How do we scale surface-atmosphere exchange?

Ankur Desai
Dept of Atmospheric & Oceanic Sciences
University of Wisconsin-Madison

Apr 30 2015, U Arizona
Why is this so damn hard to model?
What does it have to do with scale?
We face a fundamental scale mismatch

Between **observations & models**

Between the **atmosphere & ecosystems**
S. Metzger et al.: Spatio-temporal rectification of tower-based EC

Temporal scale:
- Century
- Decade
- Year
- Month
- Week
- Day
- Hour
- Minute
- Second

Spatial scale [km²]:
- 10⁻⁶
- 10⁰
- 10⁶
- 10¹²

- Earth system model prediction domain
- Satellite & spatial observations
- Ecological plots
- Eddy flux tower
- Atmospheric inversion
- Land surface model cell
- Airborne flux

Earth system model prediction domain
Fig. 2. Global distribution of NPP ($\times 10$ gm C/m$^2$/yr) at the tracer model resolution.
Spatial Heterogeneity

- Amount
- Frequency Distribution

Spatial Process

- Arrangement
- Location
- Distance
Why does it matter?
Atmospheric CO$_2$ has increased rapidly to levels above anything in Earth’s recent past.


Today
400 ppm CO$_2$
2 ppm CH$_4$

2100?
THE GREAT ACCELERATION

SOCIO-ECONOMIC TRENDS

WORLD POPULATION
REAL GDP
FOREIGN DIRECT INVESTMENT

URBAN POPULATION
PRIMARY ENERGY USE
FERTILIZER CONSUMPTION

PRIMARY ENERGY USE
WATER USE
PAPER PRODUCTION

LARGE DAMS
TRANSPORTATION
TELECOMMUNICATIONS

INTERNATIONAL TOURISM

EARTH SYSTEM TRENDS

CARBON DIOXIDE
NITROUS OXIDE
METHANE

STRATOSPHERIC OZONE
SURFACE TEMPERATURE
OCEAN ACIDIFICATION

MARINE FISH CAPTURE
SHRIMP AQUACULTURE
COASTAL NITROGEN

TROPICAL FOREST LOSS
DOMESTICATED LAND
TERRESTRIAL BIOSPHERE DEGRADATION


MAP & DESIGN: Felix Pharrand-Deschênes / Glisbia
Global fossil fuel and cement emissions: 36.1 ± 1.8 GtCO₂ in 2013, 61% over 1990

- Projection for 2014: 37.0 ± 1.9 GtCO₂, 65% over 1990

Uncertainty is ±5% for one standard deviation (IPCC “likely” range)

Estimates for 2011, 2012, and 2013 are preliminary

Source: CDIAC; Le Quéré et al 2014; Global Carbon Budget 2014
Global Carbon Budget

The cumulative contributions to the Global Carbon Budget from 1870
Contributions are shown in parts per million (ppm)


Figure concept from Shrink That Footprint
The sinks have continued to grow with increasing emissions, but climate change will affect carbon cycle processes in a way that will exacerbate the increase of CO$_2$ in the atmosphere.
Terrestrial Biosphere CO₂ Flux Dominates Carbon Cycle Prediction Uncertainty

- Atmosphere: 45%, 9.9 Gt C yr⁻¹
- Land: 29%, 0.9 Gt C yr⁻¹
- Oceans: 26%

Le Quéré et al. (2013)

- Photosynthesis: >120 Gt C yr⁻¹
- Respiration: c.120 Gt C yr⁻¹

Cumulative Atmosphere to Ocean CO₂ Flux (Gt C)

- Ocean: Ok
- Land: Not Ok

Arora et al. 2013
Terrestrial carbon cycle feedback is a leading order uncertainty for climate simulation.
What do I (we) do?

http://flux.aos.wisc.edu

- Probe spatial heterogeneity in biologically-mediated surface-atmosphere exchanges from sites to regions (meters-1000s km)
  - Forests, wetlands, lakes, urban (temperate-boreal-tropical-Mediterranean-alpine, terrestrial-aquatic, management gradients)
  - Multiple greenhouse gases (methane), esp. with eddy covariance
  - Feedbacks from energy balance and a land surface variability on the atmospheric boundary layer and synoptic-PBL interactions in observations and models (LES, PBL, mesoscale, climate)
  - Up/down scaling across multiple measurements: eddy covariance, biometric, airborne budgets, inverse modeling, hyperspectral remote sensing (leaf to satellite)
  - Informing ecosystem and atmospheric models with diverse measurements across space (data assimilation, model informatics)
    - http://pecanproject.org
What the flux?
700 points of light?
Complex Regions: $1+1 \neq 2$

<table>
<thead>
<tr>
<th>a) IKONOS.</th>
<th>b) WISCLAND.</th>
<th>c) MODIS-UMD and IGBP.</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
</tbody>
</table>

- Mixed Forest    | 7.1% Mixed Forest|
- Upland Conifer  | 13.0% Upland Conifer|
- Aspen-Birch     | 25.3% Aspen-Birch |
- Upland Hardwood | 14.6% Upland Hardwood|
- Upland Opening/Shrub | 6.8% Upland Opening/Shrub|
- Grassland       | 1.8% Grassland    |
- Lowland Conifer  | 10.7% Lowland Conifer|
- Lowland Deciduous| 1.9% Lowland Deciduous|
- Lowland Shrub   | 16.3% Lowland Shrub|
- Wet Meadow      | 1.0% Wet Meadow   |
- Open Water      | 1.8% Open Water   |
- Road            | 1.0% Road         |
- 100% Mixed Forest| 100% Mixed Forest |
Desai et al., AgForMet, 2015
Didn’t remote sensing solve the problem?
NASA HYSPIRI campaign
Ecosystem scaling: Townsend, Kruger, Desai
Maybe?

GPPmax vs. NDVI

S. Dubois, MS thesis
Maybe not?
It gets weirder once we put in humans
The scale and method we monitor land use matters

Becknell et al., Bioscience, 2015
Does the atmosphere care?
Flux footprint varies in space, projected fluxes varies in time

Tower represents different surfaces at different times

Temporally transient location bias = “location drift”
Mean and temporal-spatial variation of flux grids

- Green: tower observations
- Red: flux grids over 20 * 20 km²

`H [W m⁻²]`

`spatial scale [km]`
Large eddy simulation (LES)

- A form of spatial filtering to the full turbulent conservation equations of momentum, mass, heat, and moisture - resolve and subgrid fluxes
- Works because of dissipative and scale-free nature of small-scale shear turbulence in the turbulent atmospheric boundary layer
- Unlike traditional “closure” ensemble-average solutions, resolves energy carrying turbulent motions
- Requires high spatial resolution (meters), and consequently, high temporal resolution (seconds)
- But: Good for testing effect of small scale spatial boundary conditions on atmosphere!
Energy Cascade

• Big whorls have little whorls
• That feed on their velocity,
• And little whorls have lesser whorls
• And so on to viscosity
• (in the molecular sense)
  – -- Lewis F. Richardson, 1922, cf. J Swift
Fig. 2.1 Schematic representation of the energy spectrum of turbulence.
Tower data at 30 – 122 – 396 m to evaluate the simulations

**Boundary layer characteristics**

| $L$ | $= -1.4 \cdot 10^2$ m |
| $z_i$ | $= 1.3 \cdot 10^3$ m |
| $u_*$ | $= 8.2 \cdot 10^{-1}$ m/s |

**Simulation design**

| Timestep | $0.5 - 1$ s |
| Horizontal grid resolution | $10 - 20$ m |
| Gridpoints | $O(10^3 \times 10^3 \times 10^2)$ |
| Vertical grid resolution | $5 - 10$ m |
| Horizontal area | $100 - 400$ km$^2$ |

<table>
<thead>
<tr>
<th>$\sigma_{xy}(\cdot)<em>{het} - \sigma</em>{xy}(\cdot)_{hom}$</th>
<th>$30$ m</th>
<th>$122$ m</th>
<th>$396$ m</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$ [K]</td>
<td>$+8.7 \cdot 10^{-3}$</td>
<td>$+9.6 \cdot 10^{-3}$</td>
<td>$+1.1 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>$q$ [g/kg]</td>
<td>$+2.2 \cdot 10^{-2}$</td>
<td>$+2.3 \cdot 10^{-2}$</td>
<td>$+2.3 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>$w$ [m/s]</td>
<td>$-5.6 \cdot 10^{-3}$</td>
<td>$-2.2 \cdot 10^{-2}$</td>
<td>$-3.8 \cdot 10^{-2}$</td>
</tr>
</tbody>
</table>

Frederick deRoo (KIT IMK-IFU), TERRENO
LES simulations around the tall tower show shifts in organized structures with heterogeneity of surface forcing.
BUT: A problem...

Red: ERF-driven LES; blue: homogeneous; dots: tower data
Eddy fluxes from the homogeneous LES correspond better to the tower data

Virtual EC fluxes as fraction of the tower measurement at 12:00-13:00, 30 m
Darkgray: heterogeneous; Medium-gray: homogeneous
What are we trying to do about it?
1. Be smarter about scaling

Flux rates in Gg-C yr-1
Pool sizes in Gg-C

Forests: 64,000
Wetlands: 158,000
Surface Waters: 162,000
2. Find the appropriate scale
3. Map human impacts like ecosystems

- Passive
- Preservation
- Preservation/Change
- Production
4. Partition uncertainty and variability in models

Variability
describes the process
can be better characterized,
but doesn’t decrease
doesn’t decrease asymptotically.

Uncertainty
describes our ignorance
decreases asymptotically.

Pecanproject.org
Dietze, 2014, JGR-G
5. Make flux towers useful
Ameriflux Park Falls ‘very tall tower’ (447 m):
Eddy flux at 122 m.

Credit: Matt Rydzik (U Wisconsin)
Wavelet cross-scalogram

- Flux above every overflown cell
- Wavelet cross-scalogram (Torrence and Compo, 1998)
- Mother wavelet ($\Psi$), scale ($a$) and location ($b$)
- Wavelet coefficient: convolution of data, $a$, $b$
- Parseval: covariance from real / imaginary parts

The image shows a cross-scalogram with scales on the vertical axis and distance from the western end of the track on the horizontal axis. The scalogram includes plots for $H$ and $LE$, with surface elevation shown at the bottom.
- Process attribution!
Target area versus spatio-temporally varying patch II

- ≥70% spatial coverage
- Spatially pre-blended fluxes less erratic
- Explicit information on spatial variation

**Spatial coverage of projections**

**Flux time series**

- 25 km² projection
- 100 km² projection
- 400 km² projection
- Tower measured
- 99.9%ile spatial variation
Thank you!

• I hope my examples convinced you that scale is fundamental to understanding ecosystem-atmosphere interactions.

• I hope some of the innovations I presented actually solve some of our problems of scale.

• None of this can be done without my lab, collaborators, funders, and the opportunity to discuss these with you!