Plan to finish line

Today: Permafrost

Thursday: Clathrate Methane Hydrates, Black Carbon, Water resources. See Posted Reading Kehrwald et al 2008 and Barnett et al 2005

Next Week:

Project Presentations
  Tues Thurs next week or
  Thurs and during our scheduled Final: Friday 2:30-4:30 (then we will have a bonus class on Tues)
An ice massive/ground ice (the blue stuff) and active layer (grey above, experiences seasonal thaw)

http://gsc.nrcan.gc.ca/permafrost/suppdoc_e.php
pictures from
http://www.gi.alaska.edu/snowice/Permafrost-lab/
Amounts to 7 cm of sea level rise

Discontinuous is first to thaw in global warming scenario
Permafrost is any soil/rock with Temperature < 0°C for 2 or more years (there need not be ice present)

It has a lower reach owing to geothermal heating

The active layer experiences seasonal thaw
Soil permeability is determined by soil pore structure. Permafrost pores are often filled with ice, so water collects at surface when active layer is frozen or at a permafrost-active layer interface when active layer is thawed.
Polygons formed by ice wedges in between (to be explained shortly)
Lakes known as thermokarst sitting in polygons ice blocks their drainage (to be explained shortly)
A pingo - ice massive (to be explained shortly)
A cut-away view of the tundra in summer. The active layer is thawed.

**Sky**

**Active Layer (thaws in summer)**

**Permafrost (permanently frozen ground)**

Winter cold causes the soil to shrink, and cracks to form. The active layer is frozen, so it acts just like the permafrost soils beneath it.

**Snow**

During warm spring days, water seeps into the cracks. It freezes and expands when it is chilled by the still-frozen soil. The frozen water forms wedges of ice in the soil.

http://arctic.fws.gov/permocyc.htm
This cycle of crack, melt, and freeze continues to enlarge the wedges year by year...

until the soil above the wedges is pushed up, forming ridges. If you look down from above, these ridges create a blocky pattern on the ground, called polygons.

If the ice is exposed, a wedge may begin to melt.
until a pond begins to form.

The pond water holds heat from the summer sun, so the active layer melts deeper beneath the water.

Seen from above, these lakes (called thermokarst lakes) can become longer in one direction when prevailing winds blow waves against the downwind shore.
The lake side may break down, causing the lake to drain.

Without its insulating cover of water, the active layer begins to refreeze.

In winter, the surface freezes over a thawed remnant of the active layer.
As the unfrozen area continues to contract, the unfrozen water is squeezed under great pressure.

Eventually, the water is under such pressure that it pushes upward (the direction of least resistance)... until the unfrozen water collects under the root mat, and freezes, creating a pingo.
Flow deforms overlying surface.
Bemhard Edmair (National Geographic)
~3-30m across
rivers are braided because there isn't enough vegetation to prevent erosion.
Where O₂ is plentiful, decomposition makes CO₂. But in anaerobic environments as shown, decompositions makes CH₄, which is then oxidized over time to CO₂ and H₂O.

Warmer temperatures, rain, or thawing permafrost raises CH₄ emissions, perhaps a great deal.

Methane Sources:
A. Mining and natural gas leaks
B. Agriculture: ruminants
C. Landfills
D. Agriculture: rice paddies
E. Natural wetlands
F. Hydrates
Goal: Represent Arctic terrestrial feedback processes in a global Earth System Model

- Global warming
- CO₂ efflux
- CH₄ efflux
- Permafrost warms and thaws
- Expanded wetlands
- Lakes drain, soil dries
- Microbial activity increases
- Shrub growth
- Enhanced [nitrogen]
- Carbon sequestration
- Arctic runoff increases

by David Lawrence

Adapted from McGuire et al.
albedo
feedback

Photograph by Bernhard Edmaier
Discuss Paper
Site Location

The mean annual air temperature (1980-2005) was -1.0 °C in Healy, Alaska and the mean annual precipitation was 390 mm. During the study period, (spring 2004-winter 2006-07), annual air temperature was cooler than the mean by 1-2 °C. Annual precipitation was greater in 2005 (540 mm) and 2006 (472 mm) than the longterm average, but was less in 2004 (324 mm). Permafrost temperatures have been monitored in a 30 m deep borehole in the study area since 1985 (maximum temperature range = -0.7 to -1.2 °C at 10 m during mid-August). During this time frame, researchers recorded rapidly increasing deep permafrost temperatures (by ~0.7 °C at 10 m) from 1990 until 1998, followed by a more recent slight cooling (by ~0.15 °C) between 1998 and 2004.
Alaska Temperature Stable since 1975

- The period 1949 to 1975 was substantially colder than the period from 1977 to 2009, however since 1977 little additional warming has occurred in Alaska with the exception of Barrow and a few other locations. The stepwise shift appearing in the temperature data in 1976 corresponds to a phase shift of the Pacific Decadal Oscillation from a negative phase to a positive phase. Synoptic conditions with the positive phase tend to consist of increased southerly flow and warm air advection into Alaska during the winter, resulting in positive temperature anomalies.

Definitions

- The eddy covariance (also known as eddy correlation and eddy flux) technique is a key atmospheric flux measurement technique to measure and calculate vertical turbulent fluxes within atmospheric boundary layers. It is a statistical method used in meteorology and other applications that analyzes high-frequency wind and scalar atmospheric data series, and yields values of fluxes of these properties. Such flux measurements are widely used to estimate momentum, heat, water, and carbon dioxide exchange.

- Gross primary production (GPP) is the rate at which an ecosystem's producers capture and store a given amount of chemical energy as biomass in a given length of time – this is the amount of carbon taken out of the atmosphere.

- Ecosystem respiration is the production portion of carbon dioxide in an ecosystem's carbon flux – this is the amount of carbon released into the atmosphere. Thus, more respiration means more CO2 into atmosphere. Think of it in terms of this – in human respiration – we exhale CO2. It's a similar thing here.

- The difference between gross primary production (GPP) and ecosystem respiration (Reco) equals the net ecosystem exchange (NEE) of C.
Main point of the study?

- Obtain a better estimate of how much carbon in the permafrost could get back into the atmosphere. To do this, we must quantify the amount of old undecayed material in the permafrost.

- We find that areas that thawed over the past 15 years had 40 per cent more annual losses of old carbon than minimally thawed areas, but had overall net ecosystem carbon uptake as increased plant growth offset these losses.

- In contrast, areas that thawed decades earlier lost even more old carbon, a 78 per cent increase over minimally thawed areas; this old carbon loss contributed to overall net ecosystem carbon release despite increased plant growth.
Permafrost thaw → Release of old C → Absolute & relative old C incr in atmosphere

Temperature increases

Permafrost thaw → Ground subsidence

Hydrological redistribution

Plant metabolism

Decomposition of recently dead plant tissue

Decomposition of old C (old C loss)

Positive and proportional relationship will exist between $R_{eco}$ and old C loss

Ecosystem respiration ($R_{eco}$)

To prove the hypothesis
1) Measure $R_{eco}$ from carbon flux measurements
2) Separate contribution of the old C loss from $R_{eco}$

Once being the hypothesis confirmed,
1) Extending observed C exchange rates into the future
2) Applying the rate to the global surface permafrost
How???

- Permafrost is DEEP. The layers down below contain A LOT of stored carbon from decayed organic matter that simply did not decompose due to all the cold. Once the permafrost DEEP DOWN starts to thaw, A LOT of the stored carbon can go up into the atmosphere, causing a positive feedback with temperature.

- So the purpose of the study is to try to separate out the contributions of the DEEP layers and the SHALLOW layers of the permafrost, since they may release CO2 at different rates.

- Much of this stored carbon comes from plants. But a lot of it also comes from other organisms too – some of it comes in the form of well-preserved woolly mammoth corpses [and other of course] – and we're starting to discover MORE AND MORE of them in Siberia now that the permafrost is thawing out. And they're going to decay unless we rescue them and store them.
Measurement and Analysis I

Three sources of CO₂ (old C loss/plant metabolism/dead plant tissue) in total Reco

Significant temporal variation in $\Delta^{14}$C reflects changes in the relative contribution of the three factors, and old C loss is the only source for $\Delta^{14}$C values below the current atmospheric value

Separation of the old C contribution via a statistical isotope mass balance approach using the laboratory incubations of plants and soil
Measurement and Analysis II

Statistical of the contribution of different respiration sources (plants, surface soil, deep soil) to total ecosystem respiration.

<table>
<thead>
<tr>
<th>Site</th>
<th>Year</th>
<th>GPP</th>
<th>Reco</th>
<th>NEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimal</td>
<td>2004</td>
<td>327±20</td>
<td>-287±12</td>
<td>40±16</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>305±14</td>
<td>-276±13</td>
<td>29±4</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>329±24</td>
<td>-266±18</td>
<td>62±14</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>320±19</td>
<td>-276±15</td>
<td>44±11</td>
</tr>
<tr>
<td>Moderate</td>
<td>2004</td>
<td>445±48</td>
<td>-339±36</td>
<td>105±26</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>383±34</td>
<td>-340±24</td>
<td>43±24</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>430±51</td>
<td>-313±30</td>
<td>117±36</td>
</tr>
<tr>
<td></td>
<td></td>
<td>419±44</td>
<td>-331±30</td>
<td>88±29</td>
</tr>
<tr>
<td>Extensive</td>
<td>2004</td>
<td>449±56</td>
<td>-403±37</td>
<td>48±23</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>375±28</td>
<td>-393±36</td>
<td>-17±13</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>480±83</td>
<td>-359±58</td>
<td>121±31</td>
</tr>
<tr>
<td></td>
<td></td>
<td>435±58</td>
<td>-385±44</td>
<td>50±22ab</td>
</tr>
</tbody>
</table>

Growing season estimates of gross primary productivity (GPP), ecosystem, respiration (Reco), and net ecosystem exchange (NEE).

![Graph showing carbon loss over years](image_url)

Statistical of the contribution of different respiration sources (plants, surface soil, deep soil) to total ecosystem respiration.
Thawing – notice how respiration increases A LOT at the magic point of 0 degrees C. Also notice that the line for extensive thaw has a higher increase (in ecosystem respiration) for each increase in temperature.

Supplementary Figure 4. Ecosystem respiration as a function of average integrated soil profile temperature (10-40 cm depth) for winter (a) and on an annual basis (b). Winter respiration measurements below -2°C were described by a single exponential relationship for all sites because there were no differences. Respiration measurements between -2°C and 0°C were described by site-specific lines; here the minimal and moderate lines overlap. Growing season respiration measurements above 0°C show site-specific exponential relationships. The site-specific lines are shaded black (extensive), dark grey (moderate), and off-white (minimal) for clarity.
Also...

Winter Months Matter!

Overall, C loss during winter accounted for 15–18% of ecosystem respiration (Reco) on average across all sites. Winter C loss was large enough to switch the minimal and extensive sites, which were net C sinks in the growing season, to annual net C sources on average across years (Supplementary Table 2).

So why does winter matter? TIME LAG

Figure 4.2 Annual temperature waves in the weekly averaged subsurface soil temperatures at two depths in a sandy loam soil. Fitted solid curves are sine waves: Deacon (1969); after West (1952).
So where does this time lag come from?

Much about the physics of thermal wave propagation can be learned, however, from a simple analytic solution which is obtained when the surface temperature is specified as a sinusoidal function of time and the subsurface medium is assumed to be homogeneous throughout the depth of wave propagation

\[ T_s = T_m + A_s \sin[(2\pi/P)(t - t_m)] \]  
(4.5)

Here, \( T_m \) is the mean temperature of the surface or submedium, \( A_s \) and \( P \) are the amplitude and period of the surface temperature wave, and \( t_m \) is the time when \( T_s = T_m \), as the surface temperature is rising.

The solution of Equation (4.3) satisfying the boundary conditions that at \( z = 0, T = T_s(t) \), and as \( z \to \infty, T \to T_m \), is given by

\[ T = T_m + A_s \exp(-z/d) \sin[(2\pi/P)(t - t_m) - z/d] \]  
(4.6)

which the reader may verify by substituting in Equation (4.3). Here, \( d \) is the damping depth of the thermal wave, defined as

\[ d = (P\alpha_h/\pi)^{1/2} \]  
(4.7)

Note that the period of thermal wave in the soil remains unchanged, while its amplitude decreases exponentially with depth (\( A = A_s \exp(-z/d) \)); at \( z = d \) the wave amplitude is reduced to about 37\% of its value at the surface and at \( z = 3d \) the amplitude decreases to about 5\% of the surface value. The phase lag relative to the surface wave increases in proportion to depth (phase lag = \( z/d \)), so that there is a complete reversal of the wave phase at \( z = \pi d \). The corresponding lag in the time of maximum or minimum in temperature is also proportional to depth (time lag = \( zP/(2\pi d) \)).

The time lag in max/min of \( T \) is proportional to DEPTH, where time lag = \( zP/(2\pi d) \).

Explained in Cecilia's notes
Where does C14 come from??

There are three naturally occurring isotopes of carbon on Earth: 99% of the carbon is carbon-12, 1% is carbon-13, and carbon-14 occurs in trace amounts, i.e. making up as much as 1 part per trillion (0.0000000001%) of the carbon in the atmosphere. The half-life of carbon-14 is 5,730±40 years. Carbon-14 decays into nitrogen-14 through beta decay.[3] The primary natural source of carbon-14 on Earth is cosmic ray action upon nitrogen in the atmosphere, and it is therefore a cosmogenic nuclide. However, open-air nuclear testing between 1955-1980 contributed to this pool.
Also, one of the frequent uses of the technique is to date organic remains from archaeological sites. Plants fix atmospheric carbon during photosynthesis, so the level of 14C in plants and animals when they die approximately equals the level of 14C in the atmosphere at that time. However, decreases thereafter from radioactive decay, allowing the date of death or fixation to be estimated.

This means, basically, that if we take measurements of the permafrost, and find that our C-14 levels are below that of the ambient atmosphere, then we know that we have run into biological material that hasn't decayed for a long time – because much of the C-14 that was in there had already decayed [ANOTHER TYPE OF DECAY] into N-14 – and this is the old biological material we're looking for.

Especially important for deep-soil respiration measurements, since it's VERY hard to get into the deep soil so we know LITTLE about it right now.
Thawing => decomposition => more CO2 in atmosphere
But also, thawing => increased plant uptake of CO2. Nonetheless, most of our new plants die within one season so they don't store up CO2 like trees do.

Why measure Delta C-14? Well, we have to ask the question – what is the main point of the paper? It is to attempt a PRELIMINARY quantification of a previous unknown – that previous unknown being the contribution of carbon from undecayed biological material from LONG AGO. Basically, we are trying to quantify the AMOUNT of undecayed carbon that currently exists in the subarctic, so that we can use them as endpoints in our analysis (and then use a weighted sum of the endpoint carbon-14 values – and put them in our models). C-14 allows us to measure the age and RELATIVE PROPORTION of the UNSTORED material so that we can put that in our models (that predict the amount of material down there AND the upper/lower bounds to the amount of material that is deposited down there THROUGH biological processes) and output a BETTER estimation of how much Carbon will get back into the atmosphere.

This process (of undecayed material decaying and sending CO2 into the atmosphere) is sort of similar to what we're doing by burning coal and oil. We're transferring stored-up carbon (in the old remains of plants and animals that decayed into coal/oil) into the atmosphere. Here, stored-up carbon is also being transferred into the atmosphere through a natural process (accelerated by humans, of course).

- We have three endpoints: (a) recently decaying biological material [with C-14 ratios SIMILAR to background levels], (b) material from the 1950s [with MUCH higher ratios thank to bomb tests] and (c) material from CENTURIES ago [with much LOWER ratios since they haven't decayed for a LONG time – although their C-14 did decay]
Notes on Delta Carbon Measurement

- Radiocarbon \( \Delta^{14}C \)
- The formula for determining the \( \Delta^{14}C \) of a sample is similar to \( \delta^{13}C \):
  \[
  \Delta^{14}C = \left[ \frac{F_{N[x]}}{1} - 1 \right] \times 1000
  \]
- The difference is in the term FN[x], which is still a comparison of the sample to a standard. However, after this comparison, several other calculations occur to find FN[x].
- The ratio is corrected for "background" \( ^{14}C \) counts (see next slide), where atoms or molecules that were accidentally and incorrectly identified as \( ^{14}C \) are no longer included.
- The ratio is additionally corrected for the small amount of radioactive decay between the time the sample was collected and the time it was measured, so that the \( \Delta^{14}C \) at the time of collection rather than the time of analysis is reported.
- The final difference is that \( \Delta^{14}C \) is normalized, where the effect of fractionation is removed. That is, we know from the \( ^{13}C \) measurements that, for example, when carbon dioxide is photosynthesized by plants, it fractionates, resulting in proportionately less \( ^{13}C \) in the plant. The same thing happens to \( ^{14}C \), so plants have proportionately less \( ^{14}C \) than the atmosphere does. If we know how much \( ^{13}C \) fractionation occurs, we can calculate precisely how much \( ^{14}C \) fractionation there is. We then calculate how much \( ^{14}C \) would have been in the sample if it had not fractionated. This is the \( \Delta^{14}C \). Why go to all this trouble? The main reason is that for radiocarbon dating, scientists want to study how much \( ^{14}C \) has decayed, not how much has fractionated, and this normalization allows them to do just that. The second reason is that it makes it easier to understand the \( ^{14}C \) in the atmosphere – now when plants photosynthesize CO2, the \( \Delta^{14}C \) value in the atmosphere does not change. Of course, we can always reverse the calculations to discover the amount of \( ^{14}C \) without applying this normalization, and this is written as \( \delta^{14}C \).

http://www.esrl.noaa.gov/gmd/outreach/isotopes/deltavalues.html
C-14 measurement complications
(from background counts)
Carbon loss projections are based on the assumption that the observed three-year average fluxes are representative of longer time periods, and can be extrapolated into the future. However, this assumption is probably wrong.

What does this mean? It means that in the future, we can expect greater fluxes of carbon into the atmosphere because the zone (in depth) of thaw will increase with more thawing in the future. We simply don't know enough about the deep permafrost layers (after all, it's hard to drill into, and we're only measuring a part of it in Alaska – the biological material in Alaska is different from the material in Siberia or Scandinavia).
Also..(quoted from paper)

Our observations do not account for future thawing and active layer thickening that will expose a larger pool of permafrost C to decomposition. Also, net exchange of CO2 does not account for hydrologic C losses or methane emissions.

Also, it is known that upland and lowland sites may differ in the release rate of CO2 and methane (CH4), depending on whether aerobic or anaerobic decomposition predominates29,30. While these gases have different greenhouse warming potentials (GWP), recent calculations have suggested that the overall climate effect of thawed permafrost C decomposition is actually similar between aerobic versus anaerobic environments31. This is because total C emissions are lower from anaerobic environments, but are compensated by the higher GWP of methane.