Workshop

The Future of Geodetic-Geophysical Observational Networks in Antarctica

Colorado State University
Fort Collins, Colorado, USA
September 29 – October 1, 2022

SCAR INSTANT Subcommittee
Probing the Solid Earth
and its Interactions

CONTENT

Check-in
will be open at the Icebreaker Reception on September 29 and on September 30 from 7:30 a.m. (until about noon).

Icebreaker Reception
September 29, 2022, from ~5:30 p.m.
Lobby, Warner College of Natural Resources, Smith Natural Resources Building.

Workshop Venue
Sessions will start on September 30, 8:30 a.m.
Long's Peak (room 302), Lory Student Center.
Poster exhibition: room 308-10, Lory Student Center.

Breakfast and Lunch
will be provided at workshop venue on September 30 and October 1.

Workshop Dinner
will be announced during the workshop.

Acknowledgement
The workshop is kindly supported by the National Science Foundation, Office of Polar Program (NSF-OPP), and the Scientific Committee on Antarctic Research (SCAR).
Further, the contribution by Nanometrics Inc. is gratefully acknowledged.

Date	time am	time pm	Topic	Presenter
			29 September 2022	
THU		**06:00**	**Icebreaker Reception**	
			30 September 2022	
FRIDAY, 30 September 2022	**08:30 - 09:00**		**Opening Session**	
	08:30		Workshop opening, local information	Mirko Scheinert, Weisen Shen & Rick Aster
			Introduction, workshop goals	Mirko Scheinert & Weisen Shen
	08:40		Statement/remarks by representatives of funding agencies	
	09:00 - 10:00		**Session I: Observational networks and processing efforts**	
	09:00		U.S. ANET-POLENET: Discoveries from over a decade of continuous GPS and Seismic Measurements	Terry Wilson
	09:15		Overview of the UKANET Antarctic GNSS network	Pippa Whitehouse
	09:30		GIANT-REGAIN: A comprehensive analysis of geodetic GNSS recordings in Antarctica for geodetic and geodynamic applications	Eric Buchta
	09:45		Panel discussion I	
	10:00 - 10:30		**Coffee Break**	
	10:30 - 12:15		**Session II: GNSS - application of continuous and scattered time series**	
	10:30		GPS-observed elastic deformation due to surface mass balance variability in the Southern Antarctic Peninsula	Peter Clarke / Achraf Koulali
	10:45		Common mode error, noise, and late Holocene readvance	Matt King
	11:00		The Antarctic GNSS contribution to the International Terrestrial Reference Frame	Demián Gómez
	11:15		Future crustal deformation in Antarctica – insights from Greenland	Mike Bevis
	11:30		Partnerships with the Space Weather Research Community	Michael Hartinger
	11:45		Panel discussion II	
		12:15 - 01:00	**Lunch Break**	

Date	time am	time pm	Topic	Presenter
			30 September 2022	
FRIDAY, 30 September 2022		**01:00 - 02:30**	**Session III: Seismology - benefits of short-term vs. long-term records**	
		01:00	A Global Veneer of Subducted Materials along the Earth's Core-Mantle Boundary	Samantha Hansen
		01:15	Seasonal and long-term variations in seismic records in polar regions	Vera Schulte-Pelkum
		01:30	Upper mantle viscosity structure and lithospheric thickness of Antarctica estimated from seismic structure	Doug Wiens
		01:45	Seismic signals from the Eastern Shear Margin of Thwaites Glacier	Marianne Karplus
		02:00	Panel discussion III	
		02:30 - 03:00	**Rapid poster introduction**	
		03:00 - 4:15	**Coffee Break and Poster Session**	
		04:15 - 06:00	**Session IV: Further data synthesis**	
		04:15	Chemical composition of the Antarctica crust derived from crustal Vp/Vs and its implication on the thermal structure	Siyuan Sui
		04:30	Data products for quick glacier seismology array analysis	Eileen Martin
		04:45	Geodetic Observations and Scotia Arc Tectonics	Ian Dalziel
		05:00	Post-seismic deformation in the Northern Antarctic Peninsula following the 2003 and 2013 Scotia Sea earthquakes	Grace Nield
		05:15	The relevance of GNSS in inverse GIA estimation from complementary geodetic observations	Ingo Sasgen / Mirko Scheinert
		05:30	Panel Discussion IV	
		07:00	**Workshop Dinner**	

Date	time am	time pm	Topic	Presenter
			01 October 2022	
SATURDAY, 01 October 2022	**08:30 - 10:00**		**Session V: Broad implications - GIA and beyond**	
	08:30		GIA, marine ice-sheet instability and sea-level change	Surendra Adhikari
	08:45		Resolving GIA and the impact of Earth structure on ice sheet evolution in Antarctica and global sea levels	Natalya Gomez / Maryam Yousefi
	09:00		Evidence of large anelastic deformation in the Amundsen Sea embayment	Lambert Caron
	09:15		GIA Imaging of solid Earth Structure - Future Applications for Antarctic Dataset	Andrew Lloyd
	09:30		Panel Discussion V	
	10:00 - 10:30		**Coffee Break**	
	10:30 - 12:00		**Session VI: Infrastructure, Logistics and Coordination**	
	10:30		SAGE and GAGE Facility Polar PI Project and Network Support: Lessons Learned, Status, Opportunities, and Challenges	Glen Mattioli
	10:45		The History and Future of Global Seismographic Network stations in Antarctica and their use in Antarctic Research	Robert Anthony
	11:00		Optimizing Antarctic field deployments for conventional and data-driven solid-Earth research	Anya Reading
	11:15		Models of international coordination for large science programs	Terry Wilson
	11:30		Panel Discussion VI	
		12:00 - 12:15	**Break-out groups: Intro and organisation**	
		12:15 - 01:15	**Break-out group discussion + lunch break**	
		01:15 - 02:00	**Summary and Closing**	
		01:15	Summaries of BOG	
		01:35	Wrap-up; White paper: Outline and time schedule	
		01:55	Workshop Closing	

Session I: Observational Networks and Processing Efforts

U.S. ANET-POLENET: Discoveries from over a decade of continuous GPS and Seismic Measurements

Terry Wilson[1] & ANET-POLENET Project Team
[1]Ohio State University / Byrd Polar and Climate Research Center, Columbus, Ohio, USA

The ANET-POLENET integrated network of autonomous GPS and broadband seismic instruments, spanning much of Antarctica, was initially deployed beginning in 2007-08 during International Polar Year activities. Published science topics that have been addressed using ANET-POLENET data include sea level sensing, subglacial lake drainage, active subglacial magmatism, co-seismic ionosphere disturbances detected by GPS TEC, teleseismically triggered icequakes, the nature of Antarctic seismic sources and seismic noise, continental-scale geothermal heat flux, space weather, and aspects of the core/mantle boundary. Project science has been focused on interdisciplinary research to improve our understanding of complex Glacial Isostatic Adjustment (GIA) processes in Antarctica by integrating robust new in situ observational constraints with innovative modeling. ANET has documented extremely rapid GIA uplift rates in West Antarctic regions with low mantle viscosities where seismic inversions identify thin lithosphere and slow upper mantle seismic velocities. An increasingly sharp picture of Antarctic 3-D crust and mantle variability is being revealed by continental-scale data acquisition by ANET and partner projects. Improved solid Earth imaging and kinematic constraints on solid Earth deformation are driving development of a new generation of 3-D GIA models and coupled climate - ice sheet - solid Earth models. Data-constrained coupled modeling studies show that rapid GIA response allows for cryosphere-solid earth interactions that can alter ice sheet behavior on decadal and centennial timescales, with significant implications for the contributions of the West Antarctic Ice Sheet to sea level in the future.

Overview of the UKANET Antarctic GNSS network

Pippa Whitehouse
Department of Geography, Durham University, Durham, UK

In this presentation I will provide a summary of the NERC-funded 'UKANET' GNSS network, which encompasses ~30 continuously operating instruments installed at bedrock sites spread across an area spanning the tip of the Antarctic Peninsula to the westernmost margin of East Antarctica. I will detail the current status of the network, the work to date that has enabled us to reach this status, and the community of researchers who make use of the data. Finally, I will summarise current plans for the future of the network and the challenges associated with maintaining it.

GIANT-REGAIN: A comprehensive analysis of geodetic GNSS recordings in Antarctica for geodetic and geodynamic applications

Eric Buchta[1], Mirko Scheinert[1], Matt King[2], Terry Wilson[3], Eric Kendrick[3], Achraf Koulali[4], Peter Clarke[4], Christoph Knöfel[1]
[1]Technische Universität Dresden, Dresden, Germany
[2]School of Geography, Planning, and Spatial Sciences, University of Tasmania, Hobart, Australia
[3]School of Earth Sciences, Ohio State University, Columbus (OH), USA
[4]Geospatial Engineering, Newcastle University, Newcastle, UK

Most of the studies that already utilized geodetic GNSS to derive bedrock motion in Antarctica were limited to specific regions and time periods. Within the SCAR-endorsed project GIANT-REGAIN we aim at realizing a most comprehensive reprocessing of all Antarctic GNSS data available by now. For this, we succeeded to acquire episodic and permanent GNSS data recorded between 1995 and 2021 at more than 280 bedrock sites. We will report on the current status of the project, where one important issue concerns the treatment of metadata that are indispensable for a correct assignment of the hardware setup. In the processing, precise point positioning (PPP) and differential GNSS are applied using different scientific software packages (GIPSY, GAMIT, Bernese) which also allows to come up with a thorough assessment of uncertainty and software noise. Consistent time series of point coordinates for each station will be inferred as our major product.
We will discuss preliminary results highlighting the variable response of the solid Earth to changing ice loads in Antarctica. Since the GNSS observations comprise already two decades it will be possible to investigate the various temporal and spatial scales in the deformation pattern due to present-day and past ice-mass changes. Thus, the interplay and differentiation between elastic deformation and glacial isostatic adjustment can be discussed from new points of view. To further improve our understanding of the underlying processes, not least by feeding the GNSS results as constraints into modelling, it will be necessary to carefully discuss how to continue and to potentially even densify the GNSS recordings in Antarctica.

Session II: GNSS – Application of Continuous and Scattered Time Series

GPS-observed elastic deformation due to surface mass balance variability in the Southern Antarctic Peninsula

Achraf Koulali[1], Pippa L. Whitehouse[2], Peter J. Clarke[1], Michiel R. van den Broeke[3], Grace A. Nield[2], Matt A. King[4], Michael J. Bentley[2], Bert Wouters[3,5], Terry Wilson[6]
[1]Geospatial Engineering, Newcastle University, Newcastle, UK
[2]Department of Geography, Durham University, Durham, UK
[3]Institute for Marine and Atmospheric Research, Utrecht University, Utrecht, The Netherlands
[4]School of Geography, Planning, and Spatial Sciences, University of Tasmania, Hobart, Australia
[5]Department of Geoscience and Remote Sensing, Delft University of Technology, Delft, The Netherlands
[6]School of Earth Sciences, Ohio State University, Columbus (OH), USA

In Antarctica, Global Positioning System (GPS) vertical time series exhibit non-linear signals over a wide range of temporal scales. To explain these non-linearities, a number of hypotheses have been proposed, among them the short-term rapid solid Earth response to contemporaneous ice mass change. Here we use GPS vertical time series to reveal the solid Earth response to variations in surface mass balance (SMB) in the Southern Antarctic Peninsula (SAP). At four locations in the SAP we show that interannual variations of SMB anomalies cause measurable elastic deformation. We use regional climate model SMB products to calculate the induced displacement assuming a perfectly elastic Earth. Our results show a reduction of the misfit when fitting a linear trend to GPS time series corrected for the elastic response to SMB variations. Our results imply that, for a better understanding of the glacial isostatic adjustment signal in Antarctica, SMB variability must be considered.

Common mode error, noise, and late Holocene readvance

Matt King
School of Geography, Planning, and Spatial Sciences, University of Tasmania, Hobart, Australia

GPS time series from Antarctic sites separated by hundreds of km show coherent, time-varying signals. These are due to a combination of GPS systematic error and contemporaneous ice and snow surface mass changes. Such signal impacts on attempts to derive velocities or time series due to GIA. We show evidence for particularly large systematic and surface mass balance signals in GPS Precise Point Positioning solutions in a critical sector of East Antarctica where the Totten and Denman glaciers lie. We attempt to remove the systematic errors through data differencing, and remove the effects of surface loading changes through numerical modelling. A large surface mass balance deficit in this region produces biases as large as +1mm/yr over 2010-2020. Using a relatively new network of GPS sites deployed in this region, we show that signal that otherwise indicated strong site uplift over 2014-2018 becomes negative following these corrections, in agreement with evidence of subsidence at Davis and Bunger Hills sites. Sites nearer to Totten Glacier show sustained uplift even after these corrections, indicating Holocene ice retreat. We infer the subsidence signal, where it exists, as being due to ice sheet readvance during the Late Holocene and presenting a target for sub-glacial sampling to test this hypothesis.

Antarctic GNSS contribution to the International Terrestrial Reference Frame

Demián D. Gómez, Terry Wilson, and Michael G. Bevis
Division of Geodetic Science, School of Earth Sciences, Ohio State University, Columbus, USA

Despite the efforts from the global geodetic community to densify the GNSS coverage in the southern hemisphere, the global distribution of GNSS stations shows a heavy bias towards the northern hemisphere which is known to negatively affect the realization of the International Terrestrial Reference System (ITRS). This bias is, in part, due to the smaller landmass south from the Equator, although other issues, such as limited economical resources and the overall lower geodetic capacity of countries in the global south, also affect the station distribution, favoring a denser network in the northern hemisphere. This presentation highlights the importance of Antarctic GNSS networks in terms of the densification of the ITRS on the only continental landmass south of latitude 56° S, and also as an instrument for the achievement of the goals established by the Subcommittee on Geodesy of the United Nations Committee of Experts on Global Geospatial Information Management.

Future crustal deformation in Antarctica – insights from Greenland

Michael Bevis
School of Earth Sciences, Ohio State University, Columbus, OH, USA

The couplings between solid earth deformation and ice mass changes in response to climate change are now well established. Future crustal deformation networks should be designed with future polar Earth system interactions in mind, since the object of our studies is a 'moving target'. A comparison between Antarctica and Greenland provides useful insights. We should not design networks that are poorly suited to observe unanticipated developments.

Partnerships with the Space Weather Research Community

Michael Hartinger
Space Science Institute, Boulder (CO), USA

Many space weather phenomena represent natural hazards that can affect power grids, satellites, and other infrastructure. The space weather research field is rapidly growing, with significantly more measurements needed to improve forecasts/nowcasts and remote sensing capabilities. There are large data gaps in Antarctica that represent a major obstacle in understanding and predicting space weather. These gaps can be filled via mutually beneficial partnerships between a wide range of geophysics research communities (e.g., cryosphere, seismology, magnetotellurics) and space weather researchers who often use the same instruments (e.g., GNSS, magnetometer). For example, GNSS measurements collected by the cryosphere research community in Antarctica are already being used to examine electron dynamics in the ionized portion of the Earth's atmosphere. I'll discuss several examples of current and possible future partnerships that can be used to (1) maximize the return from logistical resources and data collections and (2) enable larger scale projects that benefit both the space weather and geophysics research communities.

Session III: Seismology – Benefits of Short-term vs. Long-term Records

A Global Veneer of Subducted Materials along the Earth's Core-Mantle Boundary

Samantha E. Hansen[1], Edward J. Garnero[2], Mingming Li[2], Sang-Heon Shim[2], Sebastian Rost[3]
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The absolute change in physical properties from the mantle to the core is greater than that between solid rock and air. As such, Earth's core-mantle boundary (CMB) is host to a variety of phenomena, including thin (5-50 km), enigmatic regions with strongly reduced seismic wave velocities (10-50%), dubbed ultra-low velocity zones (ULVZs). A wide range of ULVZ characteristics (thickness, composition) has been previously inferred, leading to many questions regarding their origin, and associated uncertainties are exacerbated by limited sampling since less than 20% of the CMB has been surveyed for ULVZ presence. ULVZ origins are important because they provide constraints on the thermo-chemical conditions along the CMB and the dynamics of deep Earth processes. Our study investigates the CMB beneath the previously unsampled southernmost hemisphere. This region is unique because it is far from the two large low velocity provinces in the Earth's lower mantle as well as from areas of recent or current subduction. Using a new analysis approach for seismic core reflections based on historical earthquake data patterns, we show widespread and geographically variable ULVZ structure across the CMB south of 35°S latitude. Mantle convection simulations demonstrate how heterogeneous accumulations of previously subducted materials could form on the CMB and explain our seismic observations. Billions of years of subduction, with a diversity in subduction histories across the planet, can thus give rise to a ubiquitous ULVZ with highly variable properties and can explain the range of previously reported ULVZ characteristics.

Seasonal and long-term variations in seismic records in polar regions

Vera Schulte-Pelkum[1], Hanxiao Wu[2], and Weisen Shen[2]
[1]University of Colorado, Boulder (CO), USA
[2]Stony Brook University, Stony Brook (NY), USA

We present time-dependent variations in two types of measurements with sensitivity to near-surface structure. One is the horizontal to vertical particle motion ration (H/V ratio) in Rayleigh surface waves; the other, H/V amplitude and delay times of direct and near-surface converted arrivals in P-wave receiver functions. We find pronounced seasonal variations in both at stations located on Antarctic ice with an up to ~20% apparent near-surface velocity shift, with a H/V ratio low in the winter in most cases. Moreover, a similar seasonal signal is found at Greenland ice cap stations, with a phase shift of 6 months relative to Antarctica. Liquid water is not a straightforward explanation for the observations since melt is present at times in Greenland but conditions at most Antarctic ice sites should be too cold for melting. Initial investigation suggests the signal is not dominated by noise variations. Seasonal variations are also seen at lower latitude seismic stations and have previously been attributed to hydrology. We compare records from colocated

surface and borehole sensors at polar and lower latitude sites to investigate whether the observed changes are due to variations in shallow velocity structure, interaction of sensors with atmospheric conditions, wind-driven and other tilt noise, or other effects. Disentangling these influences opens the possibility of monitoring of temporal changes in velocity in the top few km to meters, including seasonal and long-term changes. Such an approach requires long-term monitoring time series.

Upper mantle viscosity structure and lithospheric thickness of Antarctica estimated from seismic structure

Douglas A. Wiens
Department of Earth and Planetary Sciences, Washington University, St. Louis, MO, USA

The structure of the solid earth has a strong influence on the dynamics of ice sheets, with crucial implications for climate change and sea-level rise. We use a recent model of the shear wave structure of the Antarctic Plate upper mantle computed using adjoint tomography (*Lloyd et al,* 2020) to estimate upper mantle viscosity and lithospheric thickness, which control glacial isostatic adjustment. The mantle viscosity structure is estimated from the seismic structure assuming laboratory-derived relationships between seismic velocity, temperature, and rheology. Choice of parameters for making the conversion is guided by recent estimates of mantle viscosity from geodetic measurements. We also compare several different methods of estimating lithospheric thickness. The mantle viscosity estimates indicate several orders of magnitude variation, with low viscosity ($< 10^{19}$ Pa s) beneath the Amundsen Sea Embayment (ASE) and the Antarctic Peninsula (AP), suggesting a characteristic GIA time scale on the order of a hundred years. Somewhat higher viscosities are possible if the geodetic measurements are interpreted in terms of frequency-dependent viscosity. Lithospheric thickness is also highly variable, ranging from around 60 km in parts of West Antarctica to greater than 200 km beneath East Antarctica. Thin lithosphere and low viscosity near the coastline between ASE and the AP likely results from the thermal effects of a slab window that traversed the región as the Phoenix-Antarctic plate boundary migrated northward. Low viscosity regions beneath the ASE and Marie Byrd Land coast connect to an offshore anomaly at depths of ~ 250 km, suggesting the additional involvement of larger-scale mantle geodynamic processes. Recent ice sheet models suggest that such low mantle viscosities will cause rapid uplift during ice sheet retreat, possibly stabilizing the ice sheet by preventing marine transgressions and thus reducing the marine ice sheet instability.

Seismic signals from the Eastern Shear Margin of Thwaites Glacier

Marianne S. Karplus[1], Lucia F. Gonzalez[1], Jake Walter[2], Emma C. Smith[3], Adam D. Booth[3], Nori Nakata[4], Stephen A. Veitch[1], Ronan Agnew[3], Tun Jan Young[5], Daniel May[6], Paul Summers[6], Galen Kaip[1], Poul Christoffersen[5], Slawek Tulaczyk[7]

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Understanding the stability of Thwaites Glacier, part of the West Antarctic Ice Sheet (WAIS), is a critical science challenge of global relevance. The future evolution of ice flow in Thwaites Drainage Basin is likely influenced by dynamics at its shear margins. To investigate the processes influencing Thwaites' shear margins, the Thwaites Interdisciplinary Margin Evolution (TIME) project set up two geophysical ice observatories at the Thwaites' Eastern Shear Margin. The ice observatories are designed to produce new and comprehensive constraints on englacial properties, including ice deformation, ice fabric, ice viscosity, ice temperature, ice water content, and basal conditions. From January 2020 to January 2022, the two observatories included passive seismic recording on fourteen broadband seismic stations. The network includes two hexagonal arrays, each with 7 broadband seismometers spaced at ~5-km (6 stations in a hexagon plus one in the middle). In this presentation, we provide an overview of these new seismic data at Thwaites' Eastern Shear Margin, including a summary of various seismic analyses that are ongoing. We detect and locate icequakes with these networks, using classical short-term-average/ long-term-average techniques for local phase arrival detection as well as machine learning approaches. We further investigate possible causes of the observed seismicity, such as crevassing, calving, basal stick-slip events, or other events. We also look at other seismic signals recorded by the network and the implications of those observations for understanding processes and evolution at Thwaites' shear margins. Finally, we discuss the role and contributions of the passive seismic data in planning for future controlled-source seismic surveys at Thwaites Eastern Shear Margin.

Session IV: Further Data Synthesis

Chemical composition of the Antarctic crust derived from crustal V_p/V_s and its implication on the thermal structure

Siyuan Sui, Weisen Shen and Hanxiao Wu
Stony Brook University, Stony Brook (NY), USA

The crustal architectures of Antarctica, including its thickness, chemical composition and thermal structure have been an enigma for a long time since 99% of the continent is covered by thick ice sheet. Additionally, the dynamics of ice sheet itself remains poorly constrained as one of the key parameters, geothermal heat flux (GHF) has been measured only in limited locations. One alternative approach to derive GHF from the whole crust thermal structure model but it suffers from unreasonable values and large uncertainties, mainly due to the simple assumption in crustal heat generation (Losing et al., 2020).

Silica, one of the most abundant oxides, is closely associated with the heat generating elements and can be quantified from the seismic properties (Sui et al., 2022). In this presentation, we introduce two methods (receiver function analysis and Monte Carlo velocity inversion) on constraining the ratios between P velocities and shear velocities (Vp/Vs) of the crystalline crust. Combining the resulting Vp/Vs with the published Vs models (Shen et al., 2018; Lloyd et al., 2019), we construct local silica content models with meaningful error estimations.

Based on the 1-D silica content model, we calculate the 1-D heat generation profiles based on the "silica-heat generation" relationship from rock measurements (Hacker et al., 2015; Hasterok & Webb, 2017). The 1-D heat generation profiles with uncertainties are utilized as one input for a Monte-Carlo thermal structure inversion, together with other inputs including Moho temperature derived from uppermost mantle Vs, Curie depth from geomagnetic data, etc. The output thermal model from the inversion will be used to refine the quantification of the silica contents. After several iterations, reasonable models for both compositional and thermal structure of Antarctica can be constructed.

Data products for quick glacier seismology array analysis

Eileen Martin
Colorada School of Mines, Golden (CO), USA

There have been a growing number of fiber optic distributed acoustic sensing (DAS) studies of glacier seismology, but in polar regions, we typically lack sufficient communications infrastructure to continuously send DAS data back to the computing systems where we wish to analyze them. To this effect, our team has released open source code for calculating data products in real time using the on-board computer in a DAS interrogator, and has created new data products that are particularly meaningful for glacier seismology event detection and classification. By increasing our computing in the field, we can greatly reduce transmitted data volumes, and enable larger teams to learn from data faster.

Geodetic Observations and Scotia Arc Tectonics

Ian Dalziel[1], Robert Smalley[2] and Norman Teferle[3]
[1]The University of Texas at Austin
[2]University of Memphis
[3]L'Université du Luxembourg

Antarctica's tectonic relationship with the other southern continents and India is defined by Mesozoic-Cenozoic seafloor spreading in the Southern and Indian ocean basins. The Scotia arc reflects a more complex relationship with South America. Geodetic observations have helped us understand that critical area for the circum-polar environment. The left-lateral transform motions of the North and South Scotia ridges have been determined, and rapid eastward motion of the South Sandwich arc quantified. The motion of the South Shetland Islands northwestward from the Antarctic Peninsula has been measured and is compatible with southwesterly propagation of the Bransfield rift. The Elephant Island group appears to move with the Scotia plate. South Georgia microcontinent (SGM) is an allochthonous block displaced from the Andes. A GNSS network was established in 2013-2014 by the University of Texas at Austin, the University of Memphis and the University of Luxembourg. The principal goals were to determine the motion of the microcontinent with respect to the adjoining South American and Scotia plates, to understand its anomalously high relief, and to evaluate sea-level change by tying in to a tide gauge. Preliminary results, based on 4 years of continuous data, indicate the SGM appears to be moving as an independent microplate. While some glacio-isostatic uplift is likely, the anomalously high relief of the island relative to the hinterland of the southernmost Andes (~3000m vs. ~1000m) may principally result from the impingement of the Northeast Georgia Rise on the microcontinent within a restraining bend. The instruments ceased recording a few years ago and the network requires maintenance, plus hopefully enhancement to better record ongoing strain.

Post-seismic deformation in the Northern Antarctic Peninsula following the 2003 and 2013 Scotia Sea earthquakes

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[5]Australian Bureau of Meteorology, Melbourne, Australia

Large earthquakes in the vicinity of Antarctica have the potential to cause post-seismic viscoelastic deformation on the continent, affecting measurements of displacement that are used to constrain models of glacial isostatic adjustment (GIA). In November 2013 a magnitude 7.7 strike-slip earthquake occurred in the Scotia Sea around 650 km from the northern tip of the Antarctic Peninsula. GPS time series from the northern Peninsula show a change in rate after this event indicating a far-field post-seismic viscoelastic deformation signal is present. We use a global spherical finite element model with a suite of 1D Maxwell and Burgers earth models to investigate the extent of post-seismic deformation following this earthquake. Model output is compared with

GPS time series to place constraints on the earth structure in this region. There is a slight preference for a thin lithosphere combined with a Burgers rheology in the asthenosphere with a steady-state viscosity of 4×10^{18} Pa s and transient viscosity one order of magnitude lower. Initial tests using a 3D earth structure show lateral variations in viscosity do not improve the fit. Using the best fitting earth structure, we run a forward model of the 2003 magnitude 7.6 strike-slip earthquake and combine the predictions for both earthquakes. We show that post-seismic deformation is wide-spread across the Northern Peninsula with rates up to 1.5 mm/yr in the east direction for the period 2015-2020 and that this signal persists for decades after the events.

The relevance of GNSS in inverse GIA estimation from complementary geodetic observations

Ingo Sasgen[1], <u>Mirko Scheinert</u>[2], Matthias Willen[2], Martin Horwath[2]
[1]Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany
[2]Technische Universität Dresden, Chair of Geodetic Earth System Research, Dresden, Germany

It is important to improve the reliability of inferred Antarctic ice mass balance estimates to better predict Antarctica's contribution to global sea-level change. GIA is still a large source of uncertainty in the ice-mass change estimated from GRACE and GRACE-FO. We will review the different inverse methods to estimate GIA (together with ice-mass balance) using geodetic datasets, especially satellite gravimetry and altimetry. GNSS measurements of bedrock motion are indispensable to validate, calibrate and constrain inverse GIA estimates. We will discuss different approaches using GNSS in the inversion process and the prospects for further applications.

Session V: Broad Implications – GIA and beyond

GIA, marine ice-sheet instability and sea-level change

Surendra Adhikari
Jet Propulsion Laboratory, California Institute of Technology, Pasadena (CA), USA

Accurate projection of future sea-level change is hampered mainly by our inability to understand and model the dynamics of marine ice sheets. The so-called marine ice sheet instability (MISI) and marine ice cliff instability (MICI) are two of the most critical/uncertain processes to constrain in a dynamical ice sheet model. MISI, in particular, turns out to be sensitive to the bedrock geometry and geoid field that evolve as ice mass changes, implying a need for a coupled system of the ice sheet, solid Earth, and sea level model. Coupled model simulations over a few centuries suggest that the role of solid-Earth processes is, by and large, to slow down the progression of MISI by several decades. This negative feedback will likely strengthen in regions with a relatively weak mantle, such as Amundsen Sea Sector. It is, therefore, critical to accurately measure and characterize the crustal structure/properties and constrain the solid-Earth rheology. In this talk, I will try and get across some of these points, highlighting the need for continuous GNSS monitoring of the bedrock motion and seismic imaging of the crustal structure and densifying such measurement systems in the future.

Resolving GIA and the impact of Earth structure on ice sheet evolution in Antarctica and global sea levels

Natalya Gomez[1] and Maryam Yousefi[1,2]
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Simulating glacial isostatic adjustment (GIA) in Antarctica is challenging due to the complex structure of the solid Earth beneath regions of active ice loss, leading to a faster (annual to decadal) and more localized viscous deformation in parts of West Antarctica. In this presentation, we summarize a series of recent studies assessing what is needed to resolve viscoelastic Earth deformation in the vicinity of recent and future ice loss in Antarctica, the influence of this deformation on ice dynamics, and the consequences for Antarctica's contribution to future global sea-level changes.
In Wan et al. (2022), we perform a comprehensive analysis of the importance of grid resolution for predictions of GIA by adopting a 3-D GIA model with a range of ice loss scenarios and Earth structure models developed based on recent seismic tomography and geodetic data. The results of this sensitivity analysis reaching sub-kilometer grid resolution indicate that the error due to adopting a coarser grid is small compared to the effect of neglecting viscous effects and the uncertainty in the adopted mantle viscosity structure. Viscous deformation in the Amundsen Sea Embayment contributes up to 15% of the total predicted change over the instrumental record and equals or dominates over elastic deformation by the end of the 21st century.

We then use these results to inform the setup of future simulations to quantify the influence of solid Earth deformation on the contribution of the Antarctic ice sheet to future projections of sea-level change globally. We show that the water outflux from uplifting flooded marine basins in Antarctica amplifies future global mean sea-level rise by up to ~15%, and 3-D Earth structure contributes substantial uncertainty to predictions of global mean and geographically variable sea-level change. When we incorporate the heterogeneity in the Earth structure into simulations of a 3-D GIA model coupled to the PSU dynamic Antarctic ice sheet model, we find early and rapid changes in bedrock elevation on the order of tens of meters over the next hundred year. This GIA feedback reduces the contribution of Antarctica to global sea level by up to 30% at 2100 and 38% beyond this time. Ignoring the lateral heterogeneity in the Earth structure contributes up to 20% of this signal at the end of 21st century 30% at the end of the model runs (2500). The grounding line migration and evolution of individual glaciers depends on local bedrock geometry and elevation which highlights the importance of continuing efforts to measurements of these observables and the Earth structure that governs its deformation.

Evidence of large anelastic deformation in the Amundsen Sea embayment

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The extended Burgers material (EBM) model provides a linear viscoelastic theory for interpreting a variety of rock deformation phenomena in geophysics, playing an increasingly important role in parameterizing laboratory data, providing seismic wave velocity and attenuation interpretations, and in analyses of solid planetary tidal dispersion and quality factor *Q*. At the heart of the EBM approach is the assumption of a distribution of relaxation spectra tied to rock grain boundary and interior granular mobility. Furthermore, the model incorporates an asymptotic long-term limiting behavior that is Maxwellian.

Here, we compare viscoelastic deformation computed with EBM rheology to the Maxwell and elastic model in response to the last 4 decades of surface mass change in the West Antarctic ice sheet. The resulting vertical land motion is thus compared to GPS records in the region, where local trends show very large uplift motion amounting to up to 60 mm/yr that can neither be explained by elastic deformation nor traditional GIA models. We show that EBM rheology has the potential to explain such large deformation while maintaining a long-term viscosity compatible with GIA models.

GIA Imaging of solid Earth Structure - Future Applications for Antarctic Dataset

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The application of the adjoint method to Glacial Isostatic Adjustment (GIA) provides a critical missing link to rapidly quantifying observational sensitivities to key GIA parameters like mantle viscosity. Through the use of the adjoint method sensitivity kernels for a given observation can be computed with just two numerical simulations – a forward simulation driven by changes in ice mass and an adjoint simulation driven by a 'fictitious' load applied at the observation point. Alternatively, by deriving the adjoint loads based on a suitable misfit function we can efficiently calculate the gradient of the misfit function with respect to the model parameters (i.e., mantle viscosity) for all observations, which again requires just two numerical simulations. Thus, with the gradient in hand we can use gradient-based optimization to image 3D mantle viscosity directly from observations (e.g., relative sea level). Importantly, such inversions may also start with a 3D viscosity model and further refine it to better fit the observations. Here we discuss how we are preparing to use this approach to image the 3D viscosity structure beneath Antarctica based on GNSS observations. In doing so we leverage novel inference approaches to convert shear wave speed to steady state mantle viscosity, coupled GIA/ice sheet modeling, and finally the adjoint method along with gradient based optimization. Through this discussion we will also provide examples of sensitivity kernels and inversion results based on synthetic paleo sea-level observations that strive to recover a 3D viscosity model. In this way we demonstrate a potentially powerful application for Antarctic GNSS data that is in development and in the future can be expanded to other important GIA parameters (e.g., ice history).

Session VI: Infrastructure, Logistics and Coordination

SAGE and GAGE Facility Polar PI Project and Network Support: Lessons Learned, Status, Opportunities, and Challenges

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UNAVCO Inc., Boulder (CO), USA

The Seismological Facility for the Advancement of Geoscience (SAGE) and the Enabling Discoveries in Multiscale Earth System Dynamics: Geodetic Facility for the Advancement of Geoscience (GAGE) Facilities, funded by the National Science Foundation through Cooperative Agreements to IRIS and UNAVCO, Inc., respectively, have been supporting Polar PI Projects and Networks for decades. Staff from IRIS-PASSCAL Instrument Center and UNAVCO have coordinated support activities on POLENET (ANET and GNET) since the start of that project. In addition, IRIS-PASSCAL and UNAVCO staff have provided instruments, training, and field support for PI projects across the Arctic (primarily in Greenland) and in Antarctica (primarily through the USAP). We will provide an update on some lessons learned, status of existing seismic and geodetic networks as well as planned PI-project support for the upcoming 2022-2023 field season in Antarctica, highlight some new projects and opportunities for polar support that are being undertaken jointly by IRIS and UNAVCO, outline some ongoing challenges from the perspective of the SAGE and GAGE Facilities, and discuss the implications for future Polar support after the upcoming merger of IRIS and UNAVCO to form the EarthScope Consortium, Inc.

The History and Future of Global Seismographic Network Stations in Antarctica and their use in Antarctic Research

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For a quarter century, the U.S. Geological Survey has continuously operated four broadband seismic stations in Antarctica as part of the Global Seismographic Network (GSN): 1) Scott Base on Ross Island (SBA), 2) Casey on the East Antarctic coast (CASY), 3) Palmer (PMSA) on the Antarctic Peninsula, and 4) South Pole (SPA/QSPA). Prior to 2007, these stations contributed a substantial portion of all available, year-round seismic data from Antarctica and the operational history at QSPA, SBA, extend back the early 1960s. Therefore, seismic observations at GSN stations in Antarctica are particularly suited to decadal-scale studies seeking to both refine historical earthquake source locations and investigate long-term changes in environmental signals (e.g., ocean storm activity, sea ice). Since 2017, the GSN has been iteratively upgrading aging, 1980s vintage seismometers to modern borehole and posthole sensor packages. These sensors have greatly improved the resolution of low-frequency seismic signals at many GSN stations, but to date,

none of the Antarctic GSN stations have received this upgrade. In this presentation, we review the history, scientific achievements, and upgrade prospects for these four stations. In particular, we highlight an exciting opportunity to collaborate with the IceCube Neutrino Observatory to emplace one of these sensors at 2.4 km depth in the icecap at the South Pole.

Optimizing Antarctic field deployments for conventional and data-driven solid-Earth research

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Valuable progress has been made in understanding the Antarctic continent, particularly those areas that are covered by great ice sheets, using 'conventional' single-variate methods (e.g. seismic tomography). Community efforts have produced widely used compilations of geophysical data such as magnetic and gravity anomalies, and those for interdisciplinary use such as icebed topography and related observables (e.g. Bedmap2). Further insights are emerging through studies using mixed constraints (e.g. icebed topography, BedMachine) and multivariate studies (e.g. geothermal heat flow, Aq1), with these 'data-driven' methods including similarity approaches and those that make use of machine-learning algorithms. Conventional forward/inverse modelling, and data-driven statistical approaches are highly complementary, hence, as we plan new Antarctic deployments we should a) continue to address regions with poor constraints for single observable geophysical methods and b) also consider the additional imperatives of data-driven studies. Data products such as seismic tomography, and icebed topography maps, are revealed as especially useful 'aggregator' datasets. Uncertainty metrics such as information entropy, alongside the more familiar standard deviation, can inform the location and density of priority future deployments across a range of target properties to be inferred for solid Earth research.

Models of international coordination for large science programs

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SCAR and U.S. science vision documents pertaining to geodynamics, the changing cryosphere and sea level, all call for international collaborative efforts and joint funding by multiple nations to achieve ambitious science goals and extend observational capacities in polar regions. Logistic capabilities and science budgets of individual national Antarctic programs are limited, highlighting the need to pool international resources to carry out bold science initiatives. SCAR research programmes facilitated the network vision and collaborative relations that led to the POLENET (POLar Earth observing NETwork) network of geophysical and geodetic instruments during the International Polar Year 2007-08. Can the SCAR INSTANT SRP provide a framework for collaborative initiatives between national Antarctic programs and form a sustainable model for ongoing observations required to meet community science objectives? Encouragingly, there are successful recent models for large-scale science supported by multiple nations. Several models for international support for science programs will be reviewed to provide a basis for discussion of possible science community actions to move international, interdisciplinary science support frameworks forward.

POSTERS

Posters are listed in alphabetic order of presenting authors' names.

Microseismic Events on the Ross Ice Shelf and Identifying Ocean Swell Controlling Mechanisms

Rick Aster, Elisa McGhee
Colorado State University, Fort Collins (CO), USA

Multi-observable thermochemical tomography of Antarctica

Walid Ben Mansour
Washington University, Saint Louis (MO), USA

Deformation at the open-vent Erebus volcano, Antarctica, from more than 20 years of GNSS Observations

Ronni Grapenthin
University of Alaska, Fairbanks (AK), USA

The ice-bedrock interface of the Aurora Basin

Ian Kelly
School of Natural Sciences, University of Tasmania, Hobart, Australia

LIONESS on Ice: Activities and Plans

Won Sang Lee
Korea Polar Research Institute (KOPRI), Incheon, Republic of Korea

Vertical Land Movement and GIA estimates - key for Antarctic Sea Level Projections and Coastal Hazard Assessment

Richard Levy
GNS Science, Avalon, Lower Hutt, New Zealand

Upper Mantle Attenuation and Velocity Anomalies beneath Antarctica Constrained by Teleseismic Body Waves

Jialin Li
Washington University, St. Louis (MO), USA

Higher Latency Data Enables Minimal Logistics for Polar Research

Tim Parker
Nanometrics Inc., Socorro (NM), USA

Quantifying temporal resolving power of Antarctic GPS measurements using adjoint modeling

Evelyn Powell
Columbia University, New York (NY), USA

ANET-POLENET: Ongoing development of autonomous GNSS systems in Antarctica
David Saddler
Ohio State University, Columbus (OH), USA

Analyzing Antarctic GNSS Velocities Affected by Antenna Icing: Implications for Ongoing Observations
David Saddler
Ohio State University, Columbus (OH), USA

Controlled-source seismic imaging of McMurdo Ice Shelf near William's Airfield
Yeshey Seldon
University of Texas, El Paso (TX), USA

Broader Impacts of the ANET-POLENET Project
Stephanie Sherman
Ohio State University, Columbus (OH), USA

Revealing sub-ice shelf sediment basins with airborne magnetics: implications for solid-earth-ice interactions
Matt Tankersley
Antarctic Research Centre, Victoria University of Wellington, New Zealand

Antarctic-Plots: A Python package to help download, visualize, and present Antarctic datasets
Matt Tankersley
Antarctic Research Centre, Victoria University of Wellington, New Zealand

Status Quo of Land and Sea Level Changes around South Georgia Island prior to the Establishment of the new Tide Gauge and Jetty at King Edward Point
Norman Teferle
Department of Engineering, University of Luxembourg, Luxembourg

Cross-Evaluation of Meteorological Surface Data and GNSS-derived Precipitable Water Vapour with Re-analysis Information for South Georgia Island, South Atlantic Ocean
Norman Teferle
Department of Engineering, University of Luxembourg, Luxembourg

SCAR RINGS Action Group Activities
Kirsty Tinto
Lamont-Doherty Earth Observatory, Columbia University, New York (NY), USA

The apparent seasonal variations in seismic observations made in Antarctica and other polar regions
Hanxiao Wu
Geoscience Department, Stony Brook University, Stony Brook (NY), USA

Monitoring the Geospace Environment from Antarctica: 2-D magnetometer array

Zhonghua Xu
Virginia Polytechnic Institute and State University, Blacksburg (VA), USA

The anisotropy of the Antarctic crust and upper mantle and a new sediment thickness map of the Antarctica continent

Zhengyang Zhou
Washington University, St. Louis (MO), USA

Overview Map