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Marine Transportation and the Environment

Trends and Issues

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Commercial marine transportation is the most energy-efficient and cost-effective method of transporting goods and people globally (*1*). Domestic ports and their supporting infrastructure are critical for efficient global trade, economic competitiveness, and reduced urban congestion.

A range of environmental impacts, however, accompanies these benefits. For example, vessel and port operations affect regional air and water quality; ballast exchange can lead to the spread of invasive species; competition for market share is expanding port operations and is pushing vessel traffic into new Arctic routes; and the cruise market is sending out larger ships—literally floating cities—that are entering vulnerable ecosystems.

The global nature of trade and vessel transport presents unique regulatory hurdles and requires innovative, yet cost-effective, technologies and practices to curb the environmental impacts. The Transportation Research Board (TRB) Standing Committee on Marine Environment has identified the pressing environmental issues and has explored several of the emerging technologies and regulatory frameworks that can mitigate the effects of legacy fleet operations and can ensure strong environmental stewardship in the next-generation fleet.

(*Above*): The Port of Anchorage, Alaska. As new Arctic routes open to maritime traffic, emerging environmental issues are met with innovative solutions.

PHOTO: BBMEXPLORER.COM

Marine ecosystems are especially sensitive to the environmental impacts of waterborne transportation.

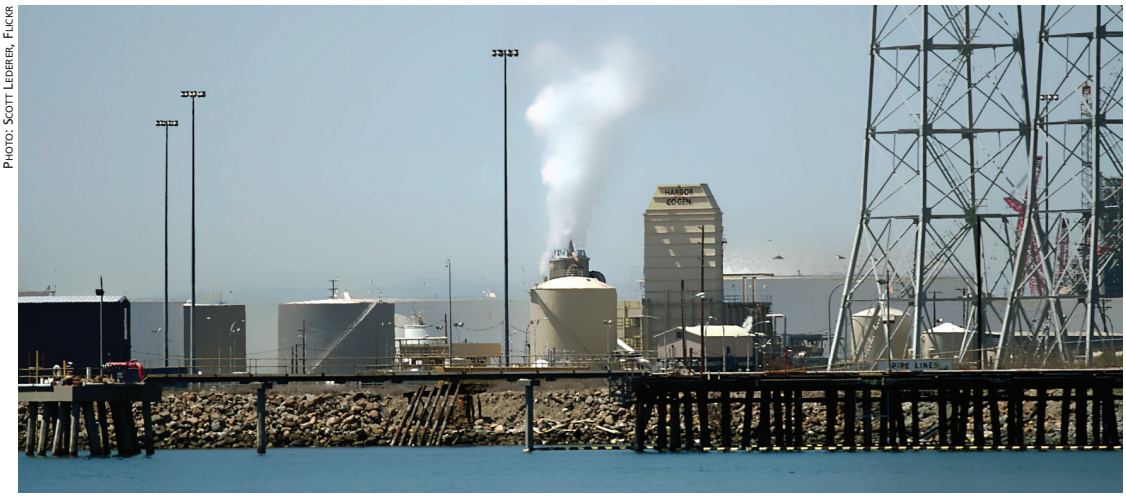


Photo: Scott Lederer, Flickr

Antipollution policies implemented by the Port of Long Beach, California, reduced diesel truck pollution by 80 percent in four years.

Air Pollution

Air pollution represents the most prominent and targeted source of environmental impacts from marine transportation. Marine vessels and port equipment are a significant source of the air pollutants that affect environmental health and climate change.

Most air pollution from port activities comes from the operation of the diesel engines that power ships, cargo-handling equipment, drayage trucks, and locomotives. Collectively, these diesel engines emit significant amounts of sulfur oxides, nitrogen oxides, volatile organic compounds, particulate matter, and carbon dioxide.

The combination of fine particulates and hazardous air pollutants can affect human health, causing a range of respiratory ailments including asthma, bronchitis, and lung cancer, as well as cardiovascular disease and premature death. These effects are magnified in lower-income and working-class communities adjacent to ports and rail yards. Emissions of sulfur oxides, volatile organic compounds, and nitrogen oxides have larger-scale deleterious effects on air quality and the environment by contributing to regional smog and ozone formation.

International shipping produces approximately 2.4 percent of global greenhouse gas emissions, and the share is expected to increase with the demands for global trade (2). Vessel emissions of carbon dioxide also affect water quality by reducing the ocean's pH—a phenomenon known as ocean acidification. Vessel emissions of nitrogen further contribute to ocean acidification.

Ocean acidification harms marine organisms that have calcareous exoskeletons, such as corals, mollusks, and crustaceans. Some of these species—particularly corals—are important in forming habitats; others have recreational or commercial significance.

Alternative technologies for marine fuels and energy sources have the potential to improve the environmental footprint of waterborne commerce. Innovations are supplying new policies, products, and methods to reduce emissions. These innovations include the following:

- National and international standards for conventional marine fuels,
- Fuel concepts,
- Exhaust remediation technology,
- Shore-to-ship alternative powering techniques,
- Improved in-port vessel scheduling, and
- Ocean-based renewable energy.

Controlling Sulfur

The International Maritime Organization (IMO) and the U.S. Environmental Protection Agency have issued standards for fuel sulfur. Designed to reduce regional and global emissions of particulate matter and sulfur oxide, the standards are evolving but have

Photo: Chris Parker, Flickr

The *MS Midnatsol* is one of a growing number of cruise ships that take tourists across the Arctic Circle.

Photo: Eni.com

The Eni's Green Refinery project at Port Marghera in Venice produces biofuels from organic raw materials.

served as key drivers. In conjunction with the designation of emission control areas, the standards have reduced emissions of sulfur oxide, nitrogen oxide, and particulate matter, largely through the combustion of light marine gas oils with a low sulfur content—however, the costs are higher.

In response, the fuel oil market is introducing low-sulfur heavy fuels that can hold down costs but satisfy the fuel regulations. These new fuel formulations are expected to become the conventional fuel globally by 2020 (*3*).

Alternative Fuels

Despite this regulatory success, additional power options are needed for vessels to meet all air quality concerns. These options include liquefied natural gas (LNG) as a marine fuel, biofuels, exhaust gas scrubbers, hydrogen, and shore-to-ship power—also called cold ironing or alternative maritime power—the provision of electrical plug-in power for vessels in port.

Vegetable-based and cellulosic-based biofuels are compatible with current fleet operations and can reduce sulfur oxide, particulate matter, and greenhouse gases, although the limited availability of these fuels and the uncertainties about powertrain maintenance and cost continue to hamper adoption. These technologies are considered most effective as regional solutions, because cost and supply are tied directly to a region's economic constraints.

Fuel processing technologies are maturing rapidly, and several integrated biorefineries have emerged. Large-scale introduction of second- and third-generation biofuels to the marine market, however, will not occur until well into the future.

Exhaust scrubbers, particularly using salt water, may allow for continued use of conventional high-sulfur fuels. But in reducing emissions of sulfur dioxide, the exhaust scrubbers could cause water pollution; moreover, the devices could require significant vessel capital and lay-up times for retrofitting. In addition, the technology requires new methods and materials to comply with pending requirements to control emissions of nitrogen oxide.

Cold ironing is increasingly available at domestic ports; the infrastructure costs are balanced by the benefits. Military bases, several California ports, and cruise terminals in Seattle and New York have implemented cold ironing. The systems greatly reduce a vessel's dockside emissions—even when the accounting includes emissions from the shoreside power plant supplying the electricity—because the production of electricity is more efficient than diesel combustion in the ship's main engine. Cold ironing has led to marked improvements in local air quality but has no effect, of course, on emissions once the vessel is under way.

A Port of Seattle, Washington, employee uses cold ironing—or shore-to-ship power—to fuel a cruise ship while its engines are turned off.

Photo: Don Wilson, Port of Seattle

Liquefied Natural Gas

LNG continues to gain attention because of competitive energy pricing, the potential for rapid global implementation, and a low rate of combustion emissions in comparison with conventional marine fuels. Lloyd's Register estimates that LNG could reach an 11 percent share of marine fuel usage by 2030 (*4*). The use of natural gas as a transport fuel has grown steadily in the past decade, with 47 registered LNG-powered vessels in operation in 2014 and 200 now in operation or on order (*5*).

The deployment of LNG-powered vessels and the construction of new infrastructure for LNG refueling and import have been steady since 2006. Three manufacturers—Rolls Royce, Wärtsilä, and MAN—

have developed LNG engine technologies for marine applications. Spark-ignited, lean-burn engines allow the gas to be mixed with an excess of air before passing through the intake valves, so that the fuel combusts more completely, improving efficiency and limiting stack emissions of methane, a greenhouse gas 25 times more potent than carbon dioxide. Dual-fuel diesel engines, which can run on LNG or petroleum distillates, are attractive for vessels operating at ports yet to complete the infrastructure for LNG.

The support infrastructure for LNG continues to evolve to meet demand. Norway has developed a system of small-scale LNG production and storage facilities to supply ferries and other working ships. New LNG shipbuilding contracts around the world are aligned with the installation of bunkering facilities to store and provide the fuel.

In the longer term, several governments are planning for expanded use of LNG in the maritime sector. For example, the European Commission has launched an ambitious plan for 139 LNG refueling facilities to serve seagoing and inland vessels starting in 2020. China has established incentives for the construction of LNG vessels, and 110 vessels are in planning or production.

Nevertheless, LNG is still in the fledgling stages as a marine fuel. Forecasts indicate that the growth of LNG-powered ships is unlikely to play a major role in the shipping market in the next decade. Moreover, concerns remain about safe handling and about methane slip—the release of noncombusted methane into the atmosphere.

PHOTO: SHELL

Shell's floating LNG facility *Prelude* can transport LNG directly to carriers at sea.

Other options for reducing fossil fuel combustion in the marine sector include wind and solar sources to supplement on board energy demand. Kite technology, for example, can tap into winds at high altitudes to reduce propulsion power demand. Also promising is the reintroduction of Flettner rotors, vertical spinning cylinders that rely on the Magnus effect[1] to generate electricity for propulsion engines. Photovoltaic systems in development may provide cheap renewable electricity for ships, although a variety of technical issues now limit use (*6*).

[1] The Magnus effect occurs when a spinning object drags air faster around one side, creating a difference in pressure that causes the object to move in the direction of the lower-pressure side.

PHOTO: DAVID MERRETT, FLICKR

Flettner rotors, like those on the ship *Alcyone*, augment traditional engines to generate electricity.

PHOTO: UNCLIMATECHANGE, FLICKR

The *National Geographic Explorer* takes travelers into areas of the Arctic that previously were impassable. Melting of sea ice has opened the area to unprecedented travel.

Changing Trade Routes

Few places on earth capture the human imagination and present nature's unadulterated beauty like the Arctic. Human industrial activity, however, has introduced profound environmental changes to the region.

Marine transportation takes several forms in the Arctic. Regional systems of tugs and barges provide local transport for the delivery of essential supplies to communities. Fishing is an important industry and provides subsistence to indigenous communities. But increasingly, larger vessels engaged in oil exploration, new trade routes, and tourism are straining the region's environmental balance. In addition, the area is sensitive to climate change, which exacerbates the effects of localized pollution.

Melting Ice Cap

The U.S. Geological Survey estimates that the Arctic contains 22 percent of all undiscovered oil and gas resources (7). Exploration and recovery require a variety of marine vessels at the sites and for transportation to markets. Large and small cruise ships also visit the Arctic (see Figure 1, below left). The melting of sea ice will increase vessel traffic and open the Arctic to commerce and recreational activities not previously possible, increasing the concern about the region's environmental health.

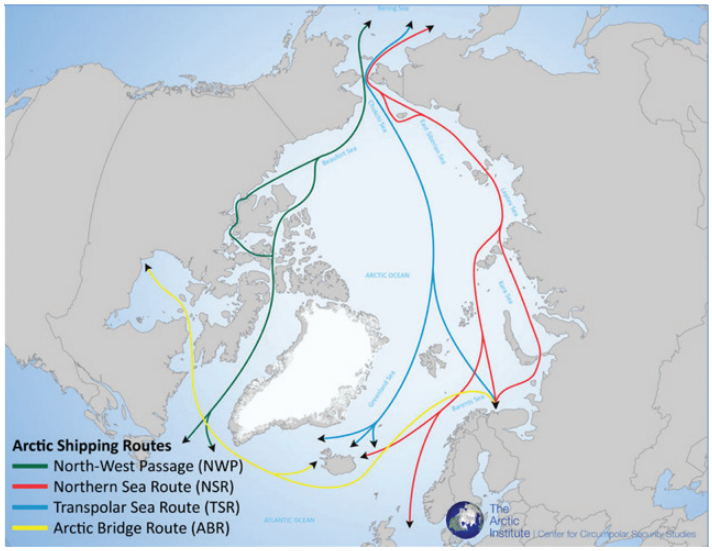
The Arctic ice cap is approximately 40 percent smaller than it was in 1979 (see Figure 2, below right). Continued shrinkage would allow for the development of Arctic shipping lanes between Asia and Europe that could reduce travel distances by 5,200 miles, cutting transit time by an estimated 30 percent. This would create the greatest restructuring of global shipping routes since the opening of the Panama Canal in 1914.

Northern Passages

Possible routes include the Northern Sea Route, which transits Russian Arctic waters, and the Northwest Passage, which transits territorial waters of the United States and Canada. Both routes are open only for several weeks during the summer but offer a commercially viable alternative to the Panama and Suez Canals.

The number of vessels passing through the Bering Strait, the entry or exit point for both passages, grew from 220 in 2008 to 480 in 2012—an increase of more than 100 percent (8). Tanker vessels had the highest growth rate, with tugs and other cargo vessels the second and third largest categories of movements, respectively.

FIGURE 1 Melting Arctic sea ice has enabled increased cargo vessel and cruise line navigation in an environmentally sensitive region. (Image: The Arctic Institute)



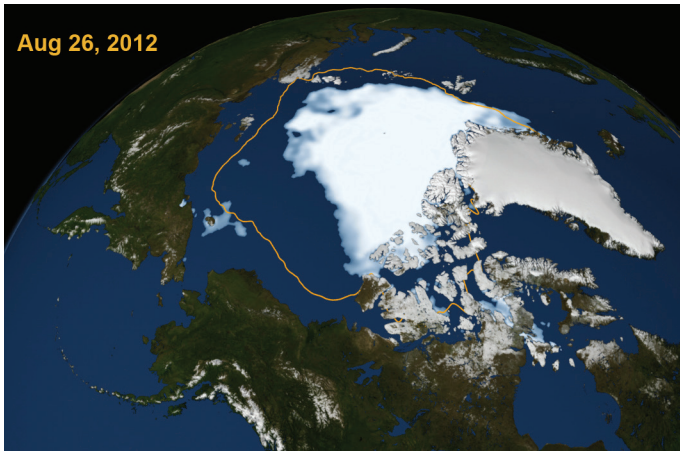


FIGURE 2 Satellite image of the Arctic ice cap, August 26, 2012, superimposed with border line (*orange*) indicating edge of ice cap in 1979.

Photo: Cheryl Strahl, Flickr

Pollutants make their way into the air and water of the Arctic, affecting local wildlife.

Passage through the Northern Sea Route is limited but is increasing. The route's ice fields and shallow straits challenge navigation, raising concerns about a potential increase in the incident rate and limited access for emergency and environmental response.

The Northwest Passage is even more challenging. IMO continues to evolve Annex 10, International Code for Ships Operating in Polar Waters, to stay at the forefront in assessing and mitigating the potential hazards from vessel traffic and in enforcing the regulations.

The first large commercial vessel, *MS Nordic Orion*, transited the Northwest Passage in 2013, and the expectation is that vessels will be able to move through this area without the aid of an icebreaker by 2050. The passage also could facilitate the movement of crude oil from the Alaskan North Slope to U.S. East Coast refineries.

Expected Traffic

Limited exploratory drilling has been permitted offshore of the Alaskan North Slope, with plans to increase the activities and eventually to develop and operate offshore oil and gas production platforms. A range of vessels will service this industry, including survey ships, drilling rigs, support vessels, crew boats, spill response vessels, offshore tugboats for the construction of gravity-based offshore platforms or artificial gravel islands, and pipe-laying vessels.

In addition, the opening of Arctic waters could increase cruise ship traffic. Crystal Cruises completed a 32-day journey across the Northwest Passage this year and has taken bookings for a cruise from Anchorage, Alaska, to New York City.

The shorter Arctic routes will reduce vessel fuel consumption and emissions substantially. Nevertheless, local air quality issues may offset the global benefits. For example, because of their physical–chemical properties, persistent organic pollutants can be transferred readily to the Arctic via air and water currents and can accumulate in the fatty tissues of the local wildlife. Increased vessel traffic in the Arctic also will facilitate the concentration of hazardous air pollutants in northern latitudes.

Photo: U.S. Coast Guard

U.S. Coast Guard Cutter *Healy* rescues a sailboat trapped in Arctic ice. Although new routes have opened in the Northwest Passage, ice and shallow waters still create challenges.

Smokestack emissions also pose a unique threat to the Arctic. Researchers have found that the black soot from ship smokestacks settles on polar ice sheets and lowers its albedo—that is, its reflection of light and radiation—and accelerates melting.

Protecting Biodiversity

Vessels also act as vectors for the introduction of invasive, nonnative species to new areas. These species often can outcompete native species and can reduce biodiversity dramatically, impairing the resilience of coastal and marine ecosystems. The short-term and long-term economic and environmental effects include the following:

Photo: Marco Verch, Flickr

Black soot from passing ships accumulates on polar ice.

PHOTO: VIV LYNCH, FLICKR

Invasive species, like the zebra mussel, attach to marine vessels and spread to nonnative environments, where they damage infrastructure and local habitats.

◆ Species extinction—the loss of any species has far-reaching effects; in particular, some Arctic species of marine life have pharmaceutical applications;

◆ Damage to infrastructure—similar to the problems caused by the spread of zebra mussels in the Great Lakes and elsewhere; and

◆ Loss of recreational and commercial fishing opportunities.

The IMO Annex 10, Part II-A, outlines measures to prevent pollution and preserve the environment in the polar region. Research is needed to enhance the effectiveness of the IMO code of regulations and to determine the need for additional measures.

Vessel Discharges

Oil and chemical spills remain a dominant issue in maritime transportation. Although accounting for approximately 10 percent of the total oils contributed to the ocean, spills have high public visibility. Improved understanding of programs to prevent oil spills and of the options for clean-up can facilitate linkages between governance, policy, and scientific knowledge.

Vessel discharges and upland maritime support operations introduce pollution from toxins, nutrients, bacteria, pathogens, pharmaceuticals, and plastics directly into waterways. For example, EPA estimates that a single 3,000-person cruise ship discharges 150,000 gallons of sewage a week.

Vessels, vessel support operations, and port operations also directly and indirectly pollute waterways through a variety of sources that include the following:

◆ Gray or used water, bilge water or excess fluids in the hull, black or sewage water, and ballast water from onboard tanks;

◆ Antifouling paints and their leachates;

◆ Hazardous materials;

◆ Garbage and other wastes; and

PHOTO: MICHAEL EDENFIELD, FLICKR

In 2004, the Malaysian cargo ship *M/V Selendang Ayu* ran aground and spilled 336,000 gallons of oil into the Bering Sea. Oil spills continue to be a predominant, high-visibility issue in maritime transportation.

◆ Aerial deposition of smokestack emissions into aquatic habitats.

A host of wastewater treatment options that systematically meet water discharge regulations is available for vessels. Typically, vessel operations include two or three systems working together to achieve compliance. The most common approach couples the physical filtration of biomass solids with chemical disinfection. Ultraviolet treatment, coagulation, thermal, deoxygenation, acoustic, and electric pulse systems are among the other options.

Although effective, the regulations for ballast and wastewater handling continue to evolve and are becoming increasingly stringent. Research and development efforts are working to identify ways to trim the cost, to lower the complexity, and to decrease the impacts of a vessel's footprint while reducing the harmful impacts of discharges.

IMO has proposed performance standards for ballast water management, following an implementation schedule based on a vessel's ballast water capacity and on its status as new or already in operation. Although IMO adopted the standards in 2004, ratification was slow, and the convention did not enter into force until September 2017. This is the first global standard for ballast water—it establishes a long-awaited framework for improving global water quality.

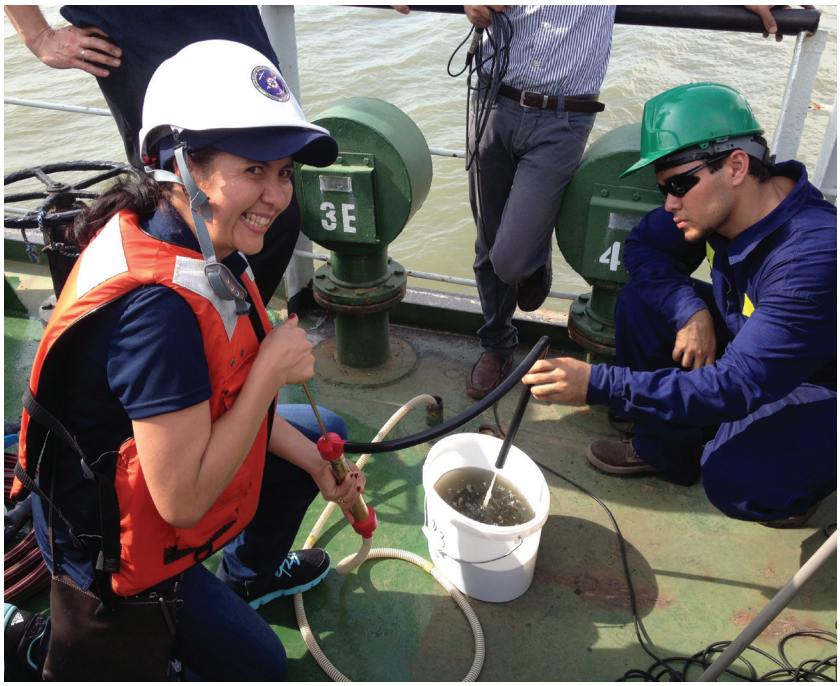


Photo: International Maritime Organization, Flickr

An IMO ballast water workshop teaches participants how to hand-pump ballast water for sampling.

Noise

In his 1953 book, Jacques Cousteau called the ocean The Silent World. Although intended as an artful expression, the title accurately characterizes aquatic biology and ecosystems. Oceans are among the quietest places on earth, despite the vast richness of the biological diversity.

Human-generated sound, however, has been increasing in the marine environment. Marine shipping is one of the major sources of underwater sound and has been linked directly to aquatic life stress and death. Commercial shipping is the major contributor to low-frequency noise—5 to 500 Hz—in the world's oceans (*9*). Ship noise is continuous and can exceed 200 decibels, and the emissions can travel over large geographic areas, especially in the higher latitudes, such as the Arctic.

The following activities also contribute to increases in underwater sound:

◆ Energy exploration and production, including the development of offshore renewable sources such as wind power;

Photo: U.S. Army Corps of Engineers

Homer Harbor, Alaska, is dredged each year to keep the basin depth safe for marine vessels. The noise, however, contributes to sound that disturbs sea life.

PHOTO: MICHAEL PADILLA, SANDIA NATIONAL LABORATORY

HYDROGEN FERRY—Hydrogen fuel cells produce power by controlling the reaction of hydrogen and oxygen to create electricity and water. This process produces zero toxic air emissions or greenhouse gases. The technology, however, has a poor power-to-weight ratio compared with conventional diesel engines and requires new vessel engineering designs. Significant capital investment in the refueling infrastructure is needed to increase the availability of hydrogen fuel. The U.S. Maritime Administration, Sandia National Laboratories, and Red and White Fleet are collaborating in the development of fuel cell–powered ferry designs for operations in San Francisco Bay.

◆ Port infrastructure improvements, such as dredging; and

◆ Structure demolition and replacement.

The effects of sound vary according to the intensity, frequency, and duration. Effects are species-specific and range from behavioral responses, such as avoidance, to injury and death. The effects are most severe for species susceptible to barotrauma—physical damage caused by differences in internal and external pressure—which can occur in certain fish, and for species that rely on sound to communicate and to find prey and mates, such as marine mammals. Federal regulations—for example, in the Endangered Species Act and the Marine Mammal Protection Act—protect many of these species in U.S. waters.

Advancing the Research

The TRB Standing Committee on Marine Environment is compiling research needs statements (RNS) focusing on these and closely associated topics, several of which were recently posted to the TRB RNS database.[2] The postings will enable the committee to solicit research funding. The committee maintains a detailed research needs statement that explores each topic in detail; for further information, please e-mail the committee chair at j-kruse@tamu.edu.

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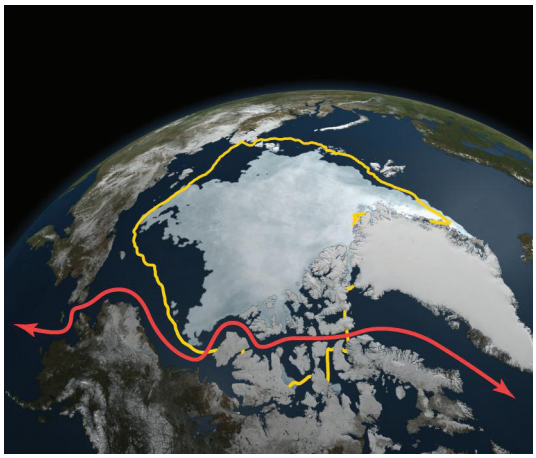

PHOTO: SCIENTIFIC VISUALIZATION STUDIO, NASA

A NASA visualization of the extent of Arctic ice. The red line shows the emerging Northwest Passage.