Avoid the Unmanageable, Manage the Unavoidable
Eight Interdisciplinary Lectures on Climate Change
Charles F. Kennel
Monday Evenings, 5:30-7 pm, Martin Johnson House
Scripps Institution of Oceanography, University of California San Diego

October 13, 2014: Origins of Modern Climate Research
Historical pioneers; the greenhouse effect; the increase of atmospheric CO2 concentrations; earth system science, climate models, space observations; earth’s radiation balance and carbon cycle; hard truths about climate change; ethical dilemmas; governance
Avoid The Unmanageable, Manage the Unavoidable
Eight Interdisciplinary Lectures on Climate Change by Charles F. Kennel
Monday Evenings, 5:30-7 pm, Martin Johnson House, except for Nov 3, Sumner Hall
Scripps Institution of Oceanography, University of California San Diego

Oct 13: Origins of Modern Climate Research
Historical pioneers; the greenhouse effect; the increase of atmospheric CO2 concentrations; earth system science, climate models, space observations; earth’s radiation balance and carbon cycle; hard truths about climate change; ethical dilemmas; governance

Oct 20: Paleoclimatology
Earth’s climate in the past 65 million years; orbital forcing and ice ages; instability of ice age climates; abrupt events; volcanoes, ice, and ocean circulation; our benign interglacial; medieval warm period and little ice age; the Anthropocene

Oct 27: Arctic Climate Change and the Present Hiatus in Warming
Why the global temperature has been constant during the past sixteen years, yet Arctic warming has accelerated and extreme events have increased; world-wide impact of sea ice retreat; ecological, economic, and diplomatic aspects of Arctic climate change

Nov 3: How Climate Change could affect us in the next 50-100 years
Inferring from today’s changes and climate models what tomorrow’s world might look like; Regional weather patterns, water availability, floods, drought, wildfires; Impacts on agriculture, ecology, human disease, regional technical systems

Nov 10: How we can slow the pace of climate change; why we still will have much to adapt to
The failure of the climate negotiations; the inertia of the of the global energy system; slowing climate change by working with short-lived climate pollutants; why we probably cannot avoid 2 degC warming at mid-century; the case for adaptation

Nov 17: Adaptation Risks: Sea Level Rise, Coastal Cities, and Island Nations
Factors affecting rates of global and local sea level rise; How advanced regions are preparing-Venice, the Netherlands, Sacramento Bay-Delta; Vulnerable cities, agricultural river deltas, low-lying island nations

Nov 24: California Prepares to Adapt
The El Nino, atmospheric rivers, floods and droughts, water resources and management; how California learned from air pollution; California’s regional assessments; Impacts on regional natural systems, regional technical systems, and populations

Dec 1: Global Adaptive Management of Climate Change
The essential role of assessment in the adaptive management of complex systems; the regional specificity of climate change impacts; the critical role of local communities; the complexity of knowledge assembly for regional and local decision-support; the need to encourage timely decisions; and the capacity problem; how “Knowledge Action Networks” comprising international experts and local decision-makers could inform and motivate good decisions
### A Timeline of Atmospheric Science


<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>340</td>
<td>Aristotle’s Meteorologica is published. Its theories remain unchallenged for nearly 2000 years</td>
</tr>
</tbody>
</table>

1590s

- Galileo invents the thermometer, a precursor of thermometers

1643

- Torricelli performs experiments on atmospheric pressure using a mercury barometer

1686

- Halley shows that low latitudes receive more solar radiation than higher ones and proposes that this gradient provides forcing for the atmosphere’s general circulation.

1714

- Fahrenheit develops the thermometer and a temperature scale

1750

- J. Black identifies CO2 in atmospheric air

1752

- B. Franklin found out that lightning is an electrical discharge by using kites

1770s

- Rutherford identifies N2 in air. Scheele and Priestley independently discover O2

1781

- H. Cavendish measures the composition of air to be 79.16% nitrogen and 20.84% oxygen.

Fahrenheit’s first thermometers contained a column of alcohol which expanded and contracted directly. Fahrenheit substituted mercury for alcohol because its rate of expansion, although less than that of alcohol, is more constant. Furthermore, mercury could be used over a much wider temperature range than alcohol.

( Crutzen and Ramanathan, 2000)
Instrumental Weather Data
Temperature Record for Central England from 1659
England & Wales Precipitation from 1766

United Kingdom Meteorological Office
Fitzroy’s technology-driven empiricism did not satisfy the savants of the Royal Society who, with some justification, complained there was no theoretical basis for the weather forecast. But, no-one then could solve the Navier-Stokes equations, either. In fact, today’s forecasting blends theory-based computations and empirical data.
Lewis Fry Richardson’s Forecast Factory, 1922

Numerical algorithm needed 64,000 human “computers”
The First Electronic Weather Calculations
If the earth were a perfect black body with no atmosphere,... it would absorb solar energy until it glows in the infrared. The surface temperature at which solar radiation in balances infrared radiation out is -18 degC. The observed temperature is +14 degC.
Solar radiation powers the climate system.

Some solar radiation is reflected by the Earth and the atmosphere.

About half the solar radiation is absorbed by the Earth's surface and warms it.

Infrared radiation is emitted from the Earth's surface.

**The Greenhouse Effect**

Some of the infrared radiation passes through the atmosphere but most is absorbed and re-emitted in all directions by greenhouse gas molecules and clouds. The effect of this is to warm the Earth's surface and the lower atmosphere.
Pathways of Discovery

Herschel (1800): Discovery of infrared heat radiation
Fourier (1825-27): Greenhouse effect keeps the earth warmer than expected from visible solar radiation energy flux alone
Tyndall (1850s): Atmospheric H2O, CO2 selectively absorb infrared radiation
Arrhenius (1896): Fossil fuel CO2 should cause global warming
Callendar (1938): Global land temperatures had increased in previous 50 years
Revelle and Suess (1957): Oceans cannot absorb all the increase in CO2 concentration
Keeling (1957-2005): Atmospheric CO2 is increasing at rate consistent with fossil fuel sources
“A Great One-Time Geophysical Experiment”
Could not have happened in the past nor be reproduced in the future

In those pre-Anthropocene days, people thought that the vast oceans would easily absorb the atmospheric carbon dioxide produced by human industrial activity. In a landmark paper, Revelle and Hans Suess (1957) ascertained the rate of CO2 exchange between the atmosphere and sea water. They estimated the CO2 lifetime to be 20 years. A fair fraction of the CO2 humans are producing would therefore accumulate in the atmosphere. The next question was, is it increasing? This needed to be measured, not calculated, and Revelle brought Dave Keeling to Scripps from CalTech.
Charles David Keeling, 1928-2005

Only two other data sets changed science and society as much: Tycho’s (Planetary Orbits) and Michelson’s (Speed of Light)
Because of CO2s long lifetime in the atmosphere, it would be well-mixed and evenly distributed globally. A measurement at a single location far from local sources would suffice.
Keeling was the first to resolve the seasonal variation in CO2 concentration. By early 1960s, it was clear the background increase was consistent with fossil fuel combustion rate. Later, he was able to measure the lengthening of the worldwide growing season.
"The primary effect of increased atmospheric CO2 on climate... is to cause more absorption of thermal radiation from the earth's surface and thus to increase the air temperature....

When...the CO2 content of the atmosphere is doubled and ... equilibrium is achieved,... modeling efforts predict a global surface warming of between 2°C and 3.5°C, with greater increases at high latitudes...

....the warming will eventually occur, and the associated regional climatic changes (will be) so important (that) socioeconomic consequences may... be significant"
Reorganization of the Earth Sciences

Earth System Science
Planetary Subsystems
Observing Systems
Cyber-Infrastructure
Earth System Science
Interdisciplinary Science for the Anthropocene

Centuries, not Eons
Francis Bretherton, 1982 ff.
Interacting Planetary Subsystems

Weather Satellites

Nimbus-1 (1964) first weather satellite
Global observations extended forecasts out to 7 days
Enabled storm track projections
Dramatically improved empirical data needed for climate purposes
Earth Observing System, 1990-
Multi-Disciplinary Observations for Earth System Science
ARGO

6-12 hours at surface to transmit data to satellite

Descent to cruising depth
~10 cm/s (~6 hours)

Salinity & Temperature profile recorded during ascent
~10 cm/s (~6 hours)

Cruising depth, 2000 db (2000m)

Drift approx. 9 days
Total cycle time 10 days
Cyber-Infrastructure

The Earth Observing System’s Data and Information System (EOSDIS) pioneered collection, integration, analysis, and distribution of “big data”; modeling used the data to create understanding and make projections.
Atmosphere-Ocean General Circulation Models
Richardson’s dream realized
The World in Global Climate Models

FAR 1988
- 500 km (T21)

SAR 1995
- 250 km (T42)

TAR 2001
- 180 km (T63)

AR4 2007
- 110 km (T106)
Key Achievements

- Earth’s Radiation Balance
- Global Carbon Cycle
- Circulation of Oceans and Atmosphere
- Role of Cryosphere
- Greenhouse Gas Emission Inventory
- Global Temperature Increase
Follow the Energy
Contemporary Radiation Balance

- **Units Wm\(^{-2}\)**
  - incoming solar TOA: 340 (340, 341)
  - solar reflected TOA: 100 (96, 100)
  - thermal outgoing TOA: 239 (236, 242)

- **Solar Absorbed Atmosphere**
  - solar down surface: 185 (179, 189)
  - solar absorbed surface: 161 (154, 166)
  - latent heat: 84 (70, 85)
  - sensible heat: 20 (15, 25)
  - thermal up surface: 398 (394, 400)
  - thermal down surface: 342 (338, 348)

- **Imbalance**
  - 0.6 (0.2, 1.0)
Follow Carbon Dioxide
Terrestrial and Oceanic Inventories and rates of exchange with the atmosphere
Oceans Absorb ~ 25% of Anthropogenic CO2

Resulting acidification has profound implications for shelled marine life

Terrestrial Biosphere Absorbs ~ 25% of Anthropogenic CO2

Net Primary Productivity
Rate of Carbon Take-up by Photosynthetic Growth of Vegetation on Land

Plant growth in northern hemisphere spring and summer draws down CO2, accounting for Keeling’s seasonal cycle. The global growing season has lengthened by several weeks since Keeling started taking data. The Northern Hemisphere has been “greening”
Land Cover Change

Essential for understanding ecology’s role in climate change

Human land use has played a role in climate since the agricultural revolution

Source: University of Texas
Deforestation

10-15% of Greenhouse Warming
Halley Quantified

Net radiative warming drives equator-to-pole circulation of both atmosphere and ocean
The Great Ocean Conveyor Belt

Heat release to atmosphere

Atlantic Ocean

Indian Ocean

Warm surface current

Cold saline deep current

Pacific Ocean

Heat release to atmosphere
Cryosphere
Ice, Snow, & Permafrost
80% of world’s fresh water

Thermal balance
Ocean and Atmosphere Circulation
Sea level rise
Human Drivers of Climate Change

Both warming and cooling; net increase since 1750 from all sources has been 2.3 W/m²

IPCC AR5, Working Group I, 2013
Figures 8.6 and 8.16
“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
Oceans absorb 93% of the energy added to the climate system by humans
Hard Truths

CO2’s Atmospheric Lifetime is 100 Years
Ocean Heat Storage Time is 1000 Years
Implications of Oceanic and Carbon Cycle Inertia

We cannot avoid significant climate change because of what we have already done, much less what we are about to do.
The oceans, right now our friend, are storing up problems

The oceans are helping us by taking up 25% of the CO2 and 93% of the energy added to the climate system by humans. If and when we reduce CO2 emissions, dissolved CO2 and embedded ocean heat will be released to the atmosphere until the entire ocean has equilibrated with the atmosphere. This will take about 1000 years. Climate change will be a problem for at least that long.
Deep emissions reductions (>80%) would be required for long-term stabilization of carbon dioxide at any chosen target (450, 550, 650 ppm....).

AND

Emission reductions near 100% would be required for manmade CO₂ to decline from any peak it reaches.

Illustrative calculations showing CO₂ concentrations and related warming in two models for a test case in which emissions first increase, followed by a decrease in emission rate of 3% per year to a value 50%, 80%, or 100% below the peak. The test case with 100% emission reduction has 1 trillion tonnes of total emission.
Long-Term Global Temperature Increase is Almost Linearly Related to Cumulative Carbon Emission

Best estimates and likely range of cumulative carbon emissions that would result in global warming of 1, 2, 3, 4, or 5°C.

It does not matter when the emissions occur. Given a maximum tolerable temperature increase, ongoing emissions draw down a finite “carbon account”
Climate change for the next 25-30 years is mostly built in. IPCC AR5 models suggest that the pace of climate change could double.
The Grand Ethical Dilemma

The global distribution and long lifetime of carbon dioxide give rise to major intergenerational ethical issues.

Things humans are doing today will change the climate and conditions for all life in unknown ways for thousands of years.

The CO2 emissions each of us causes today do not affect us directly but change the climate for every human on earth in the next generation.

Present generations pass on climate risk to future generations as well as assets such as knowledge and infrastructure. The intergenerational challenge is to strike a balance between incurring future climate debt and present investment for that future.
Everyone causes climate change and everyone is affected by it. The climate negotiations therefore seek inclusive global consensus, but this may be impossible to achieve.

Actions to reduce CO2 emissions affect the climate decades later. Those who make the effort do not reap the benefits in their lifetimes.

The free-rider problem: those who did not make the effort will reap benefit from the actions of those who did.

CO2 emissions are a fundamental byproduct of the contemporary industrial system, which is bringing prosperity and social advancement around the world. The centrality of fossil fuels in today’s global economy is pitting those who value the free market system and present prosperity against those who believe that dealing with climate change is an absolute moral imperative.

Climate change is similar to slavery and colonialism. All three are global issues in which economic benefits for some contest with moral views of others. Colonialism and slavery took a century to solve, not without great conflict.
Climate Governance
Latest CO₂ reading
July 25, 2014
398.85 ppm
Carbon dioxide concentration at Mauna Loa Observatory

Global Science, Global Policy
The long-term objective of the Convention and its related legal instruments is “to achieve [...] the stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system”
<table>
<thead>
<tr>
<th>Conference of Parties (COP)</th>
<th>Year</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>COP 1</td>
<td>1995</td>
<td>The Berlin Mandate</td>
</tr>
<tr>
<td>COP 2</td>
<td>1996</td>
<td>Geneva, Switzerland</td>
</tr>
<tr>
<td>COP 3</td>
<td>1997</td>
<td>Kyoto, Japan</td>
</tr>
<tr>
<td>COP 4</td>
<td>1998</td>
<td>Buenos Aires, Argentina</td>
</tr>
<tr>
<td>COP 5</td>
<td>1998</td>
<td>Bonn, Germany</td>
</tr>
<tr>
<td>COP 6</td>
<td>2000</td>
<td>The Hague, Netherlands</td>
</tr>
<tr>
<td>COP 7</td>
<td>2001</td>
<td>Marrakech, Morocco</td>
</tr>
<tr>
<td>COP 8</td>
<td>2002</td>
<td>New Delhi, India</td>
</tr>
<tr>
<td>COP 9</td>
<td>2003</td>
<td>Milan, Italy</td>
</tr>
<tr>
<td>COP 10</td>
<td>2004</td>
<td>Buenos Aires, Argentina</td>
</tr>
<tr>
<td>COP 11</td>
<td>2005</td>
<td>Montreal, Canada</td>
</tr>
<tr>
<td>COP 12</td>
<td>2006</td>
<td>Nairobi, Kenya</td>
</tr>
<tr>
<td>COP 13</td>
<td>2007</td>
<td>Bali, Indonesia</td>
</tr>
<tr>
<td>COP 14</td>
<td>2008</td>
<td>Poznań, Poland</td>
</tr>
<tr>
<td>COP 15</td>
<td>2009</td>
<td>Copenhagen, Denmark</td>
</tr>
<tr>
<td>COP 16</td>
<td>2010</td>
<td>Cancún, Mexico</td>
</tr>
<tr>
<td>COP 17</td>
<td>2011</td>
<td>Durban, South Africa</td>
</tr>
<tr>
<td>COP 18</td>
<td>2012</td>
<td>Qatar</td>
</tr>
</tbody>
</table>

UNFCCC Conference of Parties Meetings

Kyoto, 1997

Lima, 2014
The Intergovernmental Panel on Climate Change
The most rigorous reviews of a state of scientific knowledge ever attempted.

The IPCC was established by WMO and UNEP in 1988 to “assess on a comprehensive objective, open, and transparent basis the latest scientific, technical and socio-economic literature produced worldwide relevant to the understanding of the risk of human-induced climate change, its observed and projected impacts and options for adaptation and mitigation. IPCC reports should be neutral with respect to policy, although they need to deal objectively with policy relevant scientific, technical and socio-economic factors. They should be of high scientific and technical standards, and aim to reflect a range of views, expertise and wide geographical coverage.”
The IPCC’s policy influence grew as succeeding reports communicated a consistently evolving understanding of climate change. At the same time, the return to the same themes created a “standard narrative” that shapes the public dialog.

The IPCC devised transparent processes intended to promote trust. Its summarized only the peer-reviewed literature. Review panels were chosen with attention to balance among countries, points of view, and economic and institutional interests. Successive panels recruited a majority of new participants to avoid an institutionalized IPCC point of view. Its most important innovation was to separate assessment of science from discussion of policy. After the scientific assessment is complete, the IPCC engages in a separate process to develop summaries for policy makers. Together, scientists and policy-makers compose, line-by-line, the statements pertinent to policy, with explicit attention to the uniform characterization of uncertainty.
IPCC assessments energized the global public debate about climate. Not a day passes without media discussion of climate change. This is the most important outcome, since public awareness of the risks of climate change encourages governments to pay attention and motivates public and private initiatives. They have been unsuccessful in promoting concrete actions by governments.

The Standard Narrative

Narrow Focus: CO2 emissions, global temperature
Obscures as it clarifies: the realities and our options are much more nuanced

Moses receiving the tablets of the law, João Zeferino da Costa, 1868
CO2 is not the only driver of Climate Change
Why shouldn’t we work with them, too?
Global Temperature

Designed to simplify, the concept obscures to clarify.

We use a vast modeling infrastructure to compute a number that only a physicist could love, one that conveys a misleading impression that the world warms up uniformly. It is an imperfect index of the rate humans are adding energy to the climate system, which will distribute it in complex ways.
12-month moving average
Anomalies relative to 1950-1980 mean

With thanks to Richard Muller, UC Berkeley Annual moving land-surface average, 2-sigma uncertainty
“That's here. That's home. That's us. On it everyone you love, everyone you know, everyone you ever heard of, every human being who ever was, lived out their lives. The aggregate of our joy and suffering, thousands of confident religions, ideologies, and economic doctrines, every hunter and forager, every hero and coward, every creator and destroyer of civilization, every king and peasant, every young couple in love, every mother and father, hopeful child, inventor and explorer, every teacher of morals, every corrupt politician, every 'superstar,' every 'supreme leader,' every saint and sinner in the history of our species lived there - on a mote of dust suspended in a sunbeam.”

- Carl Sagan, from a lecture delivered at Cornell University: 10/13/94