A Wild Solution for Climate Change
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Planetary Boundaries

Dr. Svante August Arrhenius
1859-1927
Analysis of a Greenland ice core oxygen isotope proxy

Source: Wallace Broecker
The graph shows the concentration of CO₂ for the last 600,000 years. Currently, the CO₂ concentration is 385 ppm. The graph is based on research by Siegenthaler U et al. (2005) Science 310:1313 and 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

CO₂ Emissions (GtC y⁻¹)


Actual emissions: CDIAC
Actual emissions: EIA
450ppm stabilisation
650ppm stabilisation
A1FI (Avgs.)
A1B
A1T
A2
B1
B2

SRES (2000) aver. growth rates in % y⁻¹ for 2000-2010:
A1B: 2.42
A1FI: 2.71
A1T: 1.63
A2: 2.13
B1: 1.79
B2: 1.61

Observed 2000-2007 3.5%

Global Carbon Project; Raupach et al 2007, PNAS (updated)
Signals from nature

The H. John Heinz III Center for Science, Economics and the Environment
Warming trend in 37 of 39 Northern Hemisphere lakes and rivers

Grinnell Glacier, Glacier National Park
Late summer of 1938 (left) and 1981 (right)

Source: http://nrmsc.usgs.gov/research/glacier_retreat.htm
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

Blackwater National Refuge, Maryland

Photo Courtesy of NOAA
Probable Increased Frequency of More Intense Tropical Cyclones

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.
### Advances in flower opening since the 1980s

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

*Kew Magazine, Summer 2007*
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

Source: Camille Parmesan
Edith’s Checkerspot

- Range shift northward and upward during the 20th century
- Most extinctions in south and low elevations
Hardiness zones adjusted to warmer climate

1990 Map

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

Source: Beaugrand et al. Science 2002
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

Source: J.A. Pounds et al 2005
Decoupling

Snowshoe Hare (*Lepus Americanus*)

Photos: University of Michigan
Decoupling: Arctic cod and black guillemot

Source: www.sfos.uaf.edu/research/sealicebiota
Biological Response

Phenological changes attributed to recent climate change

<table>
<thead>
<tr>
<th>Variable observed</th>
<th>Species observed</th>
<th>Change</th>
<th>Time spent (years)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geographic range</td>
<td>59 bird species</td>
<td>18.9 km</td>
<td>20</td>
<td>C. D. Thomas &amp; Lennon</td>
</tr>
<tr>
<td>Geographic range</td>
<td>Edith’s checkerspot butterfly</td>
<td>92 km</td>
<td>100</td>
<td>Parmesan 1996</td>
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<tr>
<td>Geographic range</td>
<td>speckled wood butterfly</td>
<td>88-149 km</td>
<td>55</td>
<td>Hill et al. 1999</td>
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<tr>
<td>Geographic range</td>
<td>22 butterfly species</td>
<td>35-240 km</td>
<td>30-100</td>
<td>Parmesan et al. 1999</td>
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<tr>
<td>Elevational range</td>
<td>9 plant species</td>
<td>70-300 m</td>
<td>70-90</td>
<td>Grabherr et al. 1994</td>
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<tr>
<td>Breeding range</td>
<td>Adelie Penguin</td>
<td>3 km</td>
<td>10</td>
<td>Taylor &amp; Wilson 1990</td>
</tr>
<tr>
<td>Flowering date</td>
<td>6 wildflower species</td>
<td>19.8 days</td>
<td>50</td>
<td>Oglesby &amp; Smith 1995</td>
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<td>Flowering date</td>
<td>36 species</td>
<td>8.2 days</td>
<td>61</td>
<td>Bradley et al. 1999</td>
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<tr>
<td>Flight period</td>
<td>5 aphid species</td>
<td>3-6 days</td>
<td>25</td>
<td>Fleming &amp; Tatchell 1999</td>
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<tr>
<td>Spawning dates</td>
<td>2 frog species</td>
<td>14-21 days</td>
<td>17</td>
<td>Beebee 1995</td>
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<tr>
<td>Breeding migration</td>
<td>3 newt species</td>
<td>35-49 days</td>
<td>17</td>
<td>Beebee 1995</td>
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<tr>
<td>Breeding date</td>
<td>20 bird species</td>
<td>8.8 days</td>
<td>25</td>
<td>Crick et al. 1997</td>
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<tr>
<td>Breeding date</td>
<td>3 bird species</td>
<td>3-9 days</td>
<td>26</td>
<td>Winkelman &amp; Hulke 1997</td>
</tr>
<tr>
<td>Breeding date</td>
<td>Pied Flycatcher</td>
<td>13 days</td>
<td>24</td>
<td>Slater 1999</td>
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<tr>
<td>Breeding date</td>
<td>Tree Swallow</td>
<td>5-9 days</td>
<td>35</td>
<td>Duan &amp; Winkler 1999</td>
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<tr>
<td>Breeding date</td>
<td>Great Tit</td>
<td>11.9 days</td>
<td>27</td>
<td>McCleery &amp; Perrins 1999</td>
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<tr>
<td>Breeding date</td>
<td>2 bird species</td>
<td>30 days</td>
<td>35</td>
<td>MacInnes et al. 1990</td>
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<tr>
<td>Breeding date</td>
<td>Mexican Jay</td>
<td>10.1 days</td>
<td>27</td>
<td>Brown et al. 1999</td>
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<tr>
<td>Migration date</td>
<td>4 bird species</td>
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<td>50</td>
<td>Mason 1995</td>
</tr>
<tr>
<td>Migration date</td>
<td>39 bird species</td>
<td>5.5 days</td>
<td>50</td>
<td>Oglesby &amp; Smith 1995</td>
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<tr>
<td>Migration date</td>
<td>American Robin</td>
<td>14 days</td>
<td>19</td>
<td>Inouye et al. 2000</td>
</tr>
<tr>
<td>Migration date/first song</td>
<td>19 bird species</td>
<td>4.4 days</td>
<td>61</td>
<td>Bradley et al. 1999</td>
</tr>
<tr>
<td>End of hibernation</td>
<td>yellow-billed marmot</td>
<td>23 days</td>
<td>23</td>
<td>Inouye et al. 2000</td>
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<tr>
<td>Growing season</td>
<td>Europe</td>
<td>10.8 days</td>
<td>34</td>
<td>Menzel &amp; Fabian 1999</td>
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<tr>
<td>Growing season</td>
<td>northern hemisphere</td>
<td>12 ± 4 days</td>
<td>9</td>
<td>Myrseth et al. 1997</td>
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<tr>
<td>Growing season</td>
<td>northern hemisphere</td>
<td>7 days</td>
<td>20</td>
<td>Keeling et al. 1996</td>
</tr>
</tbody>
</table>

White et al. (2004)

McCarty (2001)
Looking ahead

Jaan Lepson
Sugar Maple range projections by 5 GCMs with 2 x CO$_2$

Source: A.M. Prasad and Iverson, L.R: www.fs.fed.us/ne/delaware/atlas/index.html
Climate change impacts on European beech

Niche-based model

BIOMOD

W. Thuiller

Shifts in species distributions are likely to be large

Mechanistic tree growth model

CASTANEA

A Cheaib, C François, E Dufrêne
Climate Change includes precipitation change

Projected changes for 2090
Lake Chad Basin

Lake Chad is $\frac{1}{20}$th the size it was 35 years ago.
Loss of stream segments able to support cold-water trout

Source: Poff et al. 2002, based on Keheler and Rahel 1996
American pika (*Ochotona princeps*)
Spatial Pattern of Species Richness

Dark red = high species richness

Species Extinctions

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

Mean Range Size

Sea Level Rise in the Next 100 Years

Many important places on the Texas Coast will disappear.

Source: Camille Parmesan
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
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
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Ecosystems disassemble and species reassemble into new ecosystems

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

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

S. Lewis, P. Brando, D. Nepstad, submitted
Critical thresholds in the Earth system

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

[Source: www.ipsl.jussieu.fr/~jomce/acidification]
a pteropod, or sea butterfly, is a type of planktonic mollusk
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 $\Omega_{\text{aragonite}} > 3.25$. 
Why is a CO$_2$ 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 CO$_2$, 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 CO$_2$ 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
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
Fate of Anthropogenic CO$_2$ Emissions (2000-2007)

Canadell et al. 2007, PNAS (updated)

1.5 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%

7.5 Pg C y$^{-1}$
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

Origin of land plants

Expansion of angiosperms

Present-day CO₂
Over the past three centuries, ecosystems have lost 200-250 billion tons of carbon.
Planetary Engineering Using Ecosystems

CO2 PPM

Time
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