DYNAMIC AND RESILIENT OPERATIONS IN THE ARCTIC: COLD REGIONS AND SPACE RESEARCH SYNERGY

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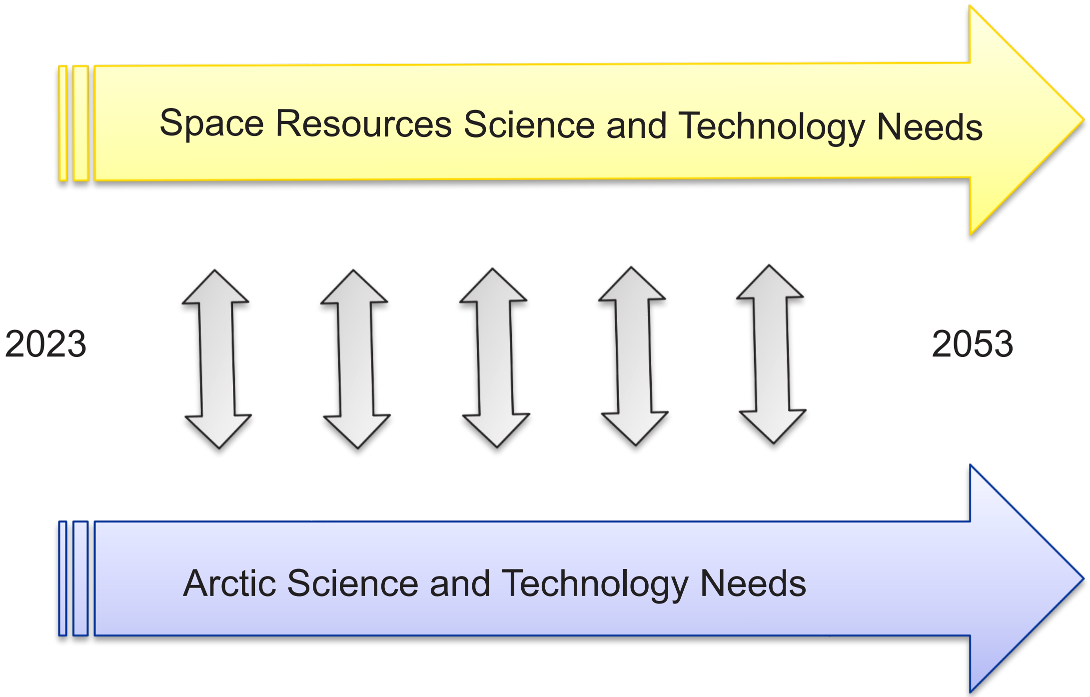
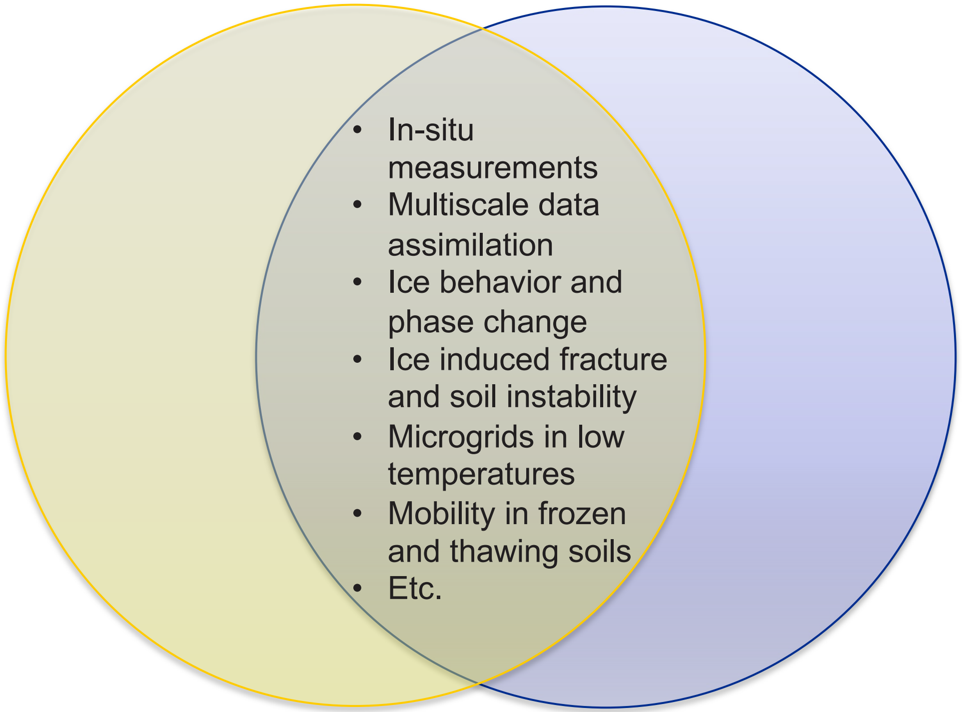
THROUGH-LINE

1) S&T needs in the Arctic are developing in parallel to space resources needs
2) Renewed interest in both field presents opportunity for further cross collaboration





THE CHANGING ARCTIC

Why is interest in the Arctic increasing?

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STAKEHOLDERS AND DOMAIN

- **Arctic States (8 members)**
  - United States (Alaska)
  - Iceland
  - Denmark (Greenland)
  - Russia
  - Norway
  - Sweden
  - Finland
  - Canada
- **Indigenous Peoples (6 permanent participants)**
  - Aleut International Association
  - Inuit Circumpolar Council
  - Arctic Athabaskan Council
  - Russian Association of Indigenous Peoples of the North
  - Gwich'in Council
  - Saami Council
- **Observers and Non-Arctic Nations**
  - China
  - Japan
  - United Kingdom
  - Switzerland
  - EU (France, Germany, Italy, Netherlands, Poland, Spain)
  - Republic of Korea
  - Republic of Singapore
  - Republic of India

"Region of peace, stability, and constructive cooperation…"

AGREEMENT ON ENHANCING INTERNATIONAL ARCTIC SCIENTIFIC COOPERATION

NON-BINDING ILLUSTRATIVE MAP

This non-binding illustrative map shows the approximate extent of the Identified Geographic Areas described in Annex 1 of the Agreement on Enhancing International Arctic Scientific Cooperation. It is intended for illustrative purposes only and does not form part of the Agreement.

- Approximate Extent of Identified Geographic Areas
- 62°N
- Arctic Circle
- Additional areas covered voluntarily by Canada

Continental shelf areas are not depicted.

U.S. Department of State, OES/OPA, April 12, 2019

Figure 1: Map of Arctic Stakeholders [1]

STAKEHOLDERS AND DOMAIN

DOMAIN FACTS

- Predominantly Ocean
- Distributed area of interest with drastically different environments longitudinally
- Time to respond can be on magnitude of days to weeks
- Extremes of – 40 C or lower
- DoD strategic goals [2]:
  - Building Arctic Awareness
  - Enhancing Arctic Operations
  - Strengthening the Rules-based order in the Arctic

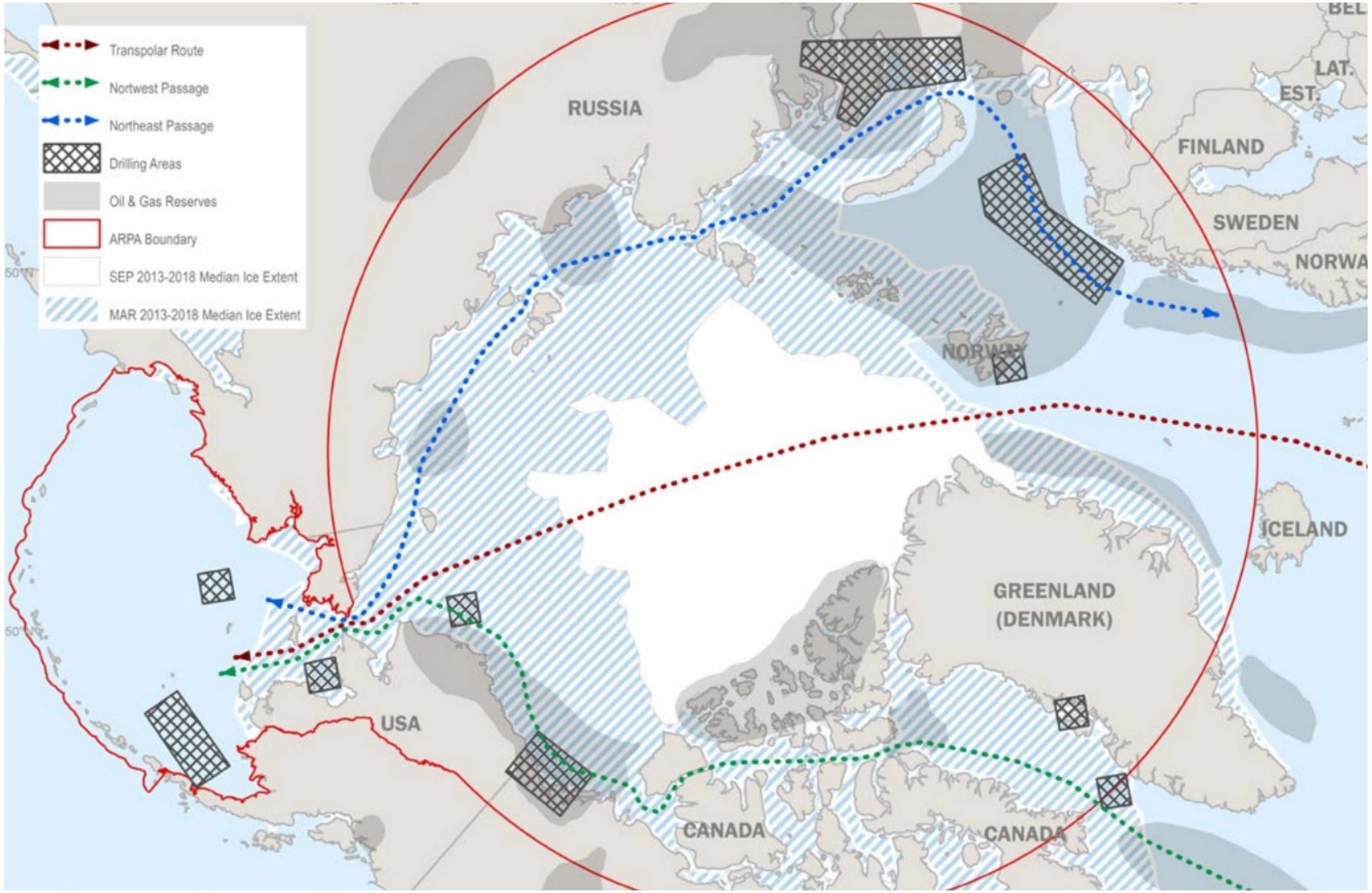

Figure 2: Arctic as defined by the Arctic Research and Policy Act of 1984 [3]

PHASE CHANGE CREATES CHALLENGES

Figure 3: Alaska Pipeline Thermosyphons

Figure 4: Thawed Permafrost Collapses Building [4]

Figure 5: Sea Spray in Bering Sea [5]

Figure 6: Thaw Reduces Mobility [6]

THE DOMAIN IS RAPIDLY CHANGING

- Thawing sea ice opens access routes
- Increased access to resources and corridors
- Increased pressure on a complex but cooperative geopolitical environment

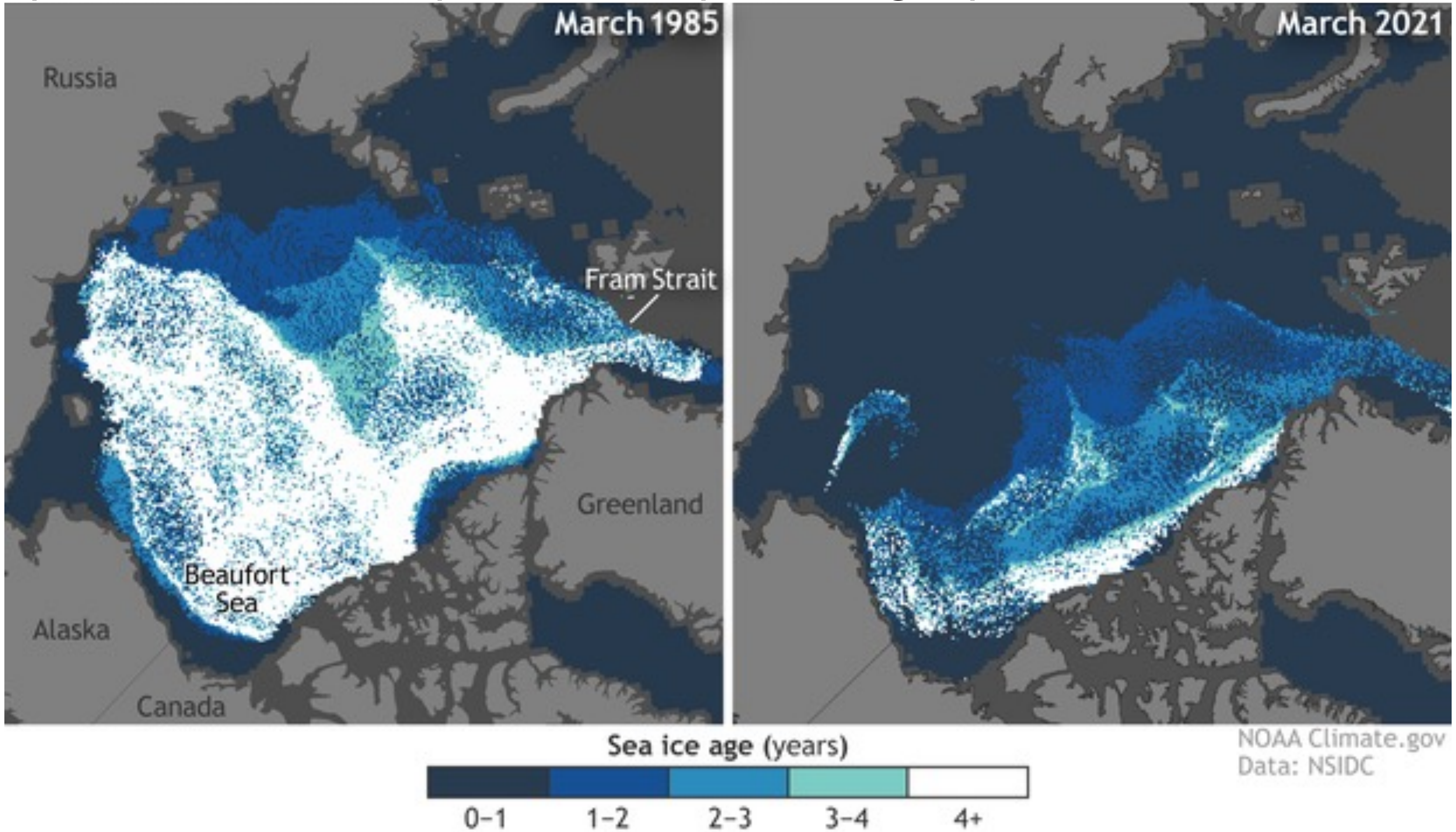

Figure 7: Sea Ice Coverage 1985 to 2021 [7]

ARCTIC RESOURCES

- Abundance of economic and security incentives for interest
  - Minerals (REEs, phosphate, iron, gold, etc.)
  - Fisheries
  - Oil and gas
  - Bioprospecting
  - Commerce (new trade routes and inland access)
  - Polar communications/monitoring

Like space resources, new science and technologies are needed for access and prosperity in the Arctic

Table 1: Discharge of Major Arctic Rivers Compared to Mississippi [8]

River	Yenisey	Lena	Mississippi	Ob'	McKenzie	Yukon	Pechora	S. Dvina	Kolyma
Discharge (km^3)	586	541	474	404	286	206	110	101	73

HOW DOES THIS RELATE TO SPACE?

1) ISRU is a novel and useful paradigm for Arctic research

2) Differences in priorities and constraints mean domain expertise and institutional memory for related problems is different, and this is useful

3) Data-based modeling and discovery is outpacing our ability to make decisions based on fundamental physical knowledge, and lessons learned deploying in extreme environments on Earth have relevance in space (and vice-versa)

ISRU AS A PARADIGM IN ARCTIC RESEARCH

How does Army R&D relate to space? Can space R&D help in the Arctic?

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CRREL RESEARCH

- "Our mission is to solve interdisciplinary, strategically important problems impacting Warfighters and the nation in cold and complex regions."
- Support a number of space related projects

Table 2: Example CRREL Projects Relevant to ISRU Operations

Project / Research Theme	Description / relevance to ISRU
Ice adhesion and chemical properties	Comparative climatology with lake sulfate minerals, Europa drill fiberoptic cable icing, general material and chemical behavior of water-ice [9].
Vehicle mobility in frozen and thawing terrain	Modeling, experimental testing, and field testing of different vehicles, tires, and treads in multiple frozen and thawing terrains [10], military vehicle autonomy [11].
Operational energy – microgrids, controls, batteries	Experimental testing of microgrid subsystems in cold conditions, prototype low-temperature battery technologies, cold specific control considerations.
Permafrost and cold regions hydrology	Permafrost-Mars analogs [12], study of permafrost tunnel in Alaska, civil engineering in permafrost areas.
Antarctic Research	Rodwell [13], utilization of ice/snow in pavement runways [14], autonomous navigation and mapping of ice masses [15].

CRREL RESEARCH

Figure 8: Views of the permafrost tunnel including ice mass and sublimation in tunnel wall.

CRREL RESEARCH

Figure 9: Frost Effects Research Facility (FERF) Exterior and Interior

Figure 10: Example Mobility Testing Vehicles and Terrain

ISRU IN THE ARCTIC

- ISRU is not a paradigm in Arctic research, but many current practices and projects could be classified as ISRU
- Reducing reliance on supply chains in operations increases resilience
- If we assumed time to respond is infinite how would that change our thought processes?
- If we assumed no supply lines?

Table 3: Example Relevant ISRU Paradigms in the Arctic

Domain	Example Technologies
Energy	Hydrogen fuel production from in situ ice, geothermal, wave, wind, solar, gas hydrates
Surface material utilization	Additive manufacturing using regolith, runways and roads from water-ice, induced permafrost as building support.
Natural engineering	Coastal erosion prevention (sea ice, permafrost), cold storage.
Data collection and monitoring	Leveraging in-situ data as a resource is crucial for awareness and decision making.

DATA-BASED MODELING IN EXTREME ENVIRONMENTS

"Data is the oil of the 21st century"

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BACKGROUND

- Data-based methods
  - Reliable action and decision making critical in operations
  - Data-based decision making is outpacing fundamental understanding of governing processes
  - Consequences of faulty decisions exasperated in extreme environments like Arctic and space
- Neural networks for complex spatiotemporal dynamics
  - "Neural networks are unreasonable"
  - How do we get the right data? How do we be confident in results?
  - Recurrent Neural Networks (RNNs) shown to be an effective tool [16]

PREDICTING FROST DEPTH PENETRATION

- Runways are expensive to build and repair
- Prediction of local frost depth penetration days ahead of time helps with damage mitigation
- This is a well-studied problem; good candidate for “black box” modeling
- Military currently uses a software which utilizes the modified Berggren equation to predict
- Leads to imperfect predictions

$$X = \gamma\sqrt{\frac{96kI}{v_s c_f}},$$

where γ is solved by

$$\frac{e^{-\frac{\gamma^2}{4\kappa_f}}}{\operatorname{erf}\left(\frac{\gamma}{2\sqrt{\kappa_f}}\right)} - \frac{T_g}{T_s}\frac{k_u}{k_f}\sqrt{\frac{\kappa_f}{\kappa_u}}\frac{e^{-\frac{\kappa_f}{\kappa_u}\left(\frac{\gamma}{2\sqrt{\kappa_f}}\right)^2}}{erfc\left(\sqrt{\frac{\kappa_f}{\kappa_u}}\frac{\gamma}{2\sqrt{\kappa_f}}\right)} = \frac{\gamma}{2\sqrt{\kappa_f}}\frac{\sqrt{\pi}}{\left(\frac{c_f T_s}{L}\right)}, \quad (1)$$

Figure 11: Analytical Modified Berggren Equation

Table 4: Tests Conducted on Soil Samples from Airfield Sites [17]

Parameter	ASTM Standard
Moisture	D2216, D6026
Liquid Limit / Plastic Limit	D4318
California Bearing Ratio	D1883
Thermal Conductivity	D5334, D6026
Gradation with Hydrometer	D7928
Porosity	D7063
Frost Heave	D5918, D2940, D1883, D2216
Frost Depth	D5918

PREDICTING FROST DEPTH PENETRATION

- Testing led to creation of finite element model called FROST
- Model proved to be more accurate than the analytical solution
- But too slow for dynamic use
- Confirmed importance of changing thermal conductivity, moisture migration at freezing front
- This led to development of AI model

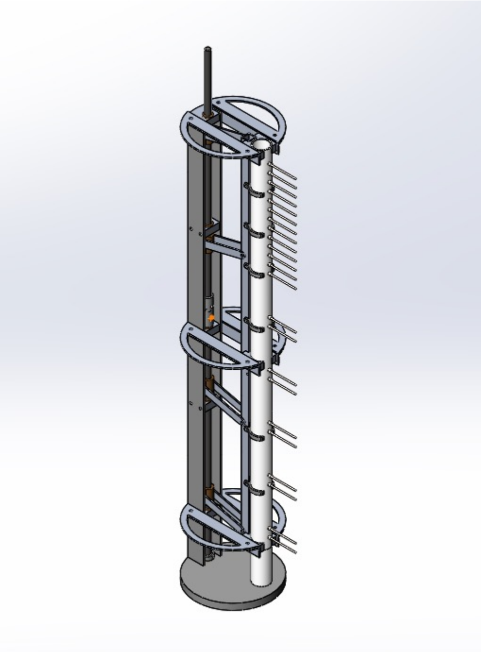

Figure 12: Sensing Probe at Airfields

PREDICTING FROST DEPTH PENETRATION

- Recurrent neural network model appears accurate enough and fast, with some flaws
- Desire is to predict 5 days ahead at a time

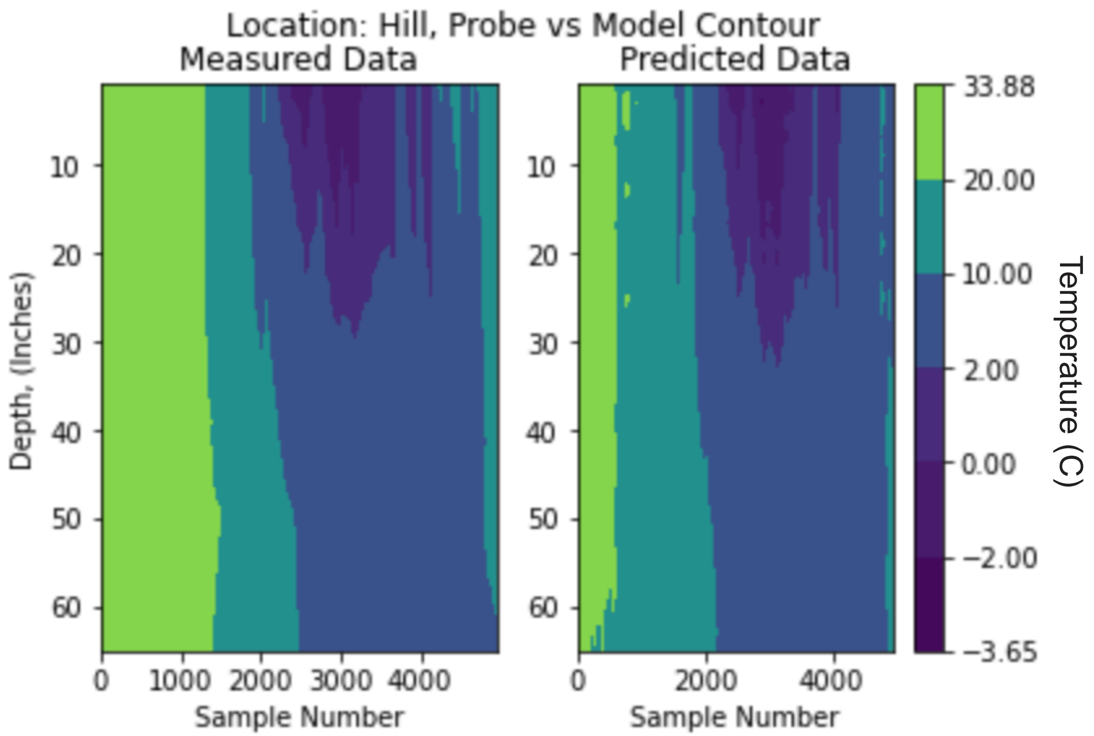

Figure 13: Measured and Predicted Temperature Field, One Winter Season

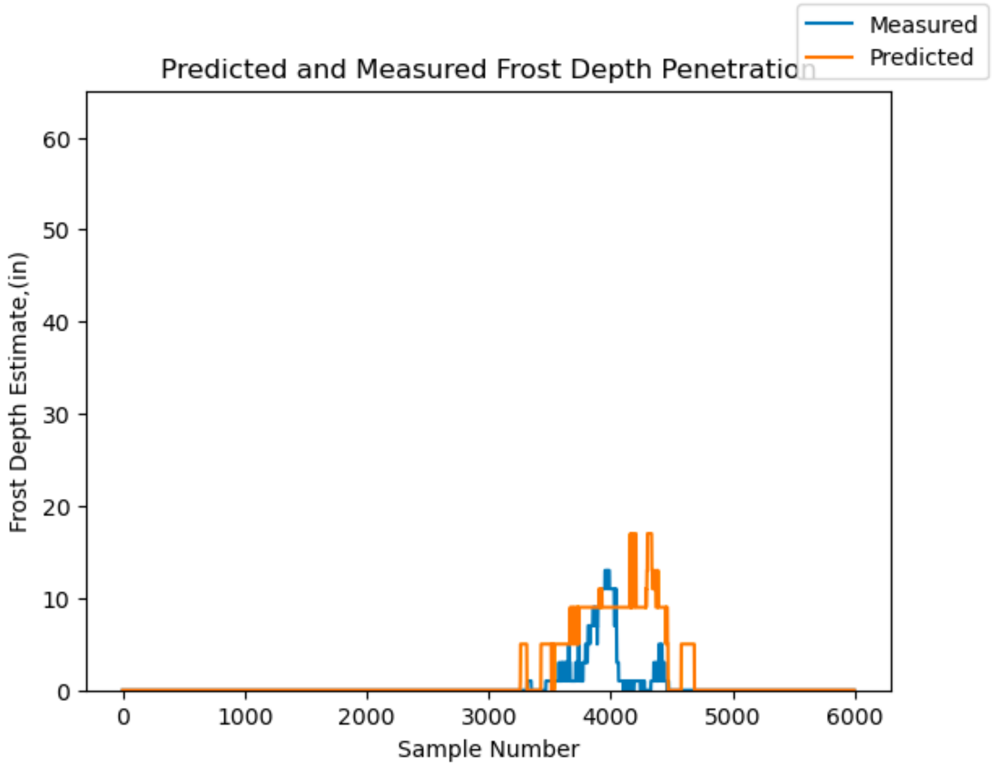

Figure 14: Measured and Predicted Frost Depth Penetration

FINAL NOTE ON NEURAL NETWORKS

- RNNs and other models will likely be widely used in the Arctic and space
- Combining with SME invaluable tool for learning about and operating in extreme environments
- Significant space for consideration of best practices and optimization of hybrid physics-data models
- Promising hybrid models with SME “baked in”
- Physics informed neural networks (PINNs) [18]
- Statistics informed neural networks (SINNs) [19]

QUESTIONS?

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