National Institute of Oceanography and Applied Geophysics

Ice-Ocean & Earth and their interactions in Antarctica

Fausto Ferraccioli
Director Geophysics Section

Challenges (& many open questions)

Climate & ice sheet interactions

1. Focus on **processes, feedbacks and physics** to reduce uncertainties in ice sheet and sea-level projections.
2. What are the **key internal & external processes**? E.g. Understand the processes and timing of ice shelf collapse
3. Quantify the **state & rates of change** in sea-ice retreat, amplified surface warming, CDW intrusions
4. Understand **ice shelf cavity circulation and grounding zone processes** of marine-based ice sheets.
5. Understand **marine ice sheet instability** mechanisms (MISI & MICI)
6. Improve or understanding of **coupled dynamic ice sheet and ocean circulation** processes (coupled models)
7. Improved understanding and quantification of **Antarctic mass balance** (including surface)

Solid Earth & Ice Sheet interactions

1. High resolution subglacial topography (especially at the grounding zone) and continental shelf bathymetry
2. Improve our understanding of geological boundary conditions, including in particular geothermal heat flux
3. Improve coupling between Solid Earth (GIA) and ice sheet models to understand feedbacks on mass loss rates
4. Improved understanding of geothermal heat flux and in its influence on hydrology & ice sheets
5. Improved understanding of subglacial and supraglacial hydrology

Tacking these challenges requires new interdisciplinary studies

Reviews of Geophysics

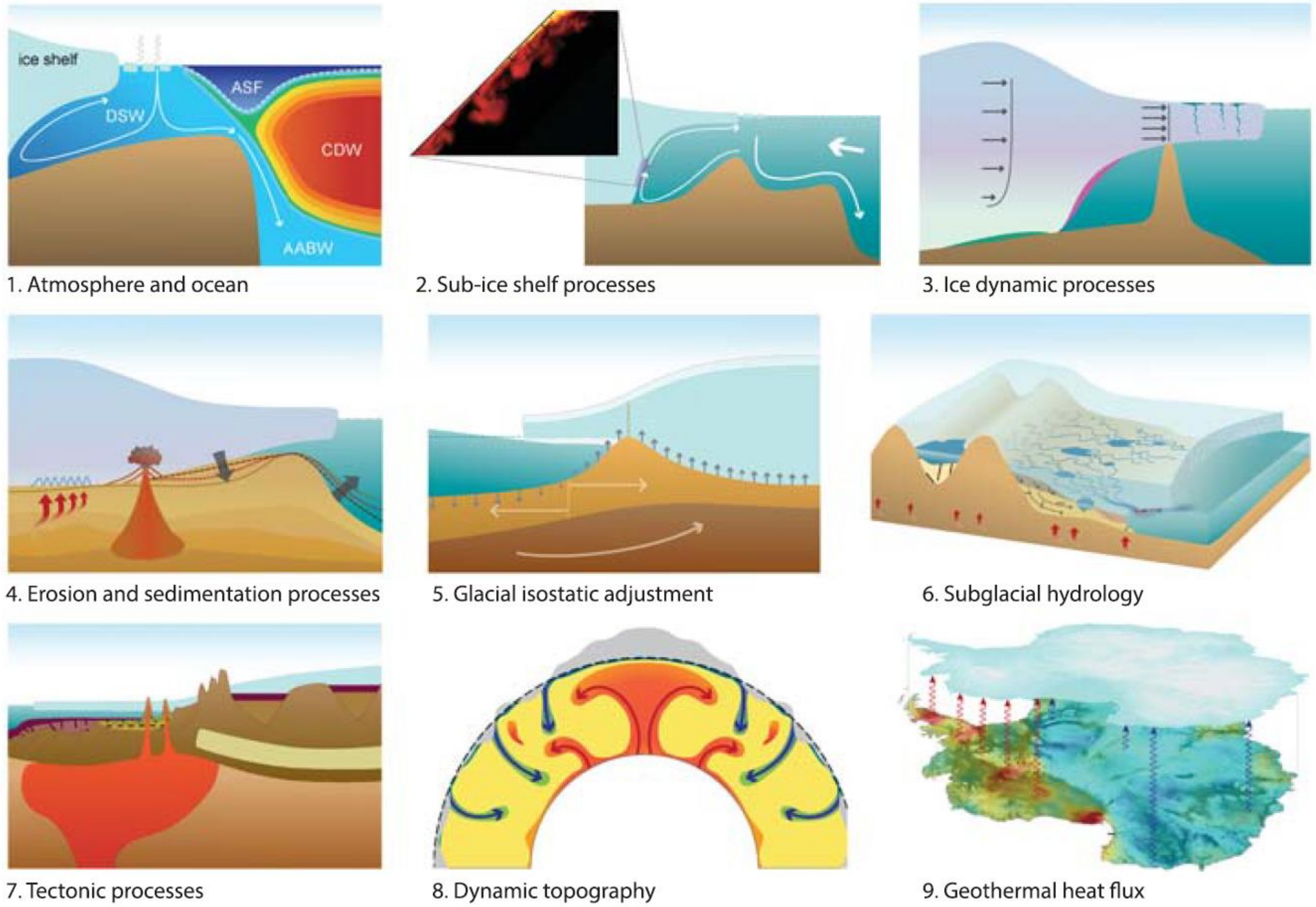
REVIEW ARTICLE
10.1029/2019RG000663

The Sensitivity of the Antarctic Ice Sheet to a Changing Climate: Past, Present, and Future

T. L. Noble[1], E. J. Rohling[2,3], A. R. A. Aitken[4], H. C. Bostock[5], Z. Chase[1], N. Gomez[6], L. M. Jong[7,8], M. A. King[9], A. N. Mackintosh[10], F. S. McCormack[10], R. M. McKay[11], L. Menviel[12], S. J. Phipps[1], M. E. Weber[13], C. J. Fogwill[14], B. Gayen[15], N. R. Golledge[11], D. E. Gwyther[1], A. McC. Hogg[2,16], Y. M. Martos[17,18], B. Pena-Molino[8,19], J. Roberts[7,8], T. van de Flierdt[20], and T. Williams[21]

Key Points:

- The AIS is a highly dynamic component of the Earth system, evolving on a broad range of temporal and spatial scales
- Paleoenvironmental evidence highlights the centennial to millennial response time scales of the AIS to atmospheric-ocean forcing
- Coupling feedbacks in Earth system components are required to reduce the uncertainty in AIS's contribution to past and future sea level rise



Tacking these challenges requires integrating existing data and acquiring next generation observations

Reviews of Geophysics

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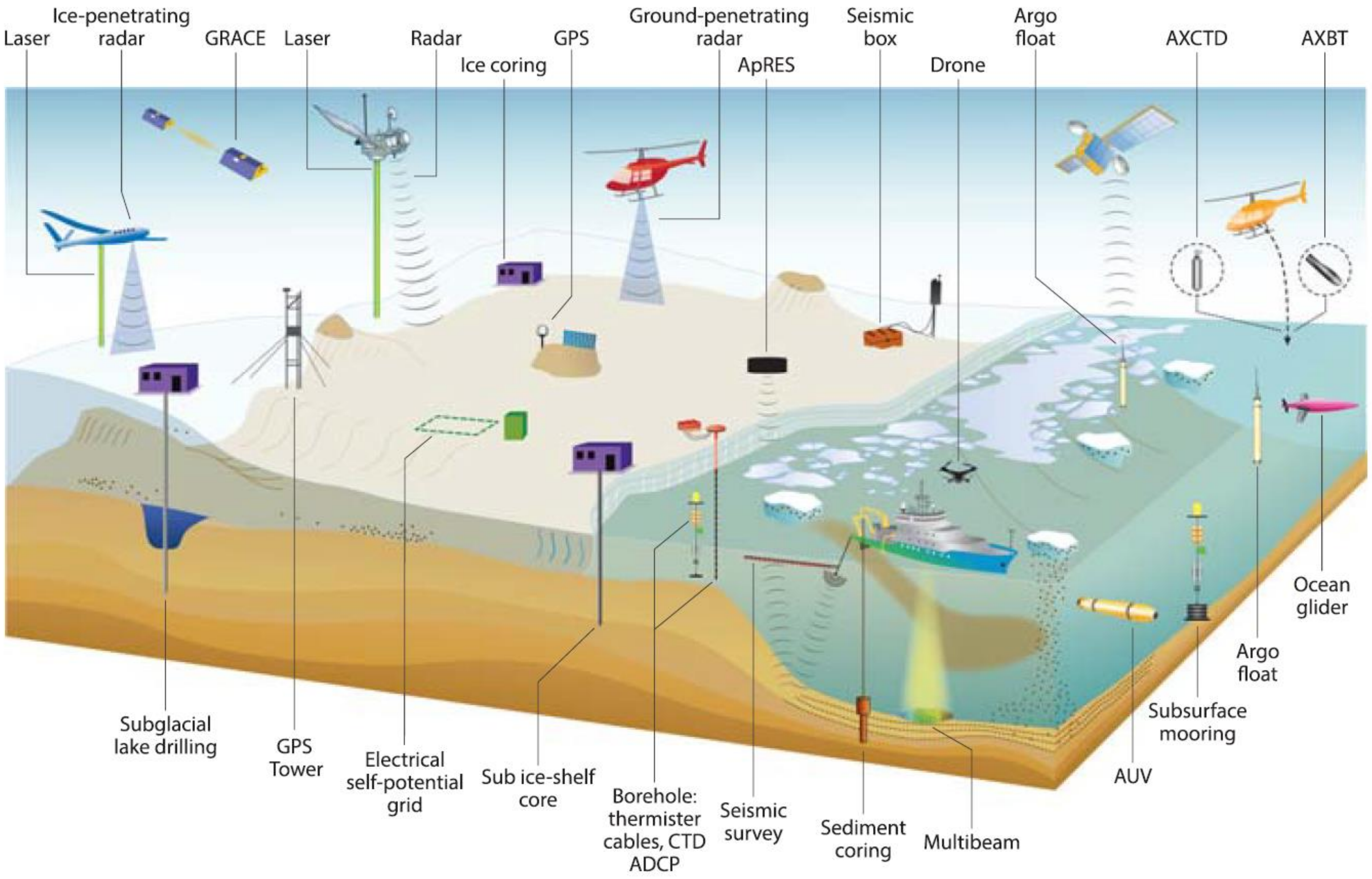


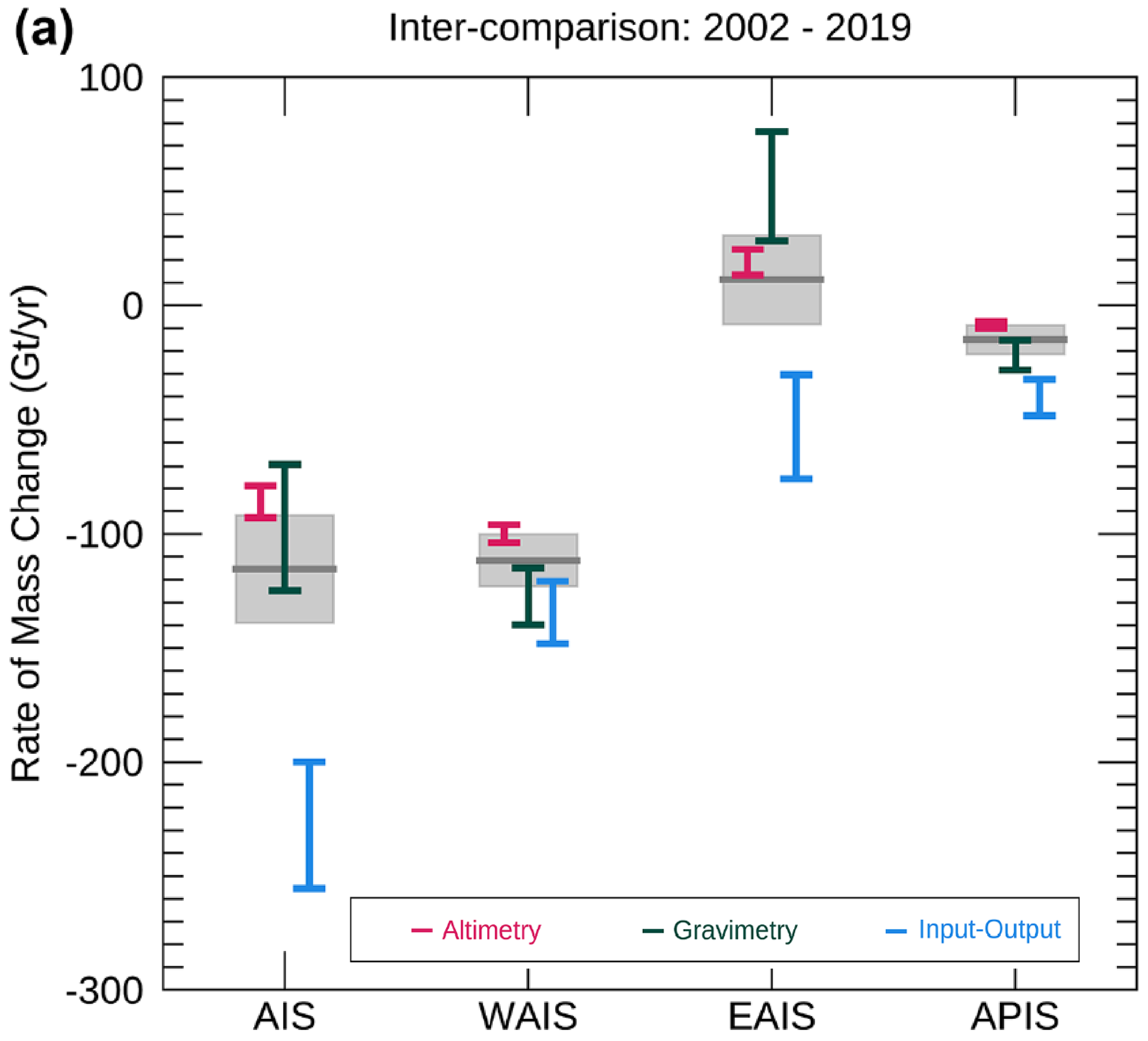
Satellite data have transformed our knowledge of recent ice sheet change

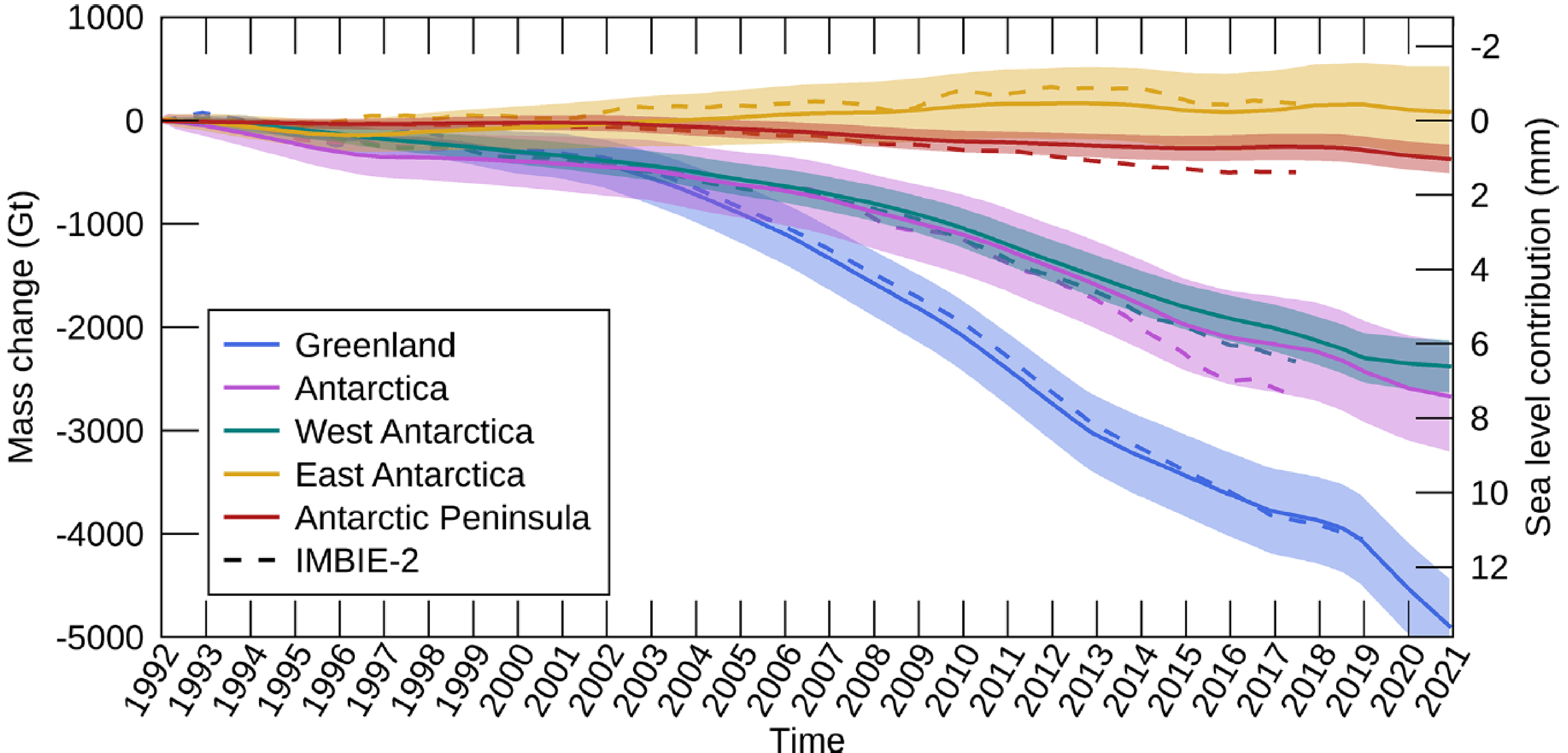
Earth Syst. Sci. Data, 15, 1597–1616, 2023
https://doi.org/10.5194/essd-15-1597-2023

Open Access Earth System Science Data

Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020

Inès N. Otosaka[1], Andrew Shepherd[1,2], Erik R. Ivins[3], Nicole-Jeanne Schlegel[3], Charles Amory[4], Michiel R. van den Broeke[5], Martin Horwath[6], Ian Joughin[7], Michalea D. King[7], Gerhard Krinner[4], Sophie Nowicki[8], Anthony J. Payne[9], Eric Rignot[10], Ted Scambos[11], Karen M. Simon[12], Benjamin E. Smith[7], Louise S. Sørensen[13], Isabella Velicogna[3,10], Pippa L. Whitehouse[14], Geruo A[10], Cécile Agosta[15], Andreas P. Ahlstrøm[16], Alejandro Blazquez[17], William Colgan[16], Marcus E. Engdahl[18], Xavier Fettweis[19], Rene Forsberg[13], Hubert Gallée[4], Alex Gardner[3], Lin Gilbert[20], Noel Gourmelen[21], Andreas Groh[6], Brian C. Gunter[22], Christopher Harig[23], Veit Helm[24], Shfaqat Abbas Khan[13], Christoph Kittel[4], Hannes Konrad[25], Peter L. Langen[26], Benoit S. Lecavalier[27], Chia-Chun Liang[10], Bryant D. Loomis[28], Malcolm McMillan[29], Daniele Melini[30], Sebastian H. Mernild[31], Ruth Mottram[32], Jeremie Mouginot[4], Johan Nilsson[3], Brice Noël[5], Mark E. Pattle[33], William R. Peltier[34], Nadege Pie[35], Mònica Roca[36], Ingo Sasgen[24], Himanshu V. Save[35], Ki-Weon Seo[37], Bernd Scheuchl[10], Ernst J. O. Schrama[38], Ludwig Schröder[6], Sebastian B. Simonsen[13], Thomas Slater[1], Giorgio Spada[39], Tyler C. Sutterley[40], Bramha Dutt Vishwakarma[41], Jan Melchior van Wessem[5], David Wiese[3], Wouter van der Wal[12], and Bert Wouters[12,5]

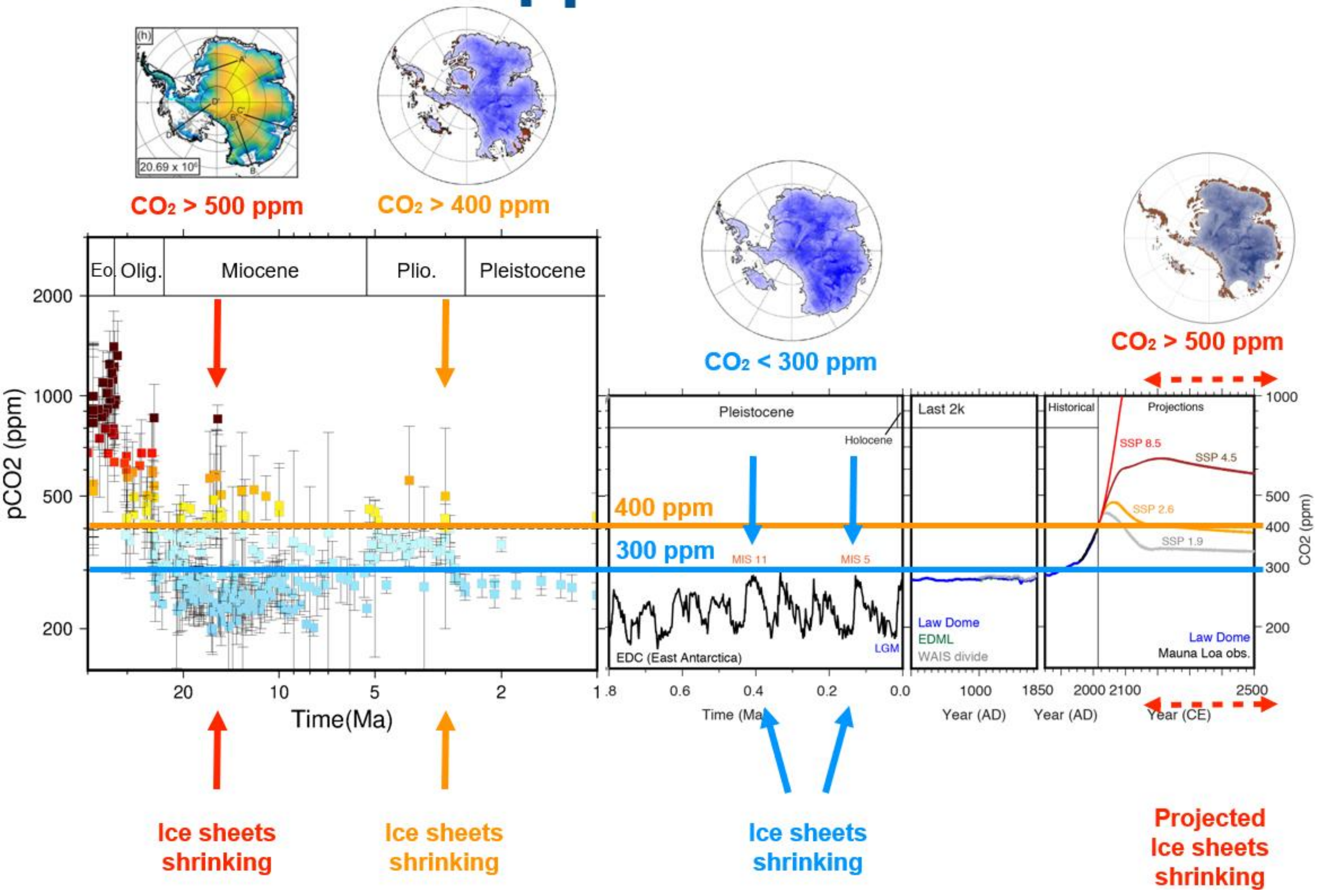




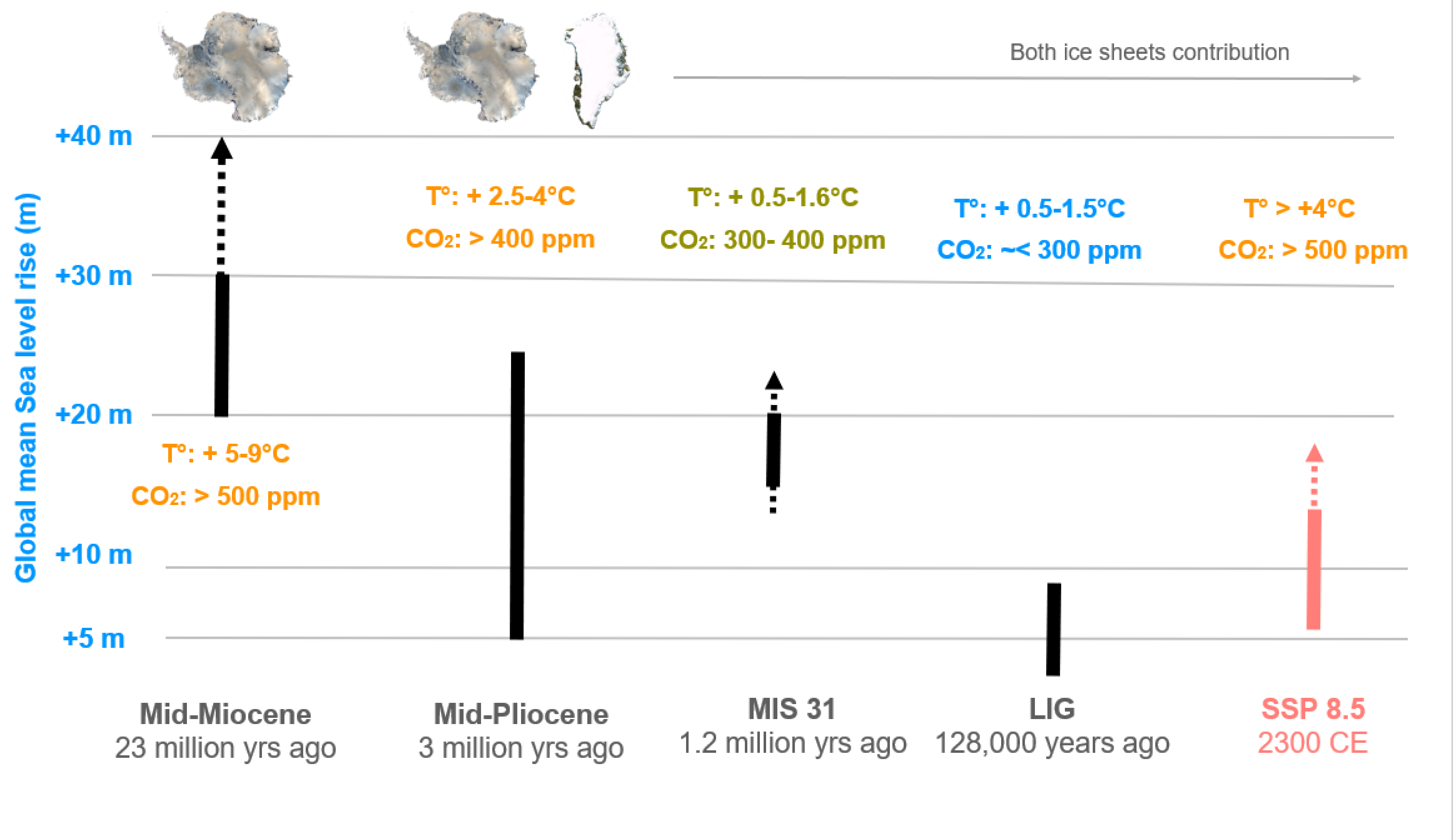
But if we want to understand processes, interactions & global SLR consequences- Learning from the past is important

When did it happen?

DeConto and Pollard (2016)
Gasson et al. (2016)



Past data show this is no science fiction



SCAR - Past Antarctic Ice Sheet Dynamics Research Program legacy

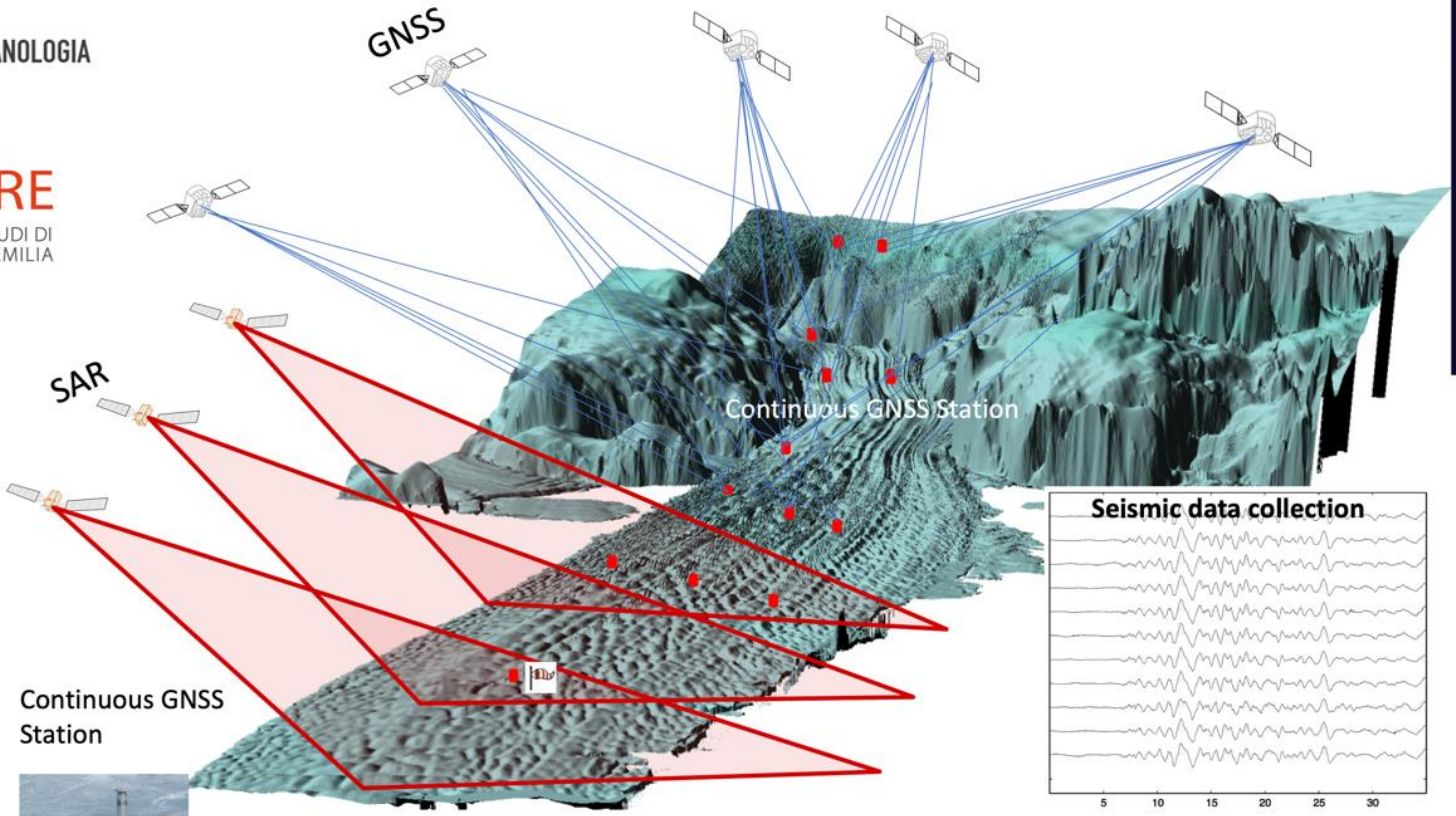
After Colleoni et al. (2022)

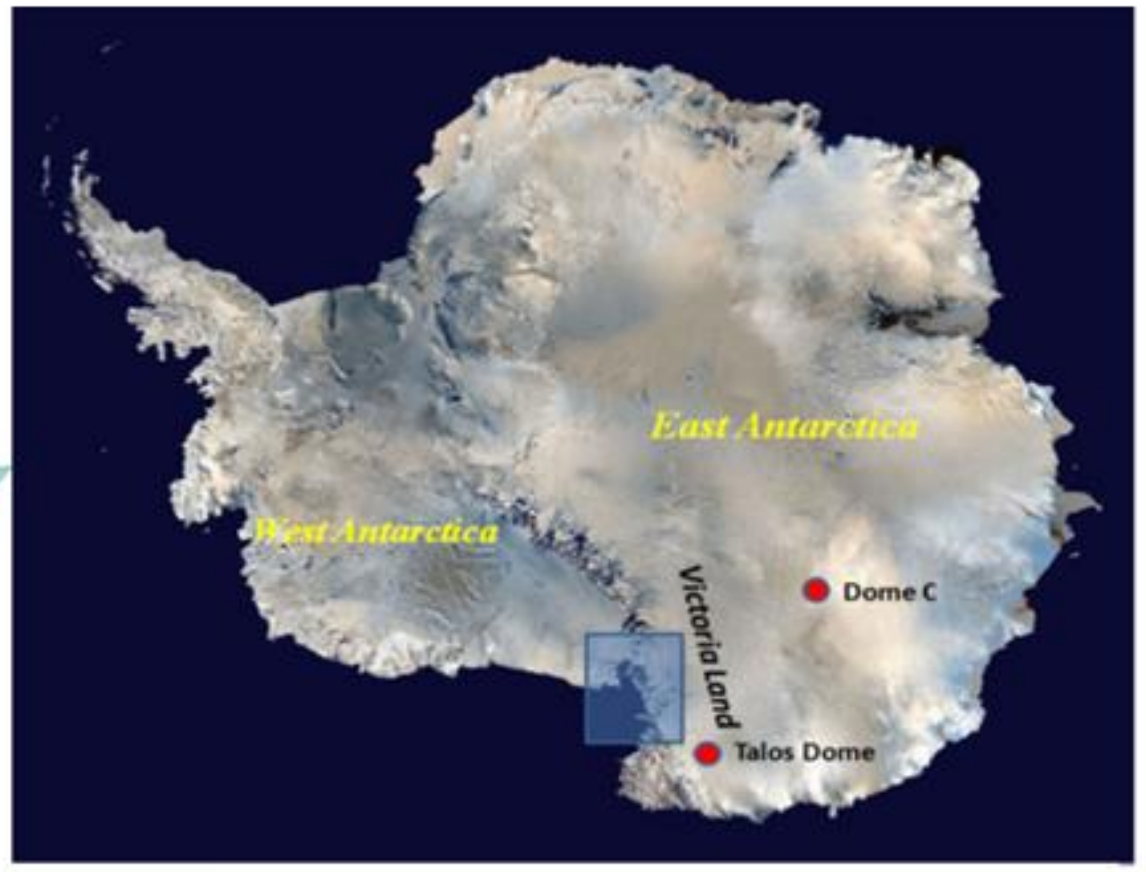
Università degli studi di Bologna

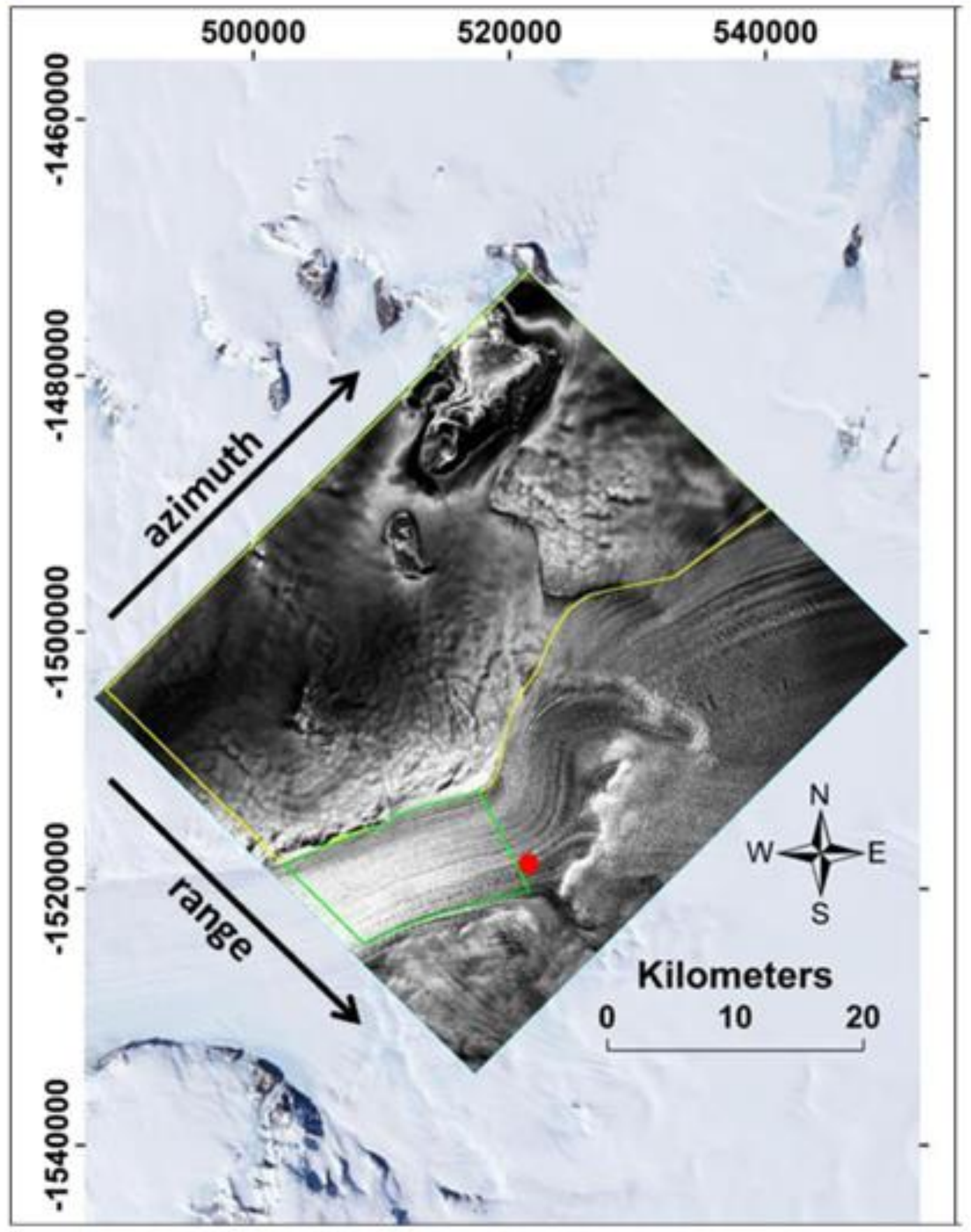
ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

UNIMORE
UNIVERSITÀ DEGLI STUDI DI MODENA E REGGIO EMILIA

ICEGIANT – Integrated geodetic, geophysic and remote sensing observations for the study of the David Glacier

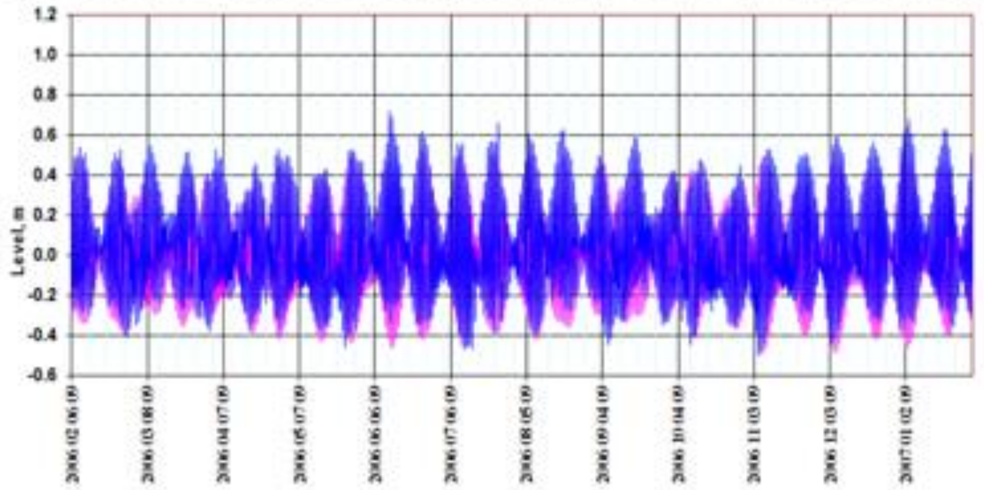


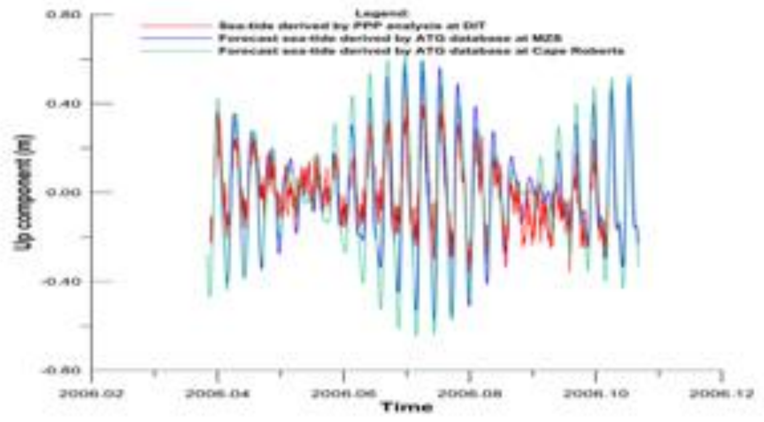




Continuous GNSS Station

Sea-tide and David-Drygalski horizontal and vertical movements derived by GNSS



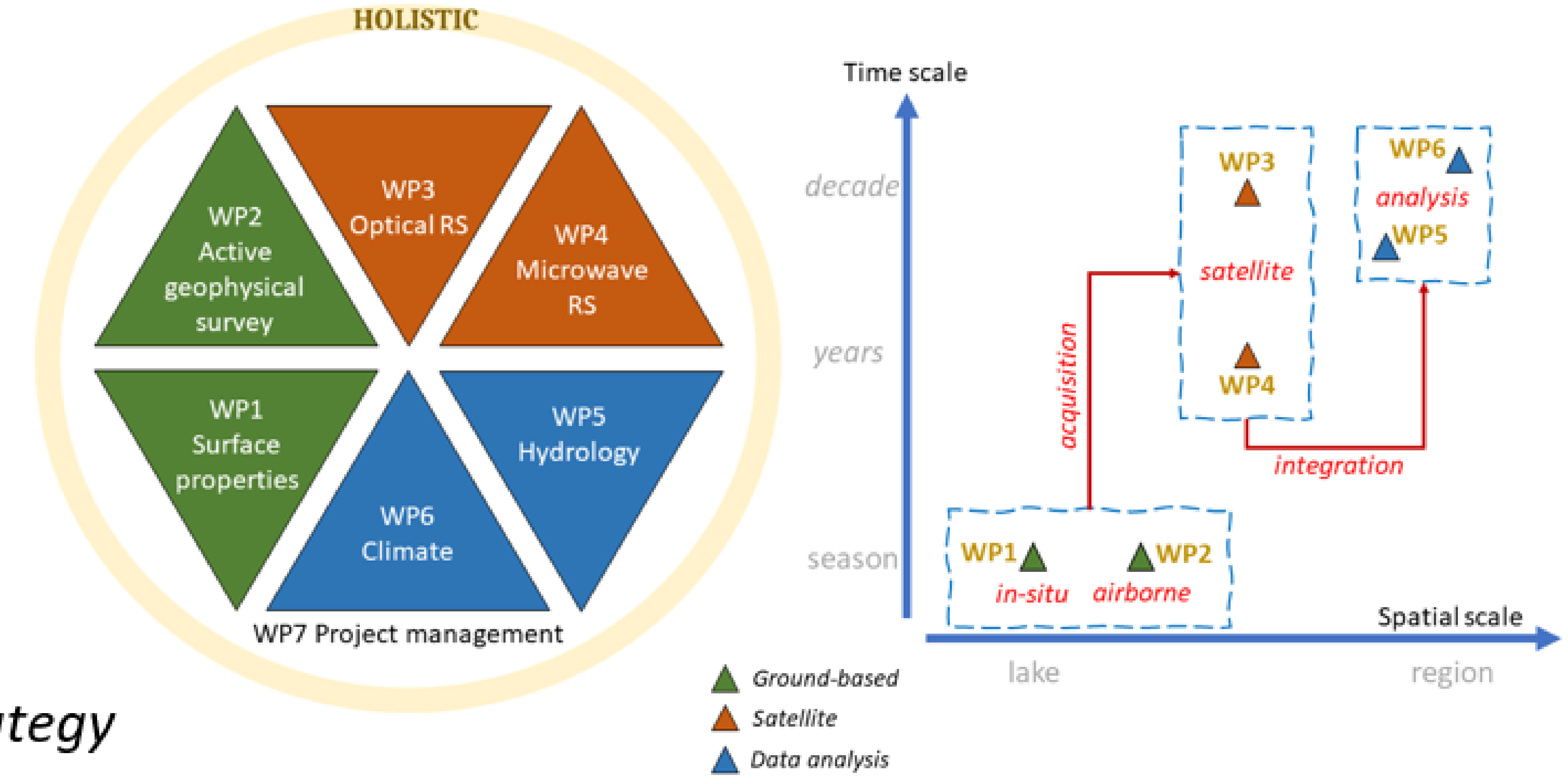


Holistic Overview of the supraglacial Lake-Ice-Snow TIming and Climate causality (HOLISTIC)

Istituto sull'Inquinamento Atmosferico, Consiglio Nazionale delle Ricerche
ISP Istituto di Scienze Polari, Consiglio Nazionale delle Ricerche
ibf CNR - Istituto di Biofisica
Istituto Nazionale di Geofisica e Vulcanologia
IUSS Scuola Universitaria Superiore Pavia

The goal of the project HOLISTIC is to describe the evolution of the cryosphere components (snow, firn, ice, and melt water) over the Nansen Ice Shelf (NIS). Here, supraglacial lakes (SGLs) and surface hydrology exist and strongly influence the drainage of the ice sheet through seasonal ice velocity changes and the energy exchange between the atmosphere and the ice sheet.

Aerial view of the SGLs in the Nansen Ice Sheet



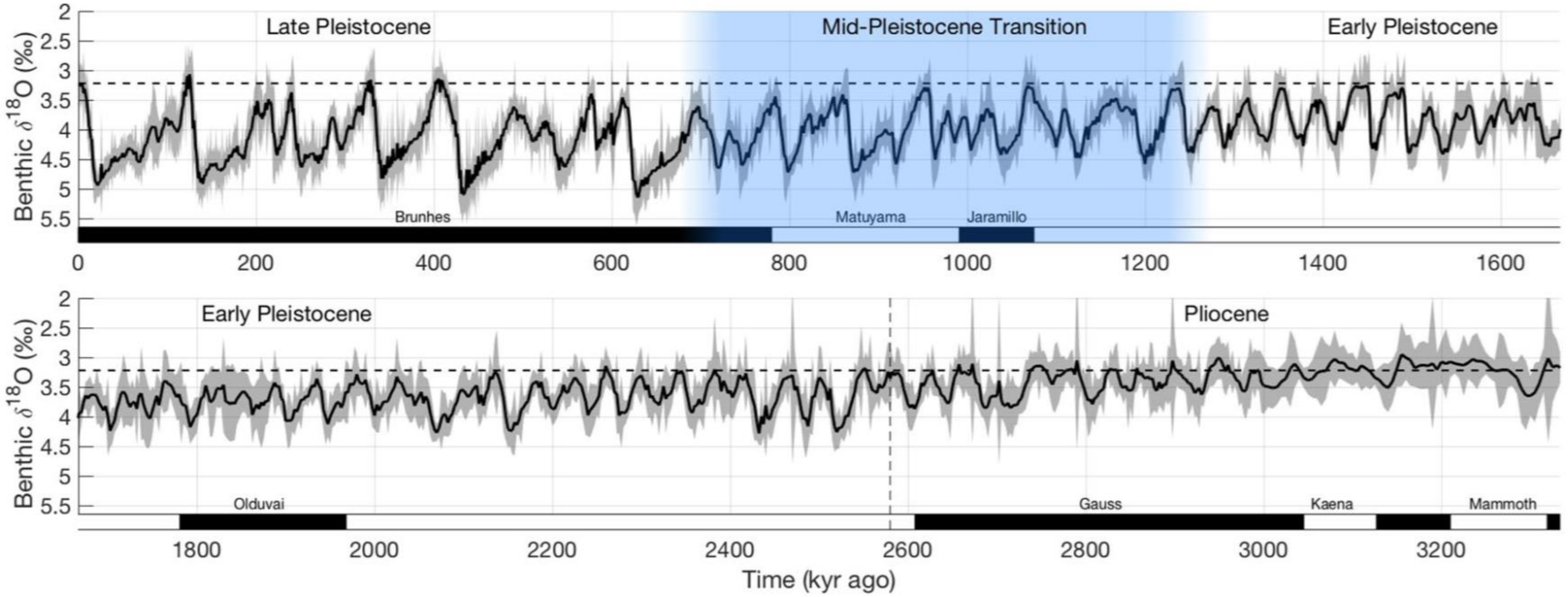
The HOLISTIC strategy

Objectives:

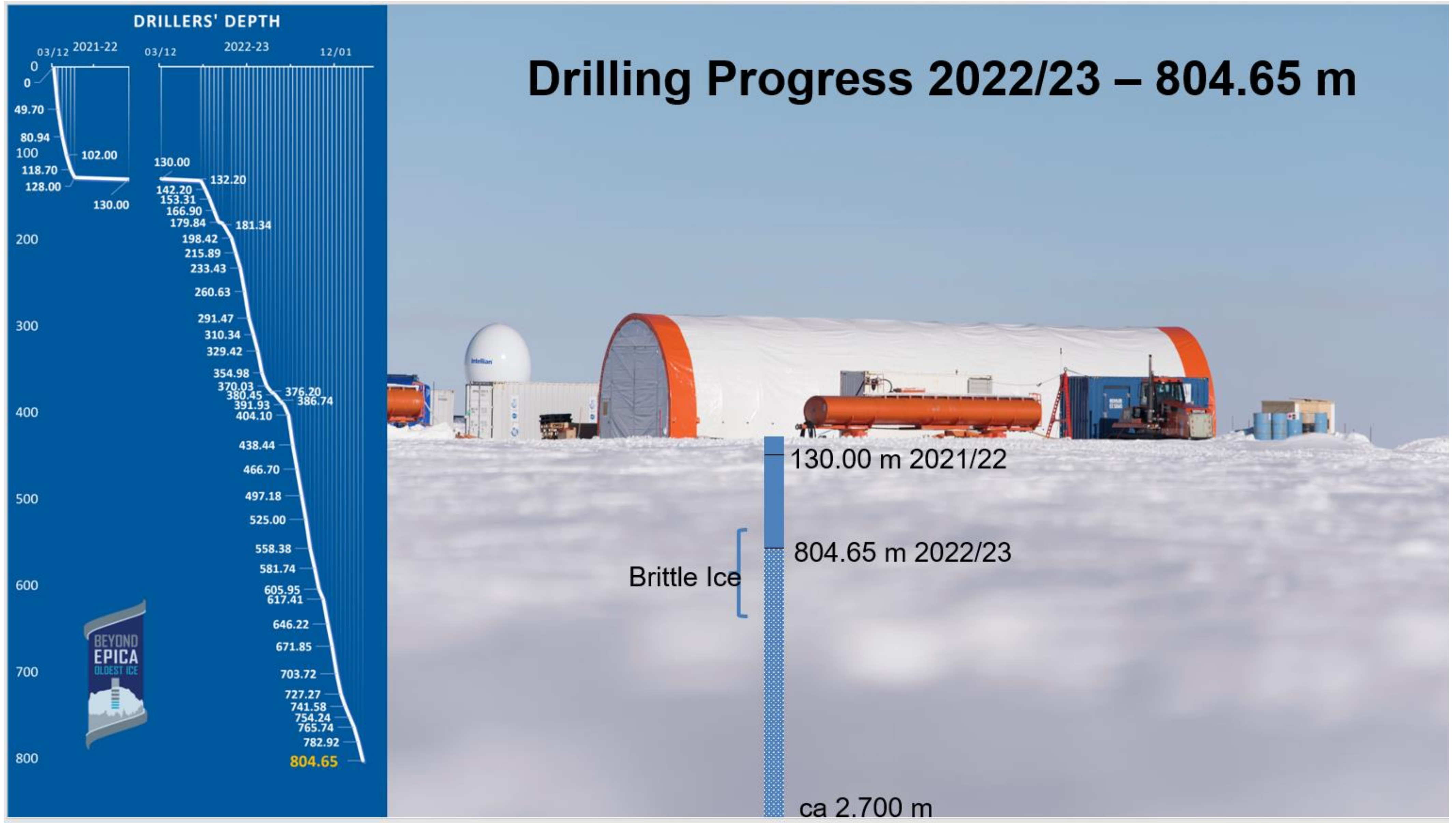
- Identify the essential parameters useful for describing the evolution of the targeted surfaces during the melting seasons.
- Assess the evolution of SGLs pattern and drainage network during different melting period.
- Describe the seasonality of snow, ice covers, and outcropping rocks during different melting period.
- Assess the role of topographic, climatic and cryospheric factors on the formation and the temporal evolution of SGLs.
- Identify the main modes of variability of the SGLs dynamics and possible large scale atmospheric circulation controls.

Beyond EPICA Oldest Ice

The Mid Pleistocene Transition in Proxy Archives



Berends et al. (2021)



1. **Why?** Beyond EPICA is the first of the Grand Challenge of the International Partnershipo for Ice Core Sciece: **The oldest ice core:** A 1.5 million year record of climate and greenhouse gases from Antarctica.

MPT is a fundamental change in the behaviour of glacial cycles during the Quaternary glaciations. The transition happened approximately 1.25 – 0.7 million years ago.

Before the MPT, the glacial cycles were dominated by a 41,000-year periodicity with low-amplitude, thin ice sheets and a linear relationship to the Milankovitch forcing from axial tilt.
After the MPT there have been strongly asymmetric cycles with long-duration cooling of the climate and build-up of thick ice sheets, followed by a fast change from extreme glacial conditions to a warm interglacial. The cycle lengths have varied, with an average length of approximately 100,000 years.

There are several international consortia looking at the Mid Plestocene Transition

2. **Where?** We are in East Antarctica, near the Concordia Station. The site has been selected after an extensive survey. More than 20.000 km of radar lines

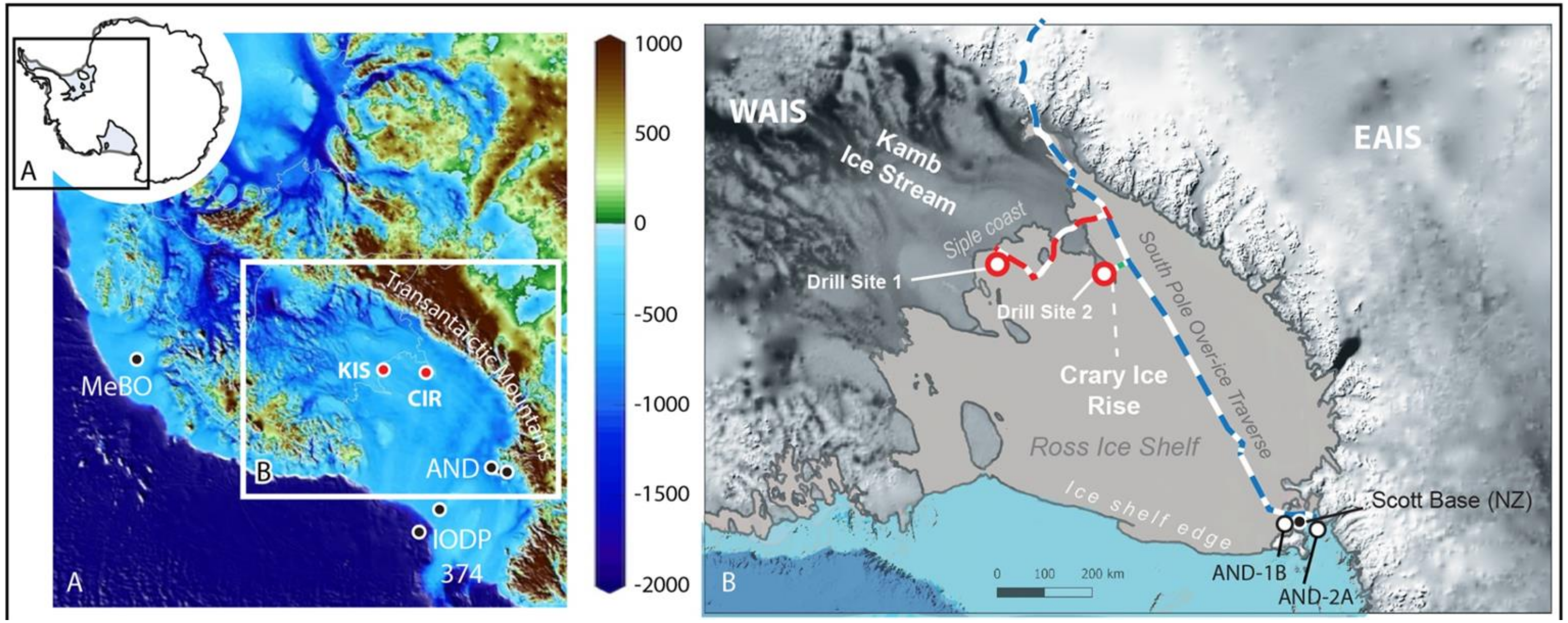
3. **How?** Ice core deep drilling
4. **What?** The project is in progress. The depth reached in 2022-23 is of 804m

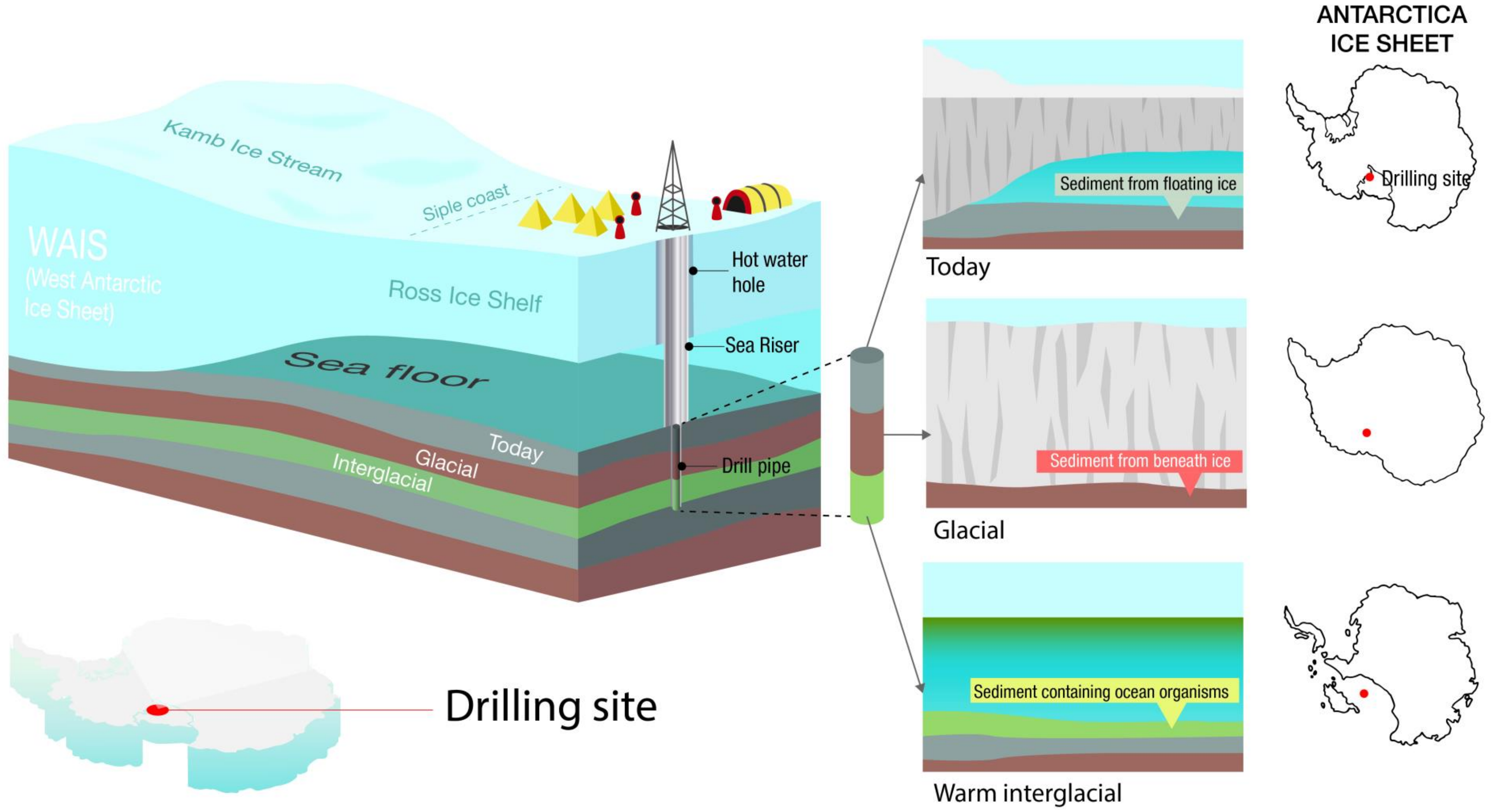
SWAIS2C

ICDP SWAIS-2C Project:

Sensitivity of the West Antarctic Ice Sheet to +2C°.

Partners internazionali (NZ, USA, Germania, Corea del Sud, Japan, UK, Australia, Italy)
Perforazione di due siti nel Mare di Ross 2023 e 2024.
Responsabili per Italia P. Del Carlo e F. Florindo INGV





SENSITIVITY OF THE WEST ANTARCTIC ICE SHEETS TO 2 DEGREES CELSIUS OF WARMING

SWAIS 2C is an international initiative involving researchers from New Zealand, the United States, Germany, Australia, **Italy**, Japan, Spain, Republic of Korea, the Netherlands, and the United Kingdom. Aotearoa New Zealand participation is supported through the Antarctic Science Platform's Ice Dynamics Project. More than 100 researchers are involved in the project, including 25 early-career researchers.

This project aims to:

Determine whether the West Antarctic Ice Sheet has advanced and retreated during the Holocene. This was a period of relatively stable climate that has characterised the last 10,000 years prior to the industrial revolution and the onset of the Anthropocene.

Determine how marine-based ice sheets respond to a world that is 1.5°–2°C and >2°C warmer than pre-industrial times.

Understand the local, regional, and global impacts and consequences of the response of the Antarctic Ice Sheet to this warming.

Past Antarctic ice sheets and Southern Ocean interaction

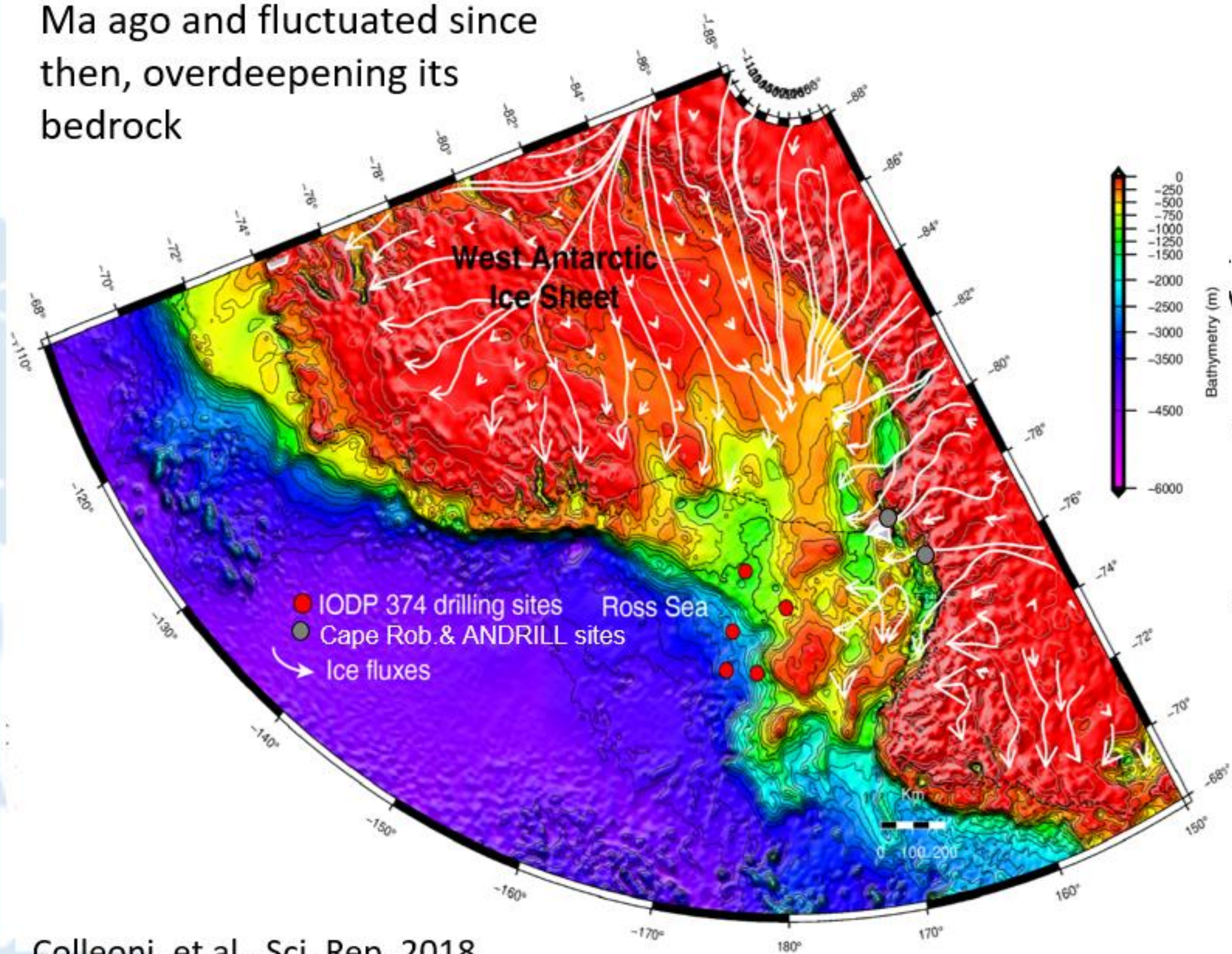
30 Years of observations in Antarctic Peninsula, Ross Sea, George V land Sabrina Coast margins……

CHALLENGES

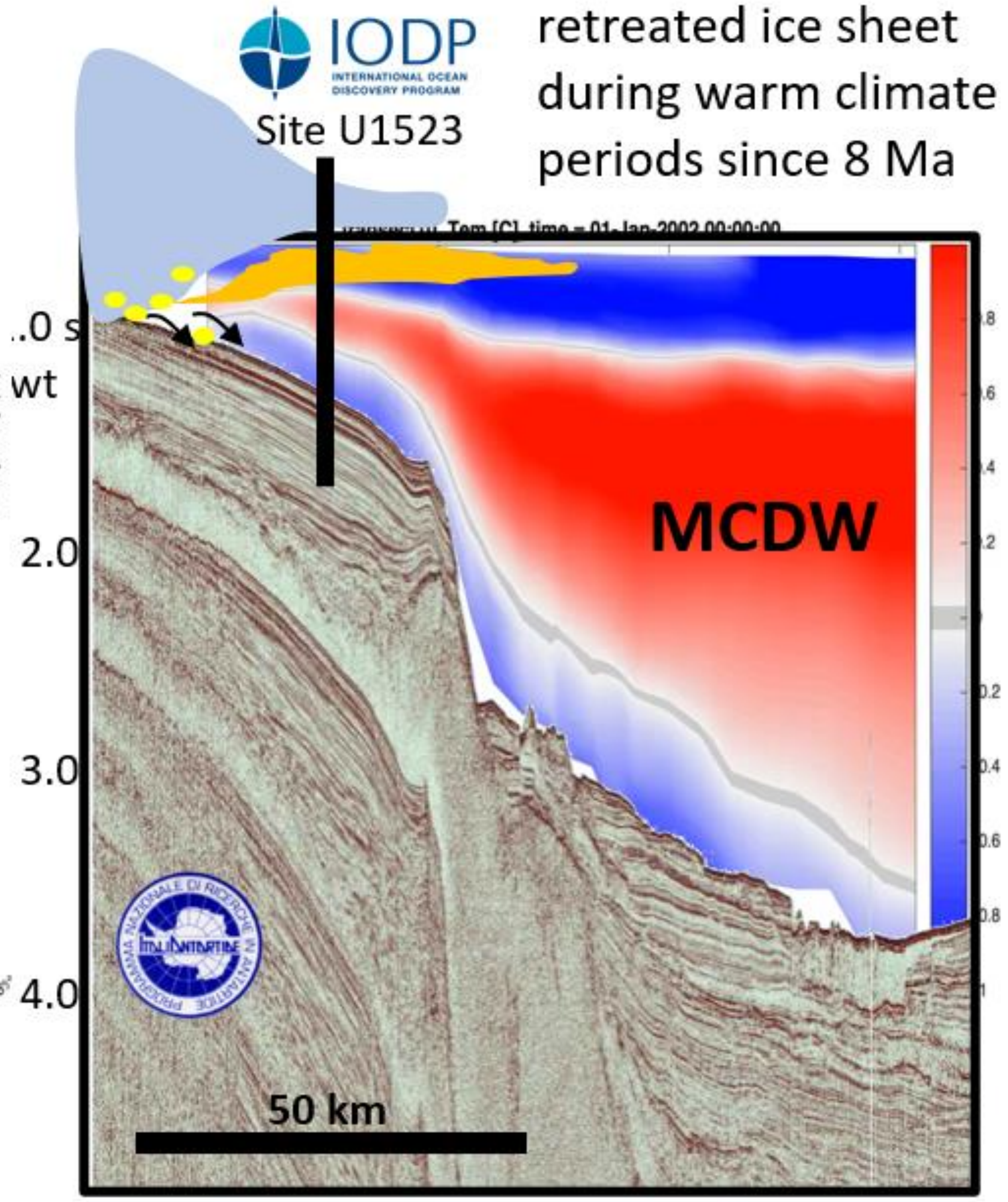
1. Reconstruct ice proximal atmospheric and oceanic temperatures to identify past polar amplification
2. Assess the role of bedrock and oceanic forcing (e.g. sea level and temperature) on marine ice sheet stability/instability
3. evaluate the contribution of West Antarctica versus East Antarctica to far-field sea level estimates

WHY&WHERE

WAIS expanded over a shallow bedrock already 17 Ma ago and fluctuated since then, overdeepening its bedrock



Slow circulation, water stratification, and retreated ice sheet during warm climate periods since 8 Ma



Colleoni, et al., Sci. Rep. 2018
Levy et al. Nat Geosci. 2019
Paxman et al., PPP 2019
Marschalek et al., Nature 2021
Perez et al., 2022 GSA Bull.

Ross Sea Physical oceanography

30 Years of observations in the Ross Sea (CLIMA, CLIMAIV, T-Rex, MORSea) and beyond……

CHALLENGES

SOUTHERN OCEAN AND SEA ICE IN A WARMING WORLD

12. Will changes in the Southern Ocean result in feedbacks that **accelerate or slow the pace of climate** change?

13. Why are the properties and volume of **Antarctic Bottom Water** changing, and what are the consequences for global ocean circulation and climate?

14. How does **Southern Ocean circulation**, including exchange with lower latitudes, respond to climate forcing?

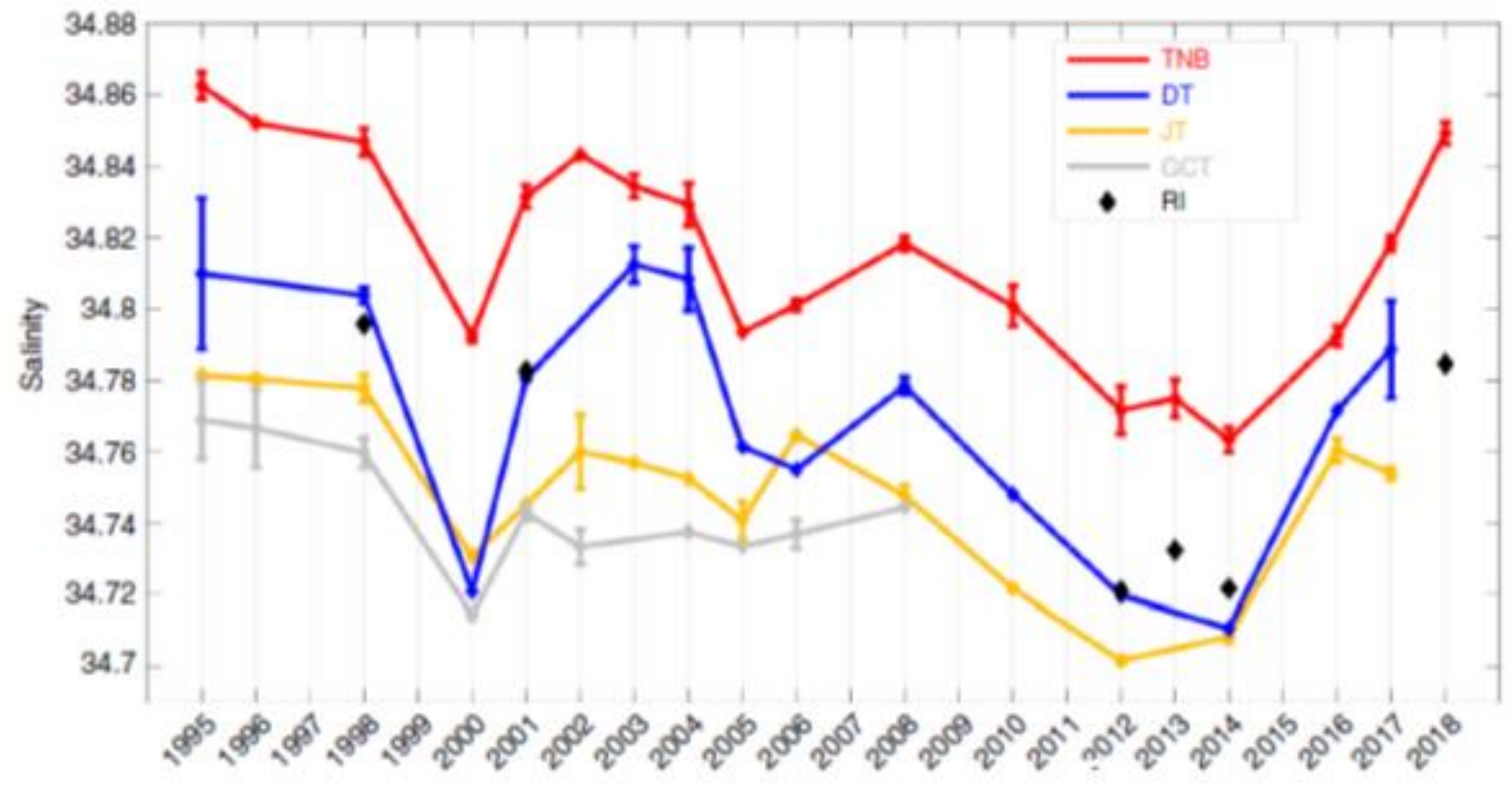
ANTARCTIC ICE SHEET AND SEA LEVEL

23. How will changes in **freshwater inputs** affect ocean circulation and ecosystem processes?

30. How do **oceanic processes beneath ice shelves** vary in space and time, how are they modified by sea ice, and do they affect ice loss and ice sheet mass balance?

WHY&WHERE

NATURE COMMUNICATIONS | https://doi.org/10.1038/s41467-019-13083-8 ARTICLE



Castagno et al., 2019, Nat. Comm.

Fig. 2 HSSW salinity time series (1995–2018) in the Ross Sea. Salinity averaged in the HSSW between 870 and 900 dbar in TNB (red line), between 850 and 880 dbar at RI (black diamonds), and in the deepest 20 dbar of the water column at DT (blue line), JT (amber line) and GCT (grey line). In each region, we have averaged CTD profiles on pressure surfaces to obtain a mean profile for each austral summer. The error bar is the mean standard deviation among all stations in the layer considered (see Methods) and is set equal to 0 in cases when only one profile was available in that year and region (see Supplementary Fig. 1 and Supplementary Table 1 for additional information on the number and location of CTD profiles used in each austral summer average).

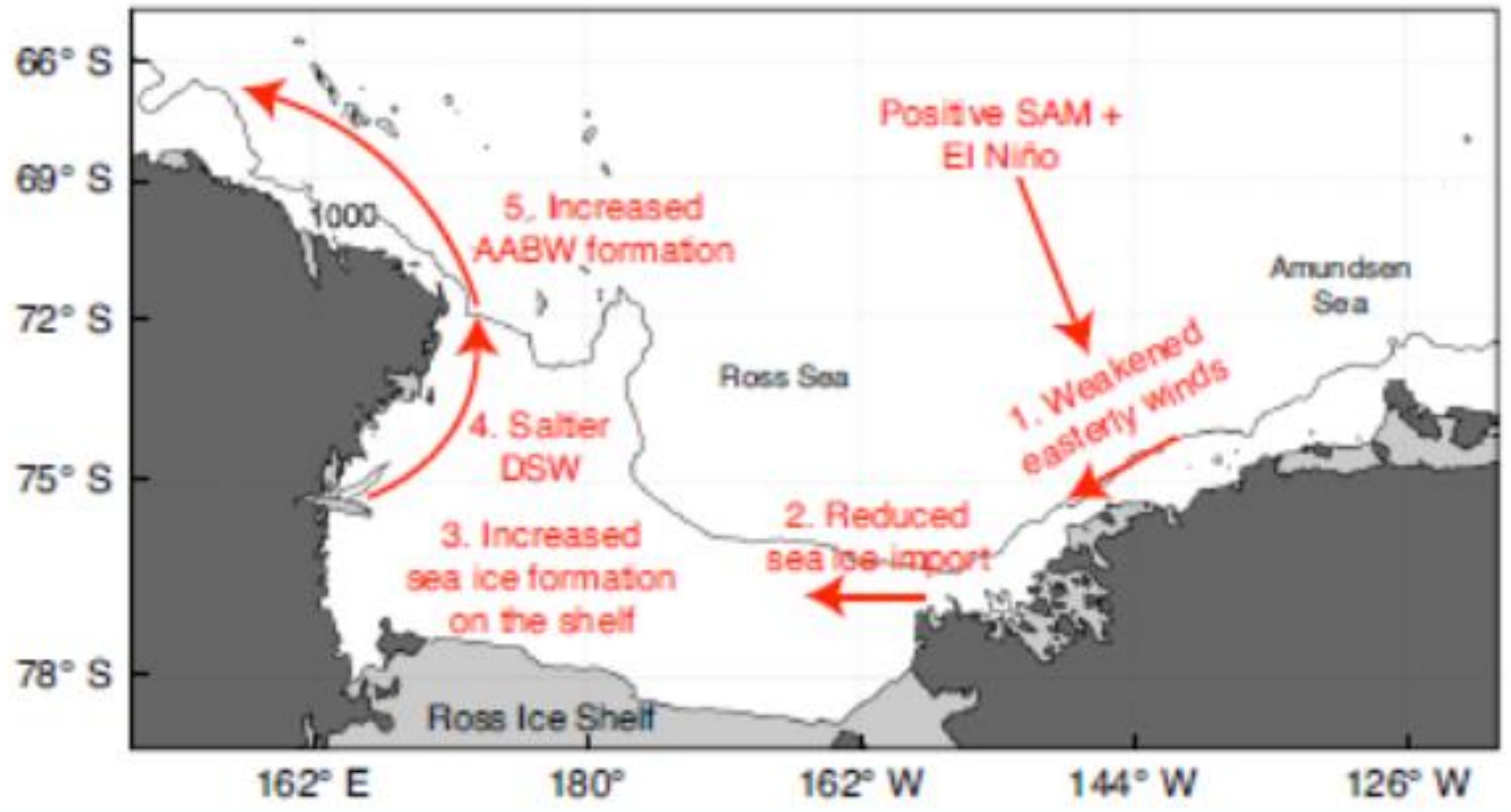
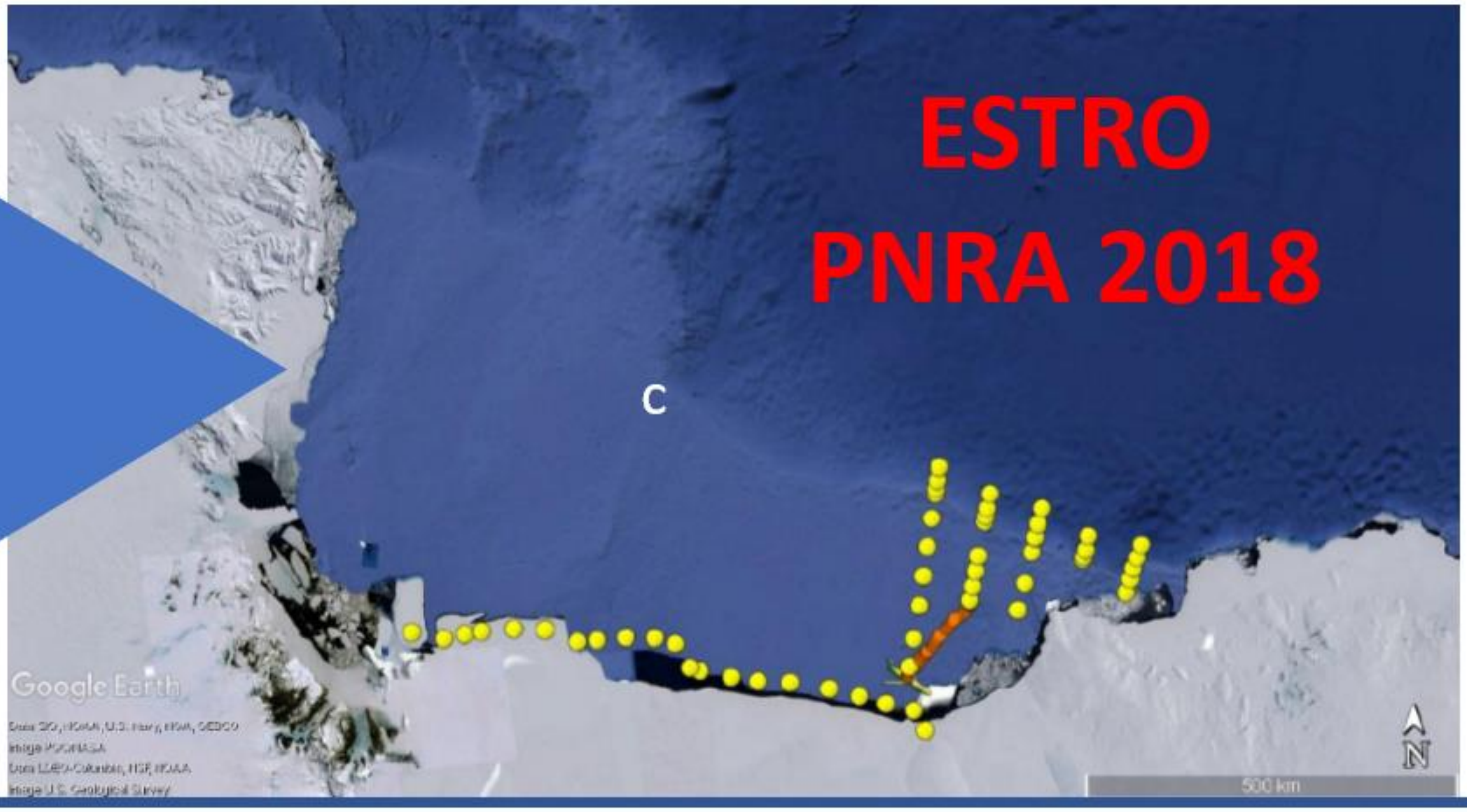


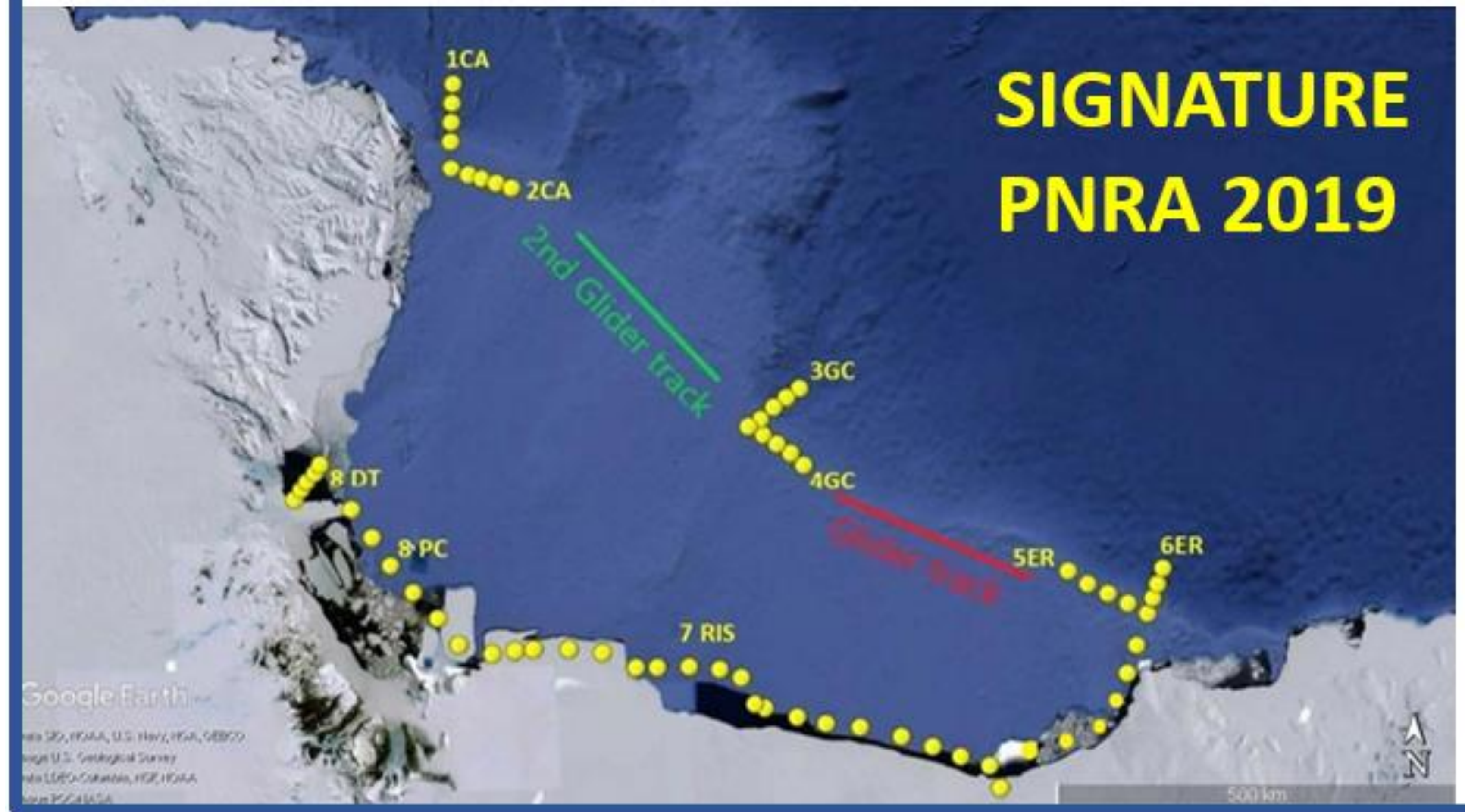
Fig. 6 | Schematic illustrating the physical mechanisms driving enhanced AABW formation in the Ross Sea. The unusual combination of positive SAM and El Niño resulted in weaker easterly winds in the western Amundsen Sea, less import of sea ice and a more open sea ice pack with higher rates of sea ice formation on the Ross Sea continental shelf. The resulting increase in DSW salinity enhanced the formation of AABW. The 1,000-m isobath is highlighted to visualize the margin of the continental shelf.

Silvano et al., 2019, Nat. Geo.

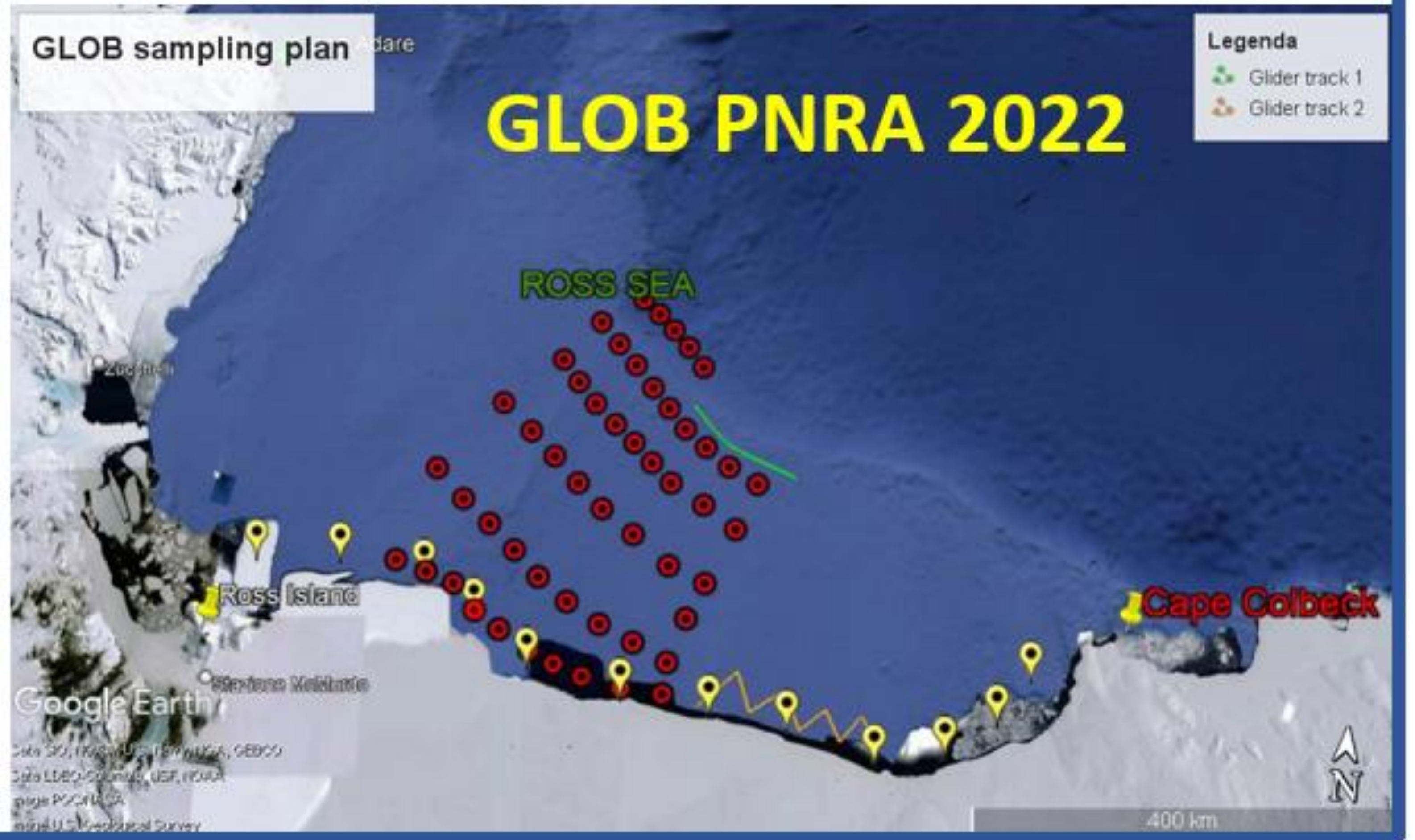
HOW


ESTRO
PNRA 2018
C
Google Earth
500 km

SO WHAT


SIGNATURE
PNRA 2019
1CA
2CA
2nd Glider track
3GC
4GC
Glider track
5ER
6ER
8 DT
8 PC
7 RIS
Google Earth
500 km


Progetto TENORE
TENORE PNRA 2019
Legenda
Google Earth


GLOB sampling plan
GLOB PNRA 2022
Legenda
Glider track 1
Glider track 2
ROSS SEA
Ross Island
Cape Colbeck
Google Earth
400 km

Antarctic precipitation, atmospheric physics and chemistry, radiation

The study of Antarctic radiation, microphysics, chemistry and meteorology is essential for the understanding of many phenomena which have global impact.

- Understanding **Ozone variability** remains of high importance due to the major role Antarctic ozone plays in climate variability across the Southern Hemisphere. In the Stratosphere, such variability is driven by the vortex meteorology and by heterogeneous chemistry on **Polar Stratospheric Clouds**, and recent publications have highlighted the potential of climate change to induce new sources of ozone depletion. In the Troposphere, Br and NOx chemistry, radiation and long range transport influence the Ozone abundance, while a link between the two region is provided by **Stratosphere-Troposphere Exchange** events, recently studied also by ground sampling of Be-7.
- Antarctic ice sheets play a crucial role in global sea level regulation. Studying atmospheric processes in Antarctica aids in predicting how changes in radiation, chemistry, and microphysics may influence ice melt and, consequently, sea level rise. In particular, improvements in the knowledge of the Antarctic hydrologic cycle are essential in order to assess future changes of the surface mass balance and to define the contribution of the Antarctic ice sheet, that hold approximately 90 percent of the world's ice, on the sea level rise. The primary mass input of the ice sheet is represented by **snow precipitation**.
- Studying **Antarctic aerosol** chemistry and microphysics helps scientists understand the formation and behavior of clouds, which, in turn, influence radiation balance and precipitation patterns, impacting broader climate systems. The chemical composition of aerosol is of particular interest for investigating the relationship between marine biological activity and chemical and climate-relevant properties of marine aerosol.
- The polar **radiative budget** is unique due to factors like its high surface albedo (reflectivity) low solar angle and clouds peculiar of the region, due to the extremely low temperatures, absolute humidity levels, and aerosol concentrations, like Antarctic Stratus, Cirrus and Polar Stratospheric Clouds. Determining surface albedo, radiation fluxes in the solar and infrared spectrum, and the effect of aerosol and cloud particles on such fluxes, helps scientists comprehend how the polar environment interacts with radiation.

Bibliography:

Bracci, A., et al. "Quantitative precipitation estimation over Antarctica using different ze-SR relationships based on snowfall classification combining ground observations." Remote Sensing 14.1 (2022): 82.

Kumar, P. et al. "The increasing surface ozone and tropospheric ozone in Antarctica and their possible drivers." Environmental Science & Technology 55.13 (2021): 8542-8553.

Virkkula, A., et al. "Aerosol optical properties calculated from size distributions, filter samples and absorption photometer data at Dome C, Antarctica, and their relationships with seasonal cycles of sources." Atmospheric Chemistry and Physics 22.7 (2022): 5033-5069.

Tian, B., et al. "Multi-year variation of near-surface ozone at Zhongshan Station, Antarctica." Environmental Research Letters 17.4 (2022): 044003.

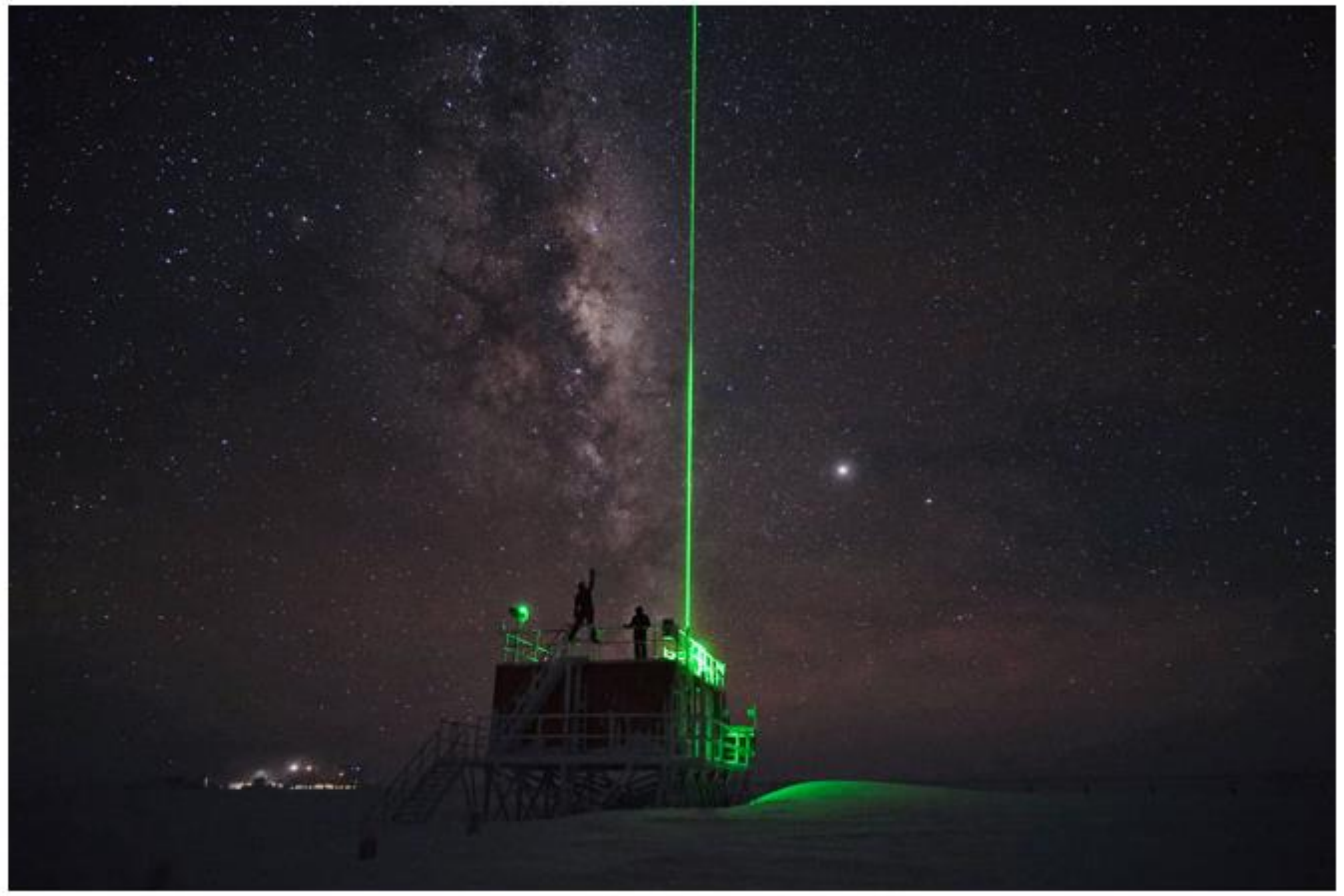
Rinaldi, M., et al. "Contribution of water-soluble organic matter from multiple marine geographic eco-regions to aerosols around Antarctica." Environmental Science & Technology 54.13 (2020): 7807-7817.

Snels, M., et al. "Quasi-coincident observations of polar stratospheric clouds by ground-based lidar and CALIOP at Concordia (Dome C, Antarctica) from 2014 to 2018." Atmospheric Chemistry and Physics 21.3 (2021): 2165-2178.

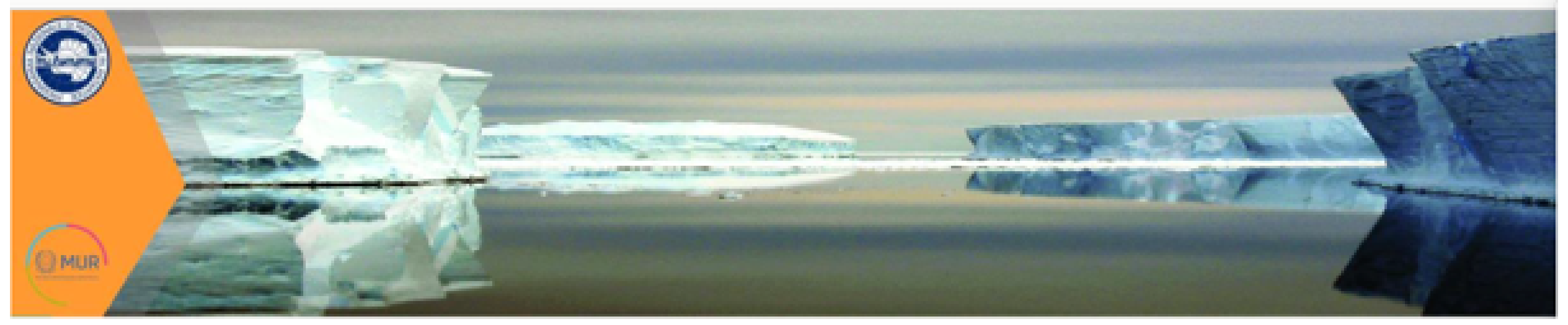
Micro Rain Radar at Mario Zucchelli research station on the roof of the logistic container.

Laura Bassi cruises hosting instrumentation for the chemical characterization of marine aerosol, with a particular focus on organic aerosols and their formation processes in relation with the oceanic biological activity.

Radiometric Observatory performs accurate and continuous surface radiation measurements, with the establishment of the BSRN network (http://www.bsrn.awi.de/)



The Lidar at Concordia allows the study of polar stratospheric clouds (PSC) which are important for the heterogeneous chemistry in the stratosphere and in particular for the processes involving ozone destruction.



Challenge: *Ocean, Climate and Interactions*

PNRA Project: ICECLIMALIZERS (ended in 2021) Line A

- Validating the role of **benthic polar biomineralizers** (bryozoans and algae) **as proxies of climate change**
- Terra Nova Bay, coastal site (Tethys Bay): 25 m
- **Experimental Ecology Approach**: high resolution underwater observatory for physico chemical and biological data (growth, biomineralization)
- **Relevance of coastal multidisciplinary underwater high resolution observatory** (Lombardi et al. 2021 & data set available), Geochemical and Structural characterization of new calcifying species (Lopez-Correa et al. 2023), **first data on benthic bioconstructional bryozoans** on: **skeletal organic matrix** (Lombardi et al. 2023, Marin et al. *in prep*) and as **proxies of climate change**, especially acidification (Lombardi, Montagna et al. *in prep*)
- High resolution data-set, **new** psycho chemical and biological **data** for the scientific community, dissemination through media (press, TV, radio)

PNRA Project: BIOROSS (on going) Line D – in cooperation with NIWA (Ross Sea Voyage TAN2023)

- Explore benthic bioconstructional ecosystems from Ross Sea banks, depth: 200-600 m
- Ecology, Taxonomy and Conservation
- Map of Vulnerable Marine Ecosystems of the Ross Sea MPA to be protected and preserved

SCAR group interactions: AntClimNow, Ant-ICON

Grand (new) Challenge: *Ocean, Ecosystems and Climate- Real Time acquisition and transmission of Underwater DATA*

Topic: Polar Network of Coastal ‘Smart’ Underwater Observatories for BIG DATA Acquisition on Ocean, Ecosystems & Climate Change

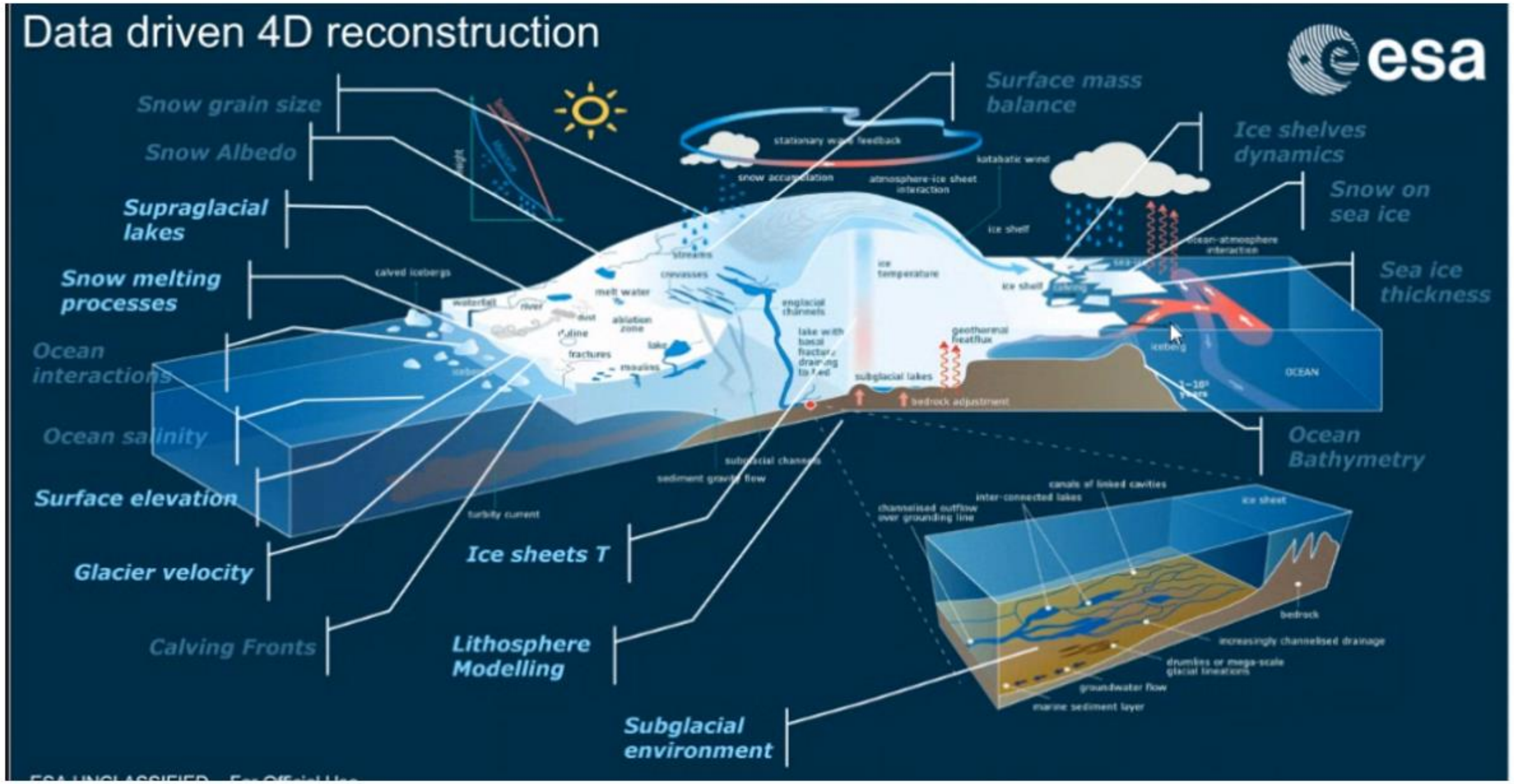
- *Where*: Antarctic coastal sites
- *How*: **Underwater observatories based on IoUT (Internet of Underwater Things) technologies** (nodes connected to multiproxy high quality probes, cameras and ROV for ‘smart’ biological monitoring) for high resolution data acquisition and transmission;
- *What*: **Big data acquisition and transmission in real time**/delayed transmission through all the year in polar coastal sites; network of sites for ‘real time’ data comparison and monitoring
- *So What:*

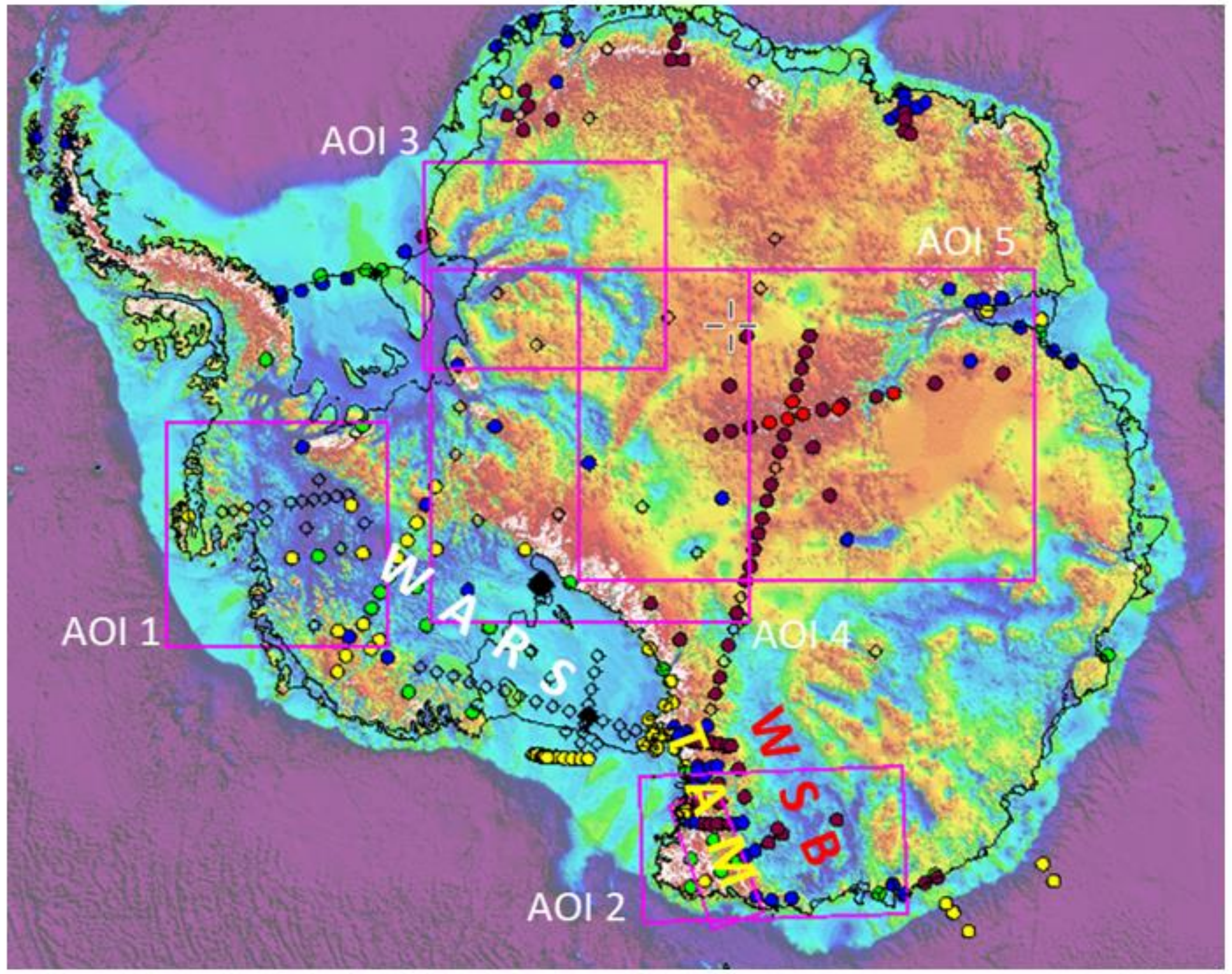
1. **Reduced ‘sampling’ impact** on biological communities through non invasive monitoring to promote their conservation;
2. High quality and **BIG data available** for scientists and stakeholders;
3. **Real time monitoring** to detect on going changes (to better address current and future project);
4. **High dissemination impact** (data visualization on a dedicated website) for students, citizens and stakeholders;
5. **Adaptable monitoring** stations to be implemented with other instruments for multiple purposes (i.e., site monitoring for logistic purposes)

Ref. projects: PNRA 2022- SMART-ICE: high resolution Monitoring station for maRine calcifiers under changing anTarCtIc ClimatE; Smart Bay S. Teresa (https://smartbaysteresa.com) – IoUT observatory to be empowered in 2024 through PNRR funding and available as Marine Test Site

Aim

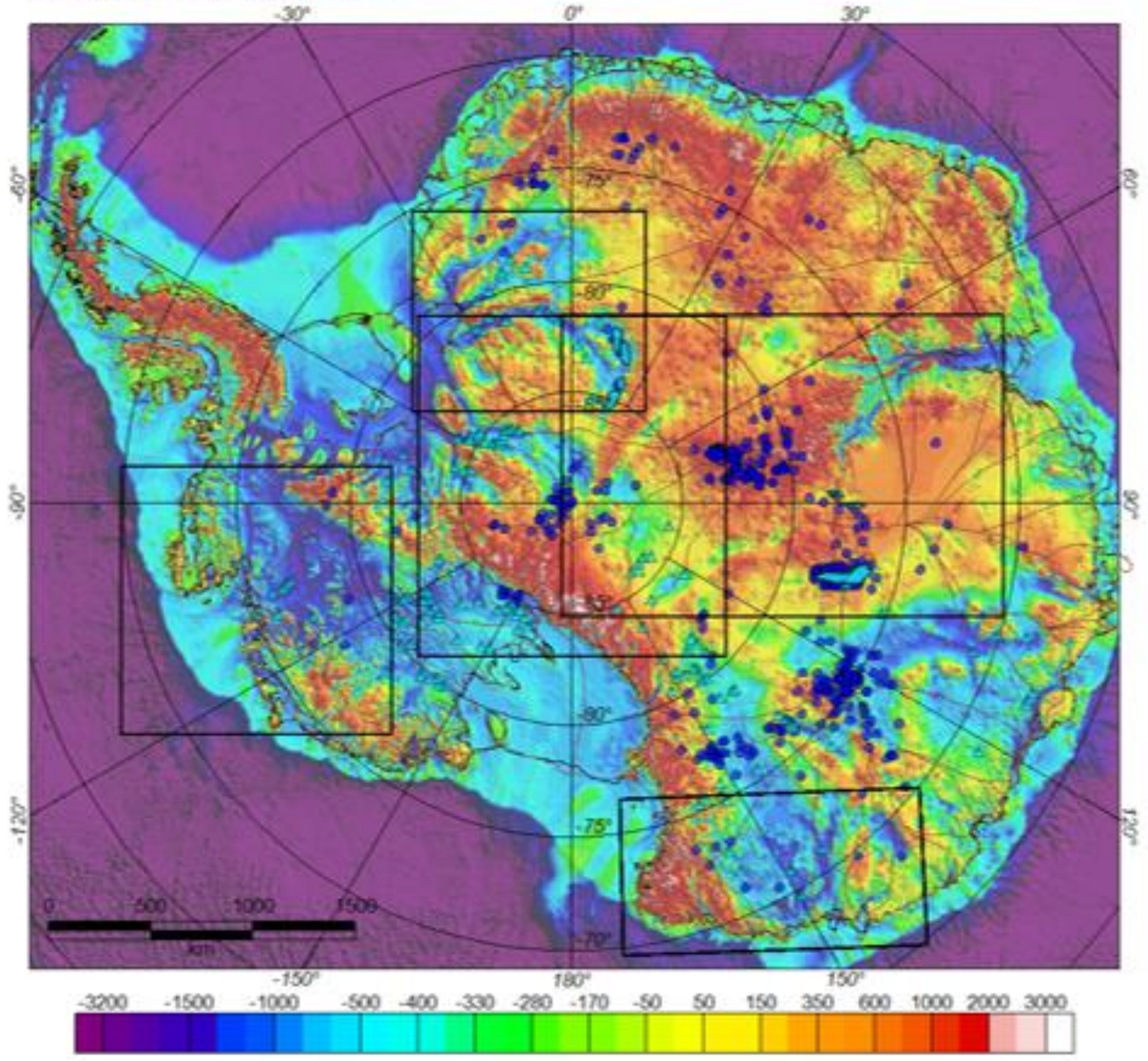
To provide basal boundary conditions for Antarctic subglacial hydrology and ice sheet studies: bed topography, lithosphere & geothermal heat flux



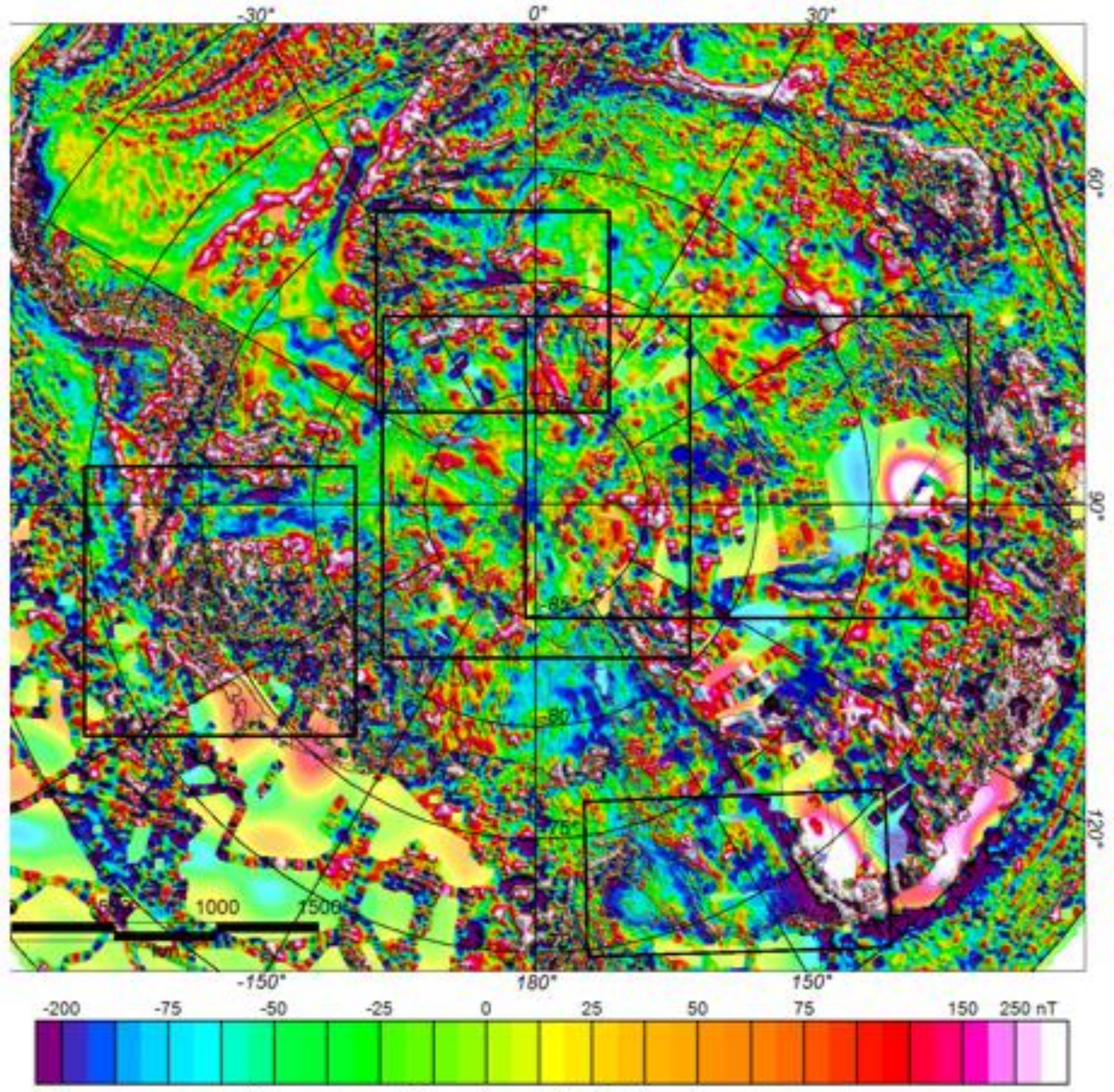


Methods: Radar & Potential Field (satellite & airborne)

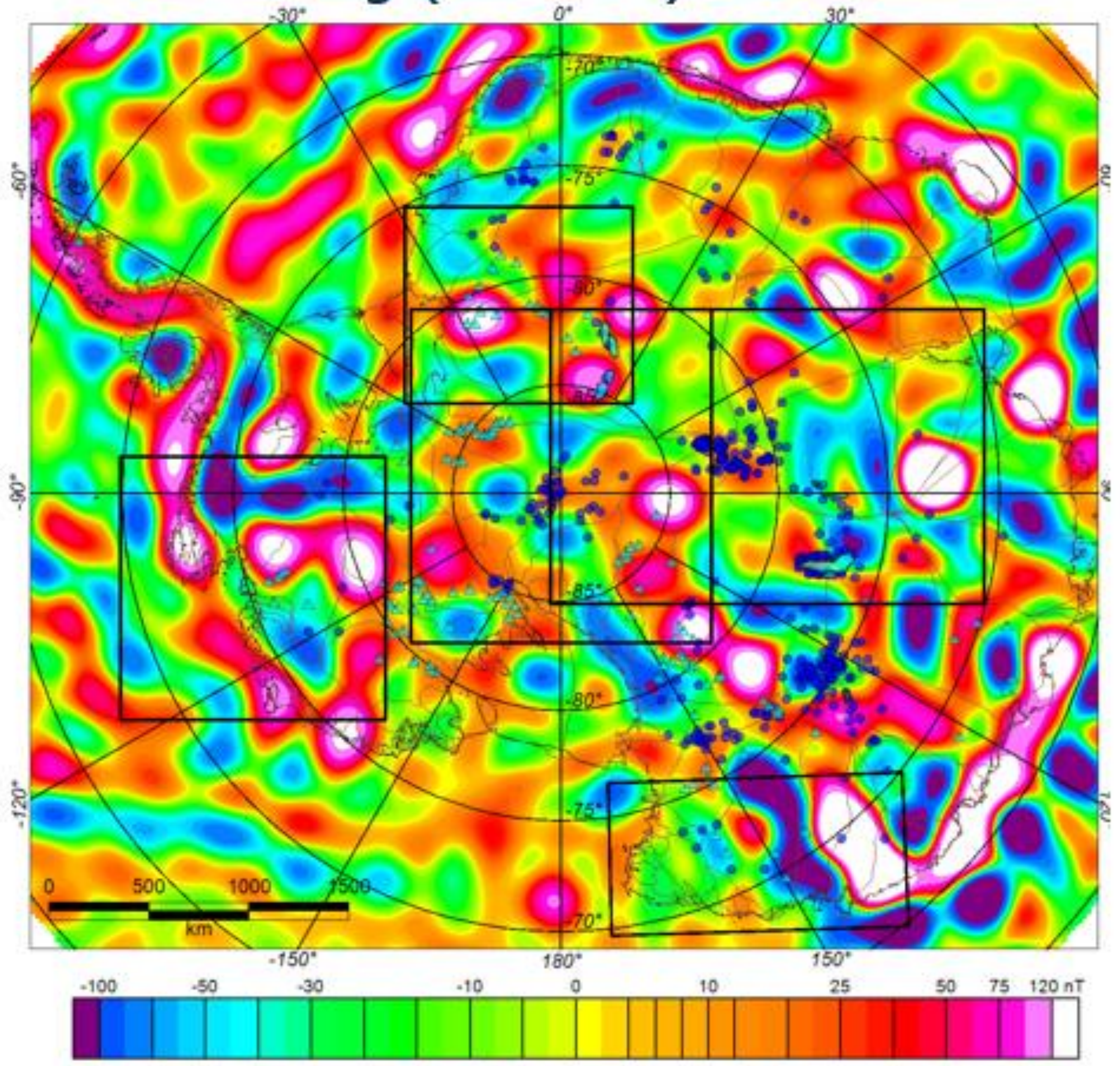
BedMachine



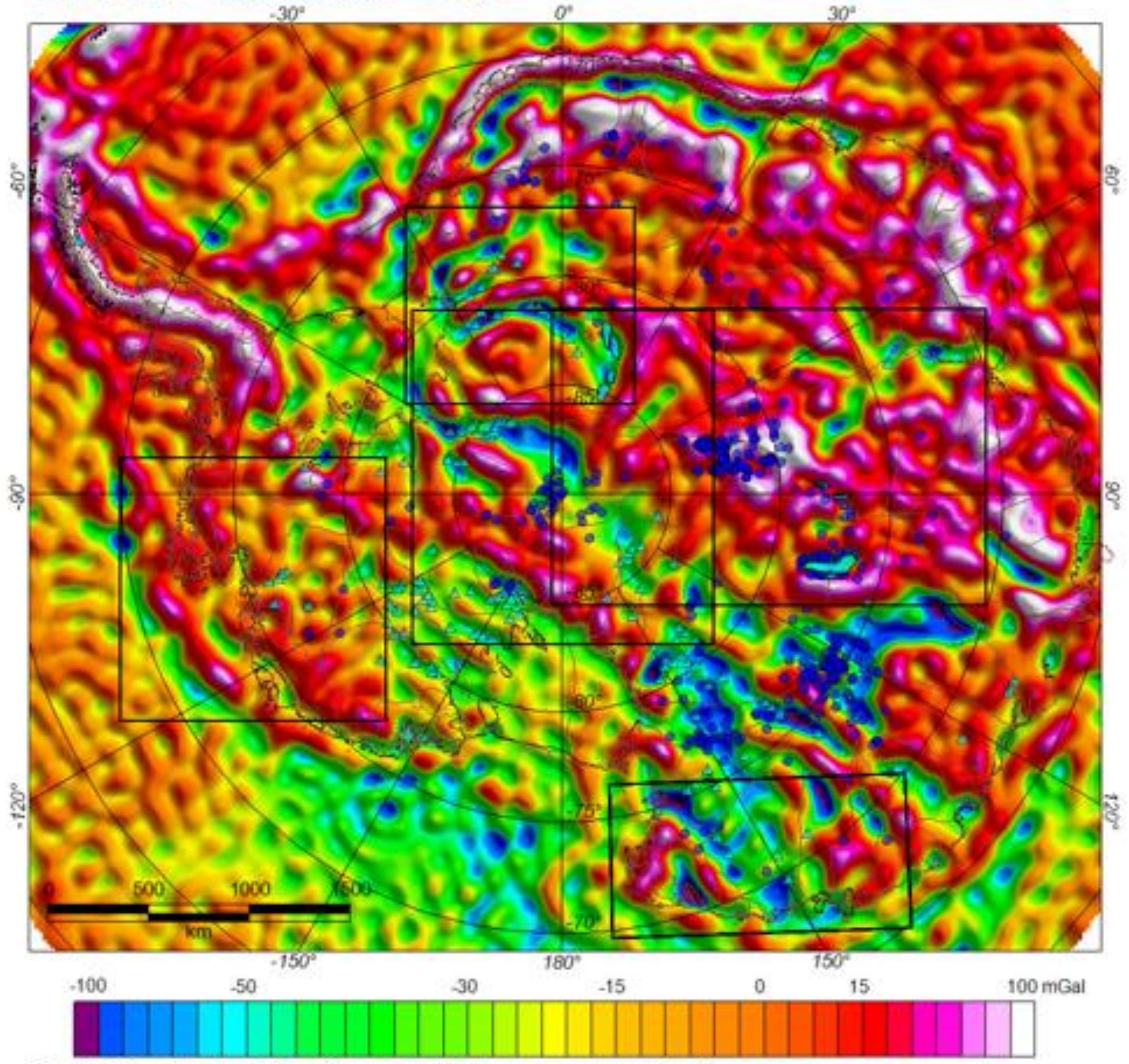
ADMAP 2.0+



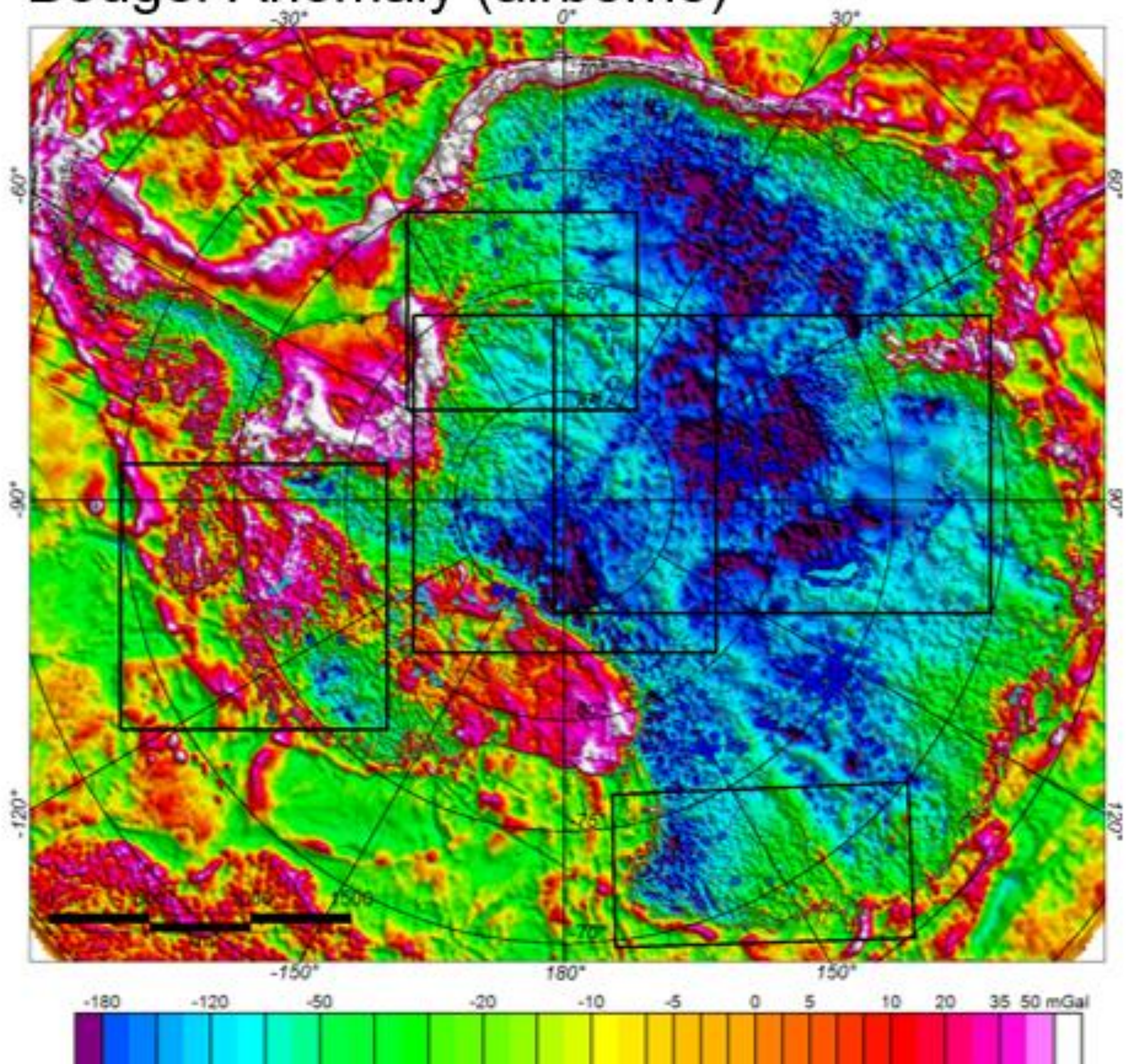
Satellite Mag (SWARM)



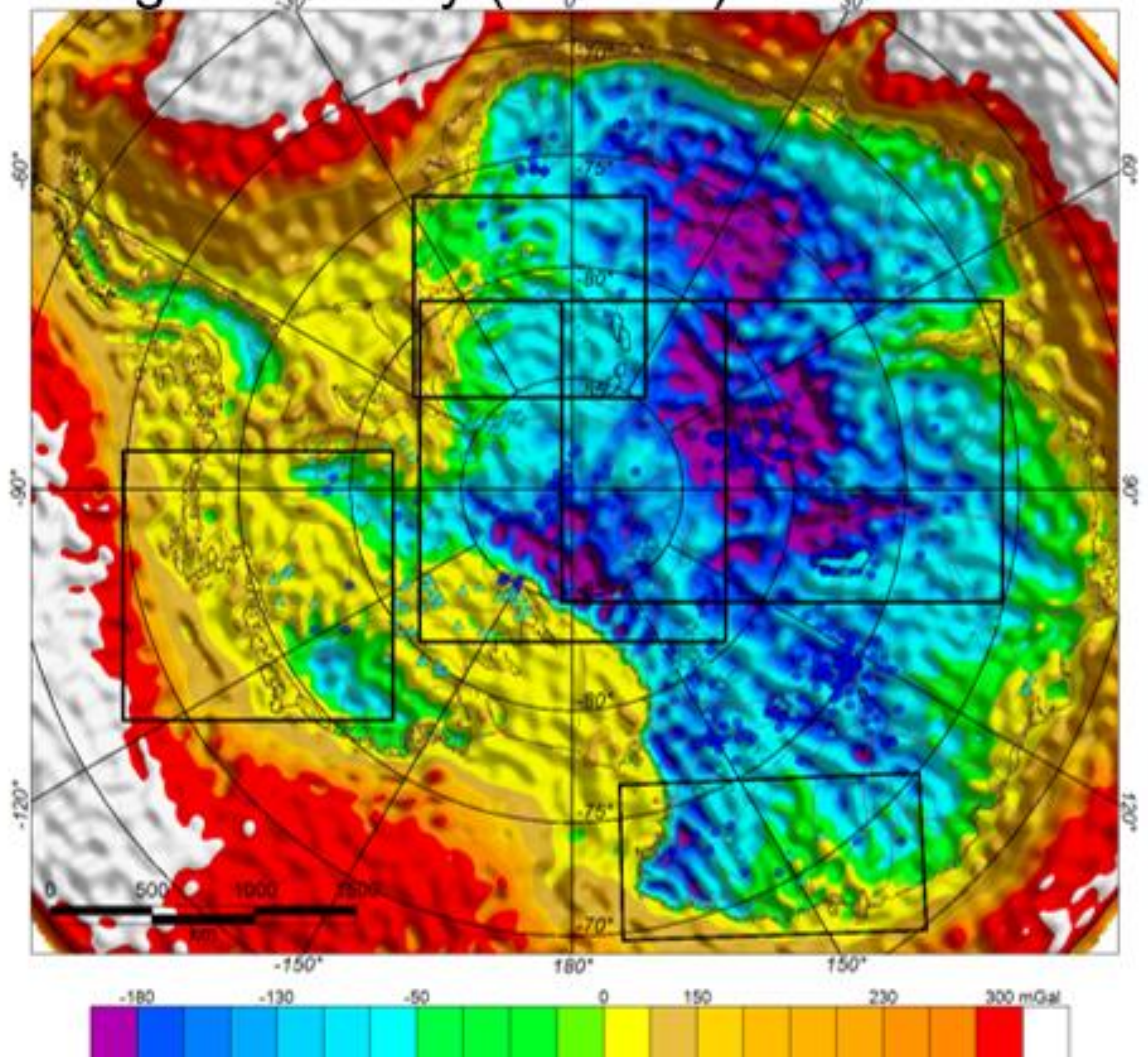
GOCE & PolarGAP



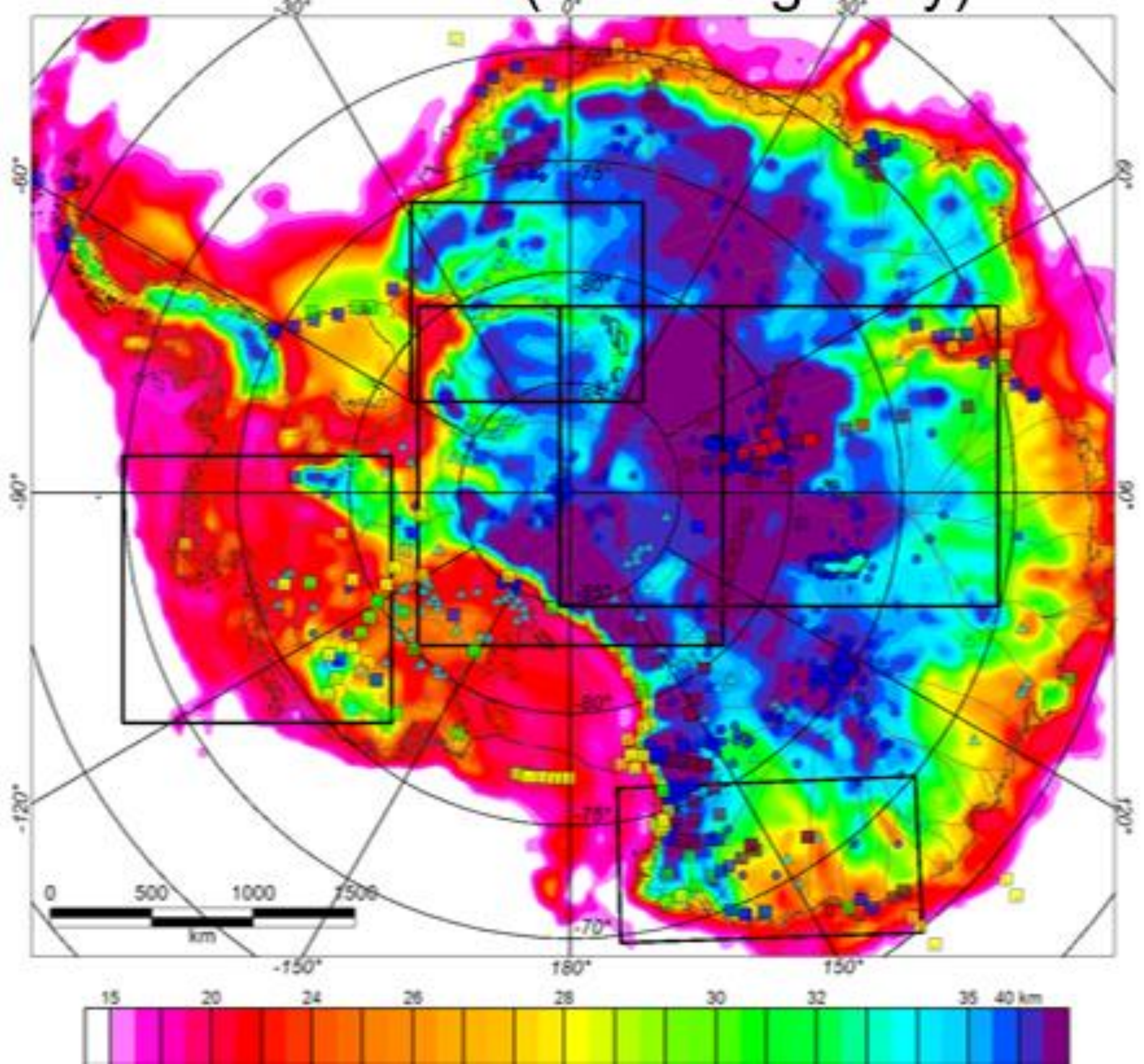
Bouger Anomaly (airborne)



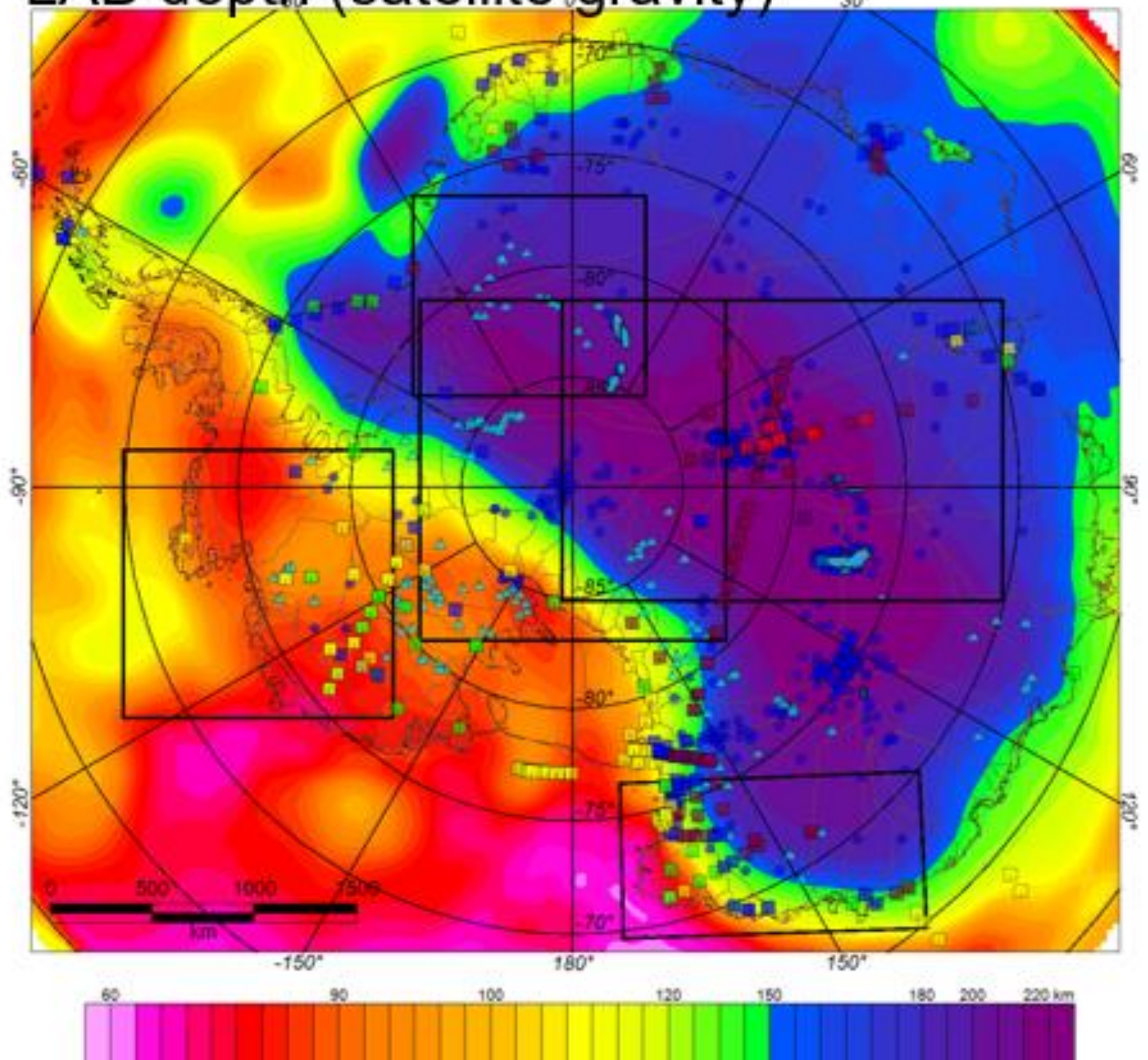
Bouger Anomaly (satellite)



Crustal thickness (satellite gravity)

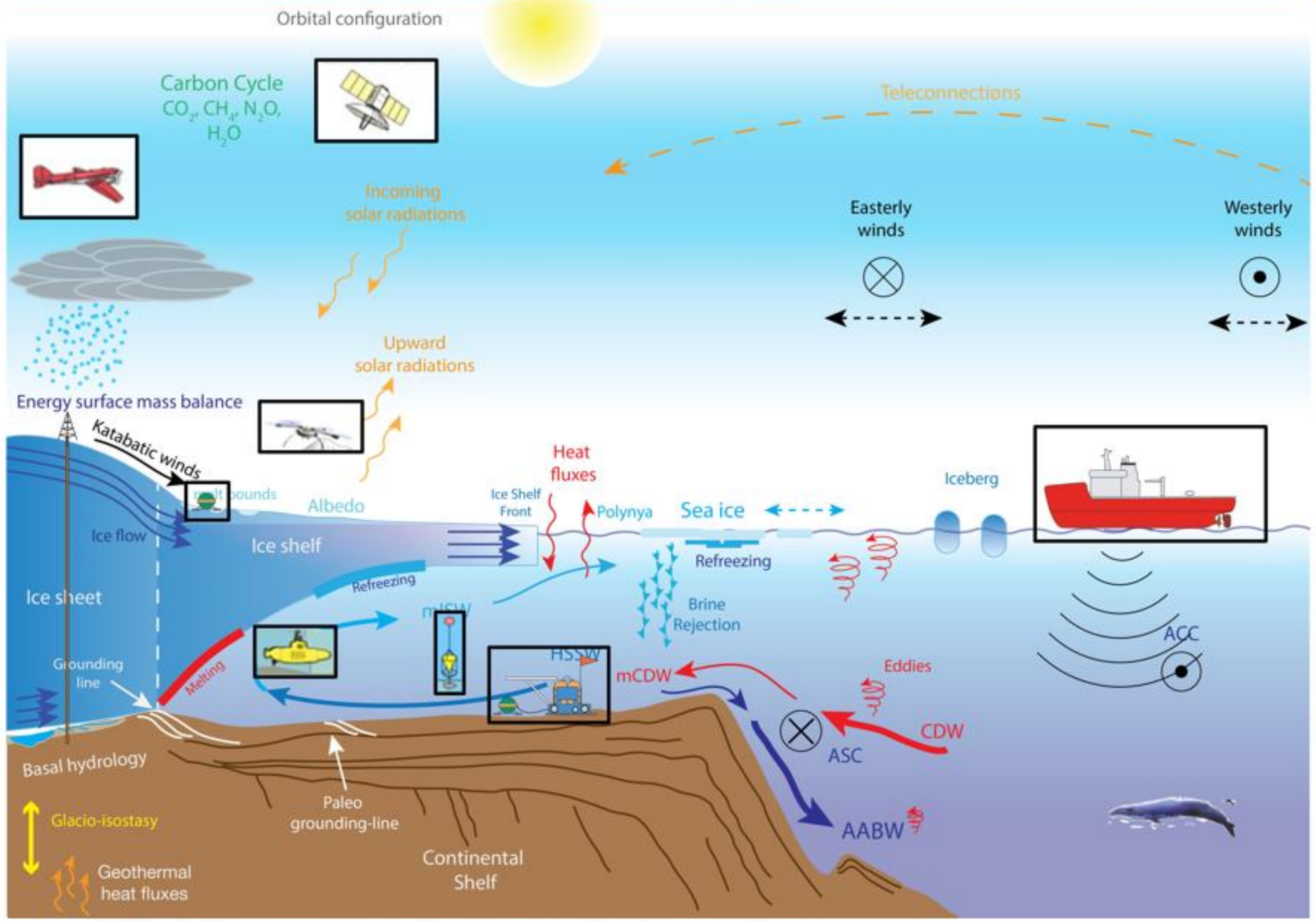


LAB depth (satellite gravity)



Potential collaboration ESA- EC & PNRA

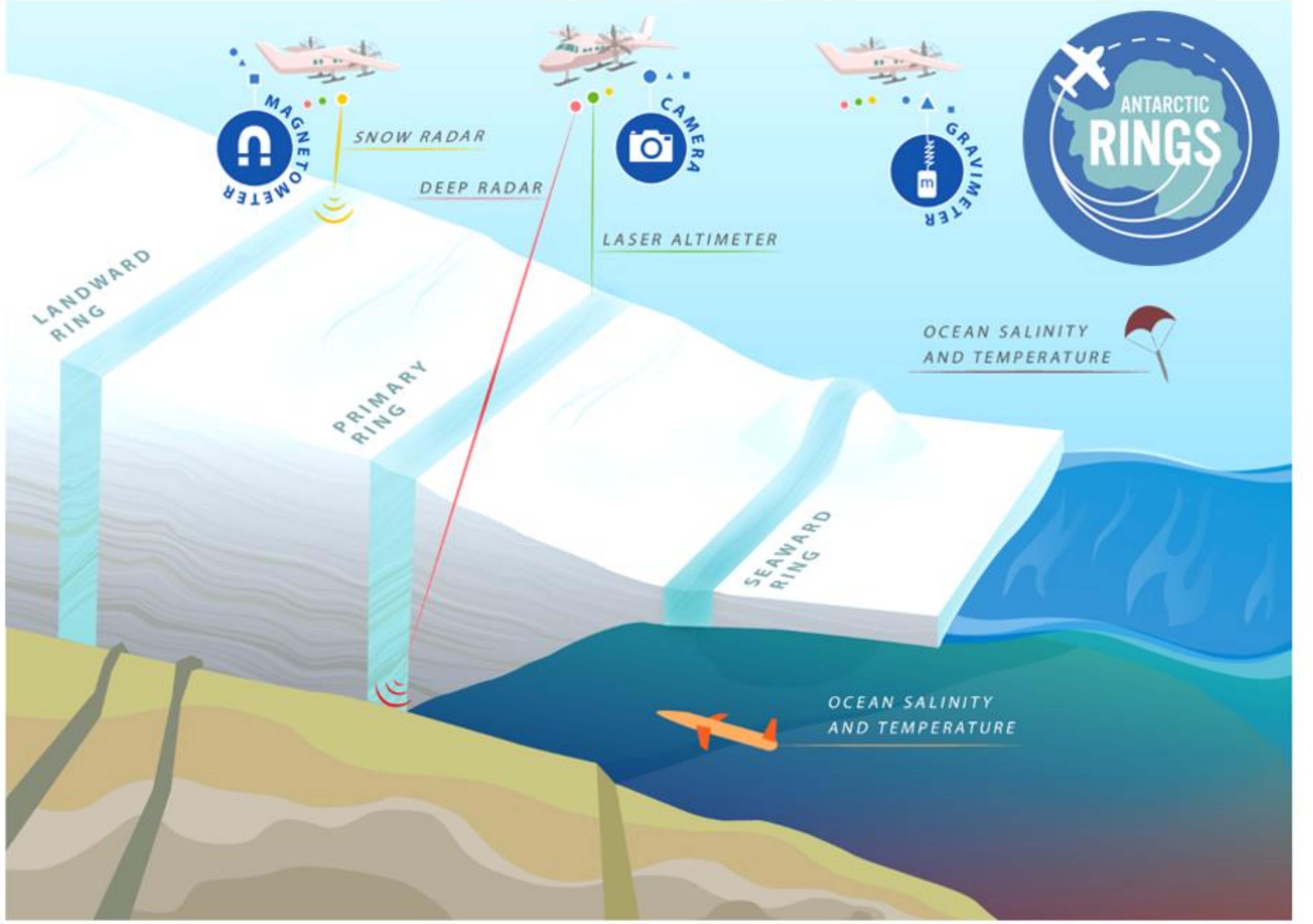
ERC-SYNERGY ICEOLIA
Ice-Ocean-Lithosphere Interplay in East Antarctica



-> multidisciplinary proposal-> synergetic observations
Oceanography, glaciology, geophysics and EO combined
To explore East Antarctic Ice Sheet-Ocean-Lithosphere interactions in the Wilkes Subglacial Basin
& model past & future ice sheet behaviour

"RINGS" in brief

- ✓ **Interdisciplinary, coordinated airborne missions**
- ✓ **Primary target = bed topography at the margin**
  - ✓ Complete reference bed topography data for robust assessments of ice discharge from all around Antarctica.
- ✓ **Primary RING + seaward + landward RINGS**
  - ✓ Prediction of future retreat of the margin
  - ✓ Sub-ice-shelf bathymetry and quantification of ice-ocean interactions
  - ✓ Geology and subglacial hydrology



Tacking these challenges requires new interdisciplinary studies

Reviews of Geophysics

REVIEW ARTICLE
10.1029/2019RG000663

The Sensitivity of the Antarctic Ice Sheet to a Changing Climate: Past, Present, and Future

T. L. Noble[1], E. J. Rohling[2,3], A. R. A. Aitken[4], H. C. Bostock[5], Z. Chase[1], N. Gomez[6], L. M. Jong[7,8], M. A. King[9], A. N. Mackintosh[10], F. S. McCormack[10], R. M. McKay[11], L. Menviel[12], S. J. Phipps[1], M. E. Weber[13], C. J. Fogwill[14], B. Gayen[15], N. R. Golledge[11], D. E. Gwyther[1], A. McC. Hogg[2,16], Y. M. Martos[17,18], B. Pena-Molino[8,19], J. Roberts[7,8], T. van de Flierdt[20], and T. Williams[21]

Key Points:

- The AIS is a highly dynamic component of the Earth system, evolving on a broad range of temporal and spatial scales
- Paleoenvironmental evidence highlights the centennial to millennial response time scales of the AIS to atmospheric-ocean forcing
- Coupling feedbacks in Earth system components are required to reduce the uncertainty in AIS's contribution to past and future sea level rise