A coordinated NASA observing system for monitoring the next decade of ice sheet-climate interactions

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Synopsis

Sea level rise is a global problem that is currently shrouded in uncertainty. The next decade of NASA research priorities must address key unknowns and monitor ongoing changes in the ice sheet-ocean system in order to improve sea level rise projections and equip government officials to legislate the appropriate policies. This will require a coordinated observing system that combines satellite remote sensing with suborbital approaches to extend the reach of satellite measurements. The fifth International Polar Year (IPY5) will take place in 2032 –2033; this international incentive provides an opportunity to leverage shared logistics between nations to collect valuable suborbital observations. The following effort summarizes four pertinent research questions that we believe should guide NASA's next decade of planning for cryosphere research, with specific recommendations as to how to address these questions.

Motivation: Interactions between Earth's ice sheets and oceans foretell future coastlines

There is a pressing need to understand the processes removing mass from Earth's ice sheets, which hold nearly all of the planet's freshwater and can reshape global coastlines by raising sea level. Rising seas are an important global problem, because of the large human population that live in coastal regions vulnerable to flooding – predicted to reach 1.2 billion by 2100 *[Jones & O'Neill, 2016; Merkens et al., 2016]*. The science community's best attempts to understand ice sheet-climate interactions have generally underestimated rates of change, with nearly 50 years of monitoring *[Hanna et al., 2024; Mouginot et al., 2019; Otosaka et al., 2023; Rignot et al., 2019]* resolving mass loss at the upper bound of what had been projected *[Alley et al., 2005]*. Future projections suggest that mass loss could accelerate from Earth's land-based ice in the twenty-first century and raise global mean sea level by up to 39 cm by 2100 *[Coulon et al., 2024; Rahlves et al., 2025]*. However, uncertainties related to unresolved and under-resolved ice sheet-climate processes in the models responsible for making sea level rise projections produce ranges too wide (-7 – 39 cm by 2100; *[Coulon et al., 2024; Rahlves et al., 2025]*) for confident risk management at the necessary regional scales. The main source of uncertainty in projections of ice sheet mass balance and resultant sea level rise relates to how changes at their margin will propagate inland *[Bamber et al., 2019; DeConto et al., 2021]*. Interactions between the ice sheet, ocean, and atmosphere at the margin occur at small spatial and temporal scales but connect to global climate through large-scale feedback mechanisms *[Li et al., 2021; Lim et al., 2016]*. It is vital that we improve observational coverage of ice sheet margins to resolve the essential processes determining their state so that these processes can be accurately fed forward to improve model projections. In this white paper, a group of US scientists that study Earth's cryosphere proposes a roadmap for the next decade of NASA scientific funding to address critical science questions and societal application needs. We recommend a set of observational and modeling efforts that will improve the accuracy of sea level rise projections, advance global coastal prediction capabilities. and strengthen capabilities to resolve science questions and application needs in the broader Earth system. This roadmap is structured around four research questions that we believe will require a coordinated observing system that augments NASA's orbital satellites with various suborbital methods such as fixed wing operations and in situ measurements (**Figure 1**).

Research Question 1: How will ocean heat delivery impact the ice sheets over the next decade and which large ice shelf cavity is most susceptible to ocean warming?

Large-scale circulation patterns deliver ocean heat from the equator and mid latitudes to Earth's polar ice sheets, Greenland and Antarctica, where it then removes mass through melting and structural weakening resulting in calving *[Rignot et al. 2012*, *Armour et al., 2016; Straneo et al., 2012]*. Increased ocean-induced melting is the dominant mechanism driving mass loss of the West Antarctic Ice Sheet *[Jacobs et al. 1996, Coulon et al., 2024]* and an equal contributor in Greenland *[Mouginot et al., 2019; Rahlves et al., 2025]*, keeping pace with losses driven by atmospheric forcing. The Arctic and Southern oceans are warming *[Cai et al., 2023; Richards et al., 2022]* from the increased poleward transport of heat due to rising temperatures at the equator and mid latitudes *[Fu et al., 2006]*. Warm and dense Atlantic Water transported to the Arctic in the Gulf Stream meanders through deep troughs in the continental shelf to intrude into narrow fjords and contact the Greenland Ice Sheet *[e.g., Schaffer et al., 2017]*. Shallow sills at the fjord openings modulate the transport of Atlantic Water into contact with some of Greenland's glaciers *[Straneo & Cenedese, 2015]*, which protects them to varying degrees. Waters sourced from the Atlantic and Pacific basins, referred to as Circumpolar Deep Water, upwell across the Antarctic Circumpolar Current with a fraction diverted into the Weddell and Ross subpolar gyres *[Thompson et al., 2018]*. A series of frontal currents over the continental slope, including the Antarctic Slope Current, regulate the transport of these warm waters onto the continental shelf *[Thompson et al., 2018]*. Deep seabed troughs *[e.g., Wåhlin et al., 2013]*, wind-driven upwelling *[e.g., Guo et al., 2022]*, and mesoscale eddies *[e.g., Stewart et al., 2014]* are essential features that facilitate the movement of Circumpolar Deep Water across the shelf break and towards the Antarctic Ice Sheet. This occurs primarily within narrow topographically steered boundary currents. Persistent areas of open water in front of Antarctica's largest floating ice shelves (Ross, Filchner-Ronne, Amery) form the final barrier to CDW's access to the ice sheet, and to a lesser degree in front of smaller ice shelves in the Amundsen Sea, for example *[Moorman et al., 2023]*. These powerful local climate feedbacks transfer ocean heat to the atmosphere to form sea ice and convert warm CDW to High Salinity Shelf Water *[Herraiz-Borreguero et al., 2016; Nicholls et al., 2009; Porter et al., 2019]*. The efficiency of polynyas is linked to the strength of winds blowing off the ice sheet and the amount of freshwater present in the upper ocean *[Bromwich & Kurtz, 1984]*. The latter is linked to ice shelf melting and has the potential to weaken convection if melting increases *[Jacobs et al., 2022; Silvano et al., 2018]*, which will then allow less modified or warmer derivatives of Circumpolar Deep Water to access Antarctica's largest ice shelf cavities *[Jin et al., 2025; Teske et al., 2024; Xie et al., 2024].*

A variety of processes across temporal and spatial scales control the transport of heat from the ocean into contact with ice shelves and glacier fronts, where it drives melting. Horizontal gradients in density, tides, eddies, internal waves, and various instabilities circulate water beneath and around the ice *[Herraiz-Borreguero et al., 2013; MacAyeal, 1984; Mack et al., 2019; Poinelli et al. 2025, Makinson & Nicholls, 1999; Sun et al., 2019].* These processes mix the water column and produce a downward cascade in turbulent kinetic energy from larger to smaller scales [e.g., *Davis & Nicholls, 2019*], which combines with the ocean heat content to produce the general pattern of melt for marine-terminating glaciers. These two factors (heat and kinetic energy) tend to be elevated where ice enters the ocean in the grounding zone [*Schmidt et al., 2023; Sugiyama et al., 2014]*, leading to high melt rates in a critical location that connects directly to the grounded ice sheet *[Ciracì et al., 2023]*. Ocean warming therefore can drive elevated melting in the grounding zone, which produces retreat, such has been observed for the ice shelves occupying the Amundsen Sea Embayment of Antarctica *[Rignot et al., 2014]*, as well as many glaciers lining the periphery of Greenland *[e.g., Millan et al., 2022; Mouginot et al., 2015]*. Grounding zone retreat can drive the Marine Ice Sheet Instability that increases mass loss from the ice sheet and its sea level rise contribution *[Favier et al., 2014]*, as well as weakening the ice shelf that extends seaward through increased crevassing and rifting *[Wild et al., 2024]*. ***With the ocean warming around Greenland and Antarctica, it is therefore critical to monitor the delivery of this heat into contact with the ice and the response of the glaciers and ice shelves that interact with it.***

Research Question 2: How does the ocean interact with ice shelf basal topography (channels, crevasses, terraces, and rifts) to impact melting and how sensitive are these features to ocean warming?

Ice shelf basal topography refers to features carved into the ice base that occupy a range of horizontal scales. Here, we focus on the several meter to several kilometer range of scales, occupied by terraces (meters scale), crevasses (tens to hundreds of meters scale), rifts (kilometer scale), and channels (several kilometers scale). These features all have distinct formation mechanisms, but once formed, they interact with the ocean to increase overall melt rates, which points to a feedback where melt sculpts topography and that evolving terrain, in turn, redirects and concentrates further melt *[Watkins et al., 2021]*. This relationship implies that the evolution of basal features carries information about ice shelf stability that is obscured when measuring only the ice surface. Basal crevasses observed with an underwater vehicle are three times wider in a warm (Thwaites Glacier- *[Schmidt et al., 2023]*) sub-ice shelf ocean cavity than a cold (Ross Ice Shelf – *[Washam et al., 2023]*) cavity. This is because melt-enhancing plumes rising along the steep crevasse sidewalls are able to access more ocean heat to accelerate melting and widen the crevasse more in the warm cavity than in the cold. When the ocean widens basal crevasses beyond a critical threshold that can be supported by the ice above, it leads to a full-thickness propagation of a rift that significantly weakens the ice shelf *[Bassis & Ma, 2015]*. Ice shelf basal terraces also experience the slope-melt feedback, where steep sidewalls melt up to ten times faster than the flat roofs *[Dutrieux et al., 2014a]*. Depending on the vertical extent of the terrace, this rapid lateral melt can remove large portions of the ice shelf.

Ice shelf basal channels are large topographic features that can be up to several kilometers wide and extend over lengths of tens of kilometers *[e.g., Rignot & Steffen, 2008]*, which also experience accelerated ocean-driven melting relative to their surroundings *[e.g., Alley et al., 2016]*. Ice shelf channels have been observed to migrate laterally in a manner consistent with Coriolis-influenced ocean melt, indicating that Earth's rotation exerts a first-order control on where channelized melt concentrates over time *[Alley et al., 2022]*. Where a basal channel intersects a shear margin, the resulting combination can weaken the ice shelf at precisely the location where it is mechanically most vulnerable *[Alley et al., 2019]*. Basal channels that initiate near the grounding zone result from outflow of subglacial freshwater *[Alley et al., 2016; Washam et al., 2019]*, generated along the grounded ice base and surface (that drains to the base through moulins and crevasses), which links ocean forcing to subglacial hydrology and atmospheric forcing *[Washam et al., 2019]*. Changes in the strength of any of these forcing mechanisms can therefore influence ice shelf stability through channelized melting.

The relationship between basal topography and ocean melt is bidirectional: just as basal geometry concentrates and redirects melt, the resulting geometry feeds back onto circulation within the ice shelf cavity itself *[Sergienko, 2013]*. This two-way linkage means basal geometry cannot be treated as a static boundary, but one that evolves jointly with the circulation it helps generate, which also affects the mechanical integrity of the ice shelf itself. As channels, terraces, and crevasses widen and deepen under continued ocean-driven melt, they thin the ice locally and concentrate stress, providing preferential sites for rift initiation and propagation that can ultimately compromise ice shelf structural support *[Alley, et al., in review; Wearing et al., 2021]*. ***This connection between concentrated ocean-driven melt in basal topography and the overall stability of ice shelves becomes critical when considering ocean warming, which makes it a critical problem to monitor.***

Research Question 3: How do grounding zone processes interact with bed topography and how important is this process for ice sheet mass balance?

The grounding zone is the region where grounded ice can intermittently lose contact with the bed and float in sea water *[Fricker and Padman, 2006]*. As ice mass discharges from the grounded part of an ice sheet into an ice shelf, its weight is no longer supported by the bed so that it contributes to sea level. Between 1996 and 2025, Antarctica lost 12,820 ± 1,873 km^2 of grounded ice *[Rignot et al., 2026]*. The current understanding of processes taking place in this transition zone is very limited, primarily due to lack of direct observations, let alone their time series. The grounding zone and its dynamics (advance, retreat, changes in its spatial extent) are affected by processes similar to those controlling the behavior of the grounded ice (e.g., interactions of ice flow with underlying bedrock or deformable sediments, subglacial hydrology (including subglacial lakes), basal melting due to the geothermal heat flux and frictional heat dissipation), and by the impacts of the local (sub-ice shelf cavities) and global oceanic phenomena (e.g., barotropic tides, Poincaré waves; *[Padman et al., 2018]*).

Basal conditions that include bed topography (its shape), the kind of the underlying strata (bed rock vs deformable sediments) and the presence or absence of the subglacial hydraulic system, determine the ice flow over the grounded part of the ice sheet. Decades of the radar field and airborne surveys and development of various techniques to constrain bed elevation variability have resulted in kilometer scale digital elevation models of the Greenland *[Morlighem et al., 2025]* and Antarctic Ice Sheets *[Morlighem, 2026; Pritchard et al., 2025]*. Decades of seismic surveys *[Blankenship et al., 1987],* as well as surface ice flow inferred from satellite interferometric synthetic aperture radar (InSAR) observations *[Rignot et al., 2011]* indicate the spatial heterogeneity of the underlying strata, with slow internal deformation ice flow over the bedrock and fast sliding flow of ice streams over deformable sediments. However, very little is known about subglacial hydraulics *[Ashmore and Bingham, 2014; Sergienko et al., 2026].*

The different physical systems that converge at the grounding zone all play a role in determining how ice will respond to external forcing, such as increasing ocean temperatures. Tidal forces drive large, high frequency grounding line migrations, extending up to the kilometer scale; recent ICESat-2 laser altimetry has revealed grounding-line migration of up to 15 km between low and high tide at some Antarctic sites, along with multiple distinct modes of migration (linear, asymmetric, threshold, and hysteretic; *[Freer et al., 2023]*). Due to their high frequency, tidal variations can be difficult to distinguish from long-term migrations signals, particularly without repeat observations within tidal cycles *[Nowicki & Seroussi, 2026].*

Theoretical *[Sergienko & Haseloff, 2023]* and modeling *[Joughin et al., 2019]* studies suggest spatial variability of basal conditions in the grounding zones have a strong impact on ice discharge from the grounded part of the ice sheet into the ice shelves. The combined effect of subglacial hydrology and tidal modulations can cause complex non-linear behavior on a variety of temporal scales. Additionally, subglacial freshwater discharge might add a further layer of complexity by potentially increasing ocean mixing in sub-ice shelf cavities close to the grounding zones. Relatively warm ocean water intruding into the cavity peripheral to the grounding zone delivers heat directly to grounded ice, and the resulting changes in basal geometry can either amplify or suppress further melt depending on whether the evolving ice base promotes stratification that insulates the ice or circulation that enhances turbulent heat transport *[Davis et al., 2023; Le Brocq et al., 2013]*. ***Sustained monitoring systems capable of spanning tidal, seasonal, and interannual timescales would substantially advance our ability to understand the ocean impacts on the ice sheet grounding zones.***

Bed topography across a wide range of spatial scales can strongly influence grounding zone migration and ice discharge *[Bingham et al., 2017]*. Fine-scale features such as ridges, troughs, and localized changes in bed slope may act as pinning points and influence the routing and storage of subglacial water, which impacts ice discharge and ice sheet mass balance. However, many of these features occur at spatial scales finer than those resolved by current bed products *[Bingham et al., 2017]*. Because these small-scale features can disproportionately control the pace and pattern of grounding zone retreat, their omission from coarse-resolution bed products represents a significant source of uncertainty in grounding line migration, ice discharge, and ultimately projections of ice sheet mass balance *[Ehrenfeucht & Dow, 2026]*. ***Therefore, it is essential to have high spatial resolution observations of bed topography near grounding zones to accurately represent the processes controlling grounding line migration, ice discharge, and ice sheet mass balance.***

Research Question 4: Which ice-sheet-climate feedback mechanisms are most important to monitor over the next decade?

Ice sheet mass balance is impacted by a wide range of climate forces, from large-scale temperature and precipitation variability to localized processes that are capable of triggering regional or broader ice-sheet responses *[Fyke et al., 2018]*. In Antarctica, the Southern Annual Mode and El Nino Southern Oscillation influence regional snowfall and atmospheric circulation *[Marshall et al., 2017; Raphael, 2007; van den Broeke, et al., 2004]*. Similarly, in Greenland, variability in precipitation and surface melt is influenced by the Atlantic Multidecadal Oscillation, North Atlantic Oscillation, and Greenland blocking *[Chylek et al., 2012; Fettweis et al., 2013; Hanna et al., 2012]*. These climate modes can lead to significant regional ice sheet responses on timescales ranging from sub-seasonal to decadal, but their relative contribution to longer term mass balance can be challenging to separate from other external forcings, such as anthropogenic climate change *[Andresen et al., 2012; Dutrieux et al., 2014b; Hanna et al., 2012]*. On the other hand, localized processes can also significantly impact the larger ice sheet system. Subglacial lake drainage can influence ice stream activity *[Bougamont et al., 2015]*, and surface meltwater has been linked to melt-enhanced fracturing and ice shelf collapse *[Scambos et al., 2004]*. Wildfire events can transport black carbon to the Greenland Ice Sheet and strongly impact albedo *[Tedesco et al., 2016; Thomas et al., 2017]*. In order to understand and predict changes in ice sheet mass balance, it is essential to identify and monitor the cryosphere-climate interactions, both large and small, that influence the ice-sheet response to climate variability and forcing.

Sea ice and ocean circulation exert a powerful, two-way control on the stability of both Antarctic ice shelves and Greenland's marine-terminating glacier fronts, extending well beyond simple thermal forcing. In Antarctica, landfast and pack sea ice dampen ocean swell reaching ice shelf fronts. When this buttressing is lost, increased wave action can flex, fracture, and accelerate ice-shelf breakup *[Massom et al., 2018; Christie et al., 2022]*. Greenland's fjords host an analogous process where dense packs of sea ice and calved icebergs (mélange) similarly suppress calving and icebergs capsize at tidewater glacier fronts, so that seasonal mélange breakup is closely tied to spring speedup and calving rate increases *[Amundson et al., 2010; Robel, 2017]*. Wind- and sea ice-driven changes in coastal ocean circulation modulate the delivery of warm water to ice fronts across both polar ice sheets, themselves paced by basin-scale climate variability, from gyre reconfigurations *[Zheng et al., 2022]* and wind-modulated shelf intrusions *[Guo et al., 2022]* in Antarctica, to wind-driven shelf-water intrusions and along-fjord circulation that control delivery of warm Atlantic Water to Greenland glacier termini on weekly *[Straneo et al., 2010; Jackson et al., 2014]* to several hour timescales *[Snow et al., 2023]*. In Antarctica, the winds and sea-ice conditions driving these circulation changes are themselves modulated by the Southern Annular Mode and El Niño Southern Oscillation on interannual timescales *[Holland et al., 2022]*, while in Greenland, comparable variability in ocean heat delivery and coastal freshwater transport is tied to the North Atlantic Oscillation and Atlantic Multidecadal Oscillation *[Christoffersen et al., 2011]*. Freshwater exported from upstream ice shelf melt and glacier runoff can also be carried far downstream by coastal boundary currents, modulating ocean heat delivery and melt rates at ice fronts far from their source *[Moorman et al., 2020; Schiller-Weiss et al., 2023].* Conversely, tides and polynya-driven brine rejection actively shape circulation near the ice front, generating internal waves and periodic melt cycles while intensifying the density-driven circulation that paces melting *[Hattermann et al., 2021; Stevens et al., 2026].* ***Together, these processes mean that wind, sea ice, ocean circulation, as well as teleconnections with processes in the low latitudes actively modulate the pace of glacier mass loss through ice shelf and mélange melting, which dictates when Antarctic ice shelves and Greenland's tidewater glaciers cross thresholds that commit them to accelerated retreat and dynamic mass loss.***

Recommendations

We propose that the next decade of NASA priorities augment orbiting satellite measurements with in situ observations to address how ocean warming and changes in sea ice cover, circulation patterns, and stratification will impact ice sheet mass loss. This approach must quantify the ocean heat flux towards the most vulnerable and critical parts of Greenland and Antarctica, the influence of meltwater released from the ice sheet on ocean stratification, and the ice sheet response. **Figure 1** outlines how a coordinated observing system can address this problem and **Table 1** provides a list of current and future satellites that can be used.

For ocean heat flux, this will require continued NASA/CNES SWOT ocean surface height monitoring alongside targeted in situ observations of ocean physical state (temperature, salinity, flow speed) on the continental shelf and near ice fronts to provide the sustained time series required to elucidate these processes; observations in winter months remain a critical blind spot. We recommend:

- NASA's sustained support for adapting SWOT's ocean- and hydrology-focused methodology to polar applications, coordinated development of comparable algorithms for ESA's Sentinel-3 Next Generation Ka-band altimeter, and a follow-on SWOT 2 mission to ensure continuity of this first-of-its-kind wide-swath altimetry capability.
- NASA leverages the fifth International Polar Year (2032 - 2033) to partner with NSF, international agencies and collaborations (Antarctica InSync), and Antarctic and Arctic programs already coordinating shipboard research cruises during this period. This will provide NASA-funded oceanographic moorings to track Atlantic Water and Circumpolar Deep Water transport towards Greenland and Antarctica, respectively. We recommend that these instruments be prioritized for cruises accessing the Amundsen and Bellingshausen Sea and Sabrina Coast in Antarctica, as these regions pose the most imminent threat of sea level rise in the coming decades *[Coulon et al., 2024]*. We also recommend prioritizing the Ross Sea, as it appears to be the next large ice shelf cavity to tip from cold to warm. This is supported by ongoing freshening in the Ross Sea *[Jacobs et al., 2022]* that can reduce polynya effectiveness and the identification of modified Circumpolar Deep Water at its grounding line in 2021 *[Washam et al., 2026].*
- NASA fund the development and deployment of ice-capable profiling floats and gliders explicitly tied to calibration and validation of NASA satellite products, particularly SWOT-derived dynamic ocean topography and surface currents, providing sub-surface oceanographic context beneath sea ice on the continental shelf where satellite altimetry alone cannot resolve the water column.

- NASA fund moored arrays and autonomous profilers across Greenland fjord mouths and sills as calibration and validation assets for SWOT-derived ocean heat delivery products, recording the Atlantic Water variability and topographic modulation *[Straneo & Cenedese, 2015; Schaffer et al., 2017]* needed to interpret and ground truth these remotely sensed measurements. Sustained observation at a small number of well-chosen sites, rather than one-time surveys spread thinly along the coast, is what allows seasonal and interannual variability to be separated from the trend to provide a multi-year record these satellite products require for calibration and validation. We recommend taking advantage of Pituffik Space Base as a location to base these instruments and their servicing out of, leveraging existing U.S. infrastructure rather than new field logistics. Furthermore, a northward shift in the locus of Greenland's mass loss over the coming decades *[Khan et al., 2022]* argues for building observational capacity in northern Greenland, which Pituffik Space Base can provide.
- NASA supports the effort to track ocean heat flux towards the ice sheets with a suborbital program, like Oceans Melting Greenland, that combines summertime ship-based research cruises with snowmobile, helicopter, and fixed-wing operations during non-summer months to sustain year-round coverage. We recommend a comparable year-round observing strategy for the Antarctic sites identified above. The NASA 777 fixed-wing airborne science laboratory is well suited to carry out the fixed-wing component of both efforts, providing radar and gravimetry surveys at each ice sheet.

For the ice sheet's response to ocean warming, NASA can mostly rely on the suite of current and future satellites (both NASA and non-NASA supported) capable of tracking surface elevation (EDGE, SWOT, ICESat-2, CryoSat-2, CRISTAL, Sentinel 3) and ice flow speeds (NISAR, Sentinel 1/2, Landsat). However, these satellite measurements can be improved upon and augmented through suborbital missions. We recommend:

- NASA supports the suborbital fixed-wing mission NASA 777 airborne science laboratory, operating similar to Operation IceBridge. This mission enables radar measurements of ice thickness in complex regions, such as the grounding zone, where satellite altimetry has limited sensitivity. It also enables airborne gravimetry measurements to infer seafloor bathymetry in ice-covered regions, which is essential for understanding pathways of oceanic heat towards the ice sheets.
- Increased temporal coverage for ice surface elevations as part of the EDGE mission, with a 30-day repeat cycle, and through improvements of SWOT near-daily over-ice measurements. This will ensure accurate surface elevation measurements over Greenland and Antarctica's periphery at sub-seasonal time scales that will allow for accurate monitoring of changes.
- Satellite and airborne ice elevation observations must be anchored by direct measurements of the ice-ocean interface. We recommend NASA fund instrumentation for ice-ocean boundary observation including sensors to measure physical ocean state (temperature, salinity, flow speed) and co-located phase-sensitive radar for deployment in hot-water-drilled access holes through ice shelves and their grounding zones. Drilling and field logistics can be provided in partnership with NSF and international Antarctic programs. This will deliver multiyear time series of melt rate and ocean heat flux at a single location
- Finally, we recommend that NASA begin planning for an orbiting satellite equipped with an ice-penetrating radar, a capability NASA has already proven at Mars (SHARAD) and is preparing to fly at Europa (REASON), but has never yet flown at Earth despite over five decades of airborne ice-sounding surveys of its own ice sheets. Repeat pass measurements of ice thickness offer the most viable long-term, spatially expansive means for monitoring ocean-driven melt rates in the grounding zone and other regions of complex ice geometry.

When considering the importance of basal topography in ice shelf melting and evolution, NASA will need to improve the spatial resolution of satellite altimeters and augment them with suborbital missions.

- We recommend increased along-track sampling resolution for ice surface elevations as part of the EDGE mission, with a 5 m spacing. This will allow for high enough resolution to capture the surface expressions of narrower basal features.

- Similar to the grounding zone, satellite altimetry struggles over narrow basal features with high relief, because the surface expression does not mirror the basal expression. We recommend that NASA address the problem of understanding the influence of basal topography on ice shelf melting and stability by targeting several locations for repeat-pass radar sounding with the NASA 777 mission to track their evolution over several years. This method has provided valuable information in the past about ice shelf evolution *[e.g., Khazendar et al., 2016; Schroeder et al., 2019]*.
- After identifying suitable locations for case study, we recommend NASA continue investing in under-ice autonomy: building on missions like *Icefin,* whose development NASA has already supported as a Europa- and Enceladus-analog technology through the planetary science program's PSTAR initiative. Continued investment in *Icefin* and comparable vehicles (e.g., Autosub, Ran) will resolve fine-scale ocean and ice base structure in terraces, channels, crevasses, and steep grounding zones *[Nicholls et al., 2006; Wåhlin et al., 2021; Schmidt et al., 2023; Washam et al., 2023]*. These vehicles can be deployed in partnership with 777 operations and NSF and international Antarctic and Arctic logistics programs. These autonomous vehicles must be developed further to sustain multi-week to seasonal deployments, with docking and recharging infrastructure to resolve temporal variability as well as spatial.

The grounding zone is a complex region that is inherently difficult to measure; however, interferometric satellite aperture radar is presently the best monitoring option. This can be improved. We recommend:

- NASA improves the grounding zone mapping by coordinating contemporaneous measurements of ice velocity, flexure, and surface elevation from multiple satellites (Sentinel, Landsat, ICESat-2, NISAR, EDGE, SWOT).
- NASA supports, in partnership with NSF and international agencies, a suborbital mission to ground truth these satellite measurements at several target locations, such as Petermann Glacier in Greenland and Byrd Glacier in Antarctica. This can be done with fixed-wing radar sounding, terrestrial scanning radar, phase-sensitive radar, and under-ice ocean surveys from robotic vehicles combined with long-term oceanographic moorings.

For large-scale climate feedbacks with the ice sheets, connecting gravity-based satellite measurements, such as GRACE and GRACE-C, with global meteorological information, such as INCUS and GPM, is critical. The connection between ice sheet mass balance and large-scale climate can be further elucidated through satellite surface measurements, such as temperature (ECOSTRESS, Landsat) and albedo (EMIT, Landsat).

- We recommend that NASA support targeted meteorological instrumentation deployed through partnership with NSF-supported Antarctic and Arctic weather station networks (e.g., the Antarctic Automatic Weather Station Program), explicitly to calibrate satellite and fixed-wing-derived (Snow4Flow) surface mass balance products.

In order to improve our understanding of the system and projections of the Antarctic Ice Sheet's contributions to sea level we recommend:

- A defined fraction of NASA support be dedicated to coupled ice-ocean modeling, data assimilation, and observing system simulation experiments *[e.g., Nakayama et al., 2017].*
- These models focus on improving the accuracy of ice-shelf melt representations *[Jenkins, 2011; Rosevear et al., 2022; Burgard et al., 2022; Zhao et al., 2024]*.
- These models accurately quantify the fracture mechanics driven by ice-ocean interactions in topographic features *[e.g., Bassis & Ma, 2015].*
- Improvement of continental-scale ocean models to accurately represent sub-mesoscale flows now shown to drive a substantial fraction of cavity melting *[Si et al., 2024; Poinelli et al., 2025]*. SWOT measurements will be valuable in this effort.

Figure 1

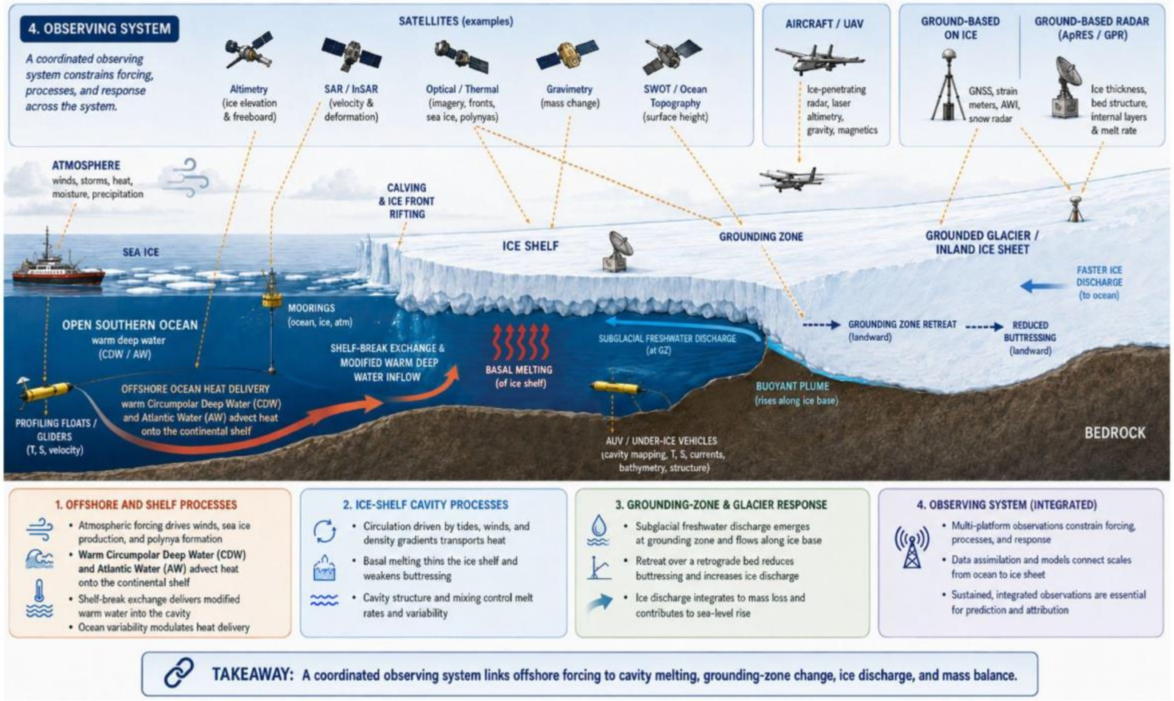

Table 1

Funding Agency	Satellite Name	Operating Years	Measurement	Application
NASA	Sentinel-6	2020 – current	Radar altimeter Microwave/ Radiometer/ 10-day repeat orbit	SSH and large-scale ocean circulation equatorward of polar regions
NASA	TROPICS	2023 – 2025	Passive microwave radiometer / 60-min repeat orbit	Atmospheric temp, humidity, precip, cyclone structure/intensity
NASA/ CNES	SWOT	2022 – current	Ka-band radar interferometer, nadir altimeter, microwave radiometer	SSH, ocean current, eddies, tides, ice-shelf and sea-ice surface elevation
NASA/ ISRO	NISAR	2025 – current	L- and S-band SAR, 12-day exact repeat	Ice velocity, surface displacement, deformation and change
NASA	ICESat-2	2018 – current	Laser altimeter, 91-day exact repeat	Ice-sheet elevation, sea-ice freeboard, leads, grounding-zone flexure and migration

NASA/ USGS	Landsat 8/9	2013 – current/ 2021 – current	VNIR, SWIR, TIR mapping, 11 bands and 16-day repeat per satellite	Ice margins, ice shelves, snow, sea ice, glaciers, velocity and feature tracking, albedo, surface temperature
NASA/ GFZ	GRACE-FO	2018 – current	Satellite to satellite laser ranging, time varying gravity	Ice sheet and ocean mass change
NASA/ JAXA	GPM	2014 – current	Dual-frequency precipitation radar and passive microwave imager	Precipitation, large-scale atmospheric forcing relative to ice-sheet mass balance
NASA	ECOSTRESS	2018 – current	Multispectral thermal-infrared radiometer	Surface temperature and emissivity
NASA	EMIT	2022 – current	VSWIR imaging spectroscopy	Surface spectral properties, surface/albedo/atmospheric characterization
ESA	Sentinel-1	2014 – current	C-band SAR and repeat pass InSAR	Ice velocity, deformation, grounding-zone change
ESA	Sentinel-2	2015 – current	12-band VNIR-SWIR imager, 5-day revisit	Ice margins, surface features, meltwater, albedo, feature-tracked ice velocity
ESA	Sentinel-3	2016 – current	SAR radar altimeter and microwave radiometer	Land-ice, sea-ice and ocean surface elevation
ESA	CryoSat-2	2010 – current	Ku-band SAR/interferometric radar altimeter coverage to 88° N/S, 369 day exact repeat	Land-ice and polar ocean elevation, sea-ice freeboard
NASA	EDGE	Planned 2030	Swath-imaging lidar	High-resolution ice-sheet surface elevation
NASA/ USGS	Landsat 10	Planned 2031	26-band VNIR, SWIR, TIR, 18-day revisit	Higher spatial and spectral resolution, ice margins, ice shelves, snow, sea ice, glaciers, velocity and feature tracking, albedo, surface temperature, emissivity

ESA	CRISTAL	Planned 2027	Ku/Ka-band radar altimeter/ + microwave radiometer	Land-ice and polar ocean elevation, sea-ice freeboard, snow depth
NASA	GRACE-C	Planned 2028	Inter-satellite laser ranging + time variable gravity	Ice-sheet and ocean mass change
NASA	INCUS	Planned 2027 or later	Precipitation/convection radar, microwave radiometer	Tropical convection and precipitation, large-scale atmospheric forcing

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