Exploratory Glider Deployments Reveal Changes in the Upper Oceanic Water Masses of the Caribbean Through-Flow

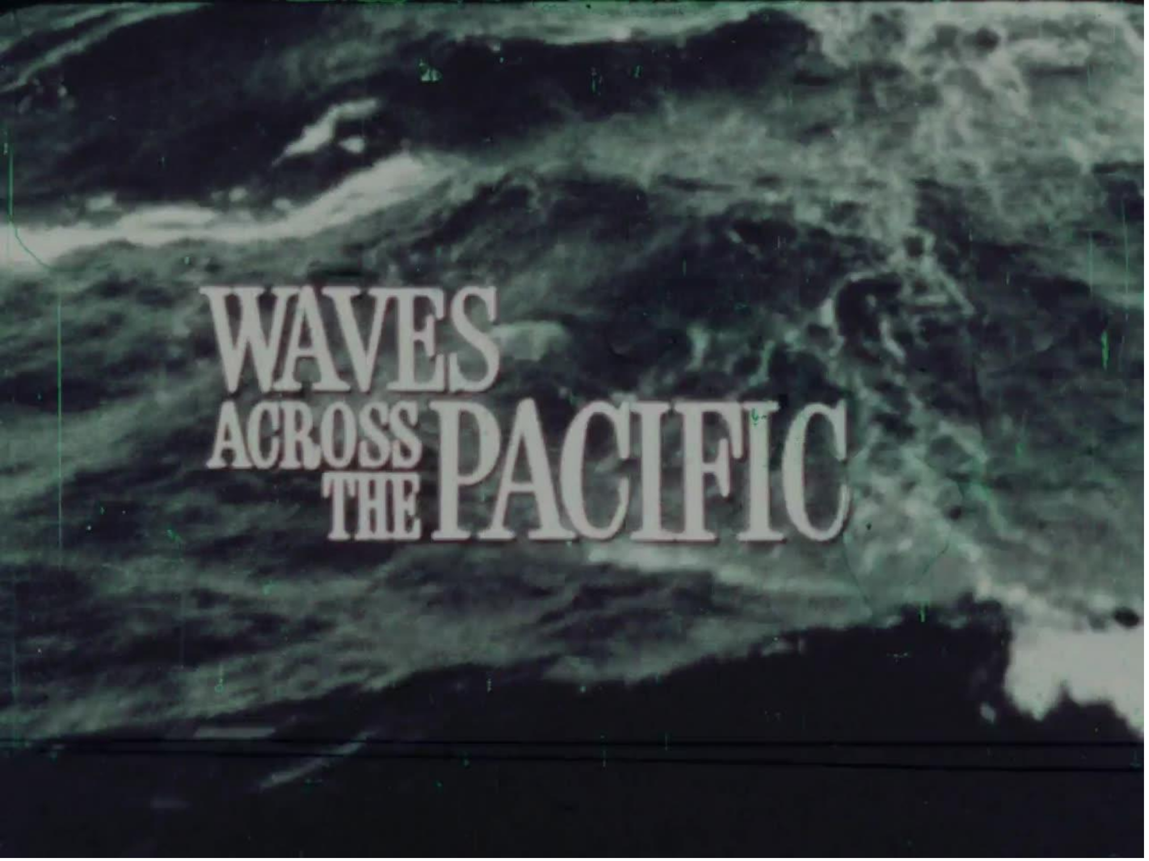
MTS
marine technology society
Opportunity runs deep™

WALTER MUNK
FOUNDATION FOR THE OCEANS

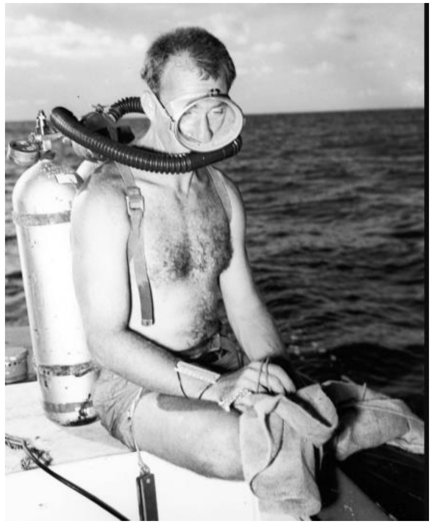
Joe Gradone

Walter Munk Commemorative Lecture

Photo Credit: Dan Mele



1. Technology development
2. Work with locals
3. Synthesize a diverse large dataset
4. Small-scale → large-scale



WAVES ACROSS THE PACIFIC 1963

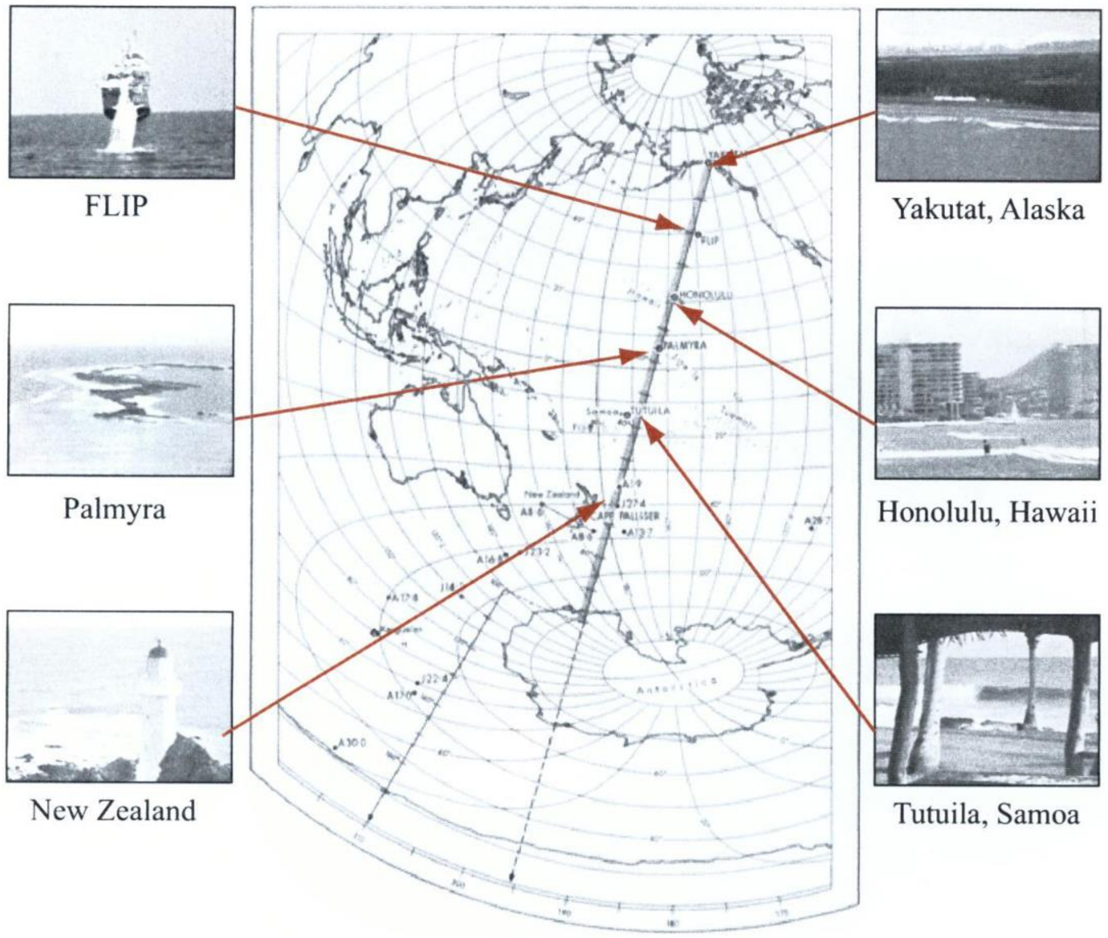
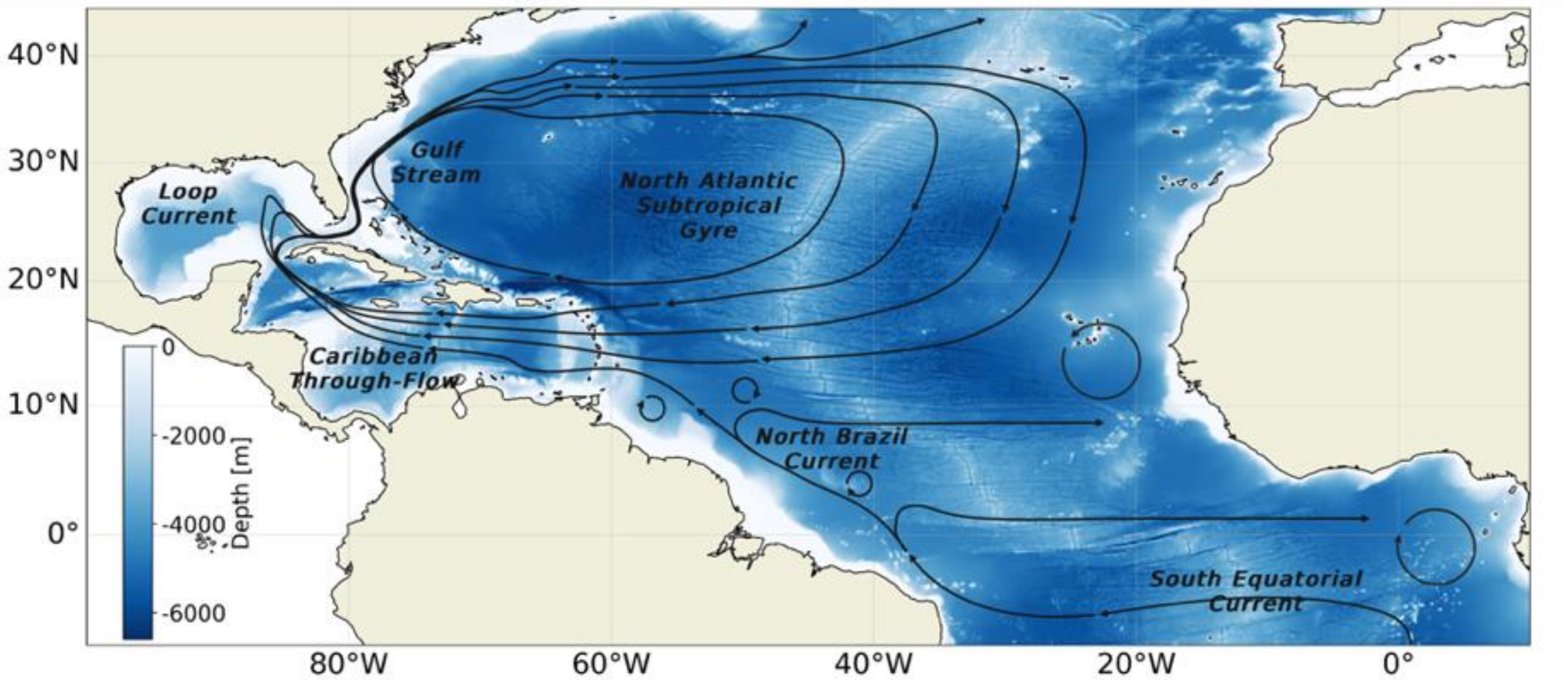
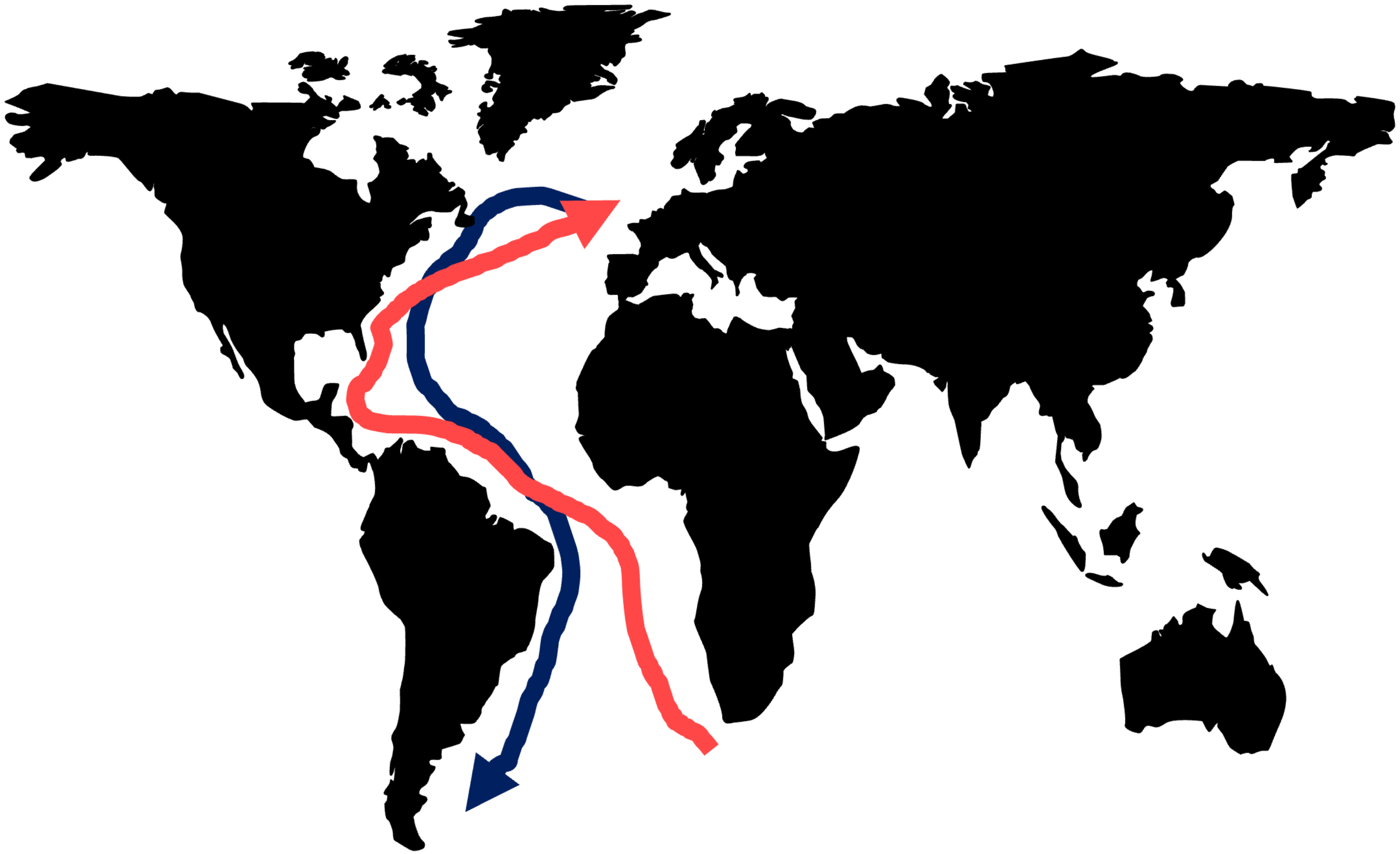


FIGURE 12. Expedition photographs of the six stations recording ocean swell along a great circle route in 1963

Caribbean Through-Flow is a **chokepoint** for **both** AMOC return flow and subtropical gyre recirculation

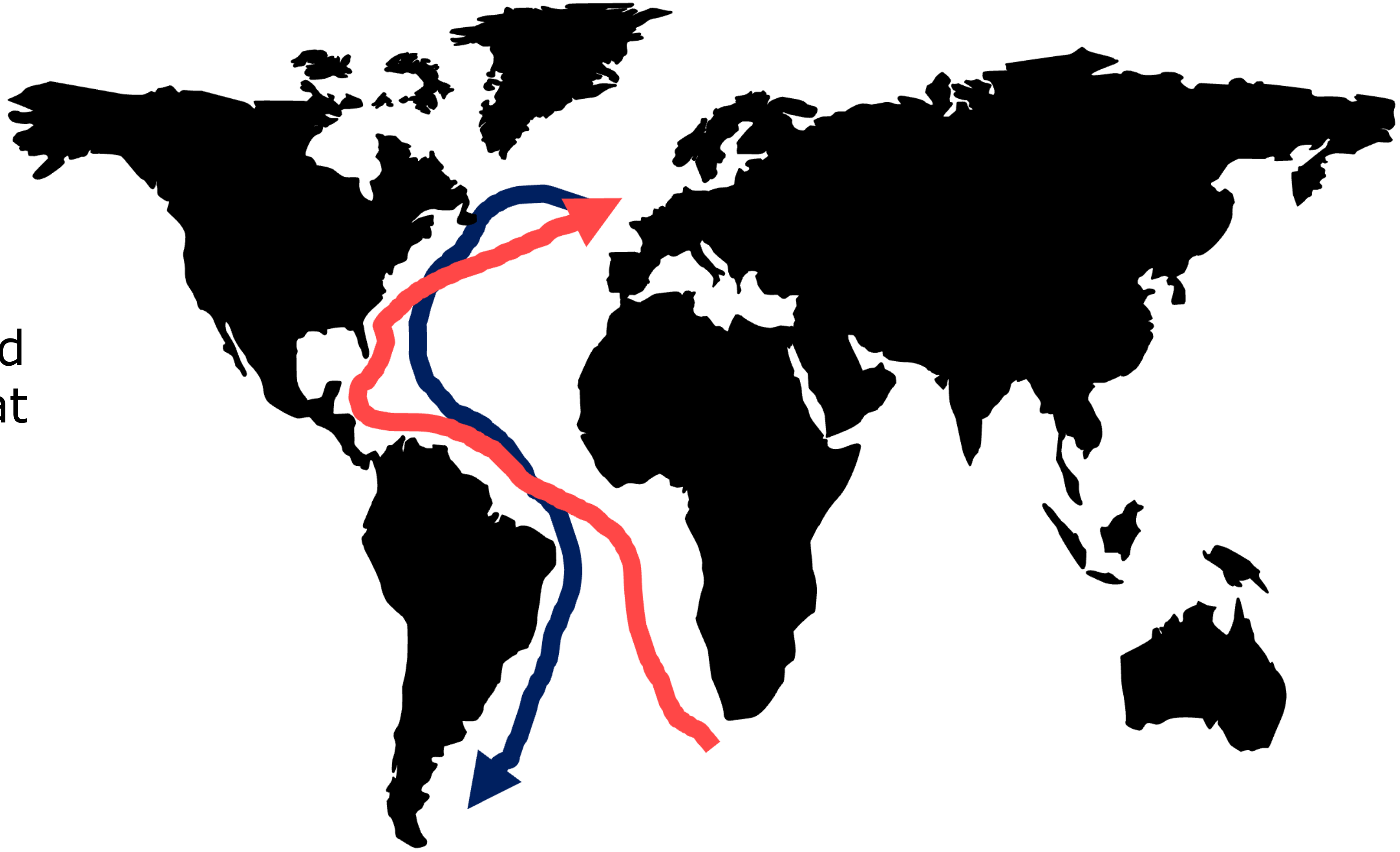


Atlantic Meridional Overturning Circulation



Why is the AMOC important?

Heat Transport:
~25% of the northern hemisphere's northward atmospheric-ocean heat transport



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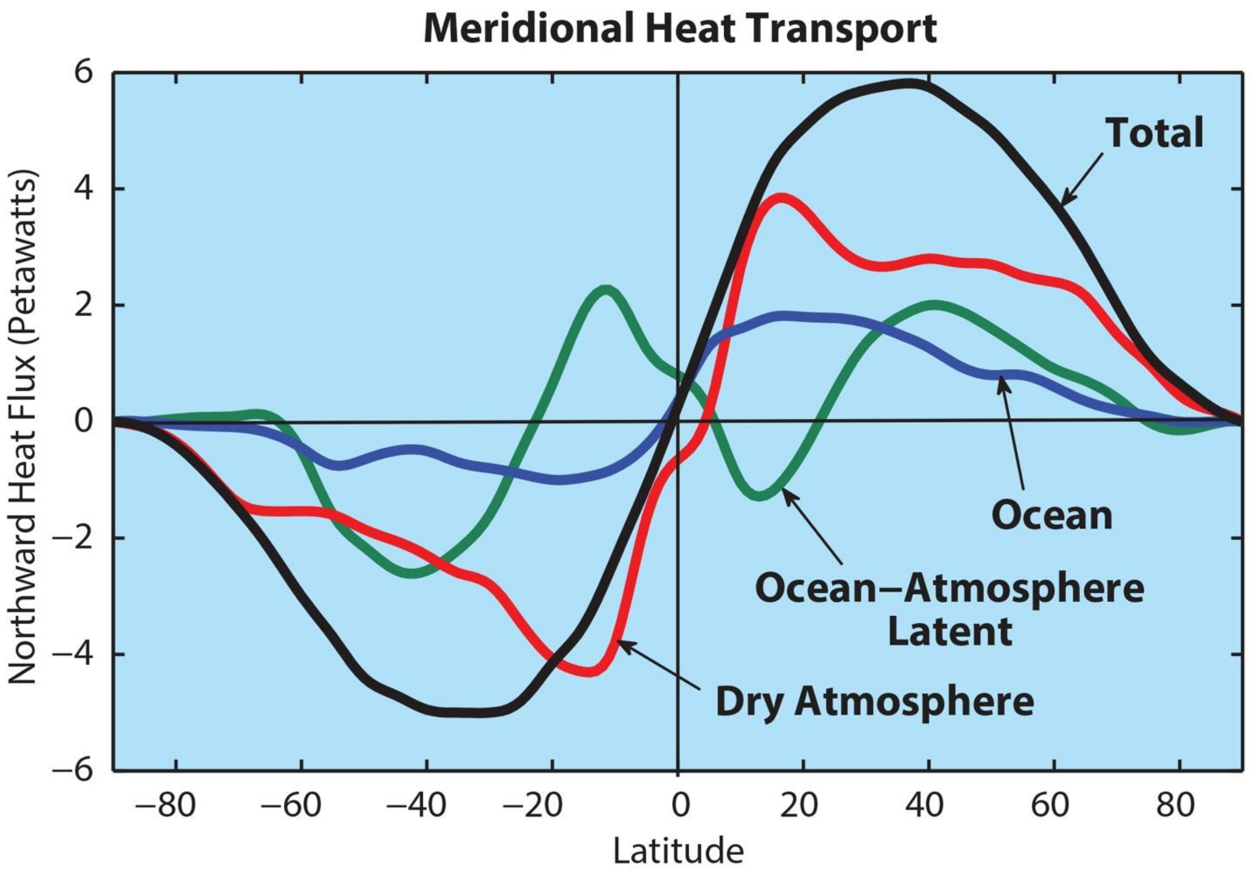
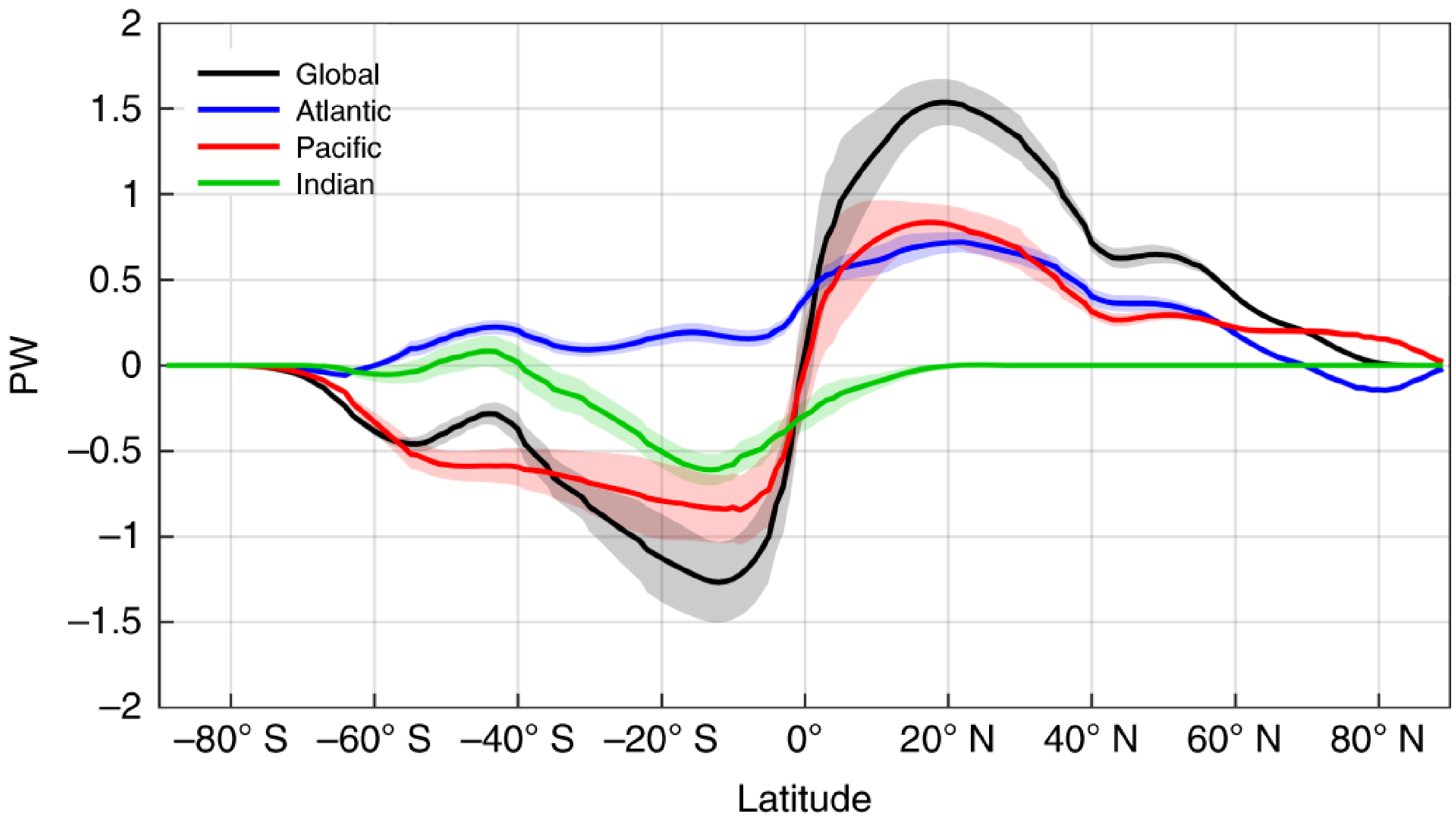


Schmitt (2018)

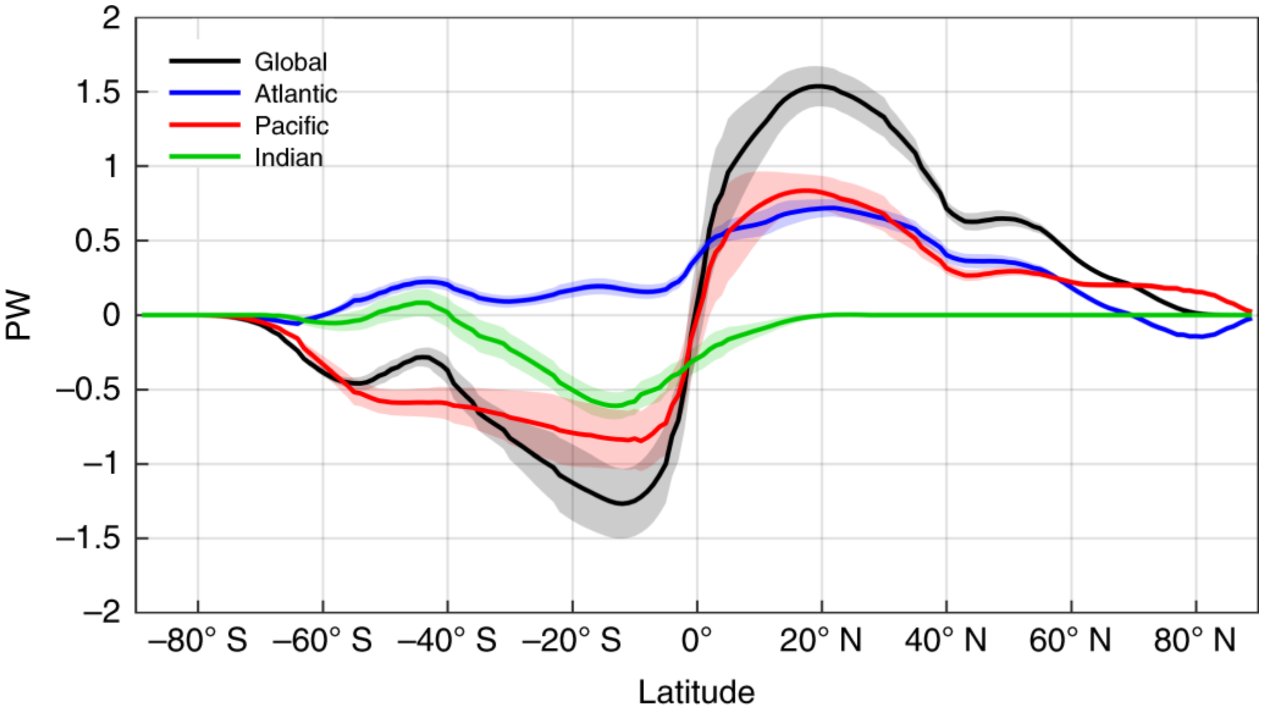
Why is the AMOC important?

Heat Transport:
Ocean heat transport is always positive in the Atlantic!



Forget and Ferreira (2019)

Why is the AMOC important?



14 MW

$$1\,Watt = 1\,\frac{Joule}{second}$$

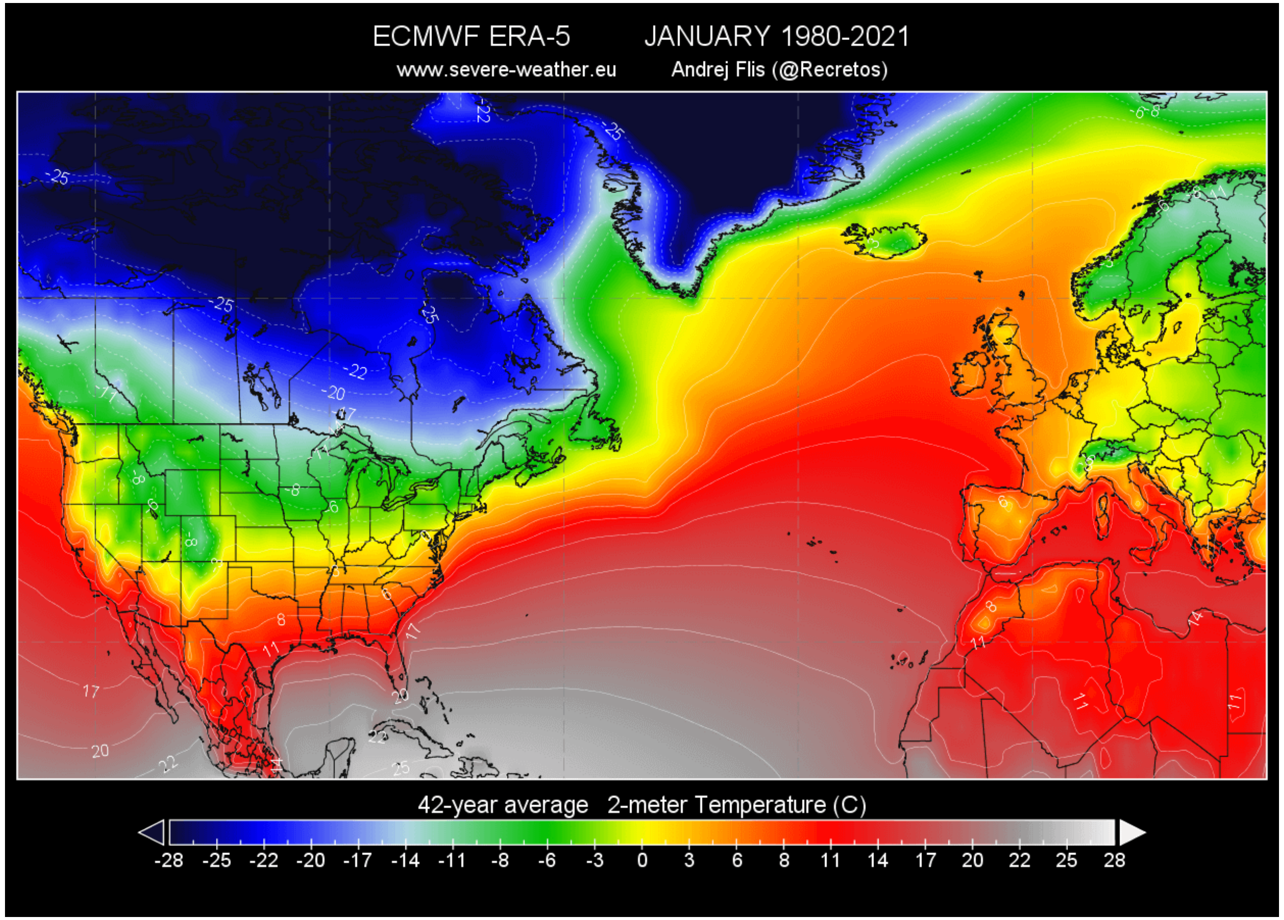
Equivalent to **~90 million** of world's largest wind turbines

Claudine Hellmuth/POLITICO (graphic); iStock (images)

Forget and Ferreira (2019)

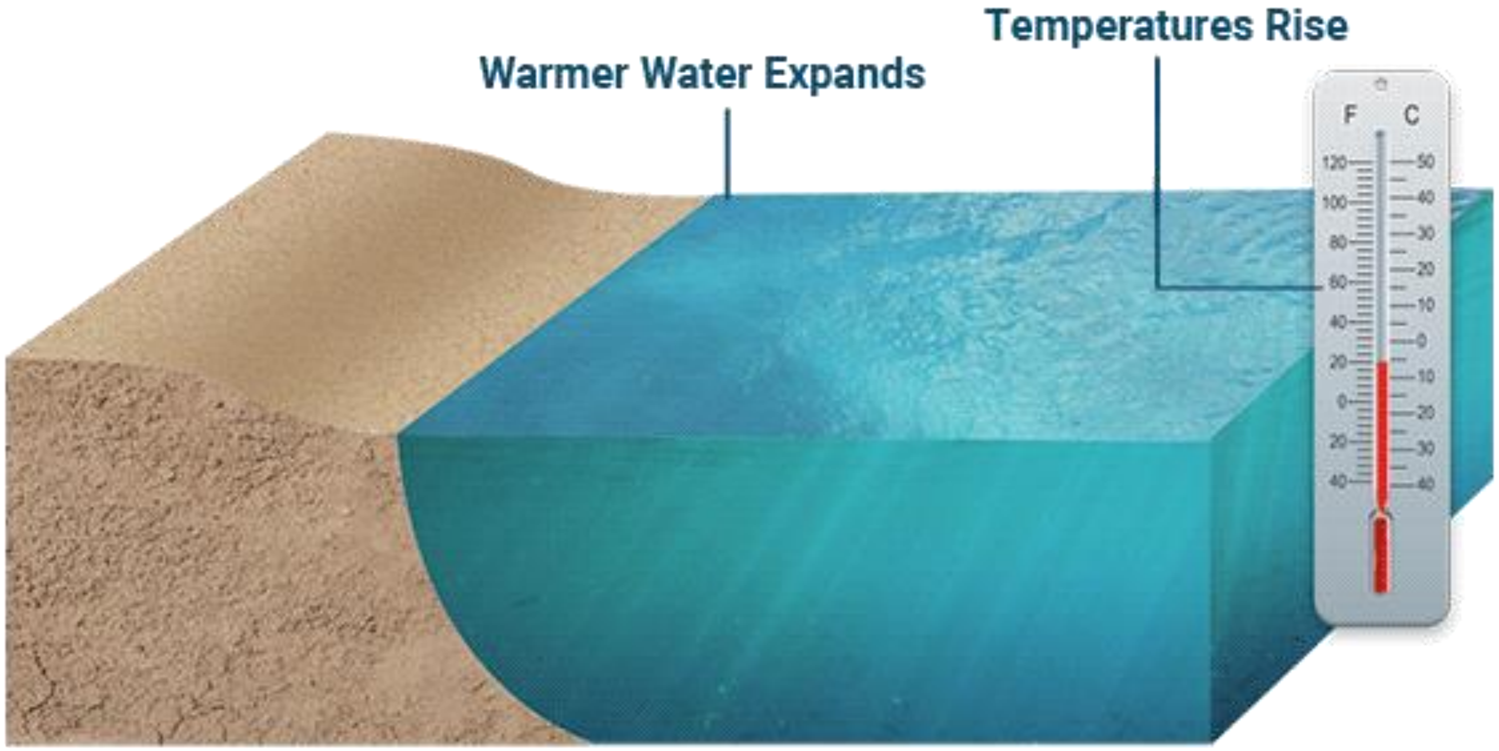
Why is **heat transport** important?

Climate



Why is **heat transport** important?

Sea Level Rise

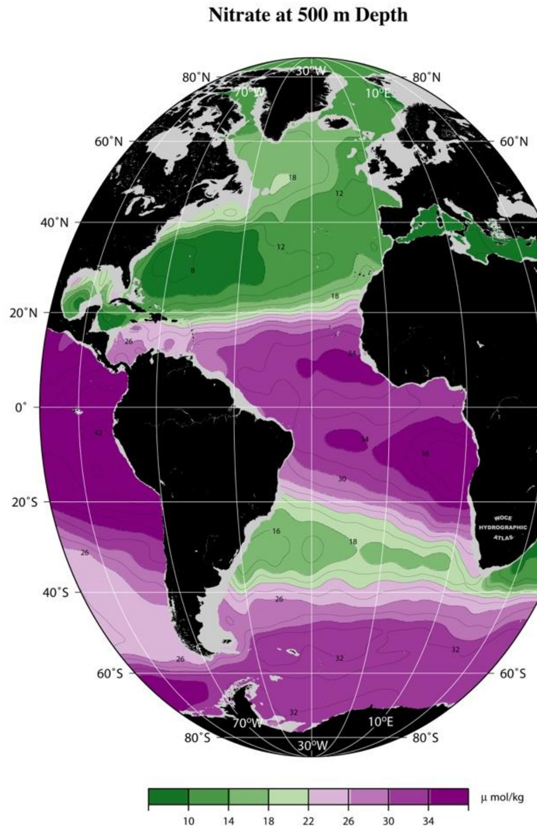


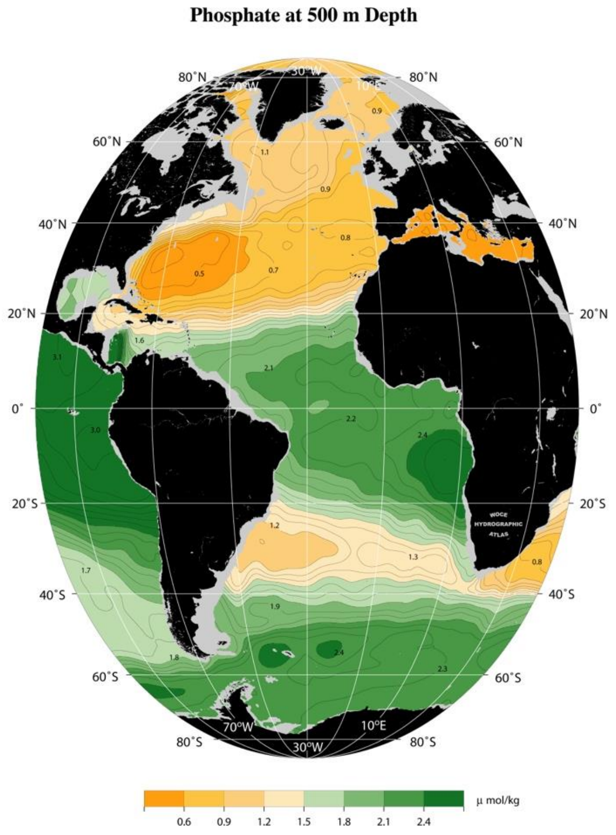
https://climateyou.org/

Why is **heat transport** important?

Marine Ecosystems

Changes in water mass pathways impact regional and global **nutrient delivery**

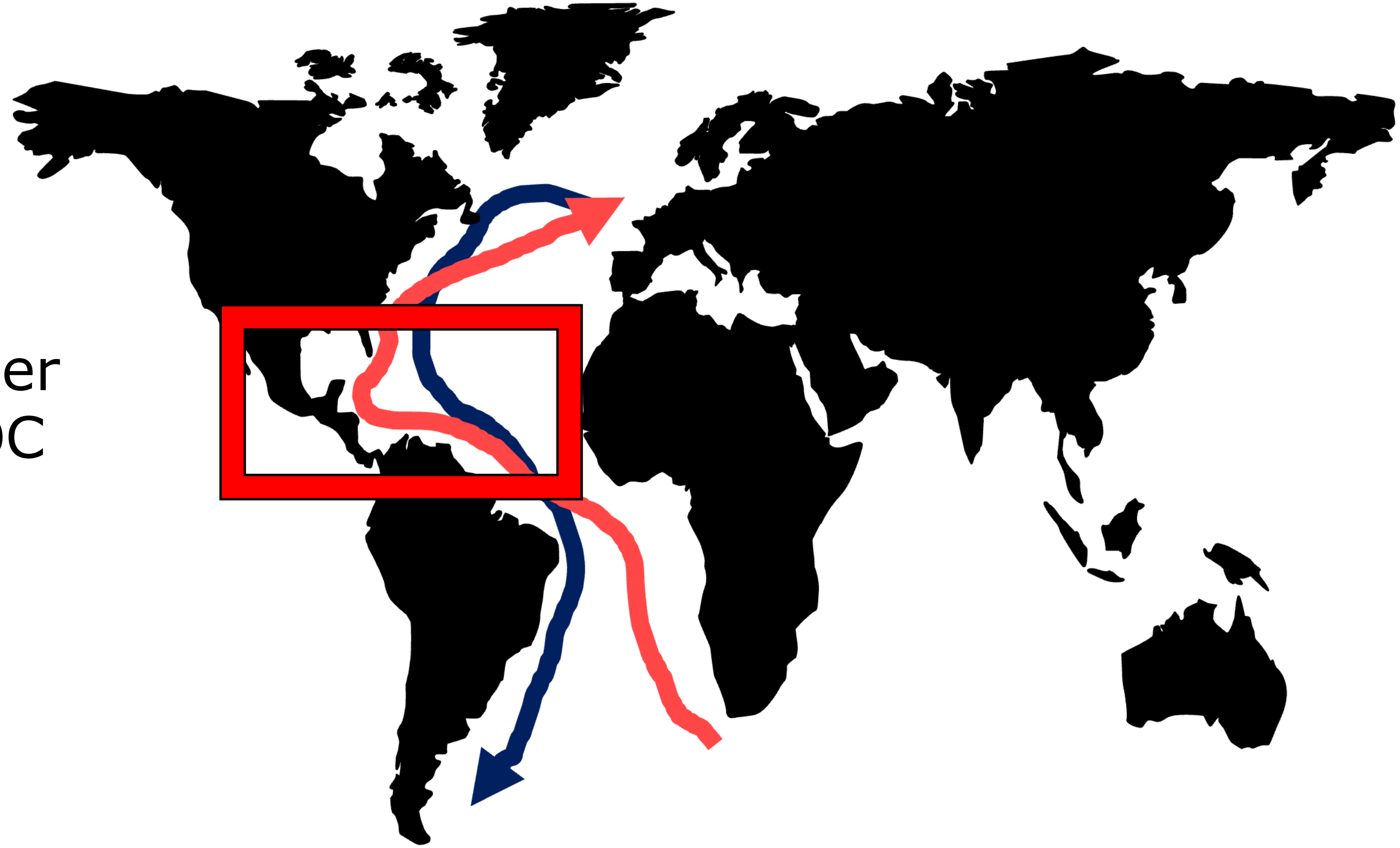


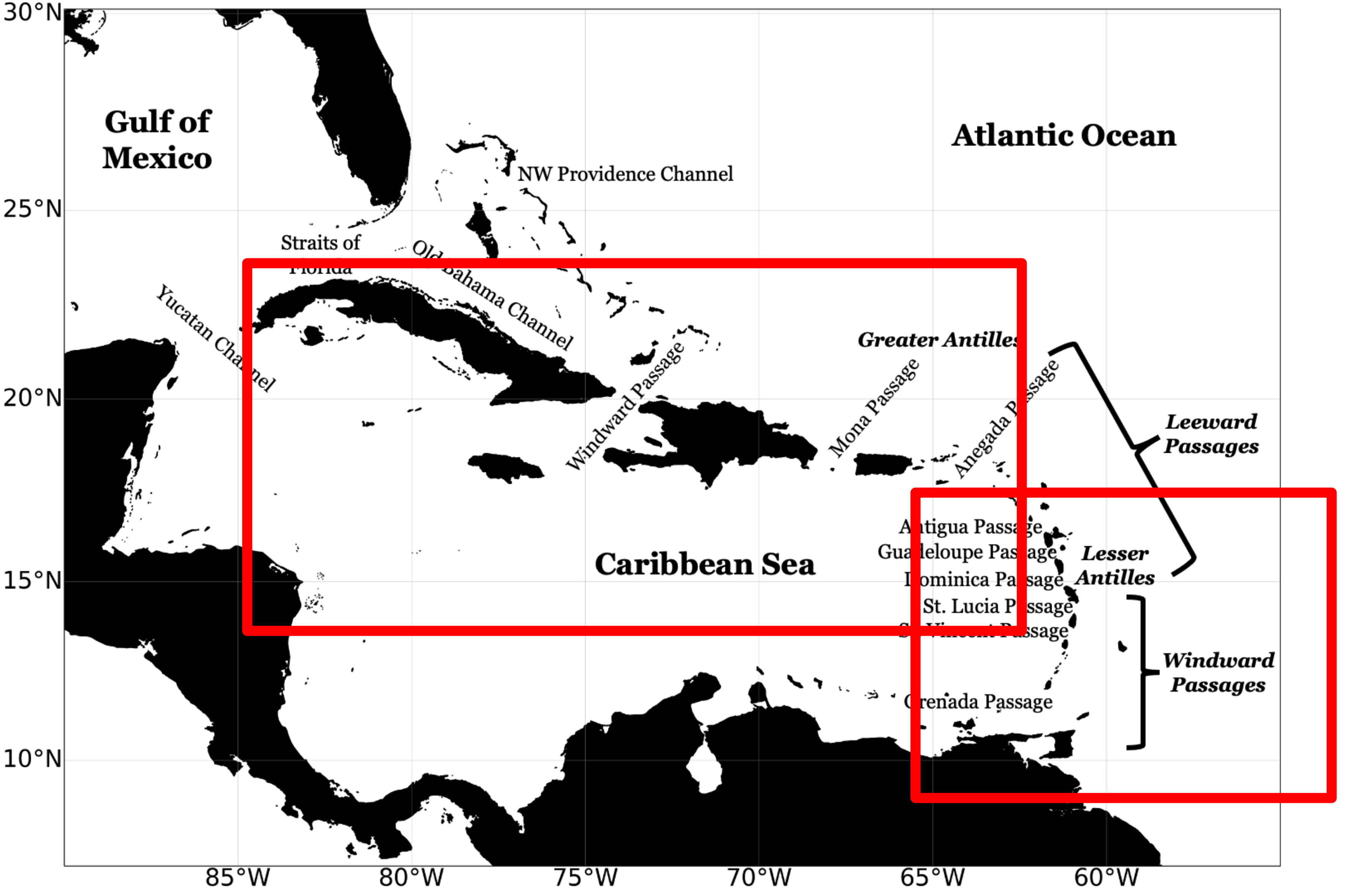


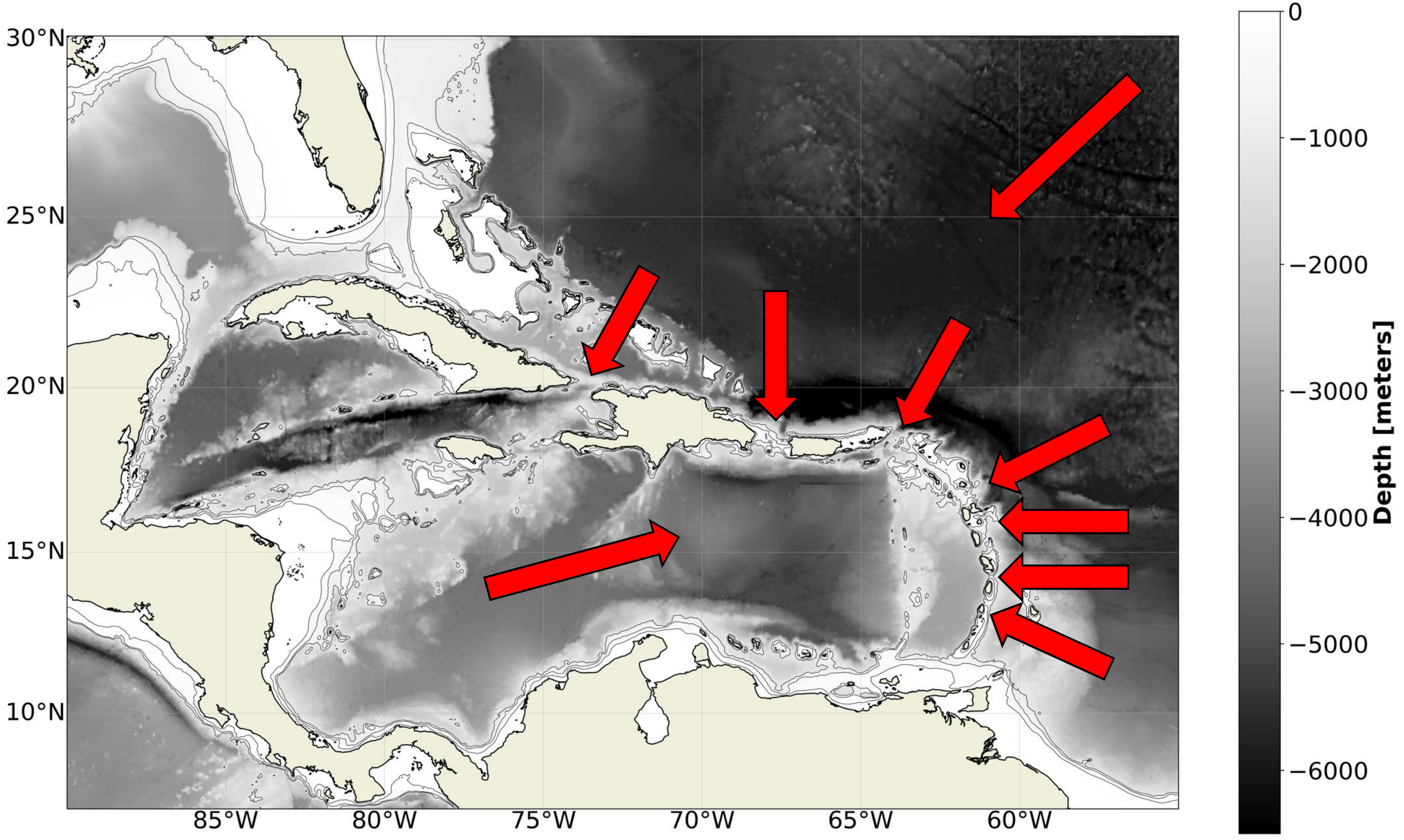
WOCE Atlas V.3

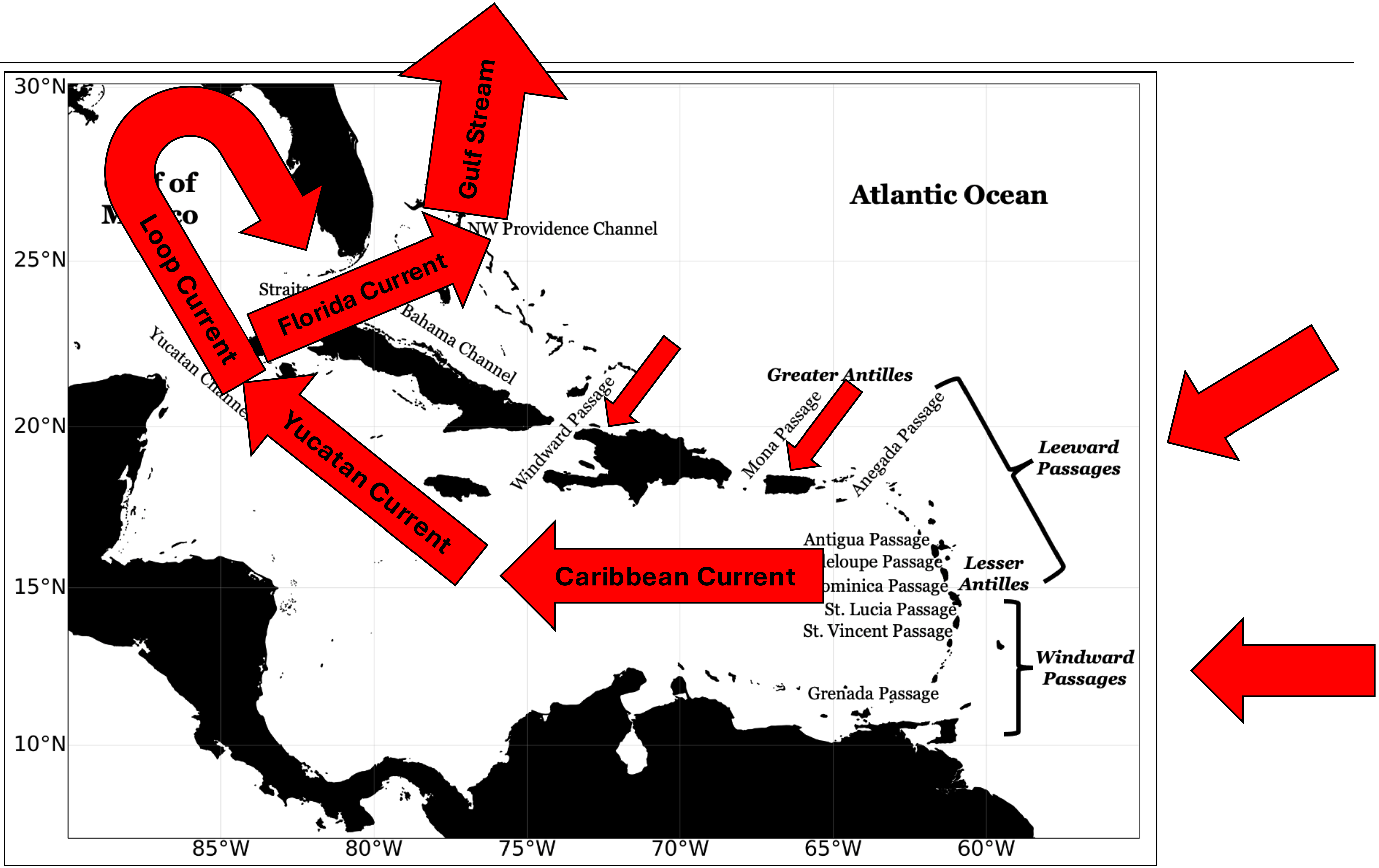
Why the Caribbean?

Start of the upper limb of the AMOC



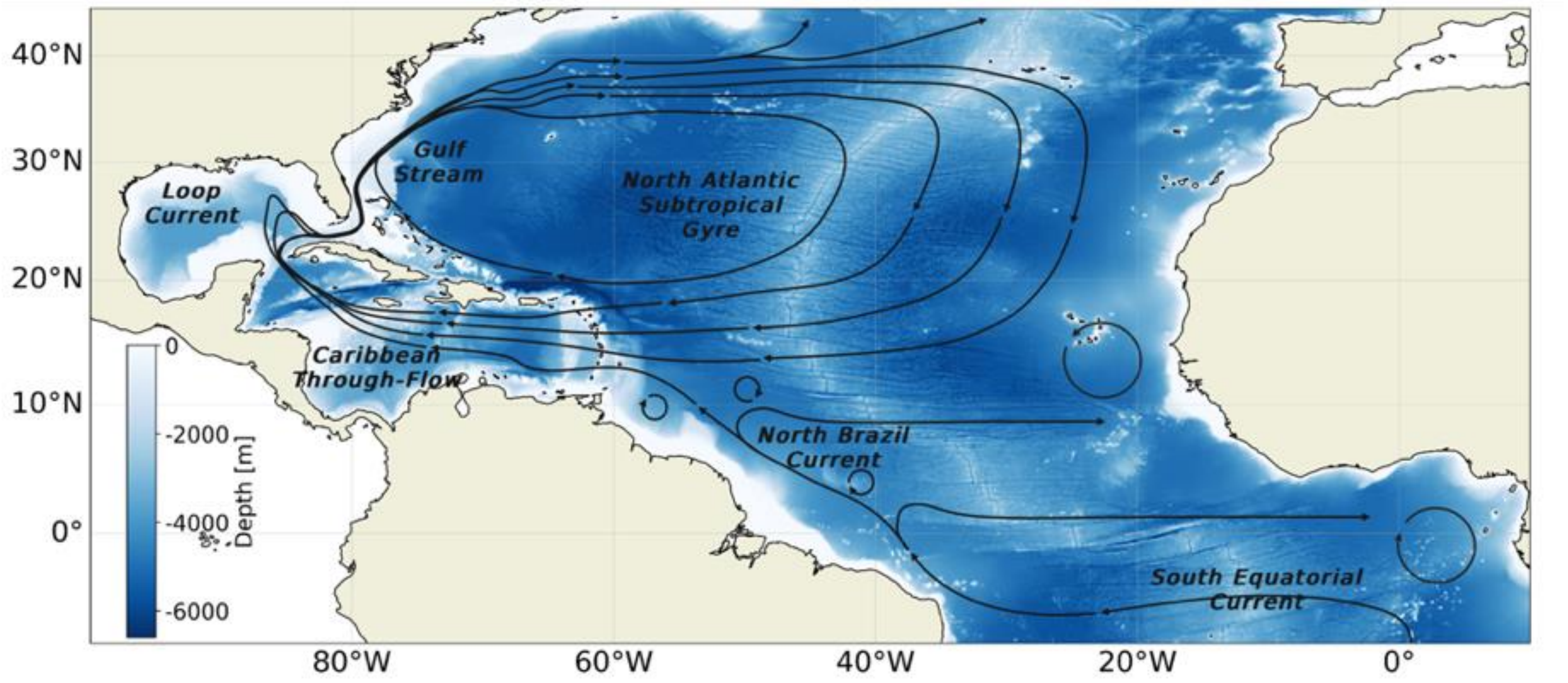

Gulf of Mexico
Atlantic Ocean
NW Providence Channel
Straits of Florida
Old Bahama Channel
Yucatan Channel
Windward Passage
Mona Passage
Anegada Passage
Greater Antilles
Leeward Passages
Caribbean Sea
Lesser Antilles
Windward Passages
St. Lucia Passage
Grenada Passage
30°N
25°N
20°N
15°N
10°N
85°W
80°W
75°W
70°W
65°W
60°W


30°N
25°N
20°N
15°N
10°N
85°W
80°W
75°W
70°W
65°W
60°W
0
−1000
−2000
−3000
−4000
−5000
−6000
Depth [meters]



30°N
25°N
20°N
15°N
10°N
85°W
80°W
75°W
70°W
65°W
60°W
Atlantic Ocean
Gulf Stream
Loop Current
Florida Current
Yucatan Current
Caribbean Current
NW Providence Channel
Bahama Channel
Yucatan Channel
Windward Passage
Mona Passage
Anegada Passage
Greater Antilles
Leeward Passages
Antigua Passage
Lesser Antilles
St. Lucia Passage
St. Vincent Passage
Windward Passages
Grenada Passage

Caribbean Through-Flow is a **chokepoint** for **both** AMOC return flow and subtropical gyre recirculation



Questions around and recent showing a slowdown/collapse in the AMOC

nature

NEWS AND VIEWS · 11 APRIL 2018

North Atlantic circulation slows down

Evidence suggests that the circulation system of the North Atlantic Ocean is in a weakened state that is unprecedented in the past 1,600 years, but questions remain as to when exactly the decline commenced.

Summer K. Praetorius

nature communications

Article https://doi.org/10.1038/s41467-023-39810-w

Warning of a forthcoming collapse of the Atlantic meridional overturning circulation

Received: 3 March 2023

Accepted: 29 June 2023

Peter Ditlevsen[1,3] & Susanne Ditlevsen[2,3]

The New York Times

In the Atlantic Ocean, Subtle Shifts Hint at Dramatic Dangers

The warming atmosphere is causing an arm of the powerful Gulf Stream to weaken, some scientists fear.

By MOISES VELASQUEZ-MANOFF and JEREMY WHITE

ScienceAdvances

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RESEARCH ARTICLE | OCEANOGRAPHY

Physics-based early warning signal shows that AMOC is on tipping course

RENÉ M. VAN WESTEN, MICHAEL KLIPHUIS, AND HENK A. DIJKSTRA Authors Info & Affiliations

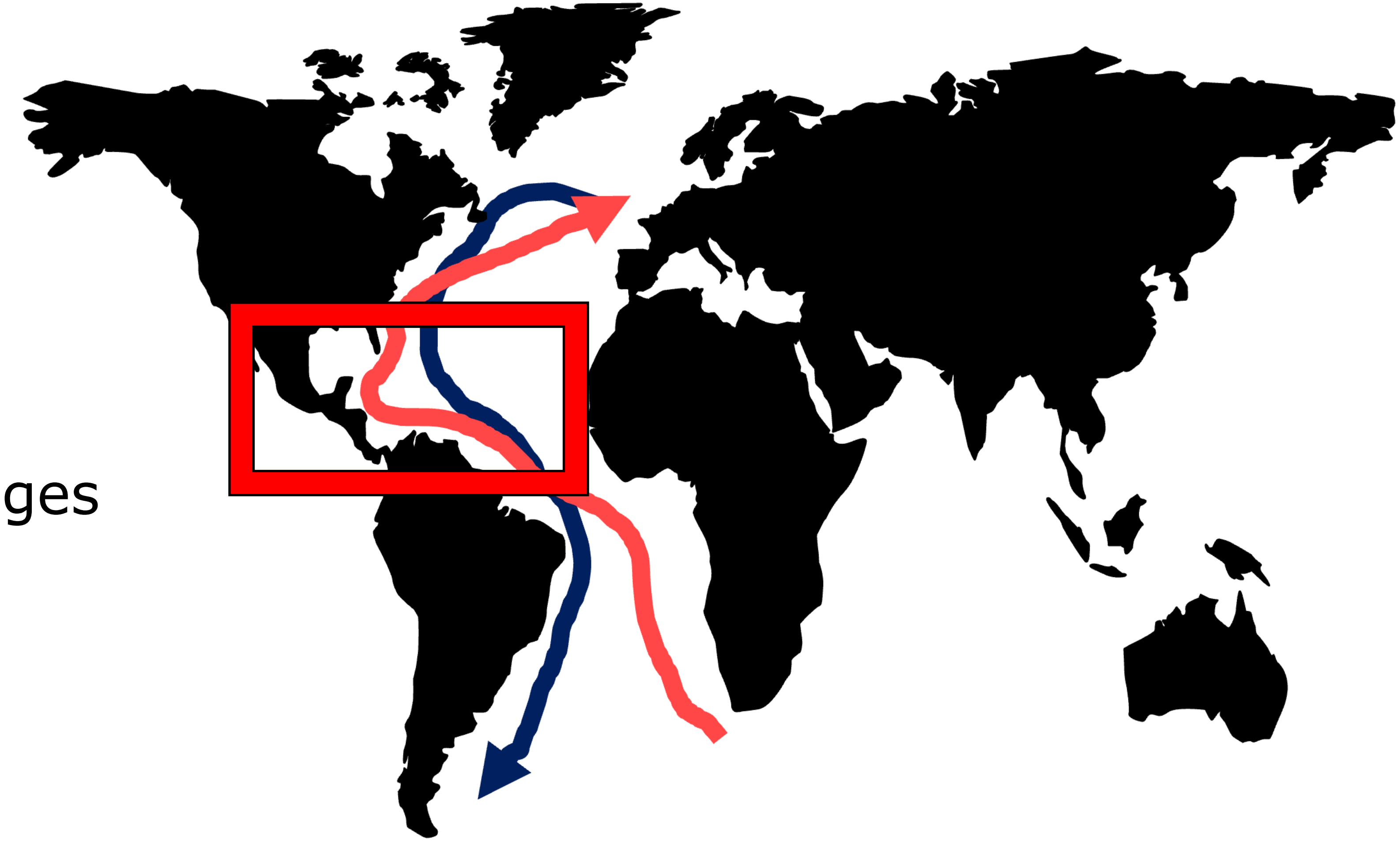
WIRED SUBSCRIBE


T IE AY AFT ER
TOM RROW

Why the Caribbean?

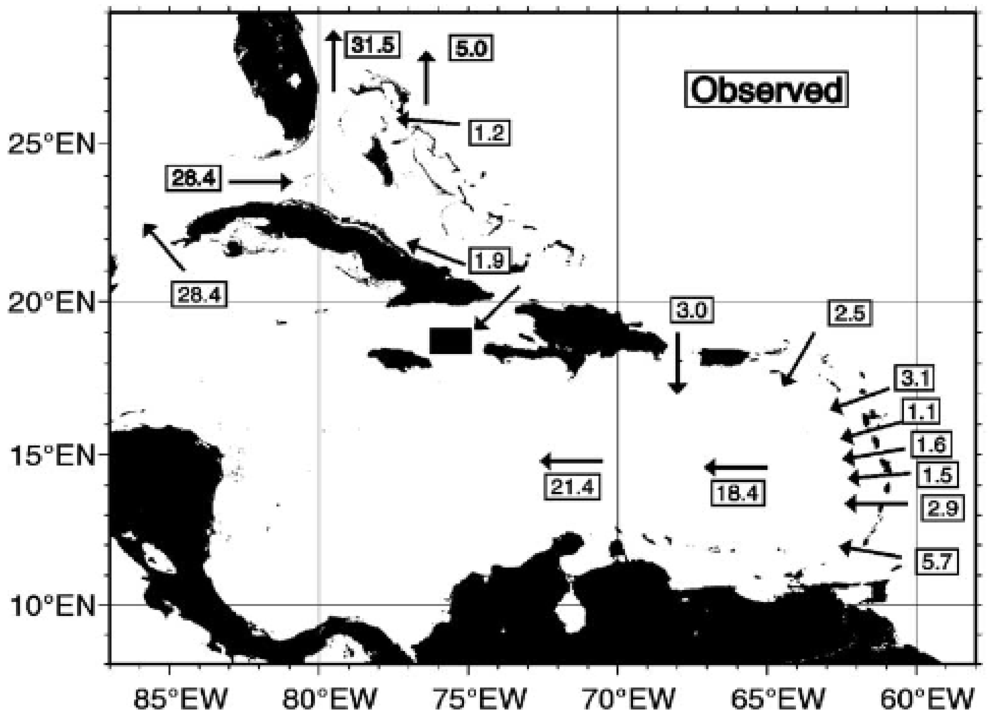
- Chokepoint for major Atlantic circulations

- Significant changes and uncertainty surrounding Atlantic-wide circulation

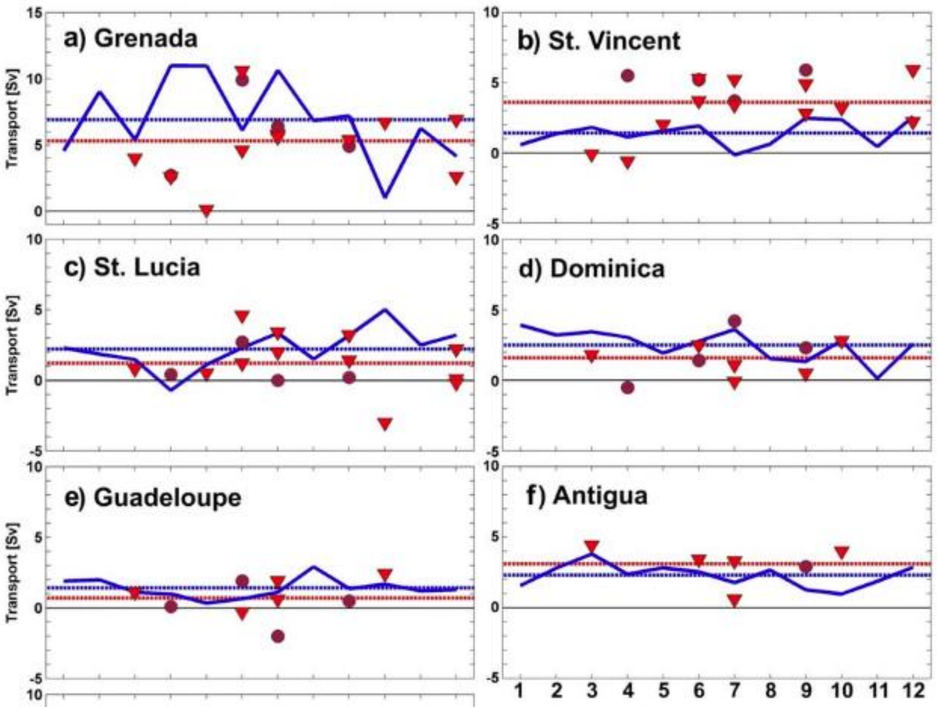


Caribbean Through-Flow is significantly under-sampled!

Wilson and Johns, 1997; Johns et al. 2002
Observations: 1991-2001

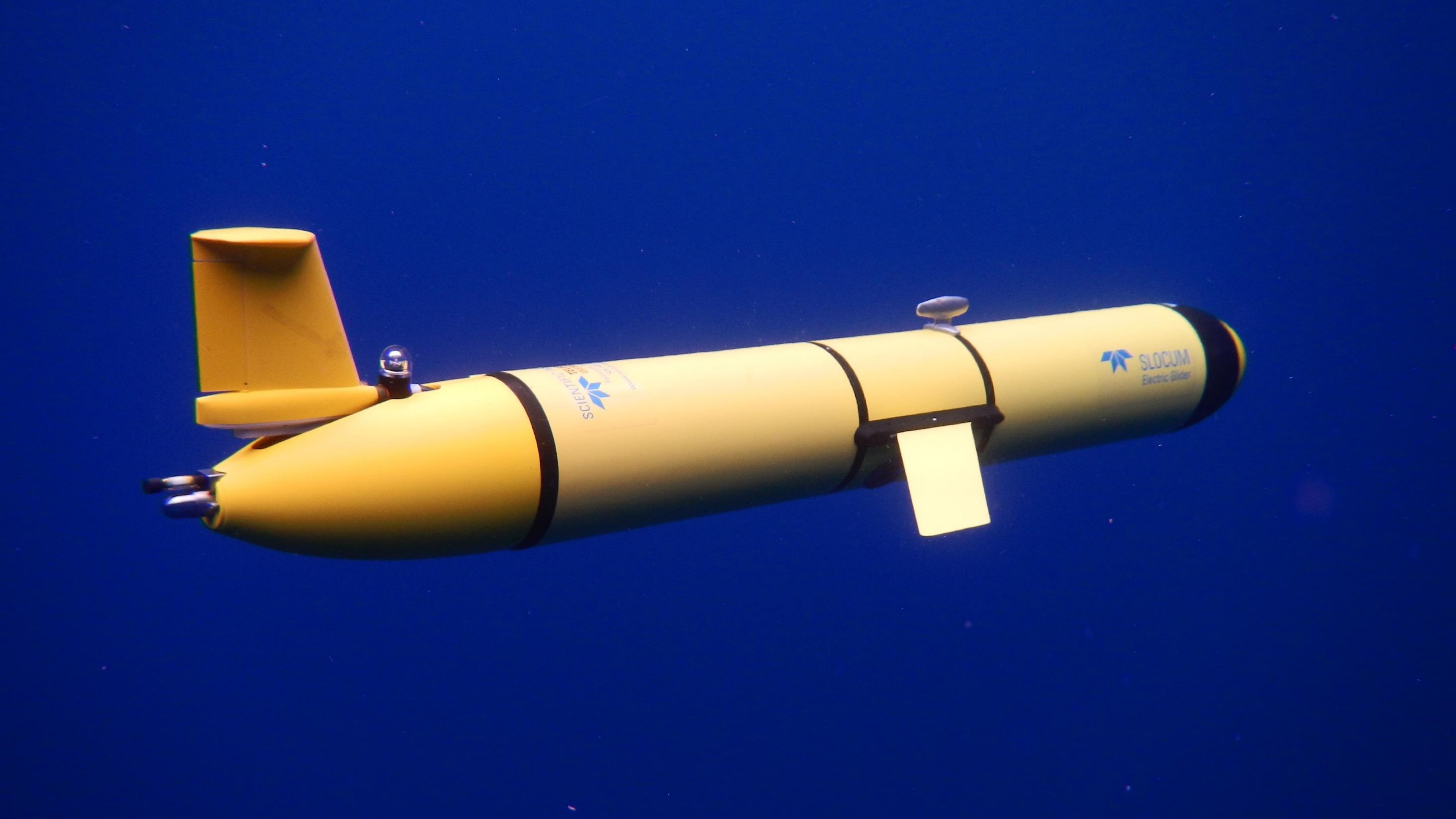


Kirchner et al. 2008
Observations: 2002 & 2005



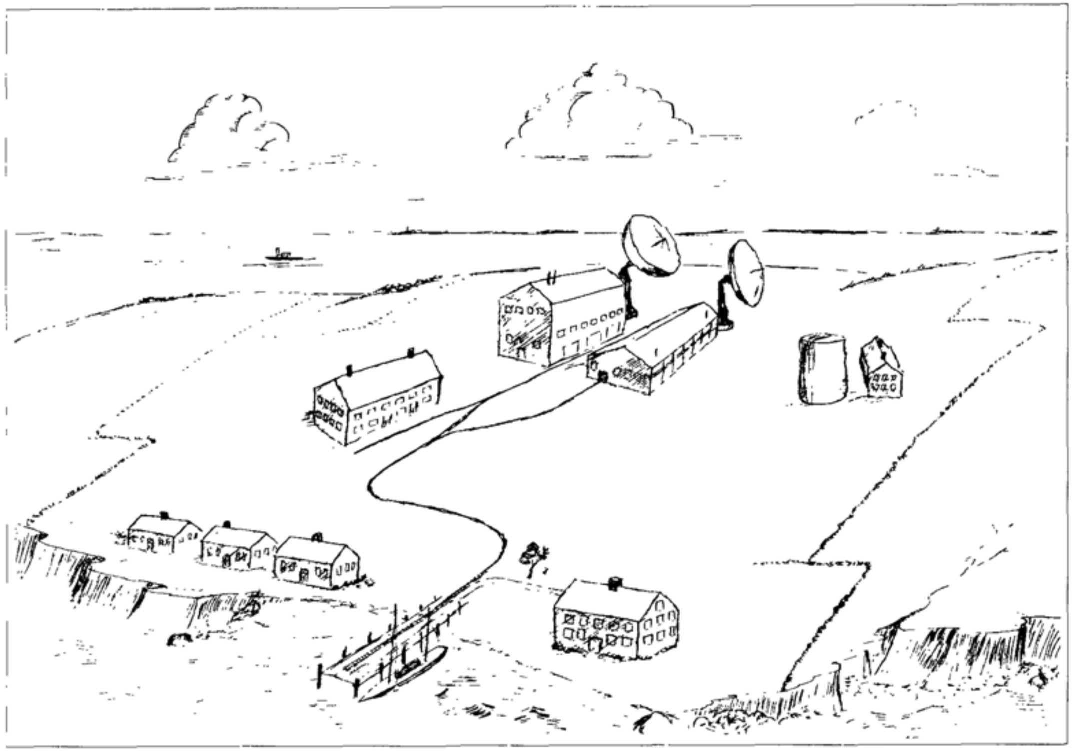
~20 years

No transport observations in the Caribbean Through-Flow in 20 years


SLOCUM
Electric Glider

THE SLOCUM MISSION

Narrative and Illustration
By Henry Stommel



The Slocum Mission Control Center on Nonamesset Island.

The payoff in increase of knowledge often is greatest the more unconventional the idea, especially when it conflicts with collective wisdom.

Each Slocum reports into Mission Control via satellite about six times a day.

SLOCUM Glider

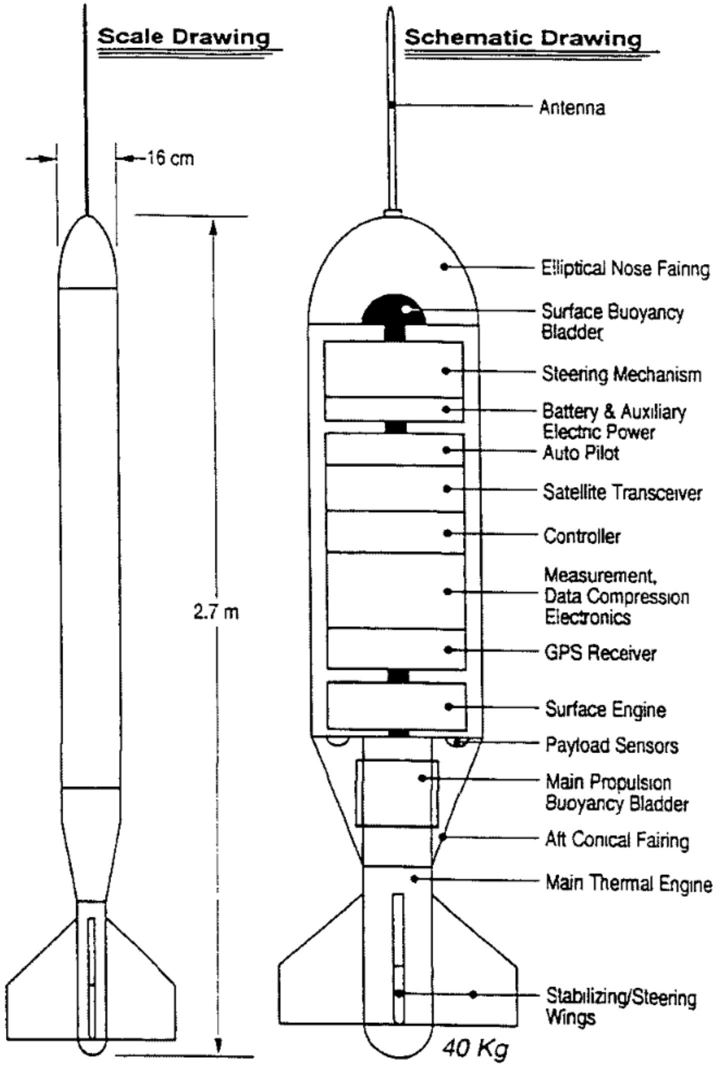
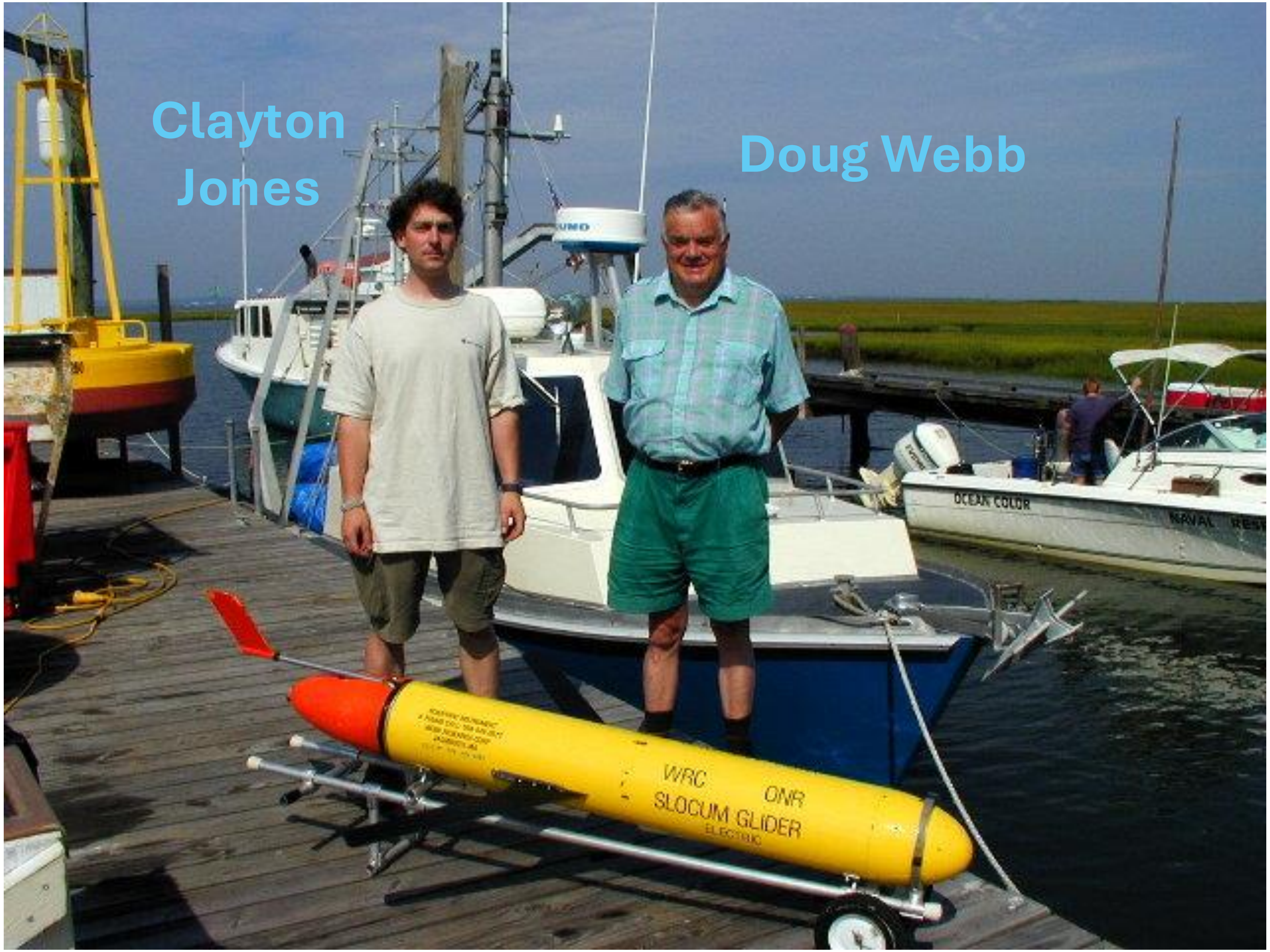


Fig. 6: Schematic of Slocum, a small almost neutrally buoyant glider that moves vertically and horizontally through the water driven by small changes in buoyancy. Steering is by control surfaces or internal center of gravity adjustment.

1989 Science Fiction

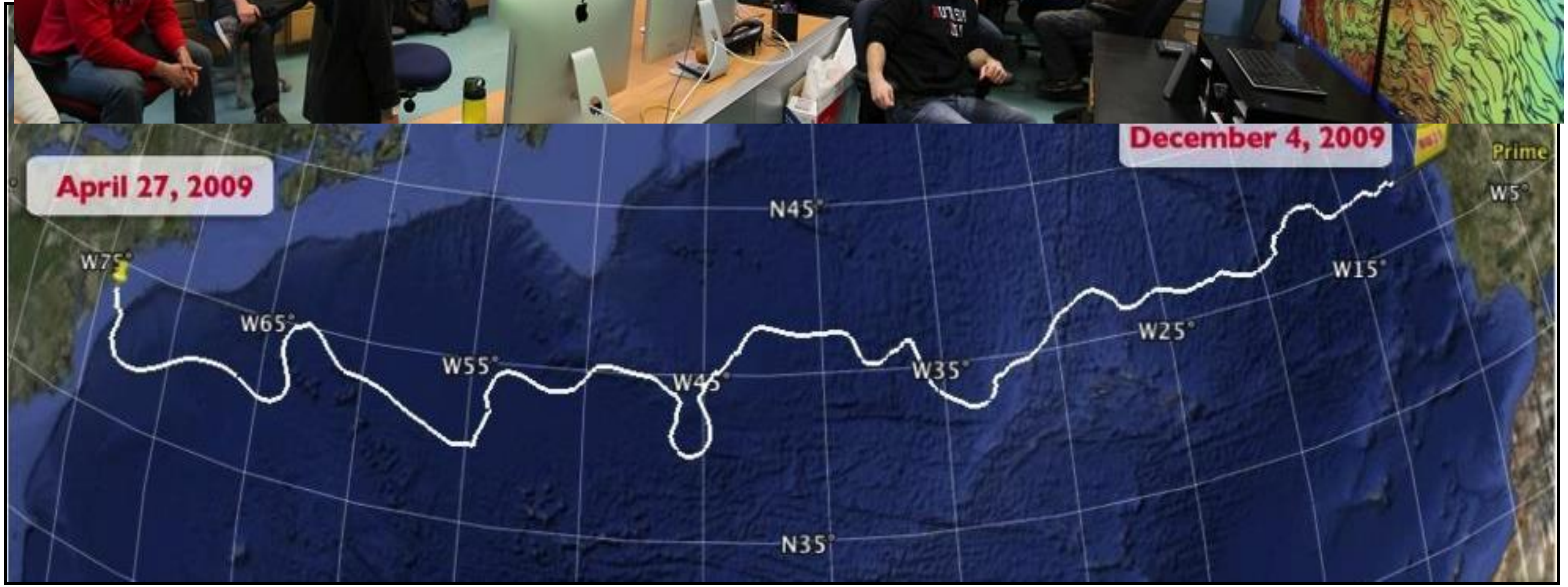


1999
First Slocum glider deployed at Sea

At the Rutgers University Tuckerton Marine Field Station

RUTGERS

TELEDYNE WEBB RESEARCH
Everywhereyoulook™



RUTGERS

2009 First Atlantic Crossing

TELEDYNE
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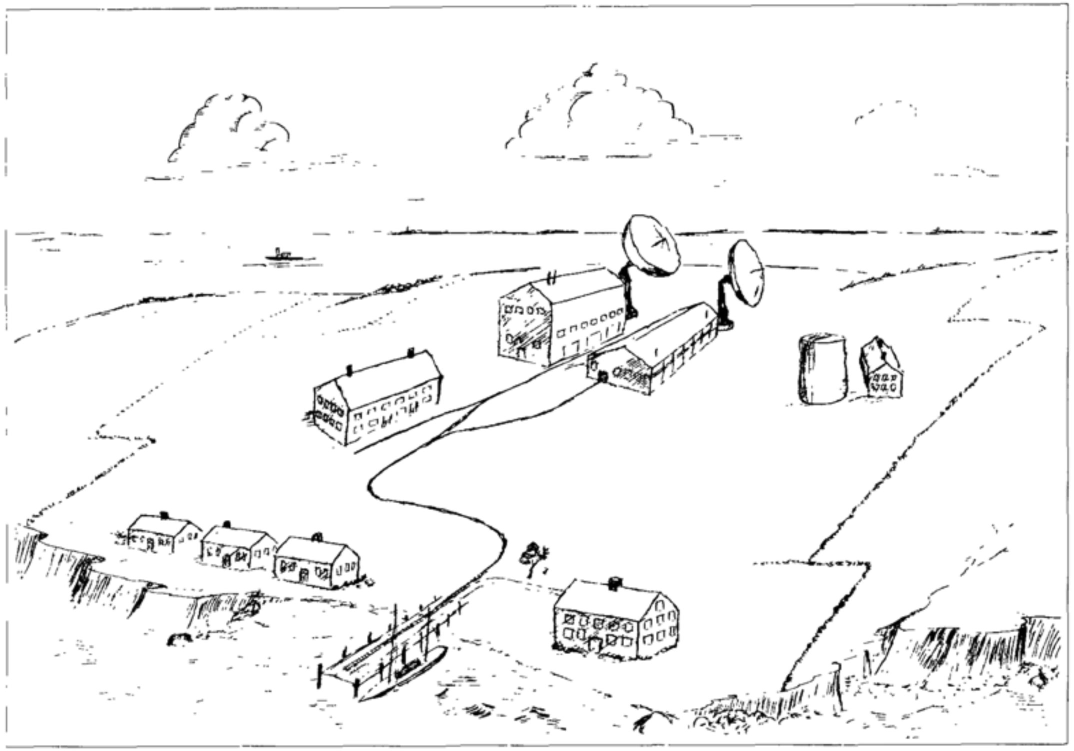
FEATURE

THE SLOCUM MISSION

Narrative and Illustration
By Henry Stommel



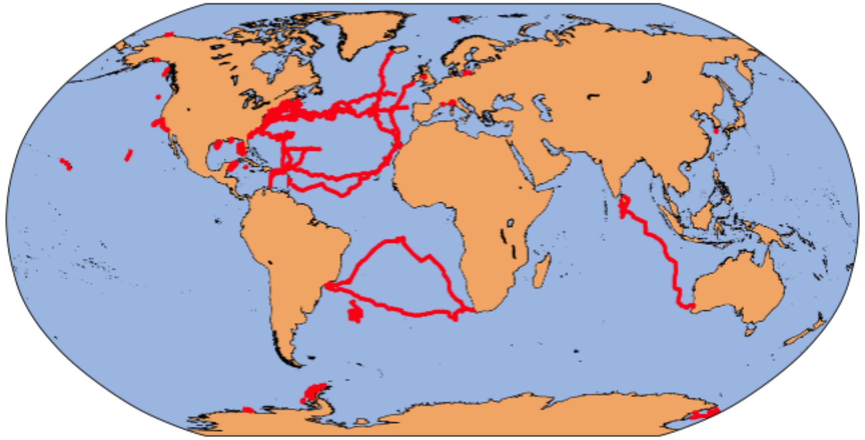
The Slocum Mission Control Center on Nonamesset Island.

1989 Science Fiction

RU-COOL Glider Fleet Totals

Total Deployments	Active Deployments
711	2

Distance Flown	Glider Days
376,327 km	19,450 days
(9+ times around the earth)	(53+ years)



2025 Sustained deployments world-wide

RUTGERS

TELEDYNE WEBB RESEARCH
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AGU ADVANCING EARTH AND SPACE SCIENCES

JGR Oceans

RESEARCH ARTICLE

10.1029/2022JC019608

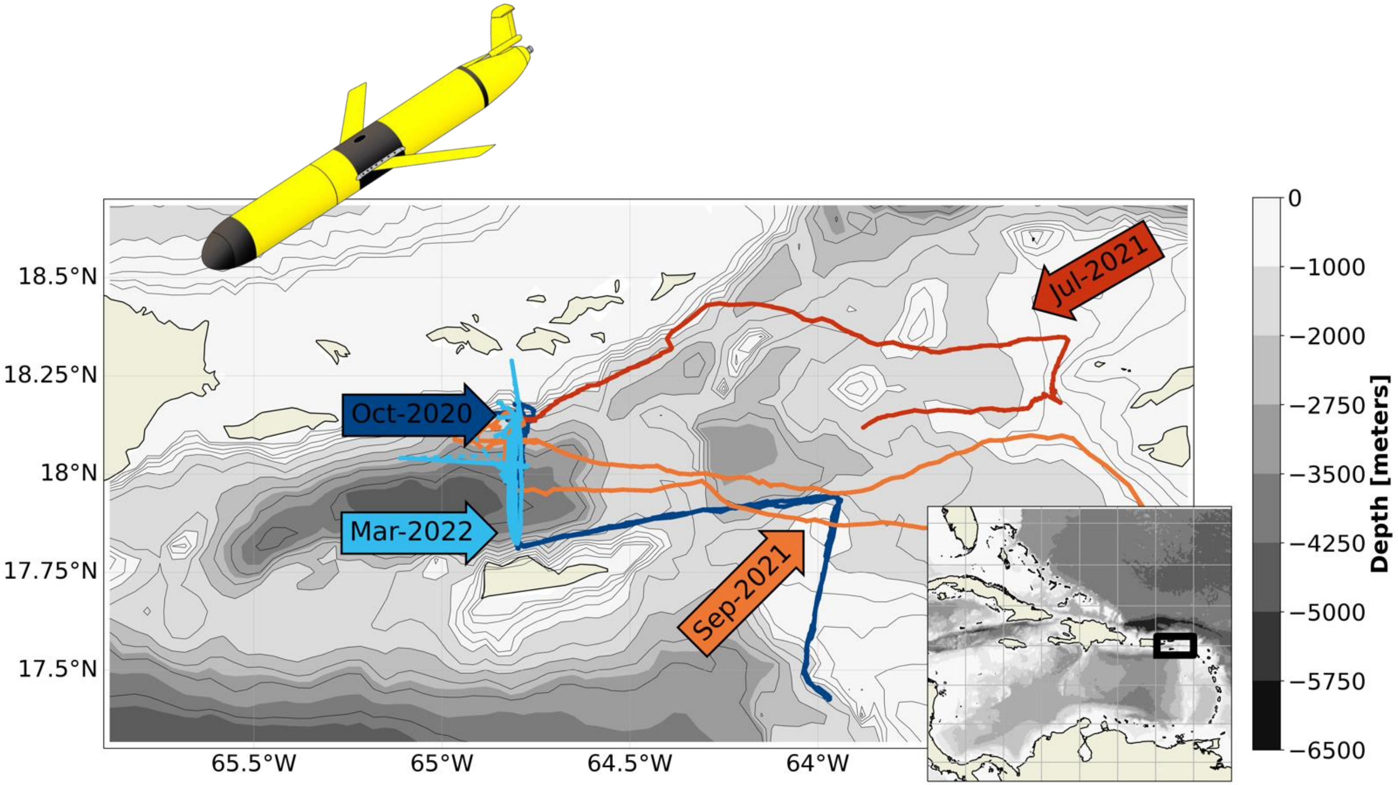
Key Points:

- Total transport and transport of South Atlantic Water through the Anegada Passage (AP) may be larger than previously estimated
- The AP is a pathway for both Atlantic Meridional Overturning Circulation return flow and subtropical gyre recirculation

Upper Ocean Transport in the Anegada Passage From Multi-Year Glider Surveys

J. C. Gradone[1], W. D. Wilson[2,3], S. M. Glenn[1], and T. N. Miles[1]

[1]Center for Ocean Observing Leadership, Department of Marine and Coastal Sciences, School of Environmental and Biological Sciences, Rutgers University, New Brunswick, NJ, USA, [2]Center for Marine and Environmental Studies, University of the Virgin Islands, St. Thomas, VI, USA, [3]Ocean and Coastal Observing—Virgin Islands, Inc, St. Thomas, VI, USA



TELEDYNE WEBB RESEARCH

THE G. UNGER VETLESEN FOUNDATION

Office of Naval Research Science & Technology

4

glider deployments

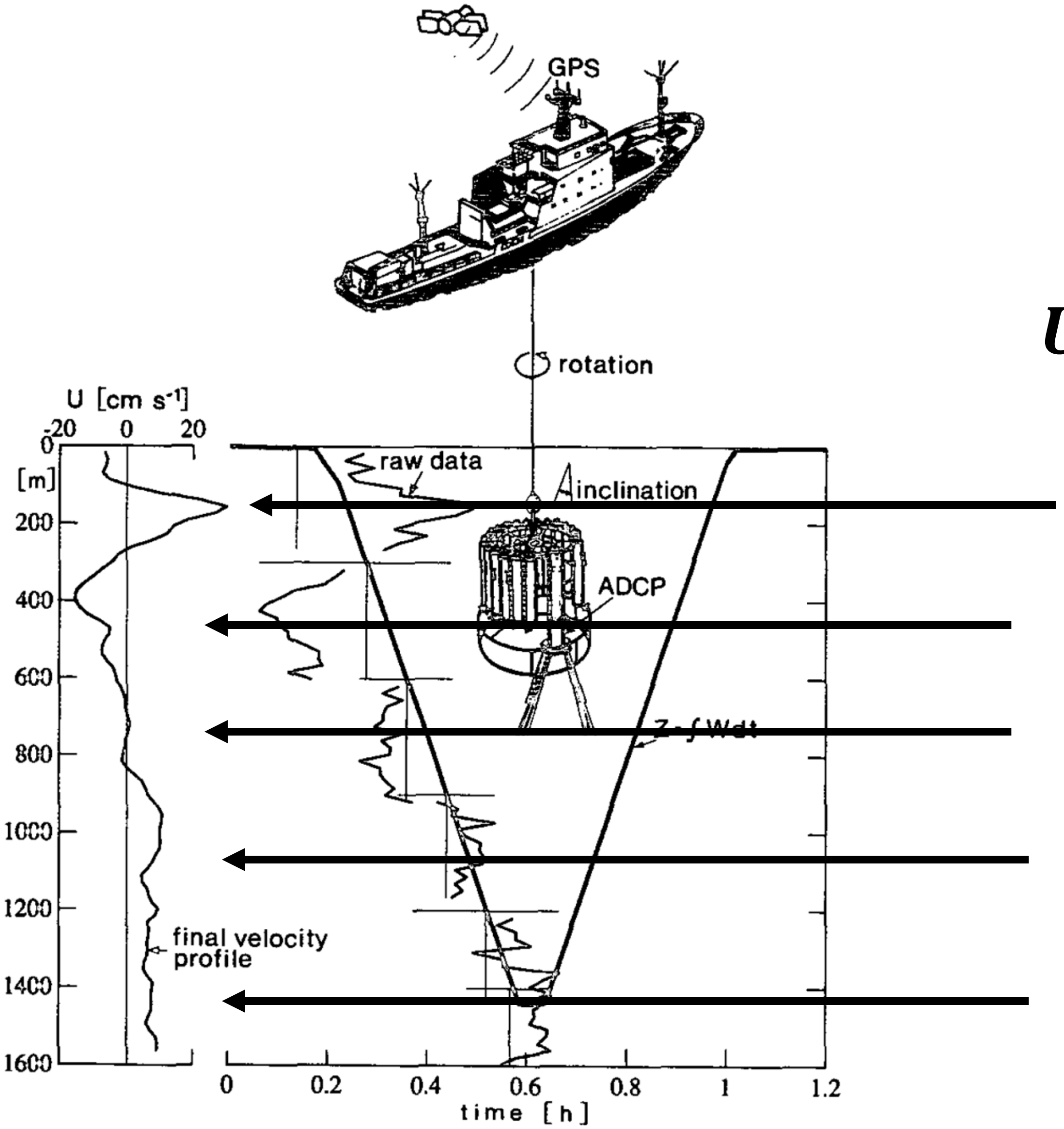
>2700

kilometers sampled

>130

days at sea

Gradone et al. (2023)



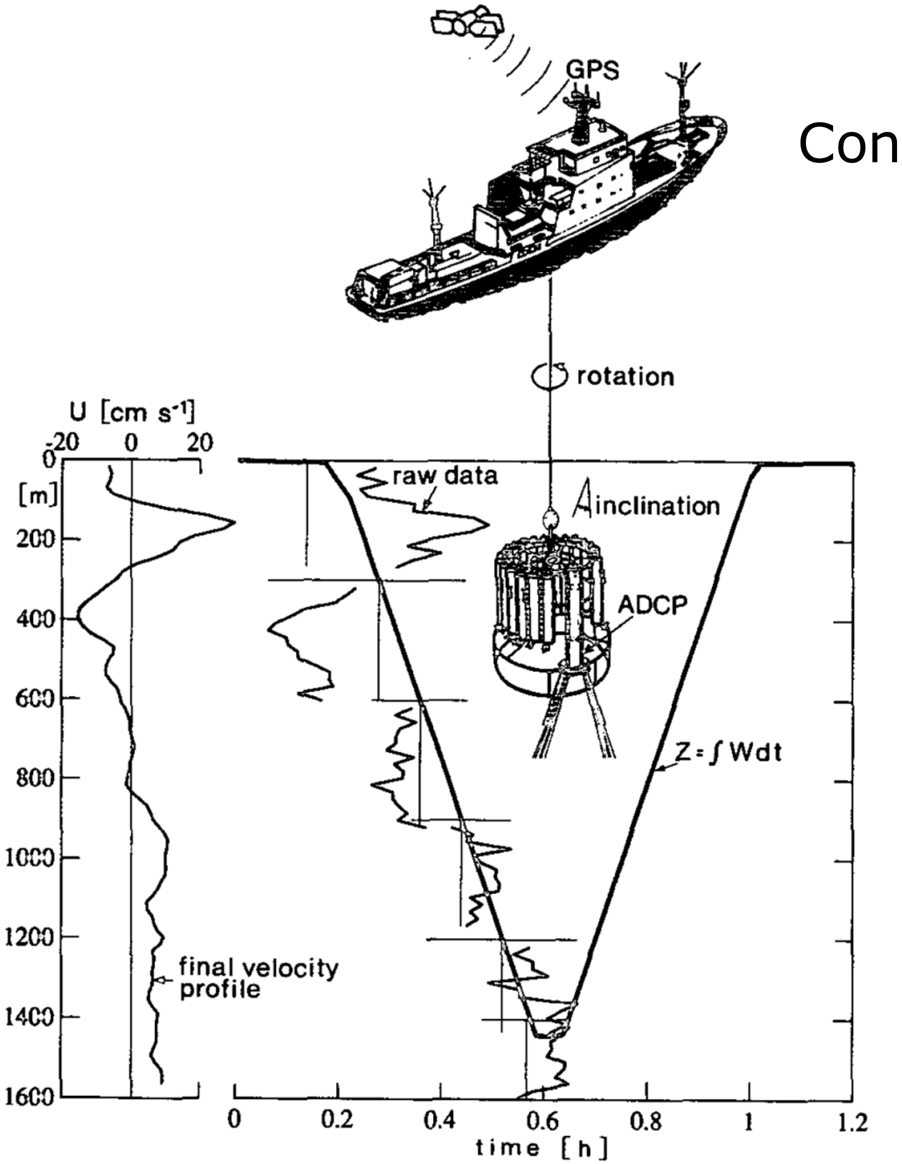
$$U_{adcp} = U_{ocean} + U_{ctd} + U_{noise}$$

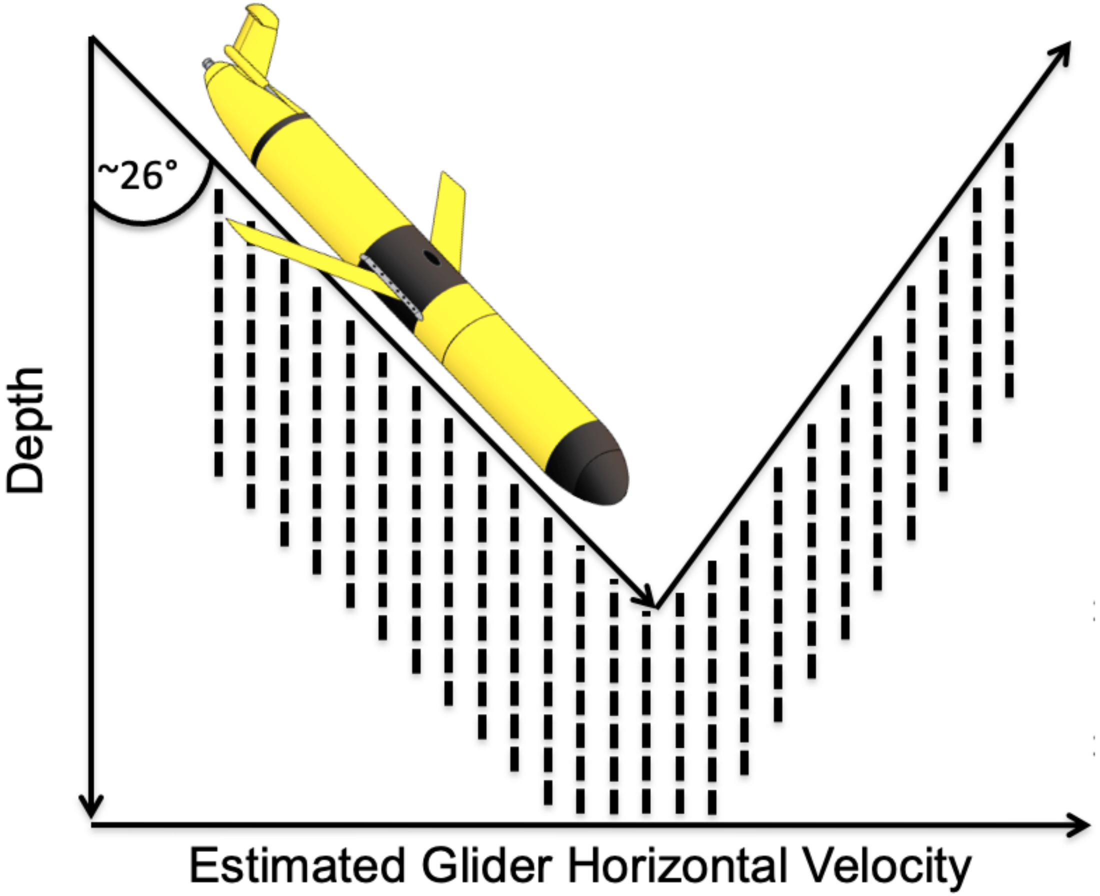
Visbeck (2002)
Least Squares Linear Inversion

Gradone et al. (2023)

Adapting for use on gliders:

Constrain solution using glider depth averaged velocity





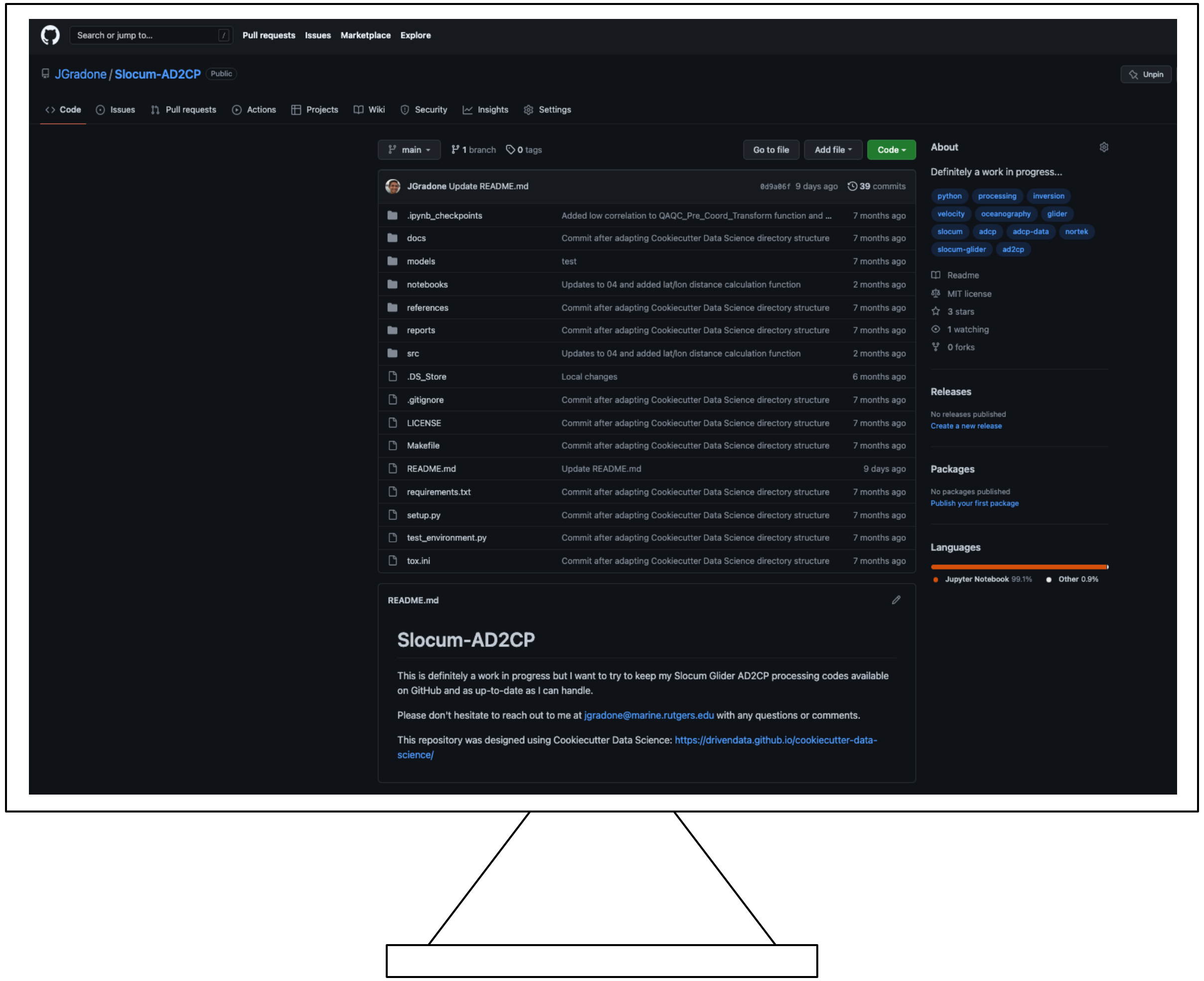
Todd et al. 2011, 2017; Miles et al. 2015, 2017;
Gradone et al. 2021, 2023; and many others

GitHub

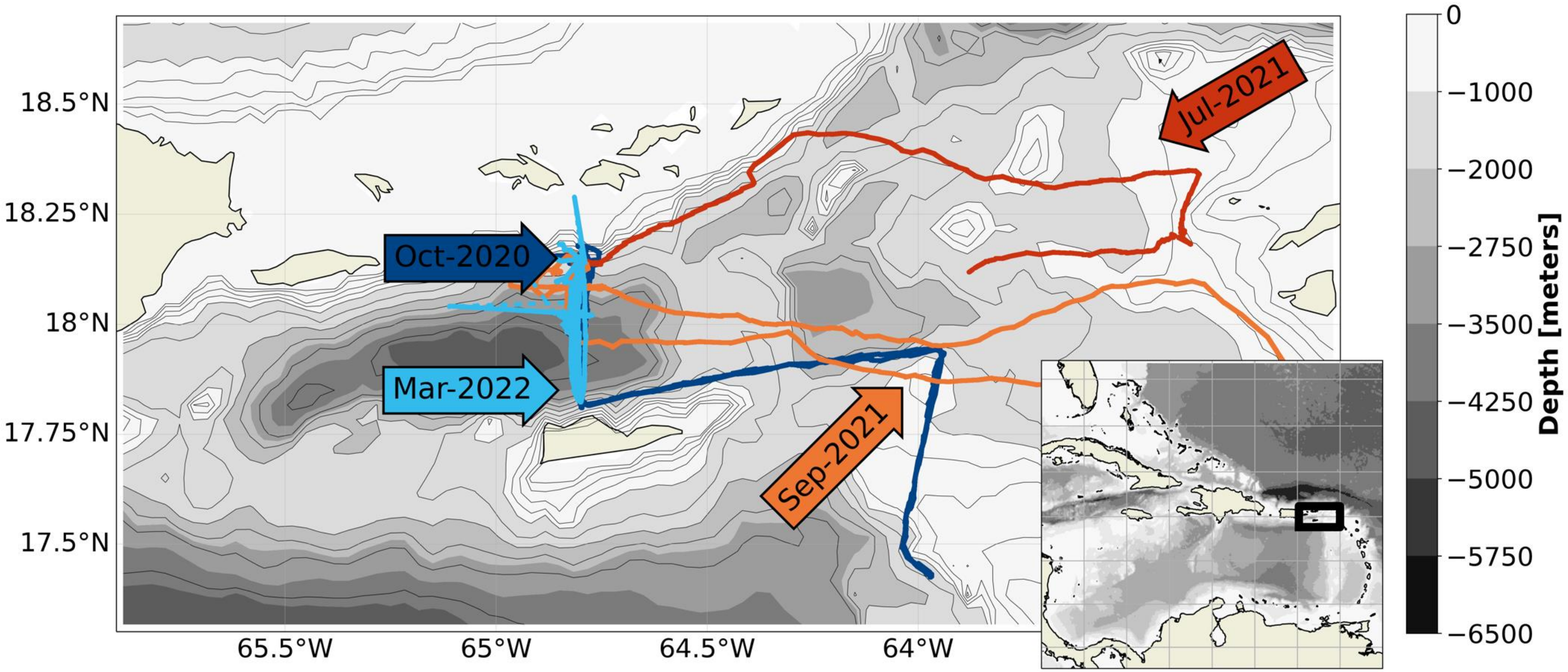
Open-Source Code.

https://github.com/JGradone/Slocum-AD2CP

Glider and sensor agnostic processing package

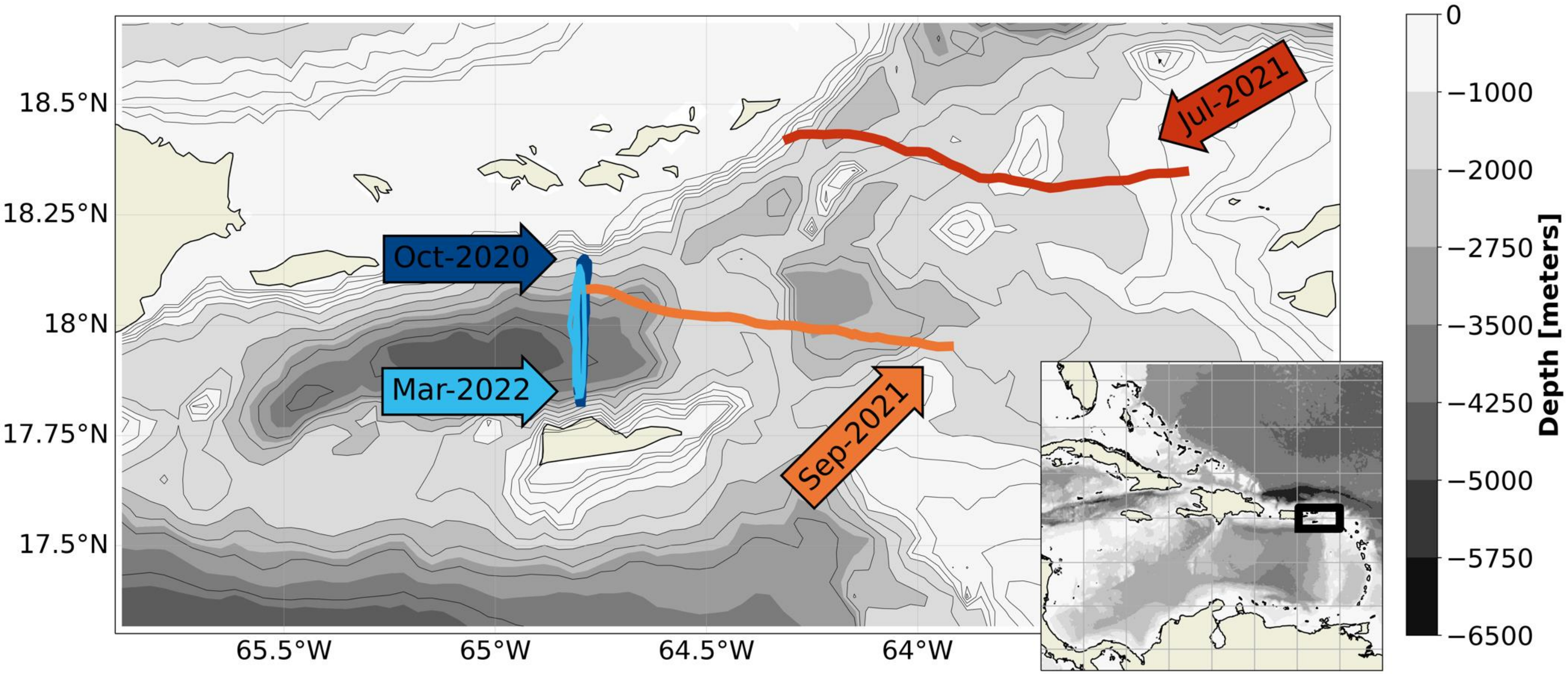


Gradone et al. (2023)



Subset these tracks to just passage “**crossings**”

Gradone et al. (2023)

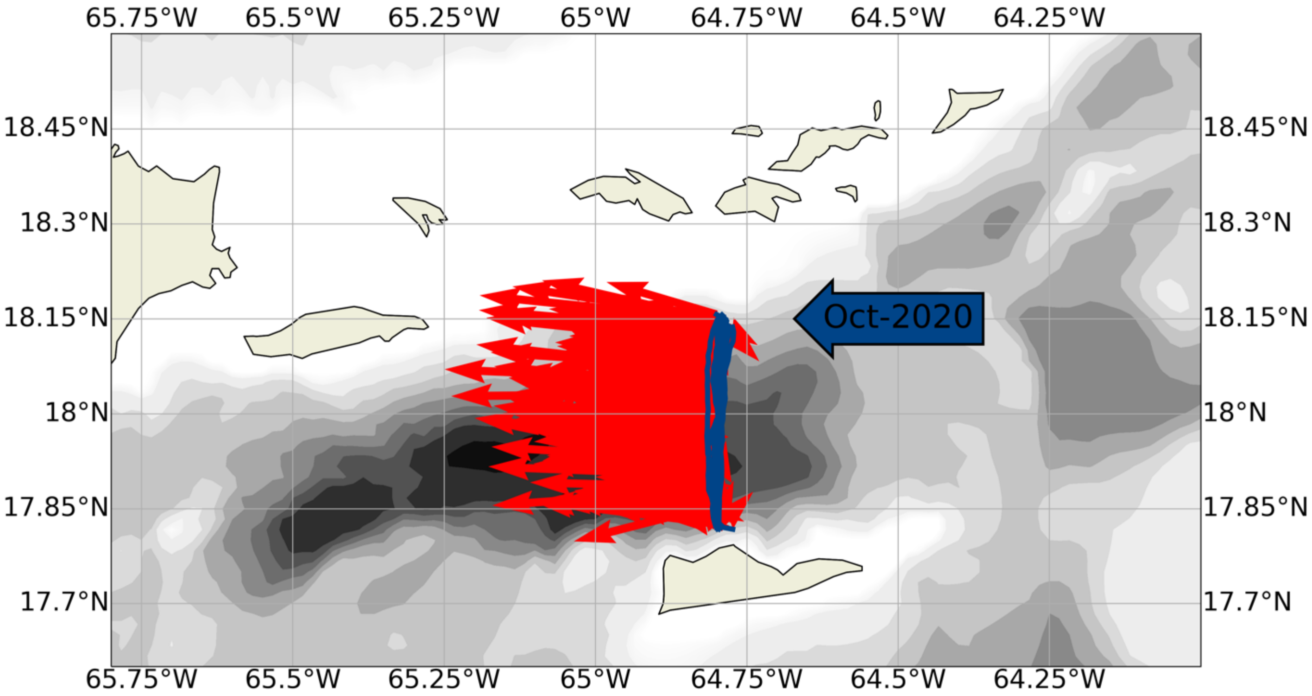


	Oct-2020	Mar-2022
Number of Transects	15	6
Current Profiler	Nortek AD2CP	TRDI Pathfinder

Gradone et al. (2023)

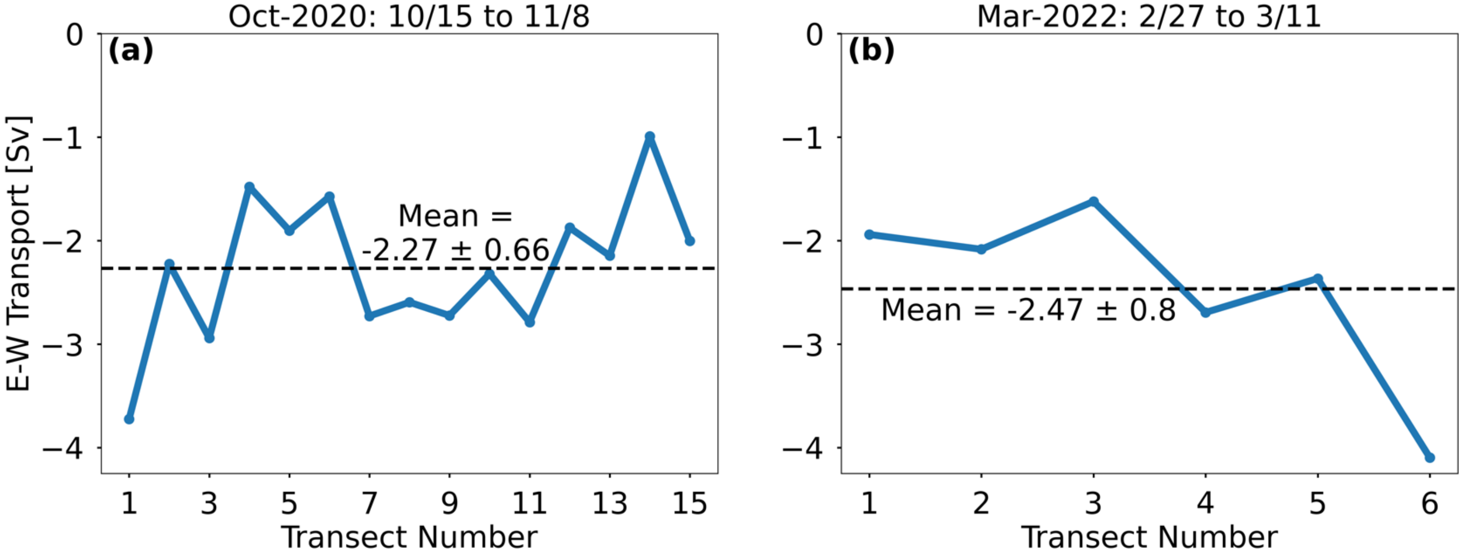
Calculating Transport

Integrate velocity horizontally and vertically across passage per transect



Gradone et al. (2023)

*Scripps Director, Harald **Sverdrup** with Walter on his graduation day (1946)*

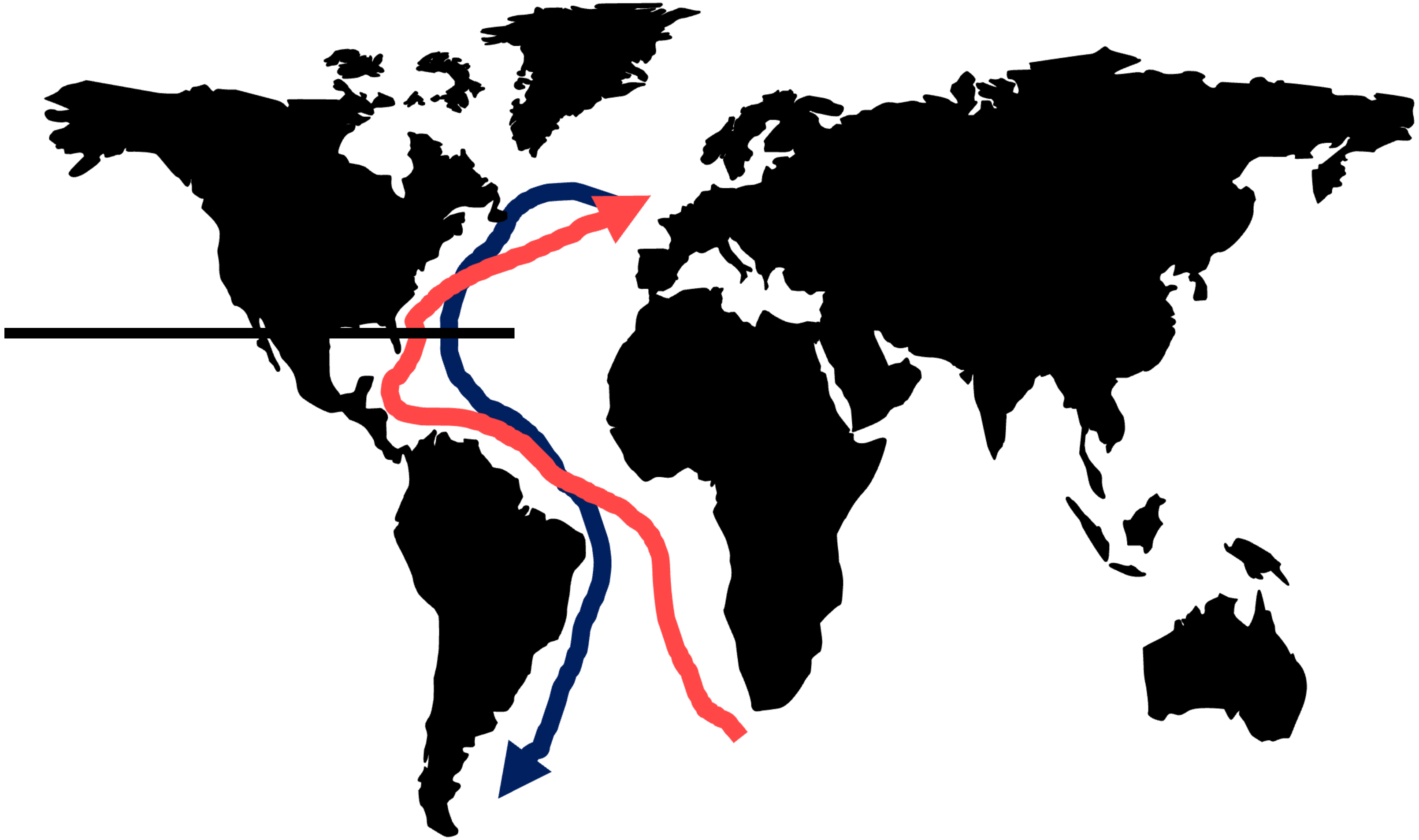


1 **Sverdrup** (Sv) = 1,000,000 $m^3\ s^{-1}$

(Johns et al. 2002; Gradone et al. 2023)

AMOC balance conundrum:

Florida Current:
~31 Sv



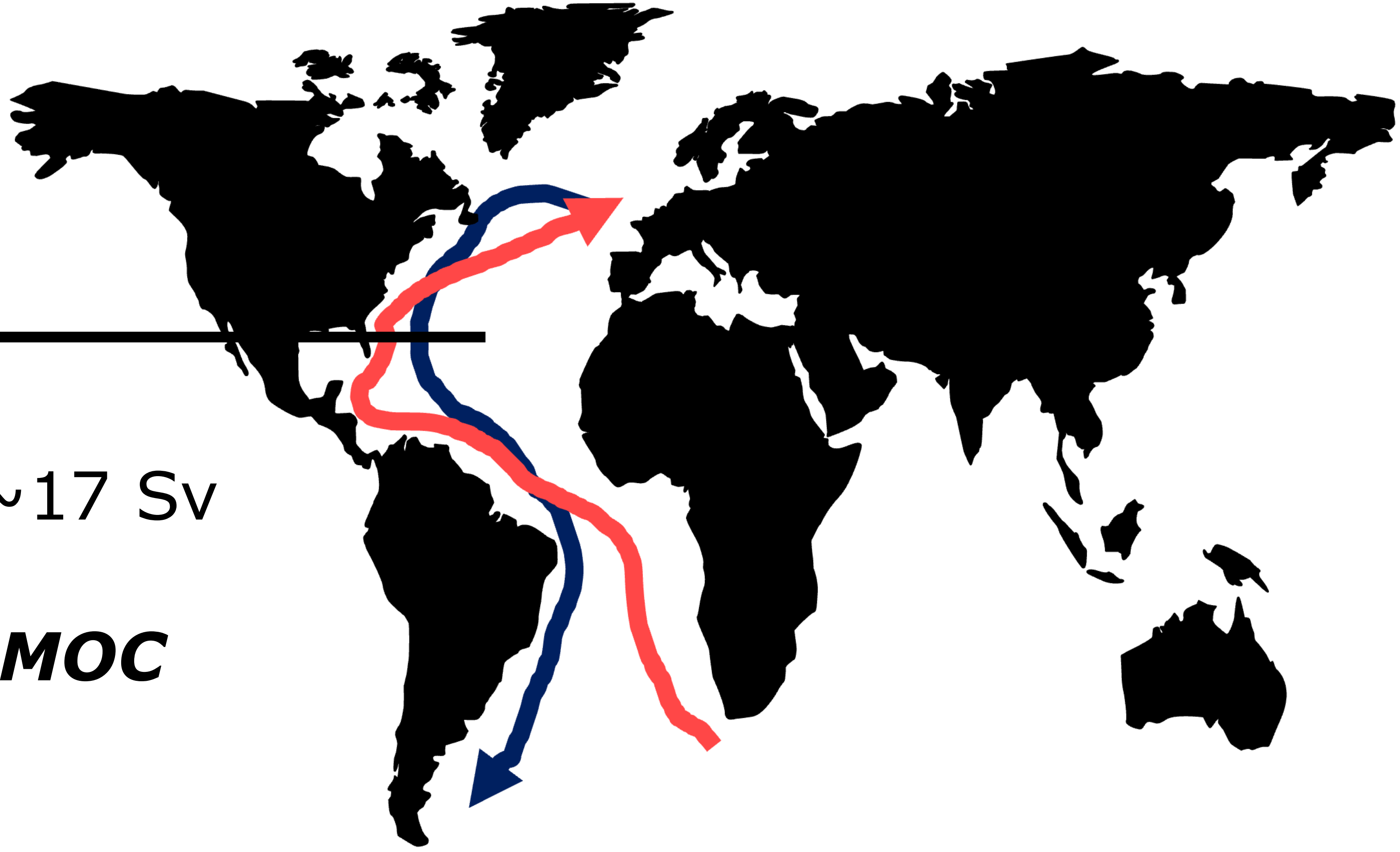
Schmitz and Richardson, 1991

AMOC balance conundrum:

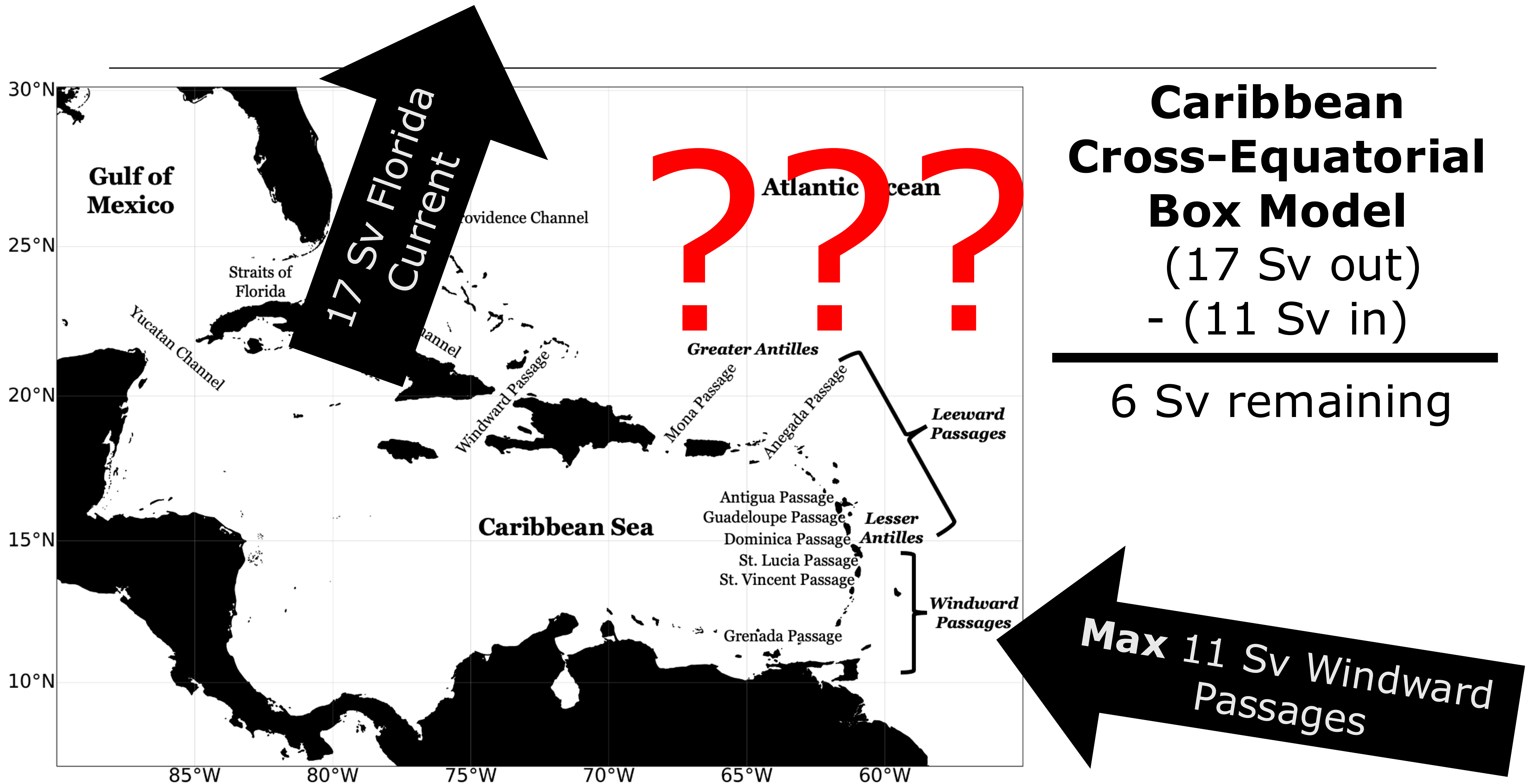
Florida Current:
~31 Sv

AMOC Strength: ~17 Sv

Cross-Equatorial MOC return flow



Schmitz and Richardson, 1991



Caribbean Cross-Equatorial Box Model

(17 Sv out)
- (11 Sv in)

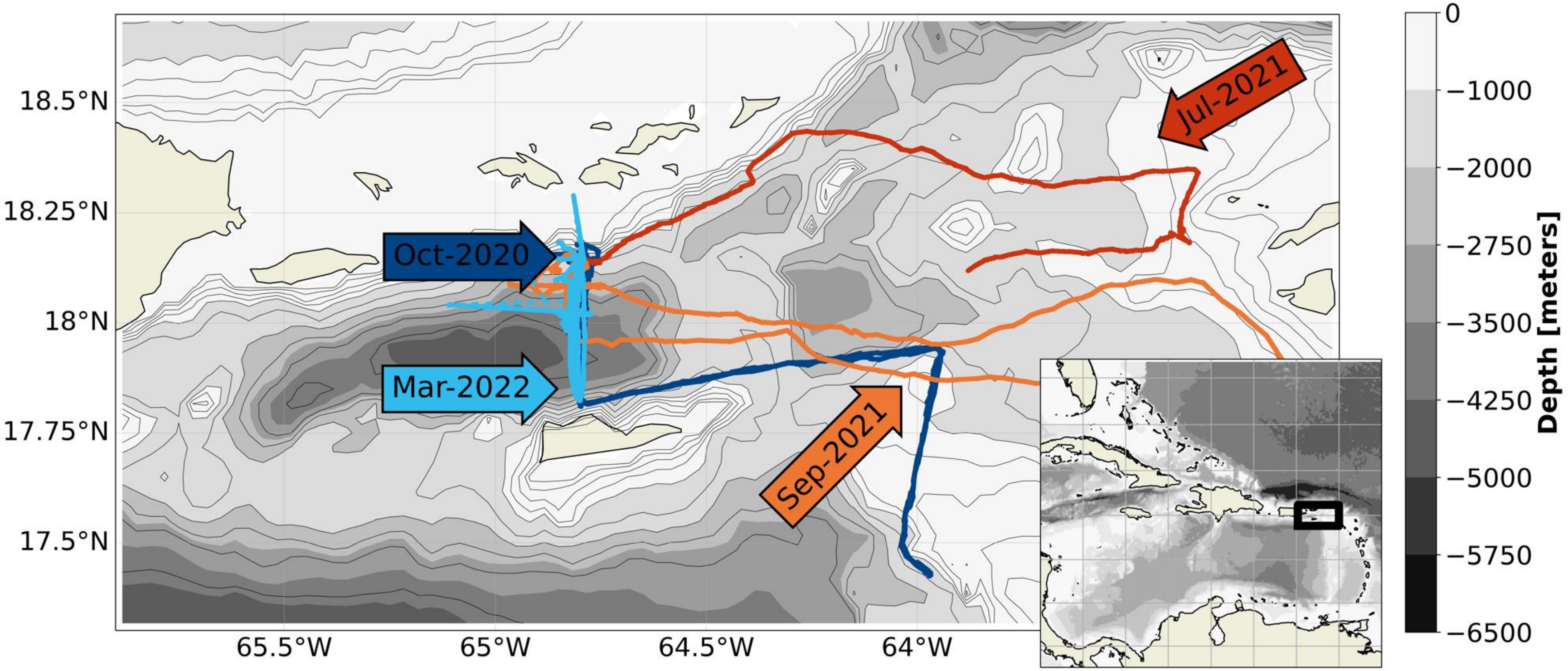
---

6 Sv remaining

(Schmitz and Richardson, 1991; Wilson and Johns, 1997; Rhein et al. 2005)

AMOC balance conundrum:

Anegada Passage has been suggested as a potential alternate pathway



(Schmitz and Richardson, 1991;
Wilson and Johns, 1997; Rhein et al. 2005)

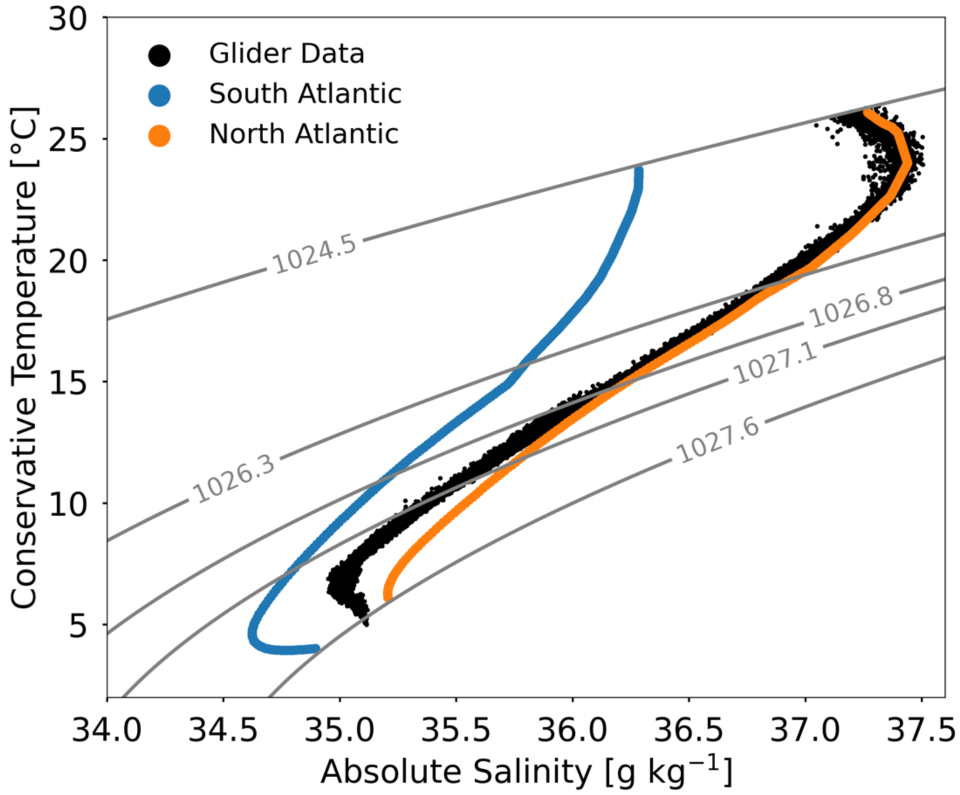
Determining Water Masses Origin

Isopycnal Water Mass Analysis

$$x_{SA}T_{SA} + x_{NA}T_{NA} - T_{obs} = R_T$$

$$x_{SA}S_{SA} + x_{NA}S_{NA} - S_{obs} = R_S$$

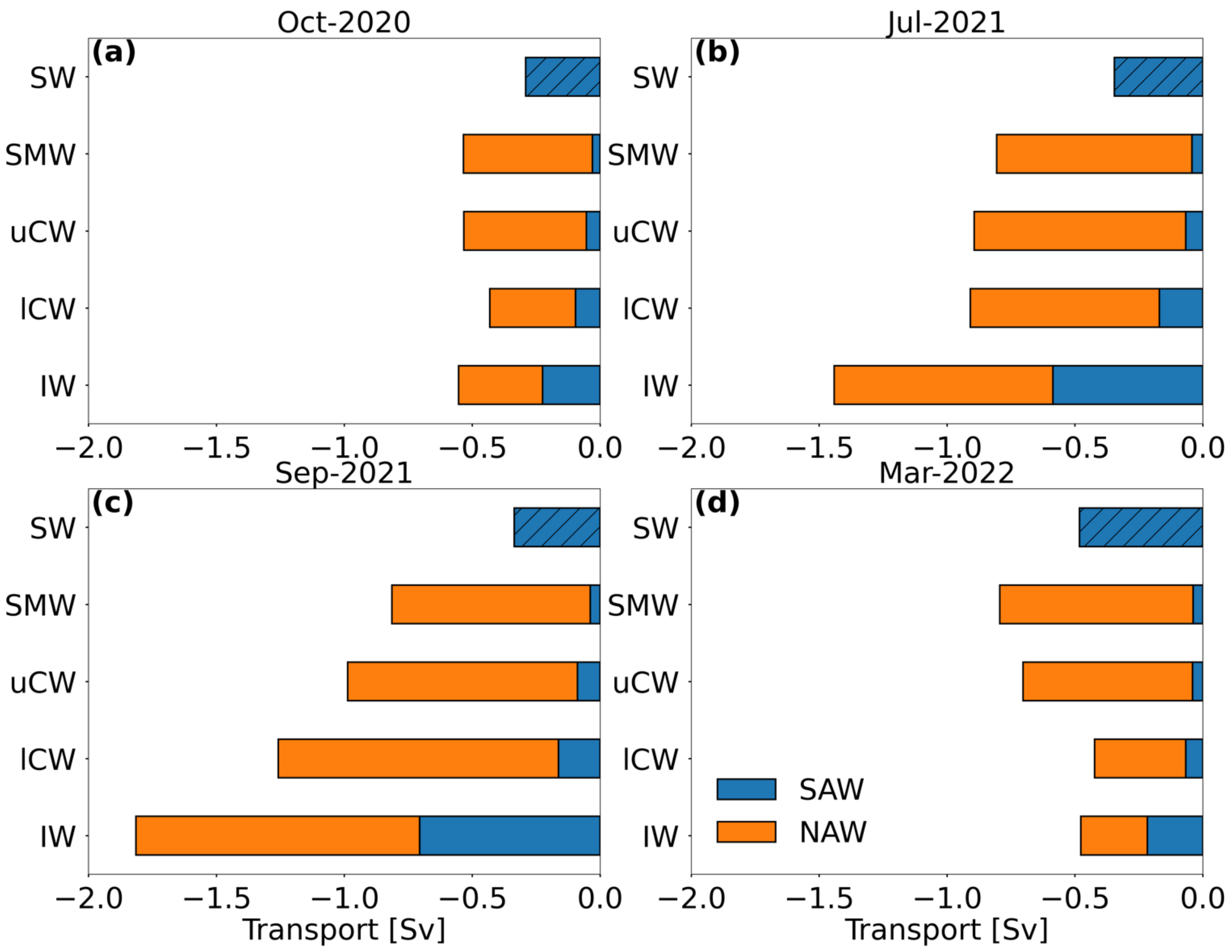
$$x_{SA} + x_{NA} - 1 = R_{MC}$$



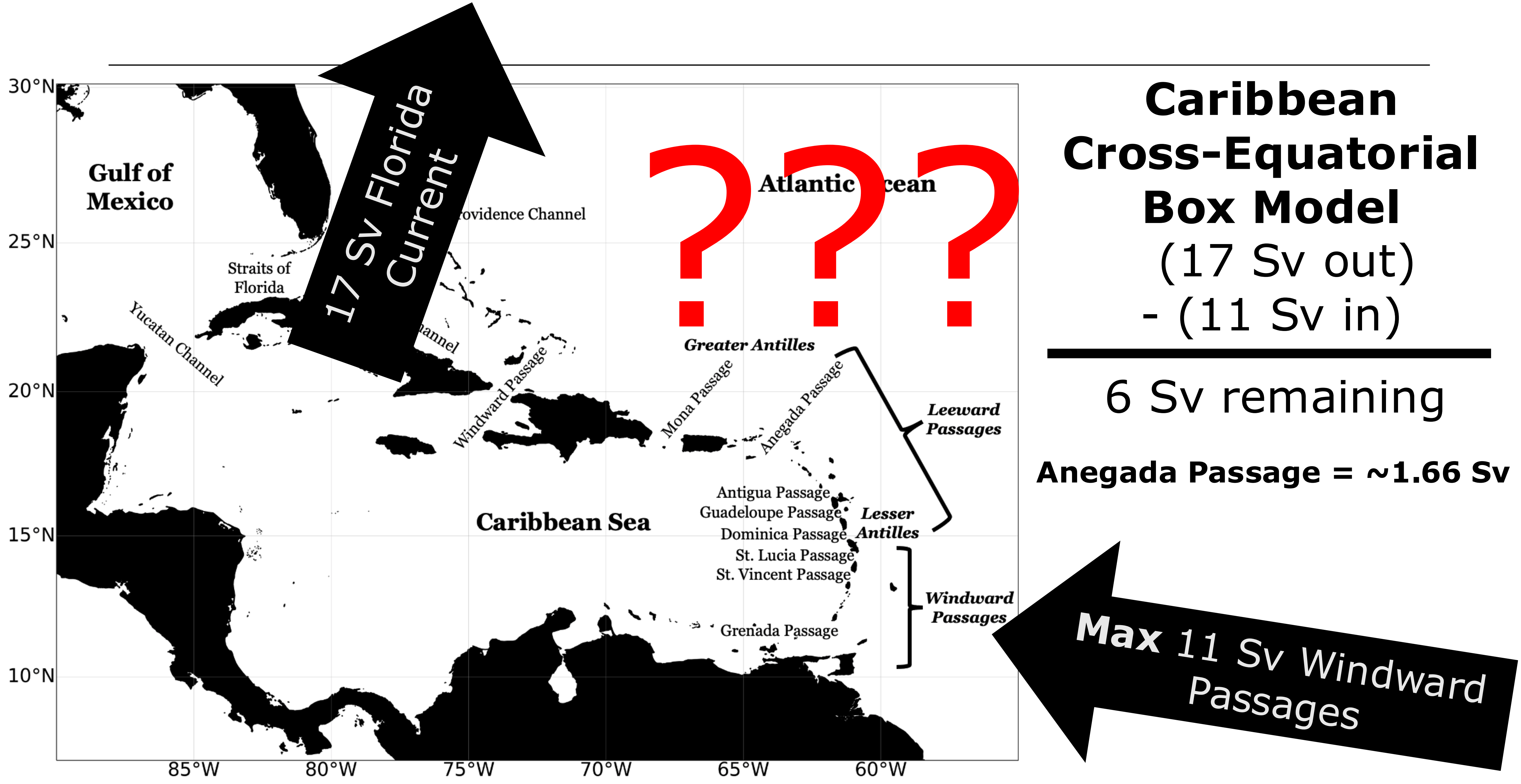
(Schmitz and Richardson, 1991; Wilson and Johns, 1997; Rhein et al. 2005)

South Atlantic Water Transport

- Transport of SAW through AP (1.66 Sv) is larger than previously estimated (0 to minimal Sv)
- 35% of the total AP transport
- 28% of the SAW transport entering Caribbean north of the Windward Island Passages



Gradone et al. (2023)



Caribbean Cross-Equatorial Box Model

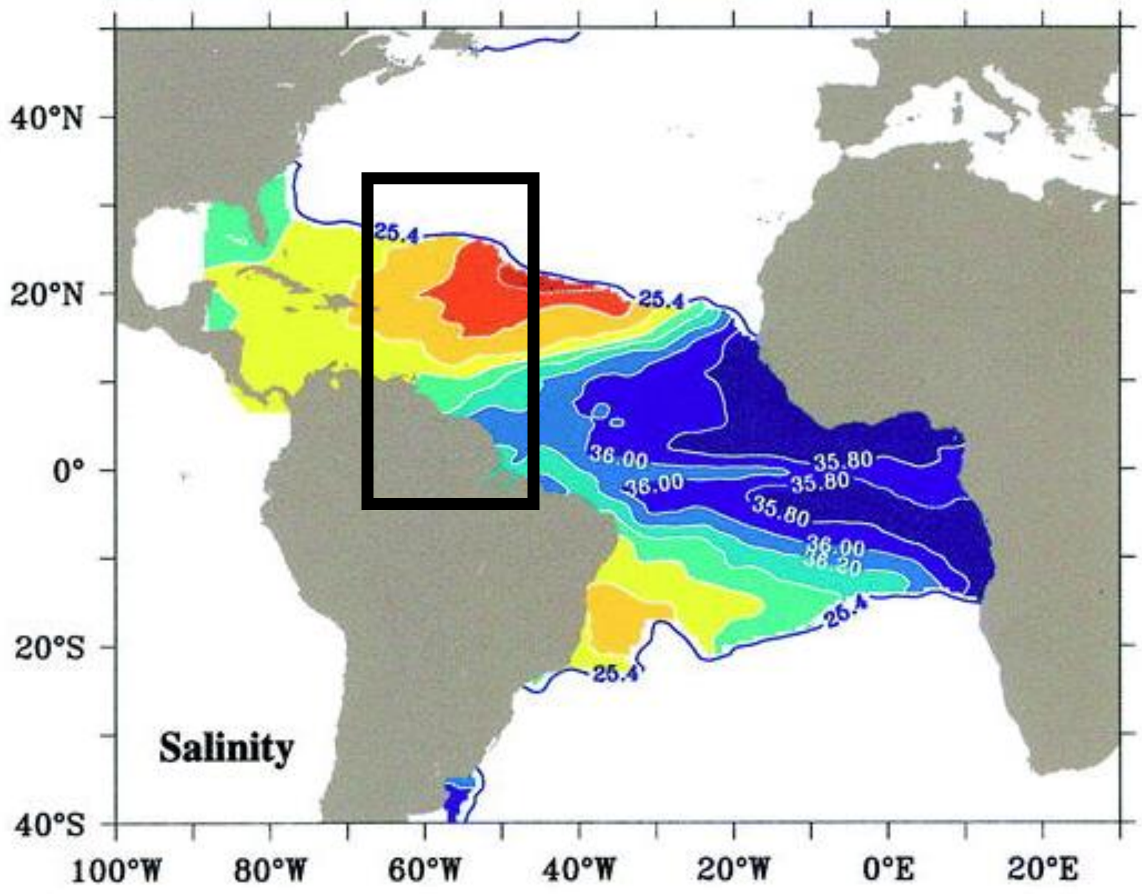
(17 Sv out)
- (11 Sv in)

6 Sv remaining

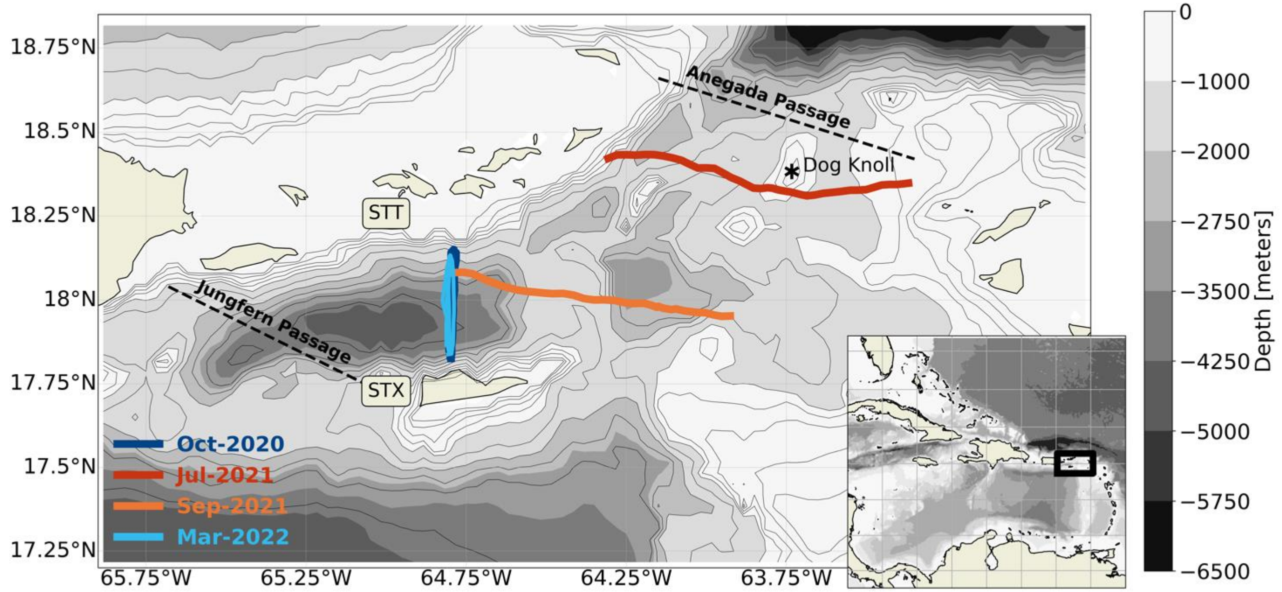
Anegada Passage = ~1.66 Sv

(Schmitz and Richardson, 1991; Wilson and Johns, 1997; Rhein et al. 2005; Gradone et al. 2023)

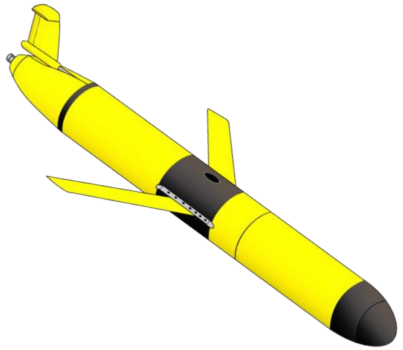
Glider observations in passages spanning north to south, a large gradient in water mass properties



(Zhang et al. 2003)



Anegada Passage



THE G. UNGER VETLESEN FOUNDATION

sanctuary marine mammals santuario mamíferos marinos AGOA sanctuaire mammifères marins french west indies ANTILLES FRANÇAISES

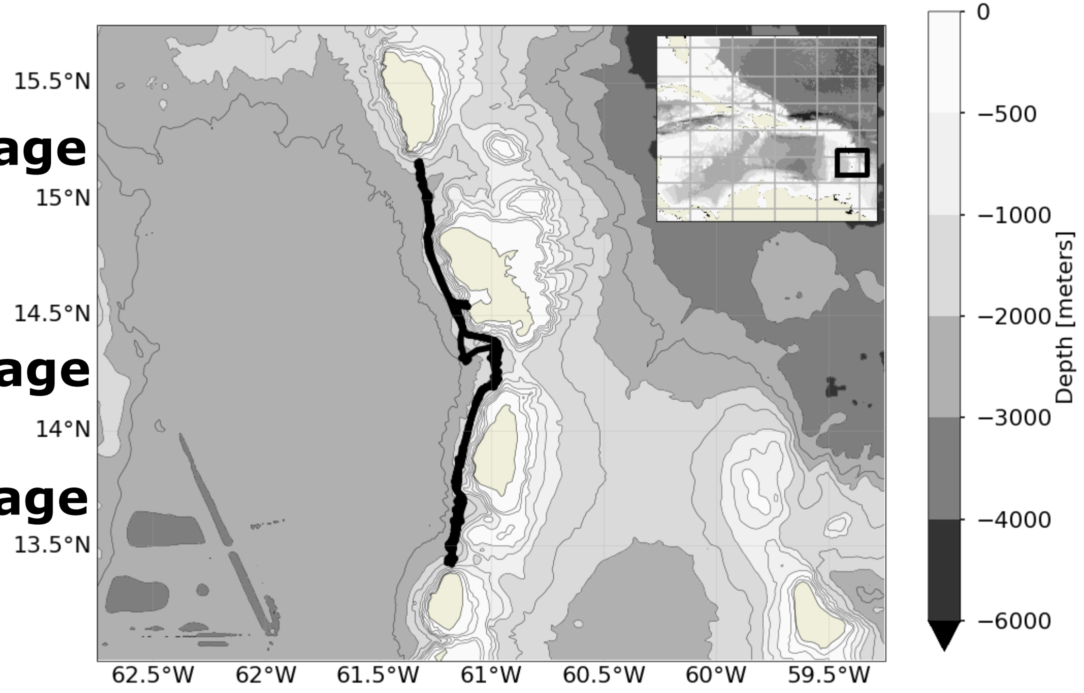
RUCOOL

UNIVERSITY OF THE VIRGIN ISLANDS 1962

Dominica Passage

St. Lucia Passage

St. Vincent Passage



Glider observations in passages spanning **north to south**, a **large gradient in water mass properties**

Windward Passages Deployments (2023)

A scientific machine surveys the Caribbean waters

a collaboration between American scientists and the Agoa Sanctuary

Field activities | Scientific monitoring | Martinique | Lesser Antilles

October 05, 2022

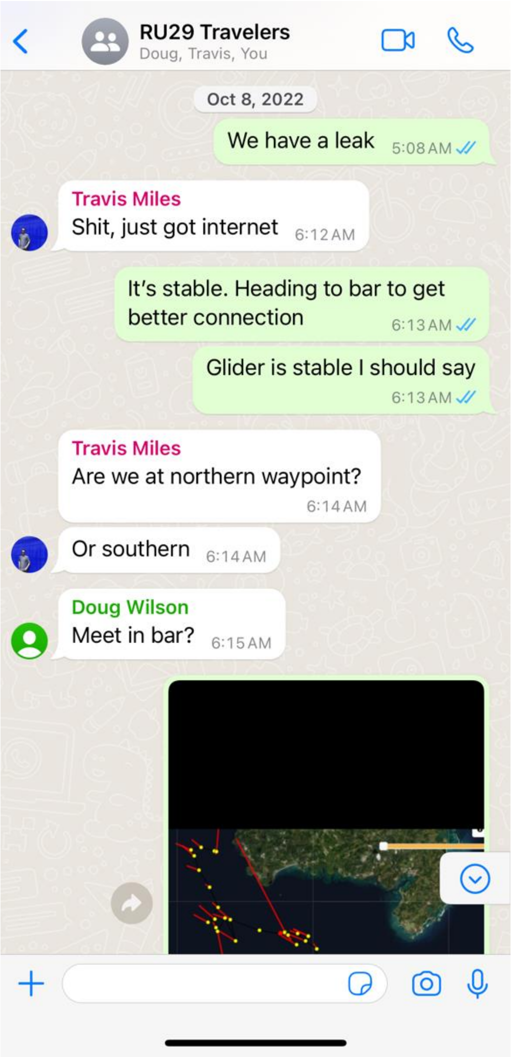
Since Monday October 3, three American scientists have been hosted in the premises of the Agoa Sanctuary as part of an opportunistic collaboration. Our scientists are taking advantage of the deployment of an American glider in the waters of the French West Indies to attach a hydrophone and test a data collection method.

Travis Miles, Joe Gradone, and Doug Wilson, American researchers from the University of the US Virgin Islands and Rutgers University in New Jersey, are working on ocean water parameters. They are carrying out a mission in the South of the Antilles arc with the aim of studying the heat transfers of currents coming from Brazil and entering the Caribbean. This mission also allows them to improve weather models for predicting cyclones, the latter requiring precise water temperature to gain strength. To carry out this mission they use an underwater glider, or glider in English.

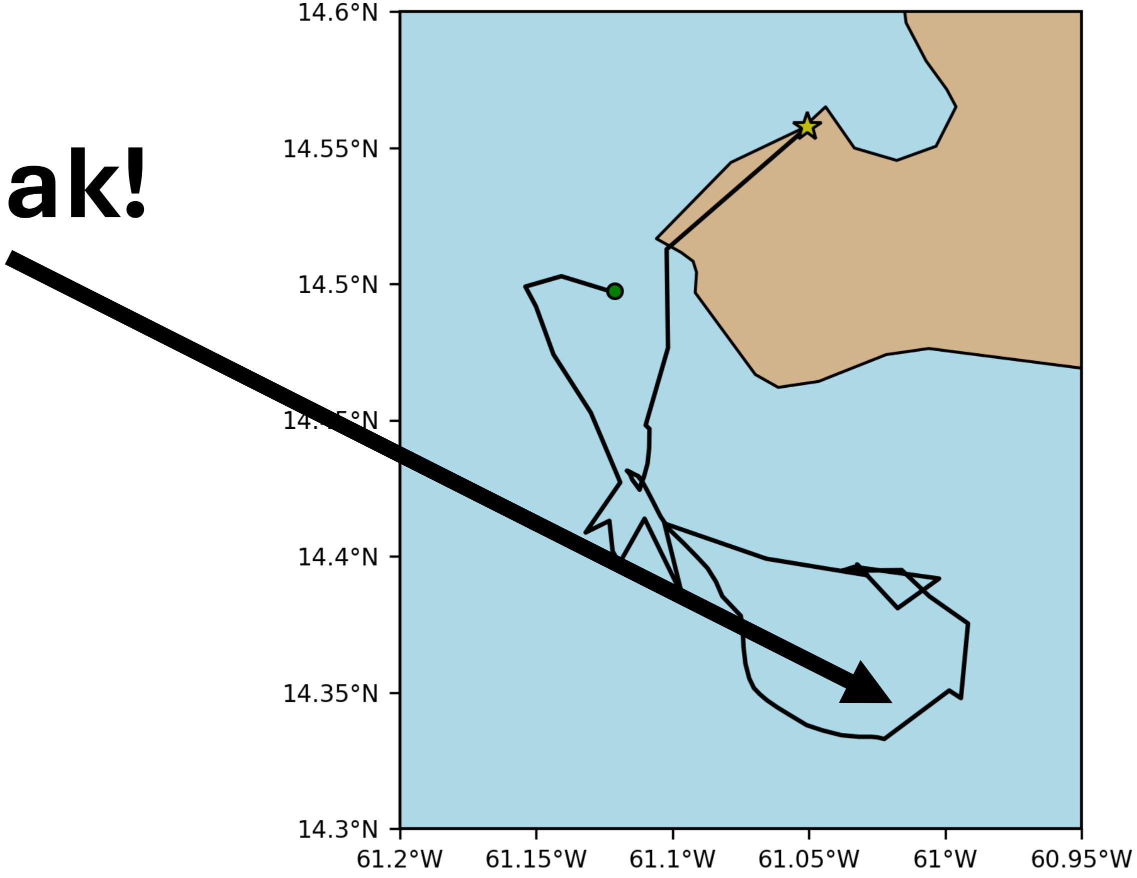
The glider is an **autonomous satellite-controlled machine** that will take measurements in the water column along its path. It carries out programmed dives up to 1000 m deep during which its sensors (oxygen, temperature, salinity) will record the characteristics of the water masses depending on the depth. Each time it returns to the surface, the glider sends the results of its dive to land via satellites.

Around the world, gliders are also used to study the chemistry of the oceans and the animals that inhabit them. Equipping them with hydrophones allows you to hear the animals that are on the mission route: whale songs, sperm whale clicks or dolphin whistles. The interest is then to obtain recordings of areas inaccessible by boats, offshore, in the depths, while avoiding the sea conditions of the hurricane season. Thus, this type of mission can help **improve knowledge on the distribution of cetaceans across the Caribbean** .

Windward Passages Deployments (2023)

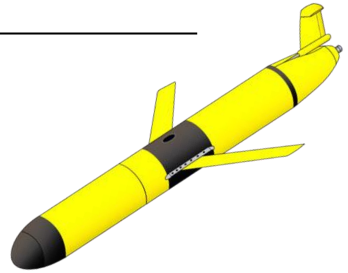


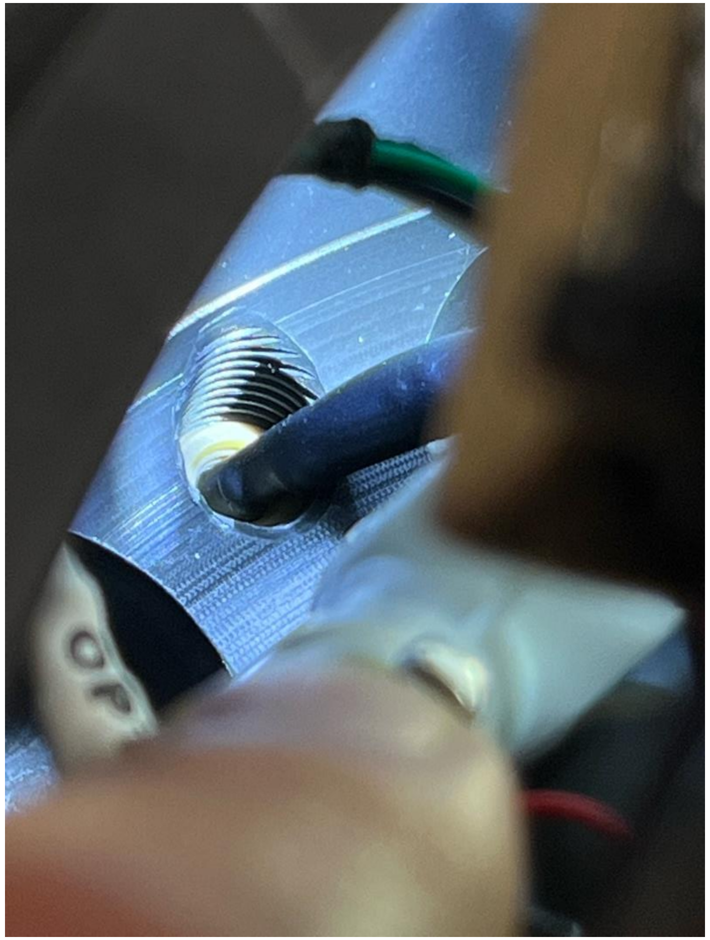
Leak!



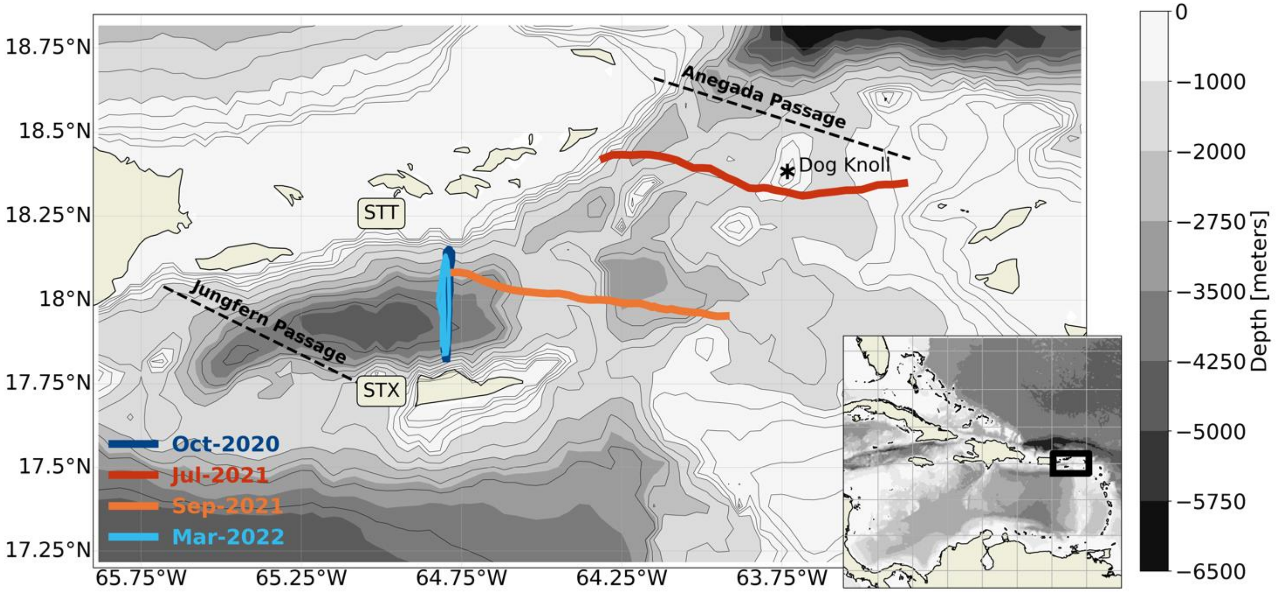
Windward Passages Deployments (2023)

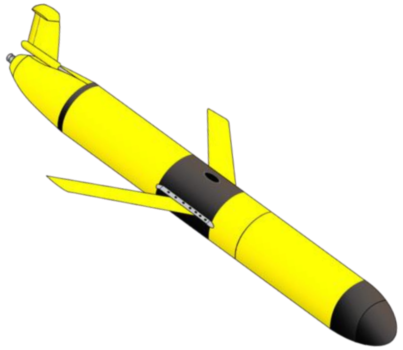
Windward Passages Deployments (2023)





Anegada Passage





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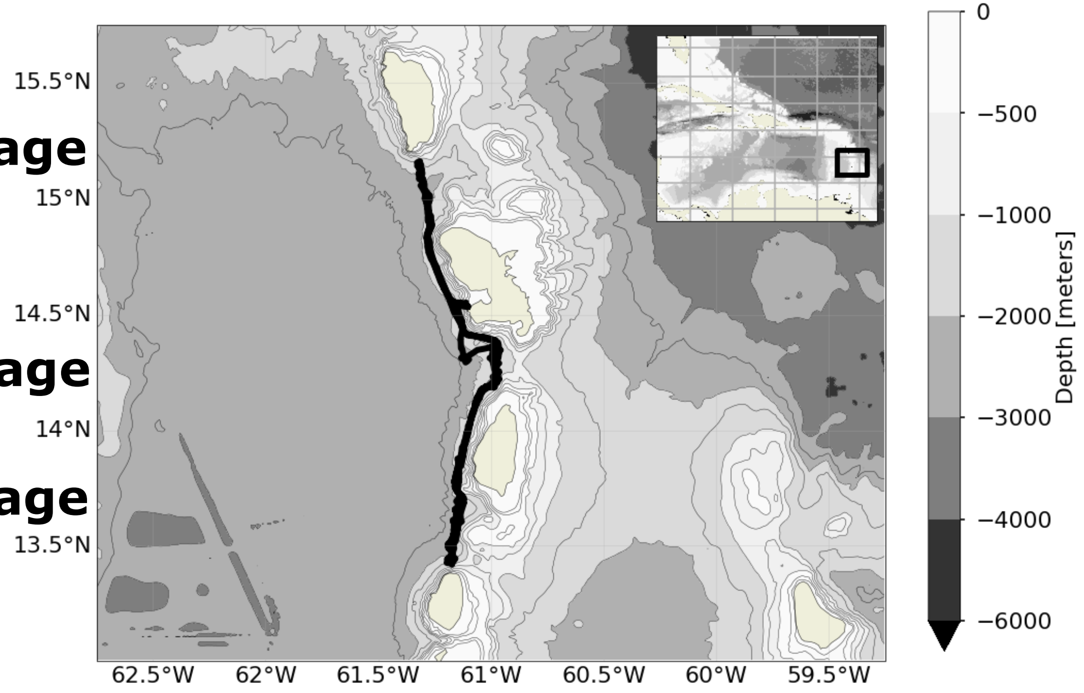
Dominica Passage

St. Lucia Passage

St. Vincent Passage



Glider observations in passages spanning **north to south**, a **large gradient in water mass properties**

PERGAMON

Deep-Sea Research I 49 (2002) 211–243

DEEP-SEA RESEARCH
PART I

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On the Atlantic inflow to the Caribbean Sea

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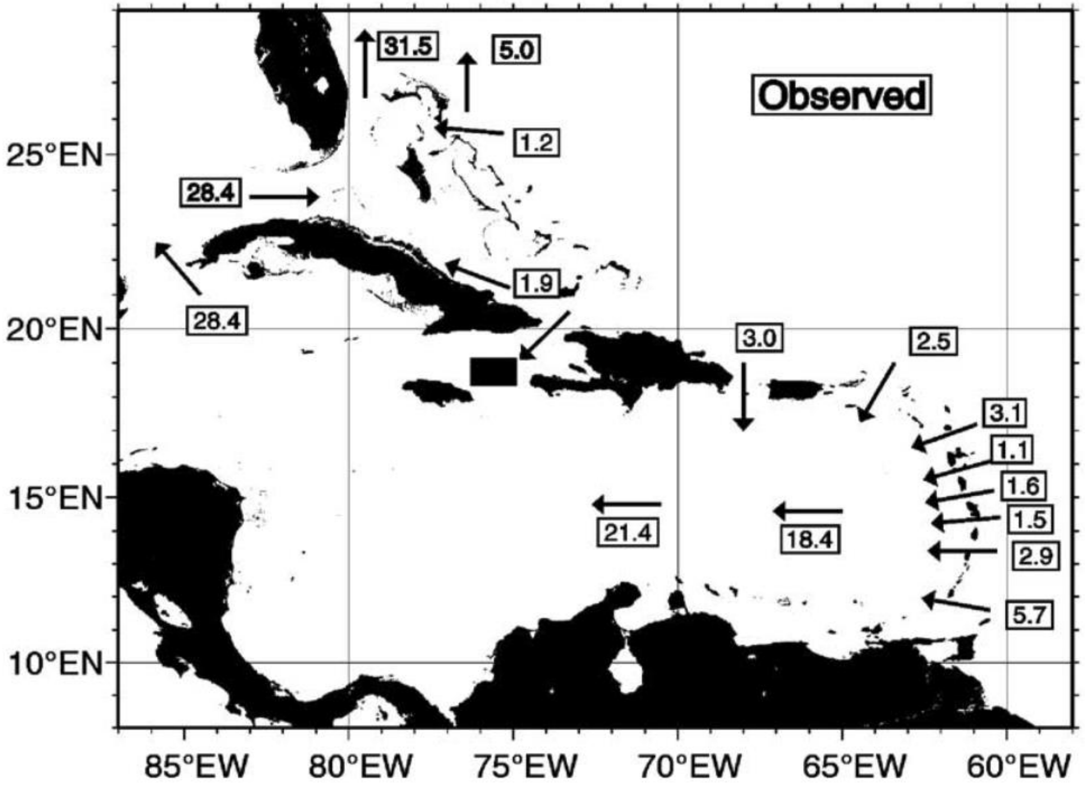
Table 1
Transport estimates derived from shipboard occupations of the Caribbean Passages, after Wilson and Johns (1997), updated with results from 5 additional cruises. Not all passages were sampled on each cruise. Average transports and related statistics from all available estimates for each passage are shown at the bottom. The quantity labeled "Mean" is the average transport from only those cruises with full water column directly velocity measurements (cruises 5 and later) the quantity labeled "Mean (all)" is the average of all cruises including early ones where part of the deep flow in the passages was determined geostrophically. The former is used for the final transport values in the paper, and the standard errors listed for each passage are also based on this data

Cruise		Passage							
		Grenada	St. Vincent	St. Lucia	Dominica	Guadeloupe	Antigua	Anegada	Mona
1	Dec 91	6.9	5.9	0.1					
2	May 92	0.1	2.0	0.5					
3	Sep 92		4.9	1.4	0.5				
4	Dec 92	2.6	2.2	2.2					
5	Jun 93	10.6	5.3	1.2					
6	Apr 94	2.6	−0.6						
7	Jul 94	5.8	5.2	2.0	−0.1	1.9	0.6	3.3	
8	Dec 94			−0.2					
9	Sep 95	5.4	2.8	3.2					
10	Mar 96	4.0	−0.1	0.8	1.8	1.1	4.4	3.5	3.4
11	Jul 96	5.6	3.4	3.4	1.1	0.6	3.3	2.2	1.7
12	Jun 97	4.6	3.7	4.6	2.5	−0.3	3.4	2.0	
13	Oct 98	6.7	3.2	−3.0	2.8	2.4	4.0	0.1	
Mean		5.7±2.4	2.9±2.2	1.5±2.4	1.6±1.2	1.1±1.1	3.1±1.5	2.5±1.4	2.6±1.2
Mean (all)		5.0±2.8	3.2±2.1	1.4±2.0	1.4±1.1	1.1±1.1	3.1±1.5	2.5±1.4	2.6±1.2
Std. error		0.8	0.8	0.8	0.5	0.5	0.7	0.6	1.2
		Windward Islands 10.1±2.4			Leeward Islands 8.3±2.3				
		Lesser Antilles 18.4±4.7							

Windward **I**sland **P**assage **M**onitoring **P**rogram (**WIPP**) 1991-2001

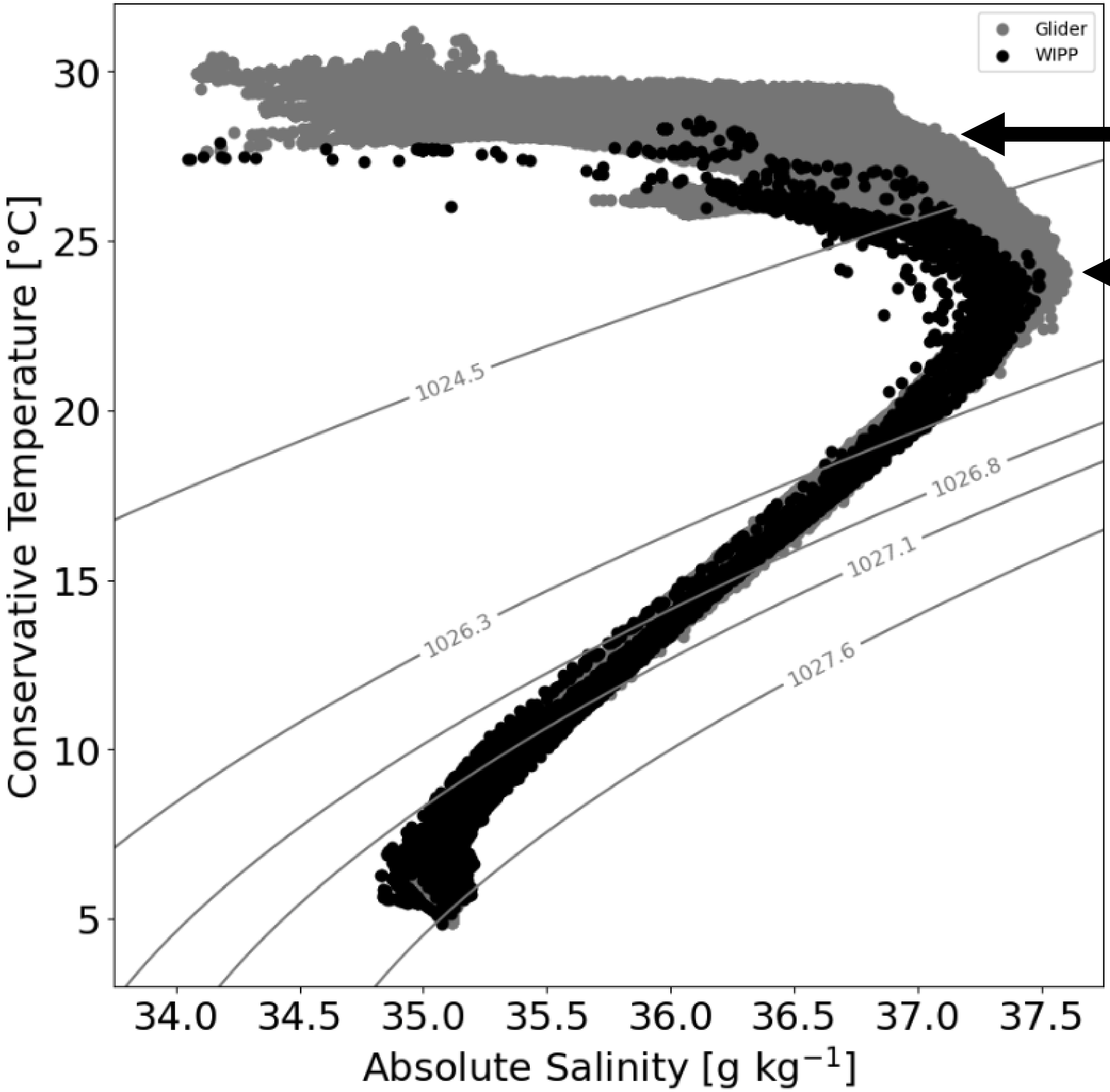


Observations of Change

Glider (2020-2023)

versus

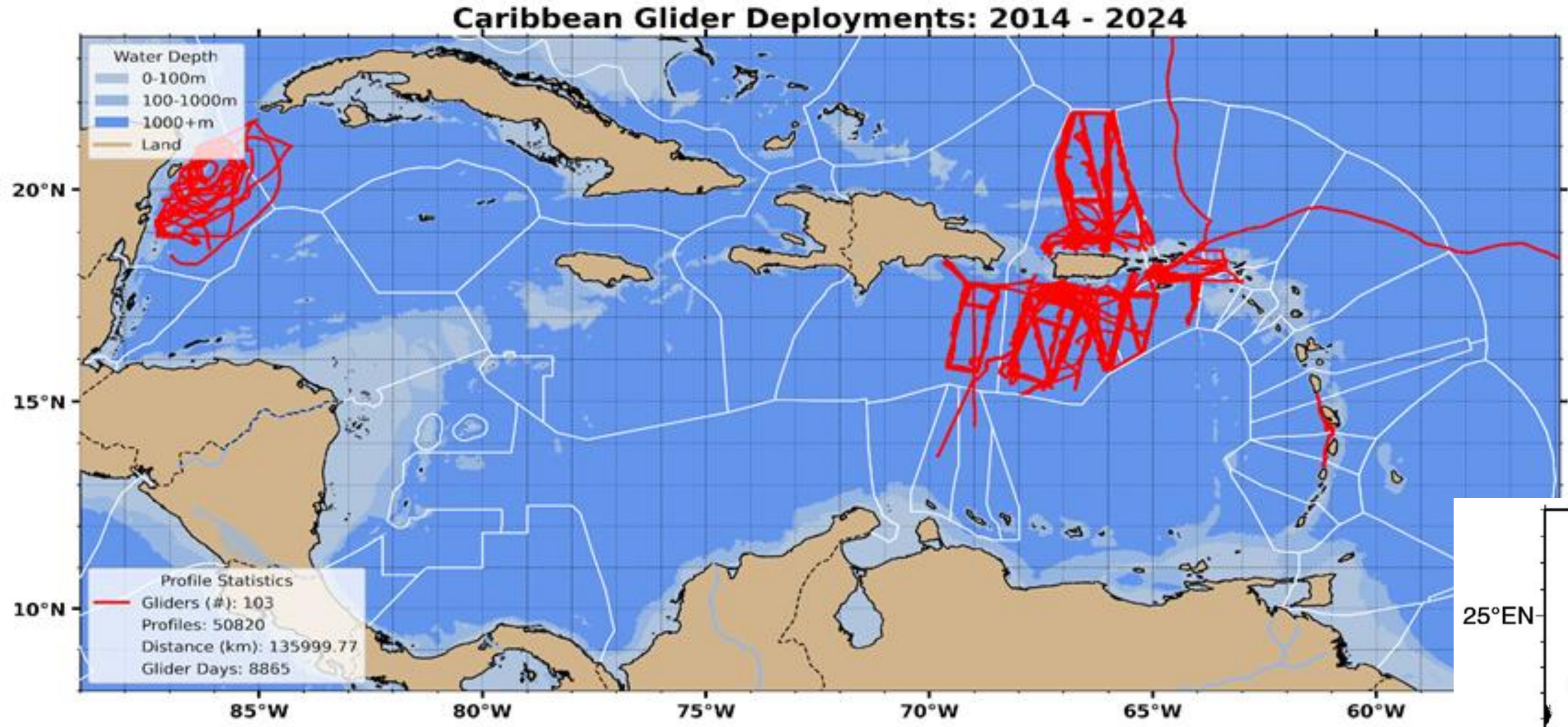
Windward **I**sland **P**assage Monitoring **P**rogram
(**WIPP**)
(1991-2001)

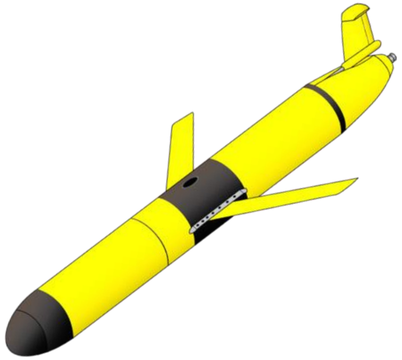


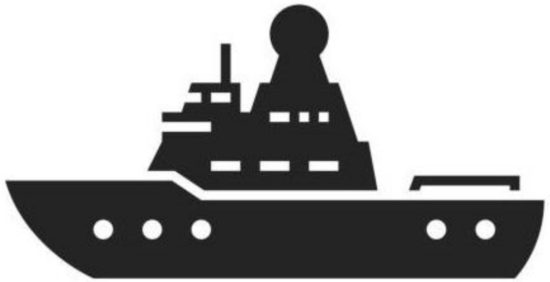
Upper ocean warming

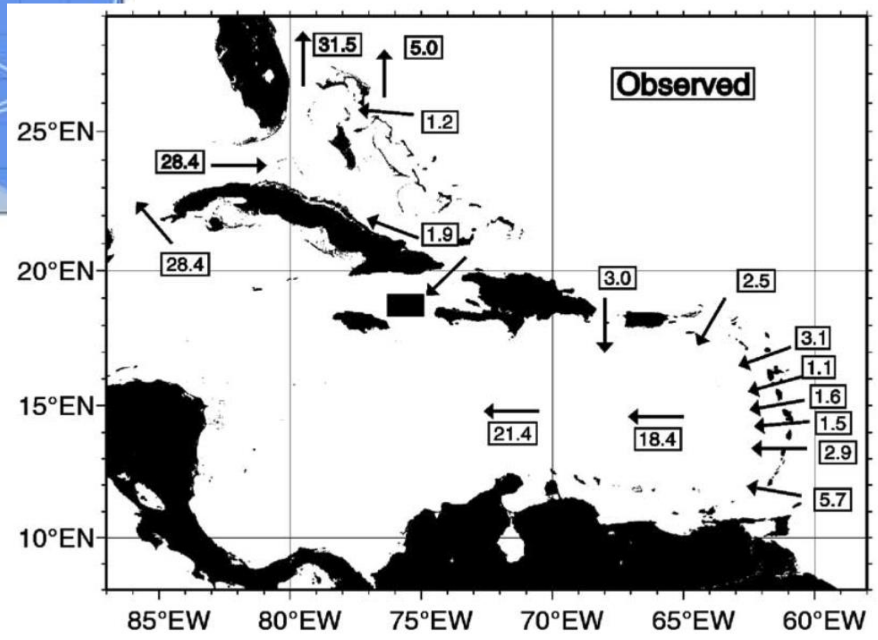
Salinification of Salinity Max Waters

- Limited deployments
- End-members/no ability to determine trends
- Does not capture bulk of Caribbean Through-Flow

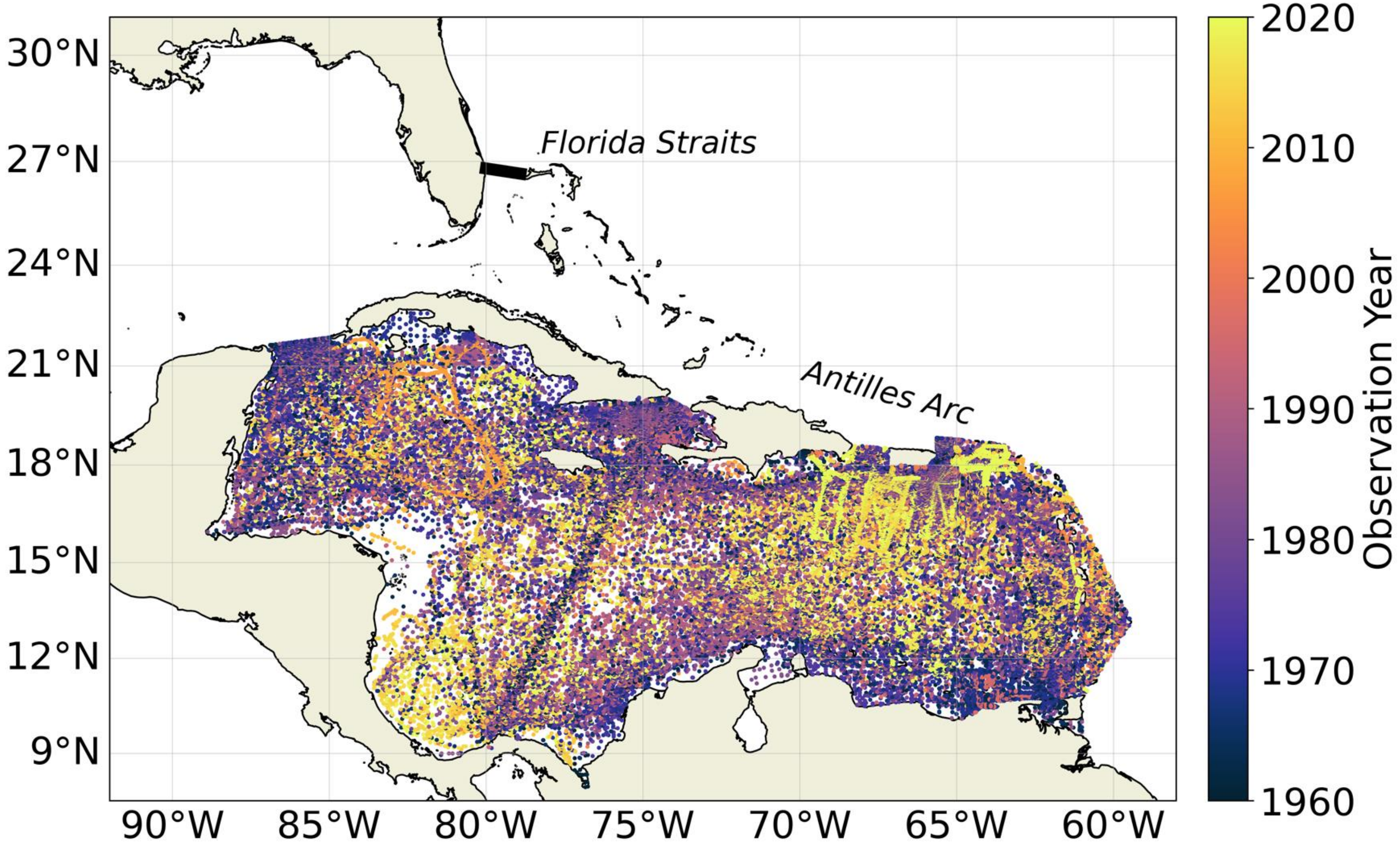

Caribbean Glider Deployments: 2014 - 2024
Water Depth
0-100m
100-1000m
1000+m
Land
Profile Statistics
Gliders (#): 103
Profiles: 50820
Distance (km): 135999.77
Glider Days: 8865
20°N
15°N
10°N
85°W
80°W
75°W
70°W
65°W
60°W






Observed
31.5
5.0
1.2
28.4
1.9
28.4
3.0
2.5
3.1
1.1
1.6
1.5
2.9
5.7
21.4
18.4
25°EN
20°EN
15°EN
10°EN
85°EW
80°EW
75°EW
70°EW
65°EW
60°EW

Leveraging glider data + all other T/S profiles in the Caribbean Through-Flow



Comprehensive Water Mass Analysis

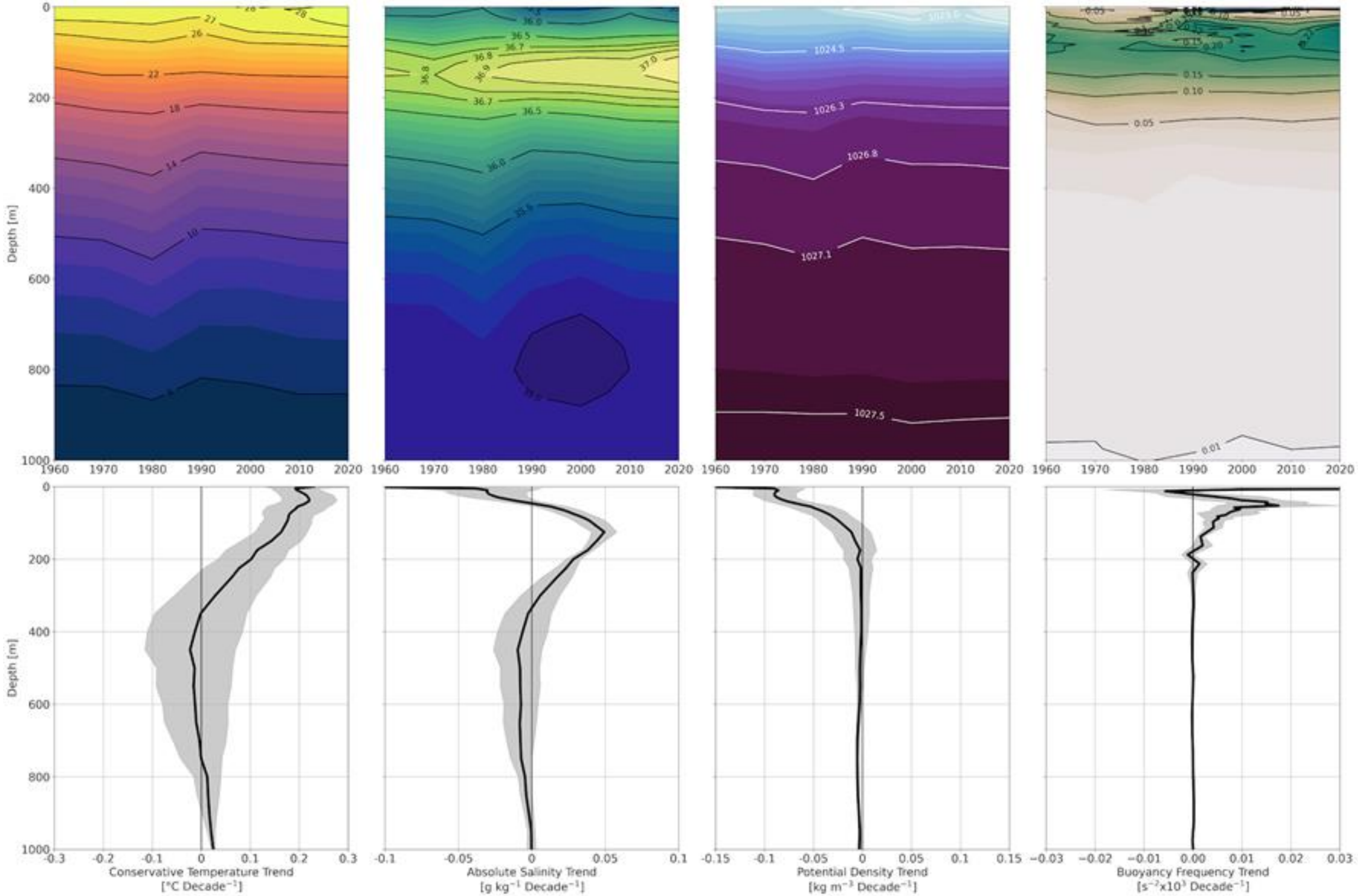
<u>EN4 Database</u>

>28,000 profiles

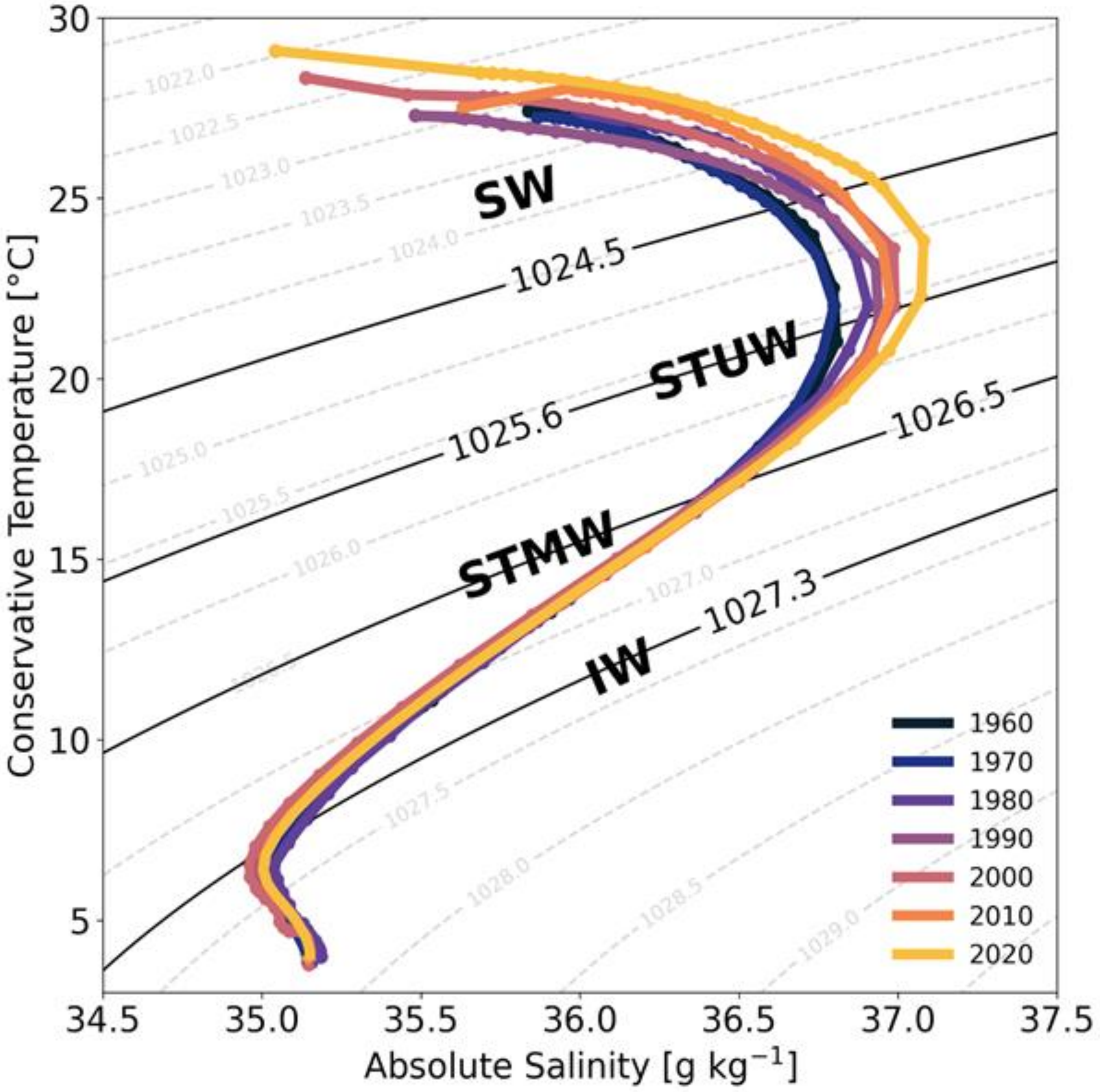
Gradone et al. Submitted: *Nature Scientific Reports*

Observations of water mass changes

1. **Warming ~0.2°C decade^{-1}**
2. **Surface freshening ~0.13 g kg^{-1} decade^{-1}**
3. **Subsurface salinification ~0.05 g kg^{-1} decade^{-1}**
4. **Surface density reduction ~0.17 kg m^{-3}**
5. **Increased stratification 20x global trends**



Gradone et al. Submitted: *Nature Scientific Reports*



Implications for:

1. Sea-level rise
2. **Tropical cyclone activity**
3. Biodiversity
4. Downstream water mass formation

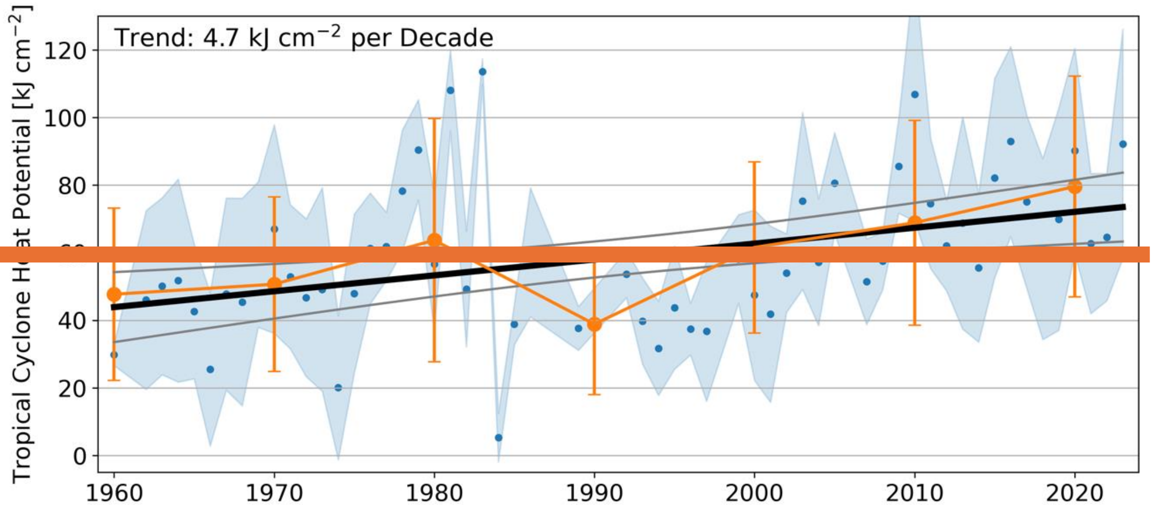
Gradone et al. Submitted: *Nature Scientific Reports*

Tropical Cyclone Heat Potential:

$$Q = \rho C_p \Delta T \Delta z$$

>60 kJ cm^{-2}

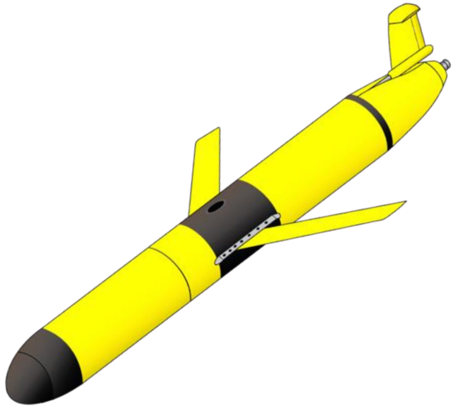
threshold for intensification

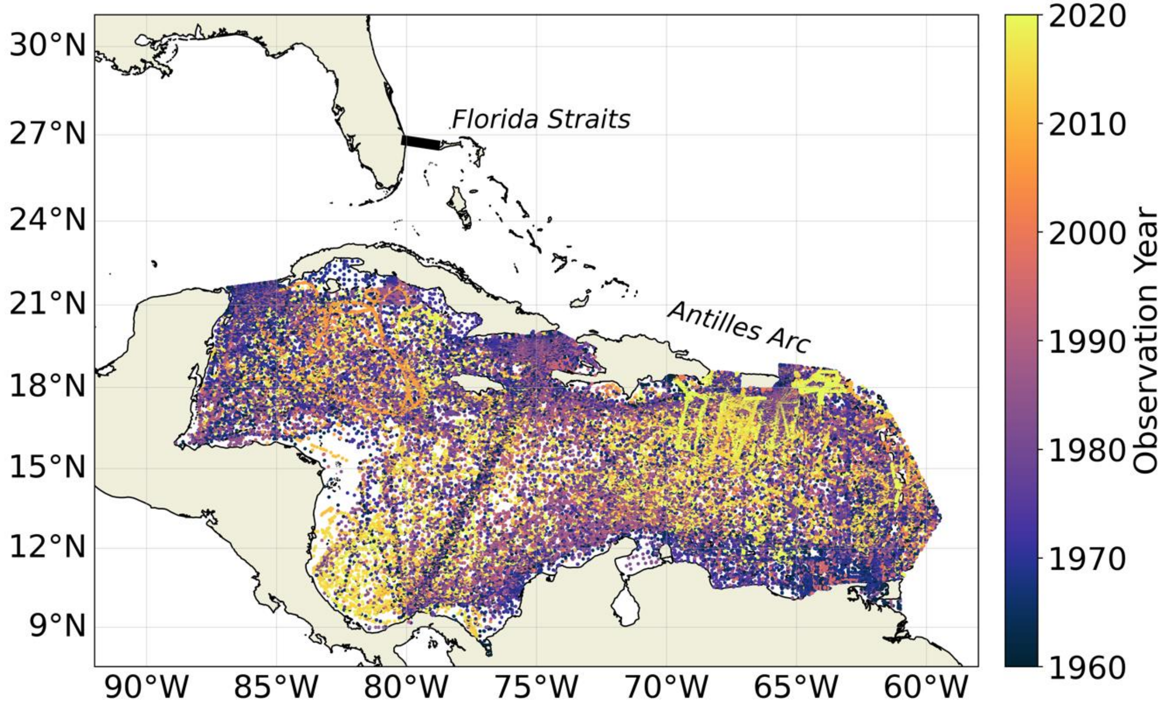


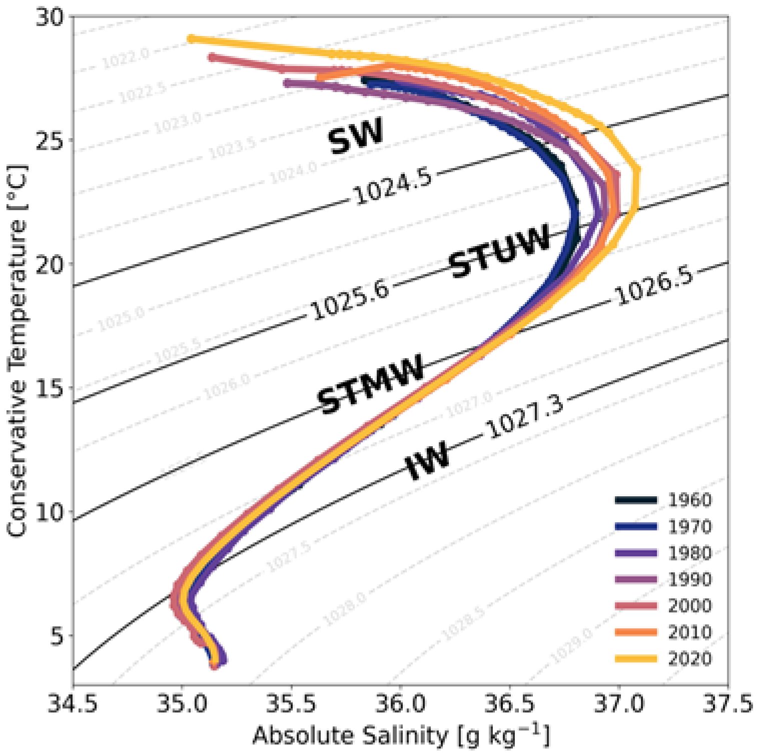
Gradone et al. Submitted: *Nature Scientific Reports*

Summary

1. Technology development
2. Work with locals
3. Synthesize a diverse large dataset
4. Small-scale → large-scale







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Yair Rosenthal
Patty Gillen
Donna Napoli
Lucy Lettini

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