Environmental Fluid Dynamics

ME EN 7710

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Definitions

- Environmental Fluid Mechanics – principles that govern **transport, mixing and transformation processes** in environmental fluids. (e.g., physical, biological, chemical)
  - Includes Stratification & Rotation
  - Micrometeorology - deals with atmospheric phenomena and processes at the smaller end of the spectrum of atmospheric scales and near the surface (ABL). Fine scale structure is important
  - Microclimatology – same physical scales much longer time averaging scales

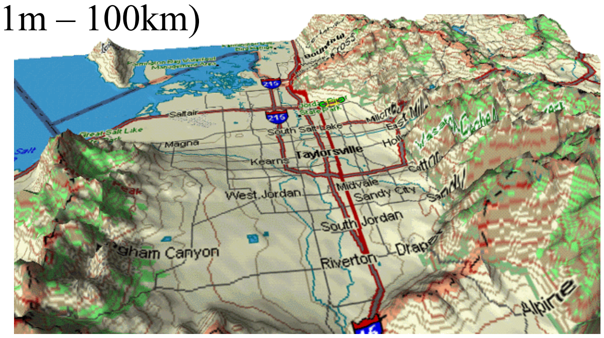
Applications

- Urban Planning
  - Air Quality (Criteria pollutants, Greenhouse gases, accidental releases)
  - Energy and Water Budget's – Green Infrastructure
- Defense Strategies
  - Toxic releases bio/chem/rad
- Agriculture & Forest Meteorology (Evapotranspiration and Water Budget)
- Aeronautical Meteorology
- Wind Engineering
- Numerical Weather Prediction and Climate Simulation
- Many more

Scales of Motion

- Synoptic scales (100+ km)
- Meso-scale (10-1000 km)
- Micro-scale (<1m - 10 km)
- Engineering scale (viscous - 10 m)

- Urban Scales (1m – 100km)



Time and Space Scales

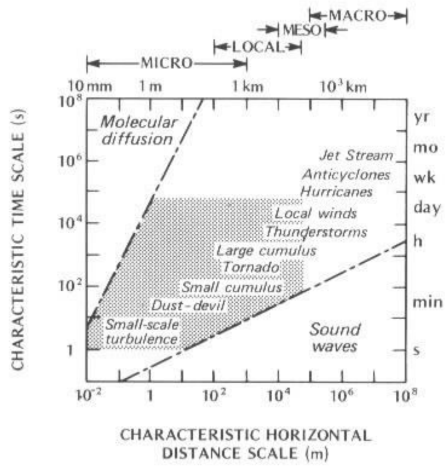


Figure 1.1 *Boundary Layer Climates* Oke, 1987

More on Scales

Table 10-1. Scales of horizontal motion.

Size	Scale	Name
20,000 km	macro α	planetary scale
2,000 km	macro β	synoptic scale
200 km	meso α	mesoscale
20 km	meso β	
2 km	meso γ	
200 m	micro α	boundary-layer turbulence
20 m	micro β	surface-layer turbulence
2 m	micro γ	inertial subrange turb.
200 mm 20 mm 2 mm	micro δ	fine-scale turbulence
	viscous	dissipation subrange

From *Meteorology for Engineers and Scientists*, Stull

Atmospheric boundary layer (ABL)

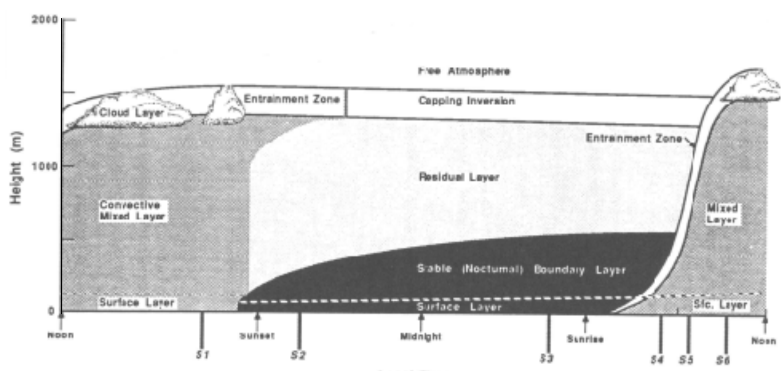
Def. – the part of the troposphere that is directly influenced by the presence of the earth's surface and responds to forcing on time scales of 1 hour or less.

Characterized by well developed mixing (turbulence) generated by:

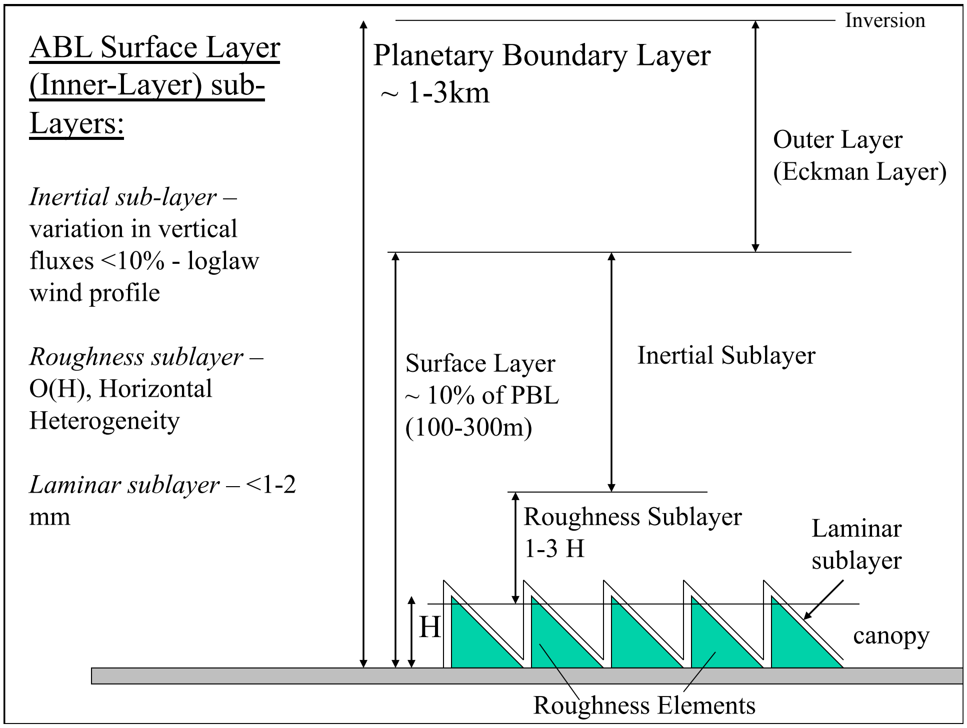
- the atmosphere moving across the earth's rough surface – <u>*mechanically driven turbulence*</u>
- by the bubbling up of air parcels from the heated earth – <u>*buoyancy driven turbulence*</u>

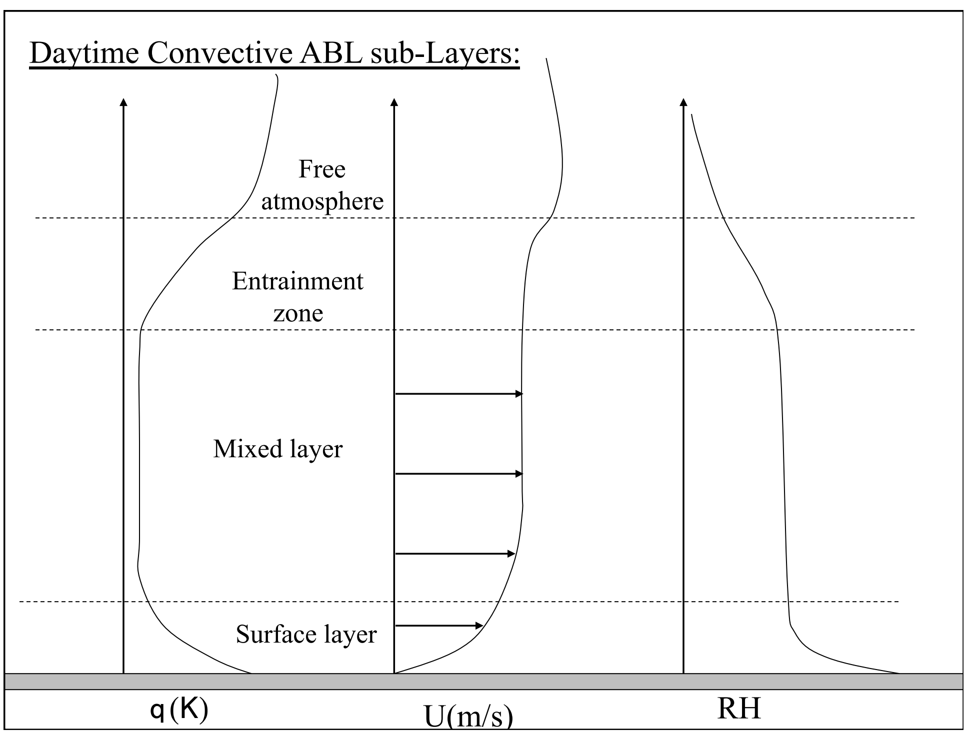
This turbulence is responsible for much of the heat transfer from the earth's surface to the atmosphere – <u>sensible heat flux</u>

Diurnal Cycle of the Convective Boundary Layer over "Simple Terrain" (Stull, 1988)



Note: this is an idealized view of the diurnal cycle typical of calm and clear days and nights in the desert southwest U.S., significant synoptic scale weather systems disrupt this cycle


ABL Surface Layer (Inner-Layer) sub-Layers:
Inertial sub-layer – variation in vertical fluxes <10% - loglaw wind profile
Roughness sublayer – O(H), Horizontal Heterogeneity
Laminar sublayer – <1-2 mm
Inversion
Planetary Boundary Layer ~ 1-3km
Outer Layer (Eckman Layer)
Surface Layer ~ 10% of PBL (100-300m)
Inertial Sublayer
Roughness Sublayer 1-3 H
Laminar sublayer
H
canopy
Roughness Elements


Daytime Convective ABL sub-Layers:
Free atmosphere
Entrainment zone
Mixed layer
Surface layer
q(K)
U(m/s)
RH

In this Environmental Fluid Mechanics Class we will focus
On the following scales:

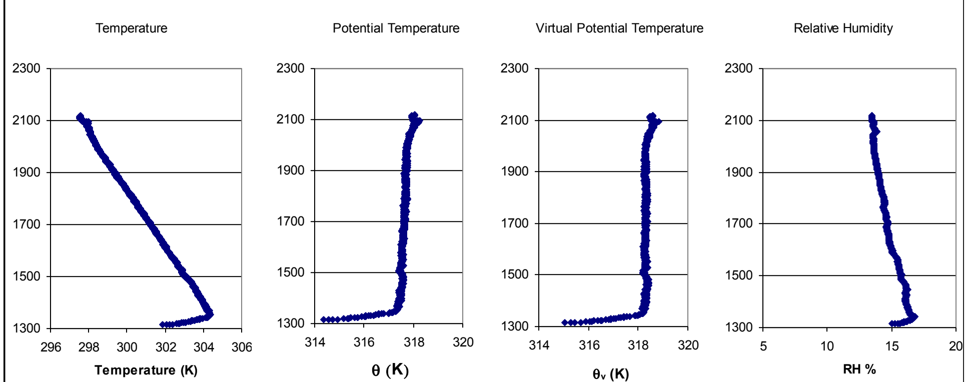
Vertical < 3km

Horizontal < 50 km (micro to meso-scale)

Time scale ~ 1 day

Night vs. Day

Night time temperature and humidity profiles



Transport in the ABL

- Mass
  - pollutants – particles
  - water
  - biological process - pollen
- Heat
  - Sensible Heat Flux
  - Latent Heat Flux
- Momentum
  - Surface drag
    - urban vs. rural vs. ocean/lake/sea

} Spatial variation

We will need to develop equations to describe these processes

Stratification

- Variation of density with space

- Most Engineering Fluid Mechanics classes focus on constant density problem or "neutral" boundary layers

- We will mostly consider $\rho = \rho(z)$

- The density variation 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?

Rossby number: $Ro = \frac{Inertial}{Rotational} = \frac{U}{fL_r}$

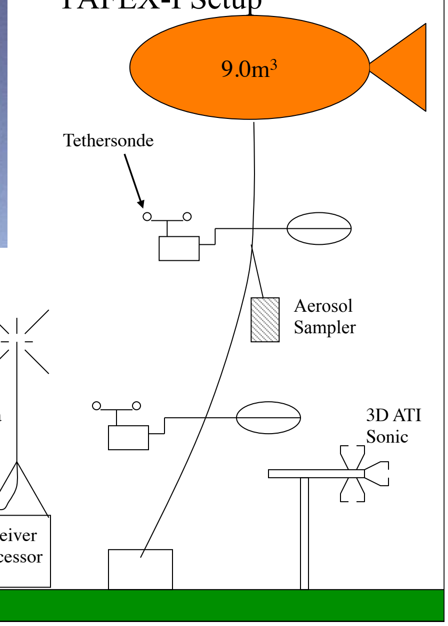
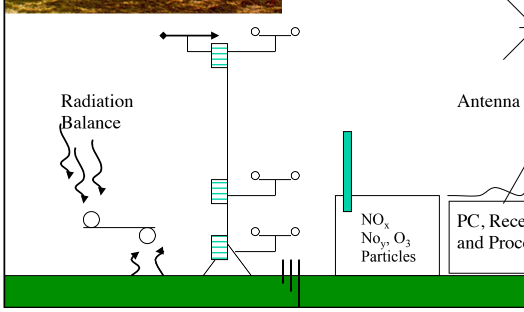
$f = 2\Omega \sin\varphi$ — φ Latitude

$\Omega = 7.292 \times 10^5 \, rad/s$ — Angular speed of rotation of the earth

L_r — relevant length scale

If $R_o >> 1$, rotation is assumed negligible (i.e. Coriolis acceleration is less than “horizontal” acceleration.

Example EFD Surface Layer Field Experiment PAFEX-I Setup

Basic Surface Energy Balance Ideas

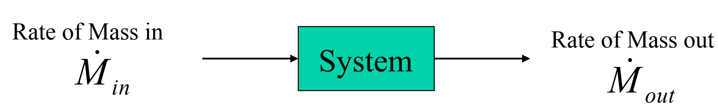
We will expand on these ideas later as we derive formal transport equations for responsive fluxes

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

Simple "Systems" Approach

Conservation of Mass (example Water) – Integral Form

$$\dot{M}_{in} = \dot{M}_{out} + \Delta\dot{M}_S$$



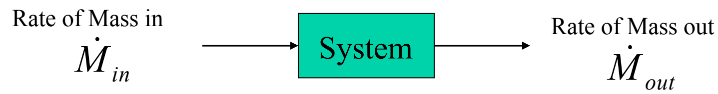
States of Water
1. Liquid
2. Vapor
3. Solid

Modes of Mass Transfer
1. Advection
2. Precipitation
3. Run-off
4. percolation

Simple "Systems" Approach

Conservation of Mass (example Water) – Integral Form

$$\dot{M}_{in} = \dot{M}_{out} + \Delta \dot{M}_S$$



Similar for other pollutants or atmospheric constituents (e.g. , CO2, Hg) where the mass stored may also include complex processes associated with sequestration, deposition, etc.

St … nsfer

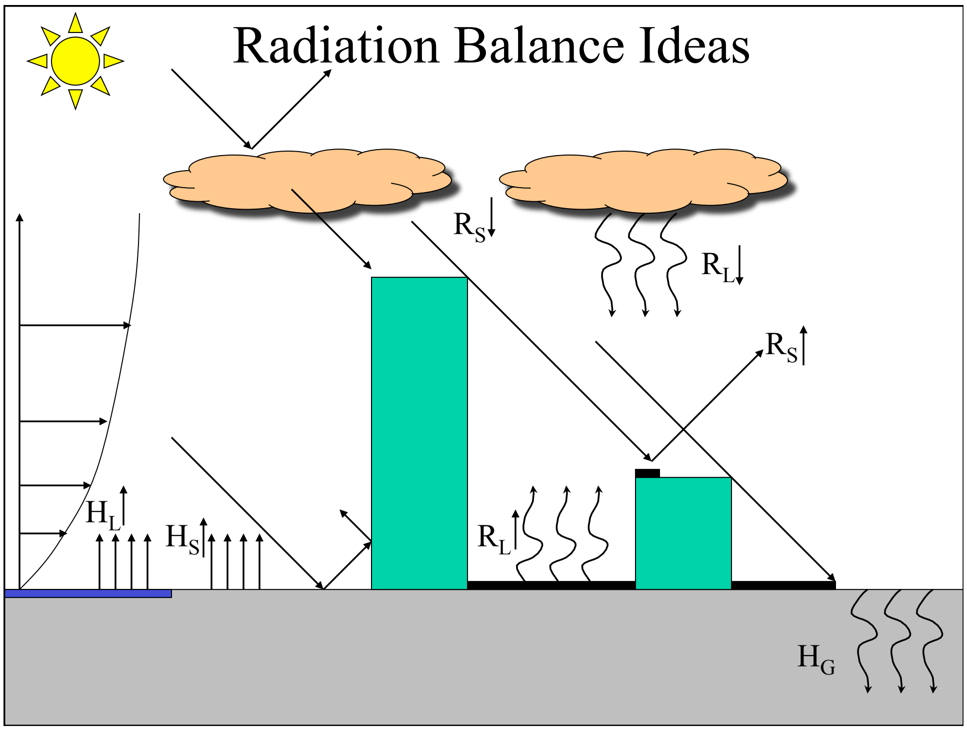
1\.

2\.

3\.

4\. percolation

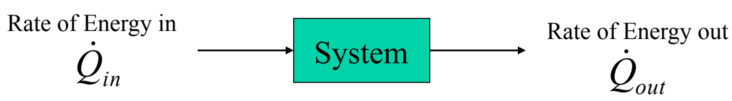
Radiation Balance Ideas



Simple "Systems" Approach

First Law of Thermodynamics – Integral Form

$$\dot{Q}_{in} = \dot{Q}_{out} + \Delta Q_S$$



Forms of Energy

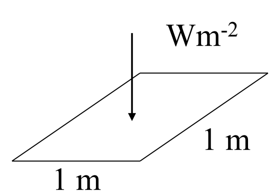
1. Radiant
2. Thermal
3. Potential
4. Kinetic

Modes of Heat Transfer

1. Conduction
2. Convection
3. Radiation

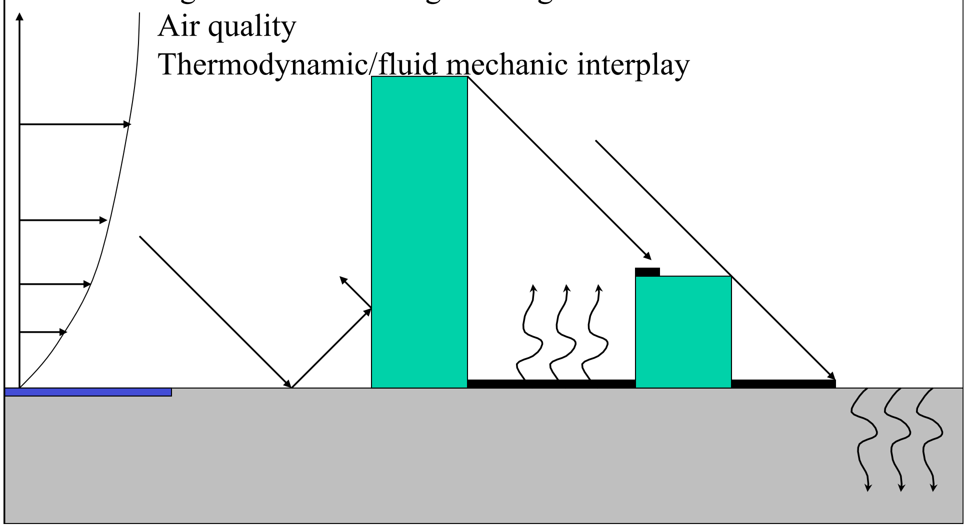
Near Surface Energy Balance (SEB)

- Energy Balance at the earth's surface
  - Net Radiation ~ Response Fluxes
  - Incoming and Outgoing Solar and Long Wave Radiation
  - Sensible, Latent, Ground Heat Fluxes

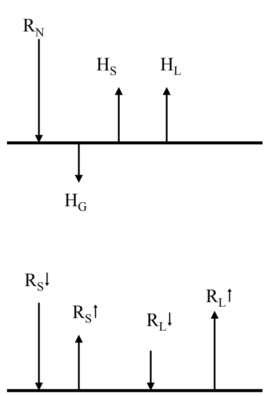


Why is it important?

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

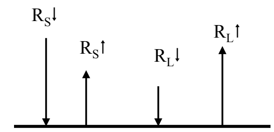
$$R_N = H_S + H_L + H_G$$

Assumptions about the surface:
•Thin – no mass (heat capacity)
•Flat
•Horizontally homogenous
•Opaque

Radiation Balance – Ideal Surface

All radiative fluxes that point toward the surface are positive

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



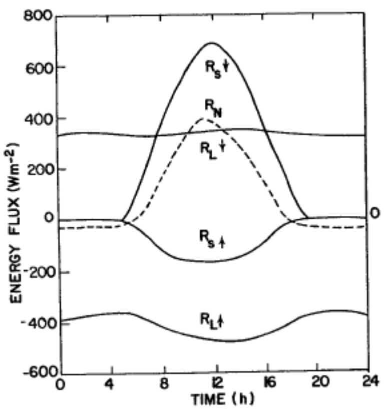


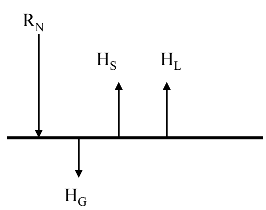
Figure 3.4 Observed radiation budget over a 0.2 m stand of native grass at Matador, Saskatchewan, on 30 July 1971. [From Oke (1987); after Ripley and Redmann (1976).]

R_S – Shortwave Radiation: ~0.15-4.0 µm

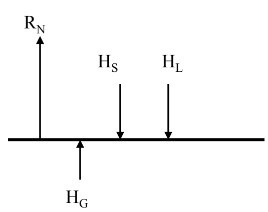
R_L – Longwave Radiation: ~3.0-100 µm

Surface Energy Budget

Daytime (over land)



Nighttime (over land)



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

Types of Energy Fluxes at the Surface
1. Net Radiation (R_N)
2. Sensible Heat Flux (H_S)
3. Latent Heat Flux (H_L)
4. Ground Heat Flux (H_G)

Assumptions about the surface:
- Thin – no mass (heat capacity)
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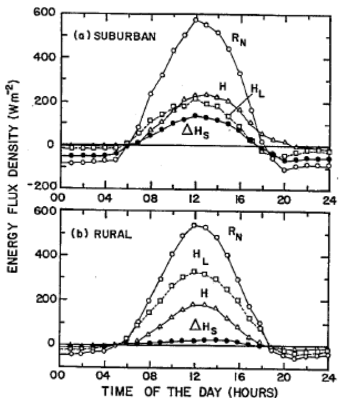
Surface Energy Budget – Finite Thickness Layer



Summer Fluxes

$$R_N = H_S + H_L + H_G + \Delta H_S$$

Forcing Term — Response Terms

Types of Energy Fluxes at the Surface

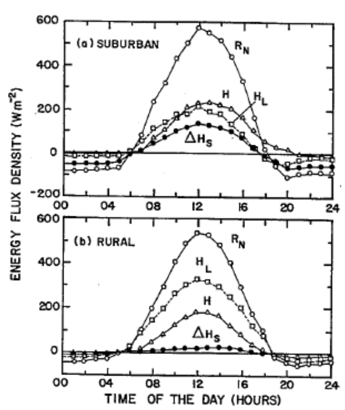
1. Net Radiation (R_N)
2. Sensible Heat Flux (H_S)
3. Latent Heat Flux (H_L)
4. Ground Heat Flux (H_G)
5. Heat Storage (DH_S)

$$\Delta H_S = \int \frac{\partial}{\partial t}(\rho C T)\,dz$$

<u>Assumptions</u> about the surface:

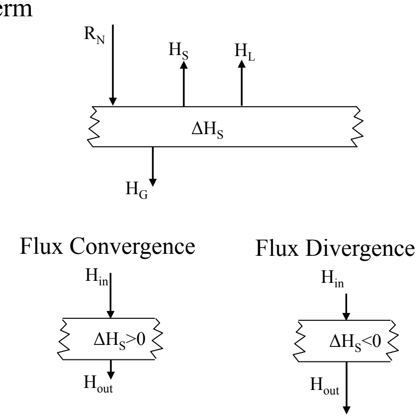
- Flat
- Horizontally homogenous
- Opaque

Surface Energy Budget – Finite Thickness Layer



$$R_N = H_S + H_L + H_G + \Delta H_S$$

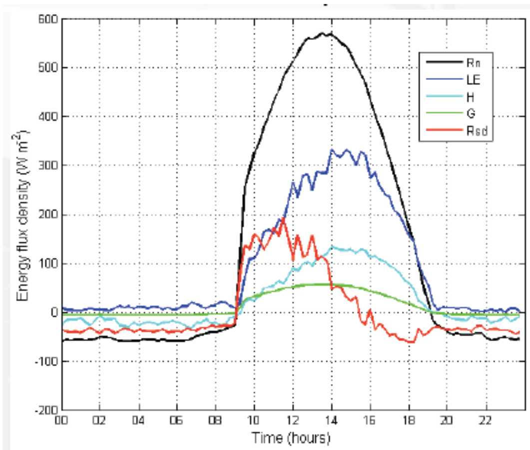
Forcing Term — Response Terms

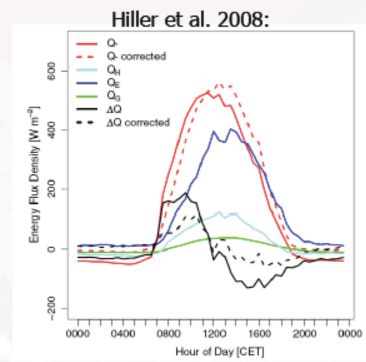


<u>Assumptions</u> about the surface:

- Flat
- Horizontally homogenous
- Opaque

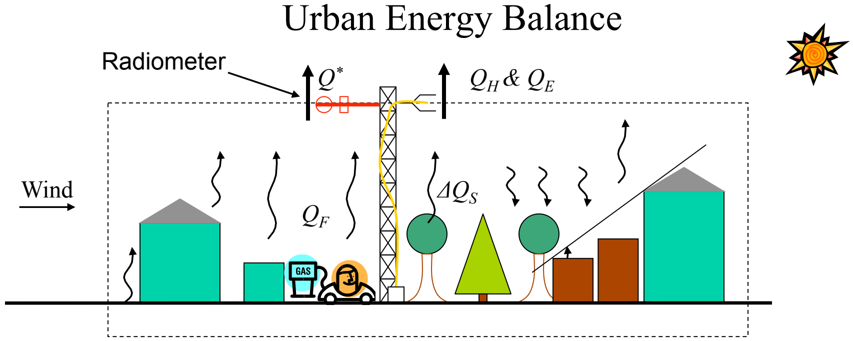
Surface Energy Budget
Mountainous Terrain - Switzerland





Evapotranspiration: 3.19 mm/day

Urban Energy Balance



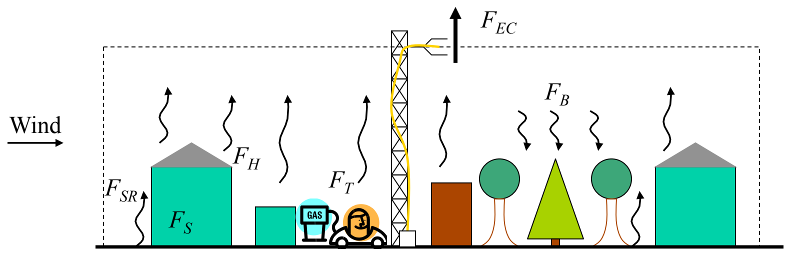
What about Energy? ⟶ Sensible/Latent Heat Flux

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

Must consider:
Radiation
Conduction
Convection

Q^*= net all-wave radiation
Q_F = Anthropogenic heat flux
Q_H = Latent heat flux
Q_E = Senisble heat flux
ΔQ_S = Heat Stored

Air Pollutant Transport in the Urban Atmospheric Surface Layer



Carbon Dioxide Net Ecosystem Exchange

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

F_{SR}= flux of CO_2 due to soil respiration

F_B= flux of CO_2 due to other biogenic contributions (e.g. photosynthesis)

Anthropogenic Contributions:

- 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

See Oke 1988

Bowen Ratio

$$BR = \frac{H_s}{H_L} = \frac{Sensible}{Latent}$$

Estimate BR from balloon profile:

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

(NOTE: we are avoiding some issues associated with turbulence temporarily):

Psychrometric constant - γ:

$$\gamma = \frac{C_p}{L_e} = 0.0004\,(g_{water}/g_{air})K^{-1}$$

Bowen Ratio

<u>Typical BR Values:</u>

Sea	0.1
irrigated crops	0.2
Grassland	0.5
Semi-arid regions	5
Deserts	10