Environmental Fluid Dynamics: Lecture 1

Dr. Jeremy A. Gibbs

Department of Mechanical Engineering
University of Utah

Spring 2017

Overview

1. Syllabus
   - Administrative
   - Course Overview
2. Introduction to EFD
   - Definitions and Applications
   - Atmospheric Boundary Layer
   - Surface Energy Balance

Syllabus

Instructor

How to contact me:

- Email: jeremy.gibbs@utah.edu
- Office: MEK 2566
- Hours: By appointment (email or stop by)

Course websites:

- Canvas
- http://gibbs.science/efd

Meeting Times

Class schedule:

- Class will be held in MEB 1225
- Tues and Thurs, 10:45a - 12:05p
- We will miss three classes:
  - Thursday, Mar. 9 (travel)
  - Tuesday, Mar. 14 (spring break)
  - Tuesday, Mar. 16 (spring break)

Textbooks

Class lectures will primarily follow two textbooks:

- **An Introduction to Boundary Layer Meteorology**
  R.B. Stull (Kluwer, 1988), 670pp.
- **Introduction to Micrometeorology, 2nd edition**
  S.P. Arya (Academic Press, 2001), 420 pp.

Recommended Textbooks

Other useful textbooks:

- **The Atmospheric Boundary Layer**
  J. R. Garratt (Cambridge University Press, 1992), 316 pp.
- **Atmospheric Boundary Layer Flows**
  J.C. Kaimal and J.J. Finnigan (Oxford, 1994), 289 pp.
- **Turbulence in the Atmosphere**
  J.C. Wyngaard (Cambridge University Press, 2010), 393 pp.
- **Boundary Layer Climates, 2nd edition**
  T.R. Oke (Routledge, 1987), 435 pp.
- **Handbook of Micrometeorology**
  X. Lee, W. Massman, and B. Law (Kluwer, 2004), 250 pp.

Grading

- Homework - 20%
- Midterm Exam - 25%
- Project #1 - 20%
- Final Project - 35%

Course Description

- An introduction to Environmental Fluid Dynamics focusing primarily on micrometeorological processes occurring in the atmospheric boundary layer (ABL; the lower 1-3 km of the troposphere)
- Since this is the part of the atmosphere that humans are directly in contact with, it is of great importance to both engineers and atmospheric scientists.
- For example, the small-scale motions responsible for pollution dispersion are related to surface fluxes of heat and momentum.

Course Outline

Introduction

- The ABL
  - basic definitions and concepts
  - scales of motion, diurnal cycles
  - introduction to rotation and stratification
- Equilibrium and departures from it
- Atmospheric thermodynamics
  - potential temperature
  - virtual potential temperature
  - buoyancy frequency
  - potential energy

Course Outline

Energy Balances

- radiation characteristics
- near-surface exchanges (fluxes)
- near-surface energy budget

Basic Equations

- rotation, stratification, boundary layer simplifications

Atmospheric Surface Layer Scaling

- Monin-Obukhov similarity theory
- Neutral, convective, and stable boundary layers

Course Outline

Atmospheric Boundary Layer Turbulence

- Intro to turbulence in the environment
  - the critical effects of buoyancy on turbulence
  - turbulent entrainment
  - stability effects
- Measuring techniques
  - intro to various measuring techniques including sonic anemometry, balloon borne measurements, and remote sensing techniques
- Analysis of turbulence data sets and application to a real world field experiment

Course Outline

Inhomogeneous Boundary Layers

- Vegetative canopies, urban fluid mechanics
- Surface inhomogeneities
  - roughness effects
  - complex terrain
  - urban
- Terrain-induced flows
- Atmospheric dispersion concepts and models
  - simple Gaussian plume to Lagrangian dispersion models
- Urban Heat Island

Coursework - Homework and Exams

Homework

- Periodic homework assignments will be given during class and then posted on the web site and Canvas.
- Homework will be collected in class and via Canvas on the due date. Late homework will generally not be accepted.

Homework

- There will be one midterm exam
- The exam will consist of an in-class part and a take-home part.

Coursework - Projects

Project #1

- Goal is to obtain a working understanding of the Surface Energy Balance (SEB) for urban areas.
- ou will model the urban SEB for a tower located in Murray, UT using the LUMPS (Local-scale Urban Meteorological Parameterization Scheme) model.
- At the end of the project you will have a working simulation tool.

Final Project

- You will investigate various aspects of turbulence by using data from recent field experiments.
- The project will consist of two parts: a written report and an oral presentation. You may work in groups of 2 or 3.

Computing Skills

All students are expected to have basic computing skills and knowledge of a programming language (FORTRAN, C, C++, Python, etc) or scientific computing software package (Maple, Matlab, EES, etc)

Introduction to EFD

Definitions

Environmental Fluid Mechanics

principles that govern **transport**, **mixing**, *and* **transformation processes** *in environmental fluids (e.g., physical, biological, chemical)*

includes stratification and rotation

Definitions

Micrometeorology

atmospheric phenomena and processes at the smaller end of the spectrum of atmospheric scales and near the earth's surface (atmospheric boundary layer - ABL)

Fine scale structure is important

Microclimatology

same physical scales much longer time averaging scales

Environmental Fluid Dynamics

Integrates different aspects of Thermal-Fluids Science (not just fluid mechanics!)

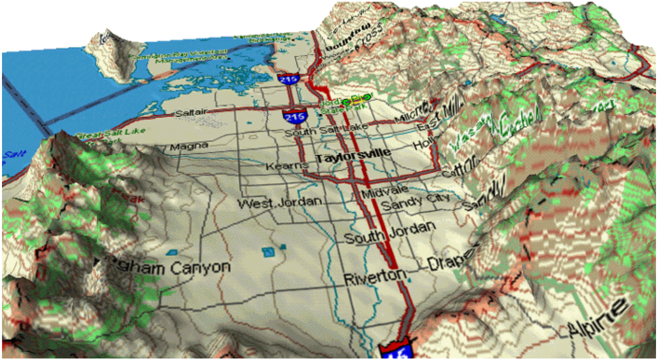
- *fluid mechanics*
- *thermodynamics*
- *heat transfer (conduction, convection, radiation)*
- *mass transfer*

Applications

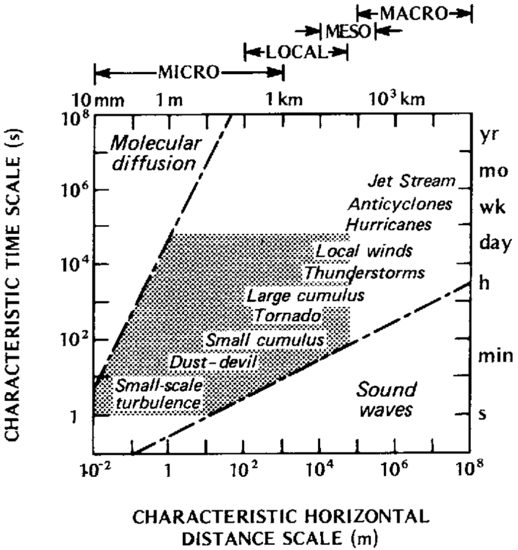
- Urban planning
  - Air quality (pollutants, greenhouse gases, accidental releases)
  - Water and energy budgets ("green" infrastructure)
- Defense strategies
  - Toxic releases: biological, chemical, radiation
- Agriculture and forest meteorology (evapotranspiration, water budget)
- Aeronautical meteorology
- Wind engineering
- Numerical weather prediction and climate simulations
- More ...

Scales of Motion

- Synoptic scales (100+ km)
- Mesoscale (10-1000 km)
- Microscale (< 1 m - 10 km)
- Engineering scale (viscous - 10 m)
- Urban scale (1 m - 100 km)

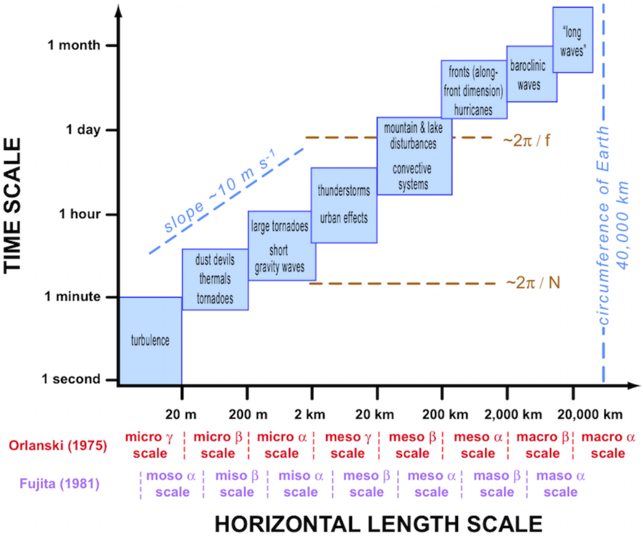


Time and Space Scales



from Boundary Layer Climates (Oke, 1987)

Time and Space Scales



from Mesoscale Meteorology (Markowski and Richardson, 2010)

Time and Space Scales

Table 10-6. Scales of horizontal motion in the troposphere.

Size	Scale	Name	
40,000 km	macro α	planetary scale	
4,000 km	macro β	synoptic scale*	
700 km	meso α	mesoscale**	
300 km	meso β		
30 km	meso γ		
3 km	micro α	microscale***	boundary-layer turbulence
300 m	micro β		surface-layer turbulence
30 m	micro γ		inertial subrange turbulence
3 m			
300 mm	micro δ		fine-scale turbulence
30 mm			
3 mm	viscous	dissipation subrange	
0.3 μm	molecular	mean-free path between molec.	
0.003 μm		molecule sizes	
0			

from Meteorology for Engineers and Scientists (Stull)

Boundary Layer Research

Aerodynamic Boundary Layer

- 1870s – Froude carried out tow tank experiments to study friction over a flat plate
- 1905 – "boundary layer" - likely coined by Prandtl - thin region of the flow near the wall where frictional effects are confined
- 1908 Blasius solution – laminar boundary layer

Boundary Layer Research

Atmospheric Boundary Layer

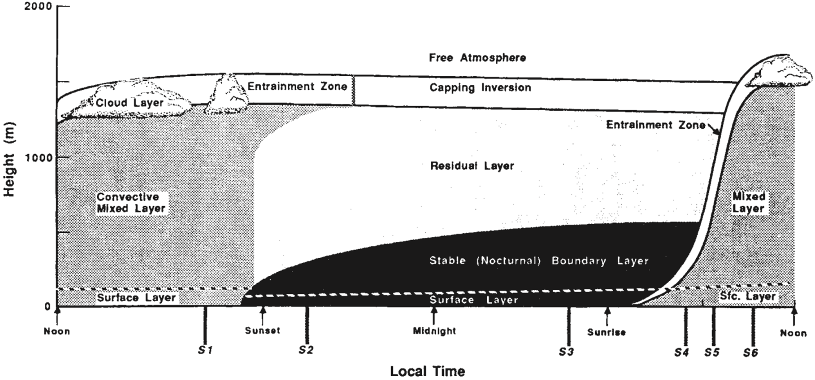
the part of troposphere that is directly influenced by the presence of the earth surface and responds to surface forcings with a timescale of about an hour or less

Characterized by well developed mixing (turbulence) generated by

- the atmosphere moving across Earth's rough surface (*mechanically driven turbulence*)
- by the bubbling up of air parcels from the heated earth (*buoyancy driven turbulence*)

This turbulence is responsible for much of the heat transfer from the earth's surface to the atmosphere (*sensible heat flux*)

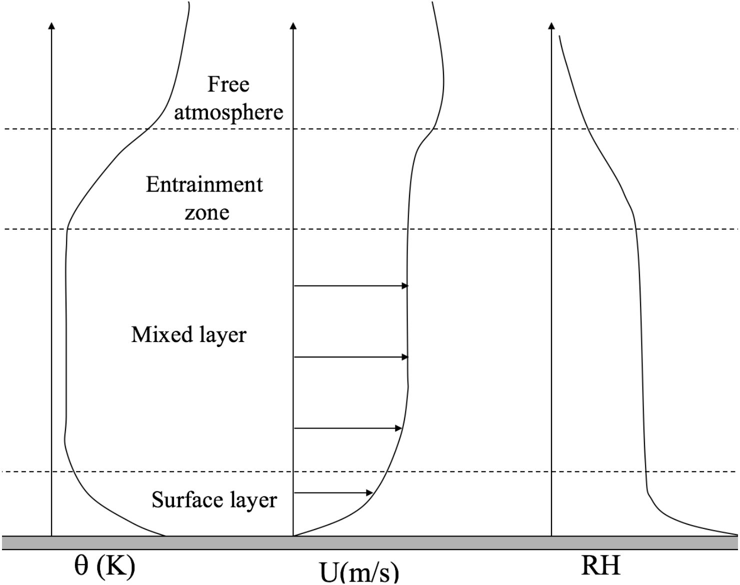
Atmospheric Boundary Layer



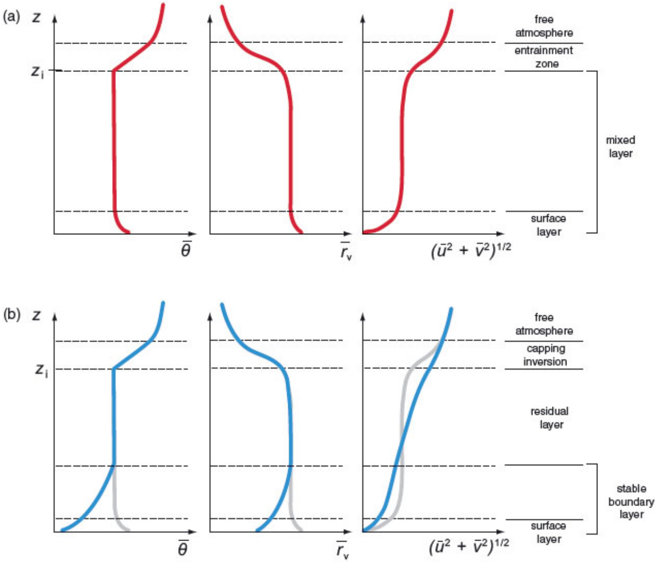
Diurnal cycle of ABL over simple terrain (from Stull 1988)

Atmospheric Boundary Layer

Daytime convective boundary layer (CBL) sub-layers

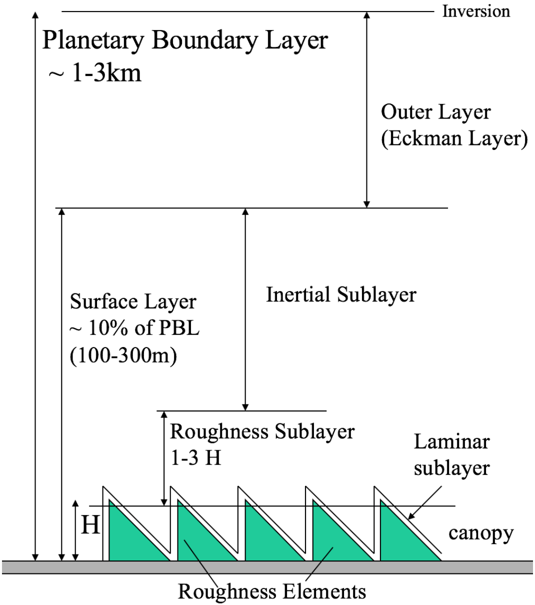


Atmospheric Boundary Layer



from Markowski and Richardson (2010)

Atmospheric Boundary Layer



Atmospheric Surface Layer

Inertial sub-layer

- variation in vertical fluxes $< 10\%$
- log-law wind profile

Roughness sub-layer

- $\mathcal{O}(H)$
- horizontal heterogeneity

Laminar sub-layer

- $< 1 - 2$ mm

Our scales of interest

In this Environmental Fluid Dynamics class, we will focus on the following scales:

- Vertical: $< 3 \text{ km}$
- Horizontal $< 50 \text{ km}$ (micro- to mesoscale)
- Time scale ~ 1 day

We will also examine night vs. day

ABL Transport

Mass

- pollutants – particles
- water
- biological process - pollen

Heat

- sensible heat flux
- latent heat flux

Momentum

- Surface drag - urban vs. rural vs. body of water

Each of these also has spatial variability

We will need to develop equations to describe these processes!

Stratification

- Variation of density with space
- Most introductory Engineering Fluid Mechanics classes focus on constant density problem or “neutral” boundary layers
- We will mostly consider $\rho = \rho(z)$
- The density variation in the atmosphere will typically be dominated by variations in temperature and humidity

Rotation

For much of the class we will neglect rotation effects, but when is rotation important?

Let's introduce the **Rossby Number**

$$\mathrm{Ro} = \frac{\text{inertial}}{\text{rotational}} = \frac{U}{f L_R}$$

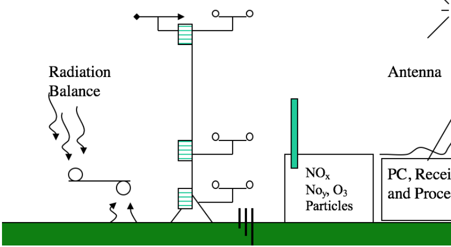
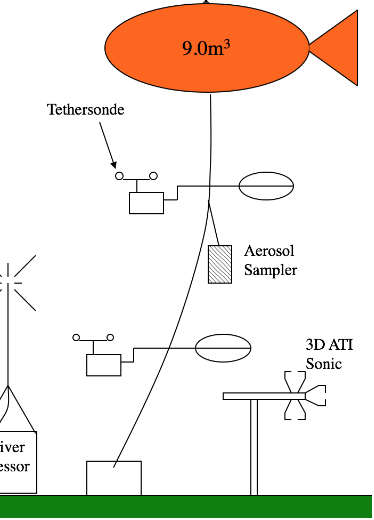
where

$$\begin{aligned} f &= 2\Omega \sin\phi & \text{Coriolis parameter} \\ \phi &= \text{latitude} \\ \Omega &= 7.292 \times 10^{5} \mathrm{rads}^{-1} & \text{Angular speed of Earth} \\ L_R &= \text{relevant length scale} \end{aligned}$$

If $\mathrm{Ro} \gg 1$, rotation is assumed negligible (*i.e.* Coriolis acceleration is less than "horizontal" acceleration)

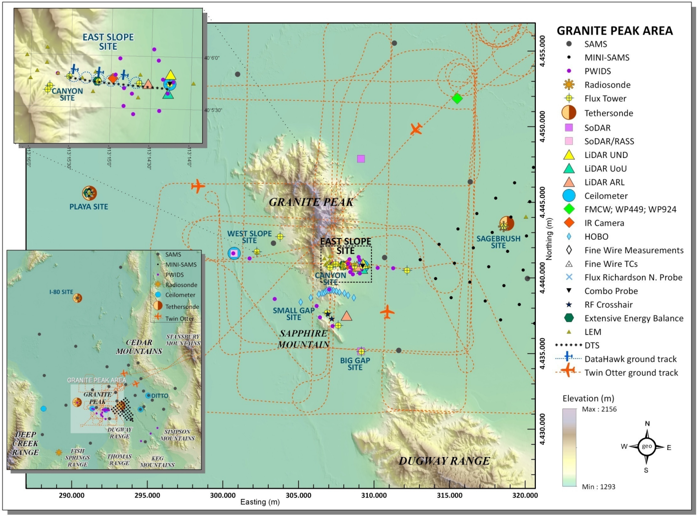
Field Experiments

Example EFD Surface Layer Field Experiment PAFEX-I Setup

Field Experiments: MATERHORN

172 Towers + 90 Sonic Anemometers

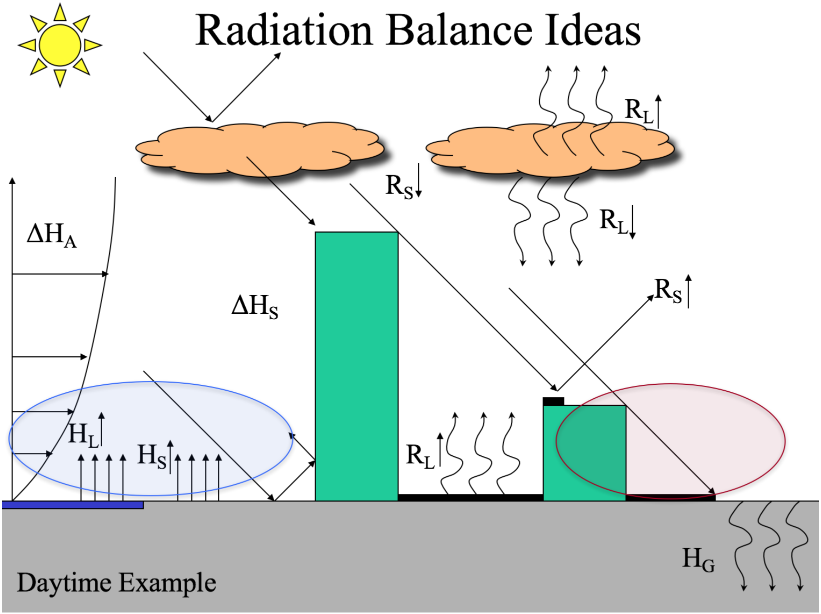


Basic Surface Energy Balance Ideas

We will expand on these ideas later as we derive formal transport equations for responsive fluxes

These initial ideas will allow us to understand the basic mechanisms of heat transfer near the surface of the earth

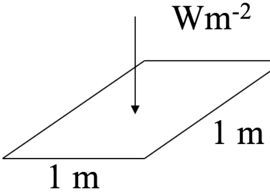
Basic Surface Energy Balance Ideas



Near-Surface Energy Balance (SEB)

Energy Balance at Earth's surface

- Net radiation $\sim$ response fluxes
- Net radiation is composed of: incoming and outgoing solar and long-wave radiation
- Responsive fluxes include: sensible, latent, ground heat fluxes



Near-Surface Energy Balance (SEB)

Why is it important?

- Energy/Water use (solar, geothermal)
- urban heat island
- Agriculture – freezing/thawing
- Air quality
- Thermodynamic/fluid mechanic interplay

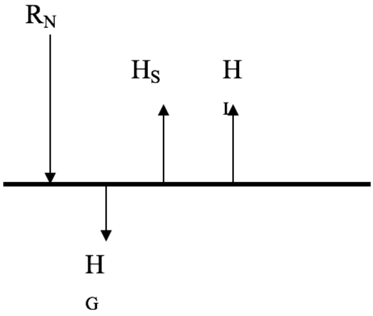
Radiation Balance - Ideal Surface

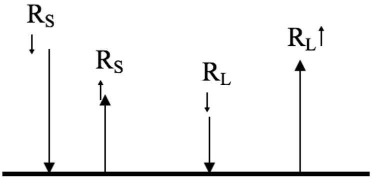
One-dimensional balance sign convention

- All radiative fluxes that point toward the surface are positive
- All non-radiative fluxes that point away from the surface are positive

$$R_N = H_S + H_L + H_G$$

- We assume the surface is thin (no mass, textiti.e. heat capacity), flat, and horizontally homogeneous



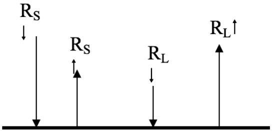


Radiation Balance - Ideal Surface

All radiative fluxes that point toward the surface are positive

$$R_N = R_S \downarrow + R_S \uparrow + R_L \downarrow + R_L \uparrow$$

- R_s – shortwave radiation: $\sim 0.15 - 4.0$ µm (solar)
- R_L – Longwave Radiation: $\sim 3.0 - 100$ µm (terrestrial)



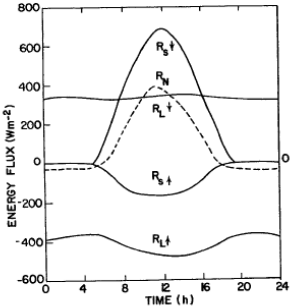
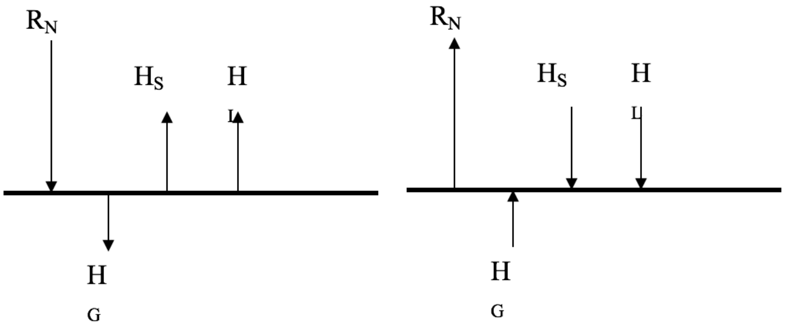


Figure 3.4 Observed radiation budget over a 0.2 m stand of native grass at Matador, Saskatchewan, on 30 July 1971. [From Oke (1987); after Ripley and Redmann (1976).]

Surface Energy Budget



Day (left) and Night (right) surface energy budget over land

Surface Energy Budget

$$\underbrace{R_N}_{\text{Forcing Term}} = \underbrace{H_S + H_L + H_G}_{\text{Response Terms}}$$

Types of energy fluxes at the surface

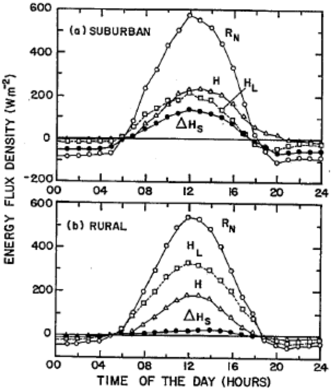
- Net radiation (R_N)
- Sensible heat flux (H_S)
- Latent heat flux (H_L)
- Ground heat flux (H_G)

We assume the surface is thin (no mass, textiti.e. heat capacity), flat, horizontally homogeneous, and opaque.

Surface Energy Budget - Finite Thickness Layer

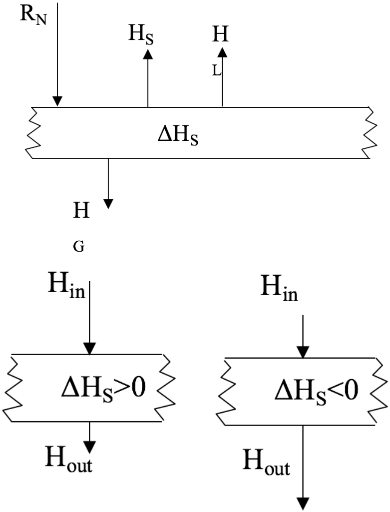
$$\underbrace{R_N}_{\text{Forcing Term}} = \underbrace{H_S + H_L + H_G + \Delta H_S}_{\text{Response Terms}}$$

- We've now added heat storage: $\Delta H_S = \int \frac{\partial}{\partial t}(\rho C T)dz$



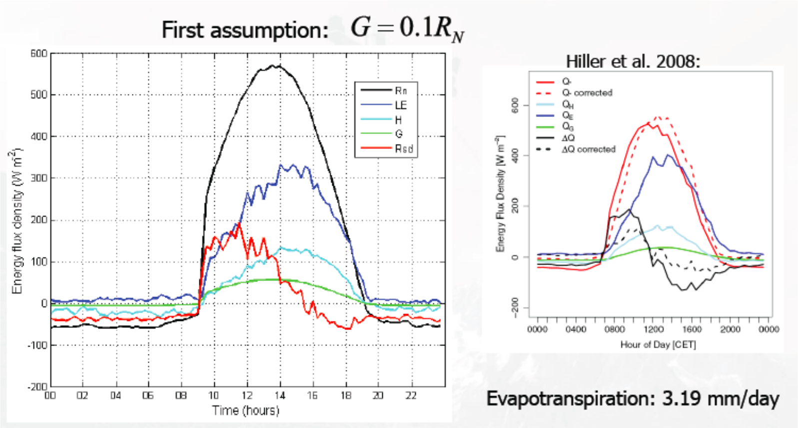
Surface Energy Budget - Finite Thickness Layer

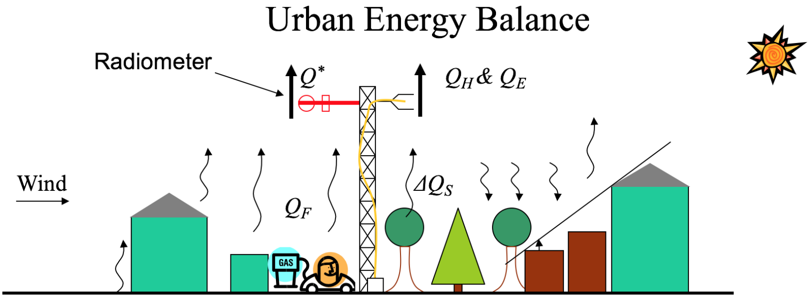
Storage can become particularly important in complex canopies such as urban areas and forests



Flux convergence (left) and flux divergence (right)

Surface energy budget in mountainous terrain - Switzerland

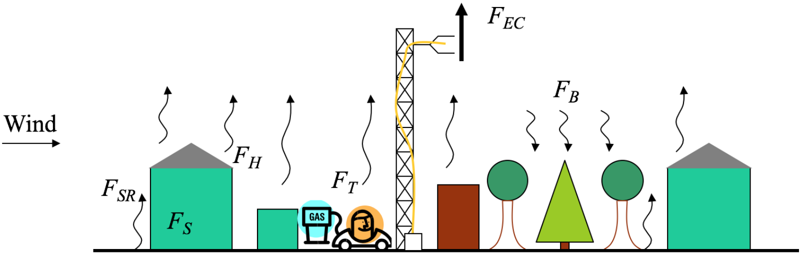




$$Q^* = Q_F = Q_H + Q_E + \Delta Q_S$$

- Q^* = net all-wave radiation
- Q_F = anthropogenic heat flux
- Q_H = latent heat flux
- Q_E = sensible heat flux
- ΔQ_S = heat stored

Urban Air Pollutant Transport



$$F_{EC} = F_{SR} + F_B + F_T + F_H + F_S$$

- F_{SR} = flux of CO_2 due to soil respiration
- F_B = flux of CO_2 due to biogenic srcs (*e.g.* photosynthesis)
- F_T = flux of CO_2 due to traffic
- F_H = flux of CO_2 due to heating
- F_S = flux of CO_2 due to other household services

Bowen Ratio

$$\mathrm{BR} = \frac{\textsf{sensible}}{\textsf{latent}} = \frac{H_S}{H_L}$$

Estimate BR from balloon profile or local gradients

$$\mathrm{BR} \approx \gamma \frac{\partial\theta/\partial z}{\partial q_v/\partial z}$$

where the psychrometric γ is given by

$$\gamma = \frac{C_p}{L_e} = 0.0004(\mathrm{g}_{\textsf{water}}/\mathrm{g}_{\textsf{air}})\mathrm{K}^{-1}$$

Bowen Ratio

Typical BR values	
Sea	0.1
Irrigated crops	0.2
Grassland	0.5
Semi-arid regions	5
Deserts	10