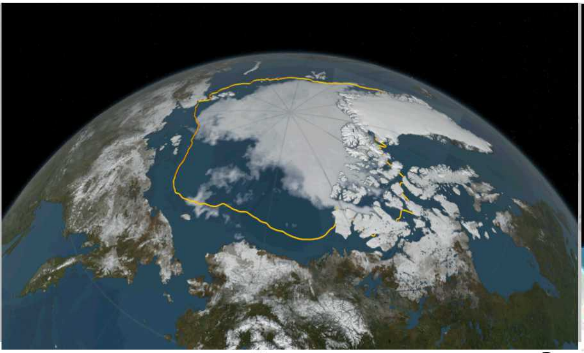
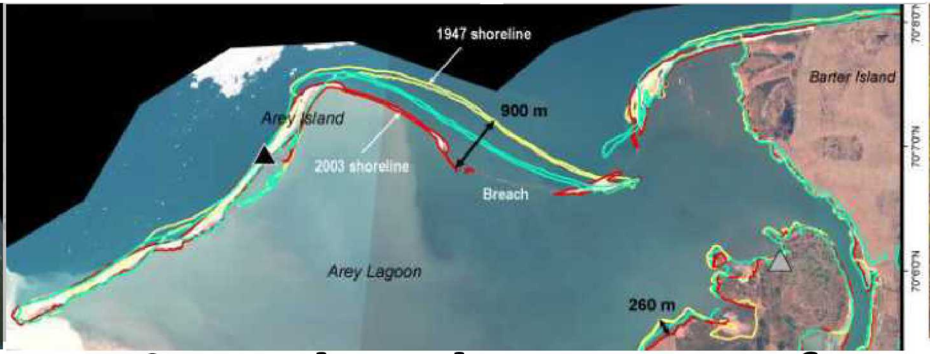
SAND2018-4777C





Arctic coastal erosion: development of a mechanistic model designed for coastal hazards evaluation

2018 DoD Arctic Science & Technology Synchronization Workshop. May 17th 2018

PI: Diana Bull, PM: Lori Parrott

Jennifer Frederick, Ben Jones, Craig Jones, Jeremy Kasper, Alejandro Mota, Jesse Roberts, Matt Thomas

Jim McClelland, Craig Connolly, Ken Dunton

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. SAND NO. 2018- PE

Team & Funding

Team Member	Qualifications and Expertise
Diana L. Bull (PI)	(SNL); Physicist with expertise in ocean wave dynamics, model development, laboratory and field testing, data analysis, and statistics
Kenneth Dunton	(UT Austin); Ecologist with expertise in coastal ecosystem dynamics, food web relationships, and biogeochemical cycling in estuaries
Jennifer M. Frederick	(SNL); Computational geoscientist with expertise in software development, validation and verification, flow and transport modeling in porous media, and permafrost thermal modeling.
Benjamin M. Jones	(USGS); Integrating field studies and remote sensing data in permafrost, research campaigns along remote arctic coastlines, field instrumentation and near-real time data transmissions
Craig Jones	(I.C.); Coastal hydrodynamics and sediment transport data analysis and modeling with expertise in field program and model development.
Jeremy Kasper	(UAF); Physical oceanography of shallow ice covered continental shelves including observations and modeling
James McClelland	(UT Austin); Biogeochemist with expertise in land to sea fluxes, composition, and bioavailability of organic matter in water, soils, and sediments
Alejandro Mota	(SNL); Computational solid mechanics, finite element analysis, numerical methods, constitutive models, large deformation, plasticity, fracture and failure.
Jesse D. Roberts	(SNL); Sediment dynamics measurement and modeling expertise in coastal environments. Extensive experience in managing large projects with multiple partners.
Matthew A. Thomas	(USGS); Experience with slope stability assessment via stochastic Factor of Safety computation, and numerical simulation of coastal slope instability.

Supported by the Laboratory Directed Research and Development program at Sandia National Laboratories.

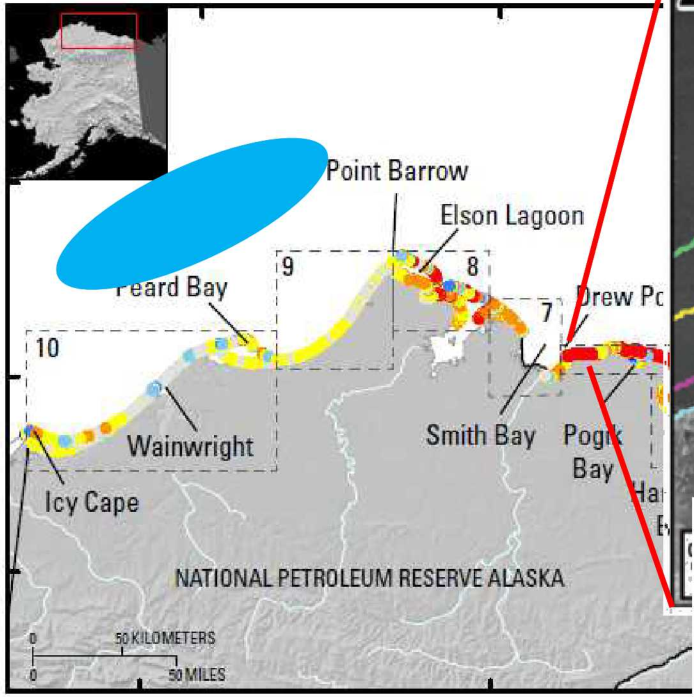
Close collaboration with USGS Pacific Coastal and Marine Science Center (Li Erikson, Ann Gibbs, Bruce Richmond, and Tom Lorenson), and strong working relationship with Scott Dallimore at the Geological Survey of Canada

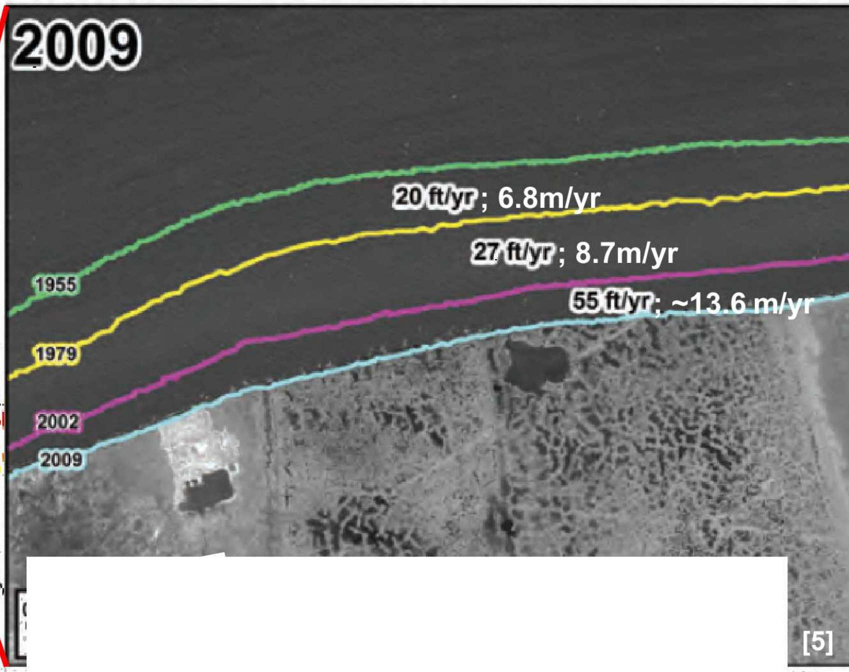
MOTIVATION

Acceleration in Historical Erosion Rates

- Long-term regional study [1]
  - 84% of the coast showing retreat between ~1940 & ~2010

	~1940-1980	~1980-2010
Icy Cape to Border [25]	**-1.2**m/yr	**-1.4**m/yr
Chukchi Sea [25]	**-0.5**m/yr	**-0.1**m/yr
Beaufort Sea [25]	**-1.5**m/yr	**-1.9**m/yr



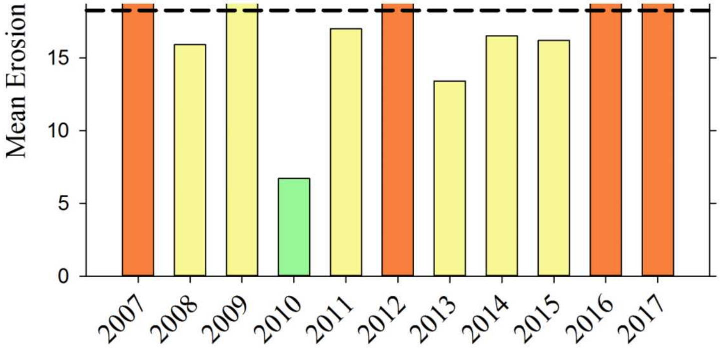


- Accelerating rates of erosion
  - American and Russian coasts (m/yr):

Drew Point, AK [2]	1955-1979: **-6.8**	1979-2002: **-8.7**	2002-2007: **-13.6**
Eastern Siberia [3]	1961-1968: **-0.6**	1990-1998: **-2.8**	1998-2010: **-4.8**

  - Anecdotal:

Decades ahead of "schedule" at Oliktok: degree of erosion expected in 2040 achieved in 2015 [4]



Source: Ben Jones, in development for paper

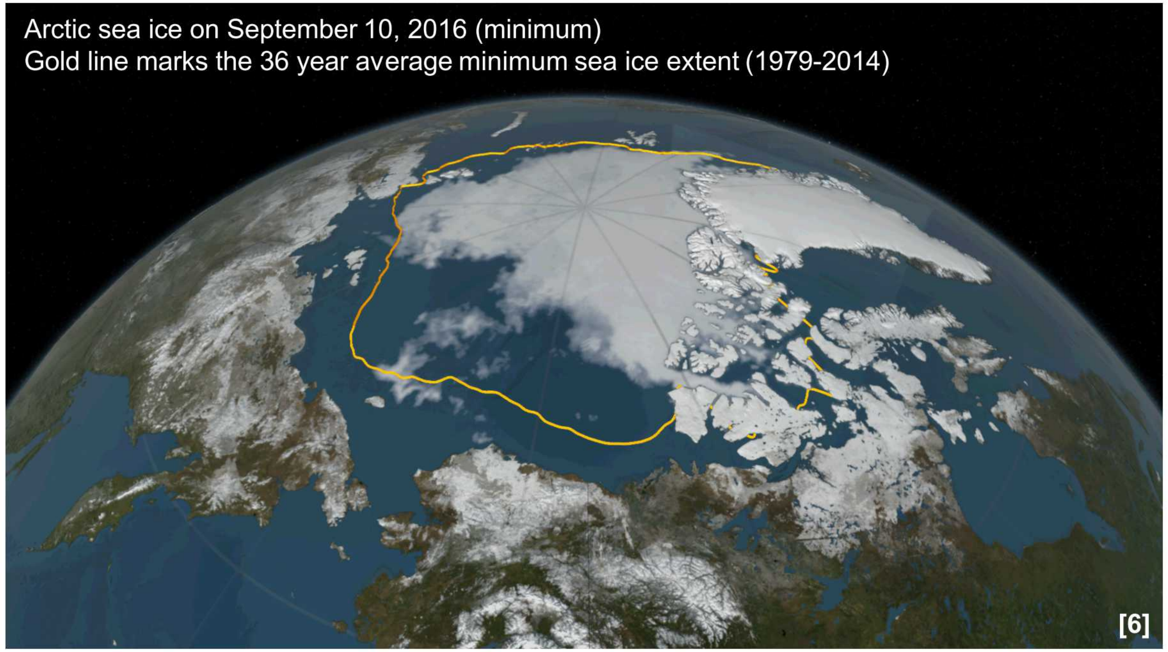
See poster by Li Erikson & Ann Gibbs for regional look and by Ben Jones for Drew Point to get more details on erosion rates!

Key Environmental Dynamics

- Increasingly Energetic Arctic Ocean
  - 66 more open water days than in 1979 (skewed towards fall) [7]
  - Wind-seas → swell-seas [8]
  - Increase in wave energy and storm surge levels

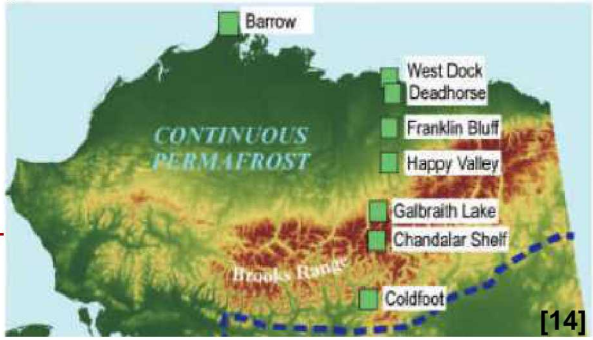
	~1990's - 2010's [9,10,11,12,13]	~2020's - 2100's [13]	
		RCP 4.5	RCP 8.5
H_s rate	+3-6 cm/yr	+4cm/yr	+5cm/yr
Max H_s	~4m	~6m	~8m
Max storm surge level	~1.3m	~2m	

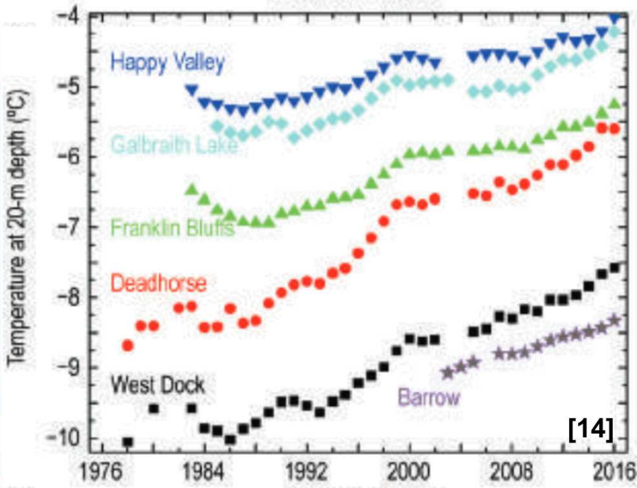
  - Increase in storm prevalence: ~5 **(2010)**→~30 **(2100)** [13]



- Warming Permafrost
  - Accelerating trend in permafrost temperature [14]

Northern AK plain [14]	1980-2016: **+0.36-0.8 ºC/decade**	2000-2016: **+0.44-0.65 ºC/decade**

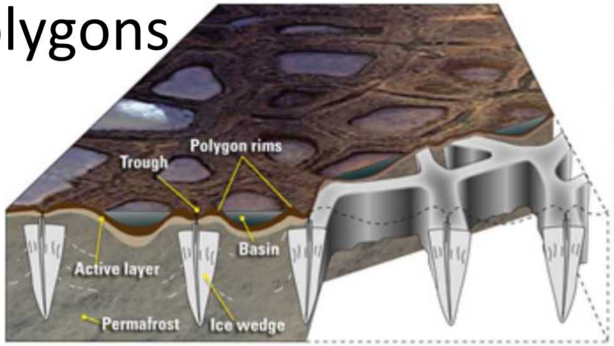




See poster by Li Erikson & Ann Gibbs for more details on evolving oceanographic conditions!

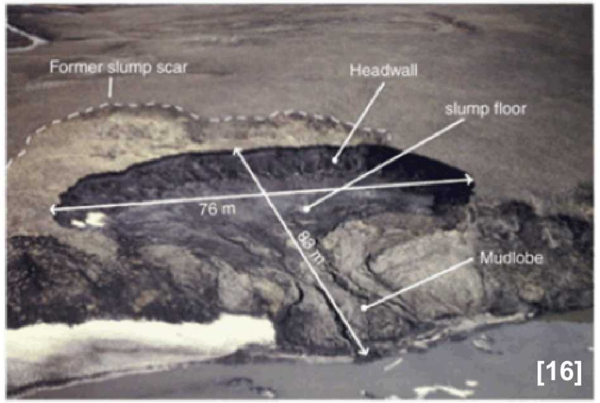
Permafrost: Unique Degradation Process

- Permafrost
  - Permafrost extends from the Brooks Range to the Continental Shelf and is up to 600m deep
  - Ice acts to bind unconsolidated material
  - Thermal, chemical, and mechanical processes can alter state of ice
- Predominant Geomorphology: ice-wedge polygons

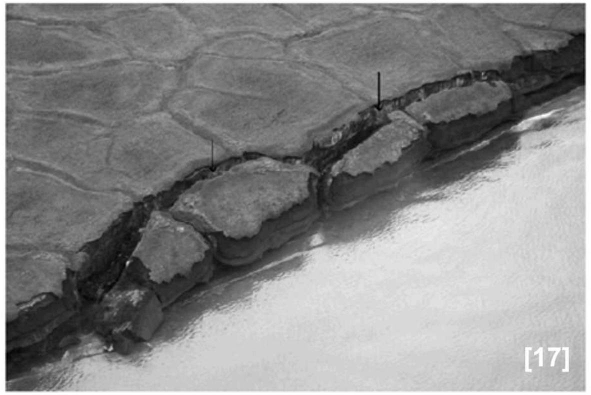


- State of the art erosion modeling
  - Trend projection, empirical relationships, 1-D steady state heat flow, …

retrogressive thaw slumping



block failure

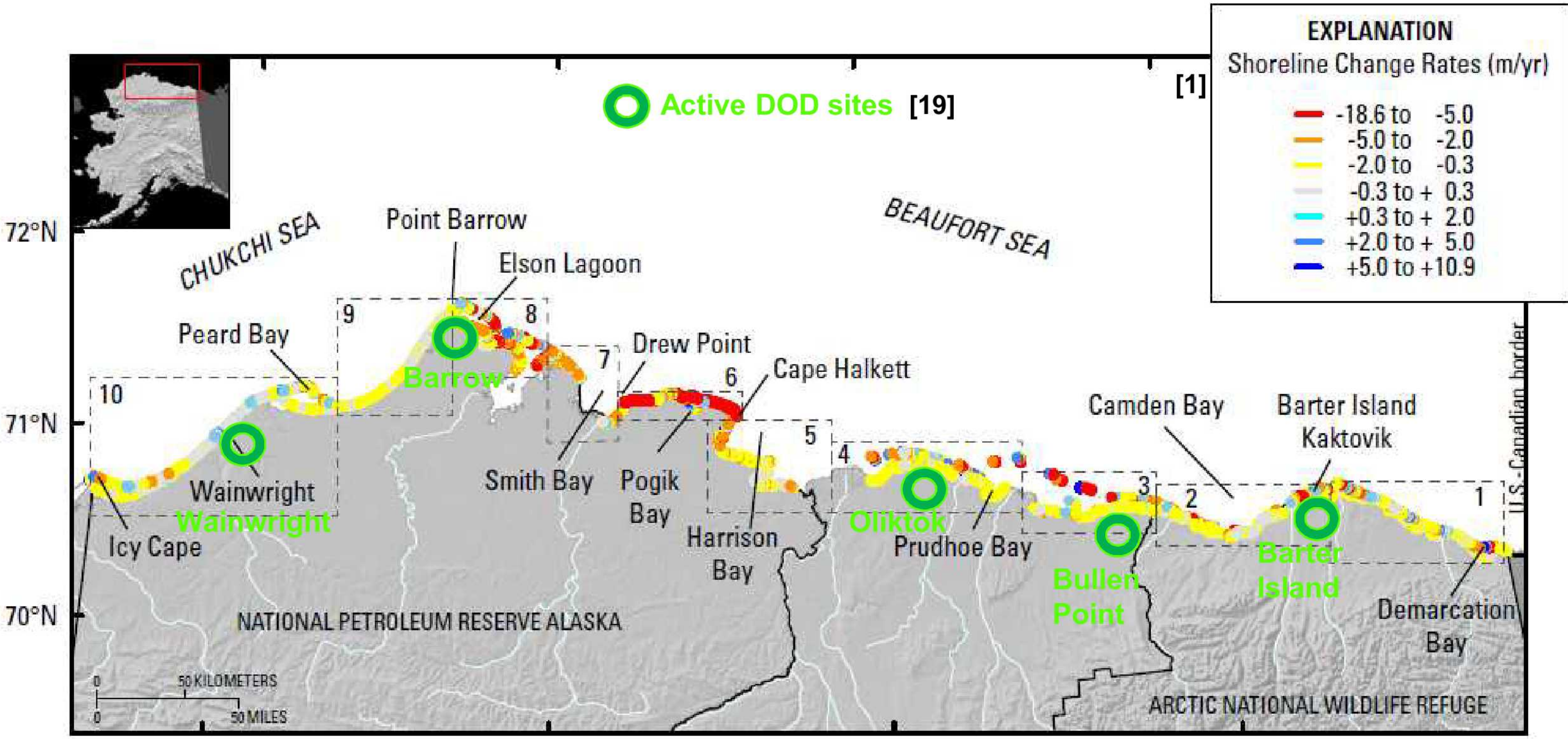


active layer detachment

Impacts

- Infrastructure
  - 6 active DOD sites along northern coastline [19,20]
  - 30 coastal villages threatened [21]
  - Anticipated economic impact is ~1Billion [21,4]

Anticipated infrastructure development should consider spatially varying erosion *and* deposition rates along Northern Alaska coastline



- Coastal food webs
  - biogeochemical influx into ocean effects ecological stability of region
- Carbon-climate feedbacks
  - Permafrost stores half of all terrestrial organic carbon (1,330-1,580Pg [22], twice the amount in the atmosphere); degrading coastline mobilizes the carbon content

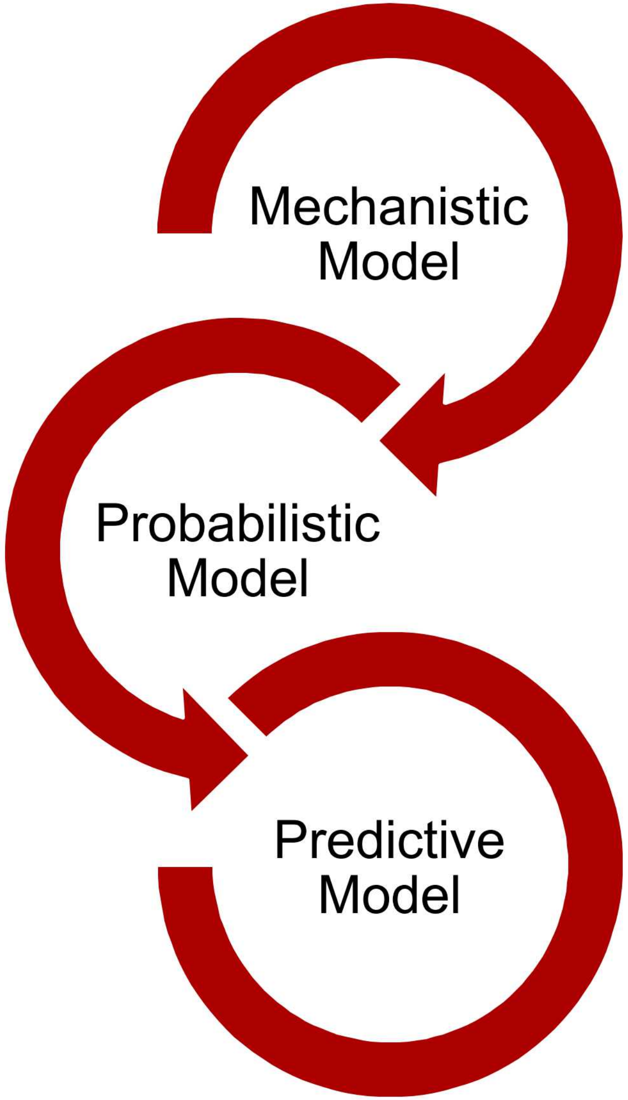
Project Goals

This project will deliver a field-validated predictive model of thermo-chemical-mechanical erosion for the permafrost Arctic coastline.

- The event-based projections will provide a quantitative tool
  - for guiding military and civil infrastructure investments, and
  - understanding coastal food webs and carbon-climate feedbacks.
- Redistributed eroded sediment in the environment enables
  - prediction of deposition locations,
  - tracing of toxic eroded materials, and
  - estimates of biogeochemical fluxes.
- Establish enduring relationships with Arctic invested parties
  - University of Alaska Fairbanks,
  - UT Austin,
  - BLM,
  - Geological Survey of Canada (GSC),
  - USGS,
  - CRREL
  - USAF,
  - Army Corp of Engineers,
  - …

FY18 – FY20

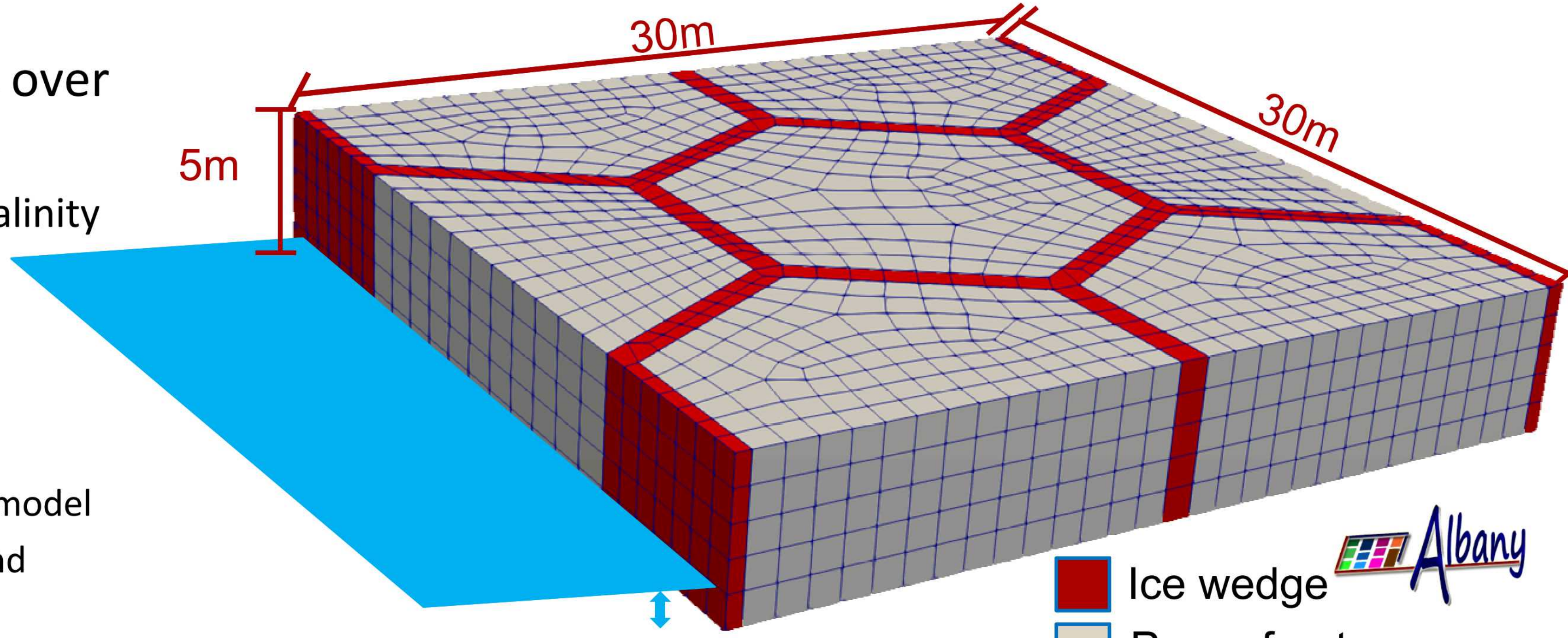
ENVISIONED MODEL PROGRESSION

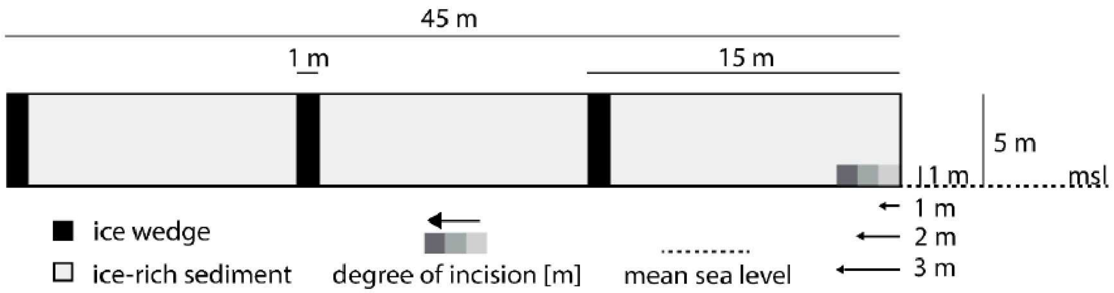


Single Event Mechanistic Modeling

validated, single storm, tightly coupled thermo-chemical-mechanical model

- Time-varying input variables over the duration of a storm:
  - Water level, temperature, & salinity
- Multi-physics finite element model of coastline
  - Physics:
    - Finite deformation plasticity model
    - 3-D unsteady thermal flow and chemical characteristics
  - Multiple archetypes to capture variability in coastline
- Validation campaign





Oceanography in Mechanistic Model

WW3 — Development of wave field in the Arctic to develop nearshore BC's

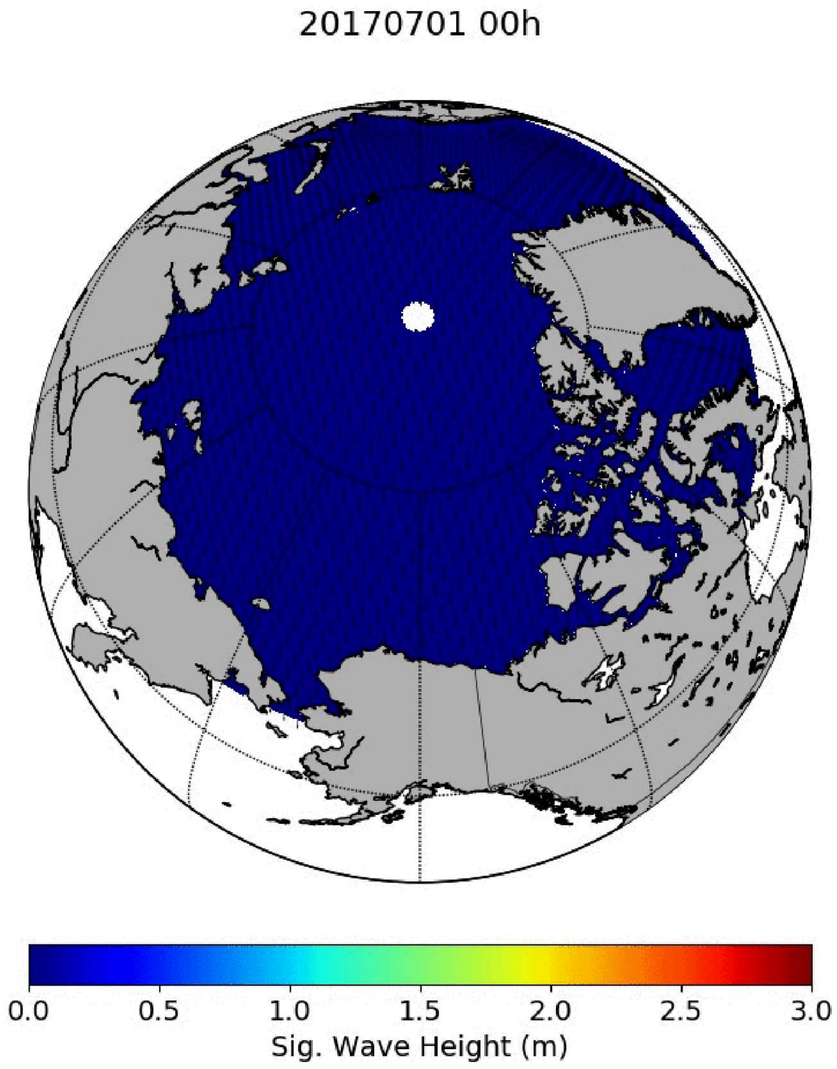
- surface winds
- ice cover
- temperature (surface and ocean)
- solar radiation
- persistent currents

SWAN — Wave set-up conditions 2-way coupled with circulation

- high resolution near shore environment
- capture set-up (storm surge and runup)
- wave energy inclusive of induced current effects

Delft3D — Circulation and thermodynamic mixing 2-way coupled with waves

- ability to model mixing of temperature and salinity clines
- capture induced currents in nearshore



- Potential Key Advances
  - Inclusion of ice coverage for fetch limited wave growth
  - Knowledge of wave energy along broad coastline
  - Set-up determination inclusive of bathymetry and wave energy
  - Ability to accurately predict temperature at bluff face through mixing of clines in the ocean

Thermo-chemical-mechanical Finite Element Mechanistic Model

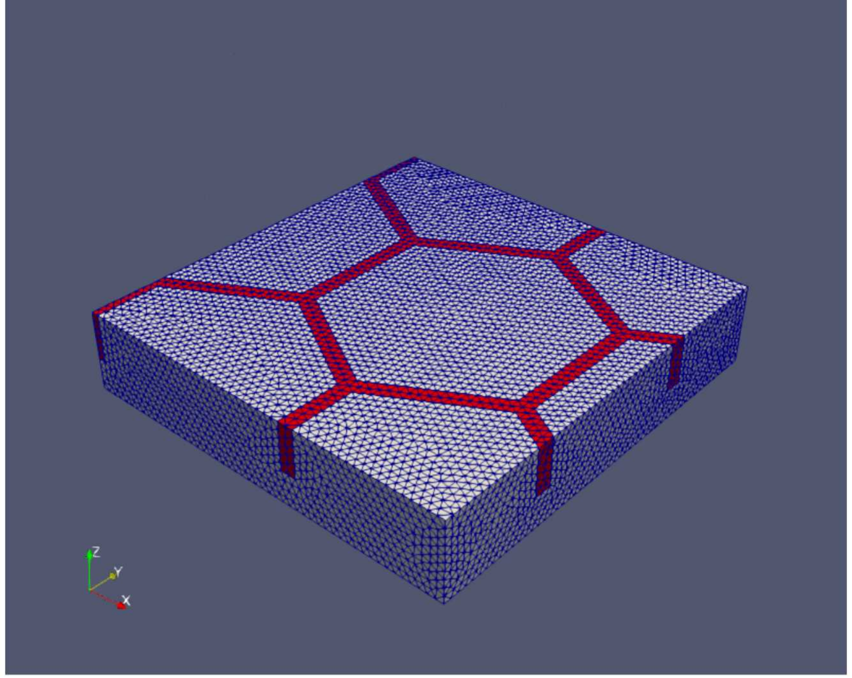
Thermo-chemical
- Sediment type
- Ice volume
- Water volume
- Pore size
- Salinity
- Temperature field

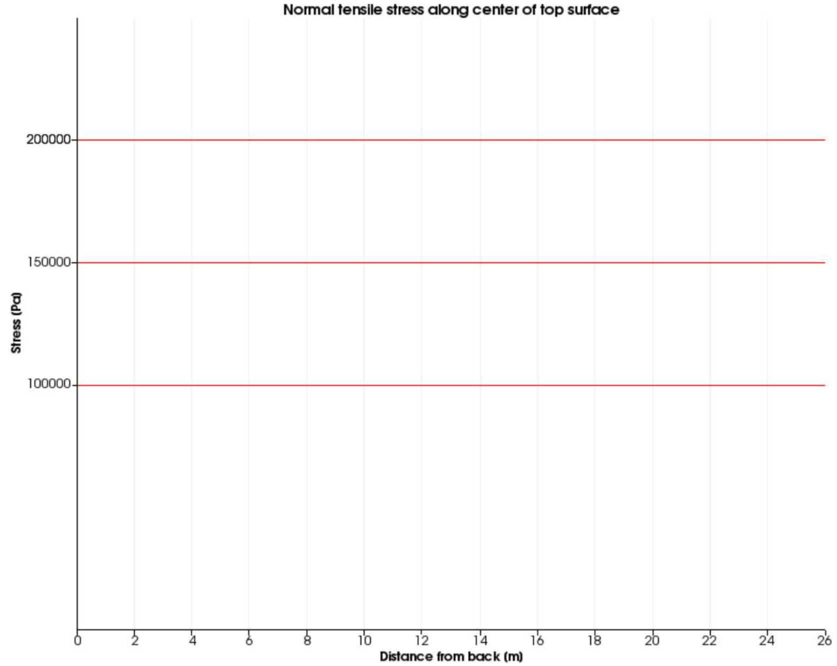
ALBANY*

Mechanical
- Strength relationships as a function of thermo-chemical state
- Morphology of coastline
- Stress-strain relationships of permafrost and ice

- Potential Key Advances
  - Tightly coupled strength and thermo-chemical states
  - Failure modes develop from constitutive relationships in FEM model (no empirical relationships!)
  - 3-D unsteady heat flow inclusive of the chemistry

*Albany is an implicit, unstructured grid, finite element code for the solution and analysis of multiphysics problems developed by SNL and released in public domain





Validation Data: Drew Point

Obtaining data at resolution needed to validate mechanistic model

Oceanography

Coastal Morphology

Permafrost

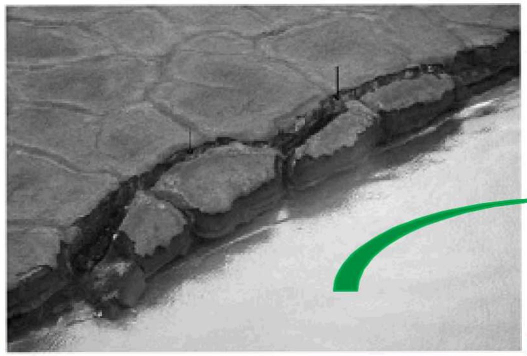
Biogeochemical

Atmosphere

Probabilistic Modeling

Parameterization enabling coastline view & historical validation

- Model Parameterizations
  - Identify the variable sensitivities that manifest distinct erosional behavior
- Coastline Parameterizations
  - Identify coastline stretches with characteristics that cause unique model parameterizations
- Multiple Archetype Runs
  - Create a "catalog" of coastline archetypes and their overall response to a set of storms
- Historical Validation
  - Using historical data for oceanographic conditions, coastline and model parameterizations, and documented shoreline retreat rates, work to match aggregate shoreline retreat rates



Predictive Modeling

Parameterizations combined with earth climate models to enable future predictions

- Using IPCC RCP8.5* project oceanographic conditions into the future
- Employ the statistical model and coastline architecture in concert with projected conditions to estimate future levels of erosion
- Use estimates of future erosion levels:
  - infrastructure impact analysis
  - nearshore ecological studies
  - tracing of eroded material

(credit: B. Jones, U.S. Geological Survey)

*The RCP8.5 combines assumptions about high population and relatively slow income growth with modest rates of technological change and energy intensity improvements, leading in the long term to high energy demand and GHG emissions in absence of climate change policies.

Technological/Scientific Impact

- Chief impacts of this model
  - predicted erosion rates over time (given climatic input data or weather forecasts)
  - designed to coupled with infrastructure impact models
  - facilitates ecological impact studies key to understanding food-webs
  - aids in tracking eroded sediment for deposition or toxic tracing studies
  - enables informed and sustainable risk management decisions with respect to infrastructure

(credit: B. Jones, U.S. Geological Survey)

[24]

References

Title slide photos (in order)

https://svs.gsfc.nasa.gov/4494

Erikson, L.H., Gibbs, A.E., Richmond B.M., Storlazzi, C.D., Jones, B.M. Arctic LCC Progress Report. "Modeling arctic barrier island-lagoon system response to projected arctic warming" June 22, 2012

Martin, P.D., J.L. Jenkins, F.J. Adams, M.T. Jorgenson, A.C. Matz, D.C. Payer, P.E. Reynolds, A.C. Tidwell, and J.R. Zelenak. 2009. Wildlife Response to Environmental Arctic Change: Predicting Future Habitats of Arctic Alaska. Report of the Wildlife Response to Environmental Arctic Change (WildREACH): Predicting Future Habitats of Arctic Alaska Workshop, 17-18 November 2008. Fairbanks, Alaska: U.S. Fish and Wildlife Service. 138 pp.

B. Jones, U.S. Geological Survey

Main Body References

[1] Gibbs, A. E., and B. M. Richmond. 2015. National assessment of shoreline change-Historical shoreline change along the north coast of Alaska, U.S.-Canadian border to Icy Cape. U.S. Geological Survey Open-File Report 2015-1048, 96 p.

[25] Gibbs, A.E., Ohman, K.A., Coppersmith, R., and Richmond, B.M., 2017, National Assessment of Shoreline Change: A GIS compilation of updated vector shorelines and associated shoreline change data for the north coast of Alaska, U.S. Canadian border to Icy Cape: U.S. Geological Survey data release, https://doi.org/10.5066/F72Z13N1.

[2] Jones, B. M., C. D. Arp, M. T. Jorgenson, K. M. Hinkel, J. A. Schmutz, and P. L. Flint. 2009. Increase in the rate and uniformity of coastline erosion in Arctic Alaska. Geophysical Research Letters, 36, L03503.

[3] Vasiliev, A., M. Kanevskiy, G. Cherkashov, and B. Vanshtein. 2005. Coastal dynamics at the Barents and Kara Sea key sites. Geo-Marine Letters, 25, 110-120.

[4] Hughes, Z. 2016. Erosion threat at remote military radars decades ahead of schedule. Alaska Public Media. http://www.alaskapublic.org/2016/07/04/erosion-threat-at-remotemilitary- radars-decades-ahead-of-schedule/

[5] Clement, J.P., J.L. Bengston, and B.P. Kelly. 2013. Managing for the future in a rapidly changing Arctic. A report to the President. Interagency Working Group on Coordination of Domestic Energy Development and Permitting in Alaska (D. J. Hayes, Chair), Washington, D.C., 59 p.

[6] NASA. Global Climate Change. Facts: Arctic Sea Ice Minimum. https://climate.nasa.gov/vital-signs/arctic-sea-ice/. Accessed 05/08/2017

[7] Barnhart, K. R., I. Overeem, and R. S. Anderson. 2014b. The eect of changing sea ice on the physical vulnerability of Arctic coasts. The Cryosphere, 8, 1777-1799.

[8] Thomson, J. and W. E. Rogers. 2014. Swell and sea in the emerging Arctic ocean. Geophysical Research Letters, 41, 3136-3140.

[9] Francis, J.A. and Vavrus, S.J., 2012. Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophysical Research Letters*, *39*(6). (satellite and obs)

[10] Wang, X.L., Feng, Y., Swail, V.R. and Cox, A., 2015. Historical changes in the Beaufort–Chukchi–Bering Seas surface winds and waves, 1971–2013. *Journal of Climate*, *28*(19), pp.7457-7469.(statistical downscaling)

[11] Stopa, J. E., F. Ardhuin, and F. Girard-Ardhuin. 2016. Wave climate in the Arctic 1992-2014: seasonality and trends. The Cryosphere, 10, 1605-1629.(altimeter+dynamical downscaling (WW3)

[12] Liu, Q., Babanin, A.V., Zieger, S., Young, I.R. and Guan, C., 2016. Wind and wave climate in the Arctic Ocean as observed by altimeters. *Journal of Climate*, *29*(22), pp.7957-7975.

(altimeter data)

[13] Erikson, L.H., Gibbs, A.E., Richmond, B.M., Storlazzi, C.D., Jones, B.M., and Ohman, K.A., 201x: Changing storm conditions in response to projected 21st century climate change and the potential impact on an arctic barrier island–lagoon system—A pilot study for Arey Island and Lagoon, eastern Arctic Alaska: ***In Press*** U.S. Geological Survey Open-File Report 201x–xxxx, xx, p., https://doi.org/10.3133/ofr201XXXXX.

[14] Romanovsky, V. E., S. L. Smith, N. I. Shiklomanov, D. A. Streletskiy, K. Isaksen, A. L. Kholodov, H. H. Christiansen, D. S. Drozdov, G. V. Malkova, and S. S. Marchenko, 2017: [Arctic] Terrestrial Permafrost [in "State of the Climate in 2016"]. *Bulletin of the American Meteorological Society* (supplement), 98(8): S147-S151.

References cont.

Main Body References

[15] Martin, P.D., J.L. Jenkins, F.J. Adams, M.T. Jorgenson, A.C. Matz, D.C. Payer, P.E. Reynolds, A.C. Tidwell, and J.R. Zelenak. 2009. Wildlife Response to Environmental Arctic Change: Predicting Future Habitats of Arctic Alaska. Report of the Wildlife Response to Environmental Arctic Change (WildREACH): Predicting Future Habitats of Arctic Alaska Workshop, 17-18 November 2008. Fairbanks, Alaska: U.S. Fish and Wildlife Service. 138 pp.

[16] Lantuit, H. and W.H. Pollard. 2008. Fifty years of coastal erosion and retrogressive thaw slump activity on Herschel Island, southern Beaufort Sea, Yukon Territory, Canada. Geomorphology, 95, 84-102.

[17] Hoque, M. A., and W. H. Pollard. 2009. Arctic coastal retreat through block failure. Canadian Geotechnical Journal, 46, 1103-1115.

[18] Ravens, T. M., B. M. Jones, J. Zhang, C. D. Arp, and J. A. Schmutz. 2012. Process-based coastal erosion modeling for Drew Point, North Slope, Alaska. Journal of Waterway, Port, Coastal, and Ocean Engineering, 138, 2, 122-130.

[19] Alaska Department of Environmental Protection. 2016. Department of Defense Sites in Alaska. https://dec.alaska.gov/, accessed 2016.09.20.

[20] Department of Defense, 2016. Report to Congress on Strategy to Protect United States National Security Interests in the Arctic Region. OUSD Policy. https://www.defense.gov/Portals/1/Documents/pubs/2016-Arctic-Strategy-UNCLAS-cleared-for-release.pdf

[21] United States General Accounting Office (USGAO), 2009. Alaska Native Villages: Limited Progress Has Been Made on Relocating Villages Threatened by Flooding and Erosion. Report to Congressional Committees. http://www.gao.gov/new.items/d09551.pdf. (08.25.2011).

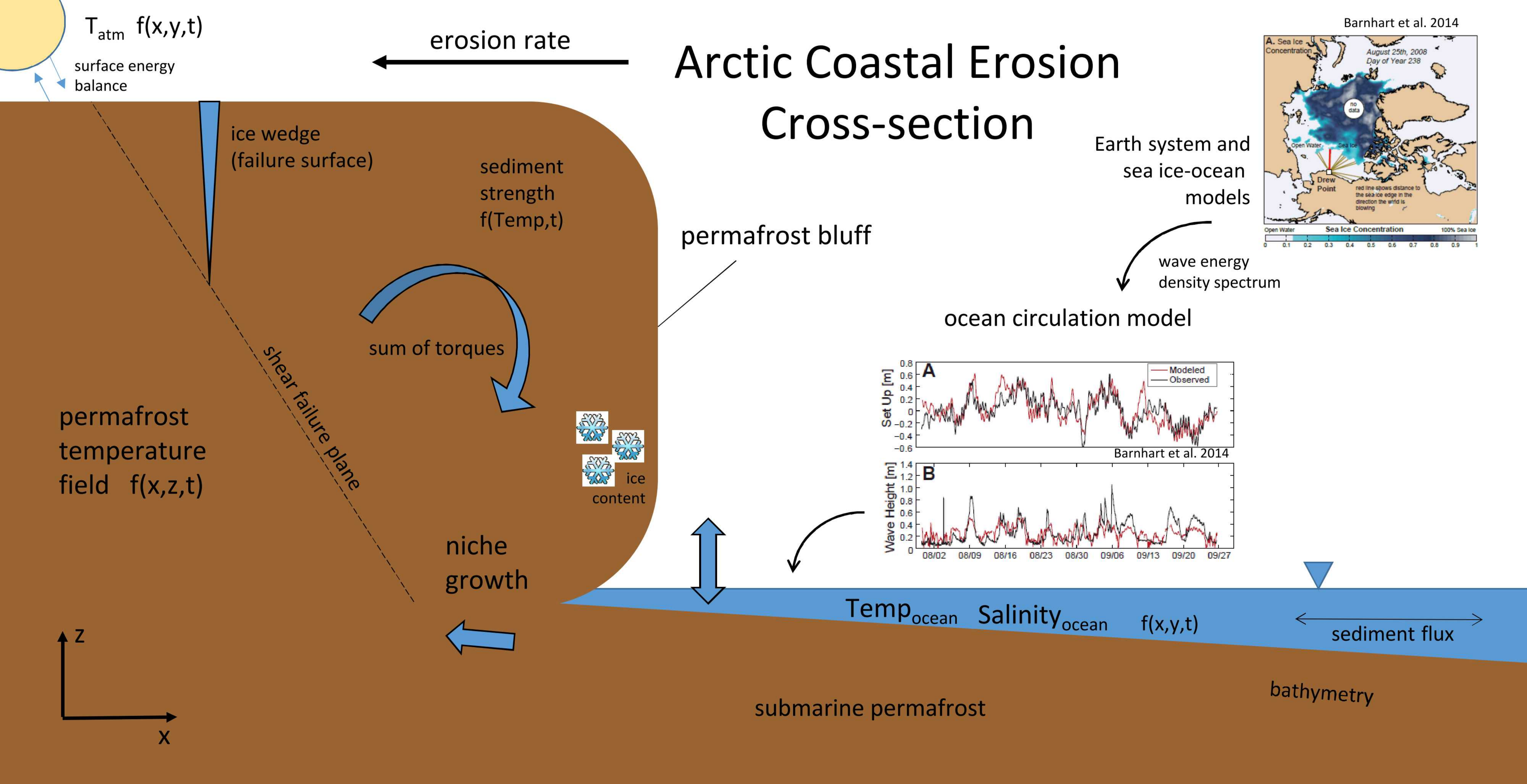
[22] Schuur, E.A.G. et al. Climate change and the permafrost carbon feedback. Nature, 520:171179, 2015

[23] Sheppard, K. 2015. Climate change takes a village as the planet warms, a remote Alaskan town shows just how unprepared we are. Hungton Post. http://www.hungtonpost.com/, accessed 2016.09.20.

[24] Arp, C. D., Jones, B. M., Schmutz, J. A., Urban, F. E., & Jorgenson, M. T. (2010). Two mechanisms of aquatic and terrestrial habitat change along an Alaskan Arctic coastline. Polar biology, 33(12), 1629-1640.

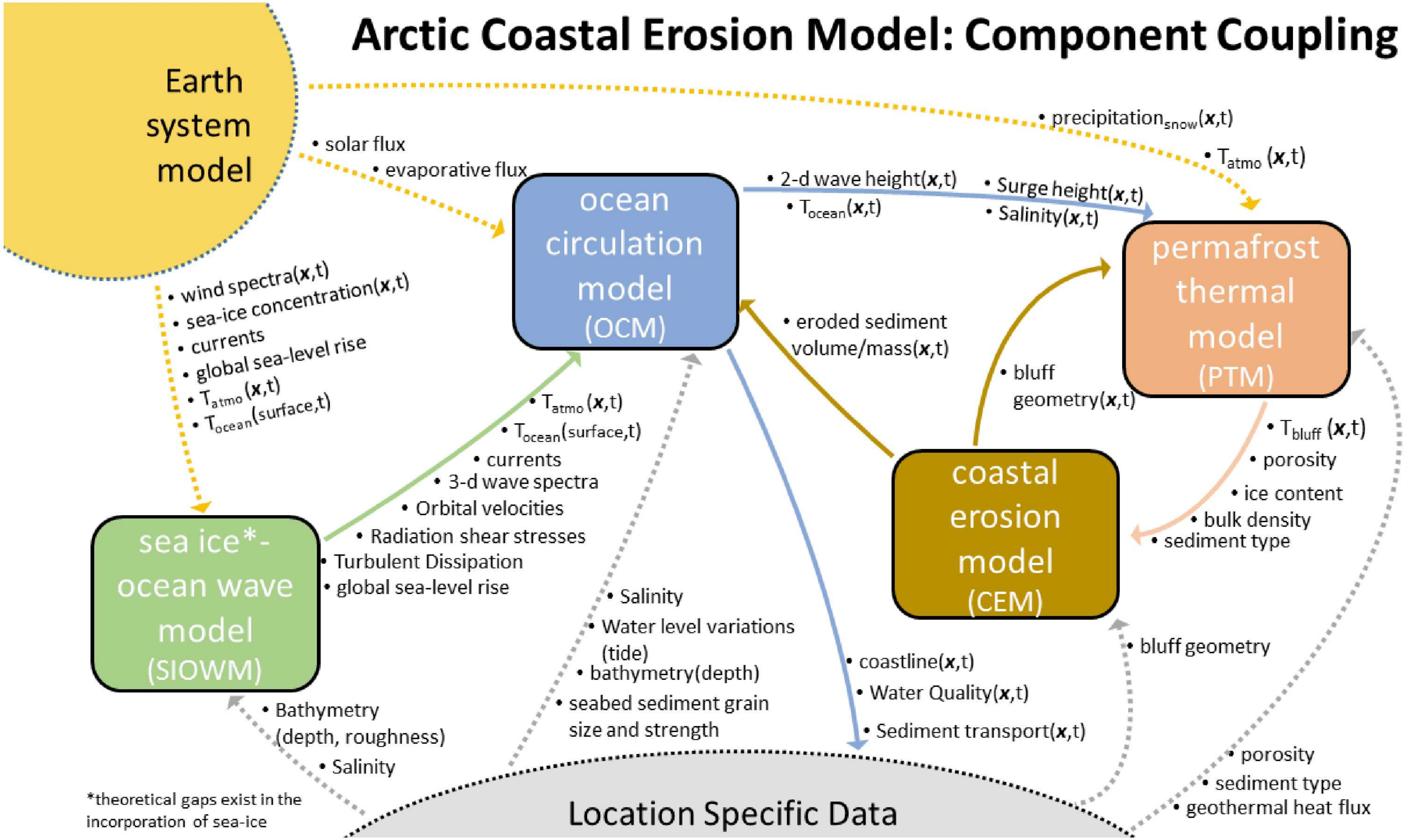
QUESTIONS / DISCUSSION

Arctic Coastal Erosion Cross-section



J. M. Frederick, M. A. Thomas, D. Bull, C. Jones, and J. D. Roberts (2016) The Arctic coastal erosion problem, SAND2016-9762, Sandia National Laboratories, NM.

Technical Approach



Validation Data: Drew Point

Obtaining data at resolution needed to validate mechanistic model

- Oceanographic
  - Wave Spectra (Significant wave height, direction and period); Water Temperature; Water Salinity; Water Depth; Water Currents; Bathymetry; Ice Thickness and Velocity
- Atmospheric
  - Air Temperature; Incident / reflected solar flux; Wind speed / direction @ 3 m above ground; Snow depth; Atmospheric pressure; Ground temperature (10 depths: 5-120cm); Soil Moisture; Rainfall
- Permafrost
  - Ice content (cryostructure & unfrozen content); Salinity content; Grain size characteristics; Silt / sand fraction; Stress-Strain Analysis (soil strength testing) as a function of temperature (up to thawing); Permafrost Temperature; Active Layer Depth
- Coastal Morphology
  - Ice Wedge Geometry; Shoreline positions; 3-D bluff mapping; Niche Geometry