Urban and regional carbon management in the context of the global carbon cycle

Michael Raupach, Pep Canadell and Shobhakar Dhakal

Global Carbon Project (IGBP-IHDP-WCRP-Diversitas)
Cities and towns are transforming the planet

- NASA Earthlights composite
Carbon, climate and humans

Human activities

(1) Forcing
(3) Impacts
(4) Response

Carbon cycle
(2) Altered biophysical feedbacks

Climate
Natural biophysical feedbacks
Carbon-climate-human system: forcing and response

Records (1850-2005) of:
- CO₂ emissions from fossil fuels
- Changing CO₂ concentrations in the atmosphere
- Changing global mean temperatures (from instrumental record with effects of urbanisation removed)

<table>
<thead>
<tr>
<th>FF Emission to 2003</th>
<th>Marland, CDIAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>FF Emission 2004-05</td>
<td>Marland PersComm</td>
</tr>
<tr>
<td>Global temperature</td>
<td>Jones et al, CRU</td>
</tr>
<tr>
<td>CO₂ 1832-1958</td>
<td>LawDome 20yr</td>
</tr>
<tr>
<td>CO₂ 1959-now</td>
<td>MaunaLoa</td>
</tr>
</tbody>
</table>
Present radiative forcing

Radiative Forcing Terms

CO$_2$

Non-CO$_2$ GHGs

Non-gaseous radiative forcing

Radiative Forcing (W m$^{-2}$)

Timescale

Scientific understanding

Global

High

~ 10 - 100 yrs

Global

High

Weeks to months

Continental to global

Med

Years

Global

Low

10 - 100 yrs

Local to continental

Very Low

10 - 100 yrs

Global

Med

Spatial scale

IPCC AR4, WG1 SPM, second draft (24-mar-2006)
Global warming

- IPCC (2001)
- Predicted warming of 1.4 to 5.8°C depends on
  1. uncertainties in climate models (around 1°C)
  2. uncertainties in emissions scenarios (around 2°C)

IPCC (2001) Third Assessment, Summary for PolicyMakers
Lags in the response of climate to emissions

CO₂ concentration, temperature, and sea level continue to rise long after emissions are reduced

Magnitude of response

Time taken to reach equilibrium

CO₂ emissions peak
0 to 100 years

Sea-level rise due to ice melting:
several millennia

Sea-level rise due to thermal expansion:
centuries to millennia

Temperature stabilization:
a few centuries

CO₂ stabilization:
100 to 300 years

CO₂ emissions

Today 100 years

1,000 years

IPCC 2001, SYM, Figure 8.3
Impacts: food

- Food supplies in developing nations are more vulnerable to climate change than in developed countries.
Impacts: water

- Water supplies in many nations are vulnerable to climate change
- Climate vulnerability compounds population vulnerability, especially in less developed nations

Vörösmarty et al 2000, Science
Carbon-climate-human feedbacks in the Earth System

The changing carbon cycle: trends, drivers, vulnerabilities
- Land-air and ocean-air CO\textsubscript{2} exchanges
- CO\textsubscript{2} emissions from human activities (I = PAT)

Carbon management
- Components of carbon management (technical, economic, policy, cultural)
- Opportunities for urban and regional carbon management
The global carbon cycle

The current carbon cycle (Sabine et al 2004)
Global atmospheric CO₂ budget

\[ \frac{dC_A}{dt} = F_{\text{Emission}} + F_{\text{LandUseChange}} + F_{\text{LandAir}} + F_{\text{OceanAir}} \]

Data Sources:
- Atmosphere: Keeling and Whorf (2005) CDIAC
- Land: difference
Vulnerability of the earth system to destabilisation of carbon pools

- **C4MIP =**
  Coupled Climate Carbon Cycle Model Intercomparison Experiment

- Intercomparison of 8 coupled climate-carbon cycle models

- Uncertainty (range among predictions) is comparable with uncertainty from physical climate models and emission scenarios

**Friedlingstein et al. 2006, in press**
Vulnerability to release of frozen carbon

- Response of CO₂
- Response of temperature

- \( C_{F0} = 900 \text{ PgC} \) (from permafrost area and permafrost soil C data)
- \( k_{FT} = 0.001 \text{ [y}^{-1}\text{ K}^{-1}] \) (Anisimov et al 1999: warming of 2 degC over 100 y decreases permafrost by 25%)
CO₂ emissions from human activities

Response (emissions) and drivers (population, GDP)
Formalism

- **Basic variables (extensive: proportional to size of a homogeneous region)**
  - $F = $ fossil-fuel CO$_2$ emission
    - $P = $ population
    - $G = $ GDP

- **Basic (Kaya) identity (Nakicenovic 2004)**
  - $[F = P \times (G/P) \times (F/G)]$
  - [Impact = Population * Affluence * Technology]

- or $F = Pgh$

- **Normalised (intensive) variables**
  - $g = G/P = $ per capita GDP (Affluence)
  - $h = F/G = $ FF intensity of GDP (Technology)
  - $j = F/P = $ per capita FF emission = gh

- **Growth rates**
  - Growth rate for quantity $X$: $r(X) = (1/X) \frac{dX}{dt}$
  - Basic identity implies: $r(F) = r(P) + r(g) + r(h)$
Growth rates in CO₂ emissions, population, GDP

\[ r_F = \frac{F'}{F} \]
\[ r_P = \frac{P'}{P} \]
\[ r_G = \frac{G'}{G} \]
Intensive variables:
Per capita emission and GDP, and FF intensity of GDP

\[ g = \frac{G}{P} = \text{Percapita GDP (k$/y/person)} \]
\[ h = \frac{F}{G} = \text{FF intensity of GDP (100gC/$)} \]
\[ j = \frac{F}{P} = \text{Percapita FF emission (tC/y/person)} \]
Vulnerability of the Earth System to CO₂ emissions: Stabilisation scenarios and the emissions gap

- Stabilisation scenario: future emissions trajectory needed to stabilise CO₂ at a given level (a goal, not a prediction)
- Over 2000-2005, actual emissions are: close to the A1 scenario
  close to the maximum for 650 ppm
  above the maximum for 450 ppm
Carbon-climate-human feedbacks in the Earth System

The changing carbon cycle: trends, drivers, vulnerabilities
- Land-air and ocean-air CO₂ exchanges
- CO₂ emissions from human activities (I = PAT)

Carbon management
- Components of carbon management (technical, economic, policy, cultural)
- Opportunities for urban and regional carbon management
Components of carbon management

- **Technical**
  - Broad portfolio of energy technologies: renewables, cleaner FF, conservation ...
  - Both supply-side and demand-side focus
  - A workable transition pathway that starts now

- **Economic**
  - Clever use of market drivers
  - GH accounting, trading mechanisms

- **Policy**
  - Carbon price signals: policies to make greenhouse costs visible to the market
  - Support for innovation (technical, economic, policy, socio-cultural)
  - Implementing favourable incentives, removing perverse incentives

- **Cultural**
  - Motivating awareness and action
  - Decoupling quality of life from continual growth in consumption
  - Protection of the global commons as a universal ethical imperative
Costs of technologies: centralised electricity generation in Australia

Paul Graham (CET) and CSIRO Energy Working Group, 2006

Coal wins without a GH cost signal
Cap and trade: New South Wales

- Target: 5% better than Australia's Kyoto commitment
## Instruments for carbon management: levels of decision and action

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Level of decision</th>
<th>Level of action</th>
</tr>
</thead>
<tbody>
<tr>
<td>T Cleaner stationary energy</td>
<td>State, nation</td>
<td>State</td>
</tr>
<tr>
<td>T Cleaner transport energy</td>
<td>State, nation</td>
<td>State, town</td>
</tr>
<tr>
<td>T Better storage and distribution</td>
<td>State, nation</td>
<td>State, town</td>
</tr>
<tr>
<td>T End use efficiency, demand limitation</td>
<td>State, nation</td>
<td>State, town</td>
</tr>
<tr>
<td>T Urban design: buildings, roads, vegetation</td>
<td>town</td>
<td>town</td>
</tr>
<tr>
<td>E Carbon accounting, verification</td>
<td>State, nation, internat</td>
<td>Public, private</td>
</tr>
<tr>
<td>E Carbon trading</td>
<td>State, nation, internat</td>
<td>Public, private</td>
</tr>
<tr>
<td>P Emissions caps (leading to carbon price)</td>
<td>State, nation, internat</td>
<td>Private, public</td>
</tr>
<tr>
<td>P Incentives for investment</td>
<td>State, nation</td>
<td>State, nation</td>
</tr>
<tr>
<td>P International consistency</td>
<td>Internat</td>
<td>INTERNAT, town?</td>
</tr>
<tr>
<td>C Motivating awareness and action</td>
<td>town, state</td>
<td>town, state</td>
</tr>
</tbody>
</table>
Populations of largest urban regions and cities

- **100 largest urban regions**
  1: Tokyo (35.2M)
  2: Mexico City (19.4M)
  100: Casablanca (3.1M)
  Total: 693M (10.7% of global)

- **60 largest cities**
  1: Mumbai (12.78M)
  9: Mexico City (8.5M)
  60: Pune (3.06M)
  Total: 351M (5.4% of global)

- **We are talking about urban settlements of all sizes!**

http://en.wikipedia.org/wiki/List_of_metropolitan_areas_by_population
August 2006
Global trends in urbanisation 1950-2015

UN Development Program data (August 2006)
Urban and rural incomes: China

- Per capita income of urban and rural households in China, 1978 - 1997


- **Caption**: This chart partly explains the attraction of cities and towns for China’s rural population. Whereas average household income has risen significantly in rural areas, incomes in urban areas have increased even more. The gap between urban and rural income has remained almost unchanged.

- **Source**: China Statistical Yearbook, Beijing, 1998 (p.325)

- **Note**: Constant prices.
Growth rates in CO$_2$ emissions, population, GDP

Growth rates (5y smoothed)

$r_F = \frac{F'}{F}$

$r_P = \frac{P'}{P}$

$r_G = \frac{G'}{G}$
Summary

- **Carbon-climate-human feedbacks in the Earth System**
  - Cities are amazing places
  - Cities are also growing to be destabilisers of the earth system

- **The changing carbon cycle: trends, drivers, vulnerabilities**
  - Land and ocean sinks take up ~half of current anthropogenic CO₂ emissions
  - The signature of CO₂ emissions is changing:
    - growth rate of emissions has accelerated since Y2000
    - fossil-fuel intensity of GDP has increased since Y2000 (after falling for 30 y)

- **Carbon management**
  - Technical, economic, policy, and cultural dimensions: all four are critical
  - Opportunities for urban and regional carbon management:
    - Understanding what are the carbon dynamics of urban regions, and how they interact with the global C cycle and earth system
    - Understanding the opportunities for urban and regional carbon management, and who controls them
    - As a research community, engaging to turn possibilities into realities
Cities are amazing places.
Indices of El Nino-Southern Oscillation (ENSO)

- SOI = P(Tahiti) - P(Darwin)
- Nino3.4 = central equatorial Pacific sea surface temperature
- MEI = Multivariate ENSO Index
Land-air and ocean-air CO$_2$ exchanges: ENSO as a driver on interannual variability

- Atmospheric CO$_2$ budget: \[ \frac{dC_A}{dt} = F_{\text{Emis}} + F_{\text{LUC}} + F_{\text{LandAir}} + F_{\text{OceanAir}} \]
- Non-fossil-fuel fluxes: \[ (\frac{dC_A}{dt} - F_{\text{Emis}}) = (F_{\text{LUC}} + F_{\text{LandAir}} + F_{\text{OceanAir}}) \]
- Main influences of ENSO:
  - on land-air CO$_2$ flux (drought, heat, wildfire)
  - on LUC flux (humans have coopted ENSO as a helper for land clearing)
Consequences of urbanisation for CO\textsubscript{2} emissions: a statistical approach

- Basic identity: \[ F = P \left( \frac{G}{P} \right) \left( \frac{F}{G} \right) = P g h \]

- Let \( U \) = population of an individual urban unit (town or city)
  \( U_{\text{min}} \) = population of smallest town
  \( U_{\text{max}} \) = population of largest city

- Consider \( \rho(U) \), the probability density function of \( U \)
  - Definition: \( \rho(U) \, dU \) is the fraction of the total population living in towns with populations between \( U \) and \( U + dU \)

- We expect the affluence or percapita GDP (\( g = G/P \)) and the fossil-fuel intensity of GDP (\( h = F/G \)) to depend on the size of the urban unit: \( g = g(U), \quad h = h(U) \)

- Then for a region with total population \( P \), distributed among towns of size \( U \) with probability density function \( \rho(U) \), the total fossil fuel emission \( F \) is

\[
F = P \int_{U_{\text{min}}}^{U_{\text{max}}} g(U) h(U) \rho(U) \, dU
\]