Toward a Predictive Model of Arctic Coastal Retreat in a Warming Climate, Beaufort Sea, Alaska

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LONG-TERM GOALS

The long-term goal of this project is to understand the environmental drivers of extremely rapid coastal erosion in the Arctic, so that we can begin to predict how present and future climate change might influence coastal evolution. We are focusing our efforts on collecting empirical data that will help us to develop process-based models of coastal change. Toward this end, we are monitoring erosion processes using time-lapse photography, collecting meteorological and oceanographic data from sites along the coast, and analyzing climatic and geographic data from the past few decades to identify trends in coastline position through time. We anticipate that our project will help us to predict future patterns of coastal change as a function of projected changes in sea ice conditions, sea surface temperature, and changes in land surface temperatures.

OBJECTIVES

Our main scientific objective is to combine detailed observations from environmental monitoring and remote sensing to understand the *processes* driving rapid coastal erosion, and the primary *environmental drivers* leading to this change. We are collecting new observational data including time-lapse photography, meteorological data, and bluff substrate properties to examine the failure mechanisms of frozen coastal bluffs. By synthesizing these field observations with remote sensing observations and process-based numerical models, we hope to be able to predict future patterns of Arctic landscape change in the face of changing climatic conditions.

APPROACH

Our technical approach can be divided into three components. The first component is to use historical datasets to document changes in both coastal morphology and climatic conditions over the recent past. This includes data describing shoreline position, sea ice position, sea surface temperatures, and climatic conditions through time. The second component of our technical approach is to collect on-the-ground data describing the material comprising coastal bluffs, the mechanisms of bluff failure, and the environmental conditions leading to failure events. Armed with these empirical datasets, we can then inform numerical models of how thermal energy penetrates different bluff substrates; what the fate of eroded material is once it enters the nearshore environment; and how erosion proceeds via thermal and mechanical avenues. The third component of our technical approach is to develop physically-based numerical models of Arctic coastal erosion and sediment dynamics. Guided by data collected in the field, physics-based models of coastal erosion will be used to describe coastal change driven by thermal and mechanical (wave) processes.

The personnel involved in these data collection activities are as follows: Analyses of satellite imagery and environmental data are being undertaken by PIs Wobus and Overeem with the aid of graduate student Nora Matell and undergraduate Cordelia Holmes. Our first round of field data were collected by Matell, Overeem, Anderson and Wobus during the summer of 2008, and will continue through the summer of 2010. USGS scientists Clow, Urban and Jones assisted with retrieval of sensors during the 2008 summer season. Wave sensors were built by collaborator Tim Stanton at the Naval Postgraduate School in Monterey, to be deployed in summer of 2009 (see below). Numerical modeling has been led by co-PIs Anderson and Overeem, with thermal modules developed by Matell.

Many of our field observational data have now been collected, and we are turning much of our attention to synthesizing these datasets to guide numerical models of coastline change. However, we are also planning another field deployment to 1) obtain a new dataset describing wave energy inputs to the Beaufort Sea coastline, using bottom-mounted pressure transducers; and 2) examine coastal mechanics along sediment-rich (clastic) bluffs.

WORK COMPLETED

During the academic year prior to this annual report, we collected and processed remote sensing data from available archives; collected a new set of field data; and we began our numerical modeling efforts to describe the relevant thermal and mechanical processes contributing to coastal change. Our remote sensing data include time-series of coastal position, sea ice position, and sea surface temperature that can be readily queried using a set of Matlab analysis tools. Our field data include time-lapse photography, quantitative stratigraphy, meteorological data, and thermal profiles through bluff materials. Our preliminary modeling describes the propagation of thermal pulses thorugh frozen bluffs; the failure mechanics of topple-failures, and the expansion of thaw lakes. During the past year, we also built upon valuable collaborative relationships with colleagues at USGS, which has improved our ability to streamline data collection efforts across multiple institutions.

RESULTS

1. Remote Sensing Datasets

Sea-ice data sets have been obtained from NSIDC DMSP SSM/I Daily and Monthly Polar Gridded Sea Ice Concentrations from the Defense Meteorological Satellite Program -F8, -F11, and -F13 daily and monthly sea ice concentrations. These data are gridded at a resolution of 25 x 25 km, beginning 25 June 1987 and ongoing. We have used these data to construct time-series of sea ice concentrations offshore from the NPR-A coastline, since the sea ice concentration ultimately controls both the fetch and the ability of offshore waters to absorb solar radiation. These data illustrate a remarkably rapid and consistent loss of sea ice, typically in the first week of July.

A compilation of sea surface temperatures (SST) from the past nine summer seasons has been reconstructed based on satellite data. We view these data as semi-quantitative, since the resolution of the MODIS satellite data is only 4 km and they therefore do not capture locally high temperatures against the Beaufort Sea coast. However, these data can now be queried to evaluate patterns in SST through the summer, and to understand which summers stand out as having particularly warm SST. Interestingly, our preliminary examination of these data indicate that the summers of 2004 and 2007 were particularly warm during late July through mid-August. Anecdotal evidence suggests that these summers also had particularly rapid coastal erosion.

In addition, a compilation of multiple years of data illustrates a consistent 2-3°C increase in SST during the first two weeks of July, immediately following the loss of sea ice. Our time-lapse photography from the Beaufort Sea coastline (see below) shows that in 2008 this was also the time at which coastal erosion began to accelerate. This is again anecdotal evidence that thawing of bluffs by warming offshore waters may be a primary driver of coastal erosion in this setting.

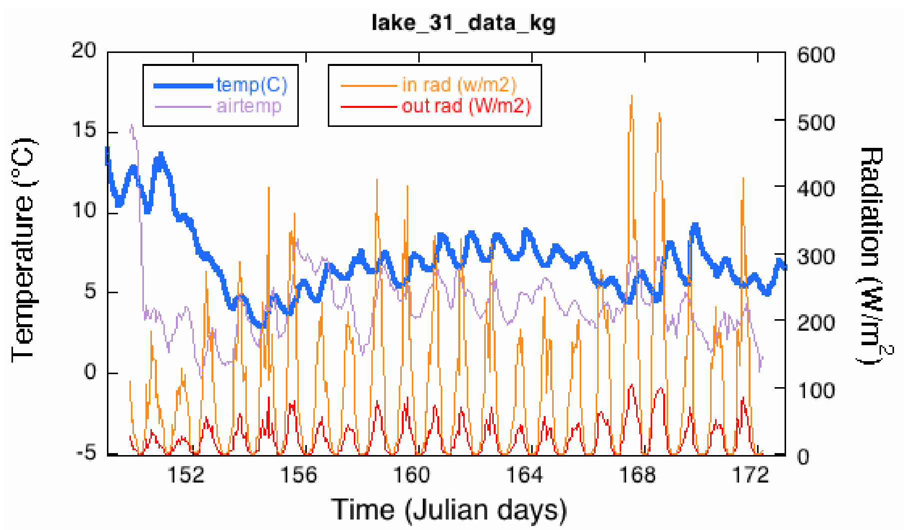
2. Field Data Collection

The most influential datasets we obtained during our summer field work were three sets of time-lapse movies illustrating coastal erosion processes along the Beaufort sea coast and the shore of Lake 31. These images underscore the role that purely thermal erosion can play in undermining coastal bluffs, and illustrate how quickly the ice-rich blocks near Drew Point can be melted away once they topple into the sea. Figure 1 below shows three successive images from one of our time-lapse cameras at Drew Point. These images, and others like it, are helping to focus our thinking about the importance of discrete storm events vs. slow, steady disintegration of the coastal bluffs by thermal processes.

Figure 1. Three successive time-lapse photos collected on July 21st, July 22nd, and July 28th, showing the topple-failure and melting of a block of coastal bluff into the sea. Note that the entire process is complete within a week, and that no major storms occurred during this time period. Length of overhang in the first photo is approximately 2 meters.

We have also begun to process meteorological data records from two stations we set up on the North Slope. These data include incoming and outgoing solar radiation, air temperatures, and wind speeds, in addition to water temperatures at our Lake 31 site. The latter site we view as a controlled experiment in bluff erosion by purely thermal processes, as waves are insignificant in this small lacustrine environment. Figure 2 shows data from Lake 31, where each of these data streams has been superimposed to enable us to understand how factors such as insolation, wind, and storm events influence shallow water temperatures. Note that in this case the temperatures in Lake 31 (shown in the thick blue line) drop substantially during a late July storm event (Julian Days 150-155), and do not recover again following this storm. Data such as these are helping us to understand how physical mixing in shallow lakes and the nearshore environment might influence water temperatures against coastal bluffs, thereby affecting their ability to erode by melting along the bluff base.

Figure 2. Example of water temperature, air temperature, and solar radiation at Lake 31, spanning a late summer storm between Julian days 150-155. Note the dramatic drop in lake temperatures, possibly due to mixing of colder waters by wind energy.



Finally, we are processing our stratigraphic samples from coastal bluffs for grain size, ice content, and ^{14}C to get a better sense of the timing of deposition, thaw lake development, and ice-wedge formation. While we do not yet have complete data to report, preliminary measurements suggest that these bluffs may be as much as 75% ice by weight, which has significant implications for their ability to withstand thermal perturbations as well as for the fate of eroded material once it enters the nearshore environment.

3. Numerical Modeling

Our most substantial headway in numerical modeling has been into understanding penetration of thermal energy into frozen soils and the mechanisms of bluff failure. We have developed simple modules to describe the thermal notching along the base of coastal bluffs, which can be fed with empirical observations on sea surface temperatures, storminess, and sea ice position. These modules are an important starting point that will be compared with our data describing bluff ice content, sea surface temperature evolution, and erosion rates through time.

We have also made substantial progress in modeling the thermal evolution of frozen ground in the subsurface. These efforts have been focused on understanding the evolution of thaw lakes; but these modules will be equally applicable to modeling the penetration of thermal energy into frozen bluffs along the coastline. Our permafrost thermal profile model successfully reproduces ground temperatures measured at a USGS meteorological station near our Drew Point field site (Figure 3). The lake ice and subsidence modules are currently in the process of being validated.

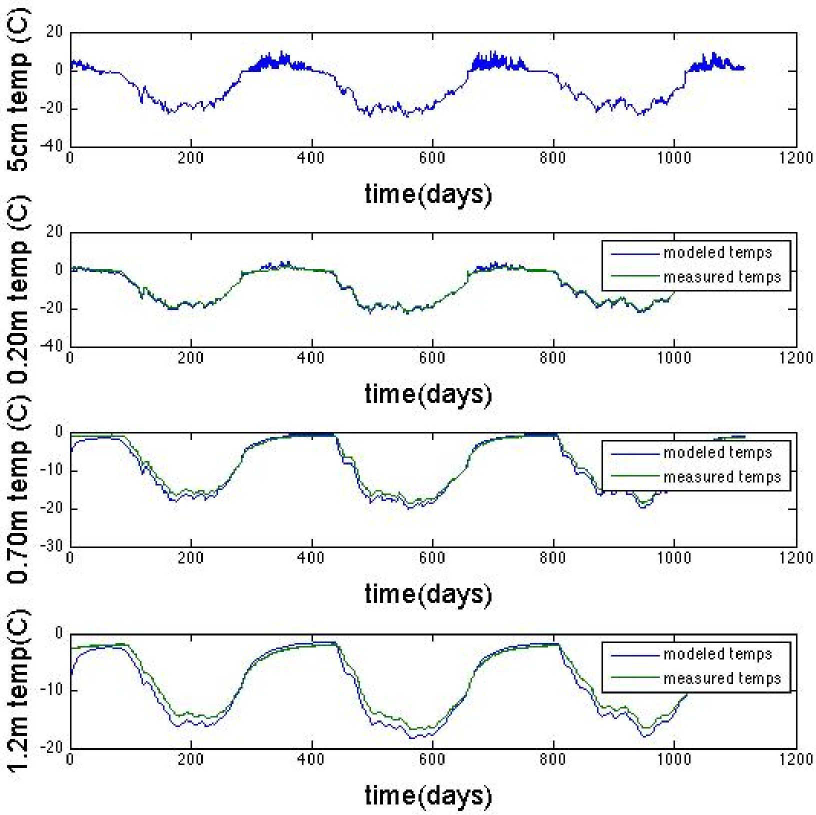


Figure 3. Measured and modeled ground temperatures at the Drew Point USGS meterological station. 5 cm soil temperatures (top panel) were model input data; modeled temperatures at depth are plotted along with measured temperatures in lower three panels.

IMPACT/APPLICATIONS

Quality of Life

Our field observations underscore the potential for continued very rapid landscape and seascape change in the Arctic: if climate change continues to increase sea surface temperatures through time, coastal erosion rates may continue to increase in areas where coastal retreat is primarily a thermal problem. This may have profound implications for the ecology of Alaska's North Slope, as an encroaching coastline leads to draining of thaw lakes and changes in the hydrology of the coastal plain. Coastal communities may also continue to be threatened by the changing coastline, and plans for protection or relocation are currently limited by our ability to predict these changes. Our goal is for our numerical models to easily interface with forecasts for future Arctic climate conditions to help predict future changes to the Arctic coastline.

Science Education and Communication

Over the past six months we have made two very tangible contributions in science education and communication. While we were in the field, we participated in an International Polar Year (IPY) "Live from IPY" event sponsored by Polar TREC, in which K-12 teachers from around the United States were able to ask us questions via web chat or telephone. We described our research, our field setting, and our observations to the group, and had very positive feedback from the IPY organizers. We anticipate that this outreach experience for K-12 educators has filtered through to their students, enhancing awareness of climate change and its impacts on ecology and coastal communities.

TRANSITIONS

Science Education and Communication

During the fall, we developed a short video clip from our time-lapse photography showing a section of Beaufort Sea coastline being undermined by thermal notching and collapsing into the sea. Andrew Revkin of the New York Times posted this video on his "Dot-Earth" website, and it has now been viewed over 18,000 times. Judging from the comments that have been posted, it is clear that this presentation has stimulated conversation in the environmental "blogosphere" and beyond. We feel that this is one of the most direct ways our research has been communicated to the public to date, and we hope to continue to develop relevant outreach materials from our future research.

RELATED PROJECTS

PI Anderson and co-PI Overeem are both members of the Community Surface Dynamics Modeling System (CSDMS) terrestrial working group (http://csdms.colorado.edu/index.html). We anticipate that our project will tap the broader expertise of the CSDMS consortium as we move further into the modeling component of our study. Photos of the eroding permafrost coast at our field site have been added to the Educational Gallery of the CSDMS:
http://csdms.colorado.edu/wiki/index.php/Coastal_GL4

PIs Wobus and Anderson are both involved in an NSF-sponsored project to understand weathering in alpine environments. Thermal models of ground temperatures as well as technologies developed for monitoring weather conditions, collecting time-lapse photographs, and deploying self-contained temperature probes are creating synergies between these two projects.