Glaciology (as opposed to Glacial Geology)
Why important? What are glaciers? How do they work?

Glaciers are important because of their role in creating glacial landscapes (erosional and depositional features).

Glacial extent over the globe is tightly linked to eustatic sea level, so the waxing and waning of global ice volume is strongly tied to the evolution of coastal landscapes.

Glacial ice contains high resolution records of climate history.

Ice has a planetary science interest - Martian ice caps and icy satellites of distant planets in our solar system.

Glacial control of hydrology; Outburst floods.
Glaciology – Glacier Definition and Density Profile

Working definition:
A natural accumulation of ice in motion due to its own weight and surface slope.

A comparison of density profiles for a wet (Upper Seward) and a dry (Greenland) glacier reveals the rapid metamorphism, from snow to firn to ice, characteristic of wet glacier environments.
Valley Glacier Anatomy: Ablation and Accumulation Regions

Examining the down valley anatomy of a glacier, we see that it can be divided into two parts:
1. Accumulation area
2. Ablation area

These are separated from one another by the Equilibrium Line Altitude (ELA).

*We’ll return to this figure

Figure 7.2  Schematic diagrams of a glacier (white) in mountainous topography (gray) showing accumulation and ablation areas on either side of the equilibrium line. Mapped into the vertical, z (left diagram), the net mass balance profile, b(z), is negative at elevations below the ELA and positive above it. We also show the net balance mapped onto the valley-parallel axis, x (follow dashed line downward), generating the net balance profile b(x). At steady state the ice discharge of the glacier must reflect the integral of this net balance profile (bottom diagram). The maximum discharge should occur at roughly the down-valley position of the ELA. Where the discharge goes again to zero determines the terminus position.
Classification – Sea Ice vs. Ice Bergs

Sea ice is frozen seawater (not originating from snow) and is relatively thin. Ice bergs are calved off from the front of tidewater glaciers and can be quite thick (~100m).
Glaciology

A thermal distinction, that has consequences for ice motion and, subsequently, erosion of the bed.

The temperate glaciers have a temperature profile close to the melting point throughout, making pressure melting and sliding at the bed possible.

Figure 7.3 Temperature profiles in polar (top) and temperate (bottom) glacier cases. Slight kink in profile in the polar case reflects the different thermal conductivities of rock and ice. Roughly isothermal profile in the temperate case is allowed by the downward advection of heat by meltwaters. Temperature is kept very near the pressure-melting point throughout, meaning it declines slightly (see phase diagram of water).
Classification – Valley Glaciers
Classification – Ice Caps
Classification – Ice Sheets
Classification – Tidewater or Tidal Glaciers
Glaciology (and the understanding of the health of a glacier) is deeply rooted in quantitative observations. Here we encounter another "Conservation of Mass" (this time, of ice).

The Local Mass Balance: $b(z)$

\[
\frac{\partial H}{\partial t} = b(z) - \frac{1}{W(z)} \frac{\partial Q}{\partial x}
\]

If $b$ is positive, there is a net gain of ice mass over an annual cycle. If $b$ is negative, there is a net loss. The elevation at which $b$ switches from positive to negative on the glacier is termed the Equilibrium Line Altitude (ELA).

\[
b(z) = \frac{\partial H}{\partial t} + \frac{1}{W(z)} \frac{\partial Q}{\partial x}
\]

Consider what happens to this equation at steady state?
The mass balance always has a positive gradient with elevation.
The ELA: Equilibrium Line Altitude

The ELA has a tendency to be low in high latitudes, where it is cold and there is little ablation, and also low near coasts, where snowfall rates are high due to the presence of oceanic water sources nearby.

Figure 7.2  Schematic diagrams of a glacier (white) in mountainous topography (gray) showing accumulation and ablation areas on either side of the equilibrium line. Mapped into the vertical, $z$ (left diagram), the net mass balance profile, $b(z)$, is negative at elevations below the ELA and positive above it. We also show the net balance mapped onto the valley-parallel axis, $x$ (follow dashed line downward), generating the net balance profile $b(x)$. At steady state the ice discharge of the glacier must reflect the integral of this net balance profile (bottom diagram). The maximum discharge should occur at roughly the down-valley position of the ELA. Where the discharge goes again to zero determines the terminus position.
Latitudinal Dependence of ELA

There is an obvious relationship between latitudinal position and ELA.

Note the comparison of modern ELA with reconstructed ELA from last glacial maximum (~20ka).

ELA has risen by 1km vertically.

Figure 7.5 Profiles of topography (gray), equilibrium line elevation (ELA, top) and glacial extent (bottom) (solid, present day; dashed, last glacial maximum (LGM)) along the spine of Western North America from California to the Arctic Ocean. Note many-hundred meter lowering of the ELA in the LGM, and corresponding greater extent of the glacial coverage of the topography. (after Skinner and Porter, 19xx)
To measure the health of a glacier for a given year (net gain or loss) we calculate the Total Mass Balance: $B$

$$B = \int_{0}^{z_{\text{max}}} b(z) W(z) \, dz$$
Total Mass Balance

Nigardsbreen, Norway
1998

Figure 7.6 Mass balance profiles for the year 1998 on the Nigardsbreen, a coastal Norwegian glacier. a) Specific balance in meters of water equivalent. Winter balance from snow probe surveys, summer balance from stake network (circles). Net balance is shown in gray; net balance is zero at 1350 m, the ELA. b) The volume balance derived by the product of the specific balance with the altitudinal distribution or hypsometry of the glacier. That the glacier has so much more area at high elevations is reflected in the high contribution of accumulation to the net balance of the glacier (gray fill). In 1998, the net balance is highly positive; there is more gray area to the right of the 0 balance line than to the left, so that the integral of the gray fill is $> 0$. In this year the positive total balance represents a net increase of roughly 1 m water equivalent over the entire glacier. (after NVE, 1999)
Figure 7.7  a) Mass balance for a section of glacier of width $W$, down-glacier length $dx$, and height $H$. Inputs or outputs through the top of the box are dictate the local mass balance, $b$. Downglacier discharge of ice into left side of box, $Q_x$, and out the right side of box, $Q_{x+dx}$, include contributions from basal sliding (shading) and internal ice deformation. (after MacGregor et al., 2002)
Model of Ice Thickness Evolution

Imposed mass balance profile held steady throughout simulation;

Glacier achieves steady state after ~600 years of simulation.

Figure 7.8 Model of glacier evolution on bedrock profile from Bench Glacier valley, Alaska, shown in evenly spaced time steps out to 600 years. Climate is assumed to be steady, with a prescribed mass balance profile. Top: profiles of ice thickness through time. Bottom: glacier draped on bedrock profile. The glacier reaches approximately steady state at ~500 years. Measured maximum ice thickness of 180 m is well reproduced by the final model glacier, implying that the mass balance profile b(x) is well chosen.
Steady-State, Uniform-Width, Down Valley Discharge Profile

\[ Q(x) = \int_{0}^{x} b(x)W(x) \, dx \]

Figure 7.2  Schematic diagrams of a glacier (white) in mountainous topography (gray) showing accumulation and ablation areas on either side of the equilibrium line. Mapped into the vertical, z (left diagram), the net mass balance profile, \( b(z) \), is negative at elevations below the ELA and positive above it. We also show the net balance mapped onto the valley-parallel axis, x (follow dashed line downward), generating the net balance profile \( b(x) \). At steady state the ice discharge of the glacier must reflect the integral of this net balance profile (bottom diagram). The maximum discharge should occur at roughly the down-valley position of the ELA. Where the discharge goes again to zero determines the terminus position.
Implications of Ice Discharge Profile

1. Ice discharge increases down valley to accommodate new snow within accumulation area.
2. Negative local mass balance within ablation area implies that ice discharge must be decreasing down valley below the ELA.
3. So vertical component of ice parcel trajectories is downward in accumulation area and upward in ablation area.
4. Likewise, ice-embedded debris is moved toward the bed in the accumulation area and toward the surface in the ablation area.
5. Topographic contours will bend up-valley above the ELA and down valley below the ELA – providing a handy way to estimate ELA position/elevation.

6. Debris moves away from valley walls in accumulation zone and toward valley walls in ablation zone, which accounts for the presence of lateral moraines only below the ELA.

7. Lateral moraines can, therefore, be used as landscape indicators of paleo-ELA position and, hence, paleo-position of the 0°C isotherm – a useful paleoclimate proxy.
Lateral Moraines as Paleo-ELA Indicators

Figure 7.19. Methods for estimating paleo-ELAs are based upon features of glaciers illustrated. Up-valley ends of lateral moraines coincide with the ELA on a glacier because the trajectories of blocks falling onto the ice are as shown in white arrows: they move toward the glacier center in the accumulation area, and outward to the edge in the ablation zone, responding to the local slopes of the glacier. Typical AARs, ratios of accumulation area to total area of a glacier, are 0.65. If the paleo-area of a past glacier can be measured using terminal moraines, the ELA can be estimated using this AAR. Translation of the change in ELA into an estimate of change in mean annual temperature is based upon application of an assumed lapse rate shown in the figure at the right.