Avoid the Unmanageable, Manage the Unavoidable

Eight Interdisciplinary Lectures on Climate Change

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Monday Evenings, 5:30-7 pm, Martin Johnson House

Scripps Institution of Oceanography, University of California San Diego

SCRIPPS INSTITUTION OF OCEANOGRAPHY UCSD

October 20, 2014: Hiatus in Warming, Arctic Amplification, Extreme Events

Three paradoxes; sulphate cooling and solar cycle do not explain hiatus; links to La Nina and AMOC ocean heat sequestration can; Arctic warming accelerated during hiatus as did sea ice and snow cover retreat; mid-latitude extreme events increased; possible unified explanation; present, future impacts of arctic warming

"Hiatus" In Global Warming

Paradox #1: Why is global temperature constant when CO2 concentration is increasing?
Paradox #2: Why is Arctic warming accelerating when global temperature is constant?
Paradox #3: Why are extreme events increasing when global temperature is constant?


Global warming stopped 16 years ago, Met Office report reveals

Graph showing tenths of a degree above and below 14C world average

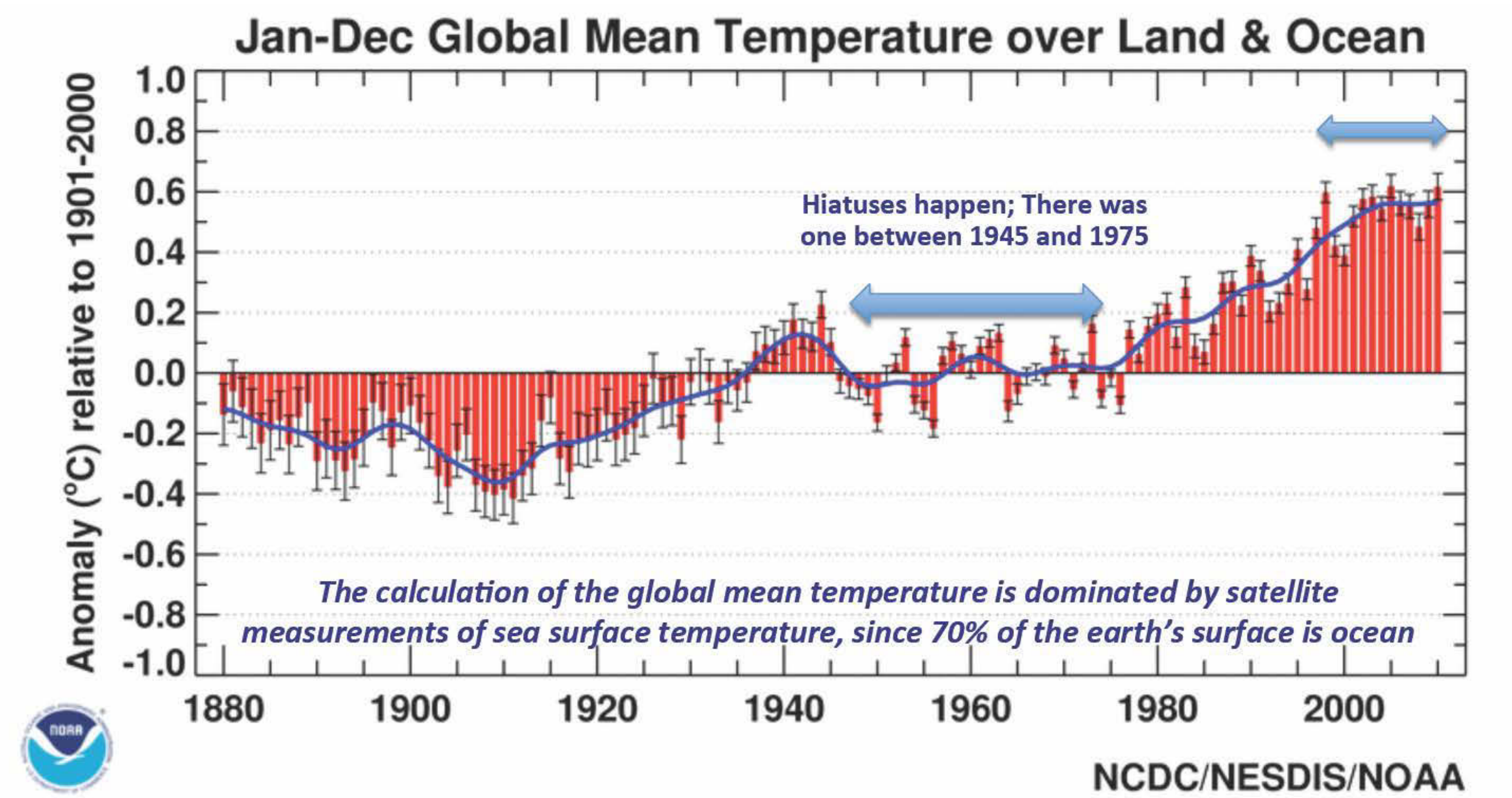
David Rose, Daily Mail (UK) 12 January, 2013

Boykoff, M.T., Media discourse on the climate slowdown, *Nature Climate Change, 4,* 156-158, 2014, published online 26 February 2014, doi: 10.1038/nclimate2156

A Longer Perspective

The present hiatus is a 16-year period of near record high global temperature

"It is certain that Global Mean Surface Temperature has increased since the late 19th century. Each of the past three decades has been significantly warmer than all the previous decades in the instrumental record, and the first decade of the 21st century has been the warmest". IPCC AR5, Chapter 2, 2013



Cherry-Picking?

Starting from strong *La Nina* after 1998 *El Nino* gives growth in Global Temperature
Starting with *El Nino* does make temperature seem constant

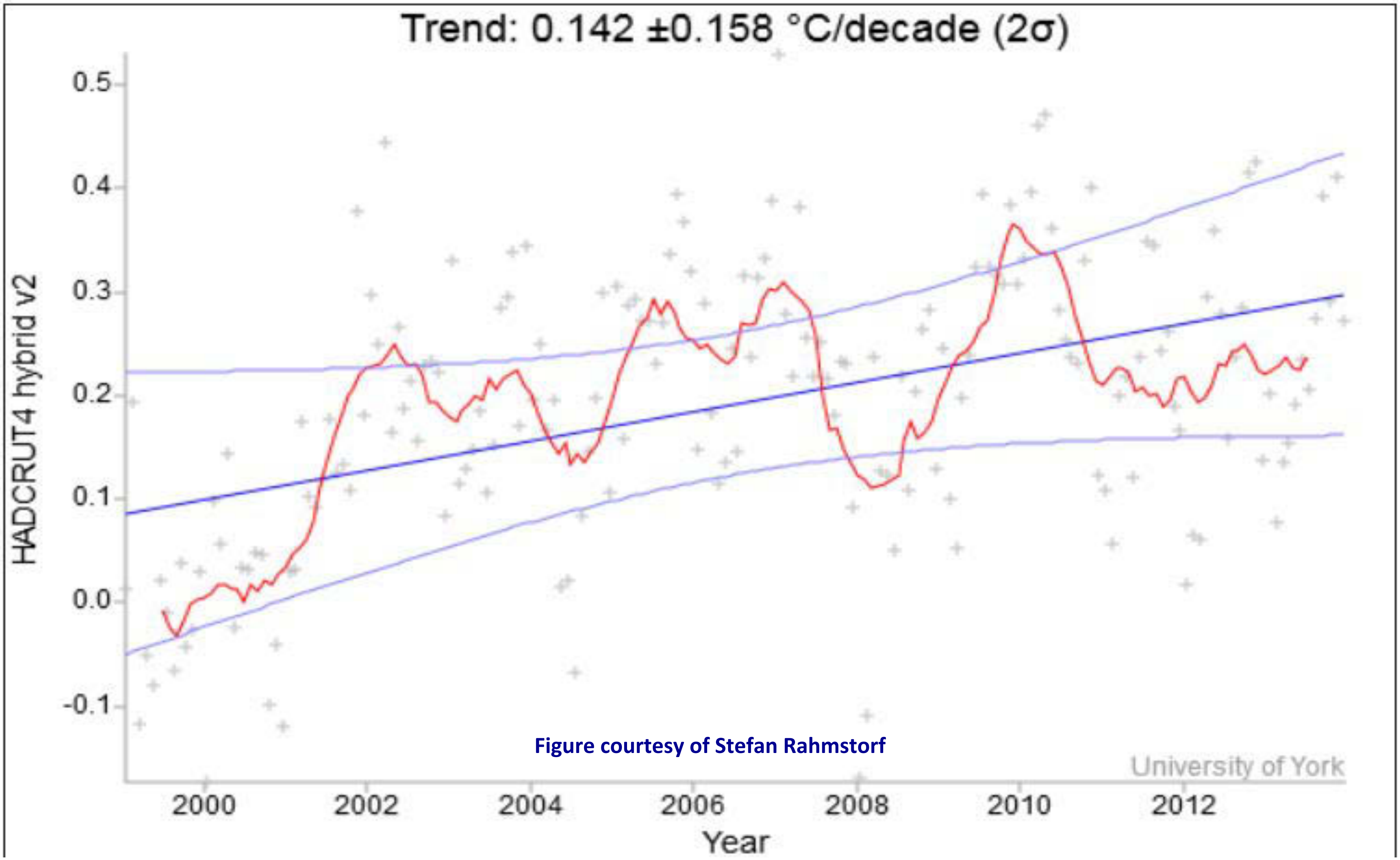
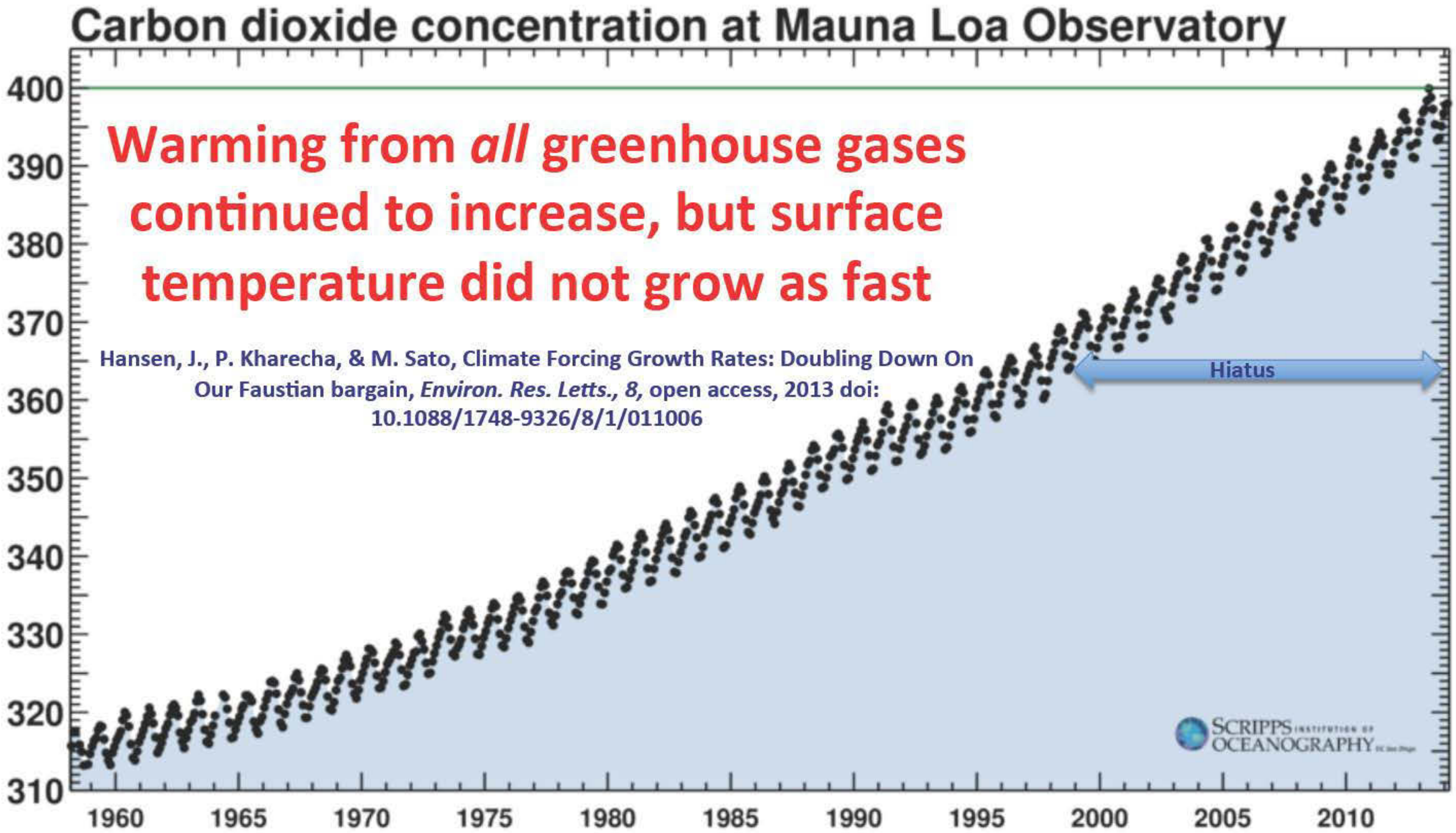


Figure courtesy of Stefan Rahmstorf



In 1700, CO_2 concentration was 277 ppm; on March 17, 2014, it was 401.34 ppm; industrial civilization has added 124 ppm, of which about 35 ppm, or 28%, was after 1998. The recent CO_2 warming rate, 0.27 W/m2 per decade (IPCC AR5), implies increase of 0.43 W/m2 in the 16 years between 1998 and 2014.

0.43W/m2 sets the scale of the counterbalancing mechanisms we must look for.

Sulphate Cooling?

Mt. Pinatubo, Philippines

Mt. Pinatubo

In 1992, Mt. Pinatubo lifted Sulfur Dioxide high into the stratosphere, where it produced aerosol particles that, acting like little mirrors, reflected sunlight back into space. A 2-year slowdown in warming followed. There were no large volcanic explosions during the post-1998 hiatus, but the many smaller ones that did occur populated a variable cooling layer in the stratosphere of about 0.1 W/m2, not enough to cause the hiatus

Solomon, *et al,* The Persistently Variable "Background" Stratospheric Aerosol layer and Global Climate Change, *Science, 333, 866, 2011*

Slow Moving Volcano

1945-1975 Hiatus

SO2 cooling from N. America and Europe nearly cancelled CO2 warming, until acid rain problem was solved. Is SO2 cooling from East Asian air pollution contributing to today's hiatus? Despite quadrupling of Chinese coal consumption, SO2 controls are working. Good for pollution, bad for climate

Kauffmann, R.K., *et al,* Reconciling Anthropogenic Climate Change With Observed Temperature 1990-2008, PNAS,108, 29,11790-11793, doi: 10.1073/pnas.1102467108

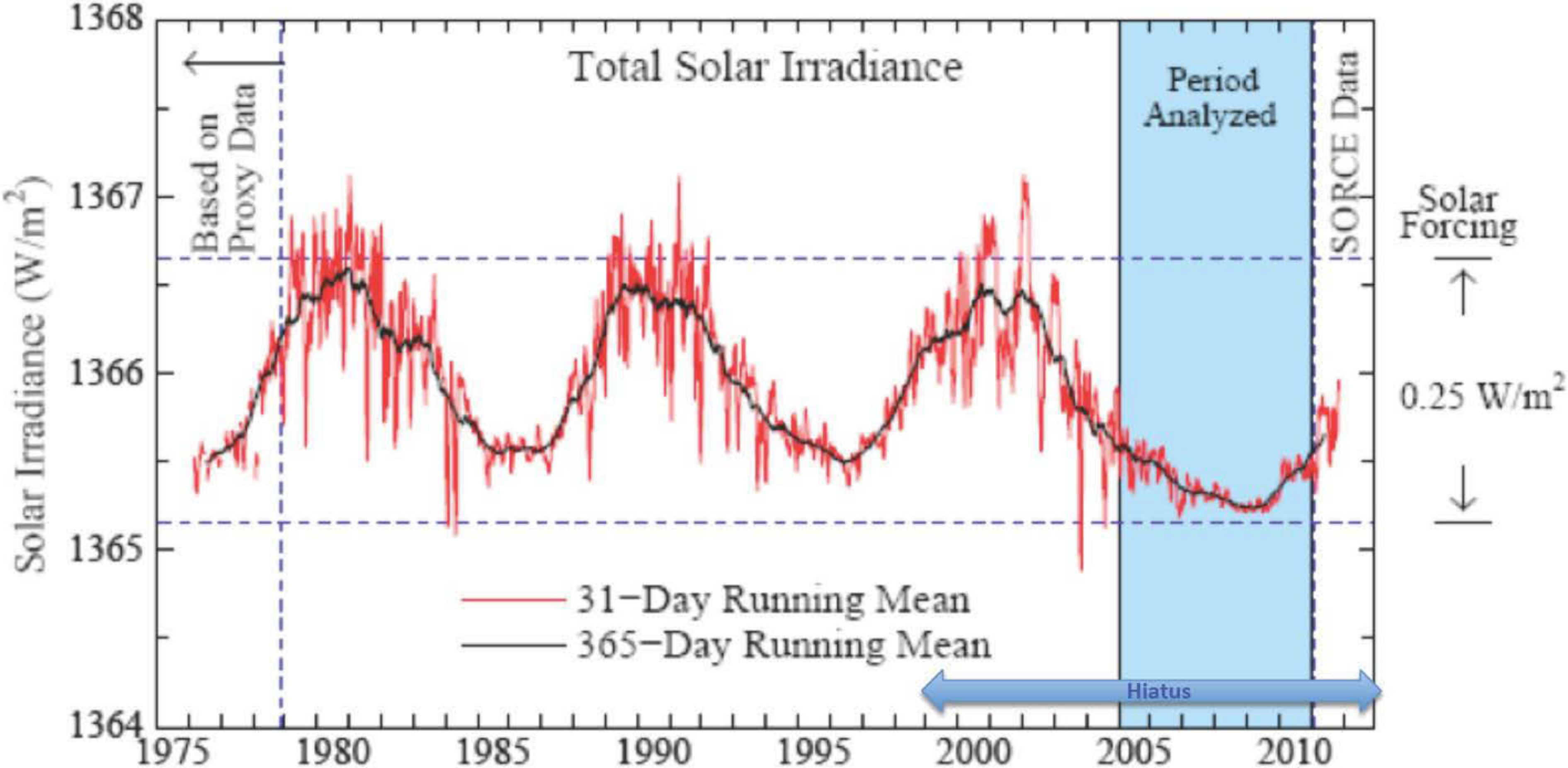
Decline of Total Solar Irradiance?

Measured sunspot maximum (2000) to minimum (2008) cooling was about 0.18 W/m2

However, during 2005-2011, the Earth *absorbed* 0.56 W/m2 more than it let off.

Hansen, J., M. Sato, P. Kharecha, and K. von Schuchmann, Earth's energy balance and Implications, *Atmospheric Chemistry and Physics, 11, 13421-13449, 2011*

See also: Kopp, G., and J. Lean, Geophysical Research Letters, A new lower value of solar irradiance: Evidence and climate **significance**



If the energy did not warm the ocean surface, the land, or atmosphere, where did it go?

Figure; Courtesy of NASA Goddard Institute of Space Studies

Did the Oceans Bury the Additional Heat?

The great ocean conveyor belt

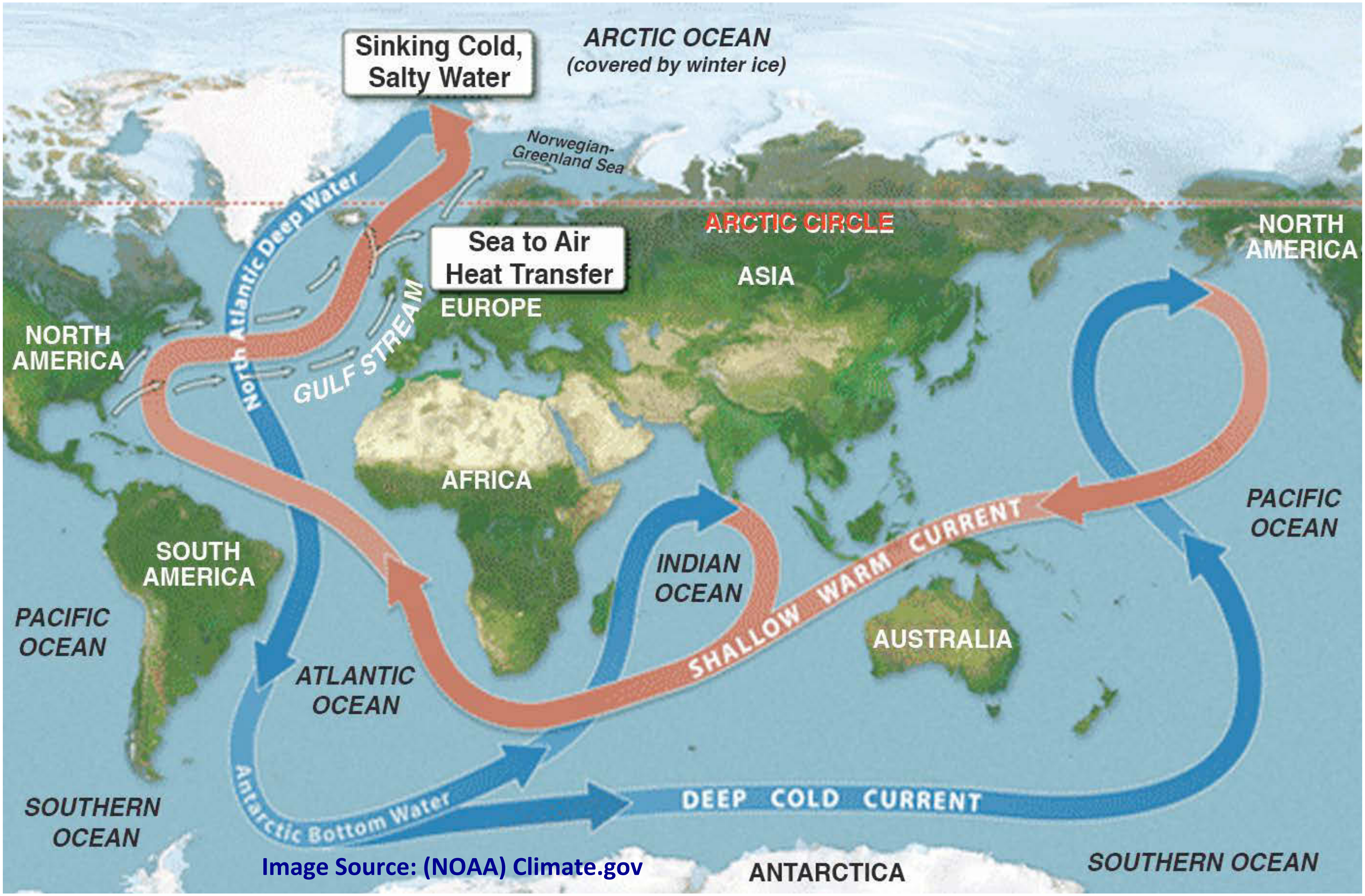


Image Source: (NOAA) Climate.gov

Potential Heat Sequestration Regions

Places where conveyor belt surface waters sink

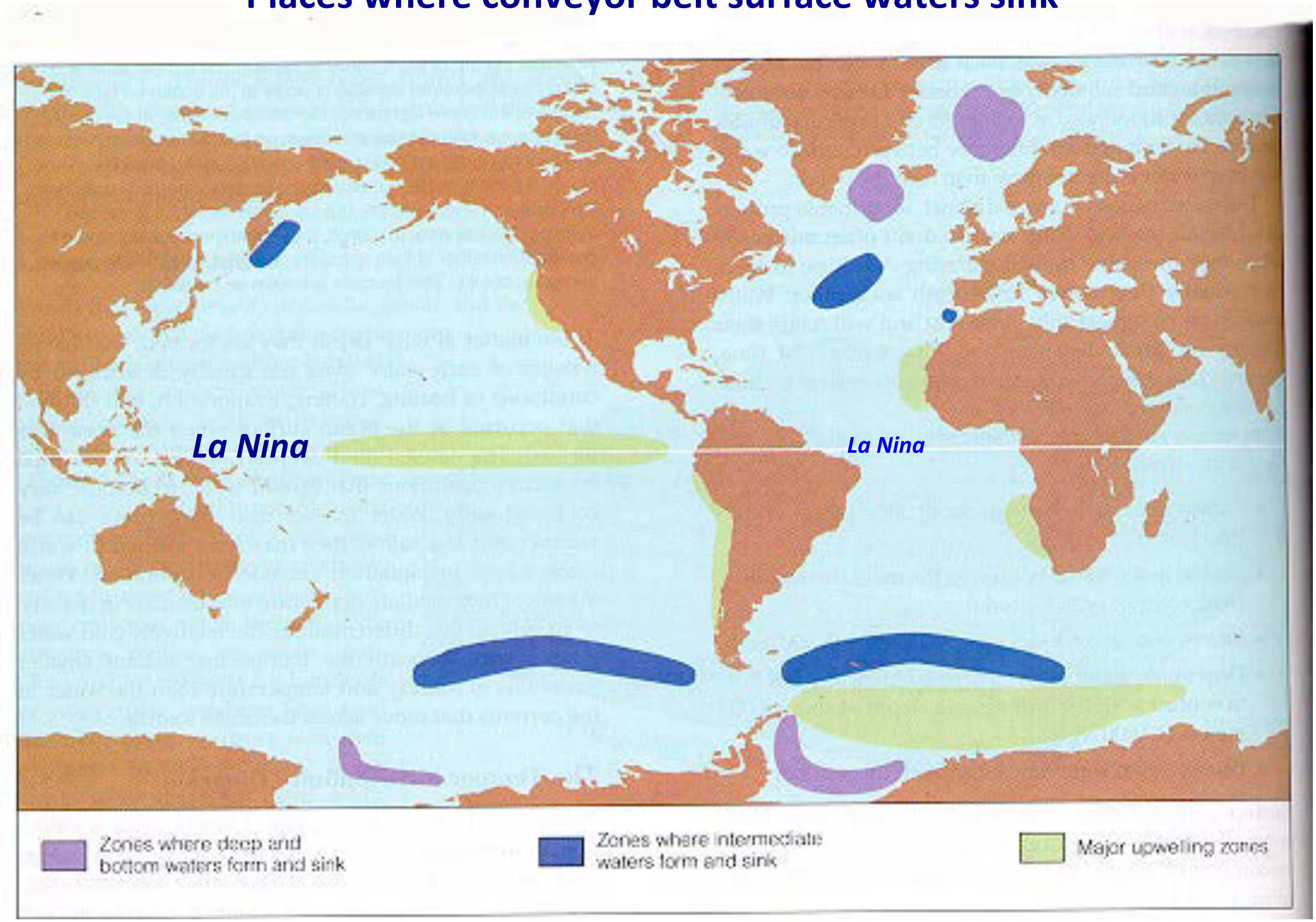
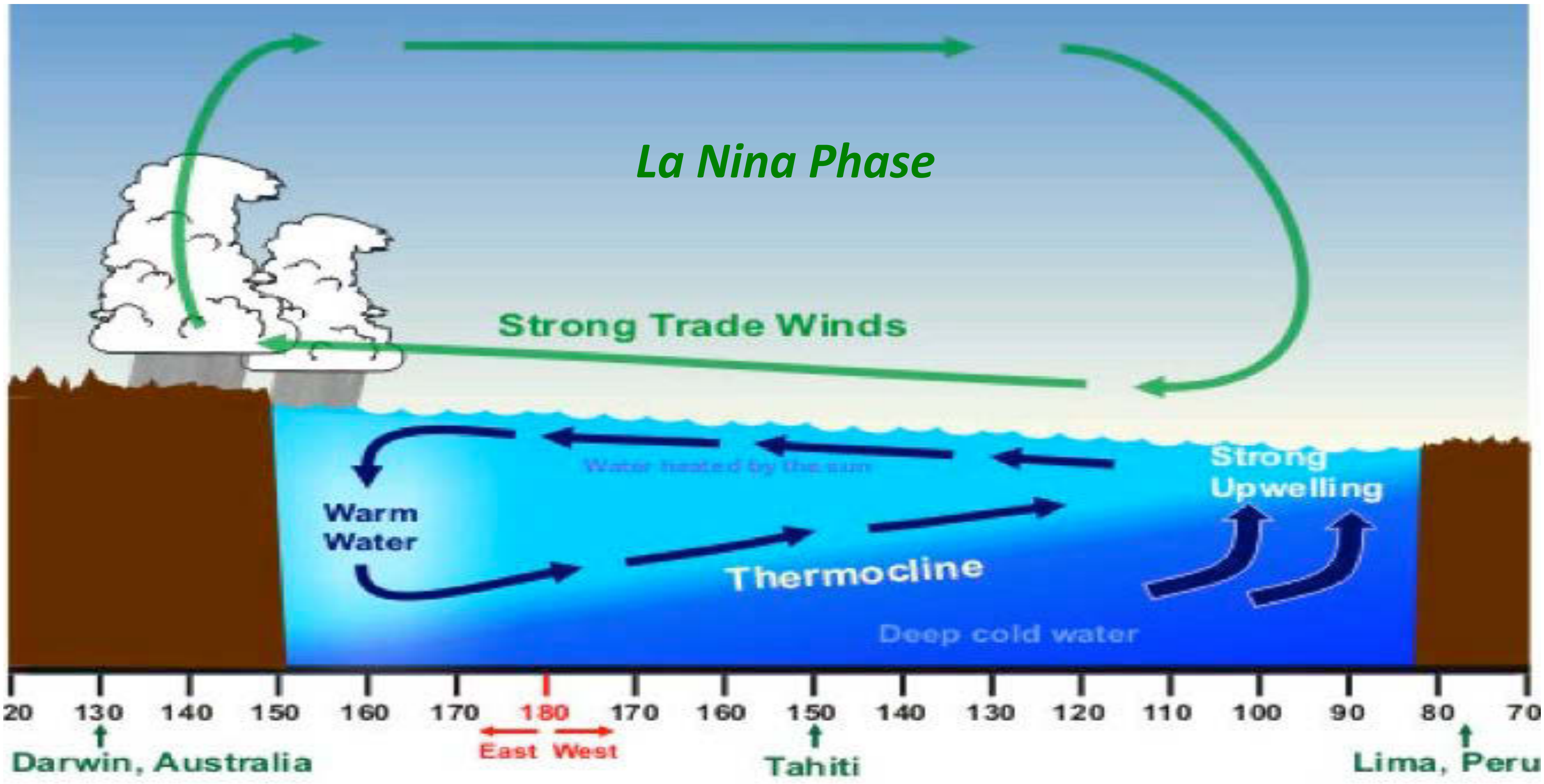


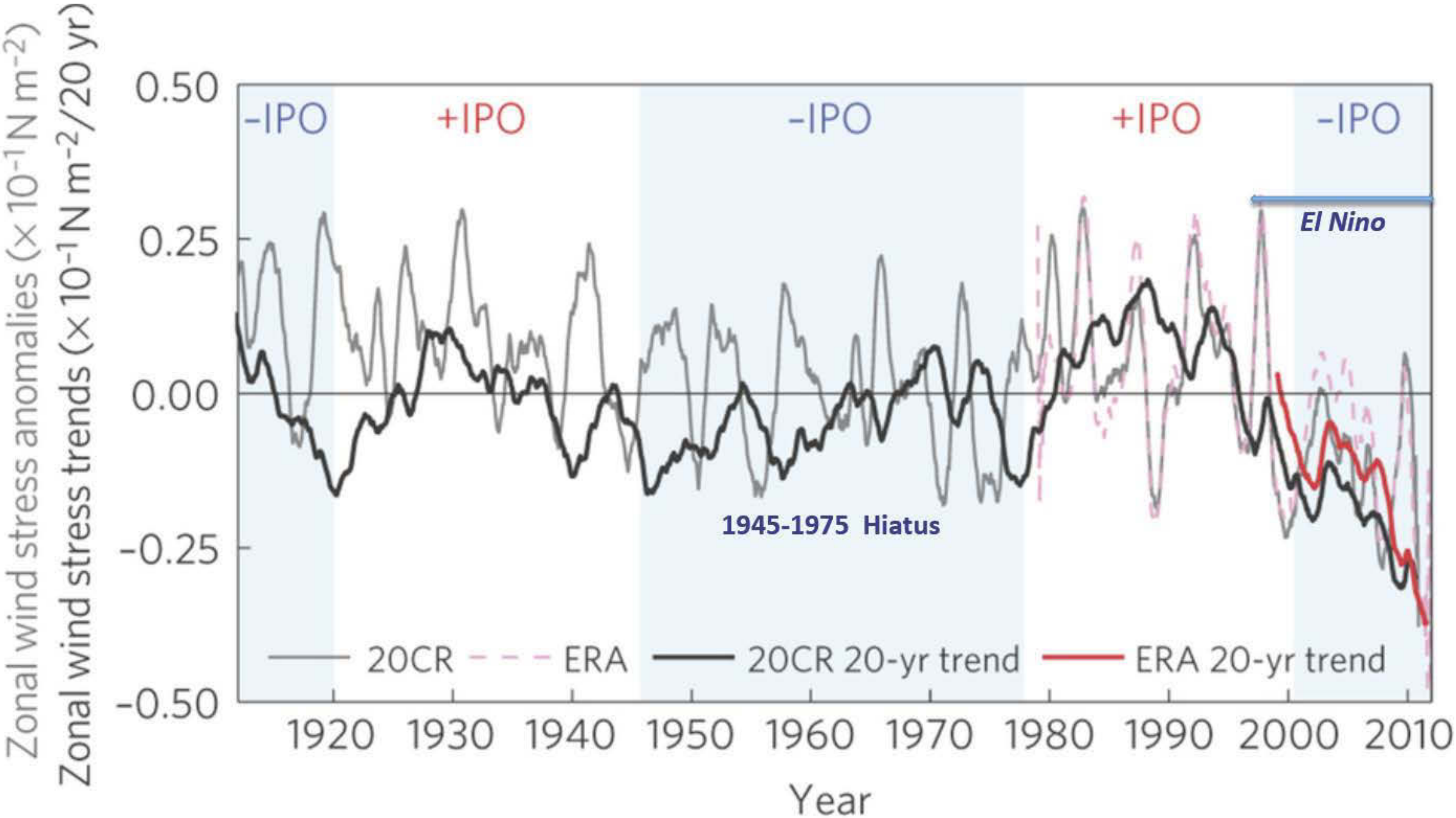
Figure Courtesy of USC earth sciences



La Nina: **Westward trade winds in the tropical Pacific strengthen, causing warmed surface water to pile up in the Western Pacific. The warm water plunges to depth there.**

El Nino**: Trade winds relax, gravity causes a rush of warm water back across the Pacific. The sea surface temperature and the sea surface itself rise across the entire tropical Pacific.**

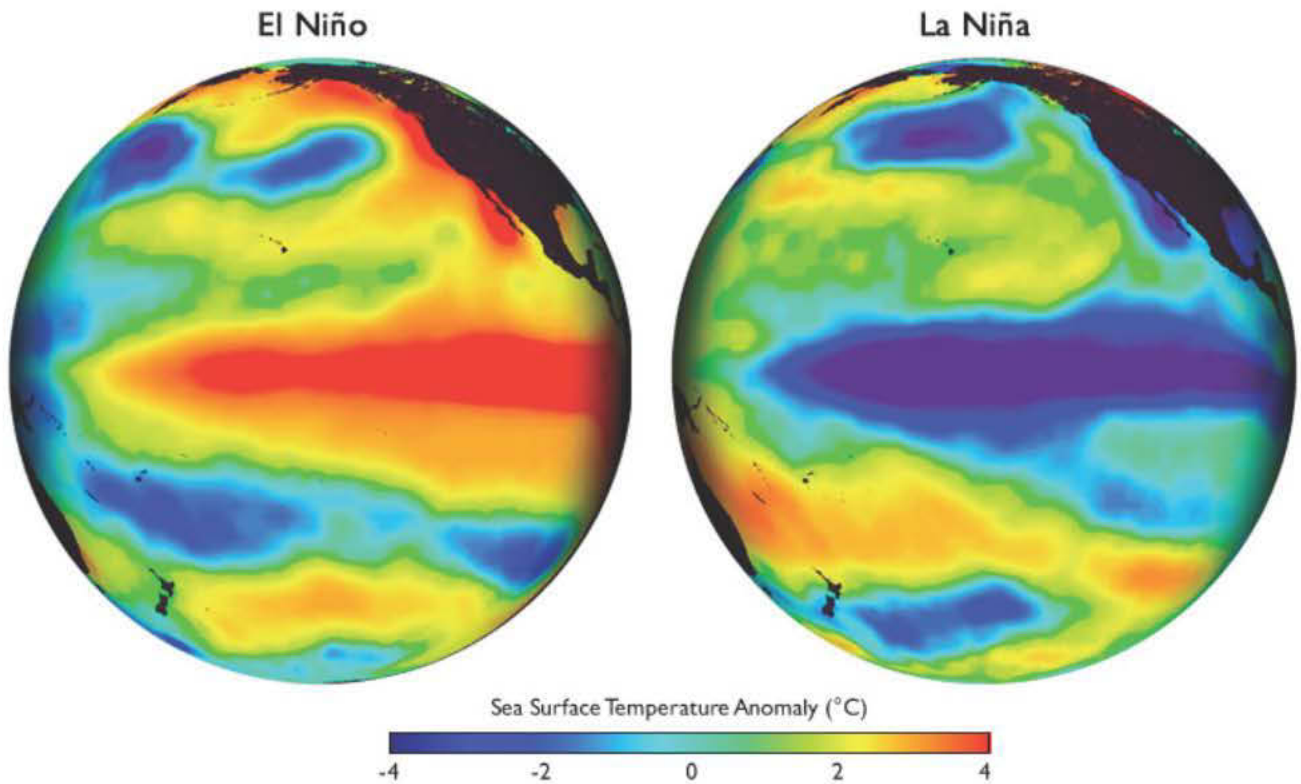
Image: US National Weather Service Jetstream

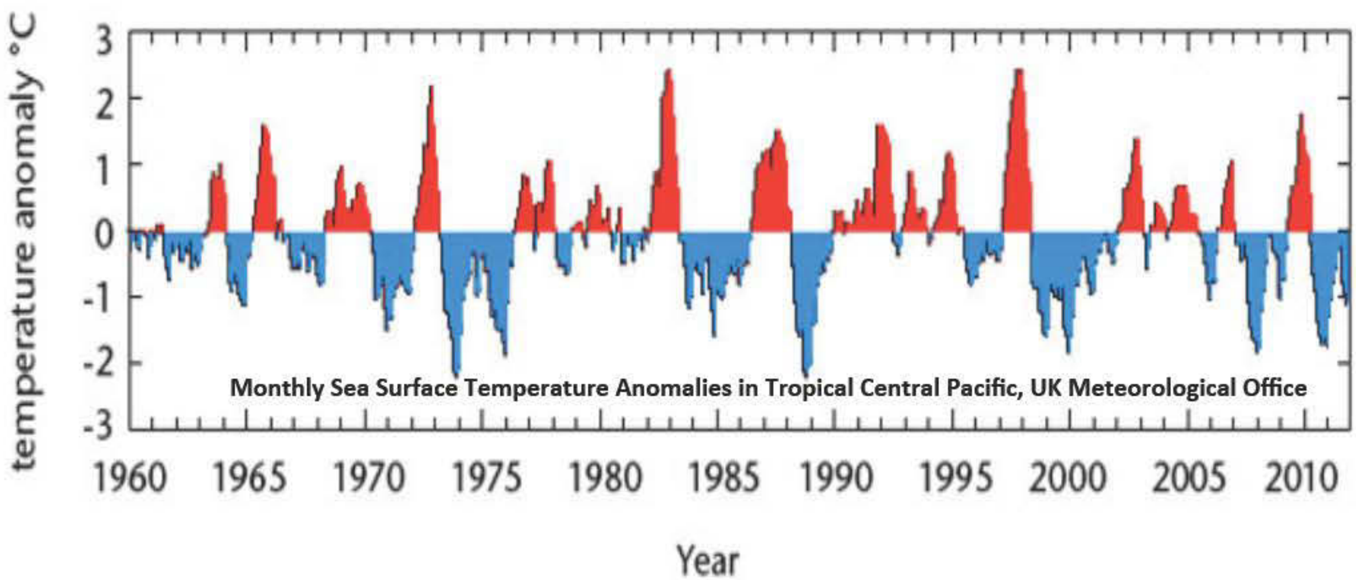


Progressive Strengthening of *La Nina* Trade Winds

Tropical Central Pacific wind stress began move toward *La Nina* sense. 1995-96; Relaxation triggered 1997-98 El Nino; trade winds strengthened after 2000, doubled previous record

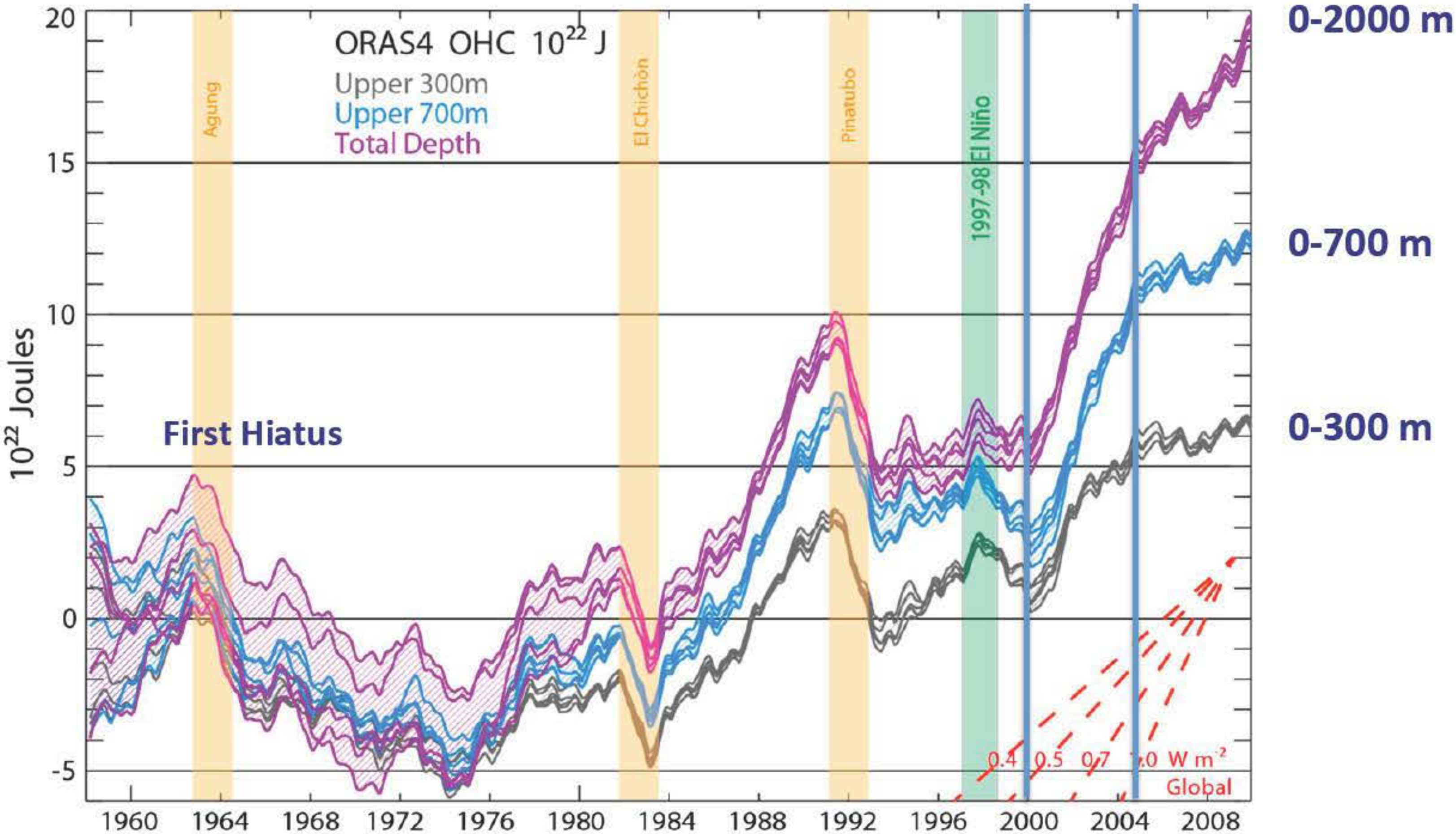
England, M.H., S. MacGregor, P. Spence, G.A.Meehl, A. Timmermann, W. Cai, A.S. Gupta, M.J. MacPhaden, A. Purich, & A. Soto, Recent Intensification of Wind-driven Circulation in the Pacific and the Ongoing Warming Hiatus, *Nature Climate Change 4,* 222–227 (2014) doi:10.1038/nclimate2106


El Niño
La Niña
Sea Surface Temperature Anomaly (°C)
-4
-2
0
2
4


temperature anomaly °C
3
2
1
0
-1
-2
-3
Monthly Sea Surface Temperature Anomalies in Tropical Central Pacific, UK Meteorological Office
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Year

Global Ocean Heat Content

SO2 cooling after volcanic eruptions (yellow) reduced OHC in all layers
OHC dropped after 1998 *El Nino* (green)- because of long-wave radiation to space
An OHC increase started in the year 2000, largest in deepest layer, slower after 2004
Effective energy sequestration rate 0.84 W/m2



Balmaseda, Trenberth, and Källén, Distinctive Climate Signals in reanalysis of ocean heat content, *Geophysical Research Letters, 40*, 1754-1759, doi: 10.1002/grl50382, 2013

Ocean Heat Uptake

AMOC, Southern Ocean, *La Nina*?

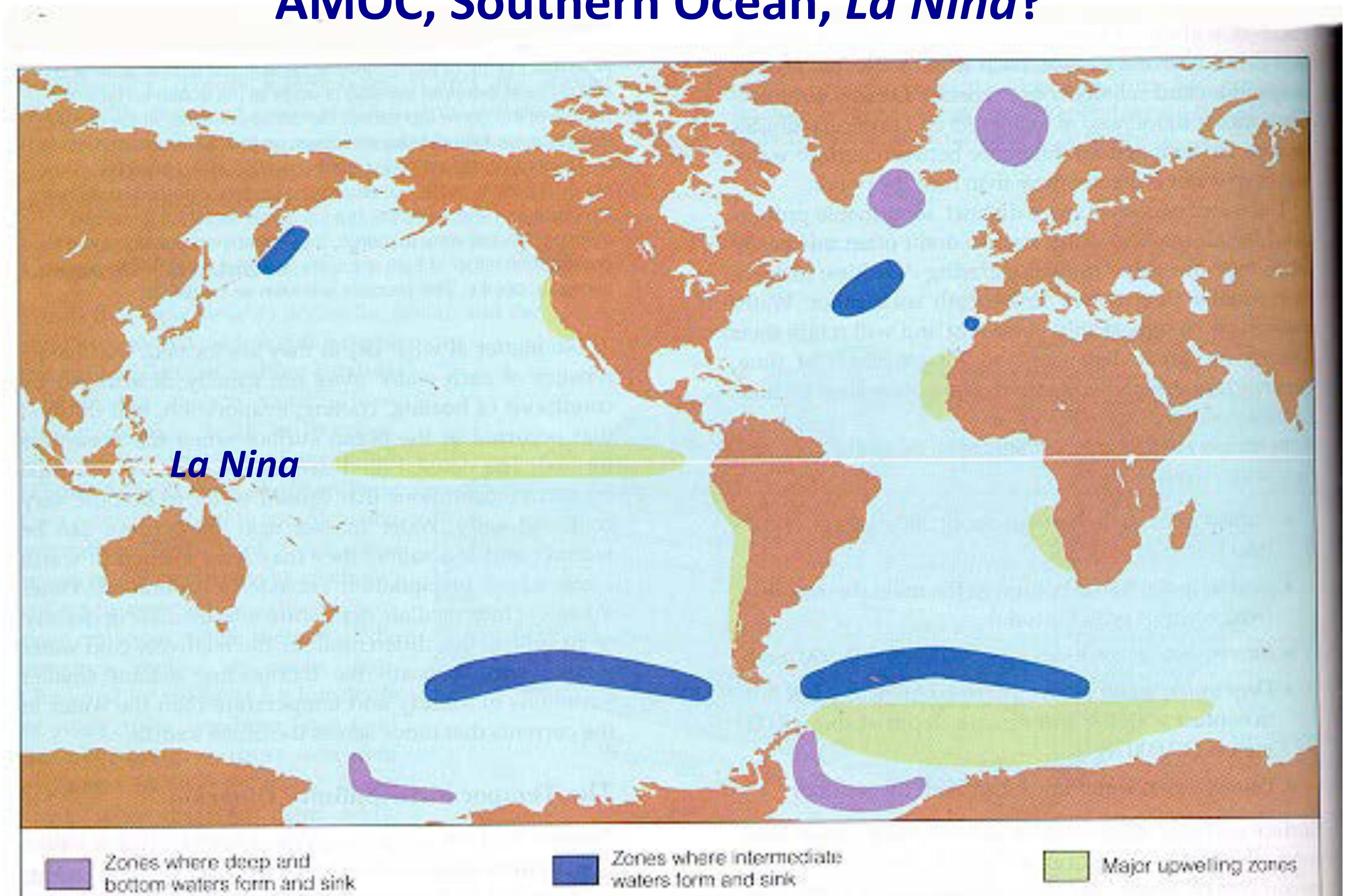


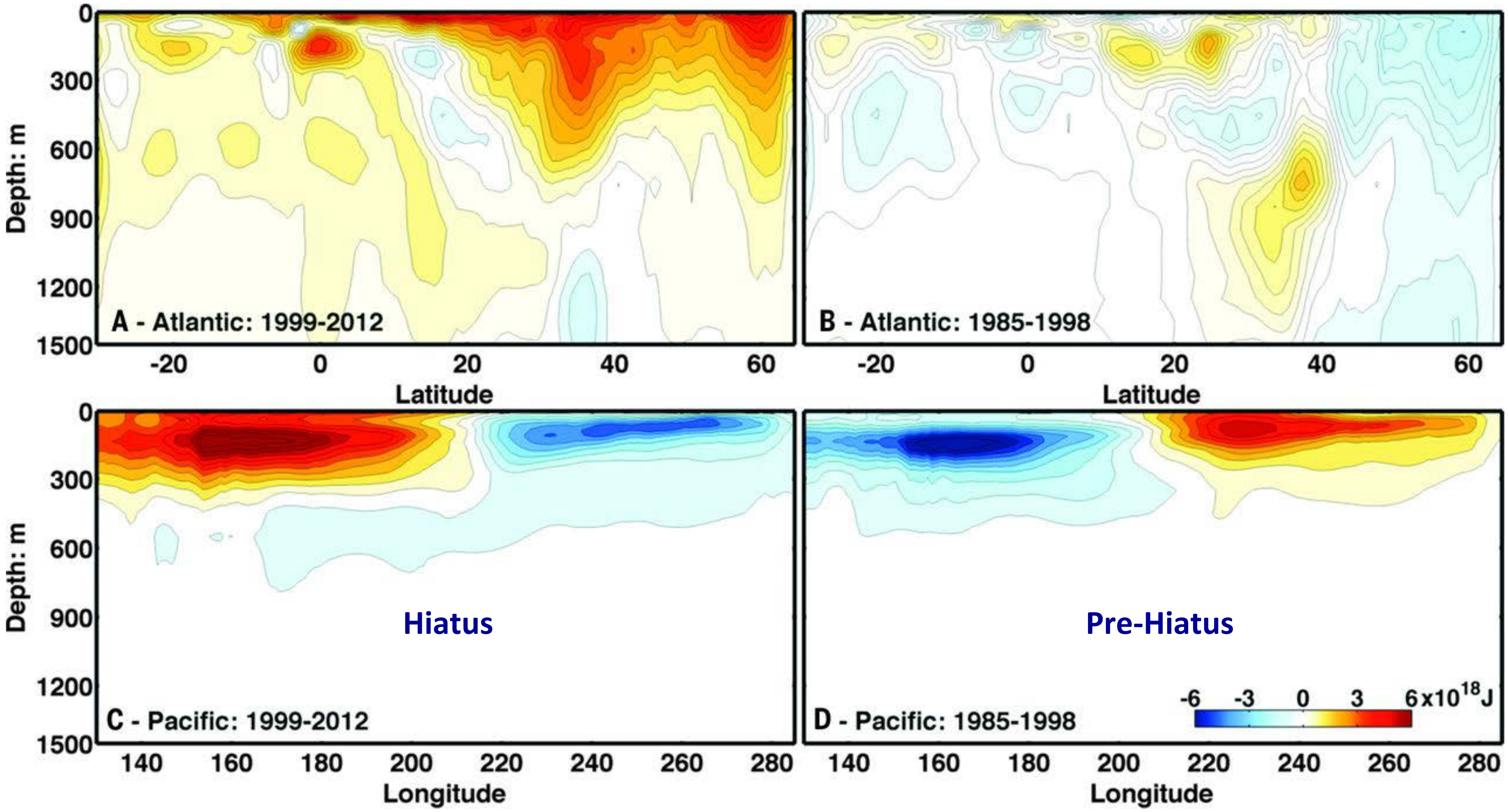
Figure Courtesy of USC earth sciences

Models suggest OHU has large atmospheric effect when concentrated at high latitudes

Rose,B.J., *et al*, , The dependence of transient climate sensitivity and radiative feedbacks on the spatial patterns of ocean heat uptake, *Geophys. Res. Letts., 41*, doi:10.1002/2013GL058955

Comparing Hiatus and Pre-Hiatus Periods

Atlantic Hiatus: mid- and high- latitude AMOC, tropical *La Nina*
Pacific Hiatus: strong tropical *La Nina*

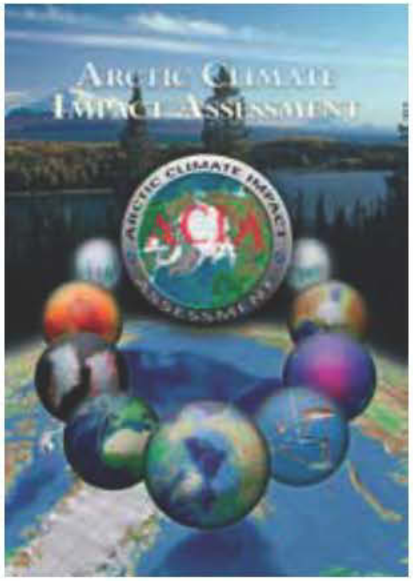


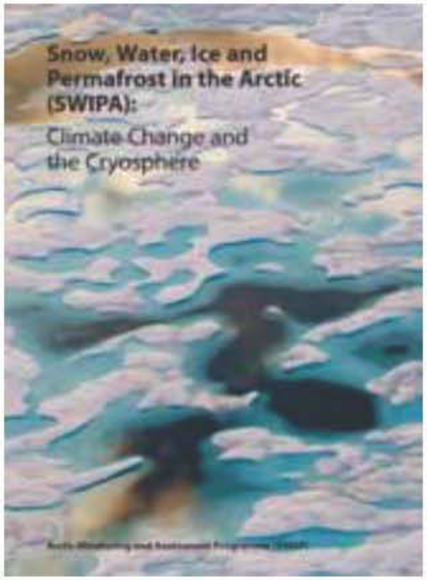
X Chen, and K Tung Science 2014;345:897-903

Published by AAAS

Arctic Regime Shift In Progress

ACIA, 2005: Poles warming twice as fast as globe; Arctic an early warning system
SWIPA, 2011: Warming accelerated, changed spatial & seasonal character after 2000





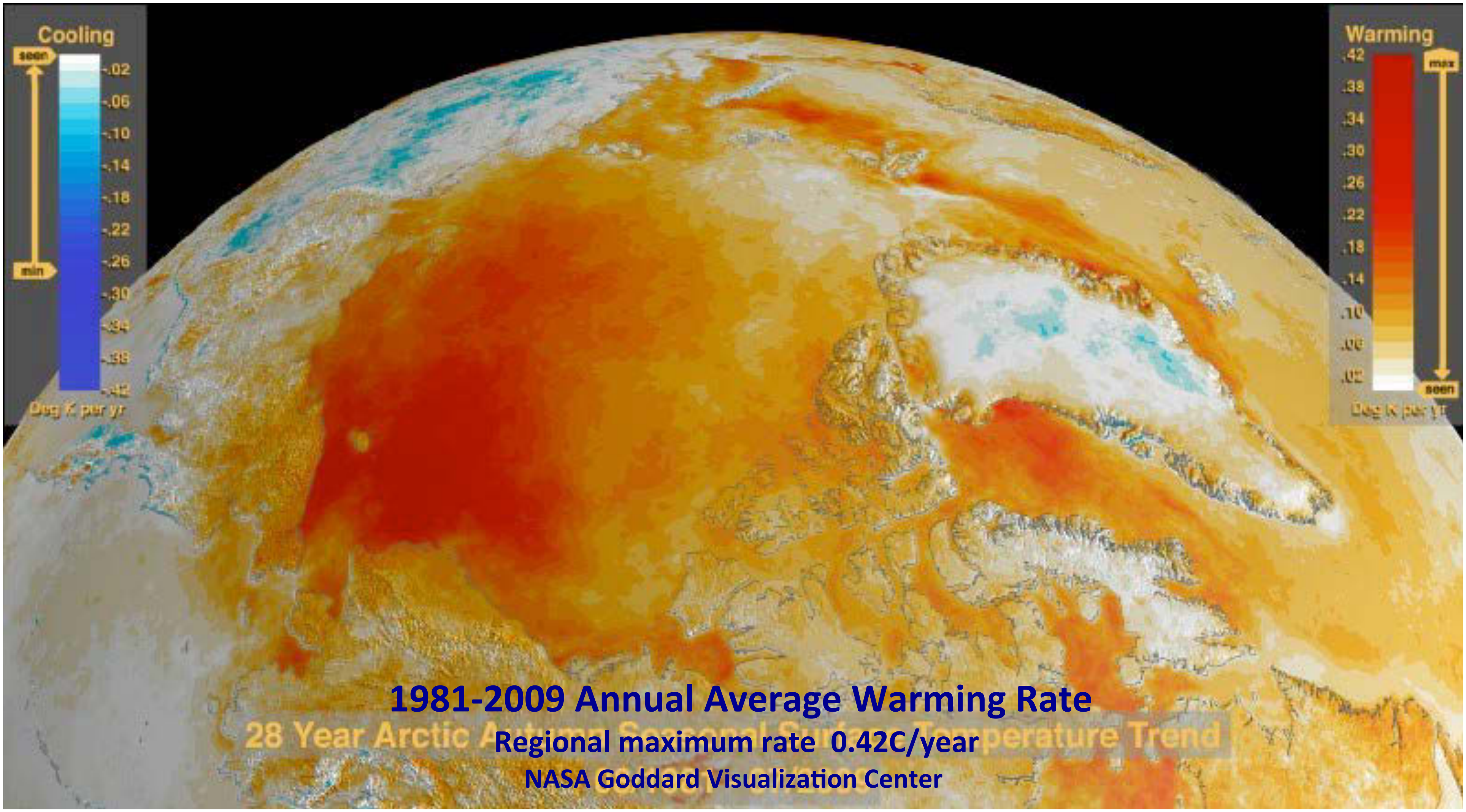
Warming during hiatus fastest in spring and autumn; before 2000, it was fastest in winter, consistent with GCMs. Warming in hiatus now faster over the oceans than over land.

New spatial and seasonal pattern suggests that declines in snow cover (spring) and sea-ice extent (fall) are related to the acceleration in Arctic climate warming.

Screen, J.A. and I. Simmonds, The Central Role of Diminishing Sea Ice in Recent Arctic Temperature Amplification, Nature 464, 1334–1337 (29 April 2010) doi:10.1038/nature09051

Polar Amplification of Greenhouse Warming

Expected in earliest analyses on basic physics premises
Poles experience local greenhouse warming *and* GHG warming from lower latitudes
Biggest relative difference from this mechanism over land in winter
Verification was principal result of Arctic Climate Impact Assessment (2005)

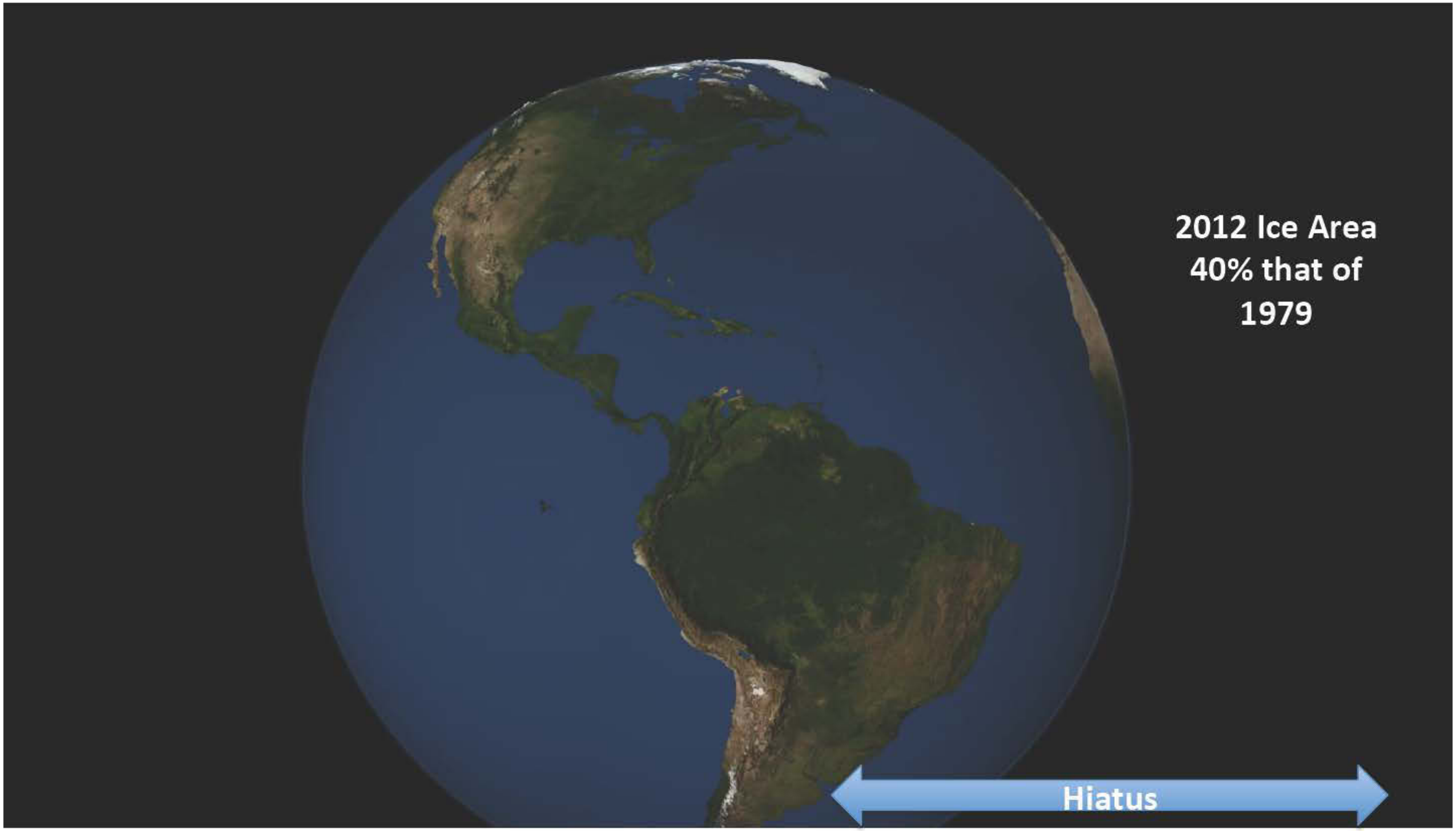


1981-2009 Annual Average Warming Rate
Regional maximum rate 0.42C/year
NASA Goddard Visualization Center

Major Reduction in Arctic Sea Ice Area.

Small irregular decline between 1979 and 1996

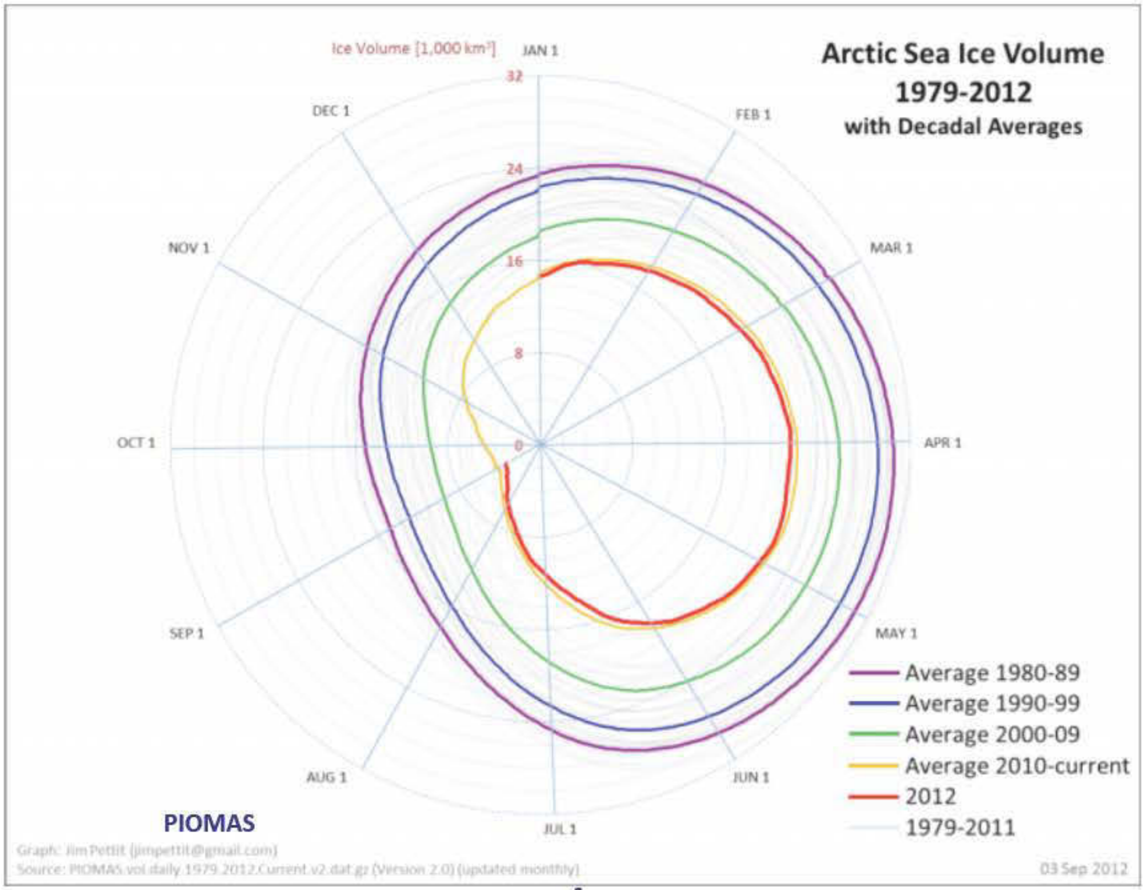
Almost monotonic decline during hiatus



"Death Spiral"

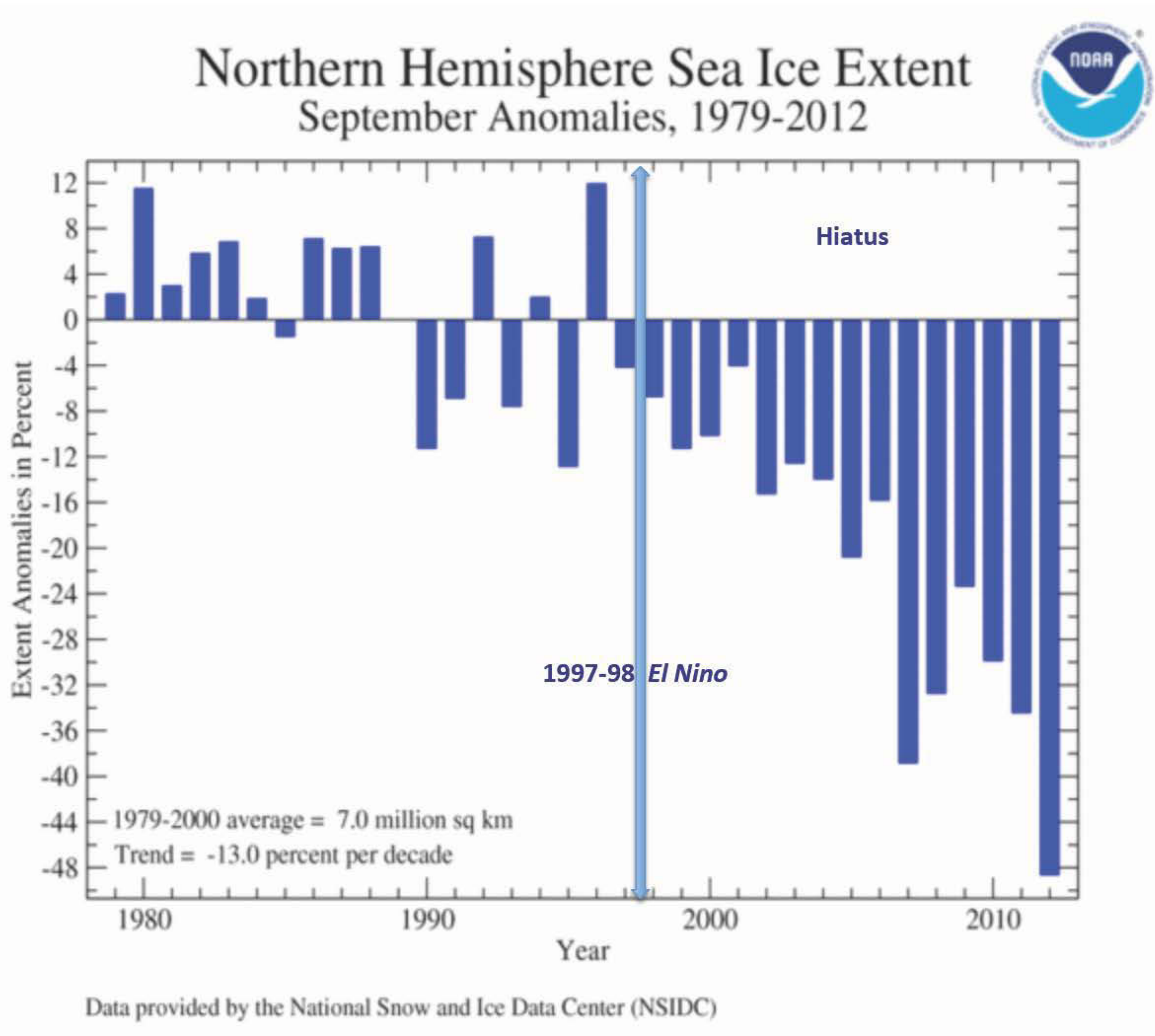
Sea Ice Volume

US/UK navies had been tracking sea ice thickness since the 1970s; by the 1990s, Project MEDEA was reporting a 10%/decade decline in thickness. Thickness, when multiplied by satellite measurements of area, gives the volume.



2012 September volume is about ¼ of 1980-1989 volume

(Figure and data from National Snow and Ice Data Center)


Northern Hemisphere Sea Ice Extent
September Anomalies, 1979-2012
NOAA
Hiatus
1997-98 El Nino
Extent Anomalies in Percent
12
8
4
0
-4
-8
-12
-16
-20
-24
-28
-32
-36
-40
-44
-48
1979-2000 average = 7.0 million sq km
Trend = -13.0 percent per decade
1980
1990
2000
2010
Year
Data provided by the National Snow and Ice Data Center (NSIDC)

Arctic Snow Cover

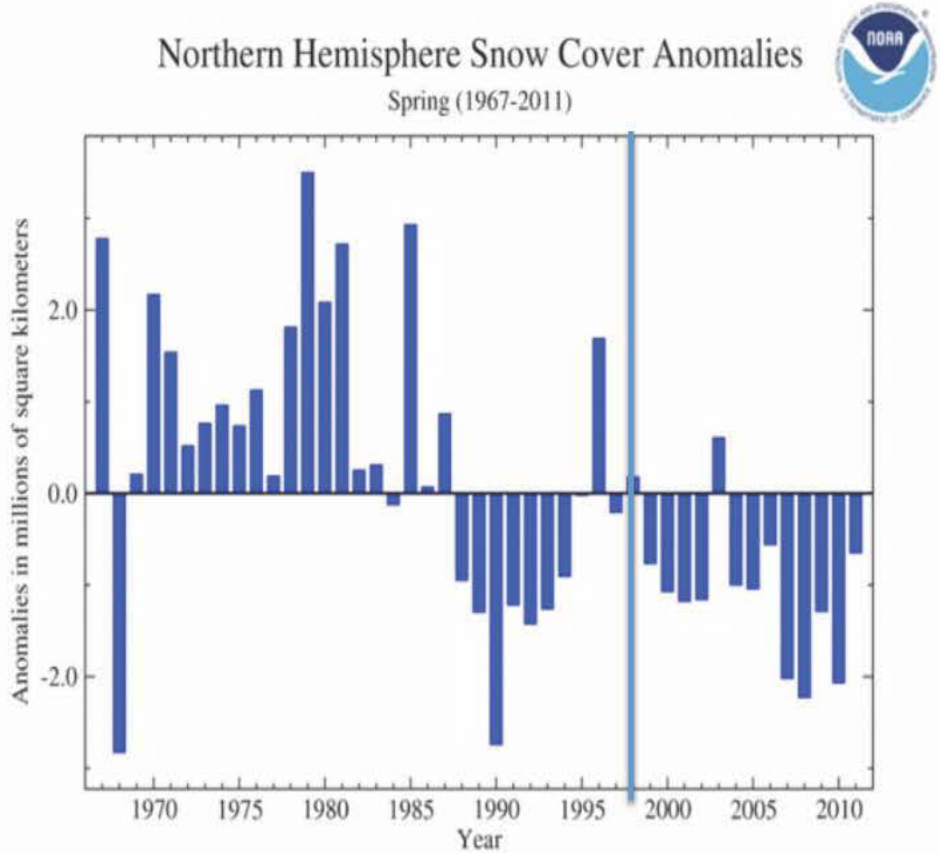
About 1/3 of Earth's land area covered by snow for some part of the year

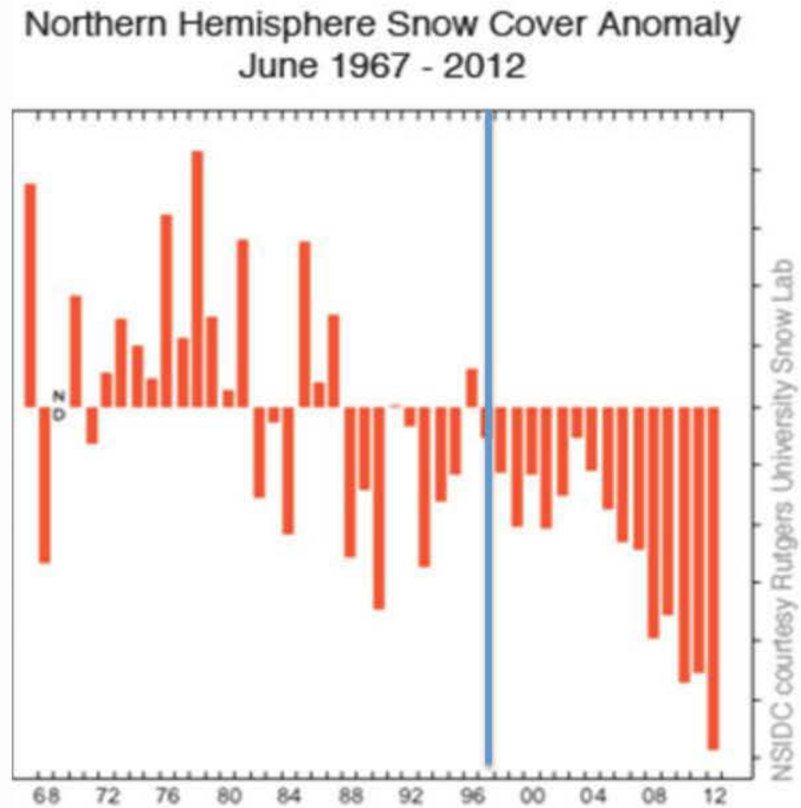
Extent and duration of snow cover are decreasing throughout the Arctic

Land area covered by snow in early summer (June) decreased by 18% since 1966

Snow depth may increase but time average cover decreases because of earlier snow melt

Snow, Water, Ice, Permafrost Assessment, (SWIPA), 2011



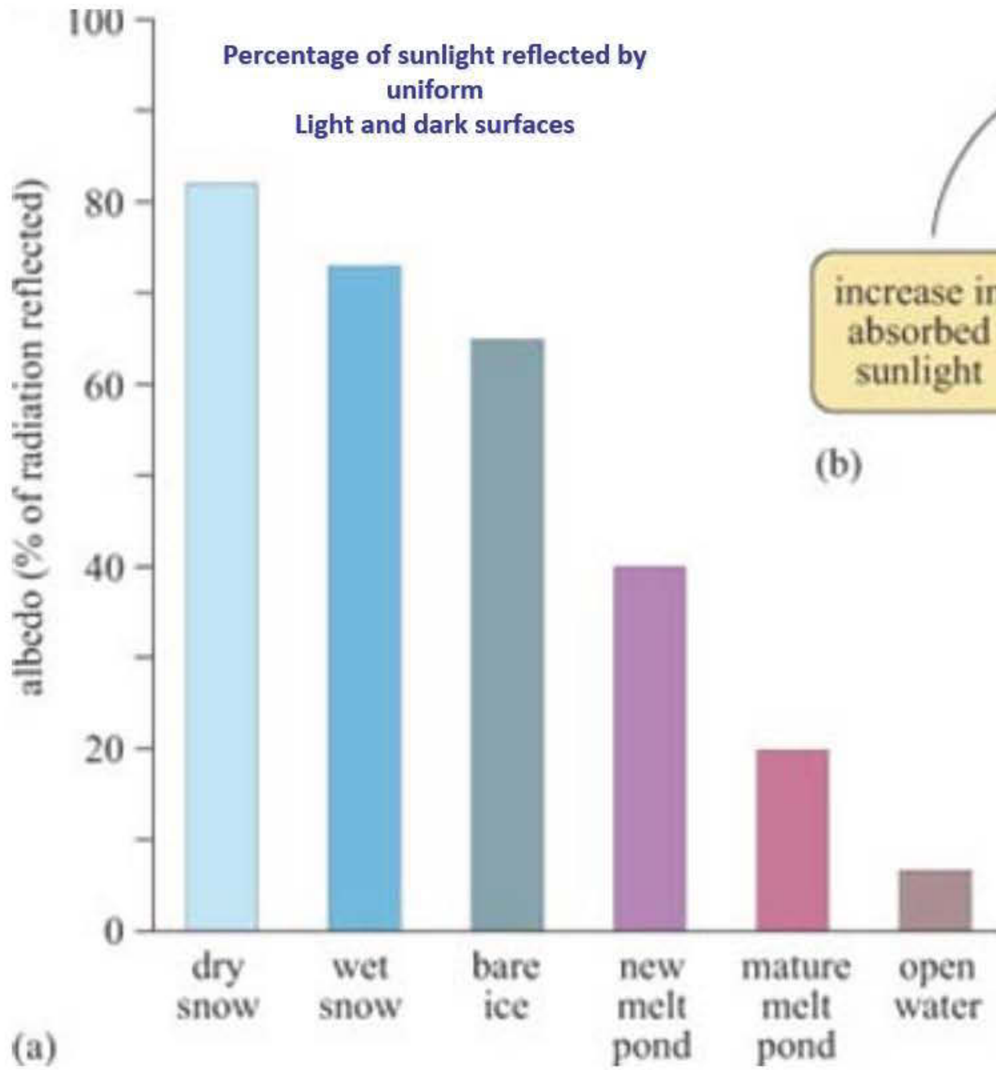


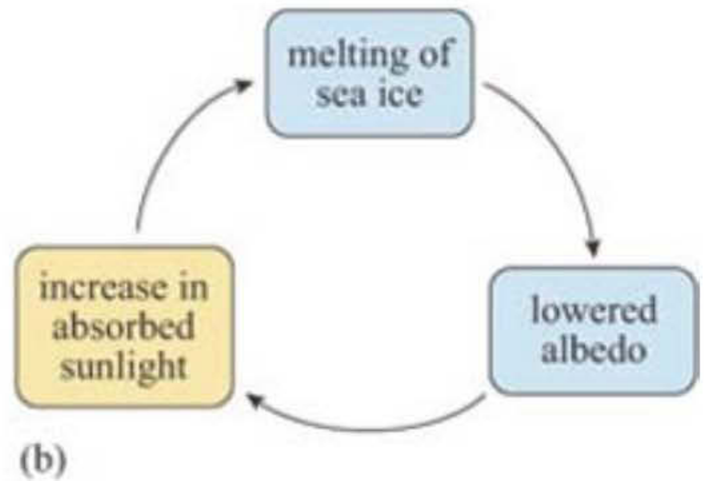
June Snow Cover Area decreased at nearly twice the rate of September Sea Ice

Dirksen, C., & Brown R, Spring snow cover extent reductions in the 2008-2012 period exceeding climate model predictions, *Geophys. Res. Letts., 39,* L19504, 2012

Snow and Ice Albedo

Changes in area of either one amplify temperature change- In either direction
Real sea and land ice cover is a mosaic, and area-averaged albedo varies with local conditions





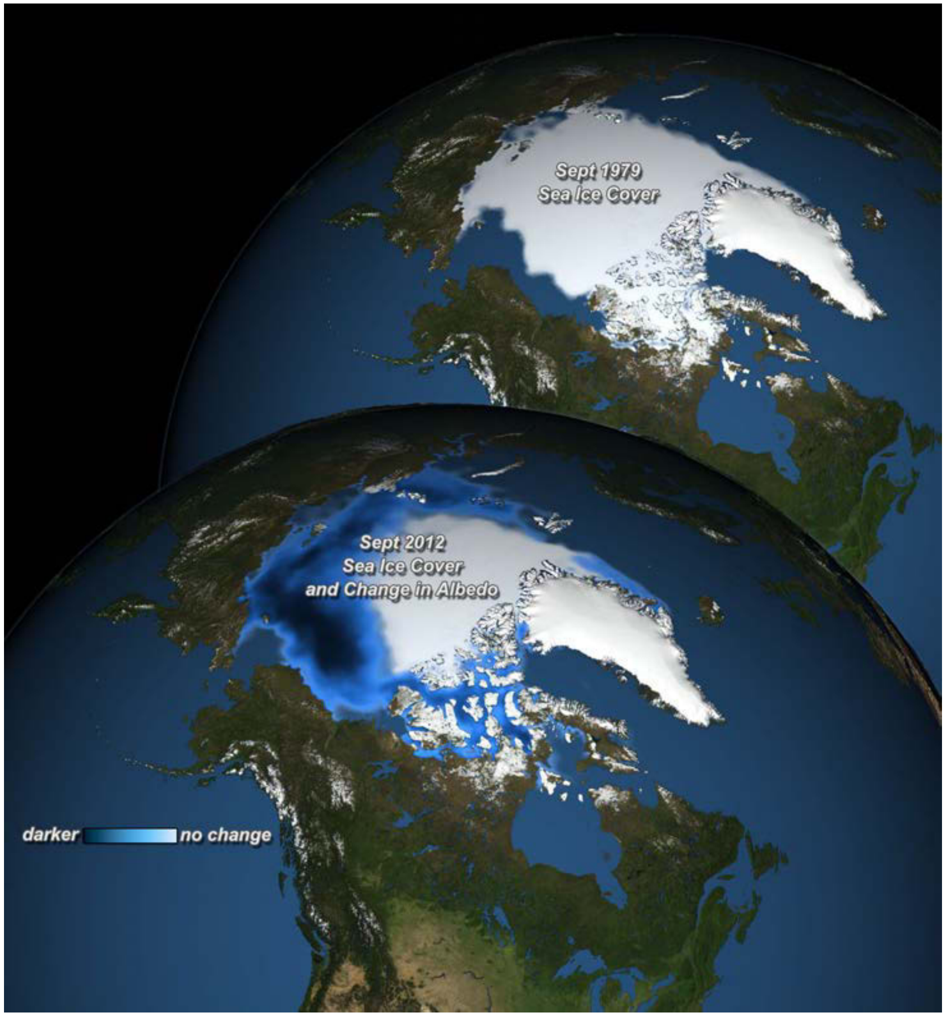
One-year Sea Ice in Summer

Arctic Region Ice Reflectivity Change, 1979-2011

Albedo decreased from 52% to 48%

Additional solar warming: 6.4 W/m2 since 1979; 4.2 W/m2 between 2001 and 2011 alone

Averaged over globe, 0.21 W/m2, ¼ of increase of CO2 forcing since 1979



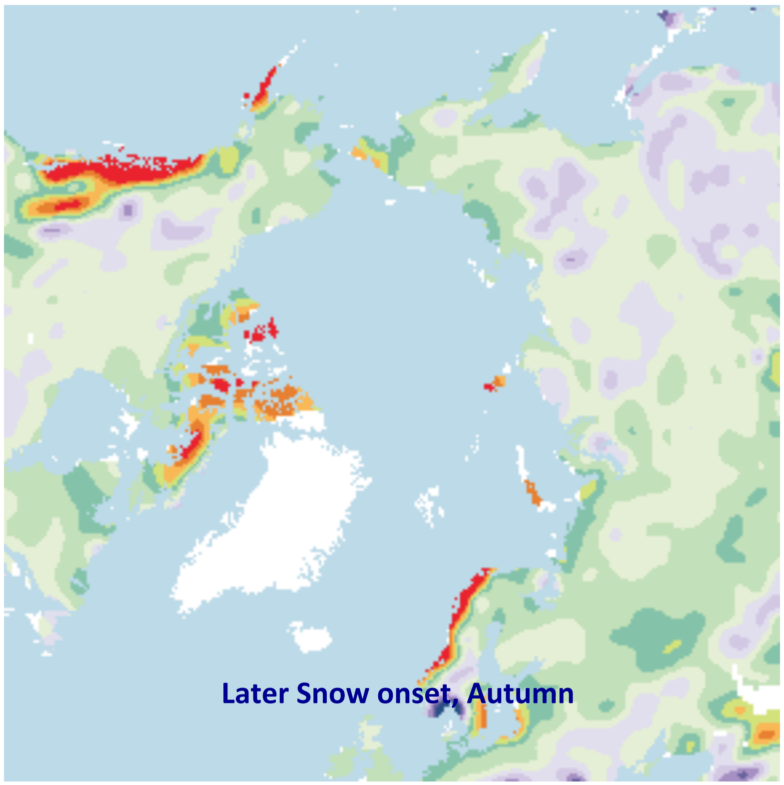
Pistone, K., I. Eisenman, and V. Ramanathan, Observational determination of albedo decrease caused by vanishing Arctic sea ice, *PNAS, 111,* 3322-3326, March 4, 2014 doi:10.1073/pnas.1318201111

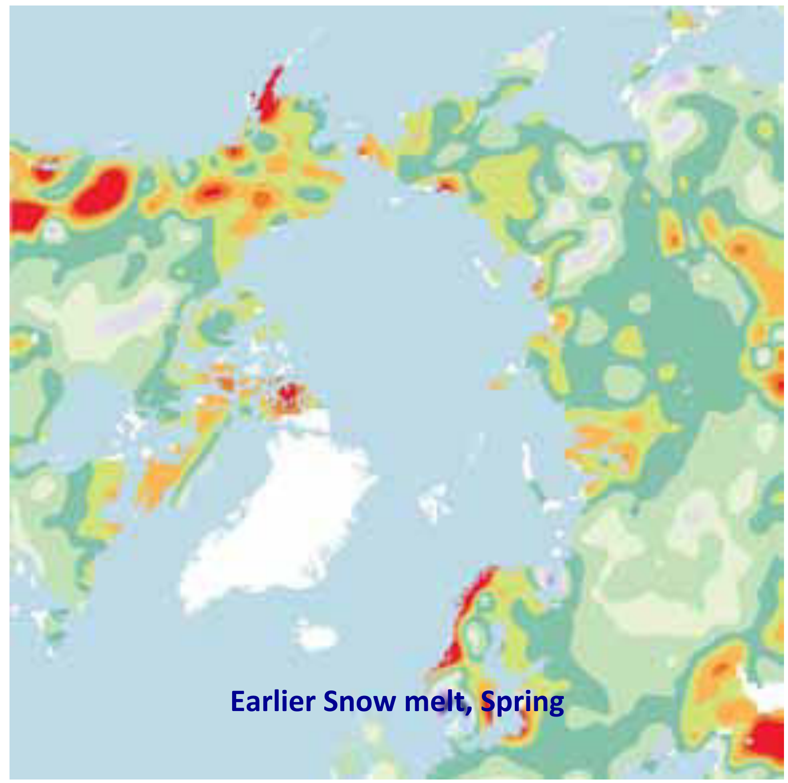
Lengthening of snow-free season increases albedo warming

“The largest and most consistent change in snow cover is earlier disappearance in spring”

Largest increases in duration on NW Pacific, Baffin, and Fenno-Scandian coasts

Snow, Water, Ice, Permafrost Assessment, (SWIPA), 2011





Change in snow-cover duration for autumn (snow-cover onset period) and spring (snow-cover melt period) between 1972/73 and 2008/09. Red = 10 days change

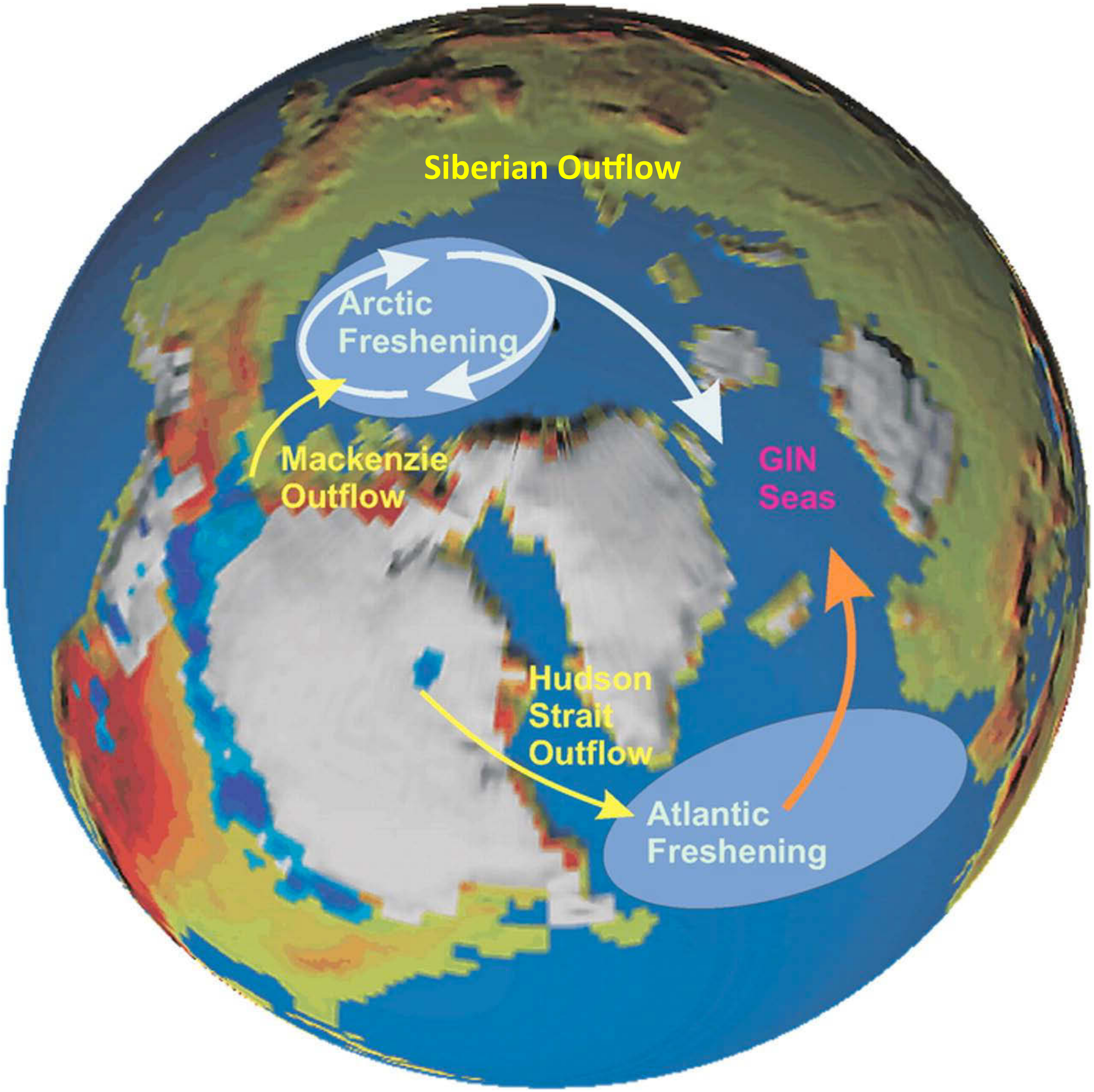
Arctic Watersheds

10% of present global fresh water flows into 1% of the ocean volume
More than half the water flowing into the Arctic comes from just six rivers

All the main sources of freshwater entering the Arctic Ocean are increasing– river discharge, rain/snow, and melting glaciers, ice caps, and the Greenland Ice Sheet. An extra 7700 km3 of freshwater – equivalent to one meter of water over the entire land surface of Australia – has been added to the Arctic Ocean in recent years (SWIPA, 2011).

The addition of fresh water on top of salty alters thermohaline circulation, and it is through the exchange of waters through the Bering Strait and in the AMOC cockpit that global circulation patterns can be affected.

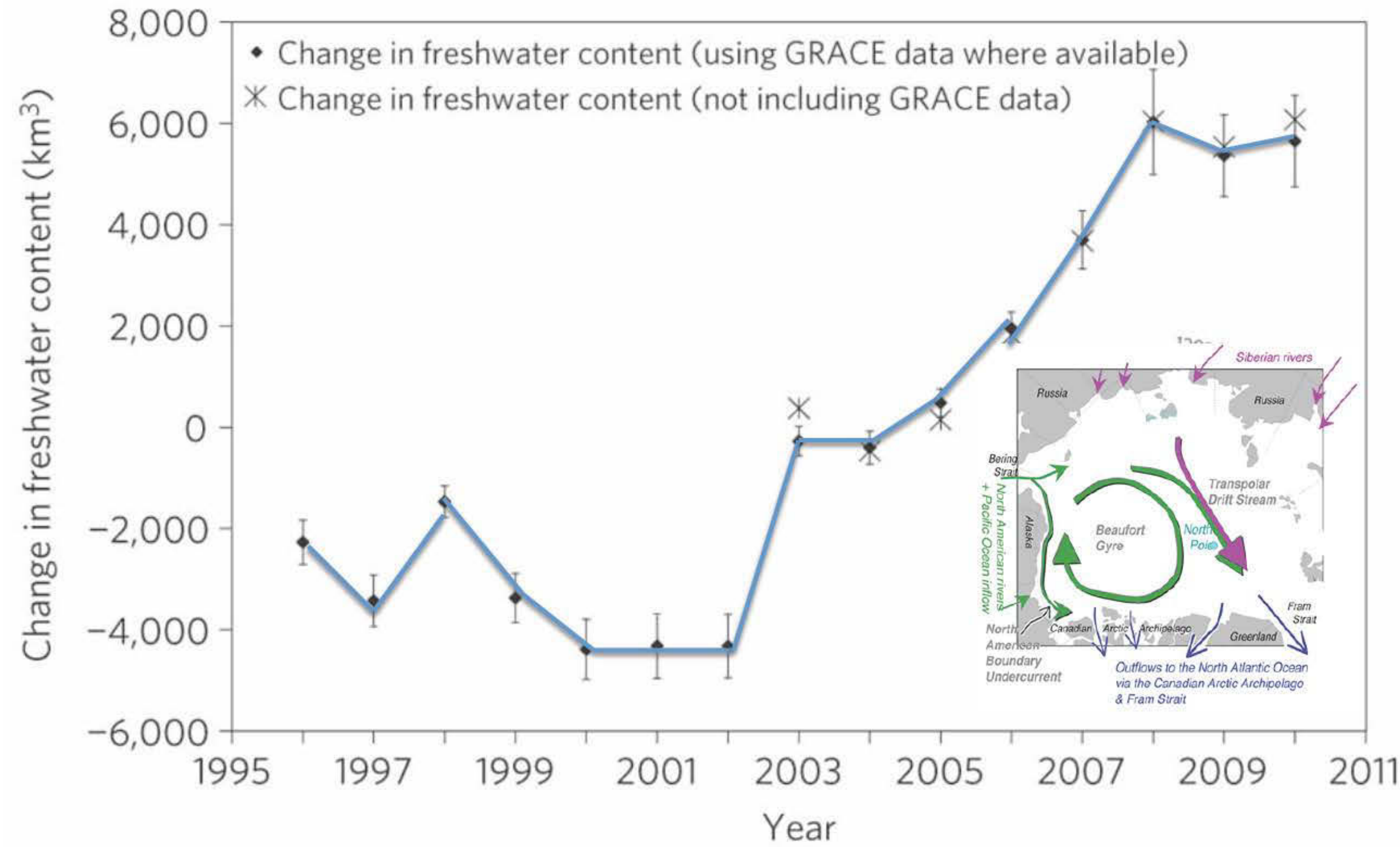
Robert M. Holmes, Michael T. Coe, Greg J. Fiske, Tatiana Gurtovaya,James W. McClelland, Alexander I. Shiklomanov, Robert G. M.Spencer, Suzanne E. Tank, and Alexander V. Zhulidov, *Climate Change Impacts on the Hydrology and Biogeochemistryof Arctic Rivers*



Injection of Freshwater Into the AMOC Cockpit

The flow of fresher, lighter water on top of salty inhibits the sinking of North Atlantic Deep Water, one of the "pumps" that drive AMOC circulation.

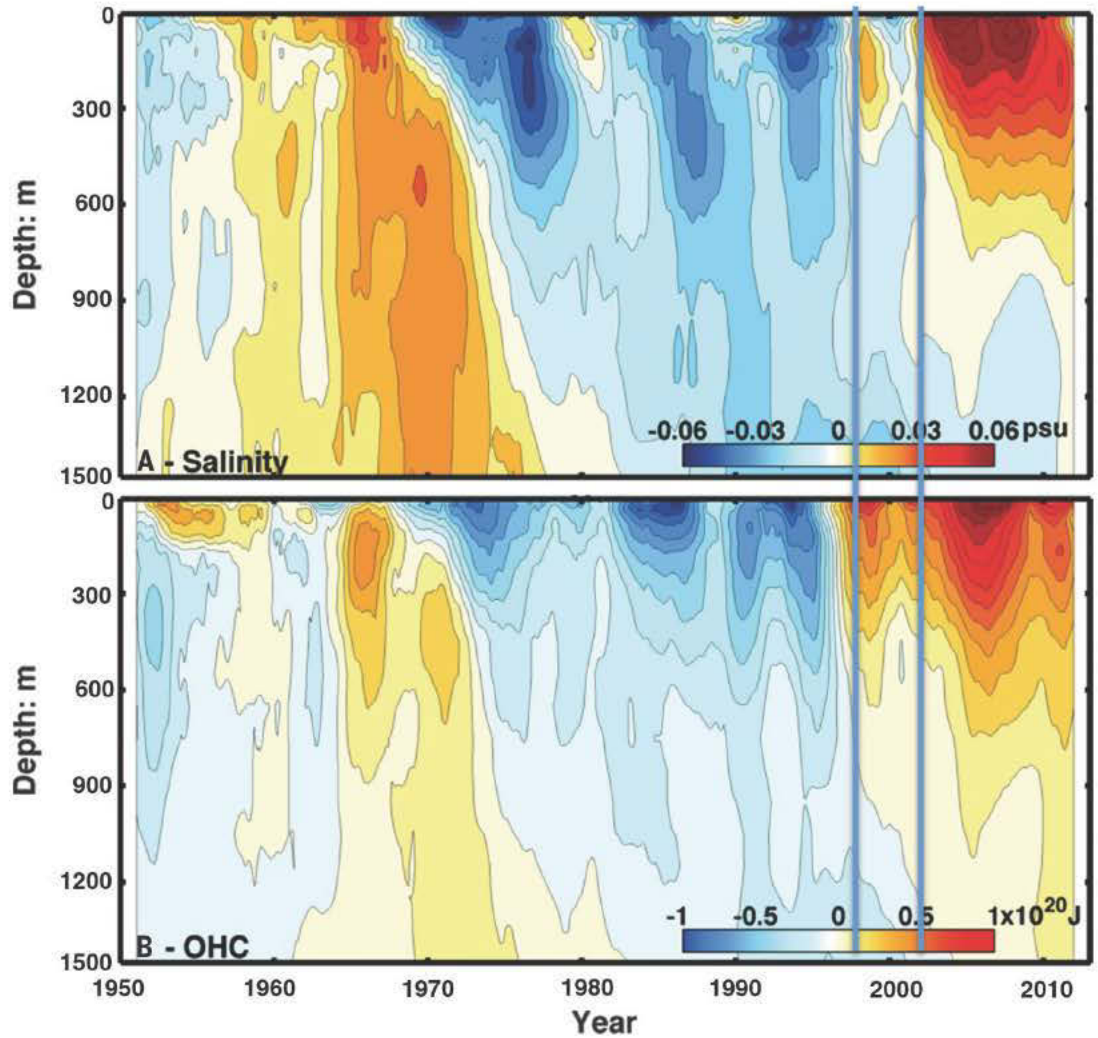
Beaufort Gyre Freshwater Storage



Katharine A. Giles, Seymour W. Laxon, Andy L. Ridout, Duncan J. Wingham & Sheldon Bacon,
Western Arctic Ocean freshwater storage increased by wind-driven spin-up of the Beaufort Gyre,
Nature Geoscience 5, 194–197 (2012) doi:10.1038/ngeo1379

Change in N. Atlantic Intermediate Water "Pump"

North Atlantic (45° to 65°N) mean salinity (A) and 5-m layer OHC (B)
Salinity and OHC increases start in 2003, 5 years into hiatus



X Chen, and K Tung Science 2014;345:897-903

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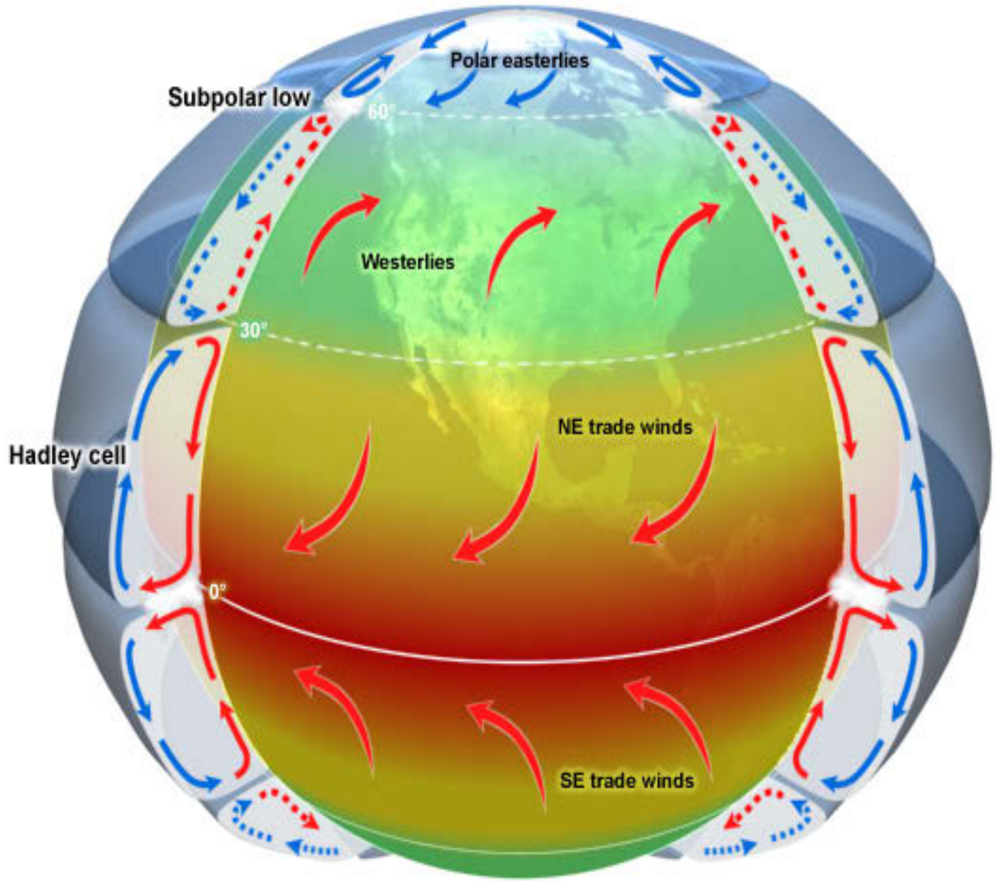
What Goes On In The Arctic Does Not Stay In The Arctic

Paradox #3: Extreme Weather Events During Hiatus

Meridional Circulation of Heat

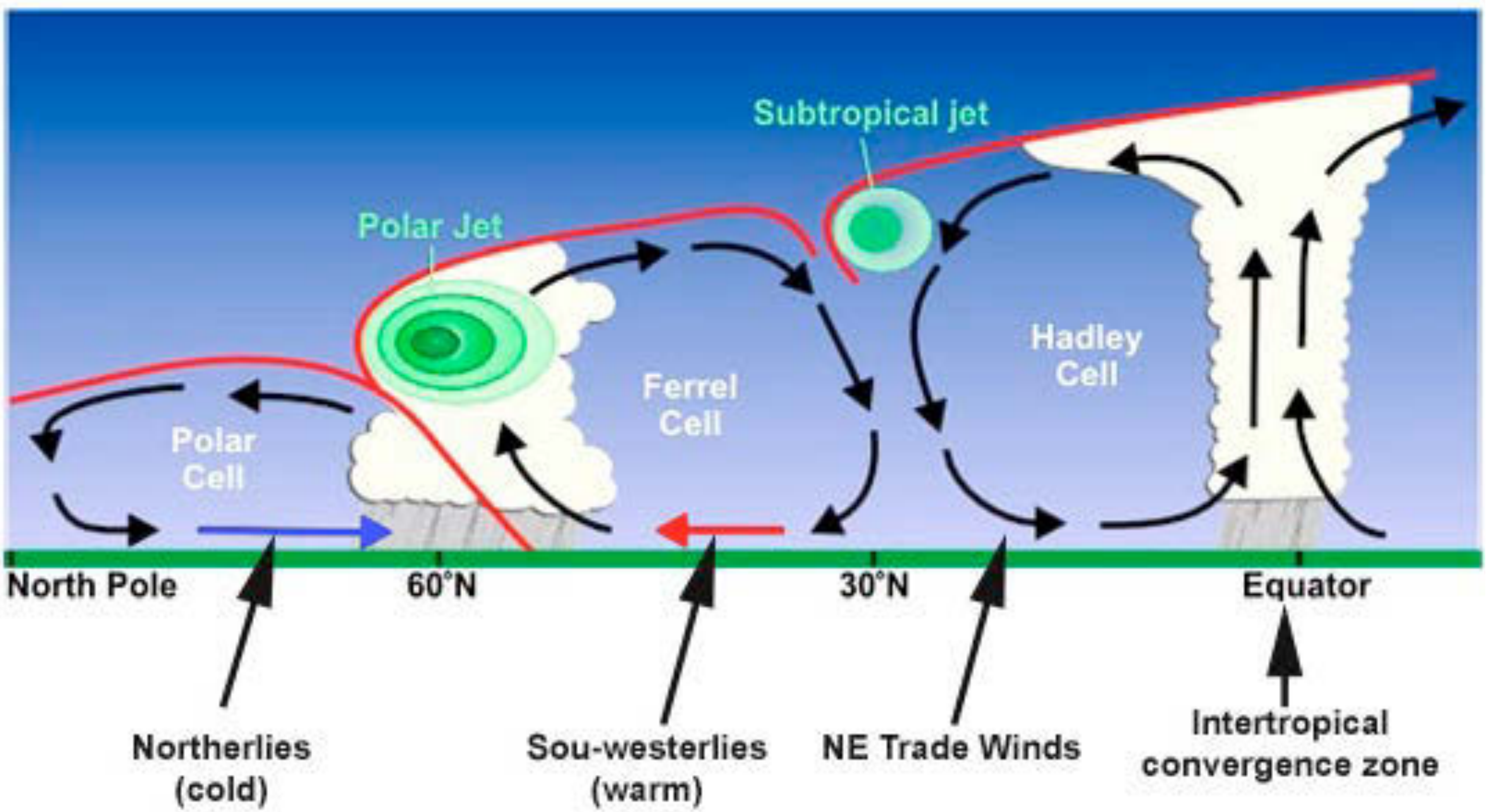
Flow of heat from equator to polar upper troposphere adds to local surface warming, and during the winter polar night is the only source of energy that offsets radiative cooling



When polar regions are sunlit, surface temperature changes are amplified by sea ice and snow advance or retreat, which changes the rate of absorption of radiant energy

Jet Streams

Harbingers of Weather



Jet Streams in La Nina Pattern During Hiatus

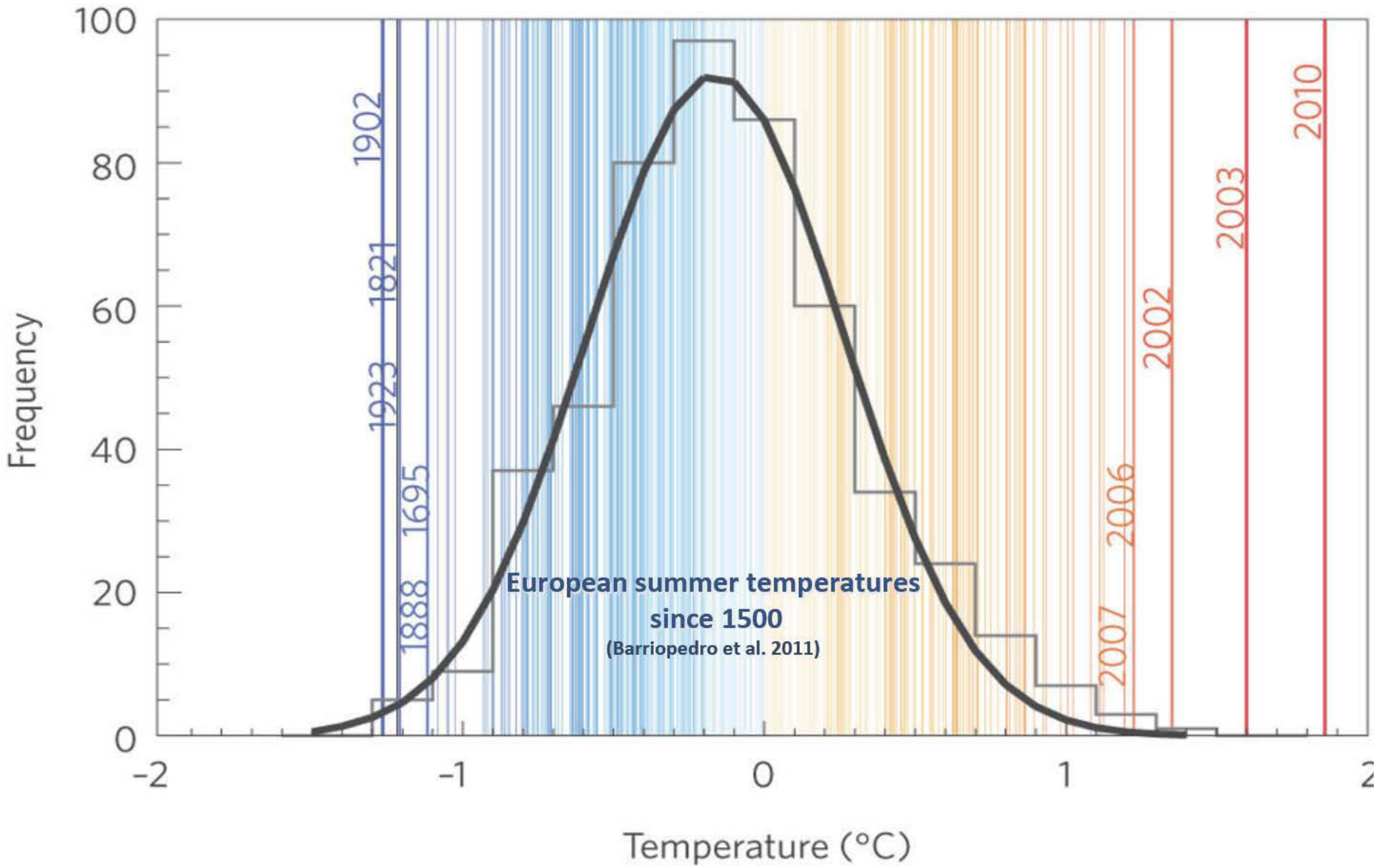
Occurrence and intensity of extreme events unusually high

Polar jet meanders and blocking associated with *La Nina*
Subtropical jet strengthening and “pineapple express” events associated with *El Nino*

Extreme European Summers During Hiatus

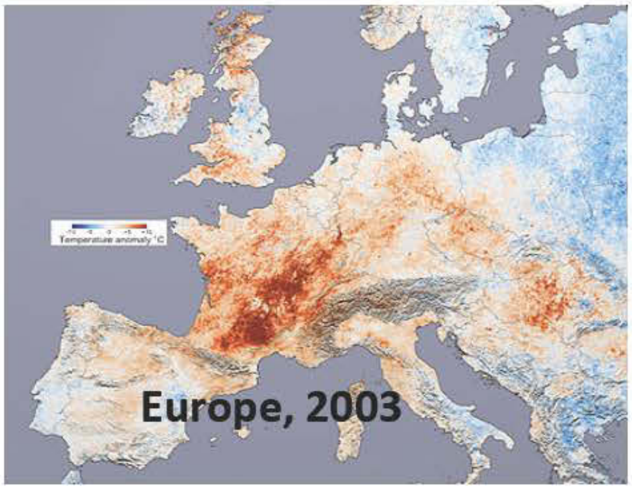
Turn Down The Heat! The World at 4C

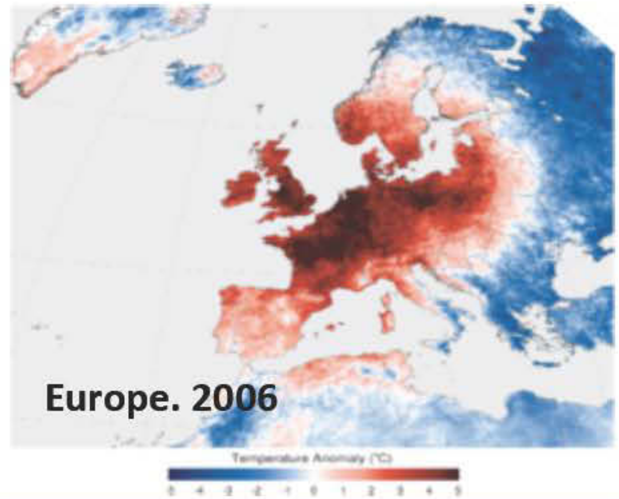
World Bank-Potsdam Institute for Climate Research

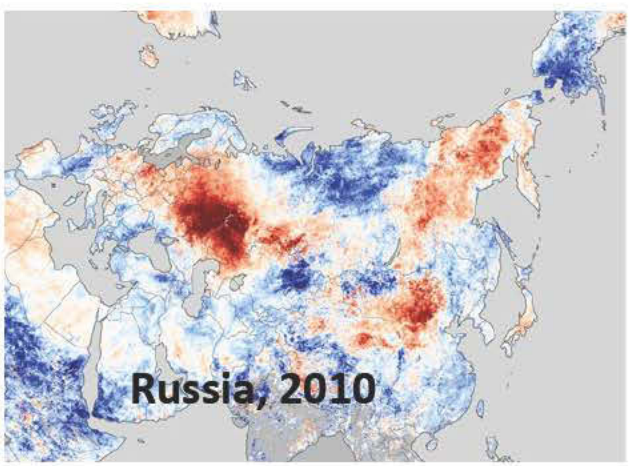


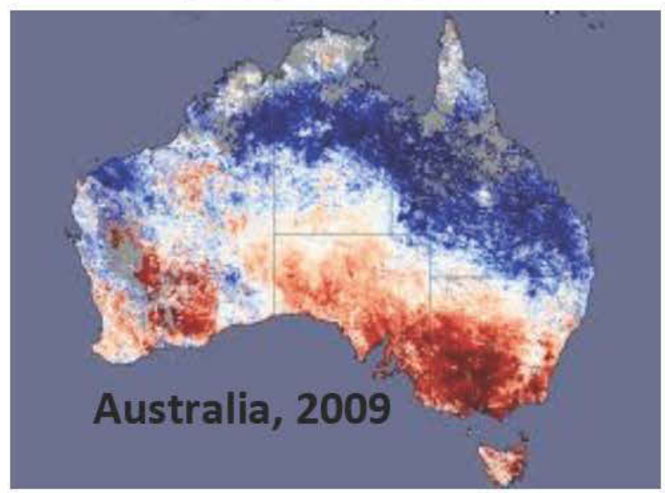
Heat Wave Area Increased During Hiatus

In the 1960s, summertime extremes of more than three standard deviations warmer than the mean of the climate were practically absent, affecting less than 1 percent of the Earth's surface. The area increased to 4–5 percent by 2006–08, and doubled by 2009–11 to 6–13 percent of the land surface. Now extremely hot outliers typically cover about 10 percent of the land area (Hansen et al. 2012).



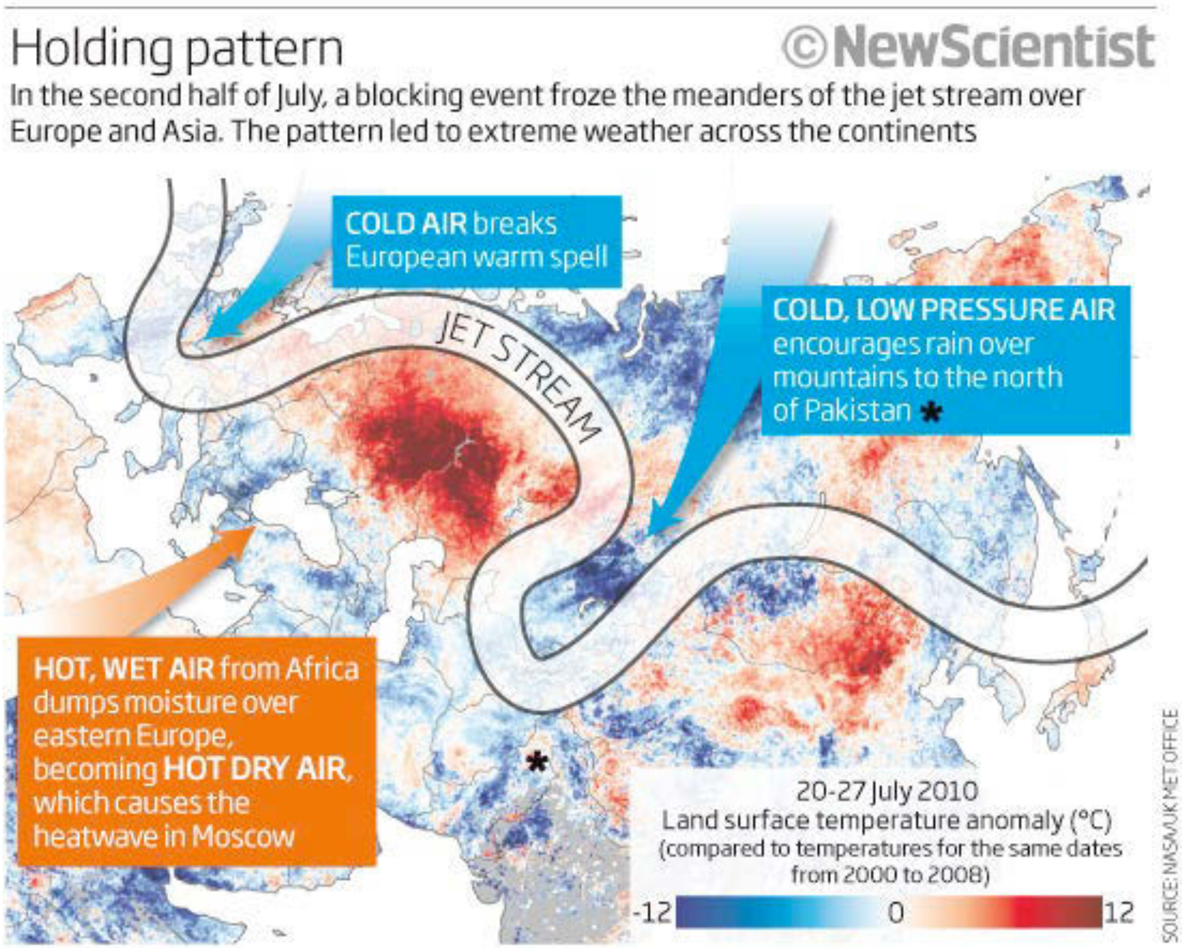






Jet Stream, Russian Heat Wave, Pakistani Floods

Slower propagation of meanders (Rossby Waves) in La Nina-like conditions
Longer persistence of extremes over one area



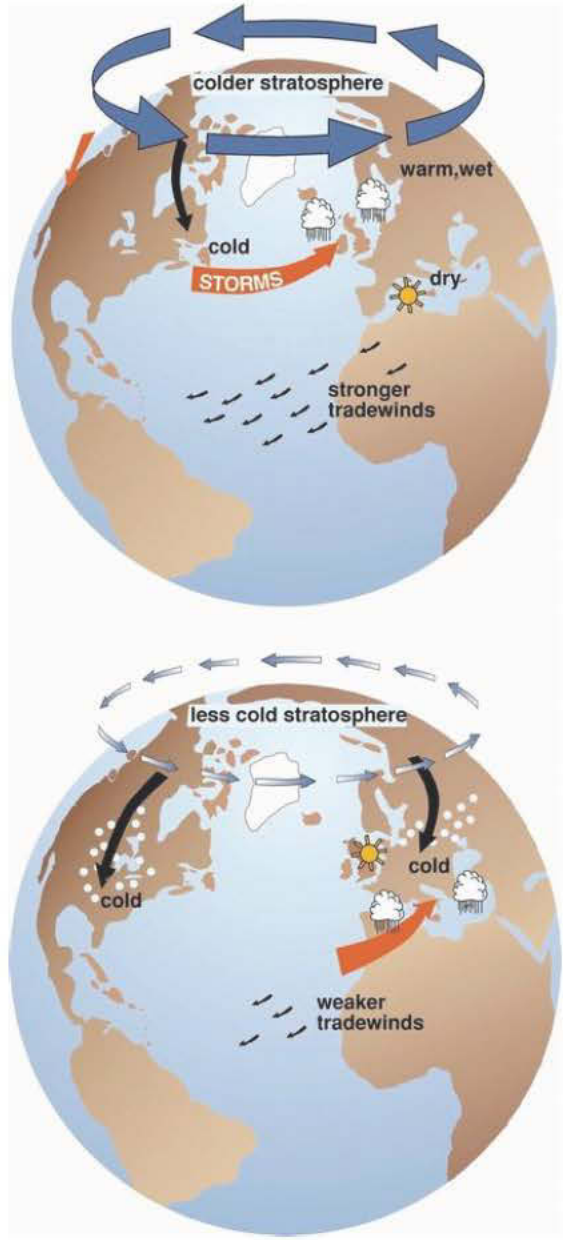
Francis, J.A., and S.J. Vavrus, Evidence linking Arctic amplification to extreme weather at mid-latitudes, *Geophysical Research Letters, 39,* L06801, doi:10.1029/2012GL051000, 2012

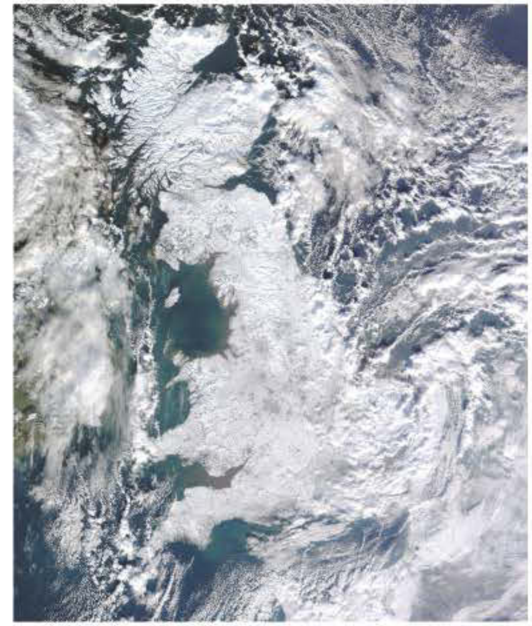
Kaiser, J., Dethloff, K., and Handorf, D., Stratospheric response to Arctic sea ice retreat and associated planetary wave propagation changes, Tellus A 2013, 65, 19375, http://dx.doi.org/10.3402/tellusa.v65i0.19375

Unstable Polar Vortex

Arctic warming is sending wintry weather south

US Snowmageddon, Feb 7, 2010





UK Snowmageddon, January 7, 2010

Sea ice and snow melt, lower atmosphere and stratospheric warming affect position of jet stream, cold Arctic air intrudes into midlatitudes

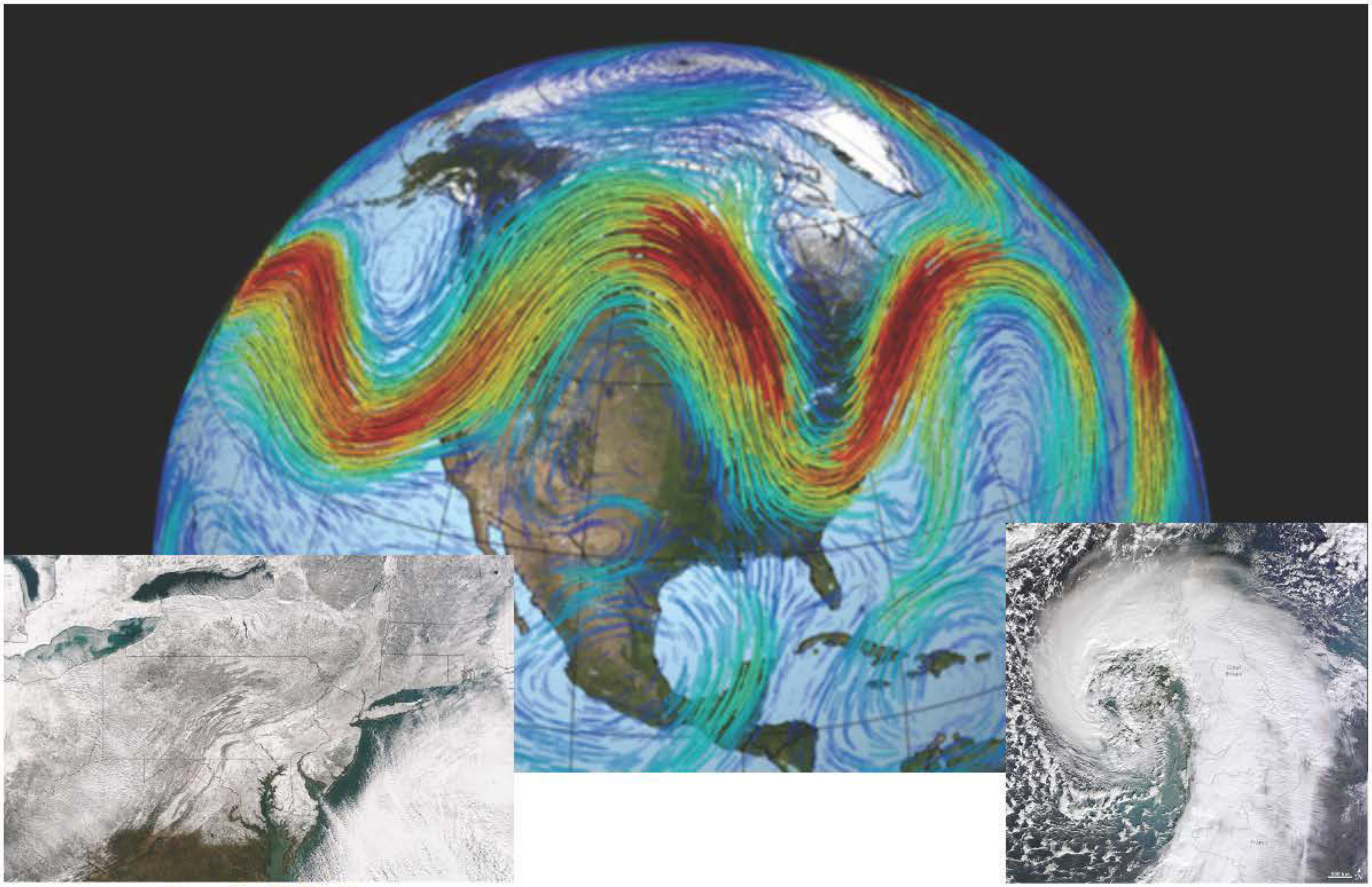
Winter 2009–2010: A case study of an extreme Arctic Oscillation event Cohen, J., *et. al.*, Geophysical Research Letters, Volume 37, Issue 17, September 2010, DOI: 10.1029/2010GL044256

Arctic warming favours extremes, Vladimir A. Semenov, Nature Climate Change. 2, 315–316. (2012) doi:10.1038/nclimate1502

Liu, J., *et. al.*, Arctic Sea Ice and Winter Snowfall, *PNAS, volume 109, 11,* 4074-4079, 2012

Northern Winter 2014

Most Precipitation in UK on Record Since 1766



Jan 3, 2014

Feb 12, 2014

Chronology of a Regime Shift

Interval	
1996-1997	September Arctic sea ice area and June NH snow cover begin progressive decline Albedo warming begins to increase Westerly Trade winds decline
1998-1999	Super-*El Nino*, followed by SST & OHC decrease Radiative cooling of ocean surface layers
2000-2001	Tropical OHC increases in Pacific and Atlantic Pacific SST recovers and stays relatively constant
2002-2003	Freshwater injection into Beaufort Gyre begins NAIW region salinity begins increase European Summer Heat wave of 2003
2004-2005	Global OHC increase slows but continues NAIW OHC reaches its peak
2006-2007	Sea ice area minimum (2007)
2008-2009	
2010-2011	Tropical Pacific trade winds continue to intensify
2012-2013	
2014-2015	Forecast of Pacific *El Nino*

A New Meta-Stable Climate State?

What started the continuing sea ice retreat post 1996, when winter regrowth could not make up for the previous year's loss?

What are the seasonal and decadal impacts of a yearly progressive increase in albedo warming due to sea ice and snow cover retreat?

Did Albedo warming, by modifying the meridional atmospheric heat flow, indirectly strengthen the trade winds, create a *La Nina* bias, and keep the Pacific Ocean surface cool?

Does changing the Equator to Arctic temperature ratio, thereby altering the meridional heat flow, affect the properties of mid-latitude Rossby waves and create the blocking responsible for extreme weather events?

Did amplified Arctic warming, by increasing freshwater runoff, freshen the Arctic ocean, and then frustrate NADW heat sequestration?

Did NADW frustration force thermohaline heat sequestration to occur in the NAIW formation zone at lower latitudes?

Has a dynamical quasi-equilibrium been created that might last until the energy added to the climate system from ice and snow retreat stops?

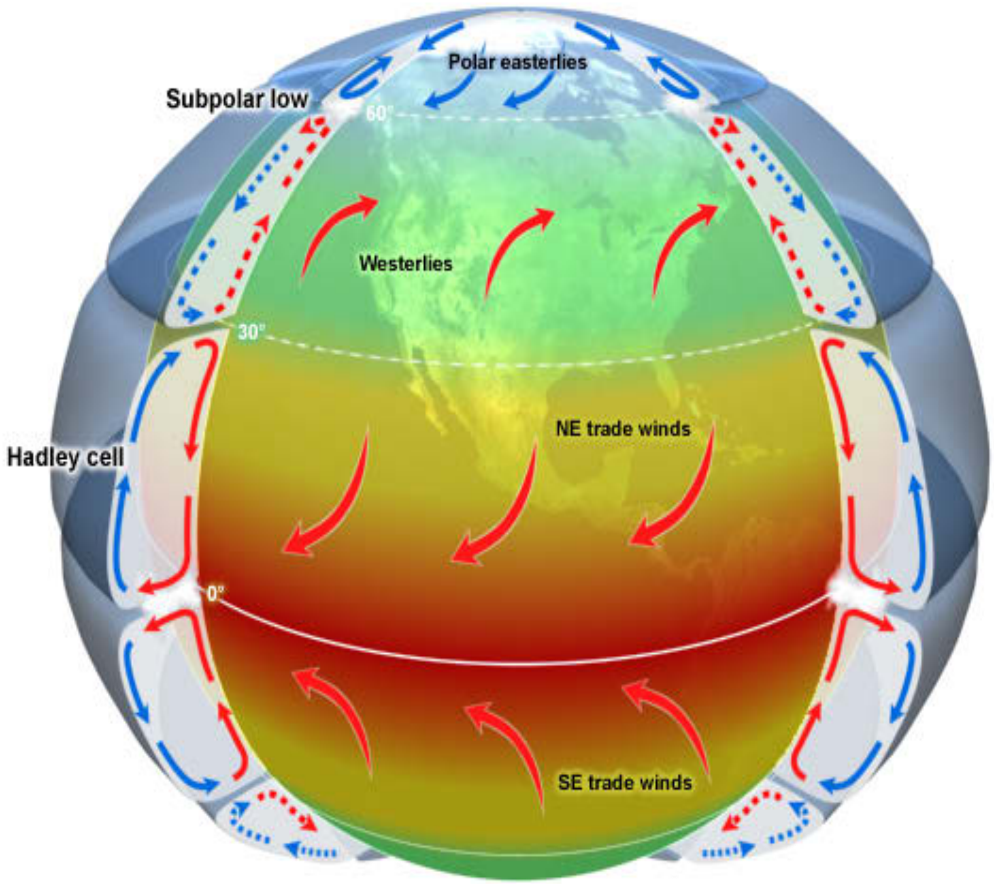
Polar Forcing of *El Nino/La Nina?*

Basic pattern set by seasonal variation of sunlight distribution at poles
Modulated by variable ice and snow albedo warming at poles
Transport in Ferrel Cell accomplished by planetary waves

Normal and La Nina

Relatively Warmer Arctic
Cooler Equatorial SST

Smaller poleward heat flux
Stronger tradewinds
Pacific Ocean sequestration
Variable jet stream
Mid-latitude blocking events

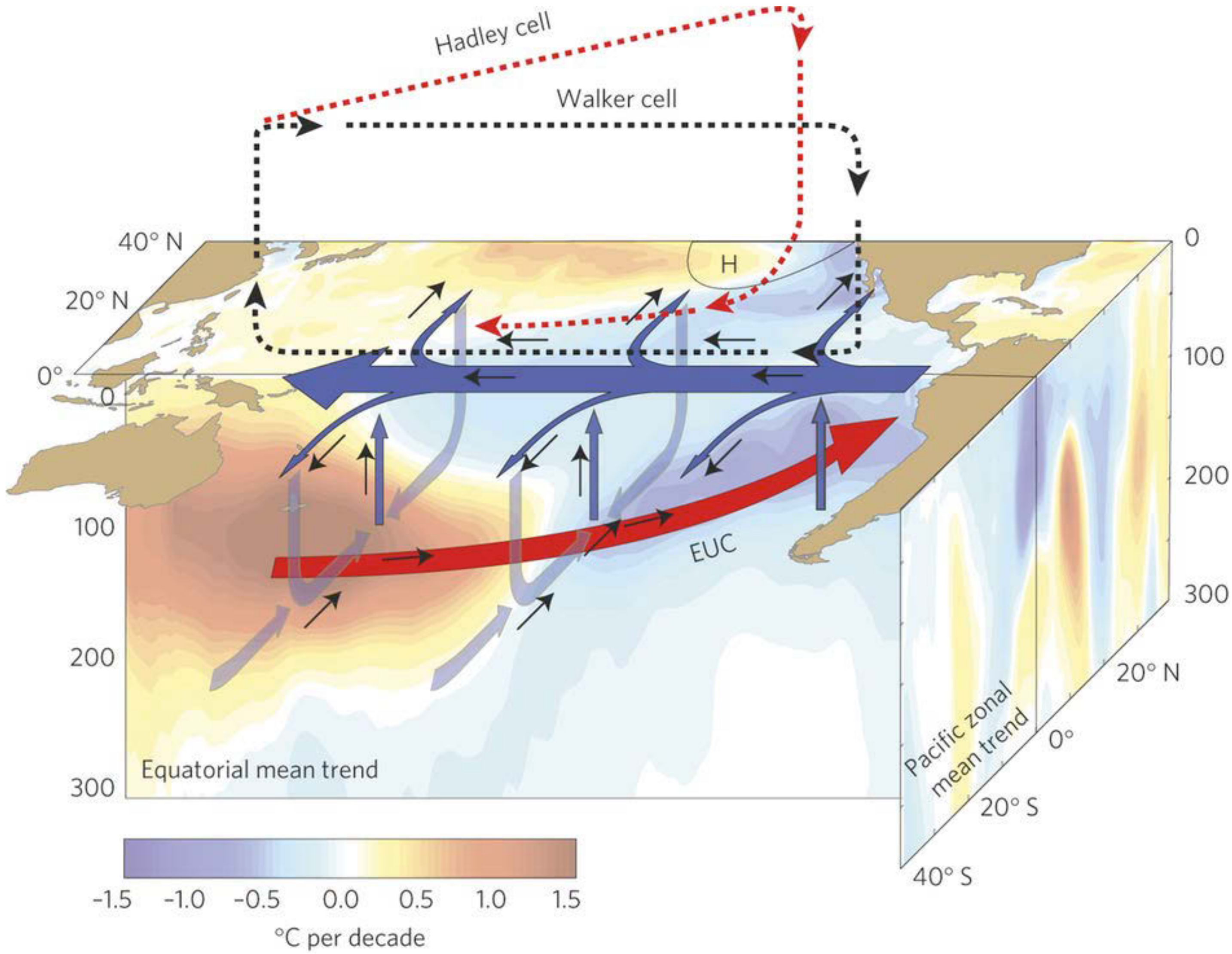


El Nino

Relatively Cooler Arctic
Warmer Equatorial SST

Larger poleward heat flux
Weaker Trade winds
Pacific Ocean sequestration fails
Smoother jet streams
"Pineapple express"

How does the division of Hadley Cell energy between the trade winds and poleward heat transport depend on Arctic Albedo warming?



England, M.H., *et* al, Recent Intensification of Wind-driven Circulation in the Pacific and the Ongoing Warming Hiatus, *Nature Climate Change 4,* 222–227 (2014) doi:10.1038/nclimate2106

Arctic Early Warning System

Impacts of Arctic Climate Change


Permafrost

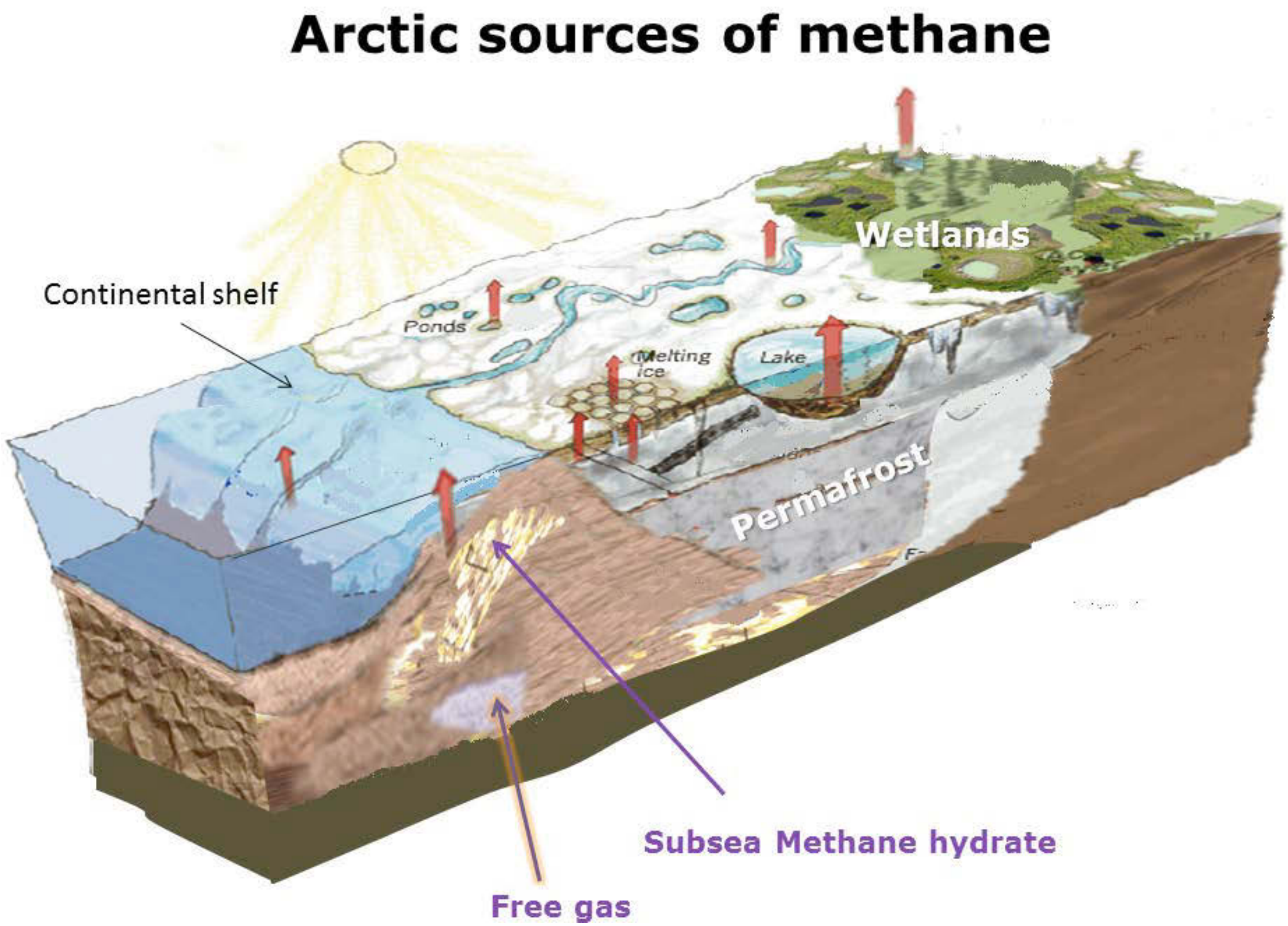
Permafrost

Permafrost has warmed by up to 2°C since the 1980s. Its southern limit has moved northward in Russia and Canada. The depth of soil above the permafrost that thaws each summer has increased in Scandinavia, Arctic Russia west of the Urals, and inland Alaska.

Possible Tipping Point

Will Arctic Warming release globally significant amounts of methane to the atmosphere?

On per-molecule basis, methane = 23xCO2



Methane Seeps

Land

Walter-Anthony, *et al*, Geologic methane seeps along boundaries of Arctic permafrost thaw and melting glaciers, *Nature Geoscience,* 2012, doi: 10.1038/ngoe1480

Undersea

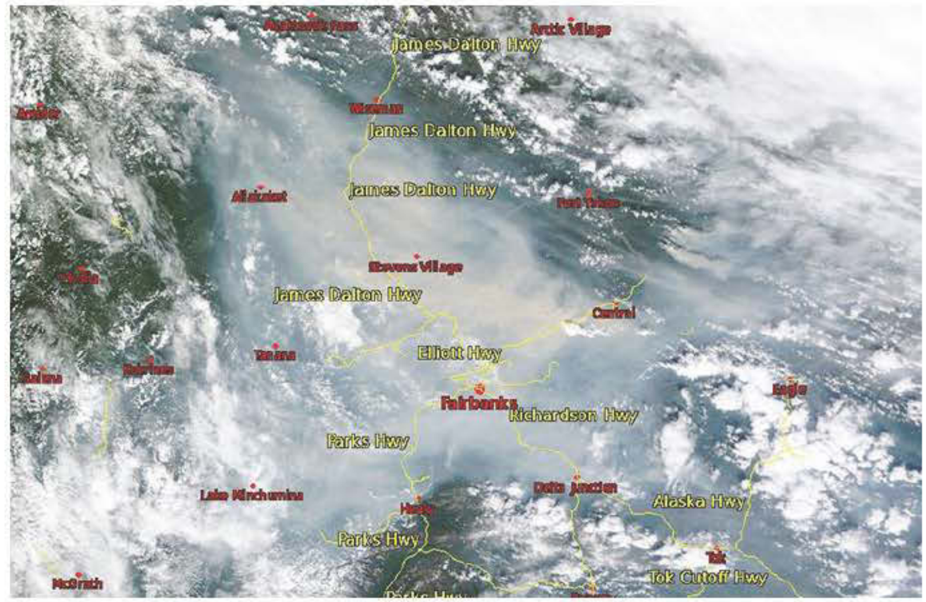
Shakhova, N., *et al,* Ebullition and storm-induced methane release from East Siberian Arctic Shelf, *Nature Geoscience, 7,* 64-70, 2014 doi: 10.1038/ ngeo2007

Summer Drying of Interior Alaska

Drying Lakes and Changing Habitat

Progressive lake drying in northern forest wetlands in the Yukon Flats National Wildlife Refuge, Alaska. Foreground orange area was once a lake. Mid-ground lake once extended to the shrub. (Photograph by May-Le Ng). Alaska accounts for 81% of the National Wildlife Refuge System and provides breeding habitat for millions of migratory birds that winter in more southerly regions of North America and on other continents (Griffith and McGuire 2008). Wetland loss would also reduce waterfowl harvest in Alaska, where it is an important food source for Native Peoples.

Increasing Wildfires



Warm and dry conditions fueled wildfires as the season advanced steadily during July, 2009. By month's end, nearly 2 million ac/809,371 ha had burned. Smoke from numerous wildfires plagued the interior during the month with Fairbanks International Airport reporting 14 days where the visibility was reduced to 6 mi/9.7 km or less breaking the previous record for July of 13 days set during the record breaking wildfire season of 2004 in which 6.6 million ac/472,133 km burned. On average Fairbanks experiences 1 smoke day during the month of July.

Great Alaskan Wildfires of 2007

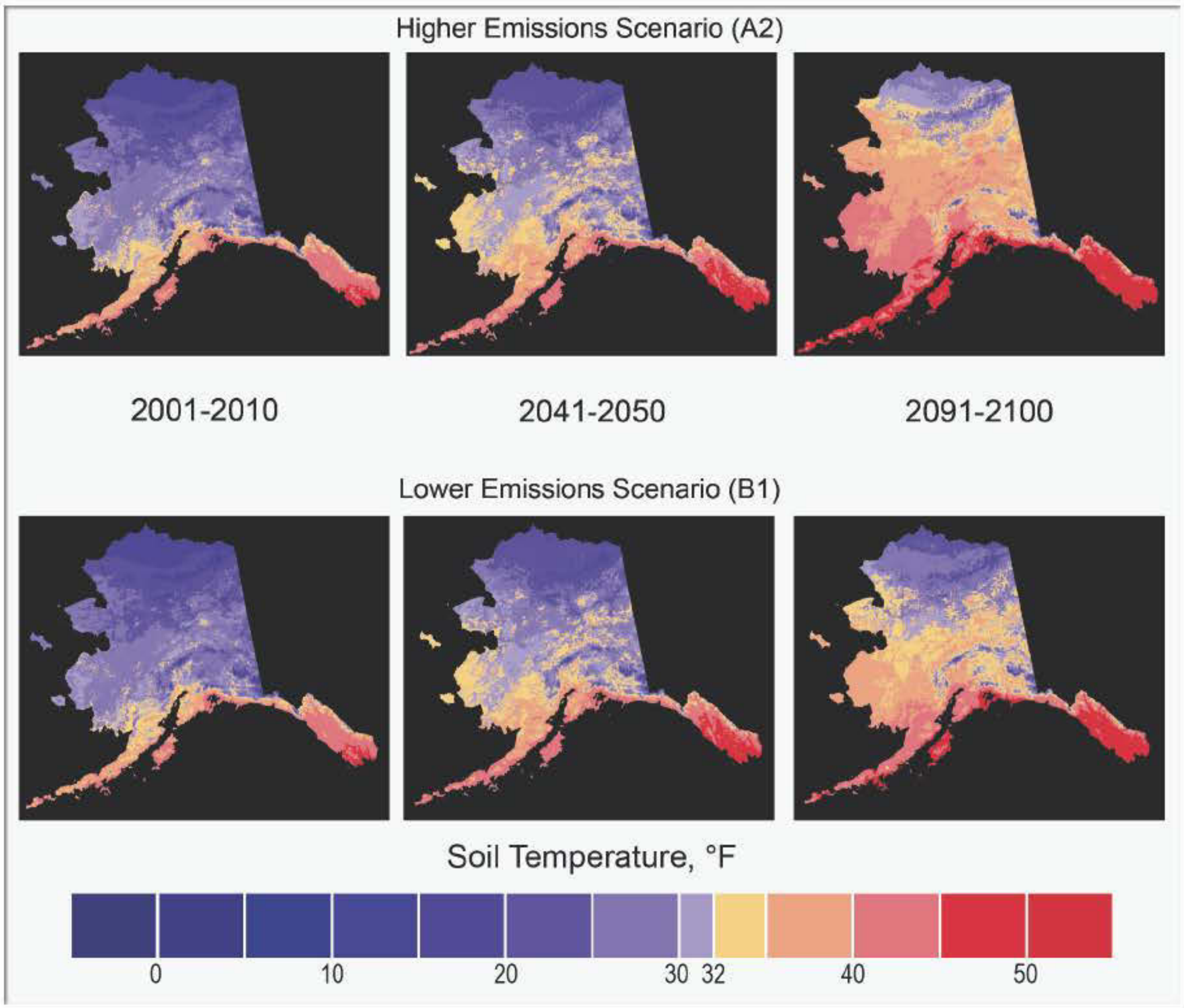
Normally, the tundra is wet in summer because of permafrost melt below, but 2007 was exceptionally hot and dry. The wildfires that year consumed 50 years of vegetation growth in the burn area and put as much CO2 into the atmosphere as the state's vegetation absorbs in a year. If such fires recur once every 100 years, ecosystem can recover. If they recur every 10 years, all bets are off.

Alaska Permafrost Melt Scenarios

Vigilance=Monitoring: Know in advance whether a tipping point is approaching

"Vigilance, Not Panic", *Global Change, 79,* IGBP, October 2012

The Big Thaw



Projections for average annual ground temperature at 3.3-foot (one-meter) depth over time. Blue shades represent areas below freezing (where permafrost is present at the surface), and yellow and red shades represent areas above freezing (permafrost-free at the surface) (Markon et al. 2012).

Social, Economic, and Political Impacts of Arctic Climate Change

Some practical consequences of tundra melt

Many people in Alaska count on permafrost to be there

Houses undermined by melting Permafrost

Alaska has strict rules for vehicle travel on permafrost to prevent environmental damage. When it is too warm, travel is not allowed. The duration of allowed permafrost travel set by the Alaska Department of Natural Resources is a climate change proxy. In the last 25 years the number of days on which oil exploration is allowed on the tundra has more than halved.

Permafrost is a slow moving underground river of ice. Above ground structures anchor their foundations in the ice below, and permafrost flow stresses foundations at the best of times; when the permafrost melts, the structures are destroyed.

Retreat of sea ice from shore exposes coastal villages to storm surges

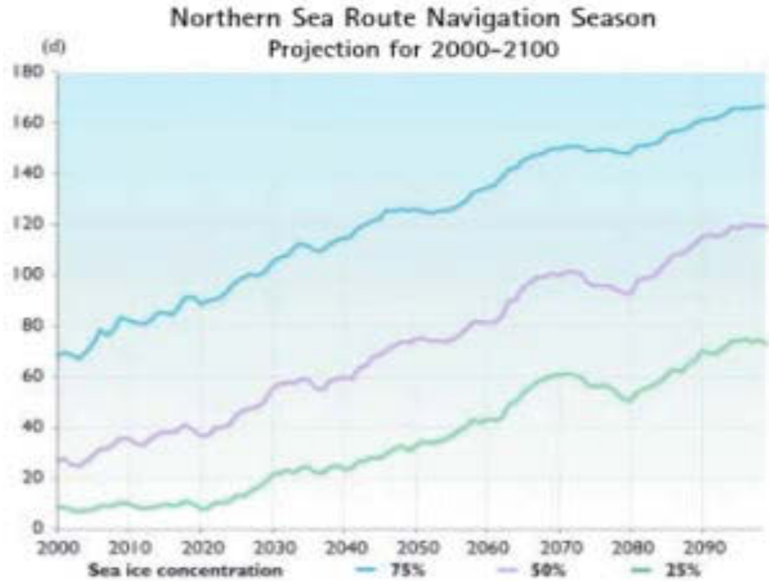
Shishmaref could eventually disappear

Village of Shishmaref, Alaska. Notice the trash can in the image on the left, before the storm, and in the image on the right, after the storm. Images courtesy of Nome Nugget Newspaper.

2009 report of the US Global Change Research Program

Sea Ice Loss Brings Big Changes to Arctic Life

Reductions in sea ice alter food availability for many species from polar bear to walrus, make hunting less safe for Alaska Native hunters, and create more accessibility for Arctic Ocean marine transport. Photographs by Gary Hufford and Carleton Ray; Caleb Pungowiyi; and Patrick Kelley.



The graph shows the projected increase in days of the navigation season through the Northern Sea Route as an average of five ACIA model projections.

Northern Sea Route and Northwest Passage

The length of the navigation season may double by 2050, perhaps earlier

Europe-Pacific shipping distance reduced by 40%

Churchill, Manitoba: high hopes for its seaport

The Arctic: A Security Issue

Now, powers do not prepare to launch missiles over the Arctic, they contest over using the Arctic

Military powers beef up Arctic presence

Wall Street Journal, April 16, 2012

Canadians willing to fight to keep true North free

Toronto Globe and Mail, Jan 25, 2011

Arctic Security Means More than Sovereignty

Toronto Globe and Mail, Jan 26, 2011

Britain Spearheads "Mini-NATO" In Arctic Ocean, Baltic Sea

Posted 15. Feb, 2011, ArcticSecurity.org in Canada, Denmark, Finland, NATO, Norway

Arctic Body Comes In from the Cold

Wall Street Journal, May 14, 2013

Race Between Sovereignty and Cooperative Governance

Economics:

Pristine fisheries
Mineral rights
Oil exploration
Shipping

Governance:

Navigation,
Resource rights,
Environment,
Pollution

P.A. Berkman and O.R. Young, Governance and Environmental Change in the Arctic Ocean, Science, 324, 3390340,April 17, 2009