Volume 34 • No. 1 • Winter 2020

It Takes a *'Superhero'* to Uncover the Climate Secrets in Fossilized Arctic Ocean Dinocysts

BY MARGIE TURRIN, ESTELLE ALLAN, JEREMY STOCK, AND LAUREL ZAIMA

SCIENTISTS ARE SUPERHEROES

The *Snow On Ice* project developed curricular materials using scientists depicted as superheroes as a means of engaging students and providing a novel method to link current climate change in the Arctic to Middle-Holocene Warming—a topic that might seem to be remote and seemingly unrelatable. The project explored whether superheroes could be a hook for introducing and retaining new science, vocabulary, and introducing scientists as role models. We recognized that the training and skills our scientists possess are akin to super-skills, and the scientists themselves could be easily viewed as superheroes. For the project, we transitioned our scientists into superheroes, each with a unique super-skill needed for uncovering past Arctic climate change. In this paper, we focus on one of those researchers, Ph.D. candidate Estelle Allan, to demonstrate how this curriculum was developed using our superhero as the center point. Our project's educational instruction incorporates both real scientific data and a STEAM interdisciplinary approach (Science, Technology, Engineering, Art, & Mathematics) to bring complex scientific concepts and cutting edge research into the classroom, while the integration of art facilitates the delivery of accessible information with long-term retention (Ghanbari 2015). We have worked with approximately 300 teachers in workshops introducing our superheros, posters, and curriculum and have tested the material with multiple middle school and high school groups with great success. We ran pre- and post-tests with over 100 high school students and include our findings in the 'Results' section. The results have indicated that presenting scientists as superheroes makes challenging science topics more attainable to students. All the project curriculum is freely downloadable from the project website (https://blog.ldeo.columbia.edu/snowonice/education-resources-scientists-are-superheroes/).

Estelle is an early career paleoclimatologist and paleo-oceanographer, and we hypothesized that her young age and her ocean-based climate research using microscopic dinocysts would make her relatable and memorable to students. In the materials, Estelle is introduced as both a superhero persona and a scientist. *Superhero Estelle* invokes the power of imagination as she dives into the underwater environment to apply her unique super-skills. *Scientist Estelle* shares that her research is conducted by collecting ocean sediment cores using a coring device off of a ship deck, and that the fossil identification occurs through meticulous microscope work in the lab. All of these skills require extensive training and practice.

FIGURE 1. Estelle our scientist superhero dives down into the Arctic Ocean to listen to the whispers of the smallest beings... dinocysts. Courtesy of Jeremy Stock

In order to develop Estelle as a superhero, we worked with artist and glaciology graduate student, Jeremy Stock.

Deep down at the bottom of the ocean buried in mud are microscopic messengers of past climate!

Some microscopic planktonic dinoflagellates form cysts high up in the water column, which then drift down on the ocean floor and fossilize in sediment. Dinocysts are dynamite information for paleoclimatologists!

Scientists are SUPERHEROES

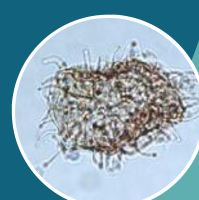
Estelle searches the Arctic Ocean for the biggest story, whispered by tiny dinocysts!

How small is a dinocyst?

Think micrometer scale! Estelle's dinocysts are 10-60 µm, less than the width of a human hair.

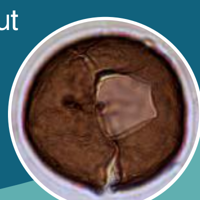
Dinocysts are the 'egg' stage (zygote) of some species of dinoflagellates, a subgroup of algae. There are over 1500 known marine species of dinoflagellates and ~1 in 5 create a cyst. A few species thrive under sea ice conditions. Some dinocysts fossilize and be used as proxies to tell us about past climate.

Four dinocyst species all found in the Arctic, yet all different.

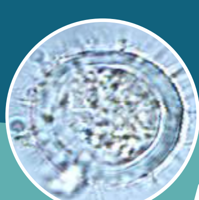


Islandinium minutum: happy in cold water and low salinity, signatures of glacial melt.

Islandinium? cezare: cold water species likes sea ice cover.



Brigantedinium simplex: shows up when there is a plenty of food available.



Pentapharsodinium dalei: very adaptable, but a tiny 10 µm so hard to find.

It takes Estelle's fossil finding fingers to uncover the secret message carried in these climate proxies!

blog.ldeo.columbia.edu/snowonice

A collaborative project by: University at Buffalo, Lamont-Doherty Earth Observatory, The Earth Institute, Columbia University, University of Washington, Jet Propulsion Lab, University of California Irvine, University of Montana, Geotop, Geus

Meet More Science SUPERHEROES

How do we know about past climate? What tools can be used to look back well before there were direct measurements? Our Superhero Scientists use *proxies*, something preserved from the past that '*stands in*' for a direct measure.

Each ***Snow on Ice*** science superhero has carefully honed super skills to measure a specific proxy. Dinocysts, leaf waxes, ^{10}Be, pollen, ice cores and plant fossils in lake sediment cores are all proxies used to unlock secrets of past climate. Used together they are powerful tools for understanding the past and modeling the future. For more information, please visit: blog.ldeo.columbia.edu/snowonice

Alia J. Lesnek

Pro-glacial lakes form layers of clay and organics such as plant fossils. These fossils can be C^{14} age dated telling us when the ice sheet retreated back, leaving behind the melt water that formed the lake. Alia uses her '***super coring power***' to '***peer into the past***'. The cores are a proxy for ice cover and retreat.

Nicolás searches along the edge of the Greenland's icesheet for quartz in the rock surface recently uncovered by a shrinking ice sheet. The quartz reacts with cosmic rays from outer space creating the radioactive isotope beryllium (^{10}Be). This can be used as a radioactive clock! Nicolás uses his '***drilling ability***' to '***capture the cosmic clock***' trapped in the quartz, a proxy for ice retreat.

Nicolás Young

Allison Cluett

Allison uses chemistry to understand the past. In her test tubes she creates a '***paleo plant potion***' to separate plant leaf waxes from mud collected from the bottom of Greenland lakes. Leaf waxes are ***biomarkers*** telling us about the temperature and moisture from the past, a proxy for past climate.

Jessica uses multiple proxies to learn about past climate. Each type of proxy record stores different information. For example, ice cores store information about temperature and snowfall on the ice sheet. Jessica uses her '***extraction powers***' to pull '***ancient climate***' secrets from several proxies, combining them to better understand past climate.

Jessica Badgeley

The Snow on Ice Project is a collaborative project of: University at Buffalo, Lamont-Doherty Earth Observatory, The Earth Institute, Columbia University, University of Washington, Jet Propulsion Lab, University of California, Irvine, University of Montana, Geotop, Geus

FIGURE 2. The back of the superhero cards introduce Estelle the scientist, her interests and the real tools of her scientific career. Courtesy of Margie Turrin

His combination of skills brought in the tools to amplify these two related disciplines. It was evident to Jeremy that *Superhero Estelle* should be displayed in the midst of her environment, descending deep into the ocean. The metaphorical descent required a special *bubble breathing ability*, allowing her to spend time deep in the Arctic Ocean exploring the tiny dinocysts, climate messengers, dispersed throughout the sediment. The illustrator focused on Estelle's *fossil finding fingers*, an apt description of the required scientific skills, and an alliteration that we hoped would be retained by the students. This is beautifully illustrated in the graceful fingers of our superhero as she examines the tiny dinocysts that swirl around her on the ocean floor, carefully examining and identifying. Her broad smile shares her pure joy in being submerged in her environment surrounded by tiny messengers of the past. Each dinocyst was accurately sketched and anatomically identifiable while lying dormant in the ocean sediments. *Superhero Estelle* is compelling as a graceful, yet powerful scientist, relishing her role as she listens for the whispers from these tiny messengers of the past. But the science lesson lies in what these dinocysts can tell her about the past.

THE ARCTIC OCEAN'S CLIMATE STORY

The Arctic Ocean is an important player in global climate through its role in forming dense bottom water to drive thermohaline circulation in the North Atlantic (Sévellec et al. 2017), and through the formation of sea ice cover at the ocean's surface (Matthiessen et al. 2005). Sea ice formation creates the density that drives ocean circulation, but the surface reflectivity of the sea ice itself provides another equally critical aspect of the Arctic's role in Earth's climate system. The reflective white cap of sea ice covers the majority of the Central Arctic, resting over a dark ocean

FIGURE 3. Self-portrait by our Superhero artist and master's student in glaciology at University at Buffalo, Jeremy Stock (http://jeremystock.com). Courtesy of Jeremy Stock

surface and radiating solar energy back into space. The sea ice cover has reduced significantly since satellite data first collected imagery of Arctic sea ice in the late 1970s, with summer thickness and extent reduced by half (Vihma 2014). The 2018 Arctic Report Card (Osborne et al. 2018) noted that Arctic sea ice remains thinner and less expansive than in the past, with the last 12 years representing the lowest sea ice extent in satellite history. Understanding how this sea ice loss might affect future climate is important.

Estelle's research for *Snow On Ice* focused on retrieving information about past Arctic climate, in order to reconstruct its sea ice cover to better inform our models of the future. She turned to the Arctic Ocean sediment archive for clues from the past, focusing on a very specific time period in the Holocene (past ~12,000 yrs.), a period called the Middle Holocene Warming. During its peak, ~7500 years ago, there is evidence of seasonal temperatures averaged 1-2°C warmer than today (Young and Briner 2015). *Snow On Ice* concentrated on the history of Arctic sea ice cover during that period looking for a glimpse into our future. Questions that the project hoped to address included:

- What was Arctic sea ice cover like during that time?
- How did Arctic sea ice cover interact with the stability of the Greenland ice sheet?
- How did the sea ice cover interact with both Arctic and global climate?

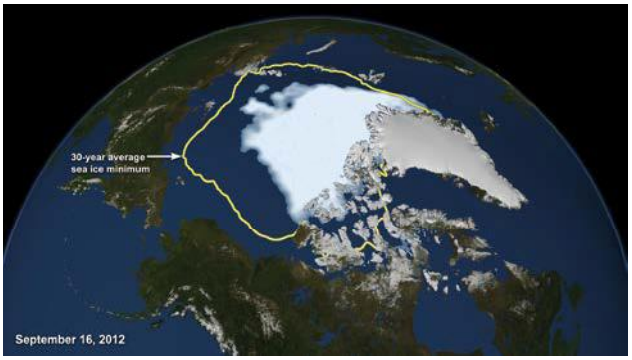


FIGURE 4. NASA satellite image of the Arctic Sea Ice minimum extent in 2012, still the lowest year on record. The yellow line represents the 30-year average minimum extent. Courtesy of NASA

FIGURE 5. Estelle reviews sediment samples from the Arctic Ocean collected by ship using a large coring rig. After collection each core is sliced open, described and carefully catalogued and prepared for transport back to the lab. Courtesy of Aarno Kotilainen

HOW DO WE KNOW ABOUT PAST CLIMATE?

How do we learn about the past when it stretches back before direct measurements existed? We use indirect measures, something preserved from the past that can stand in for a direct measure. Scientists refer to this as a *proxy*. In the study of paleoclimate, scientists use numerous proxies including tree rings and ice cores, but in the ocean some of the most valuable proxies are tiny fossils, little time capsules from the past that carry the memory of climate long ago. However, not all fossils are the same, nor are they evenly distributed. In many parts of the world, we could count on the ocean's fossil assemblages of planktonic foraminifera and diatoms, but the hostile environment of the Arctic results in reduced abundance, low diversity, and low preservation of these traditional fossils (Matthiessen et al. 2005). Paleoclimatologists and paleoceanographers have identified another microfossil (dinocysts) buried in Arctic Ocean sediments that helps to reconstruct paleo surface water conditions from the Holocene and potentially sea ice cover.

DINOCYSTS

Dinocysts, a eukaryote, are part of the lifecycle of some dinoflagellates, and an important marine primary producer by pumping energy into the planktonic food web. Over 1700 living species of marine dinoflagellate species have been identified, with new species being added through ongoing research (Hoppenrath et al. 2012). Dinocysts are fossilized cysts, part of the lifecycle and survival strategy of an estimated 10-20% of living dinoflagellate species (Mouradian et al. 2007; Rochon 2009). The cysts are a dormant cell that forms when these dinoflagellates detect non-optimal or unlivable conditions. The cysts form high up in the surface waters occupied by the dinoflagellate, but then sink to the sediments where they can remain dormant or "sleeping" until environmental conditions change. Produced under specific environmental conditions, they allow us to reconstruct various sea surface parameters like sea ice cover, sea surface temperature, sea surface salinity, and productivity. Cysts can survive for decades in the sediment before some rupture and germinate, while others remain dormant on the ocean bottom. Over time the dinocysts' highly resistant outer casing can fossilize, serving as exceptional proxies of the conditions and productivity of the area where they formed, high up in the upper water column (de Vernal and Rochon 2011). They become key 'messengers' of past climate as relative concentrations are sensitive enough to reflect even small changes in ocean conditions (de Vernal et al. 2005), and thus can be used in past temperature reconstructions.

To make reconstructions, at least 300 dinocyst specimens are counted in each sediment sample. The reconstructions of ocean parameters are obtained from the modern analog technique, which relies on the similarities between fossil and modern assemblages to assess corresponding sea surface conditions (Guiot and de Vernal 2007). This method is based on four assumptions: 1.) that the climate is the ultimate cause of changes in the paleobiological data; 2.) that the ecological properties of the species considered has not changed between the period analyzed and the present time; 3.) that the relationship between the species and the climate is uniform through time; and 4.) that the modern observations contain all the necessary information to interpret the fossil data.

Dinocyst fossils preserved in the sediment are microscopic (10-60 μm wide), less than the width of a human hair. The care that must be taken to locate, identify, and tally these small fossils is extraordinary, leading us to create the activity *Scientists are Superheroes* with Estelle, our superhero. To better understand sea ice cover in southwestern Greenland, Estelle uses her *fossil finding fingers* to locate these incredibly small messengers of our past climate, searching through sediment cores of Arctic mud from shallow coastal areas. Her samples were dominated by four main dinocyst species, all of which we included in our *Snow On Ice* curriculum activities. *Islandinium minutum, Brigantedinium simplex, Islandinium? cezare*, and the cyst of *Pentapharsodinium dalei*. (Both the question mark and the *'cyst of'* are part of their names!) Samples dominated by *I. minutum* and *I.? cezare* are indicative of longer periods of sea ice cover and cold surface water temperatures. The cyst of *P. dalei* is associated with shallow shelf waters and can be an indication of strong seasonality with cold winters and mild summers. *Brigantedinium simplex* suggests nutrient rich waters, conditions that are right for high productivity. Estelle can piece together the story of climate during different time periods using these small messengers from the past. (Allan et al. 2018).

ACTIVITIES

We developed curriculum that is aligned with Next Generation Science Standards (NGSS 2013) and follows the 5E instructional model. The materials align as follows:

- The centering ***phenomena*** is "Can fossils help scientists learn about past climate?"
- The ***time period*** is the Middle Holocene Warming (peaking ~7,500 years before present), as we consider whether this time in the past can be used as a window into understanding the present and a tool to predict the future.
- The ***location*** is along the southwestern edge of Greenland in the Arctic.
- The medium is through ***maps***. The overall lack of familiarity of people with the Arctic, particularly polar stereographic views of the Arctic, led to this being a critical part of the activity.
- The ***mechanism*** for exploring the past is through proxies, using dinocysts as environmental recorders and chronometers (clocks) to establish the time series.
- Our ***superhero***, Estelle, is used to engage students, introduce proxies, establish a connection to a scientific method, and serve as a science role model.

The activity starts with the present, mapping dinoflagellate diversity of Arctic Ocean basins. We use a polar stereographic view of the Arctic that highlights the large marine ecosystems in the Arctic Ocean (AMAP 2013). The map is part of a rich collection of Arctic maps developed through World Wildlife Federation (wwfarcticmaps.org 2019) and an excellent resource for teachers and students, and free to use, share, and download. Students use a two-dimensional bar graph from Okolodkov and Dodge (1996), locating the referenced Arctic basins as they physically build the graph in three dimensions using Legos, pennies, poker chips, and even Starburst™ candy in their construction. The physical

FIGURE 6. Back in the laboratory Estelle washes and sieves the samples to separate the dinocysts from the sediment. Once samples are prepared, Estelle uses her microscope and dinocyst reference catalogues to complete her identification. Courtesy of Jade Falardeau

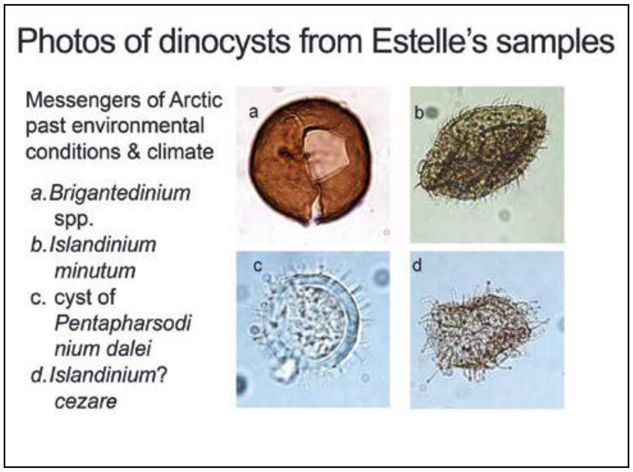


FIGURE 7. These four dinocysts hold messages about the environment. *I. minutum* and *I.? cezare* link to cold conditions and extended periods of sea ice cover; *P. dalei*, one of the smallest and hardest to locate dinocysts, suggests strong seasonality with ice free summers; and *B. simplex* suggests a nutrient rich environment. Courtesy of (Allan et al. 2019)

FIGURE 8. Student activities include building 3D graphs of Arctic dinoflagellate diversity to visualize present day distribution. Students use dinocyst identification cards to teach about the specific needs of the dinocysts and then locate them in their geographic preferences. Courtesy of Project Team

building of the graphs visually displays the high variability in the study diversity data, hopefully leading to a discussion on conditions in the Arctic. Students hypothesize on the stark difference in diversity between adjacent basins like the Chukchi Sea and the East Siberian Sea, and the low diversity in the Central Arctic Ocean. The challenging environment provides an opportunity to introduce the role of cysts in the lifecycle of these important marine primary producers (Rochon 2009) and an entry point for exploring how scientists can use fossilized dinocysts, buried in the sediments, as a proxy for past climate.

Dinocysts are unfamiliar to the students so six species, including the four Estelle is most focused on, were selected for the activity. Colorful activity cards were developed with photographs and drawings from a dichotomous key developed by Zonneveld and Pospelova (2015). The attractive, individually colored cards for each of the species includes the dichotomous key illustration, an actual image of the cyst under light microscopy, and a short, bullet-pointed description of the cyst, its habitat, and geographical preferences. Due to the complexity of the cysts' scientific names, we used a shortened form of the dinocyst names.

The six dinocyst species are representative of different oceanic habitats throughout the world so students understand that dinoflagellate cysts can be found globally. However, our primary focus is on the species that Estelle uses to understand the paleo surface water conditions and potential sea ice cover, four of the six showcased species are found in the Arctic Ocean and connected basins. The dinoflagellate cyst cards are used in a hands-on activity where students in teams review and discuss the dinocyst description cards, and then locate and place each species card in their preferred habitat on the stereographic map of the Arctic. For this activity, the map includes a covering of Arctic sea ice to facilitate the location of ice-attracted dinocyst species. Having students interact with the proxy materials by physically placing their cards on the Arctic map, not only demonstrates understanding of the conditions required by each species, but can enhance student learning and motivation (Segal 2011). The activity ends with the students reflecting on which species they predict Estelle would focus on to assess Arctic sea ice cover, and developing a hypothesis to explain the presence of more temperate-loving dinocysts in the Arctic.

Every proxy has limitations in what it can share about the past, and dinocysts are no exception. Our final activity asks students to discuss and debate the specific challenges of trying to reconstruct the past from proxies, with their often incomplete or difficult-to-interpret record (NRC 1995; Rochon 2009). Each group must consider the impact of one challenge to their sample and then brainstorm ways to minimize it. The dinocyst challenges provided to student teams include:

- The impact of currents that may catch and transport dinocysts to settle in different locations from where they formed.

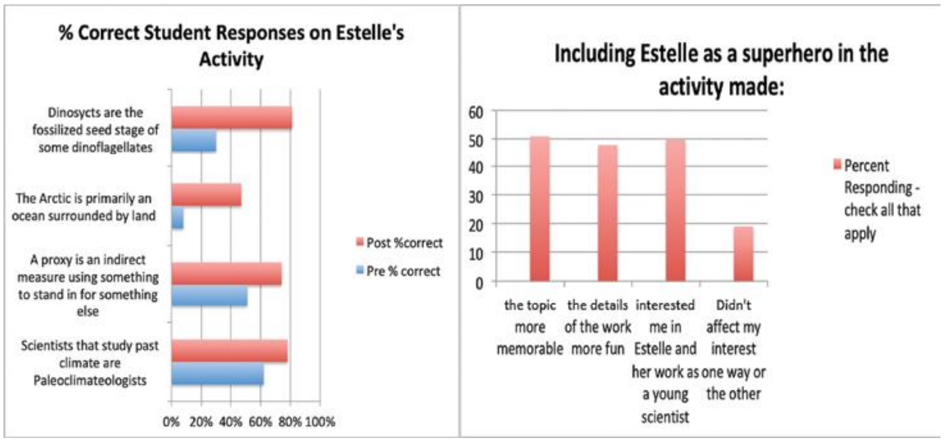


FIGURE 9. Student pre- and post-test responses on the curriculum, and student responses on how Estelle the superhero affected their interest in the activity.

- Scientists generally study dinocysts in 1 cm of sediment, yet varying rates of sedimentation can mean that 1 cm of sample material could represent 10 years or 1000 years.
- There may be selective preservation of dinocyst species due to loss of samples through destruction of their outer case during processing or predator grazing (snacking).
- Large and small Arctic events can redistribute sediment though bioturbation by bottom dwellers, storms, and even iceberg drag.

RESULTS

Our materials were refined following preliminary testing with several middle school and high school groups. We then worked with seven high school classes running pre-tests and then post-tests approximately two weeks after our classroom visit. Results are shown in the two graphs above. Responses to multiple choice questions increased in every category from a low of 16% on the name for scientists studying past climate to a high of 49% for what is a dinocyst. It should be noted that even after completing two activities using Arctic Ocean maps as a centerpiece, there is a persistent lack of recognition that the center of the Arctic is an ocean basin. For the question on whether including Estelle as a superhero affected their engagement, respondents could select multiple answers. Eighty-one percent responded positively, while 19% stated that Estelle the superhero did not affect their interest.

RESOURCES

The full set of resources for Estelle's activities and all the *Snow On Ice* resources are available for free download from the education page of the project website. This includes an activity overview, superhero postcards, superhero posters, maps for the activities, introductory PowerPoints, and all curriculum materials. They can be used as stand-alone lessons or linked together. The centerfold of this journal includes a sample of the curriculum posters. The curriculum maps to both the Ocean Science Literacy Principles (2013) and the NGSS (2013) standards outlined on next page.

https://blog.ldeo.columbia.edu/snowonice/education-resources-scientists-are-superheroes/

SUMMARY

The artwork and imagination of our superhero scientist captured the interest of students and teachers. Estelle's *fossil finding fingers* help to facilitate the recollection of the tiny dinocysts as time capsules of climate history and proxies for us to look into the past. Students enjoyed the interactive activities and retained the science through linking with the highlighted super-skills. Larger concepts like the importance of sea ice in the Arctic Ocean, and its critical role in global climate are brought to light for the students in an engaging way. Educators have noted "the data analysis and visual representation with the maps was a big hit with the students."

REFERENCES

Additional articles, and references and abstracts for all contributions are available on Polar-ICE (https://polar-ice.org/nmea_current/) and NMEA (https://www.marine-ed.org/s/Polar-Ice-Resources-Current.pdf) sites.

ACKNOWLEDGEMENTS

We acknowledge support from the National Science Foundation Arctic System Science Program. Grant #1504267 - Ice Sheet Sensitivity In A Changing Arctic System: Using Geologic Data And Modeling To Test The Stable Greenland Ice Sheet Hypothesis. (Online as *Snow On Ice: How Stable is the Greenland Ice Sheet?)*

MARGIE TURRIN is Director of Educational Field Programs at Lamont-Doherty Earth Observatory, Earth Institute of Columbia University. She works on projects in both the Arctic and Antarctic connecting the science in these remote places with residents in the U.S., focusing on innovative ways to use authentic data as a teaching tool.

Ocean Literacy Principle Addressed in the Estelle *Snow On Ice* Curriculum

#1 The Earth has one big ocean with many features:
- a) ... There is one ocean with many ocean basins...
- d) Sea level is the average height of the ocean relative to the land...It changes as ice caps on land melt or grow. It also changes as sea water expands and contracts when ocean water warms and cools.

#3 The ocean is a major influence on weather and climate.
- a) The interaction of oceanic and atmospheric processes controls weather and climate by dominating the Earth's energy, water, and carbon systems.
- f) The ocean has had, and will continue to have, a significant influence on climate change by absorbing, storing, and moving heat, carbon, and water.
- g) Changes in the ocean-atmosphere system can result in changes to the climate that in turn, cause further changes to the ocean and atmosphere. These interactions have dramatic physical, chemical, biological, economic, and social consequences.

#5 The ocean supports a great diversity of life and ecosystems.
- a) Ocean life ranges in size from the smallest living things, microbes, to the largest animal on Earth...
- f) Ocean ecosystems are defined by environmental factors and the community of organisms living there. Ocean life is not evenly distributed through time or space due to differences in abiotic factors such as oxygen, salinity, temperature, pH, light, nutrients, pressure, substrate, and circulation. A few regions of the ocean support the most abundant life on Earth, while most of the ocean does not support much life.

#6 The ocean and humans are inextricably interconnected.
- a) The ocean affects every human life... The ocean moderates the Earth's climate....

ESTELLE ALLAN, PH.D. candidate, is a micropaleontologist at the Université du Québec à Montréal, Canada. She is a paleoceanographer and paleoclimatologist studying the subpolar area during the Holocene developing environmental reconstructions through palynological records: oceanographic using cysts of dinoflagellate and continental using pollen grains.

JEREMY STOCK is an artist, musician, educator, and master's degree student studying glaciology at the University at Buffalo. He combines his creative and analytical skills to promote social, economic, and environmental awareness surrounding sustainability and climate change.

LAUREL ZAIMA is the Education Program Assistant at Lamont-Doherty Earth Observatory, Earth Institute of Columbia University. Her educational background in marine science and biology compliments the *Snow On Ice* project's outreach in disseminating past climate information through using dinocysts as a marine proxy.

Next Generation Science Standards Addressed in the Estelle *Snow on Ice* Curriculum

Science & Engineering Practices
- Developing & Using Models
- Planning & Carrying Out an Investigation
- Analyzing & Interpreting Data
- Constructing Evidence & Designing Solutions
- Engaging in Argument from Evidence
- Obtaining, Evaluating & Communicating Information

Disciplinary Core Ideas
- MS- ESS1 & HS ESS2 - Earth Systems
- MS-ESS2 & HS- ESS3 - Earth & Human Activities
- MS-LS1-4 & 5 - From Molecules to Organisms: Structures and Processes
- MS-LS2 & HS- LS2 -Ecosystems: Interactions, Energy, and Dynamics
- MS-LS4 & HS LS4 Biological Evolution: Unity and Diversity

Cross Cutting Concepts
- Patterns
- Cause & Effect
- Systems and System Models
- Stability & Change