C-RITE Workshop
Boundary Layer Flow and Turbulence: Influence of Topography and Land Use

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Science Frontiers: Influence of Topography and Land Use

http://majikphil.blogspot.com/2012/04/massive-florida-wildfire-satellite.html

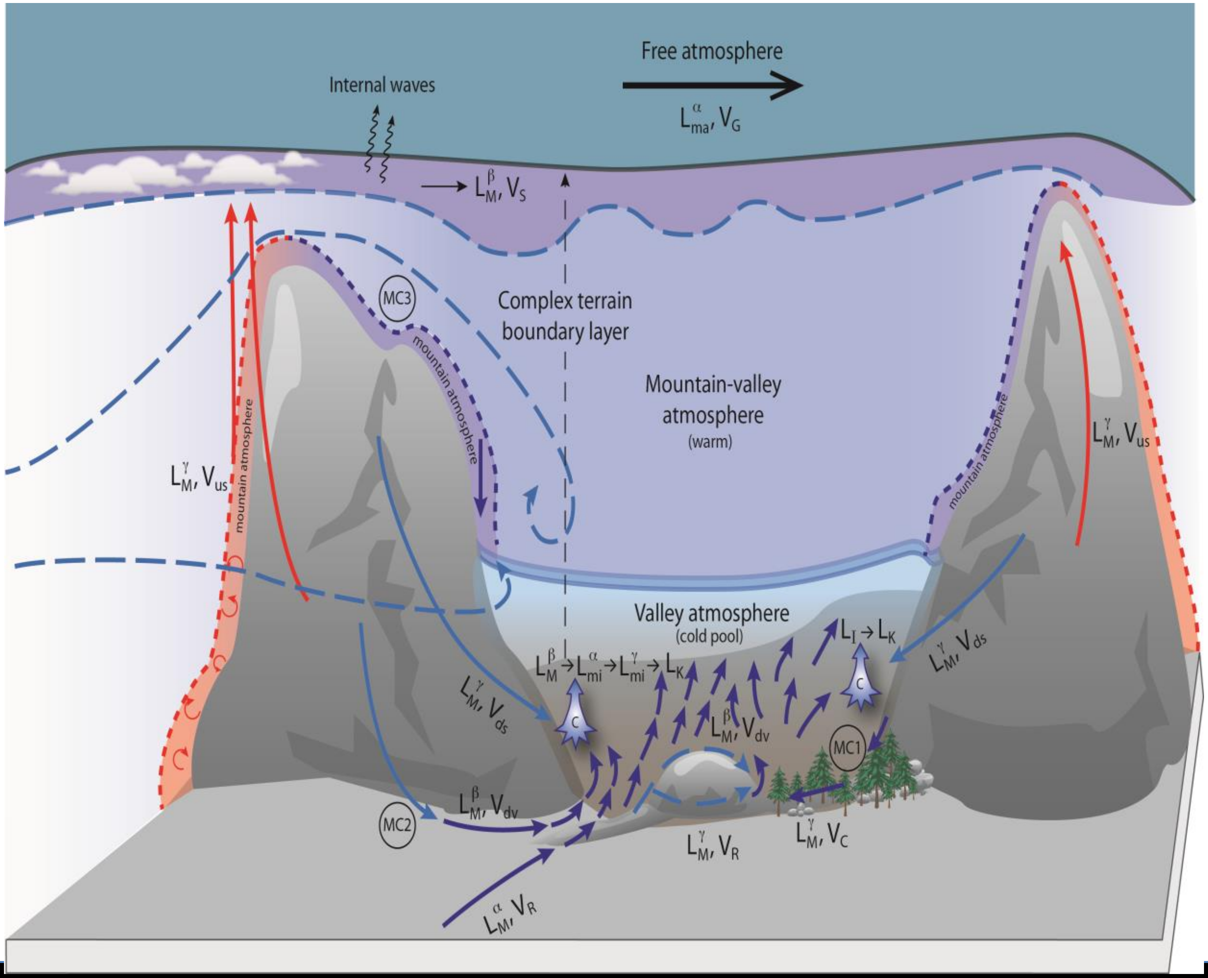
Predictability of winds and temperature in complex terrain remains poor

- 20% of Earth's land surface is covered by mountainous areas
- 70% of Earth's land surface covered by complex terrain (hills, slopes, valleys, canyons, etc.)
- Weak pressure gradient forcing allows thermal flows to develop, but more frequently, mesoscale-microscale interactions challenge simulation capabilities due to complex interactions of subgridscale phenomena

Reviews in Taylor et al. (1987), Blumen (1990), Baines (1998), Belcher and Hunt (1998), Whiteman (2000) Wood (2000), Barry (2008), Fernando (2010), Chow et al. (2013), Fernando et al. (2015)

Flow in complex terrain is highly variable in space and time, requiring comprehensive networks of observations

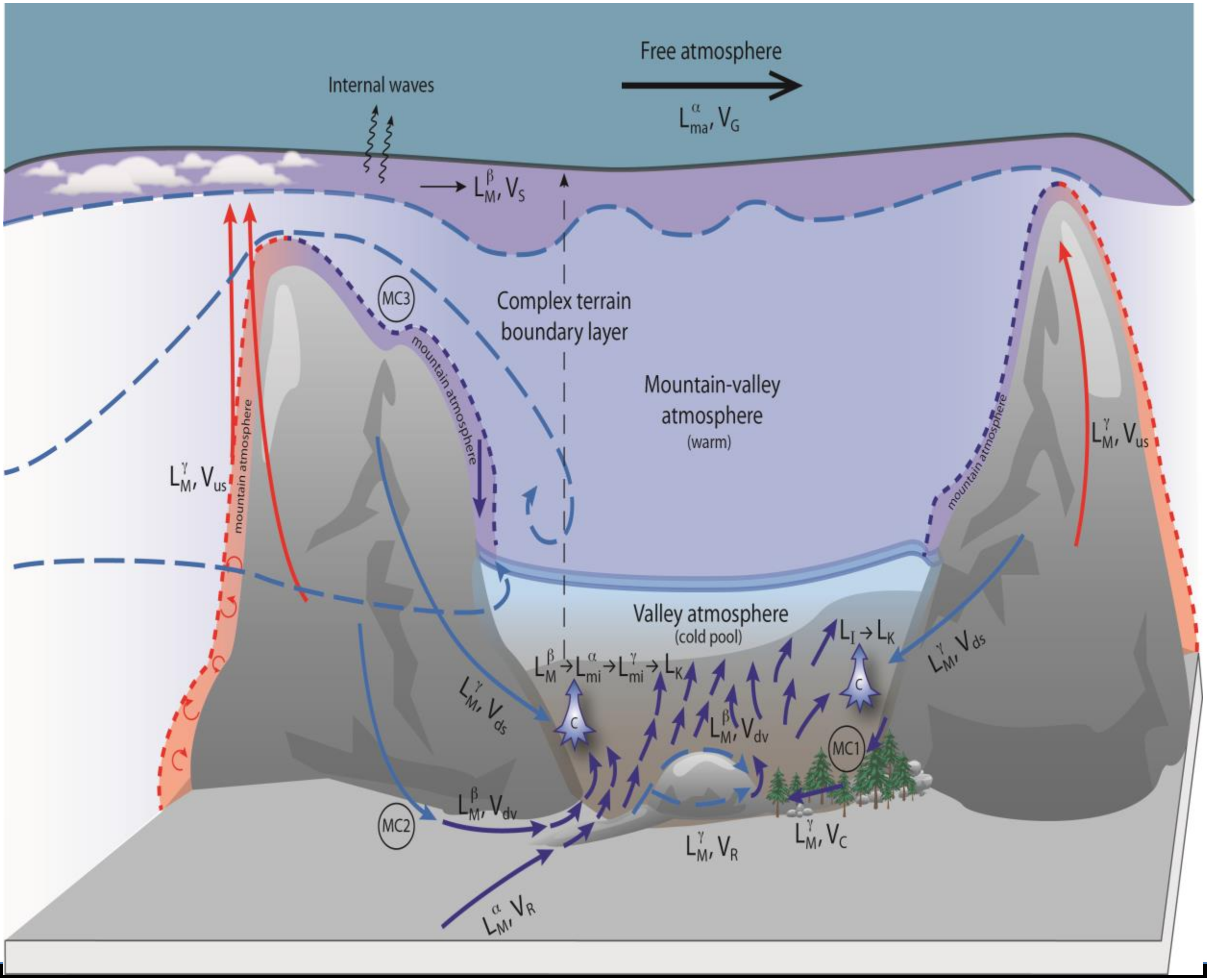
- Flow in complex terrain is extremely sensitive to non-stationary thermal forcing & complex interactions between thermal circulations, regional flow and synoptic forcing, → highly variable in space and time local flow
- Gradients of surface moisture, thermodynamic properties, roughness, slope discontinuities → 3D microcirculation, hydraulic adjustments and flow separation



Fernando, Lundquist, et al. 2015, Perdigão SPO

Flow in complex terrain is highly variable in space and time, requiring comprehensive networks of observations

- Stable stratification: lee waves, rotors, separated vortices, coherent structures… OR a downslope katabatic flow into a cold pool in the valley
- Unstable stratification: upslope flow, separation, cloud formation, flow separation at ridge → unsteady flow



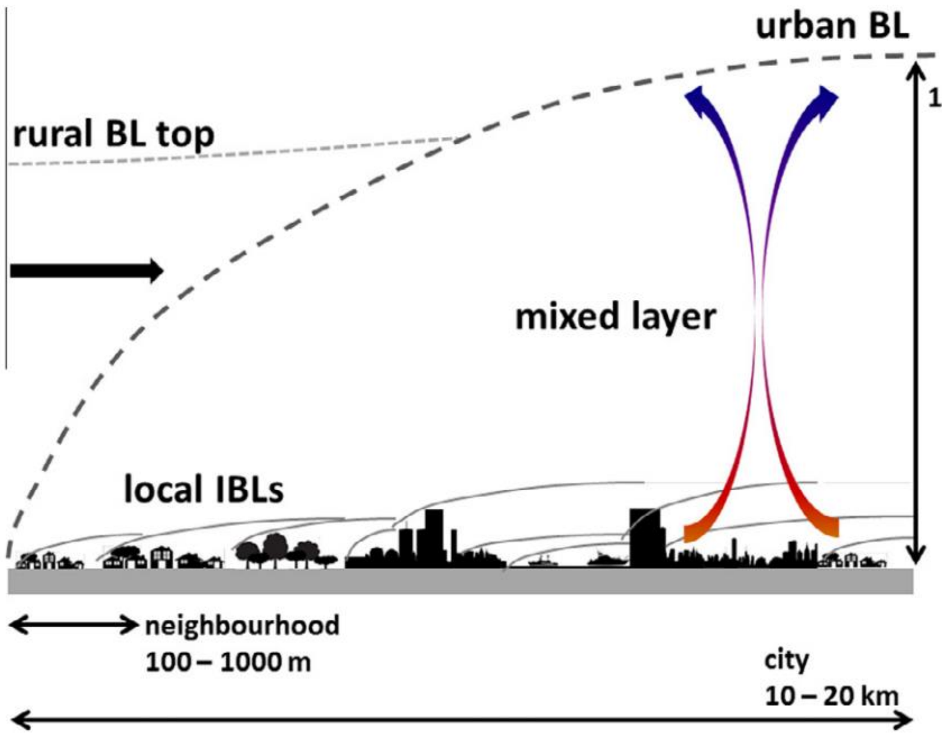
Fernando, Lundquist, et al. 2015, Perdigão SPO

Although most people live in an urban boundary layers, this complex microclimate is poorly understood

- Need for accurate forecasting at urban scale grows as cites become larger, hotter, and more polluted
- “a general theoretical basis for the UBL is still lacking … NWP models provide a largely unvalidated, “best guess” of the physical processes.” Barlow (2014) http://dx.doi.org/10.1016/j.uclim.2014.03.011

Panoramic view of Shinjuku and Mount Fuji taken from Bunkyo Civic Center in Tokyo, world’s most populous urban area
By Morio - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=16835714

In urban BLs, wind profiles respond to underlying heterogeneous roughness and thermal properties of surface

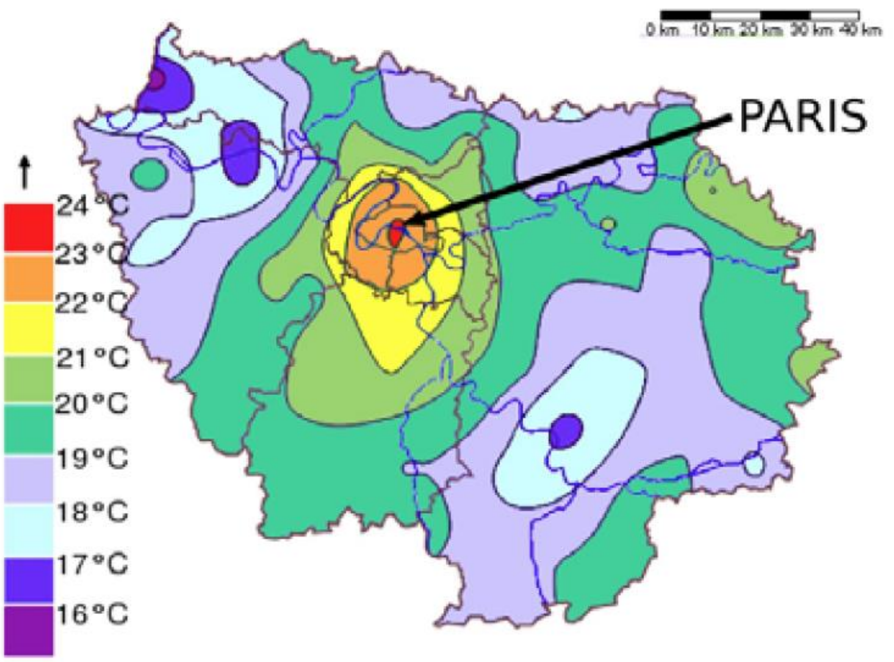


- Drew et al. (2013) employ Doppler wind lidar profiles to suggest near-neutral profiles and 1-km scale estimates of roughness length z_0
- Multiple Doppler lidars can provide networks of virtual towers throughout an urban area
- Turbulence metrics, though needed for air quality and transport and dispersion modeling, only available from tower measurements (now)
- Mixing height **seems** to correlate with length scale of lateral turbulence (not inversion height): significant difference from rural areas; critical insight for modeling

Barlow (2014) http://dx.doi.org/10.1016/j.uclim.2014.03.011

Nocturnal urban heat island (UHI) is oft described but poorly simulated due to paucity of supporting observations

- Low wind speeds: How to determine depth of nocturnal mixing in heterogeneous layouts with little turbulence or advection to homogenize?
- Moderate wind speeds: does the urban area act as a plume?
- Interactions with local terrain:
  - How do drainage flows interact with urban complexes to modify or exaggerate UHI?
  - Do sea breezes persist longer with warmer nocturnal temperatures in coastal cities?
  - How do rougher, warmer urban surface modify rural nocturnal low-level jet structures through advection and turbulent mixing?



Masson et al.
http://www.umr-cnrm.fr/spip.php?rubrique134&lang=en

Heterogeneous land use for energy extraction, geoengineering can drive local-scale circulations

Deforestation in Sumatra, www.worldwildlife.org/

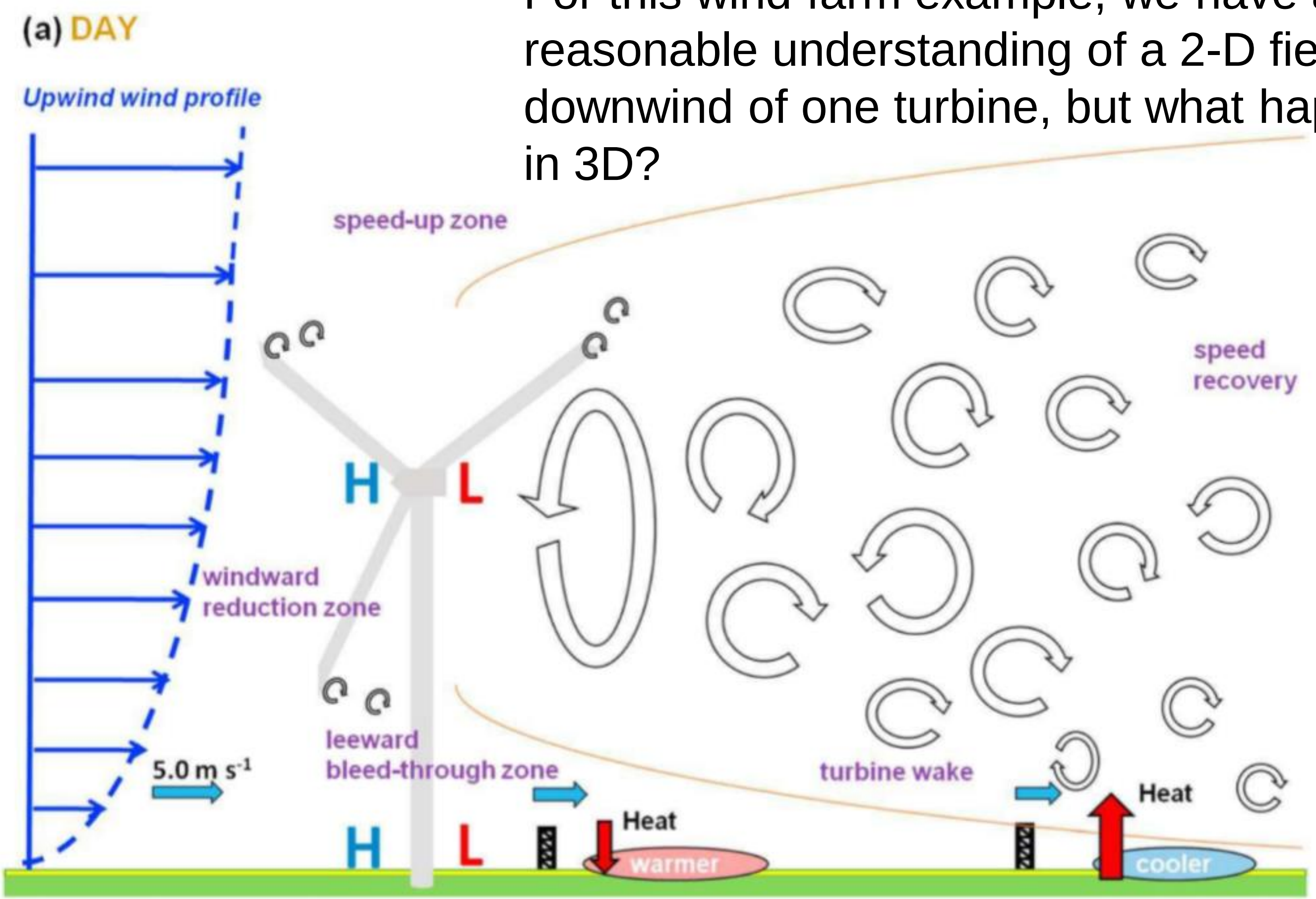
Afforestation project in Thailand, www.brotherearth.org

Wind farm near Walla Walla, WA, creative commons

Hydraulic fracturing plant, http://www.pioga.org

Heterogeneous land use for energy extraction, geoengineering can drive local-scale circulations and temperature structure

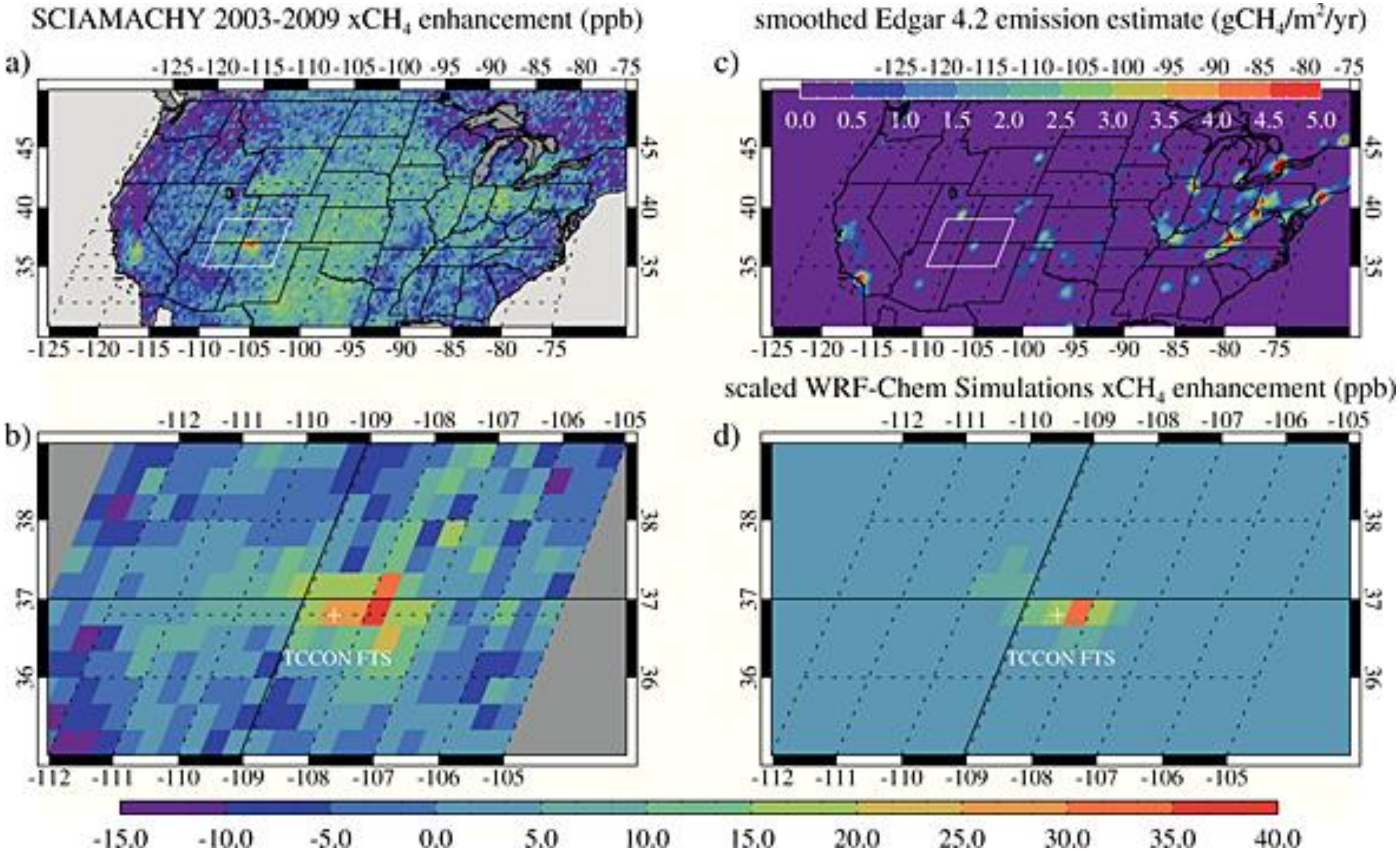
For this wind farm example, we have a reasonable understanding of a 2-D field downwind of one turbine, but what happens in 3D?



Rajewski et al. JGR-A 2016 doi://10.1002/2016JD025297

Food – energy – water nexus

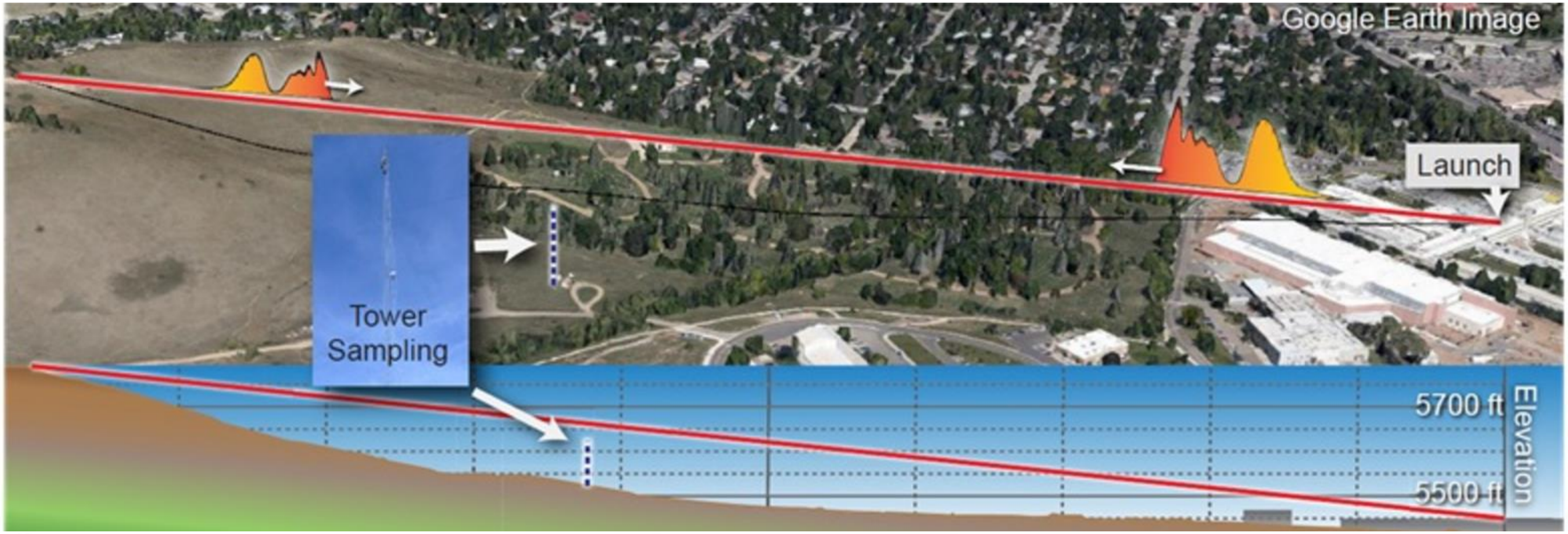
Fossil fuel energy extraction can lead to fugitive sources of greenhouse gases: need for source characterization and transport/diffusion modeling



Satellite observations can provide a coarse assessment only

Kort et al. GRL 2014 doi: 10.1002/2014GL061503

Greenhouse gas (GHG) detection and attribution requires winds, stability estimates, and localized microscale GHG concentration measurements



Greenhouse gas detection over a 2km path

Time-resolved measurements of multiple GHGs to support regional source, sink, and transport research

Wildfires modify and interact with boundary-layer structure

- Outflow boundaries can enhance or suppress wildfire spread
- Predictions of wildfire spread require accurate measurements of winds, temperature, and moisture structure within and near fire front
- Paucity of data has constrained development or improvement of simulation tools

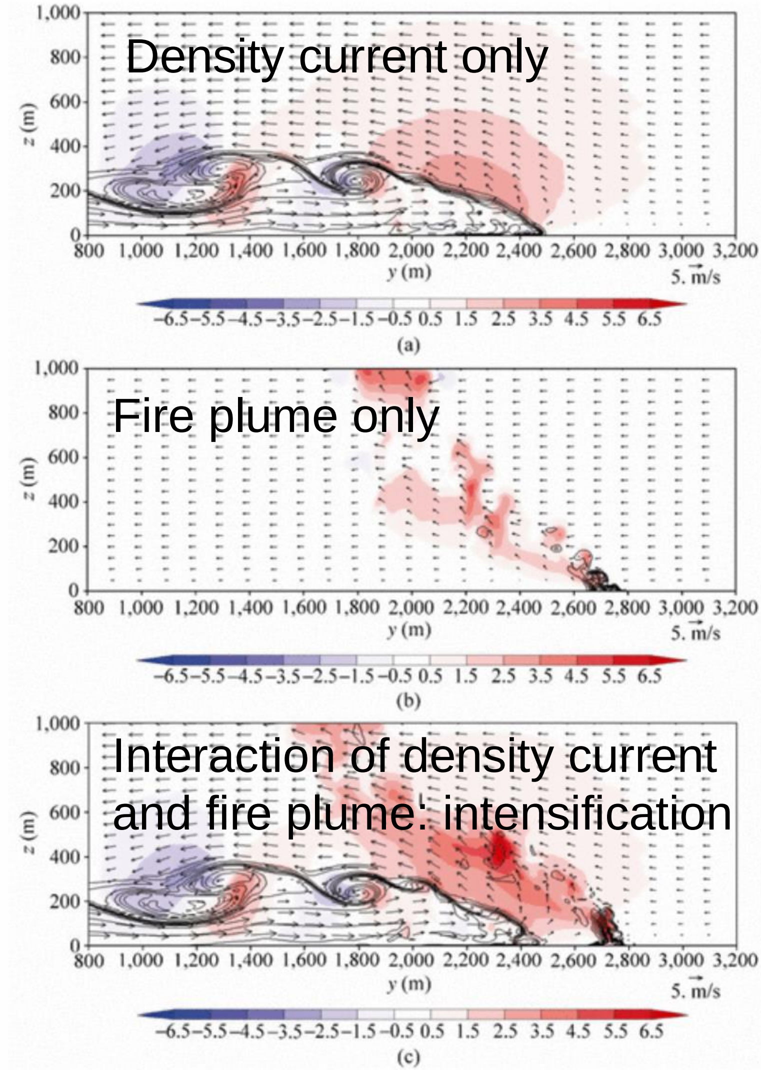


Figure 7.7 Vertical velocity (in m·s^{-1}, shaded as indicated) and potential temperatur (contour interval 1 K) in the $y-z$ plane for (a) the density current only, (b) th plume only, and (c) the density current and the plume. Vectors depict velocity i

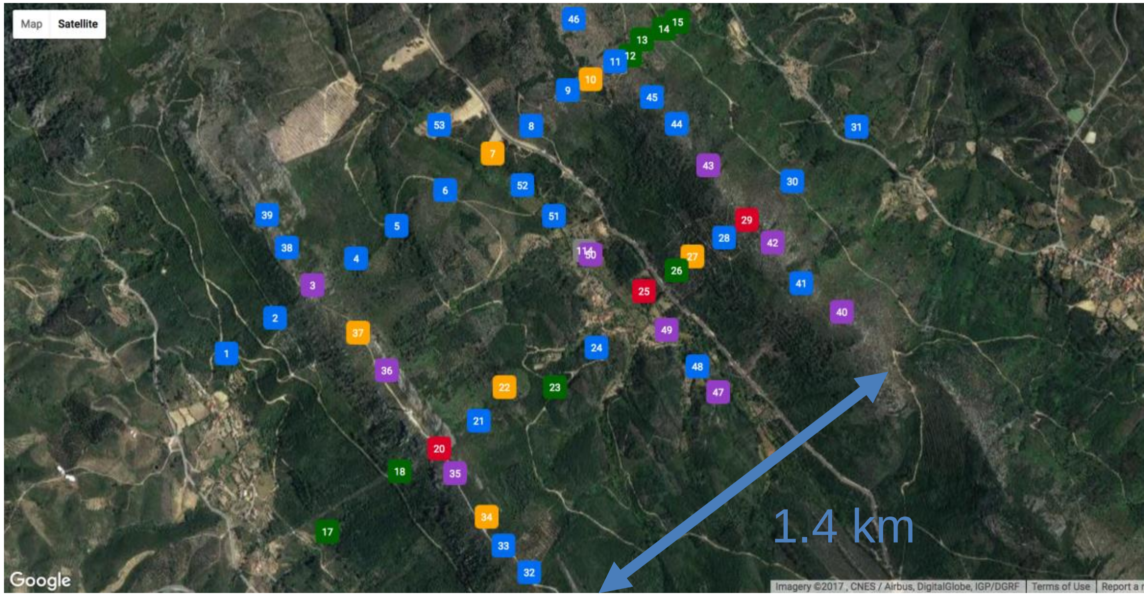
Hanley et al. 2013

https://link.springer.com/chapter/10.1007%2F978-3-642-32530-4_7#page-1

How to advance these science frontiers? Observations!

Networks of towers are vital

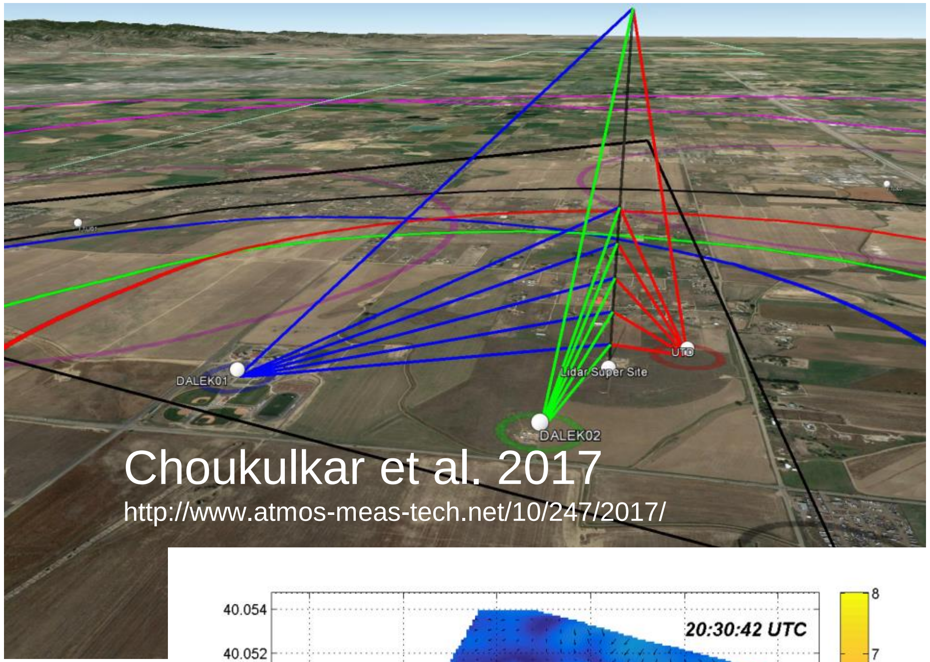
- *In situ* measurements of heat, momentum, H_2O, CO_2 fluxes are unique and irreplacable
  - Vital boundary conditions for mesoscale and LES modeling studies
  - Unique data for budgets
- Heterogenous situations require networks, which require coordination
  - Data systems
  - Data rates
  - Calibration
  - Leveling
  - Tilt correction
  - Etc.



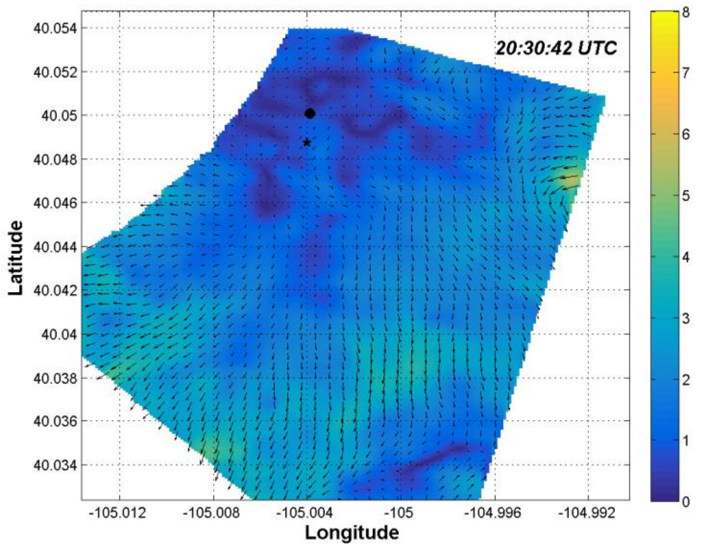
Perdigão Tower array: 2017
http://windsp.fe.up.pt/experiments/3/stations

Measurement challenges: remotely-sensed winds and turbulence

- While wind profiles are assumed to be simple, heterogeneous flows challenge even DBS scans from profiling lidar
- Science need for 3-D mapping of winds require simultaneous measurements of winds in the boundary layer over km+ range at 10s of m resolution from coordinated scanning systems
- Some advances in this area (WindScanner from DTU coordinates via hardware), but progress still to come
- Turbulence measurements from lidar volumes challenging
- Fine-resolution radar (Ka-band, X-band) may be promising but not yet well-understood



Choukulkar et al. 2017
http://www.atmos-meas-tech.net/10/247/2017/



Dual-Doppler KA-band Radar; Gunter et al.

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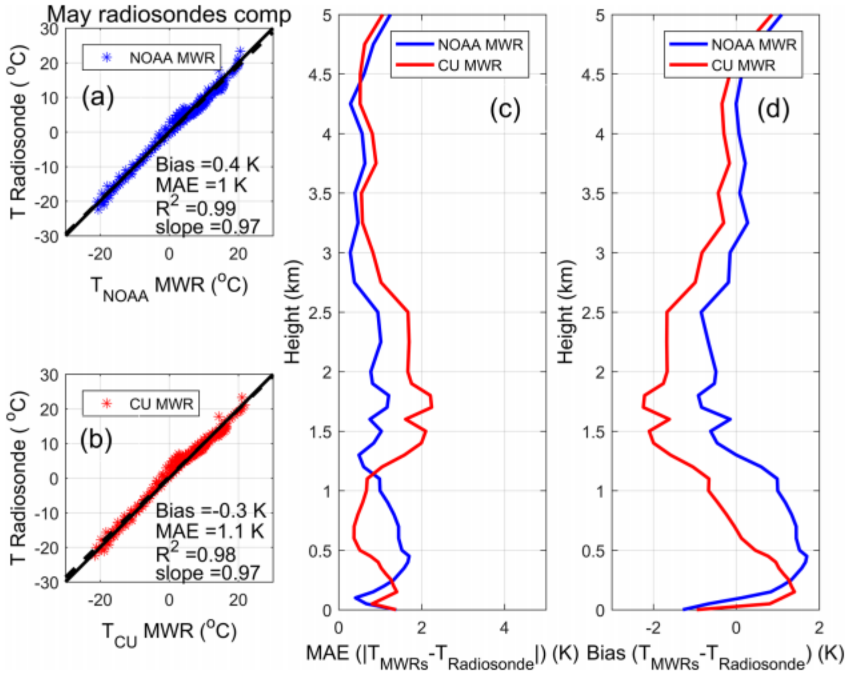
Measurement challenges: temperature and humidity profiles to assess stability

- Remote sensing instruments can provide high temporal resolution, but need:
  - Improved spatial (vertical) resolution
  - New advances in retrievals, including combination of T, RH retrievals
- Opportunities for collaboration with commercial companies, NOAA, JPL, other national labs



Bianco et al. 2017

http://www.atmos-meas-tech.net/10/1707/2017/

Networks of remotely-piloted aircraft systems or tethered systems can provide *in situ* measurements without tower limitations

- Small lightweight aircraft have demonstrated atmospheric profiling, providing T, RH, & winds to characterize ABL
- Some gas measurements are also possible (CO_2, CH_4, O_2/O_3, N_2O, SO_2)
- Fluxes of heat, momentum, moisture still challenging although very useful for modeling and studies of flow in heterogeneous circumstance
- Policies for flight permissions can be challenging

Jacob et al. 2017 https://www.eol.ucar.edu/system/files/Instrumentation%20White%20Paper.pdf

Tethered balloon , 2017

Science Frontiers: Influence of Topography and Land Use




All require:

- Coordinated networks of towers
- New advances in remotely-sensed winds and turbulence with lidar/radar
- New methods and algorithms for temperature and humidity profiles
- New approaches for quantifying GHG concentrations
- New developments for RPAS to enable *in situ* measurements of T, RH, winds, fluxes, chemistry

Thanks for your attention

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