

# Climate Change and Global Warming

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*Seminar in Mathematics and Climate*

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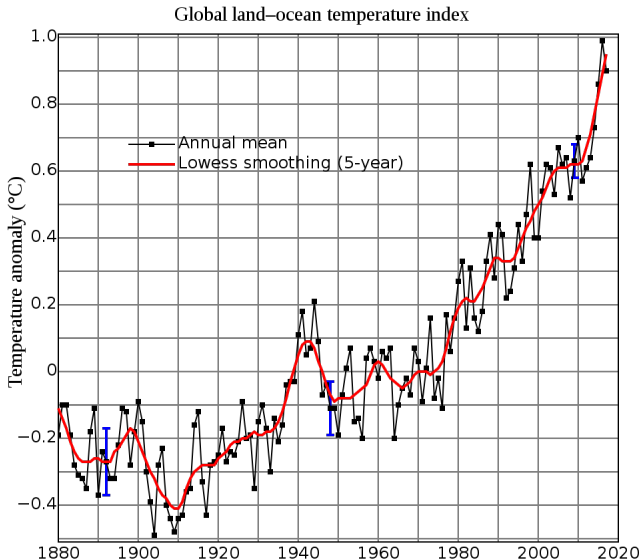
## Lecture Outline

- Evidence that the planet is warming
- Consequences and concerns of global warming
- Climate modeling and the role of mathematics
- Course overview and goals

## The 10 hottest years on record (NOAA Global Climate Report)

| Rank | Year | Anomaly $^{\circ}\text{C}$ | Anomaly $^{\circ}\text{F}$ |
|------|------|----------------------------|----------------------------|
| 1    | 2016 | 0.94                       | 1.69                       |
| 2    | 2015 | 0.90                       | 1.62                       |
| 3    | 2017 | 0.84                       | 1.51                       |
| 4    | 2014 | 0.74                       | 1.33                       |
| 5    | 2010 | 0.70                       | 1.26                       |
| 6    | 2013 | 0.67                       | 1.21                       |
| 7    | 2005 | 0.66                       | 1.19                       |
| 8    | 2009 | 0.64                       | 1.15                       |
| 9    | 1998 | 0.63                       | 1.13                       |
| 10   | 2012 | 0.62                       | 1.12                       |

**Table:** From 1880–2017, the 10 warmest years for the global combined land and ocean annual average temperature. Anomaly is computed against the 20th century average of  $13.9^{\circ}\text{C}$  ( $57.0^{\circ}\text{F}$ ). 2017 is the warmest year on record **without** an El Niño present in the Pacific Ocean.



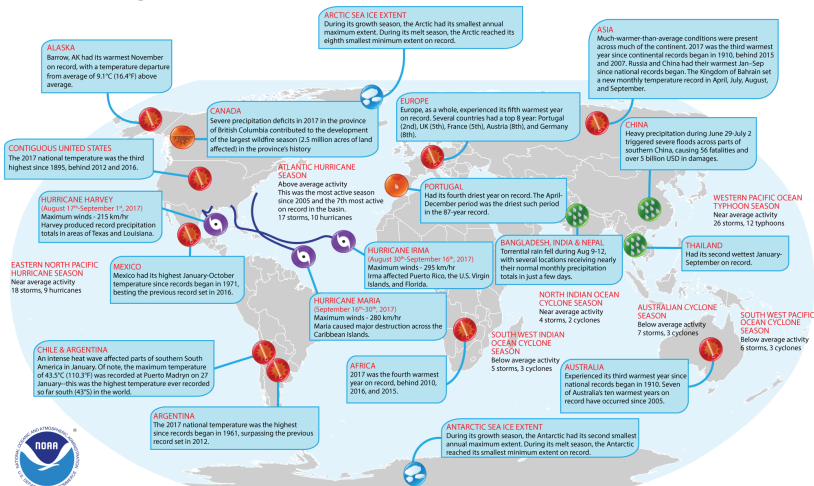
**Figure:** Global mean surface temperature change since 1880. Source: NASA Goddard Institute for Space Studies

## How much warmer was your city in 2016?

► [Click Here](#)

- AccuWeather database of 5,000 cities
- For 2016, 90% of them recorded annual mean temperatures above average.

# Selected Significant Climate Anomalies and Events in 2017

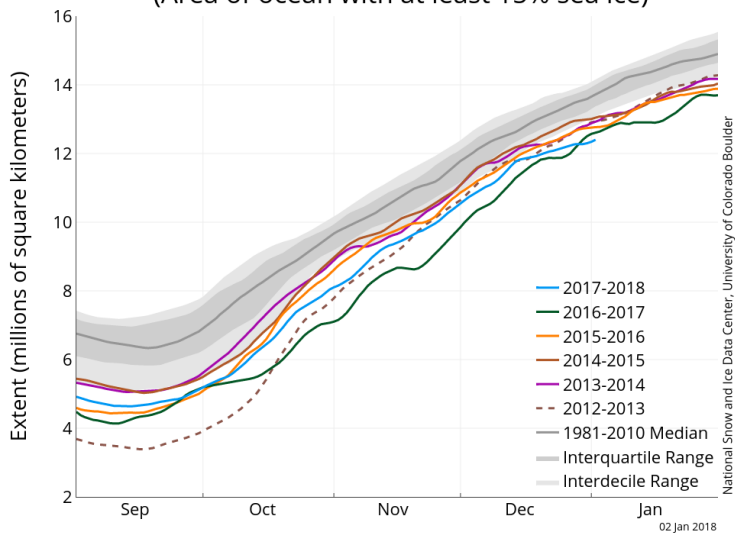


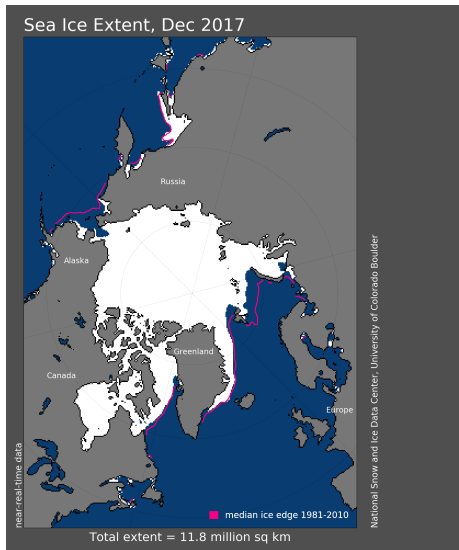
Please Note: Material provided in this map was compiled from NOAA's NCEI State of the Climate Reports and the WMO Provisional Status of the Climate in 2017. For more information please visit: <http://www.ncdc.noaa.gov/sotc>

**Figure: 2017 Global Significant Weather and Climate Events. Source: NOAA Global Climate Report** <https://www.ncdc.noaa.gov/sotc/global/201713>

# Loss of Arctic Sea Ice

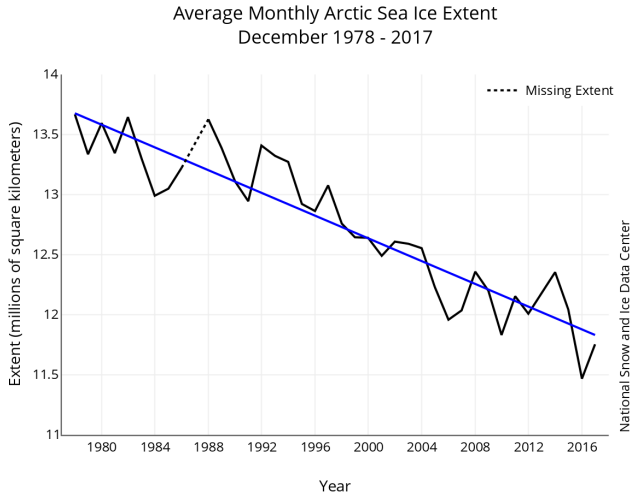
Arctic Sea Ice Extent  
(Area of ocean with at least 15% sea ice)





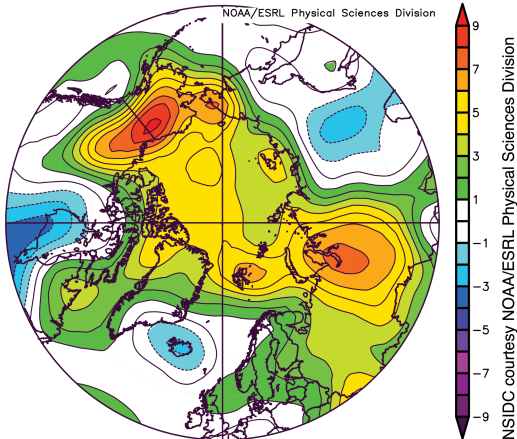
**Figure:** The Arctic sea ice extent for December 2017 (second lowest on record). The magenta line is average extent for December over 1981–2010 (satellite records).

# Loss of Arctic Sea Ice



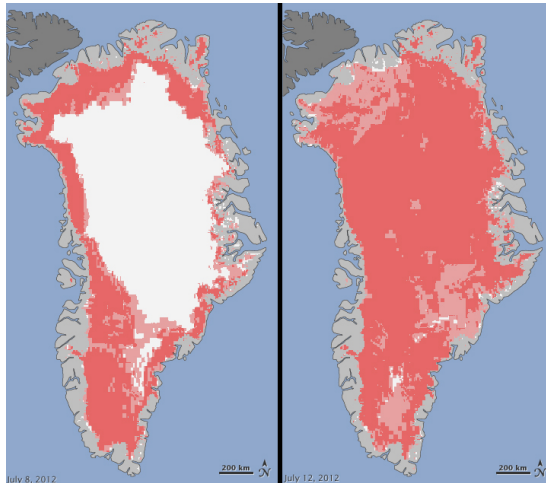
**Figure:** The monthly December sea ice extent for 1978–2017 shows a 3.7% loss per decade.

# Air Temperature Difference December 2017



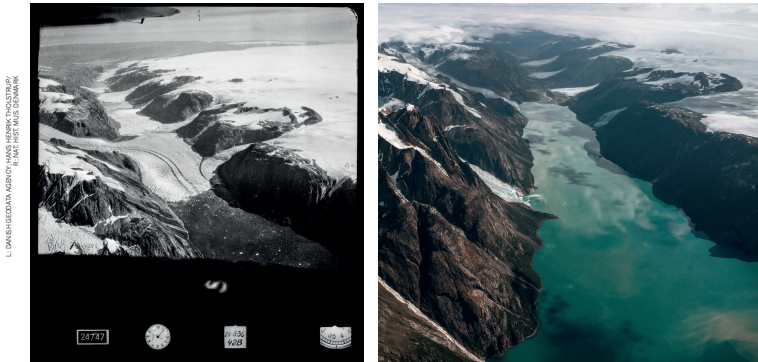
**Figure:** Differences in December 2017 air temperatures (in  $^{\circ}\text{C}$ ) from the average, measured about 2,500 feet above sea level. Parts of central Alaska were more than  $18^{\circ}\text{F}$  above average!

# The Great Greenland Thaw in July 2012



**Figure:** Around 97% of the Greenland ice sheet experienced melting during the middle of July in 2012 (pink and red), up from a usual average of 50%. Most of the melt water refreezes; however, if the entire sheet were to melt, sea level could rise 24 feet!

## Disappearing Glaciers in Greenland

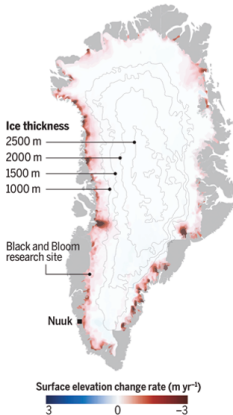


**Figure:** Aerial photos of the Ujaaraannaq Valley (southwest Greenland) taken in the summer of 1936 (left) and in 2013 (right) showing severe glacier loss. Source: “The ice historians,” Q. Schiermeier, *Nature* **535**, July 28, 2016, pp. 480–483.

# Decline of the Greenland Ice Sheet

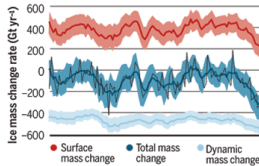
## Fraying edges

Satellite altimeters show that the ice sheet's margins are dropping as surface snow and ice melt and glaciers shed icebergs.



## Tallying the losses

Because of increasing melt, surface mass gain from snowfall no longer offsets "dynamic" losses from iceberg calving, greatly increasing total mass loss.



Cumulative mass loss has risen in recent years, along with Greenland's contribution to sea level rise.

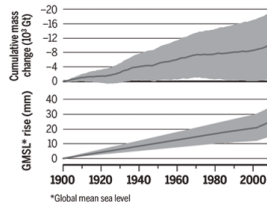
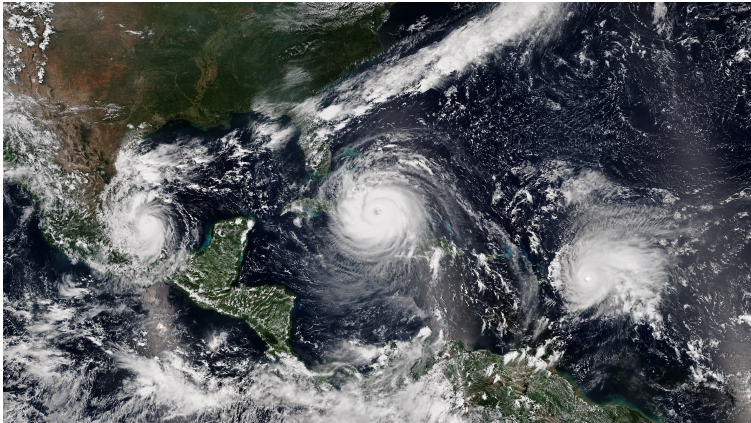


Figure: “Nobody expected the ice sheet to lose so much mass so quickly,” Isabella Velicogna, geophysicist at the University of California, Irvine. Source: “The great Greenland meltdown,” E. Kintisch, *Science*, Feb. 23, 2017, doi:10.1126/science.aal0810

## Impacts of Global Warming

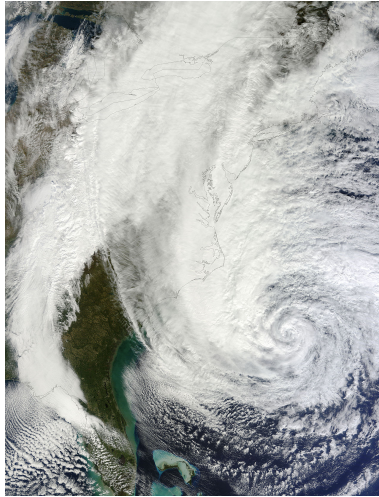
- 1 Rising sea level and increased coastal flooding.
- 2 Longer and more damaging wildfire seasons.
- 3 More powerful and damaging hurricanes largely caused by rising ocean temperatures.
- 4 Increase in extreme weather events (heat waves, coastal flooding, droughts). This has obvious impacts on our food supply.
- 5 Ocean acidification (higher acidity near surface due to excess carbon dioxide) and long-term damage to coral reefs.

# The Destructive 2017 Hurricane Season



**Figure:** Three simultaneous hurricanes on Sept. 8, 2017: Katia (left), Irma (center) and Jose (right). The year 2017 saw 17 storms and 10 hurricanes, 6 of which were Category 3 or higher. Image Source: NOAA Suomi NPP satellite

## Hurricane Sandy (2012)



**Figure:** Before 2017, Sandy was the second-most costly hurricane in US history after Katrina. It is the largest Atlantic storm on record, spanning 1,100 miles in diameter. Source: LANCE MODIS Rapid Response Team at NASA GSFC

# Hurricane Sandy (2012)



**Figure:** A roller coaster off the Jersey shore after Hurricane Sandy.

## Vanishing Rivers?!



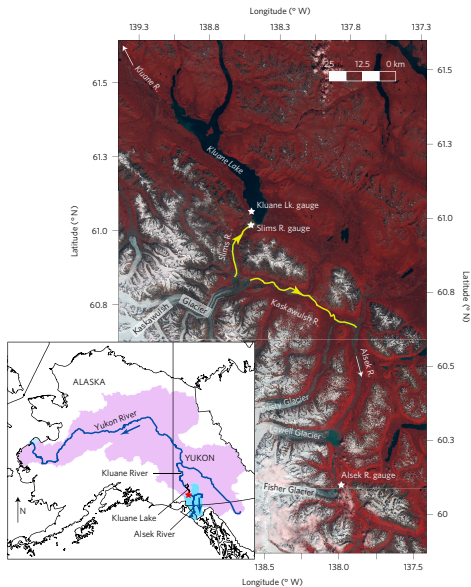
A view of the ice canyon that now carries meltwater from the Kaskawulsh glacier, seen here on the right, away from the Slims river and toward the Kaskawulsh river. Photograph: Dan Shugar/University of Washington Tacoma

“Receding glacier causes immense Canadian river to vanish in four days,” — headline in The Guardian, April 17, 2017

## River Piracy: The Loss of the Slims River

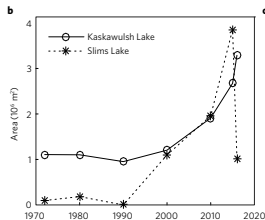
- Water melting from the vast Kaskawulsh glacier (Yukon, Canada) usually feeds the northward flow of the Slims river.
- The Slims in turn fed the Kluane river, which flows into the Yukon river and eventually into the Bering Sea (Western Alaska).
- In the spring of 2016, intense melting severely altered the drainage (gradient) flow toward the Kaskawulsh and Alsek rivers, which dump into the Gulf of Alaska **thousands of miles** from the original destination.
- “We went to the area intending to continue our measurements in the Slims river, but found the riverbed more or less dry. The delta top that we’d been sailing over in a small boat was now a dust storm.” — [James Best](#) (geologist, University of Illinois).

Reference: “River piracy and drainage basin reorganization led by climate-driven glacier retreat,” Shugar (et. al.), *Nature Geoscience* (May 2017) **10**, pp. 370–376.



**Figure 1** | Satellite image showing the Slims, Kaskawulsh and upper Alsek rivers, and Kluane Lake. Locations of river and lake gauges are shown with white stars. Yellow lines with arrows represent pre-2016 flow paths of the Slims and Kaskawulsh rivers. Inset map of Alaska and Yukon shows the Yukon (pink shading) and Alsek (blue shading) watersheds. Red star indicates study area at the south end of Kluane Lake.

# The Loss of the Slims River: Tipping Points



- Water coming from the glacier typically split between two rivers; suddenly, it began flowing to just one. Slims reduced to a trickle, while the Alsek grew to 60–70 times its previous size.
- “There are definitely thresholds which, once passed in nature, everything abruptly changes.” — [Lonnie Thompson](#) (paleoclimatologist, Ohio State University).
- A small change in one quantity (temperature) can cause dramatic changes elsewhere (loss of a river). In dynamical systems theory, this is the [butterfly effect](#). In climate science, this is called a [tipping point](#). We will call such points [bifurcations](#).

## The Vital Role of Applied Mathematics

► Click Here

**Math Behind Sea Ice and Our Changing Planet:** Video published by Society for Industrial and Applied Mathematics (SIAM) featuring [Emily Shuckburgh](#) (Deputy-Head, Polar Oceans, British Antarctic Survey) and [Kenneth M. Golden](#) (Distinguished Professor of Mathematics, University of Utah)

- “We wouldn’t be able to start understanding climate change if it wasn’t for our understanding of applied math.” — Emily Shuckburgh
- “Over the past 10-20 years we’ve lost over half of the summer Arctic sea ice pack.” — Ken Golden

## Course Overview/Goals

- 1 Climate is measured by **averaging** the weather over space and time, typically over long time periods such as decades, centuries, or millennia.
- 2 Learn and apply some of the mathematical techniques pertinent to the field of climate science. Areas: differential equations, dynamical systems, calculus, linear algebra, and statistics.
- 3 Inherently interdisciplinary study: physics, chemistry, geology, environmental studies, computer science, statistics, and applied mathematics.
- 4 We will focus on low-dimensional (conceptual) climate models. Even one-variable models can reveal interesting dynamical behavior. Can't run controlled climate experiments of the planet. Need **mathematical models!**

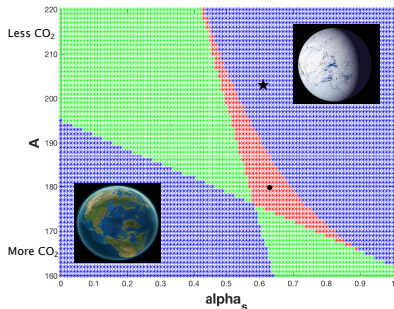
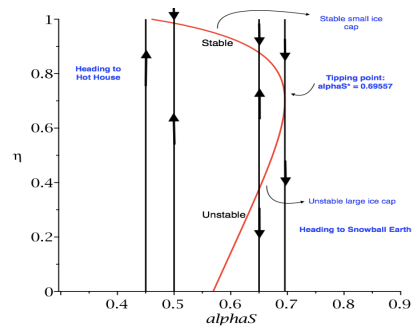
## Sample Questions of Inquiry

- 1 What determines the Earth's surface temperature and how does it vary by latitude?
- 2 What are the typical steady states for the Earth's climate system and how have these evolved over the history of the planet?
- 3 What are “tipping points” and how do mathematicians study them?
- 4 Why does the carbon dioxide in the atmosphere affect the climate?
- 5 How do changes in the Earth's celestial orbit affect the climate?
- 6 Why has the Earth cycled through ice ages over the last million years?

# Course Objectives

- 1 Learn, apply, and synthesize the mathematical techniques used in climate science.
- 2 Develop skills to understand and modify mathematical models.
- 3 **Final Project:** Conduct a detailed investigation into a research topic concerning the mathematics of climate. Create or adjust a known climate model and/or analyze real world data.
- 4 Work and communicate with your peers.
- 5 Have FUN applying your mathematical skills to an important discipline.
  - Field trip to Harvard Forest (mid-April). Meet climate scientists and learn about their research.
  - Movie night: *The Day After Tomorrow*

# Sample Research Project (Cara Donovan)



Left figure: Different phase lines for the ice-line ( $\eta$ ) as the albedo for snow-covered ice ( $\alpha_s$ ) is varied in the Budyko-Widiasih Energy Balance Model (land concentrated near equator).

Right figure: The number of equilibria and the fate of the climate as the parameters  $A$  and  $\alpha_s$  vary in the model. The star is our current climate conditions while the dot represents the Neoproterozoic era.