FINAL REPORT
December 2012

Project Title: Yosemite's Melting Glaciers
Project Start Date: January 2009
Principle Investigators: Greg Stock, Yosemite National Park
Robert Anderson, University of Colorado, Boulder

OVERVIEW

Yosemite's two remaining glaciers are rapidly retreating as the climate warms, with consequences for ecosystem health and visitor experience. This project represents a four-year study of the Lyell and McClure glaciers, the largest glaciers in Yosemite, with the goal of understanding the climate patterns forcing their retreat. Alpine glaciers respond to changes in climate and are important indicators of climate change (.e.g, Meier, 1965). Melting glaciers are a critical source of late-season cold water (Fountain and Tangborn, 1985), and the impending loss of the Lyell and Maclure glaciers may have profound impacts on ecosystems in and adjacent to the upper Tuolumne River.

Our research combined traditional glacier measurements with new techniques to evaluate the health of these glaciers, and draws heavily on the wealth of historic data collected from these glaciers since 1872. The data we collected allow us to determine the present area and thickness (volume) of the glaciers, their winter snowfall accumulation and summer melt patterns, their rate of movement, and the amount of water delivered from the glaciers to the upper Lyell Fork of the Tuolumne River. The project was jointly conducted by Dr. Greg Stock, Yosemite Park Geologist, and Dr. Robert Anderson at the Institute of Arctic and Alpine Research at the University of Colorado, Boulder (Figure 1). Additional collaborators include Pete Devine of the Yosemite Conservancy and graduate student Kali Abel of the University of Colorado, Boulder.

Data analyses of glacier mass balance are still ongoing, but we already have several key findings from this project, including the following:

- Both the Lyell and Maclure Glaciers have retreated significantly over the last century, having lost approximately 60% of their surface areas;
- Numerical modeling of glacier retreat suggests that the volume loss of the glaciers over the last century may be substantially greater;
- Despite this ice loss, the Maclure Glacier continues to move at a relatively rapid pace of about 7.2 m/year (24 feet/year), and at exactly the same rate as measured by John Muir in 1872;
- The ice loss at the Lyell Glacier has been more consequential; our velocity measurements over four years indicate that this glacier has stagnated, with no detectable movement.

These findings will be integrated with glacier mass balance modeling to predict how these glaciers will fare over the next century in the face of predicted warming temperatures, and how the loss of ice will affect water supply to downstream ecosystems.

Figure 1. Principle investigators Dr. Greg Stock, Yosemite Park Geologist (left) and Dr. Robert Anderson, INSTAAR, University of Colorado, Boulder (right).

HISTORY OF RESEARCH OF THE LYELL AND MACLURE GLACIERS

The Lyell and Maclure glaciers in Yosemite National Park (Figures 2 and 3) are among the park's more iconic features, and fortunately have been the subject of writing and scientific study for more than a century (e.g., Muir, 1875; Russell, 1889; Johnson, 1904). The first maps of the glaciers were published in 1889 (Figure 4), providing an extremely valuable base map against which to compare modern changes. John Muir first measured the velocity (speed and direction) of the Maclure Glacier in 1872 and found it to be moving about 2.6 cm/day (1 inch/day). At the suggestion of US Geological Survey geologist Francois Matthes, the National Park Service began near-annual studies of the Lyell and Maclure glaciers in 1932; these studies included both quantitative measurements of glacier extent, as well as photographic documentation of the glaciers (National Park Service, 1933-1975). More recent work has further quantified the extents of the Lyell and Maclure glaciers (Basagic and Fountain, 2011).

For this project, we have drawn upon, and reproduced when possible, all of these existing data. Although we often use new and more precise tools to reproduce these measurements and images, the essence of the measurement is the same.

Figure 2. The west lobe of the Lyell Glacier, as viewed from the summit of Mount Maclure. The summit of Mount Lyell is in the upper right of the photograph. Photo by Greg Stock.

Figure 3. The Maclure Glacier, as viewed from the north. Note the annual layering of glacier ice, and the crevasses and active bergschrund (deep crevasse at the top of the glacier). The summit of Mount Maclure is in the center of the photograph. Photo by Greg Stock.

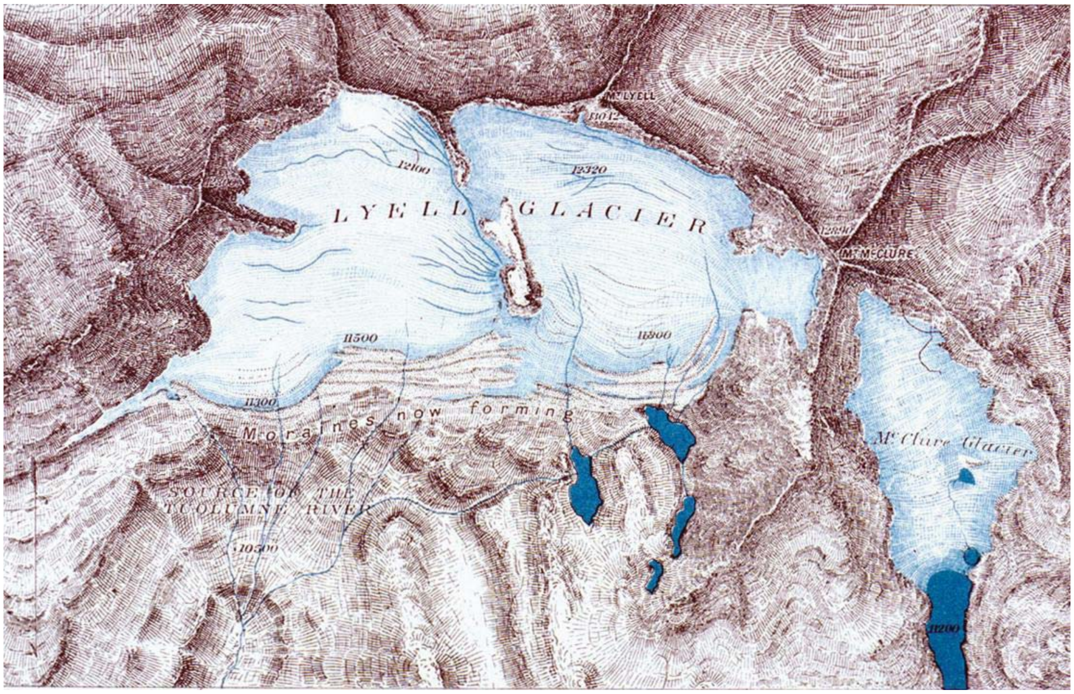

Figure 4. Map of the Lyell and Maclure glaciers as they looked circa 1885. Note the terminus of the Lyell Glacier is immediately adjacent to the Little Ice Age moraines ("Moraines now forming"). Map by W.D. Johnson, published in Russell (1889).

MEASURING GLACIER MASS BALANCE

One of the goals of this study is to determine the health of the Lyell and Maclure glaciers by studying their mass balance over a four-year period (the project was initially slated to last three years, but because of the extreme snowpack in winter 2010-2011, in which most of our instruments were buried all year, the project was extended to four years). A glacier's mass balance is the net ice gain through annual snowpack and net loss through sublimation and melting. The concept of mass balance is similar to a bank account – if more money goes in than goes out, the account grows, whereas if more money goes out than in, the account shrinks. Similarly, if glaciers receive more ice through winter snow than they lose through summer melt, the glacier will advance, whereas if glaciers lose more ice through summer melt than they receive through winter snow, the glacier will retreat.

To quantify the mass balance of the glaciers, we measured annual snow accumulation by digging snow pits and measuring snow and ice surfaces relative to the velocity stakes we placed on the glacier (see below). We also quantified the amount of melt by measuring the discharge of the streams draining the glaciers. In addition, we measured air temperature, solar radiation, wind speed and direction, and barometric pressure from a meteorological station installed on the ridge between the Lyell and Maclure glaciers.

We are still processing and analyzing the mass balance data, but are confident that we have sufficient data to effectively model the present and future mass balances of the glacier (see below).

MEASURING GLACIER RETREAT

Glaciers around the world are presently retreating, most likely in response to anthropogenic climate change, and the Lyell and Maclure glaciers are no exception. Utilizing the wealth of existing data and photographs on the historic extents of these glaciers, we have provided a series of snapshots of recent glacier retreat. This loss of ice area is evident in repeat mapping of glacier area (Figure 5), repeat photographs of the glaciers (Figure 6-8), and repeat measurements from the Little Ice Age terminal moraines to the glacier terminus (Figures 6 and 7). Based on our work, we conclude that both the Lyell and Maclure glaciers have retreated hundreds of meters horizontally and have lost roughly 60% of their surface areas since about 1900.

We also reproduced several cross-glacier transects on the Lyell Glacier that document changes in the ice surface position through time (Figures 8 and 9). These transects show that the surface of both the east lobe and west lobe of the Lyell Glacier has lowered by as much as 30 to 40 m (100 to 130 feet) since 1933. The east lobe transect is especially poignant, in that the entire transect – once established on glacier ice – is now across bedrock, and has been since at least 2007 (Figure 9). Repeat photographs of the east lobe of the Lyell Glacier show that it has disappeared almost entirely since its extent in the early 1940's (Figure 10).

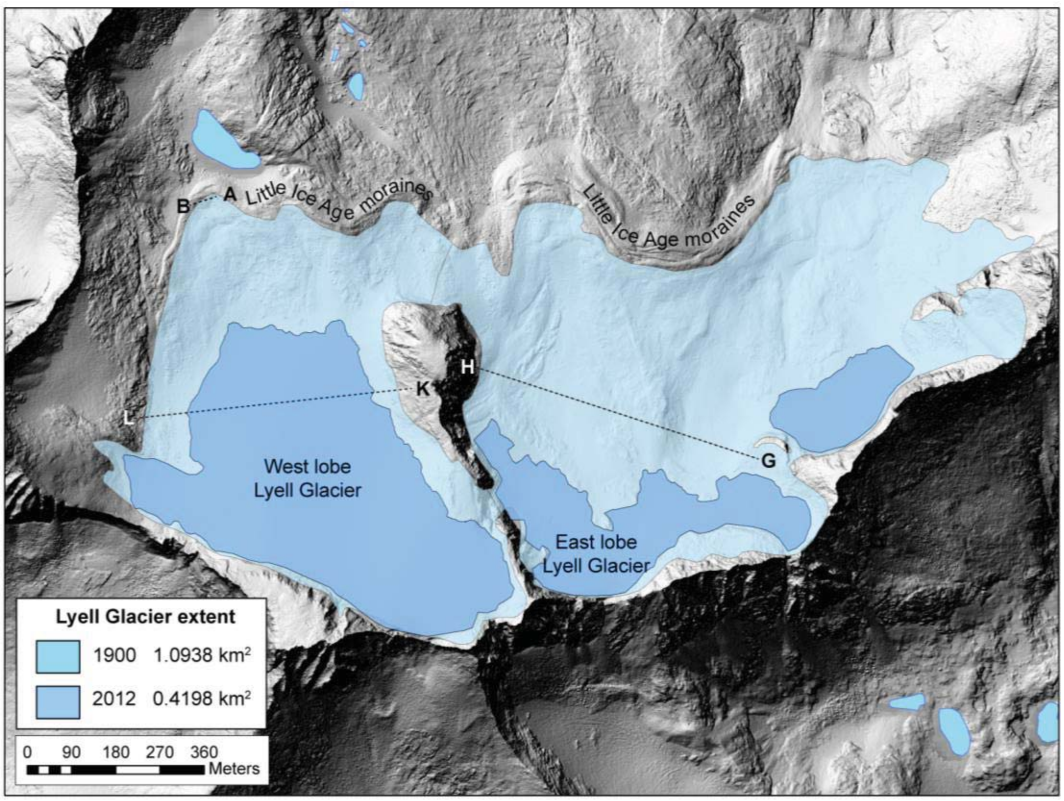

Figure 5. Retreat of the Lyell Glacier between 1900 (extent shown in light blue) and 2012 (extent shown in dark blue). Note position of the Lyell Glacier terminus immediately adjacent to the Little Ice Age moraines. During the period 1900 to 2012, the glacier experienced a 62% reduction in surface area. Note locations of survey transect A to B, G to H, and K to L.

Figure 6. Photograph of the west lobe of the Lyell Glacier, taken on 30 September 1935, showing survey transect A to B. Note the position of the glacier terminus immediately adjacent to the Little Ice Age moraine. Photo courtesy National Park Service.

Figure 7. Identification of historic survey transect A to B along the terminal Little Ice Age moraine of the west lobe Lyell Glacier. Left panel: A to B transect as it looked on 20 September 1939. The distance from the A to B transect centerpoint to the glacier terminus was 9.2 m (30 feet). Photo courtesy National Park Service. Right Panel: Same view on 6 October 2012. The distance from the A to B transect centerpoint to the glacier terminus is now 260 m (853 feet). Photo by Greg Stock.

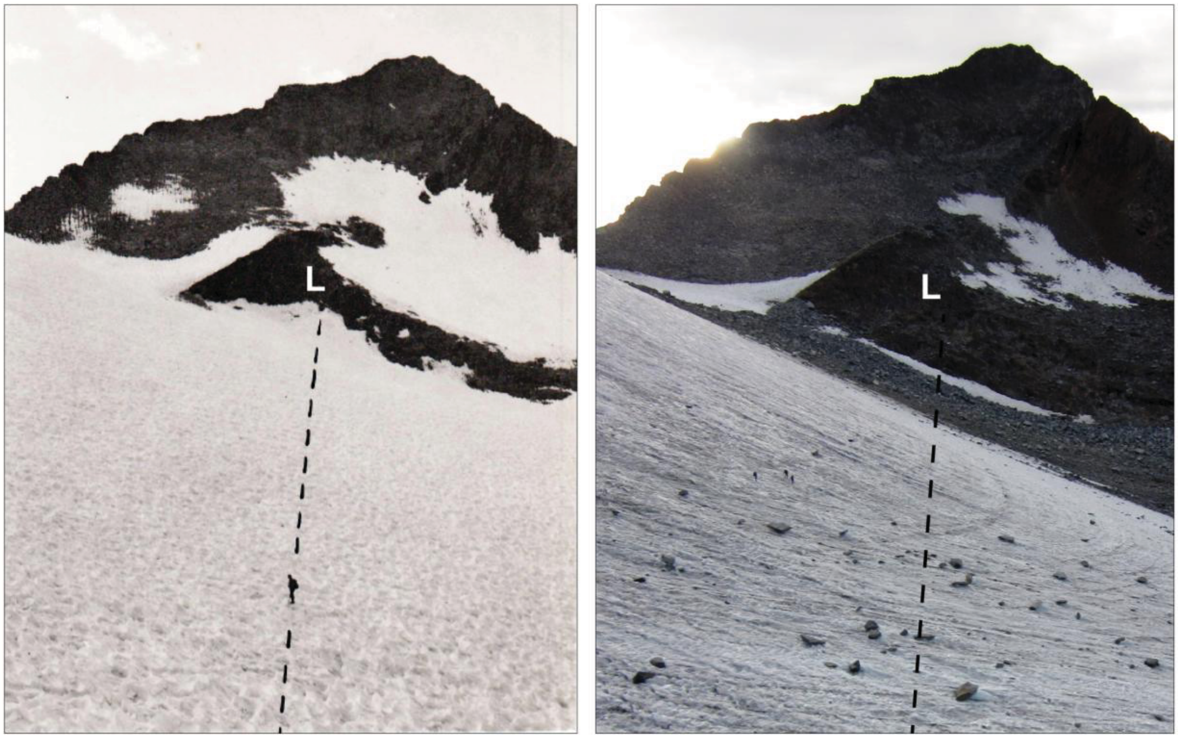

Figure 8. Seventy years of glacier thinning along transect K to L. Left panel: Photograph across west lobe Lyell Glacier from point K on 28 September 1942. Right panel: Same view on 6 October 2012. Note exposure of bare ice, substantial thinning of glacier surface exposing rock debris and lateral moraine, and greatly reduced snow pack.

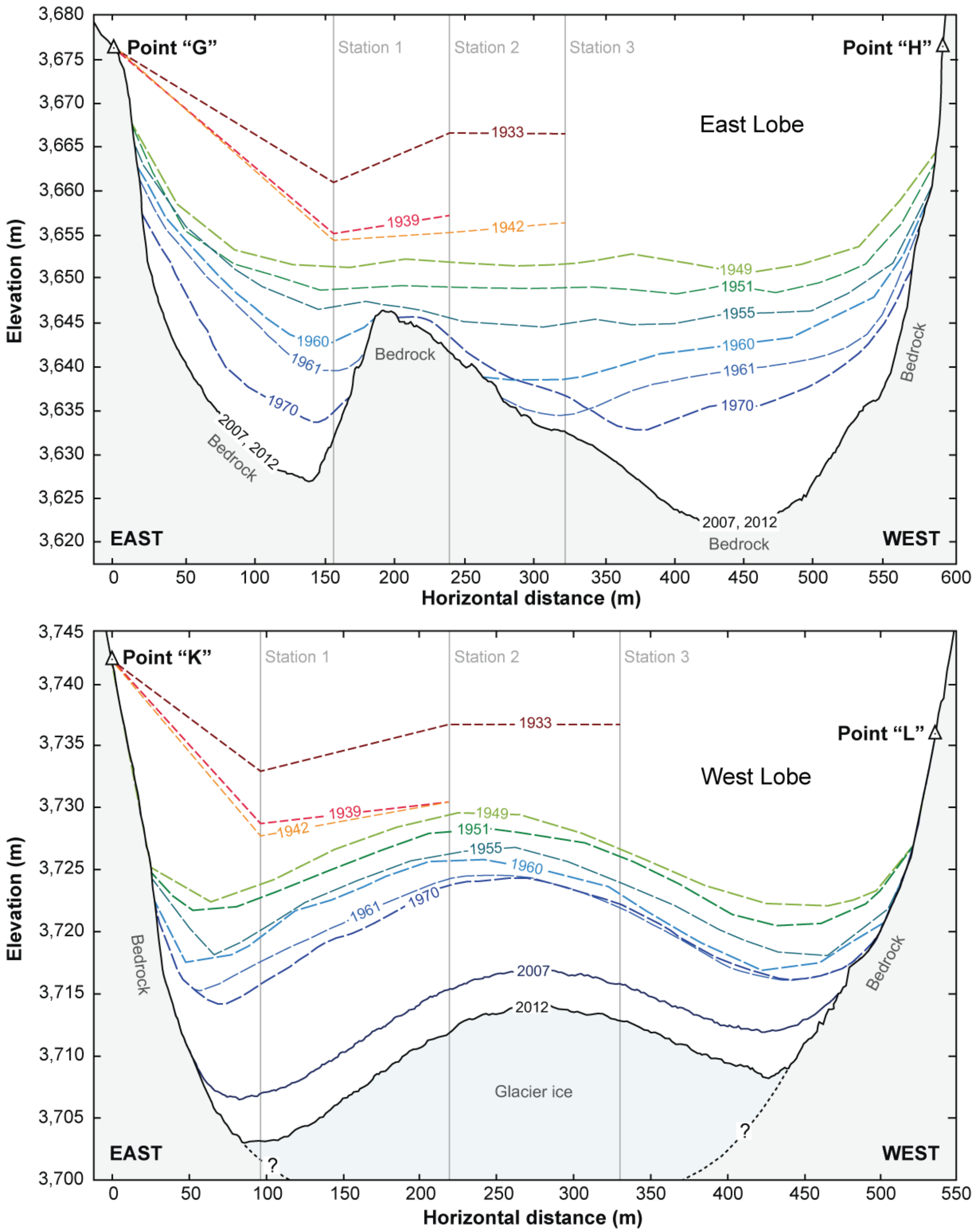

Figure 9. Topographic cross sections across the Lyell Glacier ice surface from 1933-2012. Upper panel: Cross section from points G to H across the east lobe Lyell Glacier. At least 30 m of ice thinning has occurred since 1933; all ice was gone from this transect by 2007. Lower panel: Cross section from points K to L across the west lobe Lyell Glacier. At least 30 m of ice thinning has occurred since 1933; approximately 30 m of ice remains.

Figure 10. Repeat photography of the Lyell Glacier. Top panel: The Lyell Glacier as photographed on 27 September 1941. Photo courtesy National Park Service. Bottom panel: Same view photographed on 7 October 2012. Note the substantial ice loss on the east lobe of the Lyell Glacier (left side of photo). Photo by Pete Devine.

MEASURING GLACIER VELOCITY

A hallmark of glaciers is their downslope movement in response to ice thickness, which causes the ice to deform, and in response to melting, which pressurizes and lubricates the bed of the glacier allowing it slide over bedrock (e.g., Guyot, 1998). Therefore, part of documenting the present health of the Lyell and Maclure glaciers was to measure their downslope velocity (speed and direction). We did this by placing stakes (1-inch PVC poles) into the ice and measuring the change in their position through time.

As with many aspects of this study, we benefited immensely from previous studies of the glaciers. In the case of the velocity of the Maclure Glacier, the previous studies were conducted by John Muir, who was intent on proving the existence of "living glaciers" in the Sierra Nevada. To that end, John Muir initiated what was likely the first velocity measurement of a glacier in North America:

"The Maclure Glacier… seemed best fitted for my purpose, and, with the assistance of my friend Galen Clark, I planted five stakes in it on the 21st of August, 1872, guarding against their being melted out by sinking them to a depth of five feet… On the 6th of October, or forty-six days after being planted, I found the displacement to be… forty-seven inches in forty-six days, or about one inch per twenty-four hours" (Muir, 1875a).

Thus, for the period from 21 August 1872 to 6 October 1872, Muir found that the Maclure Glacier had a maximum horizontal displacement of 1.2 m (4 feet), or a maximum horizontal velocity of 2.6 cm/day (1 inch/day) (the maximum value is that obtained from the center of the glacier where the velocity is greatest).

Of historical note is the methodology that Muir and Clark used to survey in their stakes: *"The positions of these stakes were determined by sighting across from bank to bank, past a plump-line, made of stone and a black horse hair"* (Muir, 1875b).

One of the fascinating discoveries we made during the course of this project is that one of Muir's original hand-hewn white bark pine stakes is in the park archives. The stake was discovered in the terminal moraine debris of the Maclure Glacier by NPS naturalists in 1936 and turned over to the NPS Museum. We inquired with the NPS archives and were able to view and photograph this stake (Figure 11). This direct connection with Muir's early studies of the glaciers is a real treasure.

Figure 11. One of the original hand-hewn white bark pine stakes that John Muir used to measure the velocity of the Maclure Glacier in 1872. The stake was retrieved from the terminal moraine of the Maclure Glacier by National Park Service naturalists in 1936 and has since been stored in the park archives. The total length of the stake (two pieces combined) is about 2.1 m (7 feet).

In 2009 we placed stakes on both the Lyell and Maclure Glacier to measure their long-term (four-year) velocity (Figures 12 and 13), and resurveyed these stakes periodically as they emerged from beneath the snowpack. We used more modern methods than Muir (Global Positioning Systems and laser rangefinders) but utilized essentially the same methodology of tracking the position of the stakes through time. On August 2012 we placed additional stakes on both glaciers and measured their velocity until October 2012. For the Maclure Glacier specifically, we measured the stakes on 21 August and again on 6 October, on the exact same days as measured by John Muir in 1872. Results of these measurements are shown in Tables 1 and 2.

Our measurements of glacier velocity revealed two important findings:

- The Maclure Glacier moves at relatively rapid speed for a glacier its size, at an average of about 7.2 m/year (26 feet/year). For the period from 21 August 2012 to 6 October 2012, we found that the Maclure Glacier had a maximum horizontal displacement of 1.2 m (4 feet), or a maximum horizontal velocity of 2.6 cm/day (1 inch/day) (Table 1). *This rate is identical to the rate measured by John Muir in 1872.*
- Over a four-year period, the western lobe of the Lyell Glacier did not show appreciable movement (Table 2), and showed no movement between August and October 2012. For all intents and purposes, it appears that the western lobe Lyell Glacier has stagnated. By inference, it is very likely that the much smaller eastern lobe has also stagnated.

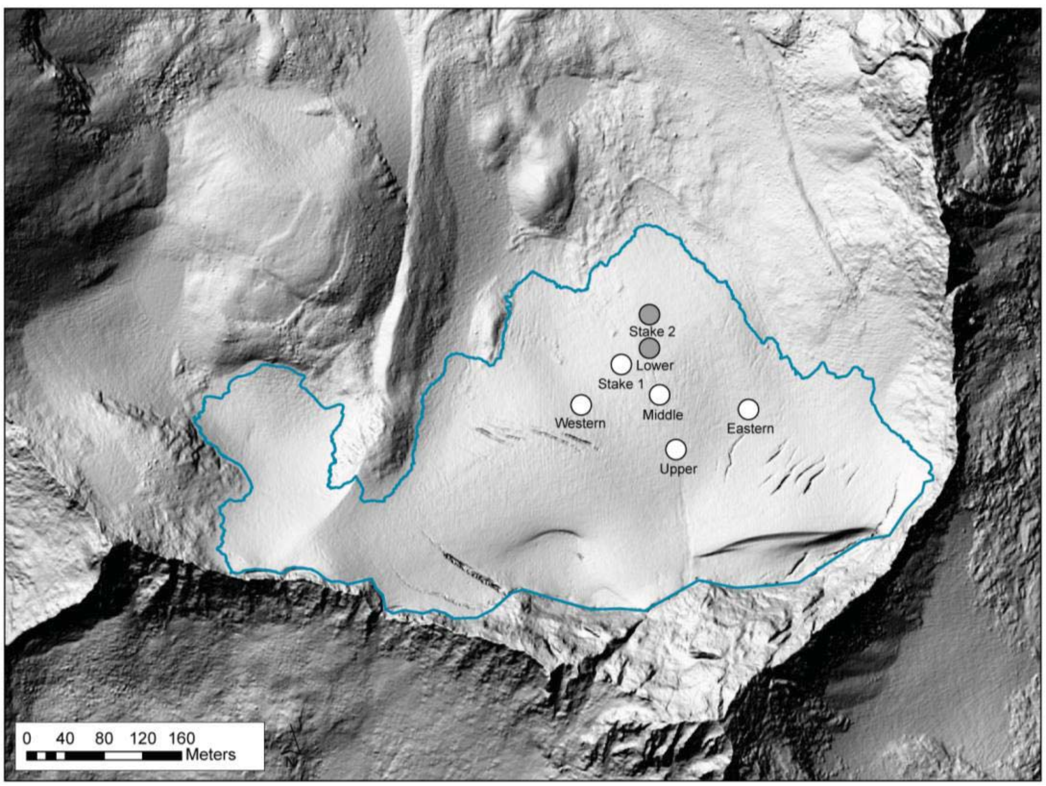

Figure 12. Stake array on the Maclure Glacier used to measure velocities.

Table 1. Maclure Glacier stake velocities, 2009-2012. Values are cumulative across the time period of measurement; values in parentheses indicate those obtained from 22 August to 6 October 2012.

Stake	18 Sept 2009	15 Sept 2010	21 Aug 2012	23 Sept 2012	6 Oct 2012
Maclure Stake 1	0.0 m	6.5 m	20.4 m (0.0 m)	21.2 m (0.8 m)	21.6 m (1.2 m)
Maclure Stake 2	-	-	0.0 m	-	-
Lower Maclure	-	-	0.0 m	-	-
Middle Maclure	-	-	0.0 m	0.7 m	1.0 m
Western Maclure	-	-	0.0 m	0.8 m	1.0 m
Eastern Maclure	-	-	0.0 m	0.5 m	0.7 m
Upper Maclure	-	-	0.0 m	0.4 m	0.6 m

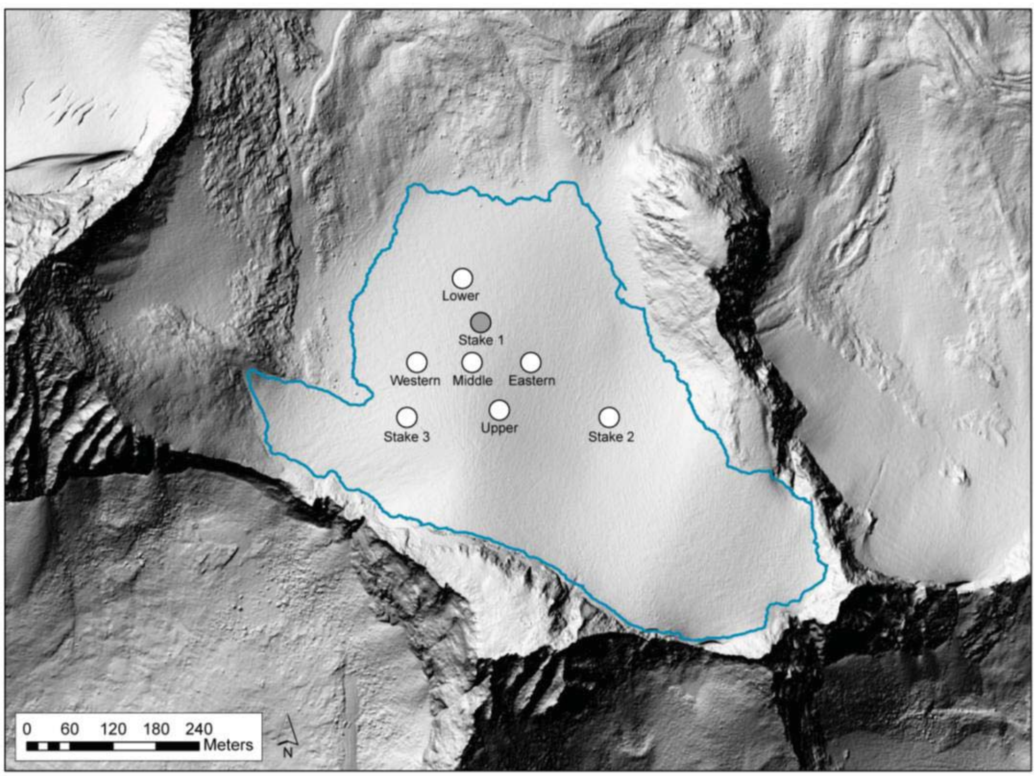

Figure 13. Stake array on the west lobe of the Lyell Glacier used to measure velocities.

Table 2. Lyell Glacier stake velocities, 2009-2012. Values are cumulative across the time period of measurement; values in parentheses indicate those obtained from 22 August to 6 October 2012.

Stake	18 Sept 2009	16 Sept 2010	22 Aug 2012	22 Sept 2012	6 Oct 2012
Lyell Stake 1	0.0 m	-	-	-	-
Lyell Stake 2	-	0.0 m	0.3 m	0.3 m (0.0 m)	0.3 m (0.0 m)
Lyell Stake 3	-	0.0 m	2.7 m (0.0 m)	2.7 m (0.0 m)	2.7 m (0.0 m)
Lower Lyell	-	-	0.0 m	0.0 m	0.0 m
Middle Lyell	-	-	0.0 m	0.0 m	0.0 m
Western Lyell	-	-	0.0 m	0.0 m	0.0 m
Eastern Lyell	-	-	0.0 m	0.0 m	0.0 m
Upper Lyell	-	-	0.0 m	0.0 m	0.0 m

TREE RING RECORDS OF PALEOCLIMATE

In order to place the present condition of the glaciers in the context of past climates, we initiated new studies of paleoclimate using records from tree rings adjacent to the glaciers. Graduate student Kali Abel, an expert in developing tree ring chronologies, cored several lodgepole pine trees in the forests below the glaciers. The tree rings preserve information on temperature and precipitation going back through the Little Ice Age, a period of several hundred years. These trees appear to be most sensitive to winter snowfall, recording the winter mass balance for the glaciers. The tree ring records, along with other climate reconstructions, instrumental records, and repeat glacier surveys, constrain the local meteorology and the climate response to it. This record is the basis for 1D glacier models that reproduce the glacier extent histories of both the Lyell and Maclure glaciers.

GLACIER MASS BALANCE MODELING

We developed a numerical model of these glaciers in an attempt to understand quantitatively the history of their terminus positions. One goal was to employ the climate history we have deduced from the tree ring records. Our numerical model is a flow line model in which we track ice thickness as a function of distance downvalley from the headwall. The model is based upon conservation of mass in a cell of ice, in which the rate of change of thickness of the ice is governed by the local meteorological mass balance (set by the weather: inputs of snow, losses by melt), and by how much ice is transported into the upvalley edge of the cell and out of the downvalley edge of the cell (Figure 14). This ice physics therefore includes both the flow due to internal deformation of the ice and any sliding at the bed of the glacier. We "drive" the model with the snowfall history as scaled by the tree ring record, and temperature history scaled by instrumental records in nearby sites. The model operates on a bedrock surface that we infer from present glacier surface geometry. Figure 15 shows the final geometry of the modeled Maclure Glacier and the modeled history of ice thickness and ice speed over the period of the tree ring record. Note that the final ice speed is close to that measured by John Muir in 1872 and by us over the past four years.

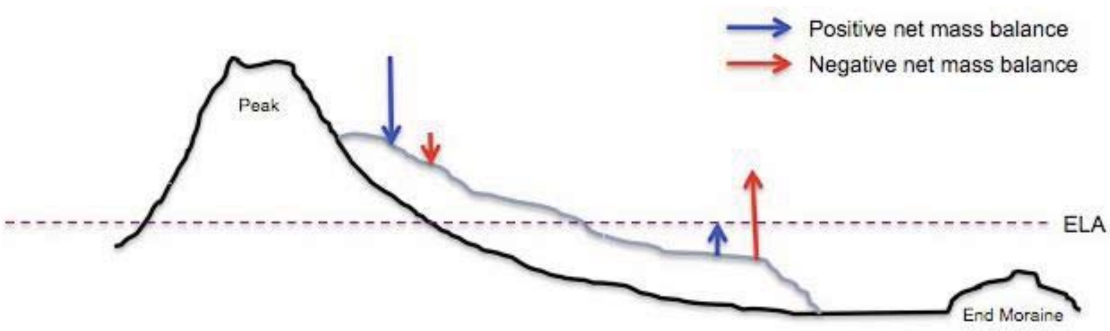

Figure 14. Schematic diagram of how the 1D glacier model works, showing the position of the glacier with respect to the end moraine and the Equilibrium Line Altitude (ELA), the point on a glacier that separates net ice accumulation and net ice loss. Greater accumulation of ice by snowfall compared to loss of ice through melting produces a positive net mass balance (blue arrows), causing the glacier to advance. Greater loss of ice through melting compared to accumulation of ice by snowfall produces a negative mass balance (red arrows), causing the glacier to retreat.

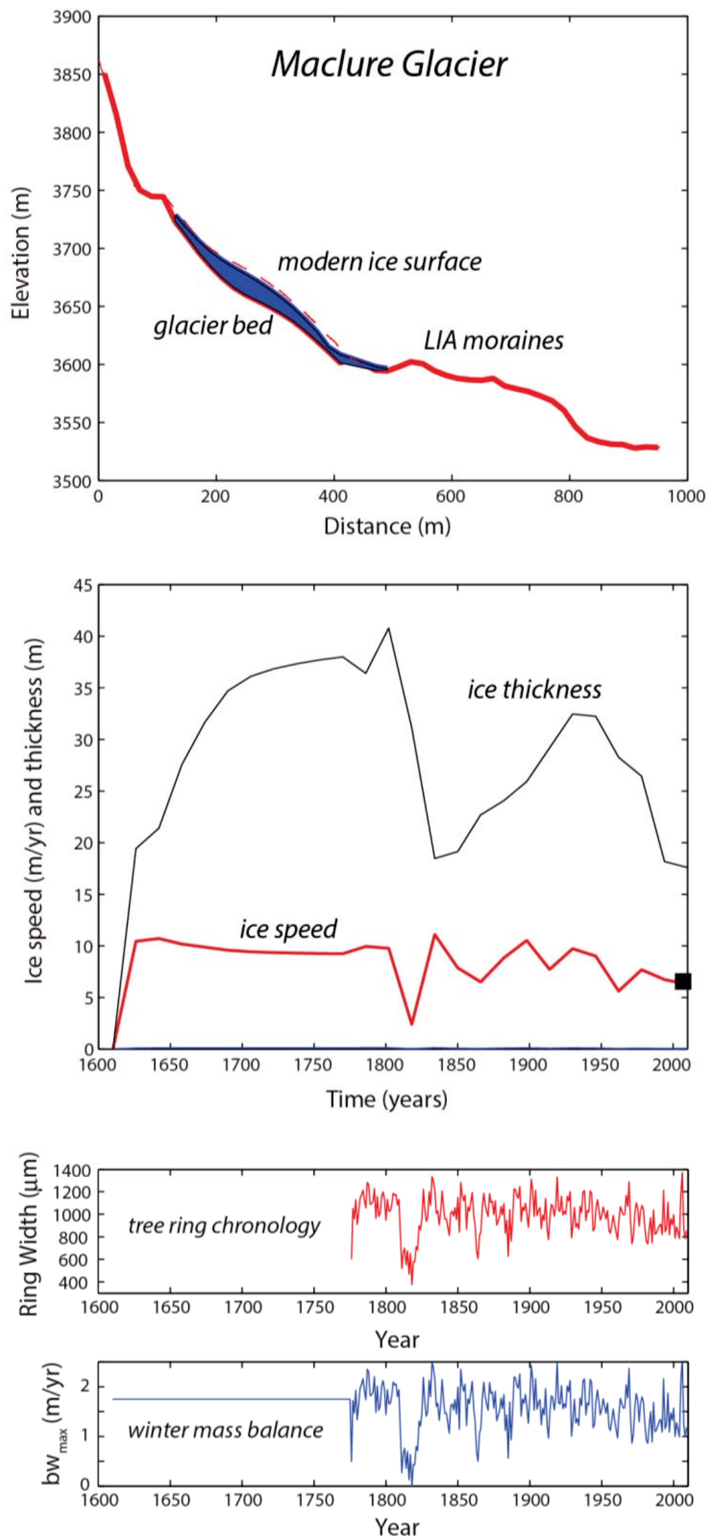

Figure 15. Example of a 1D glacier model simulation for the Maclure Glacier, where the glacier mass balance is driven by the tree ring chronology, a proxy for past changes in climate. For both the Lyell and Maclure glaciers, the tree ring chronology produces glacier extents and ice speeds consistent with field data and observations.

An important preliminary result of the glacier modeling is that the volumetric loss of glacier ice since about 1880 is very large; the present volumes are perhaps about 10% of those in about 1880. Thus, the glaciers appear to be thinning substantially as they are retreating upslope, an observation supported by our repeat profile surveys (Figure 9). Because the movement of a glacier is intimately tied to its thickness, this thinning probably accounts for the stagnation of the Lyell Glacier.

As the mass balance data are refined, we intend to utilize these data to model future behavior of the glaciers, in effect predicting when they will disappear entirely. From this, we should be able to make at least first-order predictions of the water supply impacts on downstream ecosystems in the Lyell Fork Tuolumne River.

CONCLUSIONS

This project has greatly expanded our understanding of the present state of the Lyell and Maclure glaciers. Our research combined traditional glacier measurements with new techniques to evaluate the health of these glaciers, and draws heavily on the wealth of historic data collected from these glaciers since 1872. The data we collected allow us to determine the present area and thickness (volume) of the glaciers, their winter snowfall accumulation and summer melt patterns, their rate of movement, and the amount of water delivered from the glaciers to the upper Lyell Fork of the Tuolumne River.

Data analyses of glacier mass balance are still ongoing, but we already have several key findings from this project, including the following:

- Both the Lyell and Maclure Glaciers have retreated significantly over the last century, having lost approximately 60% of their surface areas;
- Numerical modeling of glacier retreat suggests that the volume loss of the glaciers over the last century is greater, approximately 90%;
- Despite this ice loss, the Maclure Glacier continues to move at a relatively rapid pace of about 7.2 m/year (24 feet/year), and at exactly the same rate as measured by John Muir in 1872; the dominant mode of movement (deformation versus sliding) may have shifted toward sliding as the glacier is melting more rapidly than in 1872;
- The ice loss at the Lyell Glacier has been much more consequential; our velocity measurements over four years indicate that this glacier has stagnated, with no detectable movement.

These findings will be integrated with glacier mass balance modeling to predict how these glaciers will fare over the next century in the face of predicted warming temperatures, and how the loss of ice will affect water supply to downstream ecosystems.

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Russell, I.C., 1889, Quaternary History of the Mono Valley, California: Eight Annual Report of the United States Geological Survey, 1889.

PRODUCTS AND PUBLIC OUTREACH

Manuscript in preparation:

- Stock, G.M., Anderson, R.S., and Devine, P., 2013, Retreat and stagnation of modern glaciers in Yosemite National Park and implications for downstream ecosystems: *Arctic, Antarctic, and Alpine Research* (in prep).

Scientific abstracts

- Abel, K., Anderson, R.S., and Stock, G.M., 2010, A localized climate record extending through the Little Ice Age for Lyell and Maclure glaciers using tree-ring analysis: Geological Society of America Annual Meeting, Denver, Colorado.

- Stock, G.M., Anderson, R.S., and Devine, P., 2012, Update on studies of the Lyell and Maclure Glaciers, Yosemite National Park: Hydroclimate Workshop, Yosemite National Park.

- Stock, G.M., Anderson, R.S., and Devine, P., 2013, Retreat and stagnation of modern glaciers in Yosemite National Park: Geological Society of America Corilleran Meeting, Fresno, California.

Volunteers

Lev Bakin, Scott Borden, Steve Bumgardner, Jonathan Byers, Colter Chisum, Miriam Duhnforth, Dustin Garrison, Josh Helling, Matt Holly, Jen Jackson, Kirk Keeler, Taryn Mead, Jeremy Miller, Brina Mocsny, Tim Palmer, Andy Steele, Sarah Stock, Brian Whitehead, Becky Zentmyer.

Theses

- Abel, K., 2011, Listening to the trees: Tree rings, the Little Ice Age, and the response of Yosemite's Lyell and Maclure glaciers to climate change: unpublished Master's Thesis, University of Colorado, Boulder.

Public Outreach

- Yosemite Nature Notes episode “Glaciers” highlighting the glaciers and our study of them.
- Book “California Glaciers” by author and photographer Tim Palmer, published by Heyday Books, highlighting our research on the glaciers.
- Press release and subsequent media followup on research findings (e.g., http://www.sfgate.com/science/article/Yosemite-s-Lyell-Glacier-may-be-receding-4250789.php)
- Upcoming articles on the glacier work in “Men’s Journal” and “Yale Environment 360” by science journalist Jeremy Miller.