Lectures in Climate Change: Volume 1

Our Warming Planet

Topics in Climate Dynamics

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CLIMATE LECTURE 14: Arctic Sea Ice and Its Role in Global Change

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Climate Lecture 14

Arctic Sea Ice and Its Role in Global Change

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Introduction

Sea ice is an important component of the global climate system. Sea ice forms, grows, and melts in the ocean. Sea ice grows during the fall and winter and melts during the spring and summer. Sea ice can melt completely in summer or survive multiple years. Sea ice can be classified by stages of development (thickness and age), that is, first-year sea ice (ice thickness typically <1.8 m) and multiyear sea ice (ice thickness typically >1.8 m). Sea ice occurs in both hemispheres. In the Northern Hemisphere, sea ice develops in the Arctic Ocean and surrounding bodies including Hudson and Baffin Bay, Gulf of St. Lawrence, the Greenland Sea, the Bering Sea, and the Sea of Okhotsk (sea ice can be observed as far south as Bohai Bay, China, ~38°N). In the Southern Hemisphere, sea ice only develops around Antarctica, reaching a maximum equatorward extension at around ~55°S).

During part of the year, sea ice covers about 25 million km^2. That means about 7% of the world's ocean is covered by sea ice. Arctic sea ice cover usually reaches its seasonal maximum in March, about 15–16 million km^2 and minimum in September, about 7 million km^2. Antarctic sea ice usually reaches its maximum extent in September, about 18–20 million km^2 and minimum extent in February, about 3 million km^2 (https://nsidc.org/cryosphere/sotc/sea_ice.html).

As a boundary between the ocean and the atmosphere, sea ice plays an important role in the global climate system and acts as an important indicator of global climate change. Firstly, sea ice has a high albedo, that is, bare ice has an albedo of about 0.5–0.6 and ice with snow has an albedo of about 0.8–0.9. This substantially reduces the incoming solar radiation absorbed by the surface. Secondly, sea ice has a strong insulating effect on the underlying ocean. This drastically reduces the exchange of heat, moisture, momentum, and gases (e.g., CO_2) between the ocean and the atmosphere. Thirdly, the formation and melting of sea ice strongly influences ocean thermohaline circulation through dense water formation (e.g., the North Atlantic Deep Water and the Antarctic Bottom Water). Finally, sea ice holds a large amount of relatively freshwater. This has a strong impact on the freshwater budget in the Arctic Ocean and the Southern Ocean. Because the albedo, insulating and density effects are so strong, even small changes in the amount of sea ice cover might be expected to drive large changes in the regional and ultimately global climate. Additionally, sea ice is important for polar marine ecosystem, for example, sea ice provides a habitat for algae and hunting ground for polar bears.

Since the beginning of the industrial revolution, CO_2 concentration in the atmosphere has increased about 40% (from 280 to 400 ppm). Currently, CO_2 emission from human activities is about 36 billion metric tons per year. There is an increasing concern about enhanced climate change in the polar regions due to the rising anthropogenic CO_2. The average surface temperature in the northern high latitude has risen at twice the rate as the rest of the world in the past decades. A number of positive feedbacks associated with sea ice have contributed to the amplification of climate change in the Arctic. The most important is the positive temperature-albedo feedback. That is, warming of the atmosphere or ocean causes a decrease of sea ice extent, the exposure of more open water (as well as more melt ponds over sea ice), and increased absorption of solar radiation at the surface, leading to further warming. Satellite observations show that Arctic sea ice has been declining at an astonishing rate associated with the amplified warming in the Arctic. Several emerging factors have been identified that are responsible for the observed Arctic sea ice loss. These include more open water and melt ponds, more soot and dust deposition on the ice pack, more penetration of solar radiation through sea ice, faster drift of the ice pack, increased vertical advective heat flux from the warm layer of Atlantic and Pacific origin water to the surface mixed layer, and changes in poleward heat transport. One of the most active areas in climate research today is observational and modeling studies of how Arctic sea ice may progress in the coming decades. To date, estimates of when the Arctic might become 'ice free' (often defined as having ice extent fall below 1 million km^2) in September based on observational and modeling studies have ranged from this decade to the end of the century. Clearly, there is much we still need to learn about this rapidly changing region.

An even more active area of research concerns the possible links between Arctic sea ice loss and mid-latitude weather and climate. In early 2012, two research groups (Liu *et al*., 2012; Francis and Vavrus, 2012) separately linked Arctic sea ice loss — via a weakened meridional temperature gradient and westerly winds — to a meandering jet stream that led to prolonged and more frequent extreme events (e.g., cold surges). A bevy of studies have expanded on, modified (e.g., proposed links between Arctic sea ice loss, enhanced fall snow cover in Siberia, and a meandering jet stream), and called into question (e.g., with arguments ranging from natural variability driving the extreme weather events to no significant change in the jet stream) the hypothesis, using a blend of observational and modeling studies. The explosion of publications and interest in this topic is evidence of just how far we are from a definitive answer. Ironically, by the time a link has been demonstrated to be true or false, the system may have transitioned to such a new low ice state as to render the prior analyses less relevant/applicable.

David Rind has been an important figure in advancing this topic. The response of sea ice to climate change affects the Earth's energy balance in ways that may lead to more climate change. In the mid-1990s, Rind examined the effects of sea ice changes in doubled-CO_2 climate model sensitivity experiments. He found that the total effect of sea ice on surface temperature changes (including cloud cover and water vapor feedbacks that arise associated with sea ice changes) accounts for 1.56°C of the 4.17°C global warming by analyzing doubled CO_2 simulations in an experiment with sea ice not allowed to change versus a control in which sea ice did change. Results were about four times larger than the sea ice impact when no feedbacks are allowed. These results pointed out the importance of properly constraining the sea ice response to climate perturbations, necessitating the use of more realistic sea ice models in climate system models (Rind *et al*., 1995, 1997).

In 2001, Rind found that El Niño (features warmer than normal sea-surface temperatures across the central and eastern equatorial Pacific) drives changes in the subtropical jet stream, which changes the path of storms that rearrange sea ice in the Pacific and Atlantic sides. This research showed how very disparate components of the climate system are connected, requiring that they all be understood before we can properly estimate future climate sensitivity (Rind *et al*., 2001).

In closing, in a rapidly changing Arctic, sea ice plays a growing role not only in a climate sense, but also via ecosystems, indigenous knowledge and use, economic development and geopolitics. As the Arctic continues to change and grow in importance, cross-disciplinary collaborations across a variety of interest groups will support effective and sustainable approaches to adaptation.

This lecture presents changes of Arctic sea ice in the context of global climate change, and the potential impacts of decreasing Arctic sea ice.

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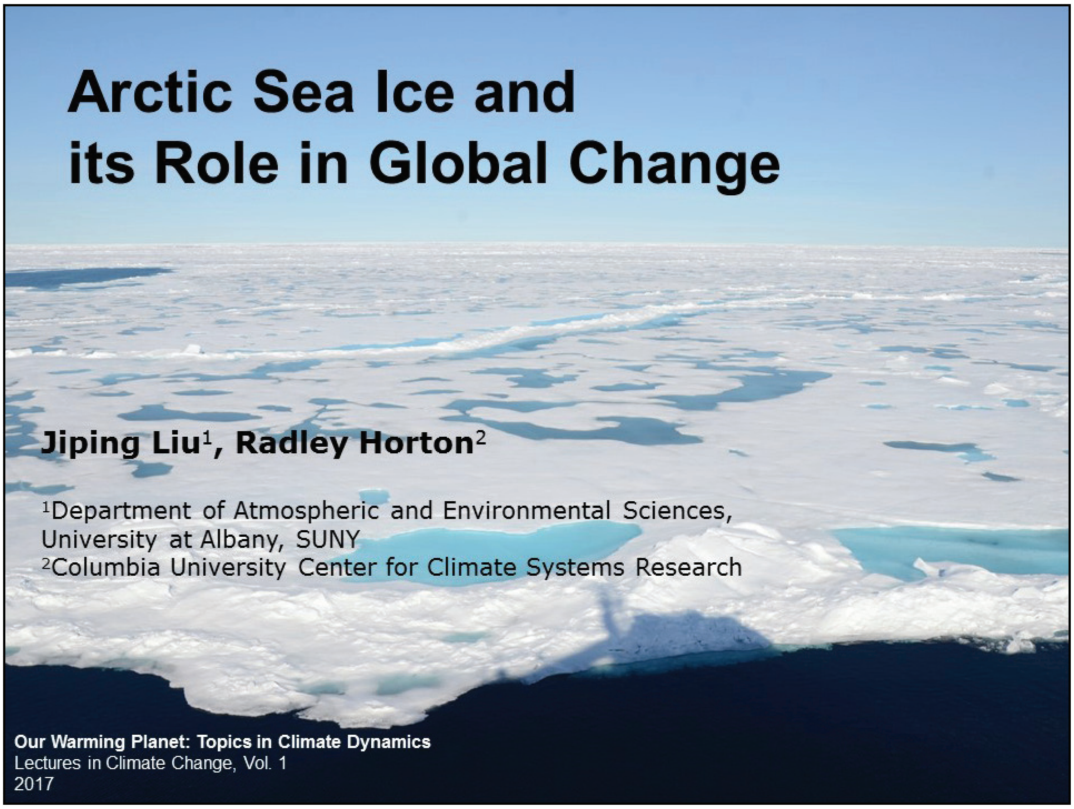
Slide 1



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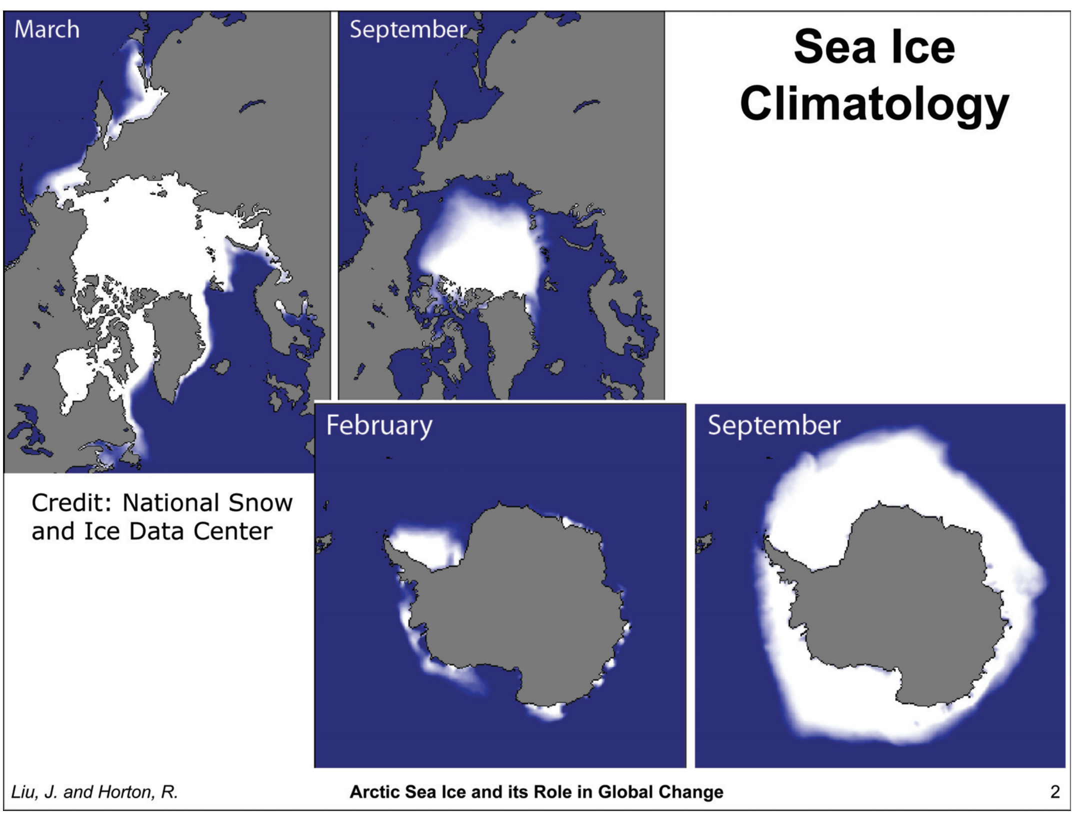

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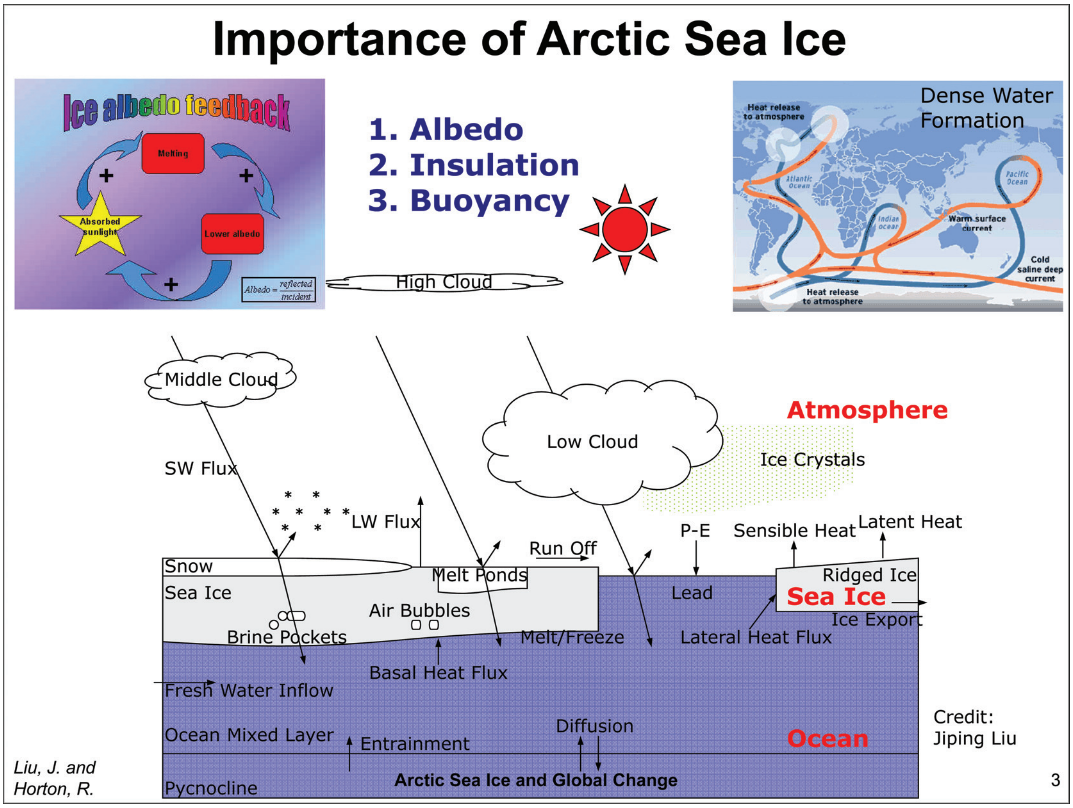

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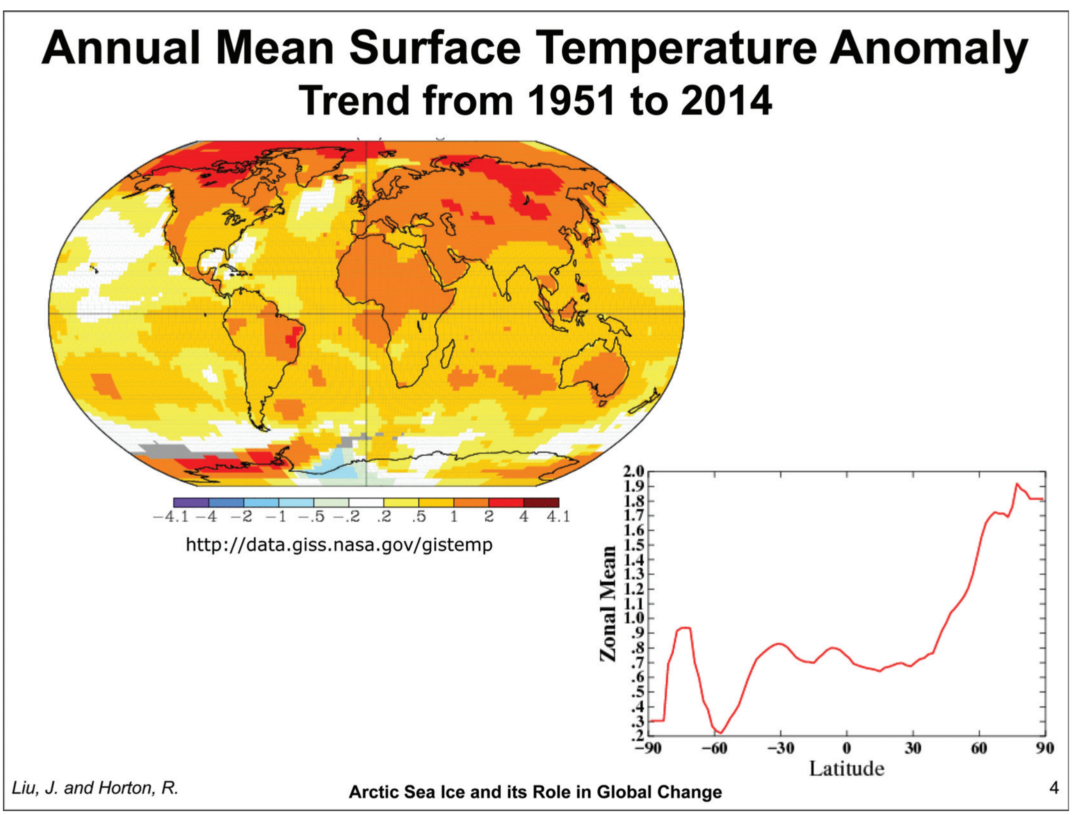

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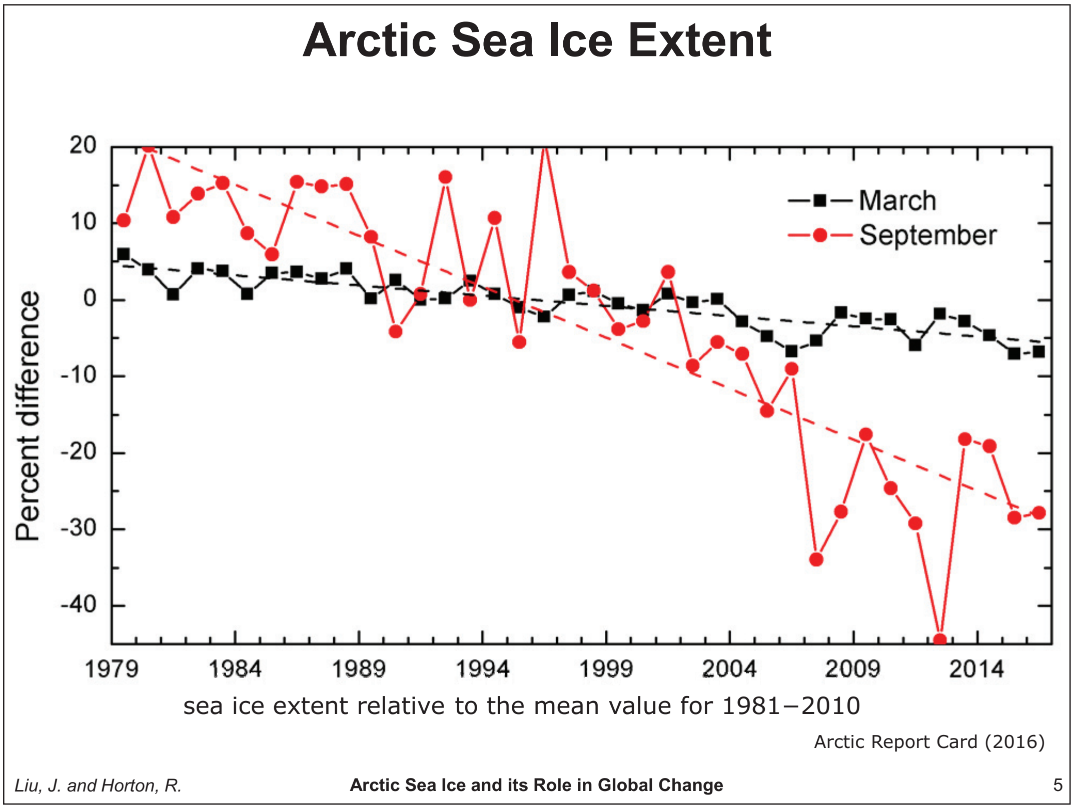

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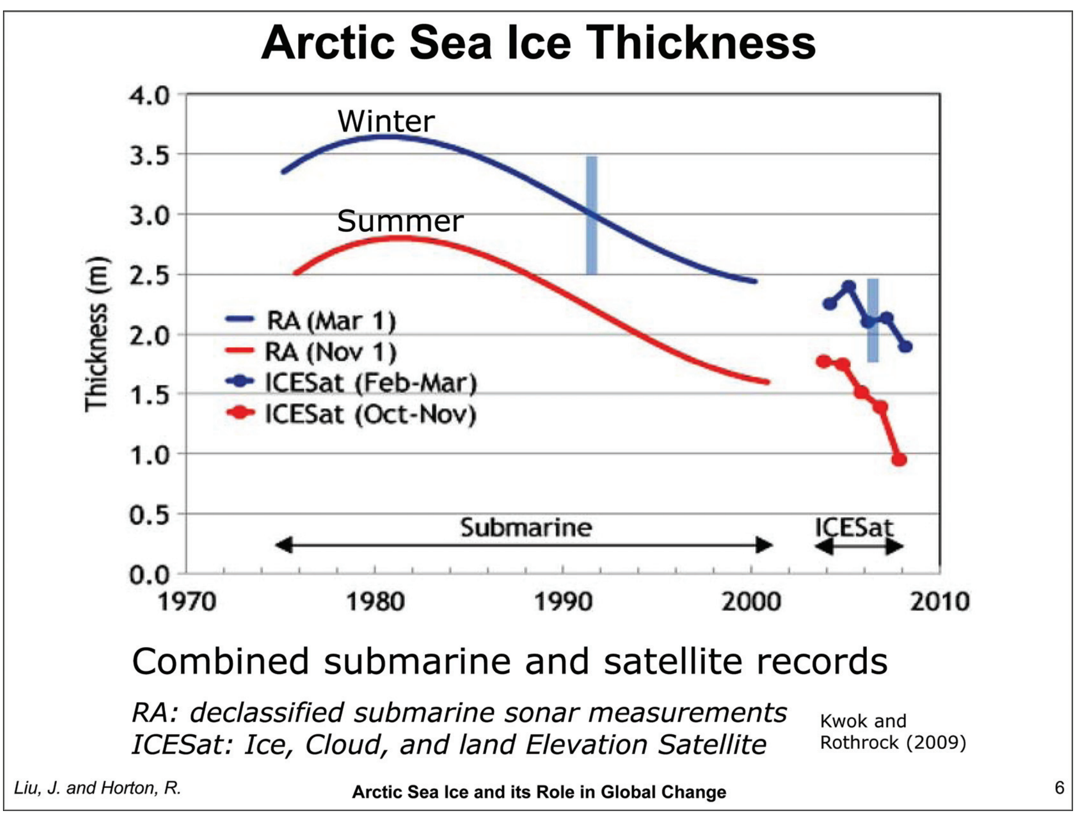

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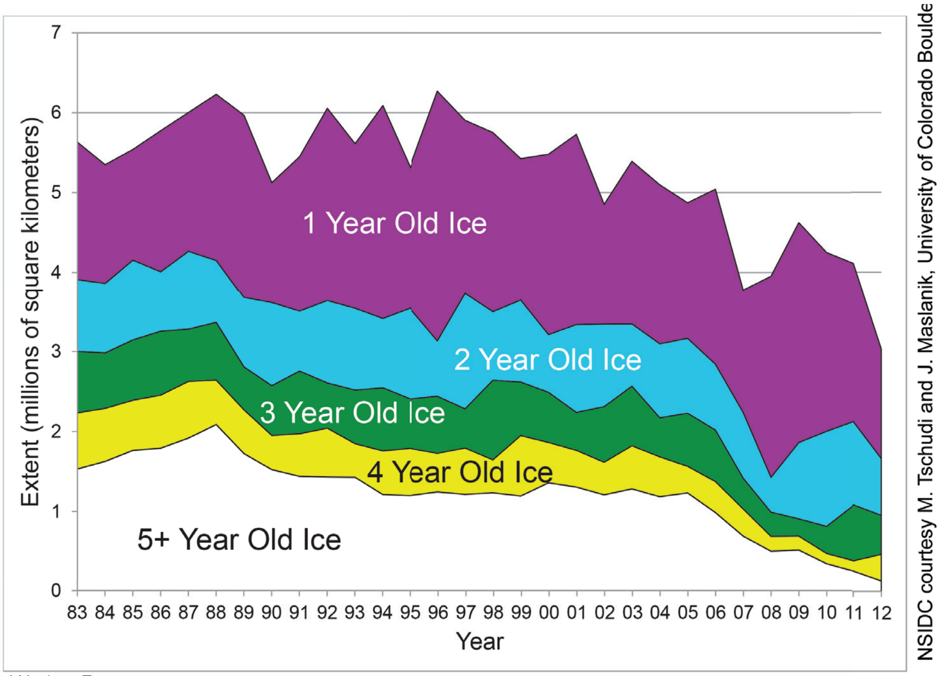
Arctic Sea Ice Age (End of Melt Season)



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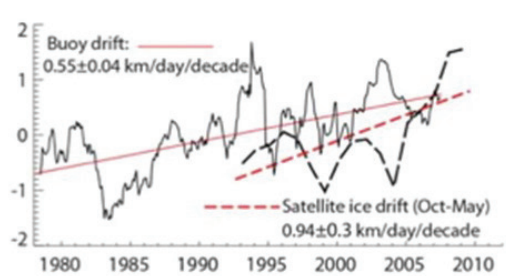
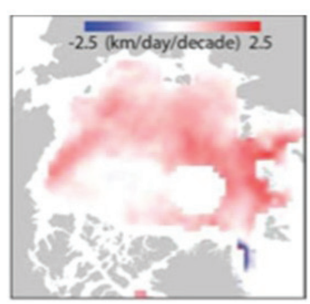
Arctic Sea Ice Drift Speed

Sea ice drift speed anomaly (km/day)

Ice drift speed



Drift speed



https://www.ccin.ca/home/sites/default/files/seaice/current

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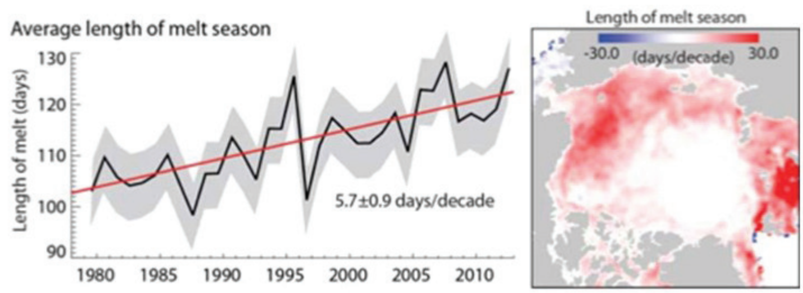
Arctic Melt Season



https://www.ccin.ca/home/sites/default/files/seaice/current

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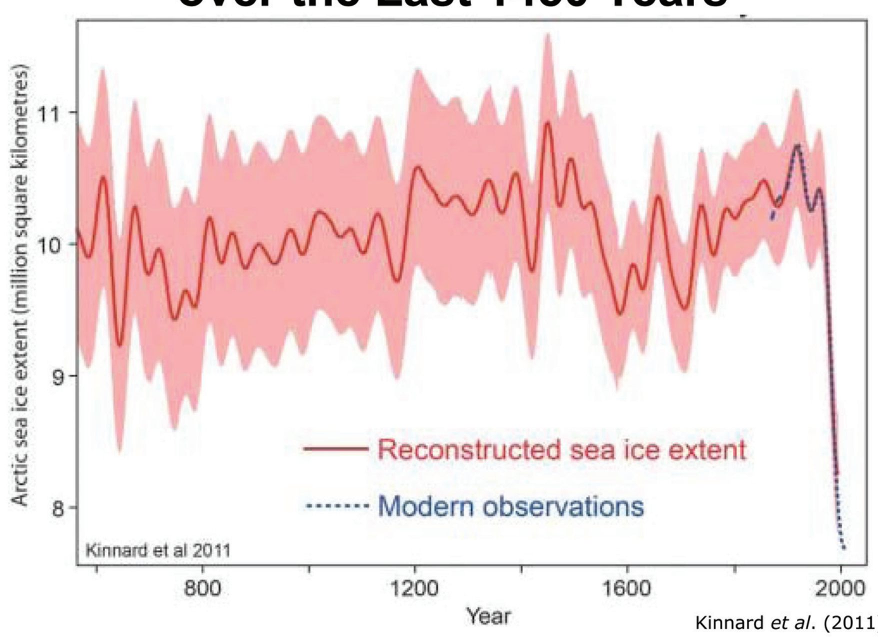
Late-Summer Arctic Sea Ice Extent over the Last 1450 Years



Kinnard *et al*. (2011)

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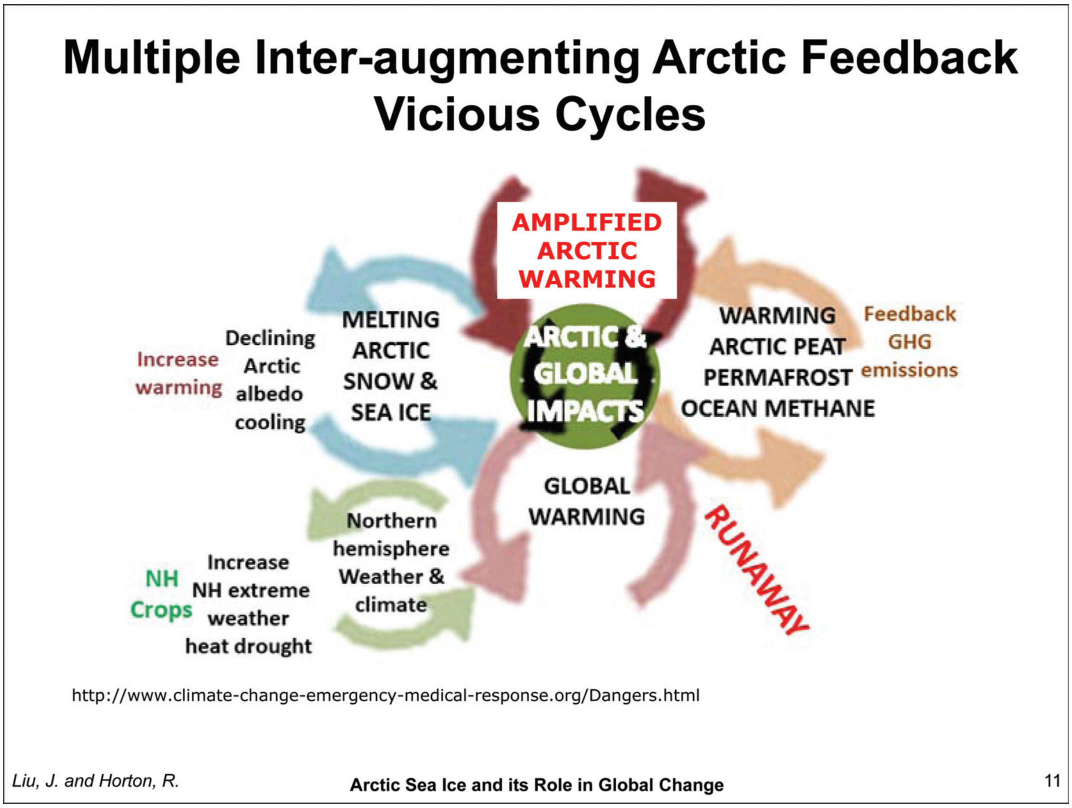

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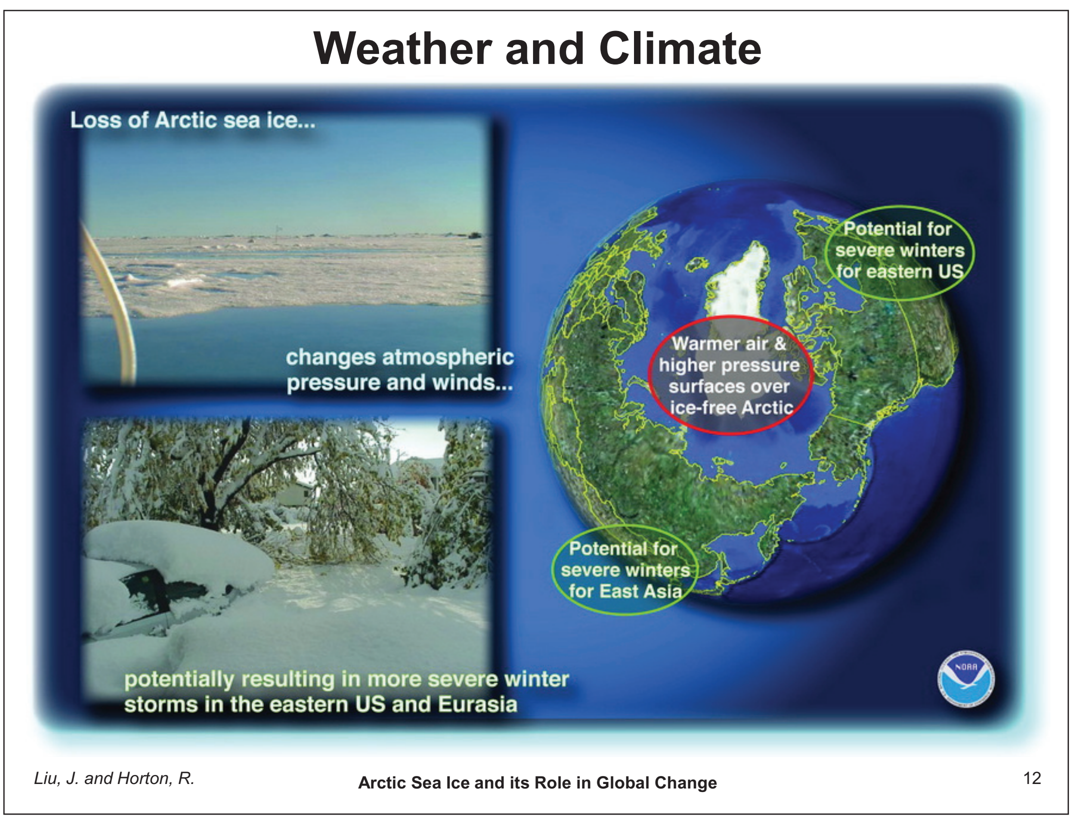

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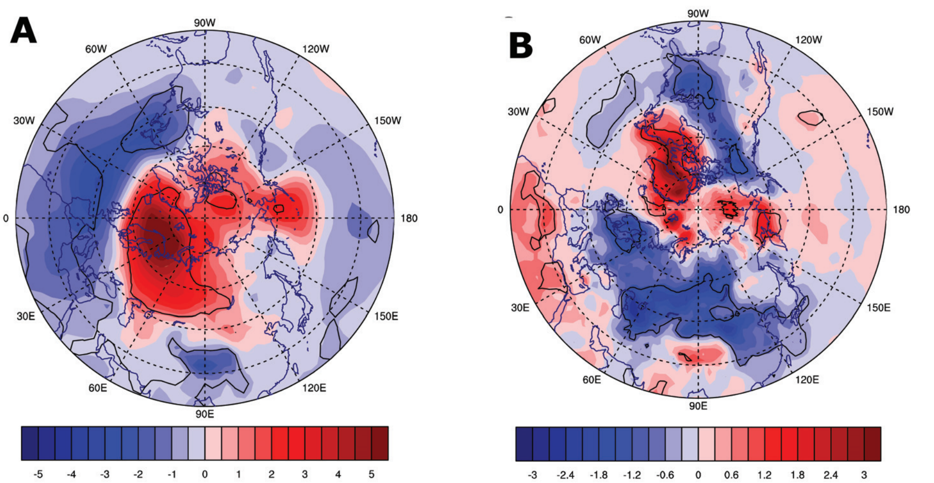
Arctic Sea Ice and Mid-Latitude Weather



Linear regression of winter sea level pressure (**A**) and surface air temperature (**B**) on the detrended autumn Arctic sea ice area index

Liu *et al*. (2012)

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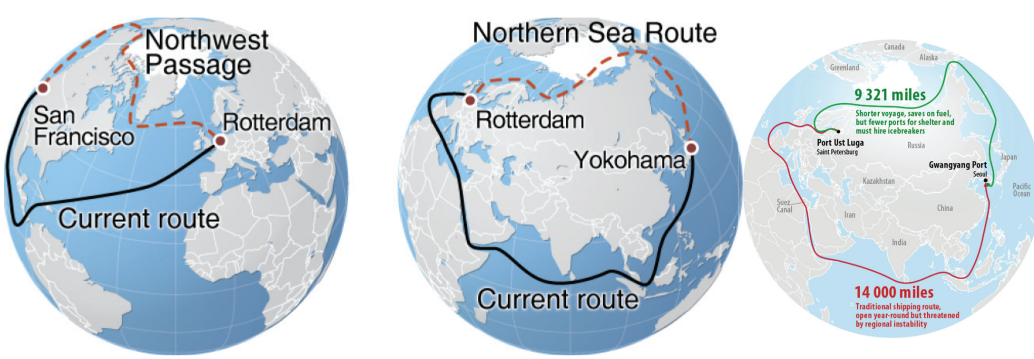
Slide 14

Ship Routes



- Northwest Passage: along the northern coast of North America via the Canadian Arctic Archipelago.
- Northern Sea Route: along the Russian Arctic coast from the Barents Sea, along Siberia, to the Bering Strait and Far East.

http://www.discoveringthearctic.org.uk/1_northwest_northeast_passages.html

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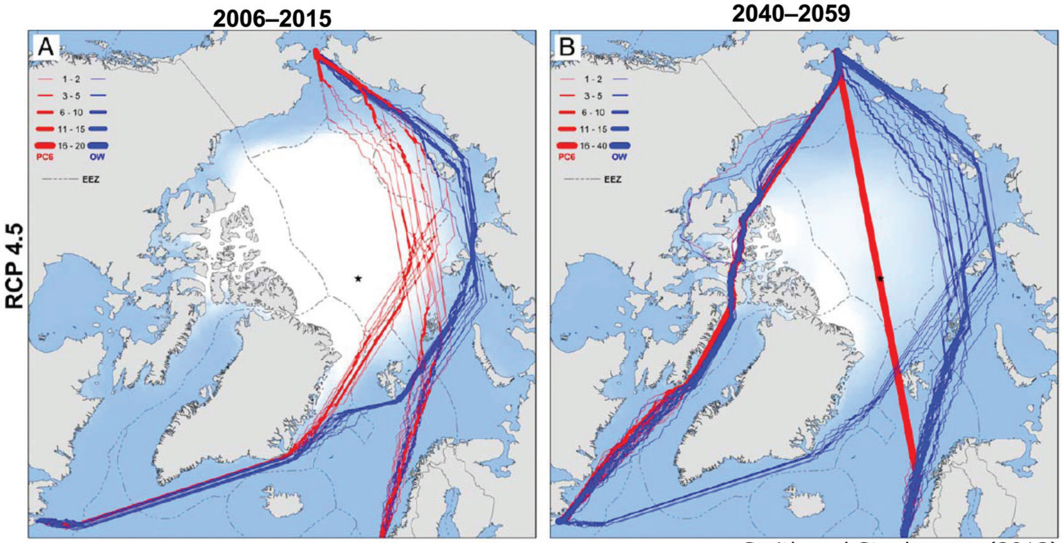
Current vs. Future Ship Routes



Smith and Stephenson (2013)

Blue lines: fastest routes available for common open-water ships
Red lines: routes available for ships with moderate icebreaker capacity
PC6: Polar Class 6 moderately ice-strengthened ships
OW: Open-water ships

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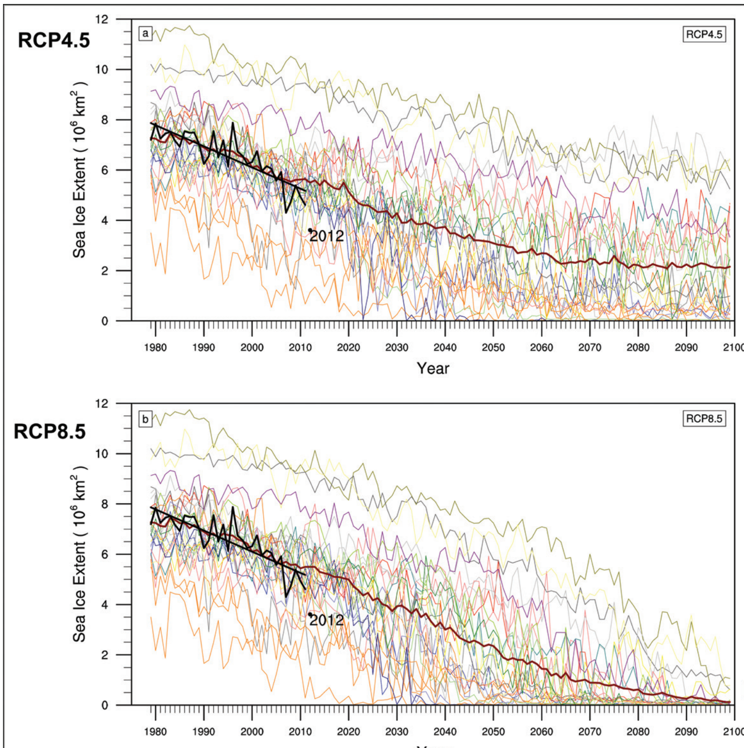
Projected September Arctic Sea Ice Extent



Liu *et al*. (2013)

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Slide Notes

Slide 2 Sea ice is simply frozen ocean water. It forms, grows, and melts in the ocean. Sea ice occurs in both the Arctic and Antarctic. Sea ice covers about 25 million km^2. About 7% of the world's oceans are covered by sea ice during part of the year.

Arctic sea ice usually reaches its maximum extent in March, about 14–16 million km^2 and minimum extent in September, about 7 million km^2. Antarctic sea ice usually reaches its maximum extent in September, about 17–20 million km^2 and minimum extent in February, about 3–4 million km^2.

Slide 3 Importance of Arctic sea ice in the climate system.

Slide 4 This shows the annual mean surface temperature anomaly trend from 1951 to 2014. The global average value is 0.85°C (land data uses GISS analysis and ocean data uses ERSST_v4). Amplified warming in the Arctic. The Arctic is warming about twice as fast as the rest of the world.

Slide 5 Since 1979, satellites have provided a consistent continuous record of sea ice. Sea ice extent is defined by the National Snow and Ice Data Center and others as the total area of all pixels in the satellite image with an ice concentration of at least 15% (Note: the decision to use 15% was made back in the 1970s at NASA Goddard Space Flight Center). Arctic sea ice extent has decreased in all months and virtually all regions. As of 2014, the trend of September sea ice extent is –13% per decade relative to the 1981–2010 average. The trend is smaller in March (–3% per decade), but still decreasing and statistically significant. The last eight years have the eight smallest minimum extents since satellite observations.

Slide 6 Arctic sea ice is not only declining in extent but is also thinning dramatically since the late 1970s. The combined records from submarine and satellite show a thinning of sea ice thickness, ~1.75 m in winter and ~1.65 m in summer.

Slide 7 First- and second-year ice made up 70% of the ice cover in the Arctic in 2012, compared to 50% on in early 1980s. The oldest ice types almost disappeared in 2012.

Continued loss of thickest and oldest sea ice has prevented the recovery of the summer minimum.

Slide 8 Drifting buoys and satellites show an increase in the mean Arctic drift speed since the late 1970s. The increase in the ice drift speed tends to reduce sea ice mechanical strength and increase sea ice deformation. This results in stronger fracturing and more sea ice leads in the Arctic Ocean.

Slide 9 The amplified warming in the Arctic has caused the melt season to last longer, that is, melt season has increased by 5–6 days per decade in the last 30 years. A longer melt season allows the Arctic to absorb more heat to thin the ice.

Slide 10 This shows late-summer Arctic sea ice extent over the last 1450 years (red line), reconstructed from a combination of Arctic ice core, tree ring, and lake sediment data. The shaded area shows the uncertainty (95% confidence interval), and the blue dashed line shows modern observations. Arctic sea ice extent is currently lower than at any time in the last 1450 years.

Slide 11 GHG: greenhouse gases; NH: northern hemisphere.

Slide 12 Although individual extreme weather events cannot be directly linked to Arctic sea ice loss, recent observational data analysis and numerical model experiments suggest a link between decreasing Arctic sea ice and mid-latitude weather and climate, such as cold winter and increased snowfall.

Slide 13 For example, research suggested that decreasing autumn Arctic sea ice favors higher sea level pressure (SLP) and geopotential heights (GPH) over the Arctic and lower SLP and GPH in mid-latitudes. So, there is a weakening of the north–south temperature gradient and hence a weakening of westerly winds. The weakened westerly winds tend to enhance blocking circulations, favoring more frequent incursions of cold air mass from the Arctic into northern continents. With future loss of Arctic sea ice, cold conditions like winter 2009–2010 may happen more often.

However, the atmospheric dynamic is so variable, and the basic equations of motion on the time scale that we are discussing have so much inherent variability in them that you can have the same situations next time but everything is different. The only thing that will ultimately answer that is the durability of the effect. If, year after year, we are getting the same type of effect, that then looks like it is not a variability issue but a climate change issue.

Slide 14 Loss of Arctic sea ice means the opening up of the Arctic for commercial ships, offering a faster route for shipments between Europe and Asia, and holds the promise of increased trade for the High North of Arctic countries (Russia, Norway, and Canada). The number of ships using the route is on the rise.

Slide 15 By 2040–2059, loss of sea ice and changing ice conditions enable expanded September navigability for common open-water ships crossing the Arctic along the Northern Sea Route and the Northwest.

RCP: representative concentration pathway; RCP4.5 is a medium-mitigation emission scenario that stabilizes direct radiative forcing at 4.5 W/m^2 (~560 ppm CO_2 equivalent) at the end of the 21st century.

EEZ: the standard 200-nm Exclusive Economic Zone of the Russian Federation.

Slide 16 Time series of the simulated (colored lines) September sea ice extent from 1979 to 2100 for 30 CMIP5 models under the representative concentration pathway (RCP) 4.5 and 8.5 scenarios. The thick black line is the observations, the thick red line is the multimodel ensemble mean, and the black circle indicates September sea ice extent in 2012.