Understanding Agricultural and Urban Land Cover Impacts on Regional Climate

Dr. Michael Puma
GISS Lunch Seminar
7th Floor Conference Room
28 March 2012
Before we start…

• **LULCC** stands for Land-Use induced Land-Cover Change; it’s a general term for the human modification of Earth's terrestrial surface

• Refers mainly to conversion of natural forests or natural grasslands for urbanization and agriculture

• Acronyms aren’t always helpful, so we’ll go with **land change** for today…
Regional importance of land change

• Most experiments => land change has a negligible global signature
• BUT consider *intense land change* – where it has transformed large regions of the Earth’s surface => a spatially organized change by region
• **Relevant Research Question**: Are climate impacts *in regions with intense land change* worth accounting for when exploring the impact of other human forcings (ie GHGs) on regional climate?
  – *NOT* whether land change has a globally-averaged significant impact

Reference: de Noblet-Ducoudre (2012)
Changes in crop/pasture extent

Red: increase in human areas
Blue: decrease in human areas

Source: de Noblet-Ducoudre (2012)
Deforestation decreases ET efficiency and surface aerodynamic roughness => tends to cause warming by suppressing turbulent energy fluxes

Historic land change (mainly deforestation) tends to increase the surface albedo resulting in cooling.
• Seven atmosphere-land models
• “a common experimental design to explore those impacts of LULCC that are robust and consistent across the climate models”
de Noblet-Ducoudré (2012) Intercomparison

- Variability from land change > from GHG increases
- Robust common features:
  - Amount of available energy used for turbulent fluxes
  - Changes in response to land change depend almost linearly on the fraction of trees removed
- No consistency on the partitioning of available energy between latent and sensible heat fluxes
Model-dependent land-atmosphere coupling

- Model differences (coupling strengths) are related to
  - Variance of evapotranspiration (ET) over land → how soil moisture controls ET
  - Precipitation parameterizations and its respond to ET changes
- Process is not entirely local
  - Advection and the general circulation of the atmosphere transport water and moist static energy horizontally
- Land horizontal transports in rivers and by irrigation

Source: Dirmeyer 2006
Outline

I. Irrigation and climate
II. Deforestation and climate
III. Urbanization and climate
IV. Land-Atmosphere Research Program at GISS
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How has irrigation modified climate over the 20th Century?

**Effects of irrigation on global climate during the 20th century**

M. J. Puma$^{1,2}$ and B. I. Cook$^{2,3}$

- Irrigation modifies energy and water budgets
- Potentially leads to:
  - Lower temperature
  - Higher humidity
  - Increased convection (contributes heat to destabilize boundary layer)

Irrigation in ModelE

- Two 5-member ensemble simulations (IRRIG, CTRL)
- 2° lat x 2.5 °long
- Observed SSTs
- Irrigation is added as a flux to the top of the vegetated soil column
- Irrigation water/energy (withdrawn from lakes/rivers)
- If insufficient, then remaining water is added to the system (fossil water)
Seasonal total irrigation

**DJF:** December, January, February

**JJA:** June, July, August
Seasonal total irrigation

DJF: December, January, February

JJA: June, July, August
Seasonal irrigation by latitude band

<table>
<thead>
<tr>
<th>Study</th>
<th>Gross Irrig. (km$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Our Study</td>
<td>2565</td>
</tr>
<tr>
<td>Sacks et al. [2009]</td>
<td>2560</td>
</tr>
<tr>
<td>Lobell et al. [2006]</td>
<td>†</td>
</tr>
<tr>
<td>Boucher et al. [2004]</td>
<td>2353†</td>
</tr>
</tbody>
</table>

JJA – June, July, August
DJF – December, January, February

Source: Puma & Cook, 2010
Seasonal evapotranspiration

DJF: December, January, February

JJA: June, July, August

Only land changes with a p<0.1 significance (based on a two sample t-test)
Seasonal evapotranspiration

DJF: December, January, February

JJA: June, July, August

Only land changes with a p<0.1 significance (based on a two sample t-test)
Seasonal precipitation

DJF: December, January, February

JJA: June, July, August
Seasonal precipitation

DJF: December, January, February

JJA: June, July, August
Seasonal 2m air temperature

DJF: December, January, February

JJA: June, July, August
Seasonal 2m air temperature

**DJF:** December, January, February

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Regional effects of irrigation

Source: Puma & Cook, 2010
Regional effects of irrigation

Source: Puma & Cook, 2010
Regional effects of irrigation

Source: Puma & Cook, 2010
Why different temperature responses?

Evaporative fraction (EF): ratio of evapotranspiration to net radiation

\[ EF = \frac{Q_e}{Q_e + Q_h} \]

- \( Q_h \) = sensible heat flux
- \( Q_e \) = latent heat flux
Note: Bowen ratio = \( Q_h/Q_e \)

Evaporative regimes

- **Regions A & B**: soil-moisture controlled; irrigation generally increases \( Q_e \) and cools surface temperatures
- **Region C**: straddles the two regimes; irrigation can lead to more limited increases in \( Q_e \) and more limited cooling
- **Region D**: energy controlled -> irrigation does not impact surface temperatures

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Irrigation induced surface cooling in the context of modern and increased greenhouse gas forcing

Benjamin I. Cook · Michael J. Puma · Nir Y. Krakauer

- What is the cooling effect of irrigation under modern and future greenhouse gas forcing? (i.e. is there a masking effect and does it change in the future?)
Irrigation and evaporative fraction

- Irrigation impacts on surface air temperature (MI-MC) related to
  - Irrigation amount (mm/d, indicated by coloring)
  - Evaporative fraction (EF)

- Two periods
  - October to March
  - April to September

*Source: Cook, Puma, Krakauer, 2011*
Current irrigation-induced cooling

**Fig. 6** Differences in surface air temperature (K) over land areas for the modern irrigation comparison (MI-MC). Insignificant differences (p<0.10) are masked out.

**MODERN IRRIGATION (MI) – MODERN CONTROL (MC)**

*Source: Cook, Puma, Krakauer, 2011*
Future irrigation-induced cooling

Fig. 10 Differences in seasonal surface air temperature (K) over land areas for the future irrigation comparison (FI-FC). Insignificant differences (p<0.10) are masked out.

FUTURE IRRIGATION (FI) – FUTURE CONTROL (FC)

Source: Cook, Puma, Krakauer, 2011
What’s changed?

(FI – FC) – (MI – MC):
Red indicates cooling effect diminished under future climate;
Blue areas indicate the magnitude increases under future climate

Source: Cook, Puma, Krakauer, 2011
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Pre-Columbian deforestation as an amplifier of drought in Mesoamerica

Benjamin I. Cook\textsuperscript{1,2}, Kevin J. Anchukaitis\textsuperscript{2}, Jed O. Kaplan\textsuperscript{3}, Michael Puma\textsuperscript{1}, Maxwell Kelley\textsuperscript{1}, & Denis Gueyffier\textsuperscript{4}

- Droughts in pre-Columbian Mesoamerica have been linked to significant upheavals in civilizations.
- May be linked to extensive deforestation associated with agriculture.

\textsuperscript{1}Earth Institute, Columbia University, New York, USA; \textsuperscript{2}School of Earth and Space Exploration, Arizona State University, Tempe, USA; \textsuperscript{3}Department of Earth and Environmental Sciences, University of California, Los Angeles, USA; \textsuperscript{4}School of Geography, University College London, London, UK.
Suggest that pre-Columbian deforestation biased the climate towards a drier mean state and amplified drought conditions in the region.
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Simple urban model

- Focus on response of model to basic urban hydrology
- **Parsimonious approach**
  - Treat as bare soil
  - Modify infiltration by specifying impermeable fraction
  - Specify fixed albedo
  - Specify fixed roughness length (underway – Sud et al 1988)
Urban Albedo

- First thought: use the NCAR urban dataset (Jackson et al. 2010)
- But… ModelE has relatively low albedo values from the 1983 model!

Set urban to lowest vegetation albedo (0.055)
Urban impervious fraction

- Based on road and roof fractions
- ModelE is sensitive to the impervious frac.
  - Impermeable (IMPERM) experiment: use NCAR impervious fraction
  - Permeable (PERM) experiment: treat as bare soil
Urban areas

- Three equilibrium runs (CTRL, URBAN_PERM, URBAN_IMPERM)
- $1^\circ$ lat $\times$ $1^\circ$ lon (cubed sphere)
- Year 2000 GHG and SSTs
Precipitation response

Relative Precip $\Delta$ (URBAN ONLY-CTRL), % (JJA)

URBAN_PERM minus CTRL

No significance masking

URBAN_IMPERM minus CTRL
Runoff ratio (urban cells only)

Runoff ratio (URBAN ONLY-CTRL), % (JJA)

Note: scale X 10

No significance masking

URBAN_PERM minus CTRL

URBAN_IMPERM minus CTRL
Maximum daily temperature

SURF TEMP, MAX (URBAN ONLY-CTRL), °C (JJA)

URBAN_PERM minus CTRL
No significance masking

Note: scale X 2
URBAN_IMPERM minus CTRL
Urban temperature response

Temperature in Northern Hemisphere Urban Cells

SURF TEMP, MAX (URBAN ONLY-CTRL), °C (JJA)

URBAN_PERM - CTRL

URBAN_IMPERM - CTRL

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ModelE Land Surface Model: ‘Mosaic’ approach

New dynamics
• Agriculture/irrigation
• Urbanization

Improved soil column
• Plant-water uptake
• Multiple columns
• Deep soil water (aka groundwater)

ModelE Land Fractions

- Vegetation
- Bare soil
- Urban
- Land ice
- Surface water
- Natural ecosystems
- Agriculture

- New component
- Modified component

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Human control of the terrestrial water cycle

- Few groups (esp. in US) have integrated impact of human activities
  - MIROC GCM (Japan): couples a water resource model (H08) with a GCM land model (MATSIRO)
Irrigation and Monsoon Research at GISS

• Lee et al (2009) analyzed observed NDVI, precip, and temp data for 1982 to 2003

At GISS, Sonali is currently analyzing monsoon dynamics with and without irrigation

Climate model simulated changes in temperature extremes due to land cover change

F. B. Avila,¹ A. J. Pitman,¹ M. G. Donat,¹ L. V. Alexander,¹ and G. Abramowitz¹

Received 8 June 2011; revised 9 October 2011; accepted 28 December 2011; published 25 February 2012.

[1] A climate model, coupled to a sophisticated land surface scheme, is used to explore the impact of land use induced land cover change (LULCC) on climate extremes indices recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI). The impact from LULCC is contrasted with the impact of doubling atmospheric carbon dioxide (CO₂). Many of the extremes indices related to temperature are affected by LULCC and the resulting changes are locally and field significant. Some indices are systematically affected by LULCC in the same direction as increasing CO₂ while for others LULCC opposes the impact of increasing CO₂. We suggest that assumptions that anthropogenically induced changes in temperature extremes can be approximated just by increasing greenhouse gases are flawed, as LULCC may regionally mask or amplify the impact of increasing CO₂ on climate extremes. In some regions, the scale of the LULCC forcing is of a magnitude similar to the impact of CO₂ alone. We conclude that our results complicate detection and attribution studies, but also offer a way forward to a clearer and an even more robust attribution of the impact of increasing CO₂ at regional scales.

• Schaeffer et al., 2005: Potentially enhanced changes in extremes compared to the mean
Information on extremes and climate adaptation

- Luber and McGeehin, 2008: Extreme events changes are likely to have a more significant direct impact on society than changes in the mean.
- UNDP’s Low Emission Climate-Resilient Development

**LECRDS Approach**

Preparing Low-emission and Climate-Resilient Development Strategies (LECRDS) – Executive Summary

This report serves as the Executive Summary to a series of manuals and guidebooks that UNDP is offering in support of LECRDS. It provides a brief outline of the approach and methodologies that these materials treat in detail.

**Step 1: Develop a Multi-Stakeholder Climate Planning Process**

Charting a New Carbon Route to Development

Integrated climate change planning - a how-to guide for local and regional policy-makers on planning a low-carbon future. This document focuses on the importance of full engagement of sub-national authorities to comprehensively address climate change and suggests that taking the necessary action to tackle climate change will be more effective if it helps address local development issues.

**Step 2: Prepare Climate Change Profiles and Vulnerability Scenarios**

Formulating Climate Change Scenarios to Inform Climate-Resilient Development Strategies

This guidebook builds on a large range of UNDP’s ongoing initiatives to support adaptation to climate change. This series is intended to empower decision makers to take action, and to prepare their territories to adapt, and hopefully thrive, under changing climatic conditions.
Questions?
Thanks to my collaborators!!

Thanks to my collaborators!!
*NASA Goddard Institute for Space Studies*
Benjamin Cook, Maxwell Kelley, Igor Aleinov
*The City College of New York*
Nir Krakauer
*NASA Goddard Space Flight Center*
Randy Koster
Net thermal radiation TOA

Net Thermal Radiation TOA (IRRIG ONLY-CTRL), W/m² (JJA)

Net Thermal Radiation TOA (URBAN ONLY-CTRL), W/m² (JJA)
Total net radiation at surface
**Introduction**

**Vegetation cover affects the Earth's energy balance**

Over land, vegetation cover mostly reduces the albedo. Lower albedo means greater trapping of solar radiation by the Earth surface. (heating effect)

Bowen ratio (sensible/latent heat = \( \beta \)) over land could range from <1 to >10, it is mostly below 3 for vegetation canopy.

By increasing ET vegetation can enhance precipitation.

**CO₂ uptake by vegetation slows the rise in atm' CO₂ concentration, thus lowering downward thermal radiation LWR fluxes. (cooling effect)**

Emitted LWR is strongly dependent on the surface temperature. Evaporative surfaces (e.g., vegetation) are usually cooler than bare surfaces in dry areas. (heating effect)

**Source:** Rotenberg, Yakir; presentation
Historical land change

Source: Klein-Goldewijk, 2010
Potential land change impacts

- **Masking potential**: Suppress the impacts of increasing CO$_2$ in some regions that cool due to land cover change
  - Miss the detection of a CO2 signal

- **Amplification potential**: Amplify the impacts of increasing CO$_2$ in regions that warm due to land cover change
  - A false-positive detection of a CO2 signal