Pairing eyes in the sky with instruments in the deep: new applications of thermal infrared imagery in Antarctic glacier-ocean systems using open cloud-computing workflows

Tasha Snow
Colorado School of Mines
New ice-ocean tools and applications

Background on ice-ocean interactions in Antarctica

New thermal remote sensing techniques and more comprehensive/collaborative ways of applying them
Collaborators

Scripps Institute of Oceanography
- Fiamma Straneo
- James Holte

MIT/Woods Hole Institute of Oceanography
- Gordon Zhang

Stanford University
- Jonathan Taylor

University of Manitoba
- Karen Alley

NASA Goddard
- Shane Grigsby

TARSAN and NBP1902 Team

University of California Berkeley
- Fernando Pérez
- Facu Sapienza
- Whyjay Zheng
- Ellie Abrahams
Ocean heat transport to a glacier:
Ocean heat transport to a glacier:

Freshened and cooled surface water

Warm, saline subsurface water
Our understanding of ice-ocean interactions in Antarctica

1978
West Antarctic ice sheet and CO₂ greenhouse effect: a threat of disaster
J. H. Mercer

1981
The weak underbelly of the West Antarctic ice sheet
T.J. Hughes
Radarsat Antarctic Mapping Mission

- September 9 – October 20th 1997
- First detailed mapping of this part of the world
- 180 degree yaw of Radarsat spacecraft to map south polar region of Antarctica

1997 mosaic

2000 mosaic
Our understanding of ice-ocean interactions in Antarctica

1978  
West Antarctic ice sheet and CO₂ greenhouse effect: a threat of disaster  
J. H. Mercer

1981  
The weak underbelly of the West Antarctic ice sheet  
T.J. Hughes

2002  
Rapid Bottom Melting Widespread near Antarctic Ice Sheet Grounding Lines  
Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment, Antarctica

2004  
Accelerated ice discharge from the Antarctic Peninsula following the collapse of Larsen B ice shelf

2014  
Marine Ice Sheet Collapse Potentially Under Way for the Thwaites Glacier Basin, West Antarctica
INVESTIGATING THWAITES GLACIER

Thwaites Glacier and Pine Island Glacier are two of the biggest and fastest-retreating in Antarctica. If both collapsed, global sea levels could rise by over a metre. Without them, the entire West Antarctic Ice Sheet could be more likely to collapse, leading global sea levels to rise by over three metres.

A five-year collaboration is investigating what’s causing ice loss at Thwaites Glacier and how it will impact global sea levels. This is a joint venture between the U.S. National Science Foundation and the UK’s Natural Environment Research Council. The eight projects use a suite of technologies.

FROM STABLE GLACIER...

1. A stable glacier is in rough equilibrium. Normally, the snow falling on the glacier equals the ice flowing into the ocean.
2. The floating part of a glacier, the ice shelf, acts like a lake or dam, holding back the ice upstream.
3. Sediments and water beneath the ice affect its speed — an ice shelf changes much of the glacier's interaction with the sea and the grounding line.

TO RETREATING GLACIER

4. The melting of the stable glacier is lost. There are no longer enough sediments to maintain the Investing line.
5. Warm currents under the ice support melting the floating ice shelf and causing more calving.
6. The floating reduces its effectiveness in grounding the flow of the glacier.
7. As more of the glacier begins to flow the glacier does not melt.

At 182,000 square km, Thwaites glacier is one of the largest glaciers on the planet. It covers an area the size of Great Britain in the State of Florida. It is so remote that only a very few human beings have ever set foot on it.

Gilliland, NERC
Detect ocean heat transport to the ice using remote sensing?

![Diagram showing ocean heat transport to the ice](image)

- Freshened and cooled surface water
- Warm, saline subsurface water

Altered from www.Antarctica.org
SST provides proxy for surface and subsurface water temperatures in southeast Greenland.
Intrusions drive warm Atlantic Water inshore and warm the subsurface waters at troughs.
New ice-ocean tools and applications

Detection of the Antarctic Coastal Current in an integrated thermal remote sensing and field observation data set

Thermal detection of ice features and warm plumes at the ice-ocean interface in Antarctica with the aid of machine learning

Where we are going next – big data ice-ocean analyses in the cloud using open science principles
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Where we are going next – big data ice-ocean analyses in the cloud using open science principles
Seasonal and interannual variability of the Antarctic Coastal Current in the eastern Amundsen Sea

Tasha Snow¹ ² ³, B. Queste⁴, G. Bortolotto⁵, L. Boehme⁵, E. Savidge³, E. Abrahams⁶, A. Wählin⁴, M. Siegfried³, W. Abdalati¹ ²  
¹CU Boulder, ²CIRES, ³Colorado School of Mines, ⁴Univ of Göthenburg, ⁵Univ of St. Andrews, ⁶UC Berkeley
Antarctic Coastal Current (AACC) in the Amundsen Sea: Largely unknown

South of Antarctic Circumpolar Current often along coastline

Fast and shallow westward flow

Meltwater concentration increases as flows west (Schubert et al., 2021)

AACC variability affects heat transport to ice shelves (Hellmer et al., 2012)
Many data sources

Ocean glider

SST spatial resolution:
- 4 km
- 100 m

Credit: Aleksandra Mazur

ADCP
Acoustic Doppler Current Profiler (water velocity)

Ship CTD
Conductivity (salinity), Temperature, Depth

Seal tag CTD
Permit#UK29/2018
Cool sea surface temperatures often correspond to AACC
AACC flows above 50-100 m deep in east Amundsen Sea

Ocean glider  Feb 11

Shipboard ADCP  Mar 11-12

Snow (In prep)
AACC flows above 50-100 m deep in east Amundsen Sea

Ocean glider: Feb 11

Shipboard ADCP: Mar 11-12

Thwaites

Burke-Lindsey

Cosgrove

W

E

S

N
NE Amundsen: AACC larger, faster, and further offshore in summer
Landsat thermal processing pipeline

- Build land mask from non-thermal bands
- Produce scene specific ice and cloud masks
- Extract ocean surface pixels from thermal band (Band 10)
Landsat SST shows AACC at W. Thwaites

Thwaites Glacier

Dec 17, 2016
Dec 26, 2016
Jan 06, 2017
Jan 09, 2017

+1°C

-2°C
Landsat thermal shows AACC at W. Thwaites

Dec 26, 2016
Dec 17, 2016
Jan 09, 2017
Jan 06, 2017

Thwaites Glacier

Uncalibrated sea surface temperature

Ocean

+1°C

-2°C
Landsat SST shows AACC at W. Thwaites

- Icebergs/sea ice
- Cloud

Thwaites Glacier

Dec 17, 2016
Dec 26, 2016
Jan 06, 2017
Jan 09, 2017
Landsat SST shows AACC at W. Thwaites

Thwaites Glacier

Dec 17, 2016
Dec 26, 2016
Jan 06, 2017
Jan 09, 2017

+1°C
-2°C
AACC typically ~15 km wide with some large deviations

Physical explanations for variability:
- Changes to influx of meltwater
- AACC diversion away from ice front
- Widening/narrowing with storms

Potential errors in technique for capturing AACC width
AACC typically ~15 km wide with some large deviations

Physical explanations for variability:
- Changes to influx of meltwater
- AACC diversion away from ice front
- Widening/narrowing with storms

Potential errors in technique for capturing AACC width
Conclusions

Combining satellite thermal measurements with field-based observations provides a more robust understanding of the AACC

AACC flows above 100 m deep, generally westward along coastline, and varies seasonally and interannually

AACC variability may modify heat transport to ice fronts, especially as ice fronts retreat
New ice-ocean tools and applications

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Thermal detection of ice features and warm plumes at the ice-ocean interface in Antarctica with the aid of machine learning

Where we are going next – big data ice-ocean analyses in the cloud using open science principles
Investigating the impact of Antarctic basal channel and persistent polynya co-evolution on ice shelf stability

Tasha Snow¹, M. Siegfried¹, E. Savidge¹, M. Field¹, K. Alley², T. Scambos³, A. Villas-Bôas¹,⁴ S. Adusumilli⁵, L. Boehme⁶, E. Abrahams⁷, F. Pérez⁷, F. Sapienza⁷, S. Grigsby⁷, W. Zheng⁷, J. Taylor⁸, Y. Zheng⁹, T. Dotto⁹, B. Queste¹⁰, G. Bortolotto¹¹, L. Boehme¹¹, A. Wåhlin¹¹

¹Colorado School of Mines, ²Univ of Manitoba, ³CIRES, ⁴Caltech, ⁵SIO, ⁶Univ of St Andrews, ⁷UC Berkeley, ⁸Stanford Univ, ⁹Univ of E. Anglia, ¹⁰Univ of Göthenburg, ¹¹Univ of St. Andrews

Credit: Aleksandra Mazur
Warm water melting the ice shelf base creates buoyant plumes and persistent polynyas.
Warm water melting the ice shelf base creates buoyant plumes and persistent polynyas.
Warm water melting the ice shelf base creates buoyant plumes and persistent polynyas

Plumes entrain warm water as they rise → may melt hole in sea ice at the ice shelf front (persistent polynya)
Seasonally open, multiple years in a row in the same location
Adjusted from Alley et al., 2016
Goal: Investigate persistent polynya variability and mechanisms driving that variability
Goal: Investigate persistent polynya variability and mechanisms driving that variability
Automated persistent polynya detection in a cloud-based workflow

Snow et al. (in prep)
Automated persistent polynya detection in a cloud-based workflow

Snow et al. (in prep)
Automated persistent polynya detection in a cloud-based workflow

Snow et al. (in prep)
Ice front hand-labeling and detection using neural nets on imagery

Eojin Lee

Ice front from Sentinel-1 SAR

MODIS image visualized through Jupyter widgets and ipyleaflet
Physics-featurized segmentation to detect persistent polynyas

STEP 1: Preprocessing

STEP 2: Combined Mask Predictions

STEP 3: Polynya Predictions

Abrahams (in prep)
Can detect polynya

Seasonal and interannual polynya variability related to basal melt

<table>
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<tr>
<th>Year</th>
<th>Oct</th>
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<td>2020/21</td>
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Landfast sea ice Melange/open

Snow (in prep)

km²
- 0.25
- 0.50
- 0.75
- 1.00
- 1.25

Cannot detect polynya
Thin sea ice and warmer ice temperatures associated with polynya

ICESat-2 Hackweek Team: Mengnan Zhao, Maria Lozano, Loïc Bachelot, Ann-Sofie Zinck, Wilson Sauthoff, Tasha Snow

Landsat thermal

Surface elevation & thermal

Thermal along ICESat-2 track

Longitude

Latitude

Pine Island Glacier

Thermal

Cold

Warm

ICESat-2 elevation [m]

Snow (in prep)
Winter seal-tag ocean measurements correspond to warm thermal anomalies at polynyas.

Requires Landsat thermal to be collected in polar winter.

Savidge et al. (accepted)
Persistent polynya detection and characterization in a cloud-based workflow

Seal-tag CTDs

Landsat/MODIS/Sentinel imagery

Neural net-derived ice fronts

Sea surface temperature

Physics-featurized segmenter

ICESat-2 polynya characterization

Persistent polynya variability
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Where we are going next – big data ice-ocean analyses in the cloud using open science principles
CryoCloud: Accelerating discovery for Cryosphere communities with open-cloud infrastructure

Tasha Snow\textsuperscript{1}, Joanna Millstein\textsuperscript{2}, Wilson Sauthoff\textsuperscript{1}, Wei Ji Leong\textsuperscript{3}, James Colliander\textsuperscript{4,5}, James Munroe\textsuperscript{4}, Denis Felikson\textsuperscript{6}, Jessica Scheick\textsuperscript{7}, Fernando Perez\textsuperscript{8}, Tyler Sutterley\textsuperscript{9}, Matthew Siegfried\textsuperscript{1}

\textsuperscript{1}Colorado School of Mines, \textsuperscript{2}MIT/WHOI, \textsuperscript{3}The Ohio State, \textsuperscript{4}2i2c, \textsuperscript{5}UBC, \textsuperscript{6}NASA Goddard, \textsuperscript{7}Univ of New Hampshire, \textsuperscript{8}UC Berkeley, \textsuperscript{9}UW
Science done in a fundamentally more open way is the future

Open science is a collaborative culture enabled by technology that empowers the open sharing of data, information, and knowledge within the scientific community and the public to accelerate scientific research and understanding.
Open-source science at the forefront

Open-Source Science Initiative

NASA is making a long-term commitment to building an inclusive open science community over the next decade. Open-source science is a commitment to the open sharing of software, data, and knowledge (algorithms, papers, documents, ancillary information) as early as possible in the scientific process. The principles of open-source science are to make publicly funded scientific research transparent, inclusive, accessible, and reproducible. Advances in technology, including collaborative tools and cloud computing, help enable open-source science, but technology alone is insufficient. Open-source science requires a culture shift to a more inclusive, transparent, and collaborative scientific process, which will increase the pace and quality of scientific progress.

To help build a culture of open science, NASA is championing a new initiative: the Open-Source Science Initiative, or OSS. OSS is a comprehensive program of activities to enable and support moving science towards openness, including policy adjustments, supporting open-source software, and enabling cyberinfrastructure. OSS aims to implement NASA’s Strategy for Data Management and Computing for Groundbreaking Science 2019-2024, which was developed through community input.

Transform to Open Science (TOPS)

From 2022 to 2027, TOPS will accelerate the engagement of the scientific community in open science practices throughout events and activities aimed at:

- Lowering barriers to entry for historically excluded communities
- Better understanding how people use NASA data and codes to take advantage of our big data collections
- Increasing opportunities for collaboration while promoting scientific innovation, transparency, and reproducibility.

The TOPS mission is aligned with recommendations from NASA’s Strategy for Data Management and Computing for Groundbreaking Science 2019-2024, the National Academies report on open science in Earth and space science, and the 2021 UNESCO draft Recommendation on Open Science. TOPS is synthesis report.

Open Science Curricula: OpenCore

github.com/learnopenscience
“...I realized that open science isn’t just about tools. Open-science innovation is being driven by a global community with diverse perspectives. The scientific questions are more interesting and nuanced, the solutions better.” - Chelle Gentemann
What is the cloud?
The Digital Watering Hole (in the cloud)

An opportunity shaped by:

- Open, FAIR and CARE Data
- Scalable computation next to the data
- Modular tools for exploration/narrative

To tackle challenges that

- go beyond disciplinary silos...
- require analysis of really big data
- integration of disparate data...
- participation of disparate, diverse communities...
- to ultimately connect with society and impact critical decision making.
Cloud computing and ICESat-2 science

Cloud computing and open science concerns from the May 2022 ICESat-2 Science Team Meeting

- Non-intuitive pricing structures, documentation, computing options, infrastructure
- Costly to use
- Time to transition workflows
- Worries around intellectual theft
- Not obviously more collaborative or faster

This didn’t ring true to our experience in the cloud!
Goal: Simple and cost effective managed cloud environment for training new users and transitioning to cloud workflows

Built and developed for cryosphere scientists by software professionals at 2i2c to make it possible to:

- Process data faster
- Democratize science
A cloud-computing platform with *bumpers*

- Persistent for (at least) three years
- Small instances for all users with option to bring in your own AWS credits
- New tool development
  - Personal cost-monitoring tool to understand your usage
  - Improved intra- and inter-hub collaboration tools
- Helping 2i2c scale with community surveys, feedback, and guidance
CryoCloud community building

cryointhecloud.com

CryoCloud Github: github.com/cryointhecloud

- New Hub tools
- CryoCloud Slack
- Community office hours
- Training, tutorials, and resources
- Bringing in related Cryosphere communities and sharing in infrastructure ideation and construction
Different kinds of users in one place to accelerate feedback and collaboration
Open science values

- Intellectual generosity
- Intellectual humility
- Right to participate in science
- Everyone deserves to be treated with dignity and respect

open.science.gov
Intellectual generosity

Sharing ideas, advancing other’s understanding
Reduce competition and enhance collaboration
Intellectual humility

Our contributions are small relative to the body of knowledge

Give and receive criticism with grace
Right to participate in science

Democratizing science
Everyone deserves to be treated with dignity and respect

Objective and constructive discourse
Open science values

- Intellectual generosity
- Intellectual humility
- Right to participate in science
- Everyone deserves to be treated with dignity and respect

*Open science as a process, not a product*
New ice-ocean tools and applications

Combining satellite thermal measurements with field-based observations provides a more robust understanding of Antarctic ocean circulation.

Integration of machine learning through interdisciplinary collaborations provides unprecedented opportunities.

Ice-ocean research in the cloud using open science principles will accelerate science to meet the global need.
Funding sources:

NASA Transform to Open Science Program (80NSSC23K0002)
NASA ROSES Cryosphere Program (80NSSC22K0385, 80NSSC22K1877)
NSF Earth Cube Program (1928406, 1928374)
NSF Graduate Research Fellowship Program (DGE1650115)
NASA Earth and Space Science Fellowship Program (NNX16AO33H)
Colorado School of Mines
Cooperative Institute for Research in Environmental Sciences
International Thwaites Glacier Collaboration (NERC/NSF)
Amazon Web Services Research Grant

Thank you

Tasha Snow
tsnow03.github.io
@tsnow03
@TashaMSnow
tsnow@mines.edu
Iceberg calving at Larsen C ice shelf in polar winter

July 23, 2017

July 30, 2017
Maximum annual extent varied by an order of magnitude, potentially indicating fluctuations in ice shelf basal melt rates.
SST or thermal records can provide insight into sub-daily changes in polynyas during winter.
AACC between 9 and 40 km wide near Thwaites Glacier
MODIS cool temps agree with MITgcm
2i2c.org

The International Interactive Computing Collaboration

- **Non-profit.**
- **Service provider** for interactive computing infrastructure.
- An R&D team that **contributes back to open source** communities.
No vendor lock-in + community empowerment

Customers have the right to replicate their infrastructure in its entirety elsewhere, with or without 2i2c.

A shared responsibility model empowers the community to learn cloud development skills and aid in maintaining the infrastructure.

2i2c.org/right-to-replicate

2i2c is committed to running its own infrastructure on open-source tools and vendor-agnostic infrastructure, though it does not force users to use only open-source tools in their own environments, code, and data. Below is a table describing how the Right to Replicate fits into 2i2c hub technology.

(Definitions of MUST, MUST NOT, SHOULD, MAY, etc are defined in RFC 2119)

<table>
<thead>
<tr>
<th>User Code and Data</th>
<th>May be Open Source</th>
<th>We encourage adopting and producing open source code and data, but this is up to the user, e.g., licenses for user content/code</th>
</tr>
</thead>
<tbody>
<tr>
<td>User Environment</td>
<td>Should be Open Source</td>
<td>Strong preference for open source tools only, although in some cases user needs may override this. e.g., Python, R, PyData stack.</td>
</tr>
<tr>
<td>2i2c Infrastructure</td>
<td>Must be Open Source</td>
<td>Strong commitment to using only open source software. e.g., JupyterHub, Kubernetes, Postgresql</td>
</tr>
<tr>
<td>Cloud Provider Infrastructure</td>
<td>Must be Portable</td>
<td>See this blog post for more information.</td>
</tr>
</tbody>
</table>
Community of Practice

- Experts in Cloud Infrastructure and Open Source Development
- Usually 2i2c staff.

Collaborate via…

- Communicate around hub deployment and incidents
- Co-develop Open Source Software
- Share infrastructure management skills (if desired)

Community Guidance Team

- Experts in service design and community guidance.
- Usually 2i2c staff.

Collaborate via…

- Communicate change requests and issues
- Co-create content to guide users
- Discuss potential cloud / OSS improvements

Community Leadership Team

- Experts in community goals, needs, and dynamics.
- Usually members of a community.

Collaborate via…

- Refine and discuss issues to improve service
- Align on direction of service and tools
- Prioritize and plan development efforts

Cloud Engineering Team

- Experts in Cloud Infrastructure and Open Source Development
- Usually 2i2c staff.
CryoCloud: accelerate discovery and enhance collaboration

Community Hub
cryointhecloud.2i2c.cloud

Custom Environments

Online Content

Cloud Infrastructure

Support and Services

2i2c
the international interactive computing collaboration

Students, researchers, developers, educators
JupyterHub: a rich workbench

- File management
- Full terminal workflow

Markdown w/preview editing (or Python, R, Latex, Bash, C++, …)
Building collaborative and transferable community standards and infrastructure

Cryosphere Communities

Community Hubs

CryoPartners

icesat.2i2c.cloud

wais.2i2c.cloud

cryointhecloud.2i2c.cloud

Community Leadership (community)

Cloud Engineer (2i2c)

Community Guidance (2i2c)

Documentation and Training

community docs

JB 2i2c-org/docs

new collaboration tools

aws

new.2i2c.cloud

Other science Communities (SMCE, future hubs)

Community Hub

CryoPartners

icesat.2i2c.cloud

wais.2i2c.cloud

cryointhecloud.2i2c.cloud

Community Hub

Cloud Infrastructure

Open Science Infrastructure Team

 Others.2i2c.cloud

icesat.2i2c.cloud

wais.2i2c.cloud

cryointhecloud.2i2c.cloud

Community Leadership (community)

Cloud Engineer (2i2c)

Community Guidance (2i2c)

Cloud Infrastructure

2i2c-org/docs

2i2c-org/infrastructure

new.2i2c.cloud

new collaboration tools