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Beneath the West Antarctic Ice Sheet: Borehole Analytics and the Revision of Instability Models

Environment * Climate Change * Glaciers

Introduction: The Planetary Stakes of the Amundsen Sea Keystone

Spanning approximately 192,000 square kilometers in the Amundsen Sea Embayment -- an area comparable to Great Britain or the state of Florida -- the Thwaites Glacier represents the single largest source of uncertainty in near-term global sea-level projections.[3] Unlike the East Antarctic Ice Sheet, which rests predominantly on continental bedrock above sea level, the West Antarctic Ice Sheet (WAIS) is a marine-based cryosphere system grounded on a submarine basin deep below sea level.[1] Thwaites alone holds enough ice to raise global sea levels by ~65 centimeters (2.1 feet), and currently accounts for roughly 4% of global sea-level rise -- a rate that has more than doubled since the 1990s.[4][7] Because Thwaites acts as a structural keystone buttressing adjacent West Antarctic ice streams, its destabilization could ultimately uncork 3.3 meters (10.8 feet) of eustatic sea-level potential.[6]

While media coverage frequently invokes the "Doomsday Glacier" moniker to suggest uniform, runaway thermal collapse, direct borehole analytics from the International Thwaites Glacier Collaboration (ITGC) -- specifically the 2019-2020 MELT campaign and seminal Nature studies by Davis et al. (2023) and Schmidt et al. (2023), alongside 2024-2026 high-resolution fracture, tidal intrusion, and ocean-forcing models -- have fundamentally revised glaciological instability models.[3][8] Deploying the pencil-shaped Icefin robotic submersible through a 600-meter hot-water borehole directly into the grounding zone revealed a striking hydrographic paradox: while broad-scale basal melting across flat ice-shelf surfaces is strongly suppressed by buoyant freshwater stratification, the glacier is simultaneously undergoing rapid, structurally targeted disintegration along steep basal terraces and crevasses.[3][9][13]

Historical Glaciology and the Physics of Retrograde Grounding Zones

Scientific concern over the marine vulnerability of West Antarctica traces back to John Mercer's 1978 warning that anthropogenic carbon dioxide warming could trigger rapid WAIS deglaciation, followed in 1981 by Terry Hughes's identification of the Amundsen Sea sector (Thwaites and Pine Island glaciers) as the continent's "weak underbelly."[1] By the late 1990s and 2000s, satellite radar interferometry led by Eric Rignot and oceanographic profiling in West Antarctic glaciology demonstrated that ice-stream acceleration was driven not by surface air temperatures, but by basal ocean forcing.[1][2]

The physics of this vulnerability is governed by the geometry of the grounding line -- the boundary where grounded continental ice lifts off the submarine geology to become a floating ice shelf -- and its interaction with deep ocean masses:

* Retrograde Bed Geometry and Marine Ice Sheet Instability (MISI): At its current grounding line, Thwaites rests on bedrock ~600 meters below sea level, but the bed slopes downward inland (a retrograde slope) into a subglacial basin exceeding 1.5 kilometers in depth.[2][11] Because ice flux across the grounding line scales nonlinearly with ice thickness, any retreat down a retrograde slope moves the grounding line into deeper water and thicker ice. This accelerates ice discharge, causing dynamic thinning and further ungrounding in a self-reinforcing positive feedback loop.[2]

* Circumpolar Deep Water (CDW) Intrusion: Shifted circumpolar westerly winds -- linked to greenhouse gas forcing and stratospheric ozone depletion -- pump dense, salty Circumpolar Deep Water (at ~1 deg C to 2 deg C) up onto the continental shelf and along submarine glacial troughs directly to the grounding cavity.[2][12] Because water possesses an immense specific heat capacity, even water 1.5 deg C above the pressure-dependent in-situ freezing point delivers substantial thermal energy to the ice base.[13]

* The Ice-Ocean Boundary Layer: Melting at the ice-water interface requires transferring thermal energy across a centimeter-scale boundary layer to overcome the latent heat of fusion. Prior to 2020, regional numerical models assumed a turbulent, well-mixed cavity where warm CDW scrubbed the ice base uniformly.[18]

Deep-Field Borehole Logistics and the Icefin Submersible

Testing boundary-layer thermodynamics in situ required the ITGC MELT team to establish a deep-field camp via ski-equipped Twin Otter and Basler aircraft hundreds of kilometers from McMurdo and Rothera stations.[3][14] Braving -40 deg C temperatures and hurricane-force blizzards, engineers operated a high-pressure Hot Water Drill fed by a 10,000-liter insulated flexible bladder nicknamed the "flubber."[7][16] Snow was melted into the flubber, heated through diesel boilers to ~80 deg C, and jetted downward to melt a 30-40 cm diameter borehole through nearly 600 meters of -20 deg C glacial ice.[9][16]

Because the borehole immediately began refreezing inward at millimeter-per-hour rates once the thermal nozzle was withdrawn, traditional wide-body Autonomous Underwater Vehicles (AUVs) could not be deployed. Instead, a team led by Dr. Britney Schmidt (Cornell University) engineered Icefin -- a 3.5-meter-long, 23-centimeter-diameter hybrid remotely operated/autonomous vehicle optimized for narrow borehole transit and holonomic hovering (Table 1).[17]

Table 1: Icefin Submersible Architecture and Oceanographic Payload

| Subsystem / Parameter | | Technical Specification | | Glaciological & Oceanographic Function |

| Hull Geometry | | Modular cylindrical frame; 3.5 m length x 23 cm diameter (130 kg) | | Clearance through refreezing 30-40 cm hot-water boreholes; ski-aircraft transportable.[17] |

| Depth & Operational Range | | 1,500 m depth rating; 3.5-5.0 km fiber-optic excursion | | Surveys deep grounding-line cavities from downstream drill sites.[17] |

| Propulsion System | | 5-thruster holonomic array (pitch, yaw, heave, strafe) | | Holds millimeter-scale station against vertical ice walls and basal crevasses.[17] |

| CTD & Geochemical Suite | | High-precision Conductivity, Temperature, Depth, DO, and fDOM | | Resolves salinity stratification and distinguishes glacial meltwater from CDW.[17] |

| Acoustic & Sonar Array | | Forward/sidescan sonar, Doppler Velocity Log (DVL), and ADCP | | Maps basal terrace topography in pitch darkness and quantifies boundary-layer shear.[17] |

The 2023 Hydrographic Paradox: Stratified Suppression vs. Crevasse Convection

Published concurrently in Nature in February 2023, the oceanography and imaging datasets acquired by Icefin and sub-ice moorings overturned uniform melt parameterizations.[3]

First, Dr. Peter Davis (British Antarctic Survey) and colleagues demonstrated that although the water column beneath the eastern Thwaites grounding zone was warm (1.5 deg C-2.0 deg C above freezing), basal melting across flat horizontal ice-shelf bases averaged only 2 to 5 meters per year -- nearly an order of magnitude lower than standard linear-friction models predicted.[3][9] As the ice base melted, the resulting cold, low-salinity freshwater formed a buoyant, density-stratified cap clinging to the flat underside of the glacier.[18] With low ambient current shear, this halocline suppressed vertical turbulent eddies, restricting heat transport to slow molecular and diffusive convection.[10][18]

Second, Dr. Britney Schmidt and colleagues revealed why Thwaites is nonetheless retreating and fracturing rapidly.[3][13] Navigating Icefin up to the grounding line, sonar and optical cameras mapped a rugged sub-glacial landscape of terraced "staircases" (flat horizontal treads separated by steep vertical risers) and deep basal crevasses:[3]

* Slope-Dependent Buoyancy Plumes: While buoyant meltwater stagnates beneath flat horizontal treads (insulating the ice), meltwater released along vertical terrace risers and steep crevasse walls cannot remain stationary. Gravity drives the buoyant freshwater upward along the sloped ice face, generating turbulent plumes that entrain warm, salty CDW from below and scrub away the insulating boundary layer.[13]

* Targeted Structural Disintegration: Inside basal crevasses and along vertical terrace walls, melt rates surged to over 30 meters per year -- roughly ten times faster than on adjacent flat surfaces (Table 2).[13] By funneling heat and turbulent mixing directly into basal fractures, the ocean widens crevasses from within, eroding the structural buttressing of the ice shelf even while average vertical thinning remains modest.[3][11]

Table 2: Basal Melt Regimes and Sea-Level Rise Potential in the Amundsen Sea Sector

| Glaciological Feature / System | | Dominant Physical Regime | | Observed Melt Rate / Sea-Level Equivalent | | Mechanistic Control & Modeling Implication |

| Flat Horizontal Ice Base | | Diffusive convection (stratified) | | 2 - 5 m/year basal melt | | Buoyant freshwater layer suppresses turbulent heat flux.[9][18] |

| Sloped Basal Terraces | | Mixed shear-buoyancy regime | | Intermediate (scales with sin) | | Steepening basal roughness amplifies local heat transfer.[13] |

| Vertical Crevasse Sidewalls | | Buoyancy-driven turbulent plume | | > 30 m/year lateral melt | | Upwelling meltwater entrains warm CDW, rapidly widening fractures.[3][13] |

| Thwaites Glacier (Direct Volume) | | MISI + crevasse unbuttressing | | ~65 cm (2.1 ft) global eustatic rise | | Currently contributes ~4% of global sea level rise (~4.5 mm/yr total).[4][7] |

| West Antarctic Ice Sheet (Total) | | Keystone buttressing loss | | ~3.3 m (10.8 ft) multi-century potential | | Destabilization of neighboring marine basins following Thwaites retreat.[6] |

Re-Evaluating Instability Models (2024-2026)

The discovery of heterogeneous, slope-dependent melting has coincided with major revisions to macro-scale ice-sheet modeling across 2024-2026 as the ITGC concluded its core seven-year observational phase.[6] First, high-resolution viscoelastic fracture simulations led by Dartmouth College researchers re-evaluated Marine Ice Cliff Instability (MICI) -- the hypothesis that complete ice-shelf loss would expose >100-meter subaerial ice cliffs to runaway mechanical collapse.[5][8] The 2024 Dartmouth study demonstrated that rapid viscous relaxation (plastic thinning of the ice front) and back-pressure from calved iceberg m lange stabilize subaerial cliffs before runaway brittle failure can occur, indicating that extreme MICI projections (>2 meters of sea-level rise by 2100) are unlikely and that retreat will instead be governed by MISI and crevasse-driven basal melt.[5][8][19] Second, radar interferometry revealed kilometer-scale tidally driven warm seawater intrusions penetrating miles beneath grounded ice,[21] subglacial lake drainage events were shown to accelerate local basal melting and grounding-line retreat,[15] and updated Solid Earth models of Glacial Isostatic Adjustment (GIA) indicate that current Thwaites retreat outpaces isostatic mantle uplift.[20] Third, a 2026 British Antarctic Survey ensemble study in Geophysical Research Letters found that even when ocean-driven basal melting is hypothetically switched off in 150-year simulations, Thwaites continues losing mass -- unlike neighboring Pine Island Glacier -- reflecting committed dynamic inertia from past perturbations.[22]

Conclusion: A New Era of Sub-Glacial Forensics

The ITGC borehole campaign and Icefin deployments have replaced monolithic "Doomsday" speculation with high-resolution physical forensics.[3] Thwaites Glacier is neither uniformly shielded by its stratified freshwater boundary layer nor succumbing to simple 1D thermal erosion; instead, buoyancy-driven convection within basal crevasses and staircase terraces, compounded by tidal seawater intrusion and committed dynamic thinning, is dismantling the glacier's structural joints.[13][18][21][22] Incorporating slope-dependent basal melt parameterizations and grounding-zone hydrology into next-generation Earth system models remains essential for constraining the 21st- and 22nd-century trajectory of global sea-level rise.[10][20]

Updates... (Nov 21, 2026): Updated instability modeling coverage through 2026 to

reflect the conclusion of the core ITGC field phase, tidal seawater intrusion beneath grounded ice (Rignot et al., May 20, 2024), subglacial lake discharge forcing (Gourmelen et al., Mar 6, 2025), and 2026 British Antarctic Survey simulations demonstrating continued Thwaites mass loss without ocean melting (Williams et al., Jul 25, 2026); upgraded undated secondary summaries to verified peer-reviewed CrossRef DOIs and added exact publication dates across all references.

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