Thawing Permafrost
“the tipping time bomb”

Dr Richard Waller
Senior Lecturer in Physical Geography
School of Physical & Geographical Sciences
GA Consultant
https://www.youtube.com/watch?v=FLCgybStZ4g
Session Outline

1. Curriculum context
2. Arctic Climate Change
3. Permafrost: a Brief Introduction
4. Permafrost Degradation & Thermokarst
5. Permafrost and the Global Carbon Cycle
1. Curriculum Context
Comment at the GA Conference in 2017...
Big surprise (and fundamental misconception) is the inclusion of periglacial landforms and landscapes within new A-level specifications.

“...modern usage of the term “periglacial” refers to a range of cold, non-glacial processes”
### 3.1.2.4 Cold environments

<table>
<thead>
<tr>
<th>Key idea</th>
<th>Specification content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold environments (polar and tundra) have a range of distinctive characteristics.</td>
<td>The physical characteristics of a cold environment. The interdependence of climate, permafrost, soils, plants, animals and people. How plants and animals adapt to the physical conditions. Issues related to biodiversity.</td>
</tr>
<tr>
<td>Development of cold environments creates opportunities and challenges.</td>
<td>A case study of a cold environment to illustrate: development opportunities in cold environments: mineral extraction, energy, fishing and tourism challenges of developing cold environments: extreme temperature, inaccessibility, provision of buildings and infrastructure.</td>
</tr>
<tr>
<td>Cold environments are at risk from economic development.</td>
<td>The value of cold environments as wilderness areas and why these fragile environments should be protected. Strategies used to balance the needs of economic development and conservation in cold environments – use of technology, role of governments, international agreements and conservation groups.</td>
</tr>
</tbody>
</table>

**GCSE Coverage (e.g. AQA)**

**3.1 Living with the Physical Environment**

**3.1.2 Section B: The Living World**

A-Level Coverage (e.g. OCR)

### 1.1.2 Option B – Glaciated Landscapes

<table>
<thead>
<tr>
<th>Key Ideas</th>
<th>Content</th>
</tr>
</thead>
</table>
| 1.a. Glaciated landscapes can be viewed as systems. | • A conceptual overview of:  
  ◦ the components of glaciated landscape systems, including inputs, processes and outputs  
  ◦ the flows of energy and material through glaciated systems  
  ◦ glacier mass balance. |
| 1.b. Glaciated landscapes are influenced by a range of physical factors. | • Potential influences on glaciated landscape systems of:  
  ◦ climate, including precipitation totals and patterns  
  ◦ geology, including lithology and structure  
  ◦ latitude and altitude  
  ◦ relief and aspect on microclimate and glacier movement. |
| 1.c. There are different types of glacier and glacier movement. | • The characteristics of different types of glacier and their movement, including:  
  ◦ the formation of glacier ice  
  ◦ valley glaciers and ice sheets  
  ◦ warm-based and cold-based glaciers  
  ◦ basal sliding and internal deformation. |

**Topic 1.1 – Landscape Systems**
No mention of periglacial landscapes as systems....

### 3. How do glacial landforms evolve over time as climate changes?

<table>
<thead>
<tr>
<th>Key Ideas</th>
<th>Content</th>
</tr>
</thead>
</table>
| **3.a. Glacio-fluvial landforms exist as a result of climate change at the end of glacial periods.** | • How landforms in glaciated landscapes are influenced in post-glacial periods, including:  
  ◦ climate changes that occurred during a post-glacial period and the effect on resultant geomorphic processes  
  ◦ the influence of these processes in forming landforms, including kames, eskers and outwash plains  
  ◦ the modification of these landforms by processes associated with present and future climate changes. |
| **3.b. Periglacial landforms exist as a result of climate change before and/or after glacial periods.**   | • How landforms in periglacial landscapes are influenced by climate change, including:  
  ◦ climate changes that occurred during a previous time period and the effect on resultant geomorphic processes  
  ◦ the influence of these processes in forming landforms, including patterned ground and pingos  
  ◦ the modification of these landforms by processes associated with present and future climate changes. |

... but they appear in relation to the influence of climate change on landforms...
4. How does human activity cause change within glaciated and periglacial landscape systems?

<table>
<thead>
<tr>
<th>Key Ideas</th>
<th>Content</th>
</tr>
</thead>
</table>
| 4.a. Human activity causes change within periglacial landscape systems. | • **Case study** of one periglacial landscape that is being used by people, to illustrate:  
  ◦ the human activity taking place and the reasons for it taking place, such as resource extraction  
  ◦ the impacts on processes and flows of material, processes and/or energy through the periglacial system, such as increased heat produced by buildings  
  ◦ the effect of these impacts in changing periglacial landforms, such as thawing of permafrost  
  ◦ the consequence of these changes on the landscape, such as development of thermokarst. |
| 4.b. Human activity causes change within glaciated landscape systems. | • **Case study** of one glaciated landscape that is being used by people, to illustrate:  
  ◦ the human activity taking place and the reasons for it taking place, such as dam construction  
  ◦ the impacts on processes and flows of material, processes and/or energy through the glacial system, such as trapping of sediment  
  ◦ the effect of these impacts in changing glacial landforms, such as increased channel scour below dams  
  ◦ the consequence of these changes on the landscape, such as changes to valley floor. |

...and in relation to the impact of human activity.
Topic 1.2 – Earth’s Life Support Systems
Combined consideration of water & carbon cycles with Arctic tundra appearing as a specific case study example.

### 3. How much change occurs over time in the water and carbon cycles?

<table>
<thead>
<tr>
<th>Key Ideas</th>
<th>Content</th>
</tr>
</thead>
</table>
| 3.a. Human factors can disturb and enhance the natural processes and stores in the water and carbon cycles. | • Dynamic equilibrium in the cycles and the balance between the stores and the flows.  
• Land use changes, such as growth in urban areas, farming and forestry, as a catalyst for altering the flows and stores in these cycles.  
• How water extraction, including surface extraction and sub-surface groundwater extraction (including aquifers and artesian basins) impact the flows and stores in these cycles.  
• The impact of fossil fuel combustion and carbon sequestration on flows and stores of carbon.  
• Positive and negative feedback loops within and between the water and carbon cycles. |
| 3.b. The pathways and processes which control the cycling of water and carbon vary over time. | • Short term changes to the cycles and the significance of these changes, including diurnal and seasonal changes of climate, temperature, sunlight and foliage.  
• Long term (millions of years) changes in the water and carbon cycles, including changes to stores and flows.  
• The importance of research and monitoring techniques to identify and record changes to the global water and carbon cycles; reasons why this data is gathered. |

Additional focus on the human impacts on the cycling of water and carbon and the nature of short and long term changes and their wider implications.
2. Arctic Climate Change
2019 Arctic Report Card

The Arctic marine ecosystem and the communities that depend upon it continue to experience unprecedented changes as a result of warming air temperatures, declining sea ice, and warming waters. Arctic Report Card 2019 draws particular attention to the Bering Sea region, where declining winter sea ice exemplifies the potential for sudden and extreme change. Indigenous Elders from the Bering Sea region offer their experiences of living at the forefront of climate change.

Highlights:

- The average annual land surface air temperature north of 60° N for October 2018-August 2019 was the second warmest since 1900. The warming air temperatures are driving changes in the Arctic environment that affect ecosystems and communities on a regional and global scale.
- The Greenland Ice Sheet is losing nearly 267 billion metric tons of ice per year and currently contributing to global average sea-level rise at a rate of about 0.7 mm yr⁻¹.
- The North American Arctic snow cover in May 2019 was the fifth lowest in 53 years of record. June snow cover was the third lowest.
- Tundra greening continues to increase in the Arctic, particularly on the North Slope of Alaska, mainland Canada, and the Russian Far East. Thawing permafrost throughout the Arctic could be releasing an estimated 300-600 million tons of net carbon per year to the atmosphere.
- The thickness of the sea ice has also decreased, resulting in an ice cover that is more vulnerable to warming and air temperatures.
- August mean sea surface temperatures in 2019 were 1-7°C warmer than the 1982-2010 August mean in the Beaufort and Chukchi Seas, the Laptev Sea, and Baffin Bay.
- Satellite estimates showed ocean primary productivity in the Arctic was higher than the long-term average for seven of nine regions, with the Barents Sea and North Atlantic, the only regions showing lower than average values.
- Wildlife populations are showing signs of stress. For example, the breeding population of the ivory gull in the Canadian Arctic has declined by 70% since the 1980s.
- The winter sea ice extent in 2019 narrowly missed surpassing the record low set in 2018, leading to record-breaking warm ocean temperatures in 2019 on the northern Bering shelf. Bottom temperatures on the northern Bering shelf exceeded 4°C for the first time in November 2018.
- Bering and Barents Sea fisheries have experienced a northerly shift in the distribution of subspecies and Arctic fish species, linked to the loss of sea ice and changes in bottom water temperature.
- Indigenous Elders from Bering Sea communities note that “[i]n a warming Arctic, access to our subsistence foods is shrinking and becoming more hazardous to hunt and fish. At the same time, thawing permafrost and more frequent and higher storm surges increasingly threaten our homes, schools, airports, and utilities.”

Citing the complete report:

Citing an essay (for example):
Change in average annual land surface temperatures between 1900-2019. Note how the rate of increase in the high latitude stations is much more rapid than the globally averaged figure.

Mean annual surface temperature for Oct 2018 – Sept 2019 was 1.9°C higher than the 1981-2010 mean.

NOAA Arctic Report Card, p6
Second lowest recorded minimum sea ice extent in 2019

http://nsidc.org/arcticseaicenews/
Arctic Sea Ice Extent

(Area of ocean with at least 15% sea ice)
Extreme summer melt events on the Greenland Ice Sheet


Below: Melt area over the summer for a series of high-melt years and the longer term average.

https://nsidc.org/greenland-today/
Arctic Wildfires

Record breaking summer temperatures in Alaska (right) and Siberia (below) have triggered extensive wildfires that have released significant amounts of black carbon (bottom right).

AMAP – Arctic Monitoring & Assessment Programme

https://www.amap.no/
Projected Surface Air Temperature Change
(change from 1981-2000 Average)

http://amap.no/acia/

Film presenting the results of AMAP's 2017 assessment of Snow, Water, Ice and Permafrost in the Arctic. An extended (10 minute) video film is also available on the AMAP vimeo site (www.vimeo.com/amap).
Melting Arctic link to cold, snowy UK winters

By Richard Black
Environment correspondent, BBC News

The progressive shrinking of Arctic sea ice is bringing colder, snowier winters to the UK and other areas of Europe, North America and China, a study shows.

As global temperatures have risen, the area of Arctic Ocean covered by ice in summer and autumn has been falling.

Writing in Proceedings of the National Academy of Sciences (PNAS), a US/China-based team show this affects the jet stream and brings cold, snowy weather.

3. Permafrost: a brief introduction…

Massive ice within the Mackenzie Delta region, western Canadian Arctic
What is permafrost?

Thermal condition in soil and rock where temperatures below 0°C persist over at least two consecutive winters.

- Dependent solely upon temperature and time.
- Not dependent upon the presence of water.
- Originally an abbreviation of permanently frozen ground. But...

Permafrost ≠ frozen ground
Massive ice at the Nicholson Peninsula…

…bedrock at Yellowknife…

…ice within a Finnish peat bog…

ALL PERMAFROST
Classic Schematic Cross Section through Permafrost

French, H.M. 2007, Periglacial Environments. p84
Transect running up through the Mackenzie Valley to the Canadian Arctic (right to left).

(Selby, M.J., 1981. The Earth’s Changing Surface)
4. Permafrost Degradation

Retrospective thaw slump on Summer Island, Mackenzie Delta
Thermokarst processes associated with the thawing ice-rich permafrost and the associated disturbance of the landscape (from French, 1994, p111)
Illustration of the volumetric loss and thaw subsidence associated with terrain disturbance and the melting of excess ice.

(Williams & Smith, 1989, p77)
One of a series of houses built on a site of ice-rich permafrost in the 1960s in Fairbanks, Alaska due to inadequate site investigation. Now undergoing thaw subsidence.
1.3 million people in Russia live in urban areas underlain by permafrost. E.g. Norilsk (176,000).

Rapid building during 1960s – 1980s has resulted in permafrost degradation between 70% of buildings.

In 2010 deformation had affected 174 buildings and over 12,000 people.

New phase of construction involving much lighter designs.
CALM project website provides access to raw data on changing active layer thicknesses over time in different places that is ideal for quantitative analyses.

https://www2.gwu.edu/~calm/

---

### CALM SUMMARY DATA

**North America**

**United States (Alaska)**

**Alaska North Slope**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>U24</td>
<td>Draw Point</td>
<td>70.62 N</td>
<td>152.55 W</td>
<td>T86/D4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>37</td>
<td>37</td>
<td>37</td>
<td>37</td>
<td>37</td>
<td>37</td>
<td>37</td>
<td>37</td>
<td>37</td>
<td>37</td>
<td>37</td>
<td>37</td>
<td>37</td>
<td>37</td>
<td>37</td>
<td>37</td>
<td>37</td>
<td>37</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U25</td>
<td>Intech</td>
<td>70.26 N</td>
<td>152.06 W</td>
<td>T86/D5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U26</td>
<td>Fish Creek</td>
<td>70.29 N</td>
<td>152.02 W</td>
<td>T86/D5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U27</td>
<td>Amaan2</td>
<td>69.17 N</td>
<td>150.01 W</td>
<td>T86/D4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U28</td>
<td>Umat</td>
<td>69.24 N</td>
<td>152.05 W</td>
<td>T86/D9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U29</td>
<td>Tenika</td>
<td>70.26 N</td>
<td>152.62 W</td>
<td>T86/D7</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U30</td>
<td>Ninigami</td>
<td>69.53 N</td>
<td>142.59 W</td>
<td>T86/D6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U31</td>
<td>Kukulaka</td>
<td>69.45 N</td>
<td>154.37 W</td>
<td>T86/B1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U32</td>
<td>Mushtasch Creek</td>
<td>69.48 N</td>
<td>154.68 W</td>
<td>T86/D5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U33</td>
<td>South Meade</td>
<td>70.36 N</td>
<td>156.20 W</td>
<td>T86/B</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U34</td>
<td>Cameron Bay</td>
<td>69.58 N</td>
<td>144.48 W</td>
<td>T86/D2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U35</td>
<td>Amaan1</td>
<td>69.69 N</td>
<td>158.02 W</td>
<td>T86/B</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U36</td>
<td>Red Sheep Creek</td>
<td>68.41 N</td>
<td>144.56 W</td>
<td>T86/B1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U37</td>
<td>Pikaayuk</td>
<td>70.71 N</td>
<td>151.01 W</td>
<td>T86/D6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U38</td>
<td>East Tuktsap</td>
<td>70.02 N</td>
<td>155.54 W</td>
<td>T86/D6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U39</td>
<td>Tuktsap</td>
<td>70.28 N</td>
<td>154.22 W</td>
<td>T86/B1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

**CALM SUMMARY DATA**

**North America**

**United States (Alaska)**

**Alaska North Slope**

The summary table is available for download in Microsoft Excel (XLS) format.
The summary table is available for download in Google Earth (KML) format.
The summary table is available for download in GIS (ArcGIS Shape) format.
Thermokarst Activity: the landscape response to rapid climate change

Degradation of ice-wedge polygons and associated thermokarst subsidence and pond development near Prudhoe Bay, Alaskan Coastal Plain
Expansion of melt ponds due to the degradation of ice-wedge polygons (thermokarst) since 1970 in uplands of the Yukon Coastal Plain.
Thaw Lakes on the Arctic Coastal Plain of Alaska
Coastal thermokarst: Thermal erosion and collapse of an ice-rich coastline on the Beaufort Sea coast, following a summer storm event.

(www.awi-potsdam.de/www-pot/geo/acd/cbs/beaufort14.jpg)
Coastal erosion in Shishmaref, Eastern Alaska

Arctic Coastal Dynamics website: Provides access to an online GIS (key skill) as well as a photoglossary.
http://arcticcoast.info/
Retrogressive Thaw Slumps
“Megaslump” on Peel Plateau, Canadian NWT

Image credit: Rob Fraser (CCRS)
Distribution of thaw slumps within the Western Canadian Arctic mapped using SPOT satellite imagery. High or medium = >6 slumps within the 15km x 15km grid cell. (Image credit: Steve Kokelj)
Conservative estimates suggest that 136,000 km² of this study area is affected by these landscape disturbances with their extent increasing rapidly over time.
Hydrological implications: Major impacts on water quality as the sediment is transported into major river systems (e.g. the Mackenzie River).
5. Permafrost Degradation and the Global Carbon Cycle
Global carbon stores and fluxes: Note how much carbon is estimated to be stored in permafrost alone - more than the carbon currently in the atmosphere. [https://nsidc.org/cryosphere/frozenground/methane.html](https://nsidc.org/cryosphere/frozenground/methane.html)
Methane and Frozen Ground

Kevin Schaefer is a permafrost scientist at NSIDC. He studies the carbon cycle, or the processes by which the Earth's carbon moves around: from the air into plants, from plants into the ground, and then back into the air (Figure 2). Dr. Schaefer studies the carbon that is frozen deep in Arctic permafrost. As the Earth warms, scientists worry that some of the carbon in permafrost could escape to the atmosphere as carbon dioxide or methane. Increasing the amount of these gases in the atmosphere could make Earth's climate warm up even more. See Climate and Frozen Ground for more information on greenhouse gases and climate warming.

Here Dr. Schaefer provides some answers to questions about methane and frozen ground.

What is methane?
Methane is a gas made up of one carbon atom and four hydrogen atoms. It's the same
Yedoma (carbon-rich permafrost)

Ice-rich silt deposited during the Pleistocene, covering >1 million km$^2$ of north plains of Siberia & Central Alaska to mean depth of ~25 m

- Contain grass roots & animal bones (av. C concentration for yedoma ~2.6%)
- Carbon reservoir in frozen yedoma ~500 Gt

Exposed carbon-rich soils from Kolyma River, region Siberia. Soils are 53 m thick; massive ice wedges are visible.

Soil close-up showing 30,000-year-old grass roots preserved in permafrost
A1.3 Permafrost temperatures have increased to record high levels (1980s-present) (very high confidence) including the recent increase by 0.29°C ± 0.12°C from 2007 to 2016 averaged across polar and high-mountain regions globally. Arctic and boreal permafrost contain 1460–1600 Gt organic carbon, almost twice the carbon in the atmosphere (medium confidence). There is medium evidence with low agreement whether northern permafrost regions are currently releasing additional net methane and CO₂ due to thaw. Permafrost thaw and glacier retreat have decreased the stability of high-mountain slopes (high confidence). [2.2.4, 2.3.2, 3.4.1, 3.4.3, Figure SPM.1]
Complex feedbacks

**Positive:** Permafrost thaw allows the frozen organic matter to be digested by microbes resulting in the release of either CO$_2$ (aerobic conditions) or CH$_4$ (anaerobic conditions).

**Negative:** Increased temperatures and longer growing seasons will increase vegetation growth, biomass production and carbon sequestration.
Thaw lake expansion & methane ebullition

- Permafrost degradation results in the expansion of thaw lakes.
- Release of methane primarily through the ebullition (bubbling).
- Estimated release of 3.8 terragrams of methane per year.
- Study estimated that accelerating thaw lake expansion resulted in a 58% increase in methane emissions between 1974-2000.


Gas Hydrates

- Ice-like combinations of natural gas and water.
- Only stable under low temperatures & high pressures.
- Onshore and offshore accumulations associated with permafrost.
- Permafrost thaw would result in release of methane.
- BUT – size of the store and potential for release is poorly understood.
https://www.youtube.com/watch?v=jc-FFhdNG9A
Present day natural vegetation of the Arctic and neighboring regions from floristic surveys.

Projected potential vegetation for 2090–2100, simulated by the LPJ Dynamic Vegetation Model driven by the Hadley2 climate model.
Conclusions

• Permafrost is a key component of the global cryosphere underlying c. 24% of Northern Hemisphere land area.
• Extensive ground ice coupled with rapid warming renders permafrost regions uniquely sensitive to climate change.
• Rates of recent and projected warming are at their most rapid in the Arctic – roughly double the global average.
• Rapid and accelerating thermokarst activity: coastal recession, thaw lakes expansion, “megaslumps”…
• Significant implications for the global carbon cycles (and associated uncertainties).
• Arctic is currently thought to be a carbon sink.
• BUT – methane emissions are rapidly increasing and the Arctic is predicted to be a net carbon source.
Thanks for listening…!

Any questions?
Email: r.i.waller@keele.ac.uk
Twitter: @wallersaur