Climate Change on Agriculture, Water and Environment

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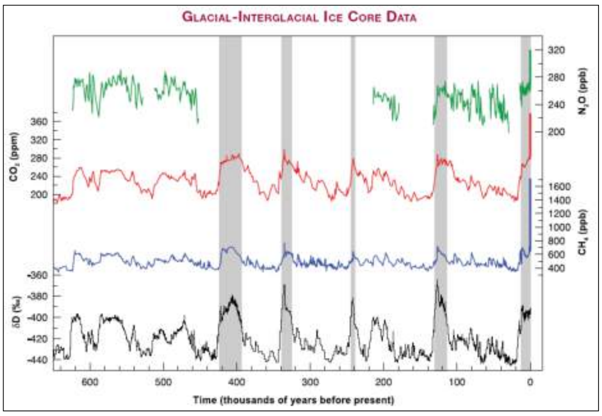
Outline

- Climate Change: Causes
- Climate Change and Agriculture: Impacts
- Climate Change on Water: Case studies in India and China Using the SWAT model
- Climate Change and Agriculture: Adaptation and Mitigation
- Summary

In 2007, IPCC synthesized knowledge on causes and effects of anthropogenic climate change

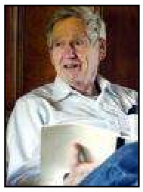


Source: Technical Summary IPCC Working Group I (Solomon et al. 2007)

But the efforts and insights started much earlier…

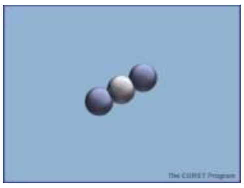
- Svante Arrhenius (1859 – 1927)
  - Physical Chemist
  - PhD thesis on electrolytic conductivity
  - Developed Arrhenius equation
  - Proposed greenhouse gas law
    - "If the quantity of carbonic acid increases in geometric progression, the augmentation of the temperature will increase nearly in arithmetic progression"

- C. David Keeling (1928 - 2005)
  - Chemist
  - Developed instrument to measure [CO_2] in atmospheric samples
  - Established Mauna Loa Observatory in 1958
  - Demonstrated the progressive buildup of [CO_2] in the atmosphere



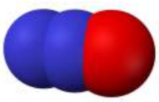
But, what is a "greenhouse gas" anyway?

- Nitrogen, O_2, and Ar make up for 99% of the atmosphere but are not greenhouse gases
- Water vapor, CO_2, CH_4, and N_2O are greenhouse gases
- A greenhouse gas absorbs infrared radiation because of their dipole moment
  - This dipole moment creates molecular vibration and bending and as a result the molecule absorbs infrared radiation
  - Collisions transfer energy to heat the surrounding gas



http://www.ucar.edu/learn/1_3_1.htm

The N_2O molecule



$N{\equiv}\overset{+}{N}{-}O^{-} \longleftrightarrow {}^{-}N{=}\overset{+}{N}{=}O$

How do we compare greenhouse gas? Two definitions and a formula

- Radiative Forcing: Change in net irradiance (W m^{-2}) at the tropopause after allowing stratospheric temperatures to re-adjust to radiative equilibrium, but with surface and tropospheric temperatures held at their unperturbed values
  - A positive value warms the system while a negative value cools it
- Global Warming Potential (GWP): Cumulative radiative forcing between the present and some chosen later time "horizon" caused by a unit mass of gas emitted now, expressed relative to CO_2

$$GWP_{N2O} = \frac{N_2O(Wm^{-2}g^{-1}(100y)^{-1}}{CO_2(Wm^{-2}g^{-1}(100y)^{-1}}$$

- The GWP for N_2O varies according to the time considered:
  - For 20 years: 310 gN_2O $(gCO_2)^{-1}$
  - For 100 years: 298 gN_2O $(gCO_2)^{-1}$

Comparing the power of greenhouse gases

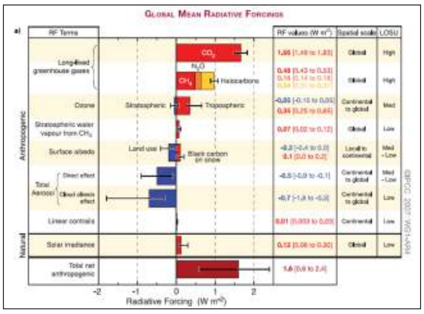
4th IPCC Assessment Report, WG I, Ch. 2

- Human activities result in emissions of four principal greenhouse gases: CO_2, CH_4, N_2O and the halocarbons (a group of gases Fl, Cl and Br)
- Atmospheric concentrations of long-lived greenhouse gases have been increasing over the last 2,000 years, especially since 1750 –the beginning of the industrial era

	Concentrations and Δs (ppm)		Radiative Forcing	
	2005	Δ since 1998	2005 W m-2	Δ since 1998 (%)
CO_2	379	13	1.66	13
CH_4	1.774	0.011	0.48	-
N_2O	0.319	0.005	0.16	11

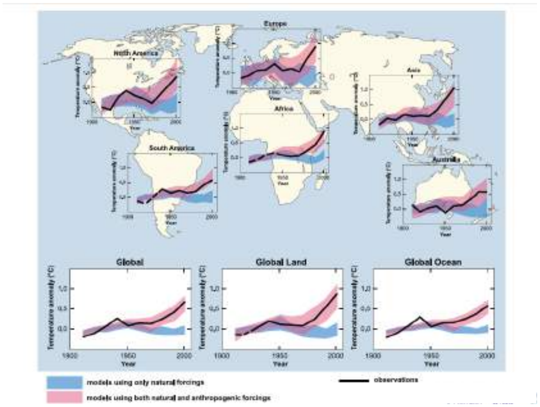
Factors Determining Climate Change

- Except for the variation in solar radiation, all human activities are connected to a radiative forcing
- Some factors induce warming…
  - CO_2, N_2O, CH_4
- …while others induce cooling
  - Sulphates (volcanic eruptions)
- Some factors are understood better than others
- A simple arithmetic sum of radiative forcings is not enough to calculate the total effect (due to the asymmetry in the ranges of uncertainty)



Source: Technical Summary IPCC Working Group I (Solomon et al. 2007)

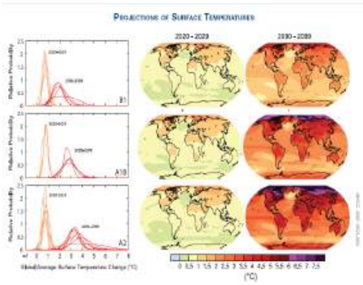
The rise in continental and global temperatures observed during the past century can only be explained with computer simulations that include the anthropogenic effect



Source: Summary for Policymakers, IPCC (2007)

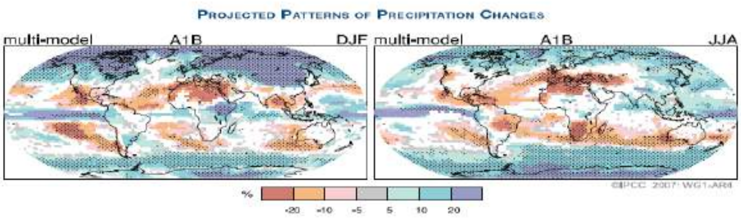
The projections of temperature changes during the current century relative to 1980-1999 vary with assumptions about the future

- Different scenarios of the future:
  - The B1 scenario has a high level of environmental and social consciousness combined with a globally coherent approach to a more sustainable development
  - The A1B future shows a world with balanced progress across all resources and technologies from energy supply to end use
  - The A2 scenario contains a world of independently operating, self-reliant nations; continuously increasing population; and regionally oriented economic development



Source: Summary for Policymakers, IPCC (2007)

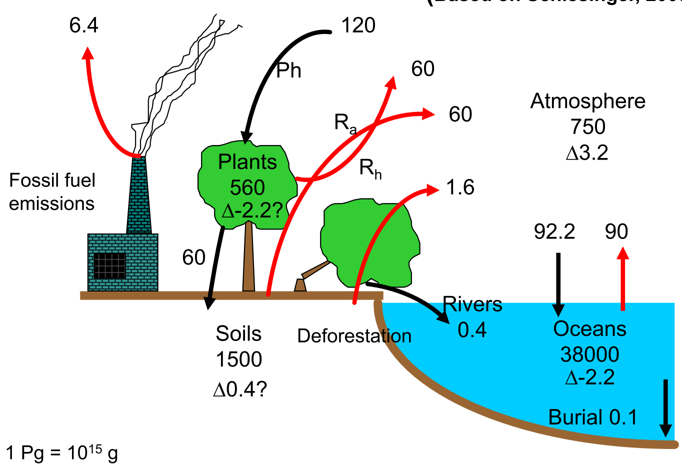
Relative changes in precipitation during 2090-2099 relative to 1980-1999 in a A1B world



Source: Summary for Policymakers, IPCC (2007)

Global Carbon Cycle (Pg C)

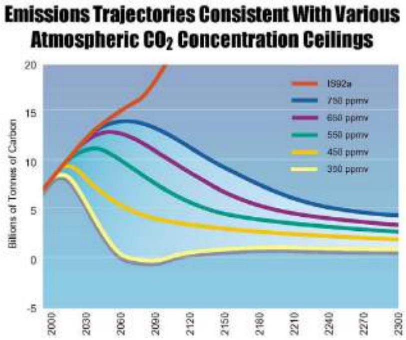
(Based on Schlesinger, 2003)



1 Pg = 10^{15} g
= One billion tons

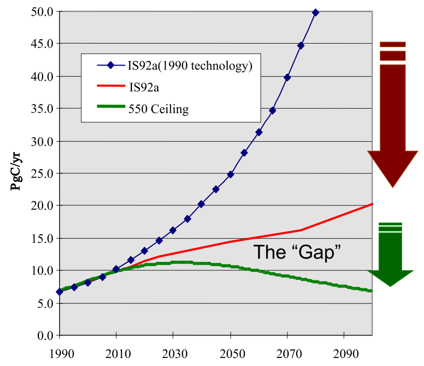
The challenge of stabilizing CO_2 concentrations…

- Stabilization of greenhouse gas concentrations is the goal of the Framework Convention on Climate Change
- Stabilization means that global emissions must peak in the decades ahead and then decline indefinitely thereafter
- Climate change is a long-term, century to millennial problem—with implications for today. It will not be solved with a single treaty, single technology, by a single country, or by a quick fix



Slide courtesy of Jae Edmonds

Filling the Global Carbon Gap… Energy technologies in the pipeline are not enough!



Assumed Advances
- Fossil Fuels
- Energy intensity
- Nuclear
- Renewables

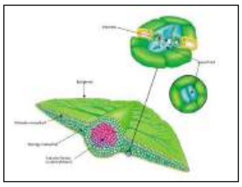
Gap Technologies
- Improved performance of ref tech.
- Carbon capture & disposal
  Adv. fossil
- H_2 and Adv. Transportation
- Biotechnologies
  Soils, Bioenergy, adv. Biological energy

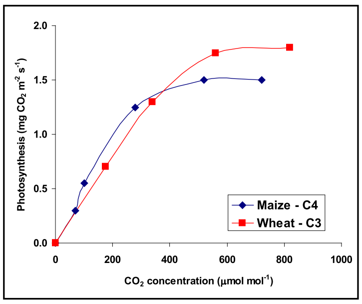
Slide courtesy of Jae Edmonds

Climate Change and Agriculture: Impacts

The CO_2 fertilization effect…

- The elevated concentration of CO_2 stimulates photosynthesis and reduces stomatal conductance





Akita y Moss (1973)

- Other effects
  - Improves water use efficiency
  - Accelerates plant growth
  - Changes the distribution of nutrients
  - Reduces foliar concentration of nitrogen
- Kimball (1983): crop yields should increase 33% when $[CO_2]$ doubles from 330 to 660 ppm

Research methods to study $[CO_2]$ effects on plants

- Laboratory chambers
- Glasshouses
- Closed-top field chambers
- Open-top field chambers
- Free-Air Carbon Dioxide Enrichment (FACE)

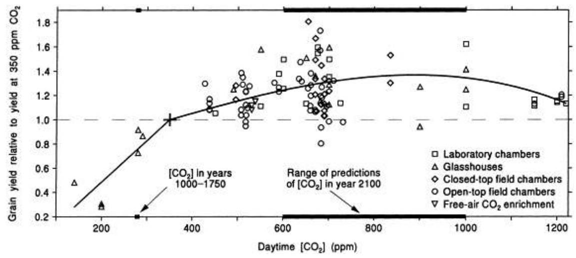
http://instaar.colorado.edu/meetings/50th_anniv/photo_album/PendallElise

http://www.uswcl.ars.ag.gov/epd/co2/co2face.htm

http://www.env.duke.edu/forest/FACTSI.htm

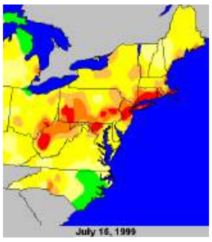
General effects of $[CO_2]$ on wheat yield

- Kimble (1983) Agron. J. 75:779–788
  - 20 experiments
  - Wheat yield increased 37% when $[CO_2]$ increased from 330 to 660 ppmv
- Amthor (2001) Fields Crops Res. 73:1-34
  - 113 lab and field experiments with wheat
  - Non-limiting water and nutrients
  - Ambient temperature
  - Wheat yield increased 31% when $[CO_2]$ doubled from 350 to 700 ppmv



Amthor (2001)

Tropospheric $[O_3]$ has increased due to human activities



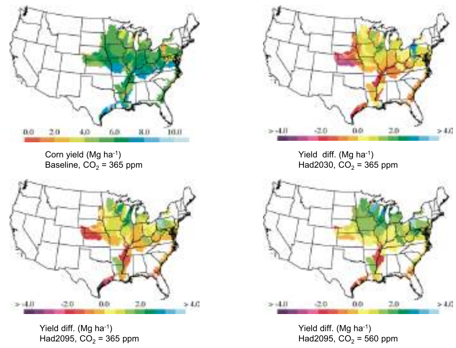
0 – 60 ppb
61 – 79 ppb
80 – 99 ppb
100 – 110 ppb
111 – 124 ppb
125 + ppb

Ozone and CO_2 concentration effects on yield and biomass of wheat in 1991

	Grain Yield ($g\ m^{-2}$)	Biomass ($g\ m^{-2}$)
Low O_3 – Amb. CO_2	538	1513
High O_3 – Amb. CO_2	414	1272
Low O_3 – Enrich. CO_2	627	1653
High O_3 – Enrich. CO_2	574	1559

Rudorff et al. (1996)

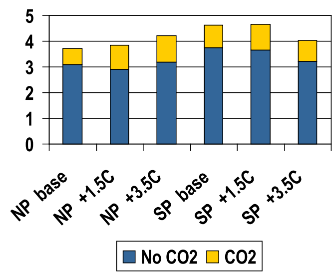
Yields and yield changes from baseline for dryland corn in 2030 and 2095 under HadCM2 GCM climate scenarios



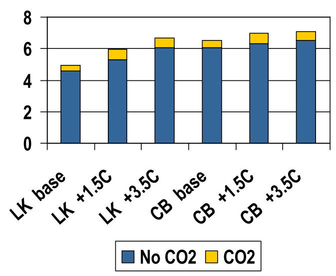
Izaurralde et al. (2003)

Modeled yields of wheat and maize as affected by CO_2 concentration and climate change in four regions: Northern Plains (NP), Southern Plains (SP), Lakes (LK) and Corn Belt (CB)

Wheat yield ($Mg\ ha^{-1}$)



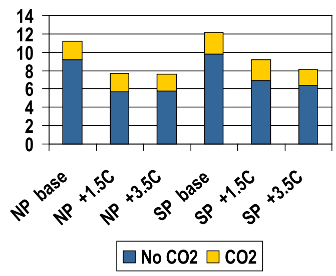
Maize yield ($Mg\ ha^{-1}$)



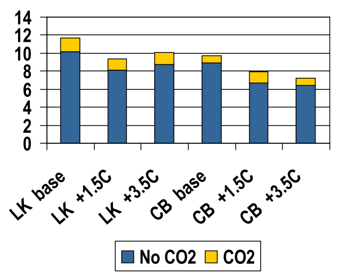
Izaurralde et al. (2003)

Modeled water use efficiency (WUE) in wheat and maize as affected by CO_2 concentration and climate change in four US regions: Northern Plains (NP), Southern Plains (SP), Lakes (LK) and Corn Belt (CB)

Wheat WUE ($kg\ ha^{-1}\ mm^{-1}$)



Maize WUE ($kg\ ha^{-1}\ mm^{-1}$)



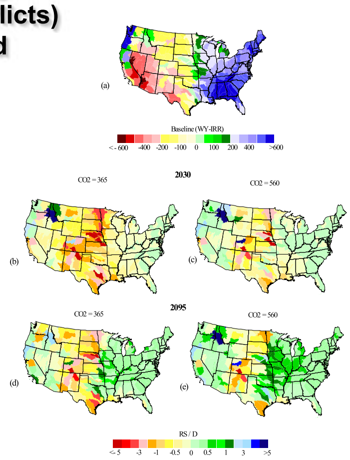
Izaurralde et al. (2003)

Climate change may bring significant changes (and conflicts) between water supply and demand

Izaurralde et al. (2003)

- Proxy measure of water supply and demand
  - WY – IRR
    - WY from HUMUS
    - IRR from EPIC
- Supply / demand relationship

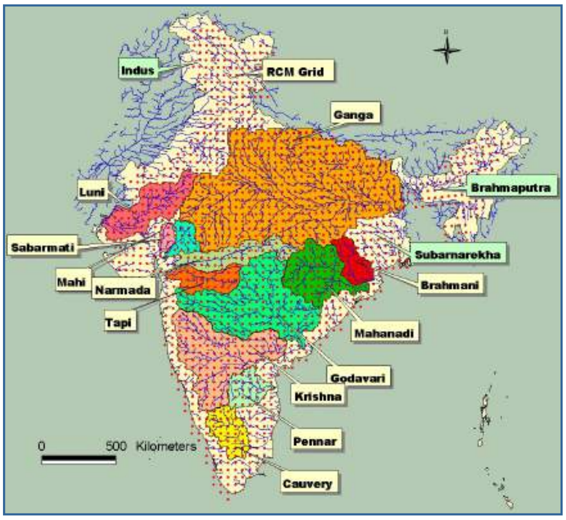
$$R_{s/d} = \frac{\Delta(WY - IRR)_{scenario}}{|(WY - IRR)_{baseline}|}$$



Climate Change on Water case studies in India and China Using the SWAT model

River Basins Modeled

India



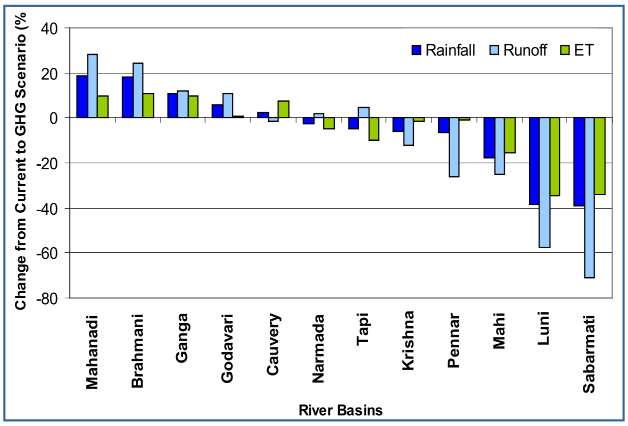
Impact studied

India

- Impact on annual water availability
- Impact on seasonal water availability
- Impact on inter annual water availability
- Regional Variability of Water availability

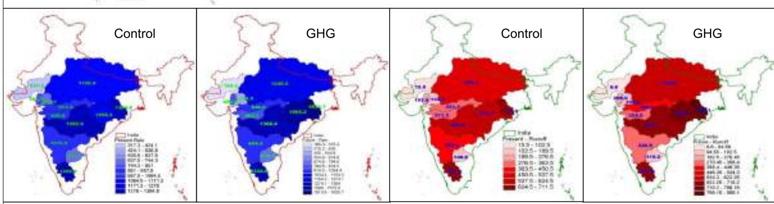
Percent change in mean annual water balance for Control and GHG climate scenarios

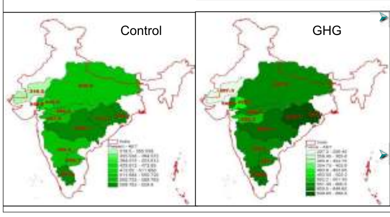
India



Trend in Precipitation, Runoff and Evapotranspiration for Control and GHG Climate Scenarios

India





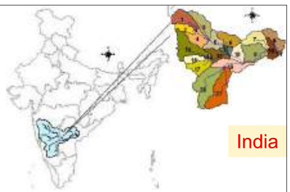
Increase in precipitation in Mahanadi, Brahmani, Ganga, Godavari, and Cauvery, for the GHG scenario

- the corresponding total runoff for all these basins has not necessarily increased
- Cauvery and Ganga show decrease in total runoff. This may be due to increase in evapotranspiration on account of increased temperatures or variation in the distribution of the rainfall

In the remaining basins decrease in precipitation has been expected

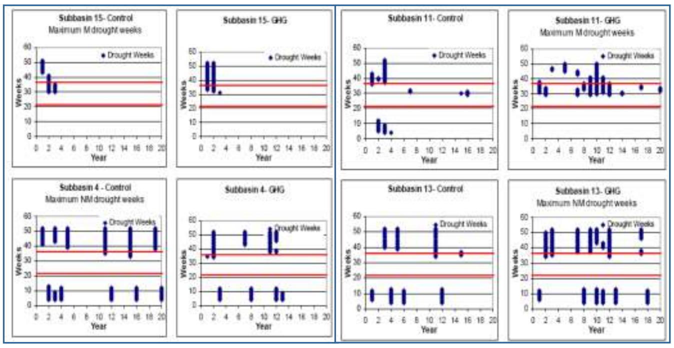
- The resultant total runoff has decreased in majority of the cases but for Narmada and Tapi

Drought Analysis



India

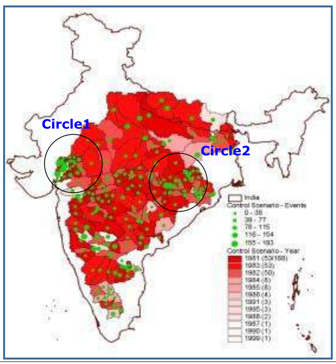
- Krishna Subbasins with maximum Monsoon & Non monsoon events in Control & GHG Scenario

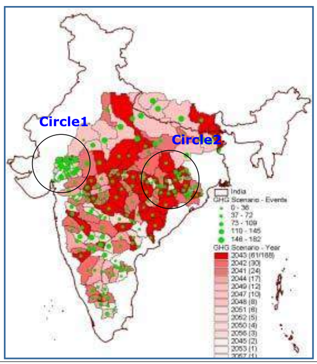


Spatial and temporal distribution of drought conditions

India

- graduated colour depicts spatial variability of concurrent severity of drought, number of sub-basins where severe concurrent conditions prevailed in that year
- size of the green dot reveals the number of drought weeks experienced in each sub-basin over the 20 years
- Sabarmati and Mahi, sever drought conditions in comparison to control scenario
- Mahanadi and Brahmani , the drought conditions seem to improve in the GHG scenario



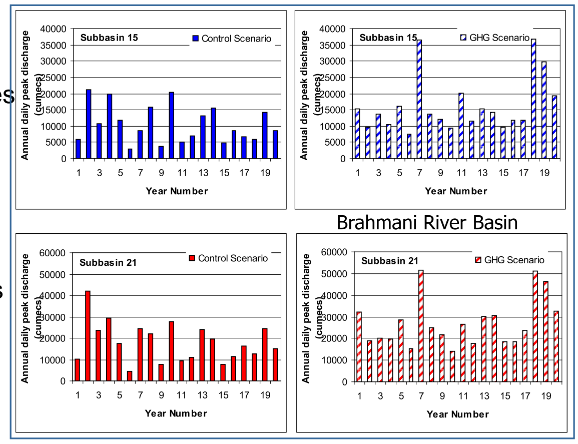


India

Flood Analysis

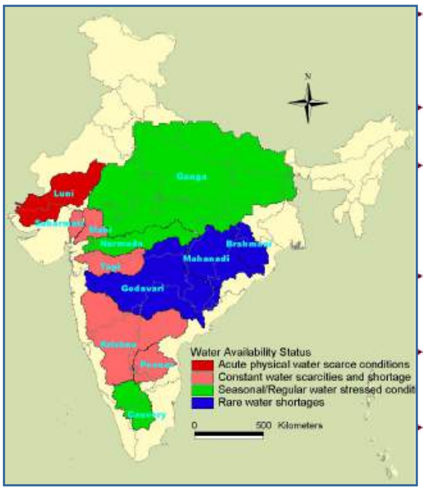
- Annual maximum daily peak discharges for two sub-basins of Mahanadi and Brahmani river basins for Control and GHG scenarios

Mahanadi River Basin



India

Key Findings

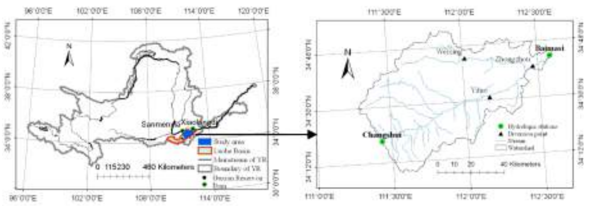


- Under the GHG scenario the conditions may deteriorate in terms of severity of droughts in some parts of the country and enhanced intensity of floods in other parts
- there is a general overall reduction in the quantity of the available runoff under the GHG scenario
- Luni with the west flowing rivers Kutch & Saurastra which occupies about one fourths of the area of Gujarat and 60 percent of the area of Rajasthan shall have acute physical water scarce conditions
- River basins of Mahi, Pennar, Sabarmati, Krishna and Tapi shall face constant water scarcities and the water shortage conditions
- River basins belonging to Cauvery, Ganga, and Narmada shall experience seasonal or regular water stressed conditions
- River basins belonging to Godavari, Brahmani and Mahanadi shall have rare water shortages and if exist are only confined to few locations

China

Downstream of Luohe River Basin

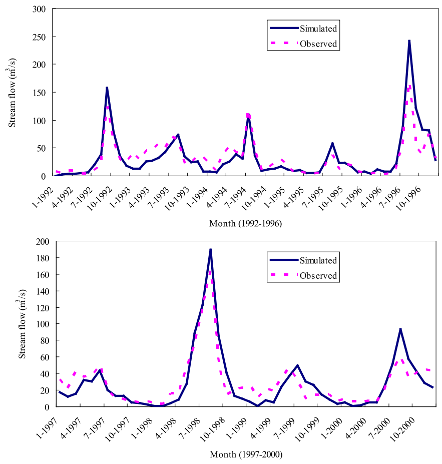
- During 1961-1990, the average flow rate at the Baimasi hydrological station was about 55 $m^3 s^{-1}$
- while in the 1990s, the average flow rate decreased to approximately 30 $m^3 s^{-1}$.



China

Model Calibration and Validation

Period	Mean ($m^3 s^{-1}$) Obs.	Mean ($m^3 s^{-1}$) Sim.	*Re*	Time Step	R^2	*NWE*
Calibration (1992-1996)	33.22	31.62	5.1%	Daily	0.82	0.65
				Monthly	0.82	0.64
Validation (1997-2000)	28.52	29.24	-2.5%	Daily	0.74	0.54
				Monthly	0.86	0.82



China

Potential Future Climate Change

- Two GCMs
  - HadCM3 by U.K. Meteorological Office Hadley Centre for climate prediction and research
  - CGCM2 model developed by the Canadian Centre for Climate Modelling and Analysis
- Two Emission scenarios
  - The A2 scenario projects high population growth and slow economic and technological development
  - while the B2 scenario projects slower population growth, rapid economic development, and more emphasis on environmental protection.
- Eight future climate conditions
  - 2020 (H2020A2, H2020B2, C2020A2, C2020B2)
  - 2050 (H2050A2, H2050B2, C2050A2, C2050B2)

China

Potential Future Climate Change

Annual and monthly average temperature changes (°C) under various scenarios.

Scenario	Month 1	2	3	4	5	6	7	8	9	10	11	12	Annual
C2020A2	2.2	1.9	2	2.3	3.8	2.9	1.6	1.4	0.9	0.4	1.6	3.2	2
H2020A2	0.9	0.8	0.8	1	1	1.7	1.1	1.5	1.9	1.4	1.2	1.3	1.2
C2020B2	2.2	1.4	2	2.5	4.7	3.1	1.5	1.7	1.4	1.1	1.4	3.4	2.2
H2020B2	1.9	1.3	1.3	0.9	1	1.4	2.1	3	1.9	1.4	2.3	1.5	1.7
C2050A2	4.1	3.8	4.2	3.6	6	4.1	2.6	2.2	2.2	1.7	2.9	6.3	3.6
H2050A2	3	3.3	2.8	1.3	1.9	2.8	3.4	4.8	3	2.4	2.7	2.2	2.8
C2050B2	3.2	2.5	3	2.8	4.1	3.4	2.2	1.7	1.7	1.6	2.4	4.5	2.8
H2050B2	2.3	1.2	1.9	1.3	2.2	2.5	3.4	4.5	2.9	2.5	2.8	1.1	2.4

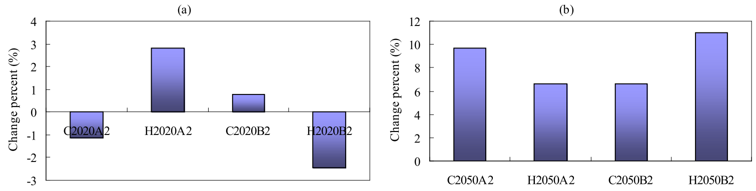
Annual and monthly cumulative precipitation changes (mm) under various scenarios.

Scenario	Month 1	2	3	4	5	6	7	8	9	10	11	12	Annual Cumulative
C2020A2	-3.4	-3.6	8.1	13.8	17.1	-12.6	-9.6	10.5	-11.7	-18.9	-12.3	-0.9	-23.7
H2020A2	-0.3	1.1	0.6	1.5	0.9	10.5	-6.8	6.8	4.8	0.9	3.0	0.3	23.4
C2020B2	-4.0	-3.1	3.4	-0.6	30.4	3.3	-11.5	2.5	2.4	0.3	-15.9	-4.0	3.2
H2020B2	1.6	1.1	2.2	2.7	-2.2	8.7	14.9	-3.7	6.6	1.2	3.9	2.2	39.1
C2050A2	-3.7	-1.7	9.3	6.6	42.8	-1.5	8.7	9.9	-6.3	-18.6	-11.4	0.3	34.4
H2050A2	2.5	3.4	4.0	2.4	4.0	9.9	8.4	2.2	16.5	5.0	1.2	2.5	61.9
C2050B2	-3.1	-2.0	14.3	12.3	30.7	-4.2	-5.0	8.1	-10.5	-9.6	-4.5	0.6	27.1
H2050B2	1.2	0.0	2.5	3.6	-0.3	3.9	20.2	10.2	9.6	3.4	4.2	-0.3	58.2

China

Annual Streamflow Change

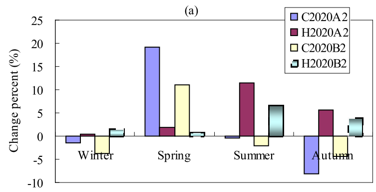
- In 2020, the predicted streamflow change is within ±3%
- In 2050, possible annual streamflow changes are expected to range between +6% and +11%.



China

Seasonal Streamflow Change

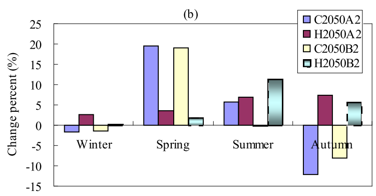
- In 2020, the predicted streamflow changes ranged from -4% to +2% in winter, from +1% to +20% in spring, from -2% to +12% in summer, and from -9% to +6% in autumn.



China

Seasonal Streamflow Change

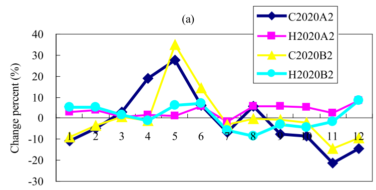
- In 2050, predicted streamflow changes ranged from -2% to +3% in winter, from +2% to +20% in spring, from -1% to +12% in summer, and from -12% to +8% in autumn.



China

Monthly Streamflow Change

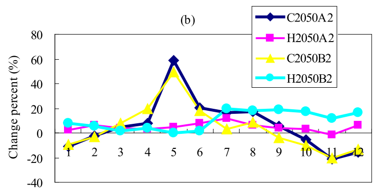
- In 2020, the possible streamflow change in January, February, March, July, August, September, and October is within ±10%. In the other months, the maximum possible streamflow change was predicted to be within ±20%, except for May, which showed a maximum possible streamflow change reaching +35%.



China

Monthly Streamflow Change

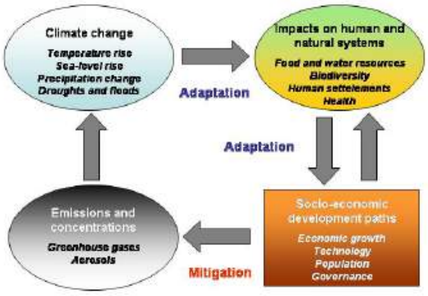
- In 2050, the possible streamflow change amplitude in January, February, and March was within ±10%. In other months, this change was within ±20%, again except for May, which had predicted streamflow changes reaching +60%.



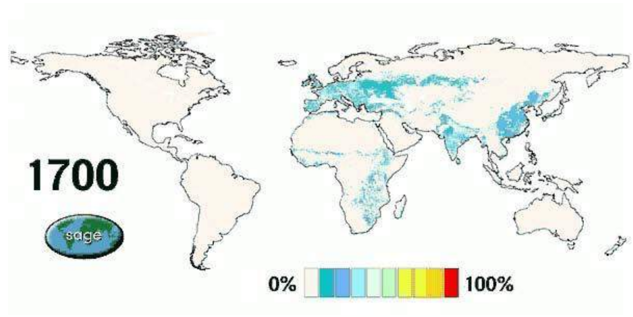
Climate Change and Agriculture: Adaptation and Mitigation

Adaptation, Mitigation, and Vulnerability: Definitions

- Adaptation: an action designed to lessen adverse impacts of climate change on human and natural systems
- Mitigation: an action designed to counteract emissions and concentrations of greenhouse gases and aerosols in the atmosphere
- Vulnerability: extent to which climate change may harm a system



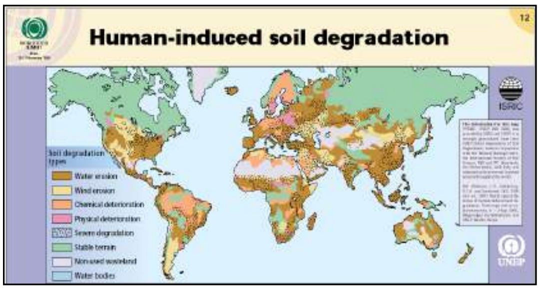
Historical development of croplands



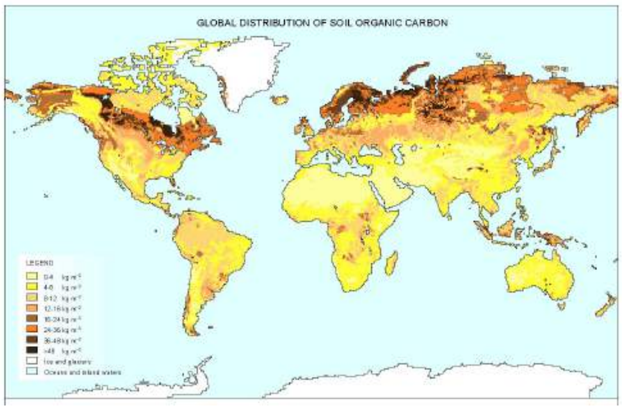
Ramankutty and Foley (1999)

Impacts of land use change and management on soil and environmental quality

- Land use and land use change have affected
  - Soil and environmental quality
  - Terrestrial carbon stocks
- Preservation of land and water quality is essential to address climate change



Global distribution of soil organic C (ISRIC, 2002)



Carbon Sequestration: Carbon removal from the atmosphere

- **Natural sinks**
  - **Forests**
  - **Oceans**
- **Enhanced sinks**
  - **Forests**
  - **Soils**
  - **Oceans**
- **Artificial sinks**
  - **Geologic sequestration**

Forest Carbon Sequestration:

An accepted mitigation technology with finite potential (40 Pg C)

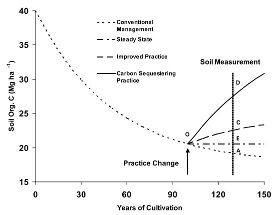
Reforestation

Afforestation

Land Use change and soil management effects on SOM levels

- Cultivation
  - Carbon oxidation and nutrient mineralization
- Erosion
  - Wind and water
- Improved practices
  - Agricultural systems
  - Land use conversions

Summer fallow

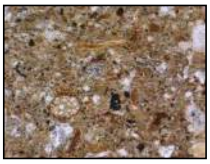


Wind erosion

Soil Carbon Sequestration: A near term mitigation technology with significant but finite potential (40 Pg C)

Net primary productivity

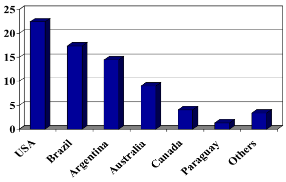
Fresh soil organic matter



Organo-mineral complexes

No-till seeding in USA

Adoption of no-till worldwide (Mha)



Izaurralde and Rice (2006)

Agricultural management plays a major role in greenhouse gas emissions and offers many opportunities for mitigation

- **Cropland**
  - Reduced tillage
  - Rotations
  - Cover crops
  - Fertility management
  - Erosion control
  - Irrigation management
- **Rice paddies**
  - Irrigation
  - Chemical and organic fertilizer
  - Plant residue management

Rice fields in The Philippines

No-till seeding in USA

- **Agroforestry**
  - Better management of trees and cropland

Maize / coffee fields in Mexico

The southeastern USA has seen significant adoption of no-tillage in cotton production systems

- As of 2004, there were 2.9 Mha (~24% of total cropland) under cotton production in the southeastern USA
- Of this land, 34% was under conservation tillage (mostly no-tillage), 17% under reduced tillage, and 48% under conventional tillage

No-tillage cotton production systems increase soil carbon in the southeastern USA

Conventional tillage cotton

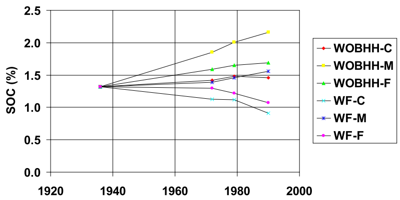
470 kg C ha^{-1} yr^{-1}

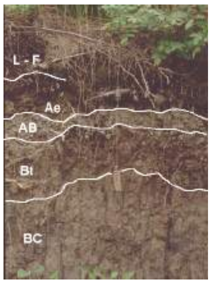
Causarano et al. (2006) J. Environ. Qual. 35:1374–1383

No-tillage cotton

Understanding management effects on soil organic C dynamics

- Breton Classical Plots
  - Forest to agriculture in ~1900
  - Experiment initiated in 1930
  - Current treatments (1938)
    - Crop rotations
      - Fallow-wheat
      - Five-year rotation
    - Fertility treatments
      - Control
      - Fertilizer
      - Manure





KBS Long-Term Ecological Research (LTER) Site

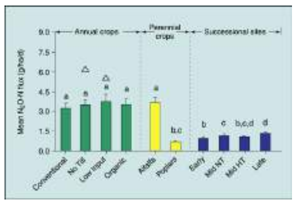
Robertson et al. Science 289:1922-1925 (2000)

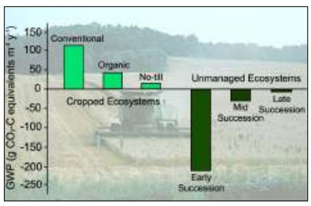
Ecosystem Type	Management Intensity
Annual Crops (Corn - Soybean - Wheat)	
Conventional tillage	High
No-till	
Low-input with legume cover	
Organic with legume cover	
Perennial Crops	
Alfalfa	
Poplar trees	
Successional Communities	
Early successional old field	
Mid successional old field	
Late successional forest	Low

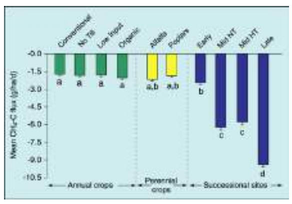
Full Carbon Accounting in Agroecosystems

Robertson et al. (2000) Science 289:1922-1925

1. Soil C Oxidation
2. Fuel
3. Nitrogen Fertilizer
4. Lime ($CaCO_3$) and Ca in Irrigation Water
5. Non-CO_2 Greenhouse Gases
   - N_2O
   - CH_4



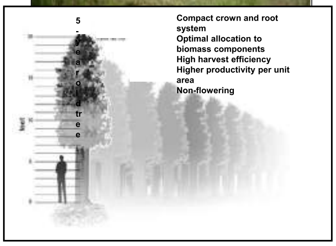




Biomass Energy Crops



- Plant biomass can be used to produce liquid fuels, electricity, and heat
  - Agricultural crops (grain and residues)
  - Forest residues
  - Municipal solid wastes
- New traits for biomass energy crops
  - Attributes
    - Native, perennial, fast growing, pest resistant, non-agronomic
  - Examples
    - Switchgrass
    - Poplar
- Research needs
  - Examine their role on land use and competition with food and fiber crops
  - Evaluate impacts on managed and unmanaged ecosystems



Can we adapt to climate change?

- In general, societies have exhibited a good degree of adaptation to weather and climate conditions
  - Agriculture: crop varieties, agronomic practices, water management
  - Urban centers: disaster management, insurance
- However, climate change presents risks of unknown consequences
  - Permafrost melt (and release of greenhouse gases)
  - Accelerated glacier retreat


Flood insurance in coastal areas


Aftermath of hurricane Katrina


New crop varieties and agronomic practices

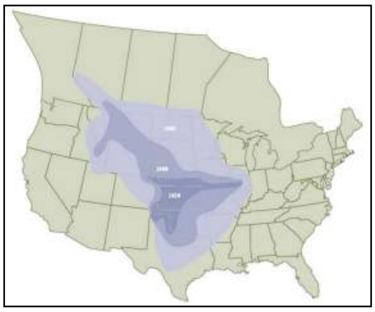


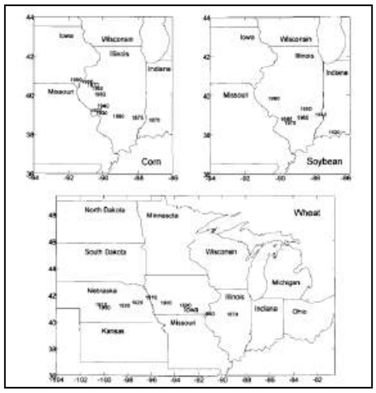
Permafrost melt in Siberia

Adaptation in agriculture

- 2nd IPPC report
  - "…global agricultural production can be maintained relative to baseline production in the face of climate changes…"
- 3rd IPPC report
  - "…downward trend in real commodity prices in the 20th century is likely to continue into the 21st century, although confidence in these predictions decreases further into the future…"

The geographic center of crop production in the US has changed over time: Adaptation to climate change?


Temporal changes in the wheat production zone from 1920 to 1999 (Rosenberg et al. 1982; Easterling et al., 2004)

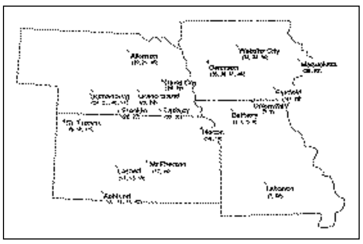


Geographic centers of production of corn, soybean, and wheat (Reilly et al. 2003)

The MINK study: a pioneer study of climate change impacts on agricultural production and the need for adaptation


- Region selected for
  - Physiographic homogeneity
  - Vulnerability of natural and socio-economic resources to climate change
- The study used
  - Historical climate records as analogs of climate change (**The Dust Bowl** of the 1930s**)**
  - Biophysical modeling of "representative farms"
    - Climate parameters
    - Soil properties
    - Management practices

Rosenberg (1992) Agric. For. Meteorol. Vol. 59

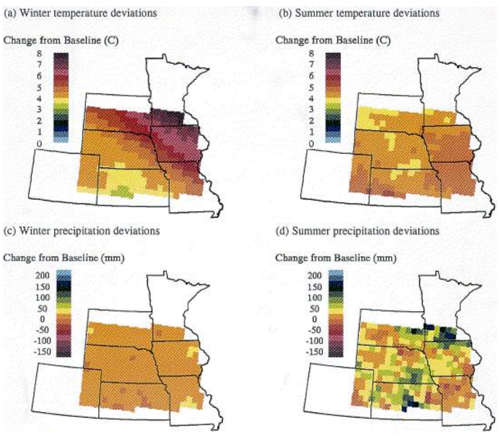

The MINK region: Missouri, Iowa, Nebraska, and Kansas

Adaptation strategies in the MINK region
Easterling et al. (1992) Agric. For. Meteorol. 59:75-102

- Planting and harvesting strategies
  - Planting dates
  - Planting depth
  - Reduce plant density
- Land management
  - Reduce tillage
  - Conserve moisture
    - Fallow
    - Stubble mulch
    - Ridge till
- Variety and crop selection
  - Switch to shorter or longer season cultivars
  - Select stress tolerant crops
  - Convert marginal land to pasture or range
- Fertility and pest management
  - Biological N fixation
  - Reduce N application
  - Chemical weed control

An example of adaptation: crop selection

Brown et al. (2000) Agric. Ecosys. Environ. 78:31-47



An example of adaptation: crop selection

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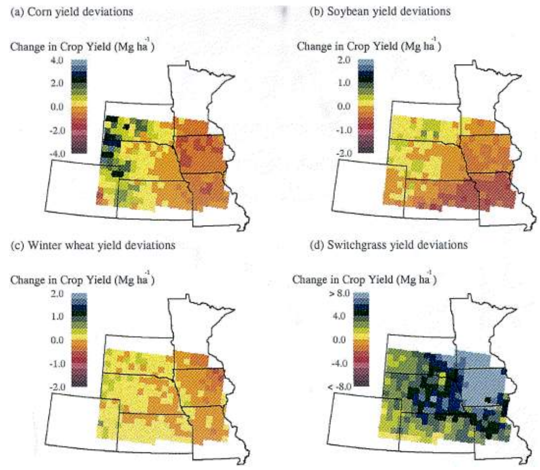

The time to start adapting to climate change is now

- UN Climate Change Conference held in Nairobi, Kenya in November 2006
  - Clear message on the need for adaptation
  - Even if emissions were to be stopped now, greenhouse gases already in the atmosphere will continue to induce global warming
- International, national, and local organization already taking action


GLOBAL WARMING

U.N. Conference Puts Spotlight on Reducing Impact of Climate Change

Summary of expected effects of global warming on agricultural crops

- An increase in temperature over the next decades will likely reduce yields of important crops such as maize, wheat, cotton, sorghum, and peanut
- The increase of atmospheric CO_2 in the next decades could favor the yields of C3 species over C4 species due the so-called CO_2-fertilization effect (i.e. increased photosynthesis and water use efficiency)
- All crops will be subject to increased recurrence of extreme climatic conditions (e.g. droughts, extreme temperatures)

Summary

- There is scientific evidence that humans are in good part responsible for ongoing changes in the climate system
- A global effort will be required to stabilize greenhouse gases to levels that are non-damaging for humanity and ecosystems
  - Mitigation (improved efficiency in energy use, new energy technology, carbon capture and sequestration)
  - Adaptation (prepare social and natural systems for climate change)
- Cotton production maybe affected in the future by a variety of environmental factors
  - Increases in temperature, especially during reproductive stages, will lead to decreases in boll yields
  - If present, the CO_2 fertilization effect may ameliorate the negative effects of temperature and even result in yield increases
  - Cotton plants will be subject to more extreme conditions (e.g. droughts, extreme temperatures) or presence of pollutants (e.g. tropospheric ozone)
  - Increasing organic matter in soils might be one of the best ways to ensure the long-term sustainability of cotton production

Acknowledgements

- US Department of Energy, Office of Science
  - Integrated Assessment Research Program
  - Carbon Sequestration in Terrestrial Ecosystems (CSiTE)
  - The Modeling of Regional Climate over China