Why a meteorologist studies forests:

The atmospheric carbon cycle,

turbulent eddies,

pessimistic trees,

and you!

Ankur Desai
University of Wisconsin-Madison
I. CARBON CYCLE
Atmospheric CO$_2$ has increased rapidly to levels above anything in Earth’s recent past.
Global fossil fuel and cement emissions: 36.1 ± 1.8 GtCO\textsubscript{2} in 2013, 61% over 1990

- Projection for 2014: 37.0 ± 1.9 GtCO\textsubscript{2}, 65% over 1990

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

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)

Data: CDIAC/NOAA-ESRL/GCP/Joos et al. 2013/Khatiwala et al. 2013

Figure concept from Shrink That Footprint

Source: CDIAC; NOAA-ESRL; Houghton et al. 2012; Le Quéré et al. 2014; Global Carbon Budget 2014
Fate of Anthropogenic CO$_2$ Emissions (2004-2013 average)

32.4±1.6 GtCO$_2$/yr  
91%

15.8±0.4 GtCO$_2$/yr  
44%

3.3±1.8 GtCO$_2$/yr  
9%

10.5±1.8 GtCO$_2$/yr  
29%

9.4±1.8 GtCO$_2$/yr  
26%

Calculated as the residual of all other flux components

Global Carbon Budget

Emissions are partitioned between the atmosphere, land, and ocean.

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.

Source: CDIAC; NOAA-ESRL; Houghton et al 2012; Giglio et al 2013; Le Quéré et al 2014; Global Carbon Budget 2014
The residual land sink is increasing with time to 9.2±1.8 GtCO₂/yr in 2013, with large variability. Total CO₂ fluxes on land (including land-use change) are constrained by atmospheric inversions. The data is sourced from various studies, including: 

- Zhang et al. (2013)
- Oleson et al. (2013)
- Jain et al. (2013)
- Clarke et al. (2011)
- Smith et al. (2001)
- Sitch et al. (2003)
- Stocker et al. (2013)
- Krinner et al. (2005)
- Zeng et al. (2005)
- Kato et al. (2013)
- Peters et al. (2010)
- Rodenbeck et al. (2003)
- Chevallier et al. (2005) 

References provided in Le Quéré et al. (2014).
Terrestrial Biosphere CO₂ Flux Dominates Carbon Cycle Prediction Uncertainty

Atmosphere 45%
Land 29%
Oceans 26%

Le Quéré et al. (2013)

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

Autotrophic
Heterotrophic

Beer et al. (2010)

Cumulative Atmosphere to Ocean CO₂ Flux (Gt C)
Cumulative Atmosphere to Land CO₂ Flux (Gt C)

Year

Ocean Ok
Land Not Ok

Arora et al. 2013
Observed Emissions and Emissions Scenarios

Emissions are on track for 3.2–5.4°C “likely” increase in temperature above pre-industrial. Large and sustained mitigation is required to keep below 2°C.

Over 1000 scenarios from the IPCC Fifth Assessment Report are shown. Source: Fuss et al 2014; CDIAC; Global Carbon Budget 2014.
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
Who we are
II. TURBULENT EDDIES
Eddy covariance is mature technology
History

- 1880-1920s Turbulence theory (Reynolds, Prandtl, Richardson, Taylor)
- 1940s-1950s Surface-layer theory (Monin-Obhukov, Kolmogorov), development of fast sensors for anemometry
- 1960s early measurements (Inoue, Wyngaard, Kaimal)
- 1970s forest fluxes (Raupach, Lenschow, Denmead)
- 1970s CO₂ fluxes (Desjardins, Leuning)
- 1980s Infrared gas analyzers (Verma, Anderson, Valentini)
- 1990s First long-term regional CO₂ flux networks (Wofsy, Baldocchi, Goulden, Law, Aubinet)
- 2000s Global syntheses (FLUXNET, Falge, Papale, Reichstein)
- 2010s Model-data integration, development of operational measurements (NEON, ICOS, you?)
\[
\frac{D \tilde{C}}{Dt} = 0 \rightarrow \frac{\partial \tilde{C}}{\partial t} + \tilde{U}_j \frac{\partial \tilde{C}}{\partial x_j} = 0
\]

**STORAGE TURBULENT-FLUX**

\[
\text{NEE} \equiv \int_0^{z_r} s dz + (\overline{w'c'})|_{z=0}
\]

\[
= \int_0^{z_r} \frac{\partial \tilde{C}}{\partial t} dz + (\overline{w'c'})_r + \bar{w}_r (\bar{c}_r - \langle \bar{c} \rangle)
\]

\[
\frac{\partial \tilde{C}}{\partial t} + \frac{\partial \tilde{c}'}{\partial t} + \tilde{U}_j \frac{\partial \tilde{C}}{\partial x_j} + u_j' \frac{\partial \tilde{C}}{\partial x_j} + \tilde{U}_j \frac{\partial \tilde{c}'}{\partial x_j} + u_j' \frac{\partial \tilde{c}'}{\partial x_j} = 0
\]

\[
\frac{\partial \tilde{C}}{\partial t} + \tilde{U}_j \frac{\partial \tilde{C}}{\partial x_j} + u_j' \frac{\partial \tilde{c}'}{\partial x_j} = \frac{\partial \tilde{C}}{\partial t} + \frac{\partial \tilde{U}_j C}{\partial x_j} + \frac{\partial u_j' c'}{\partial x_j} = 0
\]
III. PESSIMISM
Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model

Peter M. Cox*, Richard A. Betts*, Chris D. Jones*, Steven A. Spall* & Ian J. Totterdell†
Negative Feedbacks
Processes and feedbacks triggered by extreme climate events?

Peatland carbon is vulnerable to climate and hydrological change

- Peat carbon is preserved by cool temperatures and flooded conditions
- Warming and drying can disrupt the process and lead to carbon loss

Ise et al 2008
Hydrology does not drive NEE in four fens

Sulman et al., GRL, 2010
Same for bogs, but in a different way

Sulman et al., GRL, 2010
How well did models simulate peatland processes?

<table>
<thead>
<tr>
<th>Model name</th>
<th>Temporal resolution</th>
<th>Soil layers</th>
<th>Soil C pools</th>
<th>N cycle</th>
<th>Max soil moisture</th>
</tr>
</thead>
<tbody>
<tr>
<td>DLEM</td>
<td>Daily</td>
<td>2</td>
<td>3</td>
<td>Yes</td>
<td>Saturation</td>
</tr>
<tr>
<td>Ecosys</td>
<td>Hourly</td>
<td>8</td>
<td>9</td>
<td>Yes</td>
<td>Saturation (with water table)</td>
</tr>
<tr>
<td>LPJ</td>
<td>Daily</td>
<td>2</td>
<td>2</td>
<td>No</td>
<td>Field capacity</td>
</tr>
<tr>
<td>ORCHIDEE</td>
<td>30-min</td>
<td>2</td>
<td>8</td>
<td>No</td>
<td>Field capacity</td>
</tr>
<tr>
<td>SiB</td>
<td>30-min</td>
<td>10</td>
<td>None</td>
<td>No</td>
<td>Saturation</td>
</tr>
<tr>
<td>SiBCASA</td>
<td>30-min</td>
<td>25</td>
<td>9</td>
<td>No</td>
<td>Saturation</td>
</tr>
<tr>
<td>TECO</td>
<td>30-min</td>
<td>10</td>
<td>5</td>
<td>No</td>
<td>Saturation</td>
</tr>
</tbody>
</table>

Sulman et al., JGR-G, 2011
Monthly residuals were correlated with observed water table.
<table>
<thead>
<tr>
<th>Ecoregion</th>
<th>Active area fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upland</td>
<td>38%</td>
</tr>
<tr>
<td>Mineral wetland</td>
<td>27%</td>
</tr>
<tr>
<td>Shrub peat</td>
<td>29%</td>
</tr>
<tr>
<td>Graminoid peat</td>
<td>5%</td>
</tr>
</tbody>
</table>

**Maybe longer term?**

LANDIS-II model

Sulman et al., Ecosystems, 2013
Water table effects on carbon balance

Peatlands:
- 100 cm declines:
  - Short term: C gain
  - Long term: C loss
- 40 cm declines
  - Short term: C neutral
  - Long term: C loss

Mineral wetlands:
- C gain for both

Whole landscape
- Short-term: C increase
- Long-term: C steady
- Time scale of decline made little difference

Net change from control run for shallow peat simulations: Different water table scenarios
A very tall tower!

Regional
Tall tower
Mature hardwood
Shrub wetland
Old-growth mixed forest
From NEE to Productivity

- Flux tower derived “GPP” is sensitive to model selection and gaps (Desai et al., 2008)
- INSTEAD: Use a data-based approach
  - $P_d = \text{Max nighttime observed NEE} - \text{Mean noon (10-14) NEE}$
  - Reject noon NEE is $> 50\%$ gap-filled
Problem

• Every flux tower based correlation is significant when you have thousands to tens of thousands of datapoints
  – Effect sizes may be small, though
• Account for autocorrelation using “reduced degrees of freedom” metric!

Bretherton et al., 1999, J Clim
### What to test?

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_d$</td>
<td>Photosynthetic drawdown</td>
<td>Flux tower</td>
</tr>
<tr>
<td>$EVI$</td>
<td>Enhanced Vegetation Index, 8-day average</td>
<td>MODIS TERRA/AQUA</td>
</tr>
<tr>
<td>$ET$</td>
<td>Evapotranspiration</td>
<td>Flux tower</td>
</tr>
<tr>
<td>$WUE$</td>
<td>Water Use Efficiency ($P_d/ET$)</td>
<td>Flux tower</td>
</tr>
<tr>
<td>$P_{recip}$</td>
<td>Daily precipitation</td>
<td>NCDC + NARR Reanalysis</td>
</tr>
<tr>
<td>$Q_{soil}$</td>
<td>10 cm soil moisture</td>
<td>NARR Reanalysis</td>
</tr>
<tr>
<td>$T_{mean}$</td>
<td>Daily temperature</td>
<td>Flux tower + NCDC</td>
</tr>
<tr>
<td>$T_{min}$</td>
<td>Minimum daily temperature</td>
<td>Flux tower + NCDC</td>
</tr>
<tr>
<td>$T_{max}$</td>
<td>Maximum daily temperature</td>
<td>Flux tower + NCDC</td>
</tr>
<tr>
<td>$T_{range}$</td>
<td>Daily temperature range (max - min)</td>
<td>Flux tower + NCDC</td>
</tr>
<tr>
<td>$LST$</td>
<td>Land Surface Temperature, 8-day day/night average</td>
<td>MODIS TERRA/AQUA</td>
</tr>
</tbody>
</table>
What do you get?

- Only significant correlations shown
- Moisture and temperature anomalies positively correlate with $P_d$ at sub-annual scales
Lags are interesting

- Red squares = correlations > autocorrelation
- Remotely sensed variables (EVI,LST) have limited ability to predict $P_d$
- Previous year weekly-monthly temperature has a weak negative relationship to $P_d$
Tall tower

Mature hardwood
Attack of the beetles
Persistent reduced ecosystem respiration after insect disturbance in high elevation forests

Abstract
Amid a worldwide increase in tree mortality, mountain pine beetles (*Dendroctonus ponderosae* Hopkins) have led to the death of billions of trees from Mexico to Alaska since 2000. This is predicted to have important carbon, water and energy balance feedbacks on the Earth system. Counter to current projections, we show that on a decadal scale, tree mortality causes no increase in ecosystem respiration from scales of several square metres up to an 84 km² valley. Rather, we found comparable declines in both gross primary productivity and respiration suggesting little change in net flux, with a transitory recovery of respiration 6–7 years after mortality associated with increased incorporation of leaf litter C into soil organic matter, followed by further decline in years 8–10. The mechanism of the impact of tree mortality caused by these biotic disturbances is consistent with reduced input rather than increased output of carbon.
No one trusts a model except the one who wrote it; everyone trusts an observation except the one who made it – Harlow Shapley (by way of Matt Disney)
WRF-Noah Setup

- **Spatial Resolution:** 20km x 20km
- **Timestep:** 60 seconds
- For 2003, 2004, 2005, 2007, 2009, and 2010 the model was run from March 15 – October 15 with and without deforestation
- **Total of 12 seven-month simulations completed with hourly output**

Precipitation Rate (mm/month)

Dry Season Anomaly
Deforestation perturbation
### Amazon Rainforest Percent Changes with Deforestation

In nearly every measure the impact of deforestation is greater during drought years.

<table>
<thead>
<tr>
<th>% Δ Precipitation Rate</th>
<th>% Δ Sensible Heat Flux</th>
<th>% Δ Latent Heat Flux</th>
<th>% Δ Net Surface Radiation</th>
<th>% Δ Boundary Layer Height</th>
<th>% Δ Rel. Soil Moisture Top Layer</th>
<th>% Δ Rel. Soil Moisture Bot. Layer</th>
<th>% Δ 2m Specific Humidity</th>
<th>% Δ Level of free convection</th>
<th>% Δ Lifting condensation level</th>
</tr>
</thead>
<tbody>
<tr>
<td>-4.99%</td>
<td>+.48%</td>
<td>-3.63%</td>
<td>-2.41%</td>
<td>-.11%</td>
<td>-3.00%</td>
<td>-3.50%</td>
<td>-.77%</td>
<td>+2.62%</td>
<td>+1.29%</td>
</tr>
<tr>
<td>-5.93%</td>
<td>+4.28%</td>
<td>-5.57%</td>
<td>-2.70%</td>
<td>+1.36%</td>
<td>-4.38%</td>
<td>+5.09%</td>
<td>-1.31%</td>
<td>+.52%</td>
<td>+3.94%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>July - September</th>
<th>Pluvial Years</th>
<th>Drought Years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-4.99%</td>
<td>-5.93%</td>
</tr>
<tr>
<td></td>
<td>+.48%</td>
<td>+4.28%</td>
</tr>
<tr>
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<td>+3.94%</td>
</tr>
</tbody>
</table>
Final Thoughts

- Terrestrial ecosystem carbon cycle responds to a number of climatic, disturbance, and management forces, but feedbacks can go both ways.
- Ecosystem management needs to consider these and Earth system models need to consider management.
- All processes are time and space dependent.
- Meteorologists need your help!
Thanks!

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