Climate Change: Risks and Opportunities

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Summary of Main Points:

- Earth’s climate is stable within certain limits, but sensitive to change in forcing within those limits.

- Climate science has a long and illustrious history

- The idea that we are altering climate is based on simple physics, simple models, and complex models

- Human activities can and do have a strong effect on climate

- We are beginning to quantify some climate-related risks

- Where there is risk there is also opportunity
Last 450 Thousand Years

Ice Age Temperature Changes

- EPICA
- Vostok
- Ice Volume

ΔTemperature (°C)

Thousands of Years Ago

High

Low
~ 20,000 years before present
Polar radiative forcing: 10 W/m² (4 W/m² for 2 x CO₂)

Global mean temperature fluctuation: ~5 C
Climate Forcing by Orbital Variations (1912)

Milutin Milanković, 1879-1958
Strong Correlation between High Latitude Summer Insolation and Ice Volume

Black: Time rate of change of ice volume
Red: Summer high latitude sunlight

P. Huybers, Science, 2006
Tyndall’s Essential Results:

- Oxygen ($O_2$), nitrogen ($N_2$), and argon (Ar), though they make up ~99% of the atmosphere, are almost entirely transparent to solar and terrestrial radiation.

- Water vapor ($H_2O$), carbon dioxide ($CO_2$), nitrous oxide ($N_2O$), and a handful of other trace gases make the lower atmosphere nearly opaque to infrared radiation, though still largely transparent to solar radiation (but clouds have strong effects on radiation at all wavelengths). Together they increase the Earth’s surface temperature from about 0°F to around 60°F.
Atmospheric Composition

The orange sliver makes the difference between a mean surface temperature of 0°F and of 60°F.
Water Vapor (H₂O), about 0.25% of the mass of the atmosphere, is the most important greenhouse gas, but responds to atmospheric temperature change on a time scale of about 2 weeks.

Climate is therefore strongly influenced by long-lived greenhouse gases (e.g. CO₂, CH₄, N₂O) that together comprise about 0.04% of the mass of the atmosphere. Concentration of CO₂ has increased by 43% since the dawn of the industrial revolution.
“Any doubling of the percentage of carbon dioxide in the air would raise the temperature of the earth's surface by 4°; and if the carbon dioxide were increased fourfold, the temperature would rise by 8°.” – *Världarnas utveckling* (Worlds in the Making), 1906
Global Mean Surface Temperature and CO$_2$
Variation in carbon dioxide and methane over the past 20,000 years, based on ice core and other records.
The long-term cooling trend in the Arctic was reversed during recent decades. The blue line shows the estimated Arctic average summer temperature over the last 2000 years, based on proxy records from lake sediments, ice cores, and tree rings. The shaded area represents variability among the 23 sites used for the reconstruction. The red line shows the recent warming based on instrumental temperatures. From Kaufman et al. (2009).
The Instrumental Record
Decadal Land-Surface Average Temperature

10-year moving average of surface temperature over land
Gray band indicates 95% uncertainty interval
Tropospheric temperature trend from 1979-2012 based on satellite measurements (RSS)

Top of the stratosphere (TTS) 1979-2006 temperature trend.
Total amount of heat from global warming that has accumulated in Earth's climate system since 1961, from Church et al. (2011) (many thanks to Neil White from the CSIRO for sharing their data).
September Arctic Sea Ice Extent

Arctic September Sea Ice Extent: Observations and Model Runs

- Observations
- Mean of Models
- Standard Deviation of Models

Sea Ice Extent (million square kilometers)

Year

1950 1975 2000 2025 2050
White Chuck Glacier, Washington state, in 1973

White Chuck Glacier in 2006 from same vantage point. The glacier retreated 1.2 miles in 30 years.
European Alpine Glaciers

Cumulative specific net mass balance in mm water equivalent

- 50,000
- 40,000
- 30,000
- 20,000
- 10,000
- 0


- Storglaciaeren (SE)
- Nigardsbreen (NO)
- Austre Broeggerbreen (NO)
- Aalfotbreen (NO)
- Hofsjokull (IS)
- Maladeta (ES)
- Careser (IT)
- Gries (CH)
- Hintereis (AT)
- Saint Sorlin (FR)
- Sarennes (FR)
- Vernagt (AT)
Hurricanes are reaching peak intensity at higher latitudes.

Time series of the latitudes at which tropical cyclones reach maximum intensity.

From Kossin et al. (2014)
The Oceans Are Becoming More Acidic
Acidification through CO₂ threatens marine life.
Simple Models of Climate Change
MIT Single Column Model

Single Column Model Results

3.1 °C/doubling

IPCC Estimate: 2-4.5 °C
Global Climate Models
20th Century With and Without Human Influences

Based on 4-member PCM ensembles, Meehl et al., *J. Climate*, 2004
The Future
Sources of Uncertainty

- Cloud Feedback
- Water Vapor Feedback
- Ocean Response
- Aerosols
Estimate of how much global climate will warm as a result of doubling CO$_2$: a probability distribution

Source: 100000 PAGE09 runs

Chris Hope, U. Cambridge courtesy Tim Palmer
CO$_2$ Will Go Well Beyond Doubling
Past and Projected Changes in Global Sea Level

- Proxy Records
- Tide Gauge Data
- Satellite Data

Sea Level Change (feet)

Year

1800  1850  1900  1950  2000  2050  2100

1 ft  4 ft  6.6 ft

0.66 ft
IPCC 2007: Doubling CO$_2$ will lead to an increase in mean global surface temperature of 2 to 4.5 °C.

Atmospheric CO$_2$ assuming that emissions stop altogether after peak concentrations

Global mean surface temperature corresponding to atmospheric CO$_2$ above

Courtesy Susan Solomon
Known Risks

- Increasing sea level
- Increasing hydrological events… droughts and floods
- Increasing incidence of high category hurricanes and associated storm surges and freshwater flooding
- More heat stress and other health risks
- Armed conflict

Benefits

- Some increase in plant productivity
- Reduction in health problems related to cold weather
“Taken as a whole, the range of published evidence indicates that the net damage costs of climate change are likely to be significant and to increase over time.”

- Intergovernmental Panel on Climate Change
Increasing Sea Level

SATELLITE DATA: 1993-PRESENT

Data source: Satellite sea level observations.
Credit: NASA Goddard Space Flight Center

RATE OF CHANGE
↑ 3.39
mm per year

YEAR

Sea Level Change (mm)
-20 0 20 40 60
Heat
Temperature anomaly (wrt 1961-90) °C

- Observations
- HadCM3 Medium-High (SRES A2)

Heat Waves

2003

20040s

2060s
Hydrological Extremes

- Rainfall intensity (how hard it rains when/where it is raining) scales with the Clausius-Clapeyron equation, doubling for every 10° C temperature increase.

- Wet places get wetter, dry places get drier; incidence of both floods and droughts increases.

- Large potential effects on food and water supplies; major national security issue.
Hydrological Extremes Increase with Temperature

Floods
Drought
“Climate change could have significant geopolitical impacts around the world, contributing to poverty, environmental degradation, and the further weakening of fragile governments. Climate change will contribute to food and water scarcity, will increase the spread of disease, and may spur or exacerbate mass migration.”

Ocean Acidification

Δ sea–surface pH [-]

-0.12 -0.1 -0.08 -0.06 -0.04 -0.02 0
Hurricanes
Figure 11.17: Increase in average annual losses with historical and projected hurricane activity

Billion 2011 USD, RCP 8.5 ensemble tropical cyclone activity projections from Emanuel (2013)

From: American Climate Prospectus Economic Risks in the United States
Solutions and Opportunities

- **Renewables (solar and wind)**
  - Might provide up to 30% of current power needs
  - Limited by intermittency and lack of storage

- **Carbon Capture and Sequestration**
  - Currently would add \(~$200/\text{ton}\) to energy costs
  - Reasonable prospects for reducing this to \(~$100/\text{ton}\)
  - Currently little incentive to develop this

- **Nuclear fission and fusion**
Ramping up Fission Power

How much extra electrical energy can you add in 11 years?

Data Source: IEA
Nuclear power, by replacing fossil fuels, has prevented an estimated 1.84 million air-pollution related deaths worldwide (includes Chernobyl, Fukushima).
Offshore floating nuclear power plant

Floating rig + Nuclear reactor = OFNP

- Reduced capital cost (>90% cut in reinforced concrete)
- Reduced construction/decommissioning schedule
- Flexible siting + minimal local infrastructure (‘plug and play’)
- Reliable passive cooling; no land/ocean contamination

Profs. J. Buongiorno, M. Golay, N. Todreas
We Can Do Even Better: Next Generation (Gen IV) Fission Reactors

One Example: Molten Salt Reactors

- Passively safe
- Can help process waste from Light Water Reactors
- Operate at ambient pressure
- Can run on thorium; unsuitable for weapons
- Estimated plant lifetime > 80 years
Turning Electricity into Liquid Fuels

E-CEM (Electrolytic Cation Exchange Module)
- Developed by U.S. Navy
- Uses electricity to synthesize liquid fuel from CO₂ in seawater and electrolysis to get H₂, then combined into hydrocarbons
- Carbon-neutral
- Can be done for $3-6 per gallon.
Summary of Main Points

- Several aspects of climate science are well established.
- Earth’s climate is strongly bounded but shows strong sensitivity within the bounds.
- Climate science dates back well into the 19th century and is well established.
Earth’s greenhouse effect triples the amount of radiation absorbed by the surface though it is regulated by trace gases comprising no more than 0.04% of the mass of the atmosphere. The concentration of CO$_2$ has increased by $\sim$45% since the dawn of the industrial revolution.

Beginning with the calculations of Arrhenius more than 100 years ago, simple models predict an increase in global mean surface temperature of around 3 $^\circ$C for each doubling of CO$_2$. These are consistent with the results of global climate models.

Long atmospheric lifetime ($\sim$1000 years) of CO$_2$ limits window of time in which serious risks could be curtailed.
Summary of Main Points

- Solar, wind, and especially fission can replace existing power generation infrastructure in 10-20 years.

- We will eventually need to do this anyway. Why not start now?

- Real world economics: 20 years from now, will we be selling clean energy technology to China and India, or buying it from them?
Spare Slides
Figure 4.11: Global mean sea level rise

- RCP8.5
- RCP4.5
- RCP2.6
- Historic
<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Mortality Rate (deaths/trillionkWhr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal – global average</td>
<td>170,000 (50% global electricity)</td>
</tr>
<tr>
<td>Coal – China</td>
<td>280,000 (75% China’s electricity)</td>
</tr>
<tr>
<td>Coal – U.S.</td>
<td>15,000 (44% U.S. electricity)</td>
</tr>
<tr>
<td>Oil (electricity)</td>
<td>36,000 (36% of energy, 8% of Natural</td>
</tr>
<tr>
<td>Gas</td>
<td>4,000 (20% global electricity)</td>
</tr>
<tr>
<td>Biofuel/Biomass</td>
<td>24,000 (21% global energy)</td>
</tr>
<tr>
<td>Solar (rooftop)</td>
<td>440 (&lt; 1% global electricity)</td>
</tr>
<tr>
<td>Wind</td>
<td>150 (~ 1% global electricity)</td>
</tr>
<tr>
<td>Hydro – global average</td>
<td>1,400 (15% global electricity)</td>
</tr>
<tr>
<td>Nuclear – global average</td>
<td>90 (17% global electricity w/Chern&amp;Fukush)</td>
</tr>
</tbody>
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Global temperature (annual values) in the data from NASA GISS (orange) and from Cowtan & Way (blue), i.e. HadCRUT4 with interpolated data gaps.
Based on bathythermograph and ARGO (post-2004) data
The GISS data, with El Niño and La Niña conditions highlighted. Neutral years like 2013 are gray.
Adjusted annual average temperature data with the estimated impact of El Niño, volcanic eruptions, solar variation, and the residual annual cycle removed.
Figure 1: Average global temperature surface anomaly multi-model mean from CMIP5 (green) and as measured by the NASA Goddard Institute for Space Studies (GISS black). Most of this figure is a hindcast of models fitting past temperature data.
Figure 2: 2007 IPCC report model ensemble mean (black) and 95% individual model run envelope (grey) vs. surface temperature anomaly from GISS (blue), NOAA (yellow), and HadCRUT3 (red).
Figure 5: 1970-1990 aerosol loading of the atmosphere over the lower 48 United States and estimated associated surface air temperature change.

Figure 6: Observed total surface temperature change over the lower 48 United States from 1930 to 1990.
Past and Projected Sea Level vs. Temperature

- Eocene 40 million years ago
- Pliocene 3 million years ago
- Today
- Projection for 2100 (+ 1 m)

- Last Glacial Maximum 20,000 years ago

Global mean temperature [°C]

Sea level [m]

(Source: WBGU after David Archer 2006)
Paleo reconstructions of temperature change over the last 2000 years

"Hockey Stick"
Renewables Require Baseload
Can be deployed on 15-25 year time scale
Carbon Dioxide and Climate: A Scientific Assessment

Report to the National Academy of Sciences
Jule G. Charney and co-authors
1979

When it is assumed that the CO2 content of the atmosphere is doubled and statistical thermal equilibrium is achieved, the more realistic of the modeling efforts predict a global surface warming of between 2°C and 3.5 °C, with greater increases at high latitudes.
Total US Damages by Natural Hazard, 1980-2012

Percentage of Monetary Damage

- Tropical Cyclones
- Droughts/Heat waves
- Severe Local Storms
- Non-Tropical Floods
- Winter Storms
- Wildfires
- Freezees

Source: NOAA
Global Hurricane Power under RCP 8.5