What are the different temporal and spatial scales of ice mass changes in southern Alaska?
How do they influence crustal deformation and earthquake occurrence?

"Made with www.thegraceplotter.com, courtesy of CNES/GRGS"
Current distribution of cGPS stations in southern Alaska

But first a little context for interpreting precise geodetic measurements with the Bagley Ice Valley as an example
• The USGS made trilateration measurements on regional networks across different portions of the subduction plate boundary zone in southern Alaska including the region above (Savage and Lisowski, 1988) to assess earthquake hazard.

• Also in the 1980’s, as part of NASA’s Crustal Dynamics Project, the first precise space-geodetic measurements of crustal deformation at southern Alaska sites were made in a global reference frame using mobile Very Long Baseline Interferometry (VLBI) (Ma et al., 1990).
Global Positioning System receiver set up over geodetic mark that we measured multiple times to look for changes in position starting in May 1993.
HOUSTON WE HAVE A PROBLEM
Annual variations in snow and ice on glaciers: 1-8+ meters in ablation region, not well documented in accumulation region but 10s of meters estimated. Use NASA GRACE results (2002-present) and snow models to estimate the timing and magnitude of seasonal crustal deformation. Evaluate seismic rate changes.

Years Retreat (meters/yr thinning in ablation region of glaciers). Also more frequent glacier surges with ice unloading in surge reservoir region and ice loading in surge receiving area. Calculate predicted vertical and horizontal crustal deformation for warm years.

End of Little Ice Age (LIA) Wastage Most glaciers in southern Alaska have undergone km’s of terminus retreat with up to 100-1000 meters of ice thickness change. We calculated the stress changes associated with this wastage between ~1900-1979.

Late Pleistocene deglaciation Not modeled here due to low asthenosphere viscosities, frequent large events in southern Alaska that alter stress. Show calculated stresses associated with Late Pleistocene deglaciation and earthquake history for N America and N Europe.
Decade to century scale glacier changes:

September **1899** earthquakes probably occurred on plate interface and on upper crustal faults. 1979 earthquake started on plate interface with reverse faulting but included strike-slip.

Bruhn et al., 2004
Input the *cumulative* ice mass changes from **1899** to **1979** based on geologic field mapping by G Plafker and B Molnia.

Calculate the subsequent stresses and change in fault stability on *Main Thrust Zone* and on the *surface* (*Sauber et al., 2000; Sauber and Ruppert, 2008*).


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5 X 10^{25} \text{ Pa s}
5 X 10^{19} \text{ Pa s}
5 X 10^{21} \text{ Pa s}
```
$\Delta \sigma_1$ due to tectonic loading is predicted to be **NNW-SSE to N-S**

$\Delta \sigma_1$ due to glacial wastage is predicted to be variable but generally oriented northward

$\Delta \sigma_3$ due to tectonic loading is predicted to be directed *up*,

  similar to the $\Delta \sigma_3$ for ice removal

$\tau =$ shear stress necessary to induce failure on main thrust zone (MTZ)

$\tau_0 =$ the inherent shear strength

$\mu =$ coefficient of friction on fault surface

$\sigma_n =$ normal stress on fault
Influence of Ice Mass Changes on Earthquakes

The cumulative decrease in fault stability margin due to glacial wastage between the 1899 (Yakataga earthquake, $M = 8$) and 1979 St. Elias earthquake ($M = 7.2$) was $0.2 – 1.2$ MPa over an ~80 km region above the main thrust zone (MTZ).

We hypothesize that the ice-mass change induced stresses would promote the time to fault instability, especially in regions undergoing rapid uplift rates and north-northwest horizontal motion (to be discussed later).

Sauber and Ruppert, 2008
Elliot, Larsen, Freymueller, Motyka (2010) calculated the surface displacements due to the ice volume loss of 3030 km$^3$ from the collapse of the Glacier Bay Ice Field (beginning ~1780).

Best-fit Earth parameters:

- 50 km **Lithosphere**
- 110 km **Asthenosphere** (viscosity $3.7 \times 10^{18}$ Pa s)
- **Upper Mantle** (viscosity $4.0 \times 10^{19}$ Pa s)

**Figure 3.** Glacial isostatic adjustment model predictions for southeast Alaska. Vectors show the horizontal motion while the contours show the vertical motion. Contour label units are mm/a (Figure S1 shows a larger version).
What are the approximate stresses associated with continent scale deglaciation?

Fig. 1. Conceptual model for near-surface postglacial stresses during deglaciation. The exploded block model illustrates how the superimposition of changing glacial flexural stresses (light grey arrows) on a uniform regional tectonic stress field (black arrows) results in contrasting resultant stress states (dark grey) and different styles and orientations of stress-relief phenomena at the ice margin (A and D), the forebulge (B and E) and the undeformed foreland (C and F). Modified from Adams (1989a) after Walcott (1970). Note the considerably exaggerated vertical scale difference between the lithosphere thickness and the ice sheet thickness.

From Stewart, Sauber, Rose, QSR, 2000
Spatio-temporal variation in dFSM in N. America and N. Europe at 3 time periods at a seismogenic depth of \( \sim 12 \text{km} \). Model L1 (below) was used. Contours are in MPa (Wu, 1998)

At present both regions are still undergoing uplift (GRACE & GPS)
Based on earlier studies, post-glacial faulting (left) in the Lapland Fault Province appear to have much larger displacements, and much greater lengths, than the Canadian equivalents.

However, in both regions, most of the reported post-glacial faults are thrust faults (Wu, 1998; summary in Stewart et al., QSR volume, 2000)

<table>
<thead>
<tr>
<th>No.</th>
<th>Fault</th>
<th>Country</th>
<th>Length (km)</th>
<th>Max. scarp height (m)</th>
<th>Scarp height/fault length ratio</th>
<th>Trend</th>
<th>Type</th>
<th>Moment magnitude</th>
<th>Ref.</th>
</tr>
</thead>
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<tr>
<td>1.</td>
<td>Suasselkä</td>
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<td>48</td>
<td>5</td>
<td>0.0001</td>
<td>NE-SW</td>
<td>reverse</td>
<td>7.0</td>
<td>Kujansuu (1964)</td>
</tr>
<tr>
<td>2.</td>
<td>Pasmajärvi-Vencjärvi</td>
<td>Finland</td>
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<td>12</td>
<td>0.0008</td>
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<td>reverse</td>
<td>6.5</td>
<td>Kujansuu (1964)</td>
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<tr>
<td>3.</td>
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<td>Finland</td>
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<td>2</td>
<td>0.0003</td>
<td>NW-SE</td>
<td></td>
<td>6.0</td>
<td>Kujansuu (1964)</td>
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<tr>
<td>4.</td>
<td>Pärve</td>
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<td>150</td>
<td>13</td>
<td>0.0001</td>
<td>NE-SW</td>
<td>reverse</td>
<td>7.6</td>
<td>Lundquist and Lagerbäck (1976)</td>
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<td>5.</td>
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<td>Sweden</td>
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<td>30</td>
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<td>NE-SW</td>
<td>reverse</td>
<td>7.1</td>
<td>Lagerbäck (1979)</td>
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<td>NE-SW</td>
<td>reverse</td>
<td>6.3</td>
<td>Lagerbäck (1979)</td>
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<tr>
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<td>2</td>
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<td>NE-SW</td>
<td>reverse</td>
<td>6.5</td>
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<tr>
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<td>Sweden</td>
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<td>22</td>
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<td>NE-SW</td>
<td>reverse</td>
<td>7.1</td>
<td>Lagerbäck (1979)</td>
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<tr>
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<td>60</td>
<td>~ 10</td>
<td>0.0002</td>
<td>NE-SW</td>
<td>??</td>
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<td>7</td>
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<tr>
<td>11.</td>
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<td>Norway</td>
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<td>1</td>
<td>0.0003</td>
<td>NW-SE</td>
<td>normal</td>
<td>5.7</td>
<td>Tolgensbakk and Sollid (1988)</td>
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</table>
Hampel et al, JGR, 2009 used 3-D F.E.M. to investigated how arrays of normal & thrust faults near a growing and subsequently melting ice cap are influenced in their slip evolution. Their results indicate that regardless of fault dip both types of faults experience a decrease in slip rate during ice cap growth and an increase in slip during ice cap wastage IF located below ice cap.

Steffen et al., 2014 used a F.E.M. to predict the fault slip, activation time and the number of major seismic events.
Shorter-term Changes: Crustal deformation and seismic rate
The major faults within the upper crust are either under or near large glaciers. SO, GPS measurements of surface displacement include the viscoelastic response to ice mass changes:

- Glacier surges + tectonic strain — observed GPS displacements at ISLE and DON
- Predicted horizontal and vertical displacements due to average annual changes
- Seasonal variations and seismic rate changes
The GPS station positions for both sites are predicted to move to the north-northwest (NNW) and up due to (steady) tectonic forcing (PCFC relative NOAM)

1993-1995 surge interval versus post-surge time period, 1996-2001:

• A higher uplift rate for ISLE. Site is moving faster to the northwest. Ice unloading to the south of the site would cause uplift & north directed motion.

• In contrast, the station DON is undergoing vertical subsidence during the surge but uplift subsequently (as predicted for tectonic loading). The rate of the northward motion is lower during the surge.
1993-1995 Bering Glacier Surge: A Solid Earth Geophysicist View

Represent 10s of meters of drawdown (unloading) in surge reservoir and thickening & terminus advancement in receiving/terminus (loading) region as disc loads

As a “local load”, use elastic half-space model or radially stratified, gravitating Earth model to predict vertical and horizontal displacements [Farrell, 1972].

Elliot et al., 2013 estimates of horizontal site velocities between 2005-2008:
DON: ~43 mm/yr @N30°W
ISLE: ~20 mm/yr @N14°W

Assumptions & Limitations in predicted values:
1. 1993-1995 net transfer of ice mass from surge reservoir to receiving area over the duration of surge is equal (~14km³). GPS motions reflect magnitude of (un)loading & can be used to invert for process scaling factor.
2. Ignores seasonal snow/ice build-up & summer melting. Horizontal component is complex due to tectonic strain as well as possible push moraine toward DON due to surge.

Sauber et al., 2000
Thick coastal forest and brush mask important aspects of the geomorphology on aerial photographs, standard DEM, and X, C-band synthetic aperture radar (SAR) images.

ICESat-1 penetrated canopy but density of observations was not optimal, albeit useful!

Sauber et al., 2010
Land ice mass evolution from GRACE

- 41,168 equal area **1-arc-degree** mascons are directly estimated from GRACE KBRR L1B data with spatial and temporal exponential taper constraints applied.

- **10-day** temporal resolution

- **Spatial constraint:** 100 km correlation distance

- **Temporal constraint:** 10-day correlation

- **Gulf of Alaska glacier region (61 mascons)**

Overall G of Alaska Trend = -69 ± 11 Gt a⁻¹

Note **variability** in peak to peak seasonal amplitude and annual net balance (2005 versus 2012 balance year).

GSFC Mascon solution, Luthcke et al., *J. of Glaciology*, 2013
Yakutat NWS: Average Monthly Temperature (°C)

Average Monthly Temperature for 2005 (Warmer) versus 2012 (Colder)

NOTE: March 2005 temperatures are +3° C whereas March 2012, -2° C
Land Surface Temperature (LST) from Terra MODIS:

• Used Terra MODIS Channels 31 and 32 centered on 11.02 and 12.02 μm, respectively, are used to produce Land Surface Temperature (LST, MOD11A1) products; the cloud mask that is used in MOD11A1 is generated from another standard product, MOD35 [e.g. Hall et al., 2012, **].

• The monthly mean temperature (per 1 km pixel) for a swath through southern Alaska is given in the next several figures. The number of values used to estimate a monthly mean ranged from 5-14 days. Cloud cover in southern Alaska precludes use of LST for many days.

• The uncertainties in satellite-derived LST from multiple sensors have been evaluated in Greenland and over other snow- and ice-covered surfaces including mountainous regions [Hall et al., 2012; Forsythe et al., 2012; Koenig and Hall, 2010].

Here we use the MODIS derived LST values to contrast differences in the timing and spatial evolution of melt onset/warmer temperatures for one month, March in 2005 and 2012.

Sauber et al., Fall AGU 2013
MONTHLY Mean Land Surface Temperature (LST) from Terra MODIS (11.02 and 12.02 μm)

March 2005

March 2012

Melt onset

AC09

AB35

AB42
2002-2006 example of predicted horizontal and vertical elastic displacements per year of the solid Earth associated with average annual wastage of the coastal glaciers.

Δε_{11} due to tectonic loading is predicted to be NW-SE to N-S

Note displacements away from region of ice thinning dominate the incremental changes.

The red ellipses show an examples of a region where the calculated incremental displacements are similar to the orientation of tectonic strain.

Δε_{33} due to tectonic loading is predicted to be directed up

Sauber and Ruppert, 2008
The earthquake rate/year in 0.1 magnitude bins for the reference time period (1988-1992, o- purple dashed) and the 2002-2006 (x-blue solid) for the Icy Bay region. NOTE: the warmer time period has more events between M > 2.2 (threshold) and M <2.8 than the reference time period.

Tectonic earthquakes (left) as a function time (month) for the all (top) and three different time periods (lower three).

Sauber and Ruppert, 2008
Regional Variability:

Mascon 1425, South Eastern Alaska:
Large seasonal, up to 100 cm w.e. (p to p)
Small 10 year-trend in ice mass loss

Mascon 1457: Central Coastal (study area)
Moderate seasonal, 50 - 75 cm w.e.
Largest 10-year trend

Mascon 1484: North Central
Smaller seasonal signal
Moderate 10-year trend

* Seasonal signal more important in different areas *
Sauber et al, Fall AGU, 2013
Implications:

How do the different temporal and spatial scales of cryospheric change influence crustal deformation and earthquake occurrence?

Results suggested that a cumulative decrease in fault stability margin due to glacial wastage between 1899 (Yakataga earthquake, $M_w = 8.1$) and 1979 in the region of the St. Elias earthquake ($M_S = 7.2$) was up to 0.2-1.2 MPa over an 80 km region. Implication: The cumulative ice loss over the last 100+ are large in localized regions and could “promote in time” moderate earthquakes on upper crustal faults.

The frequency of small tectonic events in the Icy Bay region increased in the 2002-2006 warmer time interval; we tested whether this was due to the Denali earthquake or a significant increase in the rate of ice wastage. Ice changes are our preferred mechanism.

To use the exquisite set of new cGPS data from southern Alaska to evaluate earthquake hazard will require careful estimates of the crustal deformation due to cryospheric fluctuations on a variety of spatial scales and a rheologically complex Earth model.
Summary II

How does cryosphere mass change on times scales of months to years in southern Alaska?

1. The individual GRACE mascons located in distinctly different regions capture important inter-annual variations in the magnitude of the seasonal signal wastage trend.

2. These GRACE differences are important for estimating the timing and magnitude of broad-scale differences between regional GPS sites; however, more local estimates of changes in snow/ice extent and magnitude are needed to model cryosphere signal in GPS time series.

As estimated from EarthScope GPS data and FEM modeling, how do the surface displacements due to inter-annual and seasonal cryosphere mass change compare to tectonic displacement rates?

1. In the study region the surface horizontal displacements due cryosphere changes are generally $<10\%$ of the tectonic displacements whereas the vertical displacements can be comparable or than the predicted tectonic uplift rates (localized regions near glaciers).

2. With a longer history of continuous GPS, and careful management of the sites, we will be able to use GPS derived changes in vertical and horizontal displacements to constrain process oriented cryosphere changes and provide better estimates of earthquake hazard.