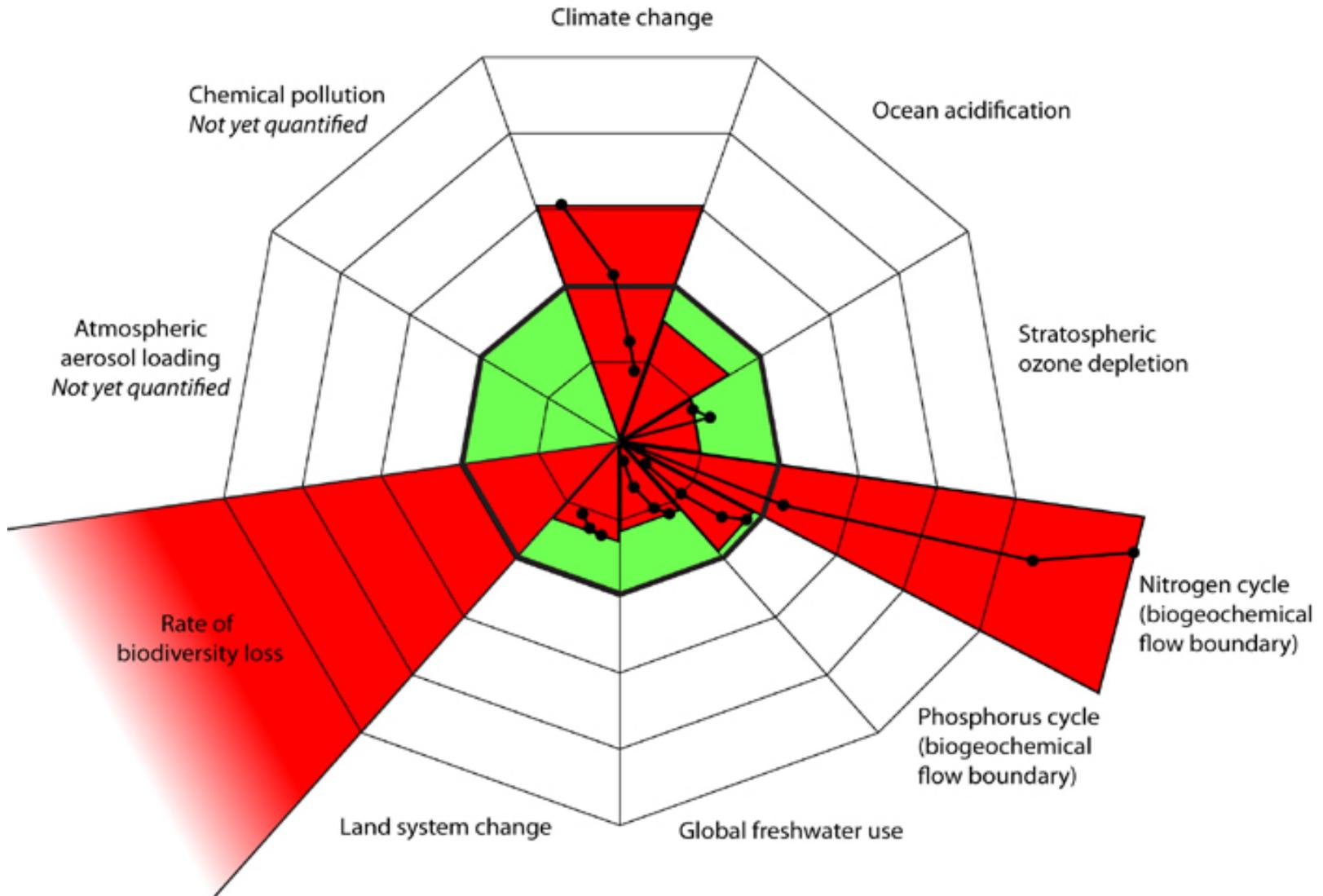


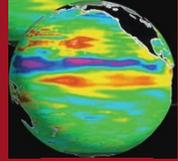
**A Wild Solution for Climate Change
Princeton Colloquium
April 15, 2015**

**Thomas E. Lovejoy
University Professor
Environmental Science and Policy
George Mason University**

Planetary Boundaries



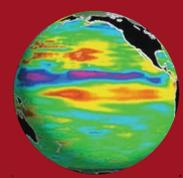
Source: Rockström, J. et al. 2009



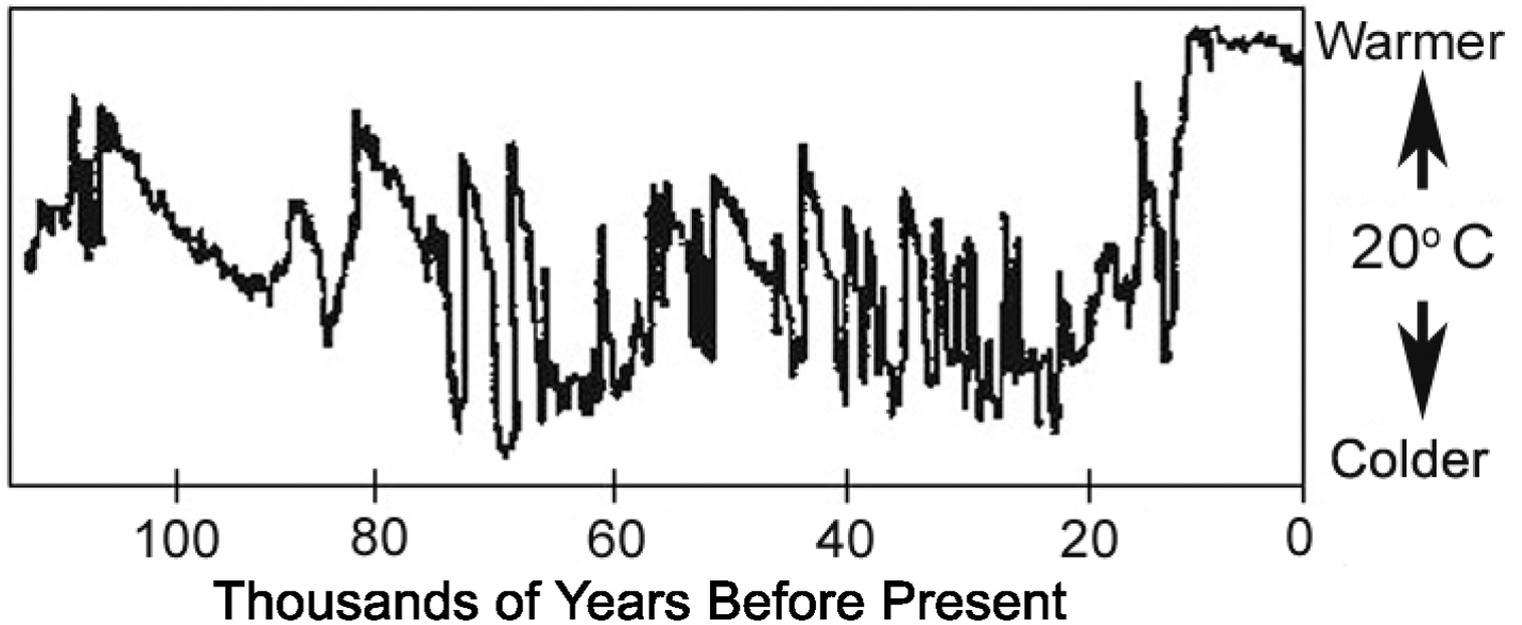
Dr. Svante August Arrhenius

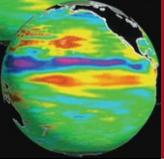
1859-1927



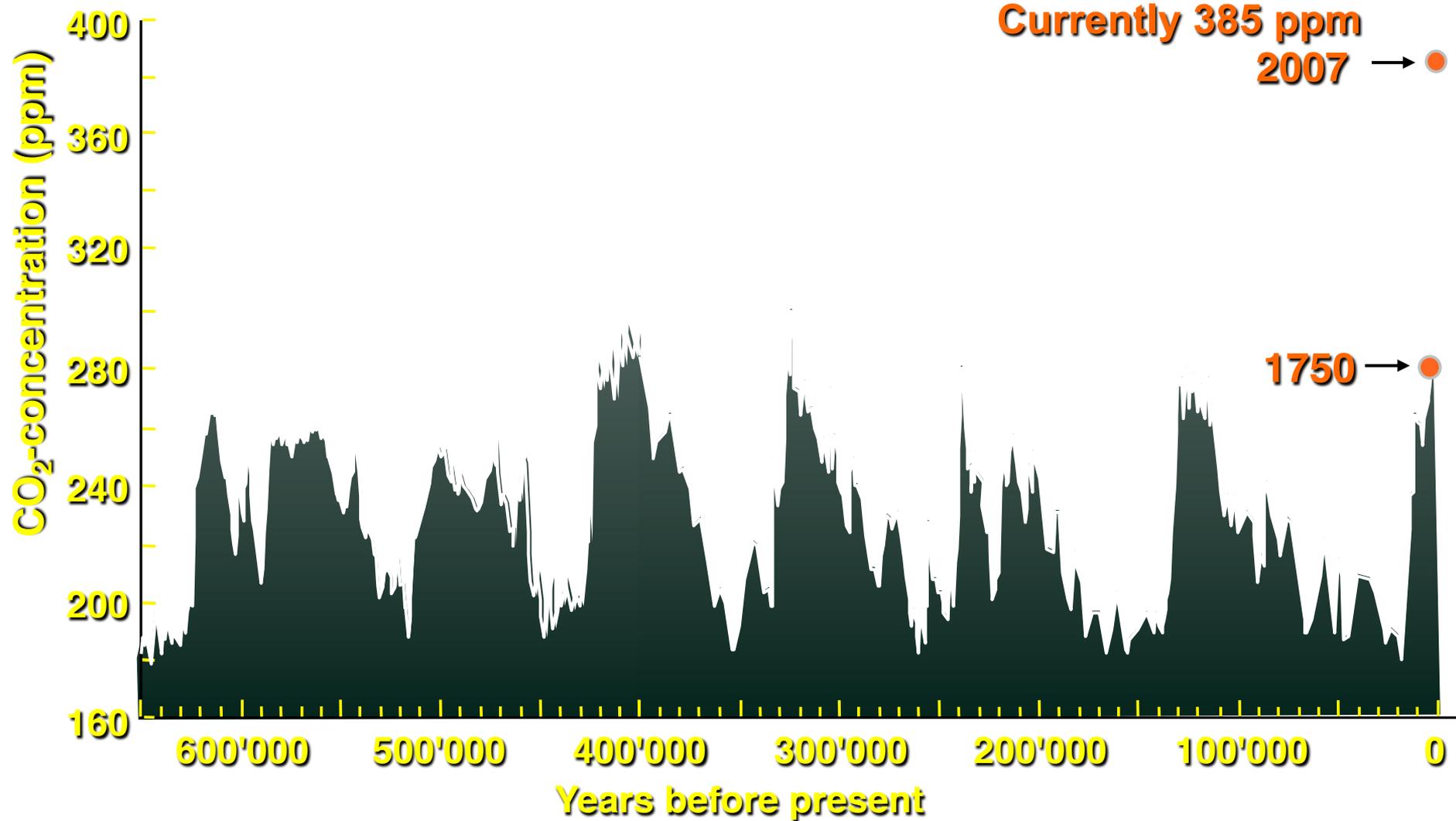


Analysis of a Greenland ice core oxygen isotope proxy

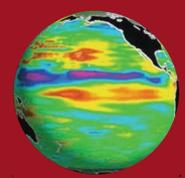




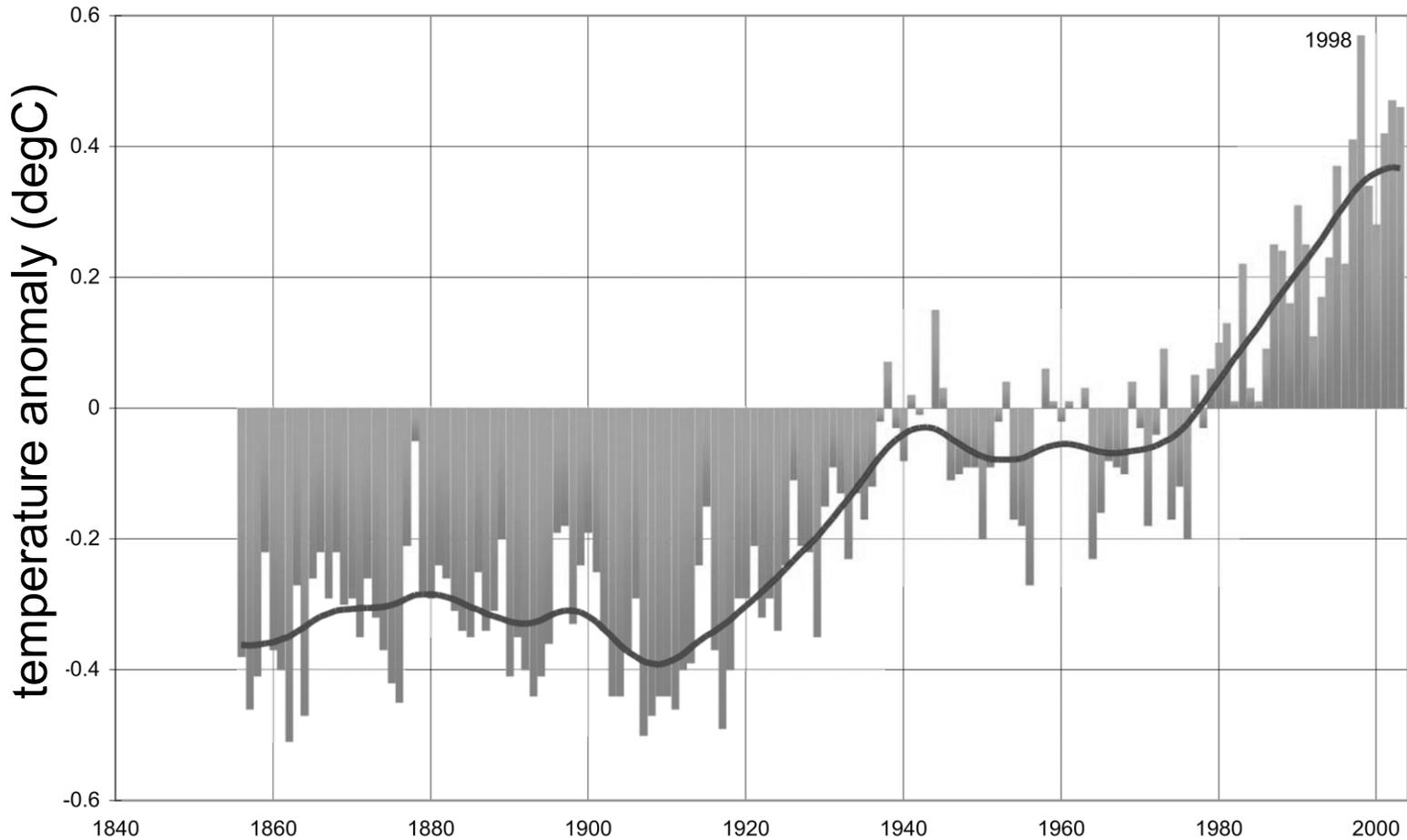
CO₂ for the Last 600,000 Years



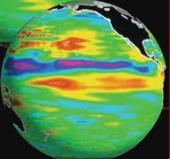
Siegenthaler U *et al.* (2005) *Science* 310:1313
Petit JR *et al.* (1999) *Nature* 399:429



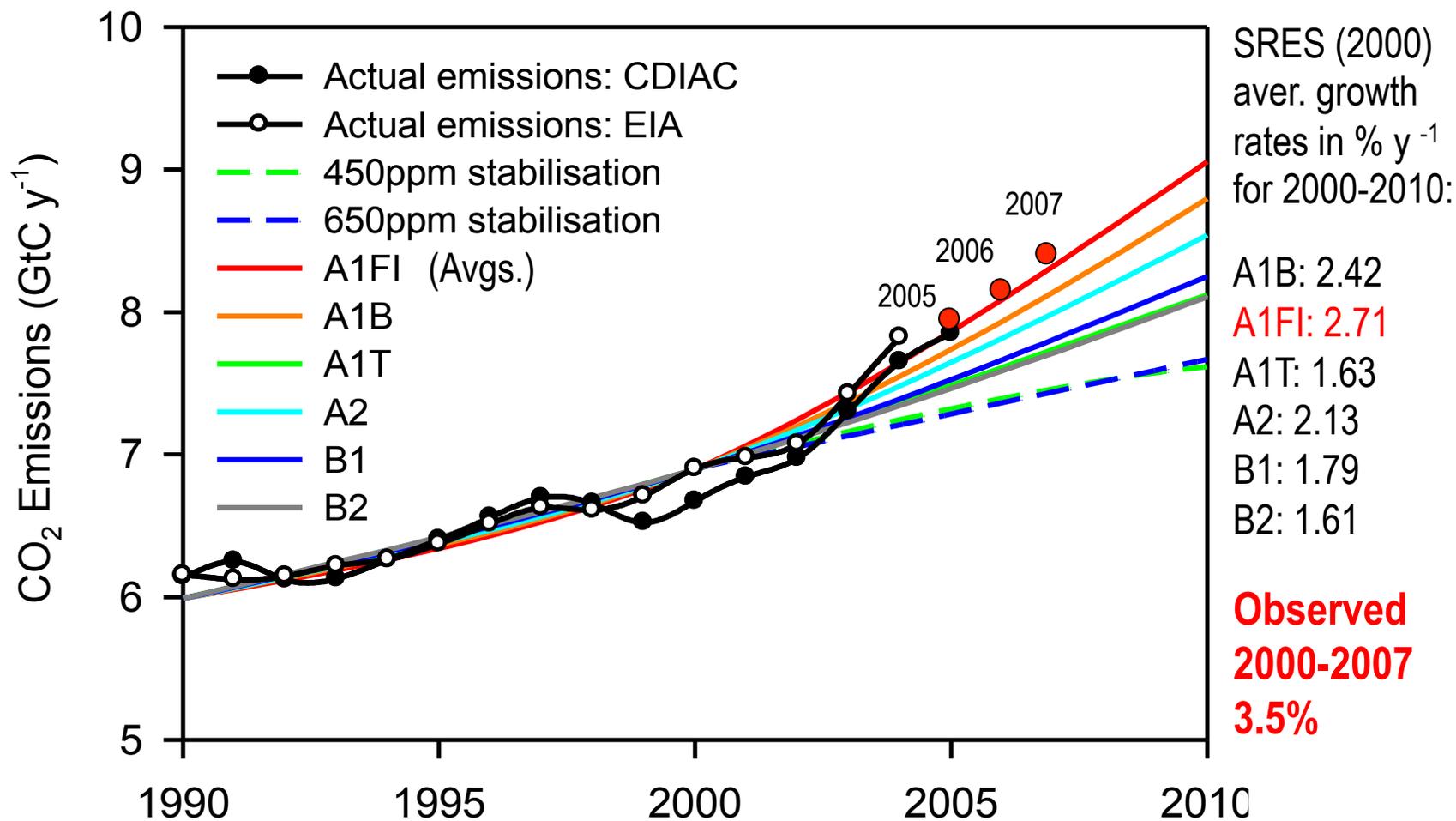
Global temperature record



Source: Hadley Centre and Climatic Research Unit, School of Environmental Sciences, UEA



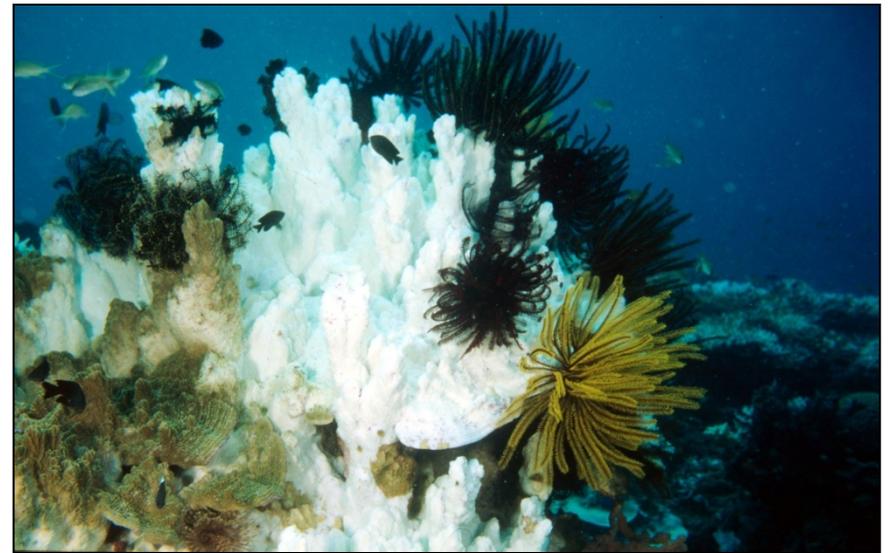
Fossil Fuel Emissions: Actual vs. IPCC Scenarios



Signals from nature



Jeremy Little / University of Washington

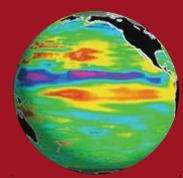


Lara Hansen / WWF

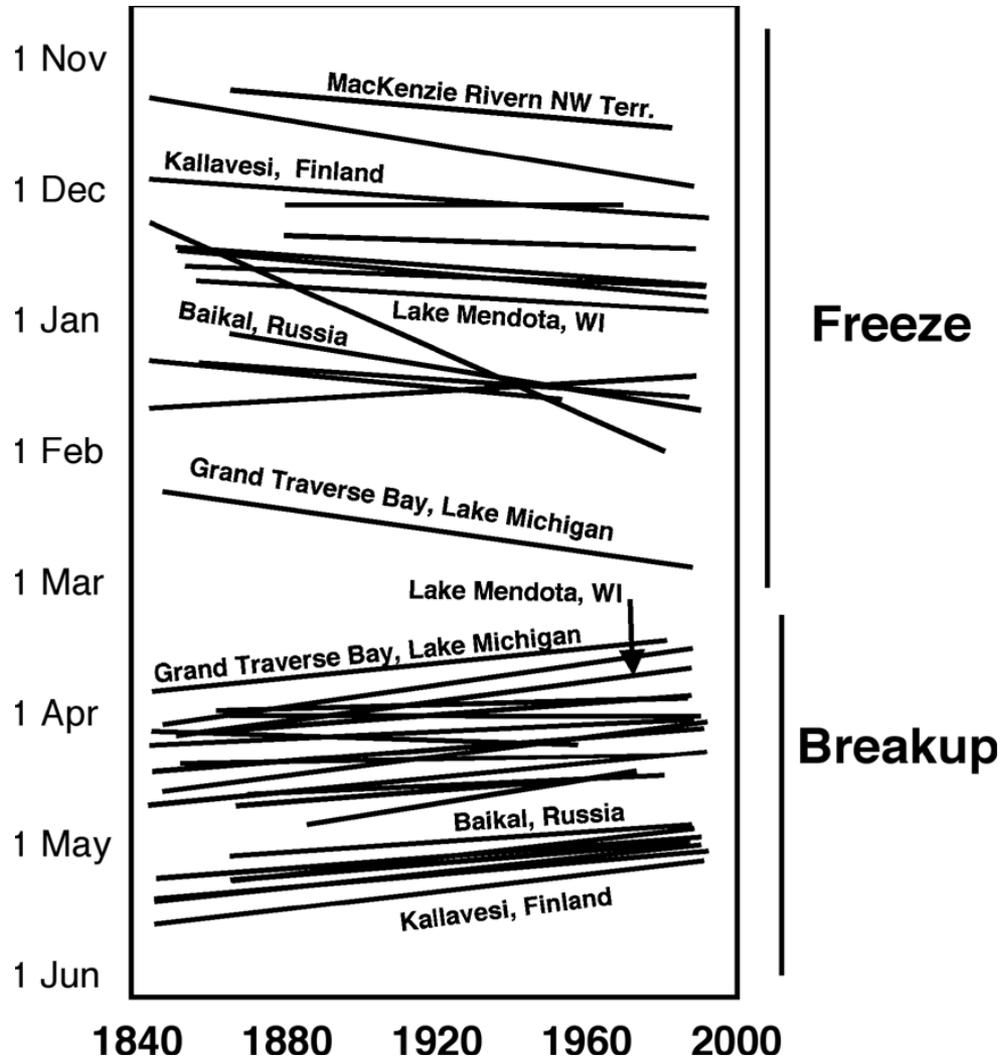
**THE H. JOHN HEINZ III CENTER FOR
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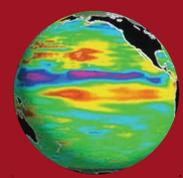
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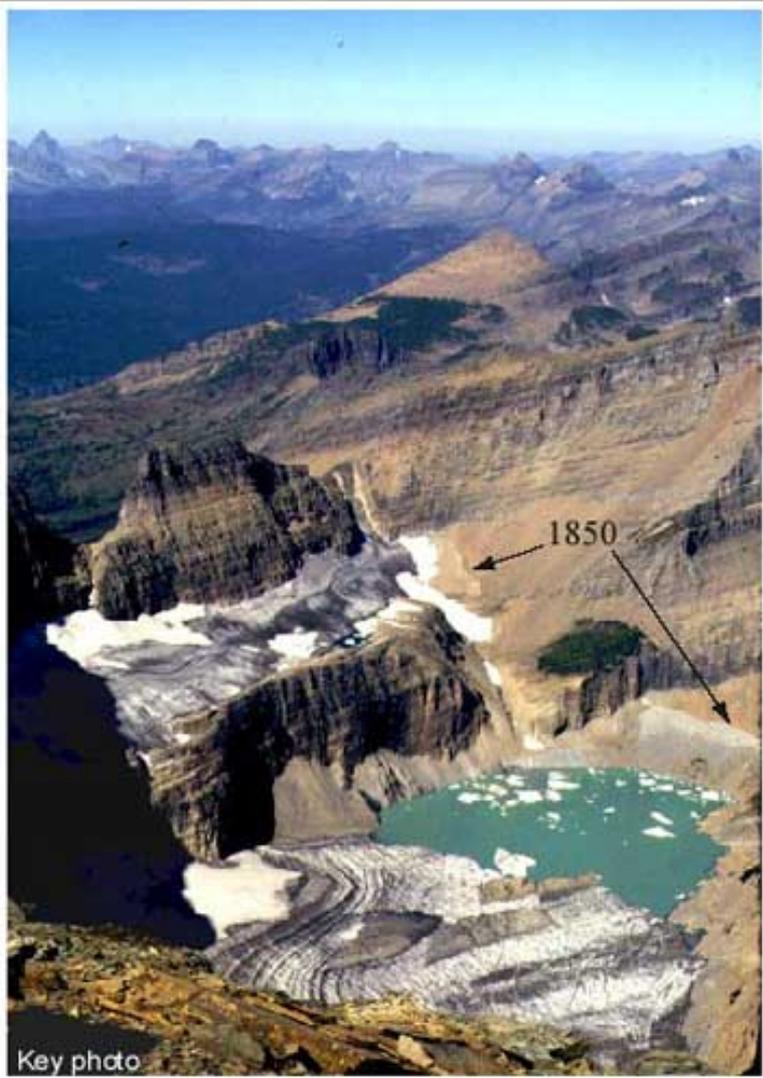
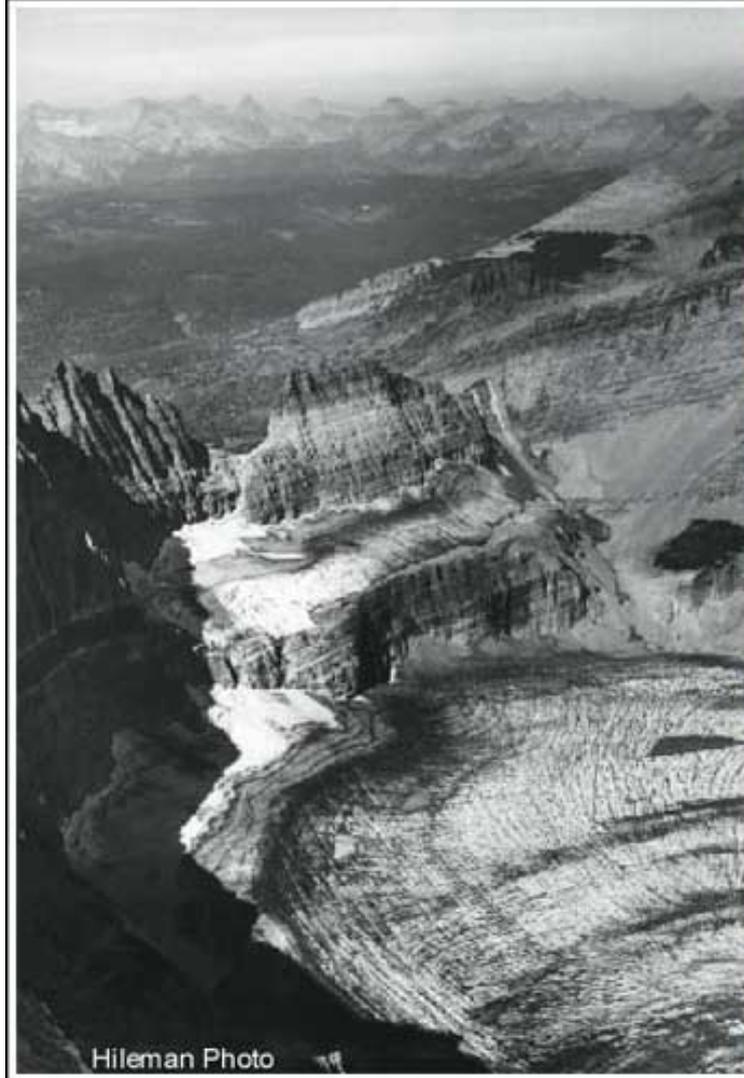
Warming trend in 37 of 39 Northern Hemisphere lakes and rivers



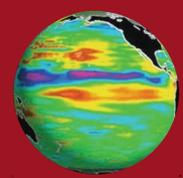


Grinnell Glacier, Glacier National Park

Late summer of 1938 (left) and 1981 (right)







Rising sea level

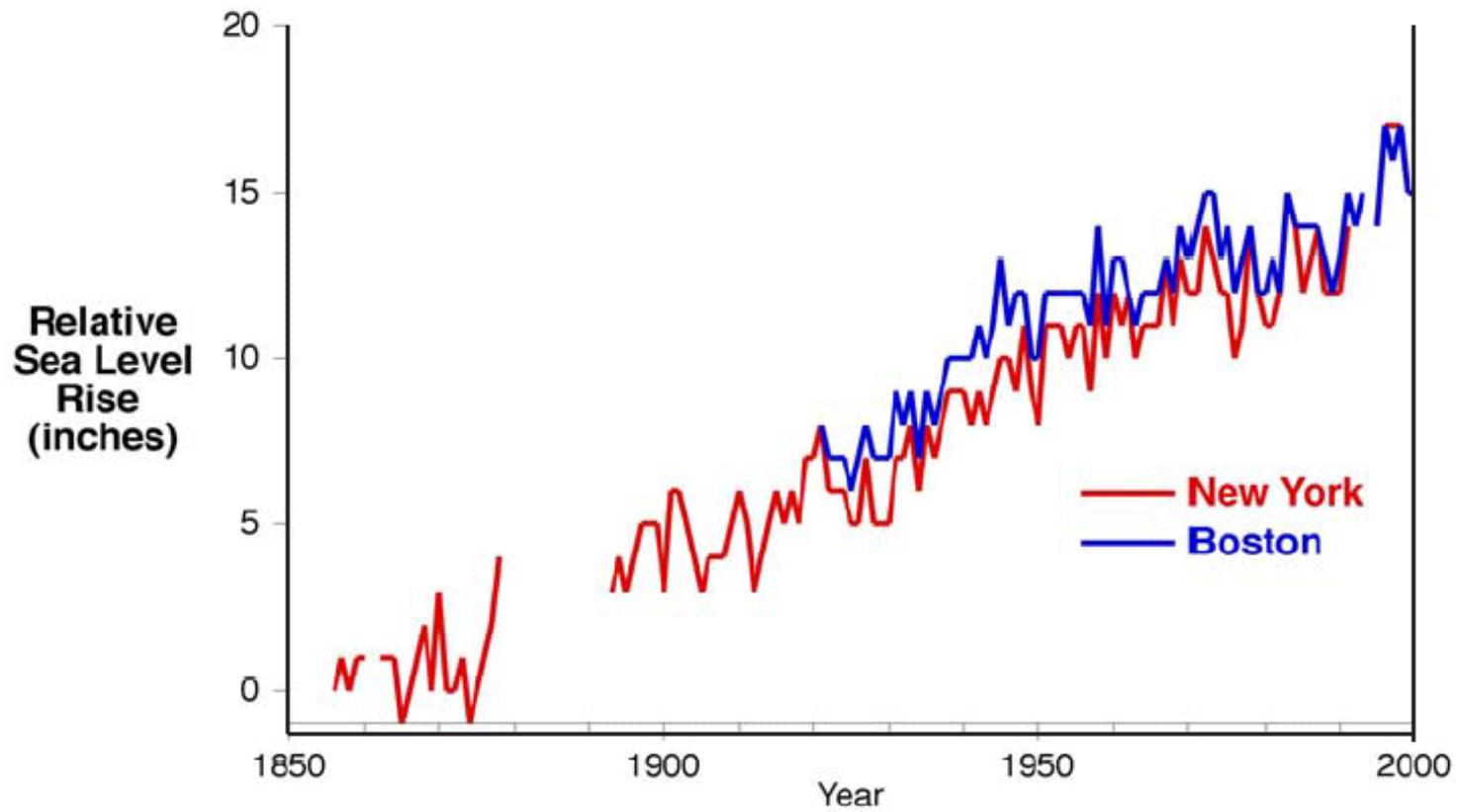
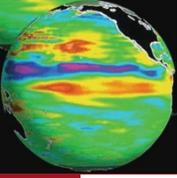


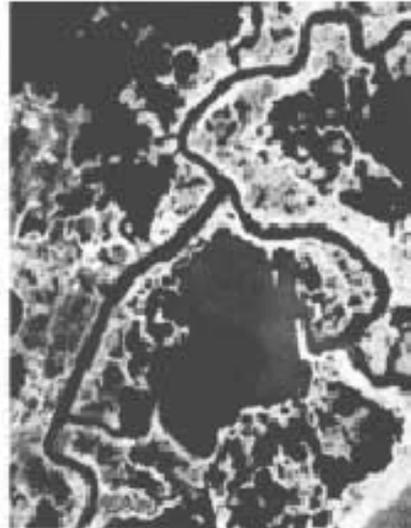
Figure 1: Sea level as measured at New York City, NY (from 1856, in red) and Boston , MA (from 1922, in blue) through 2000 in inches. The 1856 sea level was set to zero to illustrate the amount of increase over the past 150 years. Sea level has been increasing in the Northeast since it was recorded, due to natural phenomenon and perhaps human influence on climate. Human induced warming threatens to accelerate the rising sea level. Data from Permanent Service for Mean Sea Level, United Kingdom, <http://www.pol.ac.uk/psmsl/>



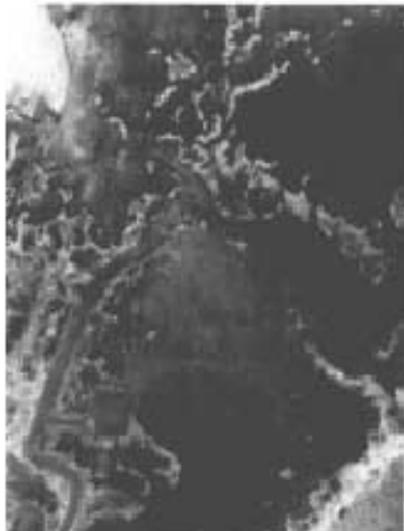
Sea Level Rise in the Chesapeake Bay



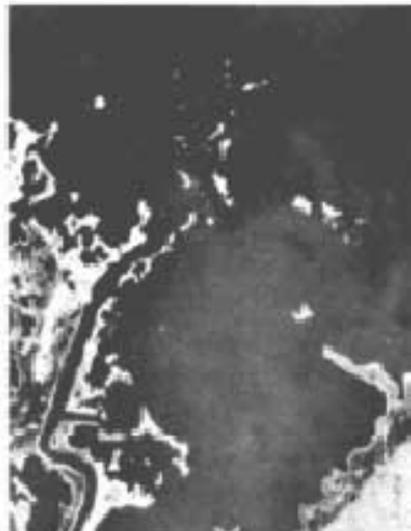
1938



1957



1972

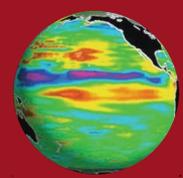


1988

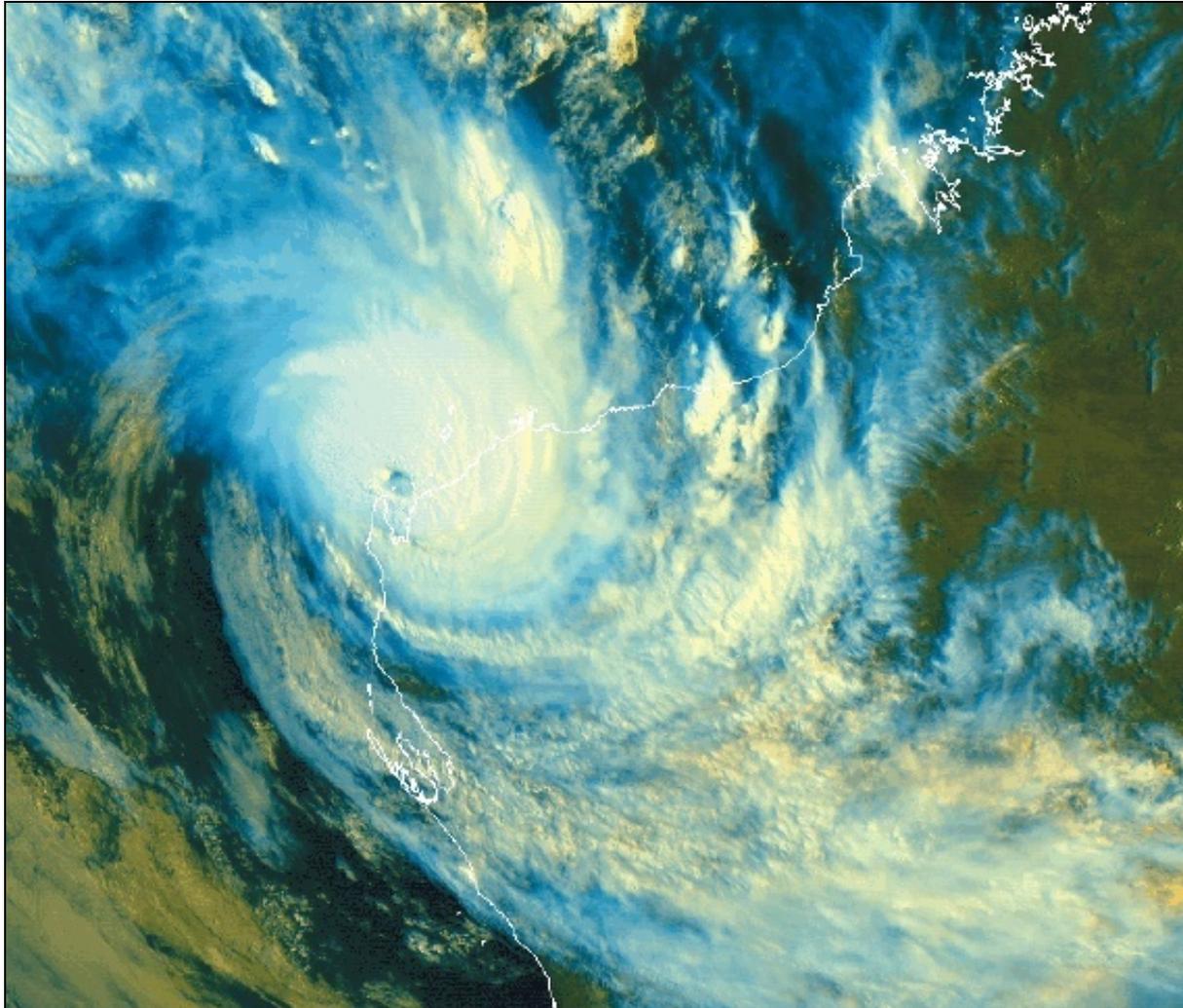
Blackwater National Refuge, Maryland

Photo Courtesy of NOAA

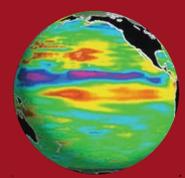
photo courtesy of NOAA



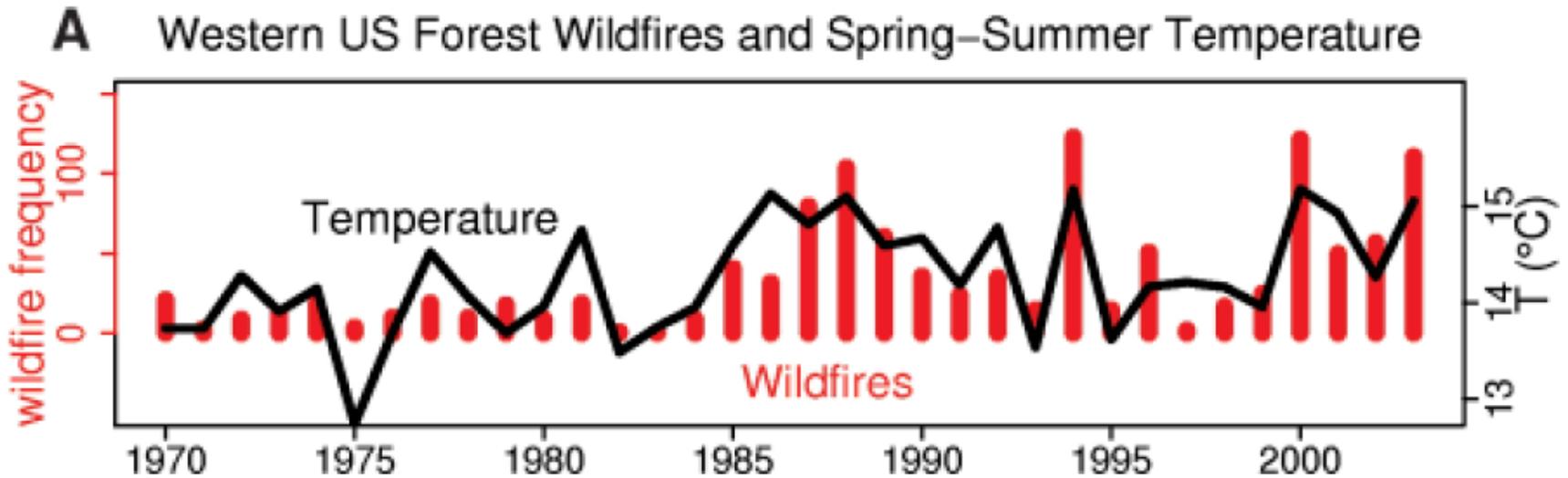
Probable Increased Frequency of More Intense Tropical Cyclones



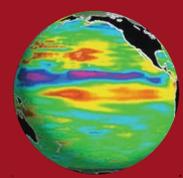
Source: CSIRO 2001 (www.dar.csiro.au/publications/projections2001.pdf).



Wildfire increase in Western U.S.



Warmer summers and earlier snow melts increased opportunities for wildfire in the western U.S. beginning in the mid-1980s



Earlier flowering date

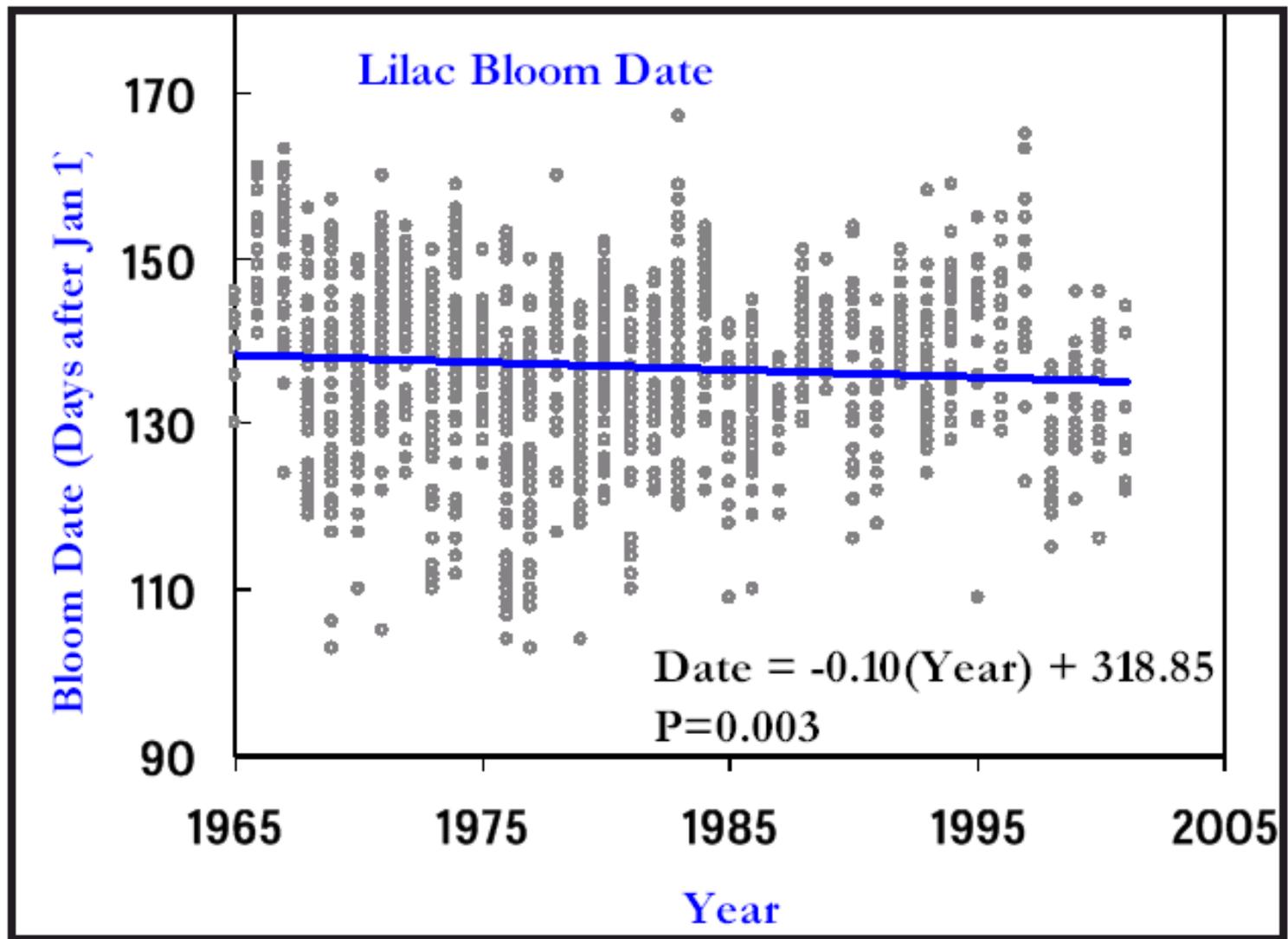
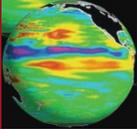


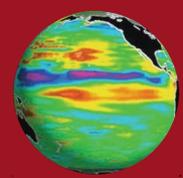
Figure 2. Trend of lilac bloom dates is indicated by the blue line.



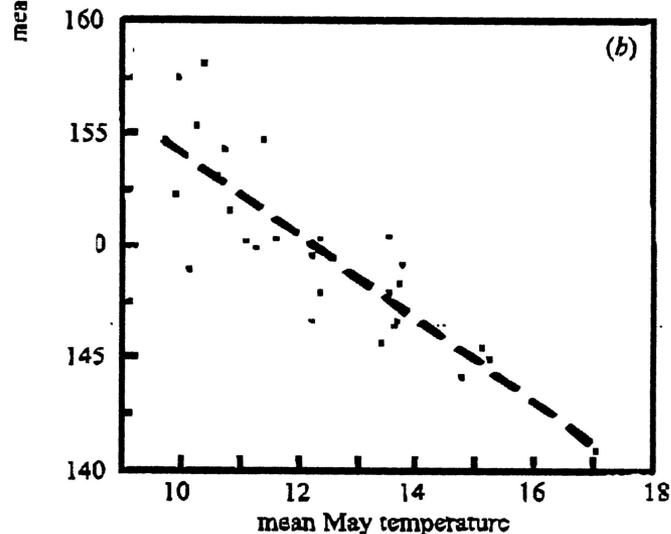
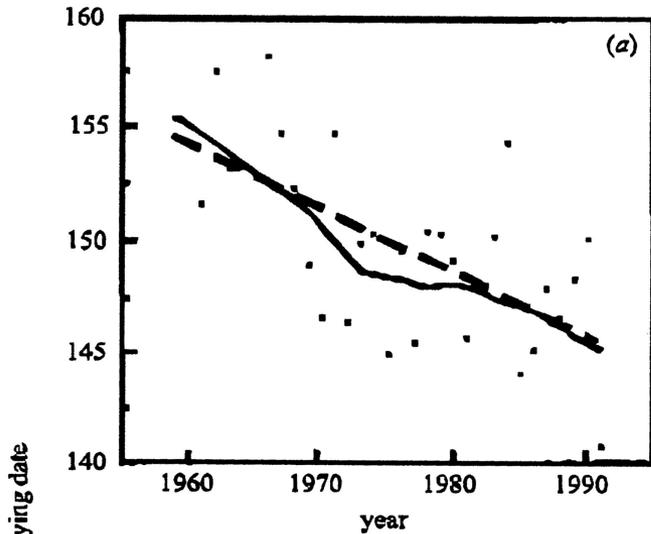
Climate Change at the Royal Botanic Gardens, Kew

Advances in flower opening since the 1980s

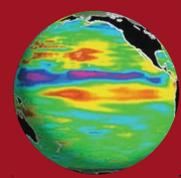
		1980s - AVERAGE OPENING DATE	2000s - AVERAGE OPENING DATE	NUMBER OF DAYS ADVANCED	
 <i>Eranthis hyemalis</i>	<i>Anemone nemorosa</i>	1 April	13 March	19 days	 <i>Galanthus nivalis</i>
	<i>Buxus sempervirens</i>	1 April	13 March	19 days	
	<i>Eranthis hyemalis</i>	29 January	11 January	18 days	
	<i>Narcissus pseudonarcissus</i>	12 February	27 January	16 days	
	<i>Crocus chrysanthus</i>	15 February	4 February	11 days	
 <i>Crocus chrysanthus</i>	<i>Galanthus nivalis</i>	10 February	30 January	11 days	 <i>Anemone nemorosa</i>
	<i>Syringa vulgaris</i>	29 April	18 April	11 days	
	<i>Cercis siliquastrum</i>	3 May	24 April	9 days	
	<i>Aesculus indica 'Sydney Pearce'</i>	1 June	23 May	9 days	
	<i>Laburnum anagyroides</i>	30 April	22 April	8 days	



Spring comes about 2 weeks earlier

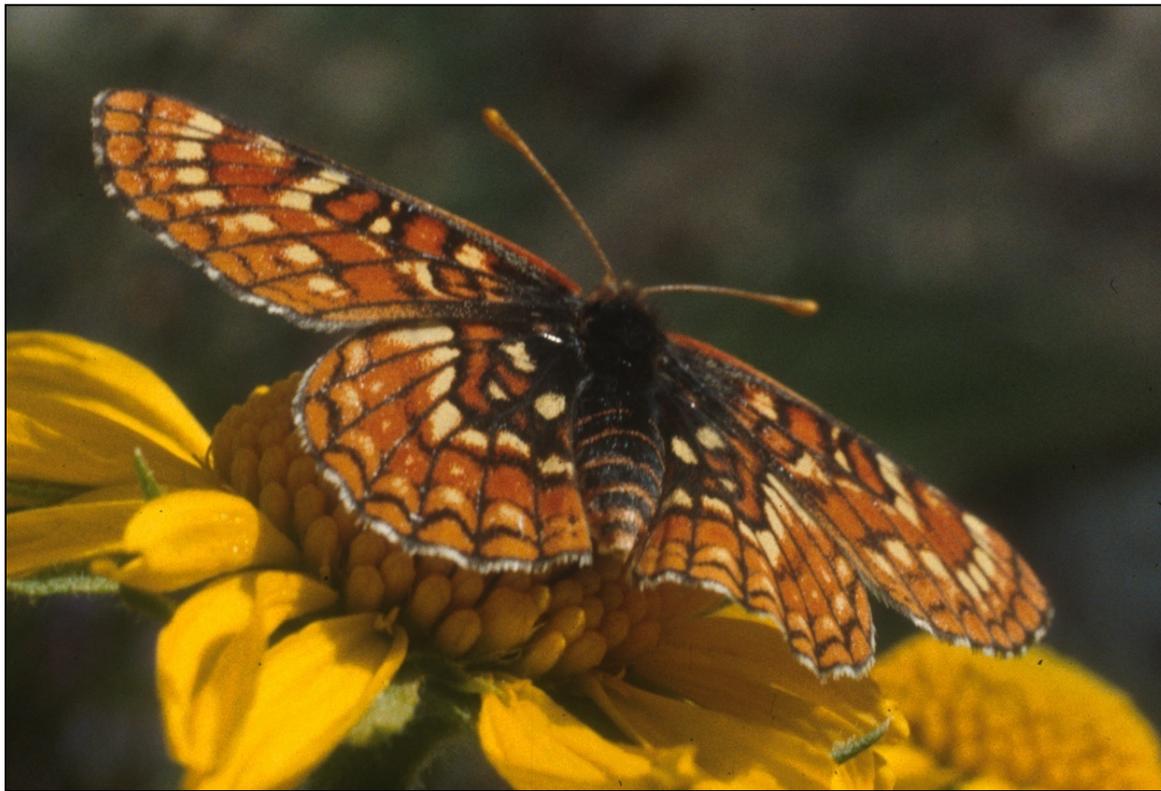


- Across the USA, tree swallows are nesting 9 days earlier than 40 years ago
- Laying date is highly correlated with May temperature

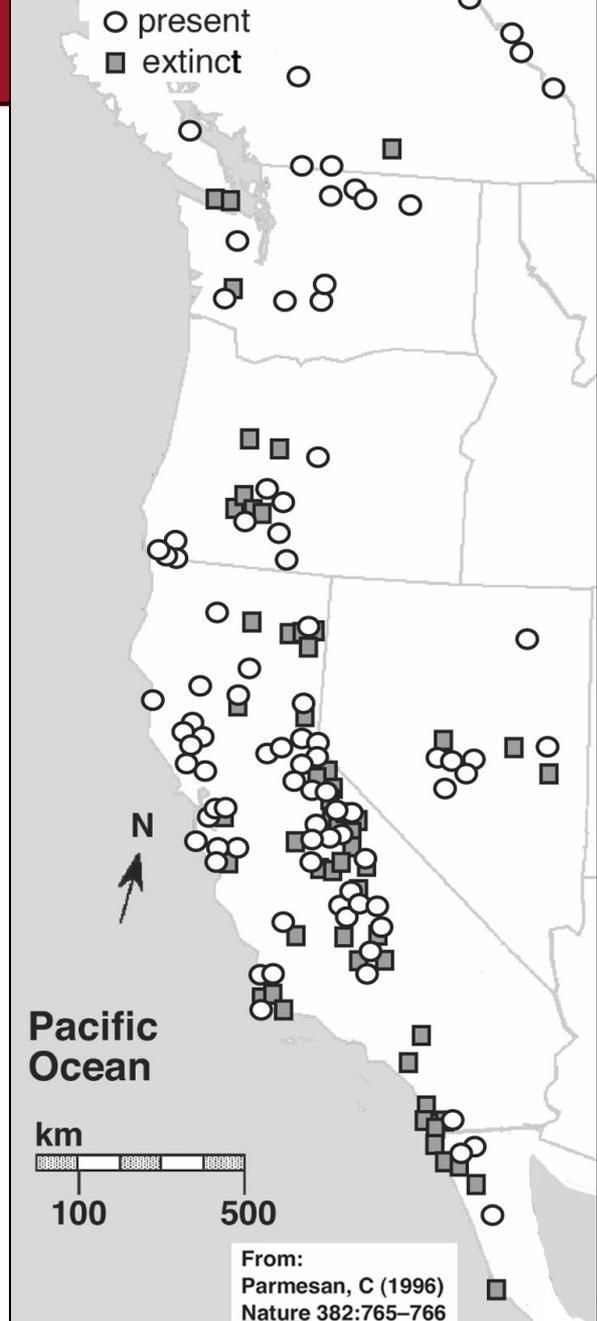


Edith's Checkerspot

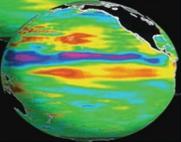
- Range shift northward and upward during the 20th century
- Most extinctions in south and low elevations

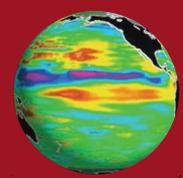


Edith's Checkerspot populations



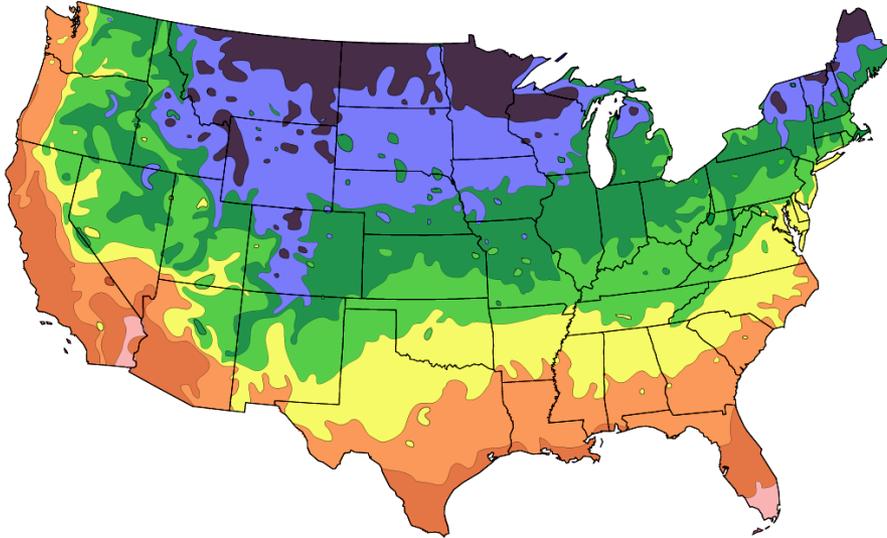






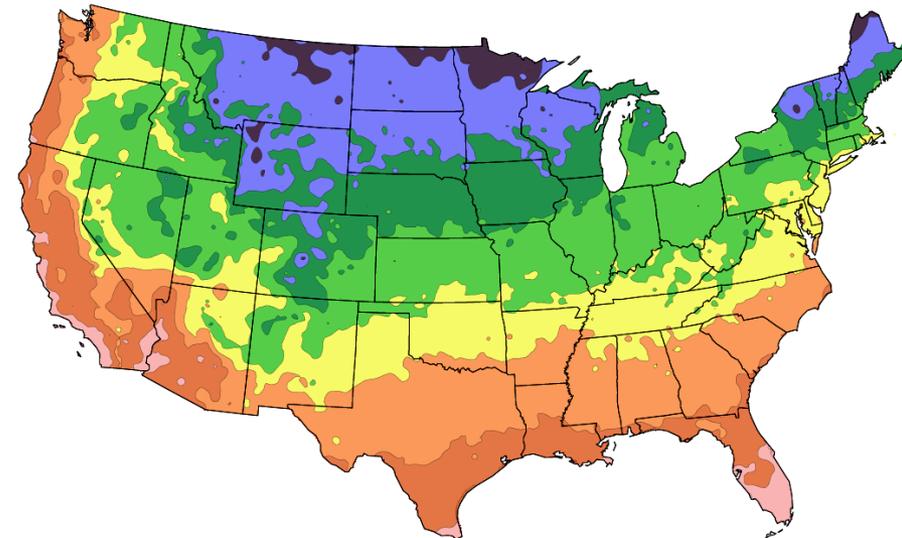
Hardiness zones adjusted to warmer climate

1990 Map



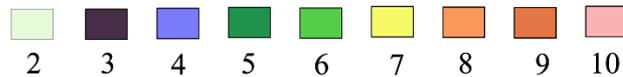
After USDA Plant Hardiness Zone Map, USDA Miscellaneous Publication No. 1475, Issued January 1990.

2006 Map

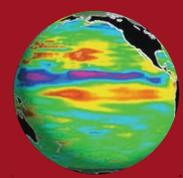


National Arbor Day Foundation Plant Hardiness Zone Map published in 2006.

Zone

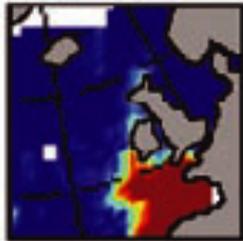


Source: National Arbor Day Foundation



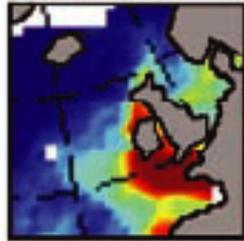
Replacement of marine copepod plankton communities in NE Atlantic

southern shelf-edge species



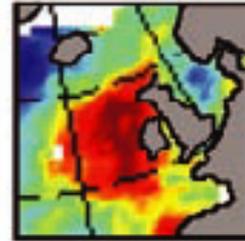
1960-1975

pseudo-oceanic temperate species



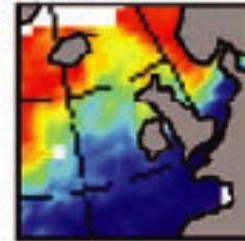
1960-1975

cold-temperate species

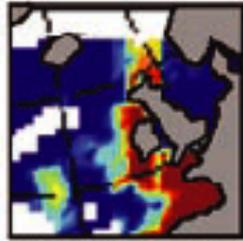


1960-1975

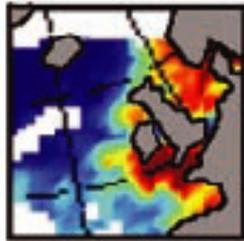
Subarctic species



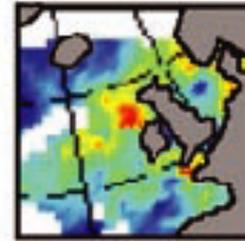
1960-1975



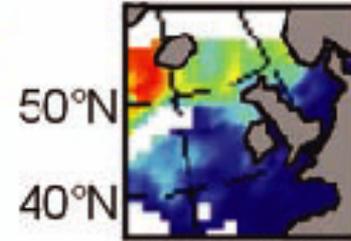
1996-1999



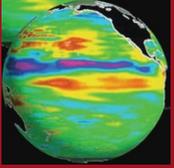
1996-1999



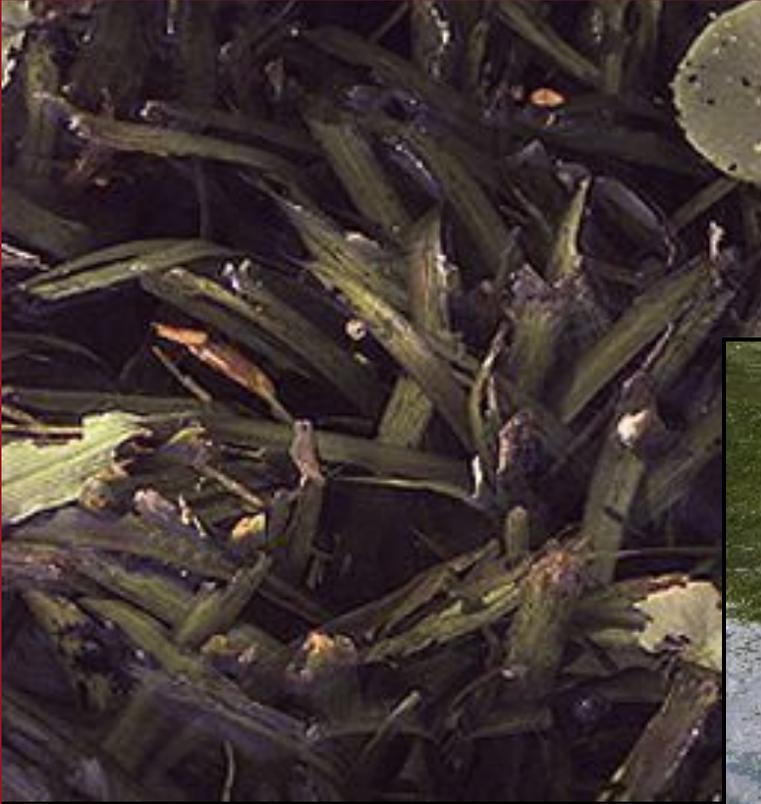
1996-1999

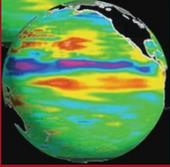


1996-1999



Eelgrass





Chesapeake Bay

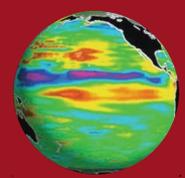


- Largest estuary in the United States

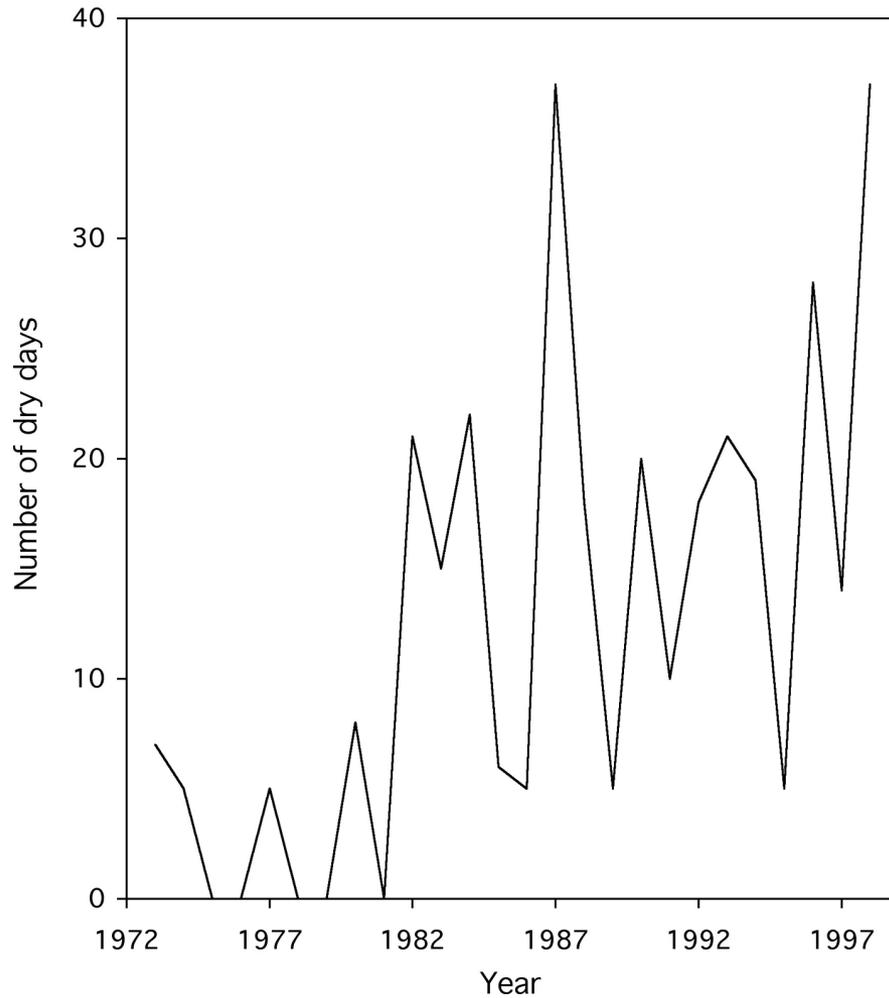
- In 2006 Underwater grasses decreased by 25% Baywide

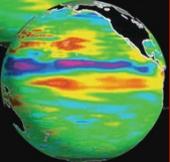
- Decrease from 78,263 acres in 2005 to 59,090 acres in 2006





Increasing number of dry days



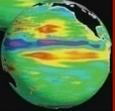


Decoupling

Snowshoe Hare (*Lepus Americanus*)



Photos: University of Michigan

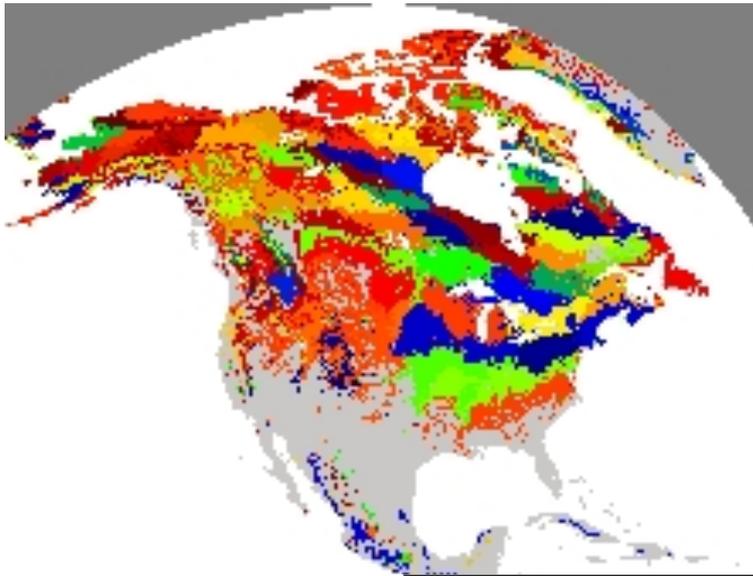


Decoupling: Arctic cod and black guillemot



Source: www.sfos.uaf.edu/research/seaicebiota





Biological Response

Phenological changes attributed to recent climate change

White et al. (2004)



McCarty (2001)

<i>Variable observed</i>	<i>Species observed</i>	<i>Change</i>	<i>Time span^b (years)</i>	<i>Reference</i>
Geographic range	59 bird species	18.9 km	20	C. D. Thomas & Lennon
Geographic range	Edith's checkerspot butterfly	92 km	100	Parmesan 1996
Geographic range	speckled wood butterfly	88-149 km	55	Hill et al. 1999
Geographic range	22 butterfly species	35-240 km	30-100	Parmesan et al. 1999
Elevational range	9 plant species	70-360 m	70-90	Grabherr et al. 1994
Breeding range	Adelie Penguin	3 km	10	Taylor & Wilson 1990
Flowering date	6 wildflower species	19.8 days	50	Oglesby & Smith 1995
Flowering date	36 species	8.2 days	61	Bradley et al. 1999
Flight period	5 aphid species	3-6 days	25	Fleming & Tatchell 199
Spawning date	2 frog species	14-21 days	17	Beebee 1995
Breeding migration	3 newt species	35-49 days	17	Beebee 1995
Breeding date	20 bird species	8.8 days	25	Crick et al. 1997
Breeding date	3 bird species	3-9 days	25	Winkel & Hudde 1997
Breeding date	Pied Flycatcher	13 days	24	Slater 1999
Breeding date	Tree Swallow	5-9 days	33	Dunn & Winkler 1999
Breeding date	Great Tit	11.9 days	27	McCleery & Perrins 199
Breeding date	2 bird species	30 days	35	MacInnes et al. 1990
Breeding date	Mexican Jay	10.1 days	27	Brown et al. 1999
Migration date	4 bird species	11.9 days	50	Mason 1995
Migration date	39 bird species	5.5 days	50	Oglesby & Smith 1995
Migration date	American Robin	14 days	19	Inouye et al. 2000
Migration date/first song	19 bird species	4.4 days	61	Bradley et al. 1999
End of hibernation	yellow-bellied marmot	23 days	23	Inouye et al. 2000
Growing season	Europe	10.8 days	34	Menzel & Fabian 1999
Growing season	northern hemisphere	12 ± 4 days	9	Myneni et al. 1997
Growing season	northern hemisphere	7 days	20	Keeling et al. 1996

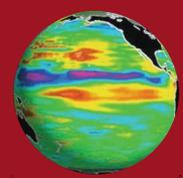
Looking ahead



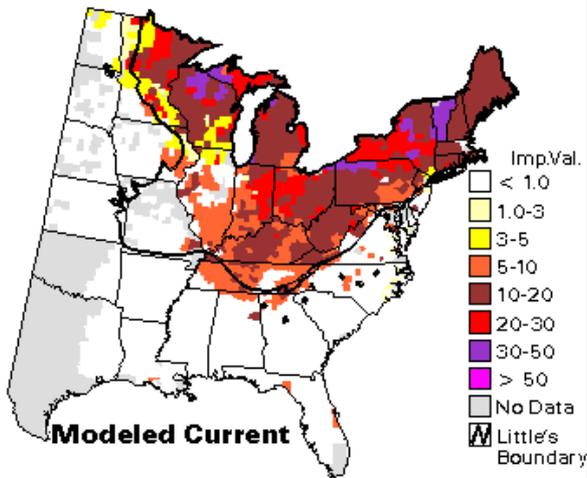
Jaan Lepson

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Sugar Maple range projections by 5 GCMs with 2 x CO₂



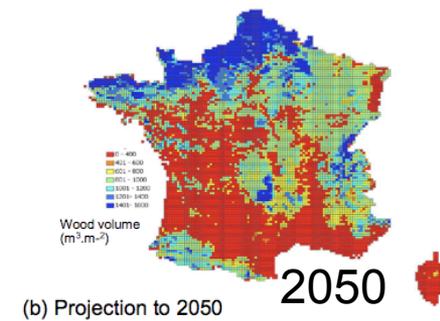
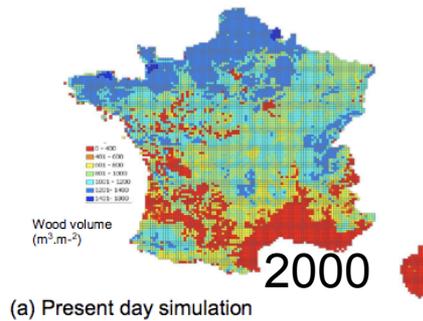
Shifts in species distributions are likely to be large

Climate change impacts on European beech

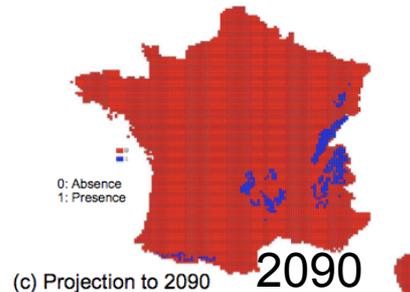
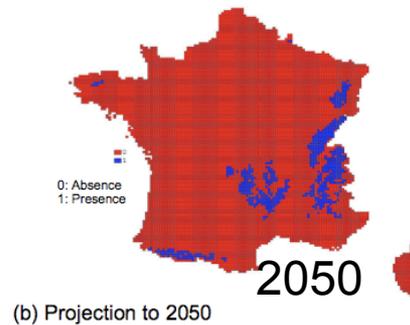
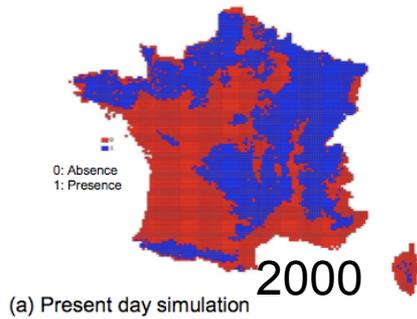
Niche-based model

BIOMOD
W. Thuille

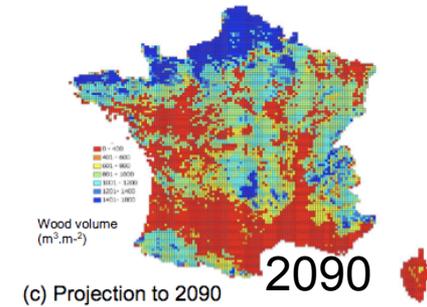
Castanea projections to 2050 and to 2090 for *Fagus sylvatica*



Biomod projections to 2050 and to 2090 for *Fagus sylvatica*

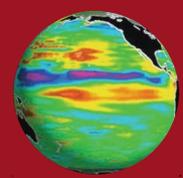


Blue = presence
Red = absence



Mechanistic tree growth model

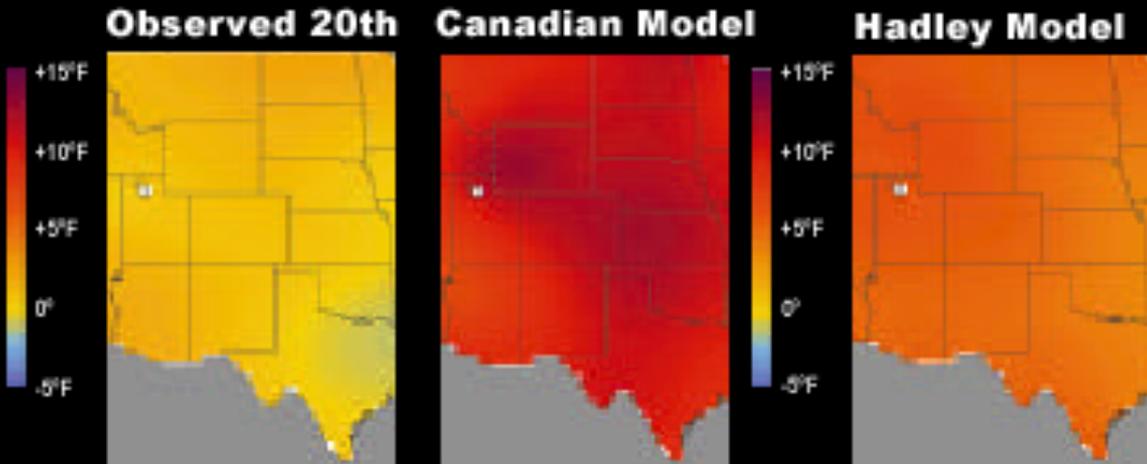
CASTANEA
A Cheaib,
C François,
E Dufrêne



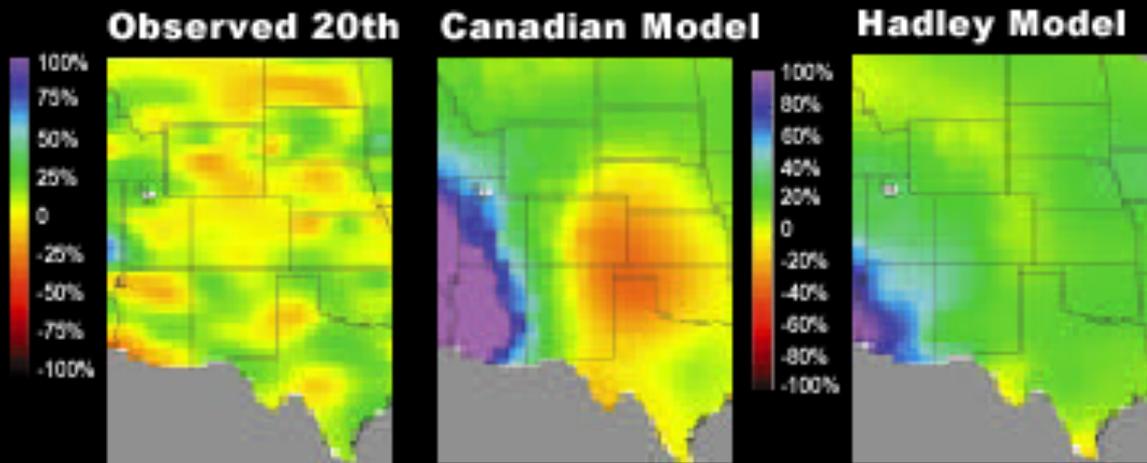
Climate Change includes precipitation change

Projected changes for 2090

Temperature



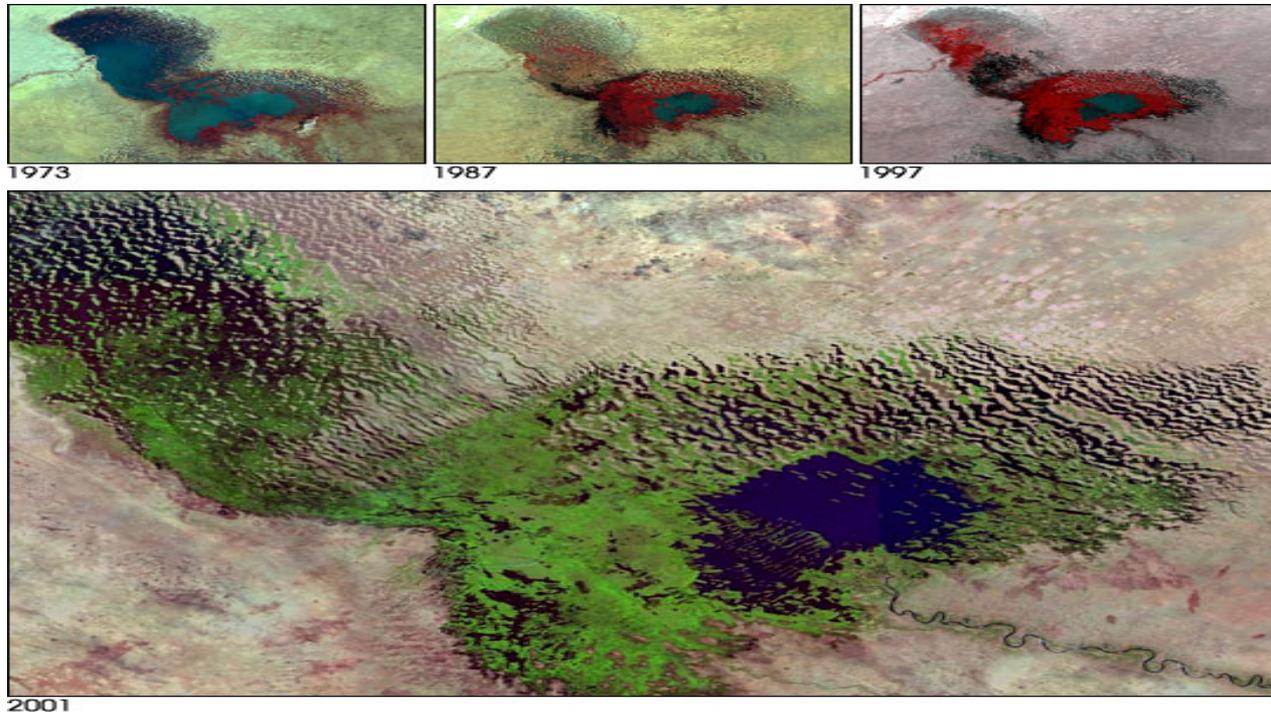
Precipitation

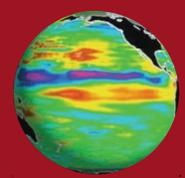


Lake Chad Basin



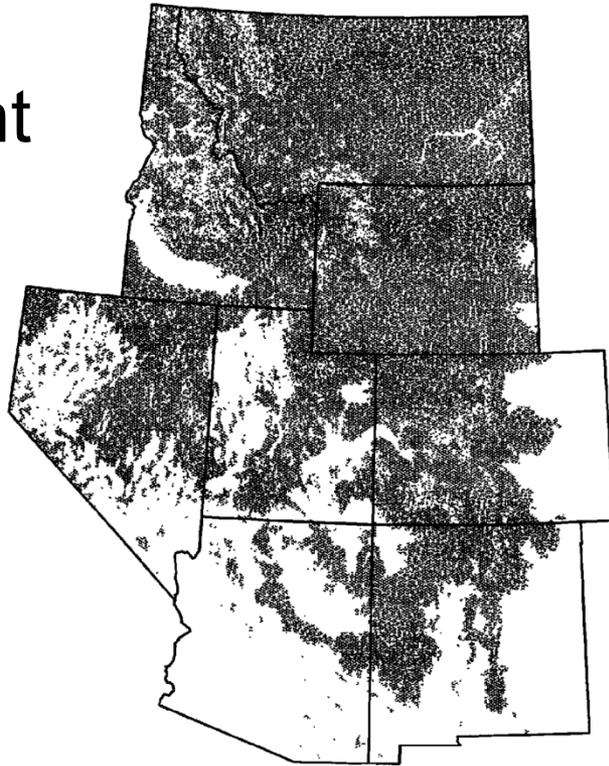
**Lake Chad is 1/20th
the size it was 35
years ago**



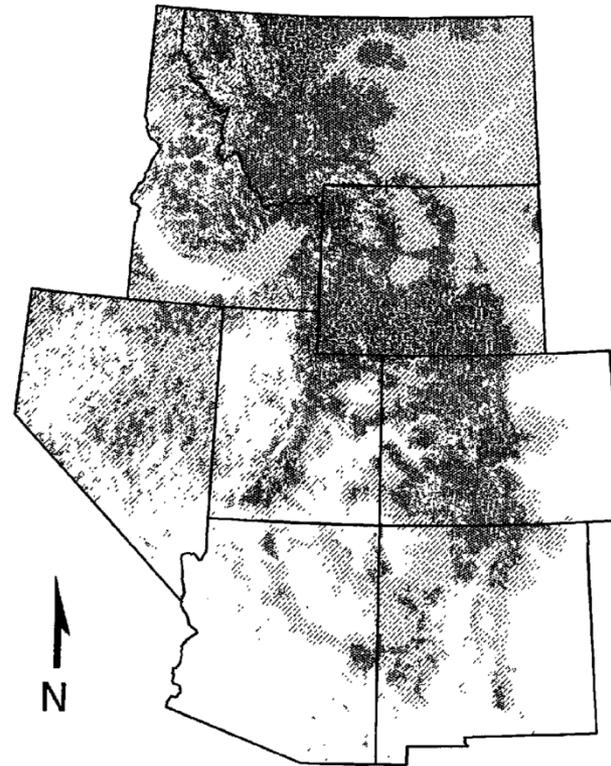


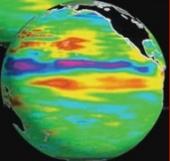
Loss of stream segments able to support cold-water trout

Present



+3°C





American pika (*Ochotona princeps*)



Spatial Pattern of Species Richness

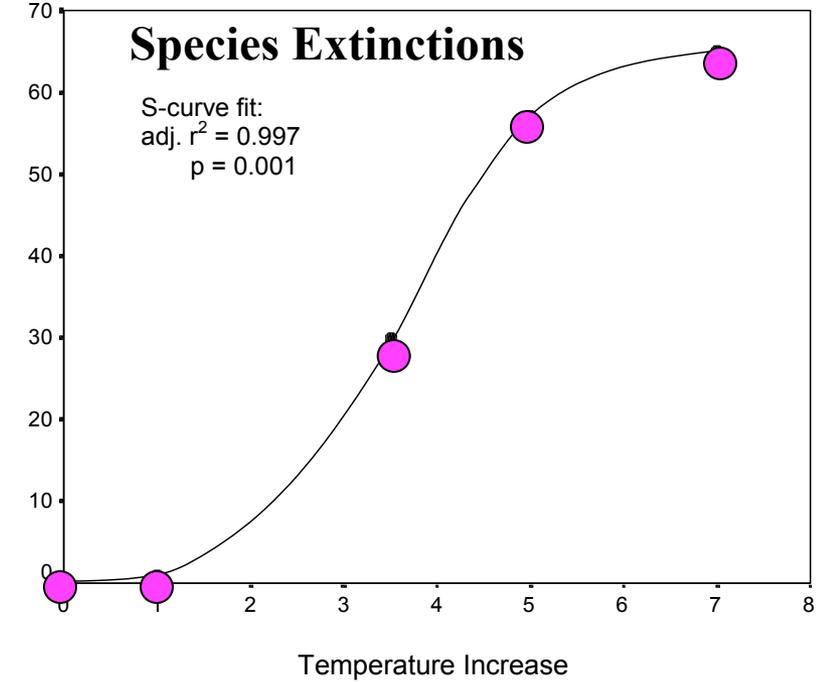
Dark red = high species richness



Williams et al. 2003. Proc Roy Soc Lond. B: 270:1887-1892

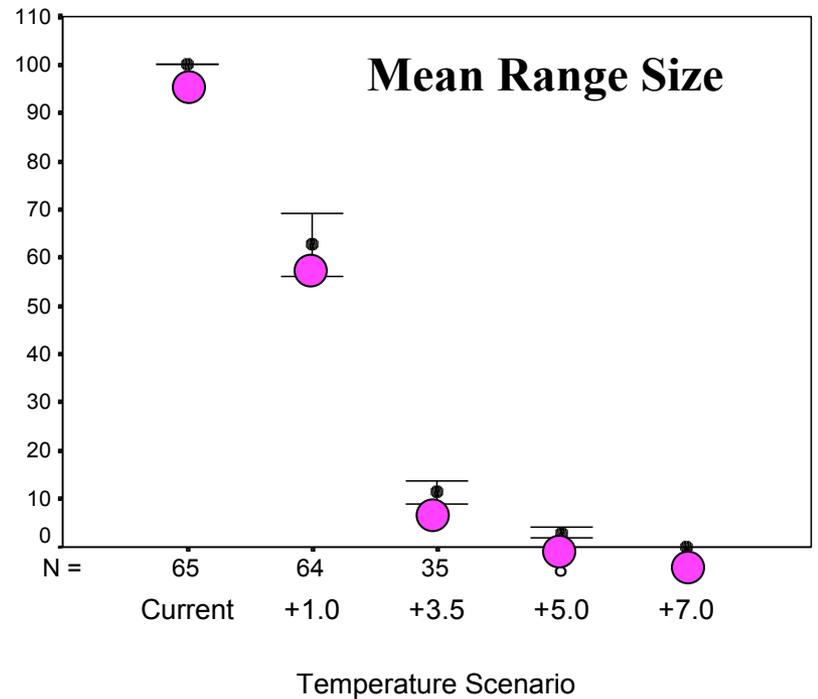
Species Extinctions

S-curve fit:
adj. $r^2 = 0.997$
 $p = 0.001$



Temperature Increase

Mean Range Size



N =

65

64

35

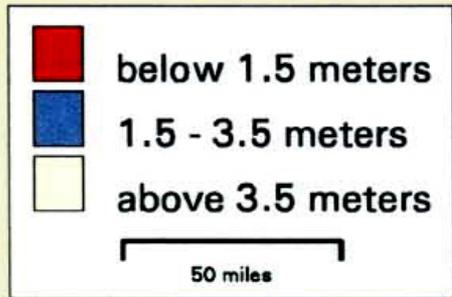
8

8

Temperature Scenario

Slide courtesy of Stephen Williams

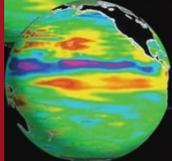
Sea Level Rise in the Next 100 Years



Whooping Crane
habitat



*Many
important
places on the
Texas Coast
will disappear*



Key Deer

National Key Deer Refuge

Big Pine Key, Florida

•84,000 acres, Established 1957

Population Low:

27 in 1957

Population today:

Between 700 and 800

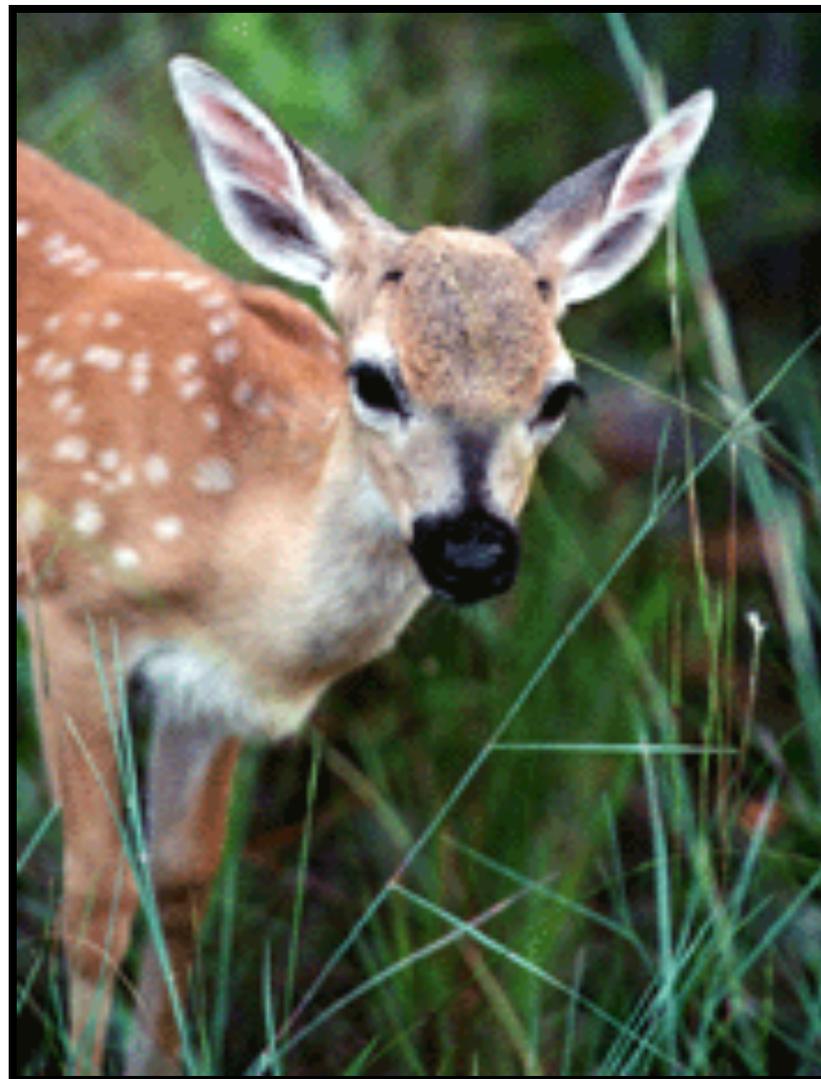


Photo courtesy of National Key Deer Refuge



Complications

1

**Landscape is human dominated
& habitat is fragmented**

2

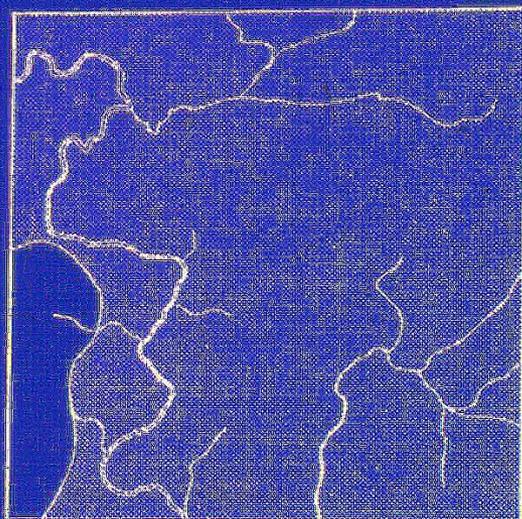
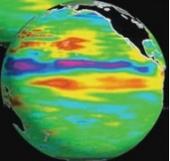
Species don't move together

3

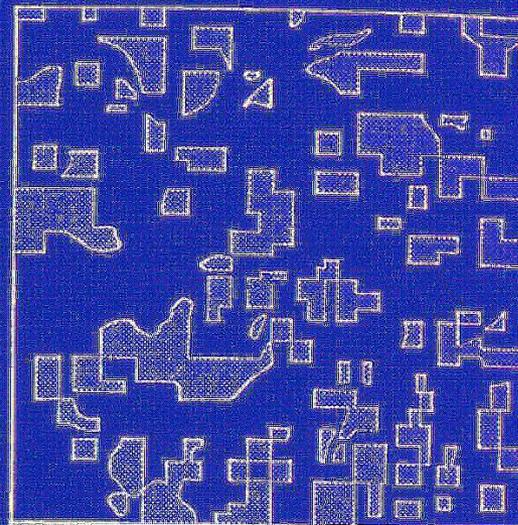
Change will not be linear or gradual

4

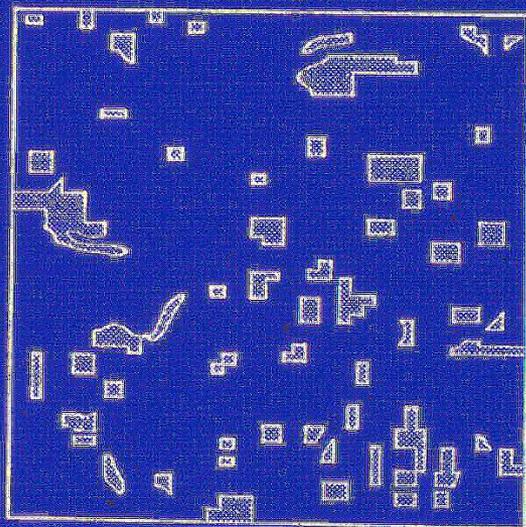
System change



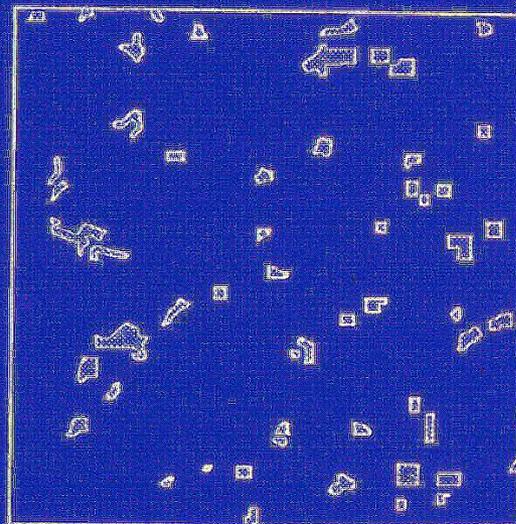
1831



1882



1902



1950

FIGURE 1. Reduction and fragmentation of the woodland in Cadiz Township, Wisconsin, 1831-1950. (After Curtis, 1956.)

Complications

1

**Landscape is human dominated
& habitat is fragmented**

2

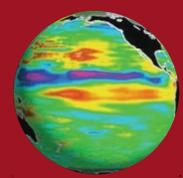
Species don't move together

3

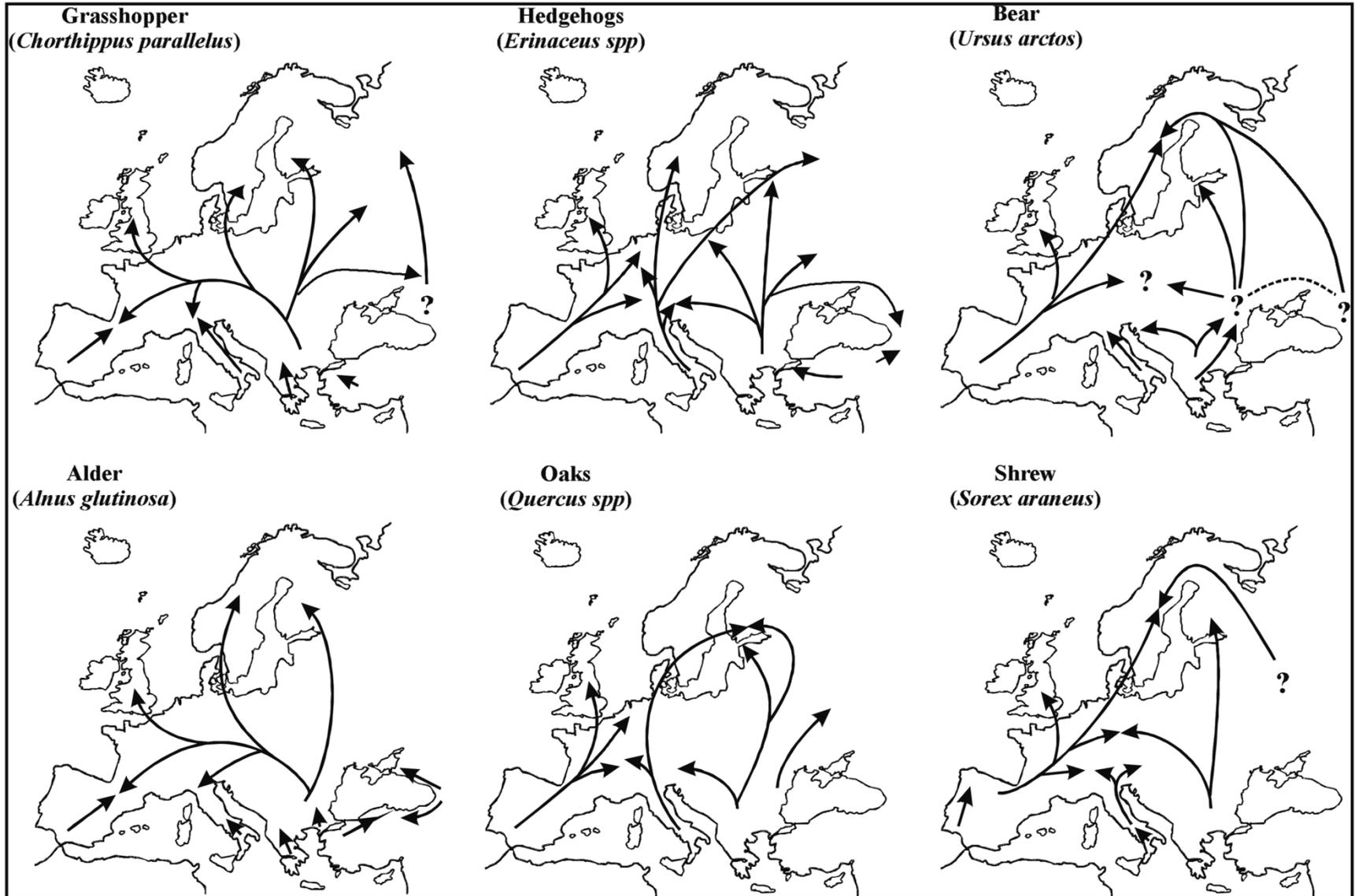
Change will not be linear or gradual

4

System change



Ecosystems disassemble and species reassemble into new ecosystems



Source: G.M. Hewitt and Nichols, R.A. 2005

Complications

1

**Landscape is human dominated
& habitat is fragmented**

2

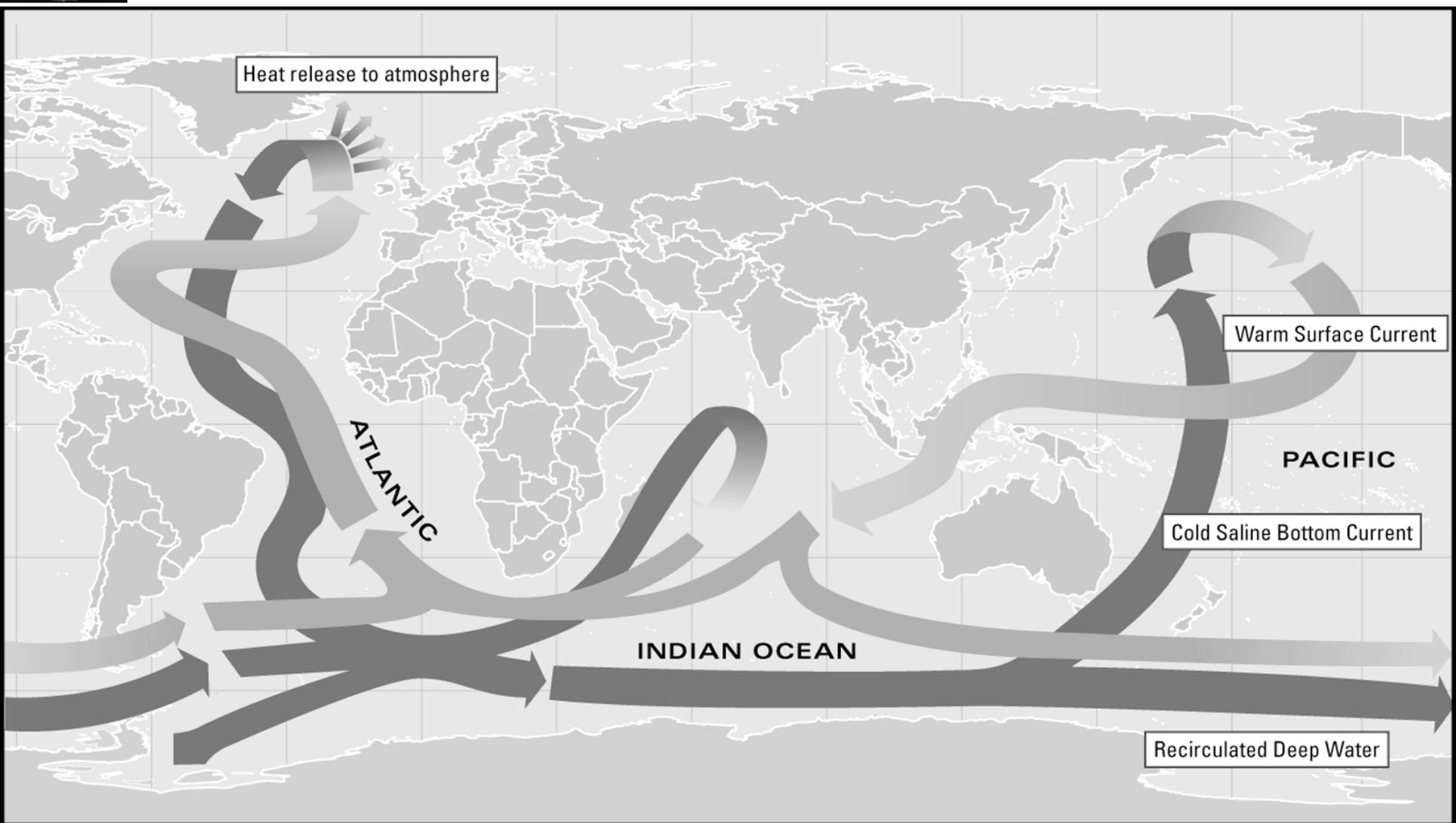
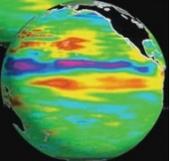
Species don't move together

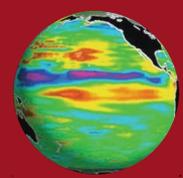
3

Change will not be linear or gradual

4

System change





Elevated night time temperatures magnify bark beetle impact

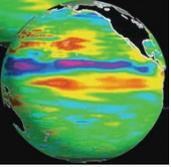
The Washington Post

Wednesday, March 1, 2006

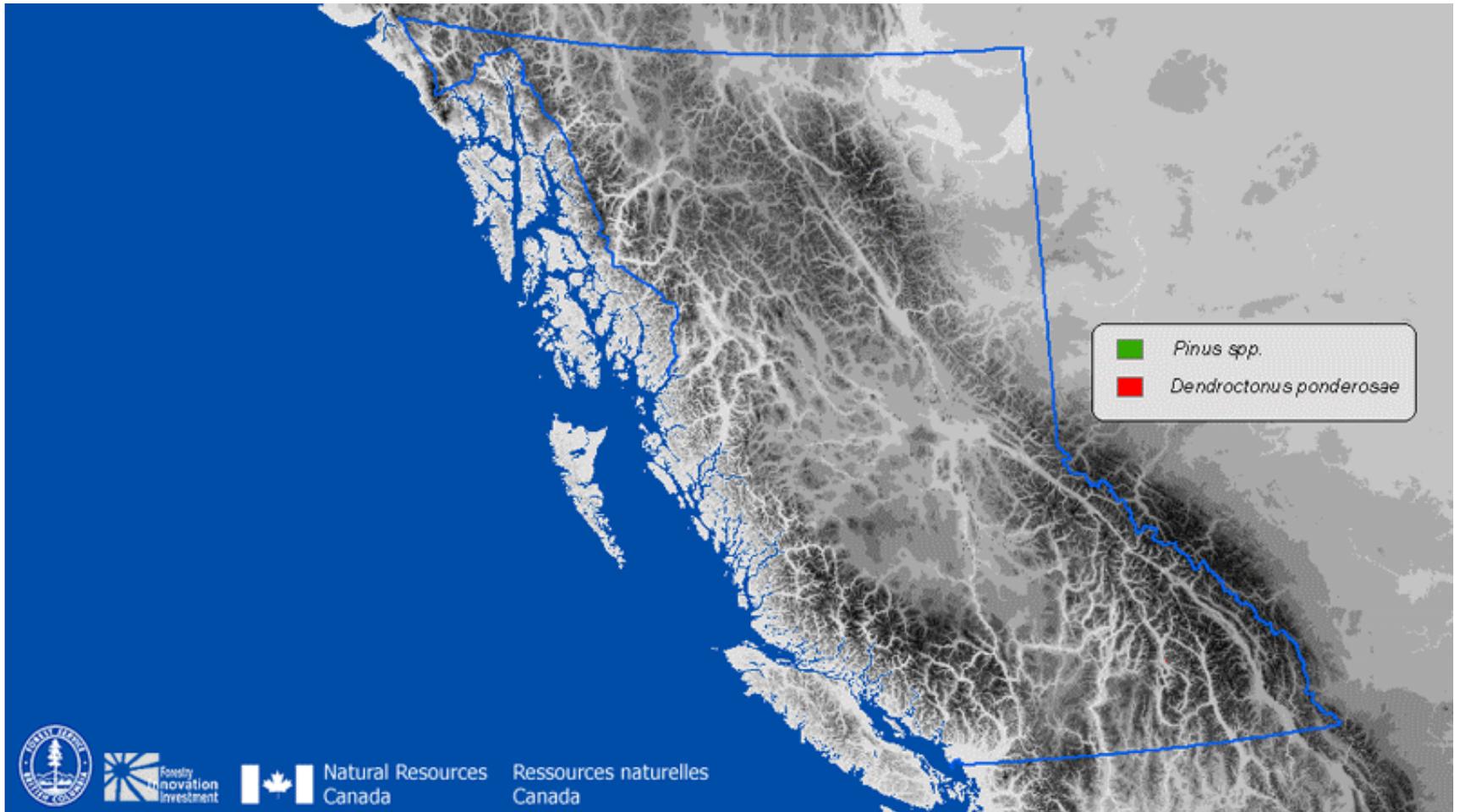
‘Rapid Warming’ Spreads Havoc in Canada’s Forests

QUESNEL, B.C. -- Millions of acres of Canada's lush green forests are turning red in spasms of death. A voracious beetle, whose population has exploded with the warming climate, is killing more trees than wildfires or logging.





Mountain Pine Beetle outbreaks (1959-2002)



Courtesy of Mike Bradley, Canfor Corporation





Complications

1

**Landscape is human dominated
& habitat is fragmented**

2

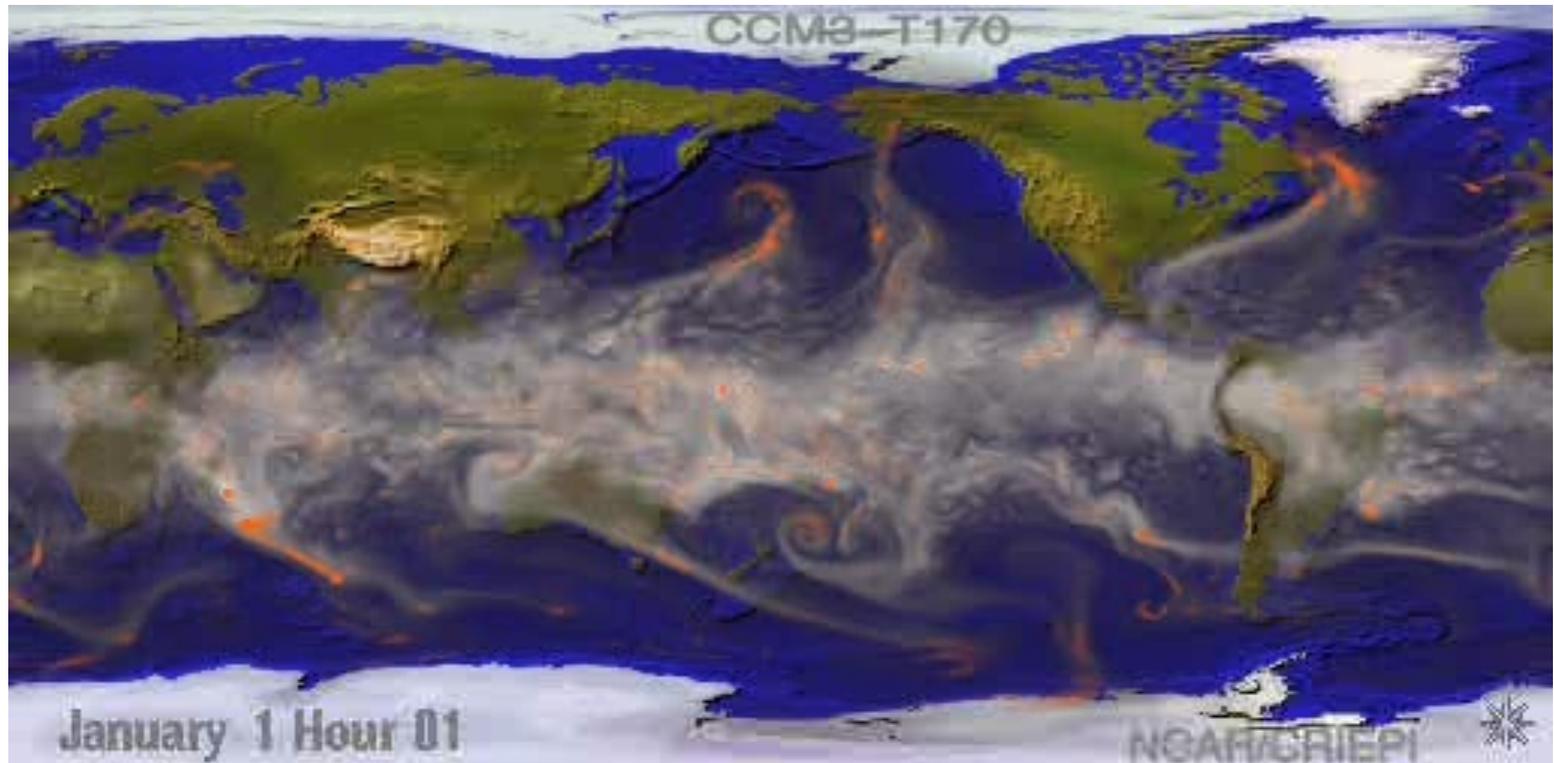
Species don't move together

3

Change will not be linear or gradual

4

System change

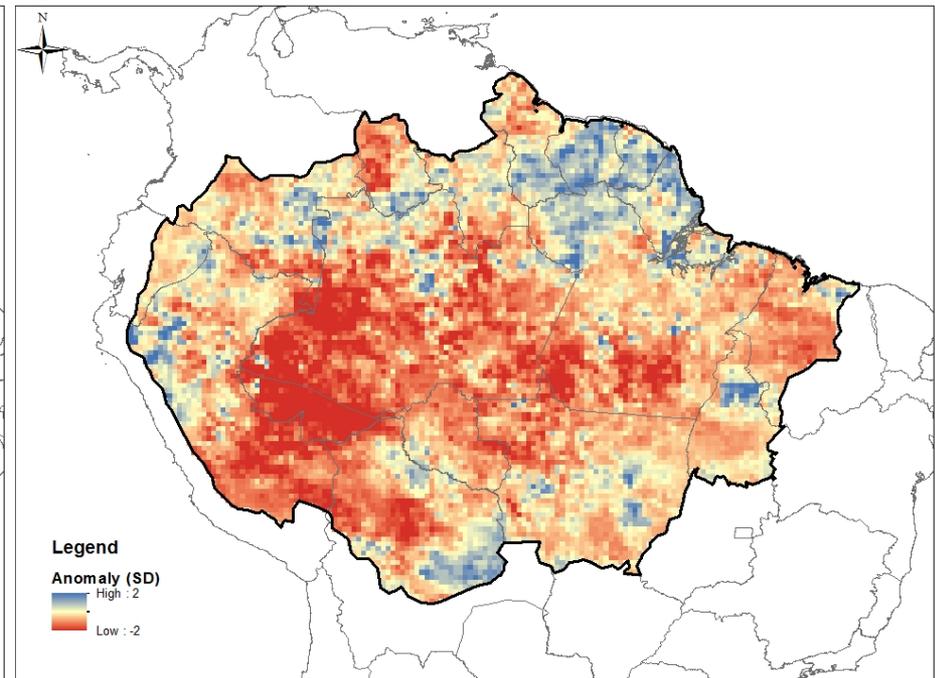
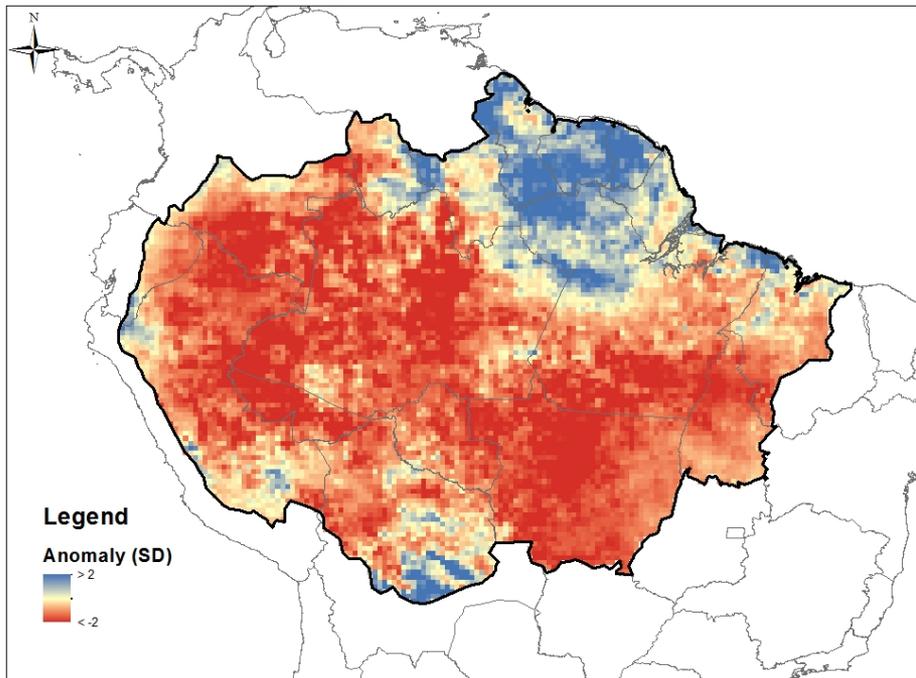


Courtesy of NOAA/NCAR

Amazon Rainfall in 2010 and 2005 (deviation from 10-year mean)

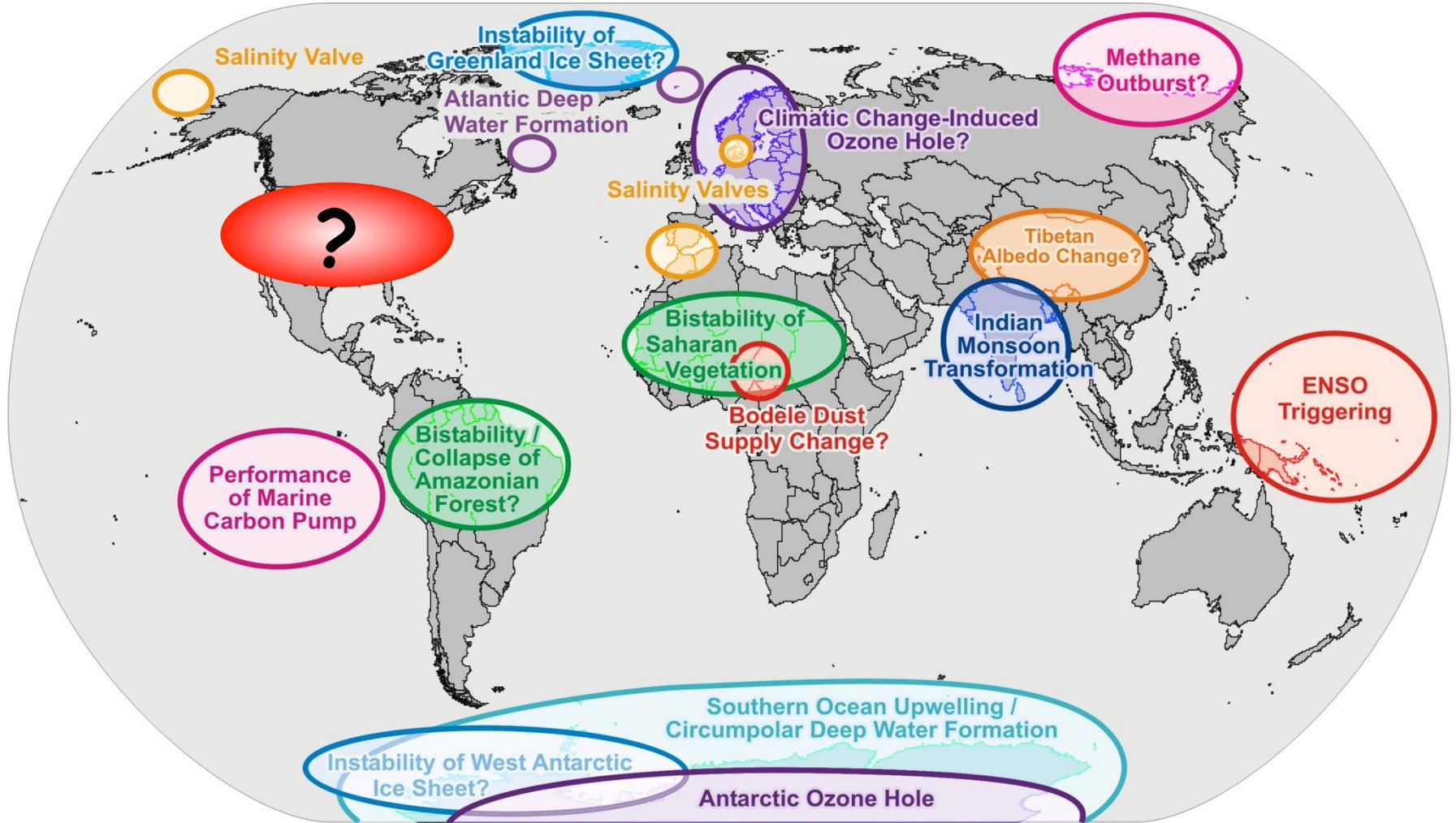
2010

2005





Critical thresholds in the Earth system



Where local or regional changes may have strong effects on earth system interactions, feedbacks, or teleconnections

Oceans II ■ By Thomas E. Lovejoy

Rising acidity threatens marine life

WASHINGTON

The problems of acid rain and acid lakes, which came to public attention in the 1980s, have been addressed to a considerable degree. Today we face a far more profound challenge: increasingly acid oceans.

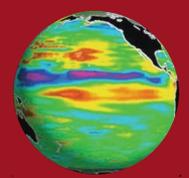
It is little known outside of scientific circles that a fundamental change has already taken place in the chemistry of the two thirds of the earth's surface occupied by oceans. The change, of 0.1 of a pH unit, sounds trivial when expressed in the logarithmic scale that science uses, but it translates to the upper layers of the oceans already being 30 percent more acid than in preindustrial times.

The change is being caused by increased atmospheric levels of greenhouse gases, in particular carbon dioxide. In addition to forcing climate change, more carbon dioxide combines with water and produces carbonic acid.

The consequences for marine ecosystems are only beginning to be understood but are bound to be far-reaching.

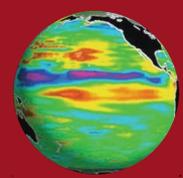


Tom Ondway/Jean-Michel Cousteau Productions via AP



Acidifying oceans are a challenge for species using calcium carbonate





Acidifying oceans are a challenge for species at the base of the marine food chain





a pteropod, or sea butterfly, is a type of planktonic mollusk

Deteriorating chemical condition for coral reefs

40-550ppm

In the pre-industrial ocean, 99.8% of coral reefs were near water with $\Omega_{\text{aragonite}} > 3.25$

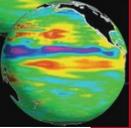
Under a 550 ppm atmosphere, < 2% of coral reefs will be near water with $\Omega_{\text{aragonite}} > 3.25$



Corrosive to coral reefs

$\Omega_{\text{aragonite}}$

Optimal for coral reefs



Why is a CO₂ target of 450ppm too high ?

Two degrees is too much



- (1) Arctic sea-ice
- (2) Greenland ice-sheet stability
- (3) Antarctic ice-sheet stability
- (4) Major ecosystem disruption

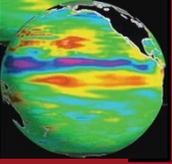
Ice-sheet collapse and sea-level rise

Last time Earth was 2°C warmer, sea-level was 4-6m higher



- At today's level of 387ppm CO₂, reefs are seriously declining and time-lagged effects will result in their continued demise with parallel impacts on other marine and coastal ecosystems.
- Proposals to limit CO₂ levels to 450ppm will not prevent the catastrophic loss of coral reefs from the combined effects of climate change and ocean acidification.
- To ensure the long-term viability of coral reefs atmospheric carbon dioxide level must be reduced significantly below 350ppm.

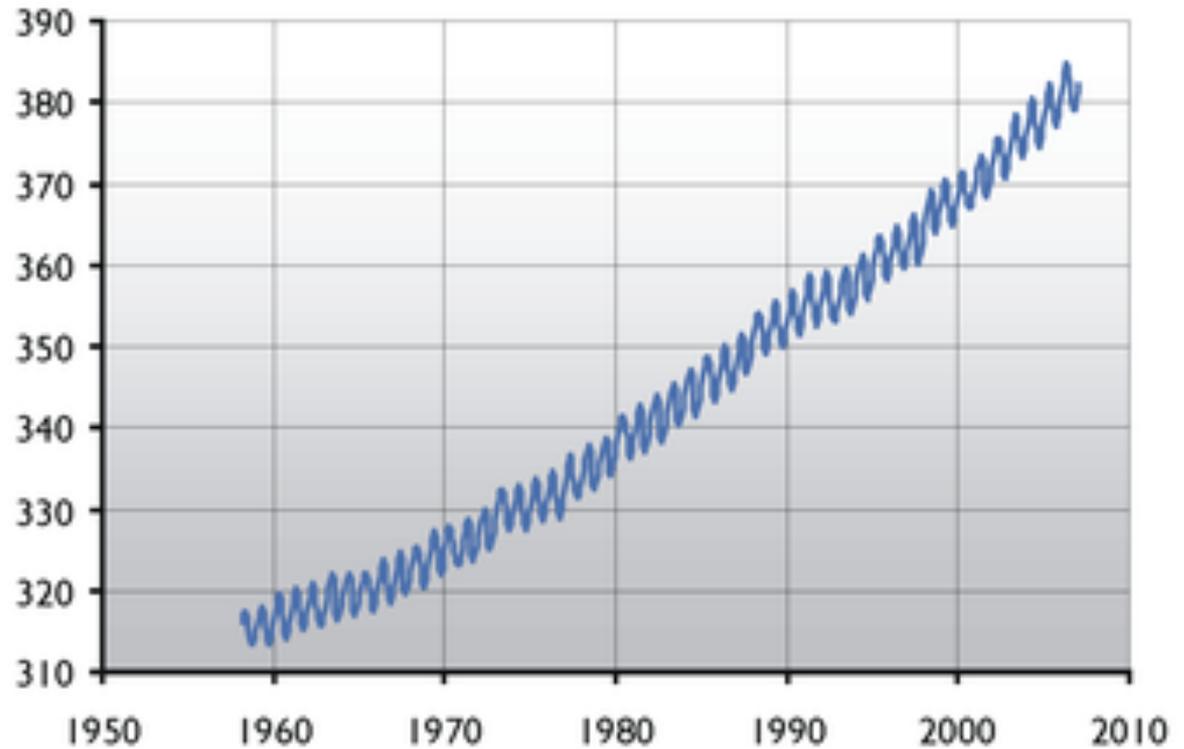
**Royal Society Meeting,
July 6th 2009**



What is a “safe” level?

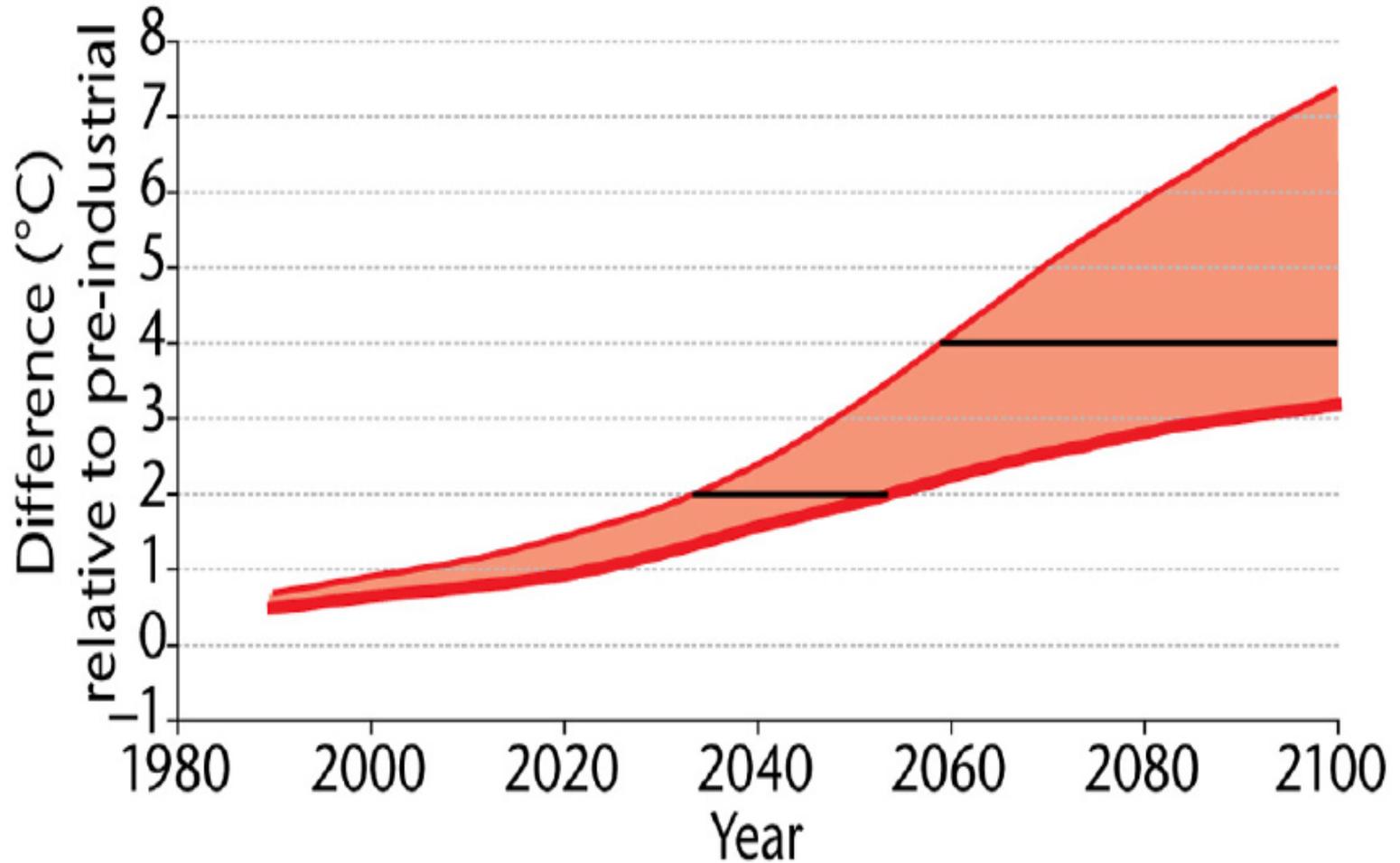
**James Hansen,
et al., 2008**

350 ppm



Projected temperature rise

for A1B & A1F1 scenarios (Hadley, 2009)



What can be done

Adaptation

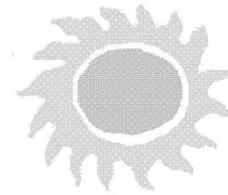
-Revise Conservation Strategies

Limit Greenhouse Gas Concentrations

-Reduce and eliminate emissions

--*revise energy base for society*

--*reduce/eliminate deforestation*





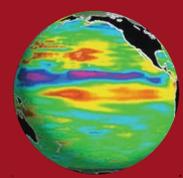
What can be done to reduce impacts?

Mitigation

- Reduction of greenhouse gas emissions or enhancement of carbon sequestration (in the subsurface or in ecosystems)

Adaptation

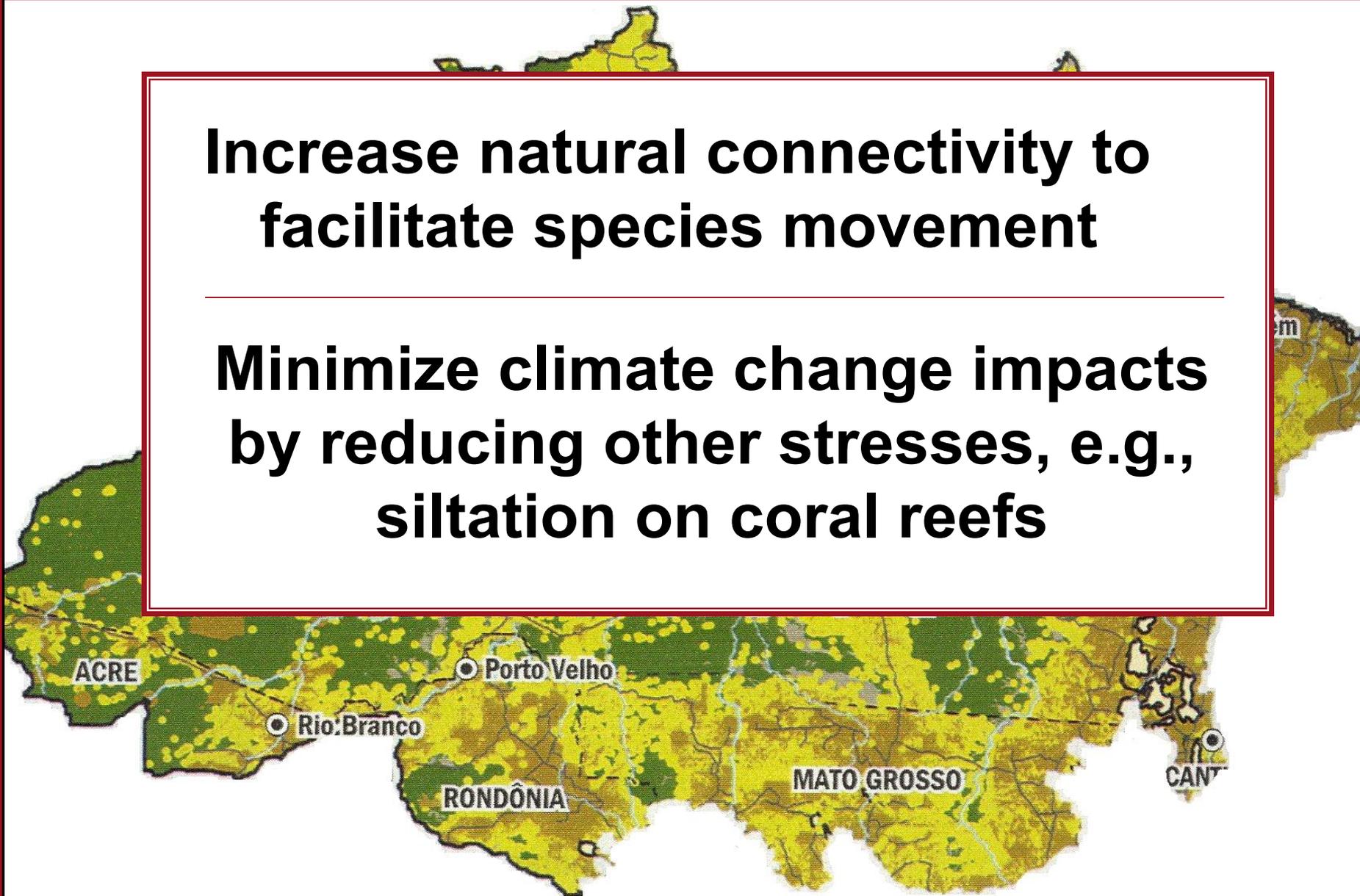
- Purposeful actions taken to reduce undesirable effects or enhance positive effects of climate change



Adaptation: Revise conservation strategies

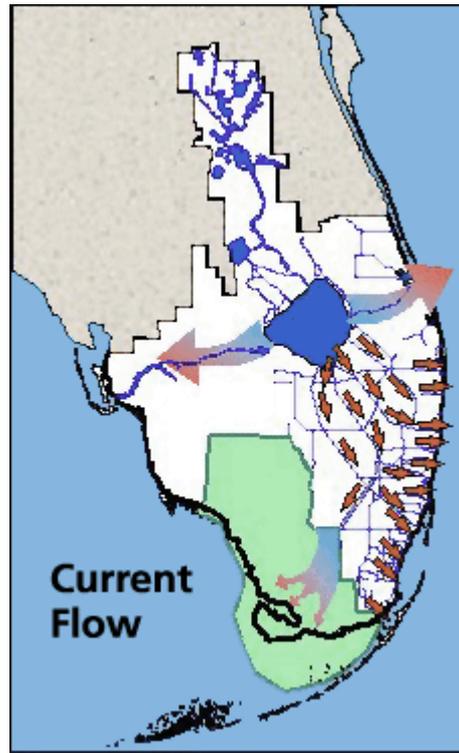
Increase natural connectivity to facilitate species movement

Minimize climate change impacts by reducing other stresses, e.g., siltation on coral reefs



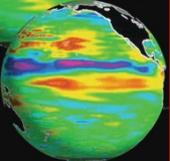
Adaptation: one example

Restore/maintain coastal ecosystems, enhance their capacity to buffer against storm surge



Comprehensive Everglades Restoration Plan

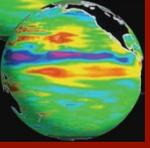




Limit Greenhouse Gas Concentrations

Revise Energy Base for Society





Limit Greenhouse Gas Concentrations

20% of Annual Emissions come from deforestation



1.5 Pg C y⁻¹



7.5 Pg C y⁻¹

+



4.2 Pg y⁻¹
Atmosphere

46%



2.6 Pg y⁻¹

Land

29%

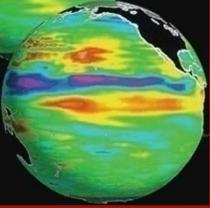


2.3 Pg y⁻¹

Oceans

26%





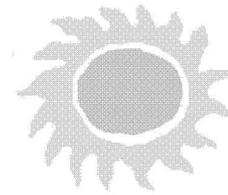
Long atmospheric residence times for greenhouse gases

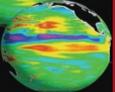


What can be done

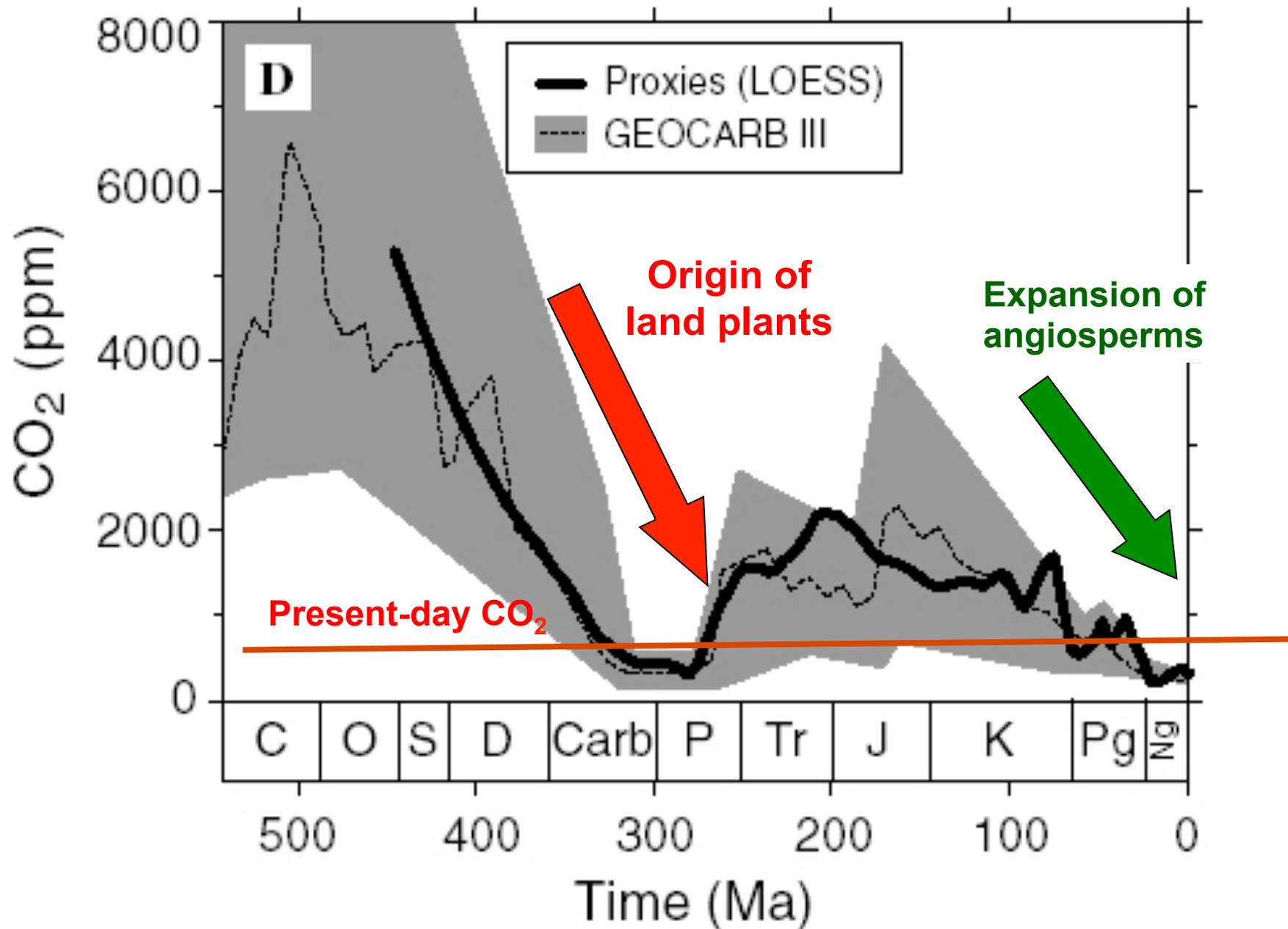
Lower Atmospheric CO₂

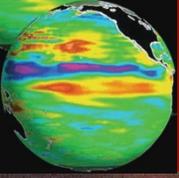
- Restore ecosystems
(biodiversity and carbon)
- Non-biological CO₂ removal





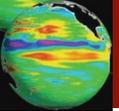
The Role of Life Processes



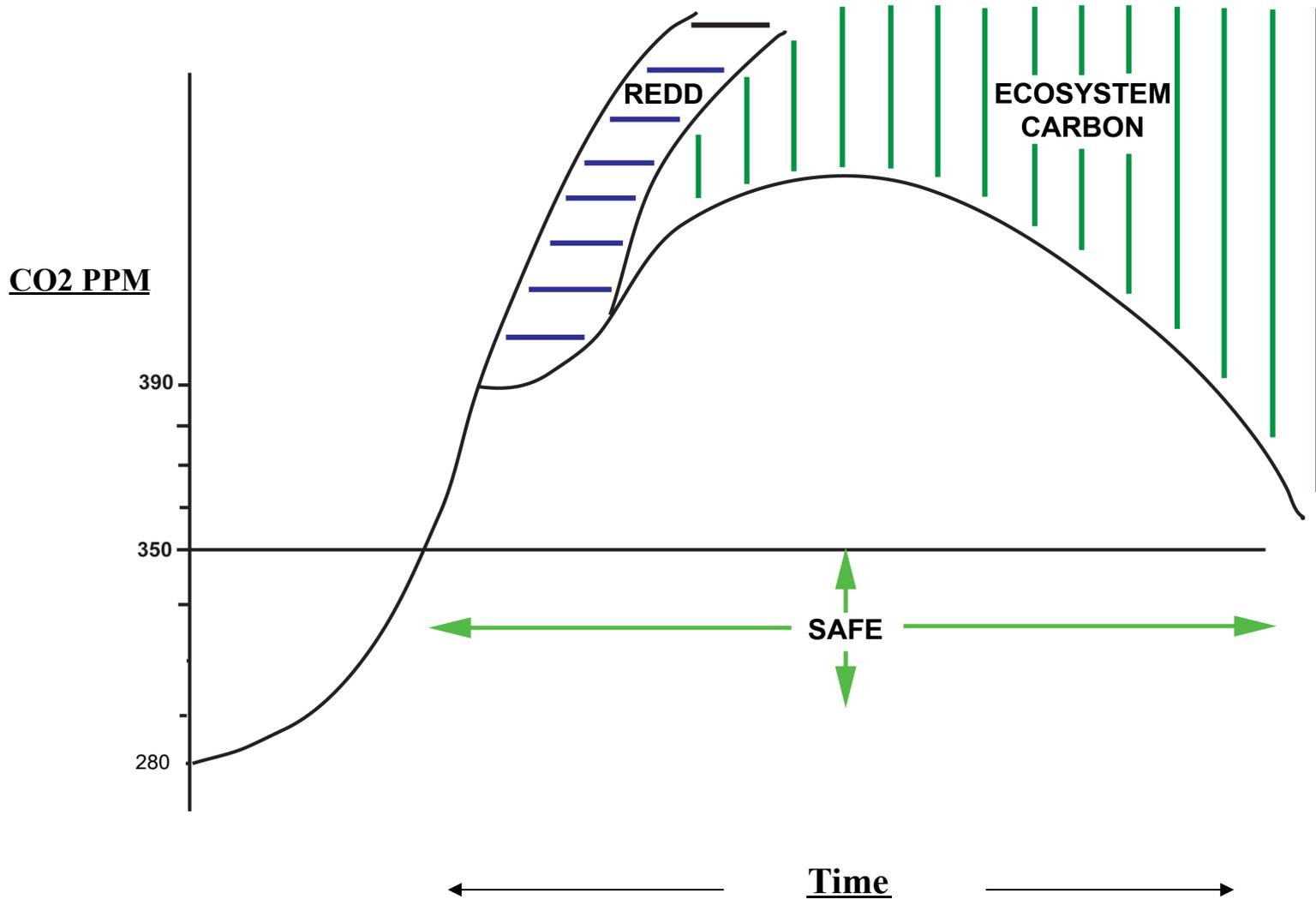


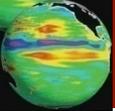
**Over the past three centuries, ecosystems have lost
200-250 billion tons of carbon**





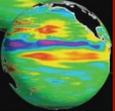
Planetary Engineering Using Ecosystems





The Role of Forests

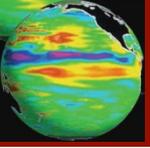




Restoring Grazing Land



Photo courtesy USDA NRCS



Modify Agriculture to Build up Soil Carbon



Photos: United States Department of Agriculture—Natural Resources Conservation Service.



Re-Greening the Emerald Planet



Image courtesy of NASA
Satellite imagery provided by NASA
and the Earth Observing Satellite
Data Center (EOS-02)

ELUGS

Environmental Leadership
University of Georgia
Athens, GA



