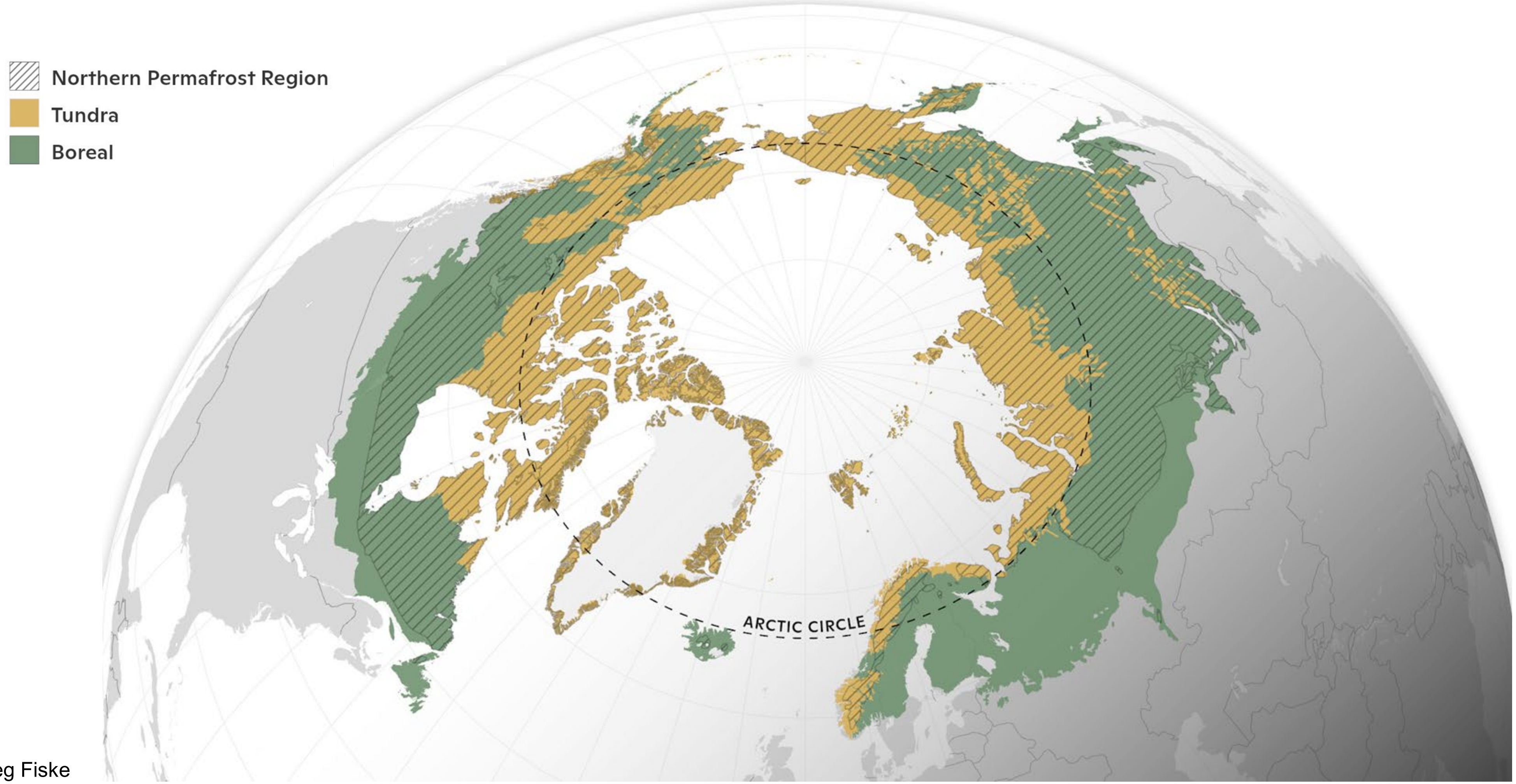
Approaches and Capabilities
Brendan Rogers

Woodwell Climate Research Center

PERMAFROST PATHWAYS

Exploring Key Research Topics for the 5th International Polar Year – A Workshop
National Academies of Sciences, Engineering, and Medicine
May 20, 2025



Map: Greg Fiske

Focal areas

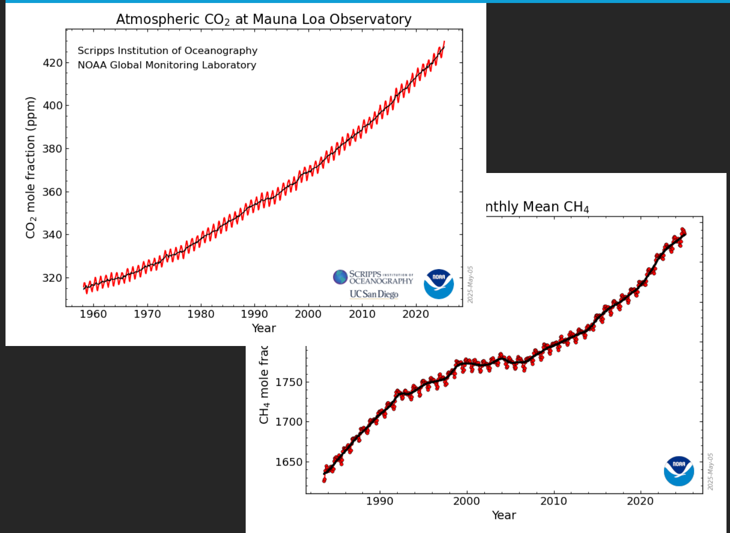
Permafrost thaw

Photo: Scott Zolkos

Wildfire

Photo: Dennis Quintilio

Carbon budget



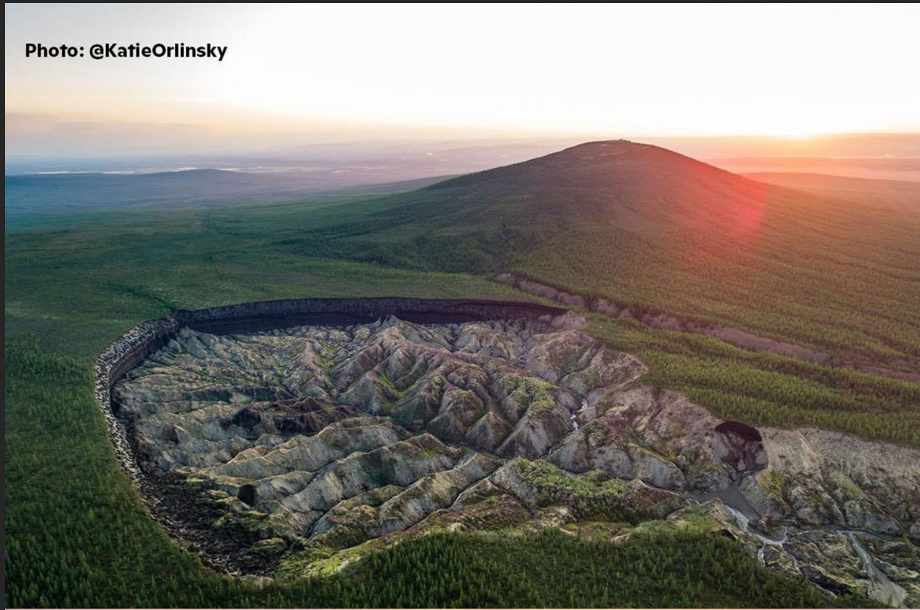
Permafrost thaw

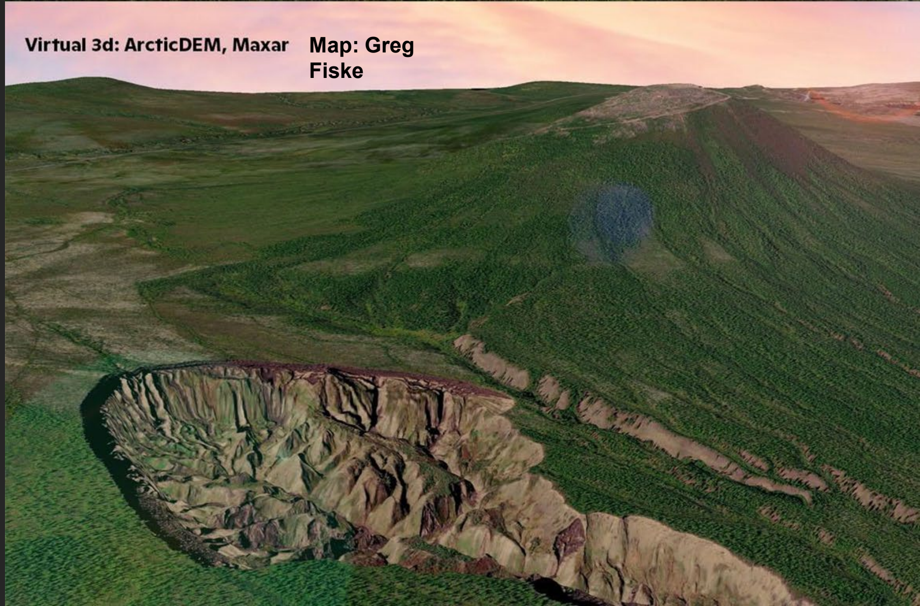
Motivation

- ‘Abrupt’ permafrost thaw impacts the land, people, infrastructure, and could have a major impact on the Permafrost Carbon Feedback
- Limited understanding of abrupt thaw distribution, changes over time, effects on carbon fluxes, and future changes

Approaches and capabilities

- Mapping abrupt thaw: High-resolution multispectral imagery (e.g., Maxar, Planet), ArcticDEM, LiDAR, interferometric SAR, training databases, deep learning, computing
- Impacts on carbon cycling: carbon transport and lability, terrestrial and aquatic surface fluxes, chronosequences
- Future changes: process models





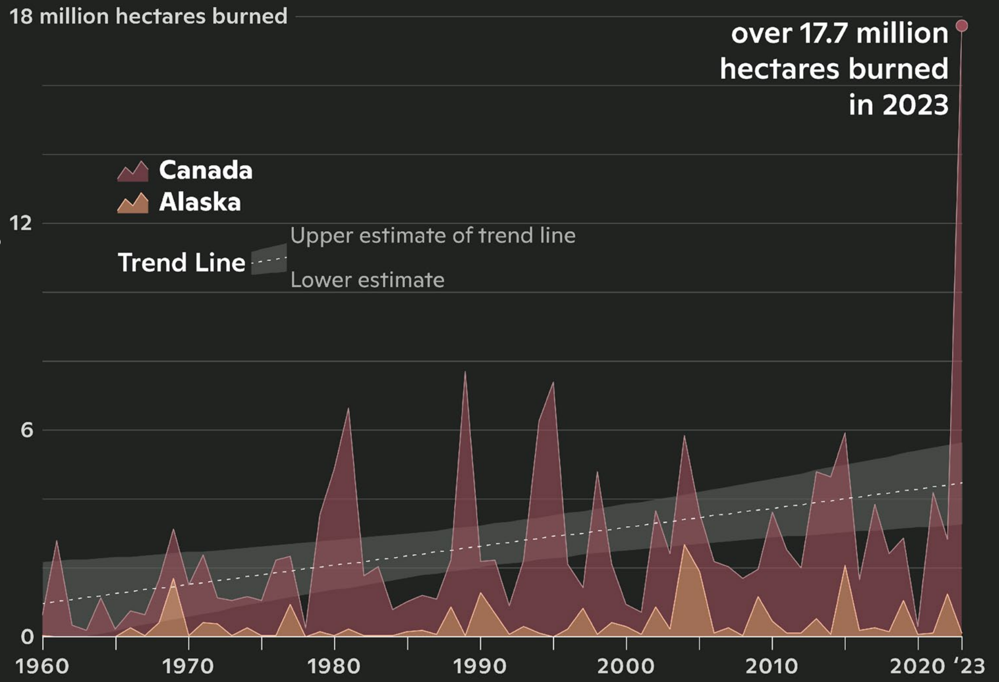
Wildfire

Motivation

- Arctic-boreal wildfires are intensifying because of climate change, impacting vegetation, permafrost, carbon budgets, human health, infrastructure, Indigenous cultural values, and more
- Limited quantification of these impacts, and understanding of how to better manage wildfires

Approaches and capabilities

- Impacts on permafrost and carbon: field observations, ground penetrating radar, eddy covariance, high-resolution multi-spectral, repeat LiDAR, SAR, process models
- Impacts on human health: improved emissions inventories, high-resolution transport models, linking exposure to morbidity and mortality, forecasting tools
- Management interventions: improved detection (e.g., FireSat), unmanned suppression, lightning suppression, new operational tools, data & models to optimize initial attack vs. fuels treatments vs. Rx and cultural burning

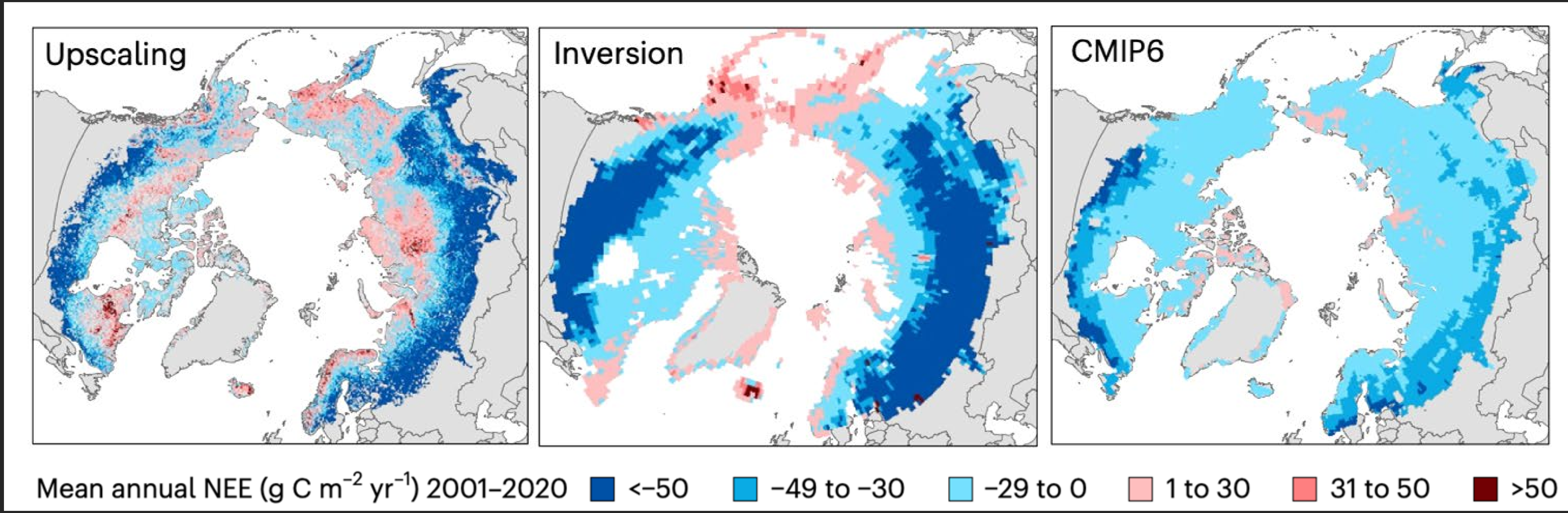


Christina Shintani

Carbon cycling

<u>Motivation</u>

- Estimates seem to be converging over the last few years, but still a large spread in estimates of current carbon balance (CO_2 & CH_4)
- Potential for large future emissions

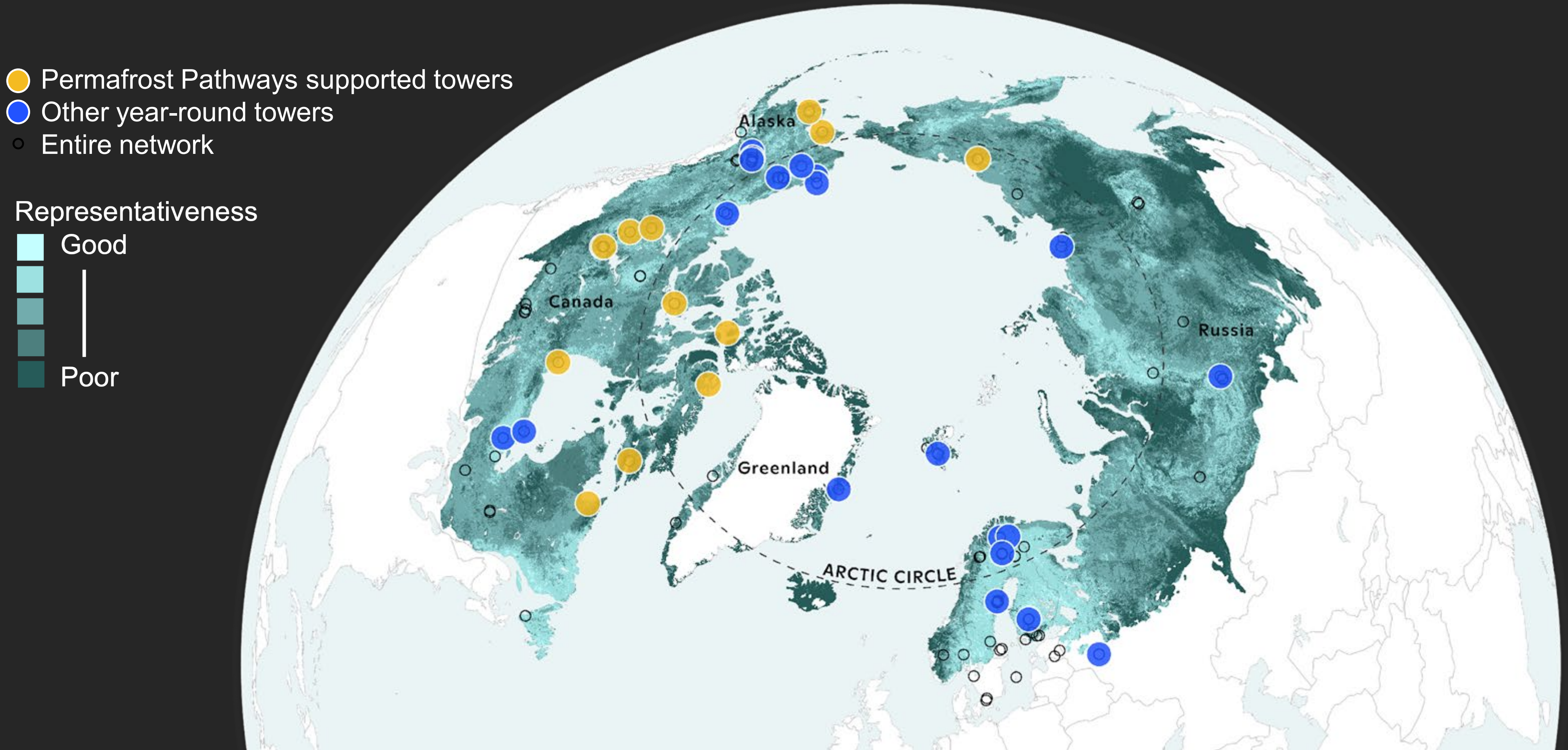


Virkkala et al (2025)

Carbon cycling

Approaches and capabilities

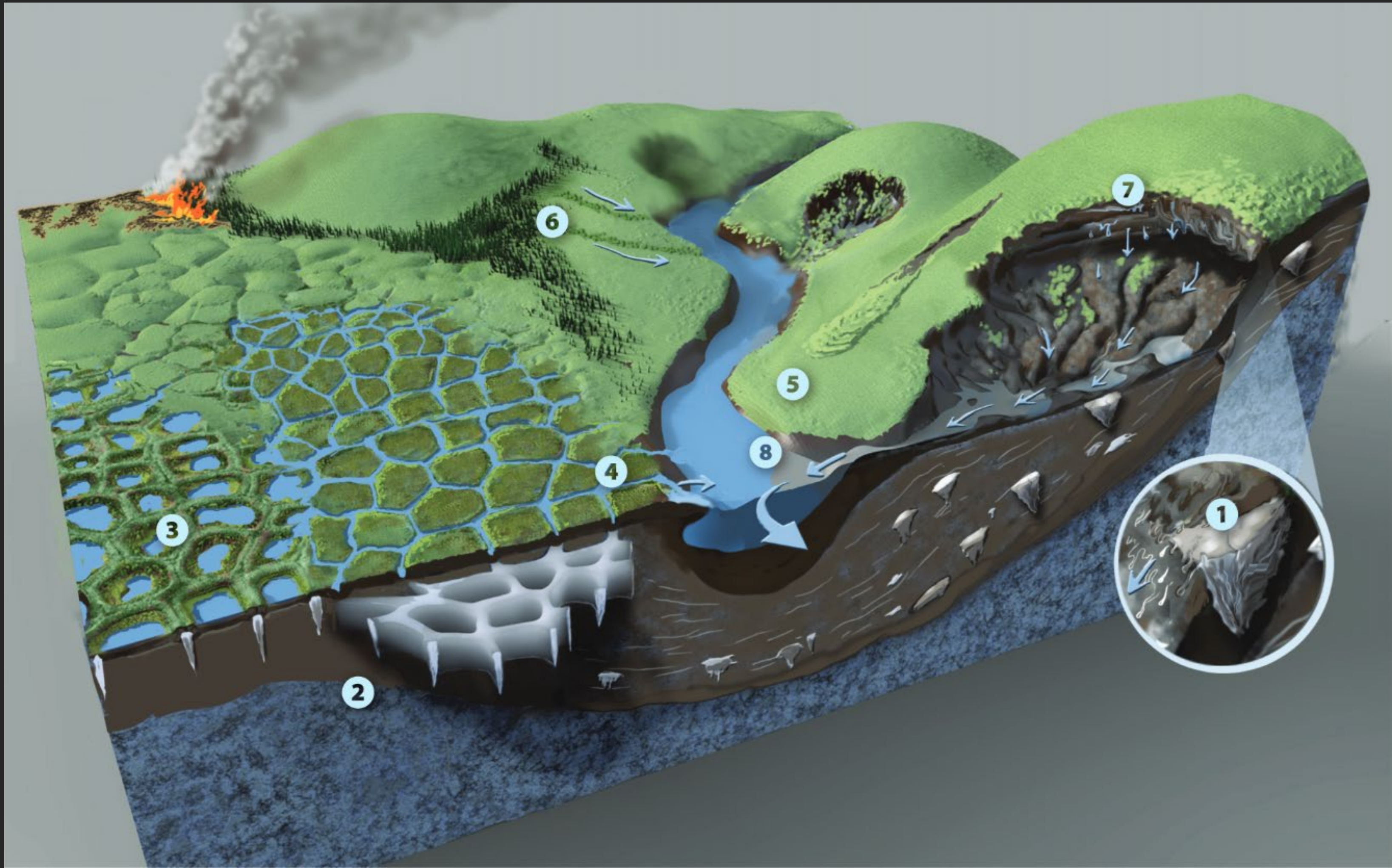
- Flux network



Carbon cycling

Approaches and capabilities

- Flux network
- Model development

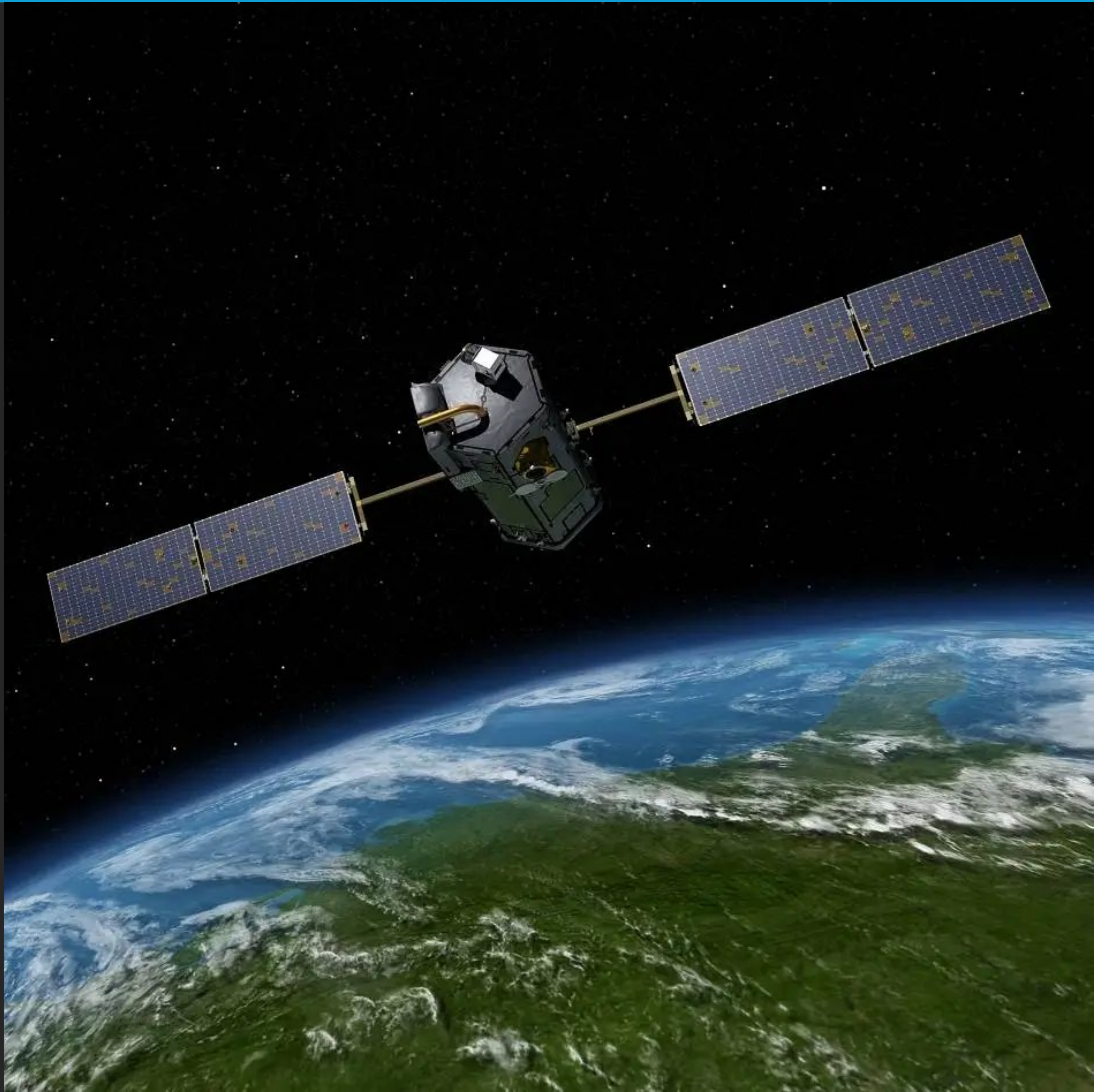


Schuur and Mack (2018)

Carbon cycling

Approaches and capabilities

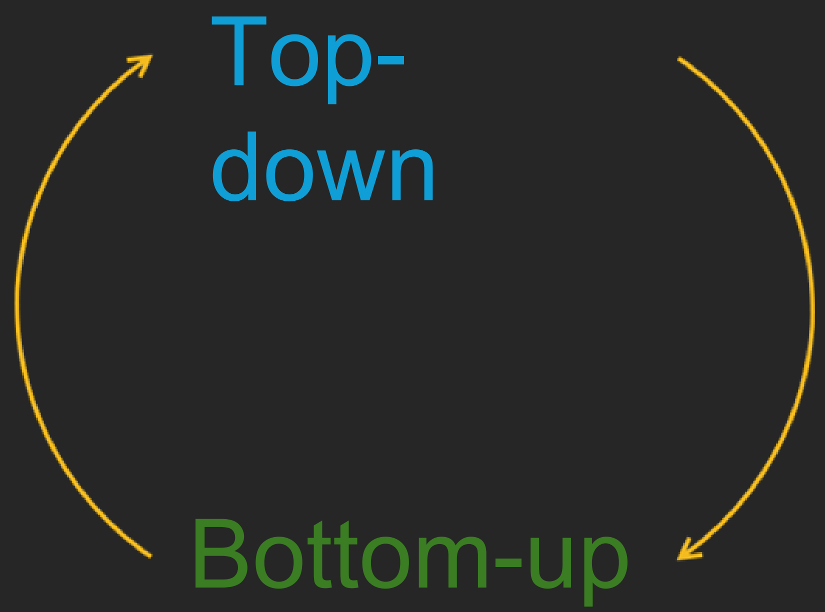
- Flux network
- Model development
- Satellite column measurements of CO_2 & CH_4



Carbon cycling

<u>Approaches and capabilities</u>

- Flux network
- Model development
- Satellite column measurements
- Coupling bottom-up and top-down approaches

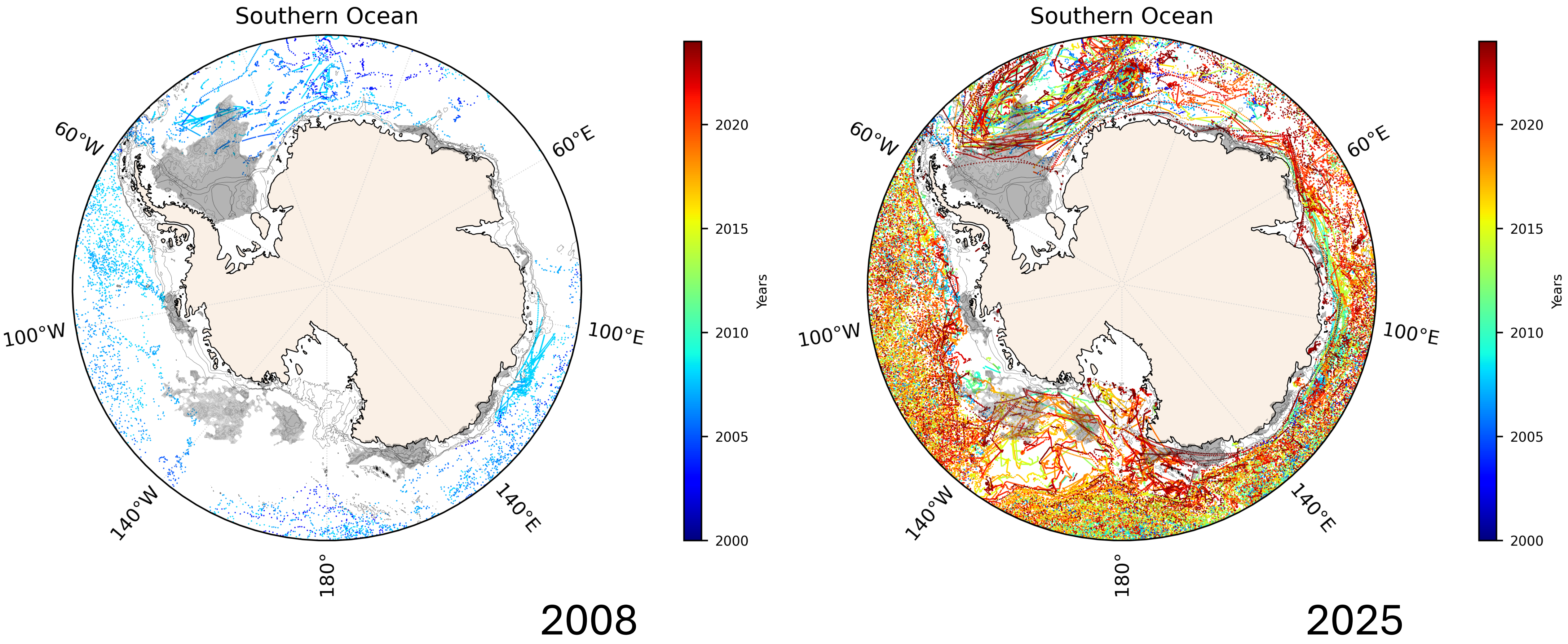



Aleut
Yup'ik
Koryak
Sugpiaq
Chukchi
DENE
EVENKI
Gwich'in
Iñupiat
Inuvialuit
Dehcho
Even
INUIT
ARCTIC
OCEAN
NENET
Nunavimmiut
Kalaalit
Sámi
Khanty-Mansi

Summary

- My perspective is largely aimed at scientific needs for permafrost, carbon, and wildfire
- Need for more ground observations on abrupt permafrost thaw and fire-permafrost interactions
- Process-based model development for (i) disturbances and carbon loss pathways, (ii) hydrology, (iii) plant processes, and (iv) snow physics
- Leverage mixture of long-term satellite records and emerging satellite platforms for CH_4 and CO_2 column concentrations, LiDAR, radar/SAR, hyperspectral, and fire detection & tracking
- Access to imagery and computing major current challenges
- International coordination and data sharing, management, and protocols paramount
- Opportunity to truly co-develop a scientific program with Indigenous knowledge

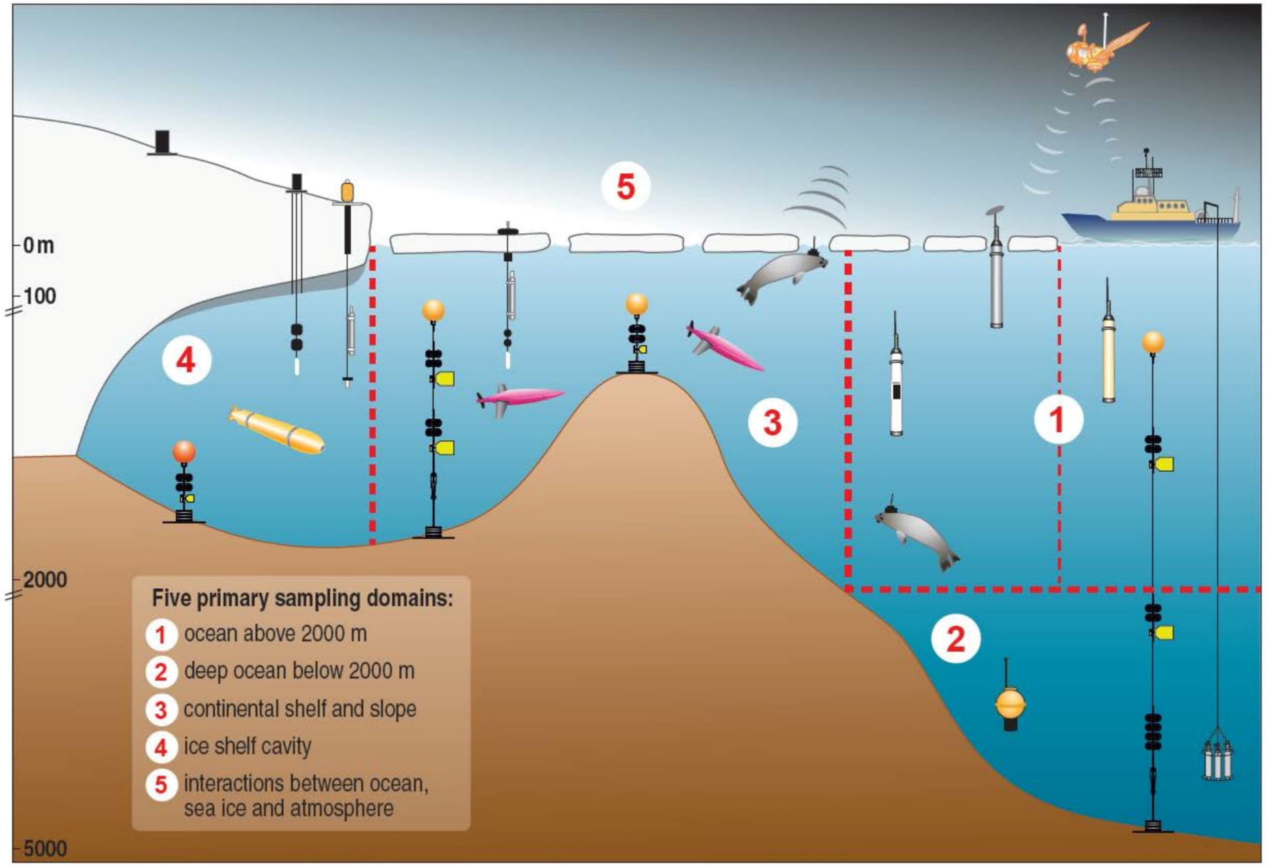
Broadscale Ocean Observations



Source: N. Kolodziejczyk

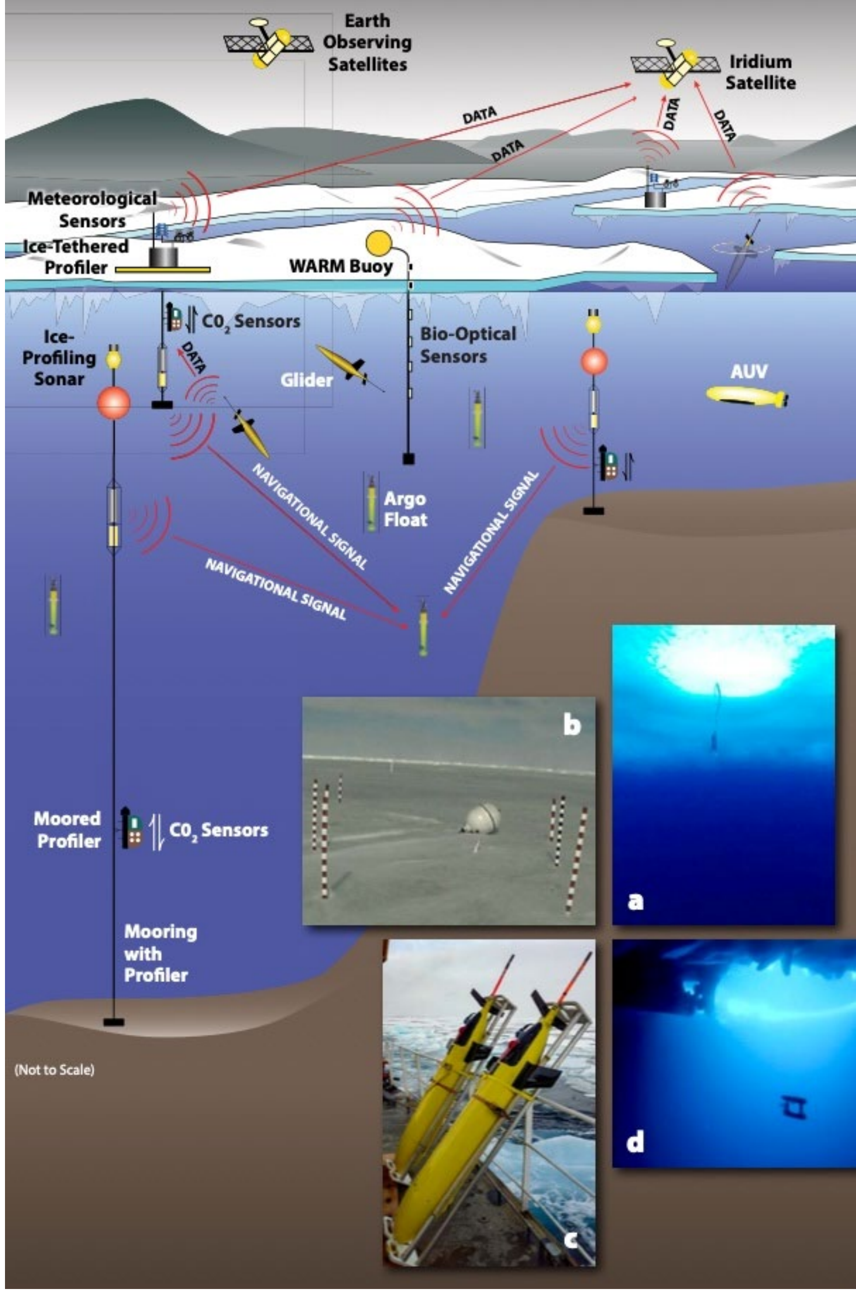
Ocean – Sea Ice - Ice Shelf Observing System

Established observing technologies: ships, floats, ITPs, gliders, moorings, ANIBOS, AUV's, AWS, ApRES, IMB, satellites, airborne capability
Newer capabilities: longer missions (gliders, AUVs), expansion of BGC and biological sensors, USV, uncrewed aircraft and drones, ROVs in boreholes (e.g., IceFin)



Source: Rintoul et al. Seeing below the ice: A strategy for observing the ocean beneath Antarctic sea ice and ice shelves Version 1.0. SOOS Report. November 2014

Basin-scale networked observing systems: including long-range geolocation, networked for communication and data telemetry



Lee, C. et al. 2022. *Oceanography* 35(3-4):210–221
https://doi.org/ 10.5670/oceanog.2022.127.

Next Steps…

Continue to develop **cost-effective, long-lived, autonomous platforms and sensors** that enable sustained broadscale measurements for climate studies and process studies.

Opportunistic sampling
- Use of commercial, tourist, fishing vessels for underway sampling and deployments in remote regions
- **Bathymetry measurements** from a wider range of vessels, from instrumented seals, floats, grounded icebergs..

Under-ice geolocation, communications and data telemetry
- Demonstrated in Beaufort Sea & Weddell Sea, can we expand these networks?
- Can we improve telemetry of data collected beneath ice in near real-time to aid operational modelling?

Clouds are still poorly represented in climate models, leading to large biases
- Need to measure aerosols, radiation and precipitation from ships and combine with satellite observations
- Aim to develop parameterisations that allow clouds to be better represented in models

Carbon cycle:
- Ships provide gold standard observations
- BGC floats help fill in basin-scale coverage with more limited set of observations
- Process studies still needed to understand coupling between physics, biogeochemistry and biology

Key Points:

- Despite great progress in filling the huge data gaps in the Southern Ocean, significant gaps remain.
- These gaps prevent us from answering key science questions of critical importance for society:
    - How vulnerable is the Antarctic Ice Sheet to changes in the surrounding ocean?
    - Will changes on the Antarctic continental shelf drive tipping points in ocean circulation (e.g. a collapse of the deep overturning circulation) with impacts on climate?
    - What is driving the regime shift in Antarctic sea ice cover?
    - How will Antarctic ecosystems respond to changes in ocean circulation and sea ice?
- New and developing tools mean that it is feasible to fill many of the remaining gaps
- National and international collaboration helps drive advances
- Integrate scientists with technical teams from project outset
- Need to scale up from targeted campaigns of short duration, limited spatial extent and single-discipline focus, to an integrated, multi-platform, multi-disciplinary observing system
- IPY5 may provide a springboard to do this…

Earth System Modeling and Land Modeling to Support IPY5

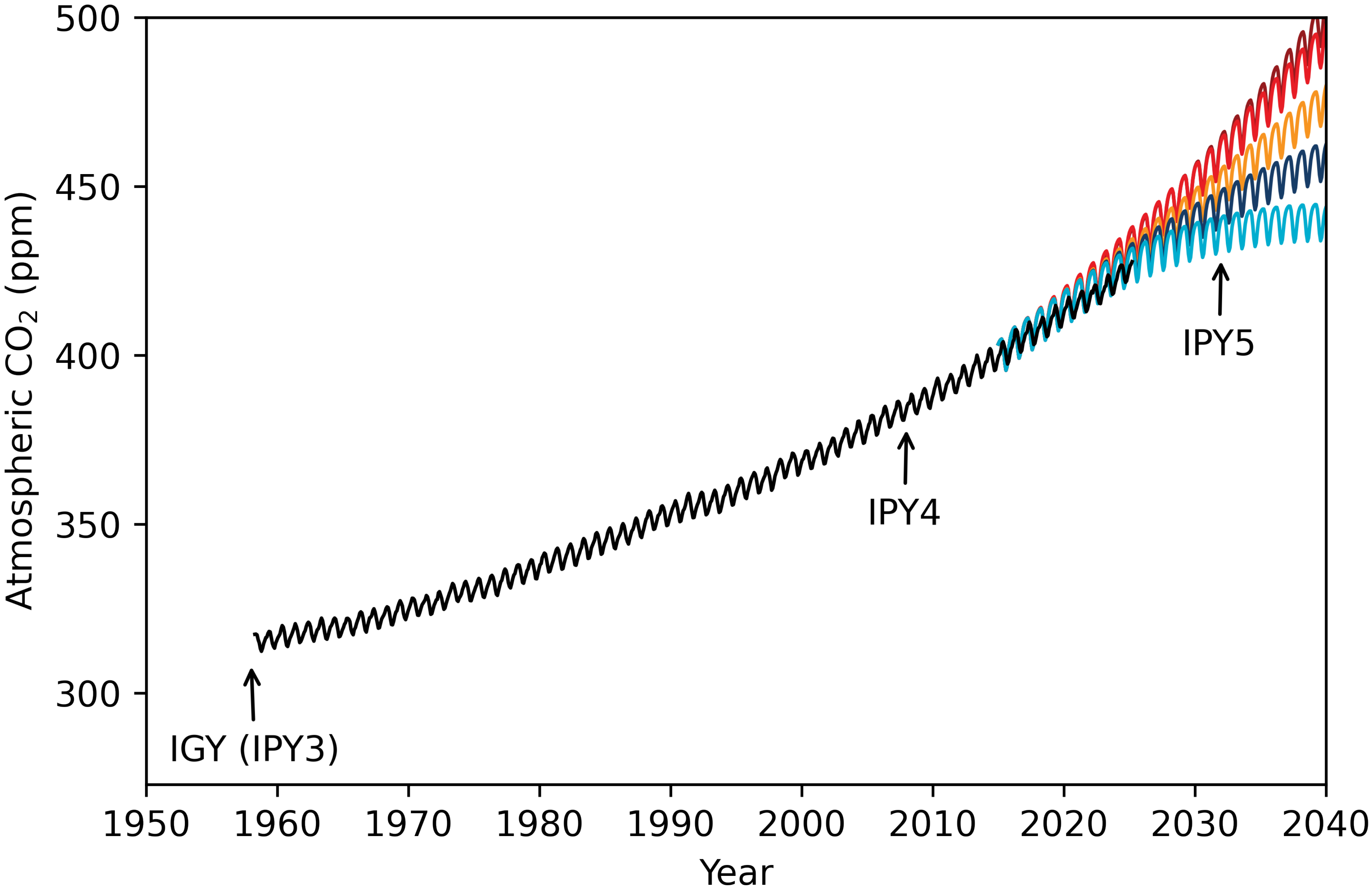
Charlie Koven

Lawrence Berkeley National Lab

BERKELEY LAB

RUBISCO

REDUCING UNCERTAINTIES IN BIOGEOCHEMICAL INTERACTIONS THROUGH SYNTHESIS AND COMPUTATION



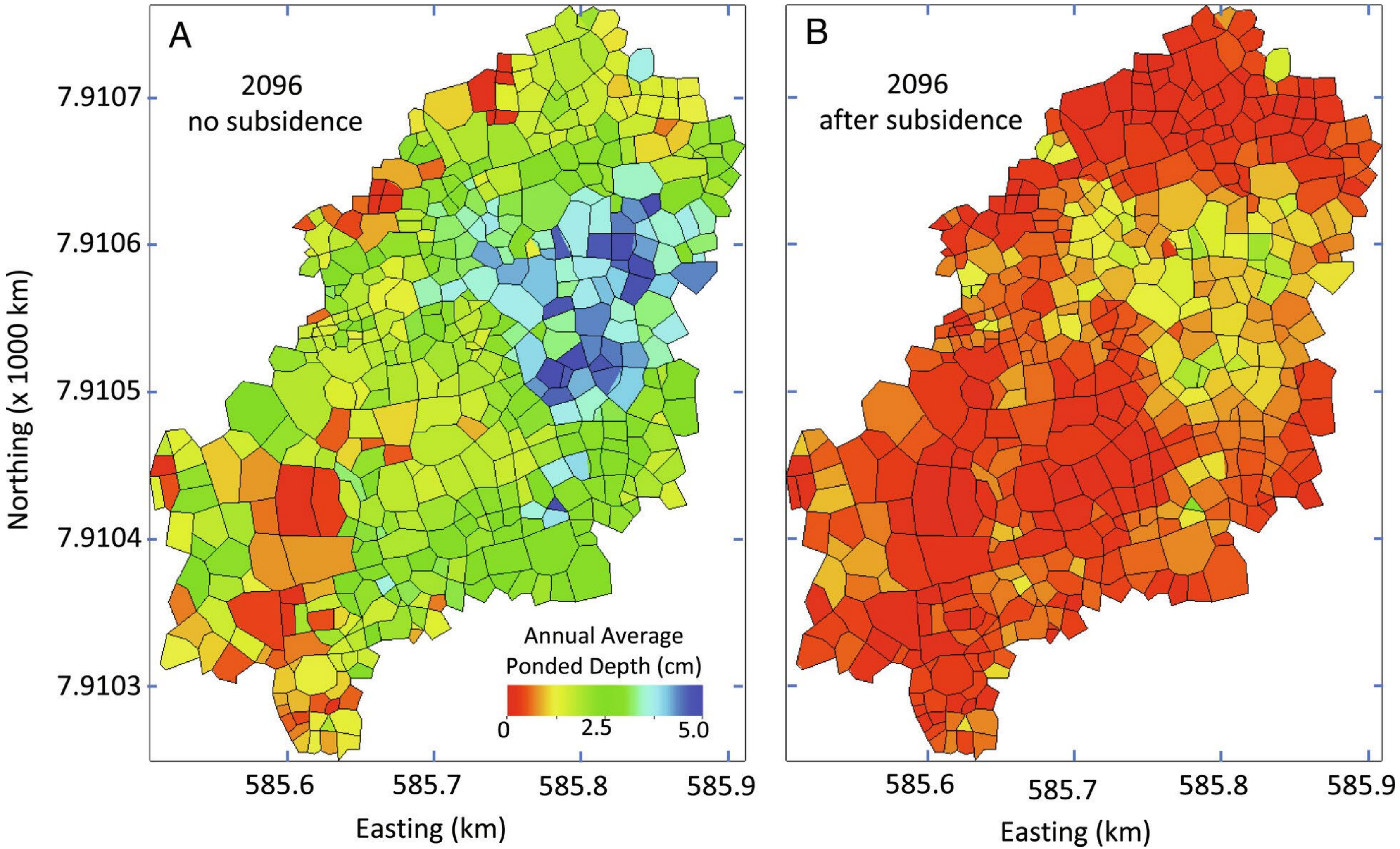
Atmospheric CO_2 (ppm)
500
450
400
350
300
IGY (IPY3)
IPY4
IPY5
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
Year

Incomplete process representation in all Earth system models (ESMs) of what is needed to capture complex Arctic feedbacks to climate change

Modelling Group	CSIRO	BCC	CCCma	CESM	CNRM	GFDL	IPSL	JAMSTEC	MPI	NorESM2-LM	UK
ESM	ACCESS-ESM1.5	BCC-CSM2-MR	CanESM5	CESM2	CNRM-ESM2-1	GFDL-ESM4	IPSL-CM6A-LR	MIROC-ES2L	MPI-ESM1.2-LR	NorESM2-LM	UKESM1-0-LL
Land carbon/biogeochemistry component											
Model name	CABLE2.4 CASA-CNP	BCC-AVIM2	CLASS-CTEM	CLM5	ISBA-CTRIP	LM4p1	ORCHIDEE (2)	MATSIRO (phys) VISIT-e (BGC)	JSBACH3.2	CLM5	JULES-ES-1.0
Veg C pools	3	3	3	22	6	6	8	3	3	3	3
Dead C pools	6	8	2	7	7	4	3	6	18	7	4
PFTS	13	16	9	22	16	6	15	13	12	21	13
Fire	No	No	No	Yes	Yes	Yes	No	No	Yes	Yes	No
Dynamic Veg	No	No	No	No	No	Yes	No	No	Yes	No	Yes
Permafrost C	No	No	No	Yes	No	No	No	No	No	Yes	No
Nitrogen cycle	Yes	No	No	Yes	No	No	No	Yes	Yes	Yes	Yes

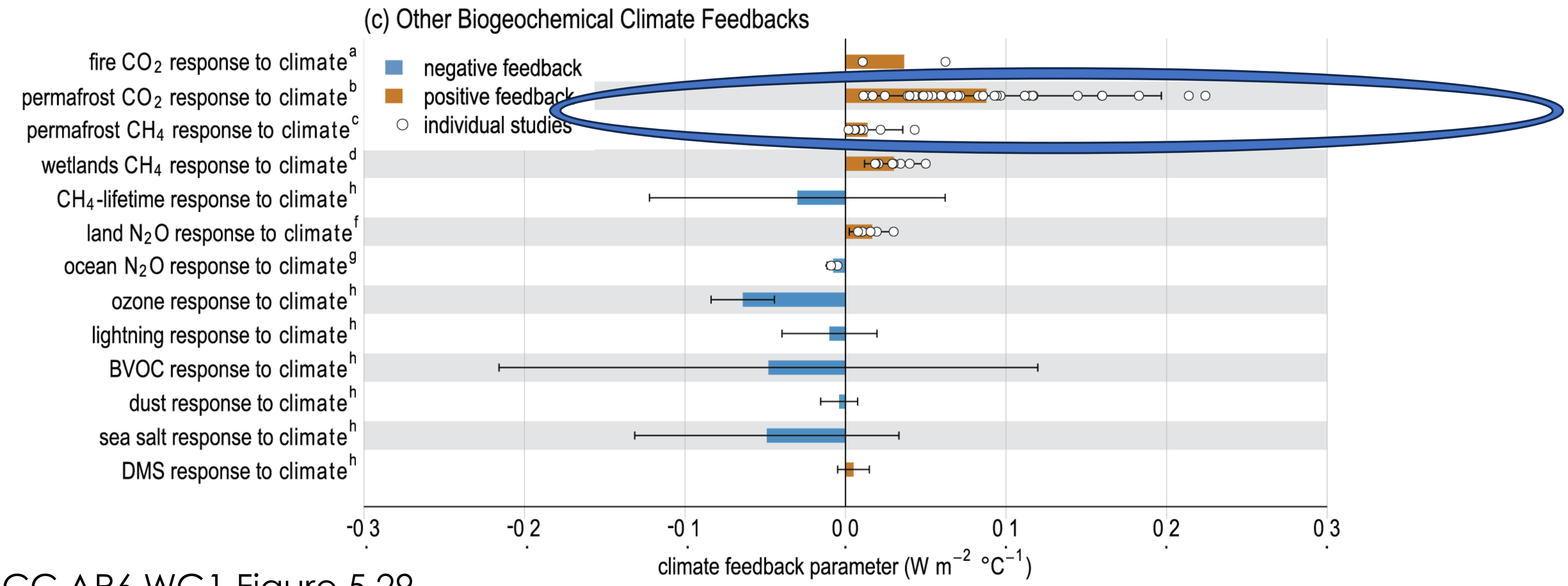
IPCC AR6 WG1 Table 5.4

Key new processes beginning to be incorporated into land models: e.g. mechanistic fine-scale thaw processes



Painter et al., 2023

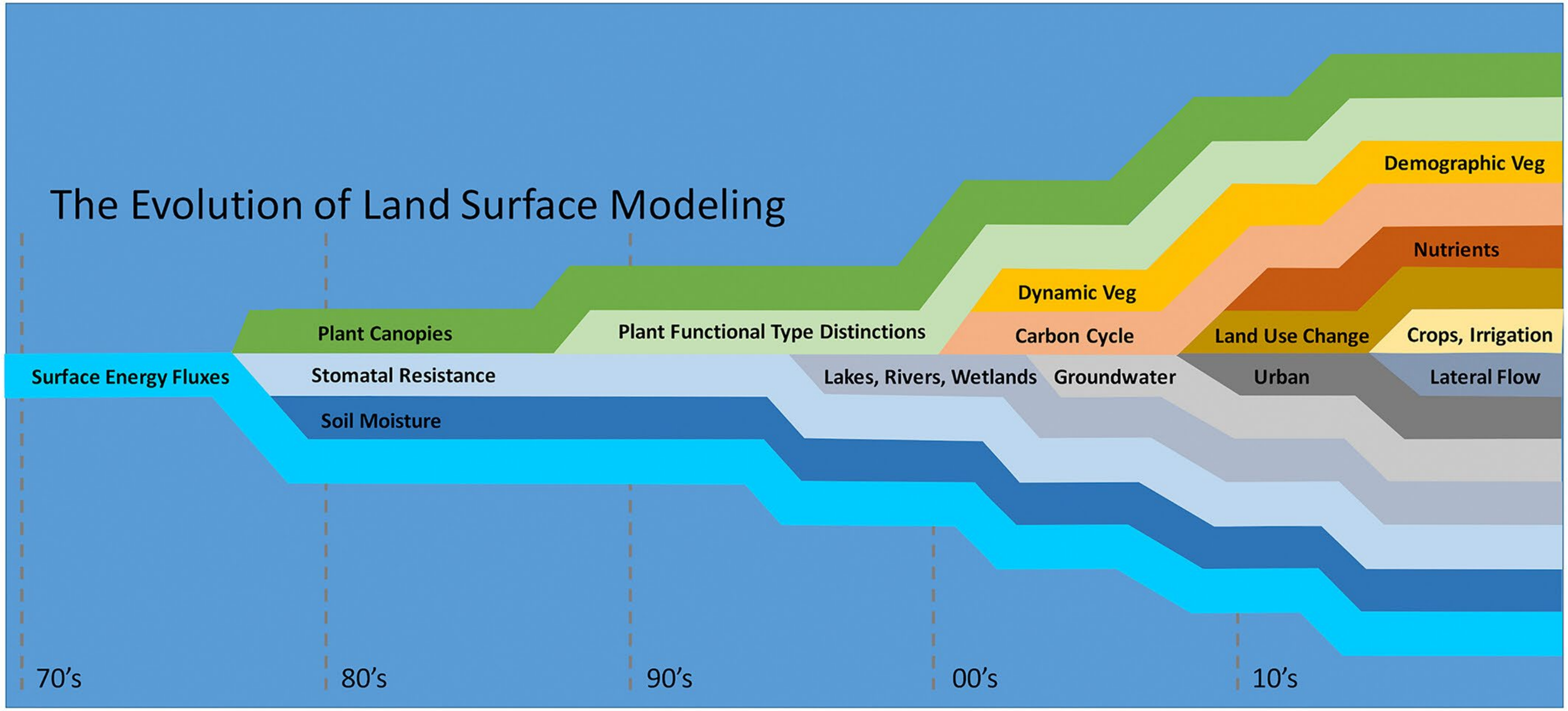
Permafrost feedbacks currently assessed mainly from standalone land models



IPCC AR6 WG1 Figure 5.29

Need to move towards larger ensembles of more comprehensive ESMs that include parameter and initial condition uncertainty

Complexification of models will likely continue into the 2030s, need ever more benchmarks to test model fidelity. Likely continued growth of ML to replace empirical representations and speed expensive computations.



Fisher and Koven, 2020

Large -scale observational benchmarks of polar system dynamics needed to test ESMs

(a) Land Benchmarking Results

CMIP5 ESMs: bcc-csm1-1 … HadGEM2-ES; CMIP6 ESMs: BCC-CSM2-MR … UKESM1-0-LL

	bcc-csm1-1	CanESM2	CESM1-BGC	GFDL-ESM2G	IPSL-CM5A-LR	MIROC-ESM	MPI-ESM-LR	NorESM1-ME	HadGEM2-ES	BCC-CSM2-MR	CanESM5	CESM2	GFDL-ESM4	IPSL-CM6A-LR	MIROC-ES2L	MPI-ESM1.2-LR	NorESM2-LM	UKESM1-0-LL	Mean CMIP5	Mean CMIP6
Land Ecosystem & Carbon Cycle	-0.72	-0.93	-1.55	-1.51	-0.13	0.60	-0.43	-1.31	0.19	-0.43	0.66	0.48	-1.09	0.22	0.60	-0.07	1.00	0.49	1.63	2.30
Biomass	0.20	-0.45	-1.52	-0.40	-1.26	-0.26	-1.07	-1.77	0.92	1.39	0.74	-0.20	-0.54	0.16	0.93	-0.96	-0.01	1.04	1.23	1.82
Burned area			-0.87				0.10	-0.83				1.60								
Leaf Area Index	-0.20	-0.64	-1.30	-2.53	-0.01	0.30	0.01	-1.85	-0.16	0.27	0.08	0.34	-0.70	1.19	0.82	0.46	0.37	0.69	1.04	1.81
Soil Carbon	0.27	1.26	-1.46	0.07	0.75	0.47	-0.03	-1.14	0.07	0.23	1.35	-0.99	-2.04	-1.55	0.90	-0.75	-0.17	0.24	1.01	1.48
Gross Primary Productivity	0.59	-1.23	0.01	-1.81	-1.40	0.29	-0.53	-0.24	-1.04	0.77	0.04	0.59	-0.38	1.17	-1.02	-0.37	0.73	0.09	1.51	2.22
Net Ecosystem Exchange	-0.42	-1.81	-0.21	-0.65	1.10	-0.24	0.80	0.02	-1.03	-1.02	-1.19	0.59	1.69	-0.42	0.63	-0.21	1.08	-1.43	1.28	1.43
Ecosystem Respiration	0.90	-0.56	-0.86	-0.24	-1.35	0.99	-0.01	-0.94	-1.54	0.81	0.59	0.51	-0.79	0.90	-0.21	-1.24	0.43	-0.94	1.34	2.21
Carbon Dioxide		-1.54	-0.36	-2.92	-0.74	1.53	-0.00	0.37	0.85		0.42	0.26	0.39	0.59	1.10	-0.87	0.21	0.69	0.09	-0.07
Global Net Carbon Balance		-1.64	-0.88	-1.13	0.17	-0.31	-0.38	-0.50	0.24		-0.23	1.34	-1.70	0.17	-0.74	1.45	1.56	0.26	0.92	1.40
Land Hydrology Cycle	-2.65	-0.42	0.44	-0.18	-0.49	-0.52	-0.57	0.17	0.70	0.15	-0.47	1.51	-1.24	0.58	-0.72	-0.83	0.97	0.87	1.00	1.70
Evapotranspiration	-0.82	-0.99	-0.27	-1.02	0.64	-1.14	-0.62	-0.60	0.28	0.39	-1.08	1.09	0.65	0.43	-1.40	-1.01	0.82	1.05	1.41	2.20
Evaporative Fraction	-0.34	0.74	0.74	-0.14	-0.85	0.21	-1.98	0.22	-0.34	0.10	0.11	1.25	-0.88	1.29	-1.65	-1.81	1.11	-0.06	0.98	1.29
Runoff	-3.66	-0.35	0.47	0.06	-0.67	-0.57	0.12	0.44	1.33	-0.07	-0.23	0.96	-0.17	-0.19	0.02	-0.05	0.47	0.99	-0.03	1.13
Latent Heat	-0.02	-0.39	-0.38	-0.93	0.24	-0.98	-0.73	-0.71	-0.21	0.66	-1.20	1.60	0.12	0.42	-1.52	-1.24	1.40	0.40	1.49	1.99
Sensible Heat	-0.85	-0.20	0.80	-0.28	-1.12	-1.23	-1.67	0.45	0.65	-1.04	0.37	1.02	-0.39	1.19	-0.54	-1.63	0.63	0.92	1.48	1.45
Terrestrial Water Storage Anomaly	-2.79	-0.45	0.47	0.50	-0.38	0.34	0.35	0.43	0.58	0.15	-0.08	0.95	-2.91	0.43	0.37	0.15	0.39	0.51	0.49	0.50
Permafrost	-0.88	-2.26	0.01	0.13	0.83	0.69	0.56	0.69	-0.56	-0.11	-3.02	0.83	0.74	-0.18	0.49	0.42	0.89	0.43	0.06	0.23

Relative Scale

Worse Value — Better Value — Missing Data or Error

(b) Ocean Benchmarking Results

CMIP5 ESMs: bcc-csm1-1 … HadGEM2-ES; CMIP6 ESMs: BCC-CSM2-MR … UKESM1-0-LL

	bcc-csm1-1	CanESM2	CESM1-BGC	GFDL-ESM2G	IPSL-CM5A-LR	MIROC-ESM	MPI-ESM-LR	NorESM1-ME	HadGEM2-ES	BCC-CSM2-MR	CanESM5	CESM2	GFDL-ESM4	IPSL-CM6A-LR	MIROC-ES2L	MPI-ESM1.2-LR	NorESM2-LM	UKESM1-0-LL	Mean CMIP5	Mean CMIP6
Ocean Ecosystems			2.18	0.20	-0.20		0.04		0.22		-0.37	0.83	-0.37	-0.26	-0.91	-0.67	-1.93	0.27	0.30	0.67
Chlorophyll		-1.50	2.15	0.44	1.02		0.49		0.56		-0.67	0.88	-0.21	0.10	-1.02	-0.41	-2.19	0.18	0.13	0.04
Oxygen, surface			0.73	-0.13	-1.98		-0.53	-1.53	-0.29		0.73	0.34	-0.09	-0.41	0.35	-0.30	0.40	0.49	0.64	1.57
Ocean Nutrients			-0.84	-0.10	0.91		-0.80	-1.25				-0.02	1.00	1.88		-0.90	-1.14	-0.17	-0.16	1.60
Nitrate, surface		0.21	-1.63	0.67	1.22		-0.18	-1.70	0.82		1.21	-0.90	0.29	1.21	1.02	0.39	-1.78	-0.56	-0.47	0.18
Phosphate, surface			-0.69	-0.04	0.04		-0.45	-0.43				0.39	-0.14	0.17	-0.41	-0.98	0.00	0.02	0.88	1.63
Silicate, surface			0.44	-0.71	0.24		-0.81	-0.20	-2.16			0.50	1.24	1.60		-1.21	-0.19	0.18	-0.29	1.37
Ocean Carbon											1.24	-0.23	-0.62	-0.69	-1.08	-1.12	1.31			1.19
TAlk, surface		-0.27	1.01	0.12	0.19		0.32	-2.31	-0.22		0.06	-0.36	0.85	-0.42	0.29	-2.40	1.27	0.06	1.27	0.54
DIC, surface		0.60	-0.14	-0.31	-0.40		-0.34	-2.85	-0.96		0.41	-0.73	0.07	1.01	0.42	0.19	1.20	0.82	0.43	0.60
Anthropogenic											1.35	-0.06	-0.77	-0.78	-1.23	-0.84	1.14			1.19
Ocean Physical Drivers	-0.22	0.02	0.29	-1.11	0.14	-0.23	-1.36	-0.70	-0.79	-0.37	0.51	0.76	0.22	0.34	-0.14	-0.23	-1.22	0.65	1.20	2.25
Mixed Layer Depth			0.39	-1.38			-1.95	0.25		-0.71	0.81	1.50	0.21	0.51	-0.82	0.61	-1.28	0.66	-0.29	1.48
Temperature, surface	-0.26	0.38	0.13	-1.30	-1.52	-0.29	-0.20	-0.48	-0.60	0.14	0.21	0.52	0.16	-0.36	-0.23	-0.29	-0.58	1.19	1.54	1.82
Temperature, 200m	-0.26	0.22	0.43	-0.87	-0.03	-0.21	-0.93	-1.14	-1.30	-0.29	0.35	0.51	-0.67	0.30	0.46	-0.34	-1.03	1.04	1.69	2.09
Temperature, 700m	-0.65	0.94	0.62	-0.19	0.79	-0.83	-2.03	0.27	0.50	-0.77	-0.97	0.35	-0.44	0.33	-0.55	-1.95	0.32	1.29	1.59	1.37
Vertical temperature gradient	-0.49	0.04	0.91	0.08	-0.11	0.08	-0.22	-1.85	-2.03	-0.57	0.66	0.89	0.62	-0.52	0.82	-0.53	-1.68	1.04	1.22	1.66
Salinity, surface	-0.08	-1.22	0.01	-0.69	0.23	-0.67	0.04	-1.42	-1.78	0.93	0.34	0.29	1.62	0.13	0.16	-0.30	-0.22	-0.99	1.43	2.19
Salinity, 200m	-0.62	-0.29	-0.07	-0.57	0.54	-0.57	-0.26	-0.75	-0.76	-0.25	0.49	-0.47	0.15	0.65	0.58	0.01	-0.98	-0.22	1.41	1.99
Salinity, 700m	0.44	-0.35	-1.06	-0.54	0.70	0.46	-0.46	-0.80	0.32	0.36	0.25	-1.16	-0.47	0.54	0.33	-0.39	-0.87	-0.54	1.58	1.64
Ocean Relationships			-1.86	-0.36	-0.29		1.50	-0.43	0.68		-0.02	0.72	1.20	0.17	-1.86	0.02		-1.12	0.39	1.25
Oxygen, surface/WOA2018			0.27	0.23	-0.63		-0.26	-0.12	-0.38		0.29	-0.21	0.19	0.18	0.14	-0.07		0.03	-0.23	0.53
Nitrate, surface/WOA2018		-2.41	-1.38	-0.18	0.06		1.41	-0.16	0.78		0.09	0.79	1.07	0.26	-1.35	0.20		-0.74	0.52	1.04

IPCC AR6 WG1 Fig 5.22

Summary: Modeling needs to support robust Earth system Science for IPY5

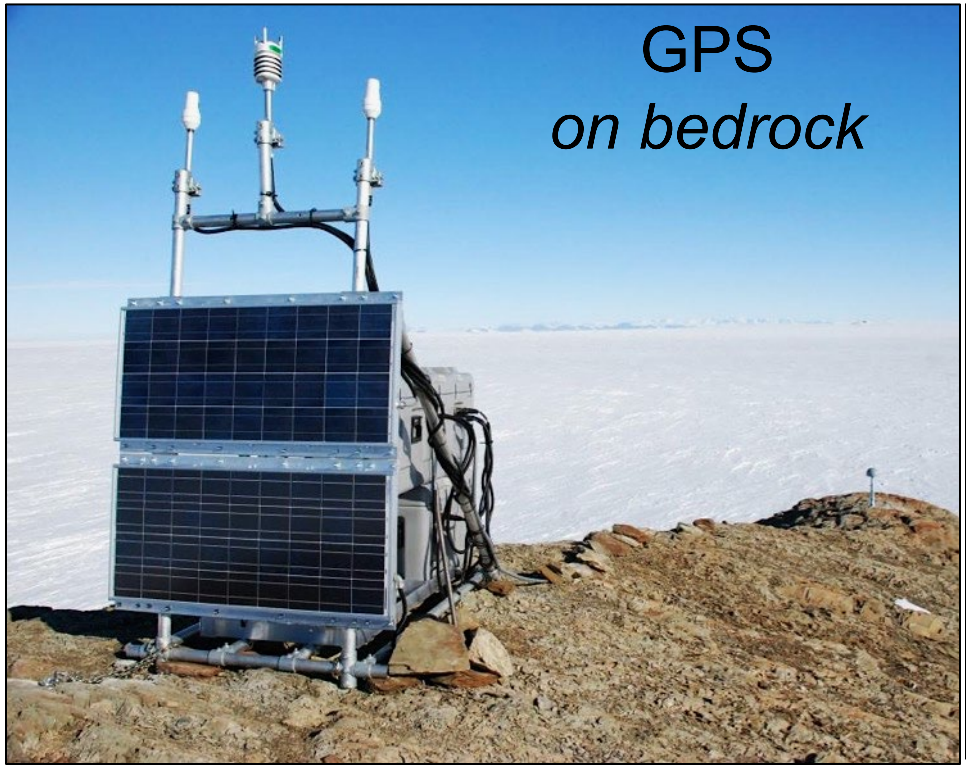
- We need to protect existing research capabilities and institutions
- More comprehensive representation of key Arctic feedbacks in models:
  - Mechanisms: Permafrost carbon feedbacks and links to fire, abrupt thaw, other disturbance, and vegetation change
  - Uncertainty propagation through large perturbed parameter ensembles and multi-model ensembles
- Better large-scale observational constraints:
  - Boundary & initial conditions (e.g. Pan-Arctic ice-rich permafrost characteristics)
  - Integrated system behavior benchmarks (e.g. response of permafrost to warming, ecosystem responses to wildfire)

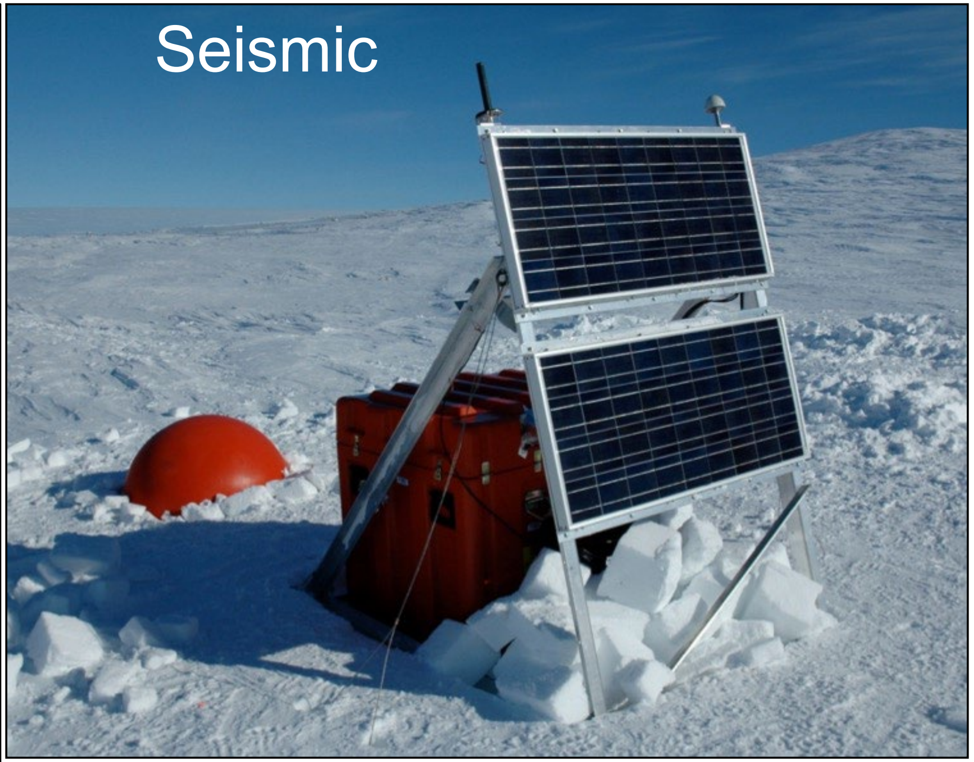
Insights – IPY4 Polar Earth Observing Network (POLENET)

Terry Wilson / Byrd Polar & Climate Research Center / Ohio State University

- IPY4 Umbrella Project: Arctic and Antarctic
- US-NSF-funded IPY Project [ending ~now]

autonomous GPS & seismic instruments at remote sites





ANET: Antarctic **Net**work – Polar Observing Network

www.polenet.org

POLENET

Path to IPY Project - *PRE- IPY4*

Science: Early 2000's: US & international Antarctic Earth Science community established interdisciplinary science objectives requiring autonomous GPS & Seismic system deployments

Antarctic Neotectonics (ANTEC)

SCAR Scientific Research Programme

ANTEC

SCAR
THE INTERNATIONAL COUNCIL FOR SCIENCE • SCIENTIFIC COMMITTEE ON ANTARCTIC RESEARCH

Technology development:

IRIS PASSCAL INSTRUMENT CENTER
Program for Array Seismic Studies of the Continental Lithosphere

UNAVCO

U.S. Facilities
+ U.S. Scientists

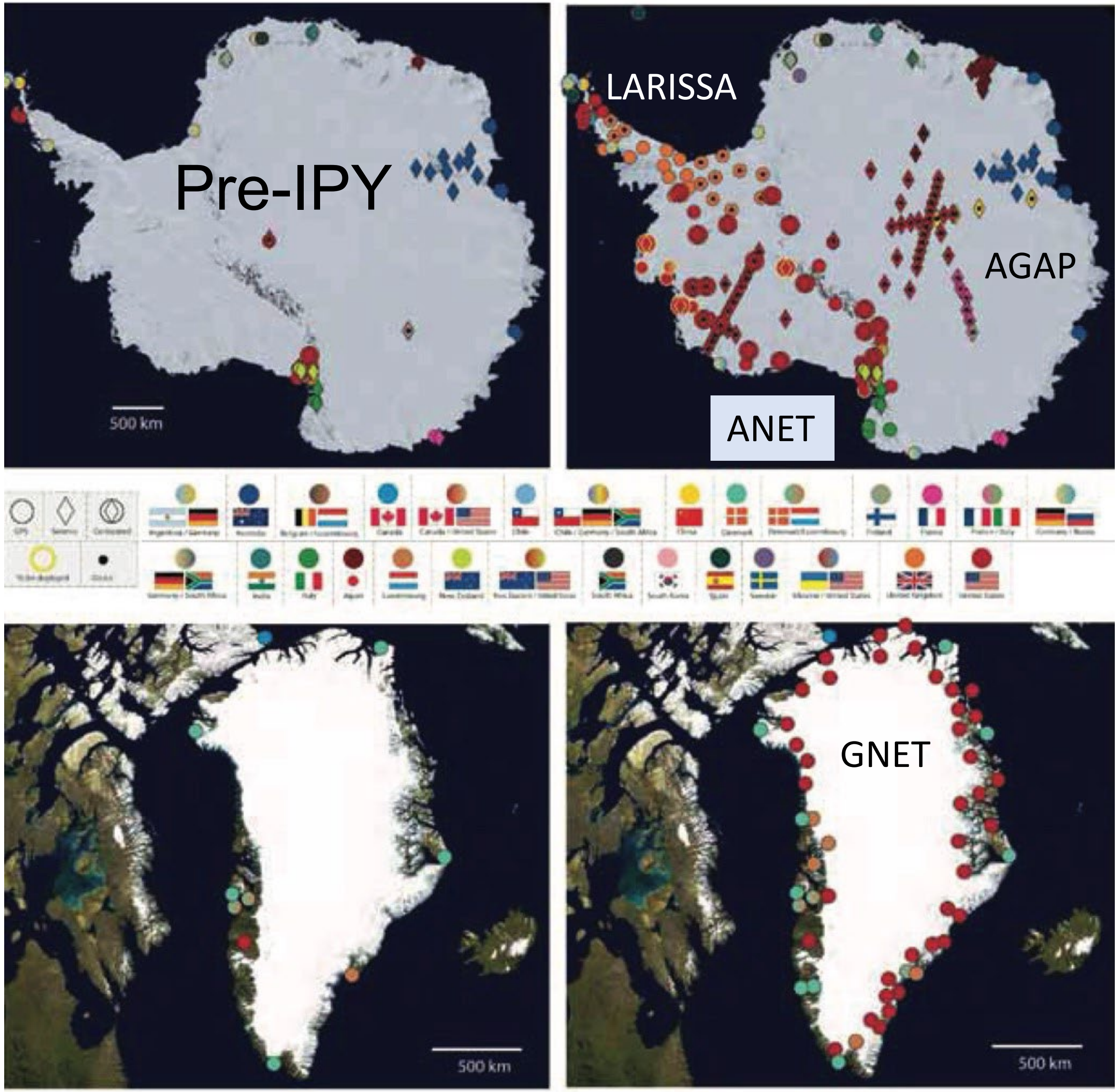
NSF Major Research Instrumentation Program

Award 2006 ~$2 million

International Polar Year 2007-09

POLENET Geophysical/Geodetic Remote Autonomous Network

- Science infrastructure – IPY+
- Open data
- Training: field & modeling
- Consortium of independent projects



28 Nations

IPY Funding &

International collaboration made this possible

Autonomous instrument systems – ***still using IPY4 technology [incrementally improved]***

Sensors — Cold rated, **Low power**

can be integrated now

*Power — Solar, Wind, Batteries – 6 mo. Darkness

lithium rechargeables – available, expensive, improving

*Communications — Iridium

need higher bandwidth systems for data transfer

Full Data Transfer + Improved Reliability = Reduced Logistics Footprint

[visits ~5-yr cycle]

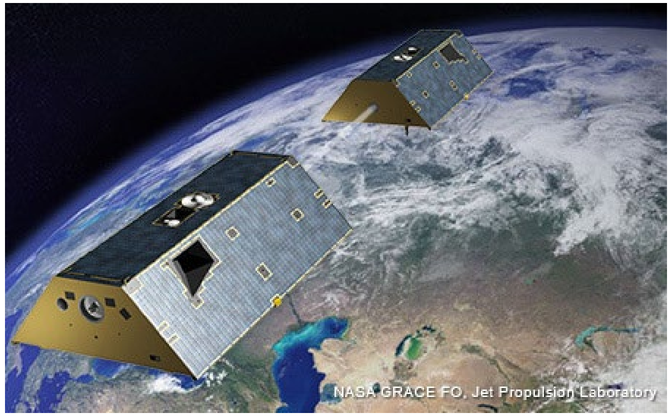
Increased data bandwidth + power = ***much more science possible***

Hardiness	extreme environment
Transportability	Cargo limits – size, weight
Ease of Assembly	Short ground time, difficult environment

Multi-instrument systems – plug-n-play power & communications hubs

Leverage technical investments, increase science value

reduce logistic requirements? - dependent on aircraft payloads



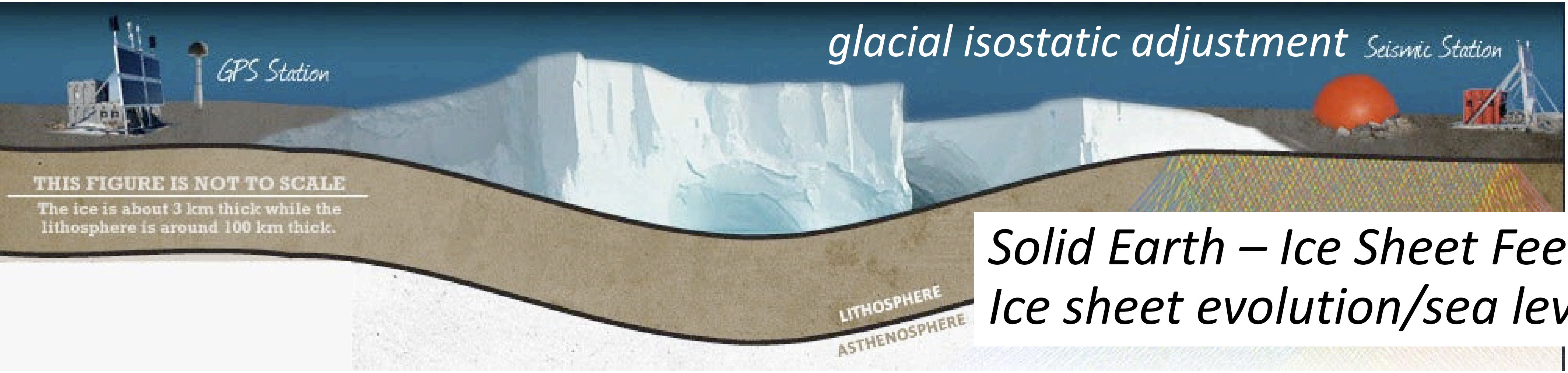
Time-varying gravity – GRACE-FO

Resolve Uncertainties in Ice Mass Change

Satellite Gravity +
In Situ GNSS

ADD: Absolute Gravity Sensors
Need advances in size, power, transportability

OPEN DATA

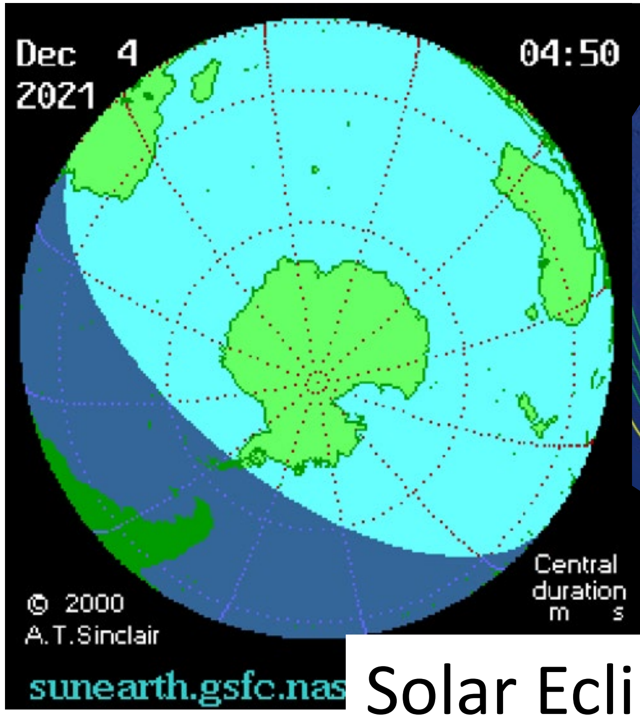


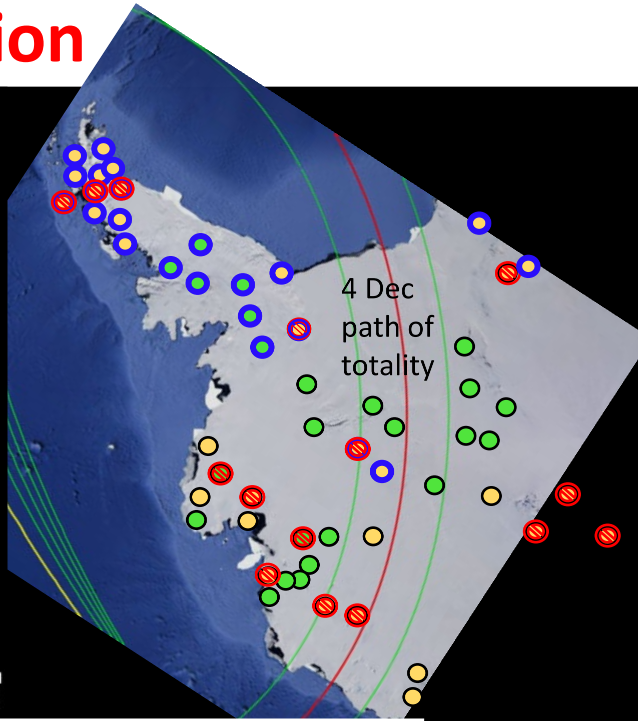
Project Science

Solid Earth – Ice Sheet Feedbacks:
Ice sheet evolution/sea level projections

More science – same assets – modify data acquisition

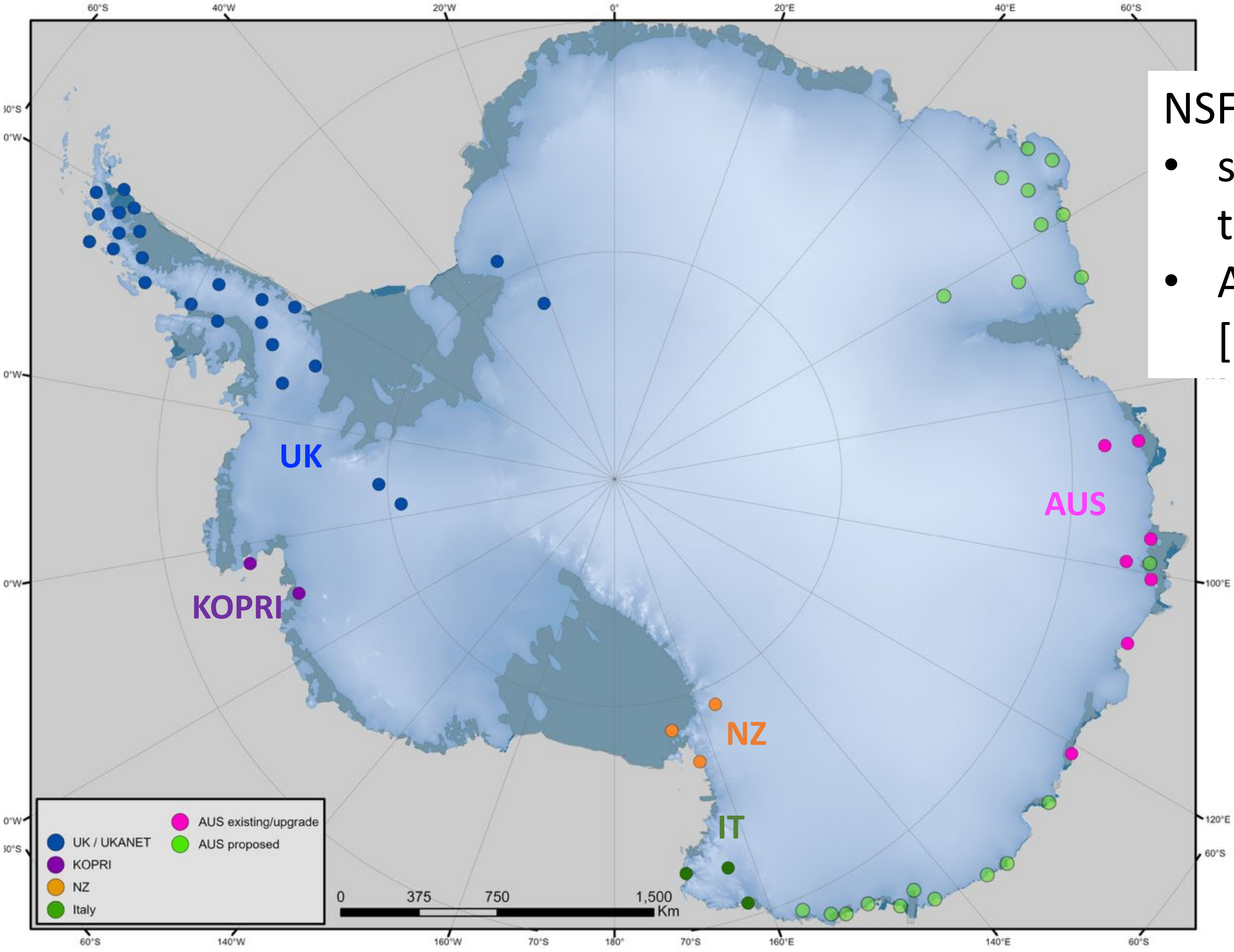
OPEN DATA – Widely used:
- Tectonics
- Global Earth structure
- Ice sheet dynamics & mass balance
- Atmospheric studies
- Ocean tides & sea level
- Geospace weather





Solar Eclipse TEC data

Open Data - IPY5 – international collaboration on data transfer

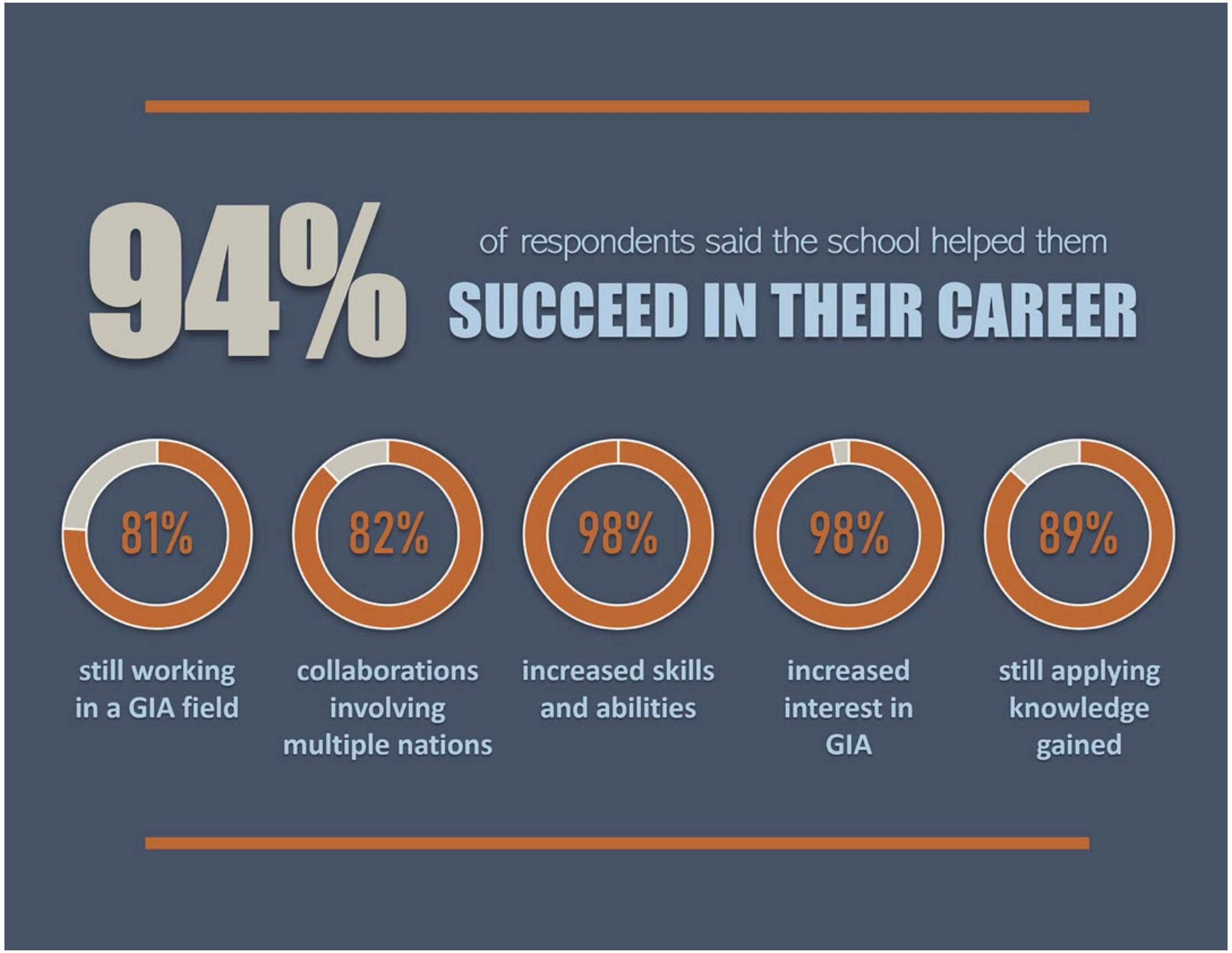


NSF-OPP Antarctic Earth Sciences

- supports cost of Iridium data transfer from GNSS stations
- All *open data* in U.S. GAGE [EarthScope] archive.

Build Science Capacity

Facilitate ECR engagement & leadership in multinational IPY projects



Glacial Isostatic Adjustment Training Schools

- Modeling skills
- Build peer networks
- Meet mentors
- Find collaborators from other nations

Upcoming EOS Feature Article: Getting Schooled in Complex Earth System Modeling
S. Konfal Sherman et al.

Funding Mechanisms

International: Coordinated, but independent, national proposals

funded nationally - Collaborative projects planned under *international coordination umbrella*

International: coordinated proposal from multiple nations

Memorandum of Understanding establishes national contributions [science, funding, in-kind support]

****Need transparent & straightforward mechanisms for international proposals**

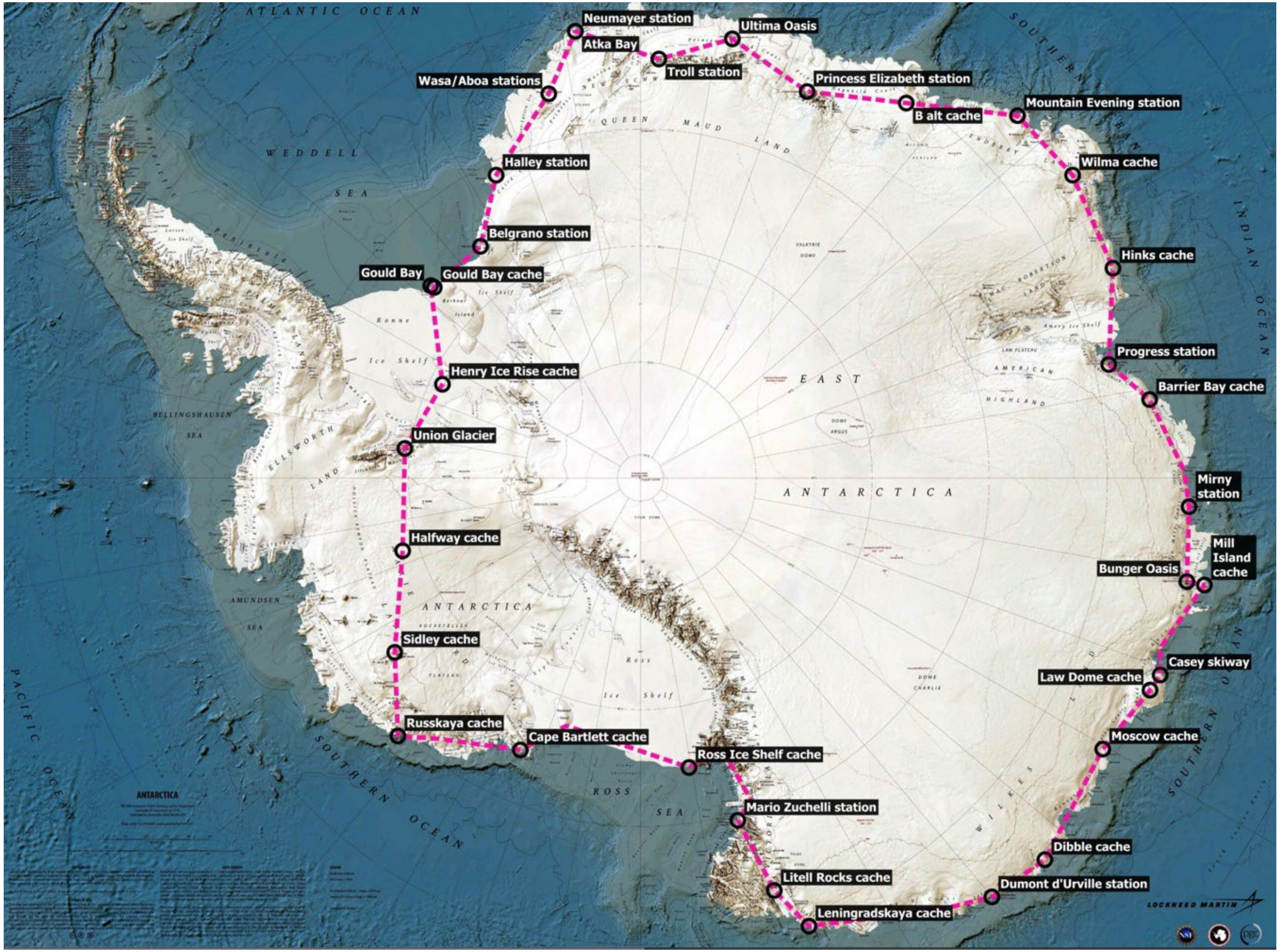
Multiple nations - No double- or multiple-jeopardy in proposal review

****Need mechanisms to pool funds, for e.g.**

Contract field support

Consortium for data transfer

New Partnerships: Expeditions & Data collection



SWIDA-RINGS

Private – Public Partnership

Reboot the cycle!

Credit: Stephanie Konfal Sherman

SUMMARY

Leading to IPY5:

- Build international community / establish priority science objectives

- Get technology development underway
  - Coordinated, build on performance metrics, operational best practices
  - Autonomous sensor systems
    - Need development of power and communication systems
    - Consider requirements & feasibility of multi-sensor platforms
    - Coordinate mode of data acquisition to meet multidisciplinary science requirements

- Workshops/Training Schools to facilitate international networks of ECRs to lead IPY projects

- Establish mechanisms for shared funding of science, logistics, communications between nations

IPY5:

- Open Data – use by multiple disciplines

- Share communication systems / costs