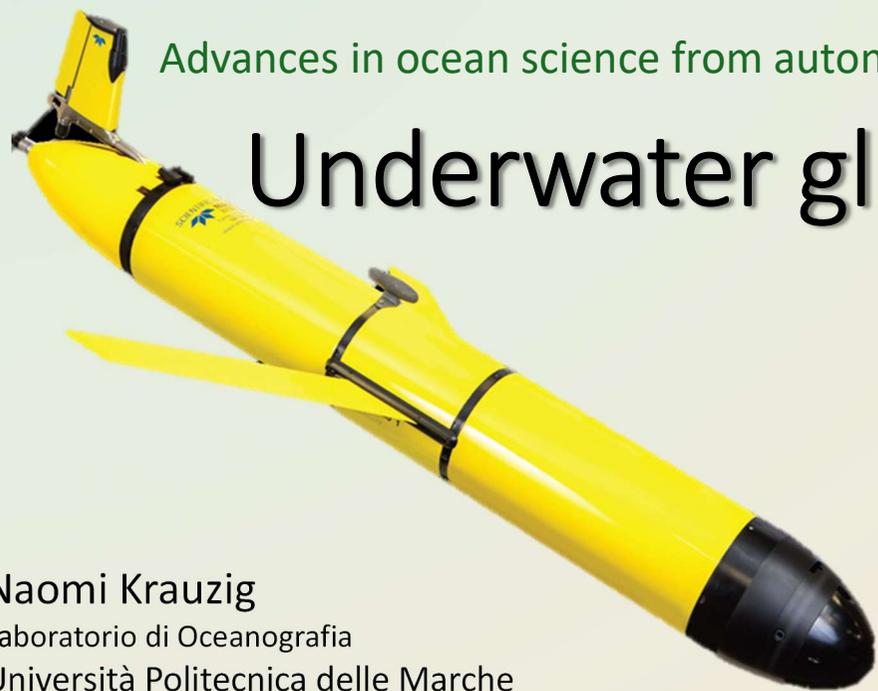




Advances in ocean science from autonomous gliders



Underwater gliders

Naomi Krauzig

Laboratorio di Oceanografia

Università Politecnica delle Marche

Autonomous Instruments in Oceanography

Università degli Studi di Napoli Parthenope

10-14 February 2025

IR0000032 – ITINERIS, Italian Integrated Environmental Research Infrastructures System

(D.D. n. 130/2022 - CUP B53C22002150006) Funded by EU - Next Generation EU PNRR-
Mission 4 "Education and Research" - Component 2: "From research to business" - Investment
3.1: "Fund for the realisation of an integrated system of research and innovation infrastructures"



Finanziato
dall'Unione europea
NextGenerationEU



Ministero
dell'Università
e della Ricerca



Contents

1) Introduction to underwater gliders

*Overview, history, design
Principles of operation*

2) Technical aspects and instrumentation

Energy efficiency, communication & navigation system and scientific sensors

3) Real-life applications and usages in different disciplines

*Capabilities and insight into diverse glider operations
Exercise on realistic mission planning with the GLIMPSE simulation software*

4) Glider data analysis and interpretation

*Data output, existing processing tools and community efforts
Practical session with sample data from recent missions*

5) Challenges, innovations and future perspectives

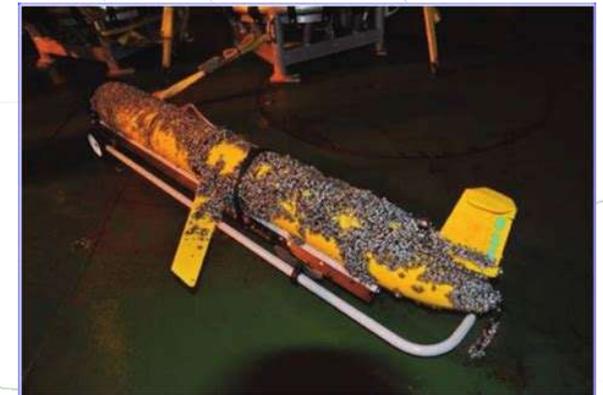
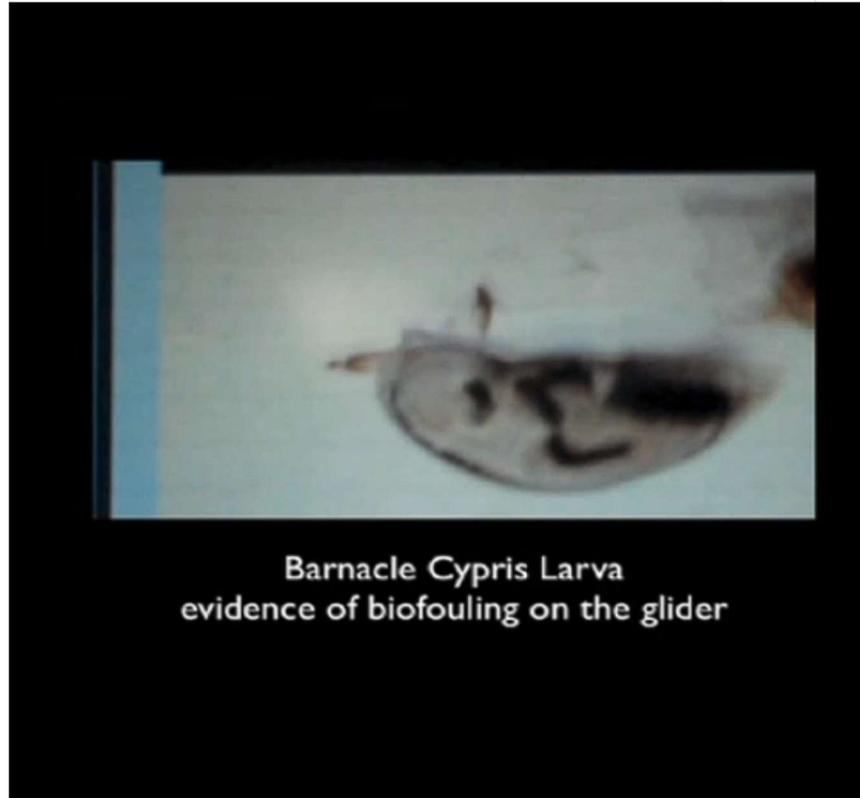
*Current limitations and challenges, tips and tricks
Ongoing innovations and future directions in glider technology*

Challenges, innovations & future perspectives



Challenges

Biofouling



Challenges

Biofouling: Barnacles → Prevention

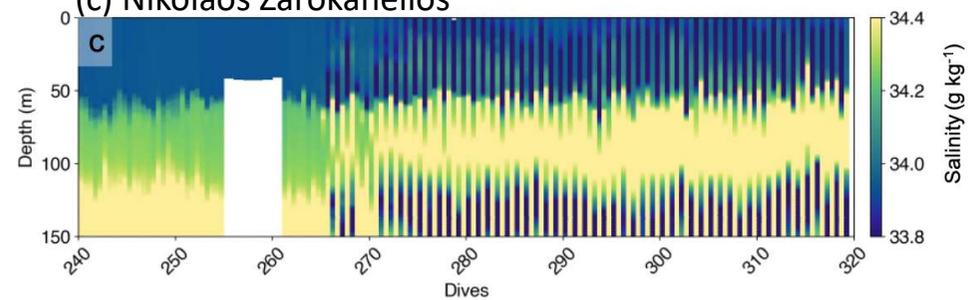


Challenges

Biofouling: Algae and particles

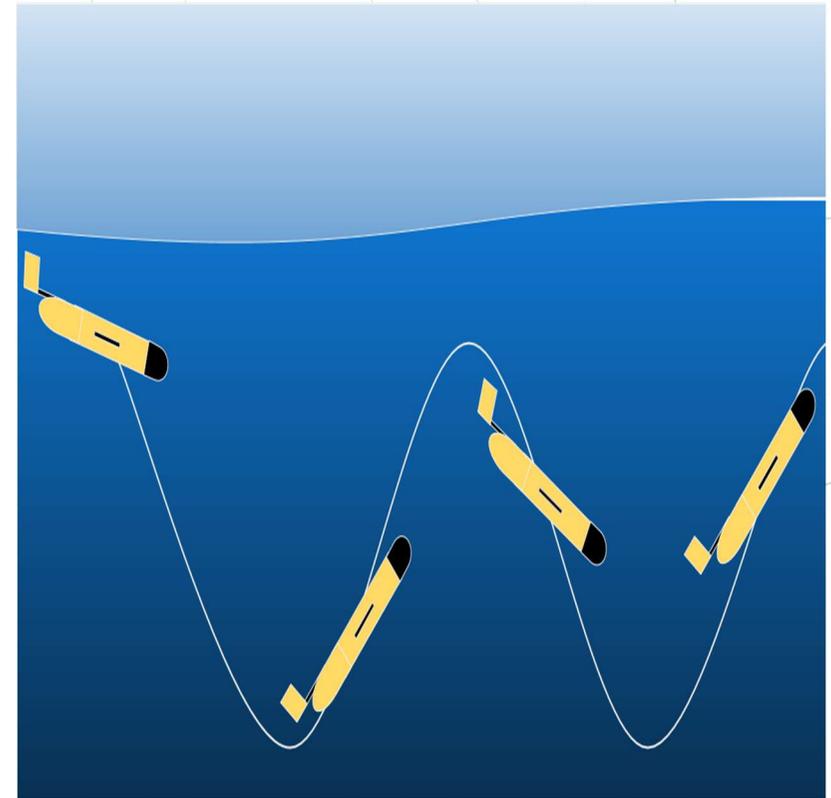


(c) Nikolaos Zarokanellos

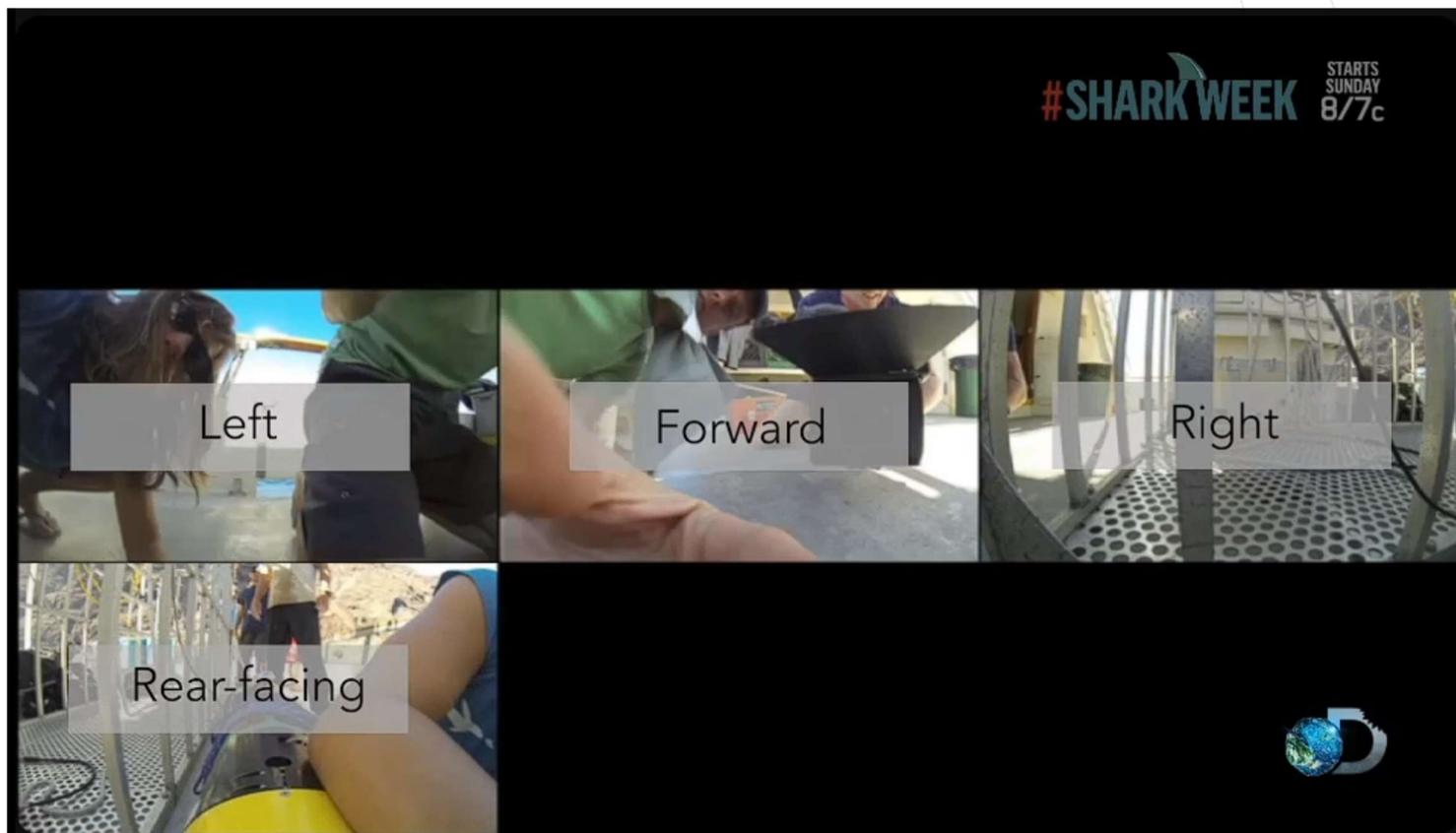


Challenges

Biofouling: Algae and particles → Prevention



Bio-interference



Specific disadvantages and ongoing progress



What about complex manouvers in shallow coastal areas ?

Seaglider C2 Specifications



- more maneuverable glider
- capable of high speeds
- fore & aft wet payload bays
- +two 10 V battery packs
- from fresh water to seawater

→ shallow water

Mechanical

- Body Length: 1.9 m (without dry payload bay)
- Body diameter: 30 cm maximum
- Wing span: 1.25 m
- Antenna mast length: 1 m (typical)
- Weight: 74 kg (nominal, in air)

Operation

- Maximum depth: 200 m
- Typical speed: 0.3 – 1.0 m/s (0.6 – 2.0 kt)
- Glide angle: 7 – 45 degrees
- Variable buoyancy: 3500 cc
- Volumetric rate of change: 20 cc/sec

Electrical

- Power source: Lithium prim. batteries, 24 V & 10 V, 25 MJ max.
- Memory storage: 1 GB compact flash
- Sensor interfaces: RS-232, frequency input

Specific disadvantages and ongoing progress



What about low density surface layers?

Specific disadvantages and ongoing progress

Low speed and difficulty in strong currents or density gradients

Buoyancy-driven propulsion with limited speed (1 kts) & power limitations with demanding maneuvers (17 MJ)

Integrated thrusters

burst speeds to 3.5 knots

Enhanced battery

23kWh \rightarrow 82.8 MJ

Increased sensor capabilities

23kWh (>2 years)



Increased buoyancy

4 L buoyancy engine

New capabilities



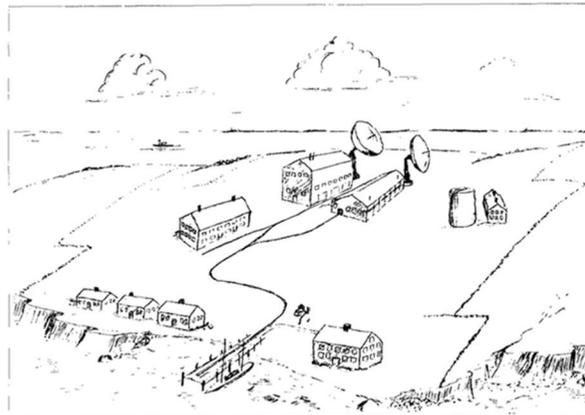
Slocum Sentinel Glider

Teledyne Webb Research Lab

FEATURE

THE SLOCUM MISSION

Narrative and Illustration
By Henry Stommel



The Slocum Mission Control Center on Nonamasset Island.

AS MOST of you know, the backbone of our climate monitoring capability is our permanent fleet of 480 **Sentinel series of Slocums**. These are able to occupy, on a monthly basis, all the 48 hydrographic sections that took the WHP 12 years to do once. We acquire data from this widely dispersed network via satellite telemetry. It is something of a wonder to

ITINERIS

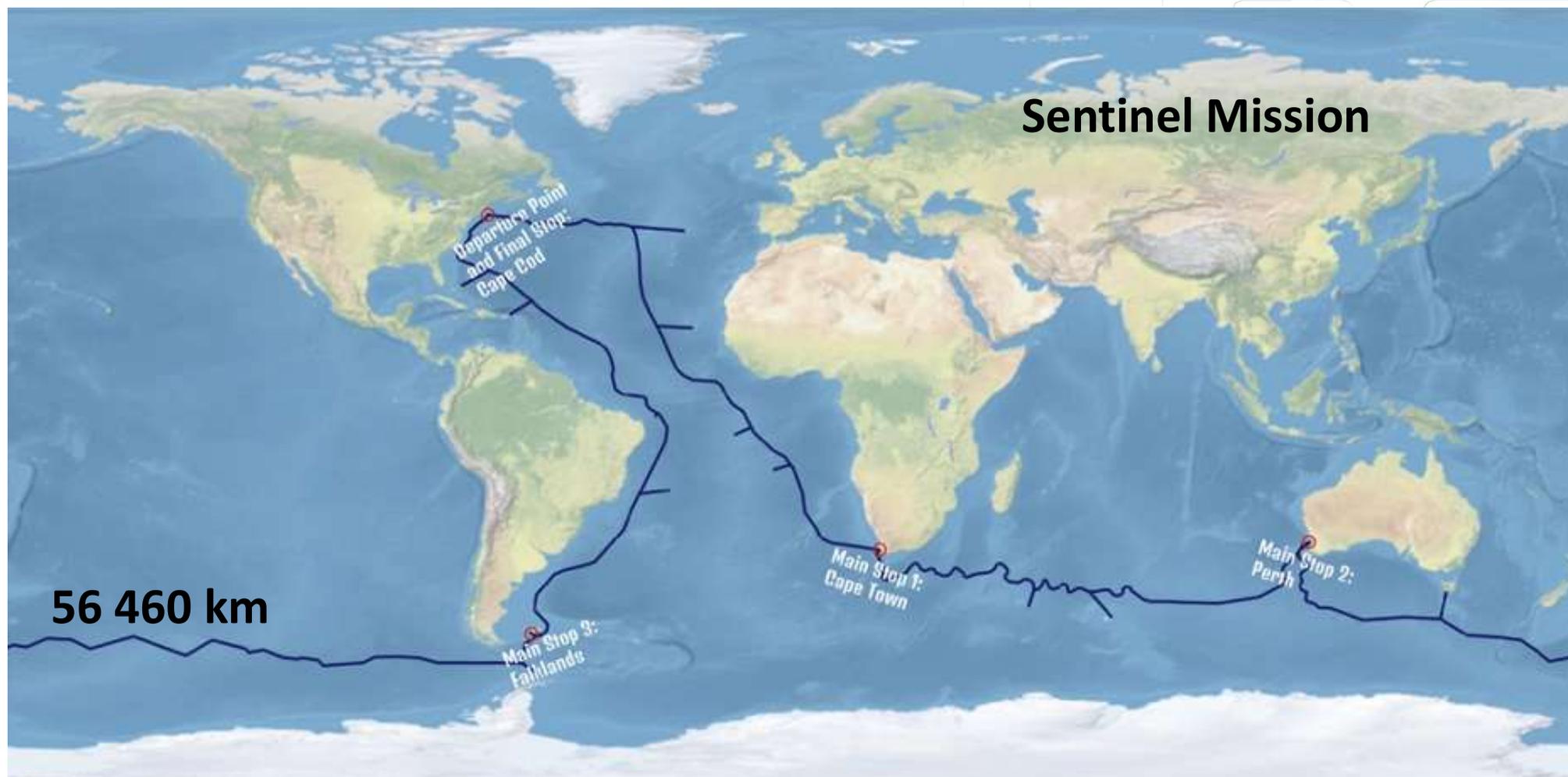


**SENTINEL
MISSION**

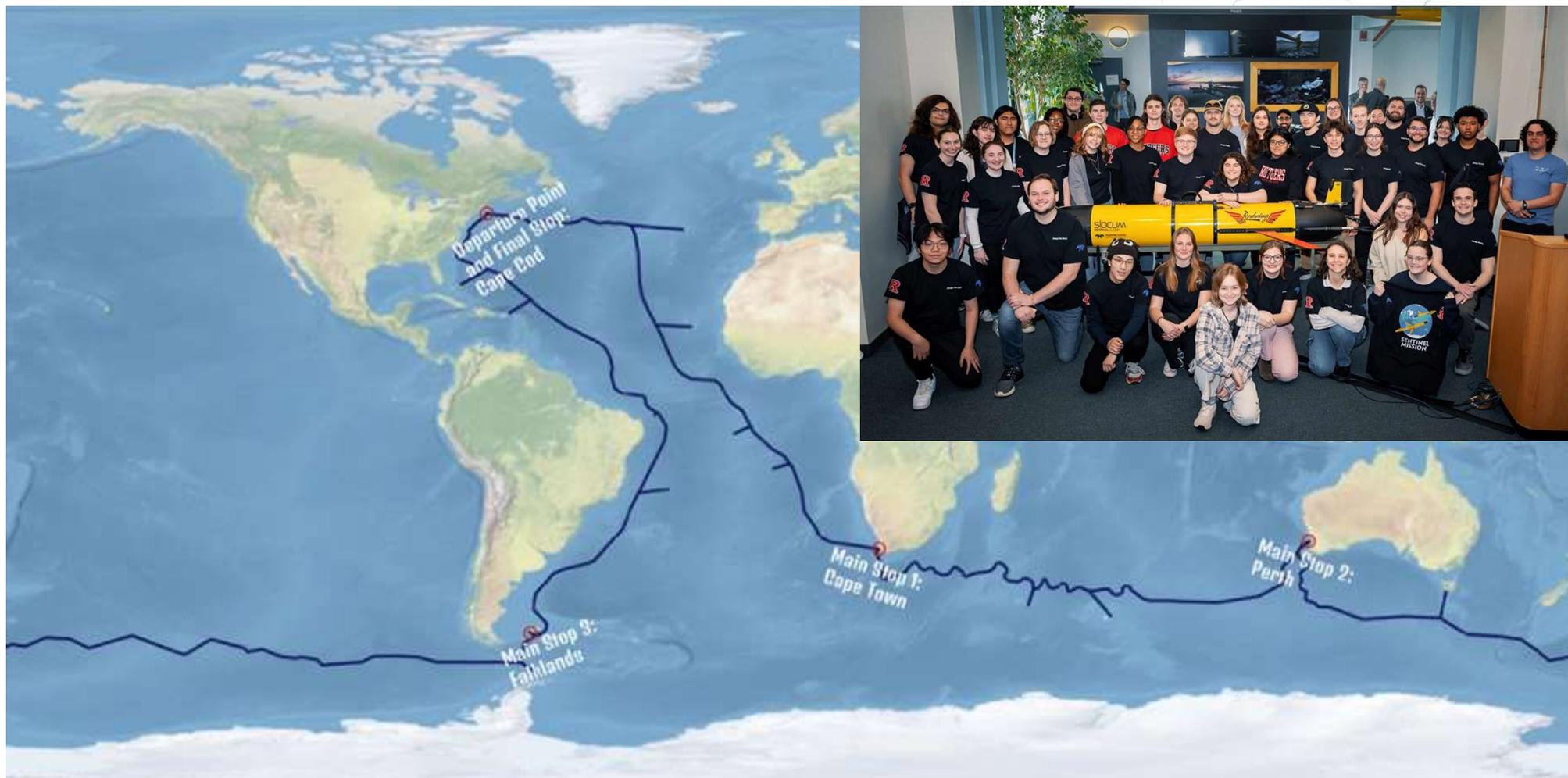


RUTGERS
THE STATE UNIVERSITY
OF NEW JERSEY

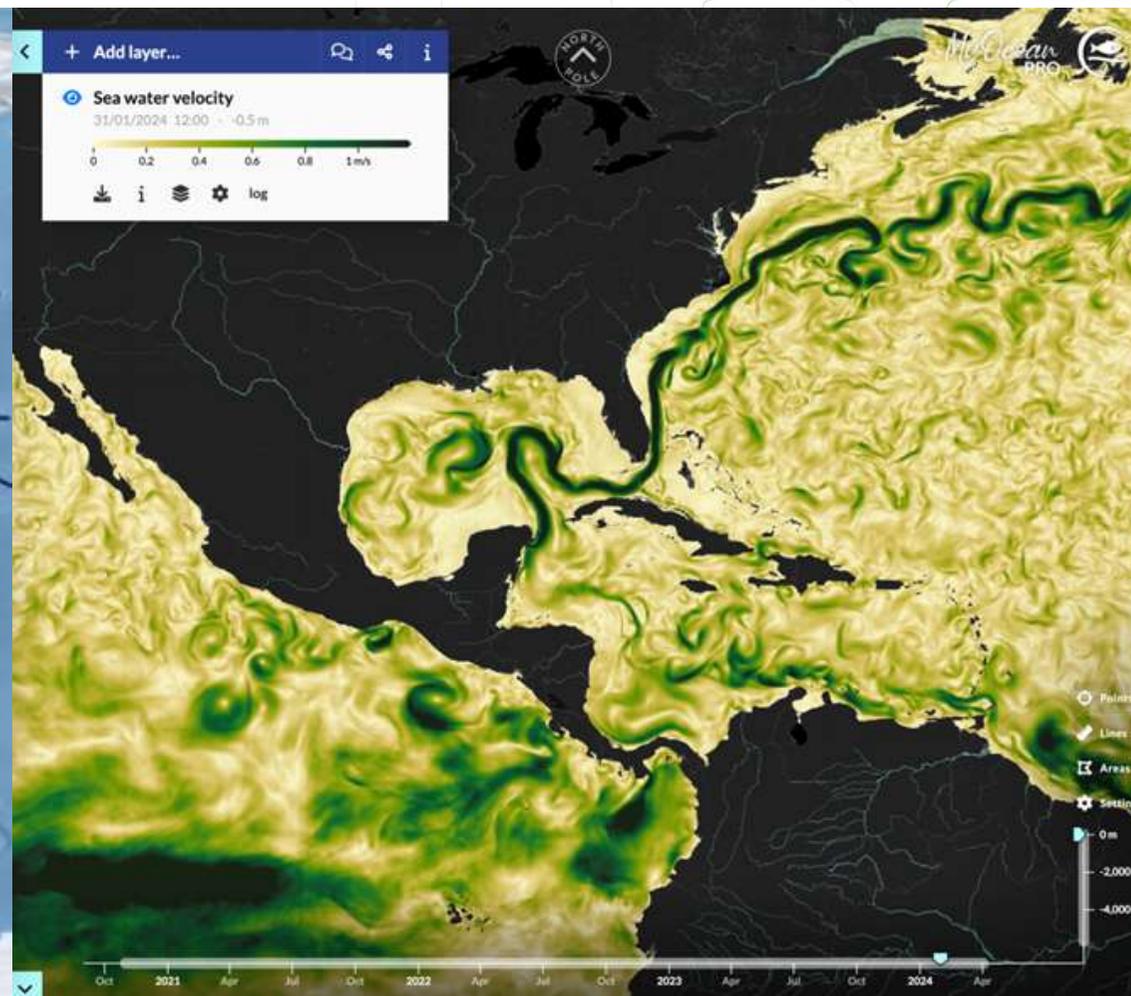
New capabilities



Insights into the Sentinel Mission



Insights into the Sentinel Mission

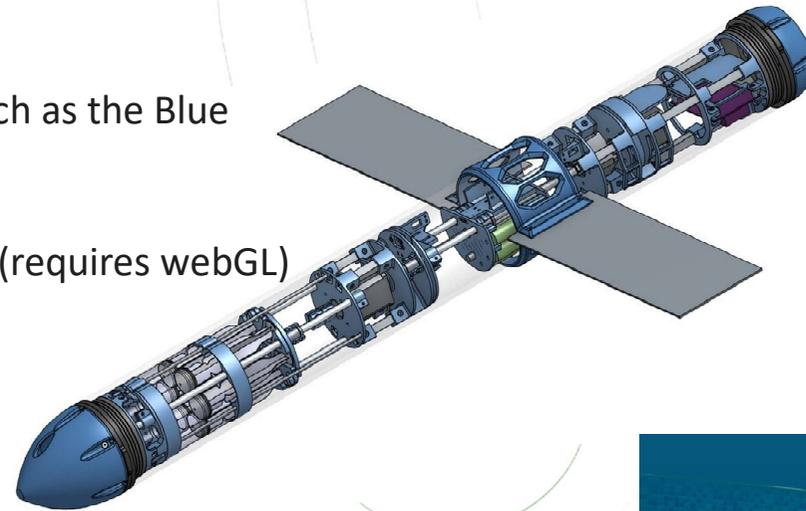


Popularity → Accessibility

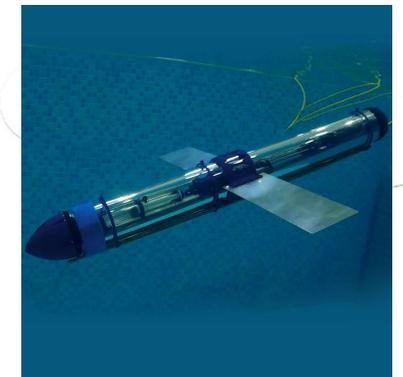
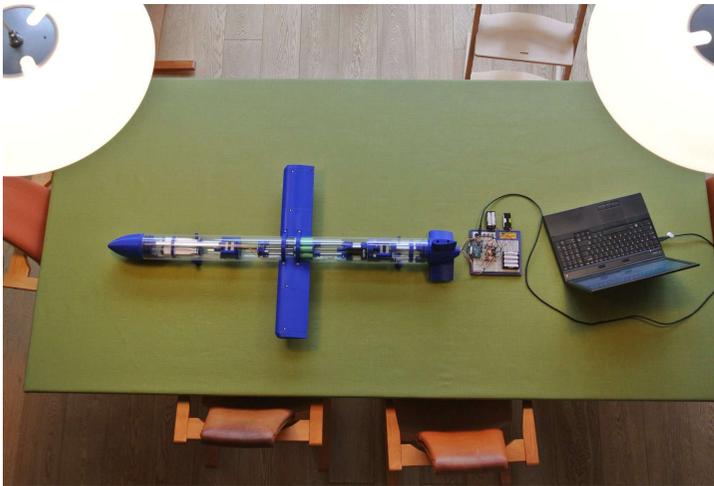
Open-source

mixture of 3D printed components and commodity parts (such as the Blue Robotics tubing/end-caps/serial communication boards).

The model is viewable on the [Onshape online platform here](https://cad.onshape.com/documents/23c169f94c57ba9867aa3c3f/w/62170f6efac11f679de9c4fe/e/8302463fee19e14abe453dcc) (requires WebGL)



<https://youtu.be/WVg47-5Skjs>



<https://cad.onshape.com/documents/23c169f94c57ba9867aa3c3f/w/62170f6efac11f679de9c4fe/e/8302463fee19e14abe453dcc>

SeaExplorer X2 Specifications

WEIGHT AND DIMENSIONS

Body Size (D x L)	0.25 m x 2 m + 1 m foldable antenna
Wingspan	56.5 cm Wingless design
Weight	59 kg in air

VEHICLE FEATURES

Communications	GPS / Satellite (Iridium) / Radio – Triple antenna
Navigation mode	Survey / Virtual mooring / Drifting / Bottoming
Safety	Autonomous drop-weight & Strobe light Optional: Locator Pinger (ULB) and/or Argos
Architecture	2 independent CPUs (Linux) for Payload & Navigation

OPERATIONAL CAPABILITIES

Depth rating	1000 m
Ballast volume	1000 cc (± 500 ml)
Speed	Nominal 0.5 kt / Maximum 1 kt
Battery	Rechargeable Li-ion / Primary Lithium
Typical Range (Endurance)*	1300 km (64 days) / 3200 km (160 days) With a GPCTD-DO, sampling at 4 s

* Range and Endurance largely depends on sensors, sampling strategy and mission environment

PAYLOAD & SENSORS

General Features	Up to 6 sensors in two sections (wet & dry): 9L / 8 kg Altimeter Opensource C++ firmware / Independent Linux CPU Compressed CSV (native) Data downloading through external Ethernet cable (no vehicle opening)
Standard Sensors	CTD (pumped or non-pumped) Dissolved Oxygen (Optode or Electrochemical) Chlorophyll / Turbidity / CDOM PAR ADCP Nitrates pCO ₂ Echo sounder Fluorometers options (Puck)
Exclusive Sensors	Hydrocarbons / Sewage / Pesticides µTurbulence Methane Passive Acoustic Recorder (customizable)
On-demand Sensors	Metal traces & Micronutrients FRRF Others upon request

ALSEAMAR

ALCEN



Salinity, Temperature, Pressure CDOM

Dissolved oxygen

Chlorophyll

Turbidity

Hydrocarbons

Methane

Acoustic recordings

+Custom
Solutions

Slocum G3 Specifications



- propeller option
- high speed
- complex maneuver

GENERAL SPECIFICATIONS

Deployment	Versatile, deployment with 1-2 people. LARS options available.
Power	Alkaline (A) / Rechargeable (Li) / Lithium (L)
Range	350-1200km/ 700-3000km/ 3000-13000km
Deployment Length	15-50 days/ 1-4 months/ 4-18 months
Depth Options	(4 to 150m) or (40 to 1000m) operating depth range*
Navigation	GPS, Pressure Sensor, Altimeter, Dead Reckoning
Communication	RF Modem, Iridium (RUDICS), ARGOS, Acoustic Modem
Horizontal Speed	Buoyancy Engine: 0.35 m/s (0.68 knot) Average, up to 0.5 m/s (1 knots) with full drive. Thruster: Up to 1 m/s (2 knots)
Mass	55 - 70kgs (dependent upon configuration)
Dimensions	Vehicle Length: 1.5 meters; Hull Diameter 22 cm

Acoustic Doppler Current Profiler
 Acoustic Modem
 Acoustic Mammal Detection
 Beam Attenuation Meter
 CTD Pumped or Unpumped
 Echosounder
 Fish Tag Detection
 Hydrophones
 Nitrate
 Optical Backscatter Options
 Optical Attenuation Options
 Optical Fluorometry Options
 Oxygen Options
 PAR
 Radiometer
 Spectrophotometer
 Turbulence

 +Custom Solutions

Slocum Sentinel Specifications



Slocum Sentinel Glider

- thruster option
- high speed
- complex maneuver
- ultra-long endurance
- wide range of sensors

PRODUCT FEATURES

Longest Endurance Glider on the Market

With 23 kWh of power available, the Sentinel Glider can operate at sea for over 2 years

Largest buoyancy engine on the Market

The 4 Liter (+/- 2 Liter) Buoyancy Engine of the Sentinel Glider offers greater flexibility in the speed of the glider and the diversity of operational areas

Integrated Thrusters

Included on Every Sentinel Glider, these thrusters allow for burst speeds of up to 3.5 knots when facing strong currents or to shorten transit times

Wide-ranging Sensor Suite

The Slocum Sentinel Glider accommodates the sensor and hardware options available for the Slocum G3s Glider – the most options available of any glider platform

Acoustic Doppler Current Profiler
Acoustic Modem
Acoustic Mammal Detection
Beam Attenuation Meter
CTD Pumped or Unpumped
Echosounder
Fish Tag Detection
Hydrophones
Nitrate
Optical Backscatter Options
Optical Attenuation Options
Optical Fluorometry Options
Oxygen Options
PAR
Radiometer
Spectrophotometer
Turbulence

+Custom Solutions

Seaglider Specifications



Weight and Dimensions

- 1.8 - 2 m long (configuration dependent)
- Vehicle maximum diameter 30 cm
- Weight 52 kg (dry)
- Wing span 1 m
- Antenna mast length between 43 cm and 1 m (configuration dependent)

Maximum travel range/duration

- 4,600 km (650 dives to 1 km depth)

Operating depth range

- 50 to 1000 m

Speed

- Typical speed 25 cm/s (0.5 kt)

Variable buoyancy volume

- 850 cc

Glide angle

- 16-45° (1:3.5 to 1:1 slope)

Battery Endurance

- Lithium Sulfuryl chloride primary batteries 17 MJ
- Up to 10 Months (dependent upon configuration, sampling rate and operational area)

Guidance and control

- Dead reckoning between surface GPS fixes using a 3-axis digital compass
- Kalman filter prediction for mean and oscillatory currents
- Bathymetry map system and acoustic altimeter for near bottom dives
- Data can be transmitted after every dive
- Web-based interface
- Control and system commands can be transmitted before each dive

Electrical features

- Ultra-lower power micro-processor
- High-capacity compact-FLASH memory
- 4 open serial channels for sensors
- 1 open frequency channel for sensors

Mechanical features

- Isopycnal pressure hull
- No external moving parts
- Low drag, flooded fiberglass composite firing

Supported sensors

- CTD
- Dissolved oxygen sensors
- Fluorometer/backscatter/turbidity
- PCO2 optode
- Microstructure turbulence
- ADCP
- Photosynthetically Active Radiation (PAR)
- Echo sounder

Seaglider C2 Specifications



- more maneuverable glider
- capable of high speeds
- fore & aft wet payload bays
- +two 10 V battery packs
- from fresh water to seawater

→ shallow water

Communications

- Telemetry: Iridium RUDICS communications
- Pre-launch test & programming: RS-232

Navigation & Control

- Integrated GPS module provides position while at surface
- Dead reckoning while submerged using 3-axis compass and pressure sensor
- Integrated altimeter & bathymetry map features for near bottom profiles
- Kalman filter for prediction of mean and oscillatory currents

Future directions

Deepglider™

Size	Body: 1.8 m long, 30 cm max. diameter Wing span: 1 m Antenna mast length: 1 m
Weight	79 kg (dry)
Maximum Depth	6000 m
Maximum Range/Duration	10,000 km (250 dives to 6000m depth)
Batteries	Lithium primary, 24V and 10V packs, 16.5 MJ
Typical Speed	20-50 cm/s (0.4-1.0 kts)
Glide Angle	14-45° (1.4 to 1:1 glide-slope)
Sensors	Sea-Bird temperature-conductivity WET Labs fluorometer-optical backscatter Aanderaa Optode dissolved oxygen Variable sample rate by sensor and depth range, both dive & climb
Mechanical Features	Carbon-fiber hull with passive compressible fluid compensation No external moving parts Low drag, flooded fore & aft fairings for external sensors
Electronic Features	1 GB Compact-FLASH memory 4 serial data channels available 1 frequency data channel available
RF Data Telemetry	Iridium satellite data telemetry
Software Features	Complete data transmitted after every dive Control and system commands transmitted on any dive
Guidance & Control	Dead reckoning between GPS fixes using pitch, roll, heading Kalman filter prediction for mean and oscillatory currents Altimeter and bathymetry map systems for near-bottom dives

<p>APPLICATIONS</p>	<ul style="list-style-type: none"> ✓ Physical, chemical, and biological oceanography ✓ Maritime reconnaissance ✓ Communication and Navigation aid
<p>OPERATIONAL MODES</p>	<p>Survey</p> <ul style="list-style-type: none"> ✓ transits a sequence of waypoint targets <p>Virtual mooring</p> <ul style="list-style-type: none"> ✓ profiles at target location <p>Loiter at depth</p> <ul style="list-style-type: none"> ✓ maintains neutral buoyancy at any depth <p>Surface</p> <ul style="list-style-type: none"> ✓ positions antenna mast for GPS/RF data telemetry
<p>MILESTONES</p>	<ul style="list-style-type: none"> ✓ First glider to complete dives >5900m deep ✓ First glider to measure barotropic current ✓ First glider to make full-depth open ocean profile sections

For more information please see:
<http://seaglider.washington.edu/>

Fritz Stahr
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206-543-7886
Seaglider Fabrication Center
School of Oceanography
University of Washington



Maximum Depth: 6000 meters
Maximum Range/Duration
10,000 km (250 dives to 6000m depth)



SEAGLIDER
FABRICATION CENTER



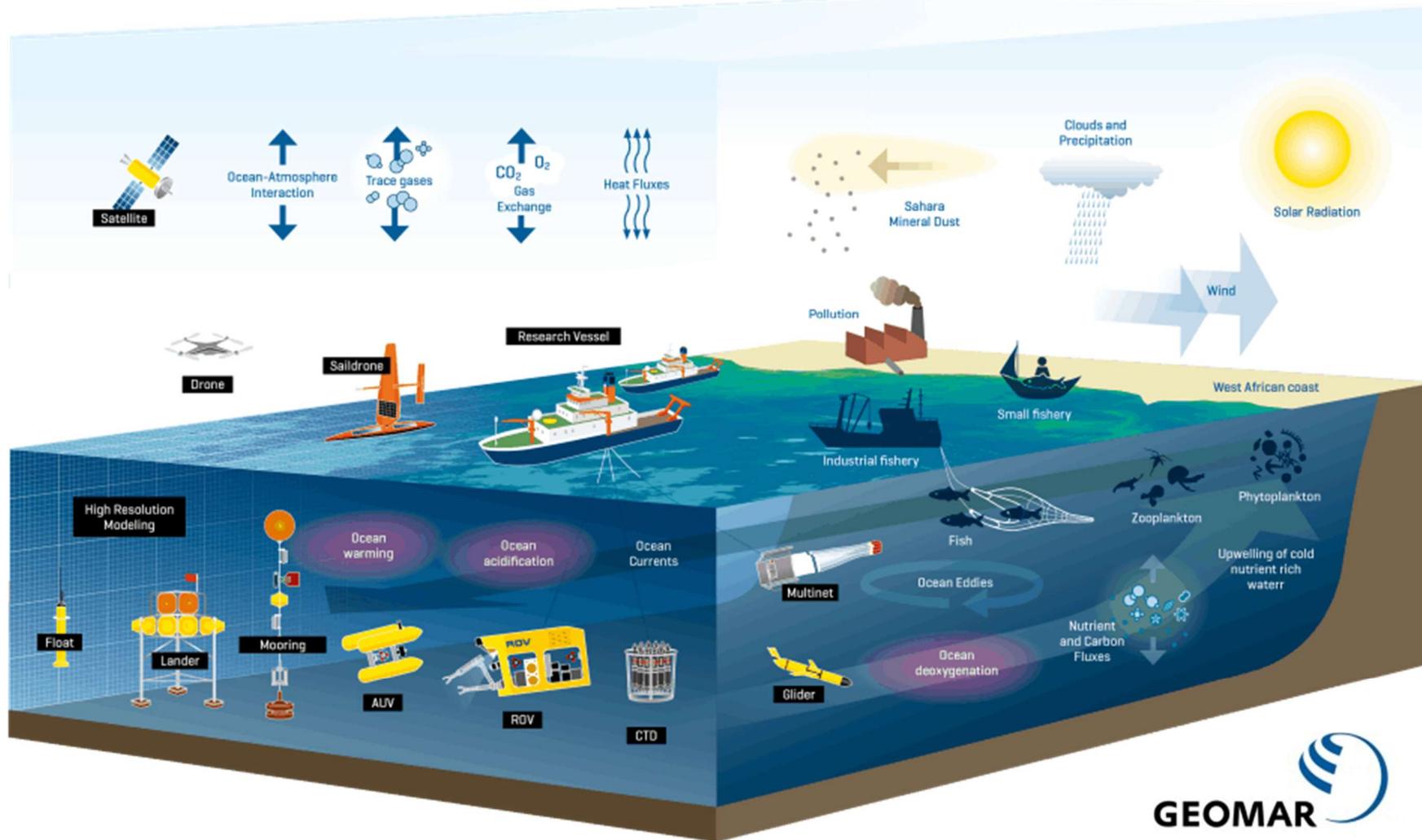
Future directions: multi-glider missions

With Backseat driver !

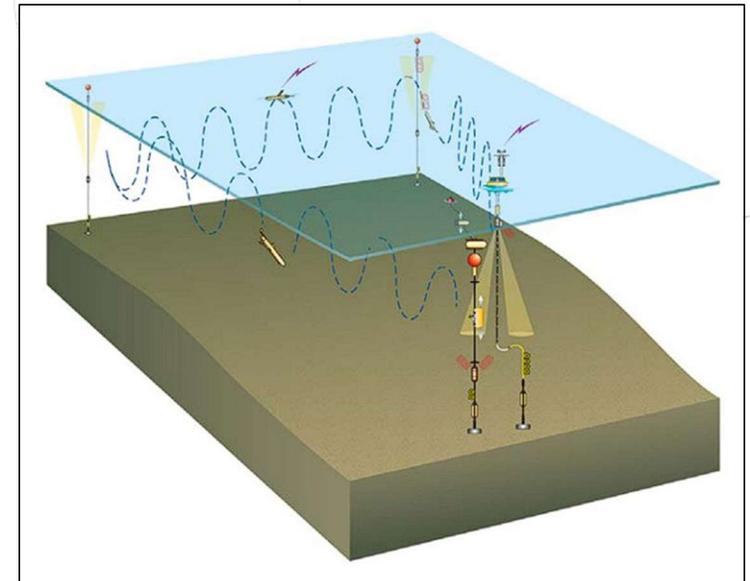
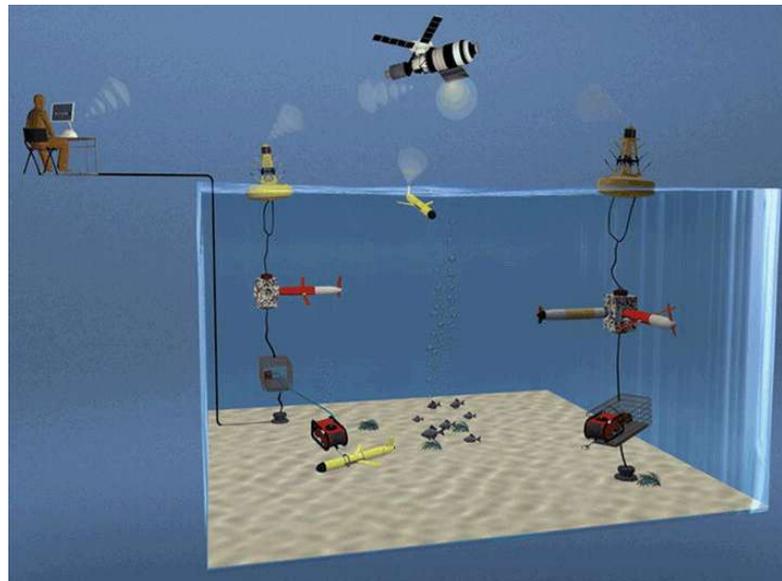
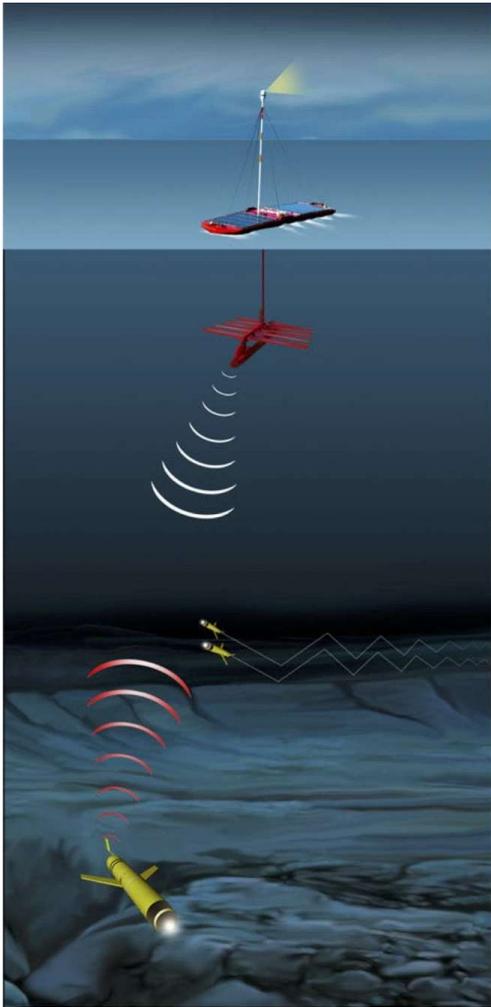
Tracking of mammals, eddies etc

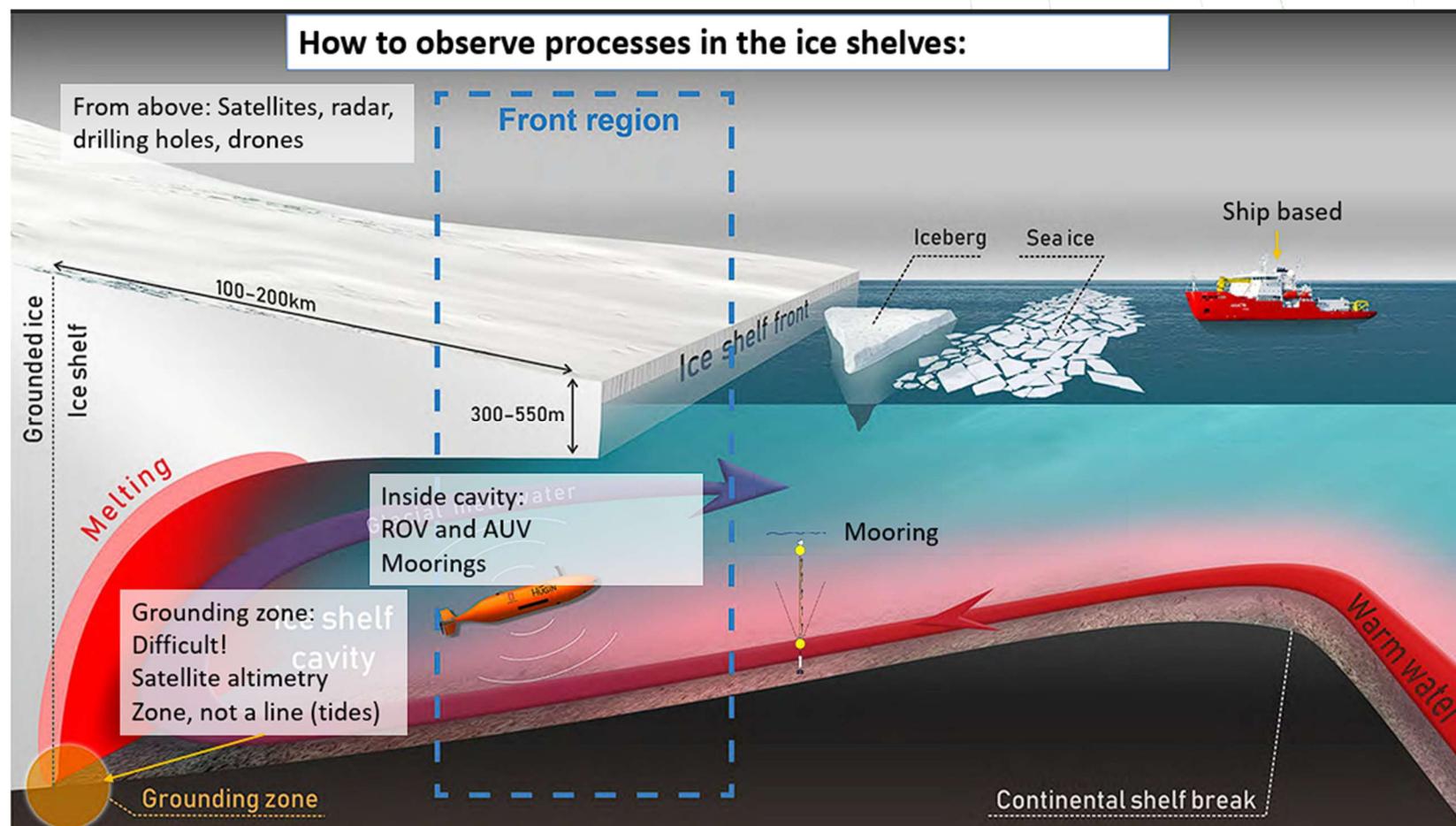


Future directions: multi-platform campaigns

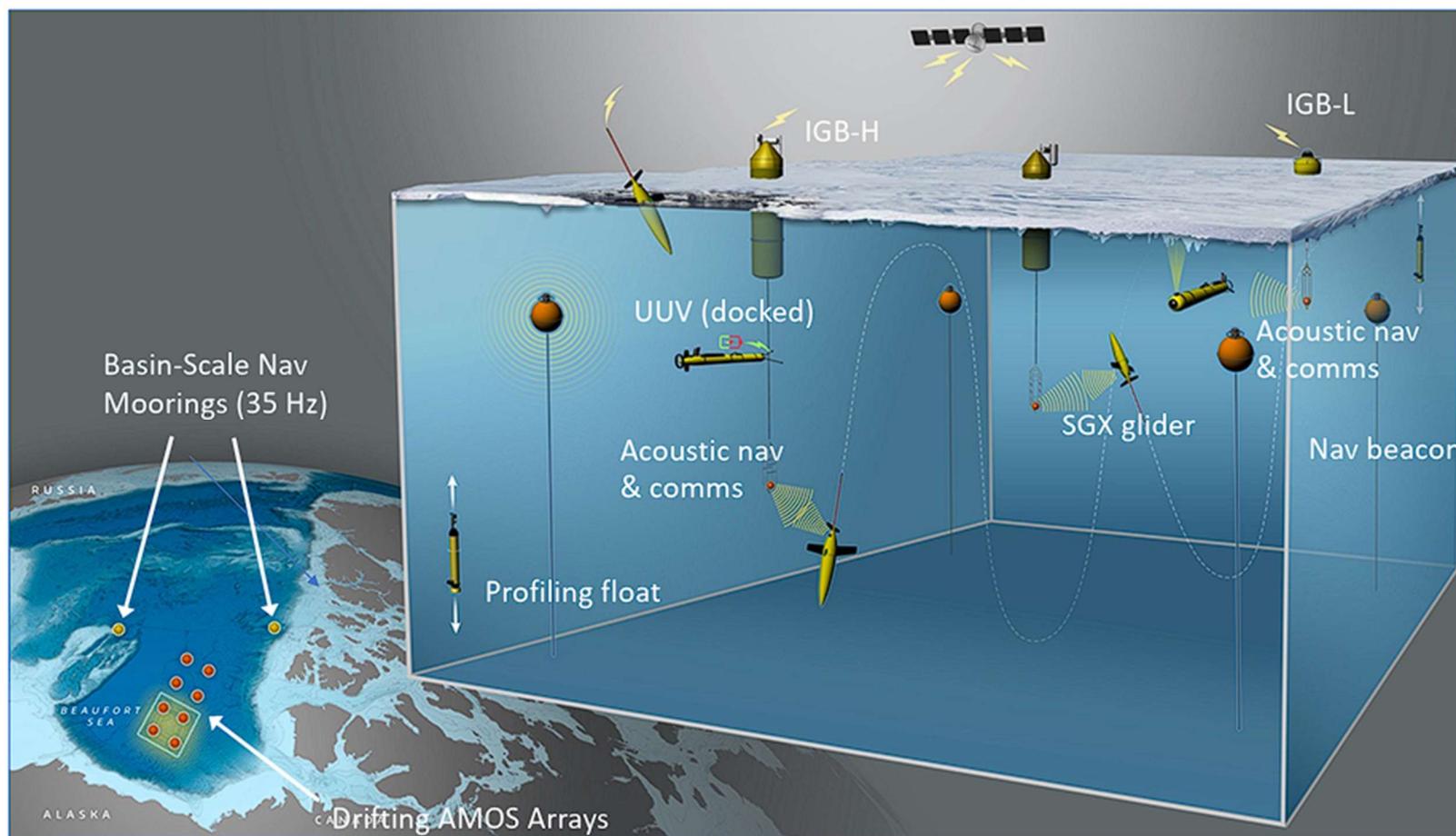


Future directions: bridging the communication gap





Future directions



Future work



□ Features

- Slocum glider
- Triangle path
- RAFOS beacons
- Under ice for months

□ Challenges

- Navigation
- Localization
- Power consumption
- Data log
- Contingency behaviours
- ...

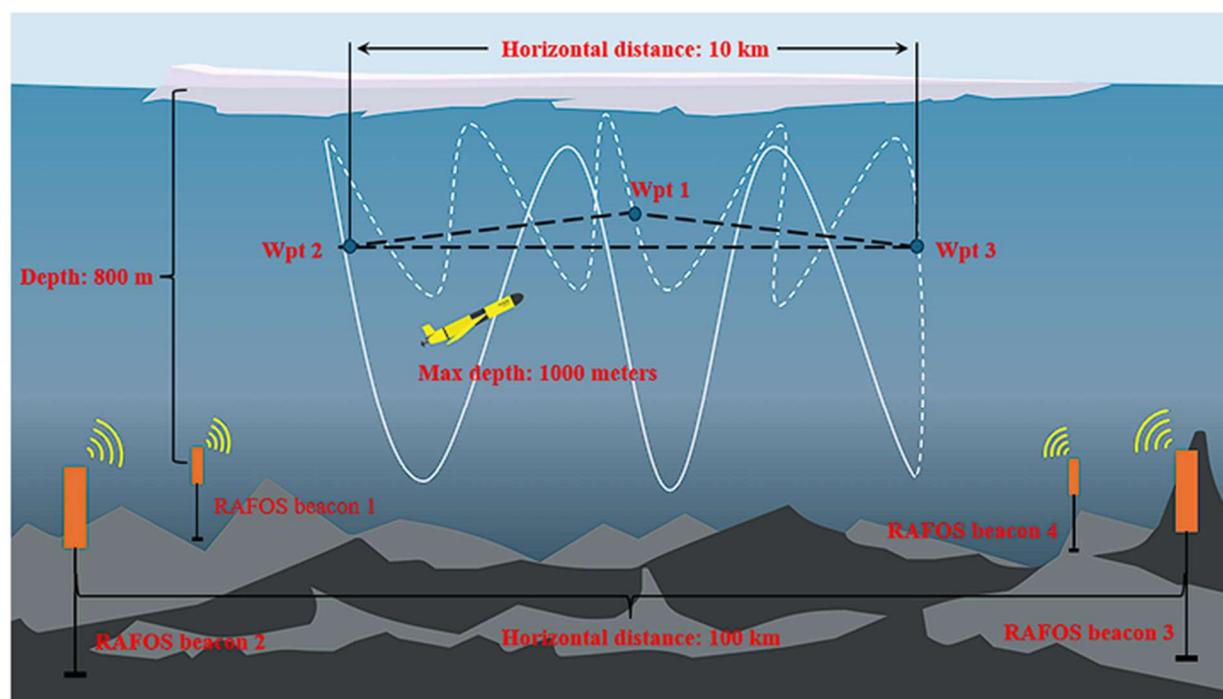
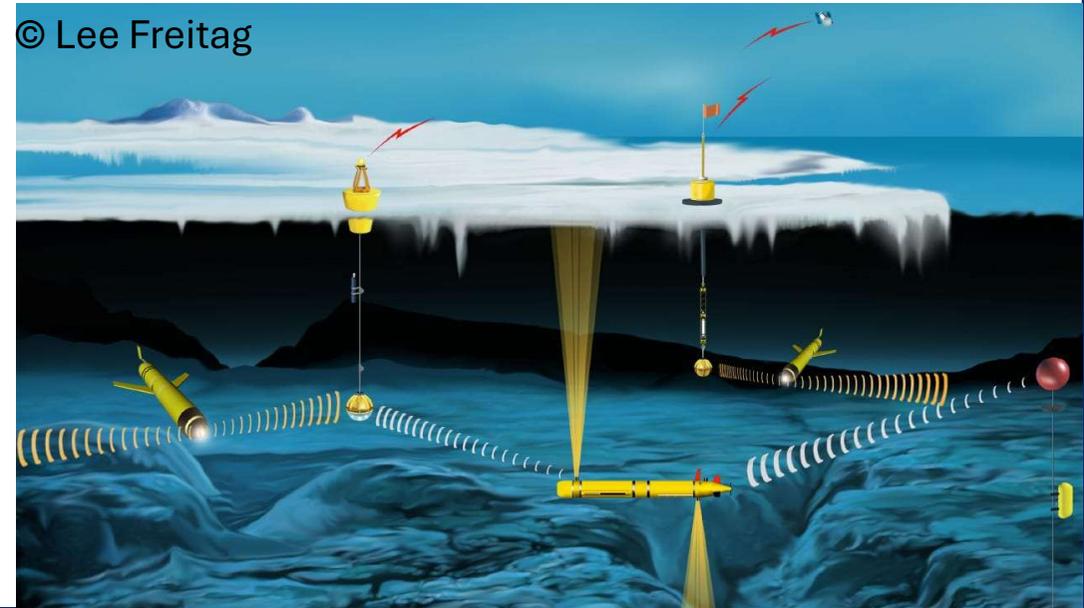
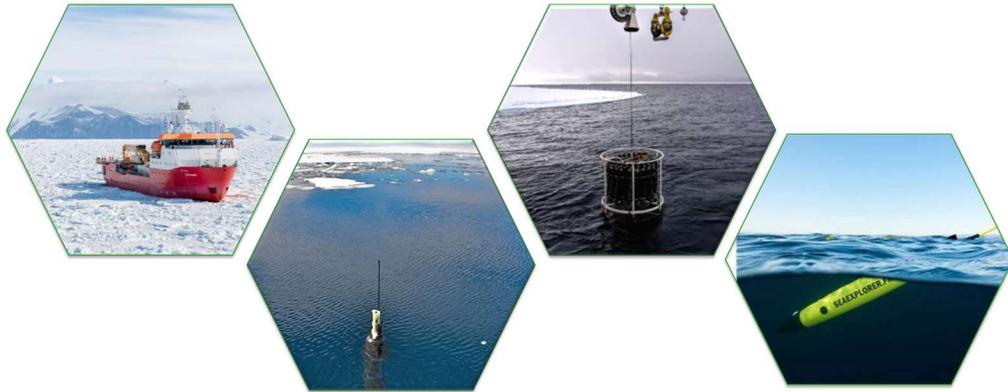


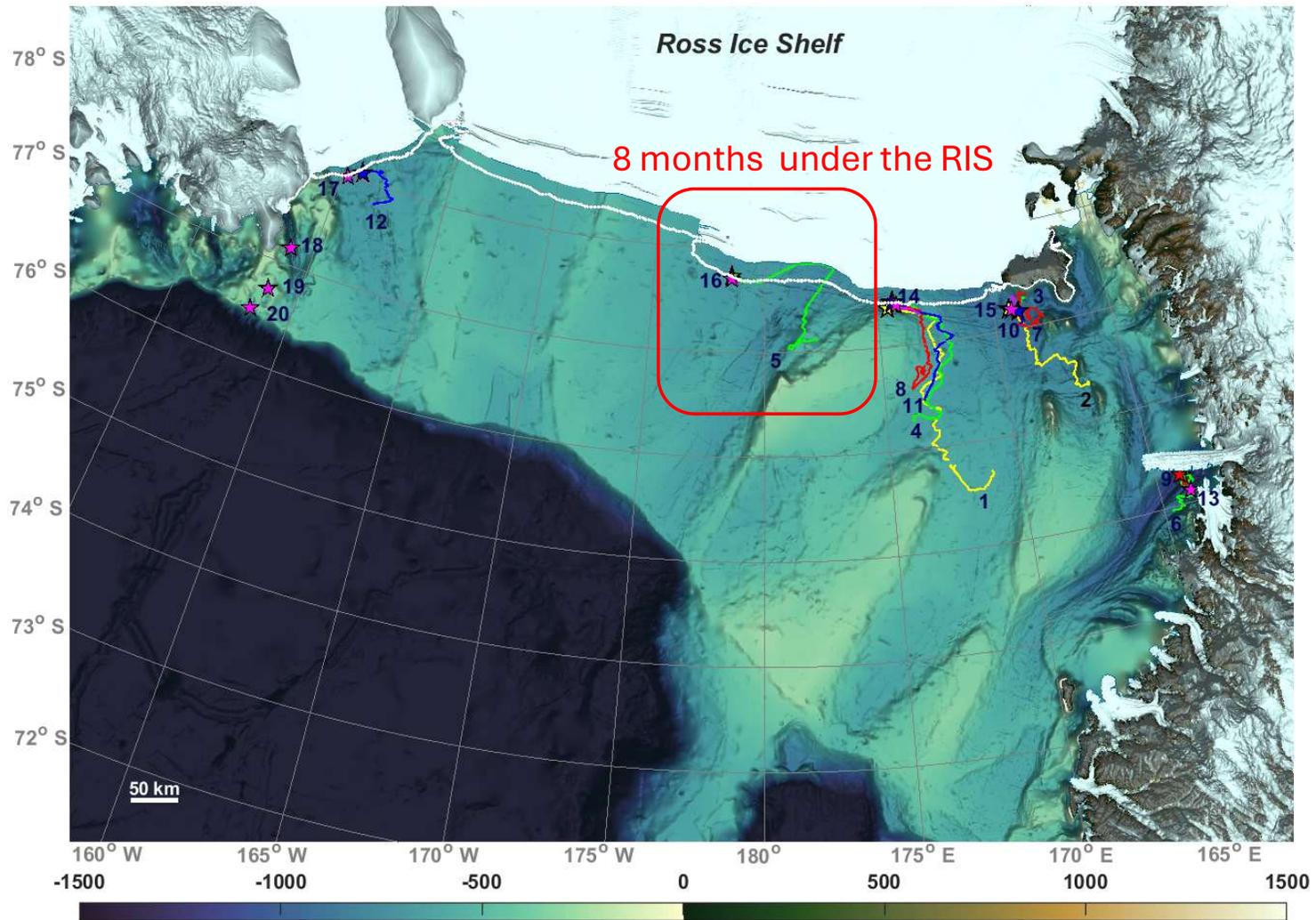
Figure 19. PycnoGen project in which a glider navigates along a triangle path, aided by RAFOS beacons under sea ice for months (Project management: Prof. Alberto Naveira Garabato, Prof. Eleanor Frajka-Williams).

Polar glider community feedback, lessons learnt and future plans ?

Challenges in polar regions → lessons learnt and community needs



Year-round “grounded” Argo floats that require geolocation estimations: example in the Ross Sea

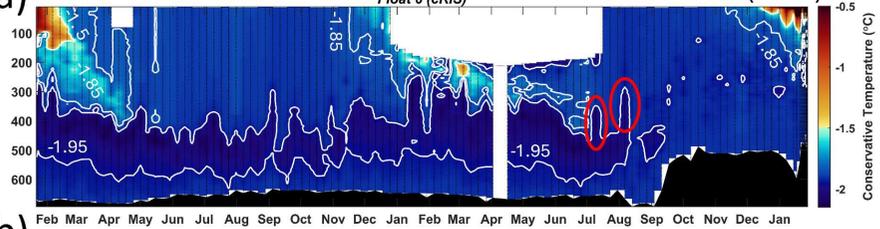


2020	1	★	6903772
	2	★	6903773
2021	3	★	6903792
	4	★	6903793
	5	★	6903794
2022	6	★	6903795
	7	★	6903810
	8	★	6903811
2023	9	★	6903812
	10	★	6903831
	11	★	6903832
2024	12	★	6903833
	13	★	5907101
	14	★	6990623
	15	★	3902580
	16	★	5907090
	17	★	1902686
	18	★	4903795
	19	★	5907104
	20	★	5907091

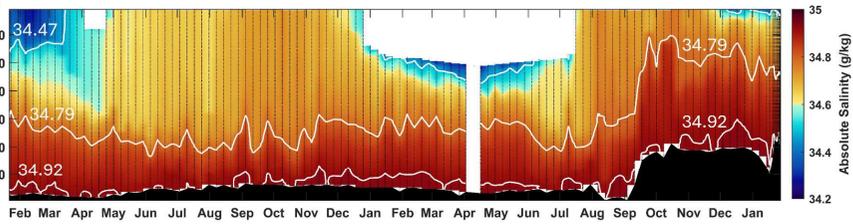


Year-round "grounded" Argo floats that require geolocation estimations: example in the Ross Sea

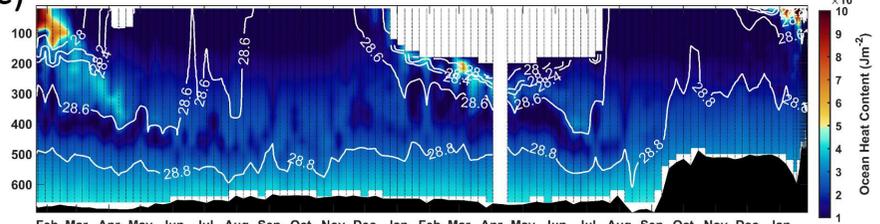
a) *Float 6 (cRIS)* Falco et al. (2024)



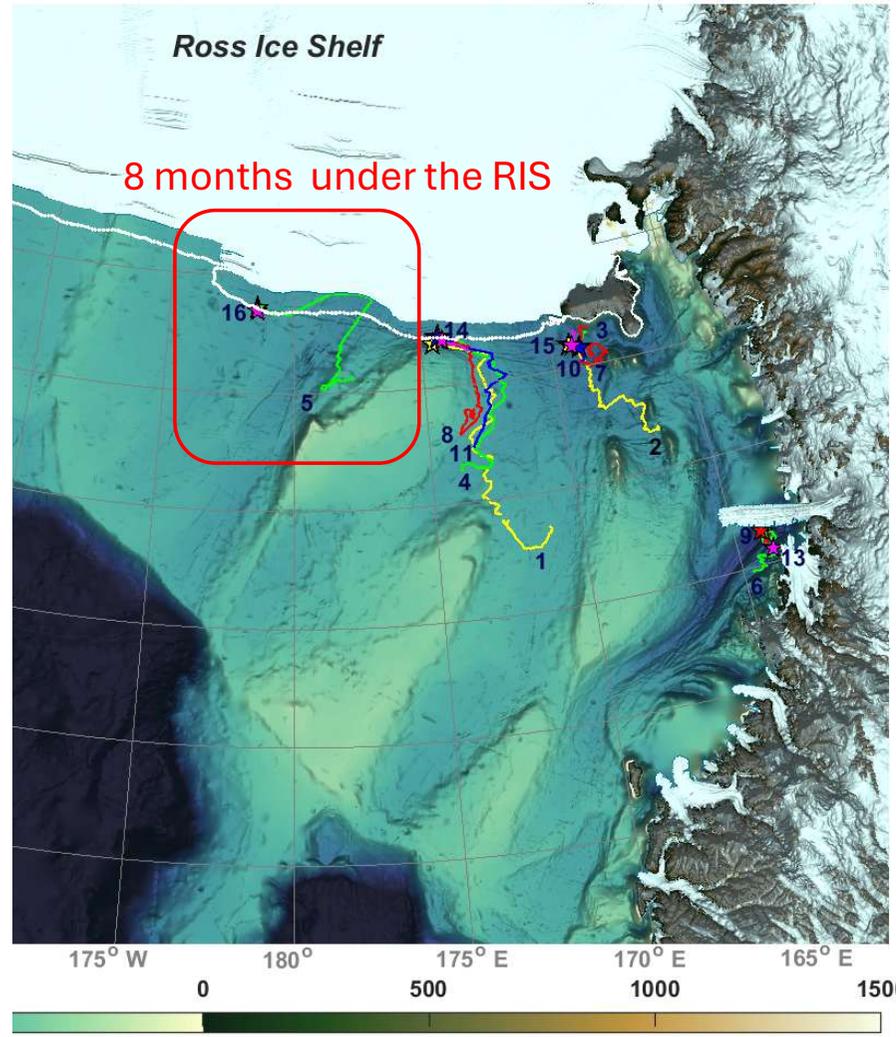
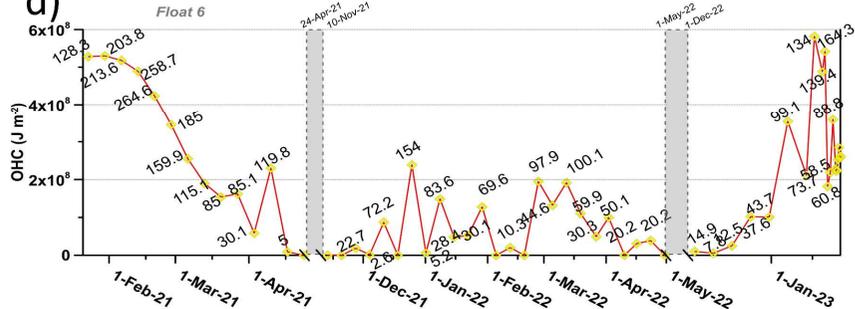
b) Absolute Salinity (g/kg)



c) Ocean Heat Content (J m^{-2})



d) OHC (J m^{-2})

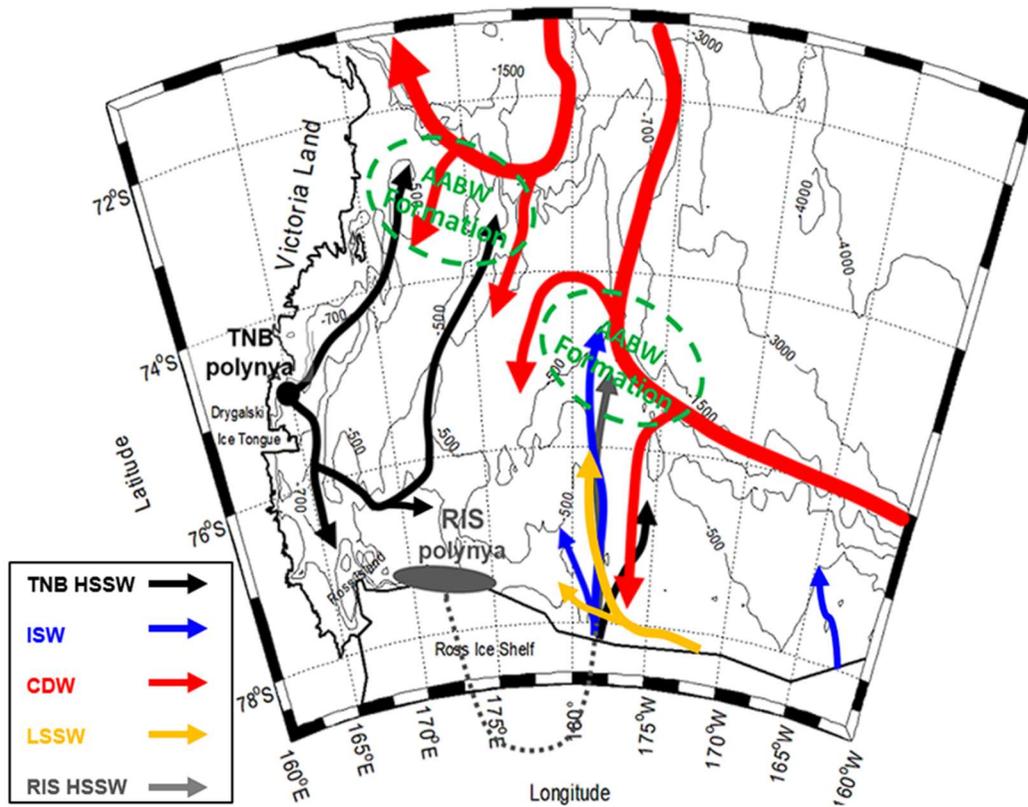


2020	1	★	6903772
	2	★	6903773
2021	3	★	6903792
	4	★	6903793
	5	★	6903794
	6	★	6903795
2022	7	★	6903810
	8	★	6903811
	9	★	6903812
2023	10	★	6903831
	11	★	6903832
	12	★	6903833
2024	13	★	5907101
	14	★	6990623
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	19	★	5907104
	20	★	5907091

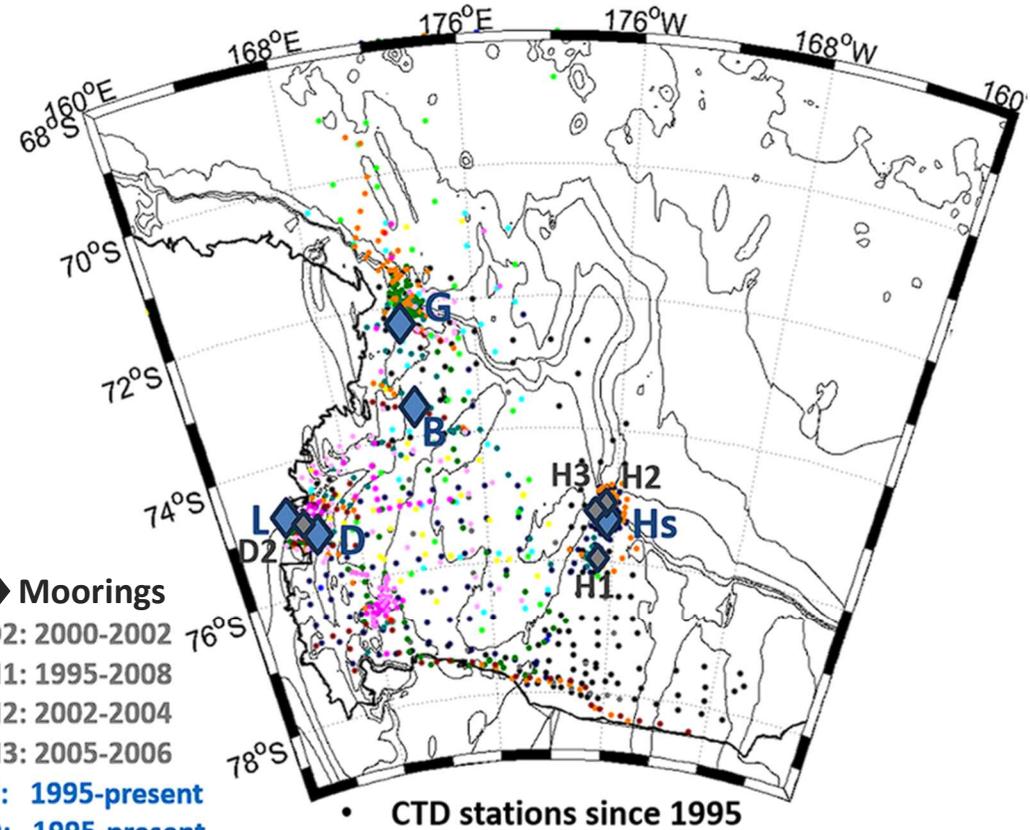


Long-term mooring observatory as an opportunistic application: example in the Ross Sea

MORSea



Modified from Budillon et al. (2003) *1



◆ Moorings

D2: 2000-2002

H1: 1995-2008

H2: 2002-2004

H3: 2005-2006

B: 1995-present

D: 1995-present

L: 1998-present

G: 2003-present

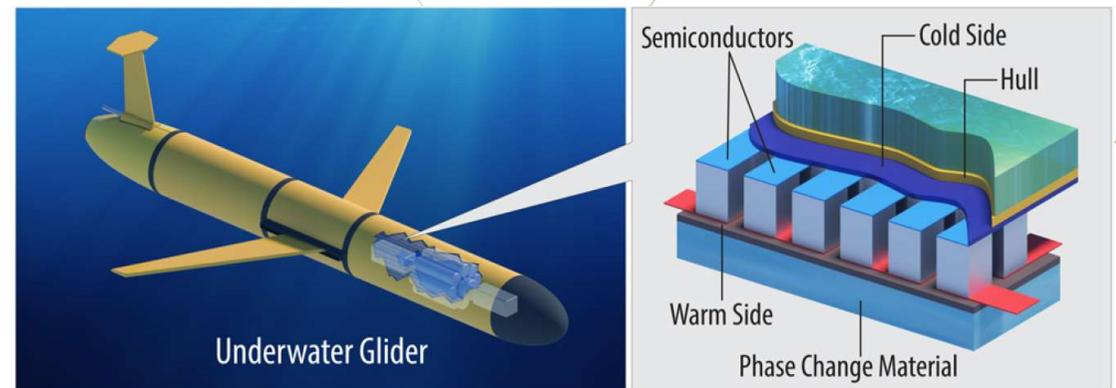
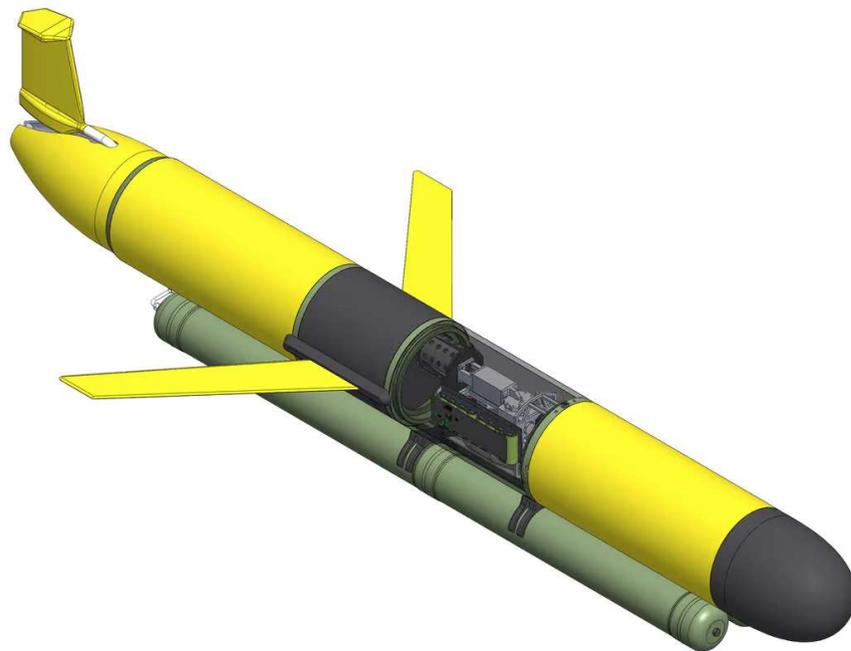
Hs: 2022-present

• CTD stations since 1995

*1 Based on: Orsi & Wiederwohl (2009); Jendersie et al. (2018); Rivaro et al. (2022)



Future (past?) directions: harnessing energy from ocean thermal gradients

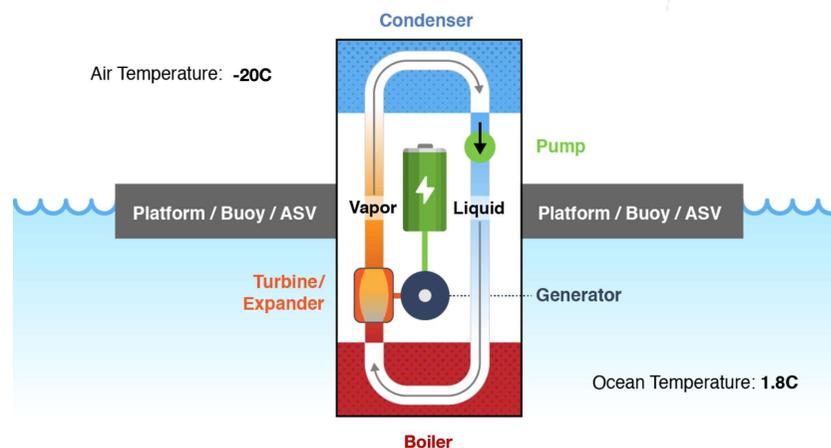
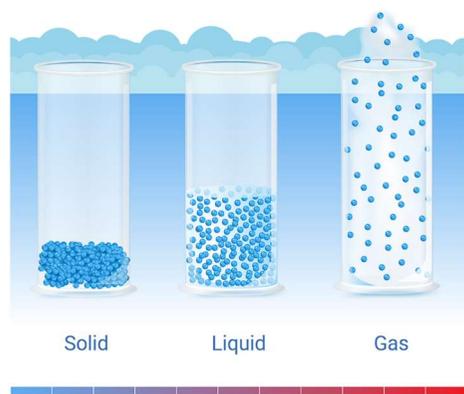


Harnessing energy from ocean thermal gradients



Seatrec's solution is based on technology from NASA's Jet Propulsion Laboratory and an idea first developed in 1989 by oceanographer Henry Stommel.

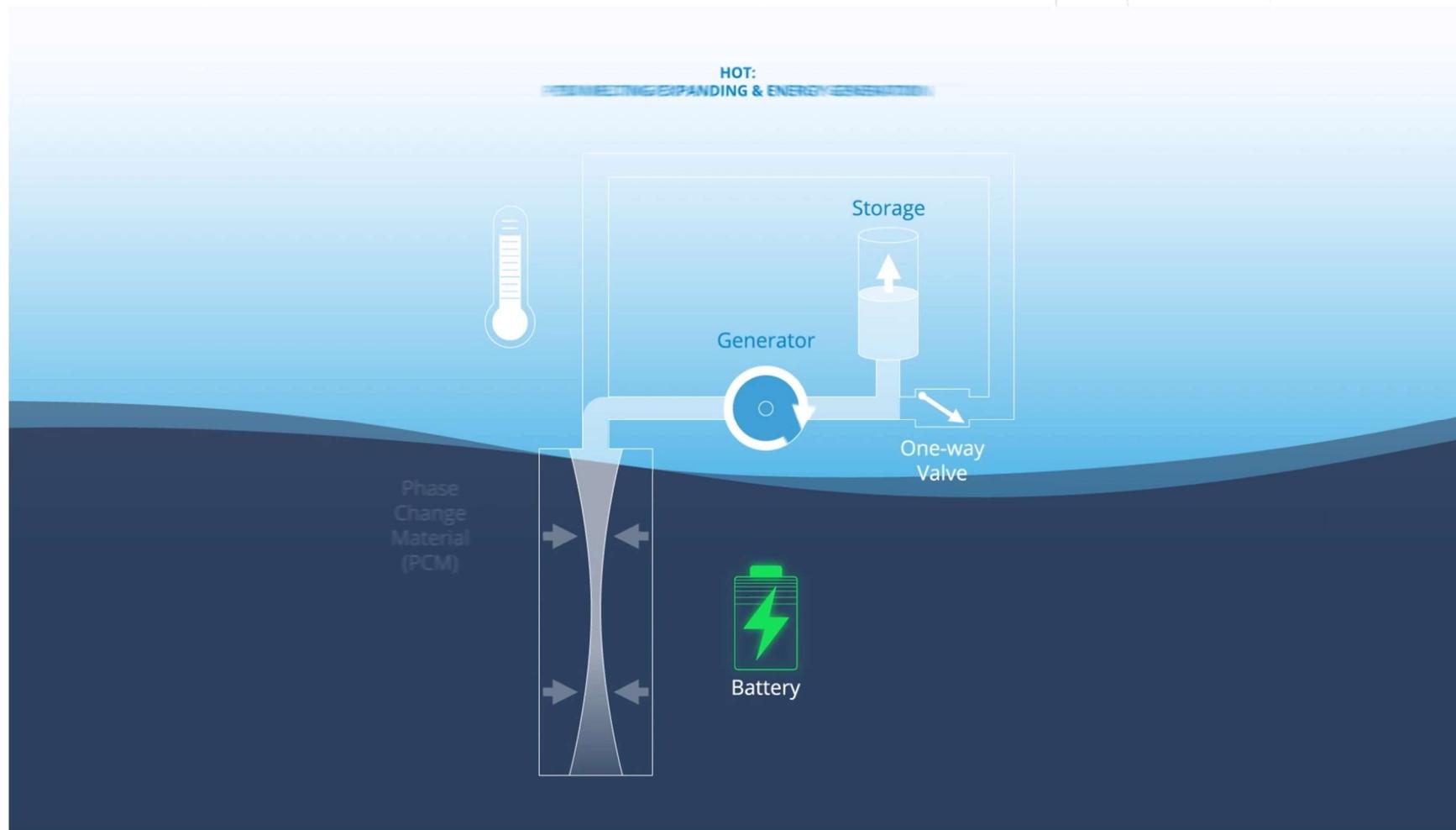
The idea is to take advantage of materials called "phase change materials." These change physical states when they are heated or cooled — think how water expands as it's heated.



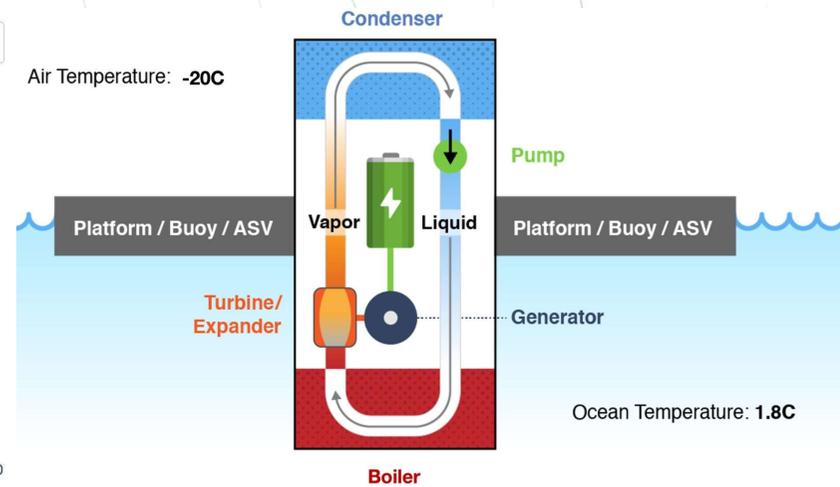
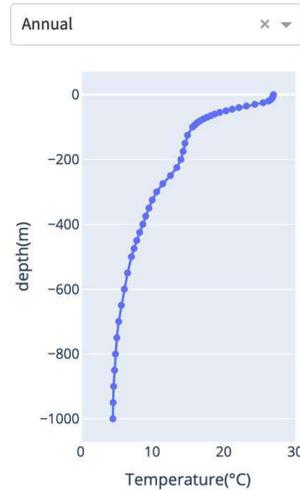
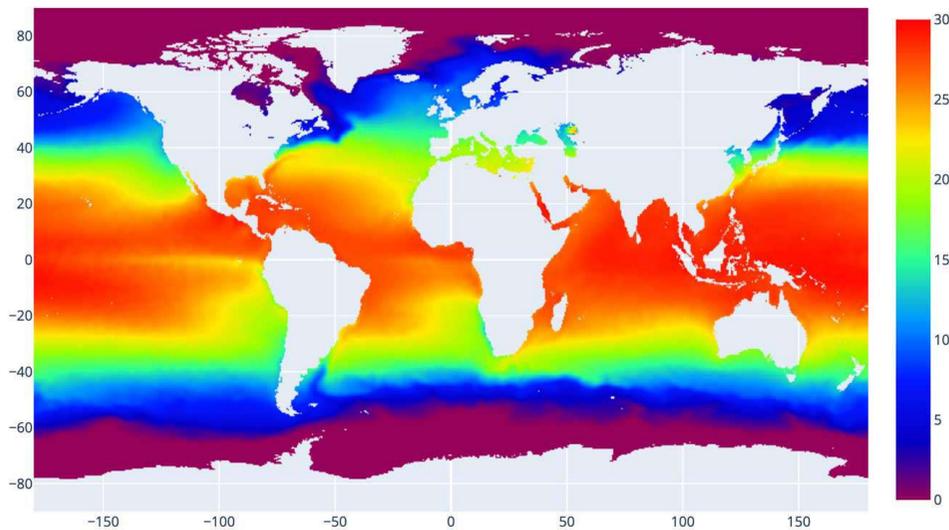
And JPL/Seatrec team filed a patent in 2011 to use PCMs to convert the energy associated with the temperature differential into electricity.

<https://youtu.be/QmDVzcD1aCc>

Harnessing energy from ocean thermal gradients



Thermal Gradients



Download csv

Future directions



Questions?



Quiz 5



Are You QRious?



<https://www.menti.com/al2pkzjuc8vg>

Offline quiz

What are some challenges associated with using underwater gliders?

Select all correct answers.

- a) Navigating under ice where satellite communication is not available
- b) Their inability to operate in dynamic conditions like boundary currents and extreme weather
- c) Potential biofouling on sensors during long missions
- d) Communication delays in remote or polar regions with limited satellite coverage
- e) High energy consumption limits mission duration to a few days with basic payload
- f) High operational costs because of the constant need for ship operation close-by

Offline quiz

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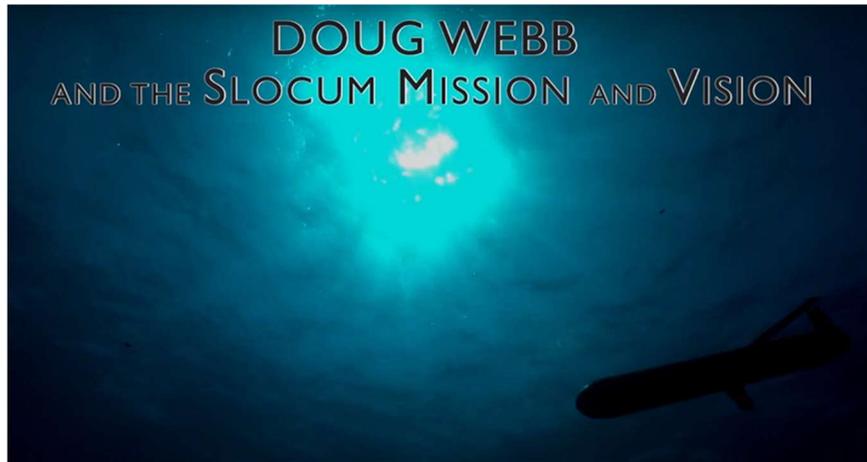
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There is no one-size-fits-all instrument for diverse scientific objectives

What advancements in technology will enable alternate methods of gathering data for the most remote areas of the ocean?

What technology being developed in the next 5-10 years will dominate the scientific community in the 2050s?

Take-home message



https://youtu.be/gd4_mMBvTaM?list=PL1cuUQt6PgLS9_7tAGS-r5xj8HXHF6SrS

Take-home message



ITINERIS



IR0000032 – ITINERIS, Italian Integrated Environmental Research Infrastructures System
(D.D. n. 130/2022 - CUP B53C22002150006) Funded by EU - Next Generation EU PNRR-
Mission 4 "Education and Research" - Component 2: "From research to business" - Investment
3.1: "Fund for the realisation of an integrated system of research and innovation infrastructures"

