</th>
<th>Water mass</th>
<th>Upper boundary</th>
<th>Lower boundary</th>
<th>Mean depth of interface (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Surface Water</td>
<td>Ocean surface</td>
<td>$\sigma_0 = 26.2$</td>
<td>146</td>
</tr>
<tr>
<td>2</td>
<td>Surface Water</td>
<td>$\sigma_0 = 26.2$</td>
<td>$\sigma_0 = 26.8$</td>
<td>325</td>
</tr>
<tr>
<td>3</td>
<td>Antarctic Intermediate Water</td>
<td>$\sigma_0 = 26.8$</td>
<td>$\sigma_0 = 27.0$</td>
<td>437</td>
</tr>
<tr>
<td>4</td>
<td>Antarctic Intermediate Water</td>
<td>$\sigma_0 = 27.0$</td>
<td>$\sigma_0 = 27.4$</td>
<td>871</td>
</tr>
<tr>
<td>5</td>
<td>Upper Circumpolar Water</td>
<td>$\sigma_0 = 27.4$</td>
<td>$\sigma_0 = 36.9$</td>
<td>1525</td>
</tr>
<tr>
<td>6</td>
<td>Upper North Atlantic Deep Water</td>
<td>$\sigma_0 = 36.9$</td>
<td>$\sigma_0 = 37.07$</td>
<td>2392</td>
</tr>
<tr>
<td>7</td>
<td>Lower North Atlantic Deep Water</td>
<td>$\sigma_0 = 37.07$</td>
<td>$\sigma_0 = 45.92$</td>
<td>4000</td>
</tr>
<tr>
<td>8</td>
<td>Lower Circumpolar Water</td>
<td>$\sigma_0 = 45.92$</td>
<td>ocean bottom</td>
<td></td>
</tr>
</tbody>
</table>

Roemmich (1983):
"The calculation shows $6 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ of layer 2 water from the Southern Hemisphere being upwelled, converted to layer 1 water, and then swept northward."

Lux et al. (2001):
"The equatorial Ekman divergence drives a conversion of Thermocline Water ($24.58 \leq \sigma_0 < 26.75$) into Surface Water ($\sigma_0 < 24.58$) of $7.5 \times 10^6 \text{ m}^3 \text{ s}^{-1}$,…"
Further discussion on upwelling

\[ 16 = 10 \text{ STC (6 WB + 4 INT)} + 6 \text{ THC upwelling (Roemmich 1983)} \]

- High-resolution Argo data suggests smaller contribution by THC upwelling

- 5.5 Sv THC upwelling, BUT recirculation in the STCs

Transports and pathways of the tropical AMOC return flow from observations | Franz Philip Tuchen | US AMOC Science Team Meeting (Apr 25, 2022)
More on the Subtropical Cells ...
Tropical Atlantic current system

Transports and pathways of the tropical AMOC return flow from observations | Franz Philip Tuchen | US AMOC Science Team Meeting (Apr 25, 2022)
Sverdrup stream function

Transports and pathways of the tropical AMOC return flow from observations | Franz Philip Tuchen | US AMOC Science Team Meeting (Apr 25, 2022)
Argo sections

Transports and pathways of the tropical AMOC return flow from observations | Franz Philip Tuchen | US AMOC Science Team Meeting (Apr 25, 2022)
Interior layer transports

Transports and pathways of the tropical AMOC return flow from observations | Franz Philip Tuchen | US AMOC Science Team Meeting (Apr 25, 2022)
Eastern boundary layer transports

Transports and pathways of the tropical AMOC return flow from observations | Franz Philip Tuchen | US AMOC Science Team Meeting (Apr 25, 2022)