Surface energy balance II

Reading: GPC Ch4, omit subsections 4.5.1, 4.5.2

Outline:

- Atmospheric boundary layer
- Sensible and latent heat flux
    a) Eddy covariance
    b) Bulk formula
- Bowen Ratio
- Surface energy balance: variations in space and time

Atmospheric (or planetary) boundary layer – ABL or PBL

Lowest part of the troposphere (typically 1-2 km, but varies - deeper where the surface is hot or rough, when the winds are strong, when the mean vertical motion in the free troposphere is upward). Boundary layer is ***strongly influenced by the surface*** - effective communication from surface to the interior of the boundary layer.

Above: free atmosphere – balance between pressure gradient and Coriolis force (geostrophic wind).

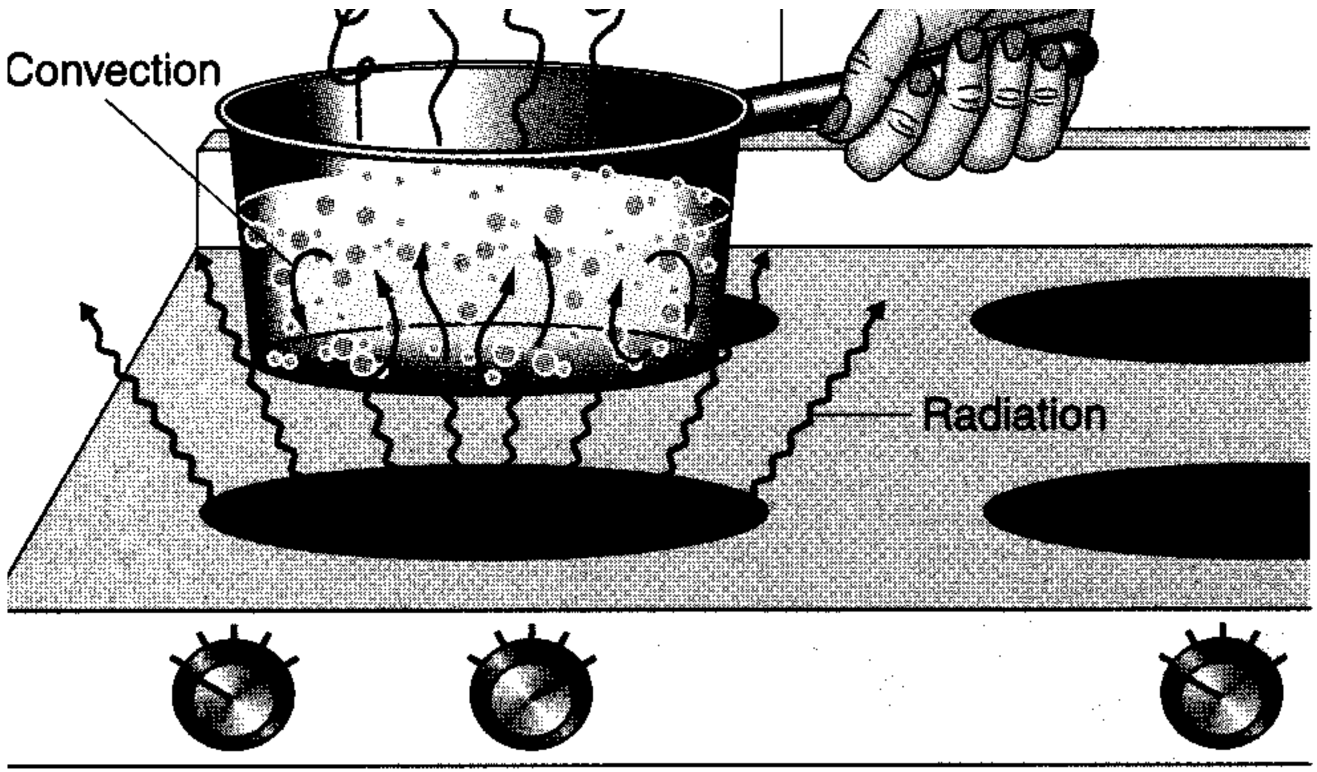
``the part of the troposphere that is directly influenced by the presence of the earths surface, and responds to surface forcings with a time scale of about an hour or less.'' (Stull 1988)

Fluxes of ***heat, moisture, momentum (and chemical constituents)*** by ***small-scale turbulent motion.*** Without this motion, exchange from surface to atmosphere would be slow.

Types of turbulence**:**

- ***mechanical*** (conversion of mean wind to turbulent motion – *shear instability)*

-***convective* or *thermal*** (buoyancy, convective cells – land, daylight hours; oceans)



Mechanical turbulence - two fluids on top of each other, top layer is less dense than bottom layer, and flowing faster than the bottom layer

(this is called a Kelvin-Helmholtz instability)

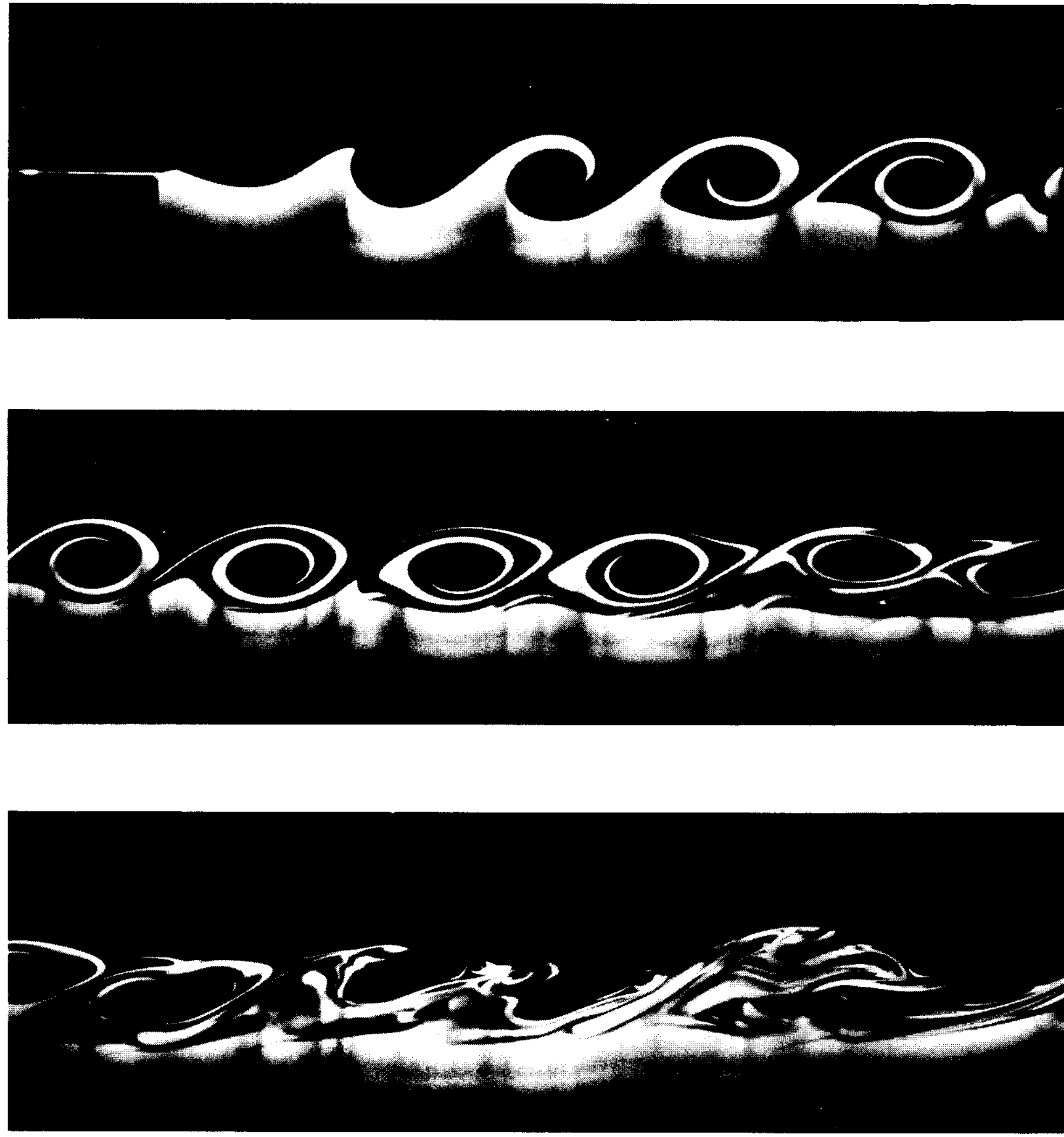
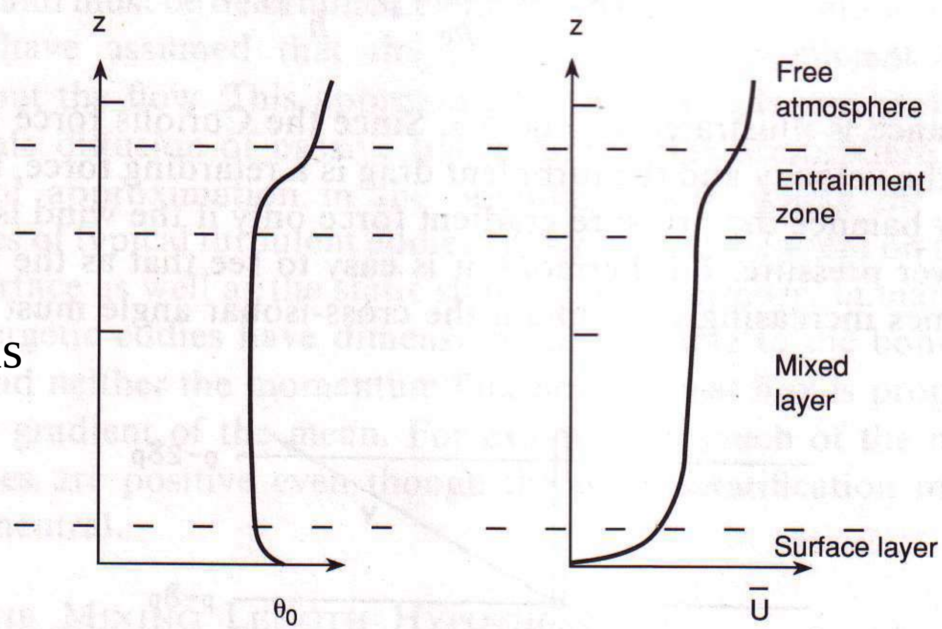


Figure 11.3 Development of a Kelvin-Helmholtz instability in the laboratory. Here

Typical profiles in the boundary layer - properties are generally well mixed (almost constant with height) in a relatively unstable PBL - hence ‘**mixed layer’.** The mixed layer is bounded above by the **entrainment zone** - interface between boundary layer and ‘free atmosphere’, and below by the **surface layer** (typically on the order of 100 m). Under strong wind conditions, the surface layer has strong vertical wind shear.

Can contain clouds



←Air from the free atmosphere is incorporated into the PBL

Surface wind =0, viscous constraint

Fig. 5.2 Mean potential temperature, θ_0, and mean zonal wind, $\bar{U}$, profiles in a well-mixed boundary layer. Adapted from Stull (1988).

(source: Holton)

Boundary layer temperature is strongly and rapidly affected by changing surface temperatures (here change due to diurnal cycle)

At night LW emission cools land more than air → stable PBL, inversion, turbulence and vertical motions greatly suppressed. Inversion disappears after sunrise.

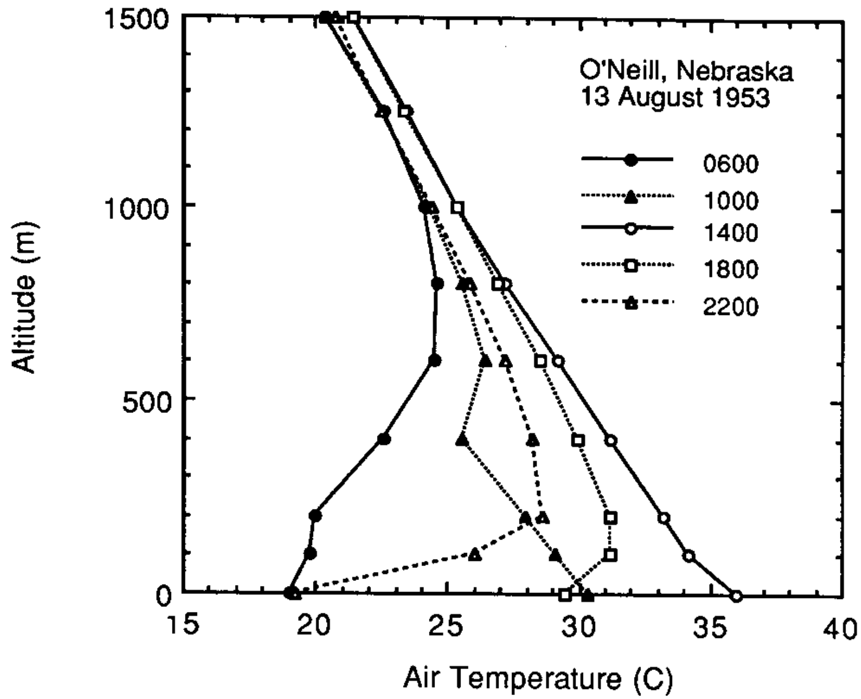
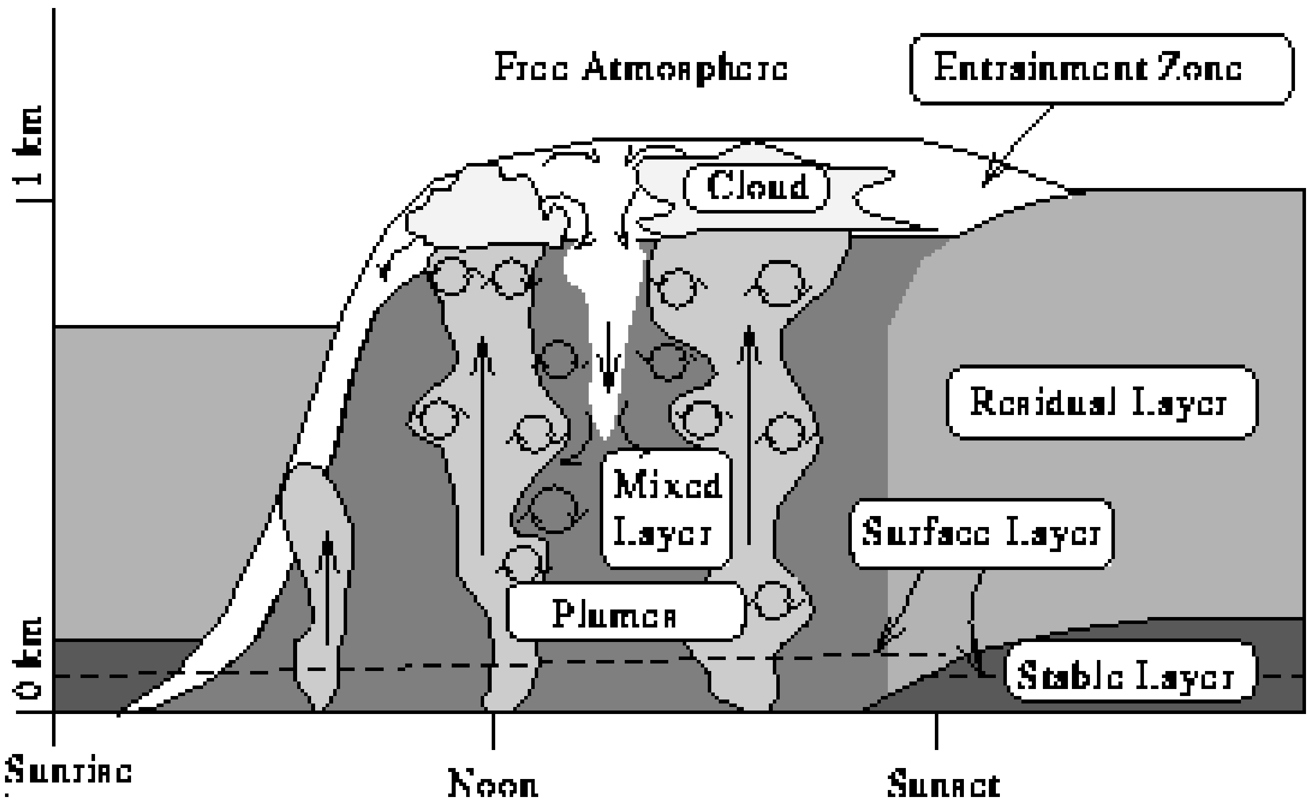


Fig. 4.8 Plot of air temperature at various local times in the lowest 1500 m of the atmosphere at O'Neill, Nebraska on August 13, 1953. Times are given using a 24-hour clock so that 1800 = 6 PM, etc. [Data from Lettau and Davidson (1957).]

Figure (next slide) illustrates a typical daytime evolution of the atmospheric boundary layer in high pressure conditions over land. The solar heating causes thermal plumes to rise, transporting moisture, heat and aerosols. The plumes rise and expand adiabatically until a thermodynamic equilibrium is reached at the top of the atmospheric boundary layer. The moisture transferred by the thermal plumes forms convective clouds. Drier air from the free atmosphere penetrates down, replacing rising air parcels. The part of the troposphere between the highest thermal plume tops and deepest parts of the sinking free air is called the entrainment zone. The convective air motions generate intense turbulent mixing. This tends to generate a mixed layer, which has potential temperature and humidity nearly constant with height. When buoyant turbulence generation dominates the mixed layer, it is called a convective boundary layer (CBL). The lowest part of the PBL is called the surface layer. In windy conditions, the surface layer is characterized by a strong wind shear caused by friction.

Source: http://lidar.ssec.wisc.edu/papers/akp_thes/node6.htm

The boundary layer from sunset to sunrise is called the nocturnal boundary layer. It is often characterized by a stable layer, which forms when the solar heating ends and the radiative cooling and surface friction stabilize the lowest part of the ABL. Above that, the remnants of the daytime CBL form a residual layer. The nocturnal boundary layer may also be convective when cold air advects over a warm surface.



http://lidar.ssec.wisc.edu/papers/akp_thes/node6.htm

Sensible and Latent Heat fluxes in the boundary layer

Vertical fluxes of mass (moisture included), momentum and energy are produced by small-scale turbulence when the parcels of air moving ↑ have different properties than particles moving ↓.

Bar denotes time average

$$\text{Upward sensible heat flux} = c_p \rho \overline{wT} \quad (4.22)$$

Split into a time mean and deviation

$$w = \overline{w} + w', \qquad T = \overline{T} + T' \quad (4.23)$$

so

$$\overline{wT} = \overline{w}\,\overline{T} + \overline{w'T'} \quad (4.24)$$

$$\text{Total} = \text{mean} + \text{eddy}$$

Since w is small, sensible (and latent) heat flux can be written as:

$$\text{SH} = c_p \rho \overline{w'T'}, \qquad \text{LE} = L \rho \overline{w'q'} \quad (4.25)$$

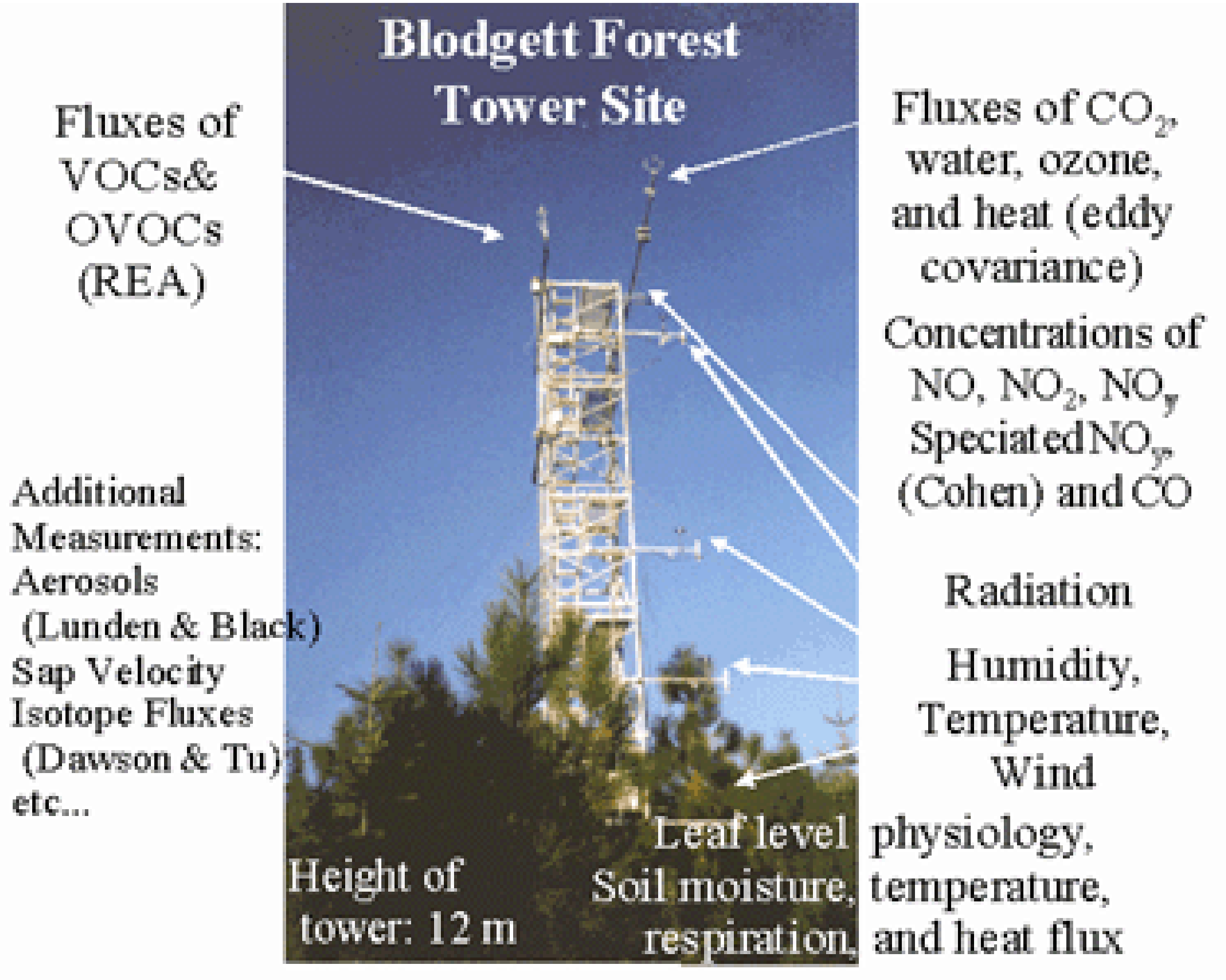
at some level in the PBL.

What is $\overline{w'T'}$?

w’T’ is large and positive if eddy motion is such that warm air is moving upwards or cold air is moving downwards.
In other words, the time mean of w’T’ is large and positive (large upward heat transport) if the upward eddy motion covaries with warm temperatures and downward eddy motion covaries with cold temperatures

Hence: “***Eddy covariance***”. The argument applies equally well to turbulent transport of other properties (moisture, aerosol …..)

Measurements (not easy): Flux towers



Impact of biogenic hydrocarbon emissions on regional tropospheric ozone and particulate matter production, the impact of ozone deposition and drought stress, and the processes controlling carbon cycling in a Sierra Nevada forest ecosystem (Blodgett Forest, Georgetown, California).

Convective boundary layer

Heat and moisture ↑ Momentum↓

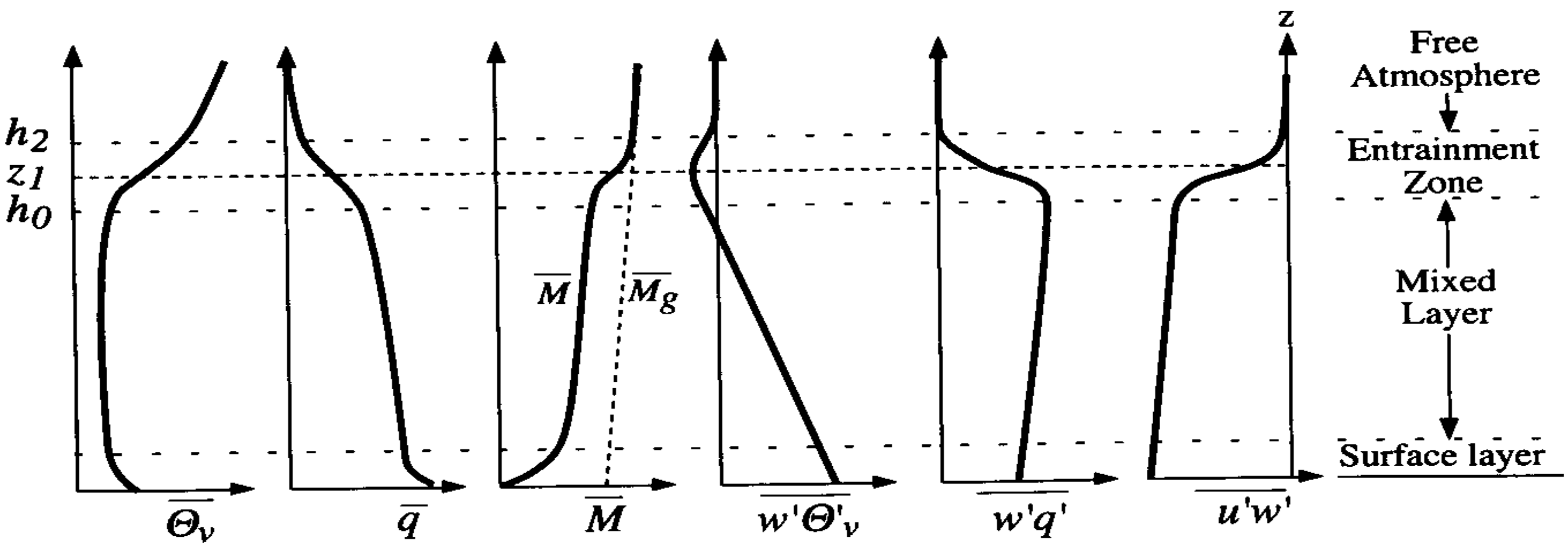


Fig. 4.6 Structure of a convective boundary layer showing the distributions of mean virtual potential emperature $\overline{\Theta}_v$, water vapor mixing ratio $\overline{q}$, momentum $\overline{M}$, geostrophic momentum $\overline{M}_g$, and the verti-al eddy fluxes of potential temperature, humidity, and momentum. [From Stull (1988) after Dreidonks nd Tennekes (1984). Reprinted with permission from Kluwer Academic Publishers.]

(Mixing ratio = mass of water vapor/mass of dry air in an air parcel
Usually expressed in g(water vapor)/kg(dry air). Usually very close to specific humidity since the water vapor content is small compared to the dry air)

Unfortunately its difficult measure eddy flux globally or even locally. So we ***parameterize*** sensible and latent heat fluxes through assuming that they are related to large-scale quantities. The parameterizations below is commonly known as the **'bulk formula'**

$$\mathrm{SH} = c_p \, \rho \, C_{\mathrm{DH}} \, U_r \left(T_s - T_a(z_r) \right)$$

Heat transfer coefficient (typically $1\mathrm{x}10^{-3}$ for ocean to $4\mathrm{x}10^{-3}$ over land - depends on roughness)

Mean wind speed at reference level (e.g. 10m above ground)

Surface temperature

Air temp at reference level z_r

An important point is that it is the ***difference*** between the property at the surface and at the reference level that matters

Likewise for latent heat flux (but T is replaced by specific humidity q)

$$\mathrm{LE} = L \, \rho \, C_{\mathrm{DE}} \, U_r \left(q_s - q_a(z_r) \right)$$

The transfer coefficient $C_{DE/DH}$ depends on the following:

- Surface "roughness" - the rougher the surface, the larger the coefficient

- The vertical stability of the air just above the surface (characterized by the ***Richardson number Ri***). If Ri dips below a threshold (the critical Richardson number, around 0.25), the flow transitions from laminar to turbulent.

$$\mathrm{Ri} = \frac{g}{T_0} \frac{(\partial\Theta/\partial z)}{(\partial U/\partial z)^2}$$

Measure of static stability (density stratification)

Measure of vertical wind shear

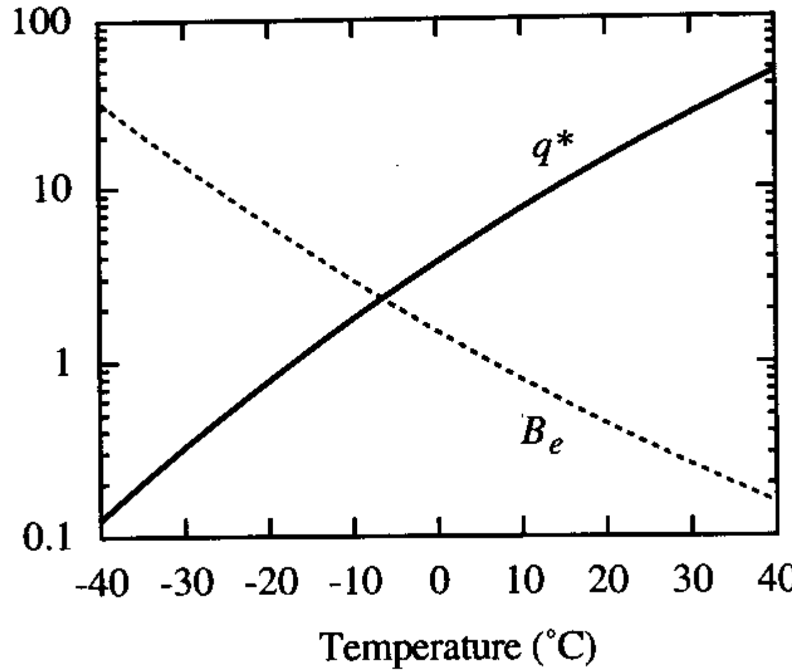
Ref. temperature

A ***neutral*** boundary layer is the special case when buoyancy does not play a role in PBL turbulence. The opposite case is that for a ***stratified*** PBL. Ri is large when the air is stably stratified and negative for a buoyantly unstable PBL.

- Reference height

Bowen Ratio

The ***Bowen Ratio*** $\boldsymbol{B_0}$ is the ratio of sensible to latent cooling of the surface: $\mathbf{B_0 = SH/LE}$**.** The smaller the ratio, the more important latent flux is relative to the sensible flux



When the surface and the air at z_r are saturated, the Bowen ratio takes a special value $\mathbf{B_0} = \mathbf{B_e}$**,** which decreases exponentially as the temperature increases.

The point is that as the temperature increases, latent flux becomes relatively more important and sensible less important in the surface energy balance.

Table 4.5

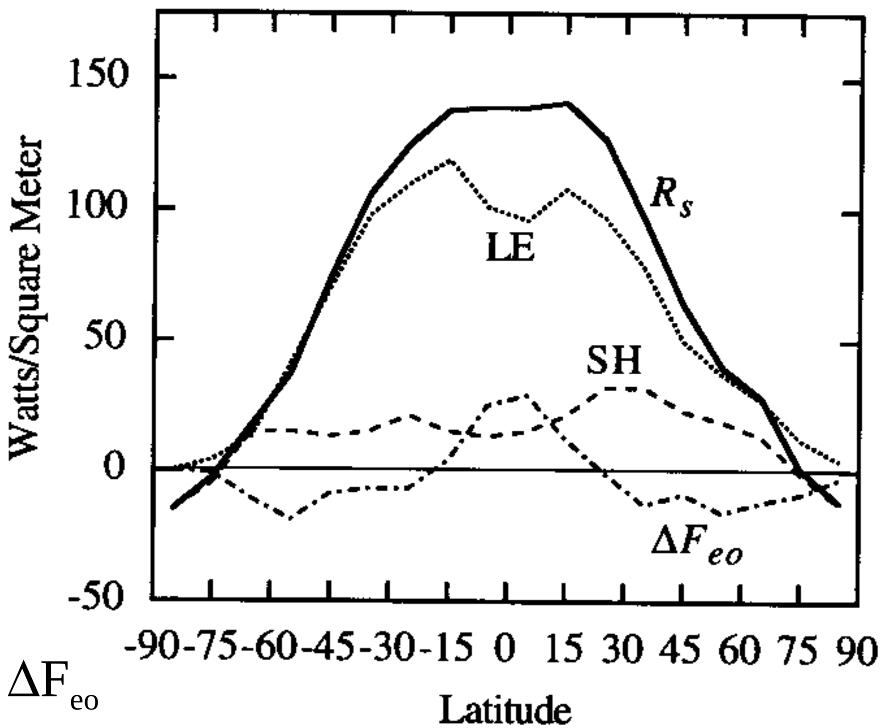
Mean Latitudinal Values of the Components of the Energy Balance Equation for Earth's Surface

Latitude zone	Oceans				Land			Earth			
	R_s	LE	SH	ΔF_{eo}	R_s	LE	SH	R_s	LE	SH	ΔF_{eo}
80–90N	•	•	•	•	•	•	•	–12	4	–13	–3
70–80N	•	•	•	•	•	•	•	1	12	–1	–9
60–70N	31	44	21	–35	27	19	8	28	27	13	–12
50–60N	39	52	21	–35	40	25	15	40	37	19	–16
40–50N	68	70	19	–21	60	32	28	64	50	23	–9
30–40N	110	114	17	–21	80	31	49	97	78	32	–13
20–30N	150	139	12	–1	92	27	65	127	97	32	–1
10–20N	158	131	8	19	94	39	56	141	108	21	12
0–10N	153	106	5	41	96	64	32	139	96	15	29
0–10S	153	112	5	36	96	66	29	139	101	13	25
10–20S	150	138	7	5	97	54	42	138	119	15	4
20–30S	134	133	9	–8	93	37	56	125	110	21	–7
30–40S	109	106	11	–8	82	37	45	106	98	15	–7
40–50S	76	73	12	–9	54	28	27	74	70	13	–9
50–60S	37	41	13	–17	41	27	15	37	41	15	–19
60–70S	•	•	•	•	•	•	•	17	13	15	–11
70–80S	•	•	•	•	•	•	•	–3	4	–5	–1
80–90S	•	•	•	•	•	•	•	–15	0	–15	0
0–90N								96	73	21	1
0–90S								96	82	15	–1
Globe	109	98	11	0	65	33	32	96	78	18	0

Values in W m^{-2}. [Data from Sellers (1965). Reprinted with permission from the University of Chicago Press.]

R_s peaks in the tropics

Polar regions:
net radiative loss balanced by ↓ flux of SH associated with the T inversion at low z in high lat., which is supported by poleward heat transport in the atm., ΔF_{eo}



LE varies with lat. more than SH

Fig. 4.11 Components of the annual-average surface energy balance plotted against latitude. [Data from Sellers (1965). Reprinted with permission from the University of Chicago Press.] (zonal mean)

Table 4.6

Annual Energy Balance of the Oceans and Continents

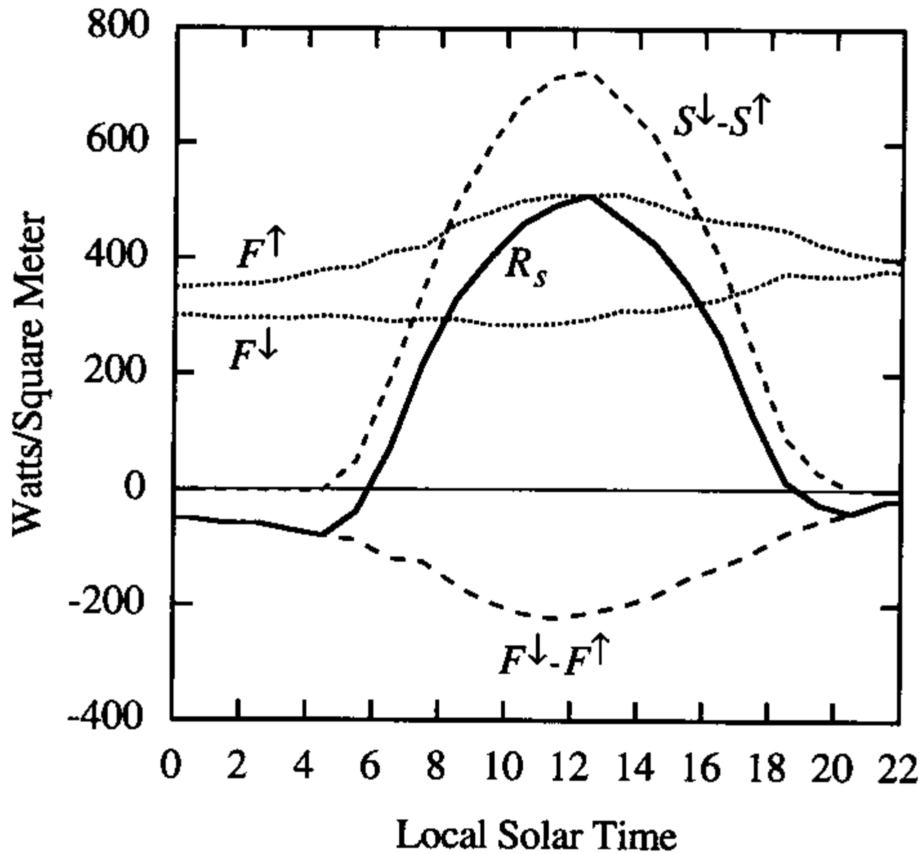
Area	R_s	LE	SH	ΔF_{eo}	SH/LH
Europe	52	32	20	0	0.62
Asia	62	29	33	0	1.14
North America	53	30	22	0	0.74
South America	93	60	33	0	0.56
Africa	90	34	56	0	1.61
Australia	93	29	64	0	2.18
Antarctica	−16	0	−15	0	—
All land	65	33	32	0	0.96
Atlantic Ocean	109	95	11	3	0.11
Indian Ocean	113	102	9	1	0.09
Pacific Ocean	114	103	11	0	0.10
Arctic Ocean	−5	7	−7	−5	−1.00
All oceans	109	98	11	0	0.11

$= B_0$

Values in W m^{-2}. [Data from Budyko (1963).]

High B_0: “desert continents” – Low B_0: “wet continents”

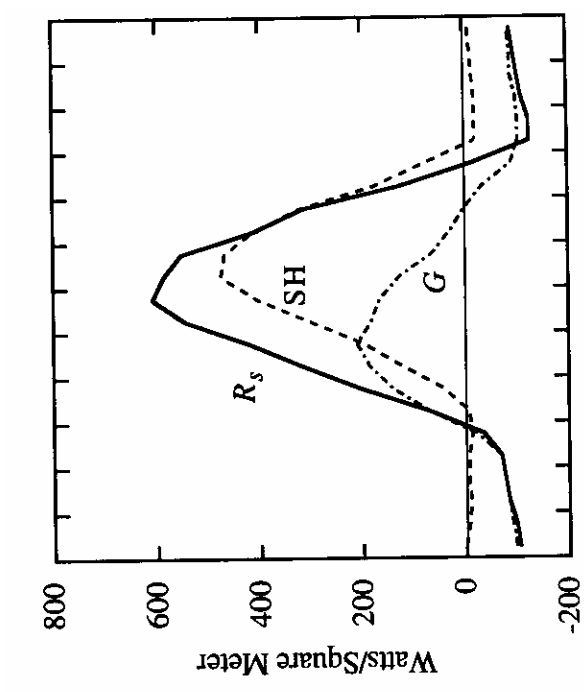
Diurnal variations in surface energy balance is strong, with the exception of polar regions.



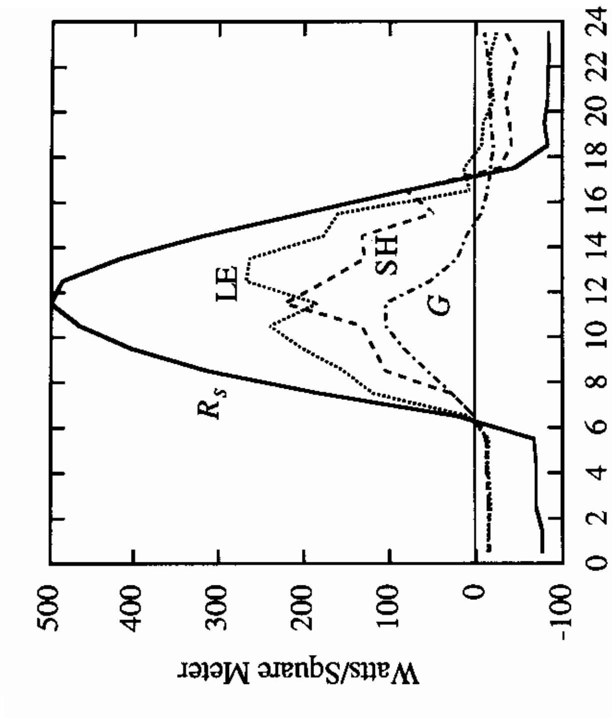
Example: grass field in Saskatchewan, Canada, 53 ^{0}N

July 30 1971, clear summer day, average wind, low humidity, albedo ~ 0.16

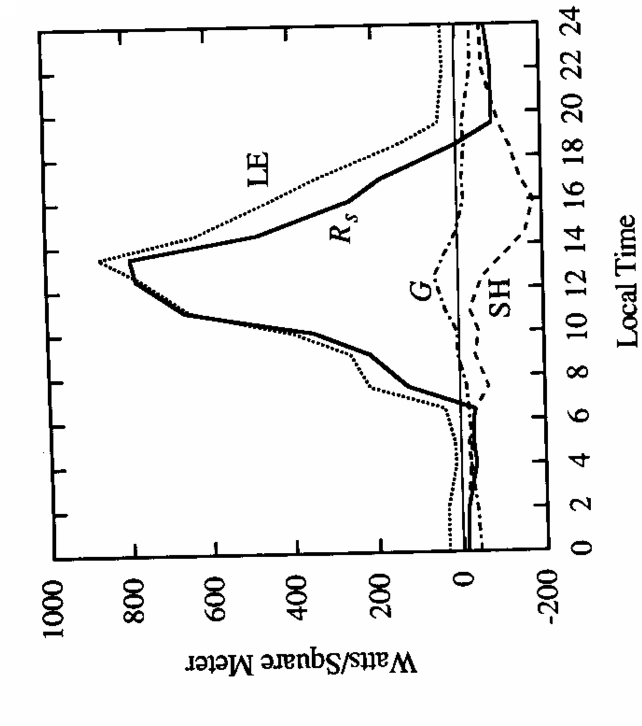
More examples



Dry lake bed in California, June 10, 1950

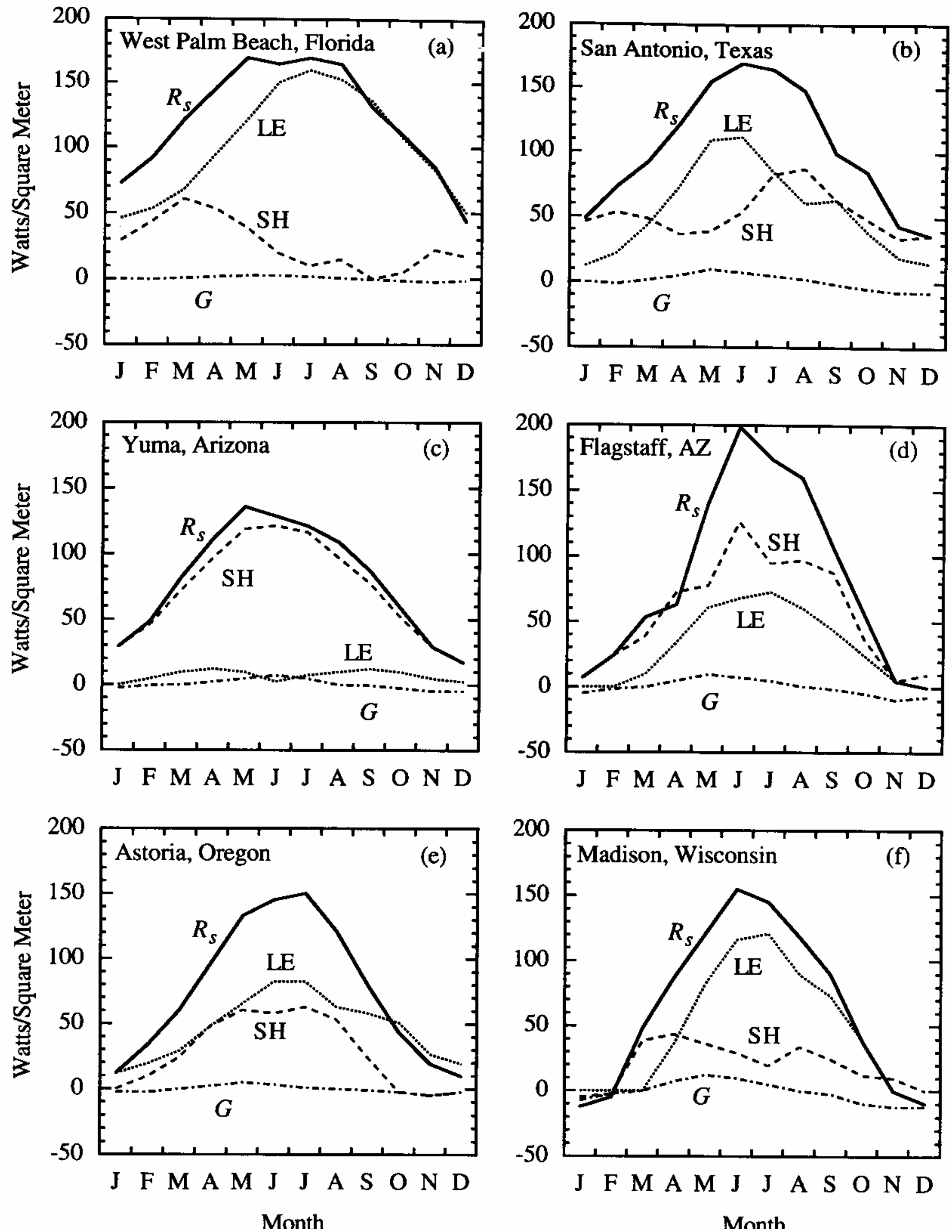


Mature corn in Wisconsin, sep 4 1952



Well-irrigated field,Wisconsin July 9 1952

Seasonal variations in surface energy balance over land – several sites in middle latitudes



Surface energy balance over oceans
Example: Gulf Stream, 38^0N, 71^0W

In winter warm water comes into contact with cold, dry air coming off the continents.
High LE is balanced mainly by release of heat stored in the water.

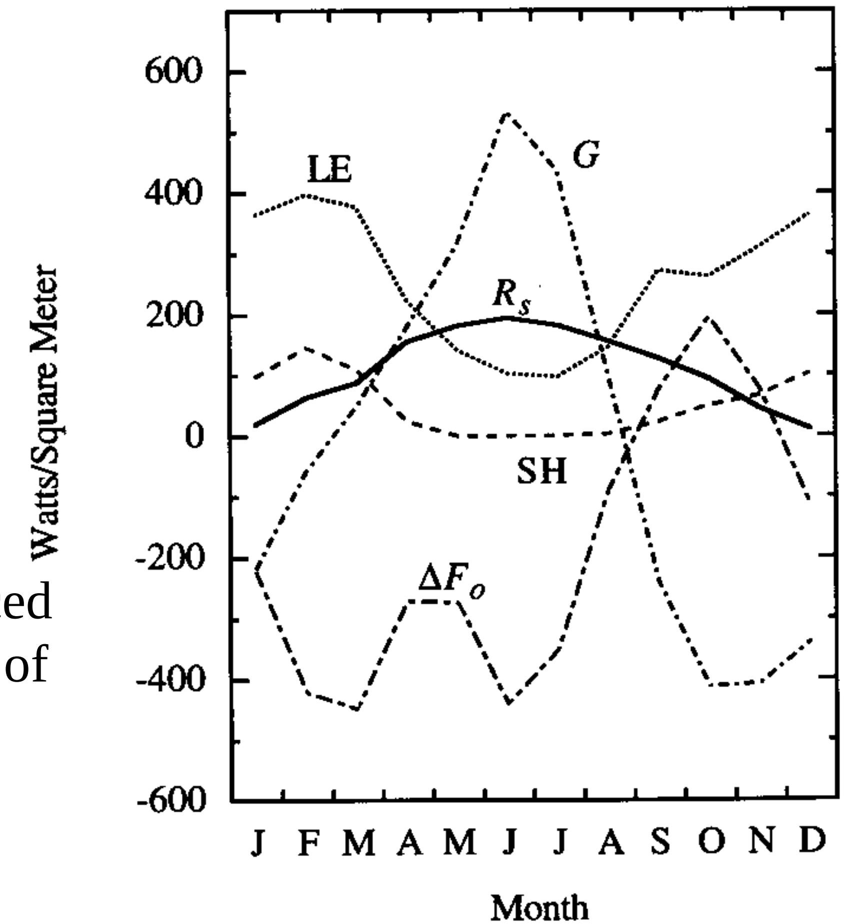
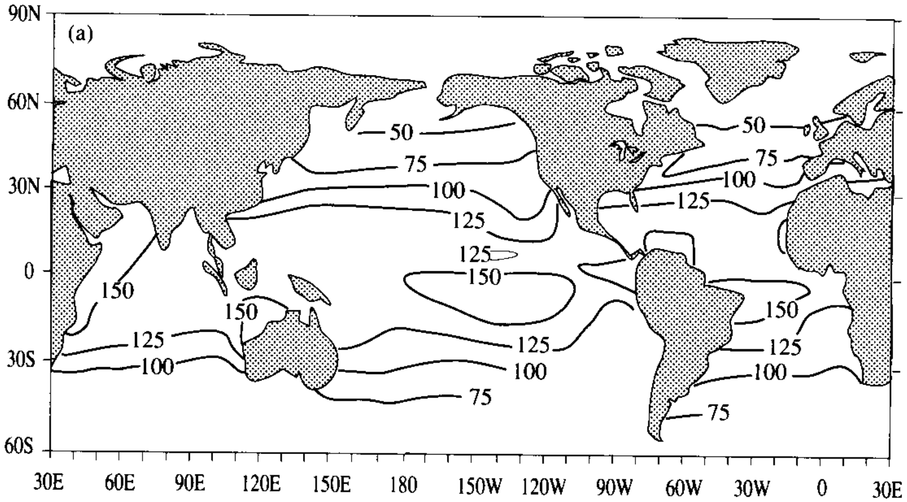


Fig. 4.17 Annual cycle of heat budget components for the Gulf Stream at 38°N, 71°W. (Adapted from Sellers, 1965. Reprinted with permission from the University of Chicago Press.)

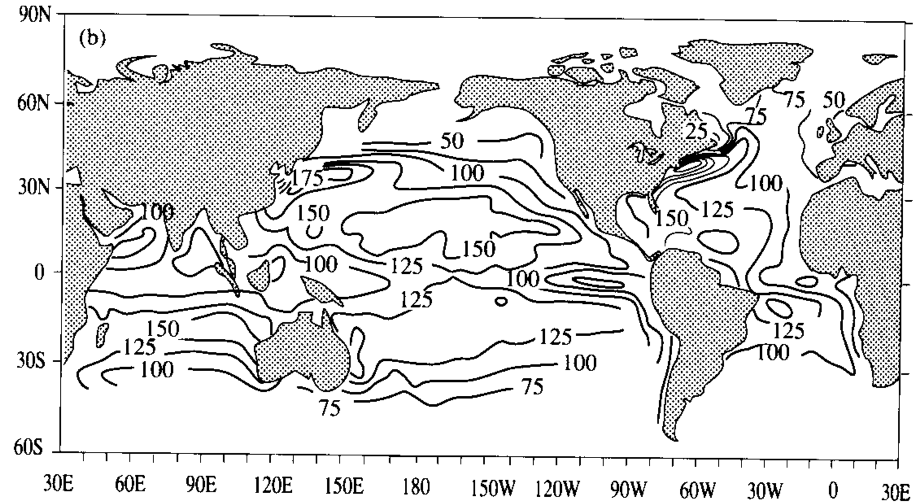
The energy for evaporation comes from the water itself (high heat capacity). LE may be less correlated with R_s than with winds, T and q contrast between the surface and the air above it.

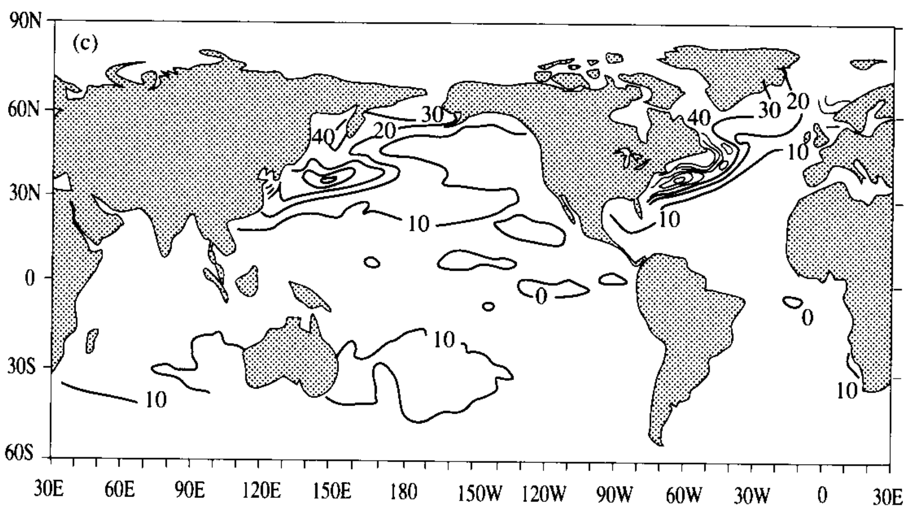
Annual means over Ocean

Net radiation

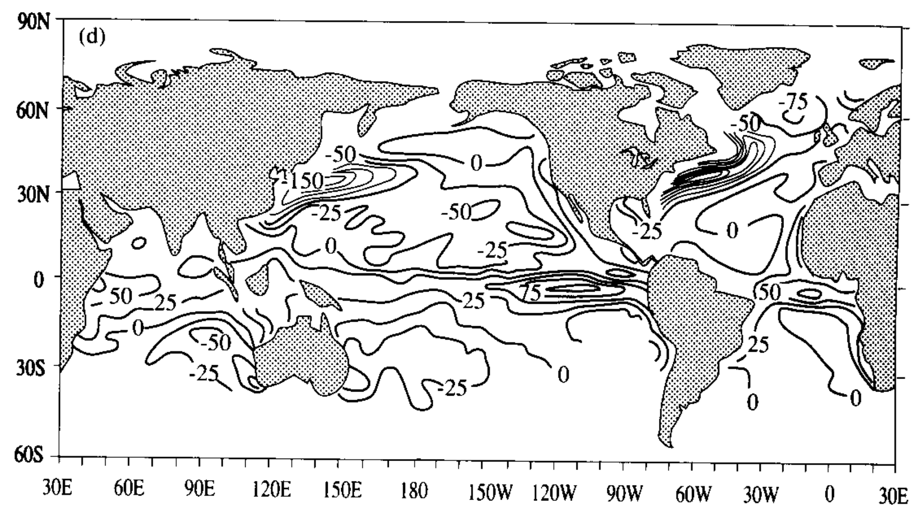


Latent



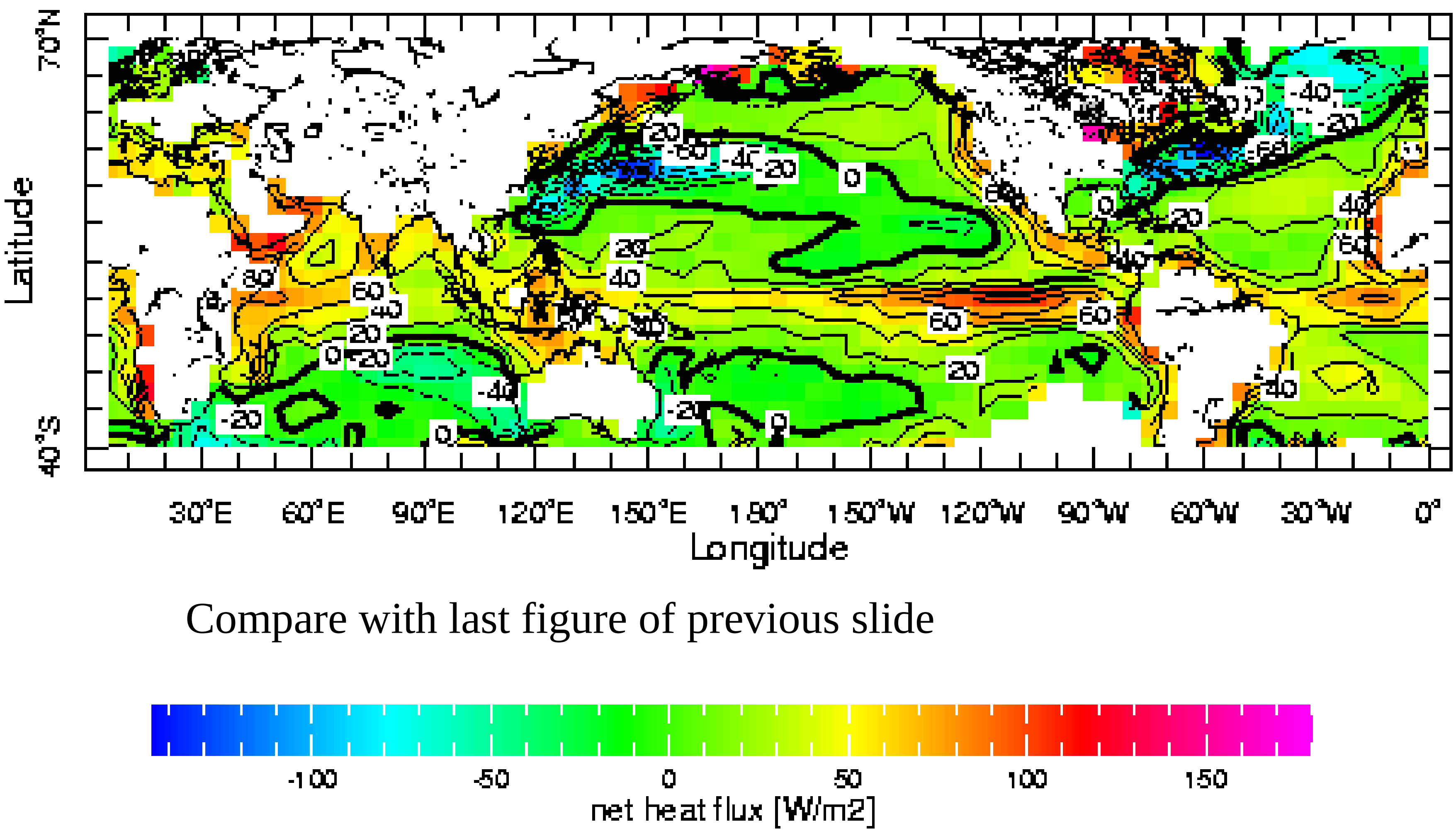


Sensible



Net downward heat into ocean

Net sfc heat flux (+ve is down) from COADS (ref: Cayan 1992)



Compare with last figure of previous slide