Global Change Research: A Historical Perspective and Future Challenges

Guy P. Brasseur
National Center for Atmospheric Research
Boulder, CO
The Planet under stress
A Profound Transformation of the Earth System is Underway

During the last 50 years,

• the **human population** has risen from 2 to 7 billion,

• **economic activity** has increased ten-fold,

• the **connectivity of the human enterprise** has risen dramatically through globalisation of economies and **flow of people, information, products and diseases.**

• **Intensification and diversification of land-use and advances in technology** has led to rapid changes in **biogeochemical cycles, hydrological processes and landscape dynamics.**
Population has been growing rapidly
Gross Domestic Product (trillions $)
Inequalities in the World

The food available to a family in different parts of the world

Deutschland: $500
Italien: $260
Ecuador: $31,55
Chad: $1,23

Source: W. Cramer
Chr. Müller,
PIK
The Great Acceleration

Global Impact

- Greenhouse gases
- Ozone depletion
- Climate
- Marine ecosystems
- Coastal zone
- Nitrogen cycle
- Tropical forests
- Land systems
- Biosphere integrity
Climate System Trends

Average Monthly Arctic Sea Ice Extent
July 1979 to 2010

Global-average mean sea level
Climate models show that the Earth is moving out of the state it has encountered at least in the last million year.
Air pollution is today the first killer in the world.

The air quality life index has calculated that air pollution cuts average life expectancy per person by almost two years.

<table>
<thead>
<tr>
<th>Index, $1 = 1$ year</th>
<th>0</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
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<tbody>
<tr>
<td>Particulate pollution 1.8 years</td>
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<tr>
<td>Smoking 1.6 years</td>
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<td>Alcohol and drug use 11 months</td>
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<td>Unsafe water and poor sanitation 7 months</td>
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<tr>
<td>Road injuries 4.5 months</td>
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<td>HIV/AIDS 4 months</td>
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<td>Malaria 4 months</td>
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<td>Tuberculosis 3.5 months</td>
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<td>Conflict and terrorism 22 days</td>
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Guardian graphic | Source: AQLI
The Anthropocene: A New Epoch in Earth History?

From Will Steffen
A Historical Perspective
In 1861, Irish physicist John Tyndall showed that gases such as methane and carbon dioxide absorbed infra-red radiation, and could trap heat within the atmosphere. They “would produce great effects on the terrestrial rays and produce corresponding changes of climate”.

La question des températures terrestres, l’une des plus importantes et des plus difficiles de toute la philosophie naturelle, se compose d’éléments assez divers qui doivent être considérés sous un point de vue général. J’ai pensé qu’il serait utile de réunir dans un seul écrit les conséquences principales de cette théorie; les détails analytiques que l’on omet ici se trouvent pour la plupart dans les ouvrages que j’ai déjà publiés. J’ai désiré surtout présenter aux physiciens, dans un tableau peu étendu, l’ensemble des phénomènes et les rapports mathématiques qu’ils ont entre eux.

La chaleur du globe terrestre dérive de trois sources qu’il est d’abord nécessaire de distinguer.

1° La terre est chauffée par les rayons solaires, dont l’inégale distribution produit la diversité des climats.

2° Elle participe à la température commune des espaces planétaires, étant exposée à l’irradiation des astres innombrables qui environnent de toutes parts le système solaire.
In 1896, Swedish scientist Svante Arrhenius is the first to calculate the sensitivity (5 °C) of climate to a doubling of atmospheric CO₂.
In 1938, Steam engineer Guy Callendar predicts a temperature increase of 0.3 °C per century, which should delay the "return of the deadly glaciers".
Starting in **1958**, monitoring of CO$_2$ at the Mauna Loa station shows that the level of this greenhouse gas is gradually increasing in the atmosphere even in remote areas: the problem is a global problem.
In 1920, Charles Fabry and Henri Buisson at the University of Marseilles, France, by measuring the absorption of ultraviolet light in the atmosphere discover that the thickness of the ozone column at STP is only of the order of 3 mm.
The Dobson Ozone Photographic Spectrometer of Gordon Dobson at Oxford, UK.

Gordon Dobson
A Century of Tremendous Progress
Numerical Weather Forecast
In 1967, at the NOAA Geophysical Fluid Dynamics Laboratory in Princeton, Syukuro Manabe et Richard Wetherald make a first calculation of the effect of greenhouse gases using a 1-D radiative convective model. They derive in 1975 with a general circulation model and derive the effect on climate of a doubling in CO₂.

The Effects of Doubling the CO₂ Concentration on the Climate of a General Circulation Model

SYUKURO MANABE AND RICHARD T. WETHERALD
Geophysical Fluid Dynamics Laboratory/NOAA, Princeton University, Princeton, N.J. 08540

(Manuscript received 6 June 1974, in revised form 8 August 1974)

ABSTRACT

An attempt is made to estimate the temperature changes resulting from doubling the present CO₂ concentration by the use of a simplified three-dimensional general circulation model. This model contains the following simplifications: a limited computational domain, an idealized topography, no heat transport by ocean currents, and fixed cloudiness. Despite these limitations, the results from this computation yield some indication of how the increase of CO₂ concentration may affect the distribution of temperature in the atmosphere. It is shown that the CO₂ increase raises the temperature of the model troposphere, whereas it lowers that of the model stratosphere. The tropospheric warming is somewhat larger than that expected from a radiative-convective equilibrium model. In particular, the increase of surface temperature in higher latitudes is magnified due to the recession of the snow boundary and the thermal stability of the lower troposphere which limits convective heating to the lowest layer. It is also shown that the doubling of carbon dioxide significantly increases the intensity of the hydrologic cycle of the model.
Atmospheric Chemistry as a Dynamic Component of the Earth System

- The photochemical theory of ozone (Chapman, Bates, Nicolet, Crutzen, Cicerone, Solomon)
- Stratospheric ozone depletion and the Antarctic ozone hole (Crutzen, Molina, Rowland)
- The photochemistry of smog (Haagen-Smit)
- The oxidation potential of the atmosphere: the OH radical and tropospheric ozone as a global pollutant (Levy, Weinstock, Crutzen)
The Ocean as a Dynamical Component of the Earth System

• The conveyor belt (W. Broecker)
• The thermohaline circulation (W. Munk)
• Ventilation of the deep ocean (H. Stommel and P. Rhines)
• The biological pump for carbon (Revelle)
• Development of ocean general circulation models (K. Bryon)
The Biosphere as a Dynamic component of the Earth System

• The importance of life for the evolution of the Earth (W. Vernadsky)

• Importance of vegetation-albedo feedback (e.g., instability of the Sahara by Charney)

• Increasing atmospheric concentration of $\text{CO}_2$ and the role of the carbon cycle in the Earth System (Keeling, Sr and Jr., Tans)

• The role of the biosphere in controlling the chemical composition of the natural atmosphere.

• The importance of large wildfires (P. Crutzen)
The Earth as a Complex Nonlinear Interactive System

- The Lorenz attractors: the limit of predictability.
- The Vostock Ice core and glacial/interglacial transitions (Oeschger, Lorius)
- The Dansgaard/Oeschger cycles
- The CLAW hypothesis (R. Charlson, M. Andreae, et al.)
- The realization of the importance of the carbon cycle (B. Bolin, R. Revelle)
- Gaia hypothesis (J. Lovelock)
Bretherton’s diagram shapes global change research for the decades ahead
The Importance of Monitoring the State of the Environment

GLOBAL MONTHLY MEAN CO₂

GLOBAL MONTHLY MEAN CH₄

Stratospheric Water Vapor over Boulder, Colorado

Boulder FPH Record
(480 Soundings)

H₂O (μmol mol⁻¹)

Altitude Intervals (km)
- 20-22
- 26-28
- 18-20
- 24-26
- 16-18
- 22-24

Year


NoAA Boulder
Earth System Science: the big picture

Ability to give the earth a “health check”

- EO for Climate (Earth system) Diagnosis & Prediction
- Cryosphere
- Geohazards
- Atmospheric Composition
- Hazardous Weather & Flooding
- Carbon Cycles
- Data Assimilation
# Timeline of Climate Model Development

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<thead>
<tr>
<th>Era</th>
<th>Components</th>
<th>Teams</th>
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<td><strong>Mid-1960s</strong></td>
<td>Atmosphere/Land Surface/Vegetation</td>
<td>Small teams</td>
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<td>Ocean</td>
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<td>Coupled Climate Model</td>
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<td><strong>Mid-1970s-1980s</strong></td>
<td>Atmosphere/Land Surface/Vegetation</td>
<td>Intermediate size teams</td>
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<td>Sulfate Aerosol</td>
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<td><strong>1990s</strong></td>
<td>Ocean</td>
<td>Large teams made up of several 10s to 100s</td>
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<td>Dust/Sea Spray/Carbon Aerosols</td>
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<td><strong>Present Day</strong></td>
<td>Ocean</td>
<td>Distributed, interdisciplinary, interagency teams</td>
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<td>Biogeochemical Cycles</td>
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<td><strong>2000-2010</strong></td>
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International Programs
and Environmental Diplomacy
An Important Milestone

This conference was followed by other UN conferences in Rio de Janeiro in 1992 and 2012.

• **The landmark UN Stockholm Conference** in 1972 recognized that:
  
  • **science** and technology should be used to **improve the environment**,
  
  • research and education in environmental sciences should be promoted,
  
  • **cooperation on international issues** should be regarded as essential.
Mission
"To provide leadership and encourage partnership in caring for the environment by inspiring, informing, and enabling nations and peoples to improve their quality of life without compromising that of future generations."
About

IGBP was launched in 1987 to coordinate international research on global-scale and regional-scale interactions between Earth's biological, chemical and physical processes and their interactions with human systems. IGBP views the Earth system as the Earth's natural physical, chemical and biological cycles and processes AND the social and economic dimensions.

photo: NASA-Visible Earth
Transformations towards Sustainability

Global Development

Dynamic Planet

Observing systems, models, theory development, data management, research infrastructures

- Water-Energy-Food Nexus
- Ocean
- Transformations
- Natural Assets
- Sustainable Development Goals
- Urban
- Health
- Finance & Economics
- Systems of Sustainable Consumption and Production
- Decarbonisation
- Emergent Risks and Extreme Events
The Future
Grand Challenges

Multiple stressors lead to major planetary problems

- Energy and Carbon
- Water Scarcity
- Food Availability
- Air Quality
- Human Health
- Urbanization and Population
- Migration
- Poverty and Education

Fundamental research remains key for addressing these complex questions

- Understand interactions and feedbacks in the entire Earth System
- Develop integrated regional studies to assess the two-way coupling between the biophysical and social systems
- Improve existing climate tools (observations, models)
- Integrate new approaches, priorities, capabilities
- Cooperate with new partners
Grand challenges addressed by WCRP
Clouds & Circulation

How will clouds and circulation respond to global warming or other forcings?

How do clouds couple to circulations in the present climate?

How do these processes determine climate sensitivity to increasing greenhouse gases?
What are the drivers of land and ocean carbon sinks?

What is the potential for amplification of climate change over the 21st century via climate-biogeochemical feedbacks?

How do greenhouse gases fluxes from highly vulnerable carbon reservoirs respond to changing climate?

A conceptual illustration of the carbon cycle. NASA Earth Observatory.
Near-Term Prediction

How can we enhance the understanding of sources of decadal predictability?

How can we serve decadal prediction information as is already done for seasonal prediction?
Changing chemical regimes are changing in a dynamical world

Changes in emissions of NO, CO and hydrocarbons (e.g., reduced urban pollution, enhanced wildfires) resulting from mitigation measures and climate change will lead to a revision of policies to combat air pollution.

Granier et al., NOAA, 2019
A new focus
Environmental Security
for Humanity

Security is not only maintaining territorial integrity and domestic peace.

It must value economic prosperity, stability, health and well-being of populations.

Citizens should have full access to our global commons and the right to be protected from the extreme environmental disruptions:

- Access to clean air
- Access to clean water
- Access to safe food
- Access to natural resources

Environmental prediction of environmental factors is key to address this issue.
What are the prospects for the future?

New environmental forecast products will be feasible

Possible threats for the summer: hot, dry and unhealthy

- Major fires
- Agricultural production at 50%, blowing dust
- Health warning: Limit outdoor activities; expect brownouts
- Swimming and Fishing prohibited
- African bacteria alerts
- Frequent floodings and Asian dust threats continue
- Air quality alerts – 75% of days
- High danger of toxic CO₂ releases
- Expect fisheries downturn; health threats
- Major fisheries regime change likely
- Agricultural production at 50%, blowing dust

What are the prospects for the future?
Capability to forecast regional air quality within the global context

Global model with 100 km resolution

Global model with regional refinement.

Substantial differences in ozone mixing ratios between coarse grid (~100 km) and regionally-refined grid (~14 km)

Lacey, Schwantes and Tilmes, NCAR
Conclusions
Which trajectory for the Earth System in the Future?

Steffen et al., 2018
Tipping Elements in the Earth System

Source: Schellnhuber, after Lenton et al, PNAS, 2008
We need to decide which direction we want to take

An Uncertain Future on a Much Hotter Planet?

A Return to Holocene-like Conditions?
“Science exists to serve human welfare. It’s wonderful to have the opportunity given us by society to do basic research, but in return, we have a very important moral responsibility to apply that research to benefiting humanity.”

Walter Orr Roberts