Climate & The Deep Blue Sea

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University of Arizona

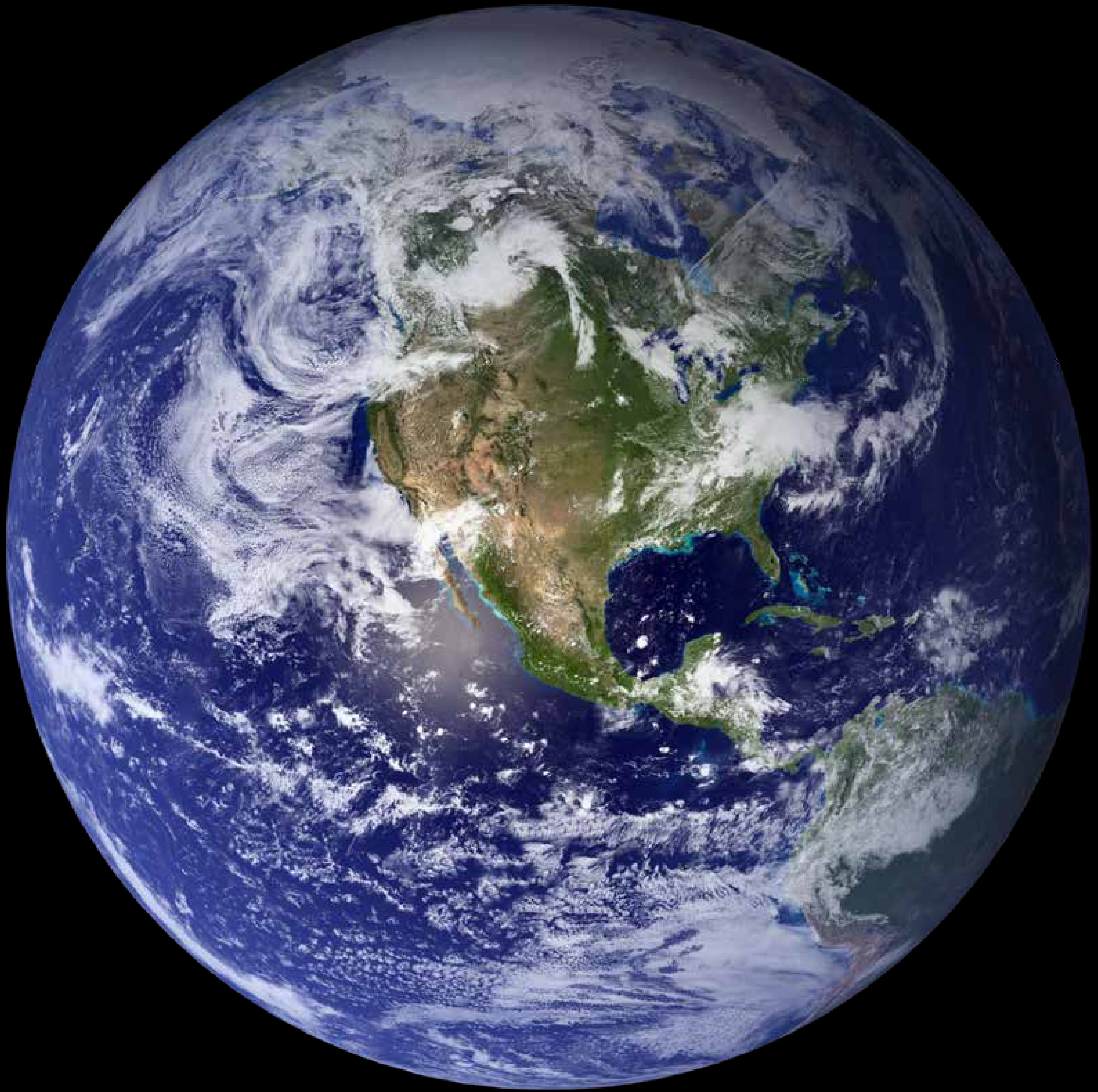
17 April 2025 – Rotary Club of Oro Valley,
Westward Look Wyndham Grand Resort, Tucson, AZ

The Pale Blue Dot

"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

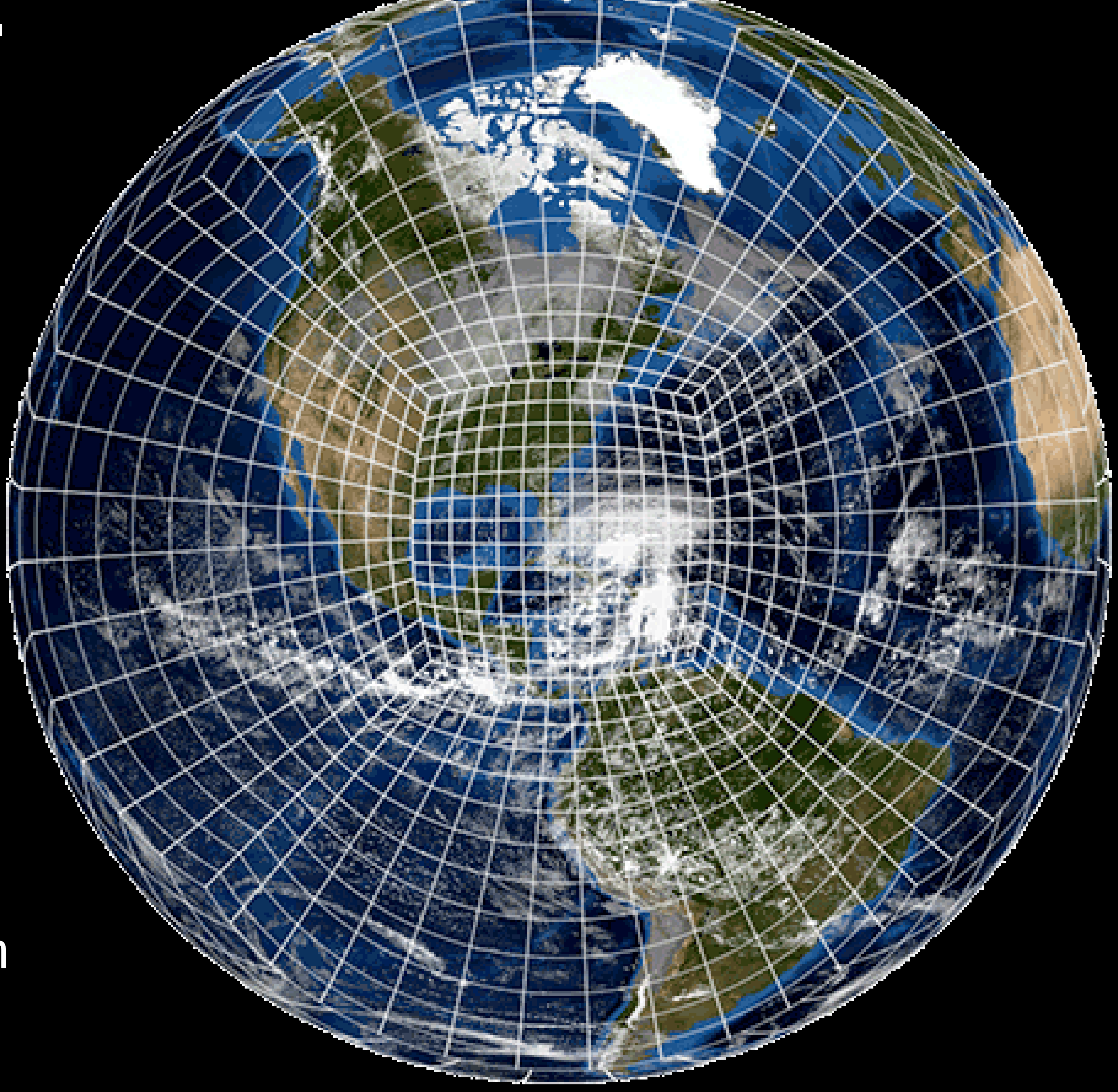
Our Blue Planet



If you like your weather forecast, thank an oceanographer!

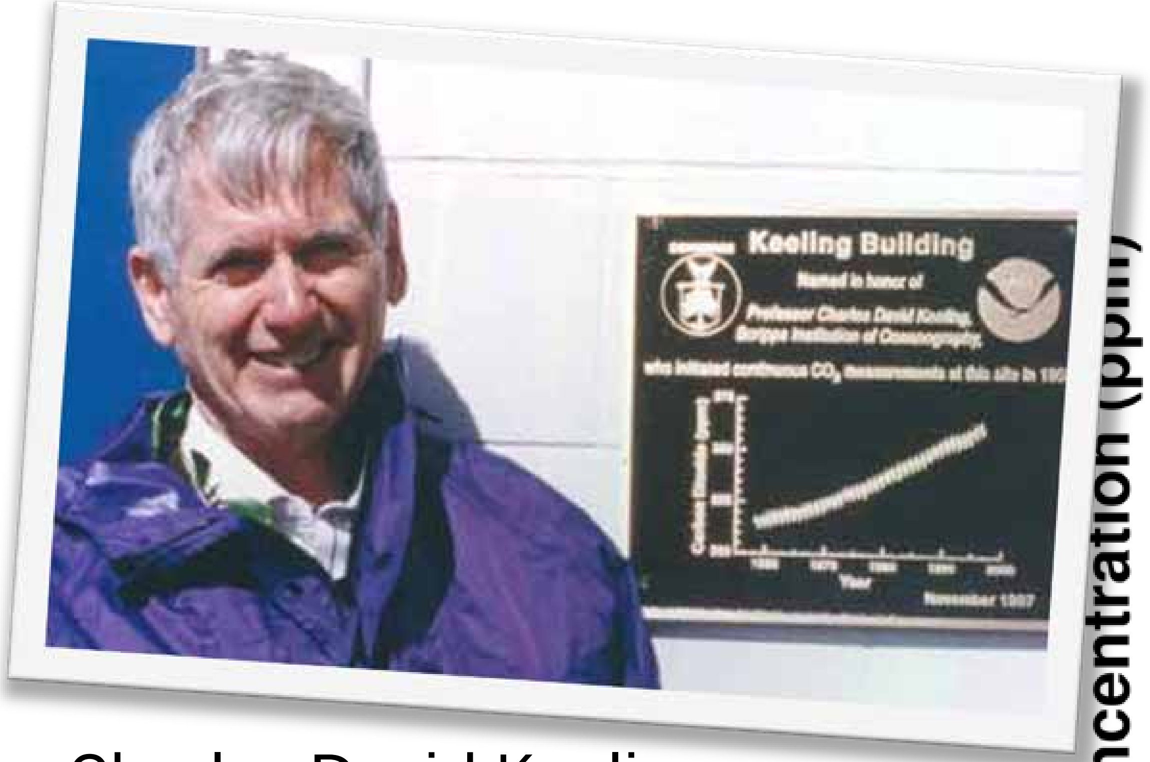
Advent of GFDL's FV3:

Convergence of Climate & Weather Modeling

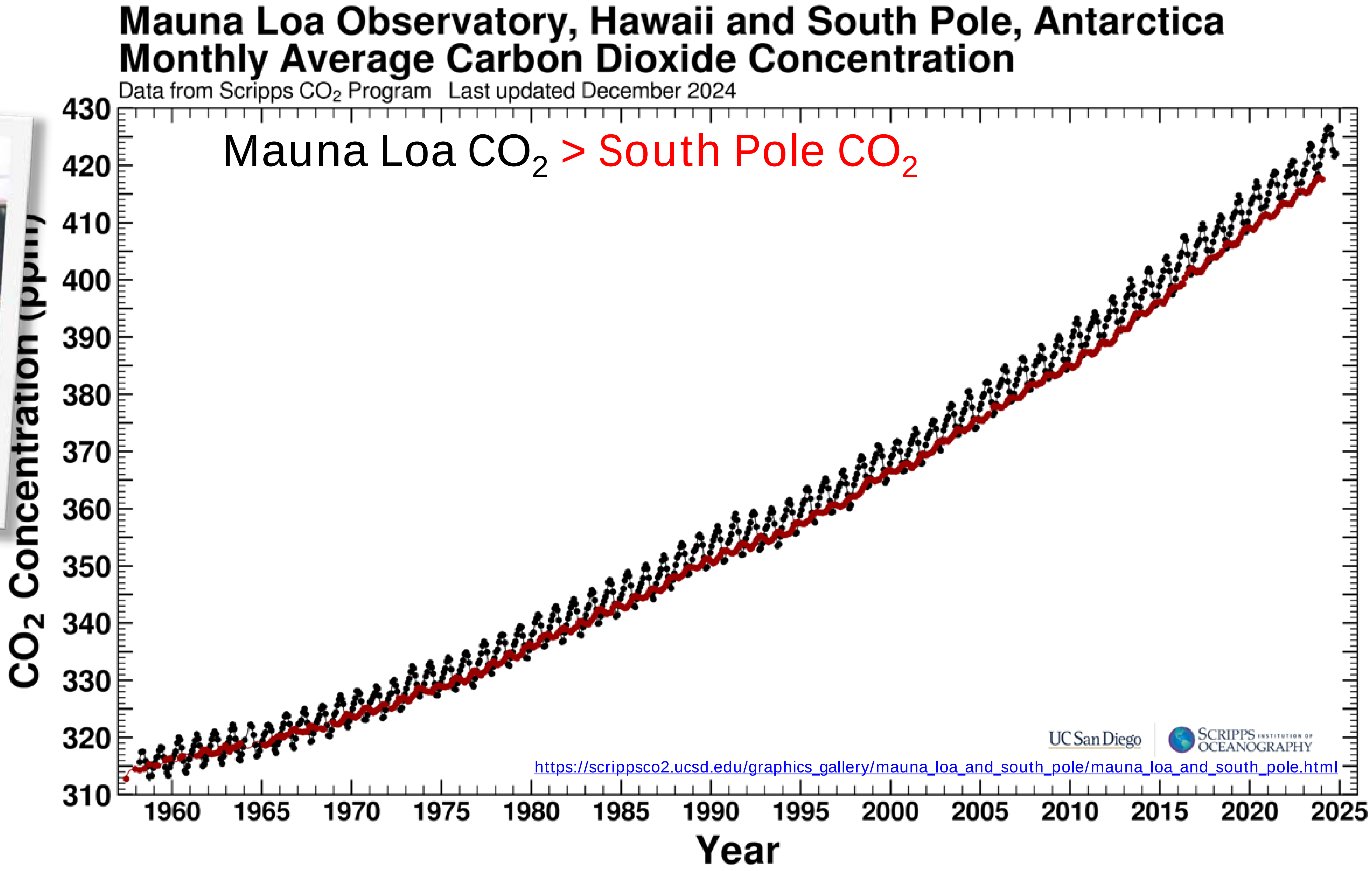


FV3 has been chosen as the dynamical core for the Next Generation Global Prediction System project (NGGPS), designed to upgrade the current operational Global Forecast System (GFS) to run as a unified, fully-coupled system in NOAA's Environmental Modeling System infrastructure.

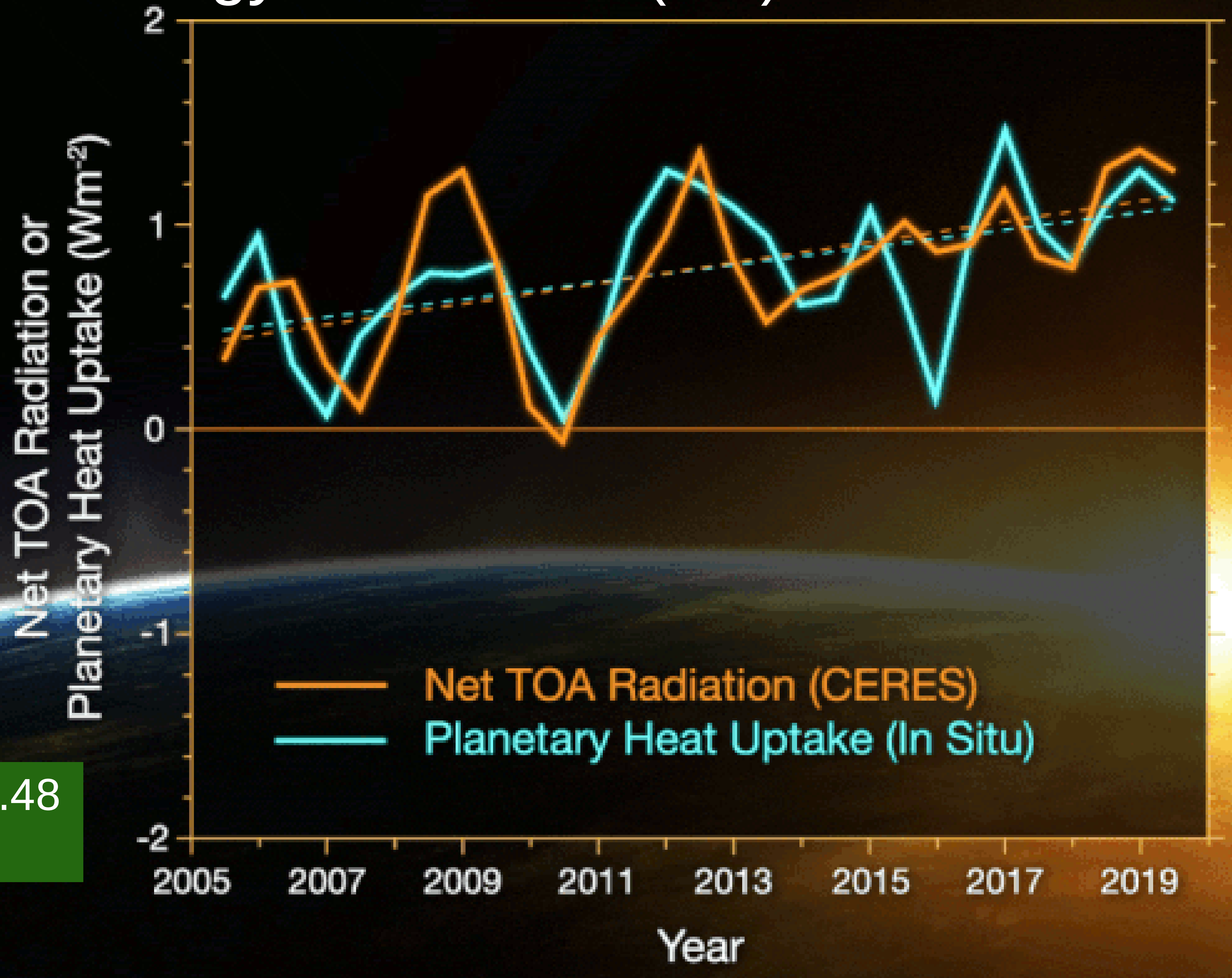
The Keeling Curve: Atmospheric CO_2 (Dec '24)



Charles David Keeling
(1928-2005)



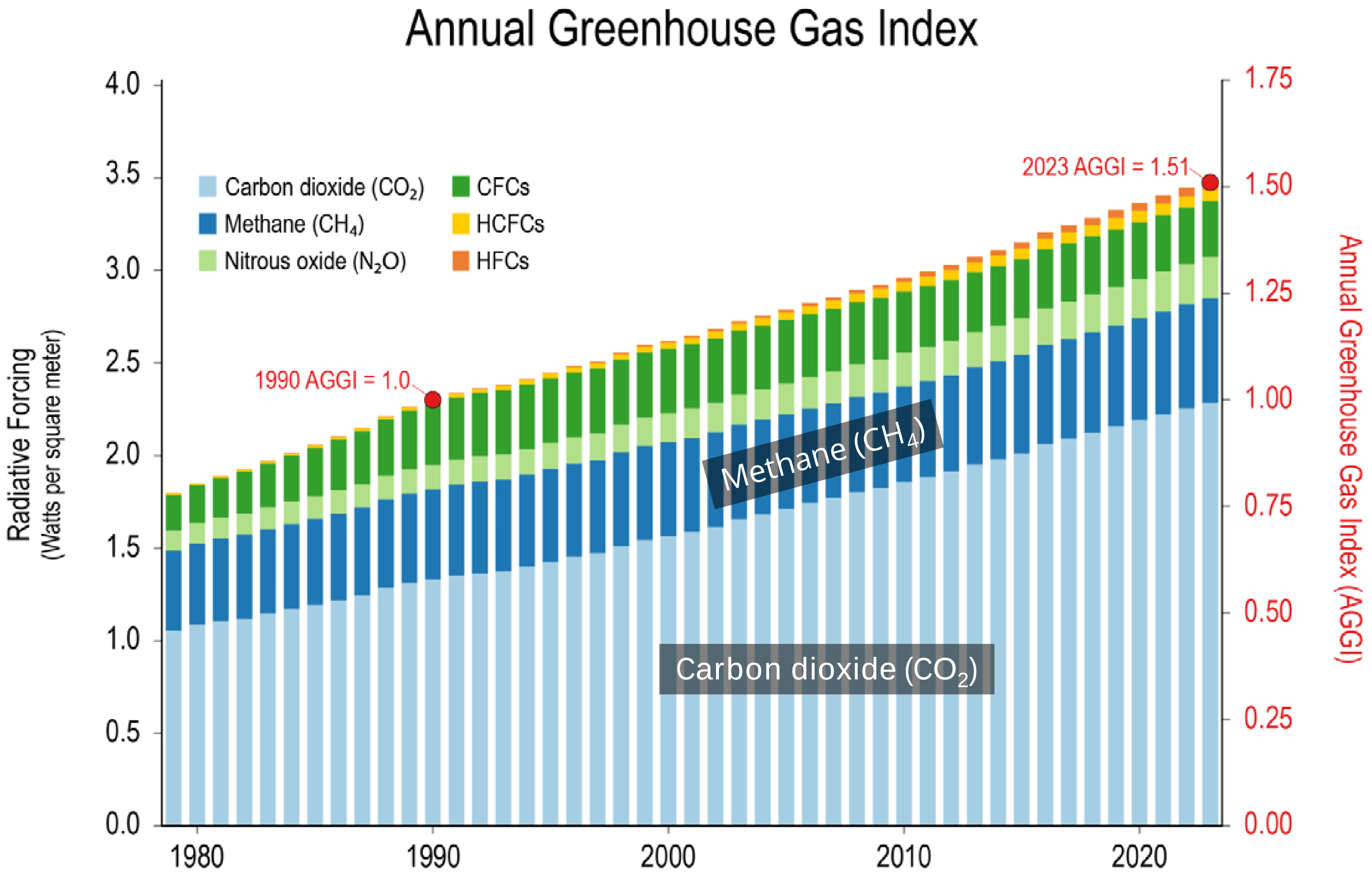
Earth's net energy imbalance (EEI) has more than DOUBLED



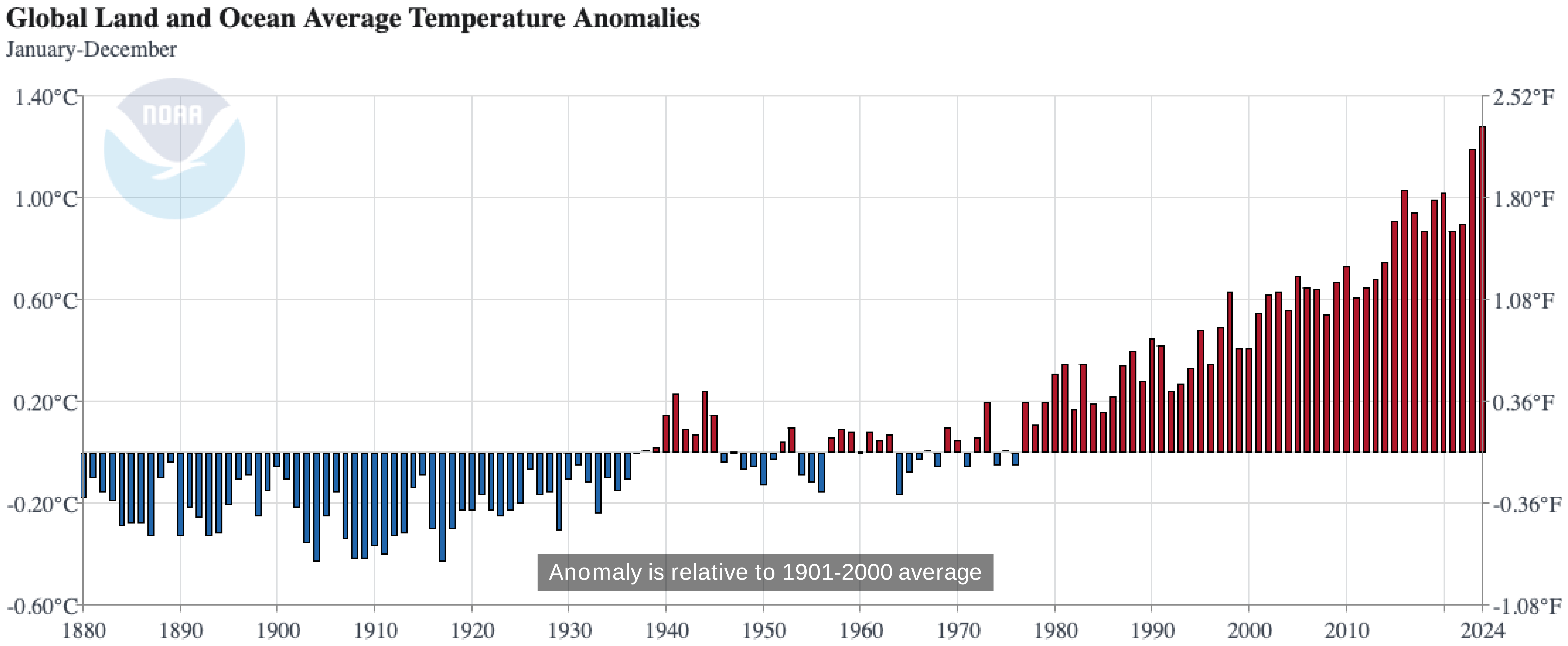
EEI = 0.42±0.48 Wm

https://research.noaa.gov/article/ArtMID/587/ArticleID/2626/Warming-influence-of-greenhouse-gases-continues-to-rise-NOAA-finds

https://www.globalchange.gov/browse/indicators/annual-greenhouse-gas-index

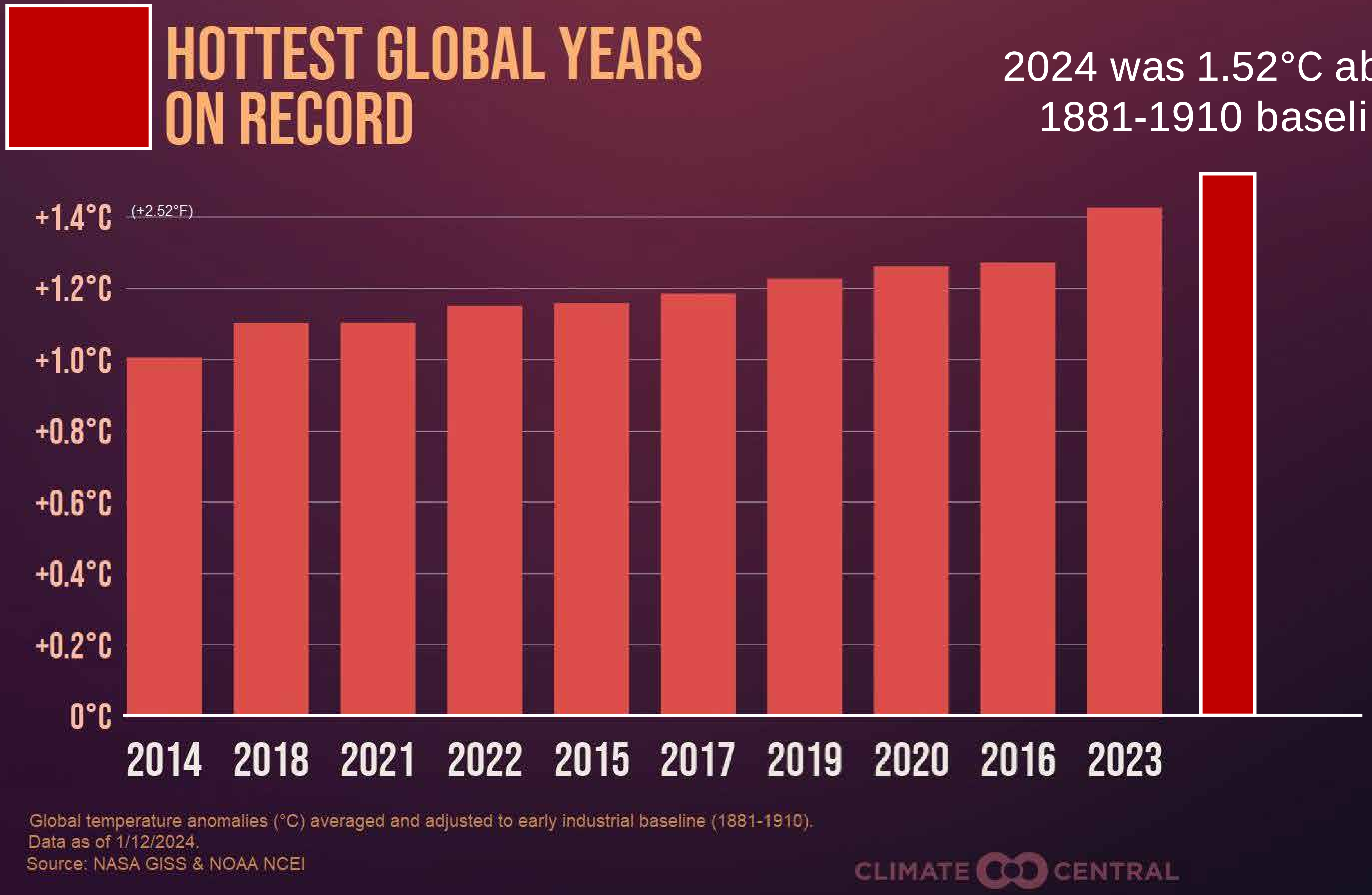


Global Atmospheric Temperature Anomalies



https://www.ncdc.noaa.gov/cag/global/time-series/globe/land_ocean/ytd/12/1880-2024

2024 was 1.52°C above 1881-1910 baseline



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°

https://www.climatecentral.org/news/report-american-warming-us-heats-up-earth-day

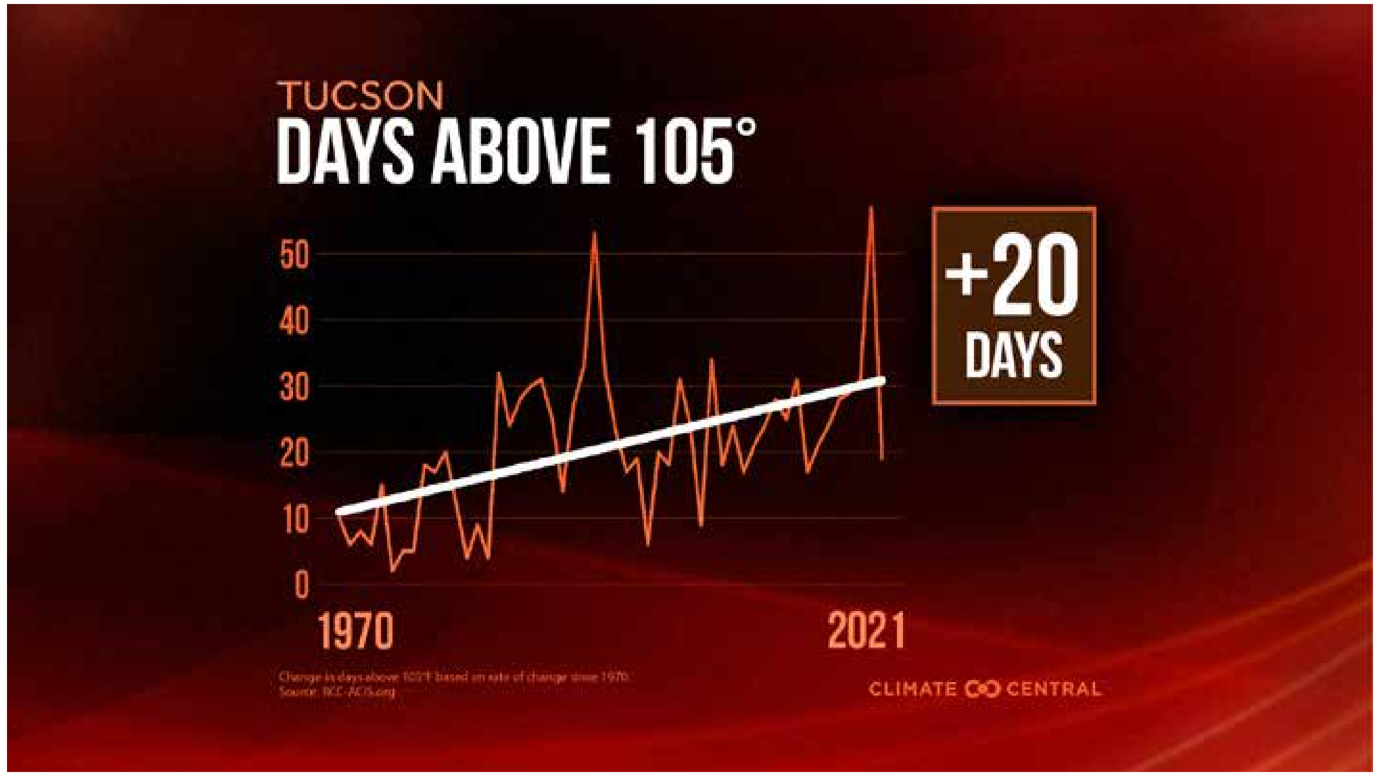
America's 20 Fastest-Warming Cities

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.

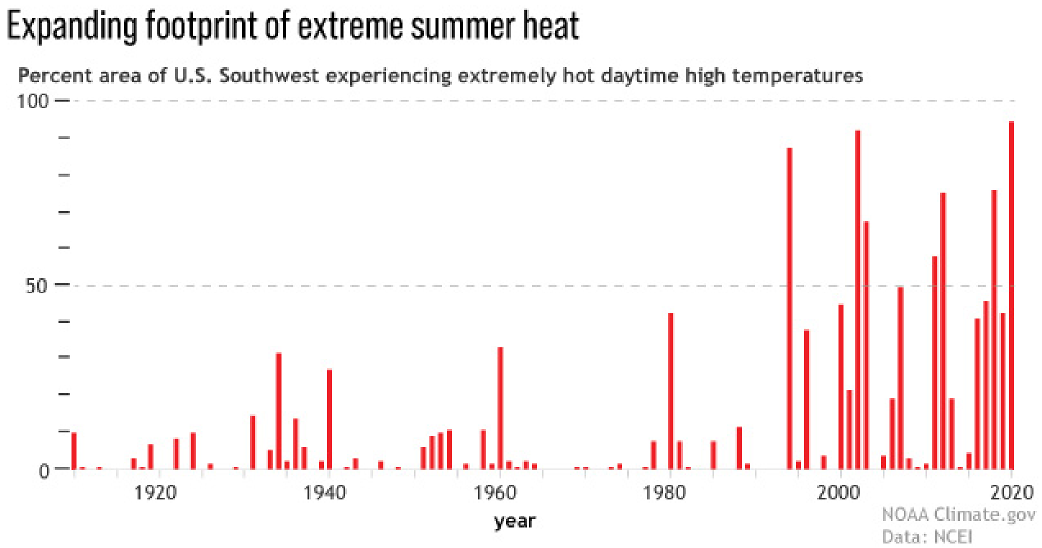
https://www.climatecentral.org/news/report-american-warming-us-heats-up-earth-day

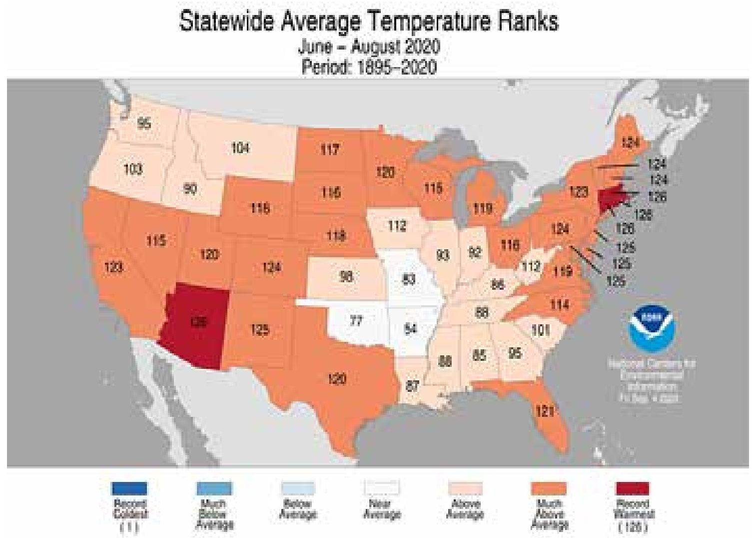

PHOENIX
DAYS ABOVE 110°
50
40
30
20
10
1970
2021
+12
DAYS
Change in days above 110°F based on rate of change since 1970.
Source: RCC-ACIS.org
CLIMATE CENTRAL

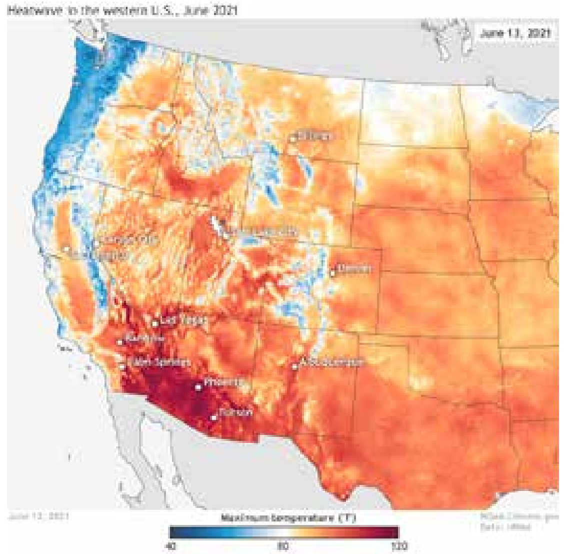

TUCSON
DAYS ABOVE 105°
50
40
30
20
10
0
1970
2021
+20
DAYS
CLIMATE CENTRAL


YUMA • EL CENTRO
DAYS ABOVE 110°
50
40
30
20
10
0
1970
2021
+19
DAYS
CLIMATE CENTRAL

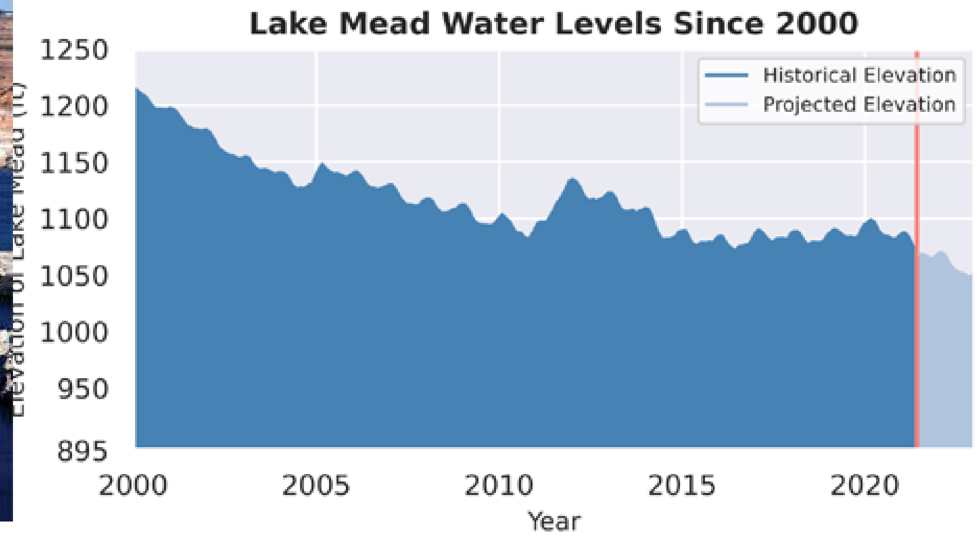
1. Heat waves





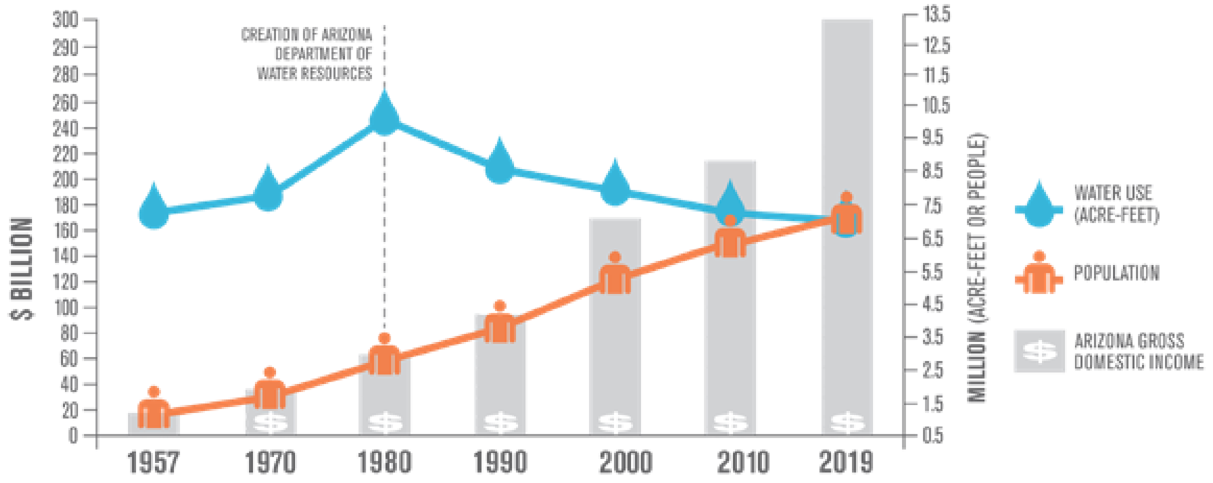


2. Drought



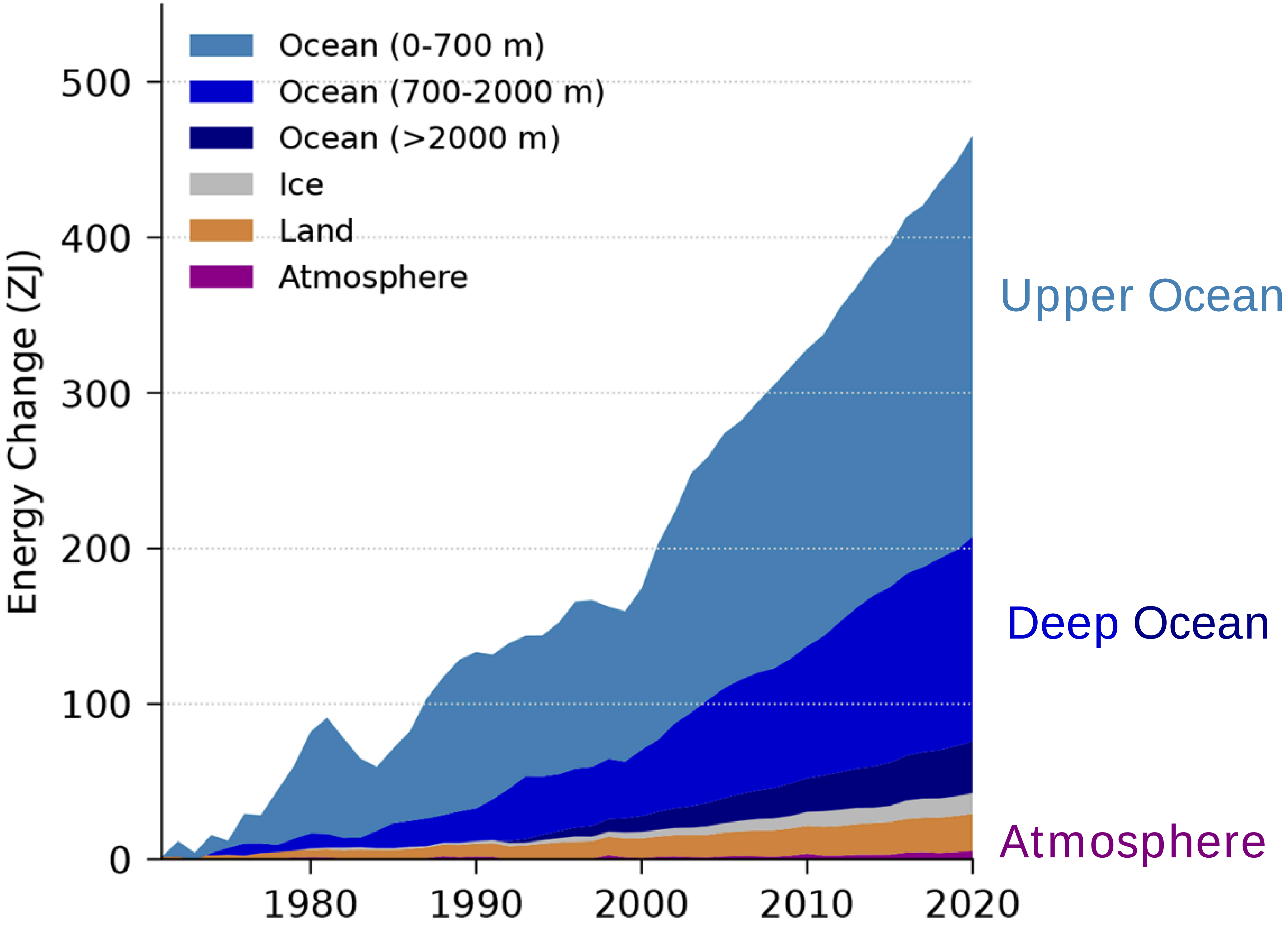
3. Flood

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



IPCC AR5 (2013) WGI Chapter 3 (ocean observations); updated Forster et al. (2023), https://doi.org/10.5194/essd-15-2295-2023

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

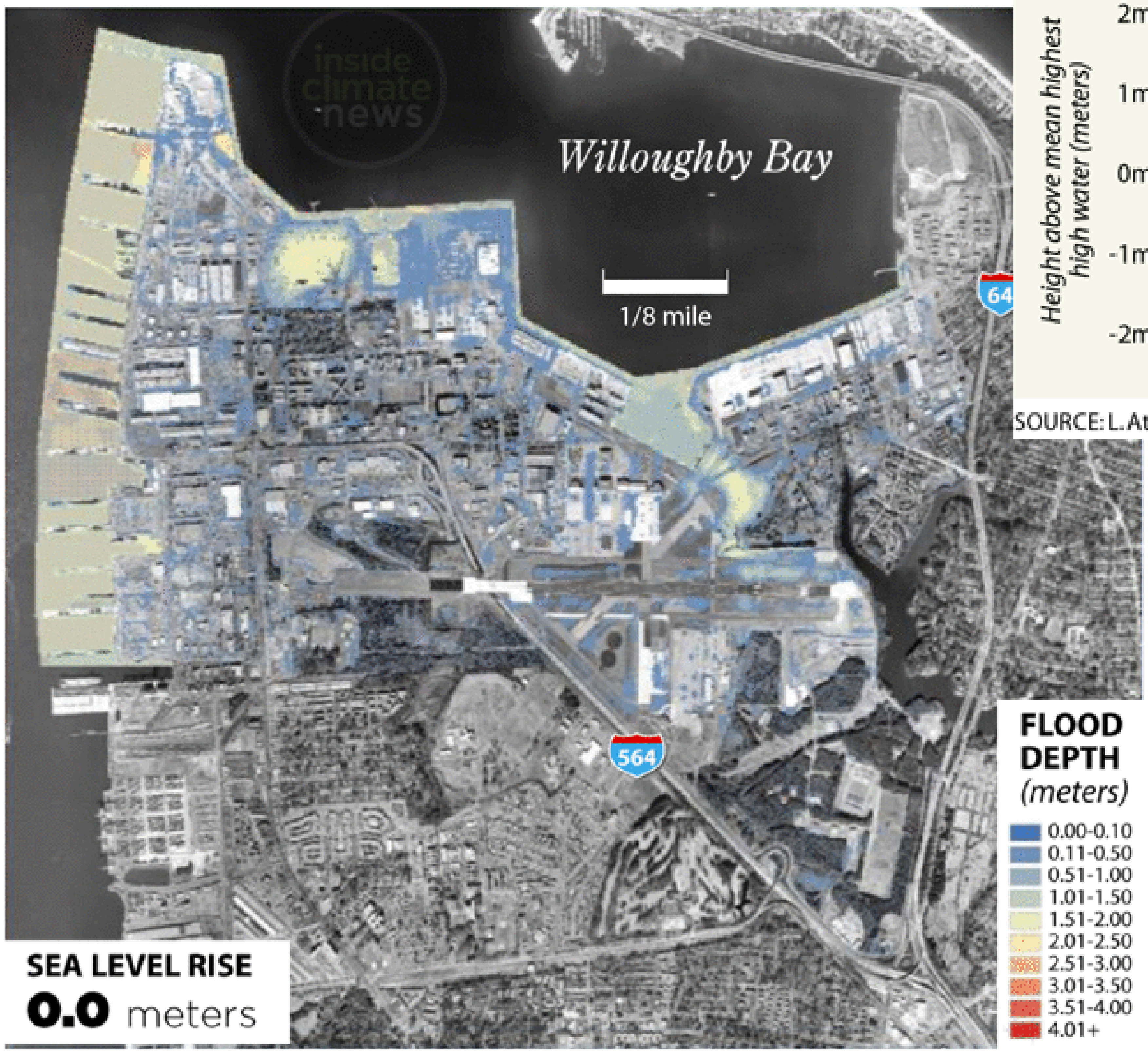
After 1.5°C Warming

After 2°C Warming

After 4°C Warming

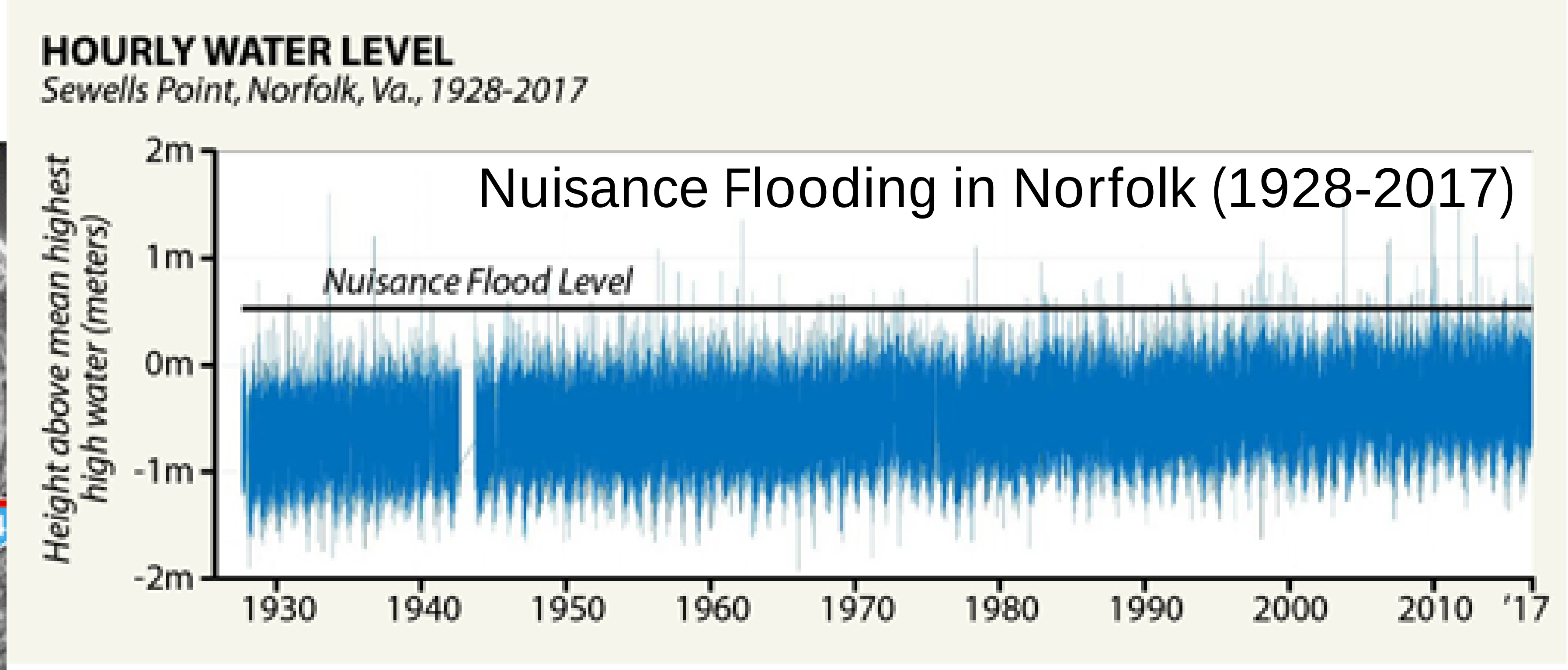
How Rising Seas Will Affect Norfolk Base

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.



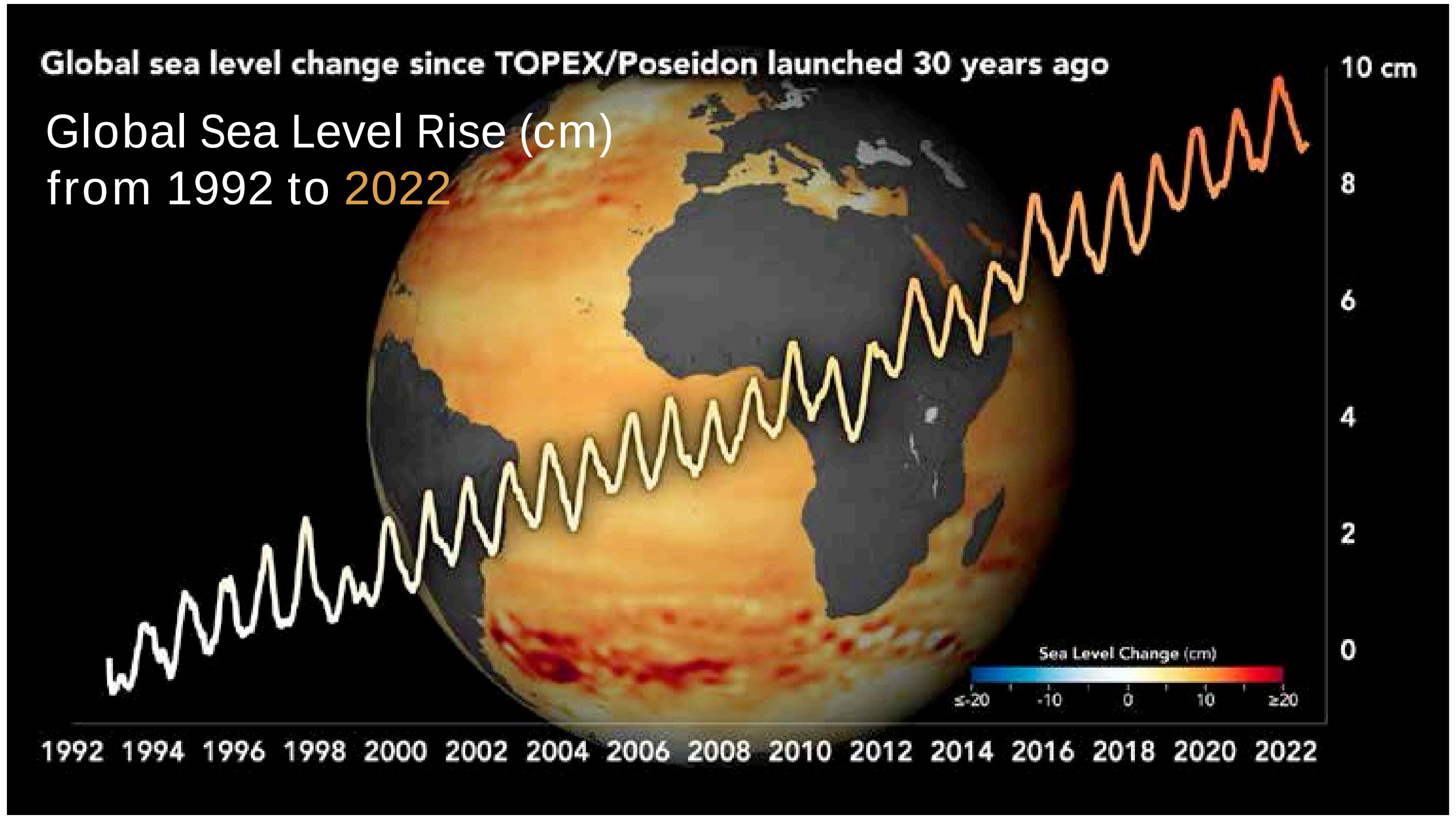
SOURCE: U.S. Army Engineer Research and Development Center

PAUL HORN / InsideClimate News

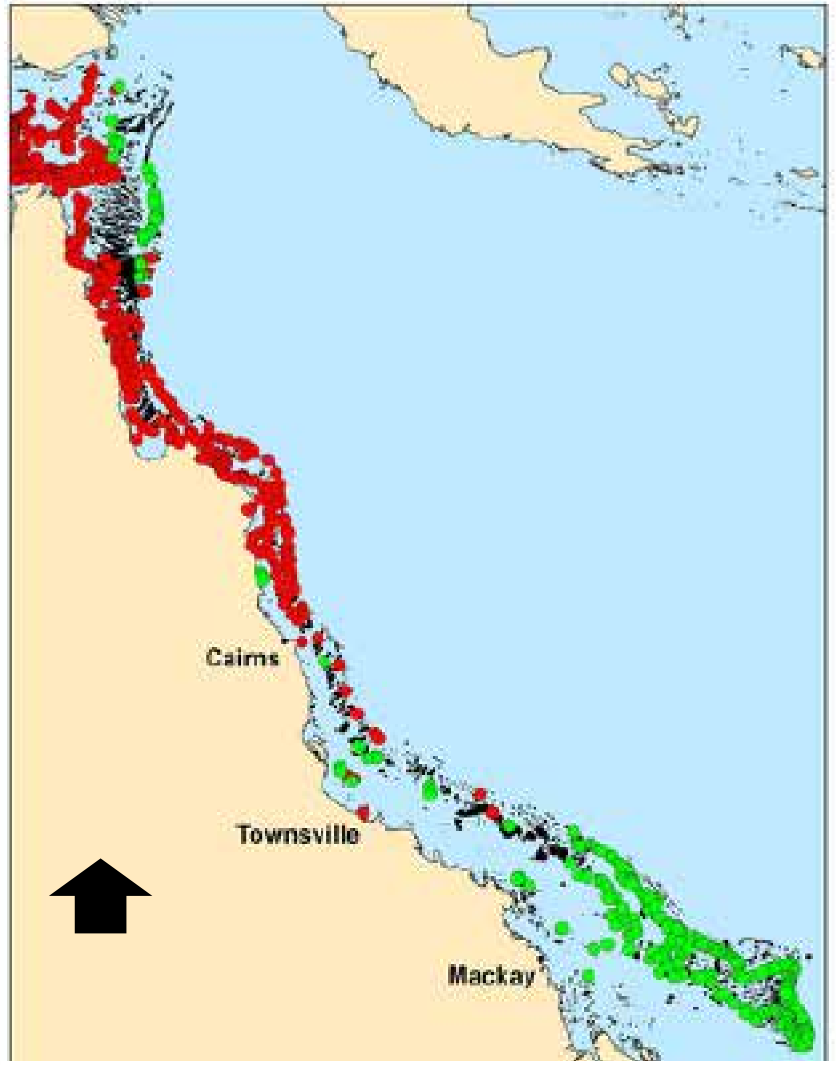


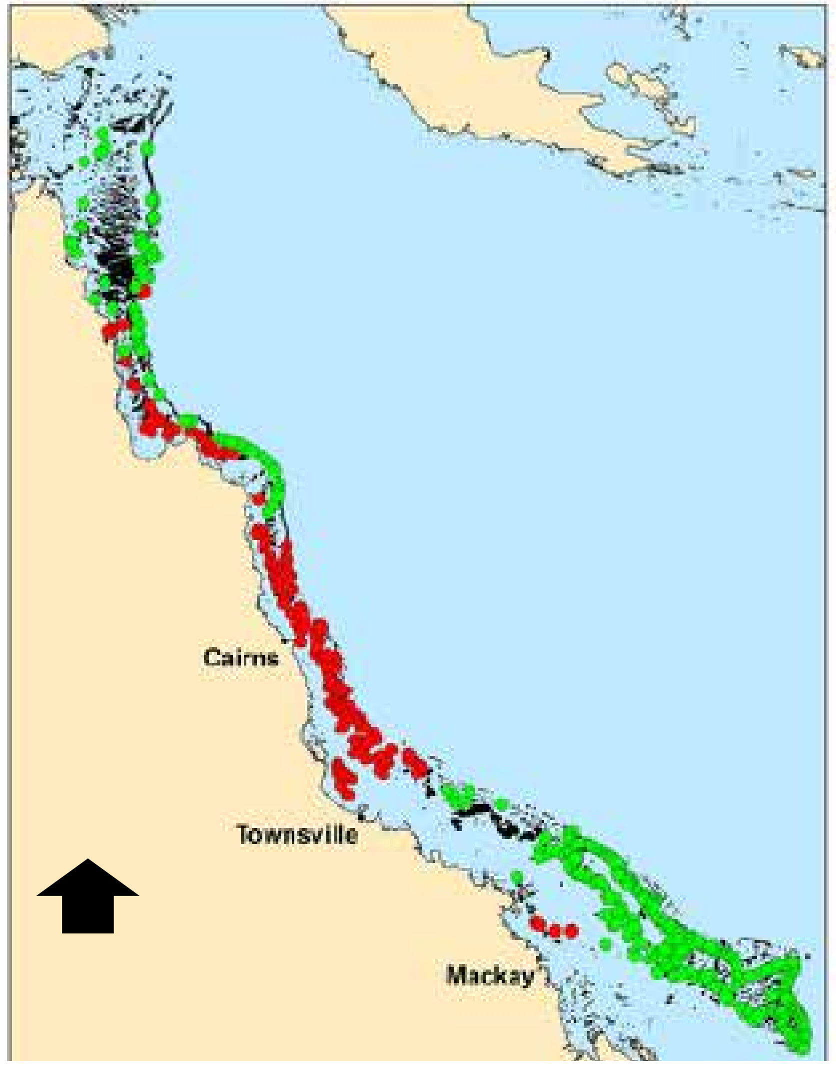
SOURCE: L. Atkinson ODU

InsideClimate News

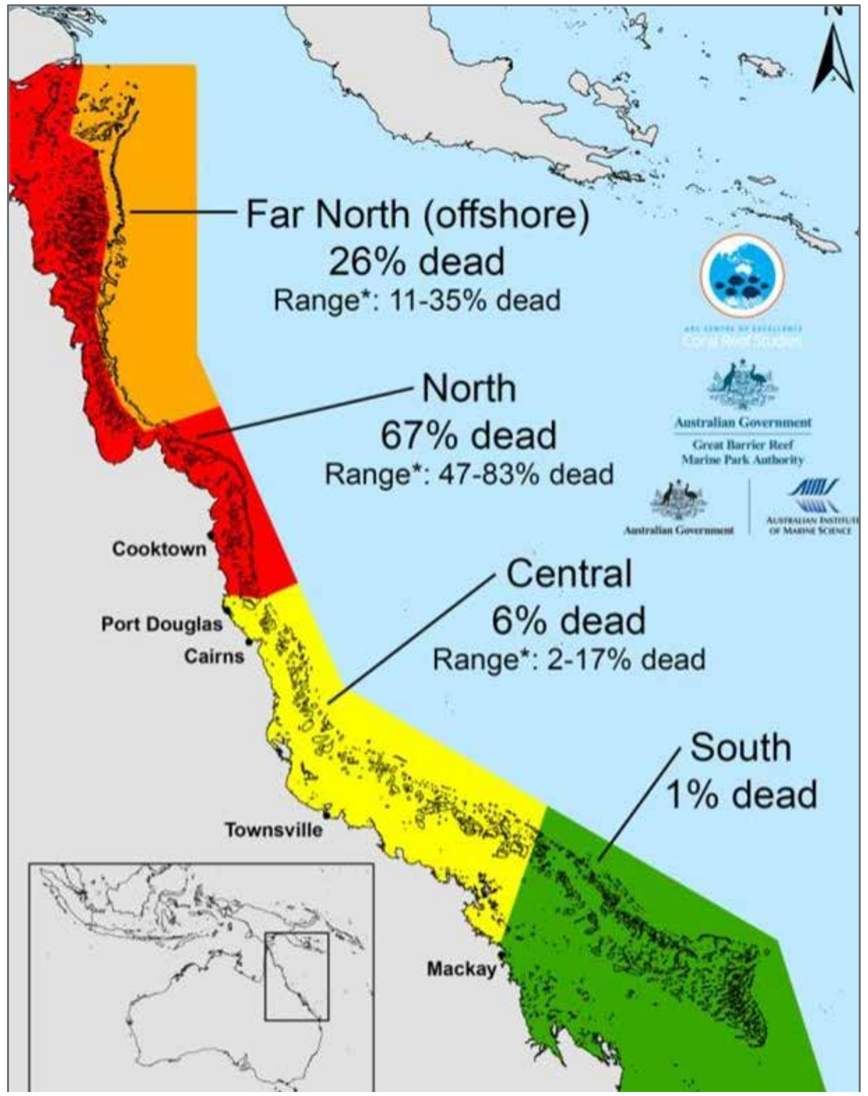


Major bleaching events on the Great Barrier Reef





● Severe Bleaching
● No or Negligible Bleaching



Coral Mortality

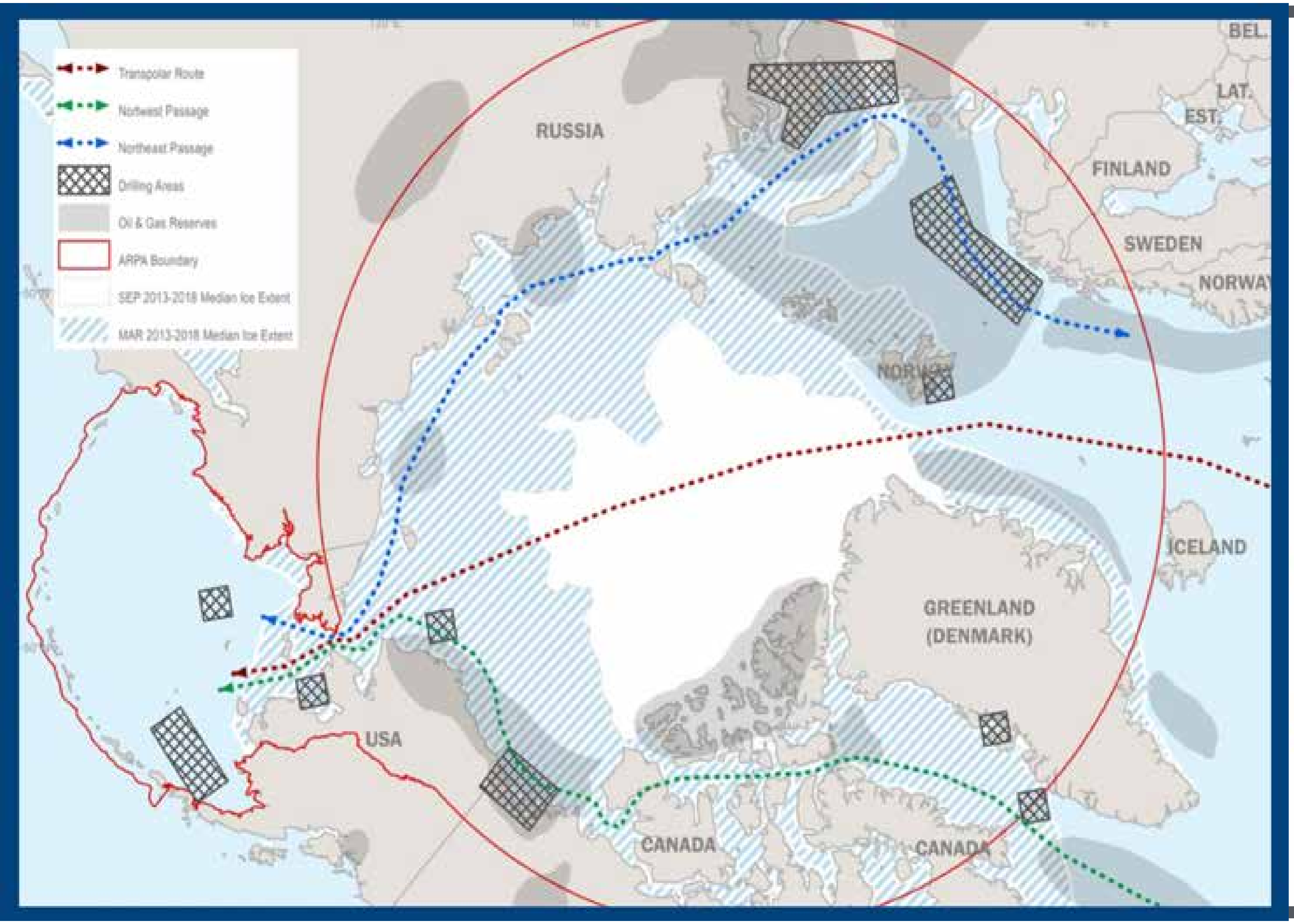
Global Shipping (June 1-15, 2012)

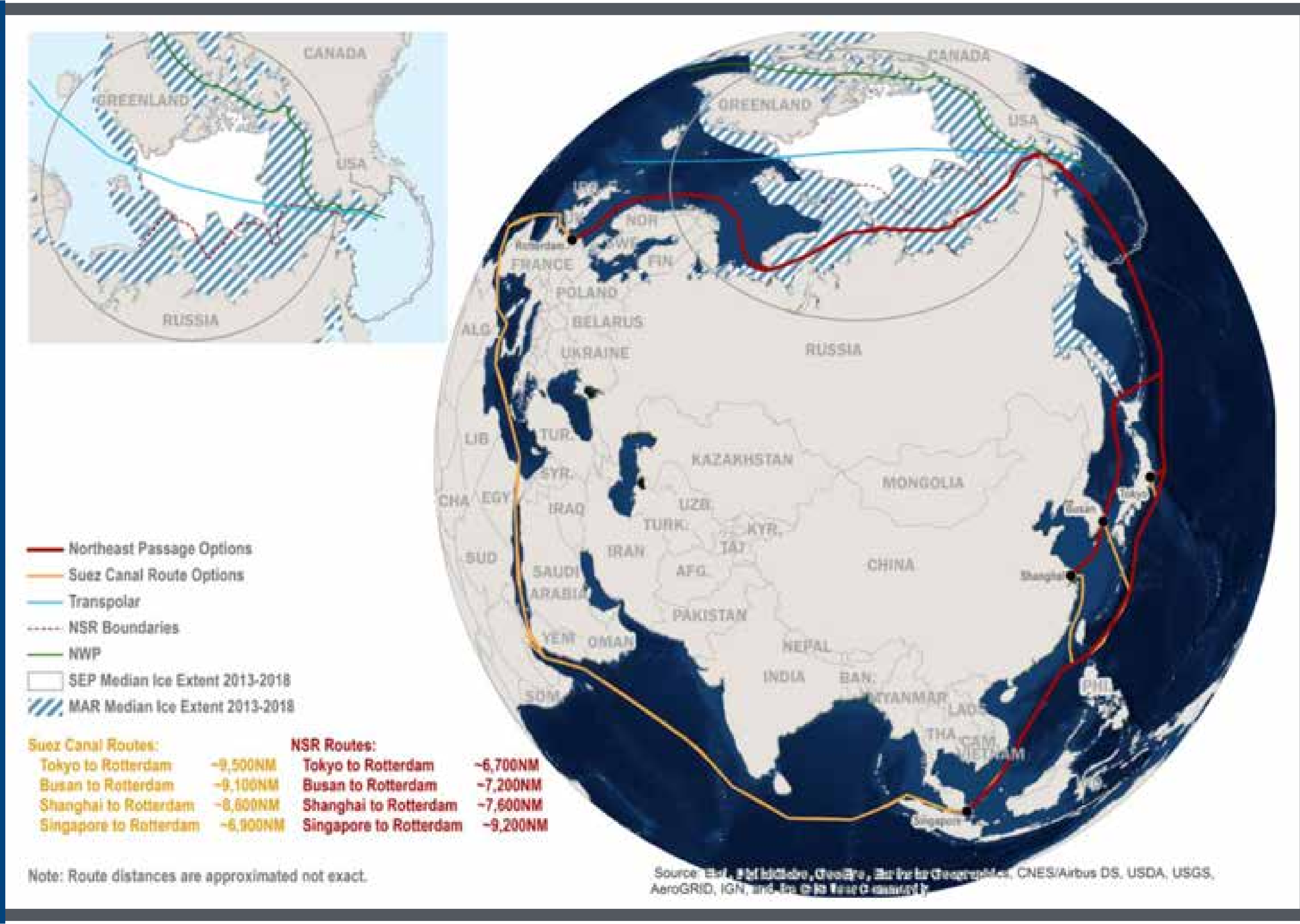
https://www.shipmap.org

Averages:
Containers (yellow, 14.3M)
Dry goods (blue, 0.5M kt)
Liquids (red, 0.4M kt)
Gas (green, 62M m3)
Vehicles (pink, 10M)

CO_2 emissions - ~150 kt

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





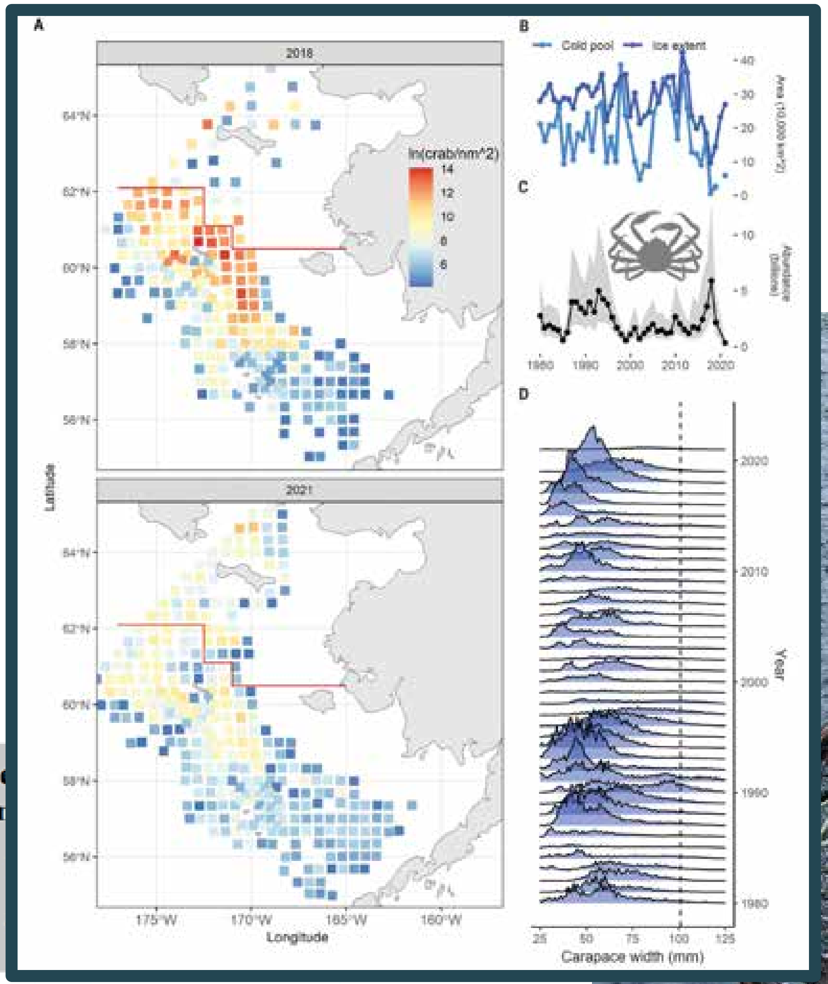
Collapse of Bering Snow Crab Fishery

MARINE HEATWAVES

The collapse of eastern Bering Sea snow crab

Cody S. Szuwalski[1]*, Kerim Aydin[1], Erin J. Fedewa[2], Brian Garber-Yonts[1], Michael A. Litzow[2]

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 Departm
Doug Vincen

ALASKA DEPARTMENT OF FISH AND GAME

Advisory Announcement

***For Immediate Release:* 10/6/2023**

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

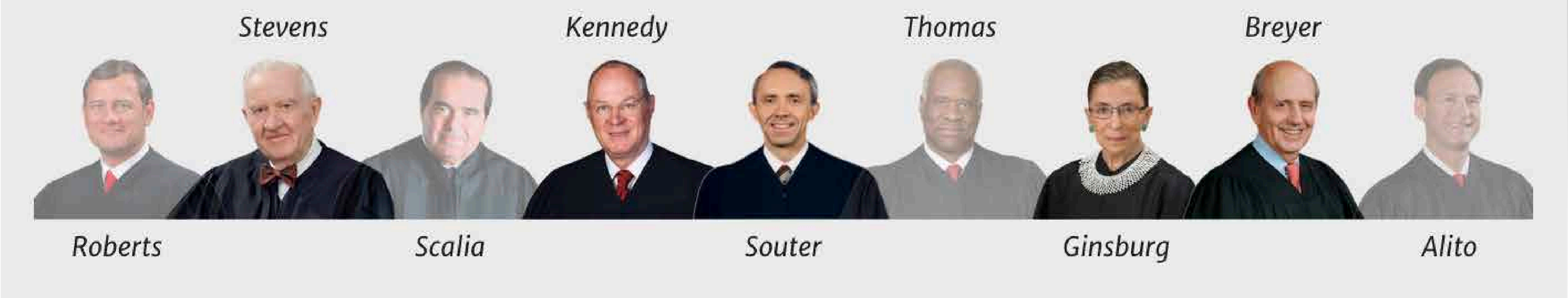
2023/24 Bering Sea Snow Crab Season Closed

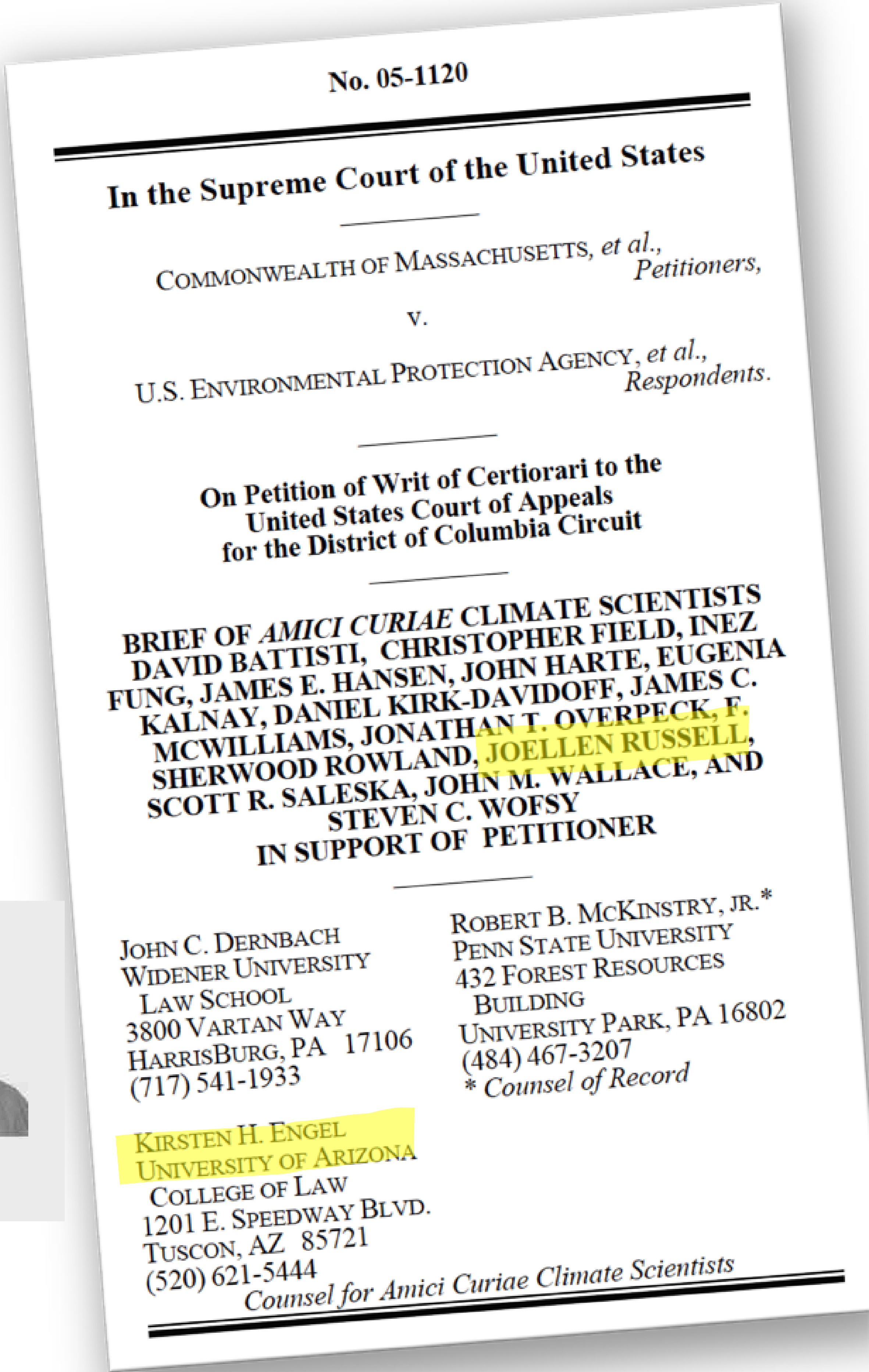
The Alaska Department of Fish and Game (ADF&G) and National Marine Fisheries Service (NMFS) have completed analysis of 2023 NMFS trawl survey results for Bering Sea snow crab. The stock is estimated to be below the ADF&G regulatory threshold for opening a fishery. Therefore, Bering Sea snow crab will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

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 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."
."





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

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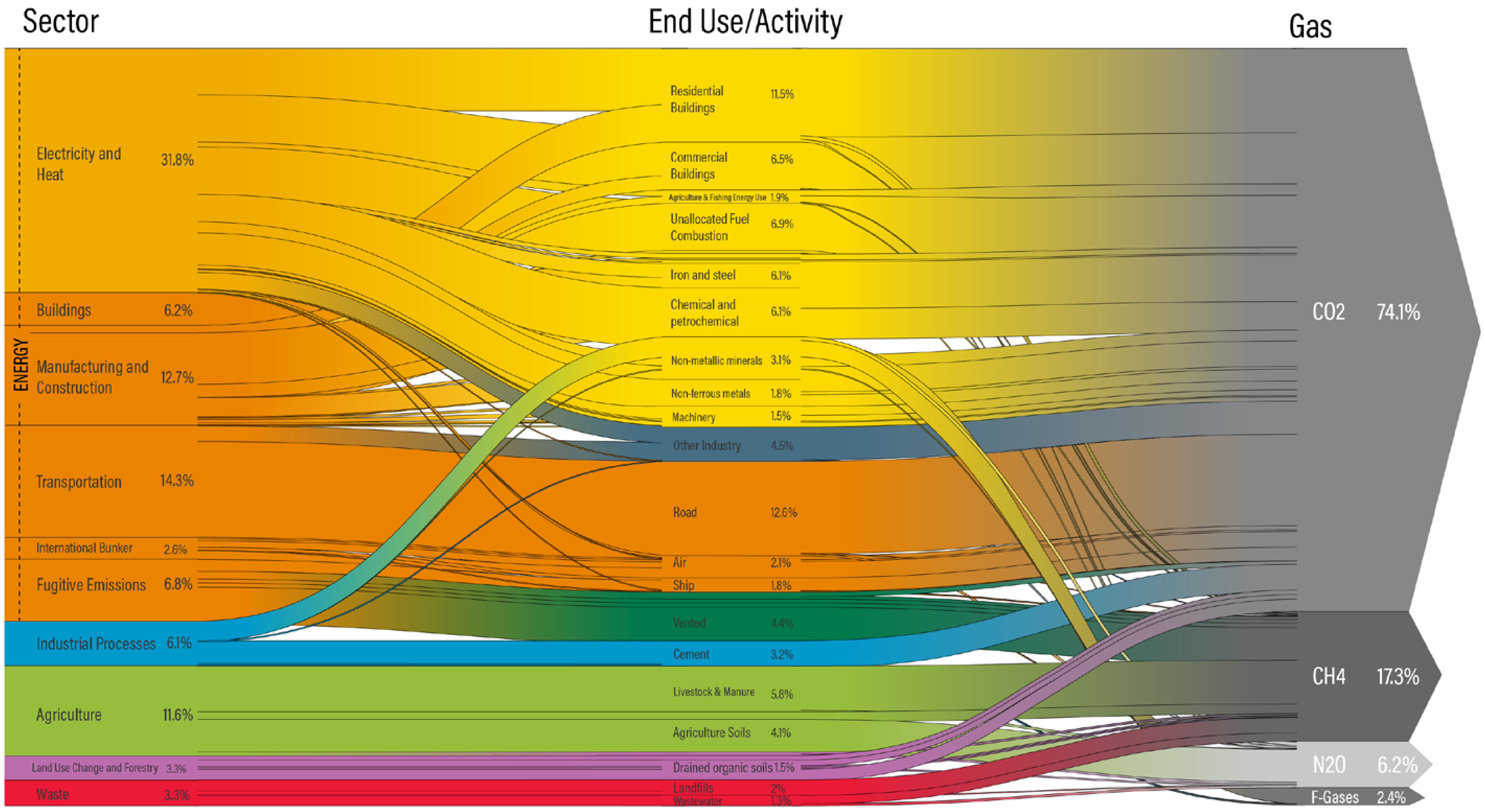
Counsel for Amici Curiae Climate Scientists

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

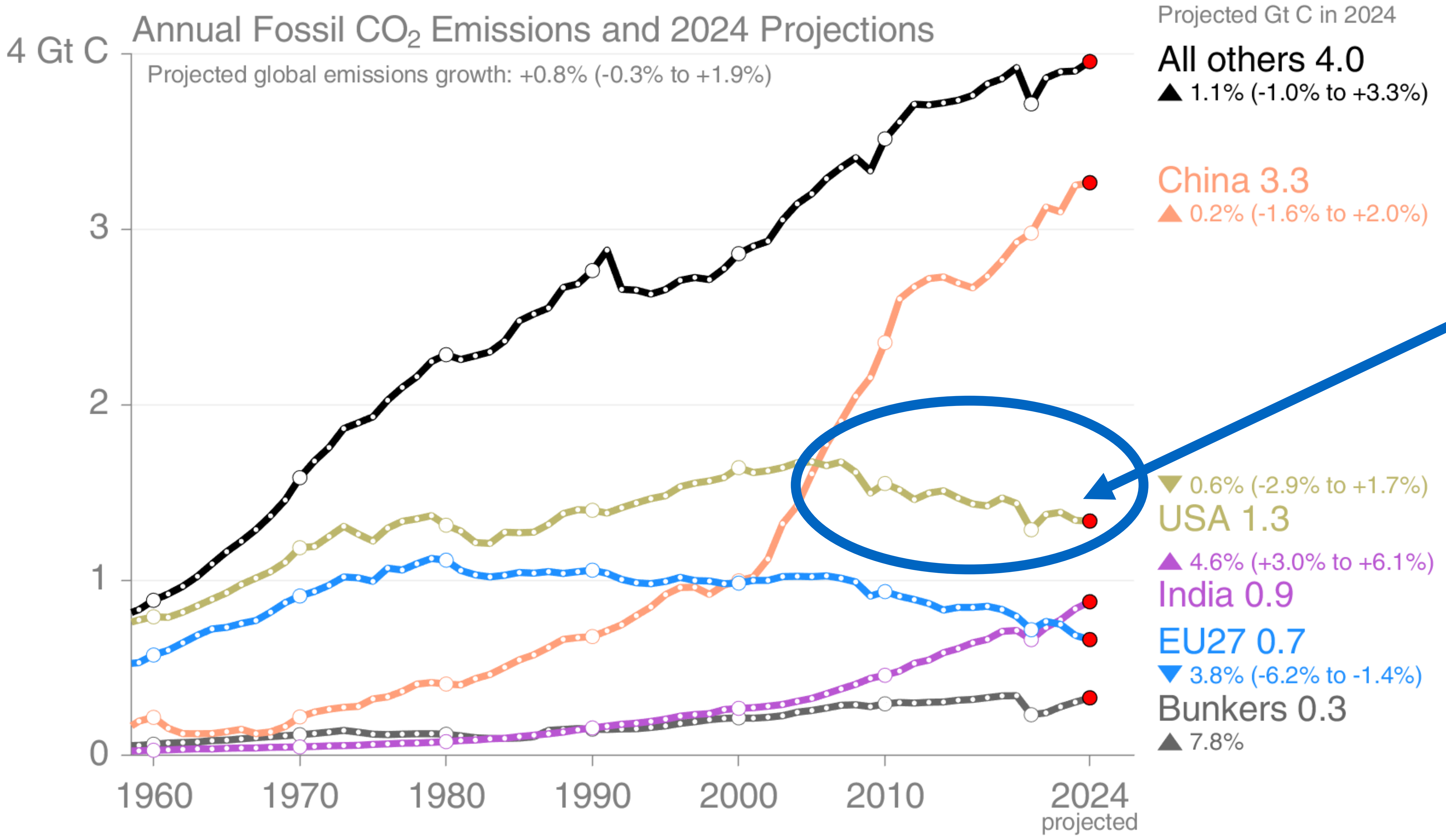
Total: 49.8 $GtCO_2e$



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

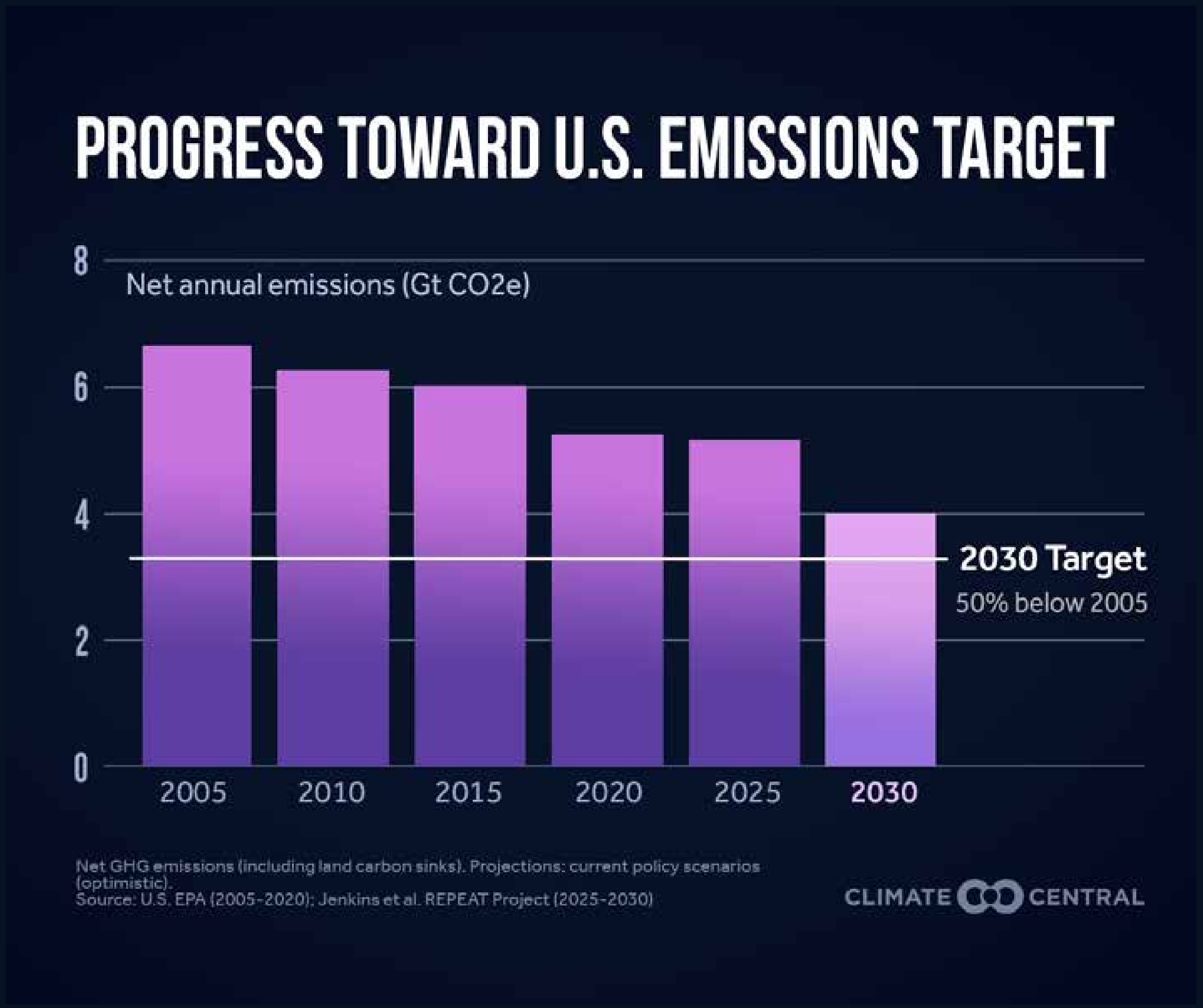
WORLD RESOURCES INSTITUTE

Fossil CO_2 emissions through 2023



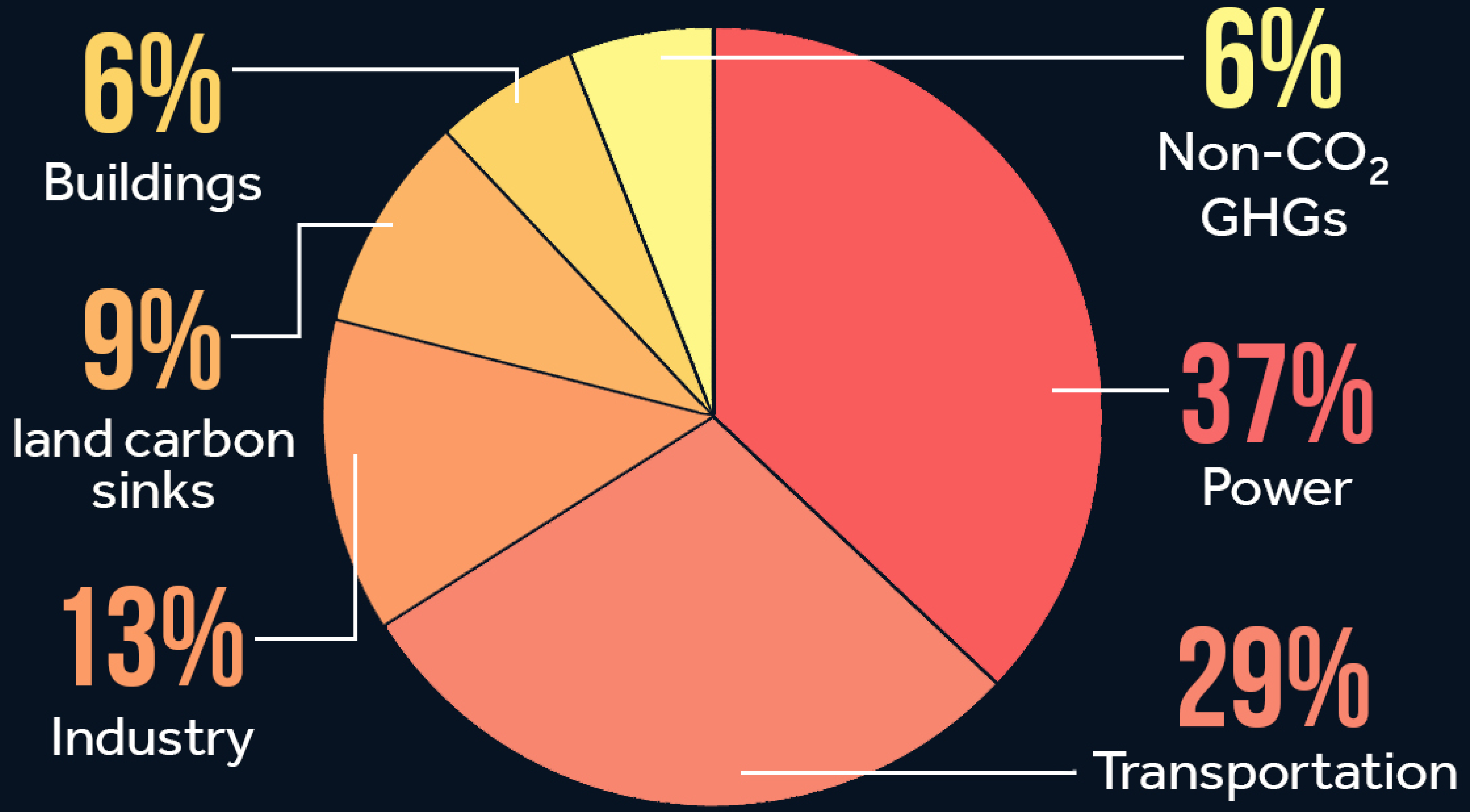
US CO_2 Emissions: Decreasing from 2007 to today

Mass vs EPA Decided: April, 2007



EMISSION CUTS BY 2030

WITH THE INFLATION REDUCTION ACT



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

CLIMATE CENTRAL

Fate of anthropogenic CO_2 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

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

Partitioning

5.2   0.02 GtC/yr

46%

2.9   0.4 GtC/yr

26%

3.2   0.9 GtC/yr

28%

Source: Friedlingstein et al. 2024 (https://doi.org/10.5194/essd-17-965-2025); Global Carbon Project 2024

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

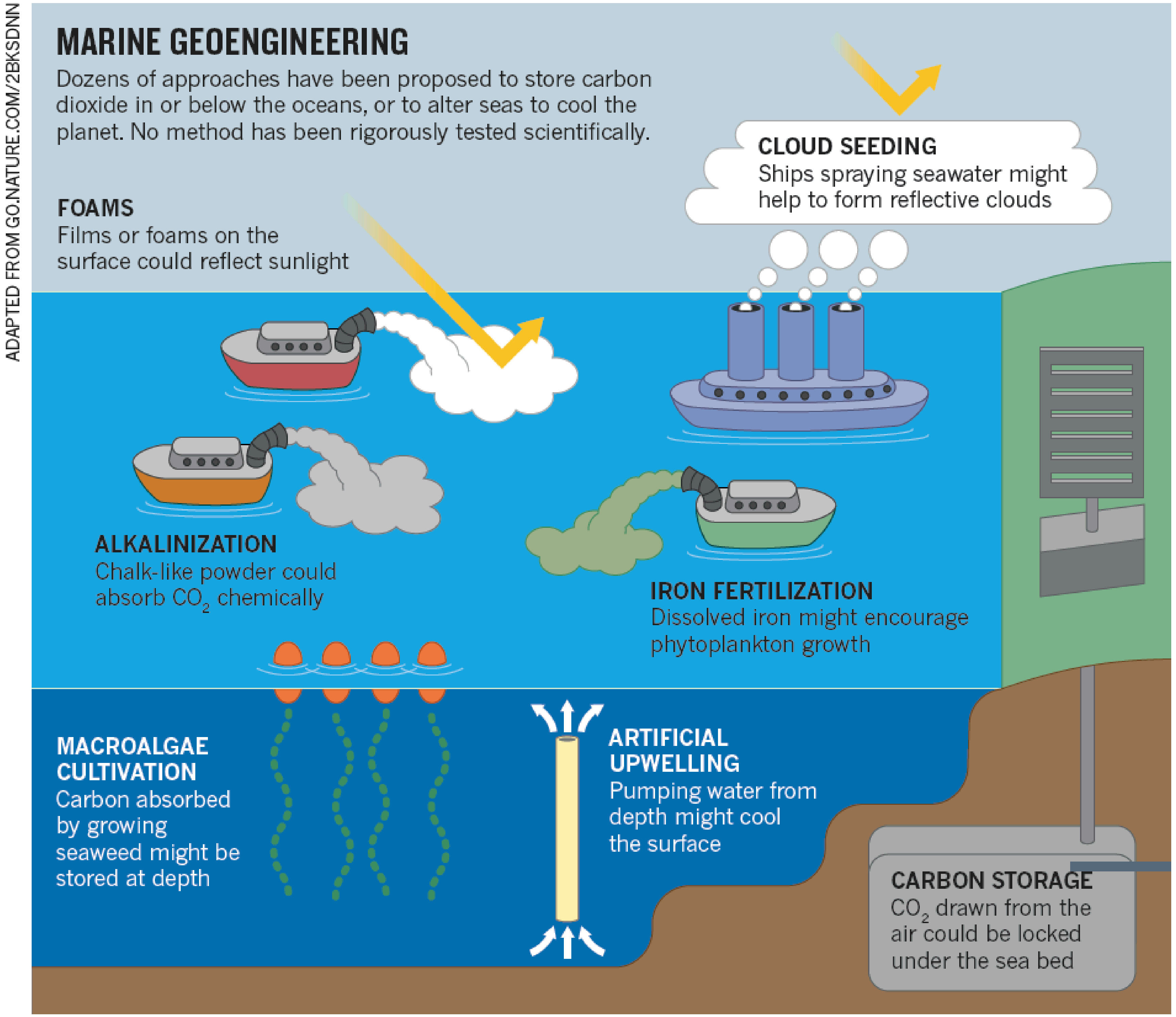
Vegetation

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

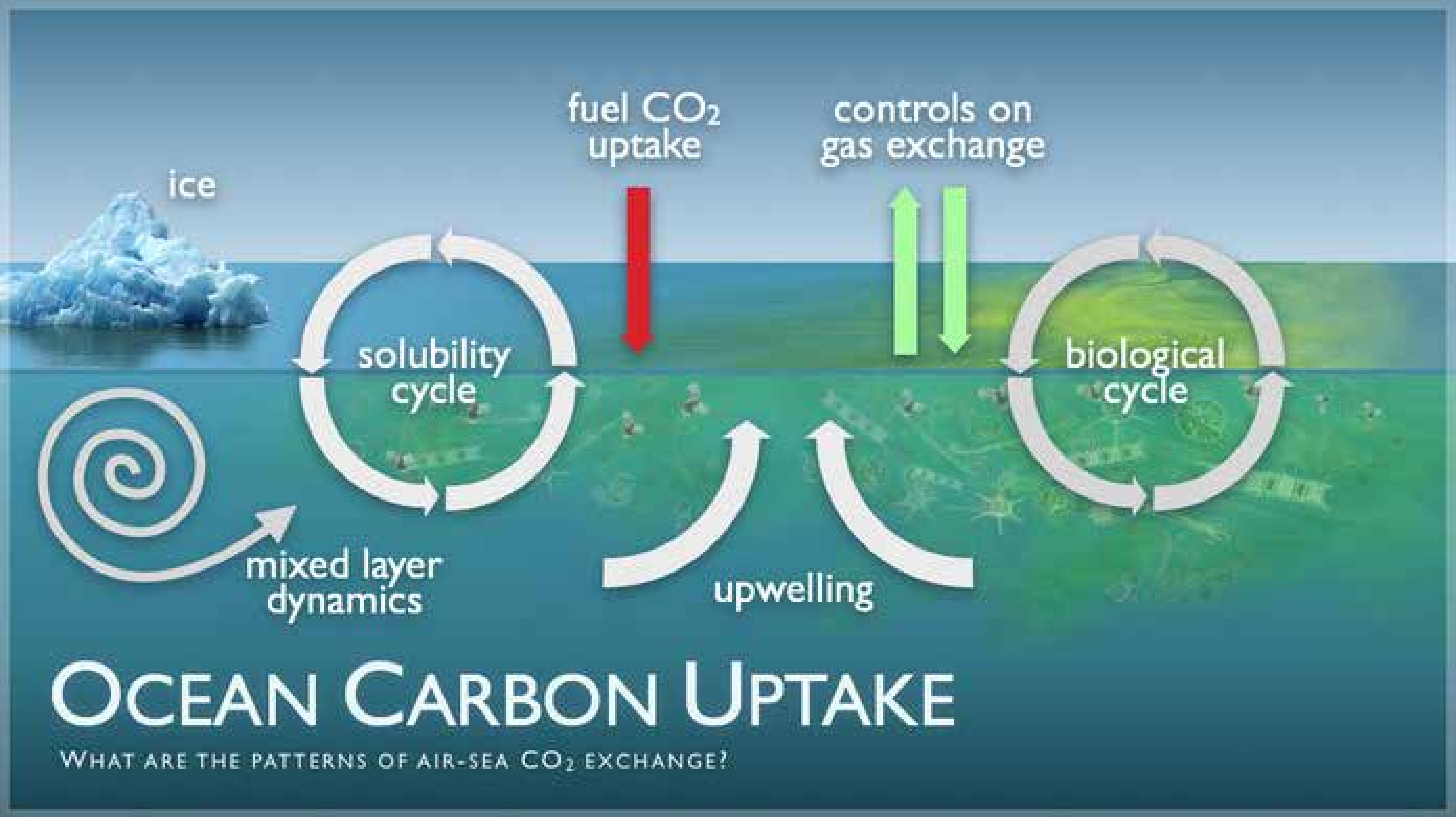
Source: CDIAC; NOAA-ESRL; Houghton et al 2012; Giglio et al 2013; Le Quéré et al 2015; Global Carbon Budget 2015

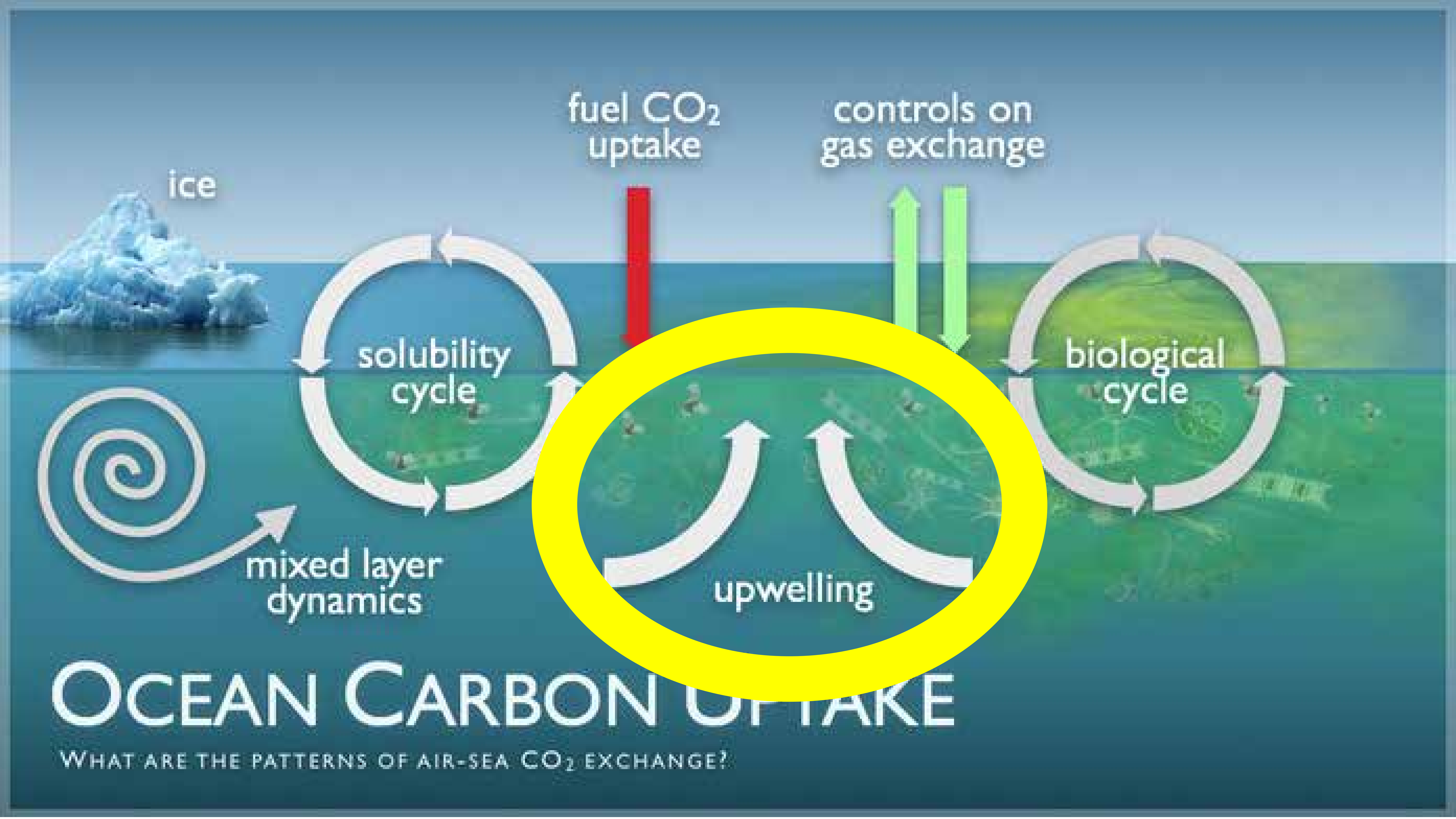
Verifying the Effectiveness of Ocean-based Carbon Dioxide Removal (CDR)

Caution Needed!



From Boyd & Vivian (2019)


ice
fuel CO_2 uptake
controls on gas exchange
solubility cycle
biological cycle
mixed layer dynamics
upwelling
OCEAN CARBON UPTAKE
WHAT ARE THE PATTERNS OF AIR-SEA CO_2 EXCHANGE?


fuel CO_2 uptake
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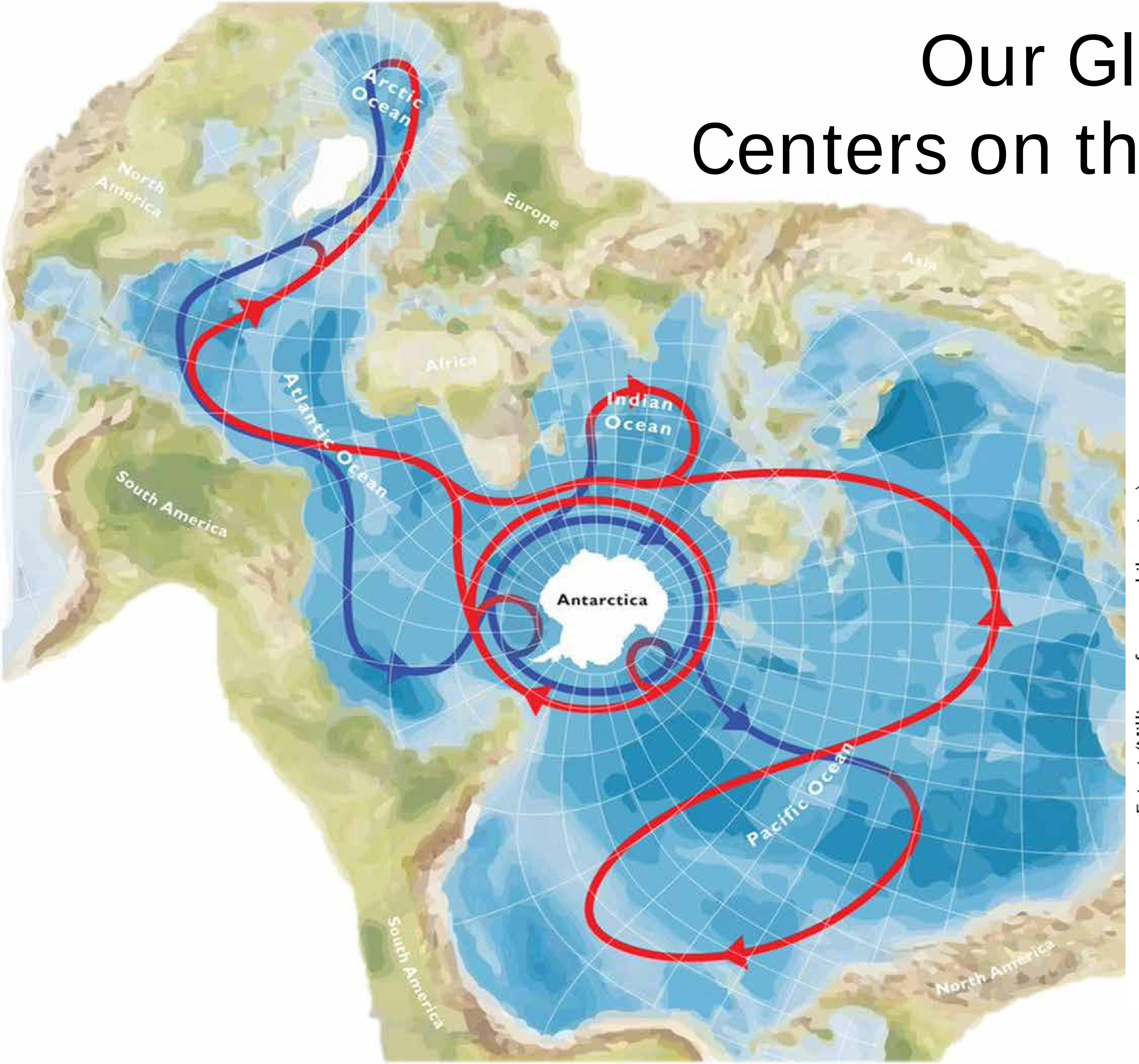
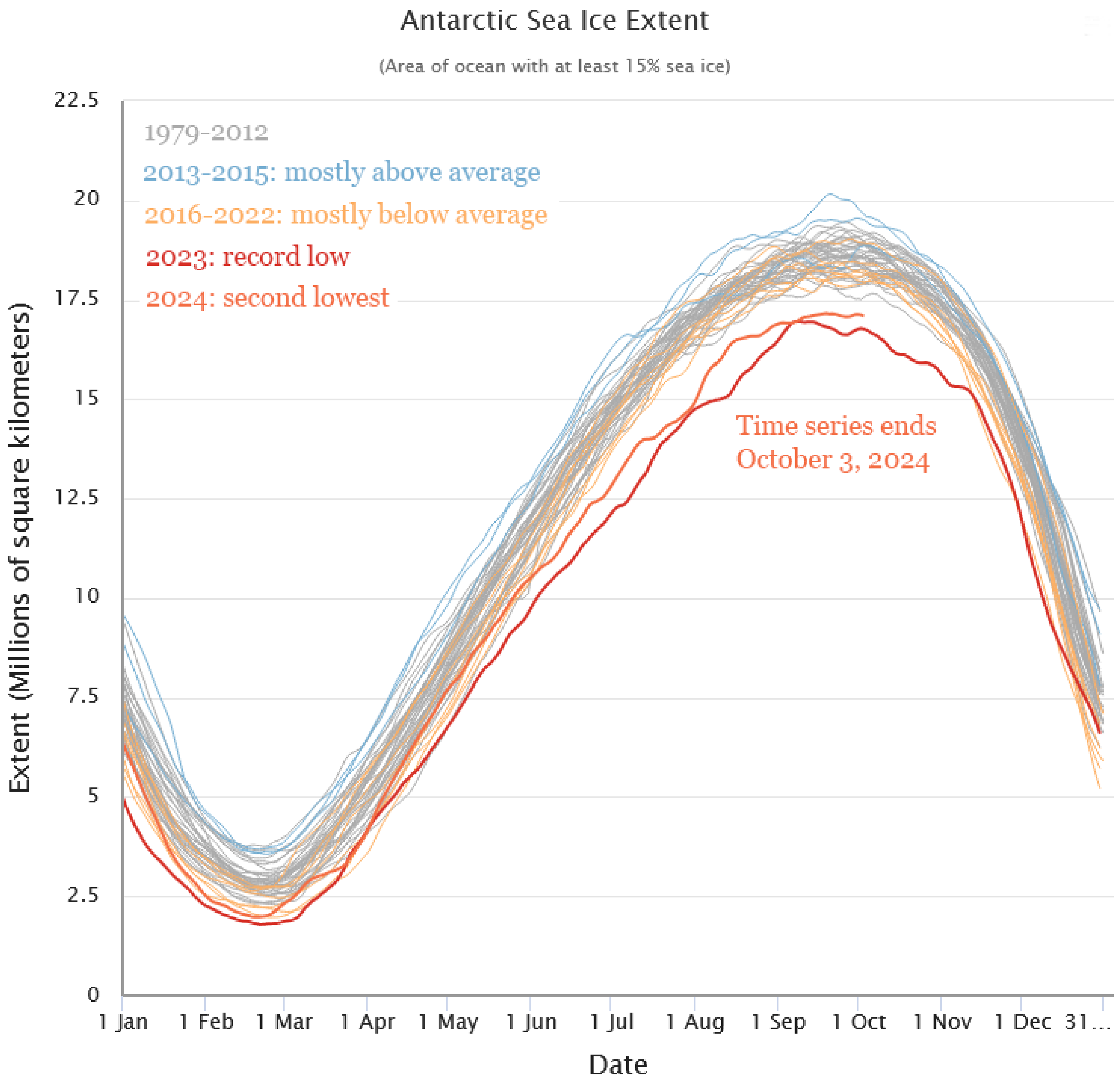
OCEAN CARBON UPTAKE
WHAT ARE THE PATTERNS OF AIR-SEA CO_2 EXCHANGE?

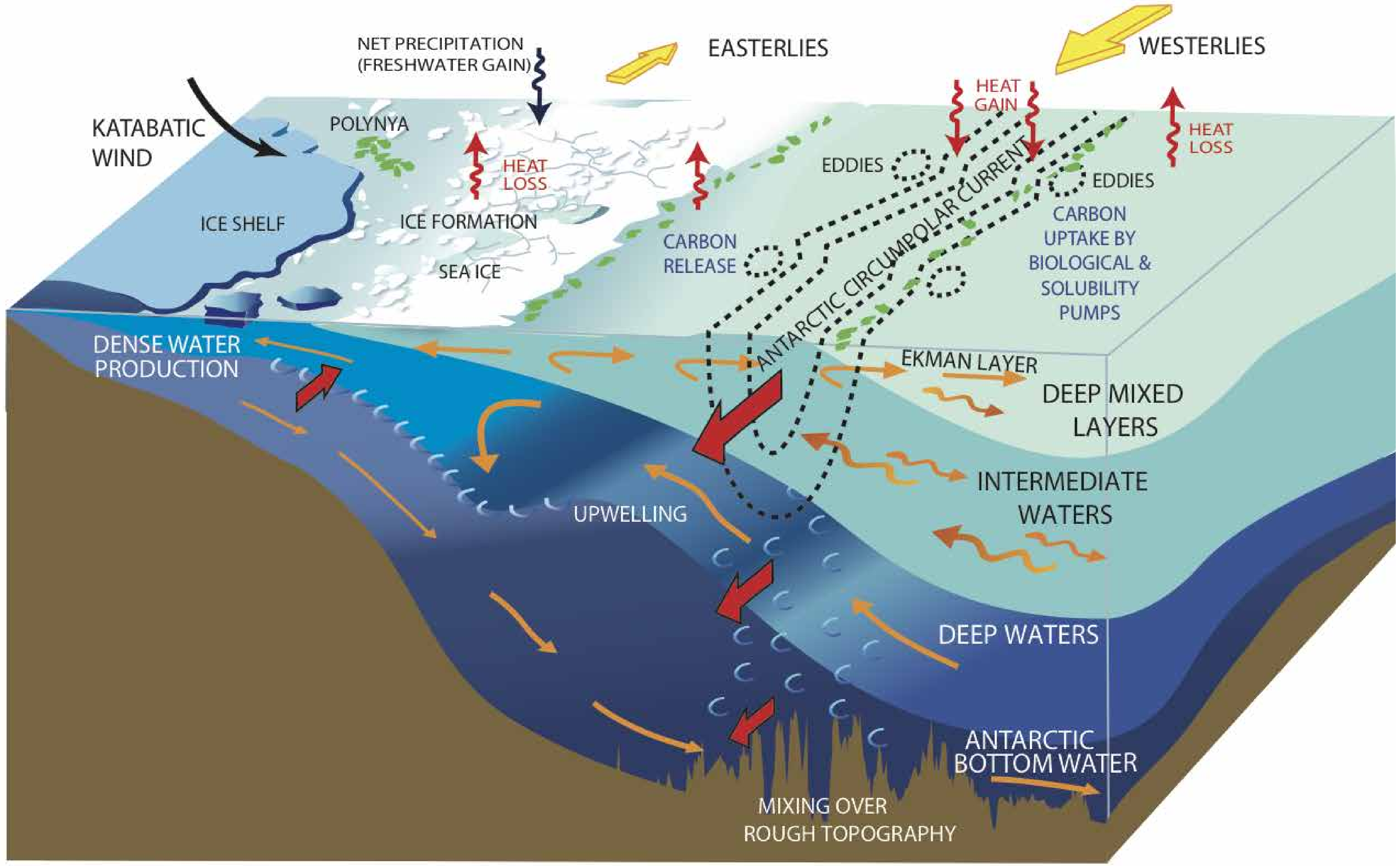
Our Global Ocean
Centers on the Southern Ocean





The Southern Ocean

Wind-driven upwelling from 2000-3000m

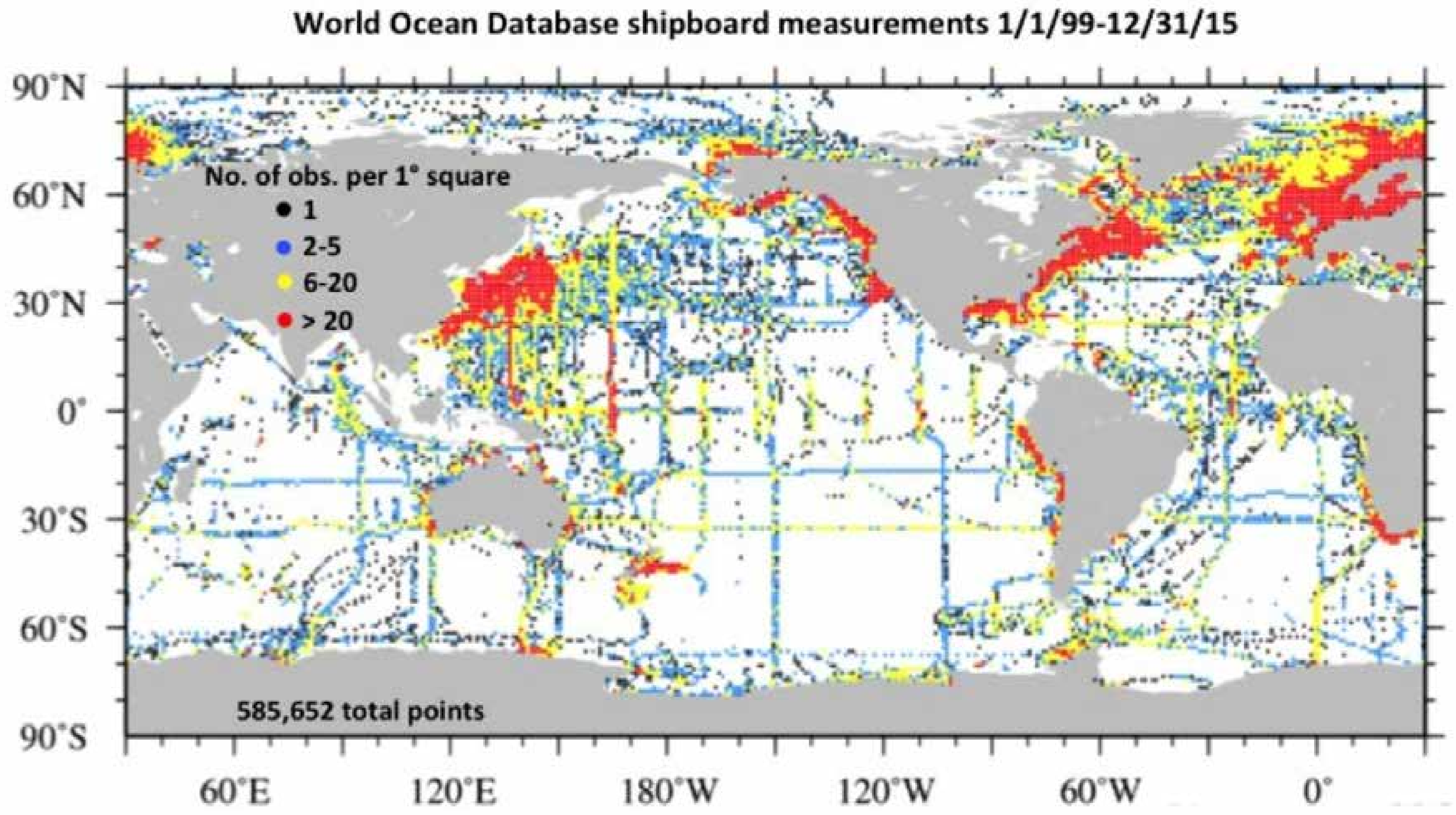


Talley & Olbers (2014, after Speer et al. 2000, and NRC 2011)


THE SOUTHERN OCEAN
up to
50%
of all the
carbon dioxide
up to
75%
of all the
heat
absorbed by the world's oceans

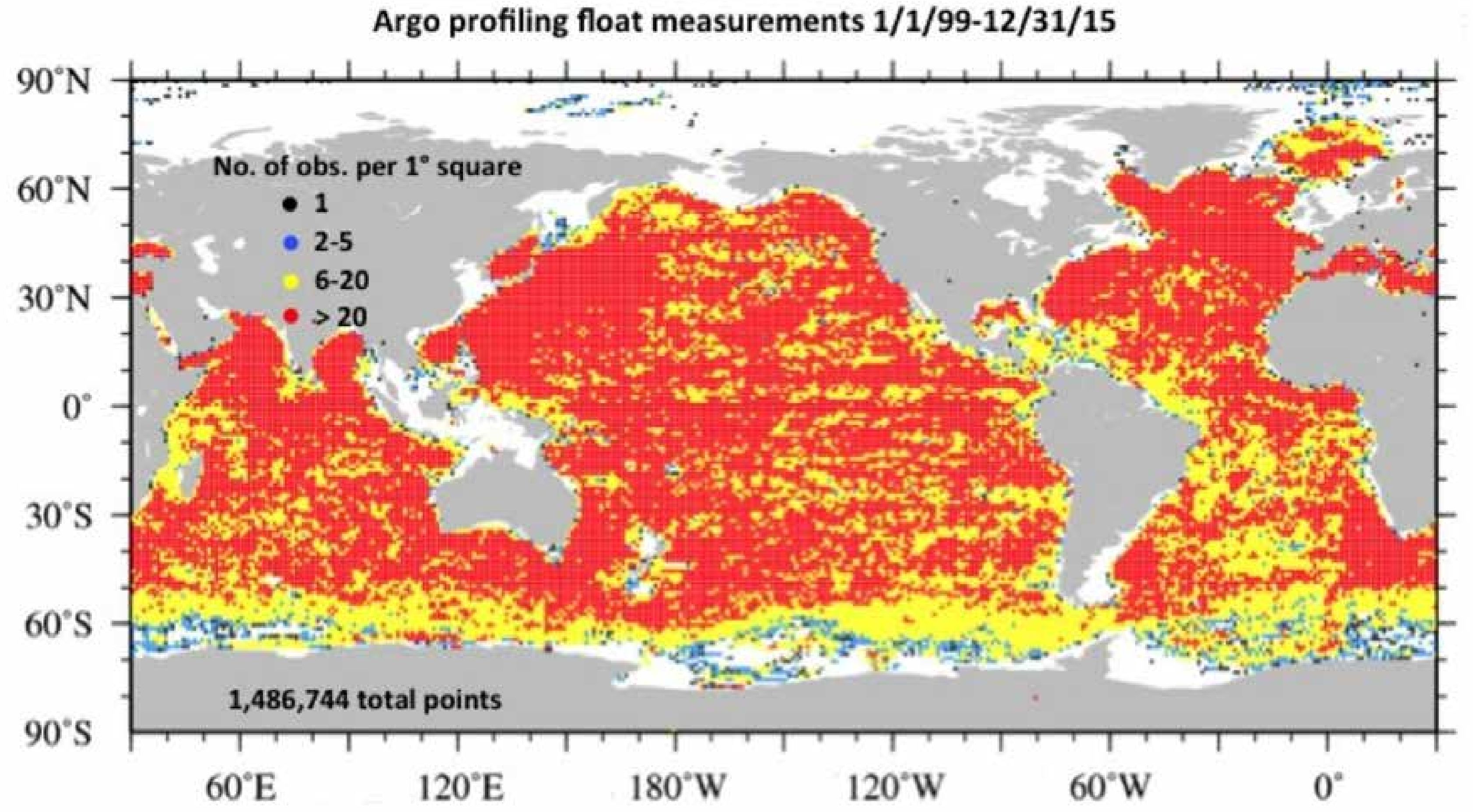
Measurements from Ships (1999-2015)

total

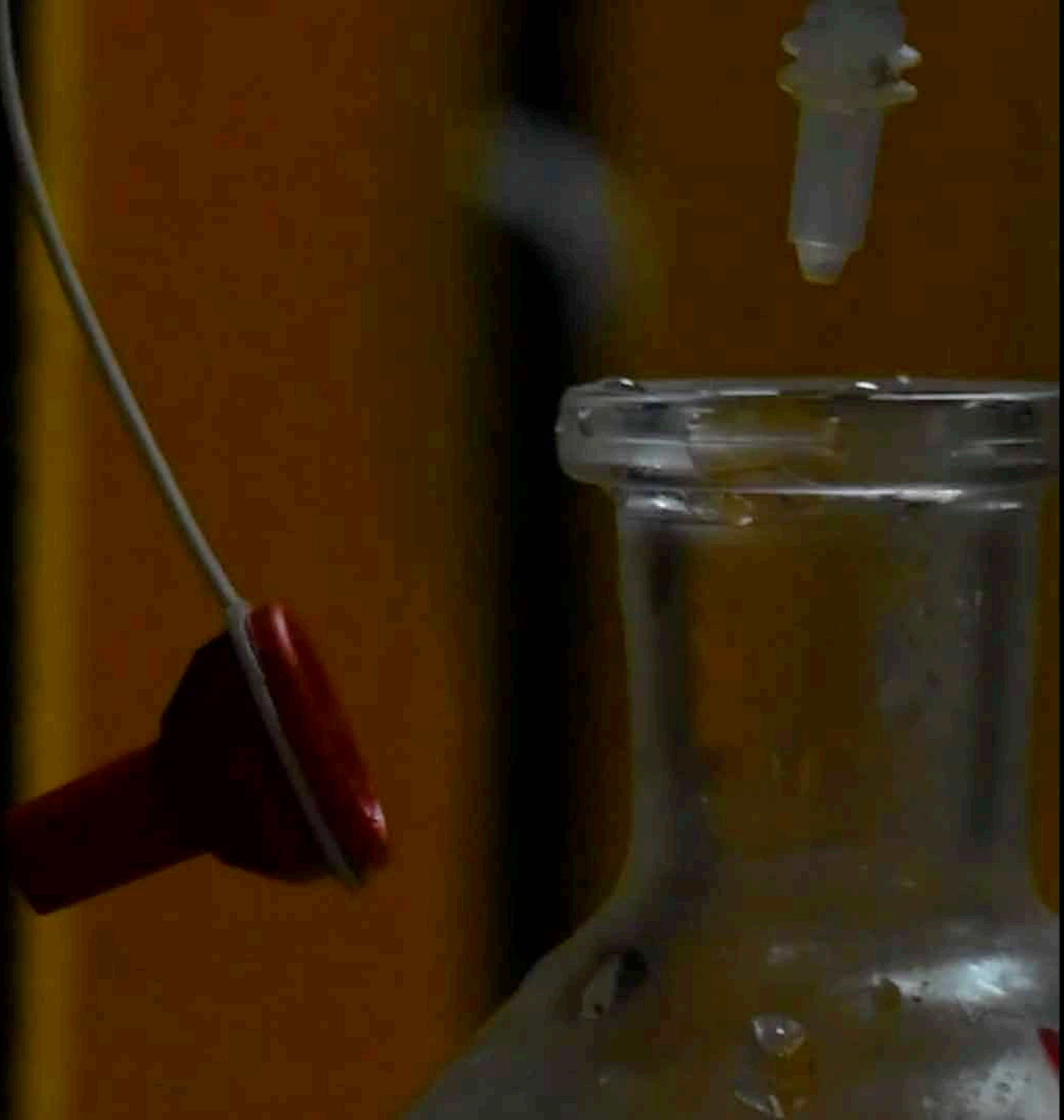


Measurements from Robot Floats (Argo) (1999-2015)

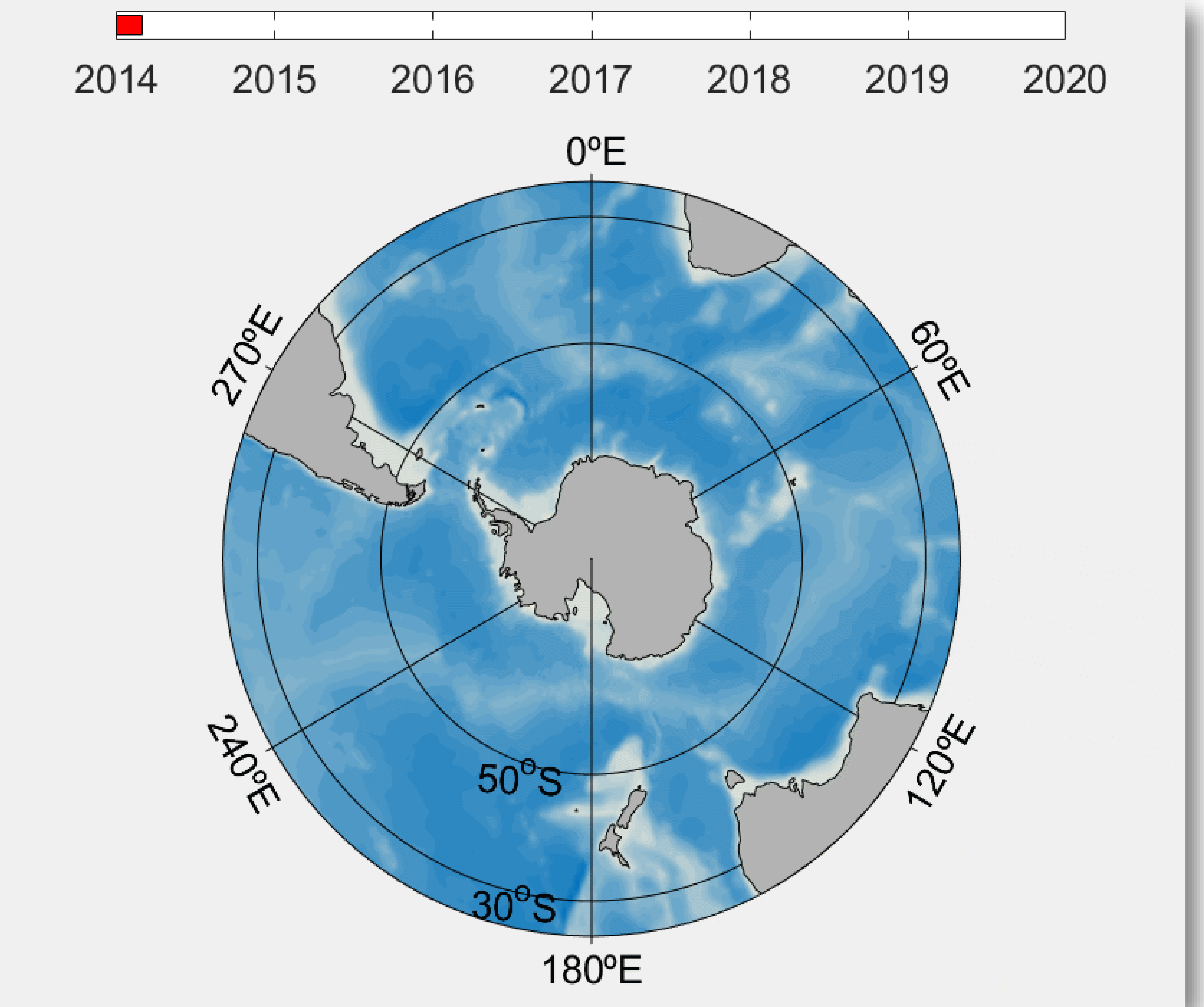
total



Southern Ocean Carbon and Climate Observations and Modeling



Courtesy: R. Beadling (clip)



SOCCOM

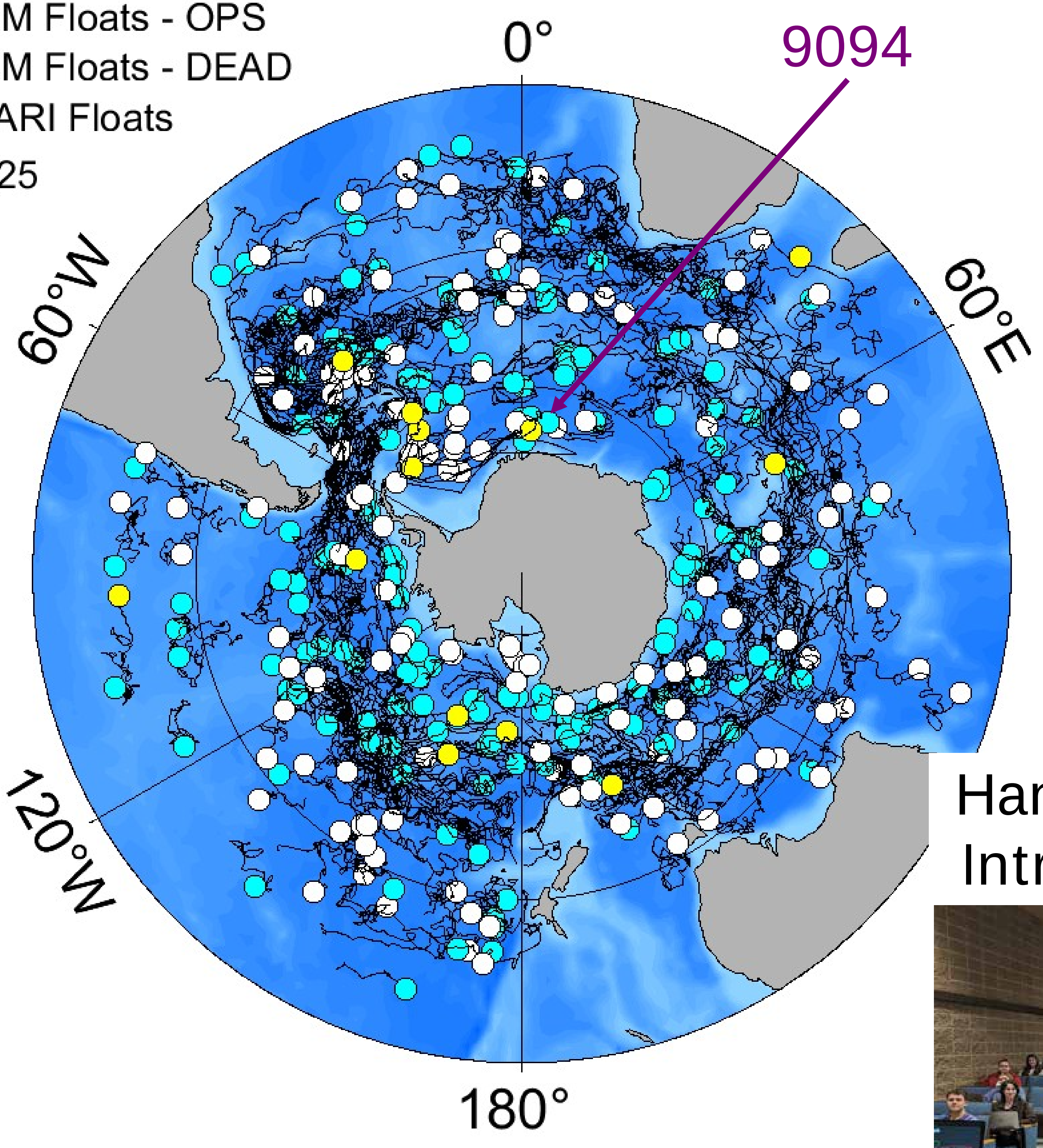
Unlocking the mysteries of the Southern Ocean

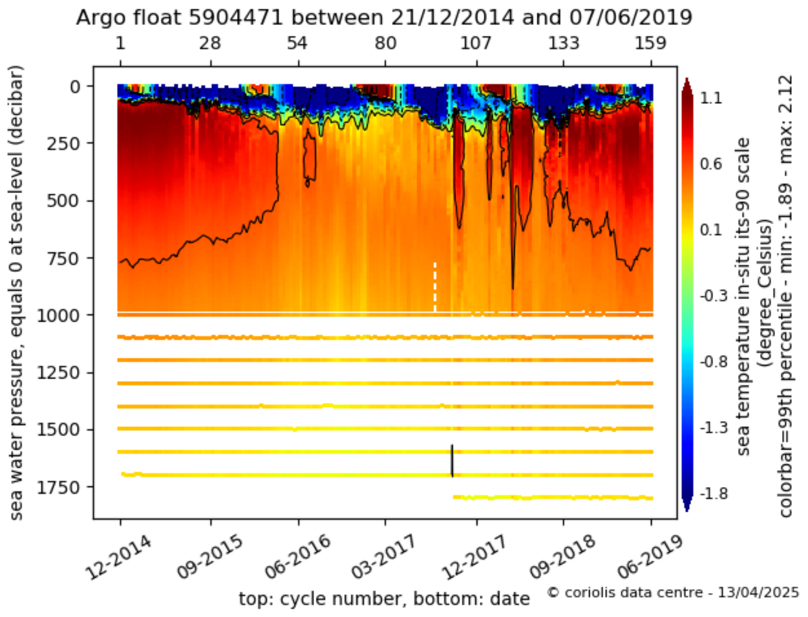
SOCCOM Floats
307 deployed,
143 operational

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!

at https://soccom.princeton.edu

Air-sea carbon flux from floats

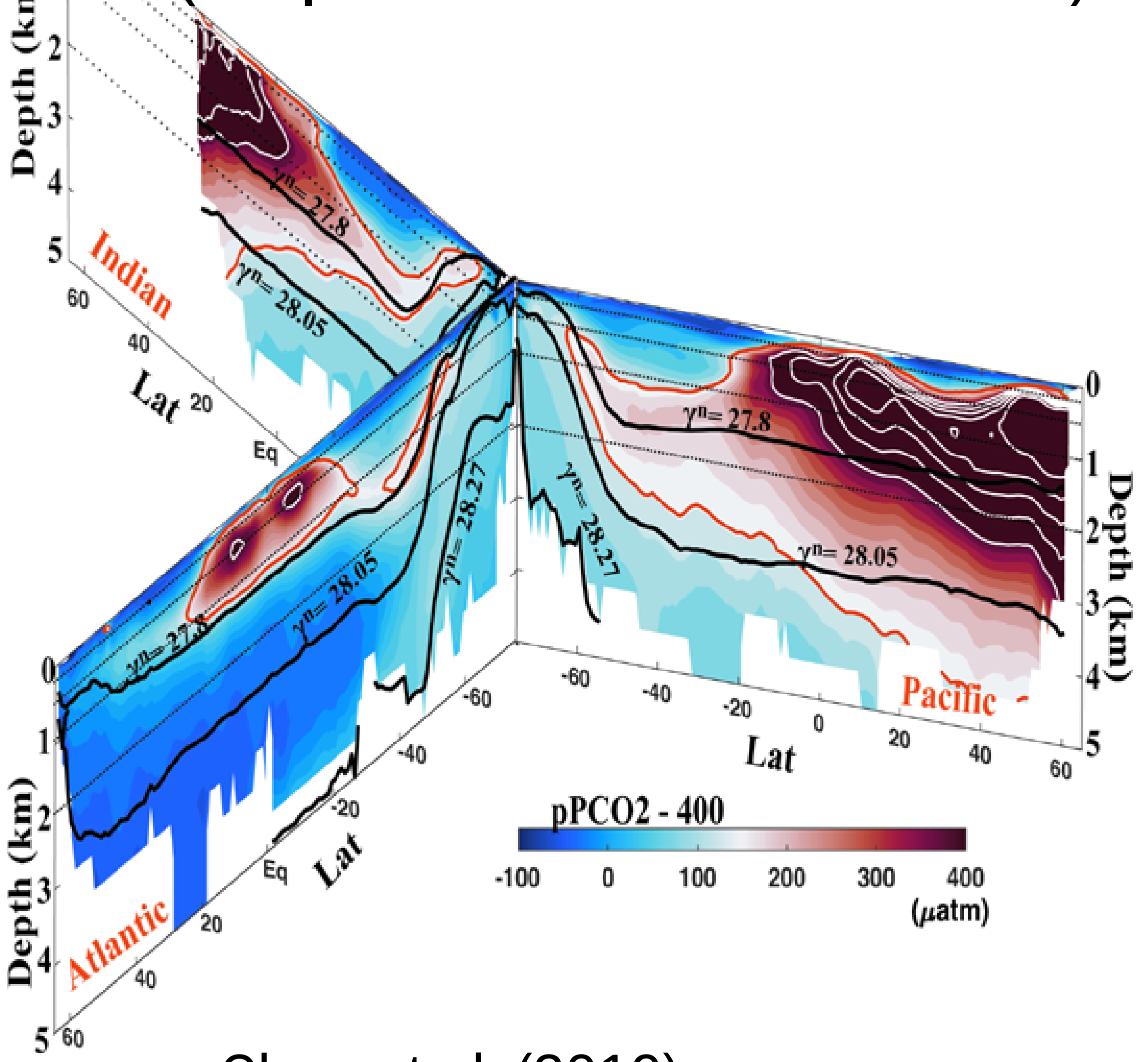
In the high-latitude ASZ, monthly mean float-based fluxes diverge substantially from ship-based fluxes. The floats exhibit much stronger outgassing in the autumn and winter and much less uptake in the summer.

SOCCOM

8)

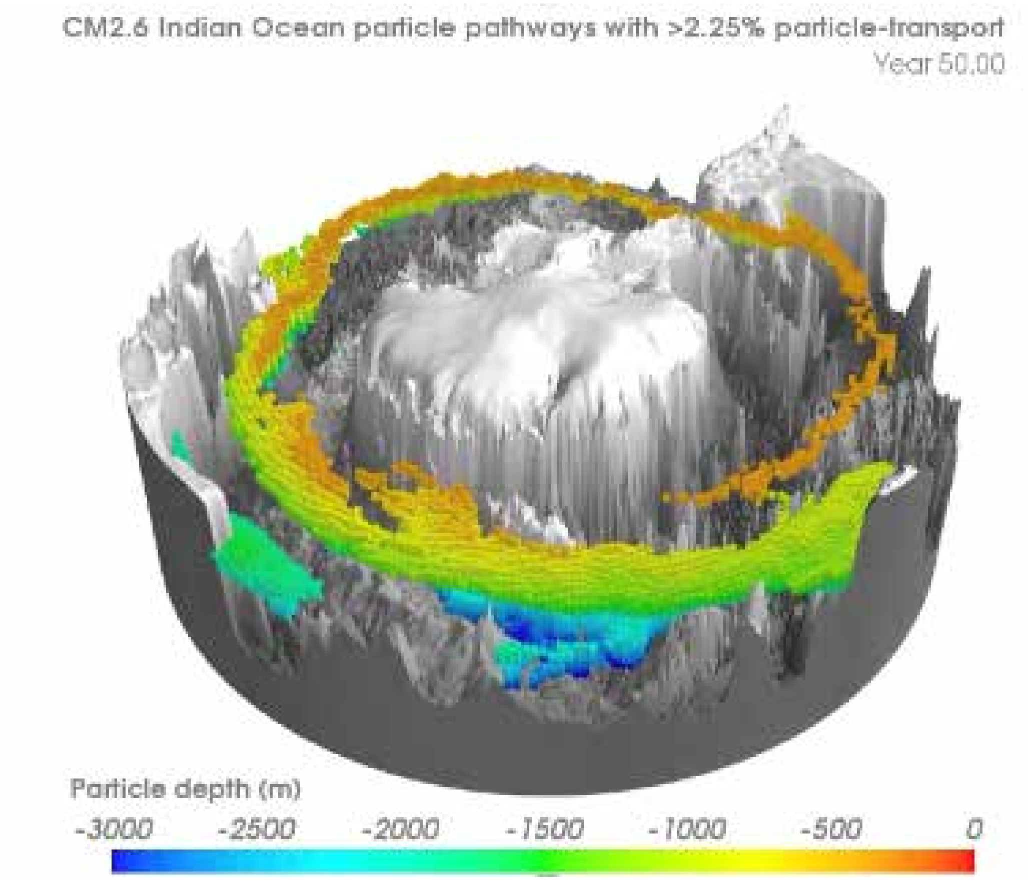
Air-sea carbon flux from SOCCOM

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



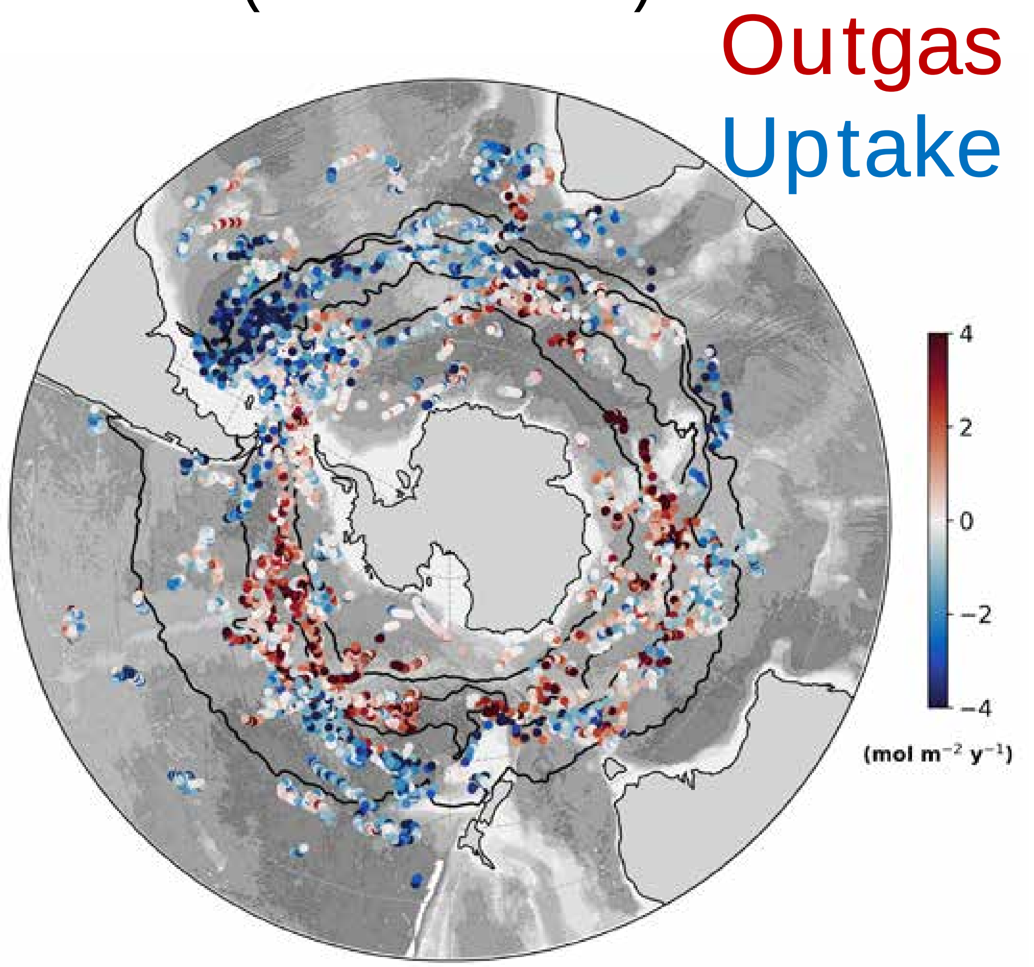
Chen et al. (2019)

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)



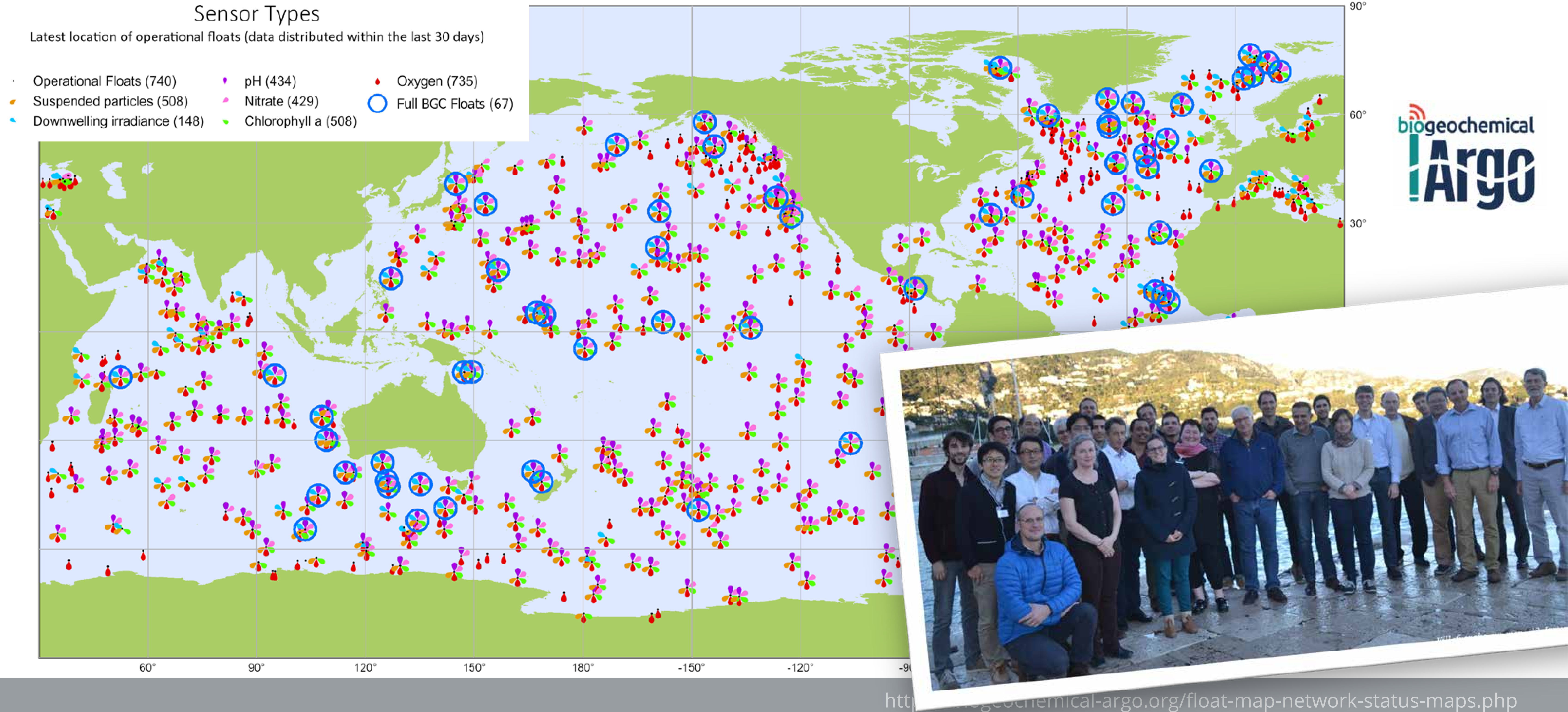
Gray et al. (GRL 2018)
Prend, Gray et al.

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

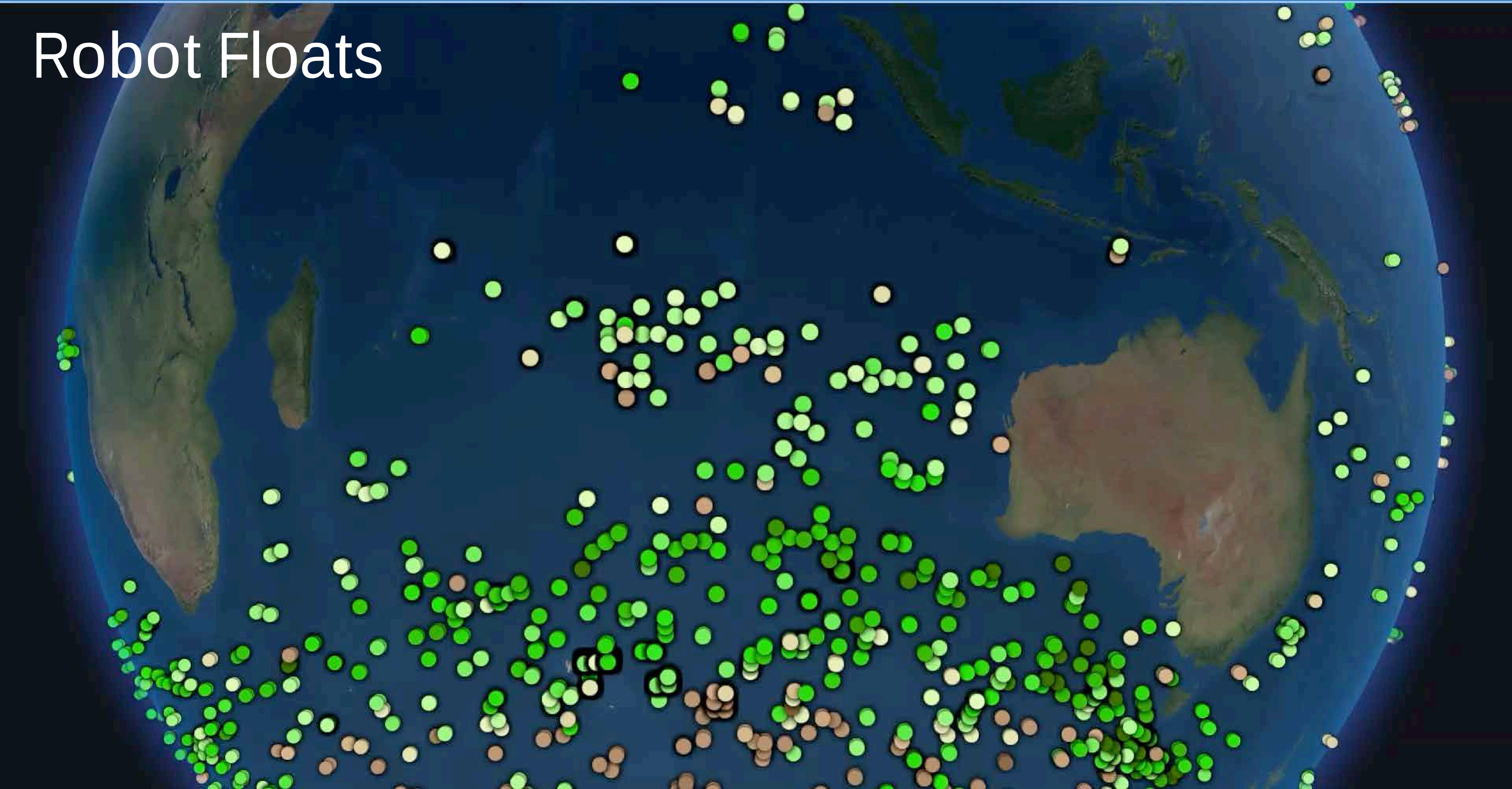
Global Biogeochemical Argo: in Mar 2025



biogeochemical Argo

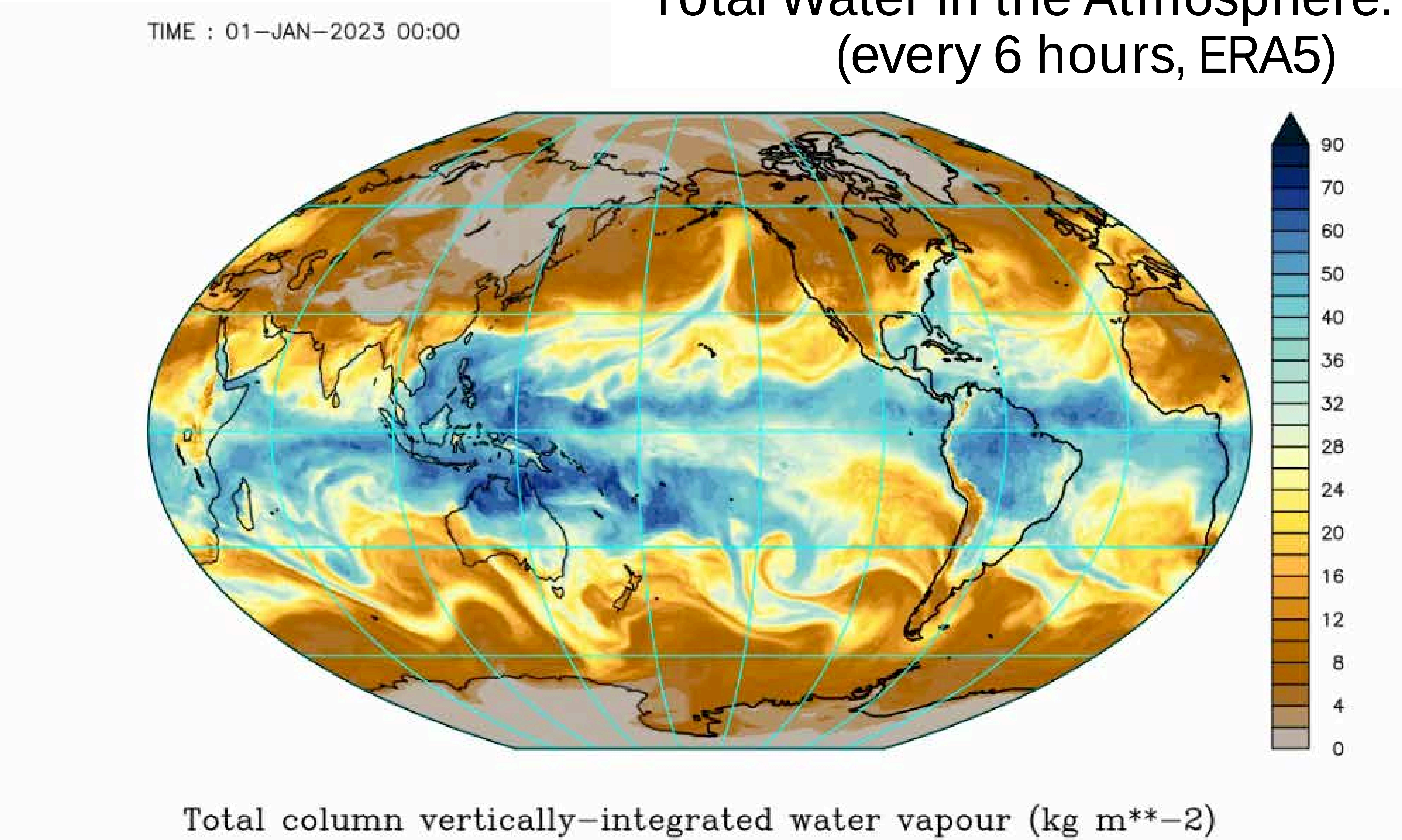
https://biogeochemical-argo.org/float-map-network-status-maps.php

Robot Floats

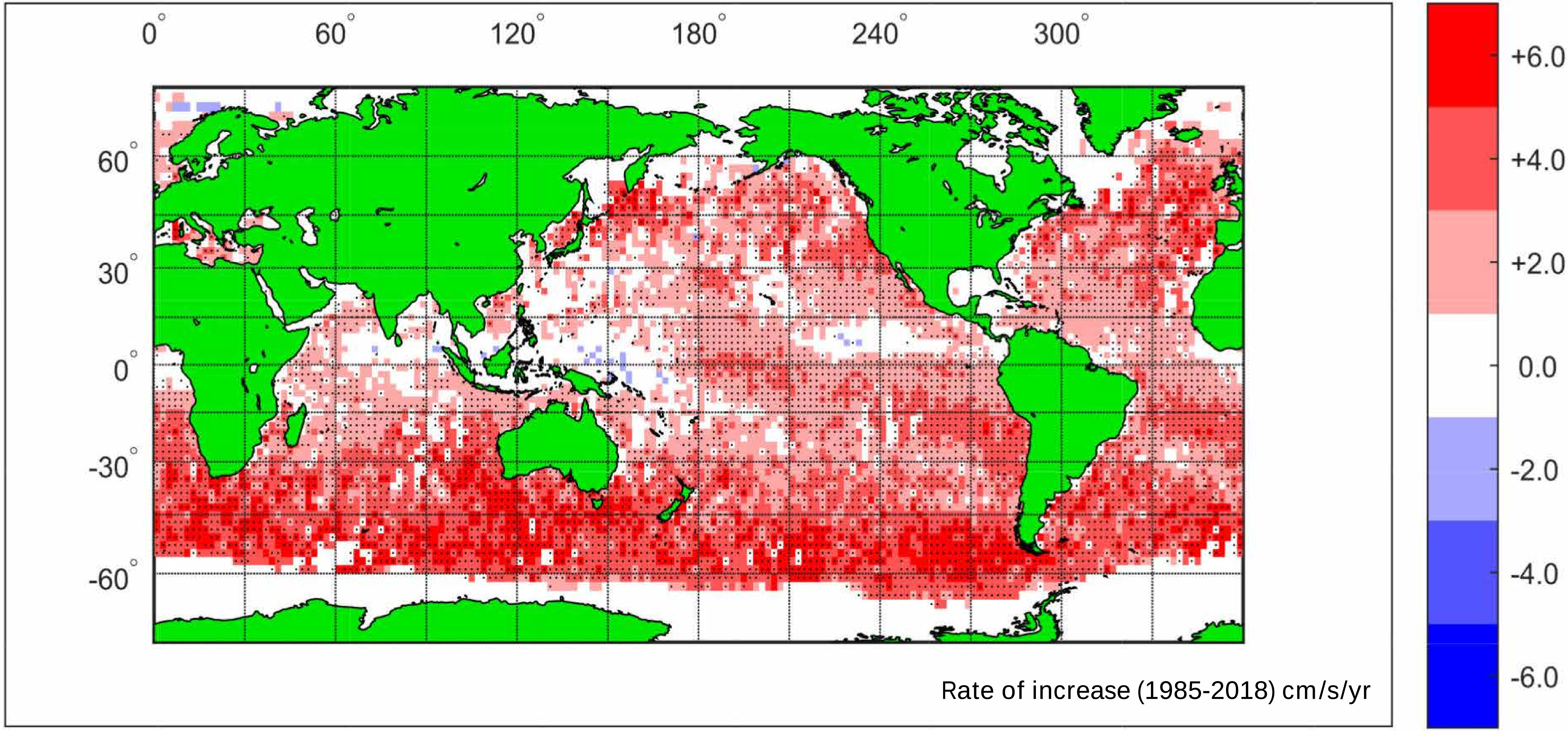


Growing Winds!

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



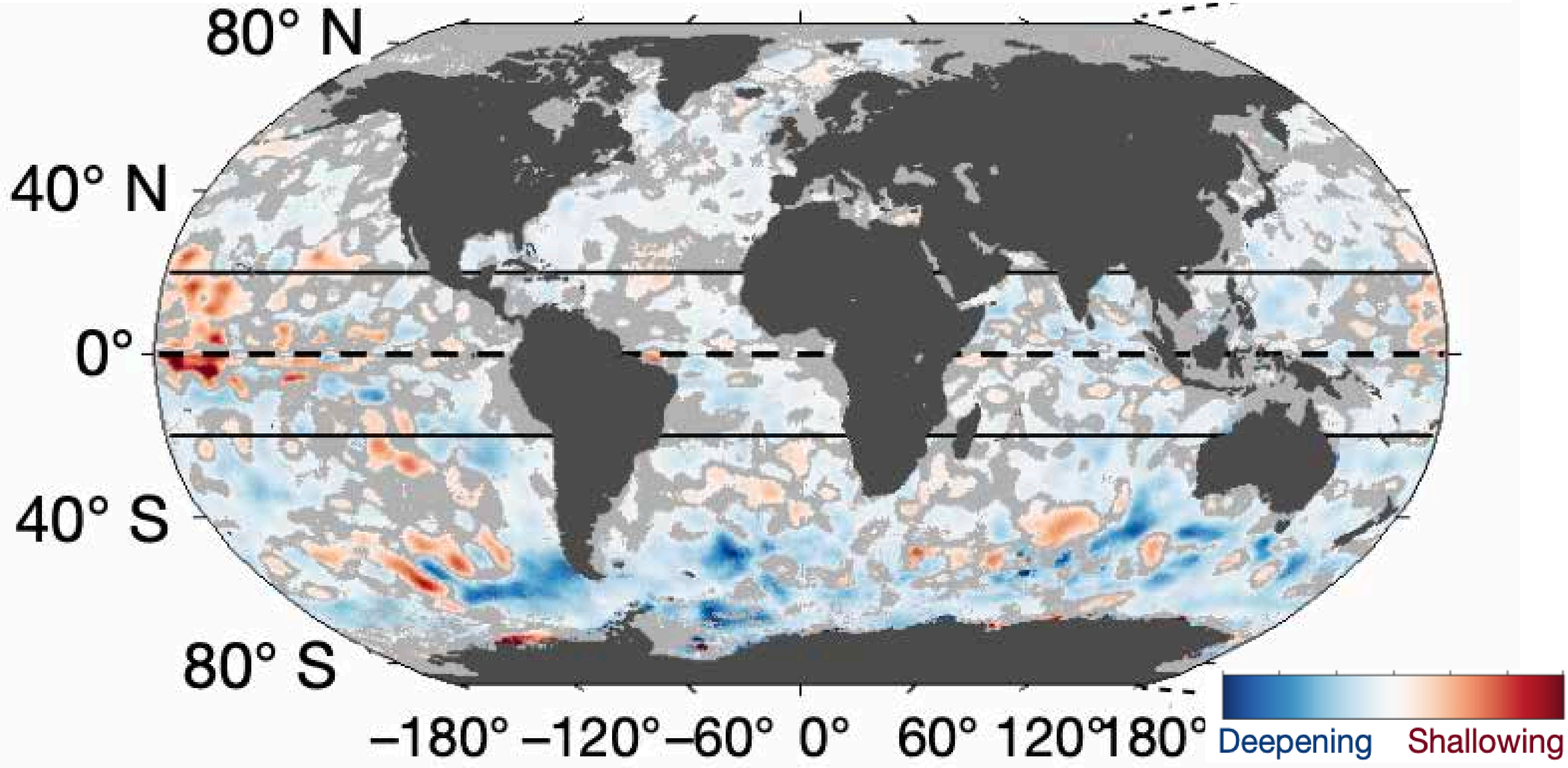
The World is Getting Windier – The fastest winds have gotten faster



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

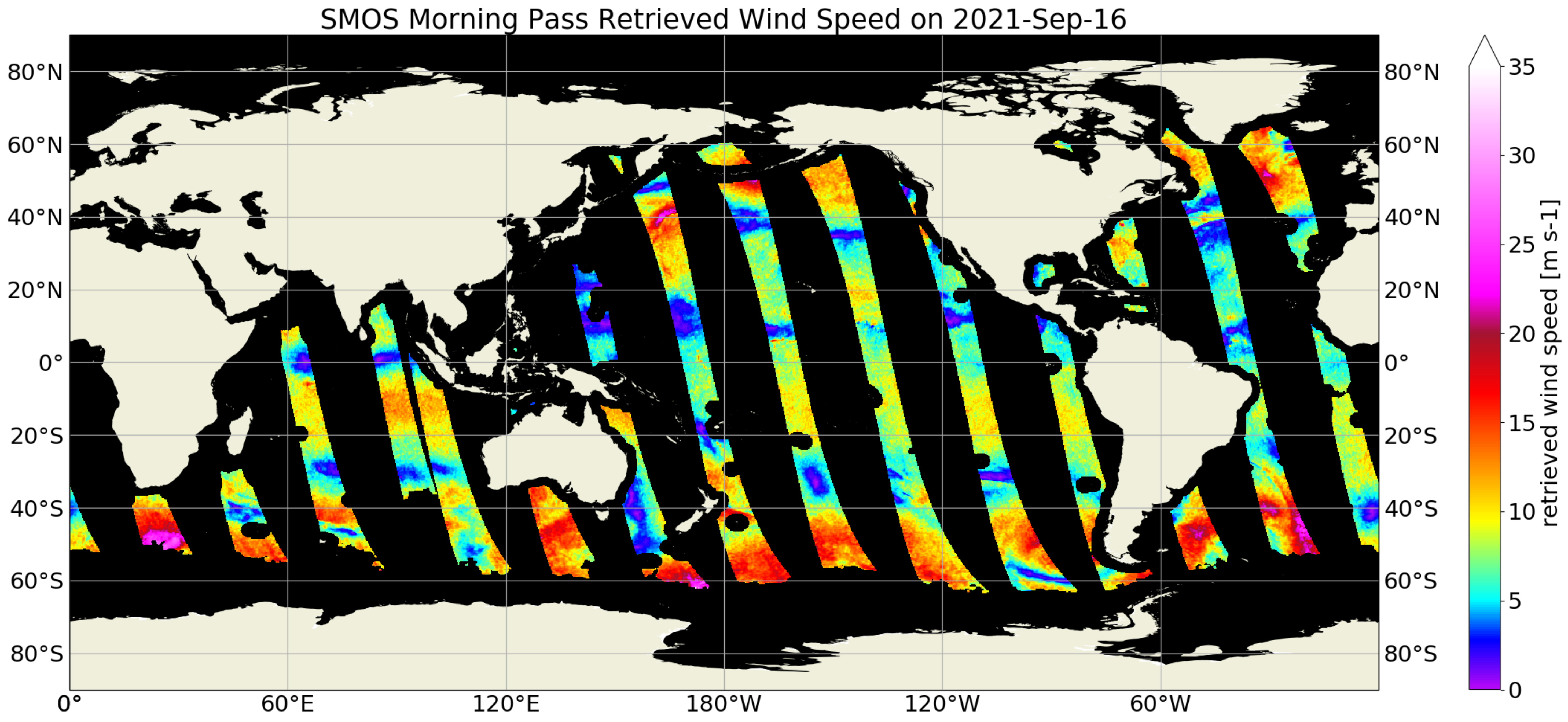
Young & Ribal, 2019: Science, DOI: 10.1126/science.aav9527

The World is Getting Windier – Driving Deeper Mixing



Sallée et al. 2021; DOI: 10.1038/s41586-021-03303-x

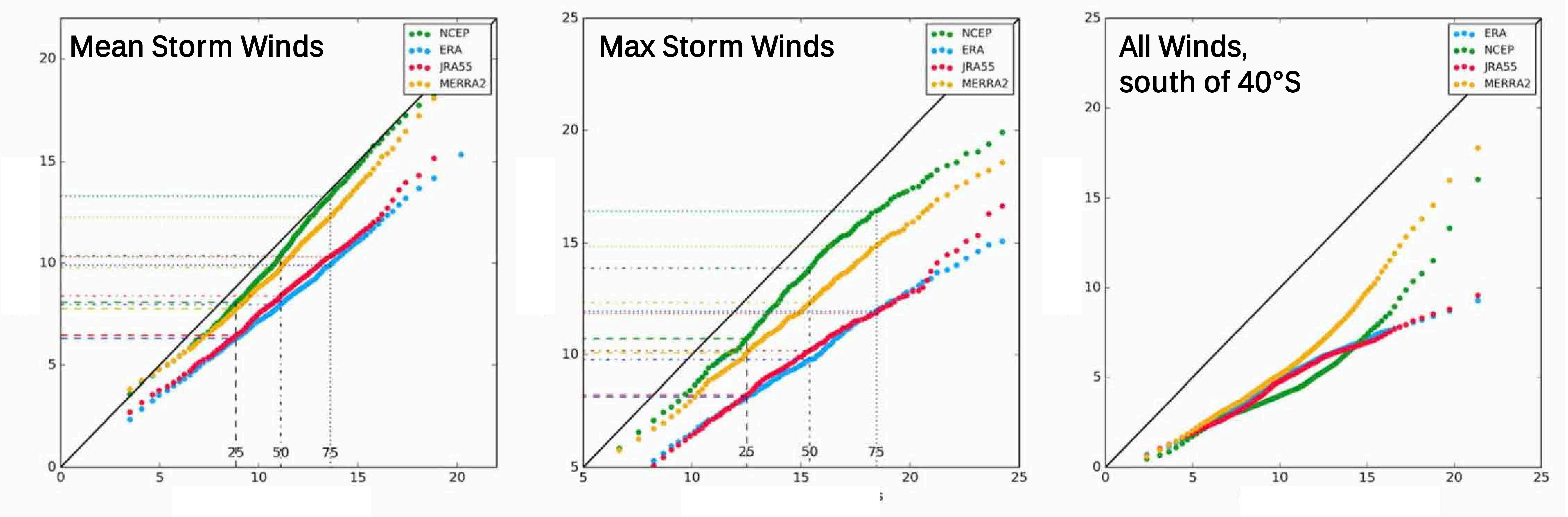
Southern Ocean Winds/Storms are Undersampled



SMOS Wind Speed

From altimeter

Southern Ocean Winds/Storms are Undersampled



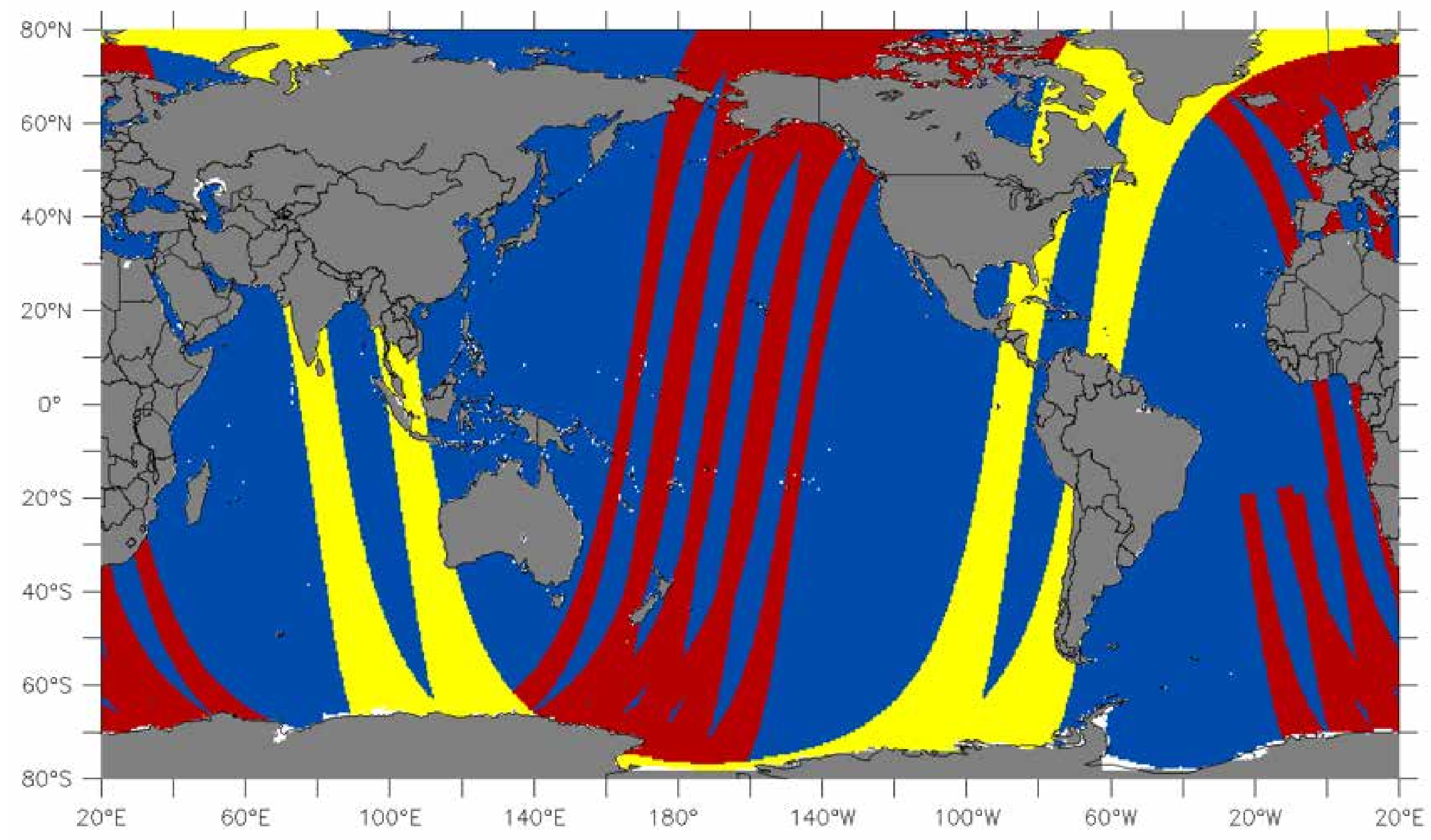
Direct comparison of QuikSCAT winds in SO storms with four different wind reanalyses (NCEP/CFSR; ERA-Interim; JRA55; MERRA)

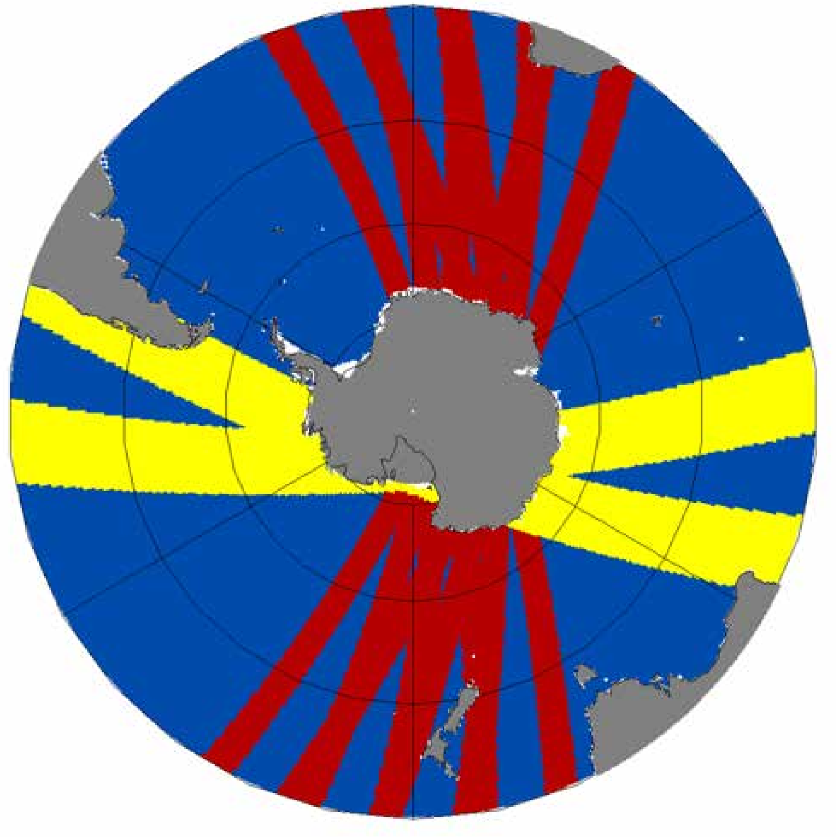
Verezemskaya et al. 2017; DOI: 10.1002/2017GL074053


SOS ZEPHYR
Capturing the Southern Ocean high winds to reduce the uncertainty in the Global Carbon Budget
UNITED STATES DEPT OF COMMERCE
Principal Investigator:
Joellen Russell, UA
Authorizing Official
Deputy PI:
David Long, BYU
BYU
LASP
INSTAAR
ODU
JPL
KNMI


S.O.S. ZEPHYR
SOUTHERN OCEAN STORMS
• CLOSING THE CARBON BUDGET •

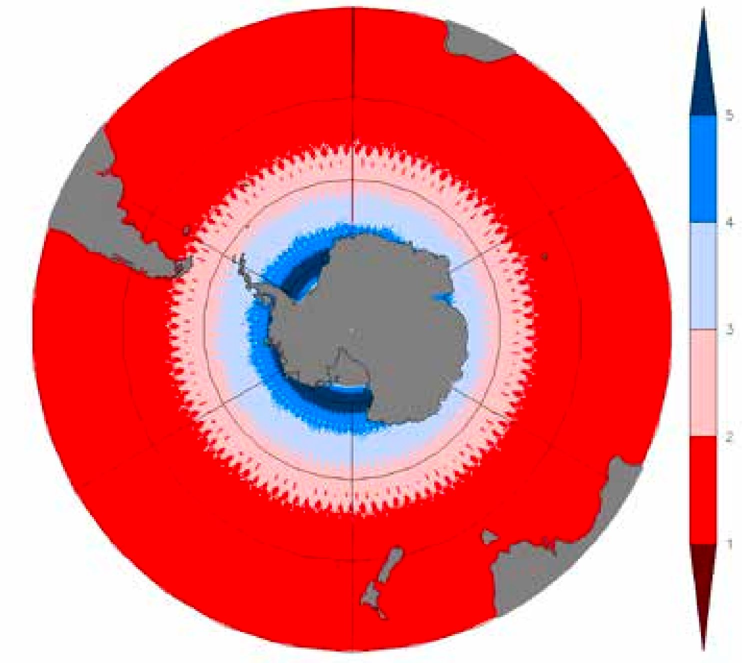
One More Scatterometer to Close the Carbon Budget



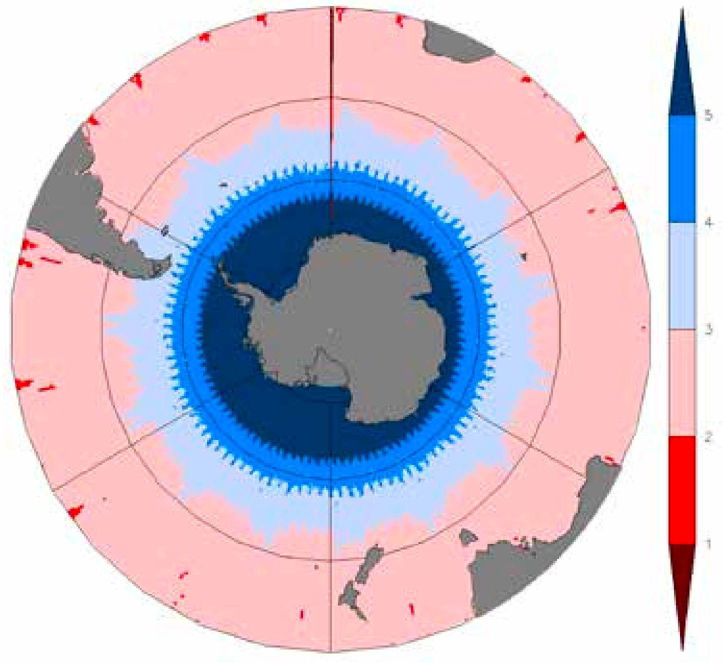


ASCAT constellation swaths over a 3-hour period (red)

Zephyr swaths over same 3-hour period (yellow)



Independent visits per day (ASCAT only)



Independent visits per day (ASCAT/Zephyr)

(Left)

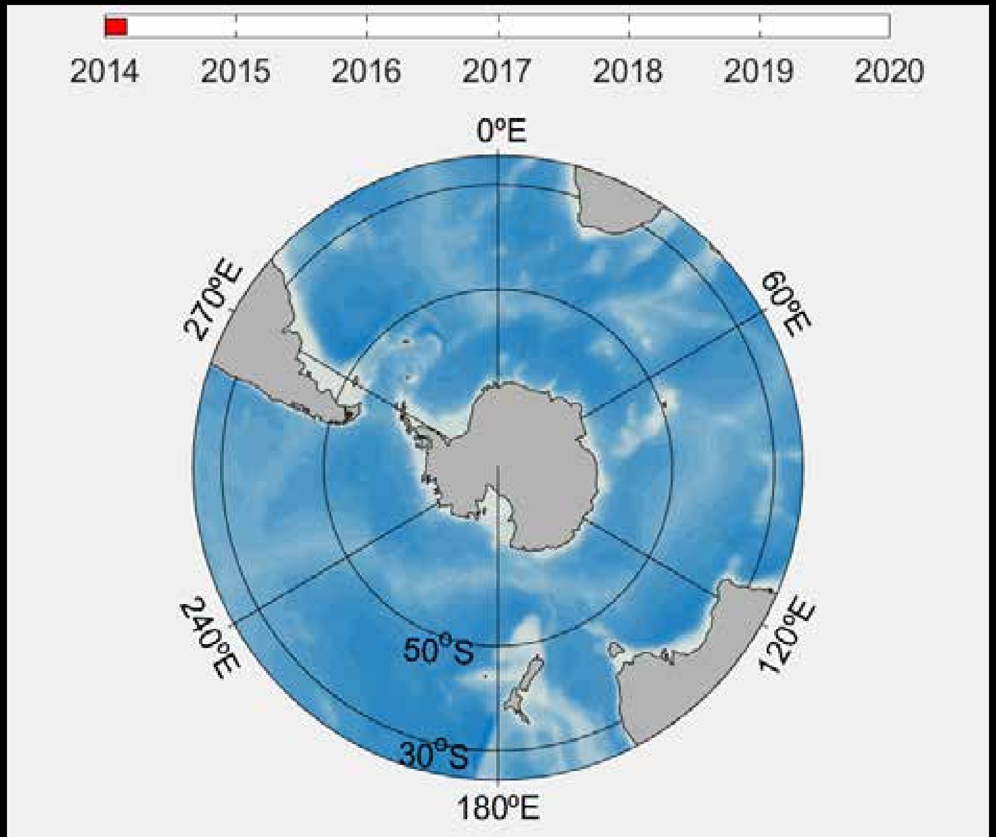
Independent visits per day by the ASCAT constellation (< 2, north of ~55°S)

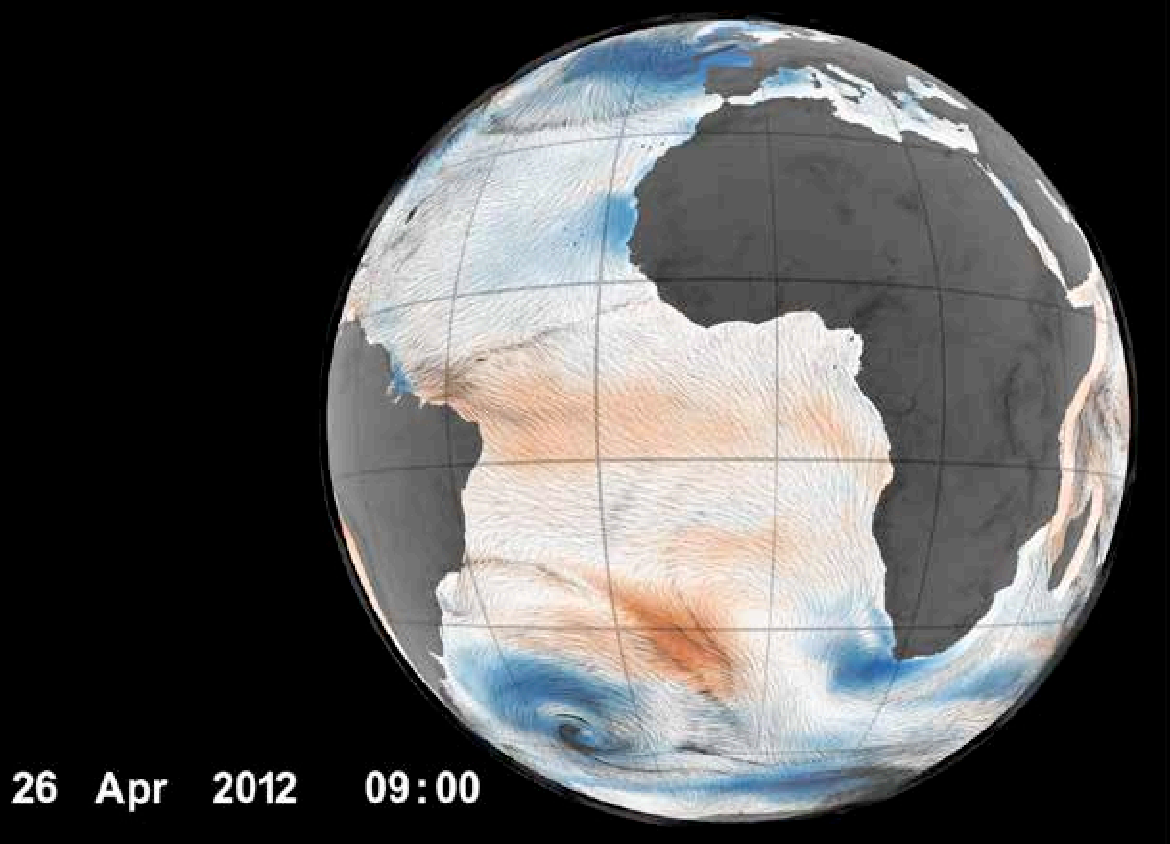
(Right)

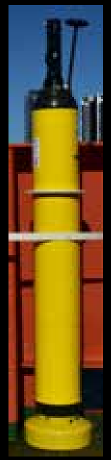
Independent visits per day by the

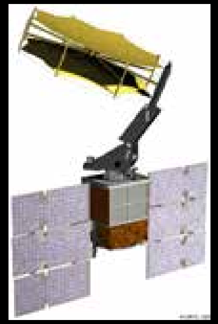
°S)

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





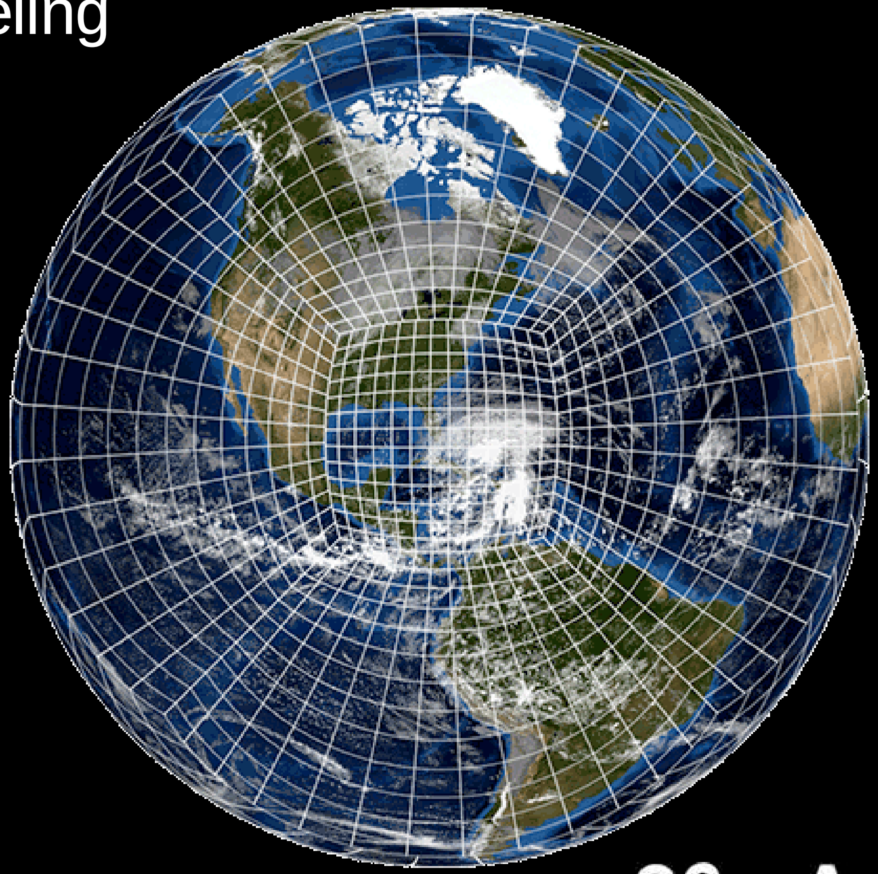




Prof. Joellen L. Russell
Thomas R. Brown Distinguished Chair of Integrative Science
Depts of Geosciences, Planetary Science, Hydrology &
Atmospheric Sciences and Applied Math
University of Arizona

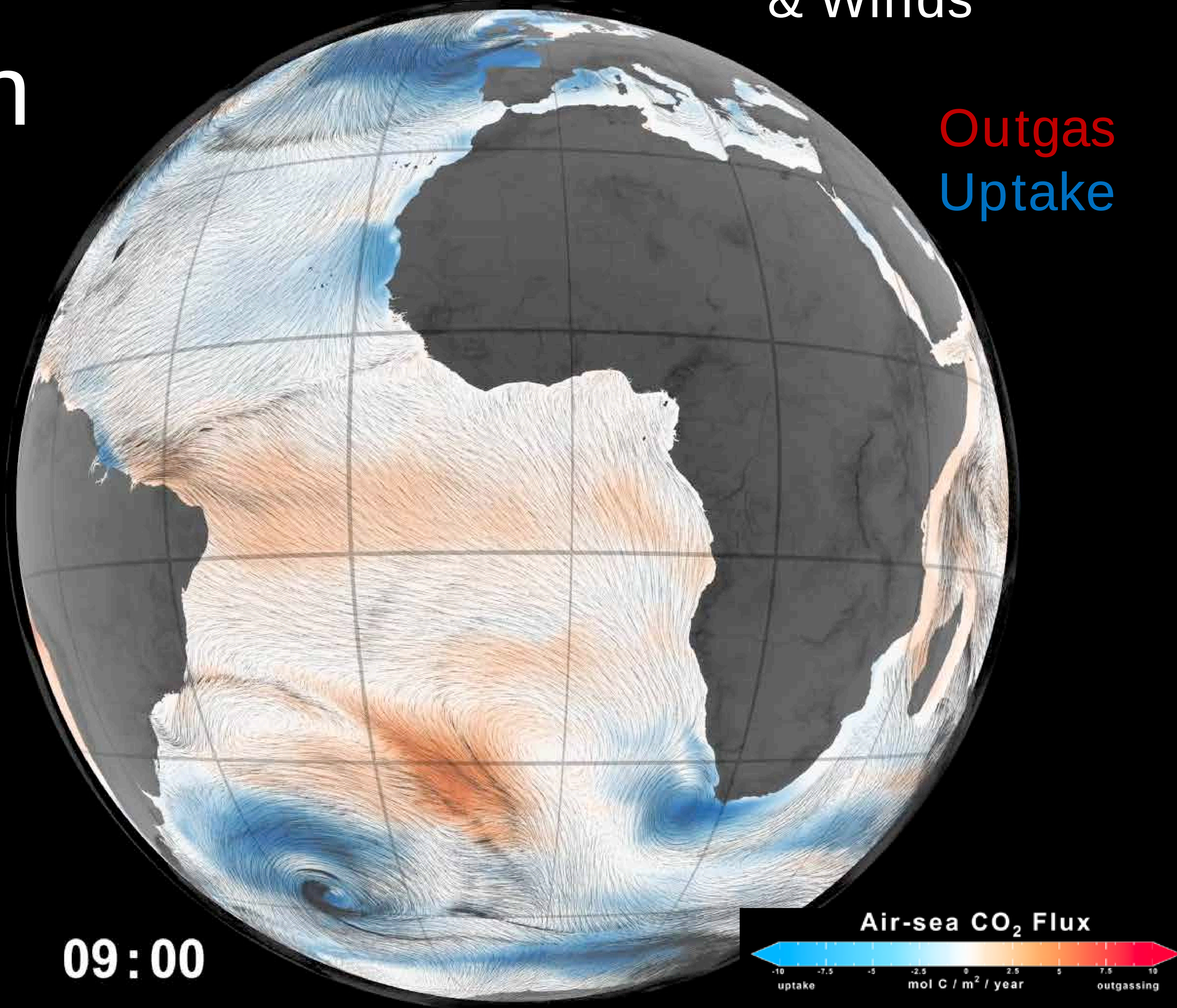
Climate and Carbon Prediction:

Convergence of Climate & Weather Modeling



Air-Sea Carbon Flux & Winds

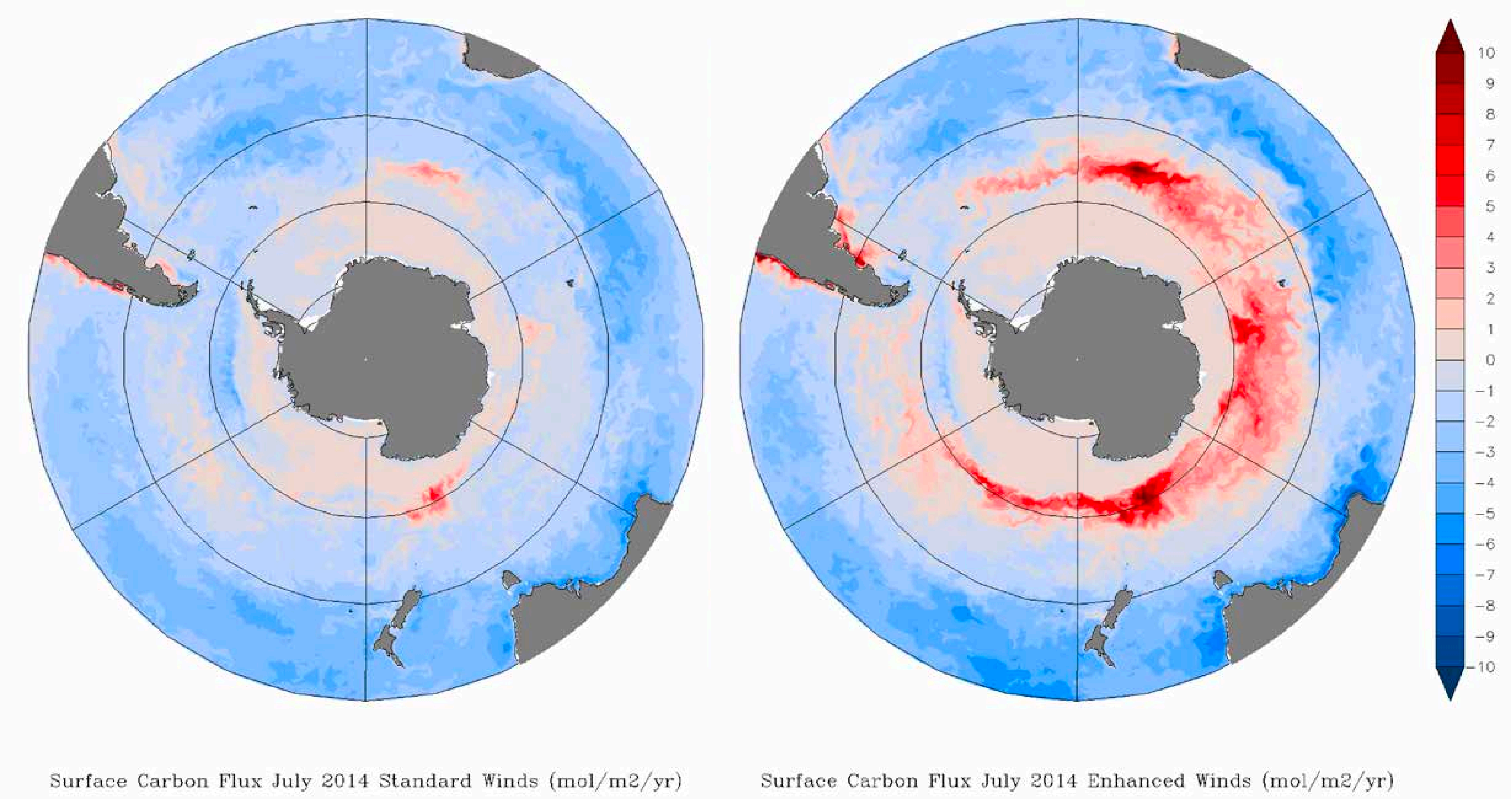
Outgas
Uptake

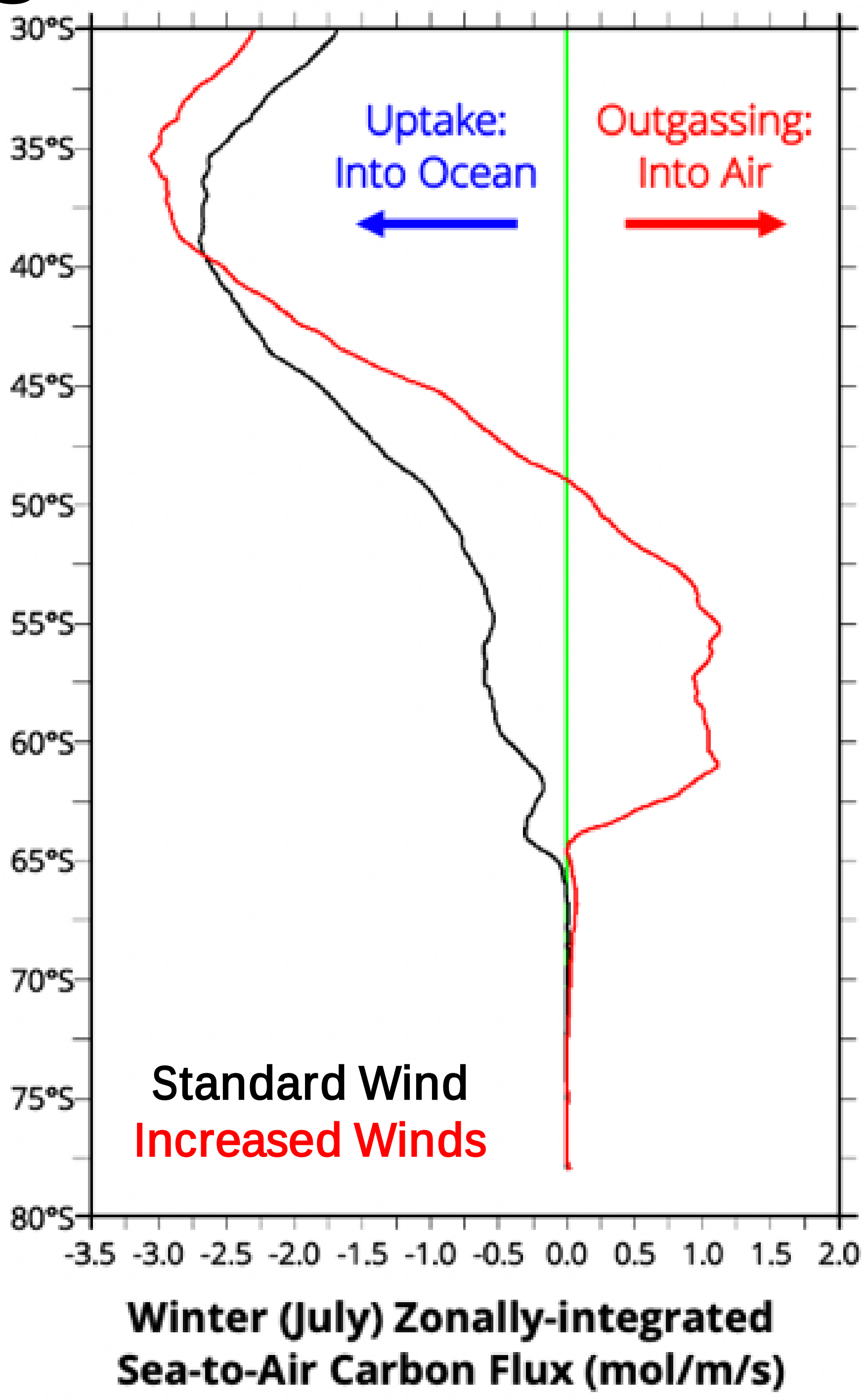


26 Apr 2012 09:00

NASA Scientific Visualization Studio; Shirah et al. (2020); https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019MS001888

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

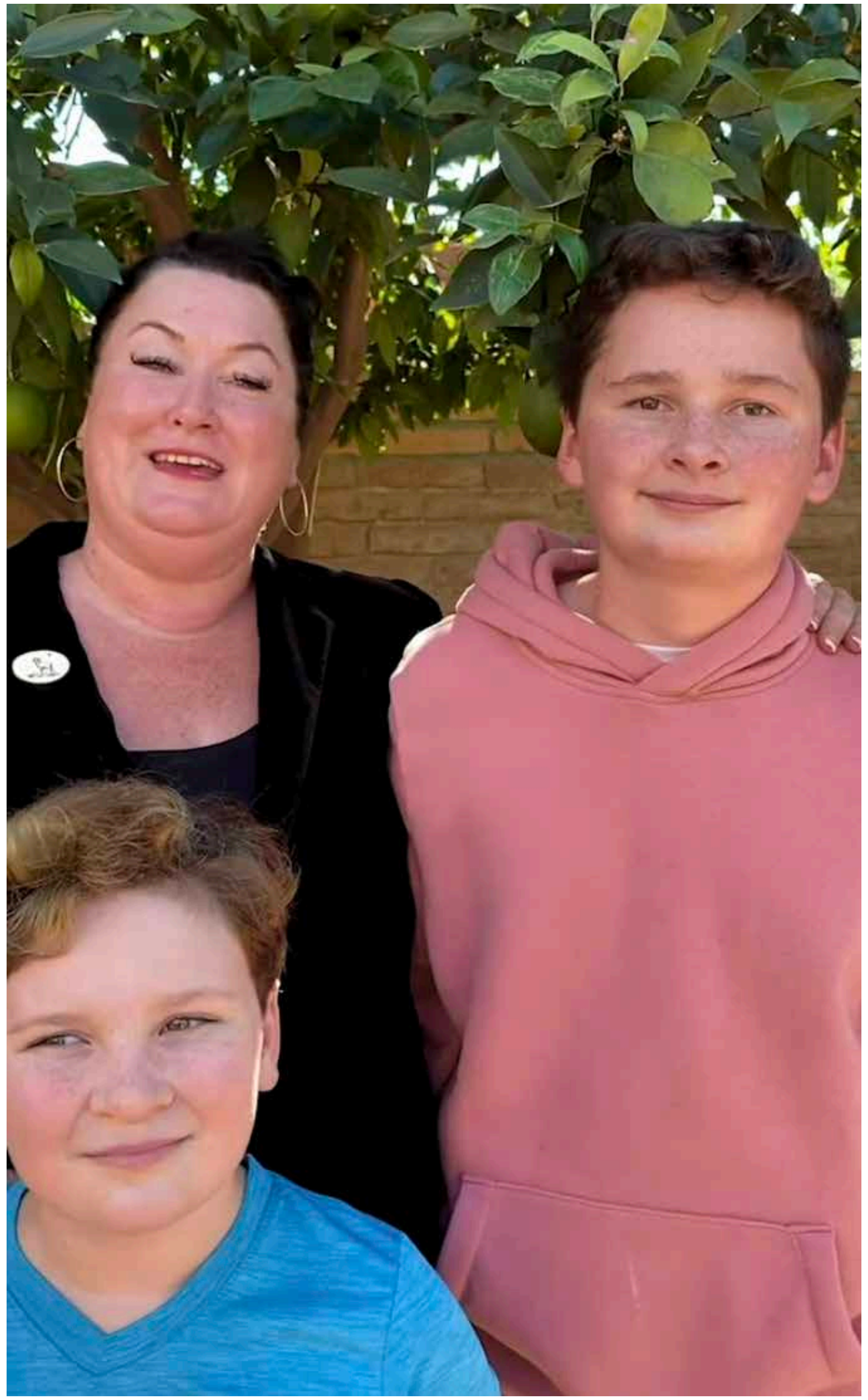

How do we spread the word?

Shining light on the path ahead ...

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

2	9	12	10	8	11	6
S	**C**	**I**	**E**	**N**	**C**	**E**
strong	caring	informed	expert	nurturing	climate-centered	entertaining

19	2	9	2
M	**O**	**M**	**S**
mobilized	objective	motivated	supportive



www.sciencemoms.com

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).

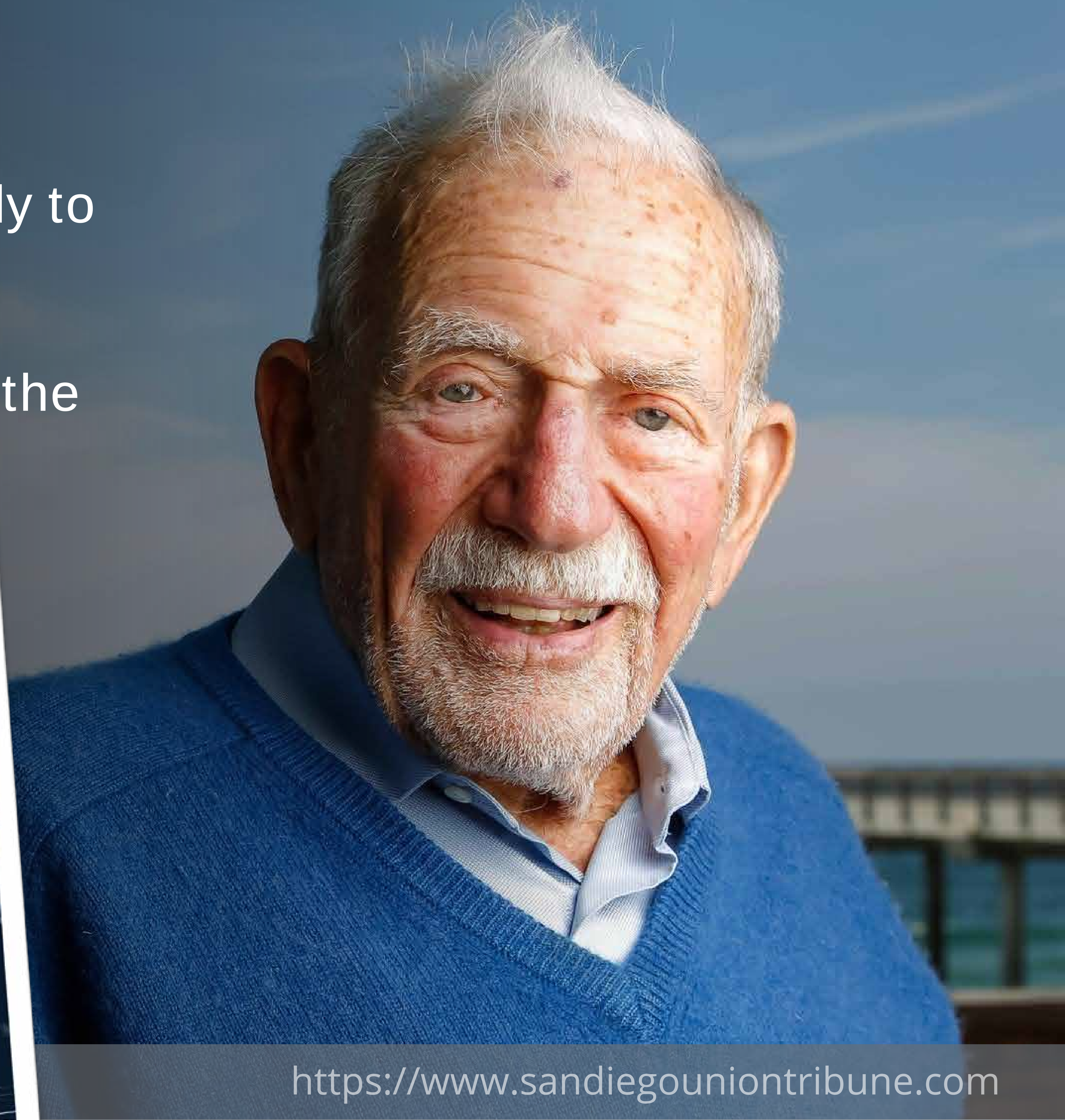
We will achieve this by:

- 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 several of his colleagues from Scripps at the U.S. Navy Radio and Sound Laboratory, where they developed methods related to amphibious warfare.

Their methods were used successfully to predict surf conditions for Allied landings in North Africa, the Pacific theater of war, and on D-Day during the Normandy invasion.



https://www.sandiegouniontribune.com


We Can Do It!
POST FEB. 15 TO FEB. 28
WAR PRODUCTION CO-ORDINATING COMMITTEE

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)!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