Volume 34 • No. 1 • Winter 2020

Key Concepts in Polar Science: Coming to Consensus on the Essential Polar Literacy Principles

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INTRODUCTION

For many people, the Polar Regions remain distant locations, unconnected to their lives, and far from their daily concern. Funded by the National Science Foundation, the goal of the Polar Interdisciplinary Coordinated Education (Polar-ICE) program was to engage the public in understanding how Polar Regions influence our lives while improving their understanding of how scientists work to measure and understand the changing Polar Regions and the global climate system. Through this work, the need emerged for a unified set of messages about the Polar Regions that identify the "big ideas" all people should know about the Poles, the regions which regulate the Earth's climate. The messages can serve as the infrastructure to enable scientists to construct more effective Broader Impacts projects to engage the public in learning about Polar Regions and for educators to integrate these big ideas into their STEM teaching both in school and out-of-school learning environments.

Our efforts to create a consensus document for Polar Science communication was inspired by the Ocean Literacy initiative. The Ocean Literacy Principles and complementary OL Scope and Sequence document, identify, articulate, and organize the core concepts of ocean sciences for educational purposes purposes (https://www.marine-ed.org/ocean-literacy/overview). These documents are a powerful tool for elevating the prominence of ocean sciences in the mainstream K-12 and informal science education systems, and to guide decisions on how to spend time and resources in educational program development. They continue to be the foundation and inspiration for numerous significant accomplishments nationally and internationally.

The development of these key concepts in Polar Science was an iterative process involving both educators and scientists in creating, reviewing, and prioritizing Polar Science communication objectives for both scientists and educators wishing to engage the public in Polar Science.

PROCESS TO DEVELOP KEY CONCEPTS FOR POLAR SCIENCE

With the help of approximately 55 polar scientists from across the country, the Polar-ICE team spent three years developing a set of seven key concepts, synergistic with the successful Ocean Literacy Principles. This initiative strives to a.) define for polar scientists, the important concepts to think about when constructing broader impact statements for their research; and b.) provide guidance for K-12 educators on significant concepts to teach in their classrooms, through the framework of the Next Generation Science Standards (NGSS).

The result of these meetings is a series of seven key concepts (Table 1). Each concept contains a set of sub- concepts and clarifying concepts for each. Although the work represents many voices of scientists and educators involved in Polar Science education, we do not consider it final. It is a living document that can grow over time.

HOW TO USE THE KEY CONCEPTS IN POLAR SCIENCE

To date, scientists and educators have implemented the concepts in a variety of context and for different purposes. A few examples are provided below for inspiration:

- Researchers proposing to the Polar Division at the National Science Foundation have used the concepts to help frame their proposed Broader Impacts work. Early career professors use the concepts to help them think about course development and the creation of public talks. The Polar Literacy materials provide a framework in the design of new undergraduate classes. As an example, Oscar Schofield designed an Earth Systems course focused on polar ecosystems. The Polar Literacy provided a template for the course that allowed him to also build in a public outreach discussion directly into class.

- Educators have used the concepts to create new lesson plans focused on Polar Science themes. For example, teachers at the Monterey Bay Research Institute (MBARI) participating in the EARTH workshop (2016, 2017) used the concepts to create novel lesson plans (see https://www.mbari.org/products/educational-resources/earth/). Educators participating in the Long-term Ecological Research (LTER) program use the concepts to help select and prepare their students for Video Teleconferences (VTCs) with scientists working at Palmer Station (polar-ice.org).

- The Polar TREC program is considering using the concepts to draft a rubric to be able to assess pre- and post-learning experiences of Polar TREC participants.

CONCLUSION AND NEXT STEPS

Through this work, Polar-ICE has responded to the need for a unified set of essential concepts about the Polar Regions. These concepts identify and clarify the "big ideas" all people should know about the Poles, the regions, which regulate the Earth's climate. We hope to expand this work by creating a databank of lesson plans, Data Stories, blogs, and audio and video pieces that bring the concepts to life. In the end, like the OL campaign, we strive to create a more literate society about these amazing and critically important regions of our world.

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.

ACKNOWLEDGMENTS

This work is funded by the National Science Foundation (No. PLR-1525635 and 1440435). We gratefully acknowledge our Polar-ICE team, Dr. Corey Garza, University of California Monterey Bay; Dr. George Matsumoto, Monterey Bay Aquarium Research Institute (MBARI); Dr. Joan Middendorf, Indiana University; Ari Daniel, Independent Science Reporter for Public Radio; Liesl Hotaling, Eidos Education; and Christine Bean, Kristen Hunter-Thomson, and Madeline Gazelle, Rutgers University.

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TABLE 1. Polar Literacy Key Concepts and Principles

OCEAN LITERACY PRINCIPLE CONNECTION **Principle #1 The Earth has one big ocean with many features.**
KEY CONCEPT IN POLAR SCIENCE **#1 The Arctic and Antarctic Regions are unique because of their location on Earth.**
1A: The Arctic and Antarctic are both cold environments but have different geographical features.
1A-1: The Arctic is an ice-covered ocean surrounded by land.
1A-2: Sea ice on Arctic Ocean averages ~2 meters thick.
1A-3: Antarctica is an ice-covered continent (land) surrounded by the Southern Ocean.
1A-4: Ice sheets on Antarctica average ~2-4 kilometers thick.
1A-5: Antarctica is remote and less accessible to humans.

OCEAN LITERACY PRINCIPLE CONNECTION

Principle #1 The Earth has one big ocean with many features.

KEY CONCEPT IN POLAR SCIENCE

#2 Ice is the dominant feature of the Polar Regions.

2A: Ice is dynamic and comes in many shapes and sizes—big, small, floating in water or layered on land, thin or thick, solid or porous soft.

2A-1: Land ice includes glaciers and ice sheets made from compacted snow (freshwater). Glaciers and ice sheets can extend over the ocean. Ice sheets that extend over the ocean are called ice shelves.

2A-2: Glaciers can break off (calve) into chunks that fall into the ocean as icebergs and cause sea level to rise.

2A-3: Icebergs are made of freshwater and float in the ocean. Icebergs move with winds and ocean currents.

2A-4: Sea ice forms when sea water freezes. The resulting ice is made from mostly fresh water because the salt precipitates out during the freezing process.

2B: Ice shapes the Polar landscape.

2B-1: Tundra is a treeless area with permanently frozen soil (permafrost) and low growing vegetation.

2B-2: Ice sheets and continental glaciers (land ice) are not static. Due to gravity, they flow downhill at varying rates of speed. Moving ice can move rocks and erode soil in its path.

2B-3: Areas of land ice larger than $50km^2$ are found only on Greenland and Antarctica. The Antarctic ice sheets are the largest on Earth, containing 90% of the world's ice, while the Greenland ice sheet contains 10%.

2B-4: It is estimated that all the world's ice caps, glaciers and permanent snow contain 68.7% of the freshwater available on Earth. Freshwater is only 1.74% of the total amount of water on Earth. "Unlocking" freshwater from ice caps and glaciers will have ripple effects on the global ecosystem.

2C: Sea ice naturally shrinks and expands with the seasons. However, this natural dynamic cycle of ice growth and loss is affected by increasing air and water temperatures occurring at the Poles due to climate change.

OCEAN LITERACY PRINCIPLE CONNECTION

Principle #3 The ocean is a major influence on weather and climate.

KEY CONCEPT IN POLAR SCIENCE

#3 Polar Regions play a central role in regulating Earth's weather and climate.

3A: Polar oceans play a key role in global circulation of ocean water and air masses that keep the Earth temperate.

3A-1: Global wind circulation involves three types of cells: Hadley, Ferrel, and Polar cells. Air rises in the hot tropics and sinks at the cold poles. Winds bring warm air toward the poles and carry cold air to lower latitudes.

3A-2: Global ocean circulation (thermohaline circulation) is driven by density differences of water masses in the ocean. The dense (cold and salty) Arctic and Antarctic water masses are two important components of global circulation patterns.

3A-2a: Warmer surface waters from the equatorial regions travel towards the poles. As the water travels, it cools and sinks at the poles.

3A-2b: The sinking (more dense water) flows into the ocean basins and eventually upwells.

3A-2c: Ocean circulation has a large impact on the Earth's climate. If ice caps, glaciers and permanent snow were to melt, that would "unlock" the freshwater which flows into the ocean—causing a "freshening" or increase of freshwater in the ocean and upsetting ocean circulation patterns.

3B: Ice and snow (white surfaces) reflect sunlight back into space. Ocean and land (dark surfaces) absorb more solar energy. As ice and snow disappear, heat is absorbed by exposed surfaces, which accelerates melting of additional snow and ice. Scientists use the term albedo to describe the measurement of the reflectivity of the Earth's surface.

3B-1: Ice and snow have a high reflectivity (albedo) while rock and ocean surfaces have a low (reflectivity) albedo. Melting ice and snow produce a positive feedback loop.

3B-2: Positive feedback loops amplify a change in a system making it more unstable.

3B-3: Negative feedback buffers change in a system making it more stable.

3B-4: Snow and ice in Polar Regions are involved in mainly positive feedbacks, which is why the Arctic region is annually warming faster than the rest of the planet.

3C: The Polar Regions are connected to temperate regions via biogeochemical cycling.

3C-1: Activities and changes in temperate regions impact the Polar Regions and vise versa.

OCEAN LITERACY PRINCIPLE CONNECTION

Principle #4 The ocean made Earth habitable.
Principle #5. The ocean supports a great diversity of life and ecosystems.

KEY CONCEPT IN POLAR SCIENCE

#4 The Polar Regions have productive food webs.

4A: Productivity (generation of life) is tied to seasonal changes in sea ice cover, water and air temperature.

4B: Sea ice cover, water and air temperature change with the seasons

4B-1: Phytoplankton, tiny plants at the base of the food web, grow abundantly during the long days of polar summer. Krill (small shrimp-like crustaceans) feed on plankton.

4B-2: Each winter, as sunlight and temperatures decrease, sea ice grows to cover large areas of ocean. Young krill survive their first winter by feeding on algae on the underside of the sea ice and the ice provides shelter from predators.

4B-3: Krill serve as food for the higher levels in the Polar food webs.

4C: The Antarctic food web is simple.

4C-1: Antarctica is home to marine mammals (whales and seals) and sea birds, including penguins. Antarctica is not home to terrestrial mammals. *Polar bears do not live in Antarctica.*

4C-2: Many Antarctic species (krill, penguins) are dependent on ice cover to survive; they serve major roles in the Antarctic marine food web.

4C-3: There is a simple terrestrial food web that exists in regions of the Antarctic, but it is not directly connected to the marine food web.

4D: The Arctic has a more complex food web.

4D-1: The Arctic has many terrestrial mammals including musk ox, reindeer, caribou, fox, hare, lemmings, bears, birds, and terrestrial plants, etc.

4D-2: The Arctic also has a marine food web that does interact with the terrestrial food web, with some animals like polar bears in both food webs. *Penguins do not live in the Arctic.*

4E: Marine and terrestrial predators are predictors (indicators) of change in food webs. Effects from climate change are causing disruptions in ecosystems. Predator displacement or food selection changes are resulting in system changes in Polar food webs. Examples include; in some regions polar bears are feeding on geese; bird migration changes; fish populations are shifting.

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OCEAN LITERACY PRINCIPLE CONNECTION

Principle #3. The ocean is a major influence on weather and climate.

KEY CONCEPT IN POLAR SCIENCE

#5 The Poles are experiencing the effects of climate change at an accelerating rate.

5A: Arctic sea ice is declining at a rapid rate.

5A-1: Scientists predict the Arctic will be largely free of sea ice during the summer months within 30 years.

5A-2: The receding ice cover affects the Arctic food webs and the global ocean circulation, however, the long-term impacts are unclear.

5A-3: Melting sea ice does not contribute to sea level rise. This ice is already floating in/on the water, therefore the water level stays the same as it melts.

5B: Antarctica is experiencing less sea ice loss than in the Arctic—for now.

5B-1: Antarctic and Southern Ocean air temperatures are predicted to rise in the future, threatening ice stability

5C: The Western Antarctic Peninsula (WAP) is the fastest winter-warming region in the world (about 10 times faster than global average).

5C-1: Antarctic ice shelves are floating extensions of the land ice. They are critical to ice stability in Antarctica, forming a buttress to hold back the ice behind them. Antarctica is surrounded by ~45 ice shelves that are susceptible to a warming atmosphere and ocean.

5C-2: The warming Southern Ocean flows close to the WAP, causing melting at the ice shelves and the base of glaciers. This accelerates the WAP glacier melt and collapse.

5C-3: Increased glacial melt affects the WAP food web.

5D: Warmer Polar Regions have a moister atmosphere, which leads to more precipitation.

5D-1: Increased precipitation, falling as snow or rain, can affect Polar animals.

5D-1a: In Antarctica, Adelie penguins' breeding can be disrupted by heavy snow cover and unseasonable rains.

5D-1b: In the Arctic, precipitation is predicted to increase by 20% by the end of the century, mostly in the form of rain. Increased rain will further melt snow, ice, and permafrost, restricting land animals nesting sites and ability to forage. Increased rain will also cause "freshening" of the ocean water, which will impact the marine ecosystem.

5E: Effects of climate change at the Poles is directly connected to changes in sea level around the world.

5E-1: The amount of water frozen to create the Greenland and Antarctica ice sheets and glaciers helps regulate our current sea level.

5E-2: Sea-level rise is caused by melting ice sheets and glaciers, combined with the thermal expansion of seawater as the oceans warm.

5E-3: Global coastlines are home to 80% of the world's population, which are being threatened by sea level rise.

5E-4: Many Polar species will face migration, adaption, death, or extinction in a changing climate.

5F: The Poles are locations of increasing Geopolitical issues.

5F-1: Decreasing ice cover in the Polar Regions will result in emerging geopolitical issues including: increased military presence, territorial boundary/sovereign rights issues, exploration and harvesting of natural resources (animal and mineral), increased tourism, failing infrastructure, and more.

5F-2: The increasing human presence in the Polar Regions compounds existing concerns (pollution, overuse of fragile infrastructure, harvesting resources).

OCEAN LITERACY PRINCIPLE CONNECTION

Principle #6. The ocean and humans are inextricably interconnected.

KEY CONCEPT IN POLAR SCIENCE

#6 Humans are a part of the Polar system. The Arctic has a rich cultural history and diversity of Indigenous Peoples.

6A: Humans have inhabited the Arctic for thousands of years. There is evidence of human Arctic presence from over 40,000 years ago. Humans continually adapted to inhabit the unique environment.

6A-1: Arctic indigenous people have traditional and spiritual connections to their ancestral land, including subsistence fishing, hunting and gathering, and reindeer herding.

6A-2: Industrialization, social change, and climate change present threats to the continuity of these livelihoods and culture.

6B: Polar systems affect humans in a variety of ways.

6B-1: Weather patterns– large dips in the jet stream can sweep cold air into lower latitudes where billions of people live.

6B-2: Climate change– changes at the Poles affect people around the world through global ecosystem changes.

6B-3: Food webs– loss of sea ice and a warming ocean is disrupting fisheries across the globe.

6B-4: Loss of sea ice is resulting in greater coastal erosion during winter storms.

6C: Climate change is affecting Arctic residents (about 4 million), including 40 different indigenous groups (about 10% of Arctic residents) through impacts to their environments, food webs, and infrastructure.

6C-1: Receding sea ice is affecting animals that depend on ice cover (fish, polar bears, walruses, seals, humans).

6C-2: Species are migrating and/or declining, affecting the people who depend on those species for food, clothing, and other uses—and larger ecosystem implications. Importing goods to these regions is very expensive which significantly increases costs, so many Arctic residents depend on hunting and fishing for food.

6C-3: Thawing permafrost is damaging homes, roads, pipelines, buildings, and ecosystems.

6C-4: Coastal villages in Alaska are particularly prone to the effects of coastal erosion and storm surge during winter storms. Some entire villages are relocating.

6D: Arctic indigenous people are important partners to the science community in understanding and observing the Arctic.

6D-1: Native knowledge of Polar Regions contributes to the understanding of natural ecological cycles and the impacts of climate change on the system.

6D-2: Traditional knowledge has proven essential for subsistence harvesting and for sustainable management of natural resources.

6E: The Arctic region of the United States holds sizable proved and potential conventional energy (oil and natural gas resources) and renewable energy (geothermal, tidal, wind, etc.).

OCEAN LITERACY PRINCIPLE CONNECTION

Principle #7. The Ocean is largely unexplored.

KEY CONCEPT IN POLAR SCIENCE

#7 New technologies, sensors and tools as well as new applications of existing technologies, are expanding scientists' abilities to study the land, ice, ocean, atmosphere, and living creatures of the Polar Regions.

7A: Historically Polar explorers took photographs and collected observational data (primarily atmospheric and meteorological observations) at various intervals during explorations to the Poles providing a discrete understanding of the Poles.

7B: Today scientists use satellites, drifting buoys, tethered buoys, subsea observatories, unmanned submersibles, and automated weather stations to constantly and remotely study the Poles.

7B-1: This baseline information is coupled with regular scientific explorations to the Poles to collect samples and measurements, including photographic evidence.

7C: Piecing together historical data recorded by early explorers and traditional knowledge from residents, with ice cores and sediment cores gives scientists an understanding of natural history.

7C-1: Combining current data with historical data, scientists can construct models to understand connections in the past and improve predictions of future environmental conditions at the Poles.

7D: Antarctica's high elevation and dry atmosphere allow measurements of cosmic microwave background (fossil light from the early universe).

7E: Scientists measure the ice and snow levels over many decades to observe the impact of climate change in the Arctic landscape.

7F: Scientists are gathering genetic information across a range of Polar species, from DNA to the broad ecosystem

7F-1: Genomic sequencing of polar species provides insight into complex biological processes and biotechnological exploitation (development of new drugs, bioremediation, food systems, etc.).