Arctic LCC Progress Report

1. PROJECT INFORMATION

Title:	**Modeling arctic barrier island-lagoon system response to projected arctic warming**
Report period	**July 1 to December 31**
Report submission date	**February 3, 2012; revised final submitted June 22, 2012**
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2. PROJECT OVERVIEW

a. Briefly (4-5 sentences) describe both the research purpose and the underlying need for this research.

Changes in Arctic coastal ecosystems in response to global warming may be some of the most severe on the planet. A better understanding and analysis of the rates at which these changes are expected to occur over the coming decades is crucial in order to delineate high-priority areas that are likely to be affected by climate changes. In this study we investigate the likelihood of changes to habitat-supporting barrier island – lagoon systems in response to projected changes in atmospheric and oceanographic forcing associated with Arctic warming. To better understand the relative importance of processes responsible for the current and future coastal landscape, key parameters related to increasing arctic temperatures are investigated and used to establish boundary conditions for models that simulate barrier island migration and inundation of deltaic deposits and low-lying tundra. The modeling effort investigates the dominance and relative importance of physical processes shaping the modern Arctic coastline as well as decadal responses due to projected conditions out to the year 2100.

b. List the objective(s) of the project, exactly as described in your Statement of Work.

- Assess the likelihood of Arctic barrier island-lagoon system habitat inundation by seawater in response to changing ocean conditions due to warming arctic temperatures, and
- Investigate the dominant forces responsible for projected changes to the Arctic coastal landscape.

3. PROGRESS SUMMARY

a. Describe report period progress.

Objective 1: Assess the likelihood of Arctic barrier-island system habitat inundation by seawater in response to changing ocean conditions in response to warming arctic temperatures.

The barrier island and mainland areas surrounding Arey Lagoon are being used as the pilot study site. The study site abuts the Arctic National Wildlife Refuge (ANWR) and is located to the west of Barter Island in the eastern segment of the Alaska Arctic coast. Wet sedge and low bluff areas serve as two focus study sites on the mainland side of the lagoon. A third focus study site is located on the barrier island (Fig. 1).

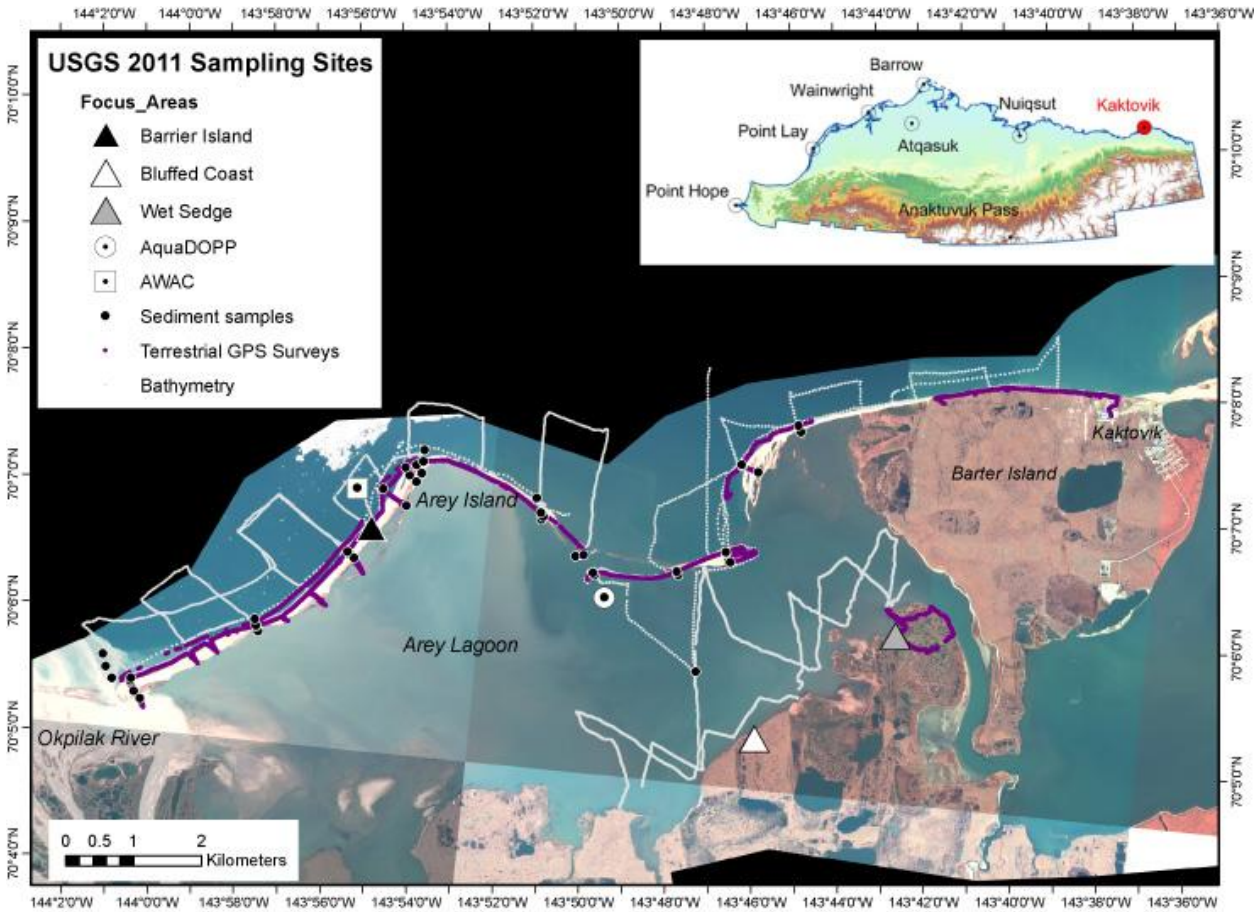

Figure 1. Map of the study area and a summary of data collection efforts. Three focus study sites are shown with triangles; instrument sites and sampling locations are listed in the legend. Inset map shows site vicinity relative to the North Slope of Alaska. Base imagery is 2003 Quickbird.

To address the first stated objective, the work was separated into three tasks: 1) compile and analyze data and information on historic and present shoreline positions and onshore habitats, 2) gather supporting field data, and 3) numerical modeling.

Historic and present shoreline positions (task 1) will be used to assess barrier-island migration patterns and rates as well as sedimentation or erosion of the lagoon mainland coast. Time evolution of the barrier island will be used as a basis for comparison to shoreline change and sediment transport computed with the numerical model. Field data collected as part of this project (task 2) will be used to provide inputs to the numerical model as well as to contribute to much needed baseline data (of which there is relatively little in this region). Field measurements of currents, waves, and water levels will be used to calibrate and validate the hydrodynamics of the numerical model. Spatial distributions of sediment grain size will be used as boundary conditions for the sediment transport and shoreline change component of the study. Measured water temperatures and salinities will provide data to assess mixing and density stratification within the lagoon, will provide inputs to the model, and will allow comparison to projected lagoon water quality changes. For example, if measurements indicate that the lagoon is currently brackish and model simulations indicate a future deterioration of the barrier island, flushing of the lagoon should increase, yielding higher salinities and a corresponding change in the ability to support some habitats. Ground temperatures collected as part of this effort will be used to investigate heat transfer through the upper soil layers that may lead to accelerated thaw and erosion of the permafrost coast. The final task (task 3: modeling) will synthesize the information generated from tasks 1 and 2 to estimate future migration of the barrier island, water quality changes of the lagoon, and inundation extents and frequencies in response to continued Arctic warming. Tasks 1 and 2 are close to completion while the last task is in its initial stage. A progress summary is provided for each of these tasks in the following sections.

- *Task 1: Compile and analyze data and information on historic and present shoreline positions and onshore habitats.*

Historical shoreline positions have been digitized and analyzed. Historical shoreline position data is available for three time periods: 1947 (from NOAA T-sheets), ~1981 (NOAA nautical charts), and 2003 (Quickbird images).

- *Task 2: Gather supporting field data.*

Field work has been completed during two field campaigns. The first field campaign (July 7-13, 2011, USGS field activity report identification (FACS ID) I-D4-11-AR) involved collection of point measurements and deployment and installation of instrumentation for collection of time-series data. The second field campaign (24-29 September 2011; USGS FACS ID I-R4-11-AR) focused on instrument retrieval and outreach.

Point measurements included collection of sediment grab samples, salinity measurements within the wet sedge focus study site and nearby thermokarst ponds, and bathymetric and terrestrial elevation measurements. A total of 43 terrestrial sediment grab samples were collected for grain size analysis on the barrier islands delineating the Beaufort Sea and Arey Lagoon. Six samples were collected on the western spit of Barter Island, 9 on the small island between Arey and Barter Islands, and 28 on Arey Island. In addition, 11 seabed samples were collected with a dredge pipe in the vicinity of the time-series data collection instrument packages (AWAC and AquaDOPP, Fig. 1) and on the ocean side of Arey Island. Pond salinity was measured along two transects traversing the wet sedge study area. In all, 35 ponds were sampled over a distance of ~1.5 km. Bathymetry was measured within the lagoon and on the seaward side of the barrier islands and western Barter Island (Fig. 1). Although a low-draft vessel (small dinghy) was used to quantify depth within Arey Lagoon, measurements were not possible in the western portion due to the very shallow water depths. Terrestrial elevation surveys were obtained with a ‘back-pack’-type global positioning system (GPS). Backpack-derived elevations were post-processed to improve precision using a fixed base station established on Barter Island for the duration of the field campaign.

Nearly three months of time-series measurements were obtained throughout the study area during the latter part of the 2011 open water season (Table 1). Waves, currents, pressures (water levels), conductivity (salinity), and temperatures were measured within Arey Lagoon as well as on the seaward side of the Arey Island, in the Beaufort Sea. Active layer ground temperatures were measured at the wet sedge, bluff, and barrier island study sites. Limited data were obtained with the autonomous time-lapse cameras, as the cameras at the barrier island and bluff study sites were knocked over and the camera at the wet sedge site ceased working partway through the sampling period. With the exception of some of the bathymetry and terrestrial elevation data, all field data have been post-processed and analyses are ongoing. Select results are presented in Section 3.b.

Table 1. Time-series measurements (July - September 2011).

Parameter	Lat/Long (DD)	Start and end dates (UTC)
Open ocean deployment		
currents	N70.11687 / W143.92597	7/7/2011 - 9/27/2011
waves	N70.11687 / W143.92597	7/7/2011 - 9/27/2011
pressure (water level)	N70.11687 / W143.92597	7/7/2011 - 9/27/2011
near-seabed water temperatures	N70.11687 / W143.92597	7/7/2011 - 9/27/2011
surface water temperatures	N70.11687 / W143.92597	7/7/2011 - 9/27/2011
near-seabed salinity	N70.11687 / W143.92597	7/7/2011 - 9/27/2011
Lagoon deployment		
currents	N70.10413 / W143.82839	7/7/2011 - 9/26/2011
waves	N70.10413 / W143.82839	7/7/2011 - 9/26/2011
pressure (water level)	N70.10413 / W143.82839	7/7/2011 - 9/26/2011
near-seabed water temperatures	N70.10413 / W143.82839	7/7/2011 - 9/26/2011
surface water temperatures	N70.10413 / W143.82839	7/7/2011 - 9/26/2011
near-seabed salinity	N70.10413 / W143.82839	7/7/2011 - 9/26/2011
Barrier island focus site		
time-lapse camera	N70.10060 / W143.71501	7/16/2011 - 7/20/2011
ground temperature array - ocean side	N70.11190 / W143.92030	7/16/2011 - 9/27/2011
ground temperature array - lagoon side	N70.11128 / W143.91774	7/16/2011 - 9/27/2011
Wet sedge focus site		
time-lapse camera	N70.10060 / W143.71501	7/9/2011 02:47 - 7/21/2011 22:39
ground temperature array - swash	N70.10072 / W143.71484	7/15/2011 - 9/26/2011
near-seabed water temperatures	N70.10068 / W143.71477	7/15/2011 - 9/26/2011
near-seabed salinity	N70.10068 / W143.71477	7/15/2011 - 9/26/2011
pressure (water level)	N70.10068 / W143.71477	7/15/2011 - 9/26/2011
Bluff focus site		
time-lapse camera	N70.08414 / W143.77867	7/8/2011 - 8/05/2011
ground temperature array - back bluff top	N70.08405 / W143.77901	7/8/2011 - 9/27/2011
ground temperature array - bluff top edge	N70.084111 / W143.77921	7/8/2011 - 9/27/2011
ground temperature array - bluff base	N70.08415 / W143.77926	7/8/2011 - 9/27/2011
ground temperature array - swash	N70.084211 / W143.77947	7/8/2011 - 9/27/2011
salinity (swash)	N70.084211 / W143.77947	7/8/2011 - 9/27/2011
water temperature (swash)	N70.084211 / W143.77947	7/8/2011 - 9/27/2011
pressure (water level)	N70.084211 / W143.77947	7/8/2011 - 9/27/2011
Reference site		
barometric pressure at sea level	N70.12875 / W143.61836	7/31/2011 - 9/27/2011

- *Task 3: Numerical modeling.*

Generation of numerical model grids has been initiated and tested within the vicinity of Kaktovik Lagoon, but not yet for Arey Lagoon. Present efforts are focused on assessing the quality of global climate model outputs and using these to develop projected wave conditions and storm surge levels out to the year 2100. Wind fields and atmospheric pressures from four recently released (Oct – Dec 2011) atmosphere-ocean coupled global circulation models (GCMs) are being evaluated against the North American Regional Reanalysis (NARR) dataset for the recent past.

Global climate model outputs used in this study were generated in support of the Coupled Model Inter-Comparison Project, phase 5 (CMIP5, http://cmip-pcmdi.llnl.gov/cmip/, http://www.wcrp-climate.org/). CMIP5 was proposed, conceived, and developed by the climate modeling community with the intent to provide a framework for coordinated climate change experiments conducted at various institutions around the globe. The prescribed experimental framework aims to address outstanding scientific questions that arose as part of the Intergovernmental Panel on Climate Change (IPCC) AR4 assessment process (IPCC, 2007), improve understanding of climate, and to provide estimates of future climate change that may be used to investigate changes in forcing. Hundreds of model simulations will be available as part of this effort.

For the purpose of assessing projected Arctic storms, a suite of GCM simulations of near-surface (10-m height) winds and atmospheric pressures were chosen based on availability of 1) "historical" runs for evaluation of how realistic the models are in simulating the recent past, 2) type of climate scenarios, 3) projections out to the year 2100, 4) completed simulations at the time of this study (fall 2011), and 5) frequency of synoptic (non-averaged) outputs (3 or 6 hr outputs). Based on these requirements a set of experiments from four modeling centers were chosen (Table 2).

Table 2. GCM modeled wind and pressure fields employed in study.

Institution and Modeling Center	**Model**	**Grid resolution (deg)**
Beijing Climate Center, Meteorological Administration, China (BCC)	BCC-CSM1.1	2.8 x 2.8
Institute for Numerical Mathematics, Russia (INM)	INM-CM4	2.0 x 1.5
Institut Pierre Simon Laplace, France (IPSL)	IPSL-CM5A-LR	1.4 x 1.4
Model for Interdisciplinary Research on Climate - AOEI, NIES, JAMSTEC, Japan (MIROC)	MIROC4h	2.5 x 1.5

The latest climate projections, developed in part for the next IPCC assessment report (IPCC AR5) due out fall 2013, are based on so-called representative concentration pathway (RCP) scenarios. In this study, the mid-range RCP4.5 and the high-range RCP8.5 climate change scenarios are being simulated. The RCP4.5 and RCP8.5 scenarios represent climate experiments which lead to an approximate radiative forcing of 4.5 W/m^2 and 8.5 W/m^2 by the year 2100. The use of RCP4.5 or RCP8.5 deviates slightly from the original statement of work for this study where it was specified that the A1B intermediate emissions scenario would be used. With the recent (September - December 2011) release of the updated GCM outputs, it is felt that these analyses and use of the state-of-the-art GCM outputs will make this study more current.

Projected wave conditions (heights and periods), assuming minimal sea-ice extents, are being developed with the numerical model Wavewatch III™ (Tolman 2009) using all four GCMs and the two climate change scenarios. Wavewatch III™ is a third generation wave model developed at the National Oceanic and Atmospheric Administration (NOAA/NCEP) and is widely used for modeling waves in offshore regions. The winds from the GCMs are being applied to the wave model at the original GCM grid resolution (Table 1). The finer grid resolution of the wave model (0.25 x 0.25), in conjunction with computation of time- and wind-field dependent wave growth. provides a method for dynamical downscaling of future wave conditions. Results of this method are being tested against wave measurements collected as part of this study.

Objective 2 - Investigate the dominant forces responsible for projected changes to the Arctic coastal landscape.

Waves and storm surges are considered to be primary factors in shaping the Arctic coastal landscape (e.g., Manson and Solomon 2007). Based on observed and projected Arctic warming and its feedback effects on atmospheric conditions, storm-surge frequency and magnitude is likely to change, impacting Arctic coastal habitats. Surges can be divided into dynamic surge, where a long wave moves along the coast in response to atmospheric low-pressure systems moving over a body of water, and stationary waves that occur at the coast during strong on- or off-shore winds. As a first step in defining the dominant forces driving storm surges in the Arctic, the relative contribution of dynamic versus stationary surges was investigated by running the numerical model under individual forcing conditions for 20 historical storm events. These results will be used in combination with outputs from the selected GCMs to investigate the potential for changes in storm surge frequency and magnitude along the Beaufort coast.

b. Describe preliminary results.

Objective 1 – Task 1

Historical shoreline data indicate that the west end of Arey Island has been relatively stable, while the eastern section has migrated landward as much as 900 m and segmented into multiple islands. Parts of the mainland shoreline within the lagoon have also undergone erosion, particularly the section of mainland coast facing the segmented eastern portion of the barrier island (Figure 2).

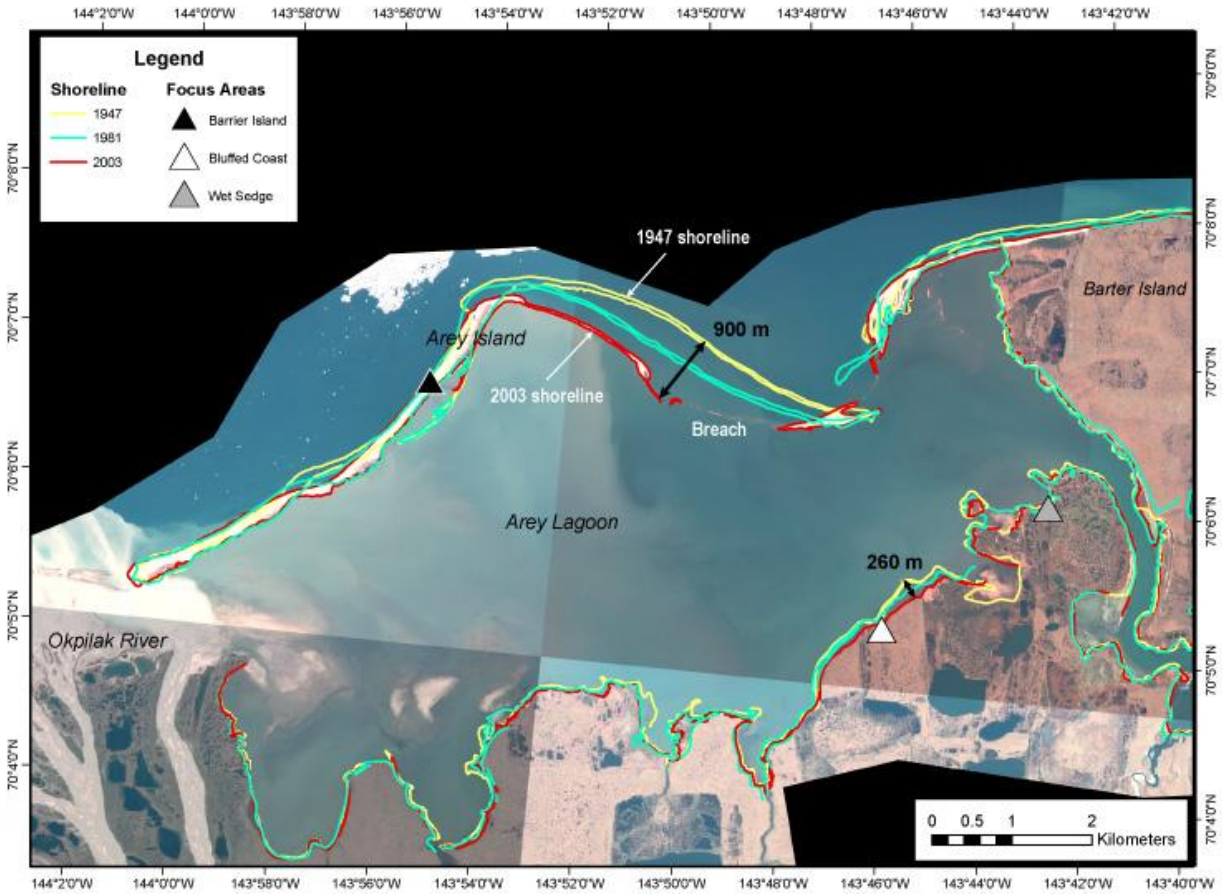

Figure 2. Map showing historical shoreline change in the study area. The eastern portion of Arey Island migrated as much as 900 m landward between 1947 and 2003 and was breached into multiple segments sometime between 1981 and 2003. Up to 260 m of land loss was measured near the bluffed-coast focus site between 1947 and 2003.

Objective 1 – Task 2

Grab samples

Sediment sizes ranged from silt/clays to a maximum median grain size (d_{50}) of 12.24 mm, with a mean d_{50} of 3.04 mm (Table 3, Figure 3). Fine silts and clay were noted within the lagoon near the AquaDOPP measurement site. Fine to medium sands (<0.5 mm) were found in the Beaufort Sea off the west end of Arey Island near the delta and off the east end of the northeast facing section of Arey Island. Medium to coarse pebbles (>8.0 mm) were measured in the near- and off-shore regions at the apex of the barrier island (i.e., just northeast of the AWAC location shown in Figure 3; one sample each location), at the berm crest (one sample), and at the shoreline on the lagoon side of Arey Island (two samples).

On the seaward side of Arey Island, the sediment consisted of coarse sands to fine pebbles, while at the berm crest and on the lagoon side of the barrier island, the sediment was coarser (Table 3). Mats of organic material were ubiquitous on the lagoon side of Arey Island; these were not included in the sediment analysis.

Table 3. Summary statistics of mean sediment-grain sizes.

Location	Min (mm)	Max (mm)	Mean (mm)	N (-)
Overall	0.26	12.24	3.04	54
Marine	0.26	12.24	3.43	8
BI Beaufort shore	0.79	3.70	2.10	14
BI berm crest	0.58	9.91	3.62	15
BI lagoon shore	1.15	9.47	3.50	13

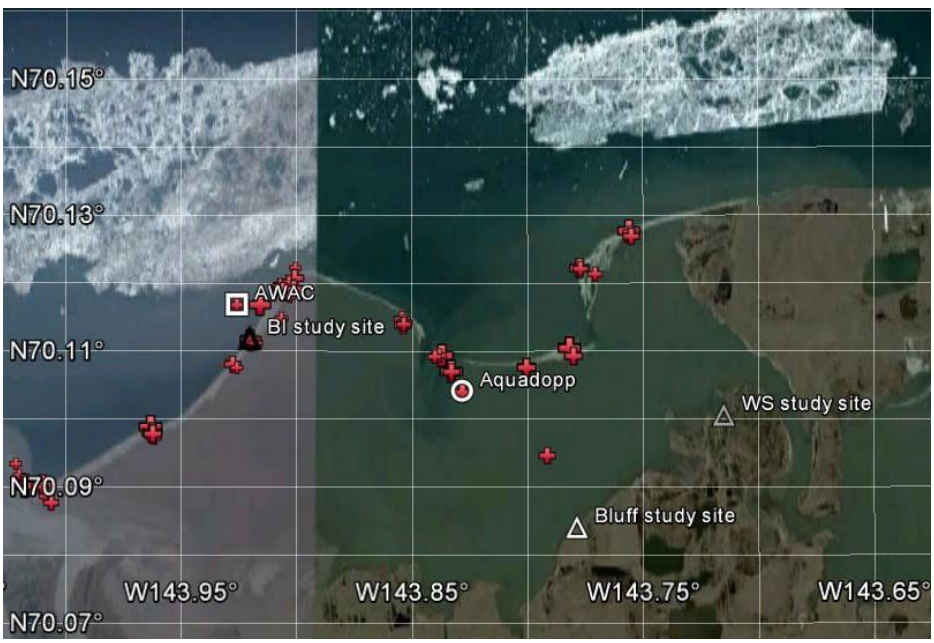

Figure 3. Map showing the locations of sediment samples collected in July 2011. Symbols are sized by three bins describing mean grain size, with values ranging from medium sands (0.26 mm) to pebbles and gravels (12.24 mm). Background image is from Google Earth, dated 7/3/2007.

Pond salinity measurements

Salinity values were almost three times as great in Arey Lagoon (37.5 psu) as in the channel connecting Arey and Kaktovik lagoons (13.4 PSU) (Figure 4). For ponds measured along transects from Arey Lagoon and the channel to the center of the peninsula, salinity values decreased with distance from the shore to the center of the peninsula, where pond salinities reached a minimum of 1.5 PSU. Topographically, the area exhibits very low relief, with a maximum elevation less than 1.5 m above sea level (unpublished USGS lidar elevation data obtained in 2009), and no storms or significantly elevated seas were measured by the Prudhoe Bay water-level gauge or noted by residents since the onset of the seasonal melt. This suggests several possibilities for the observed trends in pond salinity: (a) saline water

from extensive inundation events remain from previous storm events; (b) salt spray was carried across the peninsula by winds; (c) chemical and mechanical weathering of varied geology across the peninsula, resulted in decreasing pond salinity with distance from the shore; and\or (d) sub-surface irregularities hydraulically connect the lagoon and ponds. It is shown later in this report that extreme storm events likely inundated the peninsula several times during the recent past, and that the saline water within the ponds likely is due, at least in part, to these severe storm events.

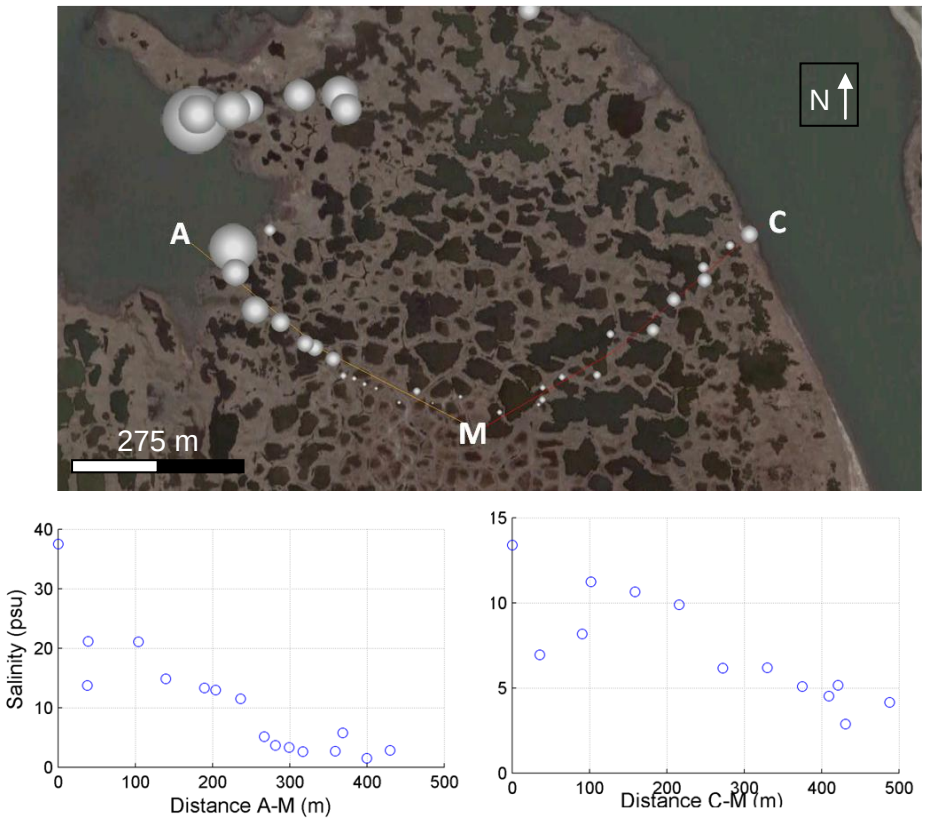

Figure 4. Salinity measurements in ponds in wet sedge focus study site (gray triangle in Fig. 1). Gray circles are sized by salinity values measured on 7/8/2011. Plots at bottom of figure show salinities as a function of distance from the open lagoon (transect AM, orange line in upper figure) and from the channel connecting Arey and Kaktovik Lagoons (transect MC, red line in upper figure). Note difference in y-axis scales in the two plots. Background image is from Google Earth dated 7/3/2007.

Water levels, waves, currents, and salinity

The diurnal astronomic tide signal is evident in the water level measurements at both the Beaufort Sea (~5 m water depth) and Arey Lagoon sites (~1 m water depth) (Figure 5). Total water-level deviations ranged from -0.36 m to +0.46 m. A low-pass filter was applied to the data in the lagoon to obtain water level fluctuations (surge) due to atmospheric forcing and circulation. The greatest surge was +0.32 m and occurred on 07 September (UTC; all times are reported in UTC throughout this report) when maximum wind speeds reached 8 m/s from the northwest (measured at the Barter Island Airport runway, 12 km to the east of the measurement sites). Atmospheric pressures were just slightly suppressed (99.6 kPa) from the mean measured over the study period (~100.9 kPa). . Overall, no substantial storm system passed through the area during the measurement period.

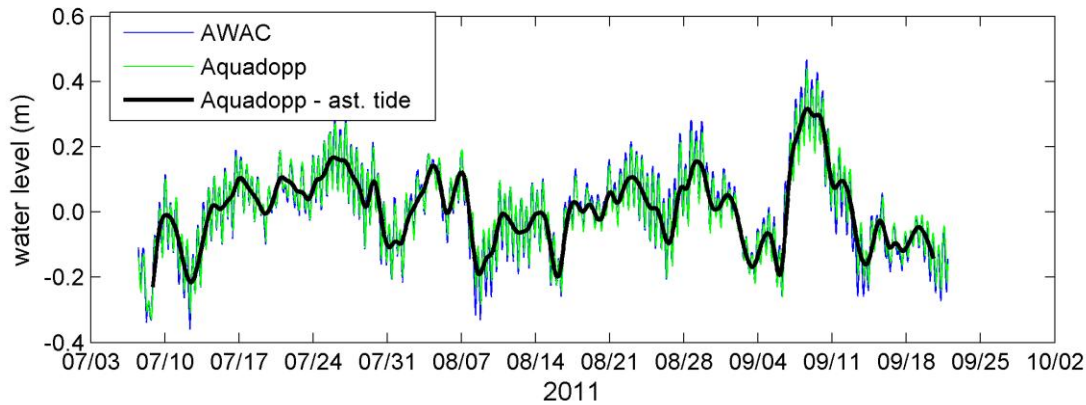

Figure 5. Water levels measured offshore of Arey Island (AWAC) and in the lagoon (Aquadopp). The overall mean of the time-series has been removed in this plot to highlight water-level deviations from the mean. The black line (Aquadopp data with the astronomical tide removed) is surge.

A maximum wave height of 1.3 m was measured on 16 September (Fig. 6). The associated short wave period (T_p = 5s) indicates that these waves were generated locally, as opposed to being generated by distant storms (swell). Swell (T_p > 7 s) was the dominant energy mode only about 6% of the time and was generally smaller than locally-generated waves, with a maximum swell height of 0.49 m. Wave heights within the lagoon were less than 0.10 m with no dominant direction (data not shown). The maximum fetch (distance over which the wind blows to generate waves) within the lagoon to the measurement site is on the order of 6.3 km. This relatively short dista+nce hinders the development of substantial wave heights and lengths, generally limiting waves to *chop* within the lagoon, which was not captured with the instruments.

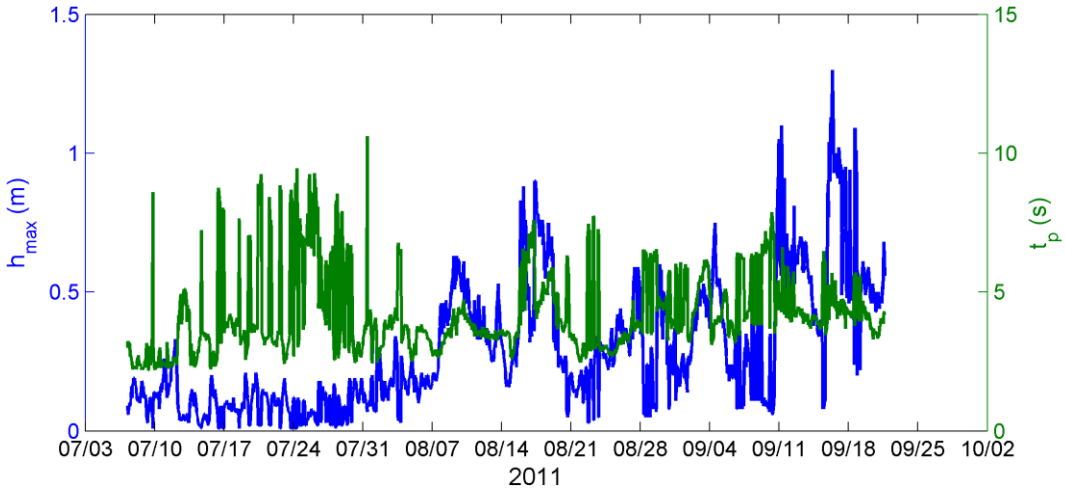

Figure 6. Wave heights and periods measured offshore of Arey Island in the Beaufort Sea.

Maximum current speeds reached 73 cm/s and 38 cm/s at the Beaufort Sea and Aery Lagoon sites, respectively (Fig. 7A). At the offshore site, current directions were clearly modulated by the presence of the barrier island, resulting in alongshore flow primarily oriented SW-NE. The net dominant direction suggests alongshore transport to the southwest (Figs. 7B-7D).

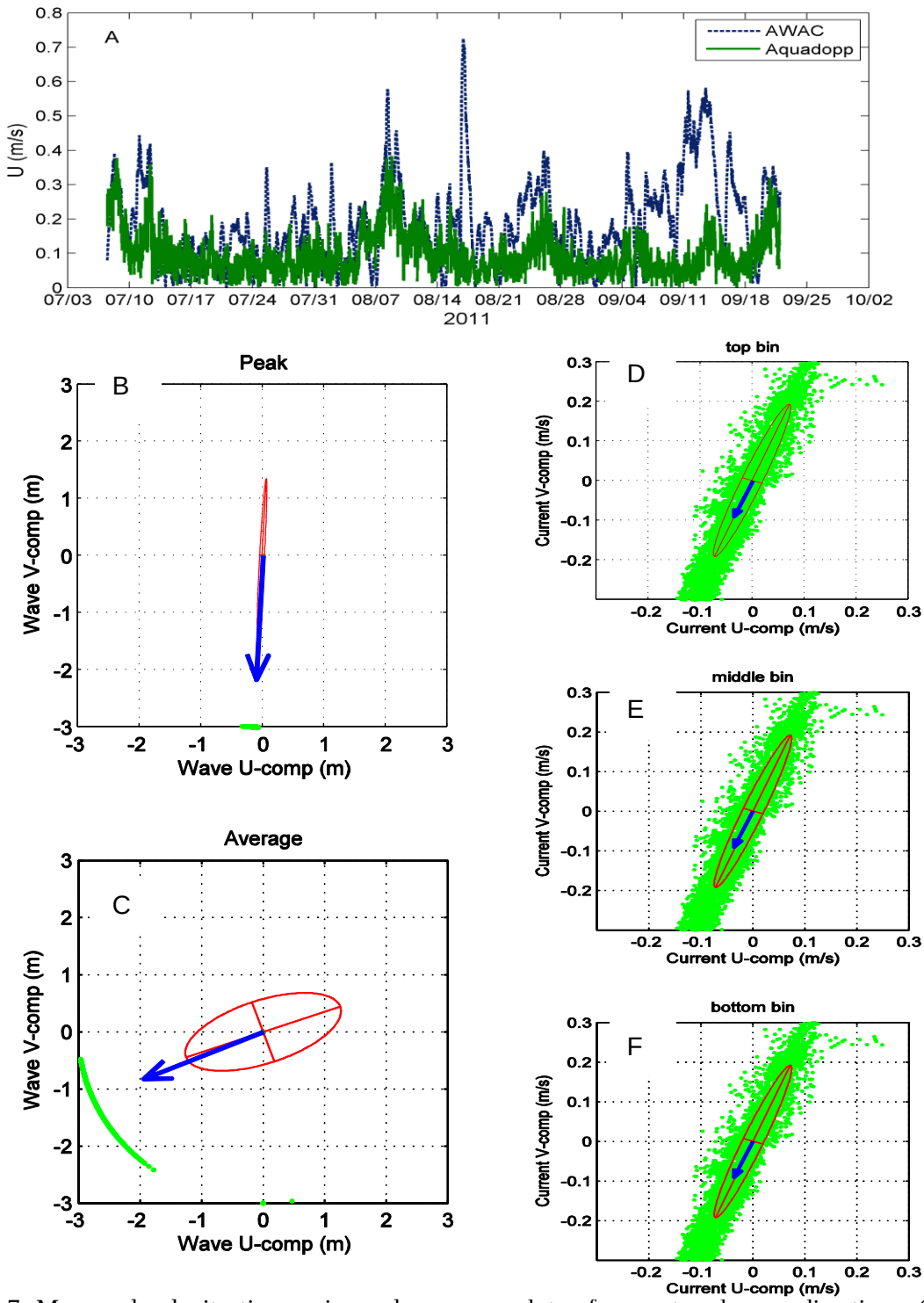

Figure 7. Measured velocity time-series and summary plots of current and wave directions. (A) Time-series of depth–averaged currents at the offshore (AWAC) and lagoon sites (Aquadopp). (B-C) Summary plots of peak (highest energy) and time-averaged wave directions measured at the offshore site. Ellipses depict the principal directions, arrows the overall mean direction and magnitude, while the green solid line indicates the standard deviation from the mean direction. U- and V- components are the east-west and north-south wave directions. (D-F) Scatter plots of currents measured near the surface (upper bin), middle of the water column (middle bin), and near the seabed (bottom bin) at the offshore (AWAC) site.

Water temperatures near the seabed ranged from -1.4°C to 4.1°C and from 0.1°C to 11.3°C at the offshore and lagoon sites, respectively (Fig. 8A). The high water temperatures (11°C) and diurnal signal at the Aquadopp site reflect the long days of the Arctic summer and shallow water depths of the lagoon (~1 m). The warm water temperatures are likely to have an impact on marine biota and the nearshore landscape where water comes in contact with permafrost-laden shores. A ground-temperature array installed at the lagoon side of the barrier island showed a decrease in temperature with depth (Fig. 8B); average values ranged from 7.3°C to 5.1°C at 10 cm and 50 cm below the surface, respectively. Cross-correlation analysis indicates that ground temperatures at 50 cm depth lagged air temperatures by approximately 4 hours. The reason for the abrupt temperature increase at the 50 cm deep gauge on July 30th is unknown at this time, but suggests that the thermistor was exposed to air for several days. The thermistor array at this site was found horizontal on the beach and apparently was extruded from the soil in early September, as suggested by the similarity between thermistor and air temperature measurements over the latter portion of the record.

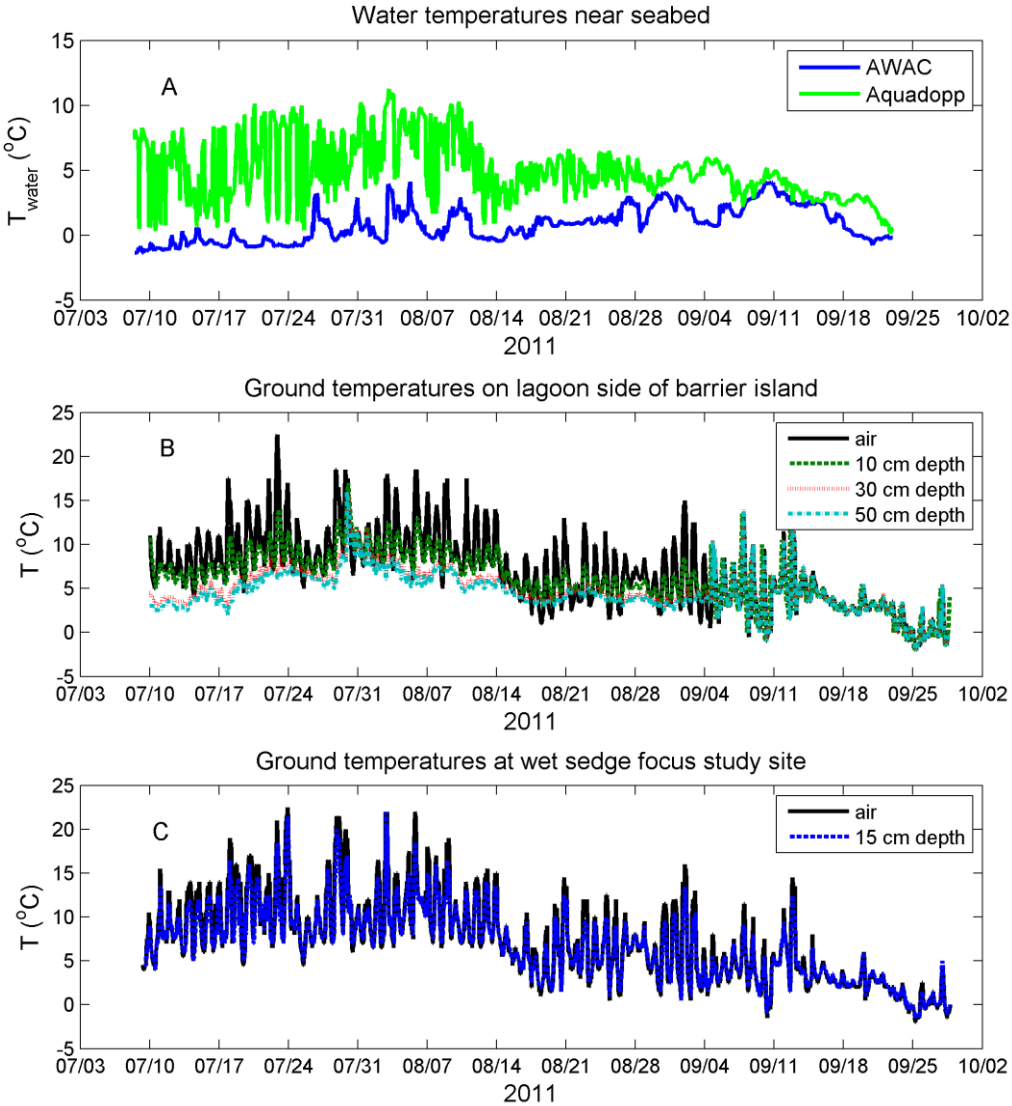

Figure 8. Water, air, and ground temperature measurements. (A) Water temperatures measured near the seabed at the Beaufort Sea (AWAC, ~5 m water depth) and Aery Lagoon (Aquadopp, ~1 m water depth) sites. (B) Active-layer ground temperatures measured on the lagoon side of the barrier island, and (C) at the wet sedge focus study site. The wet sedge site temperature logger at 55 cm depth was not recovered.

Conductivity, temperature, and depth (CTD) measurements in one of the ponds within the wet sedge focus study site (Fig. 9) adjacent to Arey Lagoon reveal some interesting processes (Fig. 10). Salinity measurements show a strong positive trend, with salinity increasing from 15 to more than 40 PSU between 09 July and 25 September (Fig. 10). This trend was inversely correlated with water temperatures, when the temperatures approached the freezing point around 09 September and likely caused separation of freshwater and brine development. Water temperatures were strongly modulated by air temperatures, but due to the high heat capacity of water and delayed thermal release, showed an average absolute difference of 2°C compared to corresponding air temperatures.

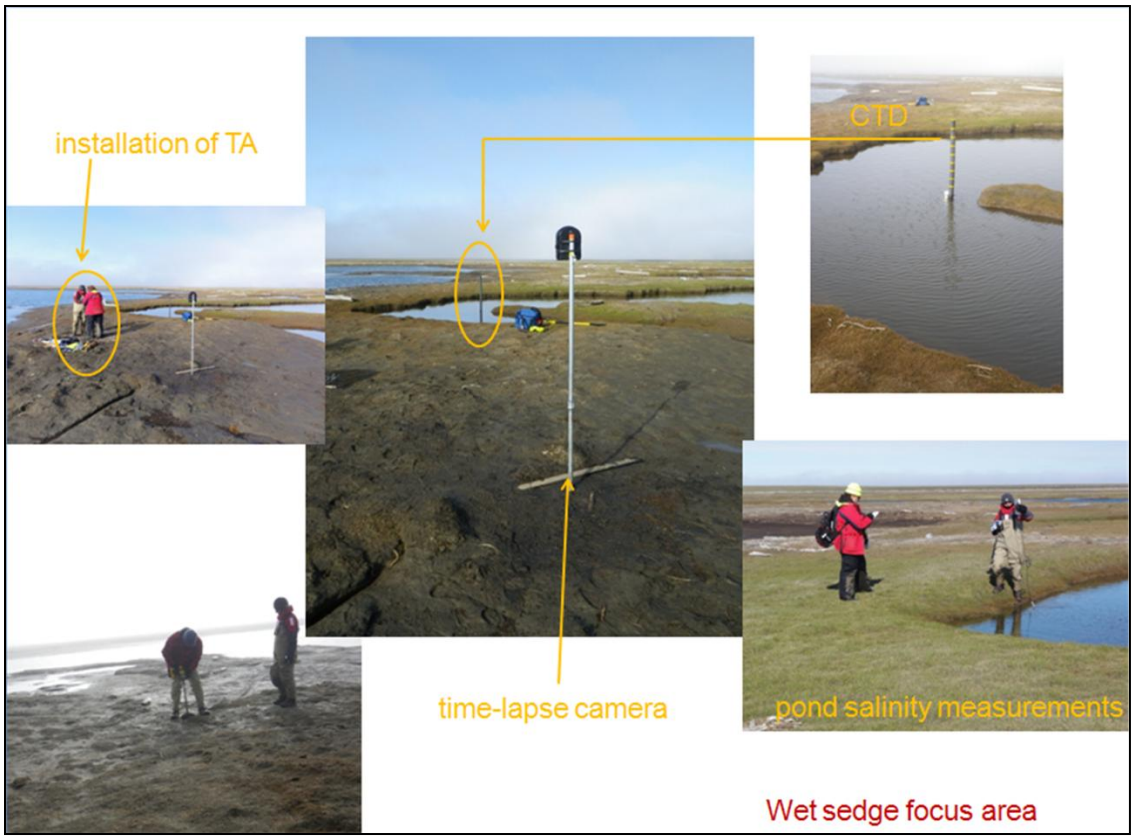

Figure 9. Time-lapse camera, ground temperature thermistor array (TA), and CTD at wet sedge focus study site.

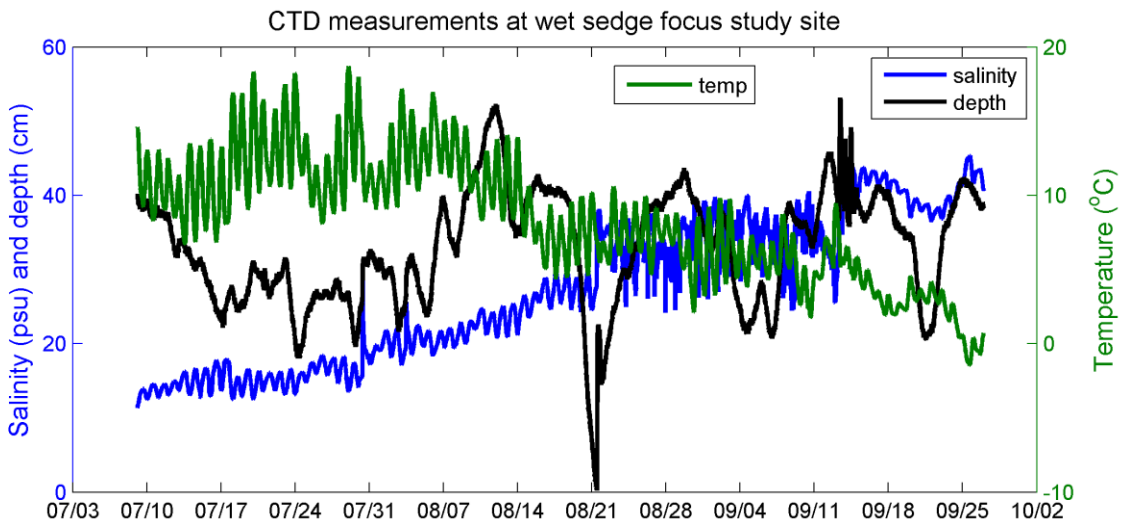

Figure 10. Salinity, temperature, and depth measurements within pond at wet sedge focus study site. The apparent depth decrease to 0 m on 8/21 likely was due to a transient blockage in the sensor.

The gradual increase in pond salinity values starting around the end of July coincided with the start of the open-water season, raising the possibility that the increase was due to evaporation. Estimates of freshwater evaporation were made using the modified pan evaporation Penman equation (Shuttleworth 1993),

$$E_P = \frac{\Delta A' + \gamma[6.43(1+0.536U_2D)]}{\lambda(\Delta+\gamma)} \quad (1)$$

where λ (=2.501-0.002361*T*) is the latent heat of vaporization of water (in MJ/kg), with *T* the air temperature in °C; δ is the rate of change of saturated vapor pressure (in kPa/°C) at air temperature; *A'* is the measured or estimated energy available for evaporation of the free water surface expressed as an evaporated water equivalent (mm/day); U_2 is the wind speed at 2 m height (m/s); *D* is the vapor pressure deficit (kPa); and γ is the psychrometric 'constant' (=0.0016286 *P*/γ, kPa/°C) where *P* is the atmospheric pressure (kPa). Studies have shown that evaporation from a natural body of water is usually lower compared to evaporation from a pan where the metal sides affect evaporation. Most textbooks suggest multiplying the pan evaporation by 0.75 to correct for this.

Cumulative volumetric evaporation, calculated with Eq. (1) using measurements at the nearby Barter Island airport and multiplied by the 0.75 correction factor and area of the pond (380 m^2), is plotted with red lines in Figure 11. Least-squares (LS) best fit lines to the salinity and volumetric evaporation (*vEv*) time-series yield similar slopes of 0.40 PSU/d and 0.42 m^3/d, respectively. The similar rates indicate that the increase in salinity was due at least in part to evaporative losses. Simple calculations indicate that ~16 m^3 (0.42 m^3/d × 37 d) of freshwater was lost due to evaporation over the measurement period prior to temporary sensor clogging on 8/21/2011 and prior to water temperatures reaching <4oC when brine development may begin. The pond was shallow with an estimated depth of ~0.35 m where the water level gauge was located. Assuming the pond shape can be represented by a sector of a sphere, a rough estimate of the total volume is 90 m^3 ($V = (2/3)\pi r^2 h$, where *r* is the radius and *h* is the maximum depth, assumed to be equal to the measured depth). Calculations suggest that a total loss of ~60 m^3 freshwater should have occurred, equivalent to two-thirds of the total pond volume, if salinity concentrations increased solely due to evaporation. The calculations employ a change in water density from 1,007 kg/m^3

to 1,025 kg/m^3 in response to increasing salinity concentrations and decreasing water temperatures. Although there was much variation in the measured water depths (+/- 8 cm) due to winds and barometric pressure changes, there was no clear decrease in the average water depth at the measurement site. So either volumetric estimates of the pond water are inaccurate and evaporative losses are the primary reason for the increased salinity concentrations, or other processes also contributed to the observed increases.

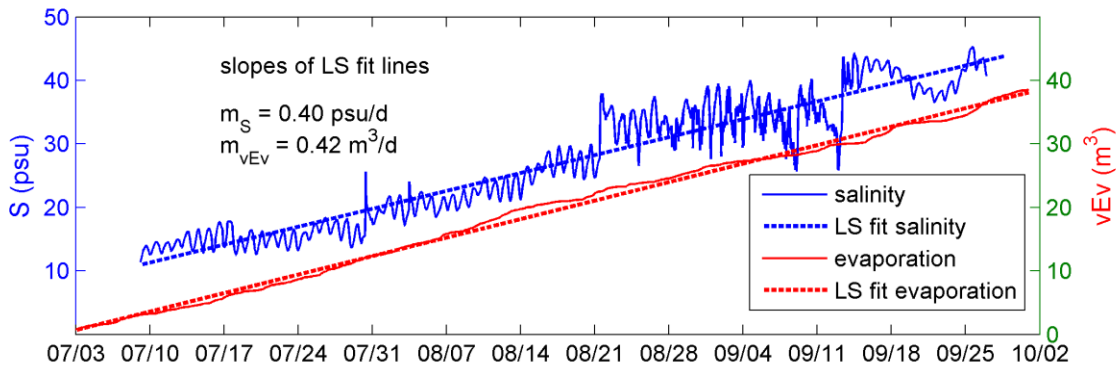

Figure 11. Calculated cumulative volumetric pond evaporation (*vEv*) and measured salinity values (from Fig. 10). Least squares linear regression best-fit lines yield similar rates of salinity increase and pond evaporation (0.40 PSU/d and 0.42 m^3/d, respectively).

Objective 1 – Task 3

Numerical modeling using projected atmospheric conditions as determined with atmosphere-ocean-coupled global models is ongoing. Simulations completed thus far indicate that under a high-emissions climate scenario (RCP8.5), wind intensities and storminess will increase. Preliminary decadal hindcasts (1996-2006) and projections (2026-2045 and 2081-2100) of total water levels (*TWL*) were calculated from the WavewatchIII^{TM} numerical model-generated waves and winds and atmospheric pressures derived from outputs of the INM-CM4 GCM model (see Table 2). Astronomic tides are relatively small and have been neglected in these estimates, but would add ~15 cm to the maximum total water level if a storm was to pass through at high tide. TWLs at the wet sedge focus study site were calculated as the sum of storm surge in response to winds (*SS*) and surge in response to the inverse barometer effect (*Δh; low atmospheric pressure results in a raised water level*),

$$\mathrm{TWL_{WS}} = \mathrm{SS} + \Delta\mathrm{h} \tag{2a}$$

Run-up (*R*) from open ocean waves were added to the TWL on the seaward side of the barrier island,

$$\mathrm{TWL_{BI}} = \mathrm{R} + \mathrm{SS} + \Delta\mathrm{h}. \tag{2b}$$

Run-up heights calculated with the Stockdon and others formula (2006) account for both wave setup and swash motion,

$$R = 1.1\left(0.35\beta_f\left(H_oL_o\right)^{1/2} + \frac{H_oL_o\left(0.563\beta_f^2 + 0.004\right)^{1/4}}{2}\right) \tag{3}$$

where H_o is the deep water significant wave height, L_o is the deepwater wavelength, and β_f is the foreshore slope. H_o and L_o were obtained from WavewatchIII™ simulation results; a foreshore slope of 1/8 was used based on field measurements in July 2011.

Storm surge levels were solved numerically with *dS/dx* in the cross-shore direction following Kamphuis (2000),

$$dS/dx = \xi(U\,cos(\phi))^2/gD \tag{4}$$

where ξ=3.2e-6, ϕ is the angle between wind direction and shore, *D* is the water depth at each grid cell, *g* the gravitation constant (9.83 m^2/s), *dx* the grid size in the cross-shore direction. Inverse barometer effect was calculated with,

$$\Delta h = \Delta p/\rho g \tag{5}$$

where ρ is the water density (average from AWAC data = 1025 kg/m^3) and Δp is the difference in barometric pressure at the site and sea.

Total water levels were calculated for the ice-free season August - September for 1996-2006 and August - October for years 2025-2045 and 2081-2100 assuming a later freeze-up (Table 3, Fig. 12). The median and extreme TWLs during the 1996-2006 time period were estimated to be 0.61 m and 1.5 m above sea level at the barrier island and 0.31 and 1.1 m above sea level at the wet sedge site.

Table 3. Hindcast and projected median and extreme TWL percentiles at the seaward side of Arey Island (barrier island, BI) and lagoon mainland wet sedge study sites.

site	50th percentile		90th percentile	
	1996 - 2006	rcp85	1996 - 2006	rcp85
open coast BI	0.61	1.6	1.5	2.5
mainland shore, lagoon	0.31	1.1	1.1	1.7

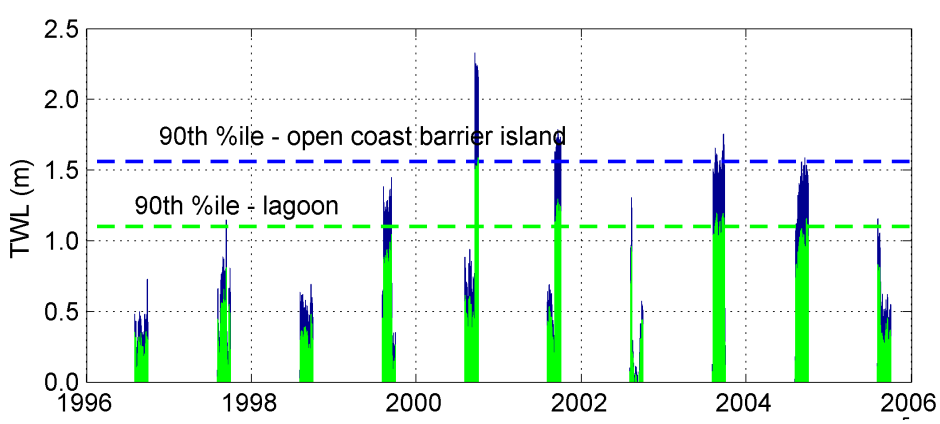

Figure 12. Hindcast total water levels at the ocean side of Arey Island (blue) and at the wet sedge study site (green). Gaps in data are when shorefast ice is present. Dashed lines show extreme values for the two sites for the 1996-2006 time period.

Because elevations are so low on the peninsula, the water level increases suggested by the hindcast modeling likely had significant impacts on the peninsula. Inundating a digital elevation model (DEM) of the peninsula shows that most of the peninsula around the wet sedge focus site would have been flooded during extreme events in the recent past (Fig. 13). At first glance this may seem surprising, as the areal coverage is rather large, but the inundation extent is supported with field data collected as part of this project. Brackish pond water was measured across the peninsula, with minimum concentrations at the approximate center of the peninsula and at higher elevations (see Figs. 4 and 13). Computed evaporation rates correspond well with increasing salinity concentrations at a pond adjacent to Arey Lagoon, indicating that the ponds are likely not hydraulically connected to the lagoon. A time-lapse camera with the field-of-view focused on the same pond and lagoon showed encroachment of lagoon water onto the peninsula (Fig. 14), even with lagoon water levels (approximately 25 cm at the time of the image) well below the extreme hindcast events. Finally, distinct wrack lines (i.e., wood debris) were observed across the peninsula, including the area surrounding the highest elevation at the study site (left photo in Fig. 13).

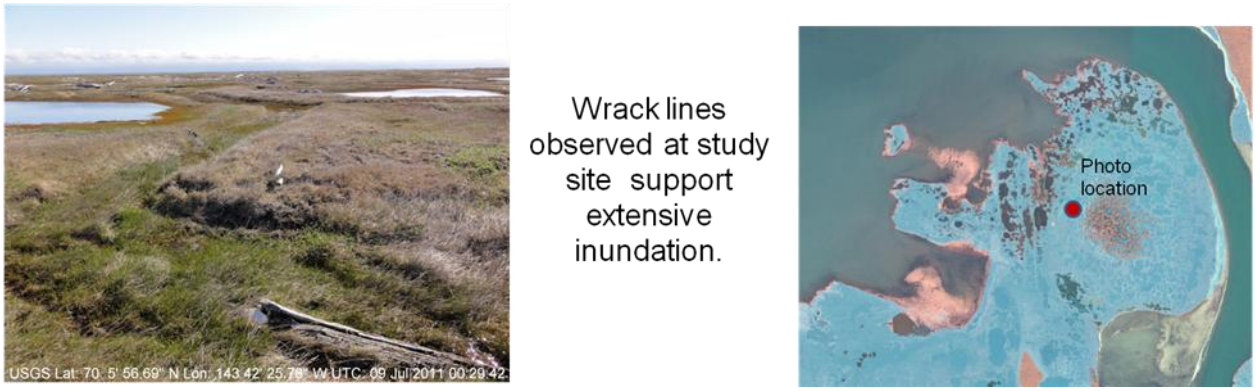

Figure 13. Modeled inundation extent during extreme hind-cast event (x.xx m TWL increase; shown in blue on right image) and observed wrack lines near center of peninsula (left image).

Figure 14. Time-lapse images of the wet sedge focus study site. Note the encroachment of saline lagoon water (left side of images) toward brackish pond (right side of images).

First order (simple estimates) projected total water levels for the middle and end of the 21st century are plotted in Figure 15. The projections assume a lengthened open water season extending from June through October for all years. Additionally it should be noted that calculations of historical events have not been validated against measurements; as a result the projections shown here should be considered preliminary. The hindcast 90th percentile extremes from Fig. 12 are also shown for comparison. Employing forcing from the INM-CM4 model and high-end climate scenario (rcp8.5), the median (50th percentile) water levels are expected to increase by two to three times, while the 90th percentile (%ile) extremes are expected to increase by approximately two-thirds. Median (50th %ile) strength storms are then expected to raise the water level to heights approximately equivalent to the 1996-2006 extreme (90th %ile) events (1.1 m and 1.6 m at the wet sedge and barrier island study sites, respectively).

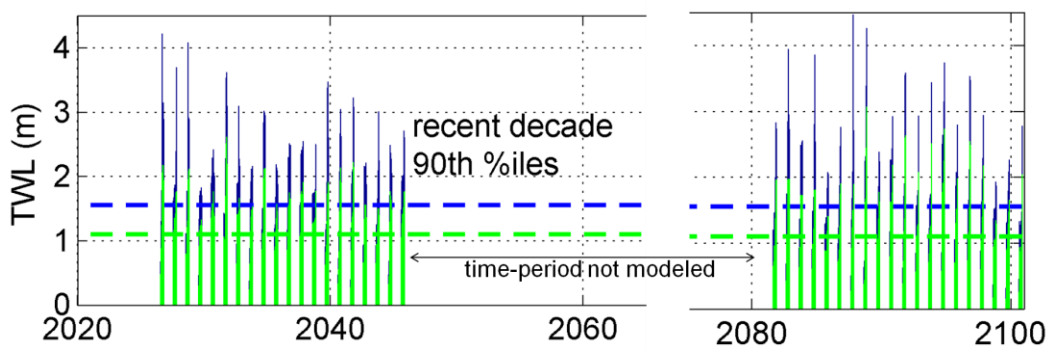

Figure 15. Projected total water levels at the ocean side of the Arey Island (blue) and at the wet sedge study site on the mainland south side of Arey Lagoon (green) under climate scenario RCP8.5. Gaps in data are when shorefast ice is present. Dashed lines indicate extreme values for the 10-year hind-cast (1996-2006) time-period.

Frequency of inundation is important in determining the future of habitat resilience. Our preliminary results indicate that the wet sedge peninsula will be inundated for most of the open-water season during the decades of 2020 and 2030 but that frequency of flooding actually will decrease thereafter (Fig. 16). At the start of the 2080s and toward the end of the 21st century, extreme flooding is projected to occur for only ~20% of the open-water season, while in the 2090s, flooding will be somewhat more frequent. The reason for the modeled decreases is unclear at this time - it may simply be part of the natural climate cycle, or a response to changes in atmospheric circulation patterns in response to global warming. The underlying cause will be further investigated as this project progresses.

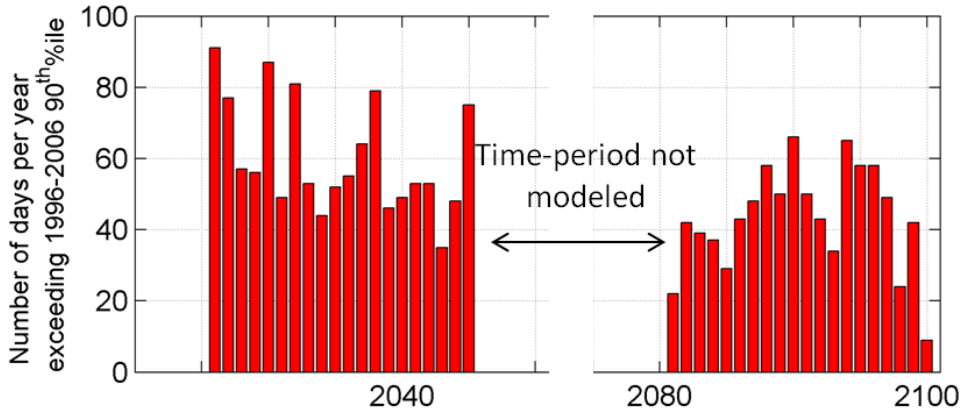

Figure 16. Number of days per year when TWLs exceed the 1996-2006 decade 90th percentile at the wet sedge study site.

Objective 2

The relative contribution of spatial- and time-varying winds and sea-level pressure gradients on the generation of elevated storm-surge levels was assessed by running Delft3D under individual forcing conditions for 20 historical storm events in the vicinity of Barter Island. The chosen storm events were identified by Lynch and others (2008) through analysis of winds measured during open-water at Barrow between 1950 and 2003. Model results indicate that at Barter Island, storm surge levels increased up to eight-fold due to pressure differentials and that, on average, storm-surge levels were approximately 70 cm greater than if only surge due to wind setup was included. Identical simulations, but with the thus far measured minimum perennial extent of the ice sheet (September 2007), showed a difference of less than 1% in storm surge levels (results not shown in plot). This small difference is consistent with findings by Kowalik (1984), who found that the influence of ice cover is typically negligible even if 60% of the low pressure zone is over ice. This finding is important in that it suggests that storm-surge projections should include atmospheric-pressure differentials and possibly storm trajectory and ground speed when calculating storm surge levels.

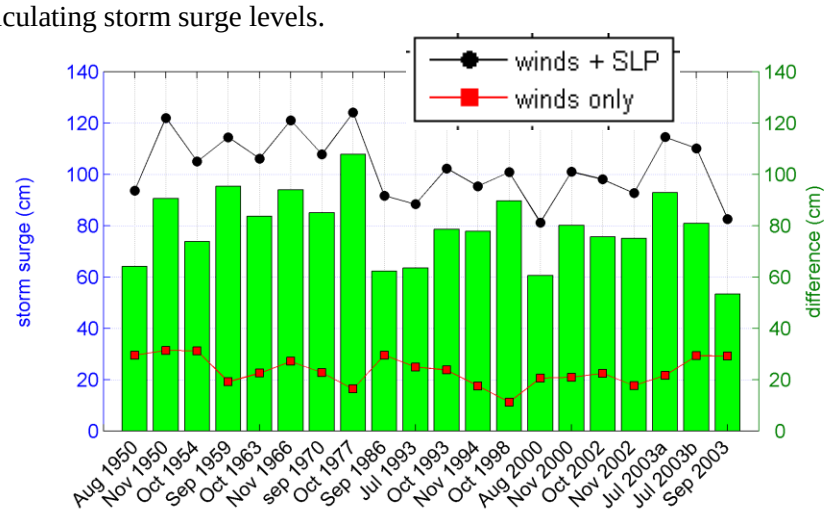

Figure 17. Numerical model simulations of wind-induced storm surge, with and without spatially and time-varying atmospheric pressures (slp). Bar height is difference between the two model runs.

c. Publications, conference papers, and presentations.

- Erikson, L.H., Gibbs, A.E., Richmond, B.M., Jones, B.M., 2012. Climate change impacts on storm-surge levels affecting habitats within a barrier-island lagoon system in eastern Arctic Alaska. *Poster*. Alaska Marine Symposium Anchorage, AK, January 2012.
- Gibbs, A.E., Jones, B.M., Richmond, B.M., Erikson, L.H., Harden, L., 2011. Coastline Change and Inundation on the North Slope. *Poster*. North Slope Science Initiative (NSSI), Barrow, Alaska, March 2011.
- Martin, P., Jones, B.M., Erikson, L.H., 2012. Arctic Landscape Conservation Cooperative coastal process studies. *Poster*. Alaska Marine Symposium Anchorage, AK, January 2012.

d. Education and outreach.

Outreach has been done in the form of meetings with government officials and dissemination of information via posters and signs throughout the village of Kaktovik. Regular contact and relay of progress is communicated to officials at the City of Kaktovik (Mathew Rexford). Meetings have been held with the principal and science teacher at the local school with the aim of sharing information and providing students with science projects related to the issues addressed in this study. Due to schedules and time constraints, actual class room time has not been carried out. However, we are maintaining communication with the school in the event that an opportunity should arise, and we are exploring the possibility of engaging one of the graduating high-school seniors in a USGS program aimed at fostering Native Americans in the sciences.

e. Other products resulting from the project.

- Metadata of field data (USGS FACS IDs: I-D4-11-AR and ID I-R4-11-AR)available at http://walrus.wr.usgs.gov/infobank/i/ir411ar/html/i-r4-11-ar.meta.html http://walrus.wr.usgs.gov/infobank/i/id411ar/html/i-d4-11-ar.meta.html) . We are currently working on making the data available for download.
- Sediment samples, and
- Model outputs.

f. Describe any concerns you may have about your project's progress.

It is slightly disappointing that no storms of significance passed through the study area during the sampling period. However, the field data strongly suggest frequent inundation in the area, so although higher measured water levels and wave heights would improve model validation, the data collected are sufficient for the purpose of the study.

4. PROGRESS STATUS

Field data have been successfully collected and are nearly fully post-processed. Historical shoreline positions have been digitized and analyzed. Airborne lidar data covering the study area has been post-processed and analyzed, and are ready for use in the numerical model. The projected wave climatology to the year 2100 is nearly complete. We have unfortunately had a setback in timing (due to circumstances outside the scope of this project) and are a few months behind the original anticipated schedule.

During the next six months, the focus will be on setting up and running the numerical model. The model will be tested against barrier island migration rates extracted from historical imagery and then used to project morphodynamic change in the study area, including extents of inundation. Simulations will differ

slightly from those outlined in the proposal - more recent climate scenario projections will be used, and the time-period will be reduced from decadal projections to the years 2026-2045 and 2081-2100. The latter change is needed to match available forcing data.

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Tolman, 2009: User manual and system documentation of WAVEWATCH III™ version 3.14. NOAA / NWS / NCEP / MMAB Technical Note 276, 194 pp + Appendices.

Part 2: Detailed report on progress made towards deliverables specified in Statement of Work

List each deliverable specified in the Statement of Work and estimate the progress made towards completion of that deliverable. If no progress has been made on a deliverable, record that as '0'. Please limit entries into the "Progress (% completed)" column to integers only, it is not necessary to include text or symbols.

The information you provide in the table is for use by LCC staff and will not be posted on arcticlcc.org.

Deliverable	Progress (% completed)
Oct 2011: Progress report including map files (ESRI ArcMap and GoogleEarth) and summary plots with (uncalibrated) numerical model-predicted inundation extents as a result of select storm surge events.	100
Apr 2012: DRAFT USGS open-file report (OFR, not yet completed internal review) presenting shoreline change data and summarizing collected and post-processed field data.	80
Oct 2012: Final USGS OFR summarizing shoreline change data and post-processed field data. Map files (ESRI ArcMap and GoogleEarth) showing barrier island migration and coastal wet sedge inundation extents, for 20-year time-periods at the mid- and end- of the 21st Century using the most recent climate change scenarios.	50
Dec 2012: Draft manuscripts for submission to peer-reviewed journals presenting field data, historical and projected barrier island migration rates and shoreline change, numerical model projected lagoon salinity, inundation extents, frequency of inundation, and coastal wet sedge sedimentation rates as a function of a projected warming trend.	5
Digital data will include imagery, ArcGIS layers, text files, and gridded model outputs. Metadata of field data collected will be available on a USGS web site as soon as a project ID is assigned.	20