LAND USE CHANGES, ENERGY FLUXES AND THE SURFACE CLIMATE

XUHUI LEE
THE TAIHU EDDY FLUX NETWORK

by Xuhui Lee, Shoudong Liu, Wei Xiao, Wei Wang, Zhiqiu Gao, Chang Cao, Cheng Hu, Zhenghua Hu, Shuanghe Shen, Yongwei Wang, Xuefa Wen, Qitao Xiao, Jiarong Xu, Jinbao Yang, and Mi Zhang

In situ eddy covariance observations reveal unusually large nocturnal CO₂ uptake by submerged vegetation in a shallow lake.

MOTIVATION AND SCIENCE QUESTIONS.
Lakes are an important component of the climate system. Even though lakes and reservoirs occupy only about 4% of the global terrestrial surface (Downing et al. 2006), their societal importance is disproportionately large because many large municipalities are located near lake shorelines. The large thermal contrast between a lake and its surrounding land often triggers thermal circulations, having significant impact on air pollution dispersion and transport in the lake catchment. Being important sources of atmospheric moisture, large lakes can enhance storm formation in the downwind area (Samuelsson et al. 2010; Zhao et al. 2012). Except at times of high algal activities (Hari et al. 2008; Balmer and Downing 2011), lake water is usually supersaturated in CO₂ with respect to the atmosphere and acts as a source of atmospheric carbon (Cole et al. 1994). Lakes are also sources of atmospheric CH₄ (Rastviksen et al. 2011) and N₂O (Huttunen et al. 2003).

Eddy covariance (EC) is an in situ technique for measuring momentum, heat, water, and greenhouse gas fluxes. It determines the flux continuously and nonintrusively from simultaneous measurements, in the atmospheric surface layer, of turbulent fluctuations in the air velocity and the scalar quantity of interest. The method is a key measurement tool deployed by several large observational networks.

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Urban airshed GHG fluxes

Box model

\[ F_{\text{NEE}} = \rho h \frac{\partial C_m}{\partial t} - \rho h \frac{u}{L} (C_a - C_m) + \rho \frac{\partial h}{\partial t} (C_t - C_m) \]

\(1^3\)C tracer technique

Nanjing

NOAA flask data

Fossil inventory

Urban flux partitioning
Drivers and pathways of atmospheric change

Atmospheric state

Physical state

Chemical state
- Climate-active agents
- Climate-inactive agents

Biophysical
- Evaporation
- Sunlight reflection
- Surface roughness

Biogeochemical
- GHGs
- VOC
- NOx and SOx
- Aerosols
- Mercury

Land use change (deforestation, urbanization)

Fossil combustion
Intensive agriculture
Effects of deforestation on the climate system

- **Biogeochemical effect**
  - arising from increases in atmospheric CO$_2$ concentration
  - causing changes in radiative forcing of the atmosphere
  - consequences at global scale; no direct local impact

- **Biophysical effect**
  - associated with changes in albedo, surface roughness and evaporation
  - causing changes in energy balance and redistribution
  - impact at both global and local scale

- **Questions:**
  - Does small-scale deforestation increase or decrease the surface temperature?
  - Which of these biophysical factors has the largest effect?
Blame the trees for global warming?

Source: alaska-in-pictures.com
Albedo comparison, Saskatchewan, Canada

Source: Betts and Ball (1997) *J Geophys Res* 102: 28901-28909
Yatir Forest, Israel
Radiation balance, Yatir Forest

Solar 238 W m\(^{-2}\)

TOA

Forest

Shrub land

Radiative forcing, longwave radiation feedback, and energy redistributions
Response of surface temperature to local deforestation
Response of surface temperature to local deforestation

\[(1 - \alpha)K_\downarrow + L_\downarrow - \sigma T_s^4 = H + LE + Q_s\]

\[T_s^4 = T_a^4 + 4T_a^3(T_s - T_a)\]

\[H = \rho C_p \frac{T_s - T_a}{r_a}\]

\[LE = \frac{H}{\beta}\]

\[\Delta T_s \approx \frac{\lambda_0}{1 + f} \Delta S + \frac{-\lambda_0}{(1 + f)^2} R_n \Delta f_1 + \frac{-\lambda_0}{(1 + f)^2} R_n \Delta f_2\]

Albedo change

\[S = (1 - \alpha)K_\downarrow\]

\[\lambda_0 = \frac{1}{4\sigma T_a^3}\]

\[f = \frac{\rho C_p}{4r_a \sigma T_s^3} \left(1 + \frac{1}{\beta}\right)\]

Energy redistribution /roughness

\[\Delta f_1 = -\frac{\rho C_p}{4\sigma T_s^3 r_a} \left(1 + \frac{1}{\beta}\right) \frac{\Delta r_a}{r_a}\]

Energy redistribution /Bowen ratio

\[\Delta f_2 = -\frac{\rho C_p}{4\sigma T_s^3 r_a} \left(\frac{\Delta \beta}{\beta^2}\right)\]
Climate sensitivity

Intrinsic sensitivity

- \( \lambda_o = \frac{1}{4\sigma T^3} \) and \( \Delta T_o = \lambda_o \Delta Q \)
- 0.3 K per W m\(^{-2}\) at the global scale
- 0.2 K per W m\(^{-2}\) at the local scale

Apparent sensitivity

- At the global scale
  \[ \Delta T_a = \frac{\lambda_o \Delta Q}{1 - \sum g_i} \approx 0.8 \text{ K per W m}^{-2} \]
- At the local scale
  \[ \Delta T_s \approx \frac{\lambda_0}{1 + f} \Delta S + \frac{-\lambda_0}{(1 + f)^2} R_n \Delta f_1 + \frac{-\lambda_0}{(1 + f)^2} R_n \Delta f_2 \]
NCAR’s Community Land Model

Source: Oleson et al (2013) NCAR’s Technical Note
Urban heat island intensity for cities in North America

\[
\Delta T \approx \frac{\lambda_0}{1 + f} \Delta R_n^* \\
+ \frac{-\lambda_0}{(1 + f)^2} (R_n^* - Q_s + Q_{AH}) \Delta f_1 \\
+ \frac{-\lambda_0}{(1 + f)^2} (R_n^* - Q_s + Q_{AH}) \Delta f_2 \\
+ \frac{-\lambda_0}{1 + f} \Delta Q_s \\
+ \frac{\lambda_0}{1 + f} Q_{AH}
\]
Urban heat island intensity for cities in North America

Sum of components – another formulation

\[ \Delta T_s = \lambda_o [\Delta R_n^* - \Delta H - \Delta (LE) - \Delta Q_S + \Delta Q_{AH}] \]
Attribution of deforestation effect

a: Boreal / harvested
b: Boreal / burnt
c: temperate humid
d: temperate semi-arid
e: tropical
f: tropical

FluxNet: A global network of CO\textsubscript{2} flux measurements

Source: http://www.fluxnet.ornl.gov
Weather stations

Great Mountain Forest, Connecticut

Poznan, Poland

Dongshan (东山), Jiangsu, China

Braunschweig, Germany
Annual mean difference in surface air temperature (open land minus forest)

\[ y = -0.070(\pm 0.020) x + 2.6(\pm 0.9) \]

\[ n = 37, R^2 = 0.30, p < 0.005 \]

Source: Lee, Goulden, Hollinger et al. (2011)
Nature 497: 384-387
Annual mean difference in surface air temperature (open land minus forest)

Environ Res Letters 9: 034002
Annual mean difference in surface air temperature (open land minus forest)

Environ Res Letters 9: 034002
Diurnal temperature range

*Environ Res Letters* 9: 034002
Dependence of daytime urban heat island on precipitation

Attribution of urban heat island

daytime: b, e, d
nighttime: c, g, f

Efficient “convectors”
“Smooth surfaces help make cities into sizzling urban heat islands”
Summary

- Sub-grid scale microclimate variables produced by climate models can be used for attribution of the biophysical effect.
- Small-scale deforestation cools the surface at high latitudes and warms the surface at low latitudes.
- The high-latitude deforestation cooling is greater than the low-latitude warming.
- Changes in convection efficiency are the main driver of UHI variations across climate gradients.
Albedo Change Detection
Chicago

Source: Mackay et al. (2012) Building & Environ
49: 348-358

Chicago Reflectivity Change
1995 - 2009

- Green: Albedo Increase (> +.05)
- Red: Albedo Decrease (< -.05)
- Yellow: Albedo Constant
Albedo along a jack pine chronosequence
Saskatchewan, Canada

Data source: Alan Barr