

Climate & The Deep Blue Sea

Prof. Joellen L. Russell

*University Distinguished Professor
Geosciences, Planetary Science, Hydrology & Atmospheric Sciences and Applied Math*



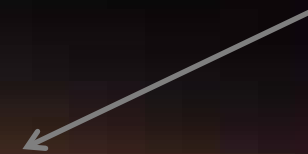
University of Arizona

*17 April 2025 – Rotary Club of Oro Valley,
Westward Look Wyndham Grand Resort, Tucson, AZ*



The Pale Blue Dot

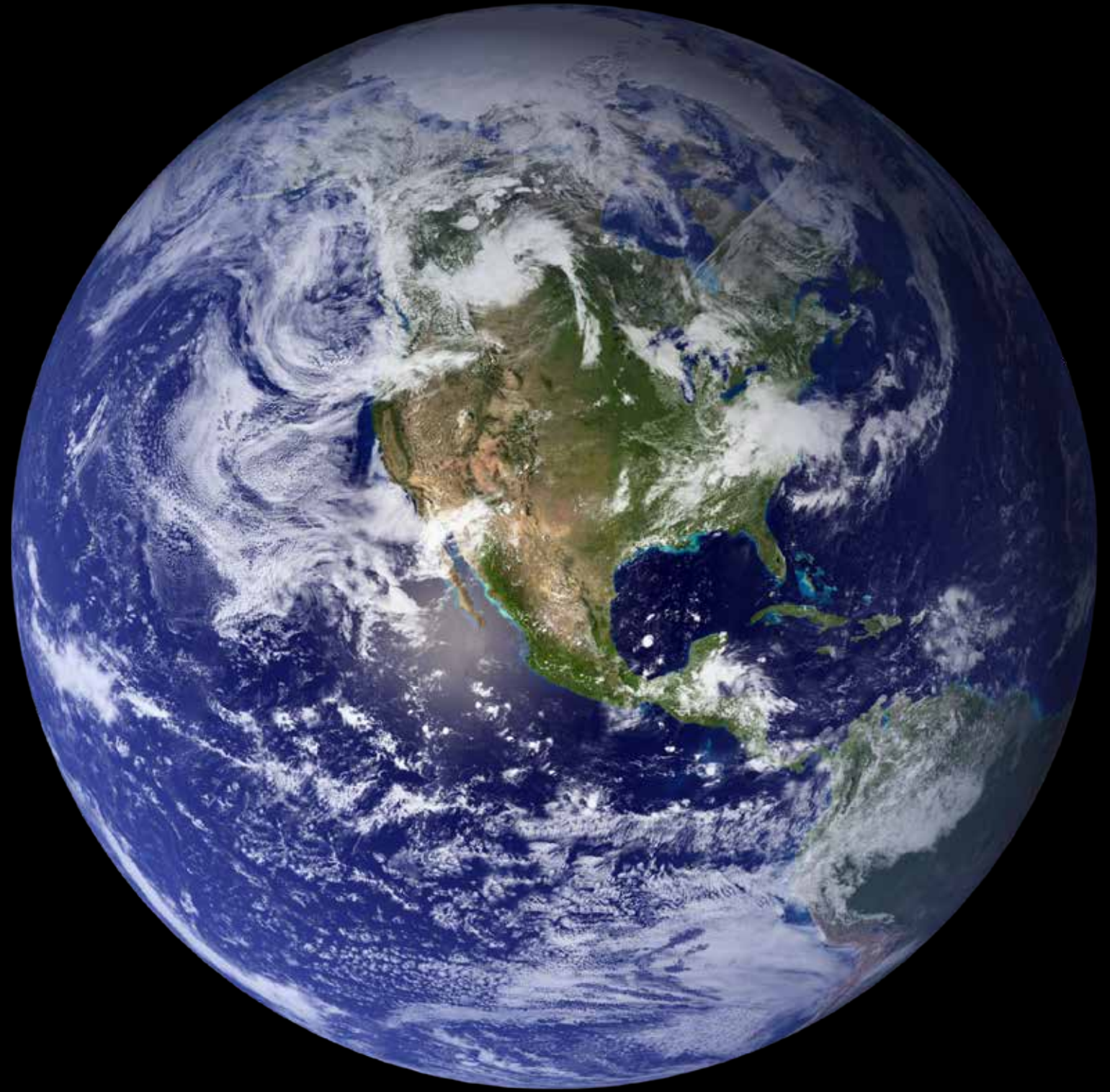
Earth as seen
from 4 billion
miles away.



“Like it or not, for the moment the Earth is where we make our stand.”
– Carl Sagan, *Pale Blue Dot*, 1994

Voyager 1 Image, February 14, 1990

Our Blue Planet



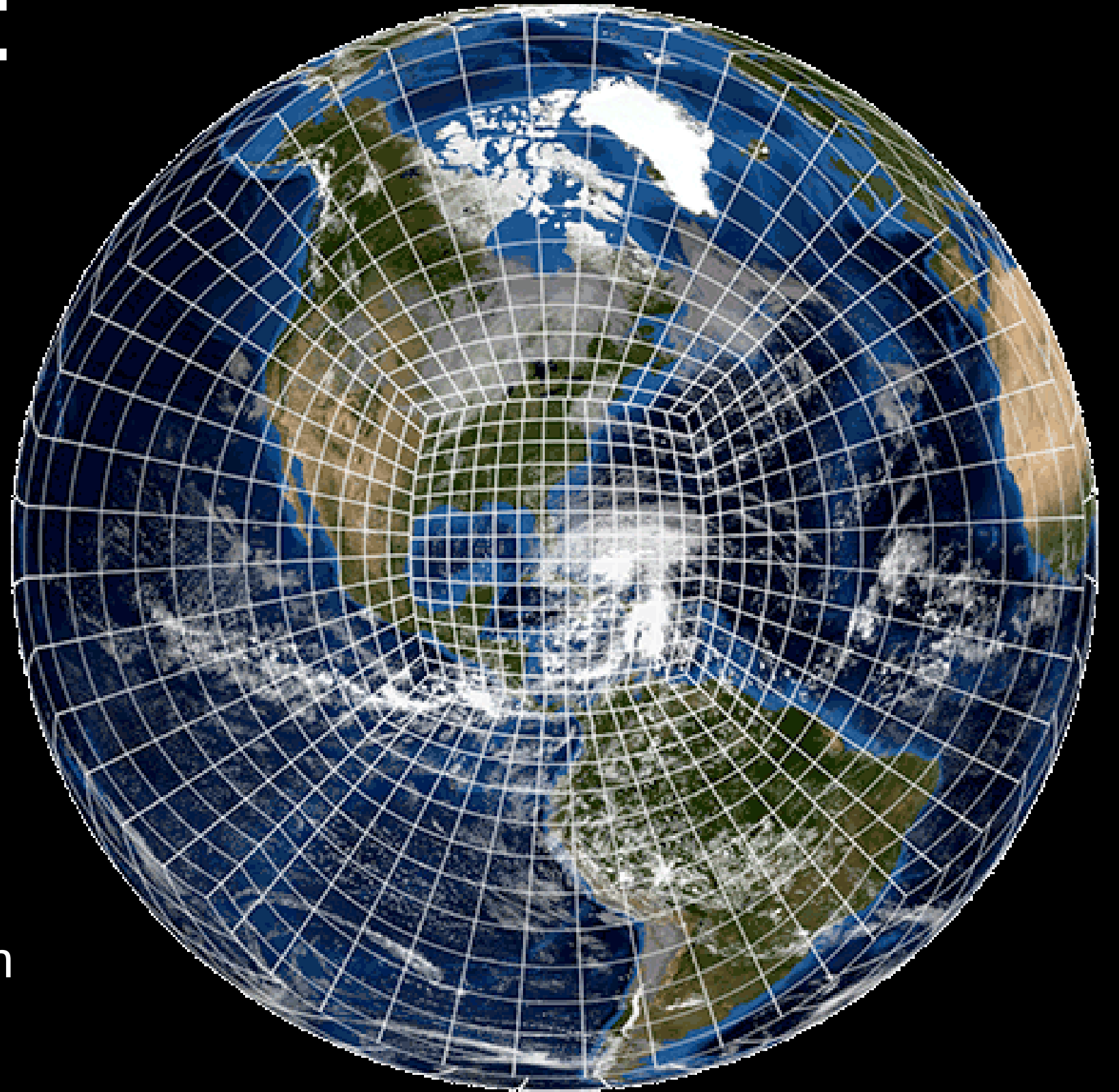
If you like your weather
forecast, thank an
oceanographer!



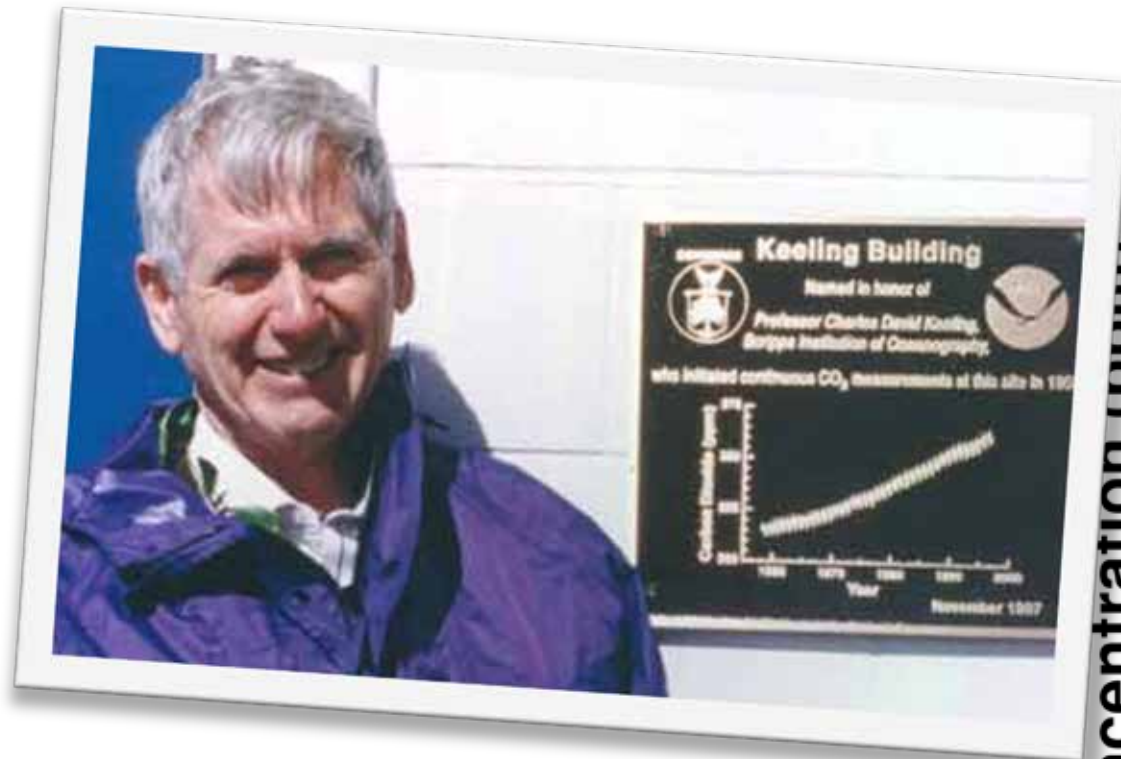
Advent of GFDL's FV3:

Convergence of Climate & Weather Modeling

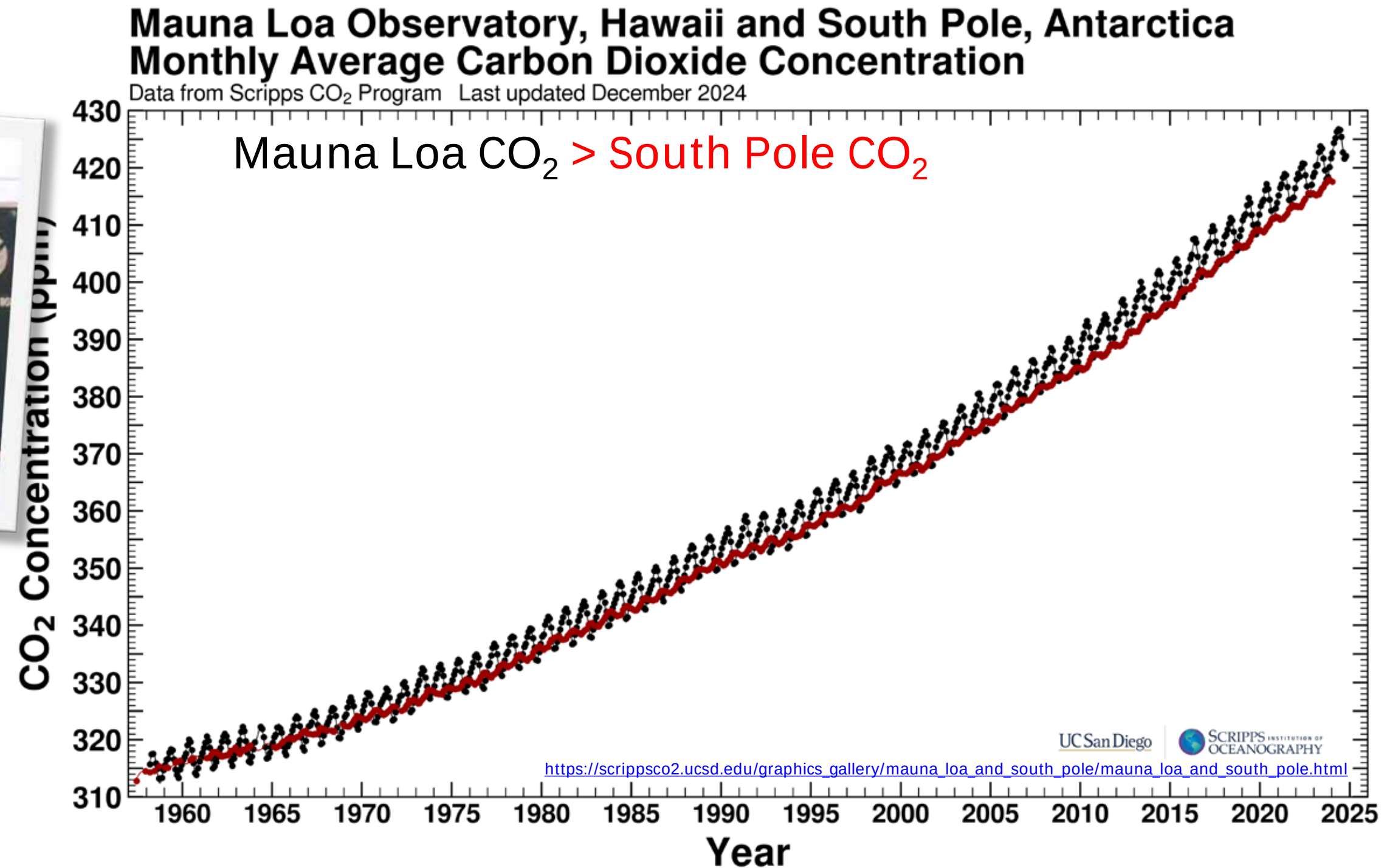
FV3 has been chosen as the dynamical core for the Next Generation Global Prediction System project (NGGPS), designed to upgrade the current operational Global Forecast System (GFS) to run as a unified, fully-coupled system in NOAA's Environmental Modeling System infrastructure.



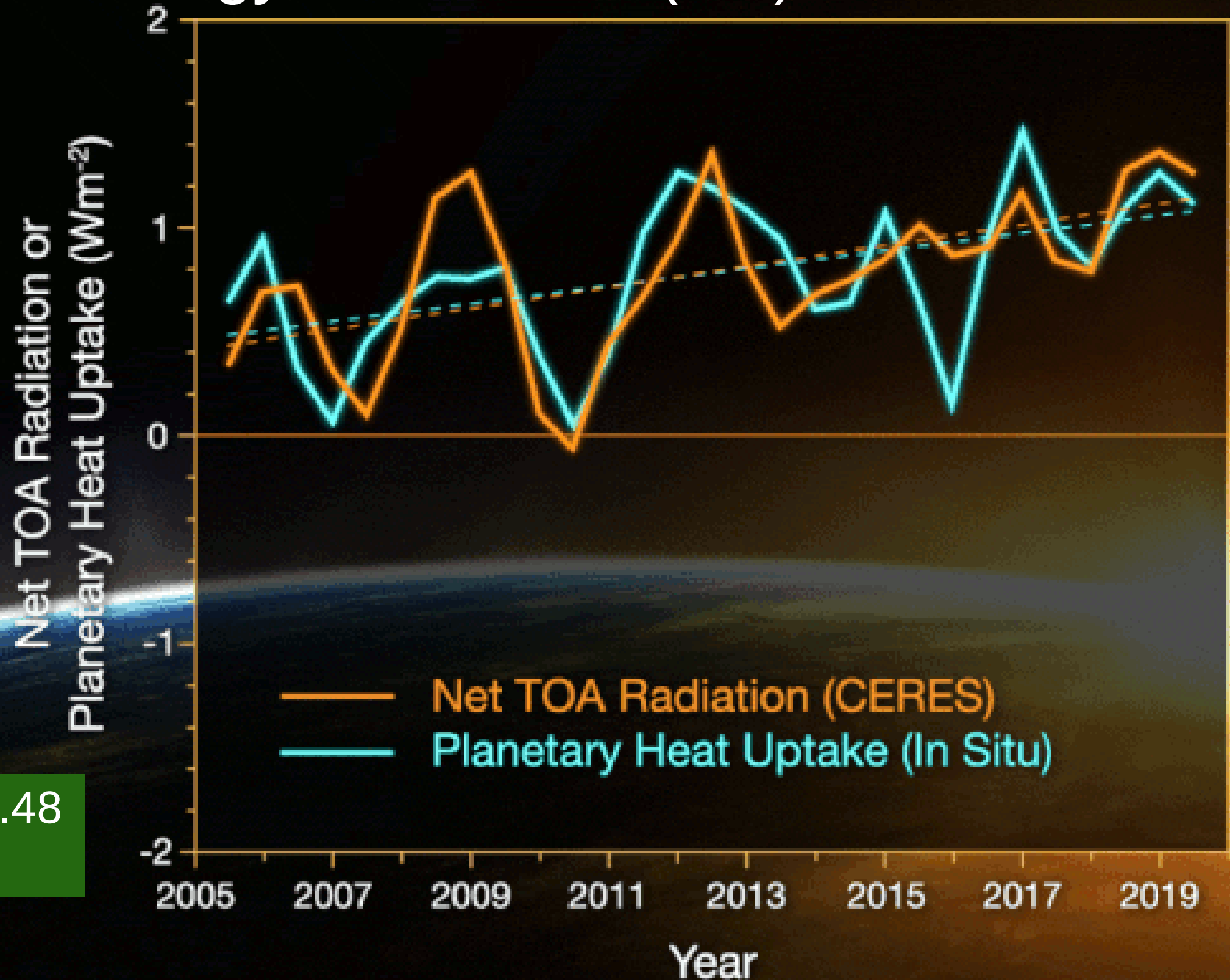
The Keeling Curve: Atmospheric CO₂ (Dec '24)



Charles David Keeling
(1928-2005)



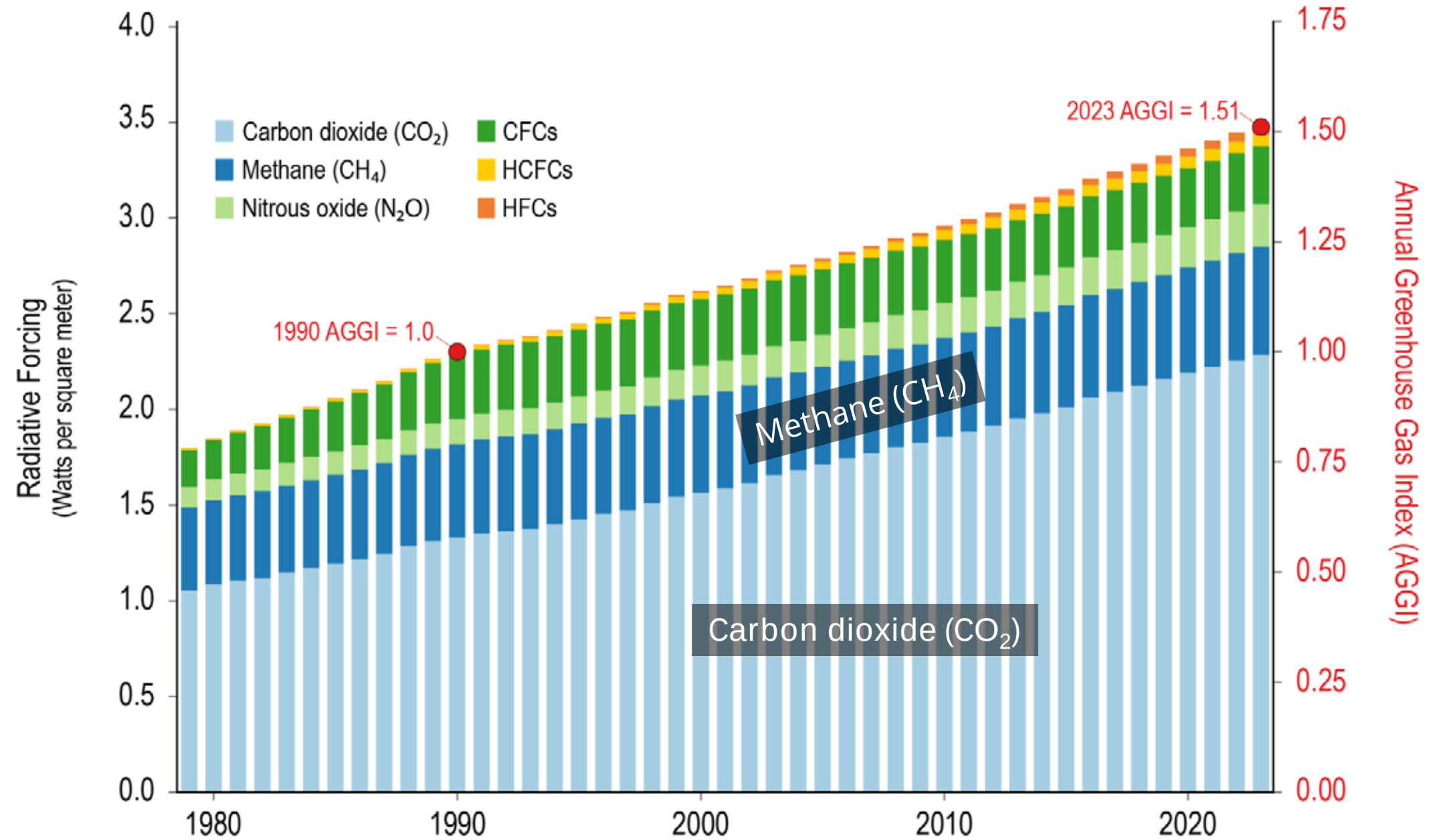
Earth's net energy imbalance (EEI) has more than DOUBLED



EEI = 0.42 ± 0.48
 Wm

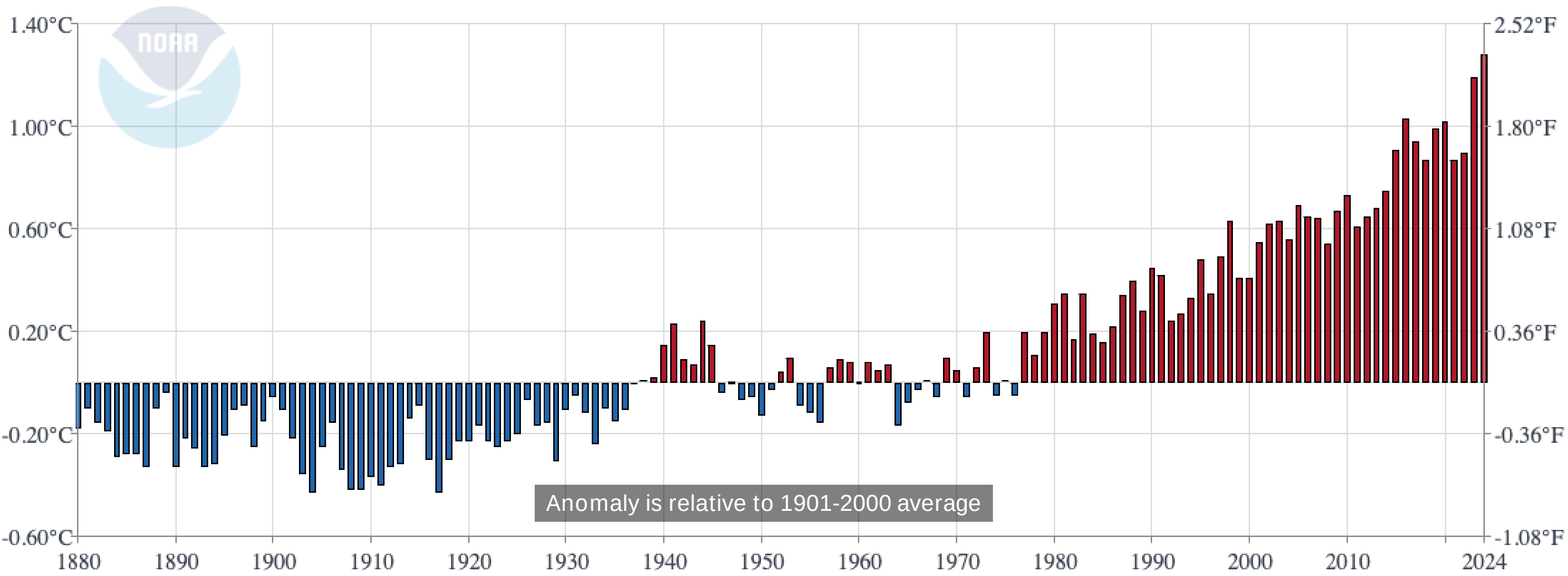


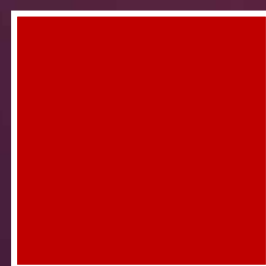
Annual Greenhouse Gas Index



Global Atmospheric Temperature Anomalies

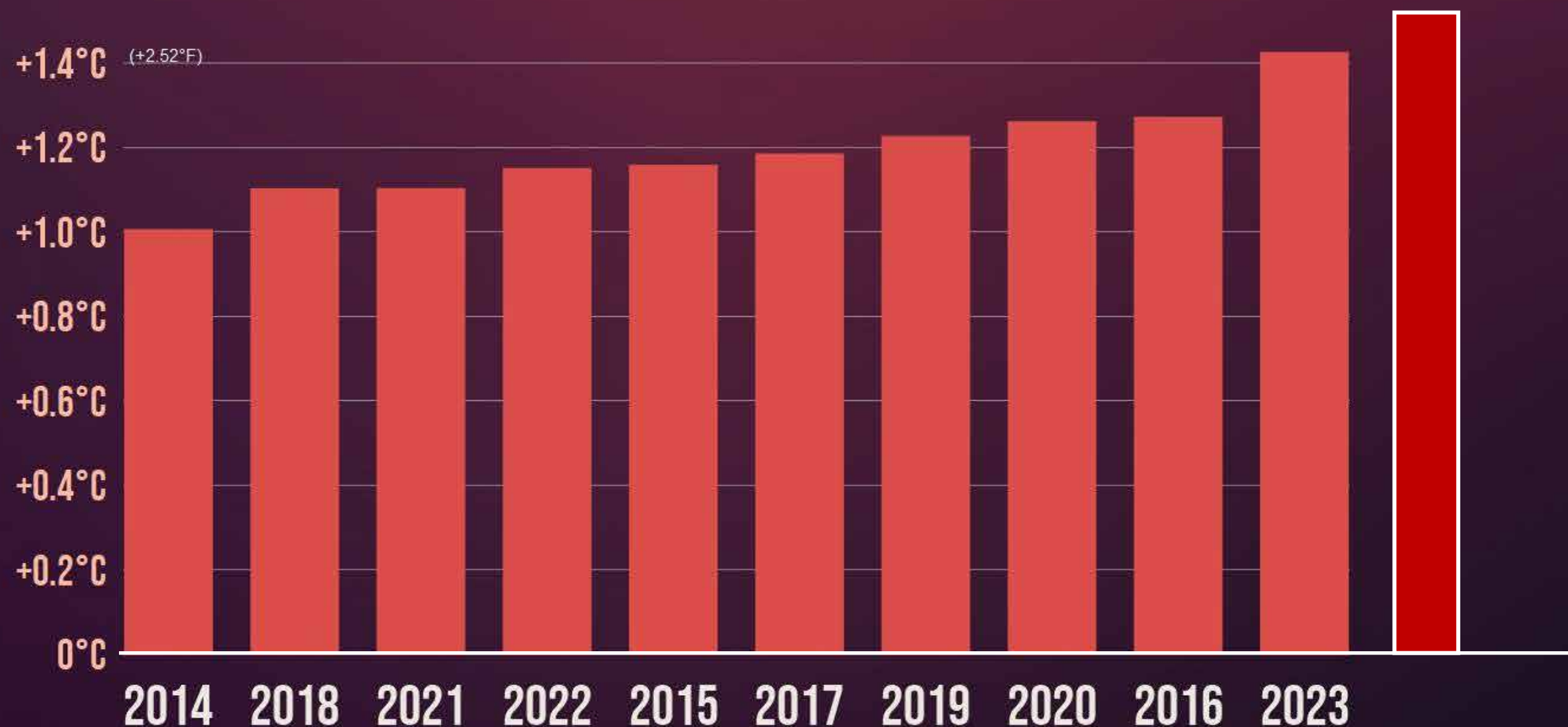
Global Land and Ocean Average Temperature Anomalies
January-December





HOTTEST GLOBAL YEARS ON RECORD

2024 was 1.52°C above
1881-1910 baseline



Global temperature anomalies (°C) averaged and adjusted to early industrial baseline (1881-1910).

Data as of 1/12/2024.

Source: NASA GISS & NOAA NCEI

CLIMATE  CENTRAL

2024: Hottest year ever; last 11 years are the 11 hottest!

America's 10 Fastest-Warming States

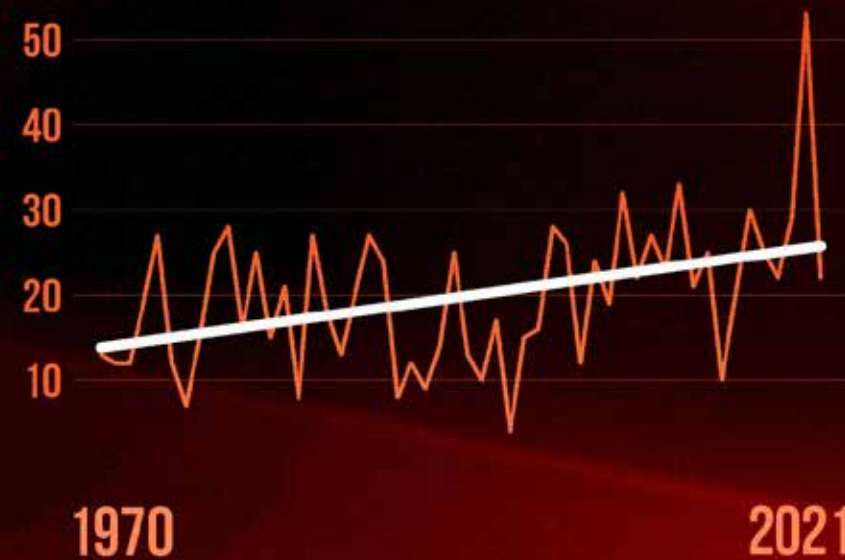
State	Temperature Change (1970-2018)	State	Temperature Change (1970-2018)
1. Alaska	4.22°	6. New Jersey	3.00°
2. New Mexico	3.32°	7. Colorado	2.90°
3. Arizona	3.23°	8. Vermont	2.85°
4. Delaware	3.15°	9. Rhode Island	2.84°
5. Utah	3.02°	10. Connecticut	2.84°

America's 20 Fastest-Warming Cities

City	Temperature Change (1970-2018)	City	Temperature Change (1970-2018)
1. Las Vegas, NV	5.76°	11. Ft. Smith, AR	3.92°
2. El Paso, TX	4.74°	12. St. Louis, MO	3.85°
3. Tucson, AZ	4.48°	13. Boise, ID	3.84°
4. Phoenix, AZ	4.35°	14. Minneapolis, MN	3.72°
5. Burlington, VT	4.13°	15. Milwaukee, WI	3.70°
6. Chattanooga, TN	4.11°	16. Duluth, MN	3.67°
7. Helena, MT	4.11°	17. Fresno, CA	3.66°
8. Erie, PA	4.06°	18. Odessa, TX	3.59°
9. McAllen, TX	4.03°	19. Houston, TX	3.58°
10. Las Cruces, NM	4.01°	20. Medford, OR	3.51°

Reno, NV excluded. See methodology.

PHOENIX DAYS ABOVE 110°

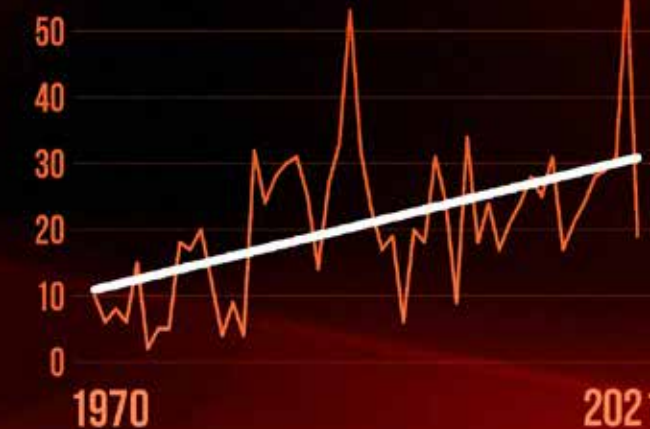


**+12
DAYS**

Change in days above 110°F based on rate of change since 1970.
Source: RCC-ACIS.org

CLIMATE  CENTRAL

TUCSON DAYS ABOVE 105°

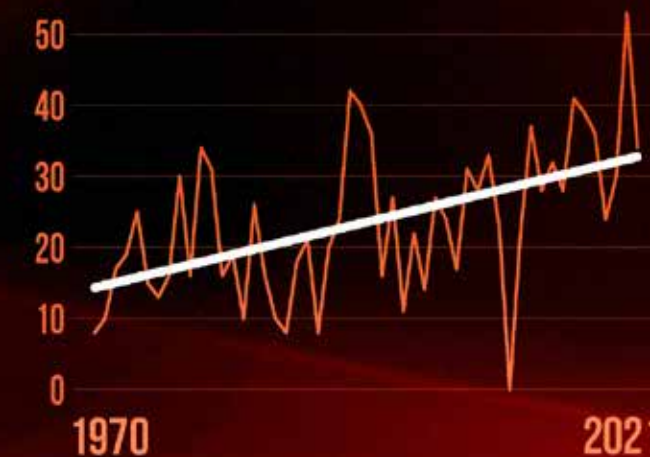


**+20
DAYS**

Change in days above 105°F based on rate of change since 1970.
Source: RCC-ACIS.org

CLIMATE  CENTRAL

YUMA • EL CENTRO DAYS ABOVE 110°

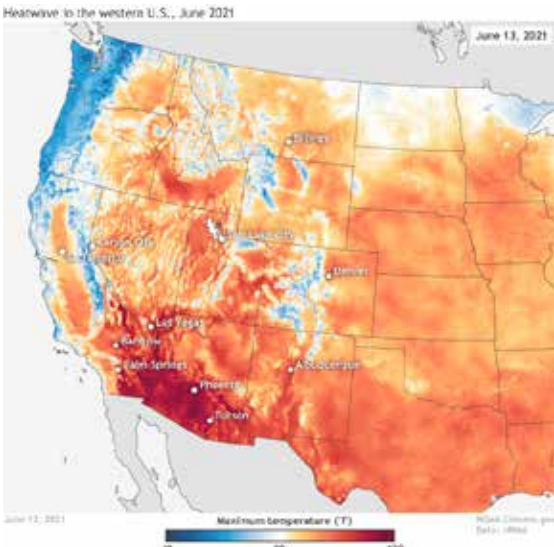
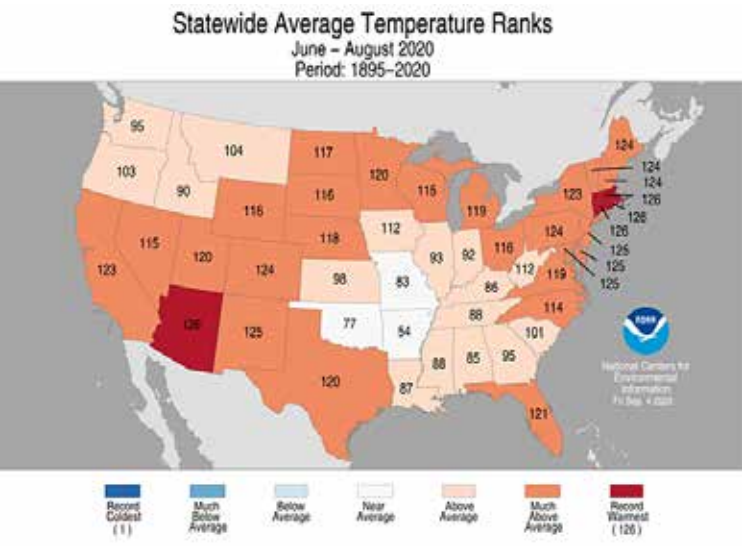
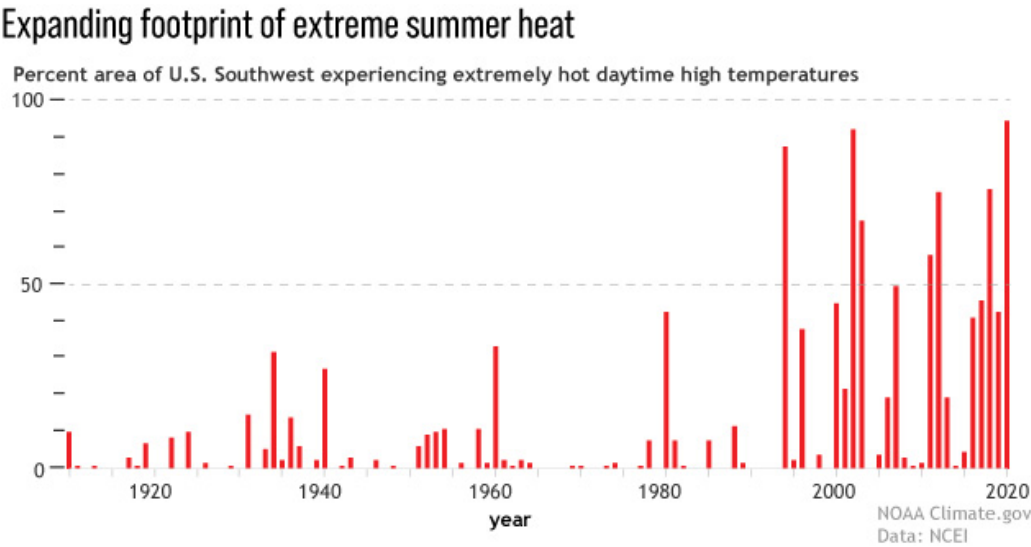


**+19
DAYS**

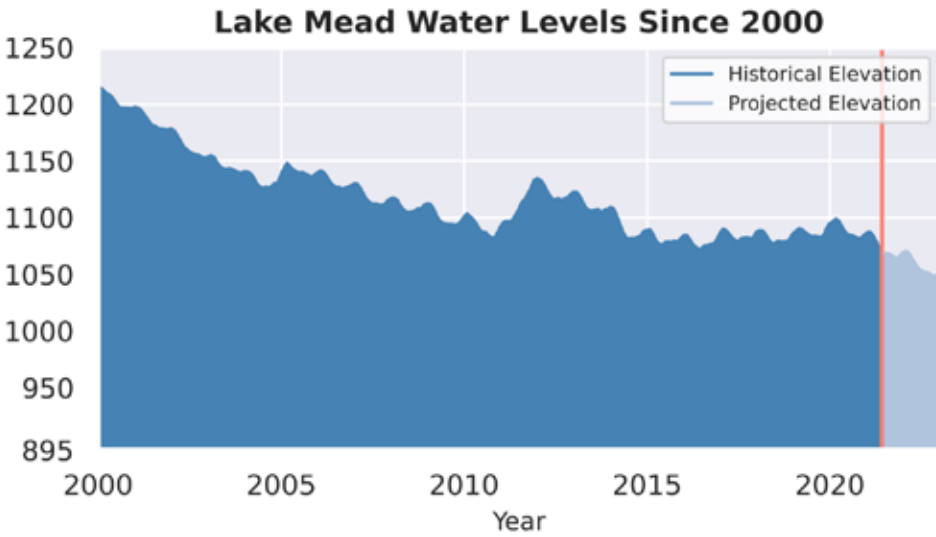
Change in days above 110°F based on rate of change since 1970.
Source: RCC-ACIS.org

CLIMATE  CENTRAL

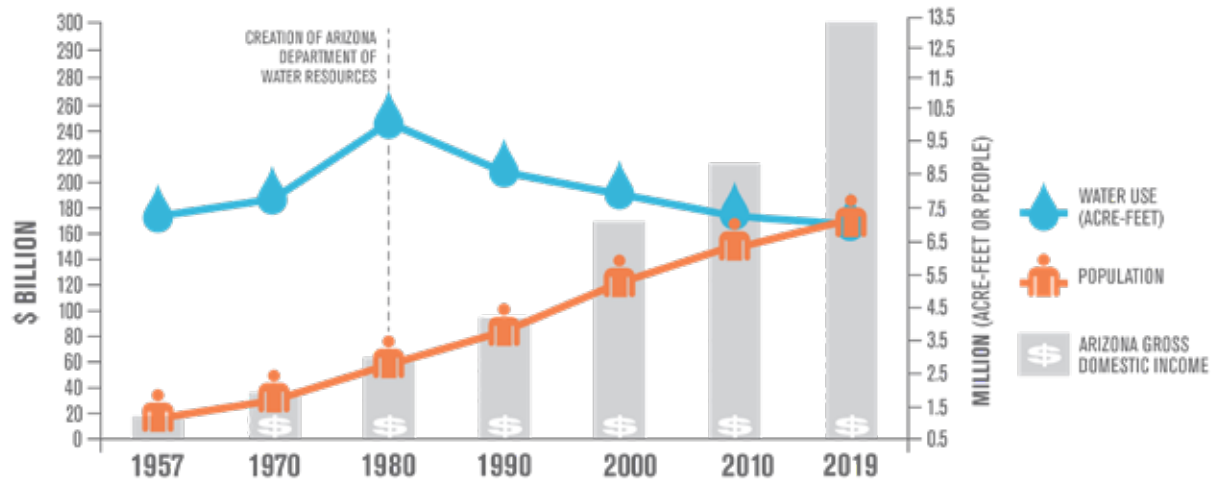
1. Heat waves



2. Drought

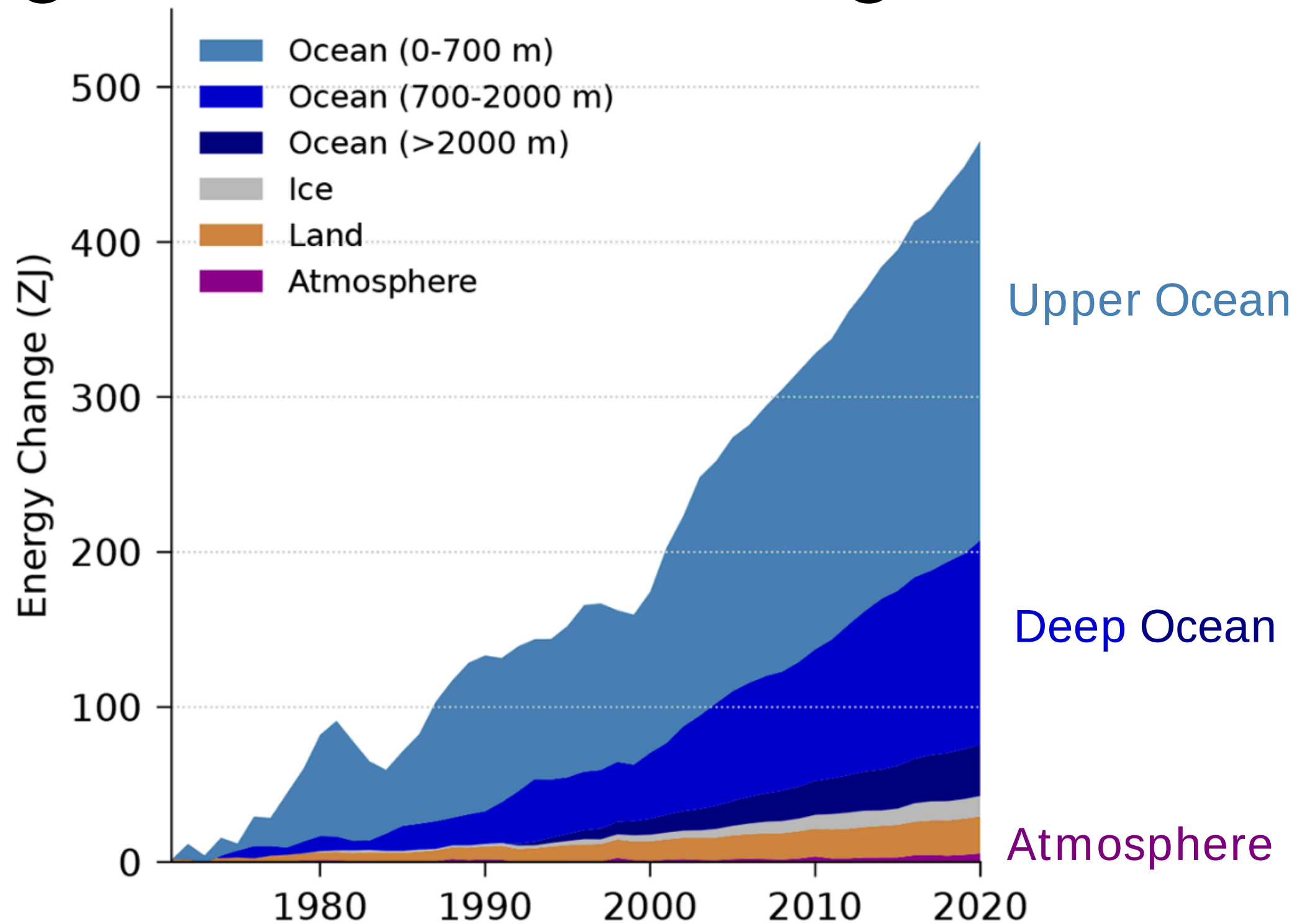


4. High-tech jobs in climate observations and prediction science



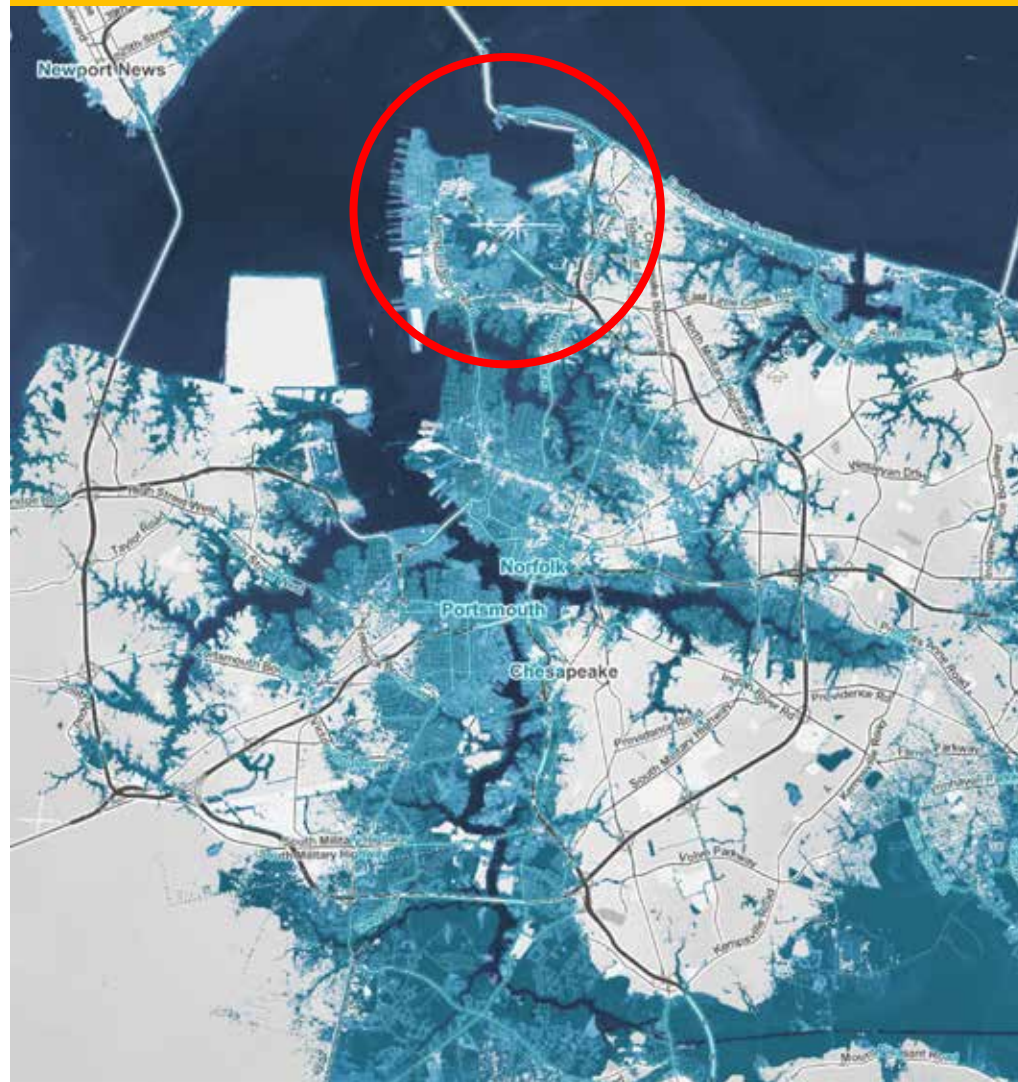
Global warming is ocean warming!

Observed changes in the Earth heat inventory for the period 1971–2020

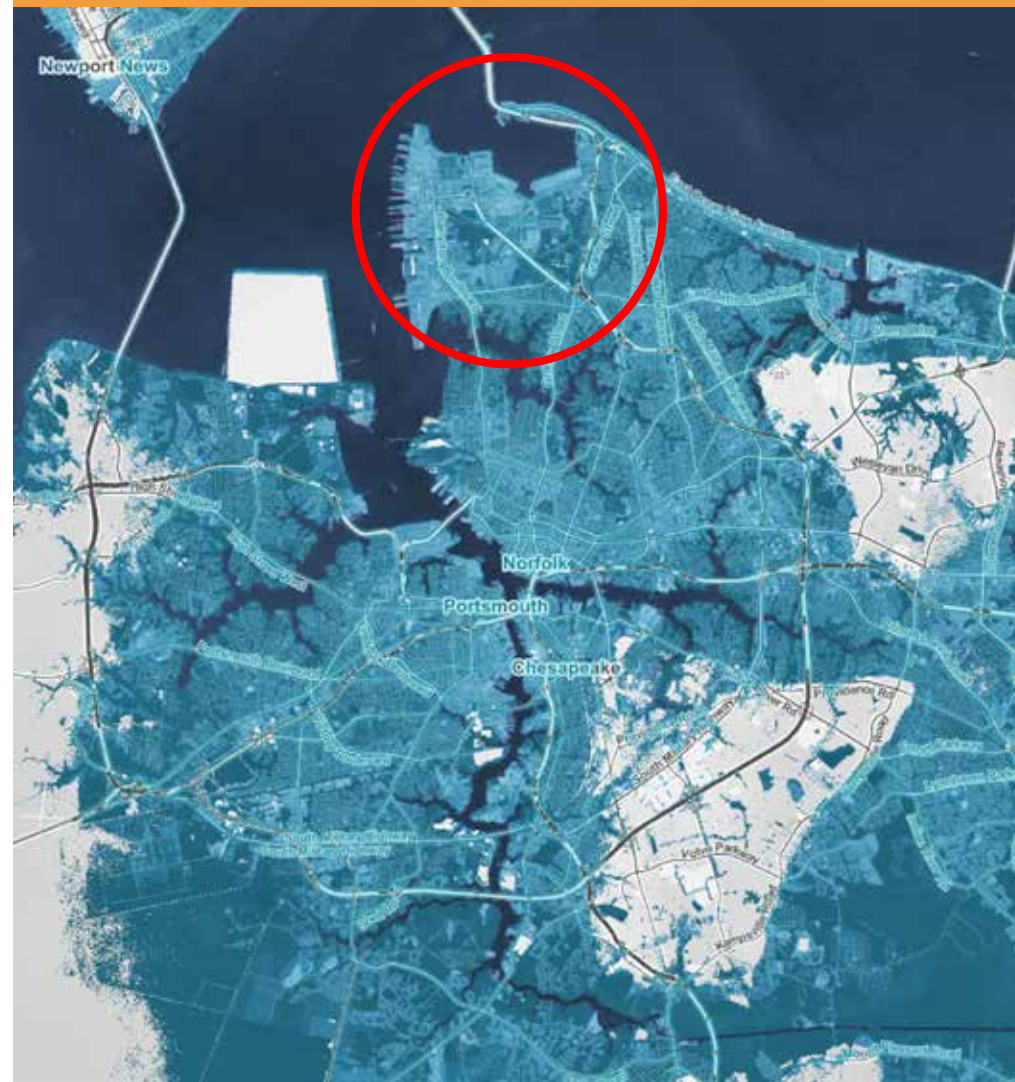


Sea level is rising – big changes are already locked in (e.g. Norfolk)

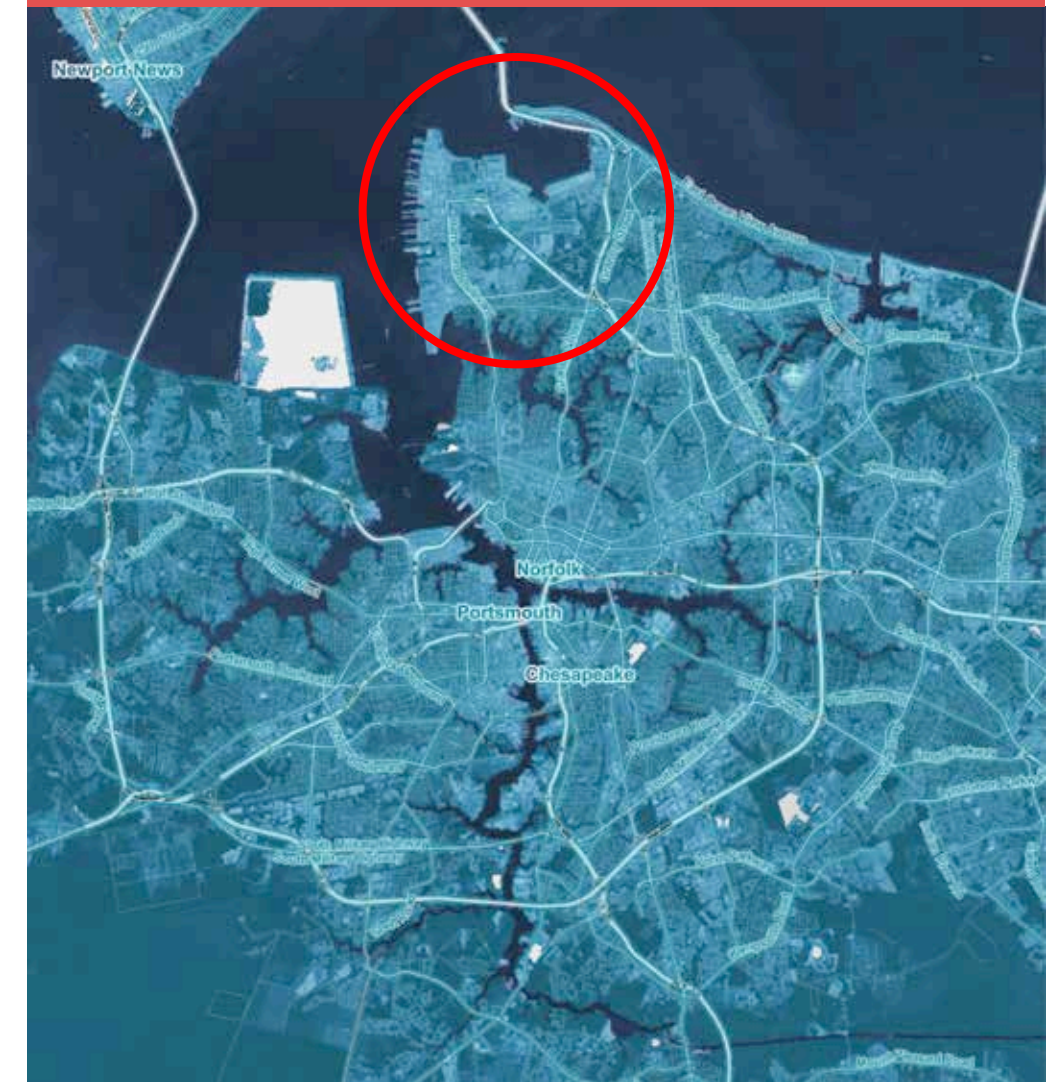
After 1.5°C Warming



After 2°C Warming

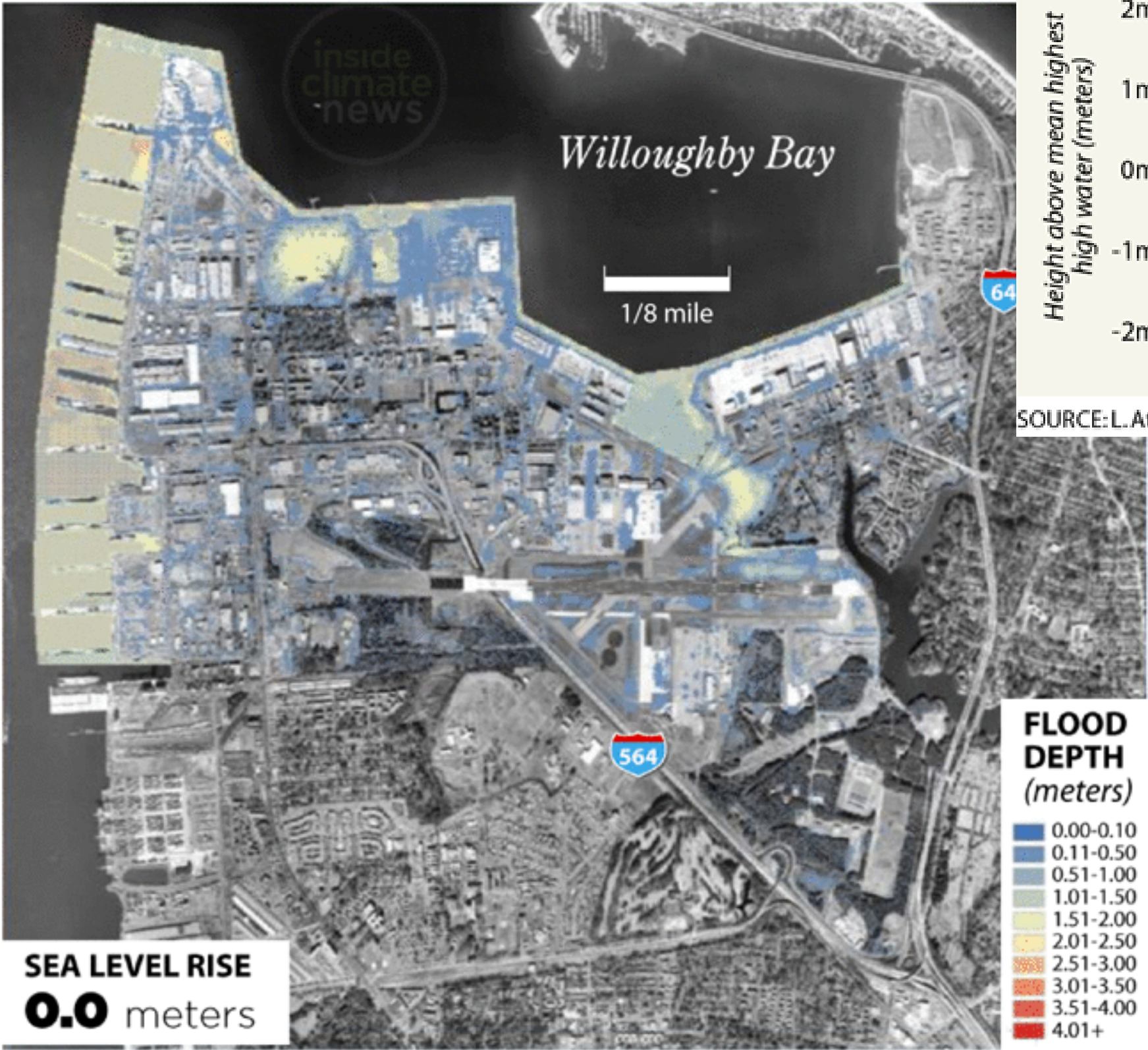


After 4°C Warming



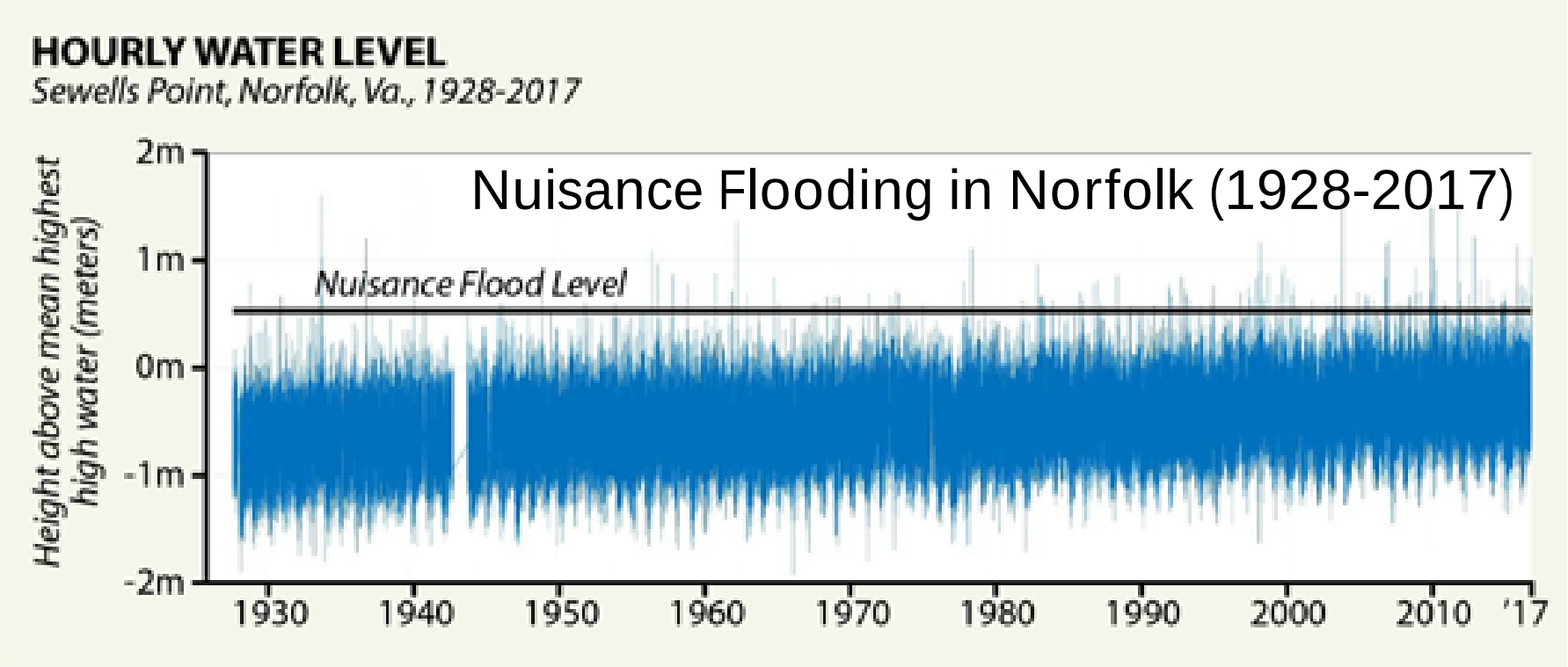
How Rising Seas Will Affect Norfolk Base

This animation shows the flooding that's likely to occur at Naval Station Norfolk, at current and higher sea levels, during the type of storm that hits on average once a year.



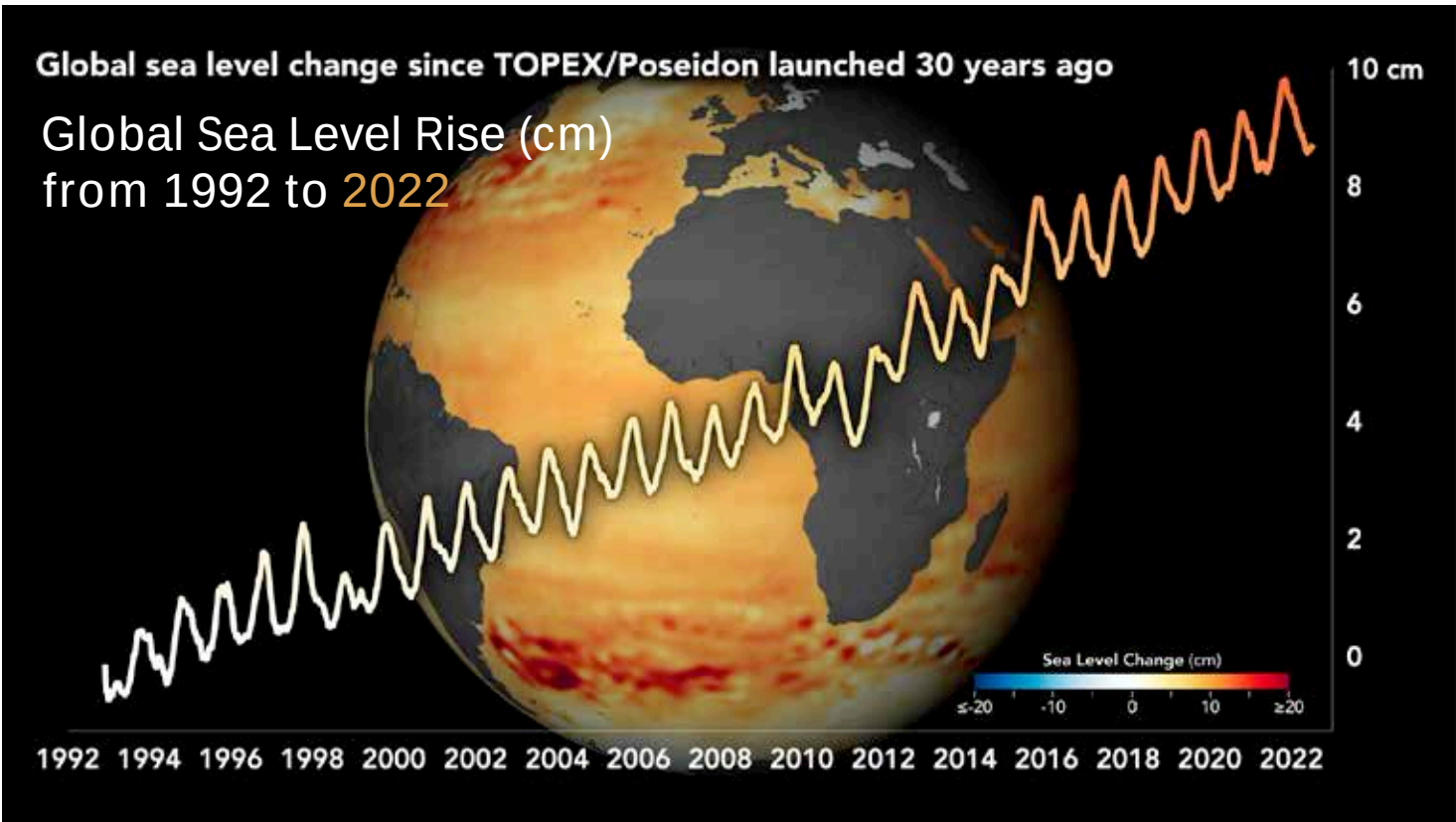
SOURCE: U.S. Army Engineer Research and Development Center

PAUL HORN / InsideClimate News



SOURCE: L. Atkinson ODU

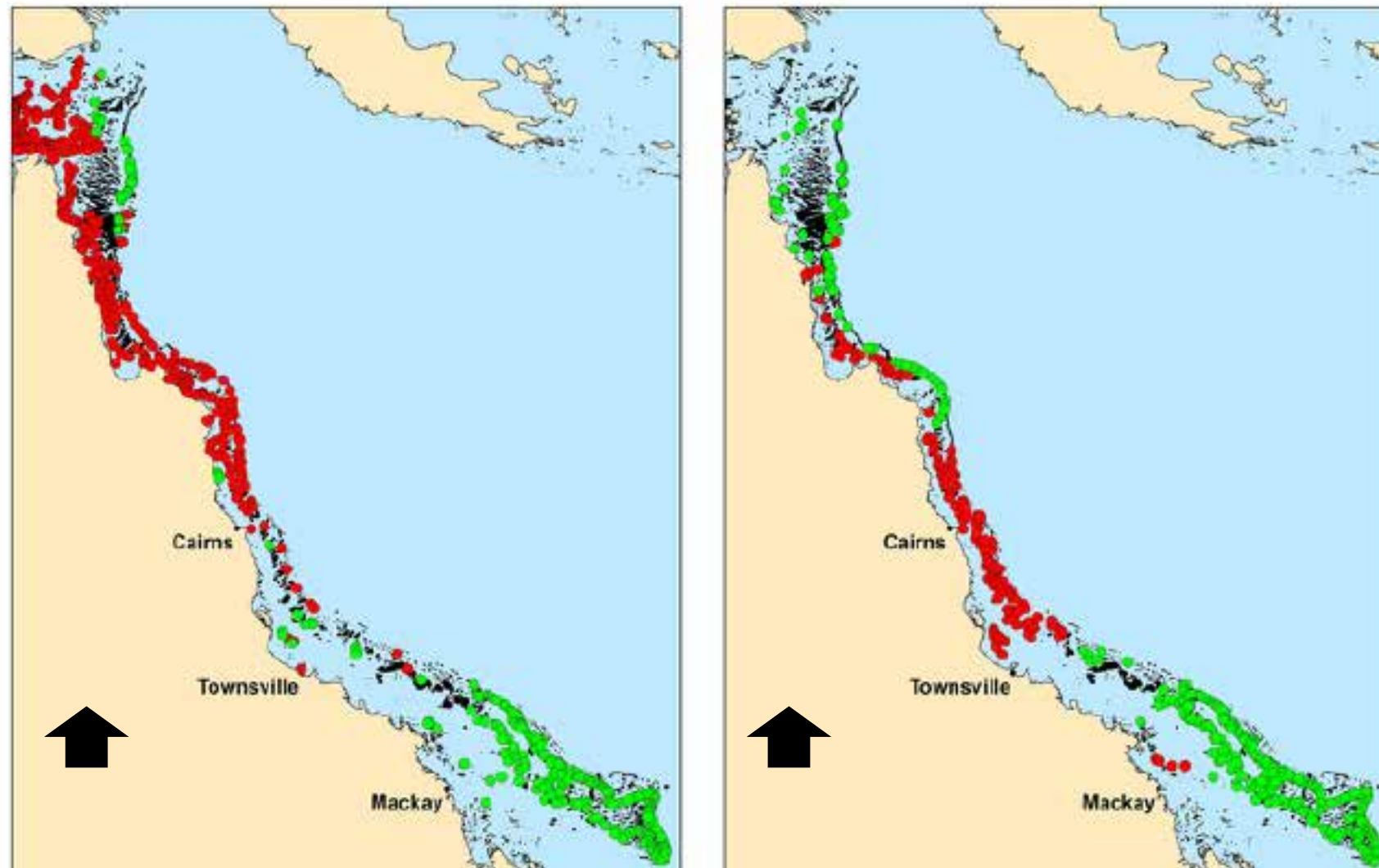
InsideClimate News



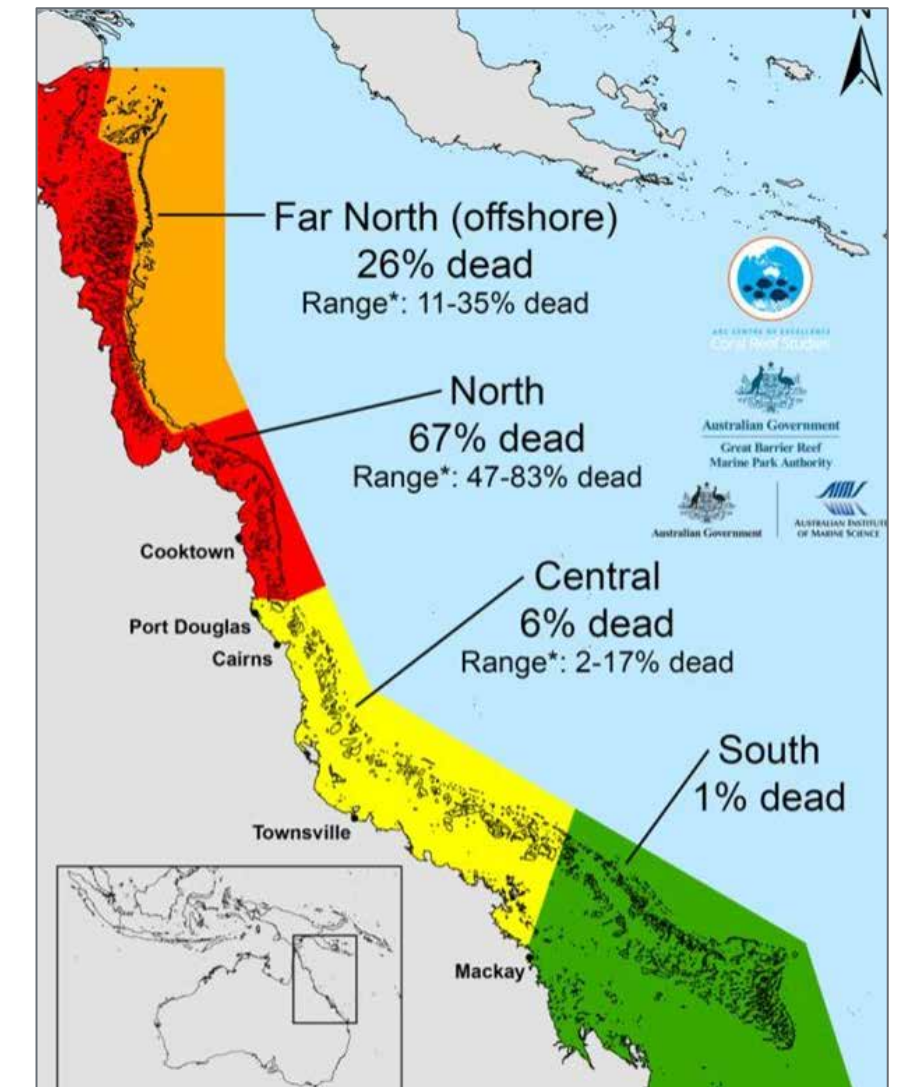
Major bleaching events on the Great Barrier Reef



ARC CENTRE OF EXCELLENCE
Coral Reef Studies



- Severe Bleaching
- No or Negligible Bleaching



Coral Mortality

Global Shipping (June 1-15, 2012)

<https://www.shipmap.org>

Averages:

Containers (yellow, 14.3M)

Dry goods (blue, 0.5M kt)

Liquids (red, 0.4M kt)

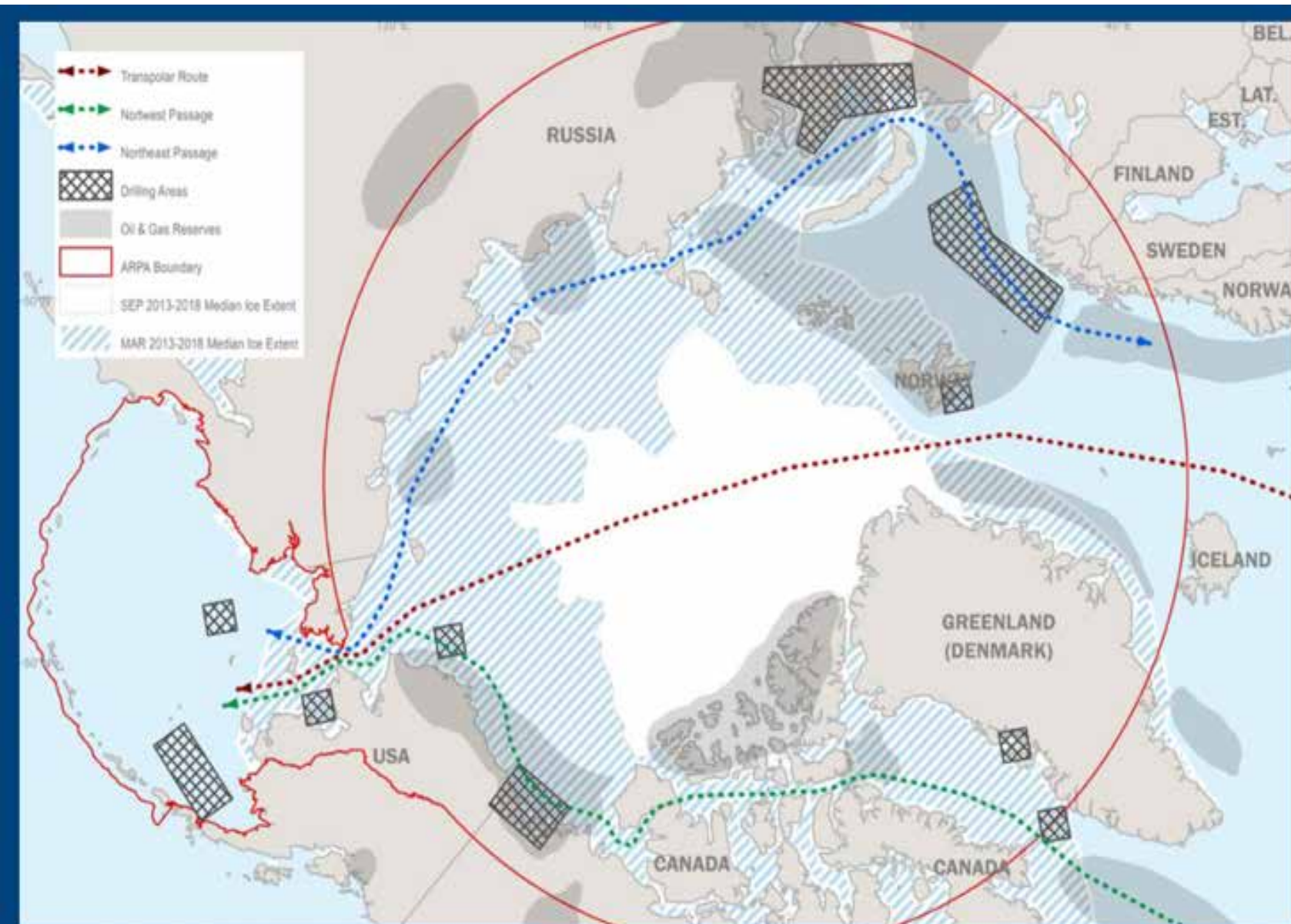
Gas (green, 62M m³)

Vehicles (pink, 10M)

CO₂ emissions - ~150 kt

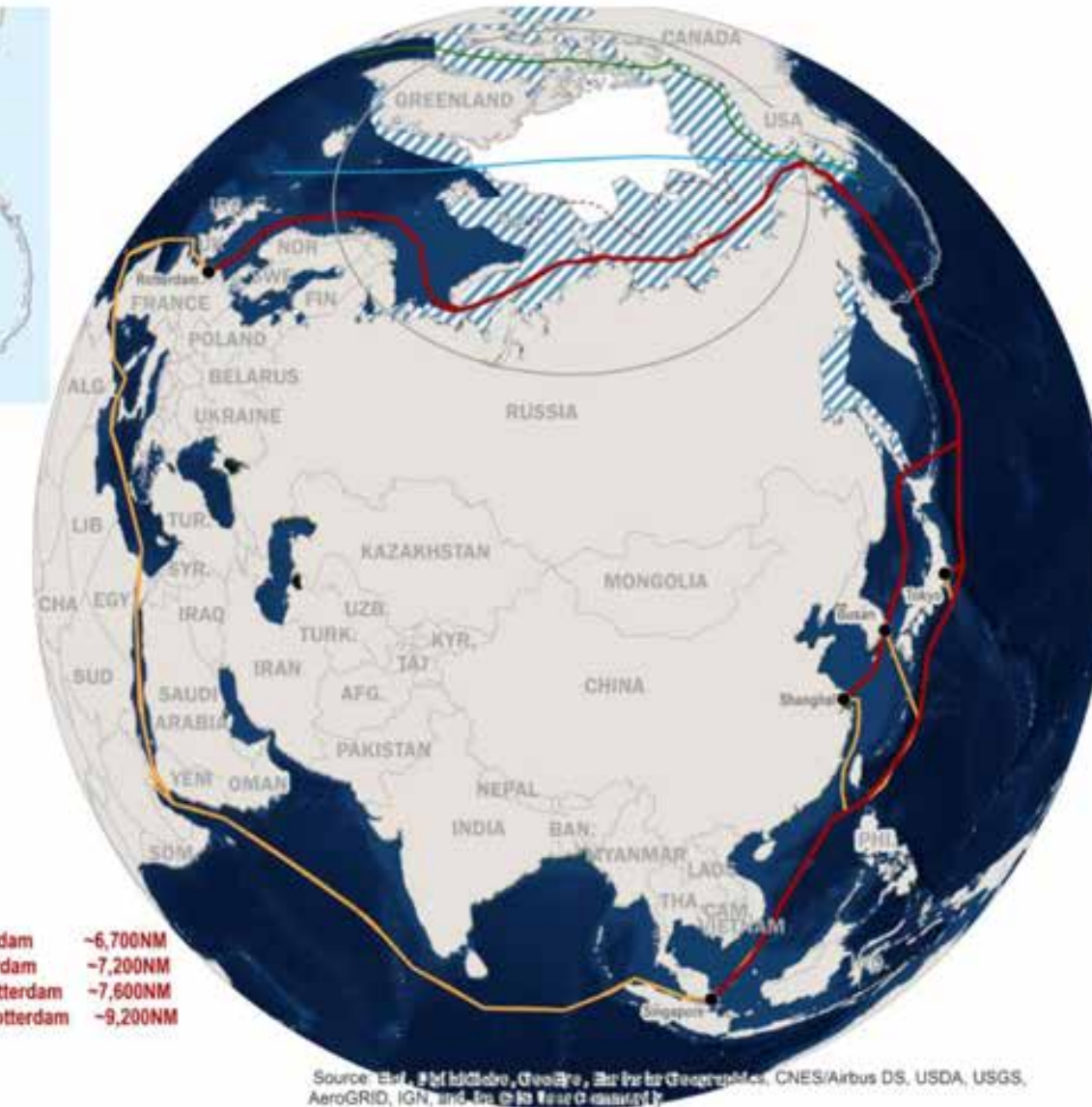


Shipping through an ice-free Arctic saves 1000's of miles, but requires sea ice prediction



Suez Canal Routes:		NSR Routes:	
Tokyo to Rotterdam	~9,500NM	Tokyo to Rotterdam	~6,700NM
Busan to Rotterdam	~9,100NM	Busan to Rotterdam	~7,200NM
Shanghai to Rotterdam	~8,600NM	Shanghai to Rotterdam	~7,600NM
Singapore to Rotterdam	~6,900NM	Singapore to Rotterdam	~9,200NM

Note: Route distances are approximated not exact.



Collapse of Bering Snow Crab Fishery

MARINE HEATWAVES

The collapse of eastern Bering Sea snow crab

Cody S. Szuwalski^{1*}, Kerim Aydin¹, Erin J. Fedewa², Brian Garber-Yonts¹, Michael A. Litzow²

The snow crab is an iconic species in the Bering Sea that supports an economically important fishery and undergoes extensive monitoring and management. Since 2018, more than 10 billion snow crab have disappeared from the eastern Bering Sea, and the population collapsed to historical lows in 2021. We link this collapse to a marine heatwave in the eastern Bering Sea during 2018 and 2019. Calculated caloric requirements, reduced spatial distribution, and observed body conditions suggest that starvation played a role in the collapse. The mortality event appears to be one of the largest reported losses of motile marine macrofauna to marine heatwaves globally.

Division of Commercial Fisheries
Sam Rabung, Director

Dutch Harbor Area Office
PO Box 920587
Dutch Harbor, AK 99692

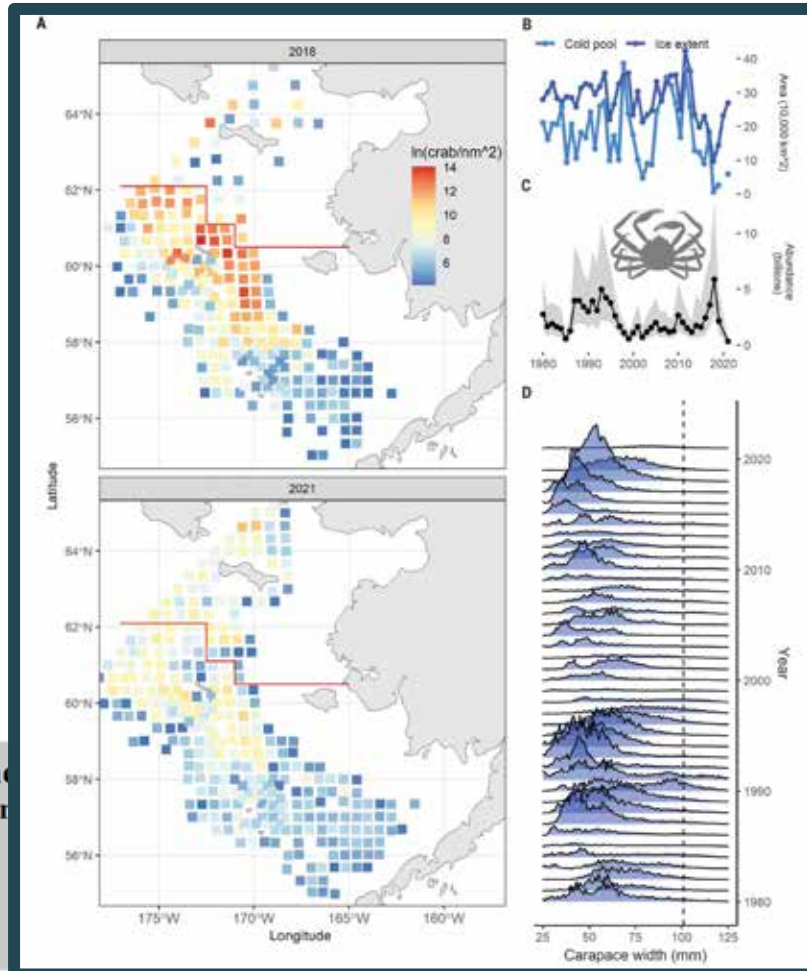


Alaska Department of Fish and Game
Doug Vincen

Advisory Announcement
For Immediate Release: 10/6/2023

2023/24 Bering Sea Snow Crab Season Closed

The Alaska Department of Fish and Game (ADF&G) and National Marine Fisheries Service (NMFS) have completed analysis of 2023 NMFS trawl survey results for Bering Sea snow crab. The stock is estimated to be below the ADF&G regulatory threshold for opening a fishery. Therefore, Bering Sea snow crab will remain closed for the 2023/24 season.



CONTACT:
Ethan Nichols, Acting Area Management Biologist
907-581-1239



Trust but verify: Carbon Accounting



Massachusetts v. EPA (2007)

“The Clean Air Act’s sweeping definition of “air pollutant” includes “air pollution agent or combination of such agents, including any physical, chemical, or biological substance or matter which is emitted into or otherwise enters the ambient air.” § 7602(g) (emphasis added). ... [is] without a doubt “physical [and] chemical substance[s] which [are] emitted into the ambient air.”

”

.

Stevens

Kennedy

Thomas

Breyer

Roberts

Scalia

Souter

Ginsburg

Alito

No. 05-1120

In the Supreme Court of the United States

COMMONWEALTH OF MASSACHUSETTS, *et al.*,
Petitioners,

v.

U.S. ENVIRONMENTAL PROTECTION AGENCY, *et al.*,
Respondents.

On Petition of Writ of Certiorari to the
United States Court of Appeals
for the District of Columbia Circuit

BRIEF OF *AMICI CURIAE* CLIMATE SCIENTISTS
DAVID BATTISTI, CHRISTOPHER FIELD, INEZ
FUNG, JAMES E. HANSEN, JOHN HARTE, EUGENIA
KALNAY, DANIEL KIRK-DAVIDOFF, JAMES C.
MCWILLIAMS, JONATHAN T. OVERPECK, F.
SHERWOOD ROWLAND, JOELLEN RUSSELL,
SCOTT R. SALESKA, JOHN M. WALLACE, AND
STEVEN C. WOFSY
IN SUPPORT OF PETITIONER

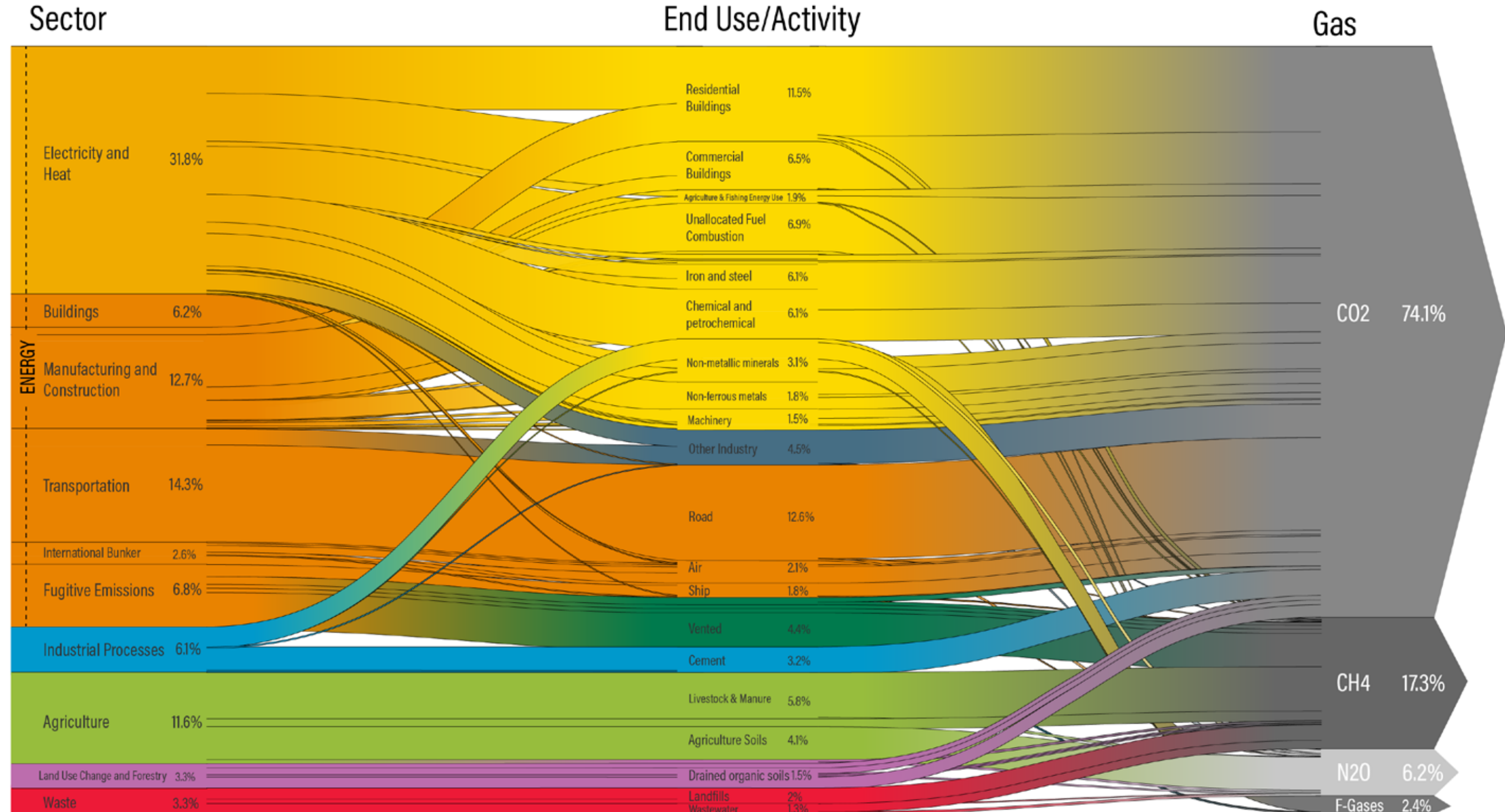
JOHN C. DERNBACH
WIDENER UNIVERSITY
LAW SCHOOL
3800 VARTAN WAY
HARRISBURG, PA 17106
(717) 541-1933

ROBERT B. MCKINSTRY, JR.*
PENN STATE UNIVERSITY
432 FOREST RESOURCES
BUILDING
UNIVERSITY PARK, PA 16802
(484) 467-3207
* Counsel of Record

KIRSTEN H. ENGEL
UNIVERSITY OF ARIZONA
COLLEGE OF LAW
1201 E. SPEEDWAY BLVD.
TUSCON, AZ 85721
(520) 621-5444
Counsel for Amici Curiae Climate Scientists

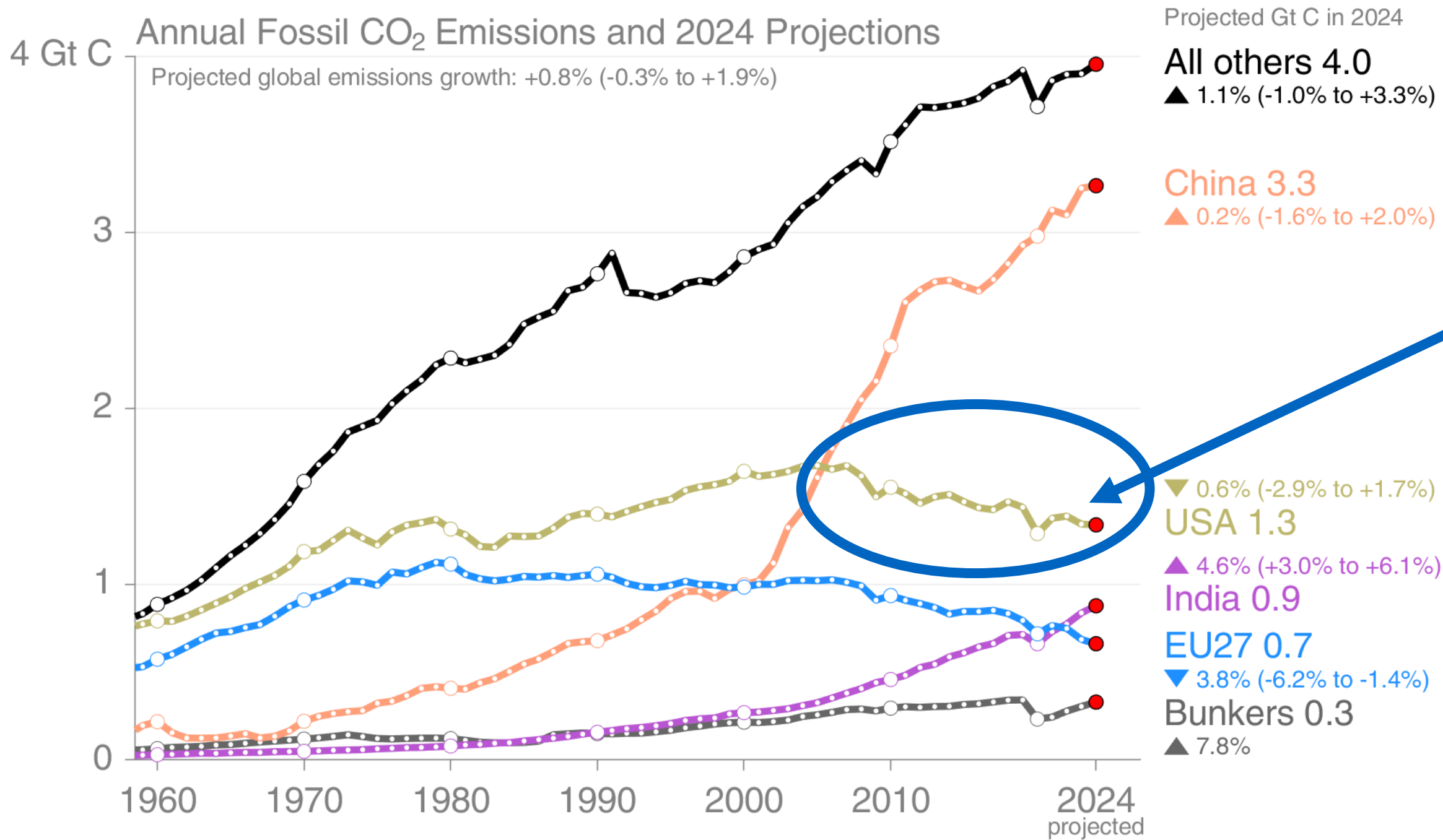
World Greenhouse Gas Emissions in 2019 (Sector | End Use | Gas)

Total: 49.8 GtCO₂e



Source: Climate Watch, based on raw data from IEA (2021), GHG Emissions from Fuel Combustion, www.iea.org/statistics; modified by WRI.

Fossil CO₂ emissions through 2023



US CO₂ Emissions:
Decreasing from
2007 to today

Mass vs EPA Decided:
April, 2007

EMISSION CUTS BY 2030

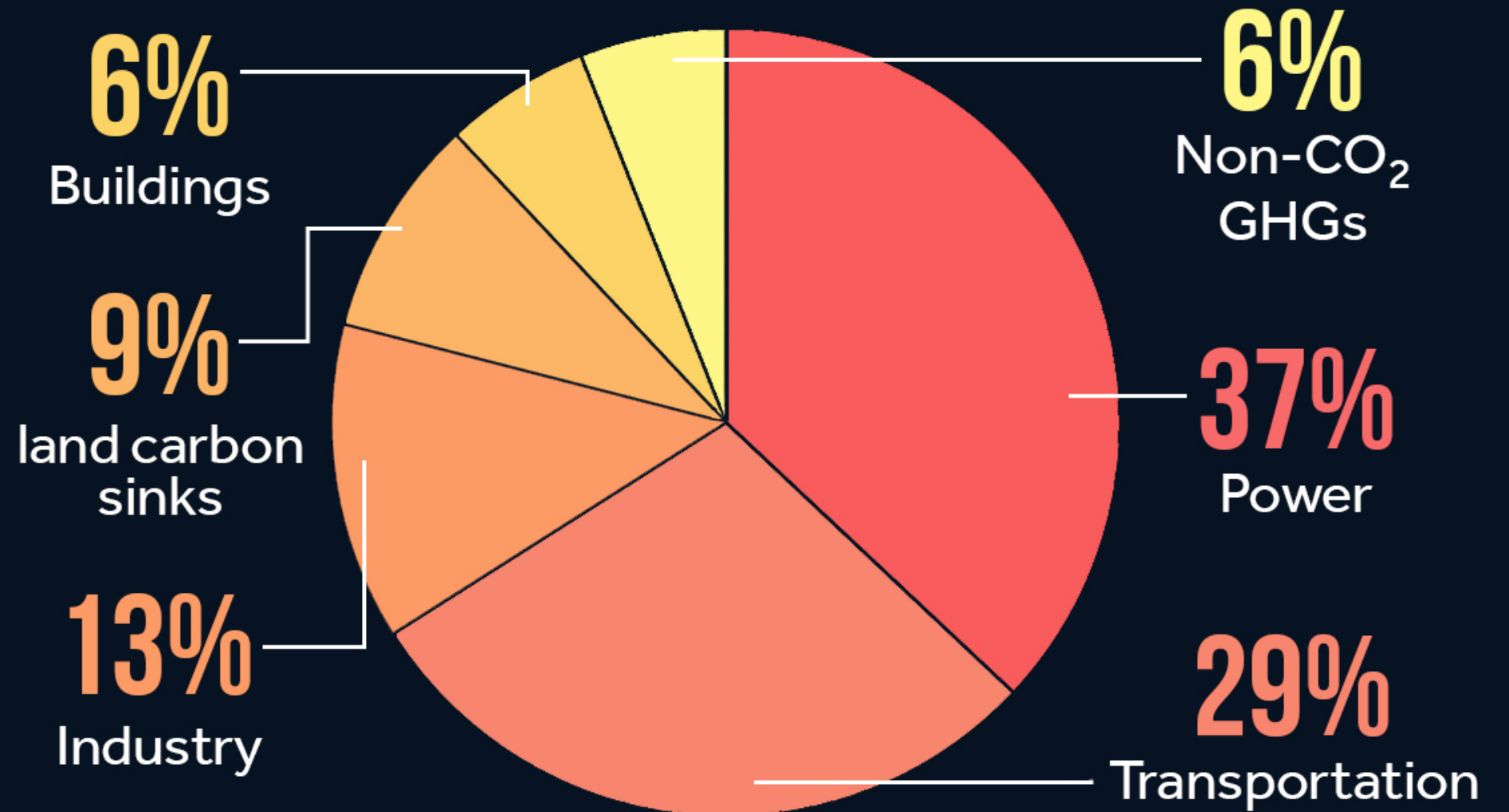
WITH THE INFLATION REDUCTION ACT

PROGRESS TOWARD U.S. EMISSIONS TARGET



Net GHG emissions (including land carbon sinks). Projections: current policy scenarios (optimistic).
Source: U.S. EPA (2005-2020); Jenkins et al. REPEAT Project (2025-2030)

CLIMATE CENTRAL



GHGs = greenhouse gases
Source: Jenkins et al. REPEAT Project (August 12, 2022).

CLIMATE CENTRAL

Fate of anthropogenic CO₂ emissions

2014-23 average

Sources

9.7 0.5 GtC/yr
89.8%



1.1 0.7 GtC/yr
10.2%



Total Emission 10.8 0.9 GtC/yr

Partitioning



5.2 0.02 GtC/yr
46%



2.9 0.4 GtC/yr
26%



3.2 0.9 GtC/yr
28%

Budget Imbalance (Net Source – Net Sink) = -0.4 GtC/yr

Atmosphere + Ocean = Land

Where Land = (Emissions + Land Use Change – Vegetation)

0.02



Atmosphere

0.4



Ocean

0.5



Emissions

0.7



Land Use

0.9



Vegetation



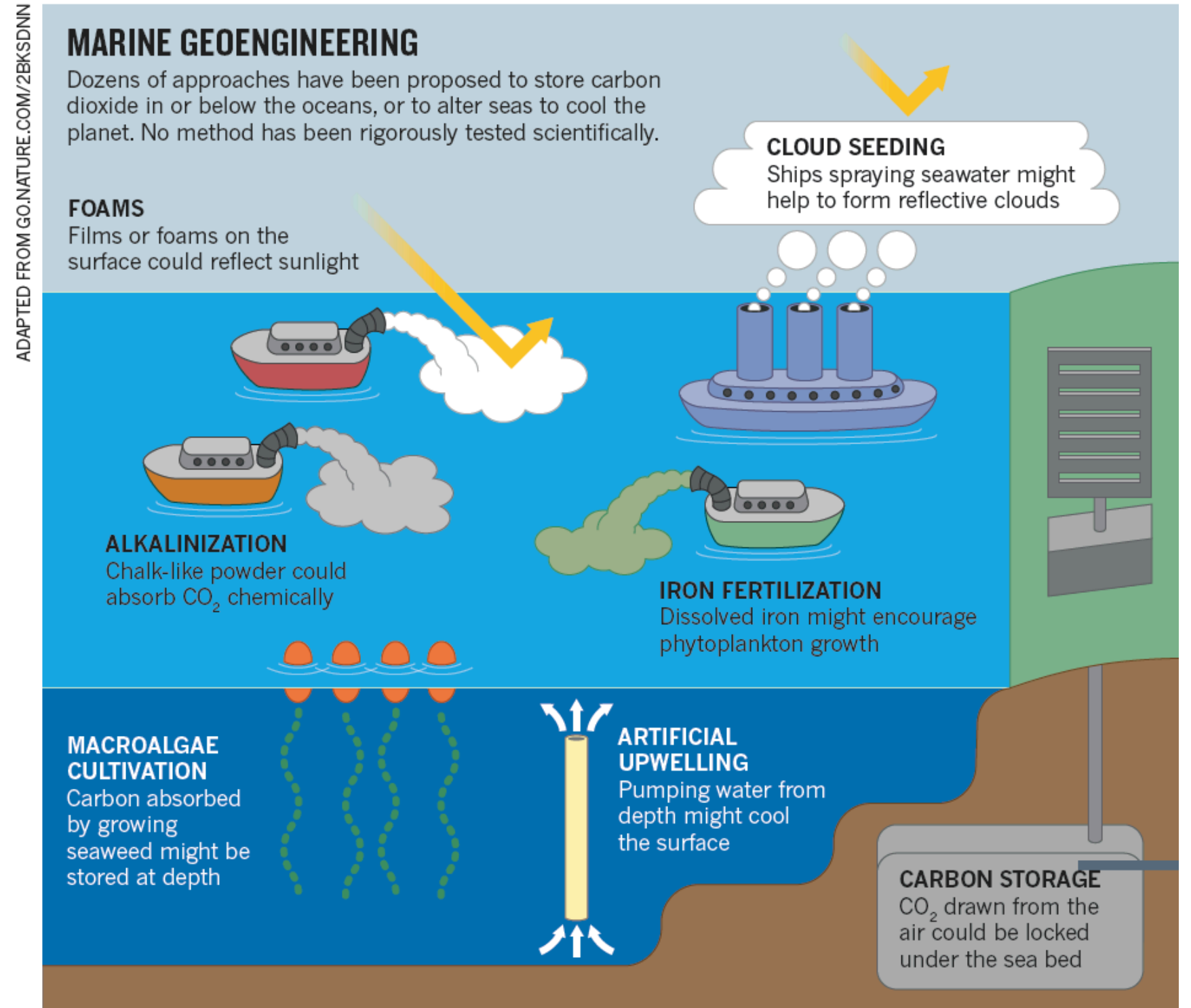
Reducing uncertainties in the ocean sink
can reduce the total uncertainty in the
global constraint on the carbon budget

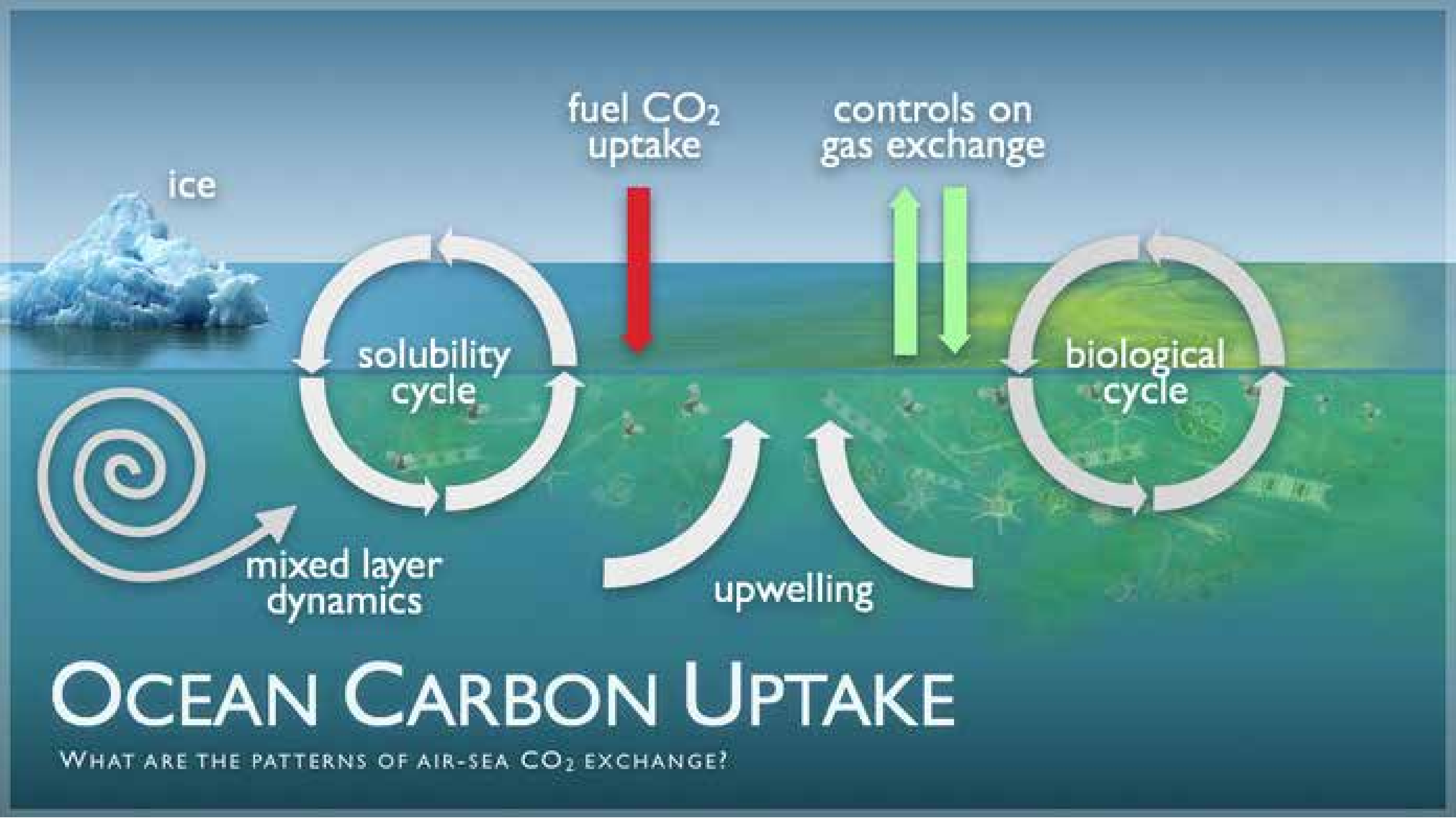
Verifying the Effectiveness of Ocean-based Carbon Dioxide Removal (CDR)



Caution Needed!

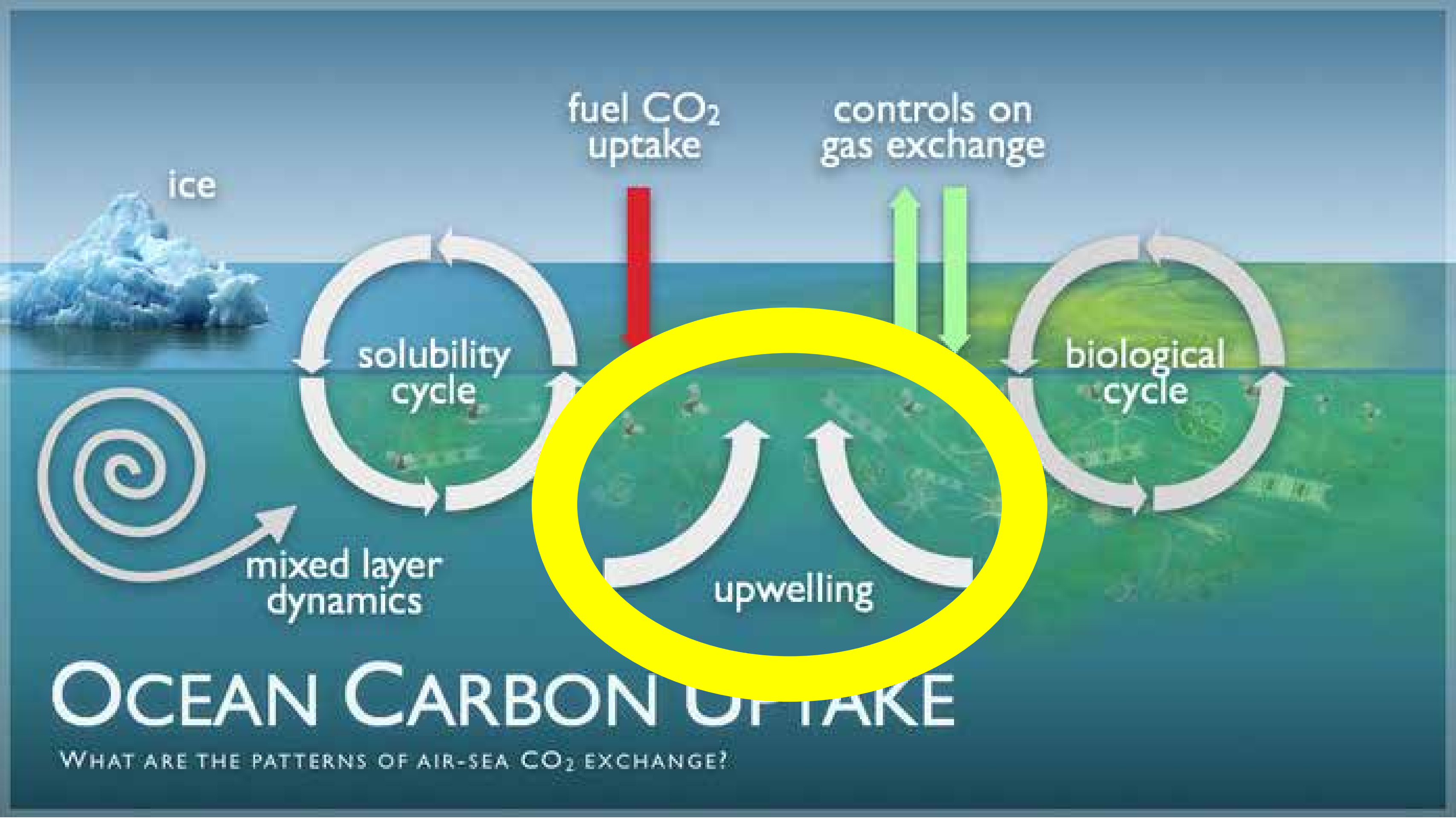
From Boyd & Vivian (2019)





OCEAN CARBON UPTAKE

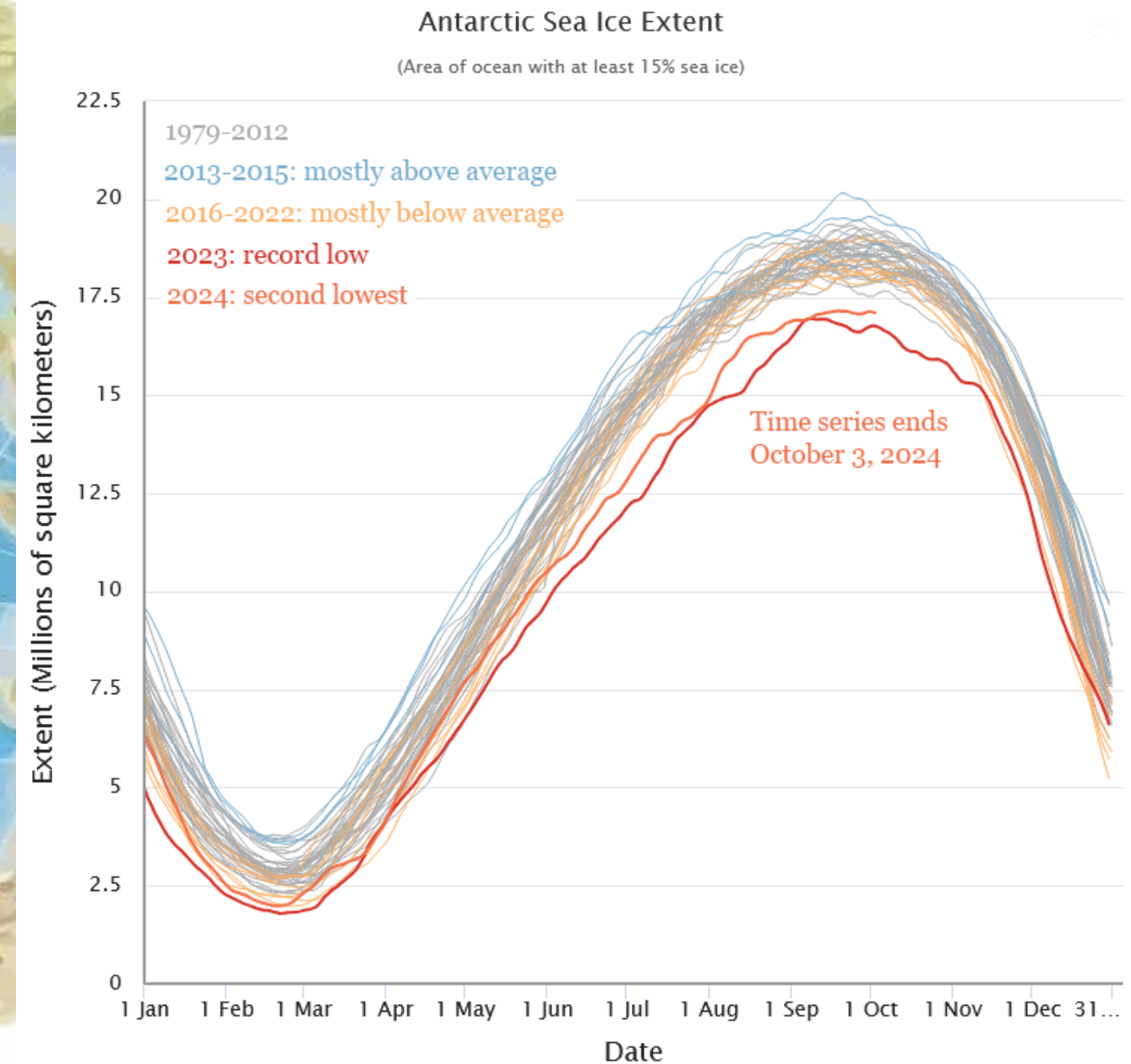
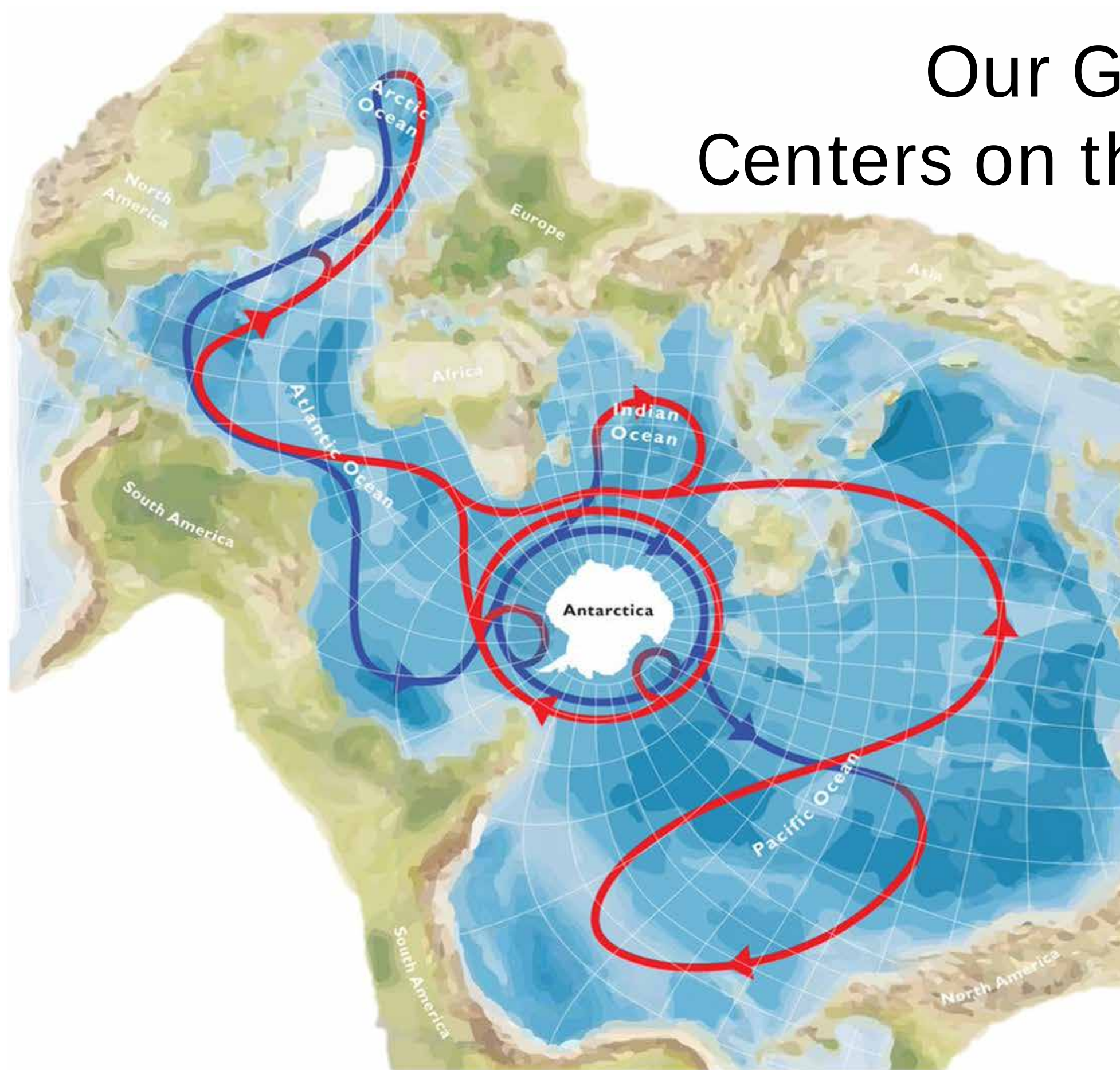
WHAT ARE THE PATTERNS OF AIR-SEA CO₂ EXCHANGE?



OCEAN CARBON UPTAKE

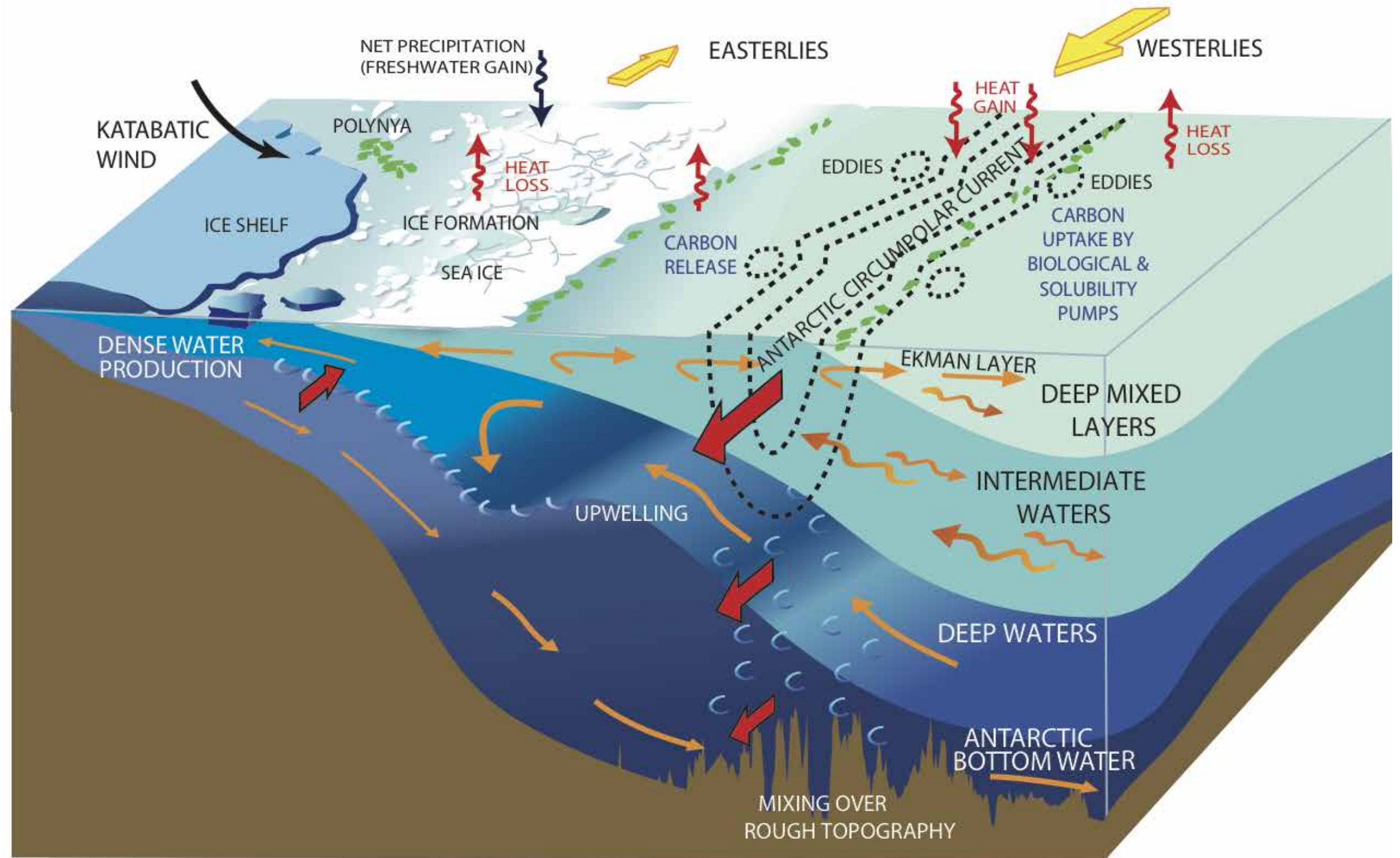
WHAT ARE THE PATTERNS OF AIR-SEA CO₂ EXCHANGE?

Our Global Ocean Centers on the Southern Ocean



The Southern Ocean

Wind-driven
upwelling from
2000-3000m



THE SOUTHERN OCEAN

up to
50%
of all the
carbon dioxide

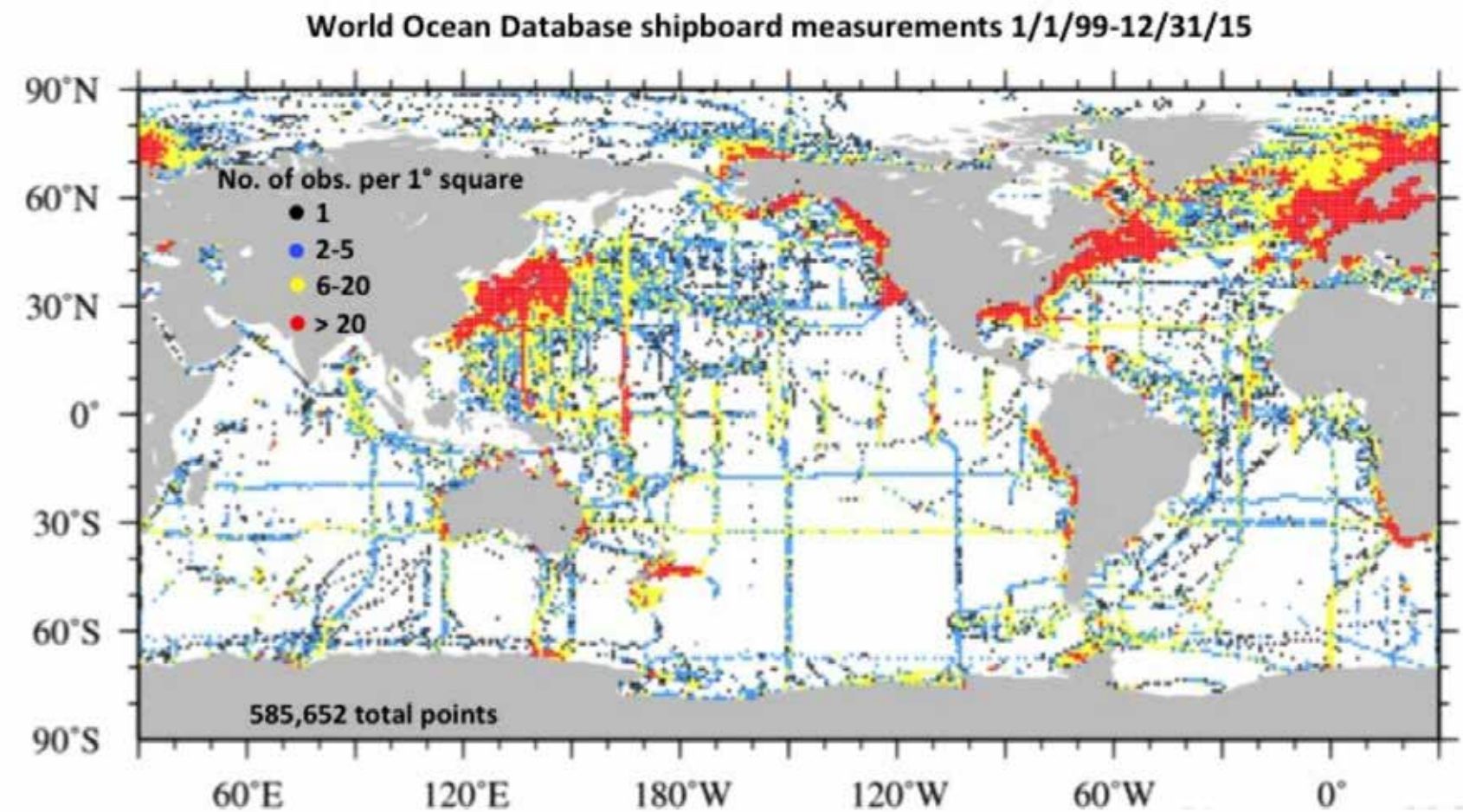
up to
75%
of all the
heat

absorbed by the world's oceans



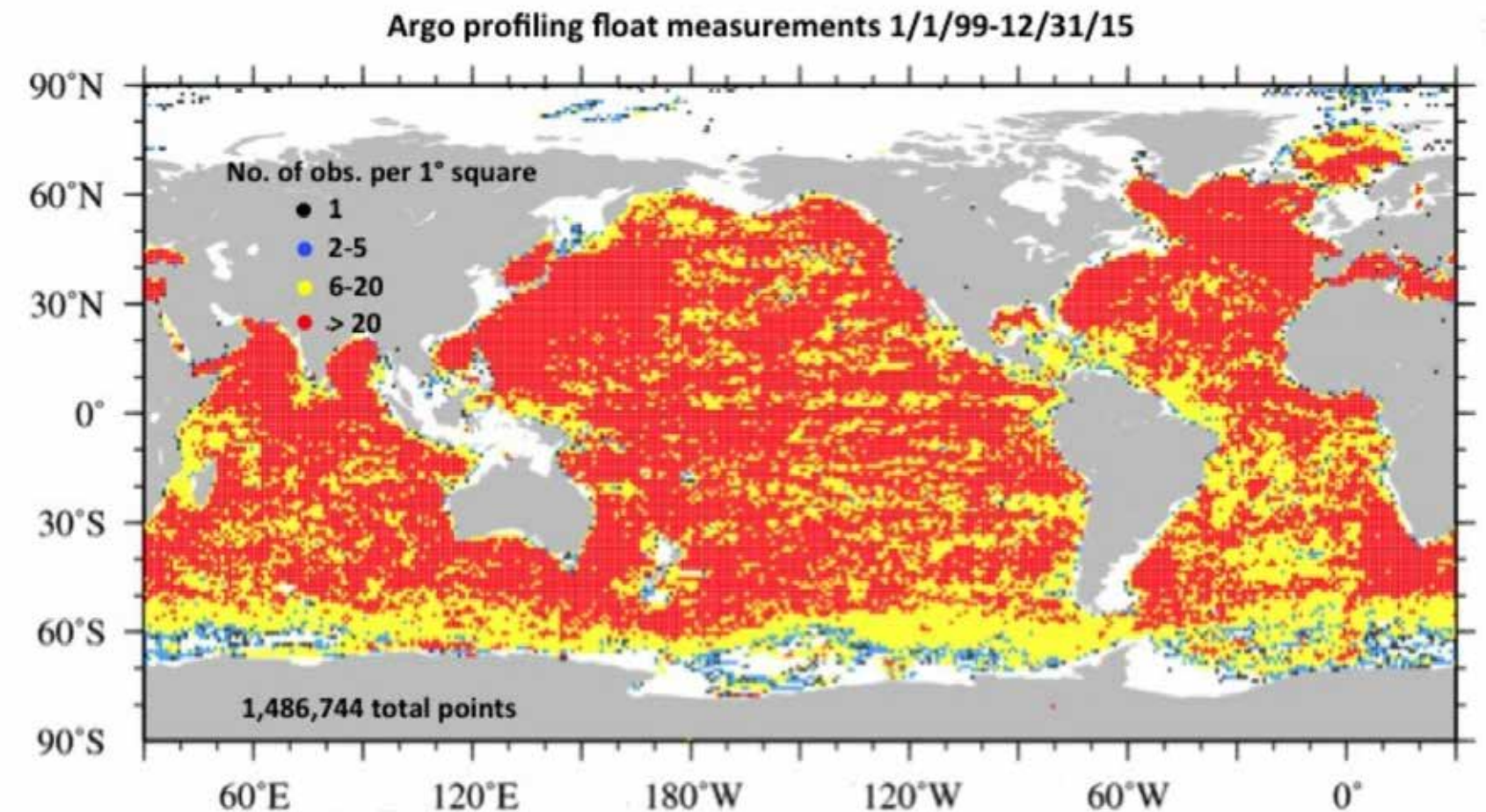
Measurements from Ships (1999-2015)

total



Measurements from Robot Floats (Argo) (1999-2015)

total

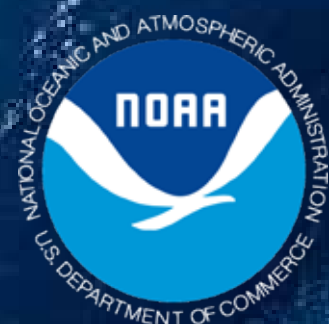




SOCCOM

Southern Ocean Carbon and Climate Observations and Modeling

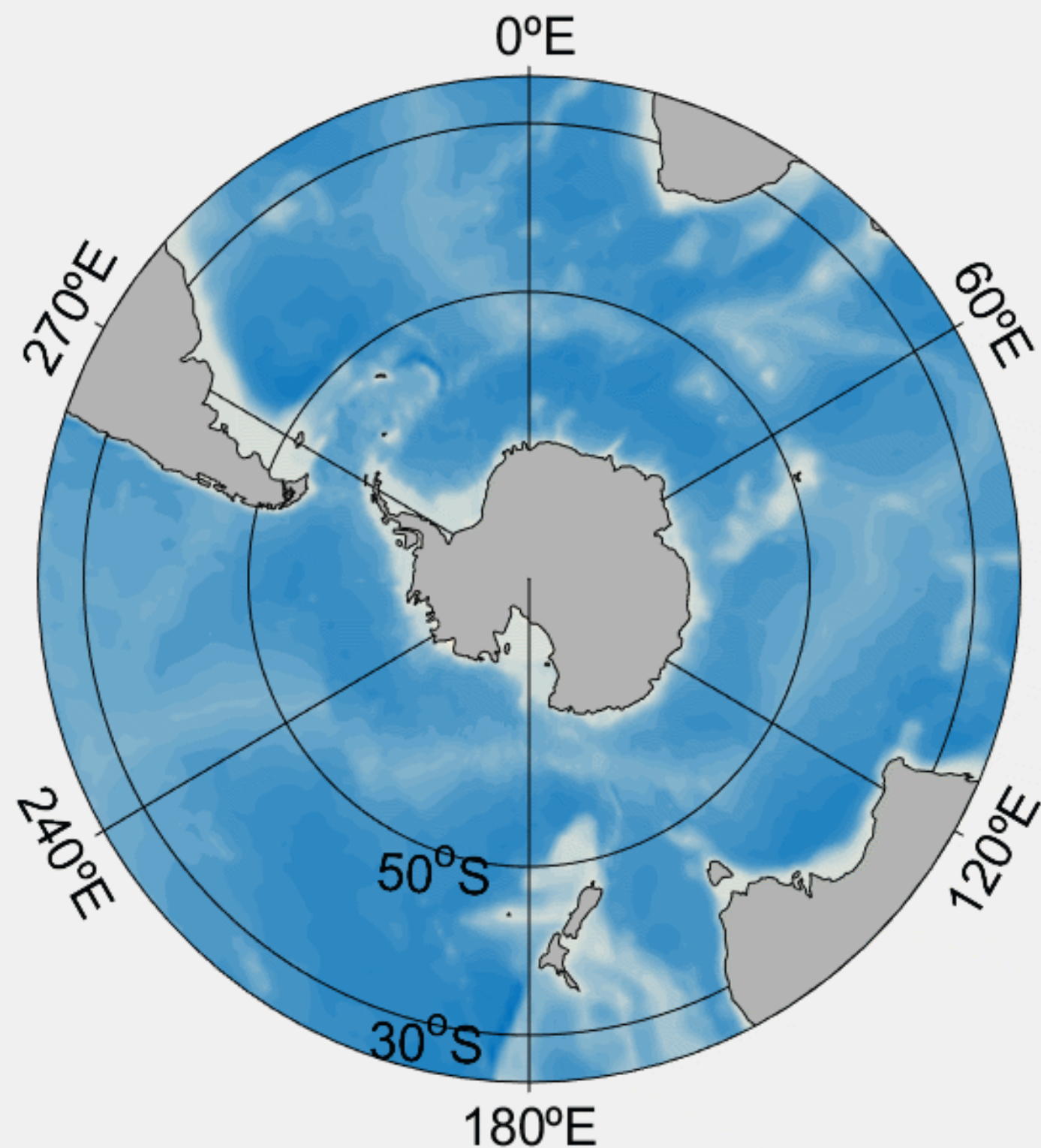
Southern Ocean Carbon and Climate Observations and Modeling





Courtesy: R. Beadling (clip)

2014 2015 2016 2017 2018 2019 2020



SOCCOM

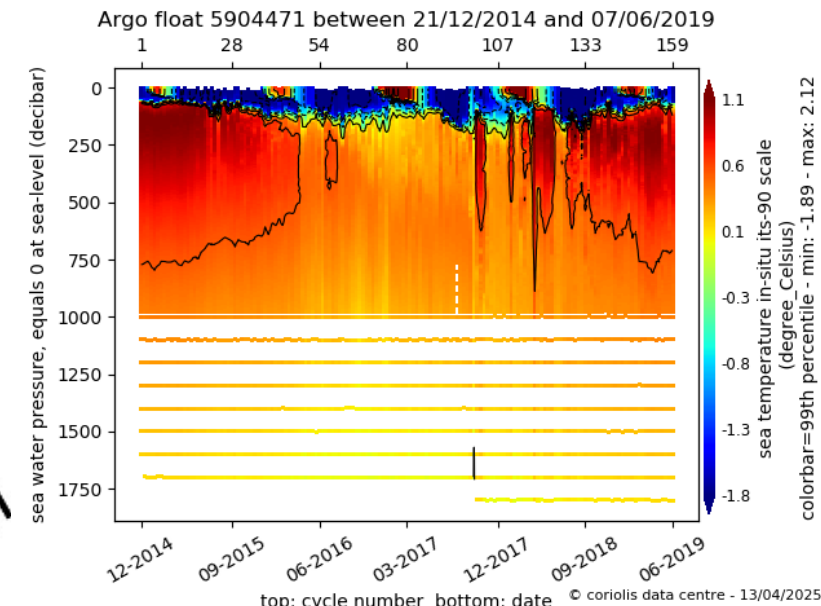
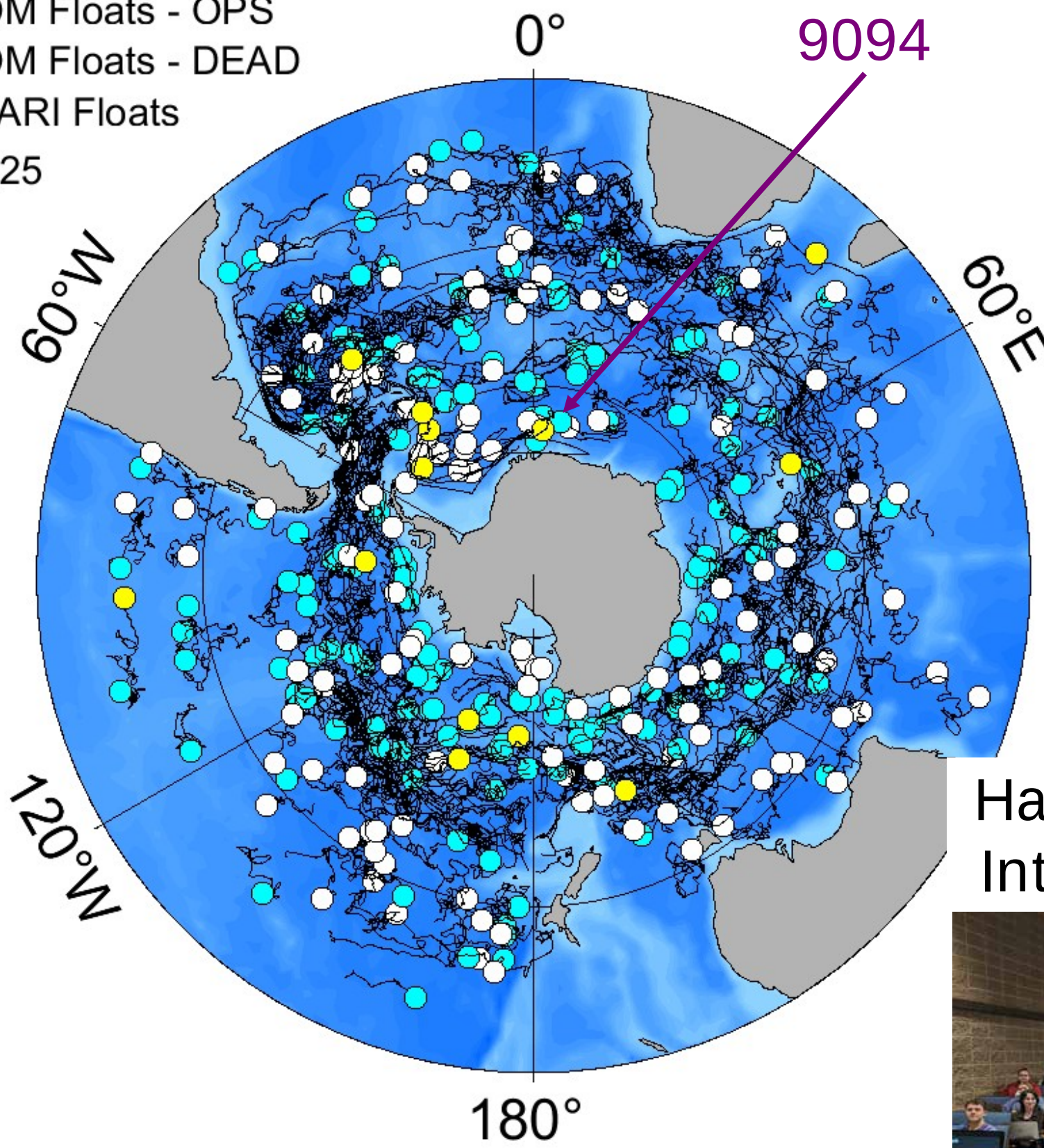
Unlocking the mysteries of the Southern Ocean

SOCCOM Floats

307 deployed,
143 operational

Hannah Zanowski
U. Arizona B.A. (2010)
Now: Asst. Prof. U. Wisc.-Madison

- SOCCOM Floats - OPS
 - SOCCOM Floats - DEAD
 - UW/MBARI Floats
- 16-Apr-2025



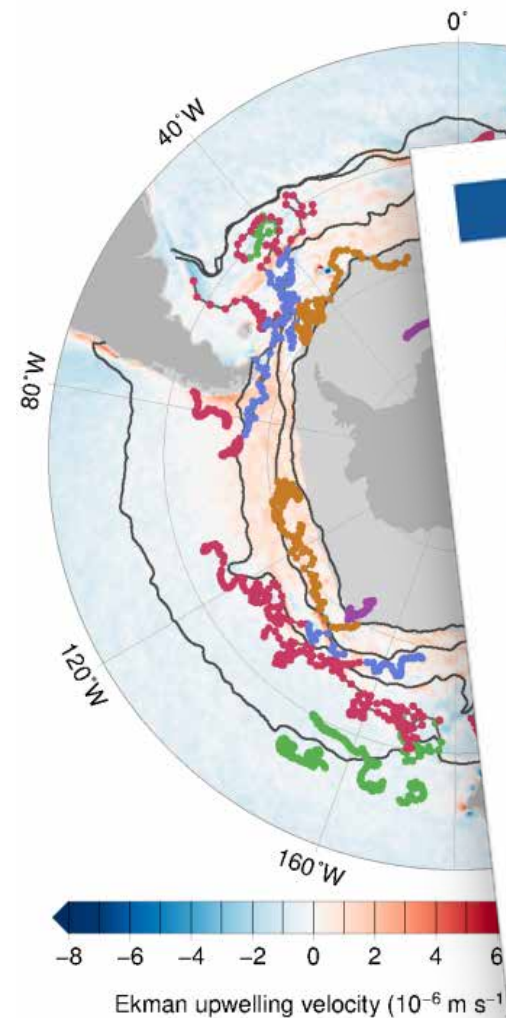
12/21/2014 –
6/7/2019
(122 cycles)

Hannah now teaches
Intro Oceanography!



Air-sea carbon flux from floats

In the high-latitude ASZ, monthly mean float-based fluxes diverge substantially from ship-based fluxes. The floats exhibit much stronger outgassing in the autumn and winter and much less uptake in the summer.



AGU100 ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

Research Letter

Autonomous Biogeochemical Floats Detect Significant Carbon Dioxide Outgassing in the High-Latitude Southern Ocean

Alison R. Gray, Kenneth S. Johnson, Seth M. Bushinsky, Steven D. Talley, Rik Wanninkhof, Nancy L. Williams, Jorge L. Sarmiento

First published: 14 August 2018 | <https://doi.org/10.1029/2018GL078881>

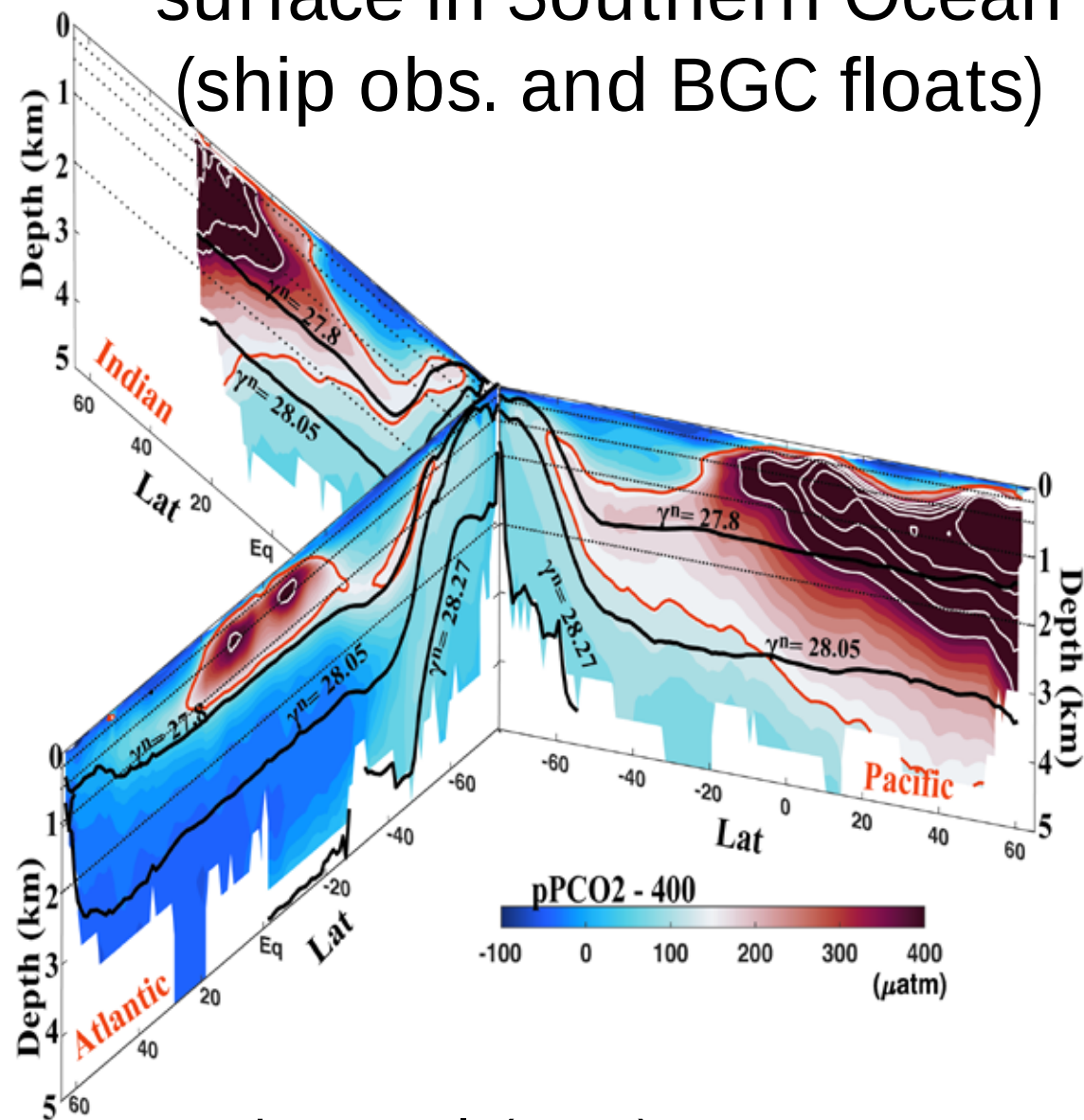
Abstract

Although the Southern Ocean is thought to account for a significant portion of contemporary oceanic uptake of carbon dioxide (CO_2), estimates based on sparse observations that are strongly biased toward the summer season. New estimates of Southern Ocean air-sea CO_2 fluxes from autonomous biogeochemical profiling floats deployed by the Southern Ocean Observations and Modeling project during 2014–2017. Contrary to previous estimates, the float-based fluxes find significantly stronger outgassing in the zone of deep waters upwell to the surface ocean. Although the magnitude of outgassing principally stems from the lack of



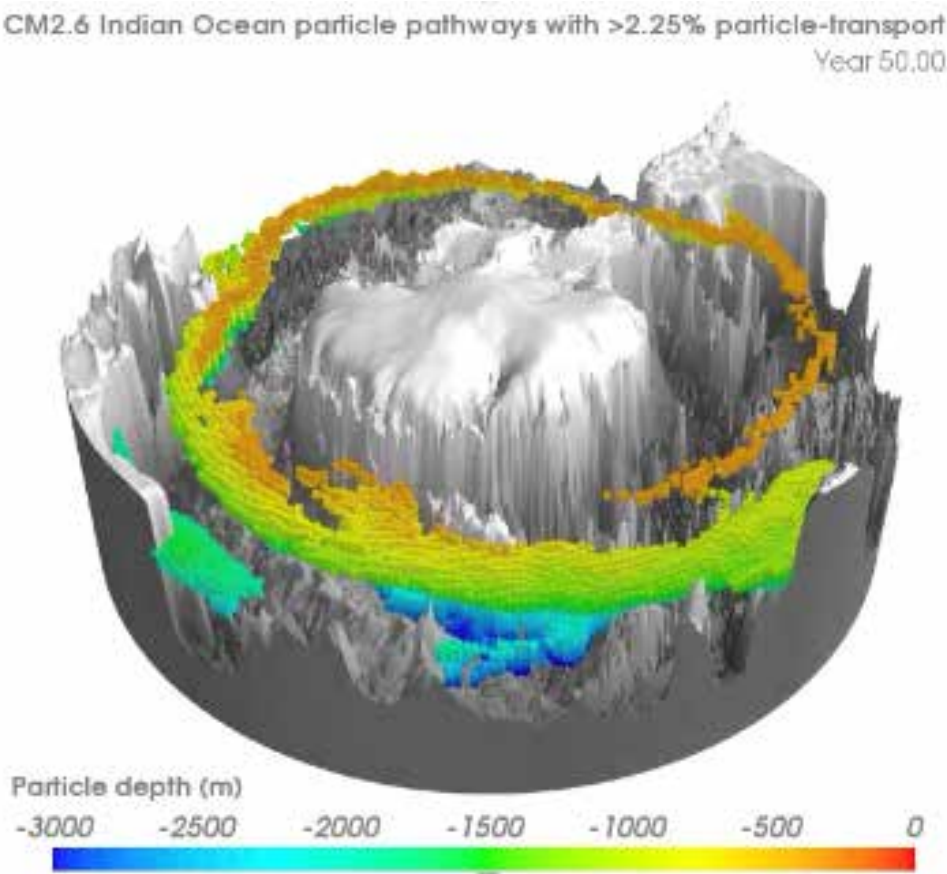
Air-sea carbon flux from SOCCOM

High carbon Deep Waters reach surface in Southern Ocean (ship obs. and BGC floats)



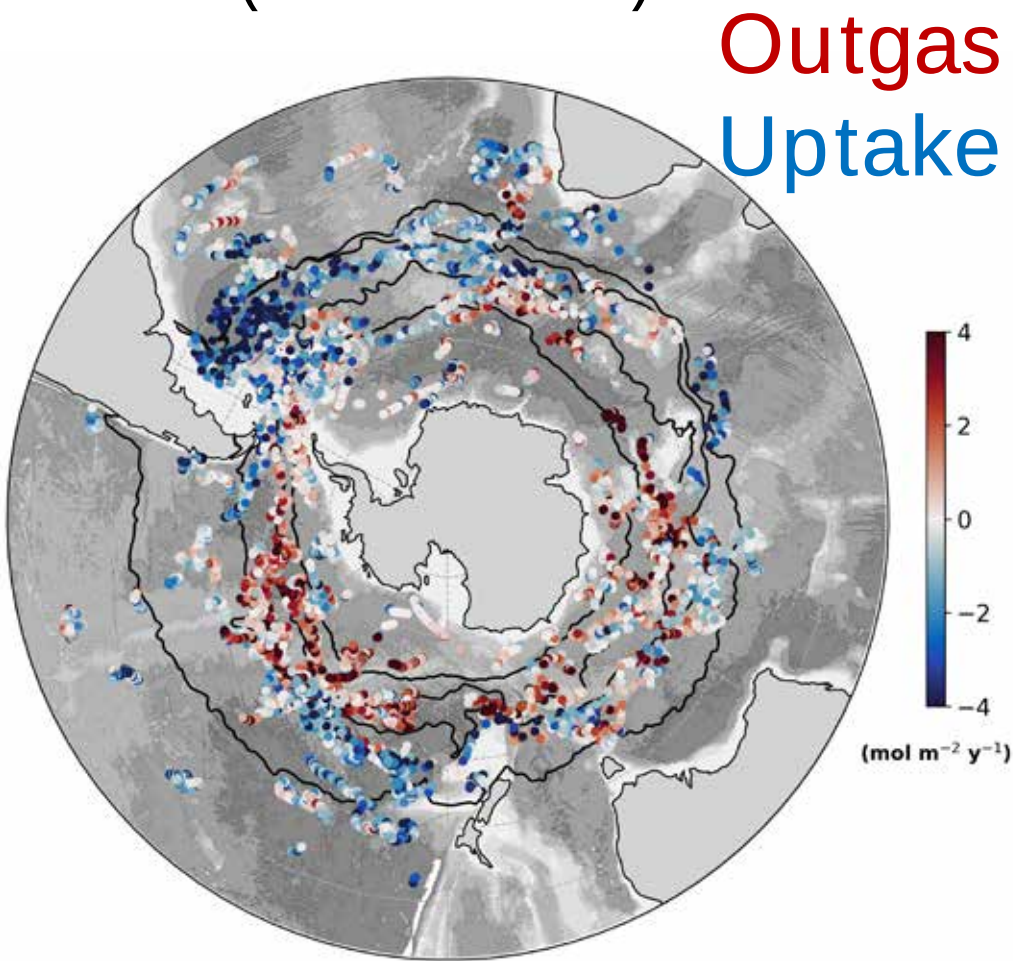
Chen et al. (2019)

Pathways of high carbon spiral inward and upward (ship obs. and B-SOSE)



Tamsitt et al. (Nat. Comm. 2017)

Carbon outgases in southern ACC (BGC floats)



Gray et al. (GRL 2018)
Prend, Gray et al.

Rising From the Antarctic, a Climate Alarm

Wilder winds are altering currents. The sea is releasing carbon dioxide. Ice is melting from below.

By HENRY FOUNTAIN
and JEREMY WHITE

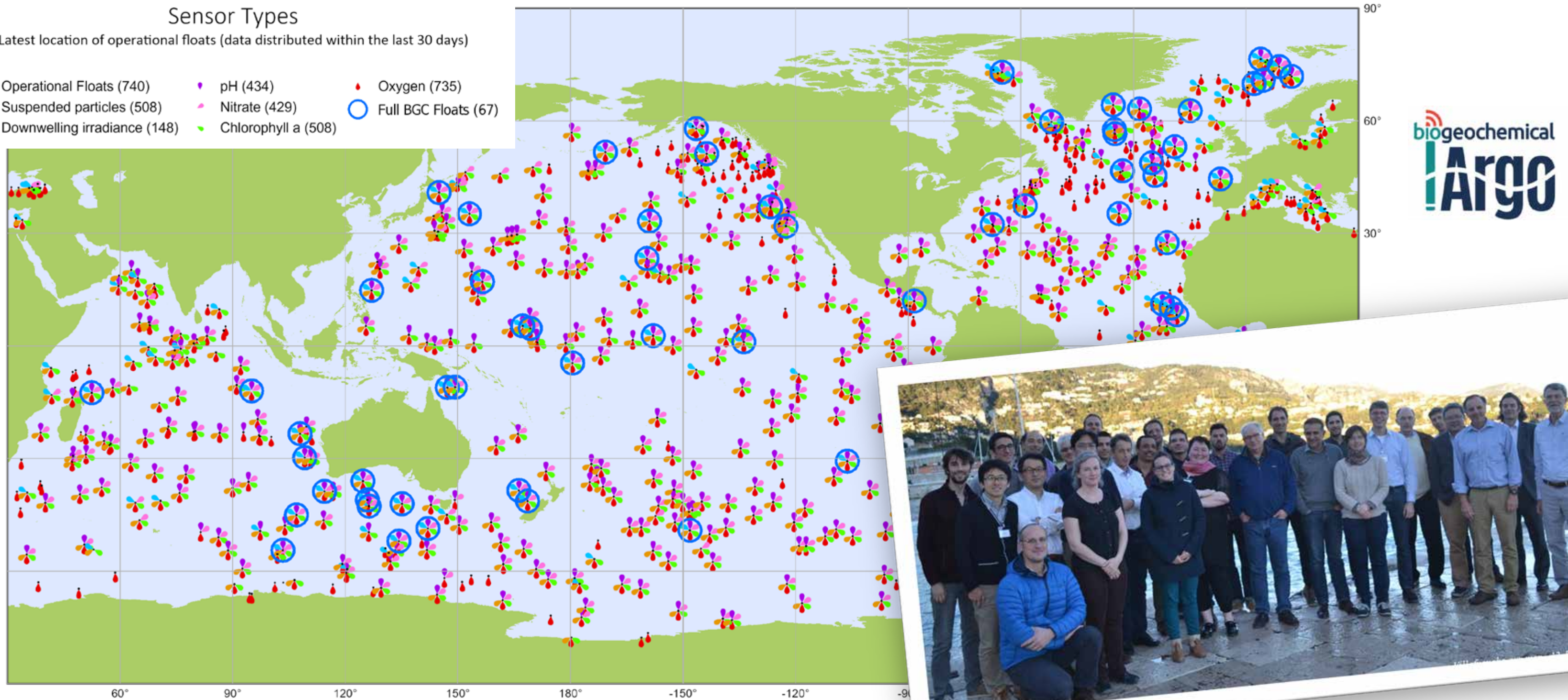


Global Biogeochemical Argo: in Mar 2025

Sensor Types

Latest location of operational floats (data distributed within the last 30 days)

- Operational Floats (740)
- Suspended particles (508)
- Downwelling irradiance (148)
- pH (434)
- Nitrate (429)
- Chlorophyll a (508)
- Oxygen (735)
- Full BGC Floats (67)



OXYGEN SATURATION

FEB

90%

110%

Robot Floats

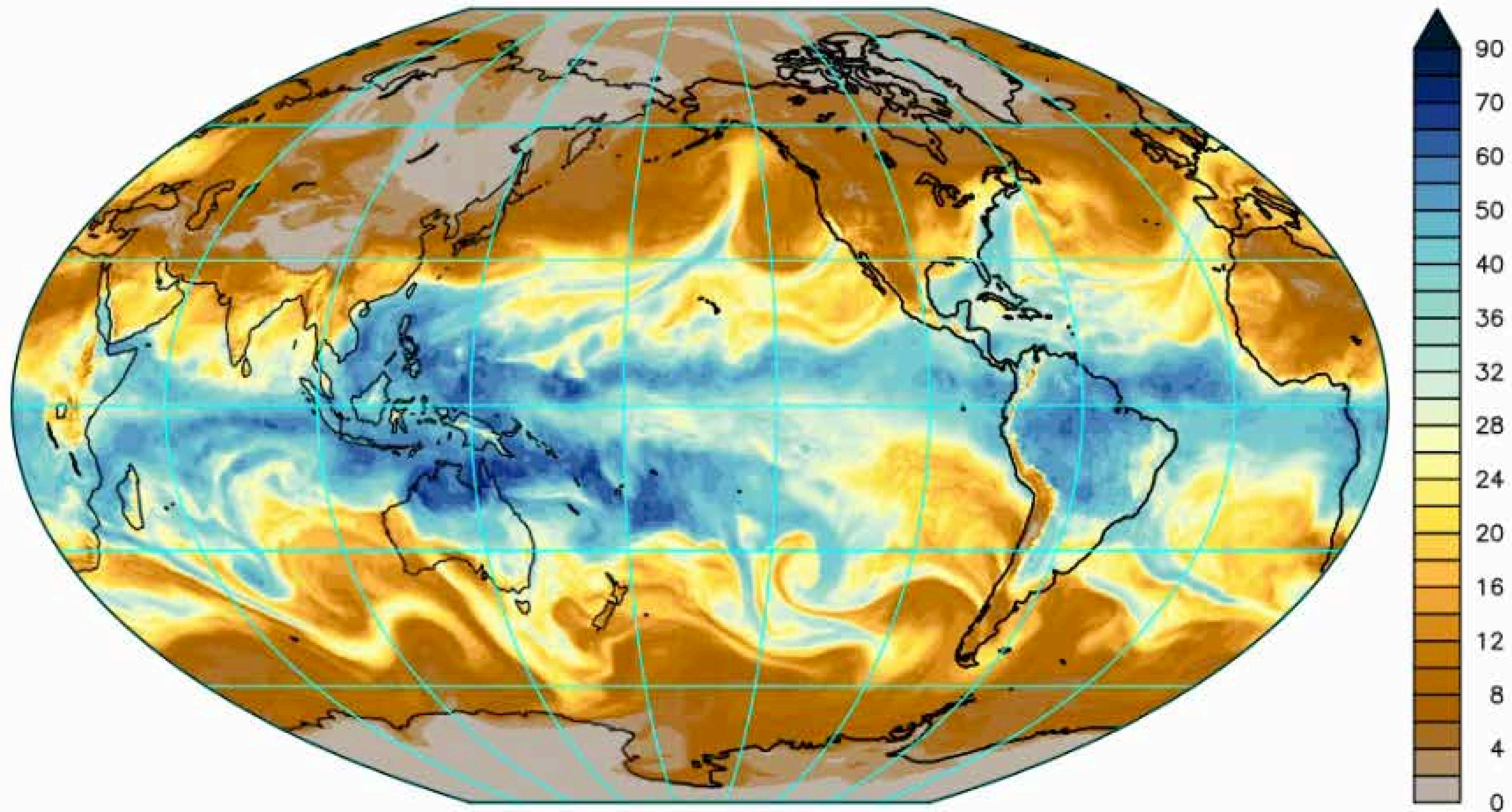


An underwater photograph showing sunlight filtering through the water surface, creating a dappled light effect. The water is a deep blue color.

Growing
Winds!

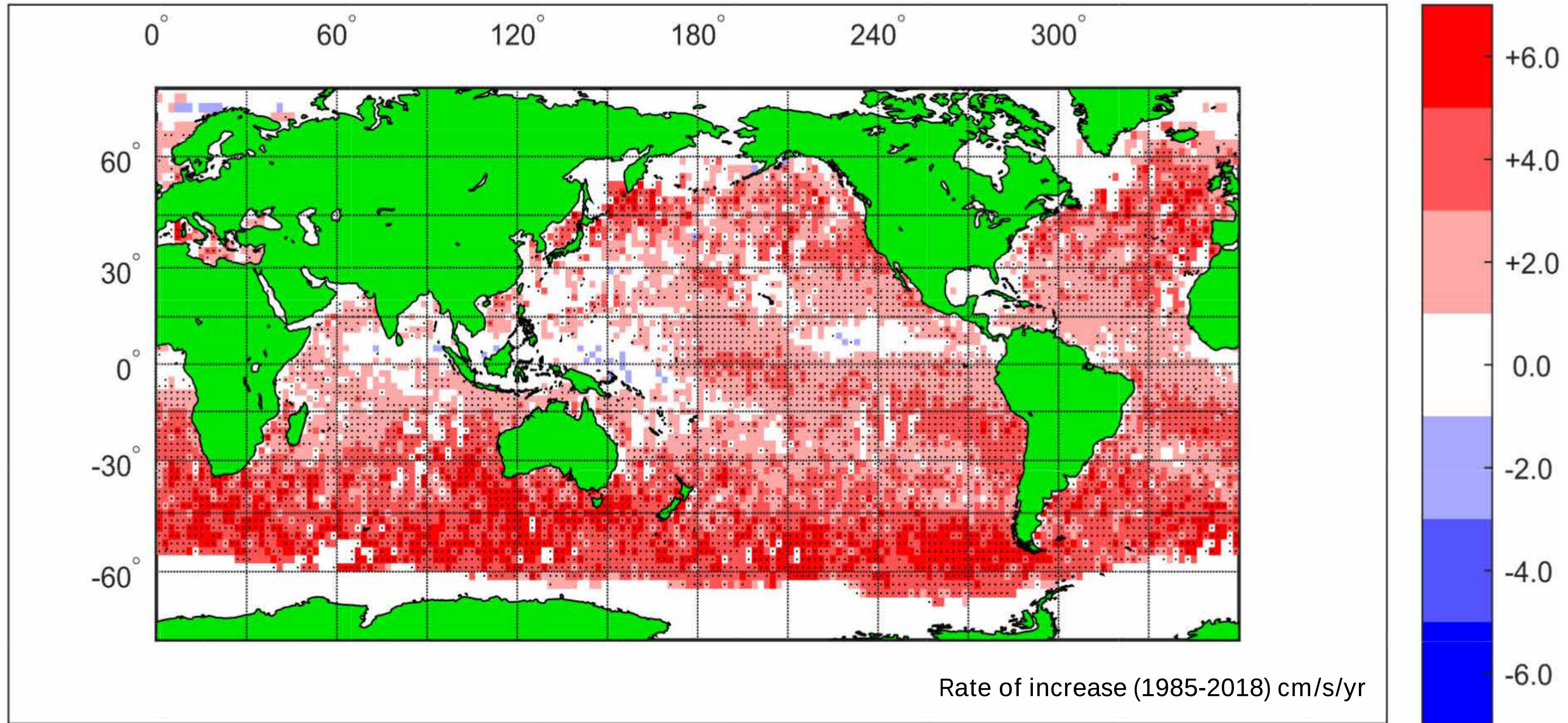
Total Water in the Atmosphere: 2023 (every 6 hours, ERA5)

TIME : 01-JAN-2023 00:00



Total column vertically-integrated water vapour (kg m⁻²)

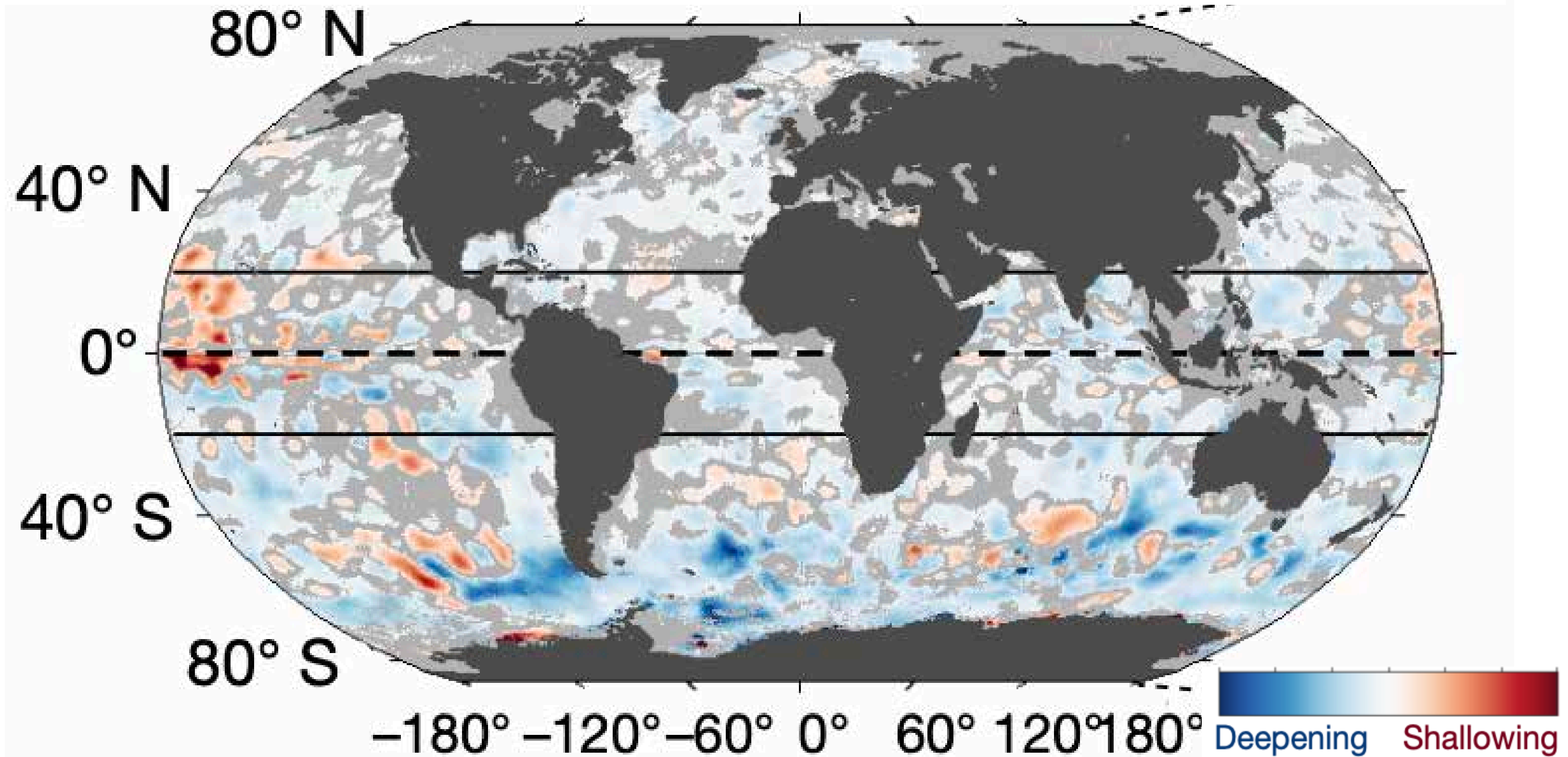
The World is Getting Windier – The fastest winds have gotten faster



6 cm/s per year for 33 years is 2 m/s faster

Young & Ribal, 2019: Science, DOI: [10.1126/science.aav9527](https://doi.org/10.1126/science.aav9527)

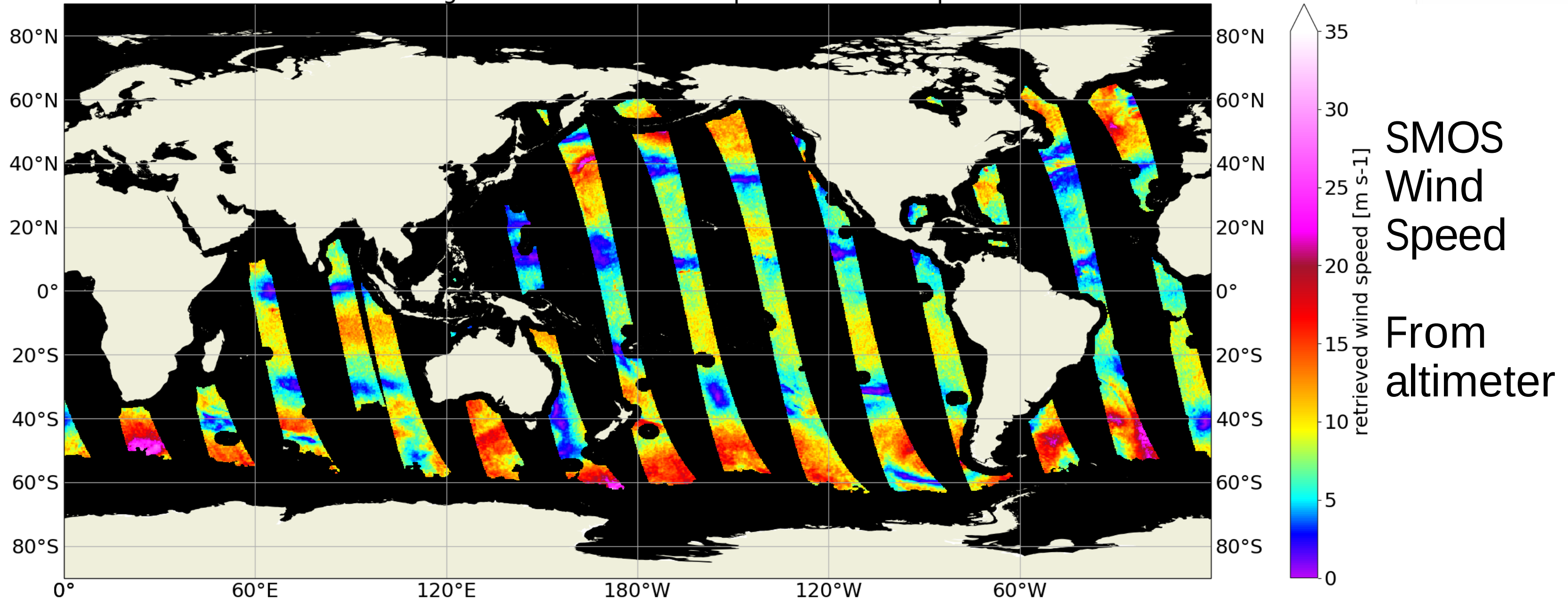
The World is Getting Windier – Driving Deeper Mixing



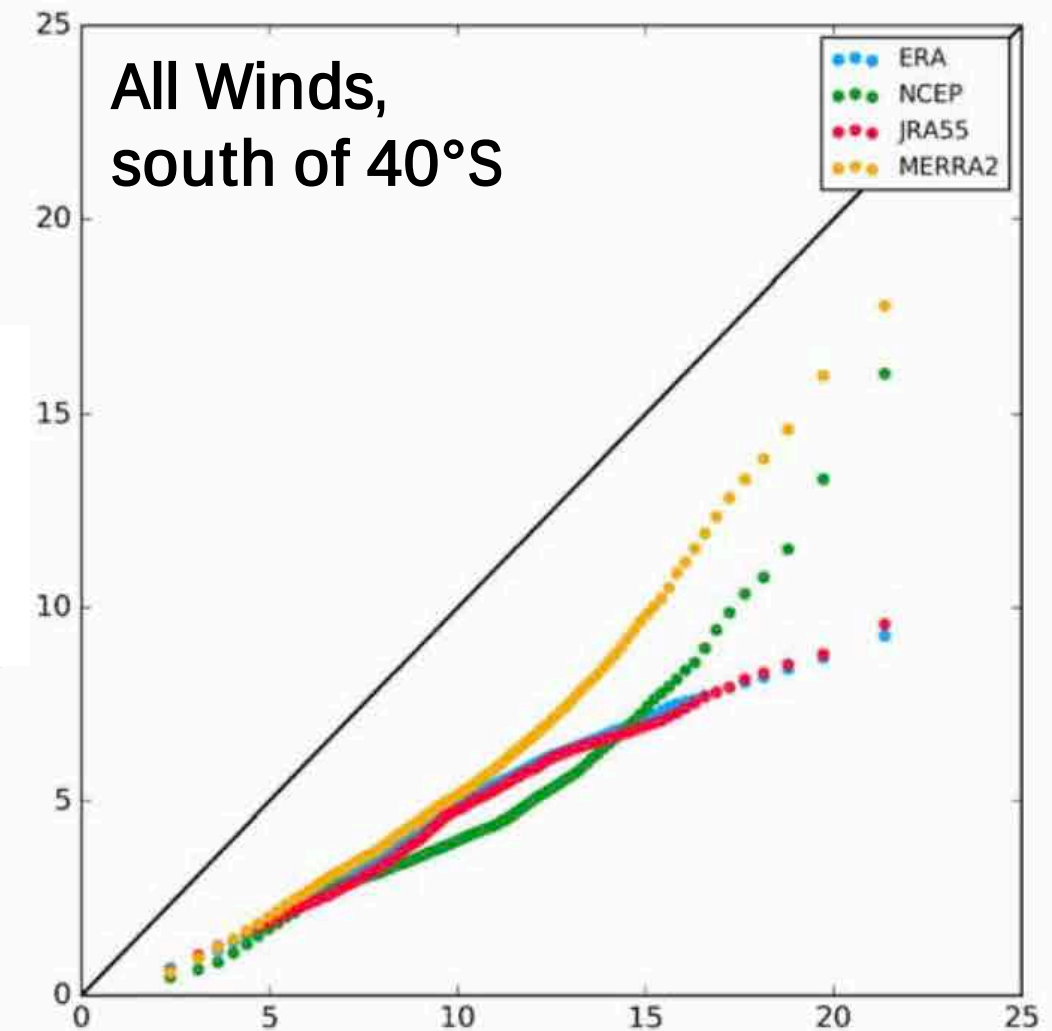
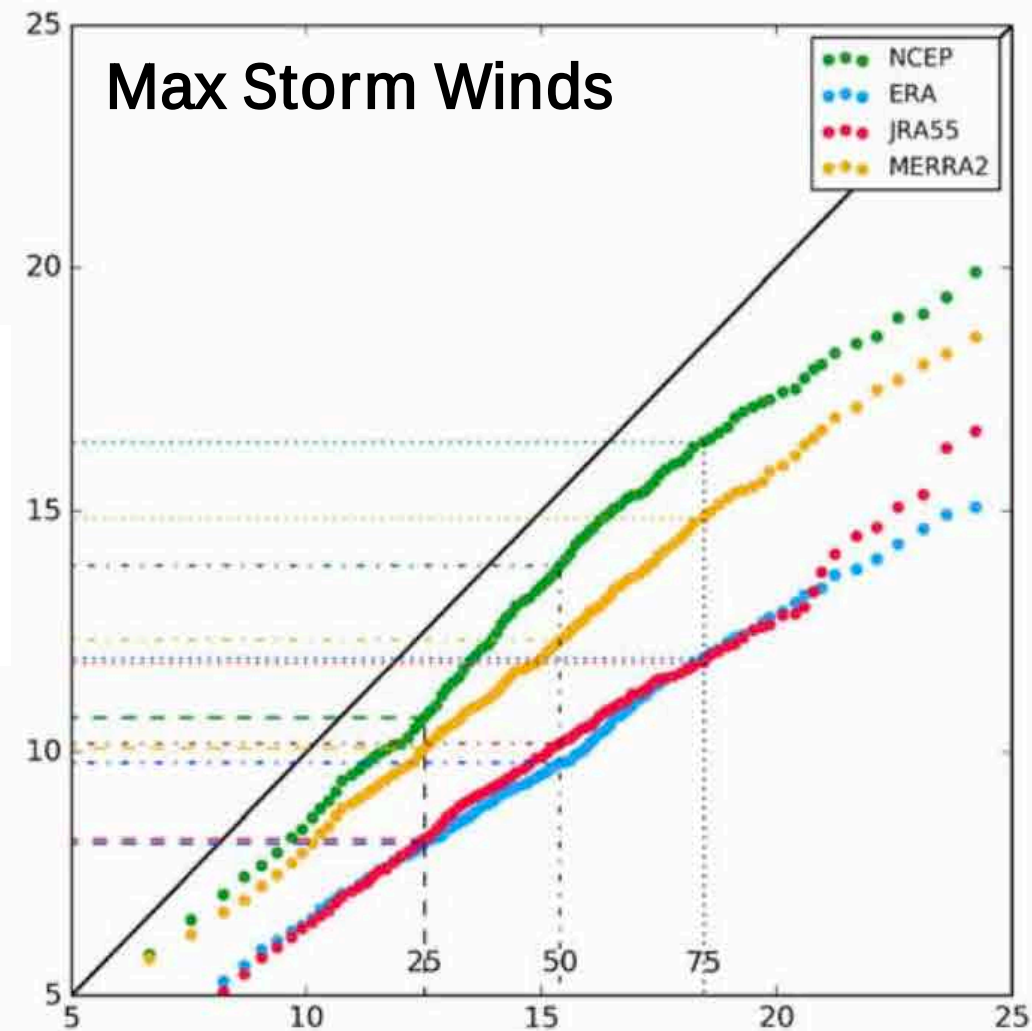
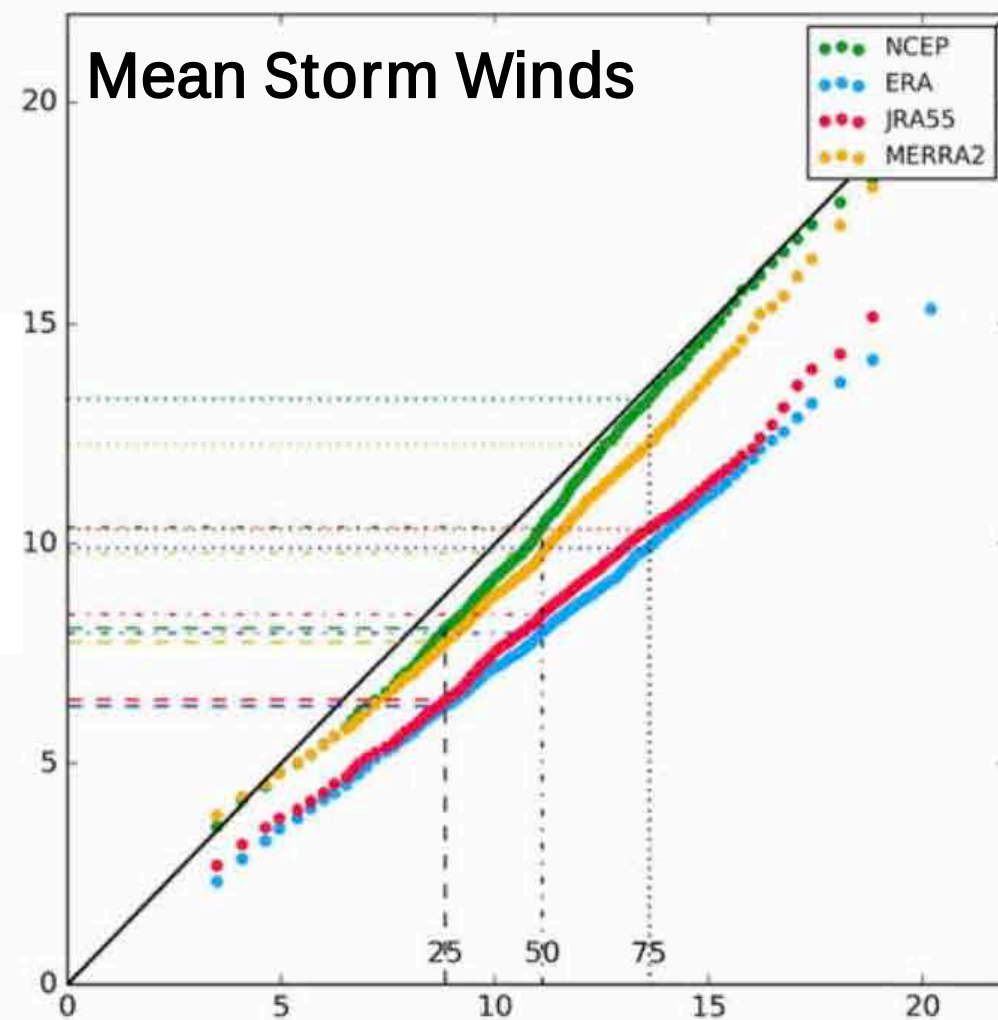
Southern Ocean Winds/Storms are Undersampled



SMOS Morning Pass Retrieved Wind Speed on 2021-Sep-16



Southern Ocean Winds/Storms are Undersampled



Direct comparison of QuikSCAT winds in SO storms with four different wind reanalyses (NCEP/CFSR; ERA-Interim; JRA55; MERRA)

SOS ZEPHYR

Capturing the Southern Ocean high winds to reduce the uncertainty in the Global Carbon Budget



Principal Investigator:
Joellen Russell, UA

Authorizing Official

Deputy PI:
David Long, BYU



BYU



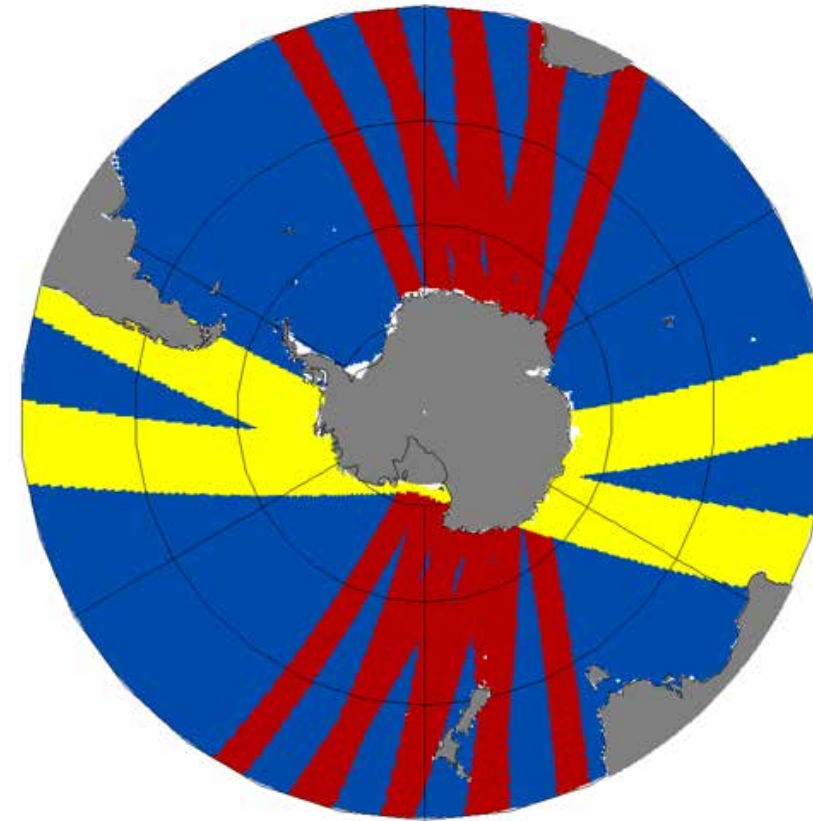
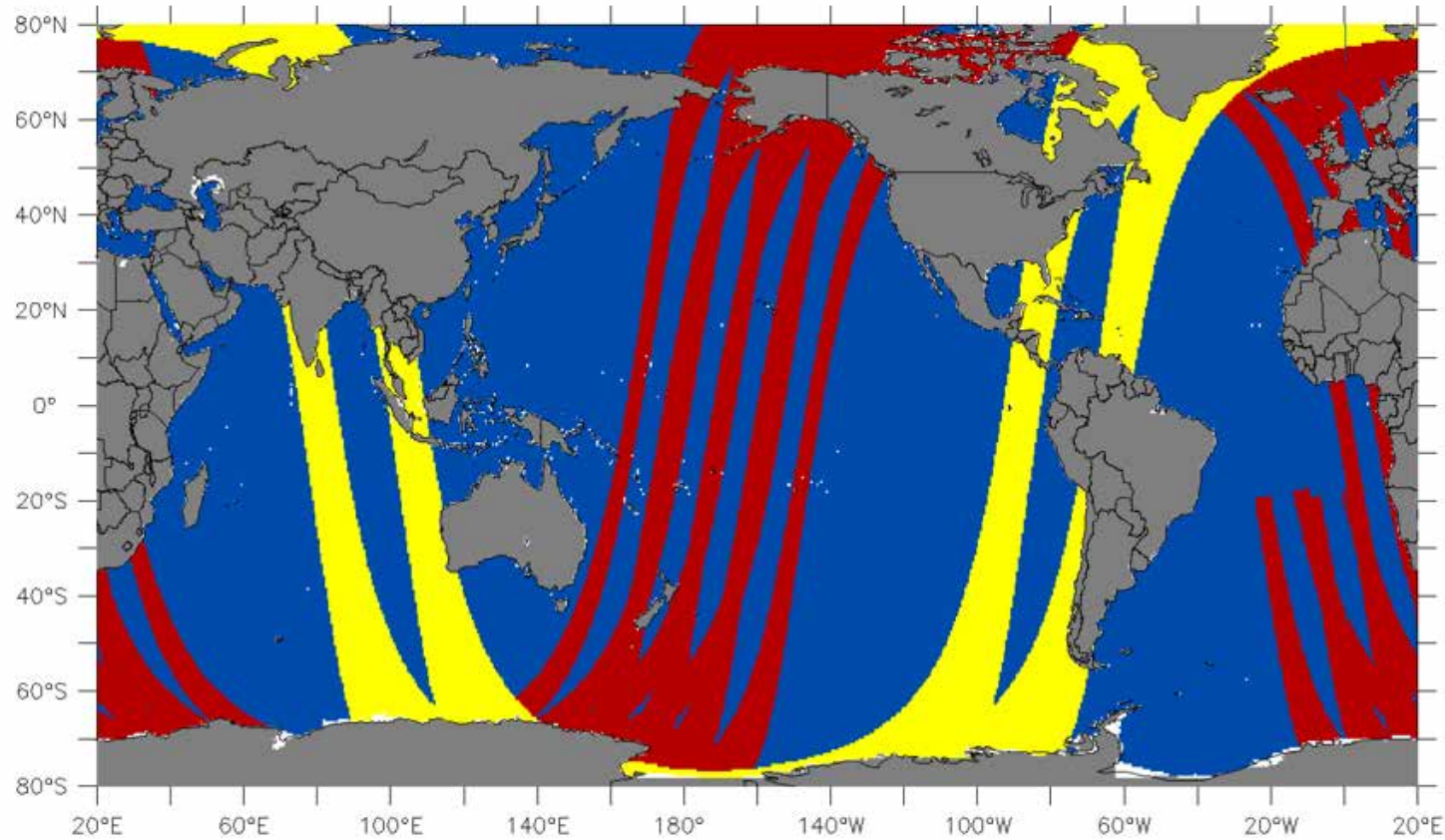
CLASP



JPL

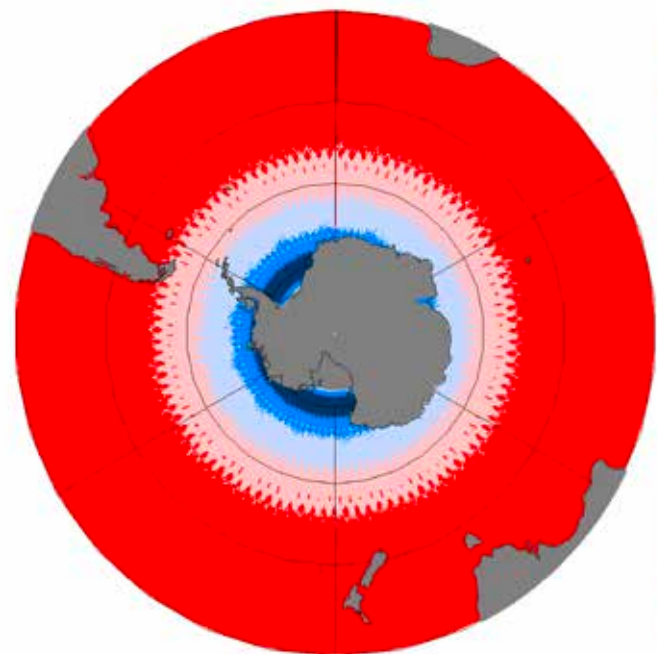


One More Scatterometer to Close the Carbon Budget

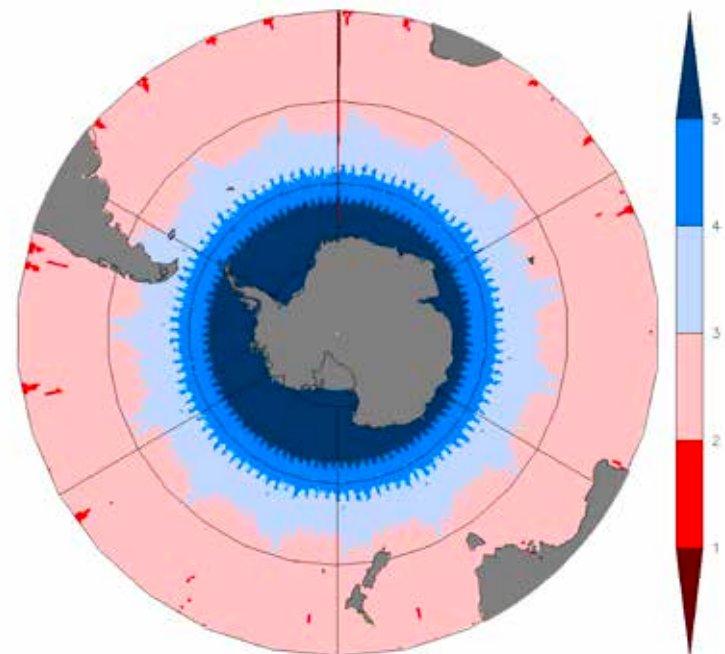


ASCAT constellation swaths over a 3-hour period (red)

Zephyr swaths over same 3-hour period (yellow)



Independent visits per day (ASCAT only)



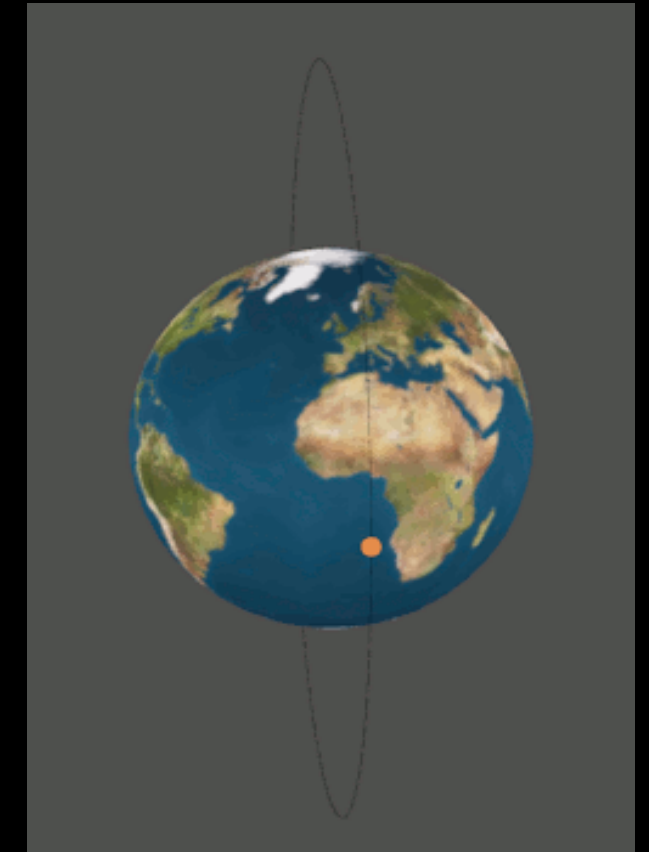
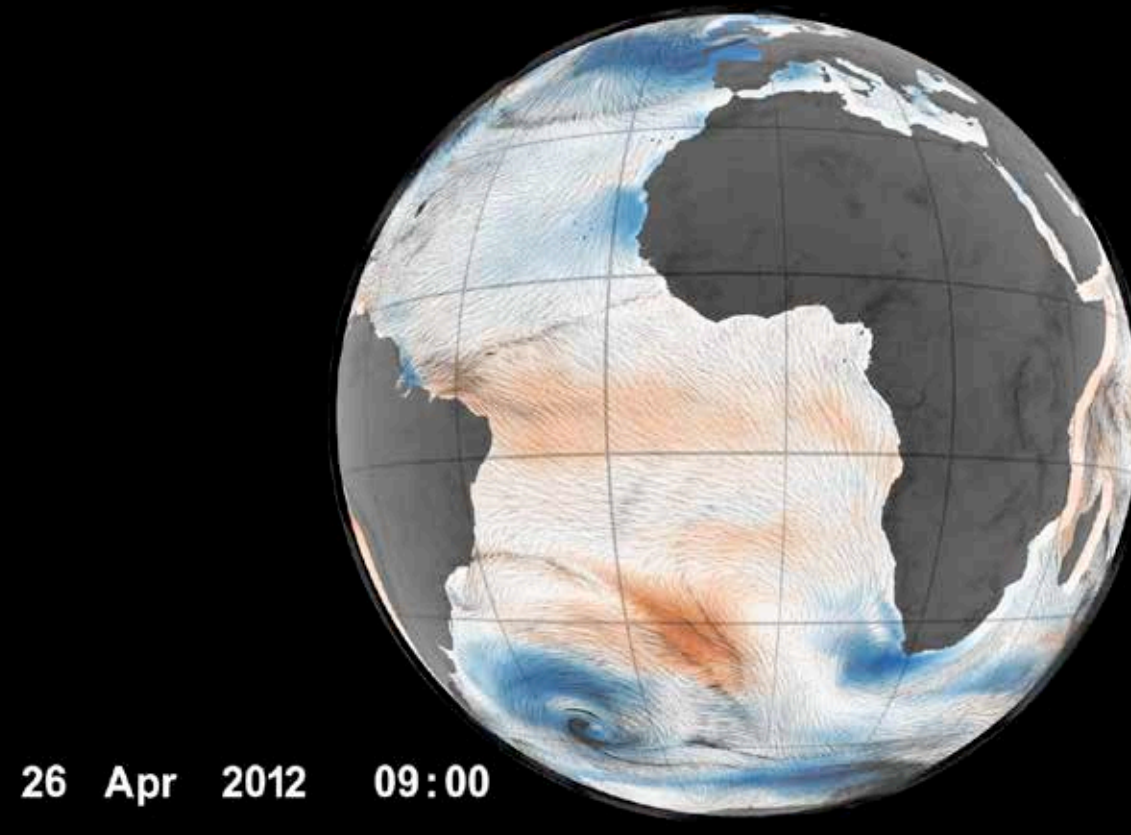
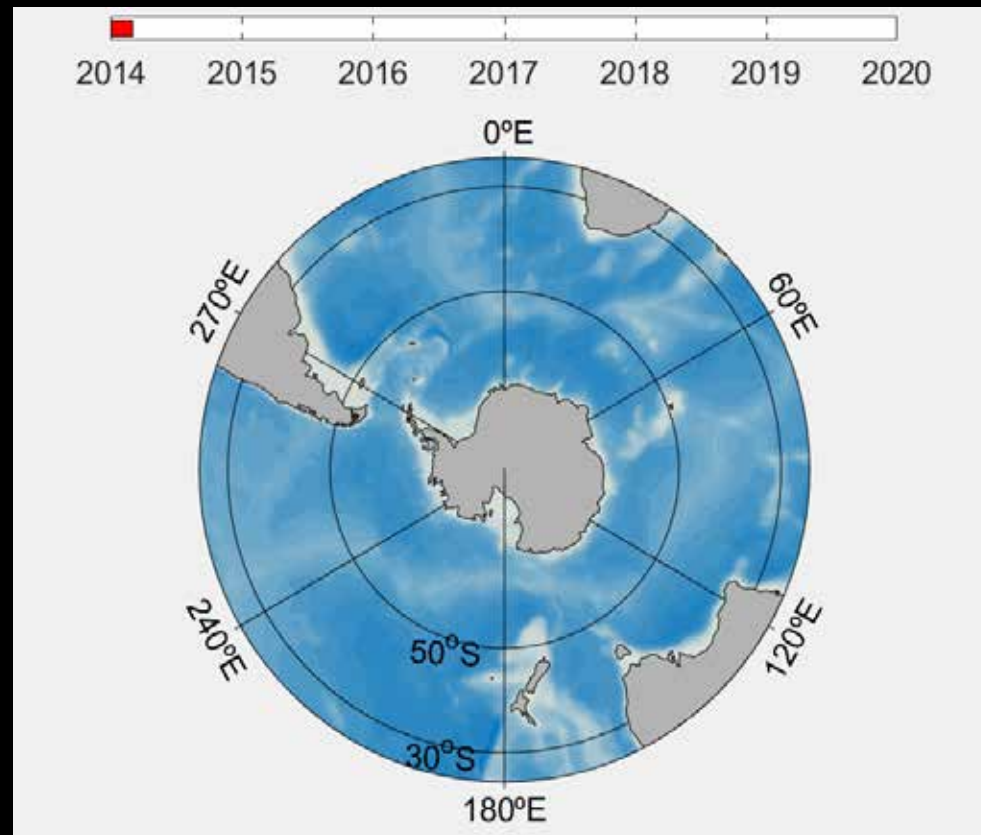
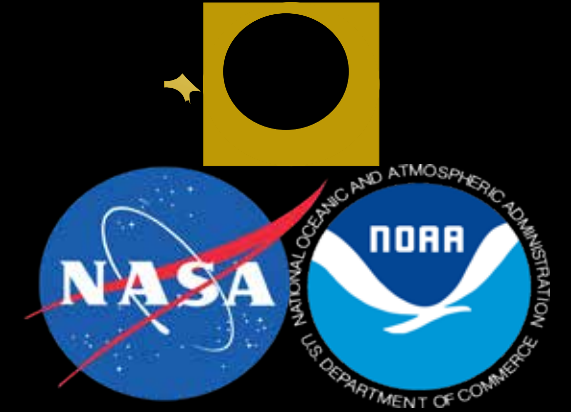
Independent visits per day (ASCAT/Zephyr)

(Left)
Independent visits per day by the ASCAT constellation (< 2 , north of $\sim 55^{\circ}\text{S}$)

(Right)
Independent visits per day by the

$^{\circ}\text{S}$)

PROPOSAL for Progress: The Role of Wind in the Ocean's Heat & Carbon Uptake





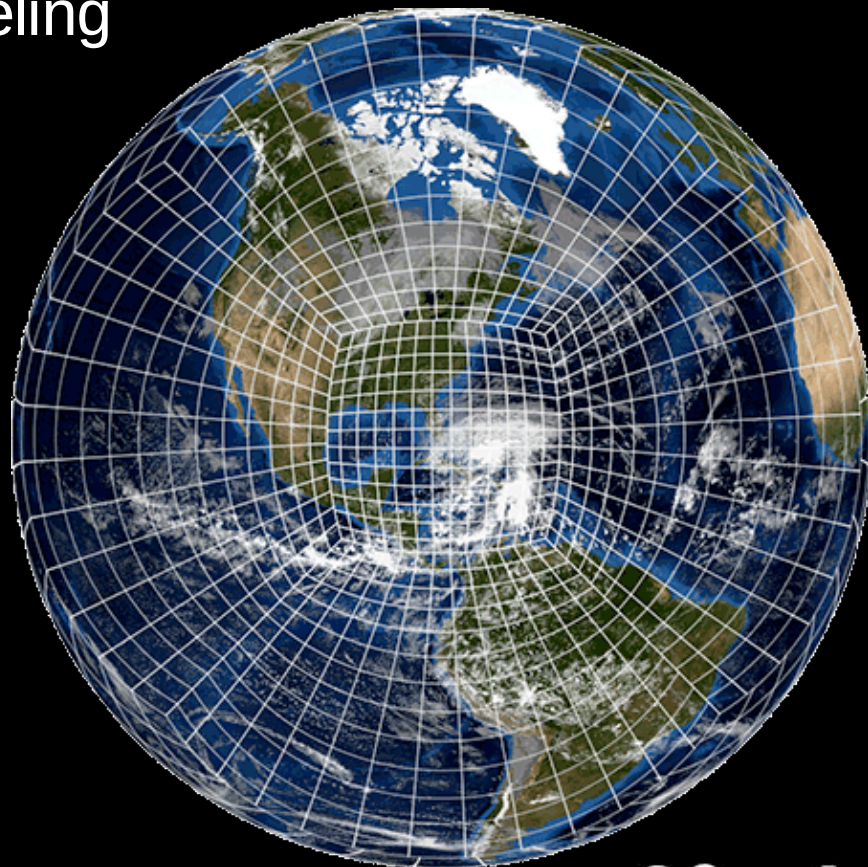
Prof. Joellen L. Russell

Thomas R. Brown Distinguished Chair of Integrative Science
Depts of Geosciences, Planetary Science, Hydrology &
Atmospheric Sciences and Applied Math
University of Arizona

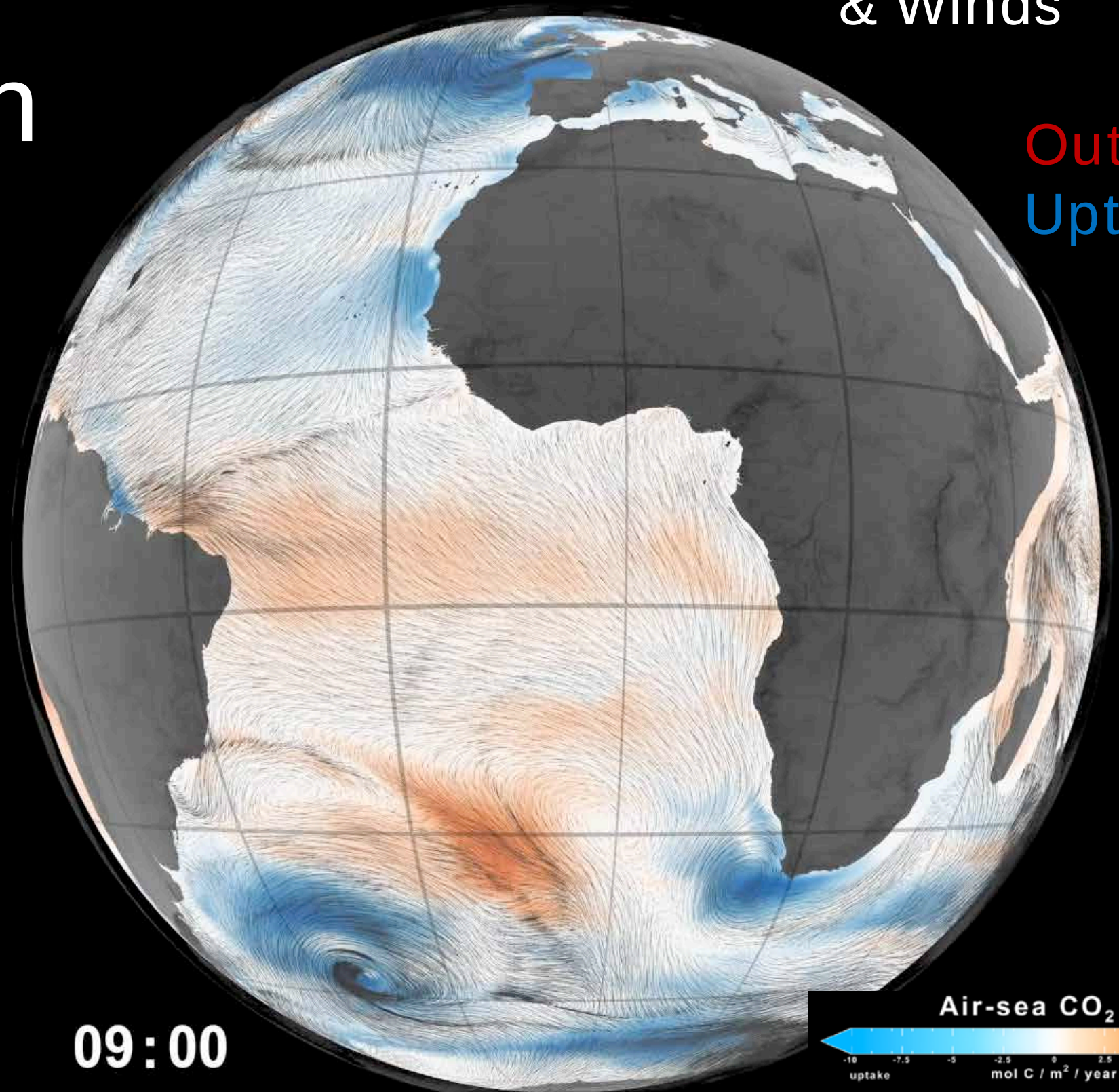
Air-Sea Carbon Flux & Winds

Climate and Carbon Prediction:

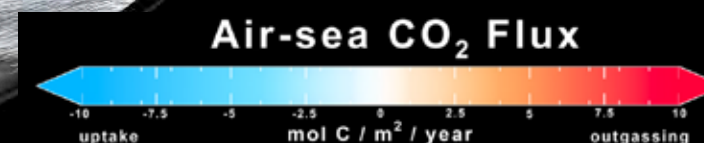
Convergence of
Climate & Weather
Modeling



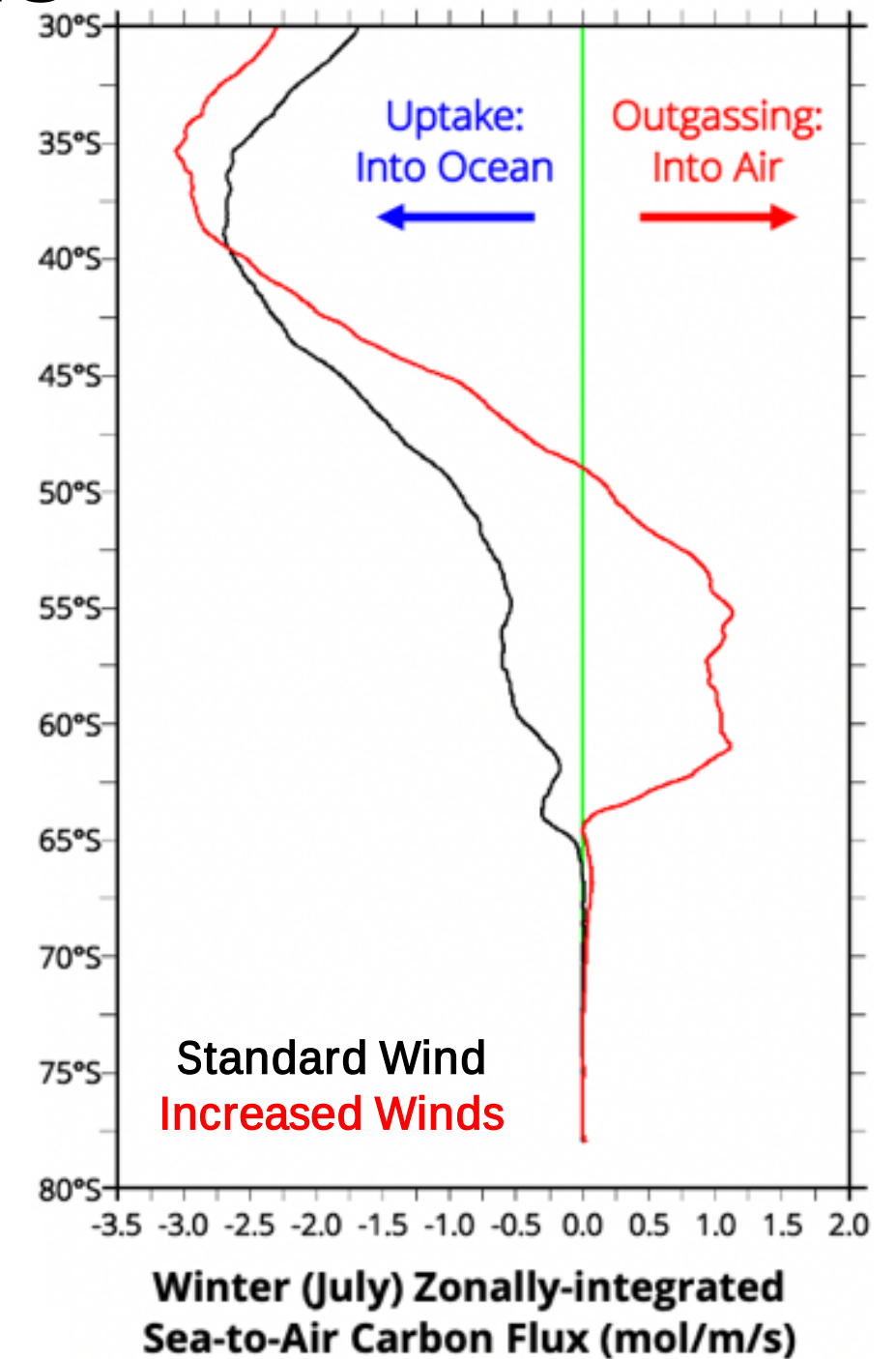
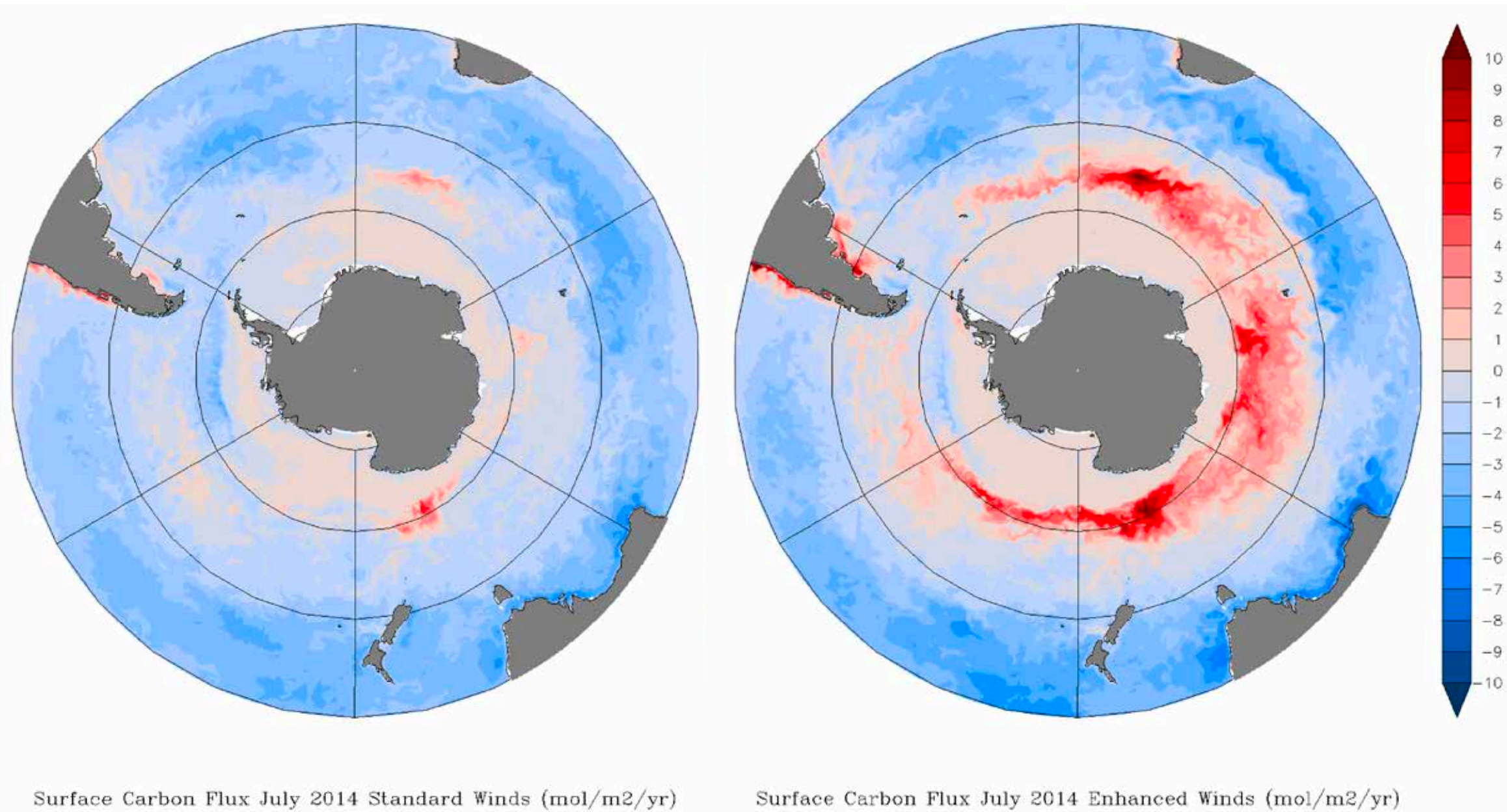
26 Apr 2012 09:00



Outgas
Uptake



Southern Ocean Flips from SINK to SOURCE with 20% increase in winds



Russell et al, in revision at GRL

<https://doi.org/10.1002/essoar.10506276.1>



How do we spread the word?

Shining light on the path ahead ...

WORLD VIEW

A personal take on events



Ocean sea level rise progress

Uncertainties around carbon emissions to enforce. The answer floats

Almost 200 nations have pledged to reduce carbon emissions under the Paris Agreement. But how to know whether they are

For the accord to work, each nation must reduce its share of the total carbon dioxide emissions and deforestation. Both human emissions and natural emissions are incomplete, inaccurate or

As a result, the picture of global climate change is incomplete. For instance, China admitted to increasing its coal consumption by up to 17%.

A solution lies in the seas. About one-quarter of the world's population lives near the oceanographers can better understand the data, along with other atmospheric

nature
climate change

PERSPECTIVE

<https://doi.org/10.1038/s41558-018-0355-y>

Taking climate

Veronika Eyring^{1,2*}, Peter M. Caldwell⁵, William D. Collins⁶, George C. Hurtt¹², Alexandra J. Iijima¹³, Lester Kwiatkowski¹⁶, Ruth L. Angeline G. Pendergrass¹⁹, Benjamin M. Sanderson¹⁹, Benjamin M. Sanderson¹⁹, Ronald J. Stouffer²¹ and Mar

Earth system models are complex, resulting in a range of projections for a given future scenario. Comparing these against observations and the results of other models is now evidence that giving equal weight to all projections is suboptimal. This paper introduces tools that facilitate a more realistic comparison of model simulations with observations, using constraints that are a promising way to combine observations most relevant to the model with the most credible information

ARTICLE

Change in future meltwater

Ben Bronselaer^{1,2,3*}, Michael Winton², Stephen J. Stouffer^{1,2} & Joellen L. Russell¹

Meltwater from the Antarctic ice sheet contributes to a metre of sea-level rise by the end of the 21st century. The concentration trajectory of meltwater from the ice sheets and the widely used CMIP5 climate projections. Here we use the CMIP5 model 'GFDL ES-M2.3.2' to project Antarctic Ice Sheet meltwater under the RCP8.5 scenario, accounting for the maximum global-mean

<https://doi.org/10.1038/s41586-018-0712-z>

nature
geoscience

ARTICLES

<https://doi.org/10.1038/s41561-019-0502-8>

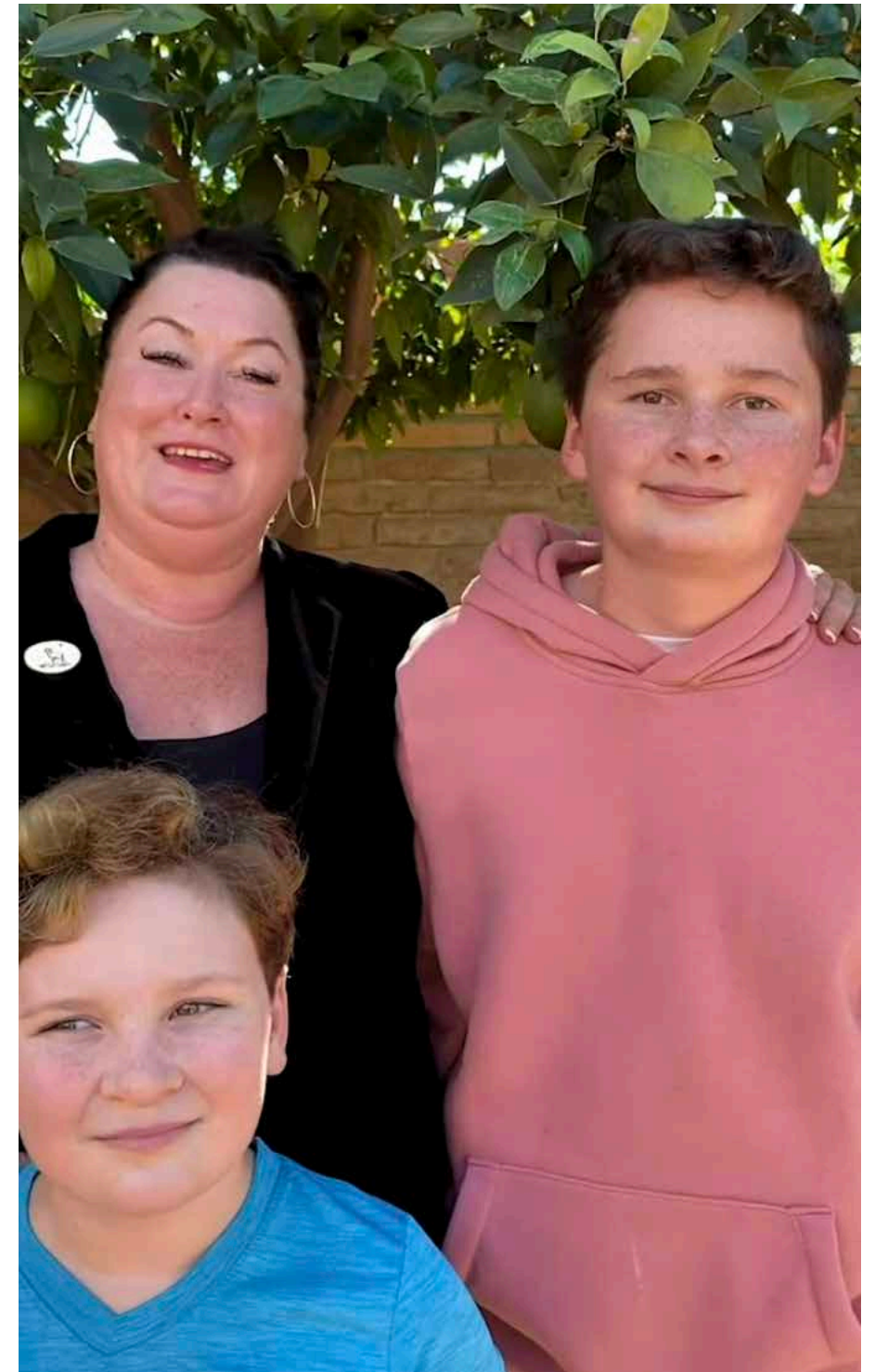
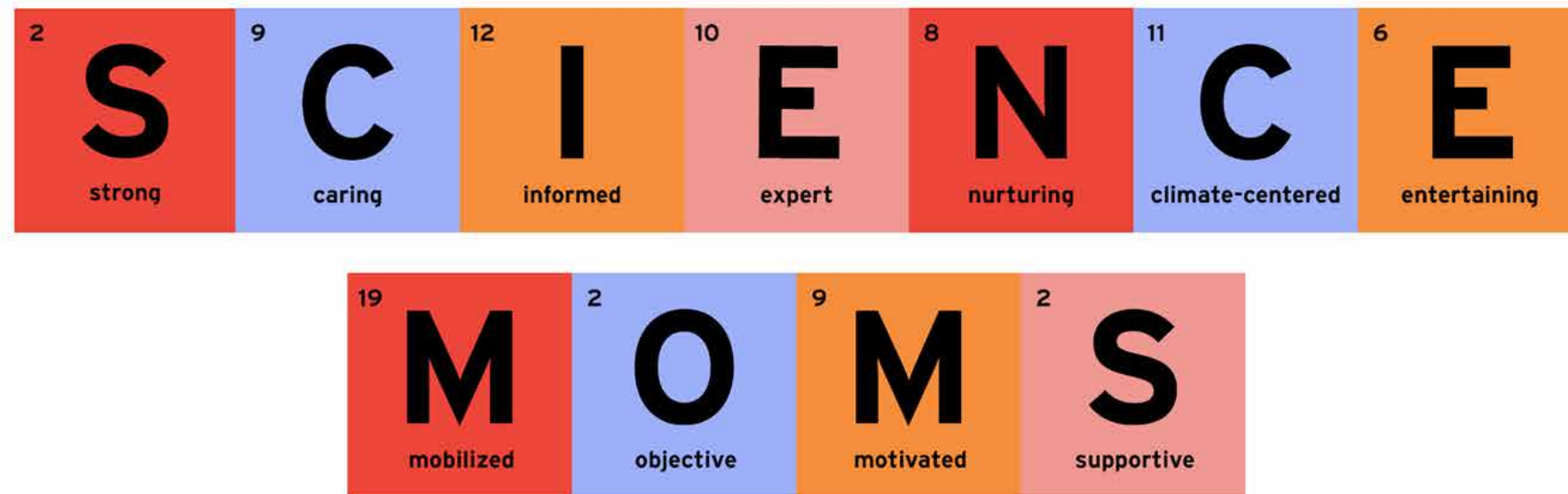
Importance of wind and meltwater for observed chemical and physical changes in the Southern Ocean

Ben Bronselaer^{1,2,3*}, Joellen L. Russell¹, Michael Winton², Nancy L. Williams⁴, Robert M. Key³, John P. Dunne², Richard A. Feely⁵, Kenneth S. Johnson⁶ and Jorge L. Sarmiento³

The Southern Ocean south of 30°S represents only one-third of the total ocean area, yet absorbs half of the total ocean anthropogenic carbon and over two-thirds of ocean anthropogenic heat. In the past, the Southern Ocean has also been one of the most sparsely measured regions of the global ocean. Here we use pre-2005 ocean shipboard measurements alongside novel observations from autonomous floats with biogeochemical sensors to calculate changes in Southern Ocean temperature, salinity, pH and concentrations of nitrate, dissolved inorganic carbon and oxygen over two decades. We find local warming of over 3°C, salinification of over 0.2 psu near the Antarctic coast, and isopycnals are found to deepen between 65° and 40°S. We find deoxygenation along the Antarctic coast, but reduced deoxygenation and nitrate concentrations where isopycnals deepen farther north. The forced response of the Earth system model ESM2M does not reproduce the observed patterns. Accounting for meltwater and poleward-intensifying winds in ESM2M improves reproduction of the observed large-scale changes, demonstrating the importance of recent changes in wind and meltwater. Future Southern Ocean biogeochemical changes are likely to be influenced by the relative strength of meltwater input and poleward-intensifying winds. The combined effect could lead to increased Southern Ocean deoxygenation and nutrient accumulation, starving the global ocean of nutrients sooner than otherwise expected.



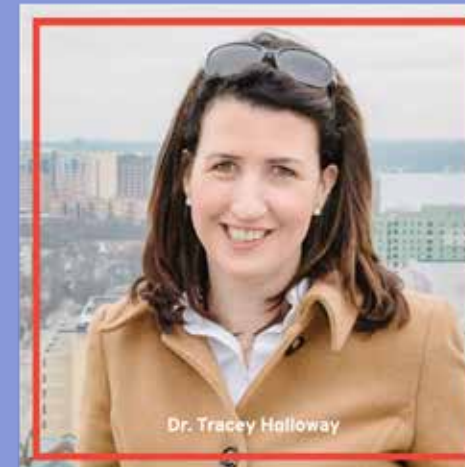
Melanie Stetson Freeman/Staff; Christian Science Monitor; <https://www.csmonitor.com/Environment/2022/0111/Meet-the-scientist-moms-fighting-climate-change-for-their-children>



Science Moms is a nonpartisan group of mothers who work in climate science and are concerned about the future their kids will face.

Together, they have over a century of experience studying our changing climate and the effects it will have on our kids and their kids after that.

As a team, they aim to break down climate change in ways that are simple, fresh and relevant to moms. And give them tangible ways to take action.



Science Moms wants all mothers to prioritize action on climate change.

To do that, we need to persuade them that this issue is as important as all the other things they're worried about (the economy, education, putting food on the table, etc).

We will achieve this by:

- Reframing the problem

- Explaining what's at stake

- Building her confidence to talk about it

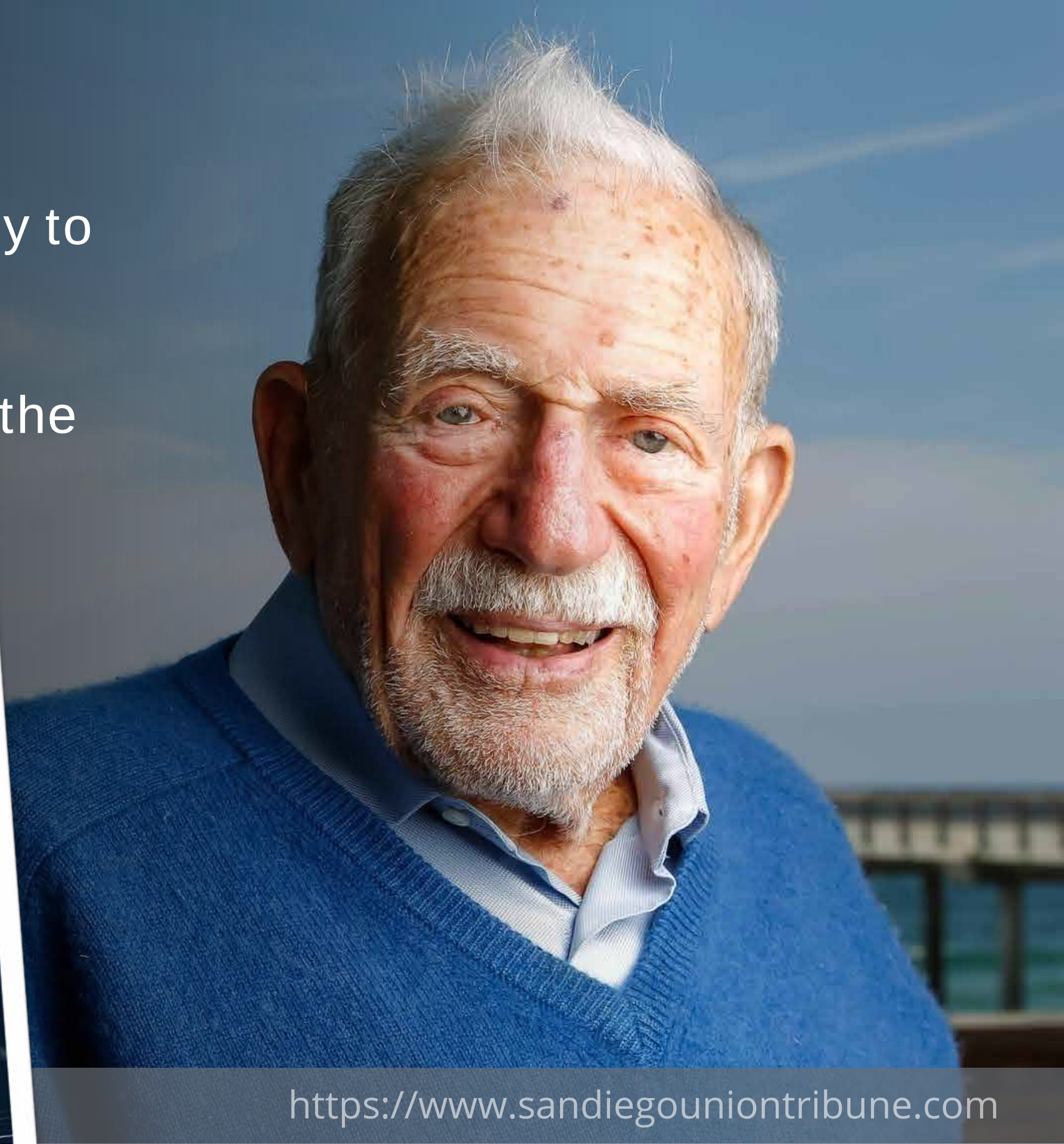
- Making solutions achievable

- Giving her the tools to act



Walter Munk

He joined the service willingly to
friendships and the U.S. Navy Radio
and Signal School at Annapolis
the week before the attack during the
Pearl Harbor attack.



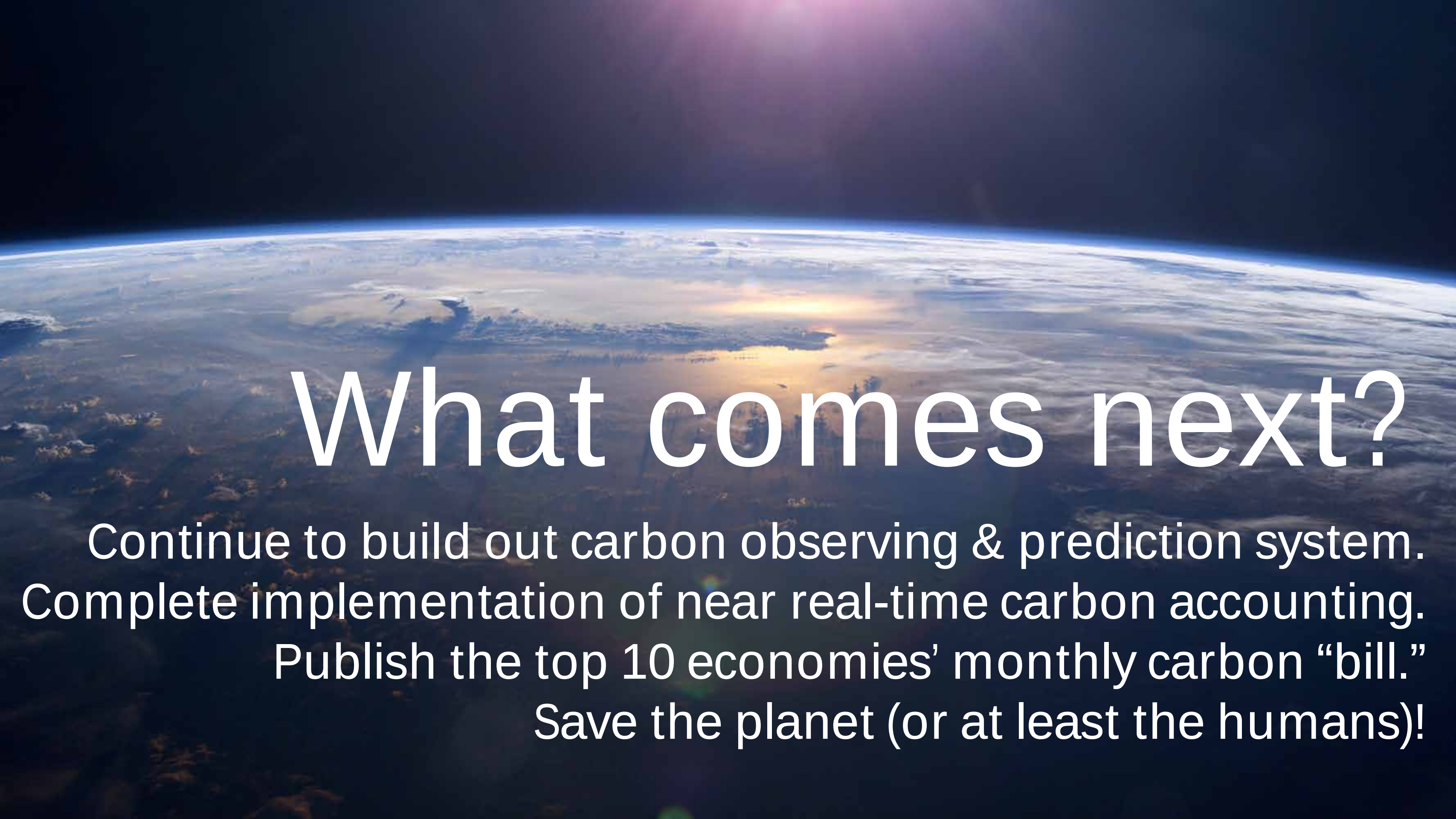
We Can Do It!



POST FEB. 15 TO FEB. 28



WAR PRODUCTION CO-ORDINATING COMMITTEE

A view of Earth from space, showing the horizon and clouds. The sun is visible in the distance, creating a bright glow and lens flare effect. The text is overlaid on this background.

What comes next?

Continue to build out carbon observing & prediction system.

Complete implementation of near real-time carbon accounting.

Publish the top 10 economies' monthly carbon "bill."

Save the planet (or at least the humans)!

GEOSCIENCES

THE UNIVERSITY OF ARIZONA



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