DEVELOPING POLAR-EXTREME ENVIRONMENT COLLABORATIONS TO SUPPORT NASA EARTH AND SPACE SCIENCE MISSIONS

White Paper to summarize potential NASA-JIRP Partnership for Polar Testing, Training, and Proving Grounds on the Juneau Icefield, Alaska

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INTRODUCTION

The National Aeronautics and Space Administration (NASA) and the Juneau Icefield Research Program (JIRP) share the missions of promoting research, discovery, and education in Earth and Space science. The purpose of this document is to highlight the potential for JIRP to support NASA research, development, and education. In particular, JIRP can provide:

- Logistics, resources, and research infrastructure in a harsh, glaciated environment
- Collaborative, multi-disciplinary research consortium
- Integrated science education and outreach

JUNEAU ICEFIELD RESEARCH PROGRAM

The Juneau Icefield Research Program is the longest operating polar research and training program in North America. Our expeditionary field school focuses on educating and inspiring new generations of Earth and climate scientists, policy-makers, educators, and the broader community. Further we are a hub for multi-institution collaborative Earth Systems Science research. We aim to promote an inclusive science community, one that can more effectively tackle the challenges we face as a society.

JIRP is like no other polar science education program on Earth. Our students spend eight weeks living on the icefield, conducting cutting-edge research, and gaining hands-on experience in both the science and impacts of environmental change. Students learn communication and outreach skills to engage the communities neighboring the icefield as well as their home communities. Our students build lasting collaborations on JIRP and our alumni become leaders in their fields.

In conjunction with our education program, JIRP supports collaborative research across a range of disciplines. As an institution we maintain the longest-running glacier monitoring program in North America. Further, we bring together researchers from dozens of institutions to probe questions in everything from climate and geophysics to microbiology and engineering. In just the past three years we have supported 12 projects with partners at seven institutions and involved faculty from almost three dozen institutions.

Founded in 1946, JIRP maintains a number of permanent field stations across a network of glaciers in Southeast Alaska and British Columbia, and have developed extensive logistical and safety expertise in the region. JIRP provides a unique opportunity for extreme testing and research in a rugged, glaciated environment, with simpler and lower-cost logistics than comparable sites (e.g. U.S. stations in Greenland or Antarctica). Further, these sites are in principle accessible year-round. This landscape is relevant not only to terrestrial polar research but also as an analogous environment for planetary science.

NASA & JIRP OVERLAP

NASA's mission focuses on research, development, and scientific discovery in Space, our solar system, and our own planet. There is significant potential for JIRP to support both the terrestrial and extraterrestrial research objectives of NASA projects as well as education and outreach. Central to planetary science is a deep interest in water, ice, and life on other celestial bodies, including ice-bearing worlds such as Mars, Europa, Enceladus, Pluto, and even Earth's moon. The race to develop next-generation technologies capable of exploring these extreme environments requires analogous-terrain proving grounds for testing and training here on Earth. Relatedly, the continuous monitoring of Earth's atmosphere, oceans, and cryosphere from space is central to understanding our changing planet. This research too benefits from ground-truthing and from complementary terrestrial research, particularly in the polar regions. Modern Earth and Space science requires collaboration and communication between scientists with a range of expertise from a variety of fields. Further, this science should be communicated widely and effectively with the public. Earth and space sciences must significantly improve engagement with communities that are both severely underrepresented in these fields and disproportionately impacted by environmental change.

JIRP can help to support these objectives. We can provide sub Polar testing grounds and training facilities with well established logistical support. We bring together a wide breadth of Earth, space, and polar scientists within a single-expedition framework. These research endeavors integrate with our field-education and outreach programming. JIRP has a special interest in expanding the reach and techniques of education focused on polar and extreme environments, and the engagement of underrepresented communities. We are planning to double the scope of our field school in the coming years (up to 70 students per season) and have capacity to facilitate even more research efforts. JIRP has supported multiple successful NASA funded projects between 2017-2020 and has a history with the NASA Space Grant.

POTENTIAL RESEARCH & DEVELOPMENT ON THE JUNEAU ICEFIELD

The following is a non-exhaustive list of potential research and education projects that highlight overlap in NASA and JIRP interests.

1. Unmanned Terrestrial & Aerial Vehicle Development

1.1. Autonomous Ground-based Rover Systems with Sampling Capabilities

Objective: Development of multiple and potentially modular all-terrain autonomous rover systems with multi-use Polar capacities and modular autonomous sampling capabilities.

Rationale: Broadly, autonomous rovers are needed for both Earth and extra-terrestrial research in extreme environments. Well constructed systems ultimately can reduce human risk, increase data collection capabilities, and expand field time for data collection. In polar Earth environments, rovers are already used for autonomous geophysical surveys (e.g. Arcone et al.

2016), terrain assessments, surface snow assessments (e.g. Elliot et al., 2019) and rock sampling, aerosol sampling, and autonomous snow, firn, or ice core subsurface sampling. These systems could be customized for extra-terrestrial sampling. The ultimate system we envision on the Juneau Icefield would be able to:

- Traverse the icefield safely and efficiently while avoiding obstacles including moulins, crevasses, icefalls, steep slopes, other terrain traps, and soft snow/sediments.
- Remain powered for the duration of the research
- Collect and analyse aerosol samples in real time
- Collect and analyse surface snow or rock samples in real time
- Collect and analyze shallow snow, firn, ice, or mixed ice-sediment samples in real time
- Tow and operate other sophisticated geophysical instruments for subsurface geological investigations (e.g. ground-penetrating radar, for ice or sediment structure, thickness, and internal layering)

1.2. Terramechanics

Objective: Improve the ability for autonomous systems to quantify real time surface conditions and adjust to those conditions through machine learning and artificial intelligence.

Rationale: Military and NASA terramechanics studies have a long history and are shifting more towards computer model simulations. For example, the successful Curiosity mission and the planned Perseverance mission both have wheel systems designed for relatively complex terrain. However, future missions will require further and more complex designs for other terrain such as ice cap surfaces. Concurrently, autonomous systems likely have a significant future role to play in polar exploration on Earth, particularly in challenging or dangerous to reach locations such as ice sheets, ice shelves, and shear margins where long term data are needed. Therefore, there is significant need for developing and improving upon wheeled or track vehicles on surfaces which vary laterally and temporally upon which autonomous vehicles traverse. The combination of field observations and computer simulation represent a powerful combination for the development of improved autonomous rovers for the next NASA missions. The Juneau Icefield provides multiple complex accessible environments including scree and rocky debris-laden surfaces, blue ice, wet firn, wet snow, and dry snow, within easy access to our field stations, due to the elevation change over 80 km in linear distance.

1.3. Hazard Detection/Avoidance, Machine Learning, & Artificial Intelligence

Objective: Development of Machine Learning and Artificial Intelligence systems for Autonomous Earth and Space Rovers to assist with navigating complex Polar terrain.

Rationale: The range of environments encountered on the Juneau Icefield provide a plethora of opportunities to incorporate machine learning and artificial intelligence into hazard detection and avoidance. Crevasses, moulins, steep or unstable terrain (e.g. synced with terramechanics research), and changing conditions spatially and temporally on the Juneau Icefield, simulate the many environments which will likely be encountered on other icy locations across Earth as well as at extra-terrestrial sites such as the moon and Mars.

1.4. Drone and Lighter-than-Air (LTA) Systems with Multi Sensor Capabilities

Objective: Develop a fleet of long-duration, variable range, multi-mode (tethered, untethered, remotely piloted, autonomous), programmable, multi-deployable (programmed for multiple timed launches and landings), drones and LTA crafts with aerosol, optical, thermal, LiDAR, and other remote and *in-situ* sensing capabilities.

Rationale: Over the past few decades there has been significant improvements in drone technology. Additionally, lighter than air (LTA) airship technology shows substantial promise as a future resource. Commercial drones provide relatively short-duration missions and small payloads but can be programmable to cover specific tracks for detailed aerial surveying. LTA Airships, due to their inherent buoyancy, can perform vertical takeoff and landing, offer long endurance and adequate payload capacity for modern sensor technology, but, as of yet, are not commonly used in Polar research activities. Both systems have a role in Earth science applications, therefore expanding drone/LTA flight duration, payload capacity, and improving autonomous or remote operation are worthy goals. The development of multi-mode repeat-deployable UAV systems for remote Earth study locations could provide high temporal and spatial scale quantitative observations superior to any current satellite based platform. Likewise, the airborne field of view and spatial coverage provided by drones and LTA is also generally superior to most ground-based observations. Using the Juneau Icefield to develop, test, and improve upon such technology could potentially revolutionize our understanding of dynamic systems such as glaciers, sea ice, and coastal marine environments.

2. Sensors and Scientific Systems

2.1. Subglacial and Englacial Probe Development

Objective: Develop new autonomous probe systems to study the englacial and subglacial regions on Earth, and ultimately extra-terrestrial planets.

Rationale: The ability to probe to the maximum depths of surficial features, such as water filled crevasses and moulins with autonomous submersible systems, would enable exploration to a region never before analyzed on Earth. Due to the control of subglacial hydrology on glacier behavior, understanding the depths of the englacial and subglacial hydrological system of glaciers and ice sheets is perhaps one of the last great mysteries and most important problems to address in glaciology. If we intend to explore the ice caps of extraterrestrial bodies such as those that exist on Mars in search of water, voids such as these will need to be explored. On the Juneau Icefield, we have the opportunity to develop new cutting edge technology, capable of safely exploring the underbelly of one of the deepest temperate glacier systems on the planet, both in terms of navigation as well as sampling instrumentation. Likewise, developing autonomous probing systems with a range of sensors to drill through the ice could provide similar important information about glacier structure, chemistry, biology, history, and dynamics.

2.2. Rock and Ice Drilling and Sampling

Objective: Develop autonomous or easily deployable human-operated drill systems for a range of rock, debris-rich ice, snow, firn, and ice environments.

Rationale: The paleoclimate community has recently embraced acquiring sub-glacial rock samples for developing constraints on numerical models that are being used to predict the advance and retreat of glacier systems across Earth. Subglacial rock drilling has successfully occurred at several locations around West Antarctica (Ohio Range, Mount Waesche, Mount Murphy, Pirrit Hills, Minna Bluff) and is planned for several other locations across Antarctica, Greenland, and the Juneau Icefield. We envision similar studies being conducted in extra-terrestrial environments to determine the long-term stability of polar ice caps in these extreme environments. The U.S. Ice Drilling Program (IDP) joined JIRP in 2019 to test a thermal drill to depths reaching 294 m. They plan to return to JIRP each consecutive year from 2021-2024 to continue testing drills, including the Winkie subglacial rock drill system. The Juneau Icefield also has ice thicknesses reaching over 1500 m depth, as the thickest temperate glacier in North America and potentially the world, thereby opening up significant complex sediment-rich and deep ice drill testing opportunities. We envision collaboration between NSF-funded scientists, NSF-funded IDP, and NASA scientists to pursue further research and development in debris-rich ice or complex drilling environments, as could be encountered on extra-terrestrial planets. Improvement of drill systems and clean access (i.e. avoiding contamination of the subsurface environment) for Space activities will also lead to significant improvements in our ability to rapidly drill across a range of complex Polar Earth environments.

2.3. Autonomous Water Stable Isotope Analysis

Objective: Develop and test laser spectroscopy instrumentation for autonomous measurement of water stable isotope concentrations in vapor at the surface and in ice at depth below the surface.

Rationale: Water isotope ratios can provide insight into a planet’s water cycle and the measurement of these ratios preserved in terrestrial ice have formed the basis of much of our understanding of Earth's climate history. Measurement of these water isotope ratios of ice on other celestial bodies may similarly provide insight into non-terrestrial water cycles, climate, and potentially climate history of those bodies. This will require the development of autonomous instrumentation to make these measures in severe conditions. The ultimate goal would be to remotely retrieve stratigraphic records from Martian polar ice caps- analogous to ice core records on Earth. Other targets could include interstitial ice in shadowed craters on the moon or surface ice on other bodies in the solar system. This instrumentation development would also have tremendous terrestrial applications. There is further opportunity for additional water chemistry measurements, such as methane concentration, which may be useful in non-terrestrial circumstances where methane ice may be a large component of surface ice.

2.4. Life Detection

Objective: Advance the science and technology needed to search for life beyond Earth.

Rationale: The study of icy habitats on Earth provides important analogs for determining the likelihood of life in extraterrestrial environments. In general, icy environments are characterized by nutrient and energy limitation, low temperatures and water activity, resulting in low biomass. These conditions present technological challenges for life detection missions. There is a need for clean sample extraction and handling techniques, novel instrumentation and improvements in detection limits of current instruments. With its range of glacial habitats, JIRP would provide an important test bed for these instruments and methods useful for detecting and characterizing life, organics, and biosignatures.

3. Energy and Power

3.1. Renewable Energy and Power Systems

Objective: Development of long term Polar Earth and Space renewable power solutions for operating missions in harsh and extreme environments.

Rationale: The development of long-duration power systems and systems which incorporate smart and fast charging capabilities based upon local resources are a need both in Earth and Space science research. The Juneau Icefield has variable and challenging weather conditions to test the functionality of solar, wind, biofuel, and hybrid power systems over long durations. The annual field program and associated field camps means that systems could be left for testing over winter or over longer durations than most other challenging locations which do not have local infrastructure and returning scientists, year after year.

3.2. Sustainability: Extreme Environment Waste Management with Integrated Renewable Energy Systems

Objective: Develop new integrated waste systems and renewable energy systems that are useful for sustainable living and/or reducing pollution in extreme environments.

Rationale: The infrastructure needed to sustain operations in extreme environments must be robust, semi-autonomous, and ideally rely on renewable energy. Safe and hygienic disposal of human waste is also an issue that has long plagued polar research camps. The development of more sustainable energy systems capable of powering research and exploration outposts and instrumentation are important next steps that can be deployed and tested at JIRP. New technologies for waste management that move away from burial are currently being developed, as well as power systems that allow for maximum integration into renewable power grids. A wide range of commercial technologies exist that make up power grids, including batteries and electrical components, however, they require testing in cold and extreme conditions. Many of these developments are necessary in remote, polar areas, and are of interest to the US Forest Service which maintains Tongass National Forest where JIRP is situated.

4. Science

4.1. Repeat Ground Truth of Satellite Glaciological Observations

Objective: Develop annual and seasonal Calibration and Validation (Cal-Val) programs for NASA ICESat-2, GRACE-FO, and other satellite observations.

Rationale: Alaskan and Canadian glaciers are currently retreating more rapidly than any other mountain glacier system in the world due to their low elevation, recent increasing summer temperatures, longer associated melt seasons, and temperate nature. ICESat-2, GRACE-FO, and other NASA satellite systems provide an unprecedented opportunity to better understand these rapid changes. However calibration and validation is still needed, particularly in complex terrain and under variable surface conditions. Antarctica and Greenland provide generally cold-polar snow, firn, and ice conditions and their lower sloped Polar regions are well covered by Cal-Val efforts, whereas most mountain glaciers and steep terrain are not represented in Cal-Val studies. The Juneau Icefield provides more variable (wet to dry and steeper terrain) environments than Greenland and Antarctica, therefore covering entirely different environments for study under several ICESat-2 tracks. Our ability to study 1) surface grain size, 2) snow-firn water content, 3) particulates and biology within snow, firn, and ice 4) surface reflectance, 5) water depth of supra-glacial lakes, and 6) surface elevations could provide an unprecedented level of comparative data relative to ICESat-2 data. Likewise, JIRP monitors overall surface elevation change, depth-density profiles, and velocities, thereby providing an opportunity to improve existing firn models in temperate regions and to differentiate mass balance (for comparison to GRACE and GRACE-FO observations) from dynamic glacier signals.

4.2. Snow Accumulation Studies

Objective: Reduce snow model uncertainties in the Pacific Northwest

Rationale: A recent modeling effort in support of NASA SnowEx ran a 12-member ensemble of land surface models with forcing data over North America to quantify snow estimation uncertainty across a range of snow classes, terrain, and vegetation types (Kim et al. 2018). The results suggested that some of the greatest uncertainty in SWE exists in the Pacific coastal ranges including across the Juneau Icefield. Developing the Juneau Icefield as a NASA test site could be beneficial to the SnowEx program which is focused on developing a better understanding of Snow water equivalent (SWE) across scales in North America and ultimately developing future SWE satellite missions to address snow-security and water resource concerns across the globe. Despite this project focusing on the icefield over glaciated terrain, observations of SWE could be made annually across the Juneau Icefield providing constraints and validation of existing SWE models.

5. Education and Training

5.1. NASA Undergraduate, Graduate, & Postdoctoral Research-Education Program

Objective: Establish new NASA undergraduate, graduate, and postdoctoral research and education programs focused on Polar regions of Earth and Space, with particular research and education emphasis on the Juneau Icefield as a natural laboratory.

Rationale: The cryosphere is perhaps the most fragile Earth system with respect to current climate change and predicted future change. The development of advanced high spatial and temporal resolution methods to understand Earth processes related to the cryosphere, and predict changes to it, are more important now than ever before. Marine terminating glaciers make up over 50% of glacier systems, worldwide, and Alaska is particularly susceptible to glacier retreat considering its temperate glaciers reside near 0°C. In fact, Alaska has contributed more to global sea level than any glacier or icecap system in the world since the early 1960's (Kemp et al 2019). Taku Glacier, a major component of the Juneau Icefield, and one of the thickest temperate glaciers on the planet, just recently entered retreat stage (McNeil et al., 2020) meaning we have the chance to capture the dynamic processes of a major retreating glacier at high spatial and temporal resolution using a combination of satellite, airborne, and terrestrial methodologies and resources. Taku Glacier has a 40 km long marine subglacial overdeepening and an associated history of significant calving and retreat within this trough in the late 1800's, suggesting a similar event may be on its horizon.

We propose that now is the time to develop an integrated all-hands-on-deck research campaign focusing on a tidewater glacier system (Taku) in an unprecedented fashion: integrating large numbers of undergraduates, graduate students, postdoctoral scientists, research scientists, and educators across all career levels and fields, in real time. JIRP offers the opportunity to place over a hundred scientists at eleven field camps across the Juneau Icefield, annually, to study the multiple complex facets of Taku Glacier over the long-term, and in particular during this retreat stage. The United States does not currently have such a program. Concurrently, support for a combined research and education program promises to significantly bolster women, non-binary, underrepresented, other minority, and first generation student opportunities. Lastly, the opportunity for dozens of early to late career Earth and space scientists to merge forces promises to ultimately bolster learning about both Earth and Extra-terrestrial icy planets through collaborative engineering, research, development, and education activities that are pursued on the Juneau Icefield.

5.2. Astronaut Training Program

Objective: Develop a Polar glaciology training program for astronauts and NASA employees for future missions.

Rationale: Future missions such as NASA Artemis plan to incorporate astronauts into extra-terrestrial field research. This potentially includes missions such as drilling ice-rich craters from the moon. Both manned and unmanned missions to extra-terrestrial icy environments require general knowledge of glaciology, glaciological research methods, and instrumentation and equipment. The Juneau Icefield is an easily accessible and cost efficient location to complete such training. JIRP has the capacity to host large NASA teams using our 11 remote on-ice facilities for field based education, training.

6. Summary of Broader NASA Benefits

- Multiple science teams working together collaboratively
- A consortium of institutions working together to attain a range of collaborative objectives
- Existing range of students and dozens of faculty from multiple institutions
- Ease of access to the icefield relative to other locations
- Eleven existing field stations situated across the icefield with local helicopter or plane access
- Existing and Long term knowledge of the icefield
- 10:1 cost savings relative to conducting research in Greenland and Antarctica
- Potential easy access multi-year Polar/extreme environment testing site for Earth and Space science technology.

- Particularly valuable when science and research funding is limited, JIRP offers the opportunity to leverage resources towards the collaborative common good for society.
- Existing educational program with over 40,000 hours of donated volunteer time each year by committed scientists and educators across the globe involved in JIRP currently which can be leveraged for establishing broader new programming.

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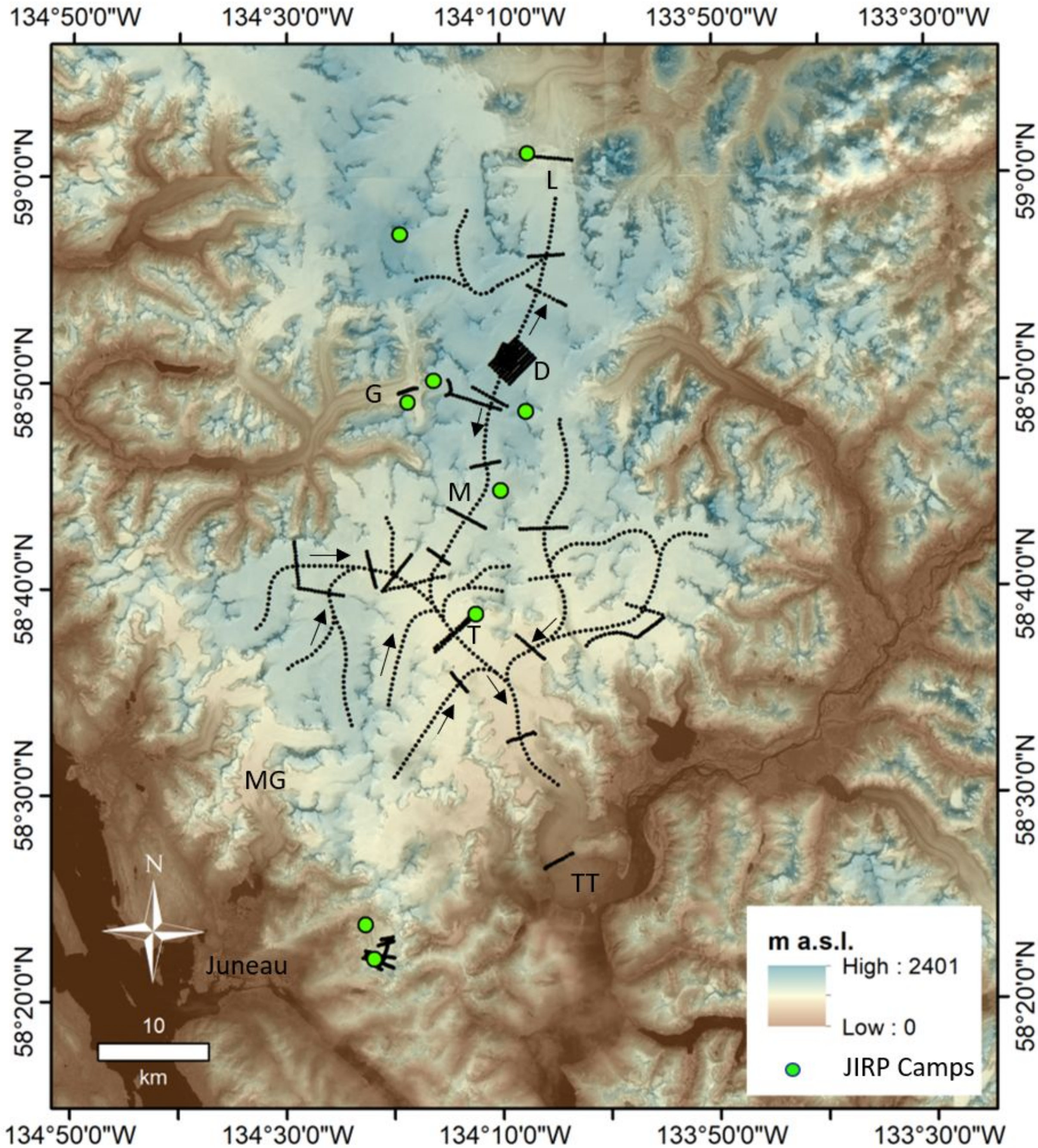

Figure 1. Map of the Juneau Icefield showing primary JIRP Camps (green dots), GPS survey tracks (black dots) suggesting general ease of access across the icefield via snowmachine, general ice flow directions, (black arrows) and labeled features including: Juneau, Taku Glacier terminus (TT), Mendenhall Glacier (MG), Taku Glacier (T), Gilkey Glacier (G), Matthes Glacier (M), Llewellyn Glacier (L), and the ice divide between Matthes and Llewellyn Glaciers.