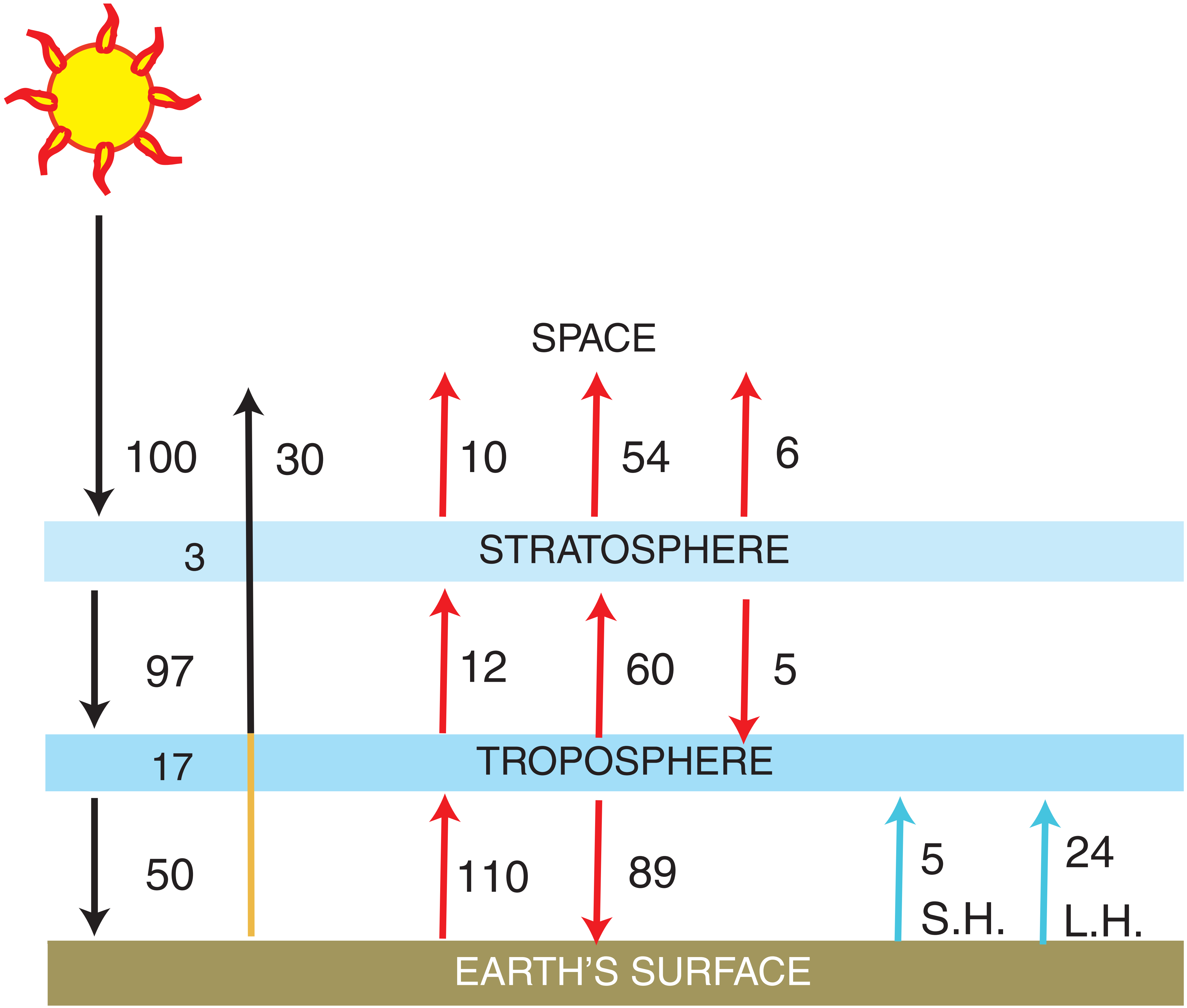
The Atmospheric Boundary Layer

- Turbulence (9.1)
- **The Surface Energy Balance (9.2)**
- Vertical Structure (9.3)
- Evolution (9.4)
- Special Effects (9.5)
- The Boundary Layer in Context (9.6)



Adapted from Dennis L. Hartmann, *Global Physical Climatology*, p. 28 (Copyright 1994), with permission from Elsevier.

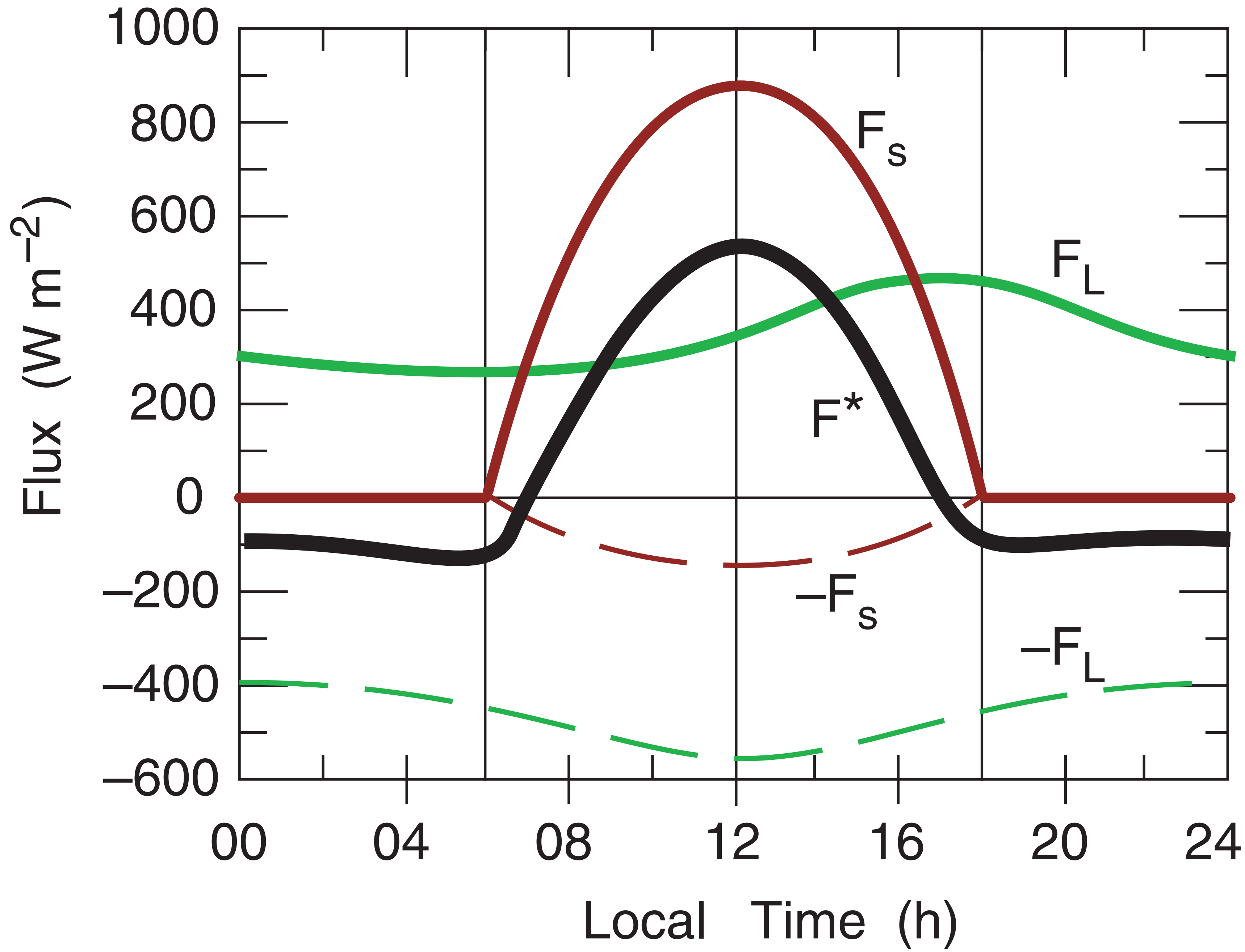
Radiative Fluxes

The *net* (downward) *radiation flux* absorbed at the surface is

$$F^* = F_S^{\downarrow} - F_S^{\uparrow} + F_L^{\downarrow} - F_L^{\uparrow}$$

where $F_S^{\downarrow}$ is the downward shortwave (solar) radiation flux at the surface, $F_S^{\uparrow}$ is the upward (reflected) shortwave radiation flux at the surface, $F_L^{\downarrow}$ is the downward longwave radiation flux at the surface, and $F_L^{\uparrow}$ is the upward (emitted and reflected) longwave radiation flux at the surface.

Radiative fluxes at the surface under clear skies



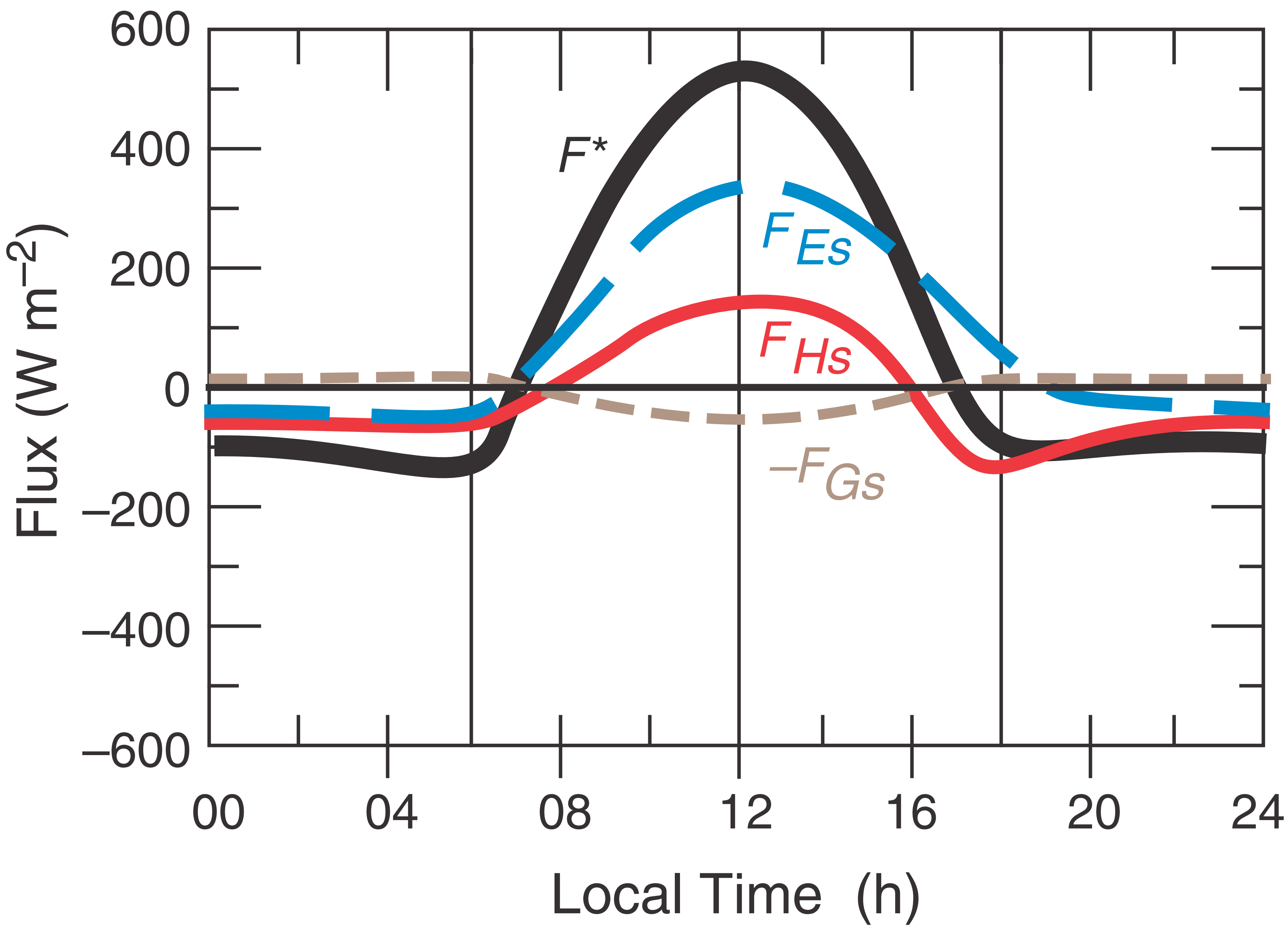
Surface Energy Balance over Land

The surface energy (flux) balance over land is

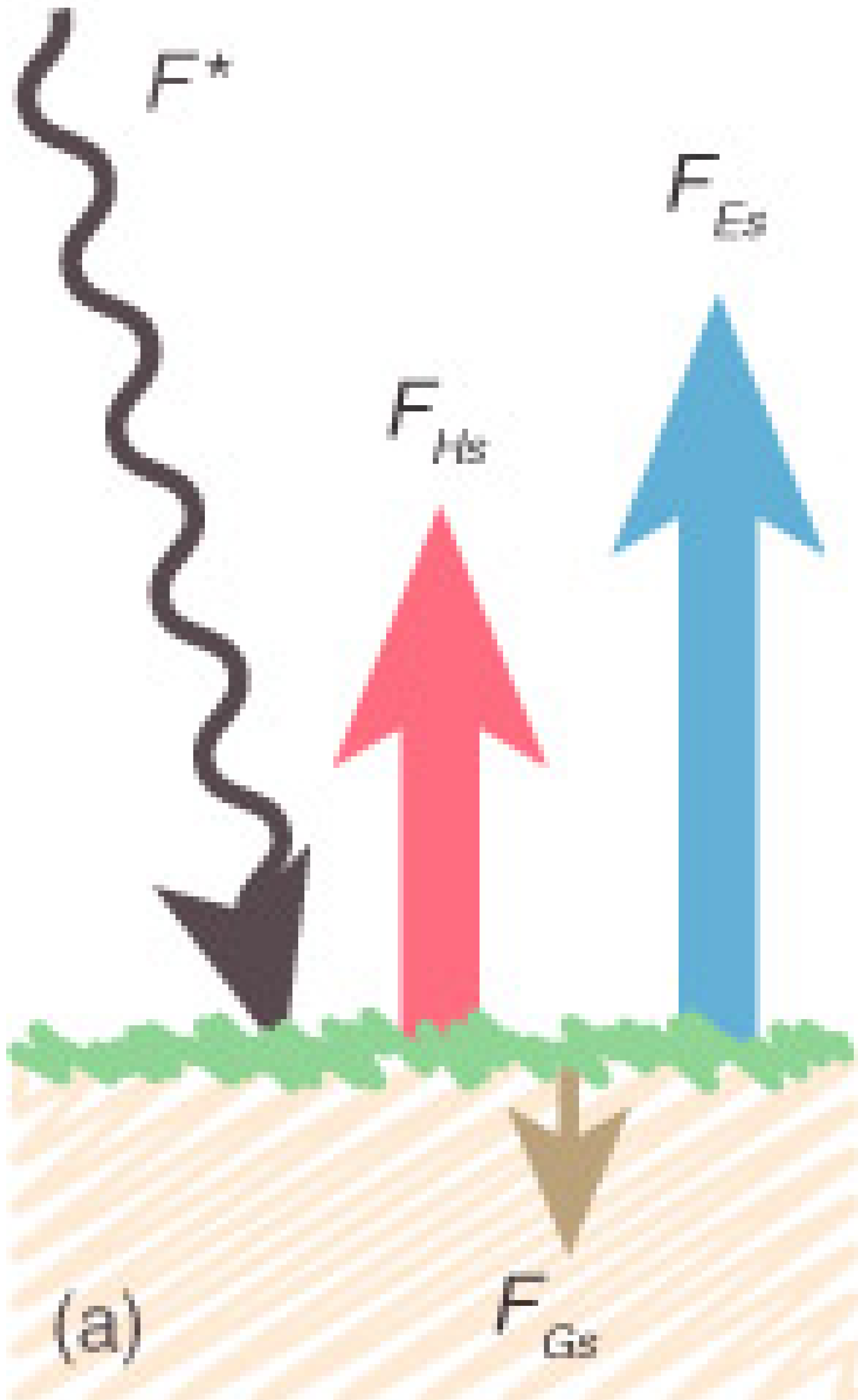
$$F^* = F_{Hs} + F_{Es} + F_{Gs}$$

where F_{Hs} is the (turbulent) *sensible heat flux* (positive upward, away from the surface), F_{Es} is the (turbulent) *latent heat flux* (positive upward), F_{Gs} is the (conductive) *ground heat flux* (positive downward, away from the surface), and the subscript s denotes surface.

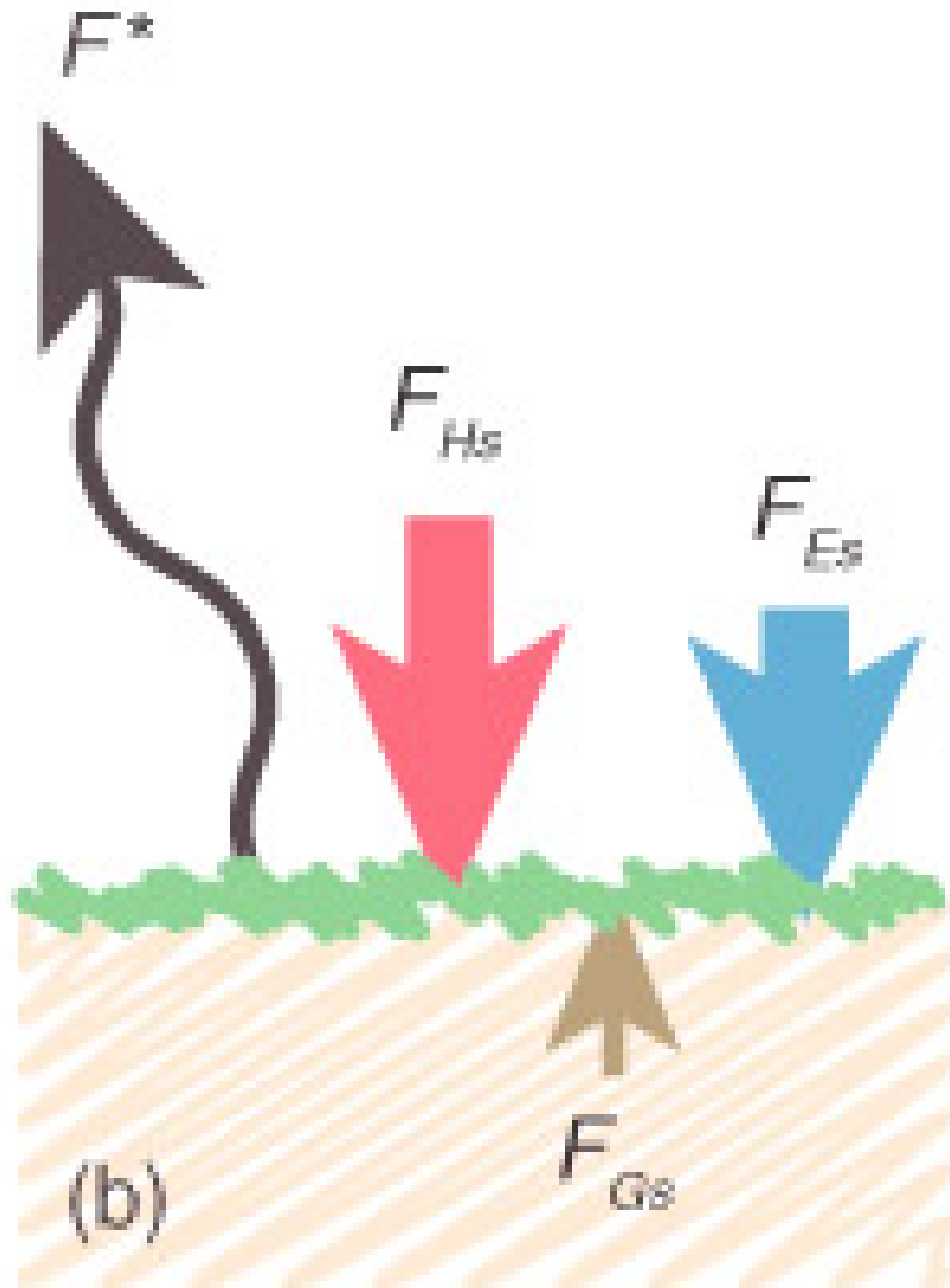
Turbulent and conductive fluxes at the surface under clear skies



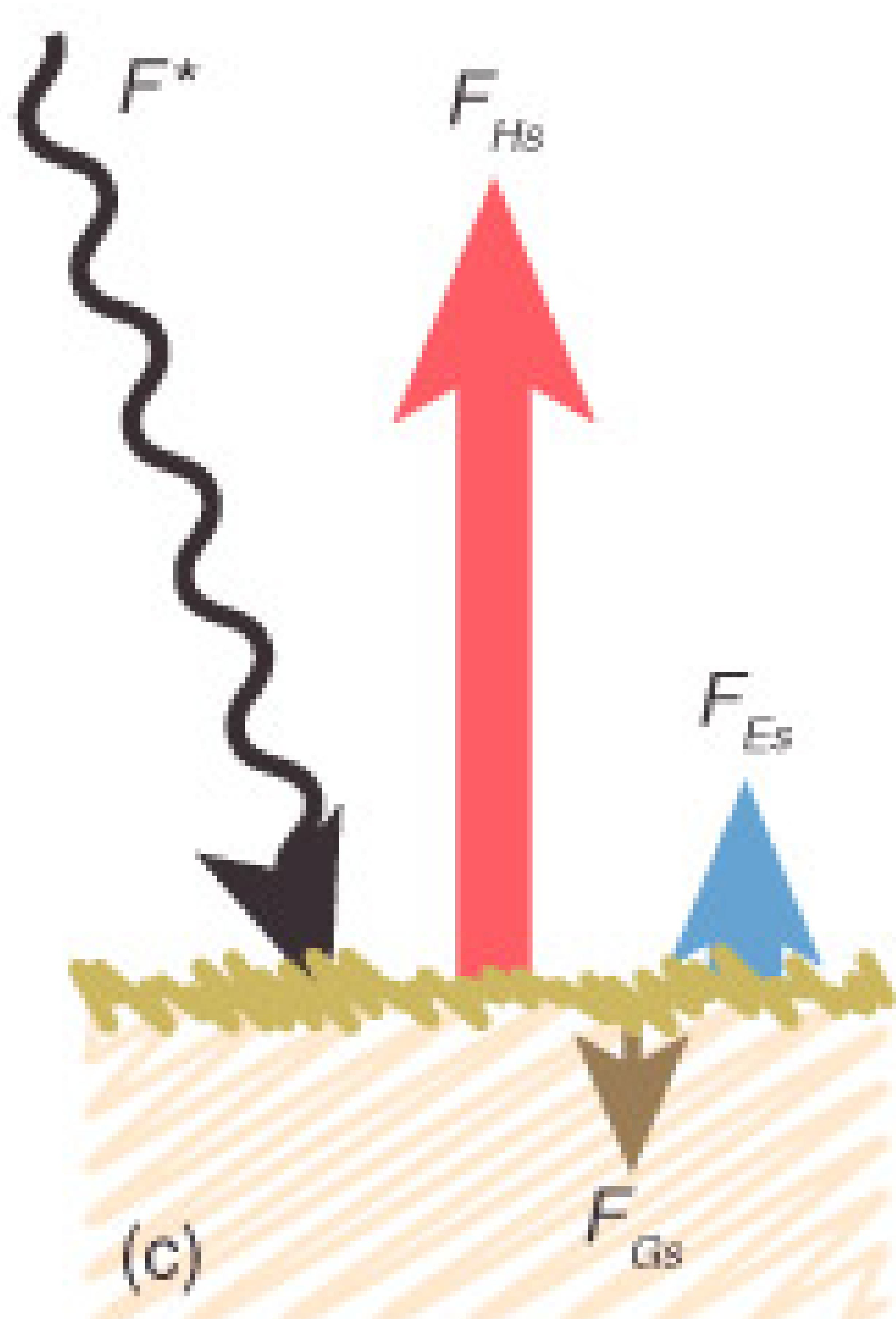
Daytime over moist vegetation



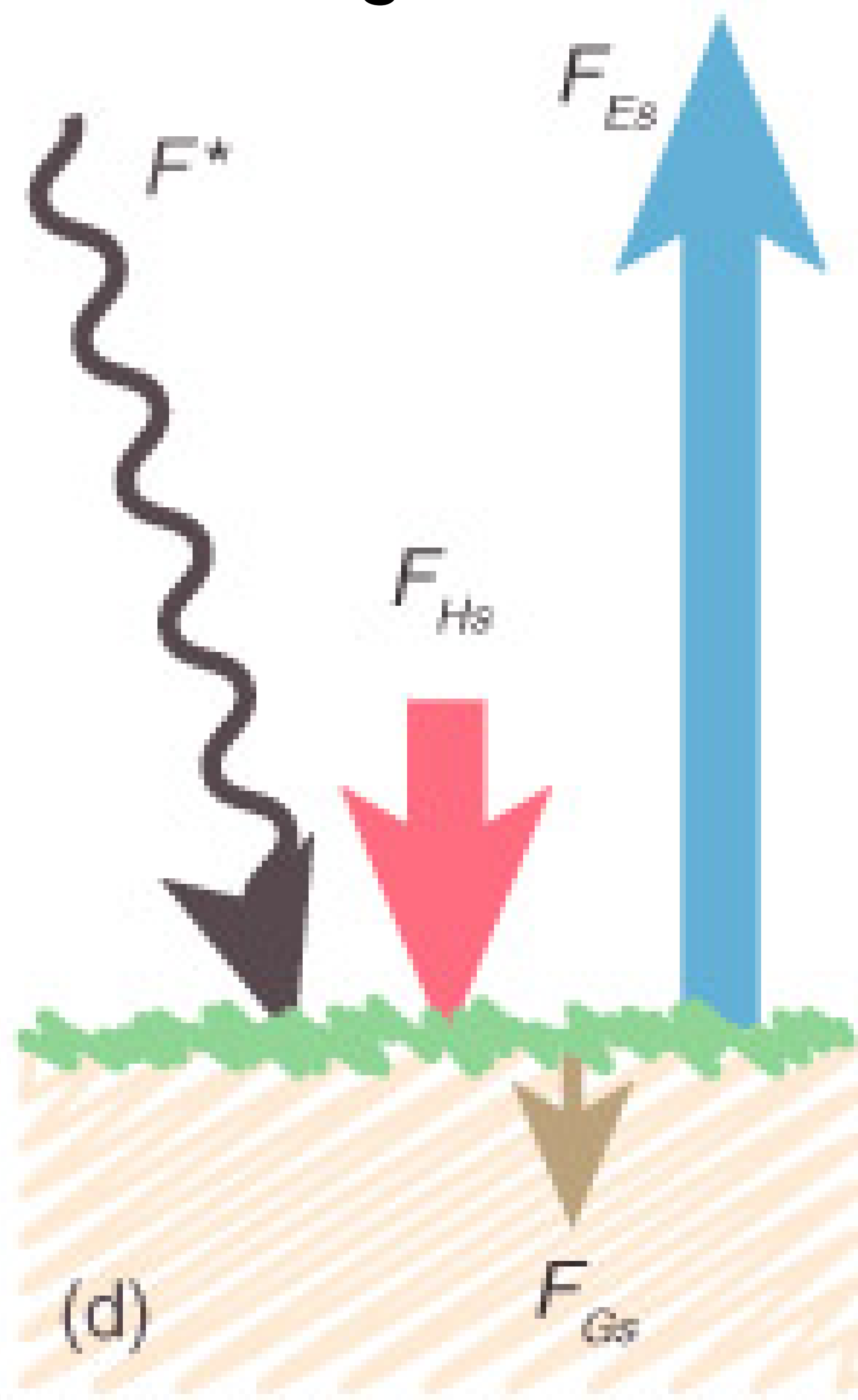
Nighttime over moist vegetation



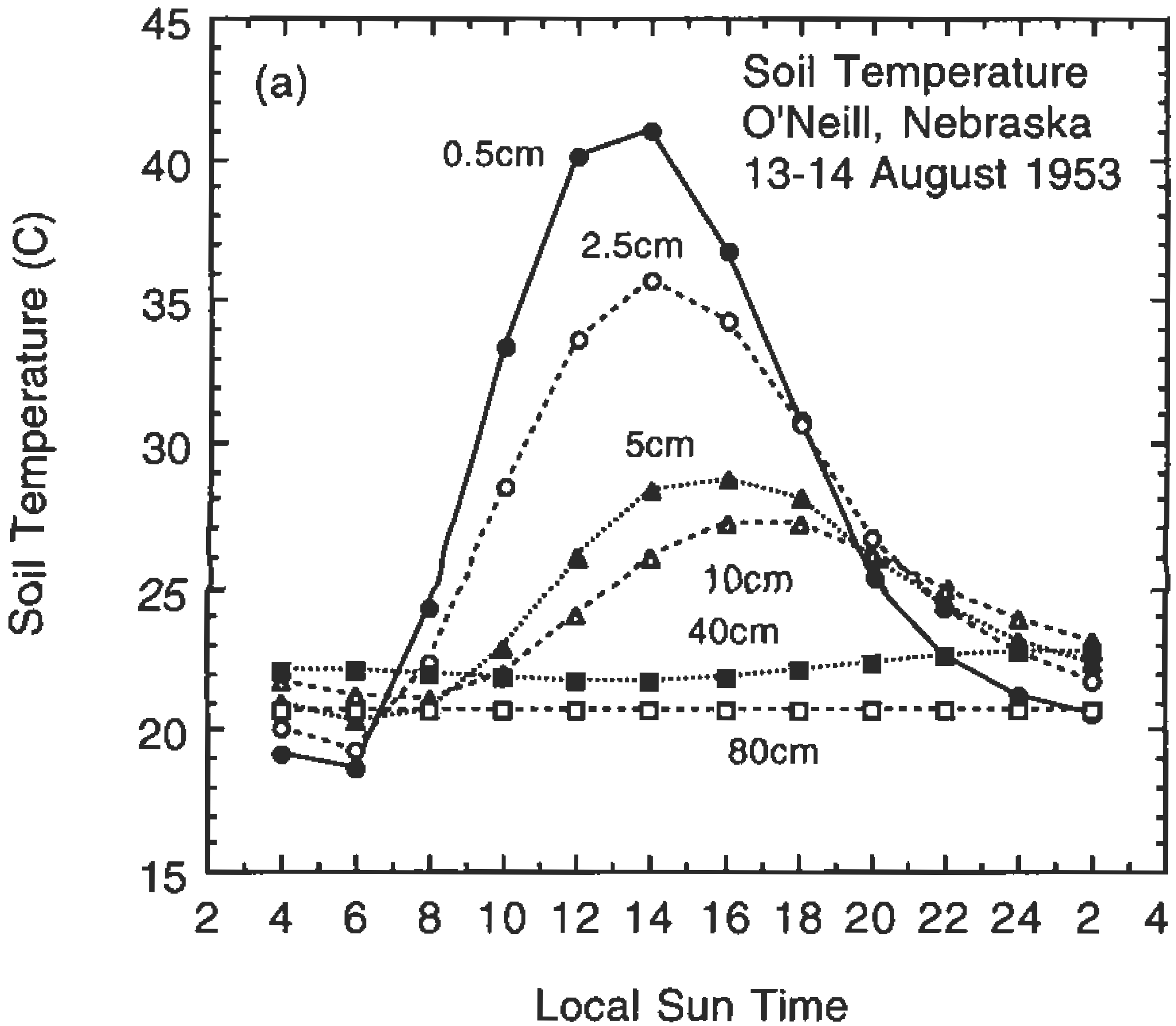
Daytime over a dry desert

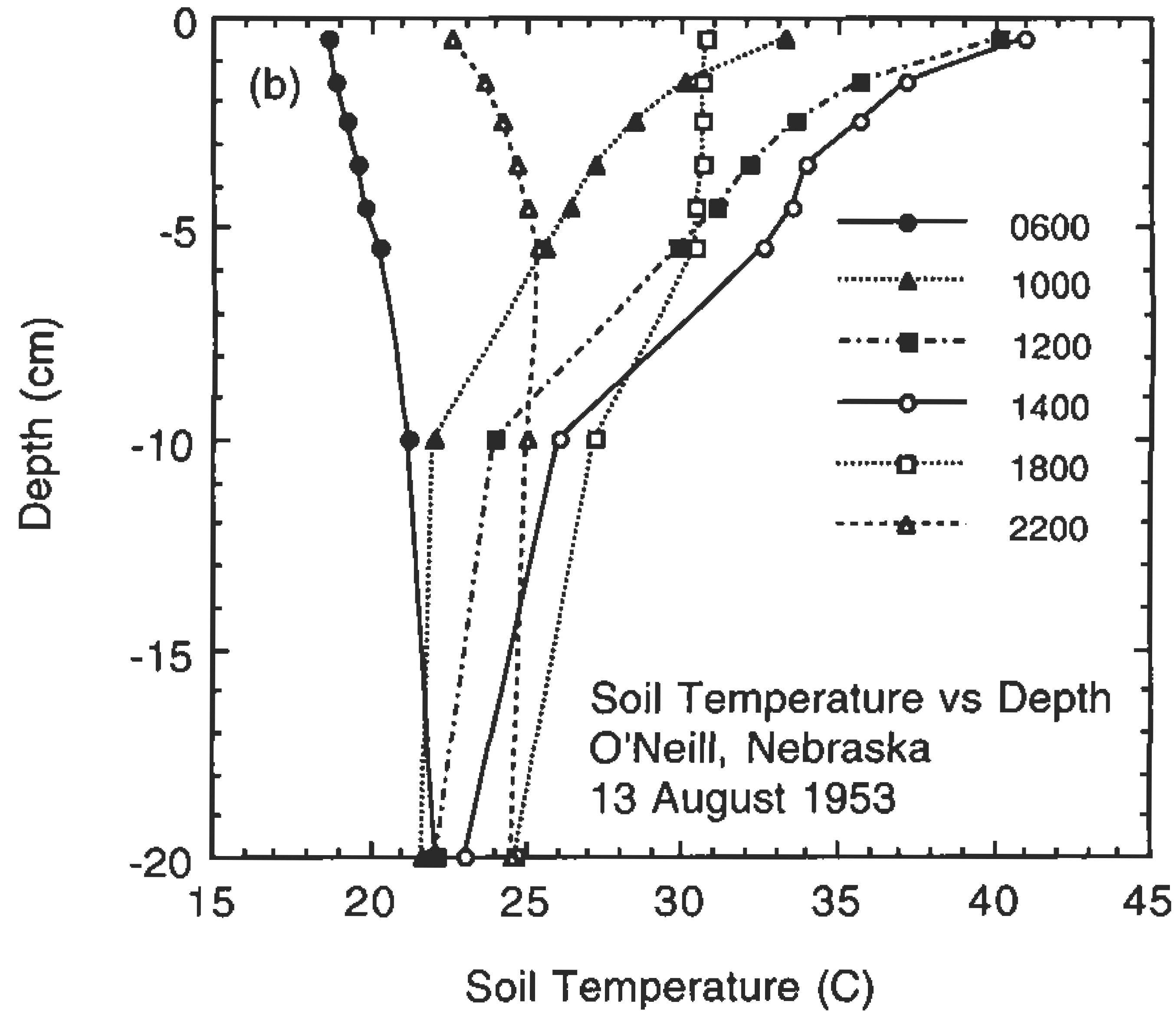


Oasis effect during daytime: hot dry wind blowing over moist vegetation



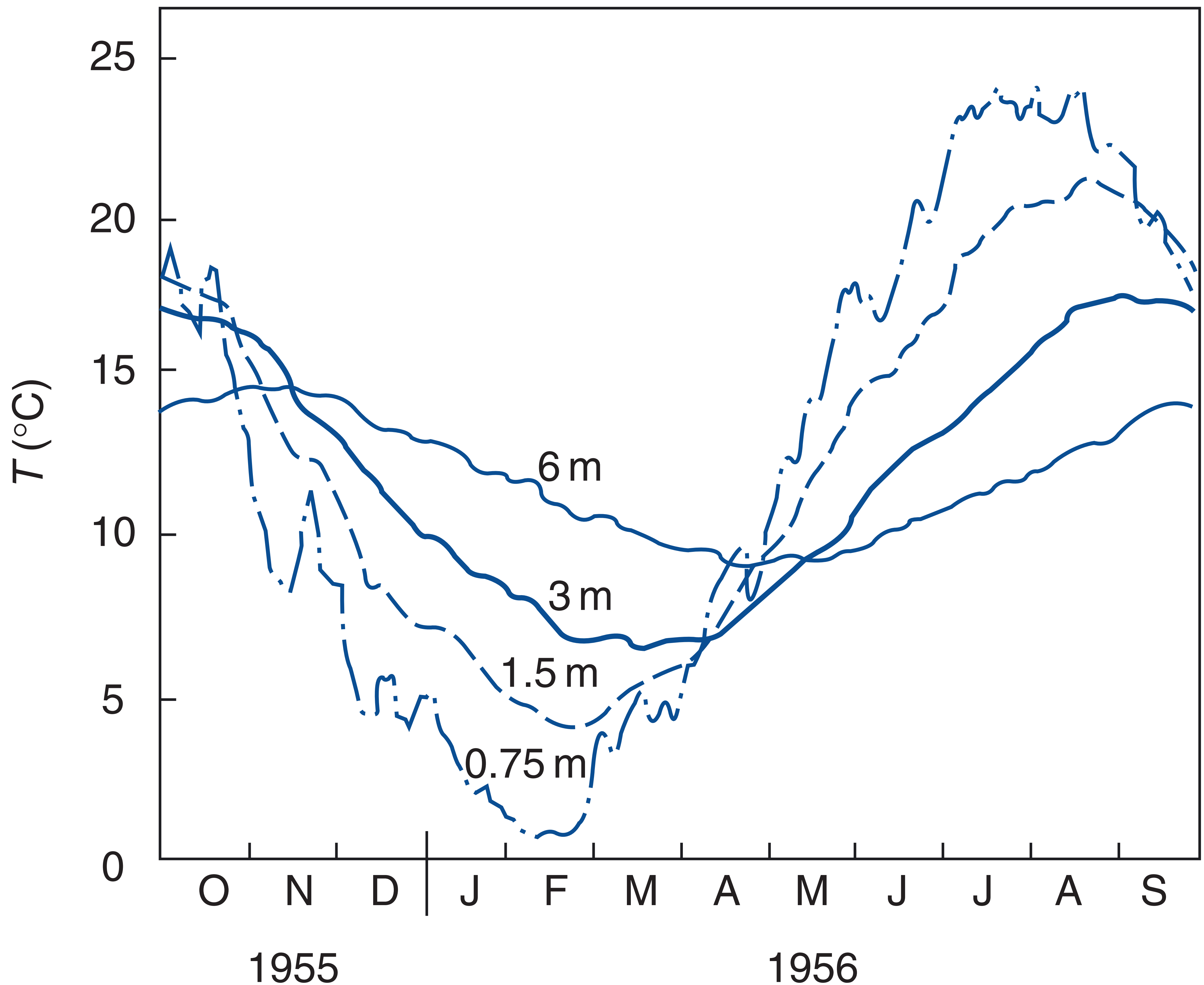
Soil tempeature at various depths under a grass field





How is the diurnal cycle of the surface skin temperature related to the conductivity of the soil?

Soil temperature at 4 levels below the surface



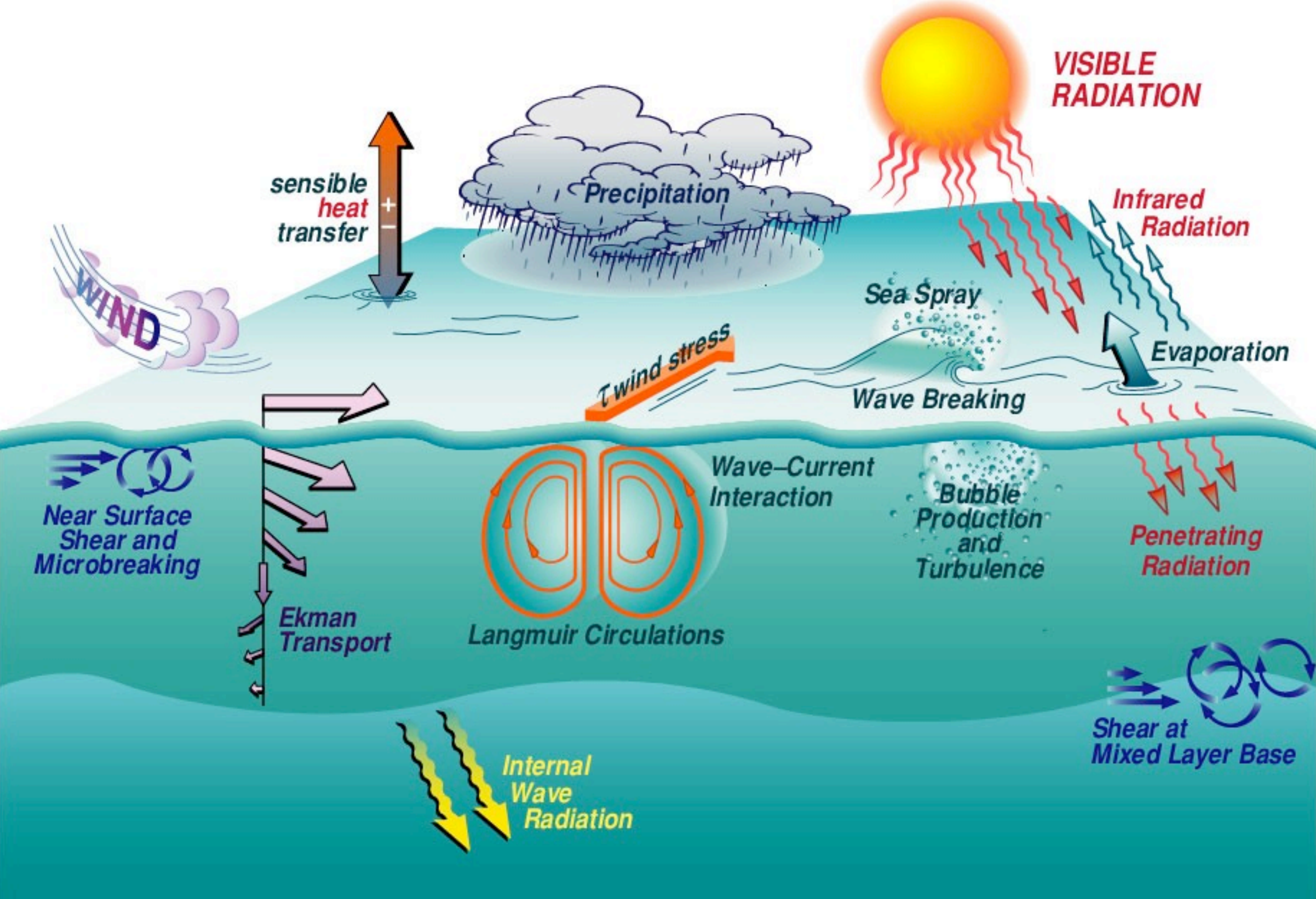
Soil Temperature

- *Conduction* is down the gradient of temperature.

- The *annual* cycle penetrates to greater depth than the *diurnal* cycle.

- *Amplitude* decreases with increasing depth (for a given forcing frequency).

- *Phase* delay increases with increasing depth (for a given forcing frequency).


VISIBLE RADIATION
sensible heat transfer
+
−
Precipitation
Infrared Radiation
WIND
Sea Spray
τ wind stress
Evaporation
Wave Breaking
Wave–Current Interaction
Near Surface Shear and Microbreaking
Bubble Production and Turbulence
Penetrating Radiation
Ekman Transport
Langmuir Circulations
Shear at Mixed Layer Base
Internal Wave Radiation

Surface Energy Balance of Ocean Surfaces

- Does it make sense to say that F_{Gs} for ocean surfaces is much larger than for land?
- Solar radiation is more readily absorbed by the ocean for two reasons. What are they?
- Turbulence quickly mixes heat through the *ocean mixed layer.*
- The specific heat of water is larger than that of soil.
- As a result, the diurnal cycle of ocean surface temperature is almost negligible.

Table 4.1

Properties of Soil Components at 293 K

	Specific heat (c_p) ($\mathrm{J\ kg^{-1}\ K^{-1}}$)	Density (ρ) ($\mathrm{kg\ m^{-3}}$)	$\rho\, c_p$ ($\mathrm{J\ m^{-3}\ K^{-1}}$)
Soil inorganic material	733	2600	1.9×10^6
Soil organic material	1921	1300	2.5×10^6
Water	4182	1000	4.2×10^6
Air	1004	1.2	1.2×10^3

[After Brutsaert (1982). Reprinted with permission from Kluwer Academic Publishers.]

Bulk Aerodynamic Formulae

- The *bulk aerodynamic method* can be used to estimate the surface sensible and latent heat fluxes, as well as frictional drag on surface winds.

- In kinematic units (K m s^{-1})

$$F_{Hs} = C_H |\mathbf{V}| (T_s - T_{air})$$

where C_H is a dimensionless *bulk transfer coefficient* for sensible heat, $|\mathbf{V}|$ is the wind speed and T_{air} is the air temperature at standard measurement heights (such as 10 m and 2 m), and T_s is the ocean surface temperature.

Bulk Aerodynamic Formulae

- The formula for F_{HS} does not involve a (vertical) turbulent velocity scale. Why not?

- What determines the surface skin temperature T_s over land during a sunny day?

- What happens to T_s at night when the ground surface is cooled by longwave radiation?

Bulk Aerodynamic Formulae

- *Statically neutral conditions over flat land:* $C_H = C_{HN}$ is 0.001 to 0.005 and depends on surface roughness similar to C_{DN} (Table 9.2).

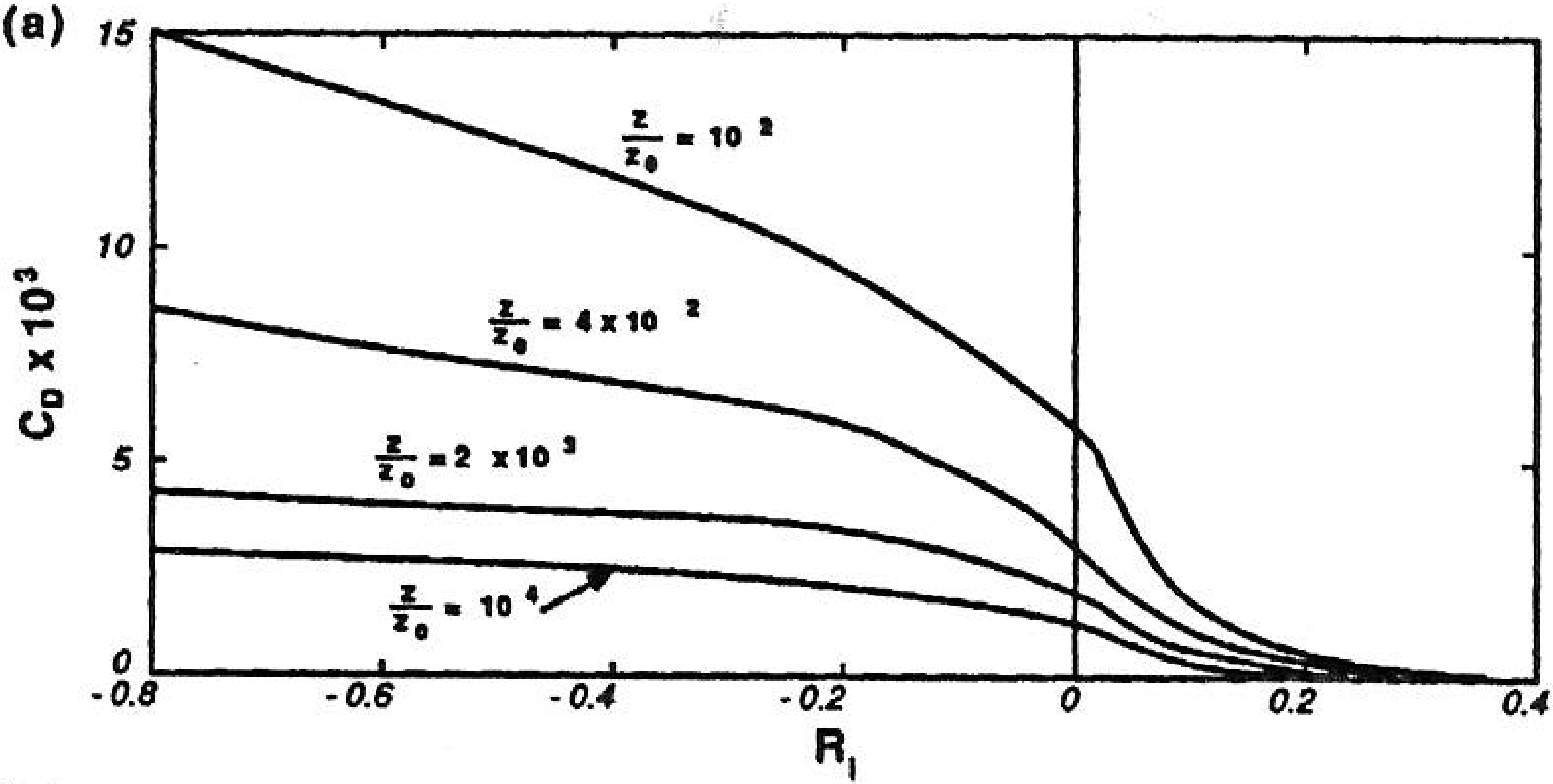
- *Statically unstable conditions over flat land:* C_H is 2 to 3 times larger than C_{HN}.

- *Statically stable conditions over flat land:* C_H decreases towards 0.

Table 9.2 The Davenport classification, where z_o is aerodynamic roughness length and C_{DN} is the corresponding drag coefficient for neutral static stability[a]

z_0 (m)	Classification	Landscape	C_{DN}
0.0002	Sea	Calm sea, paved areas, snow-covered flat plain, tide flat, smooth desert.	0.0014
0.005	Smooth	Beaches, pack ice, morass, snow-covered fields.	0.0028
0.03	Open	Grass prairie or farm fields, tundra, airports, heather.	0.0047
0.1	Roughly open	Cultivated area with low crops and occasional obstacles (single bushes).	0.0075
0.25	Rough	High crops, crops of varied height, scattered obstacles such as trees or hedgerows, vineyards.	0.012
0.5	Very rough	Mixed farm fields and forest clumps, orchards, scattered buildings.	0.018
1.0	Closed	Regular coverage with large size obstacles with open spaces roughly equal to obstacle heights, suburban houses, villages, mature forests.	0.030
≥2	Chaotic	Centers of large towns and cities, irregular forests with scattered clearings.	0.062

[a] From Preprints *12th Amer. Meteorol. Soc. Symposium on Applied Climatology*, 2000, pp. 96–99.


(a)
15
10
5
0
$C_D \times 10^3$
$\frac{z}{z_0} = 10^2$
$\frac{z}{z_0} = 4 \times 10^2$
$\frac{z}{z_0} = 2 \times 10^3$
$\frac{z}{z_0} = 10^4$
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
R_i

PART 2

Bulk Aerodynamic Formulae

- *Bulk aerodynamic relationships* exist for water vapor fluxes over water and saturated soil.
- Assume that the surface water vapor mixing ratio = saturation mixing ratio.
- In kinematic units (kg kg^{-1} m s^{-1})

$$F_{water} = C_E|\mathbf{V}|(q_{sat}(T_s, p_s) - q_{air})$$

where C_E is a dimensionless *bulk transfer coefficient* for water vapor ($C_E \approx C_H$), $|\mathbf{V}|$ is the wind speed and q_{air} is the mixing ratio at standard measurement heights (such as 10 m and 2 m), T_s is the ocean surface temperature, and p_s is the surface pressure.

Bulk Aerodynamic Formulae

F_{water} is related to the latent heat flux $F_{E\,s}$ in kinematic units (K m s^{-1}):

$$F_{E\,s} = \frac{L_v}{c_p} F_{water}$$

and to the evaporation rate of water (mm/s):

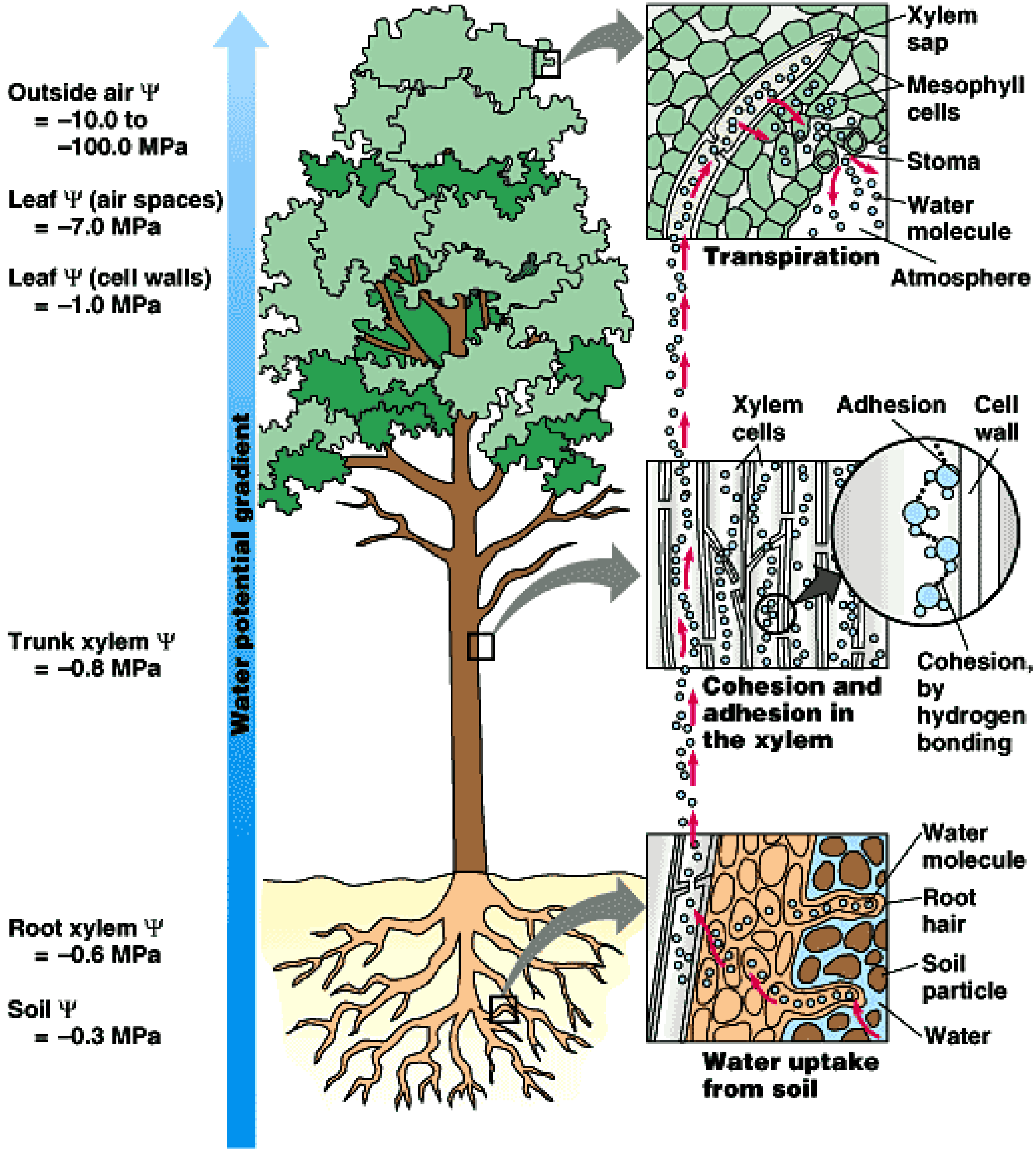
$$E = \frac{\rho_{liq}}{\rho_{air}} F_{water}$$

Bulk Aerodynamic Formulae

The ratio of sensible to latent heat fluxes at the surface is the *Bowen ratio:*

$$B = F_{H\,s}/F_{E\,s}$$

- Over the oceans B decreases as T_s increases from about 1 in the polar regions to 0.1 in the Tropics.
- Over land the evaporation rate depends on soil moisture and *transpiration*.
  - Irrigated crops: $B \sim 0.2$
  - Grassland: $B \sim 0.5$
  - Semiarid regions: $B \sim 5$
  - Deserts: $B \sim 10$



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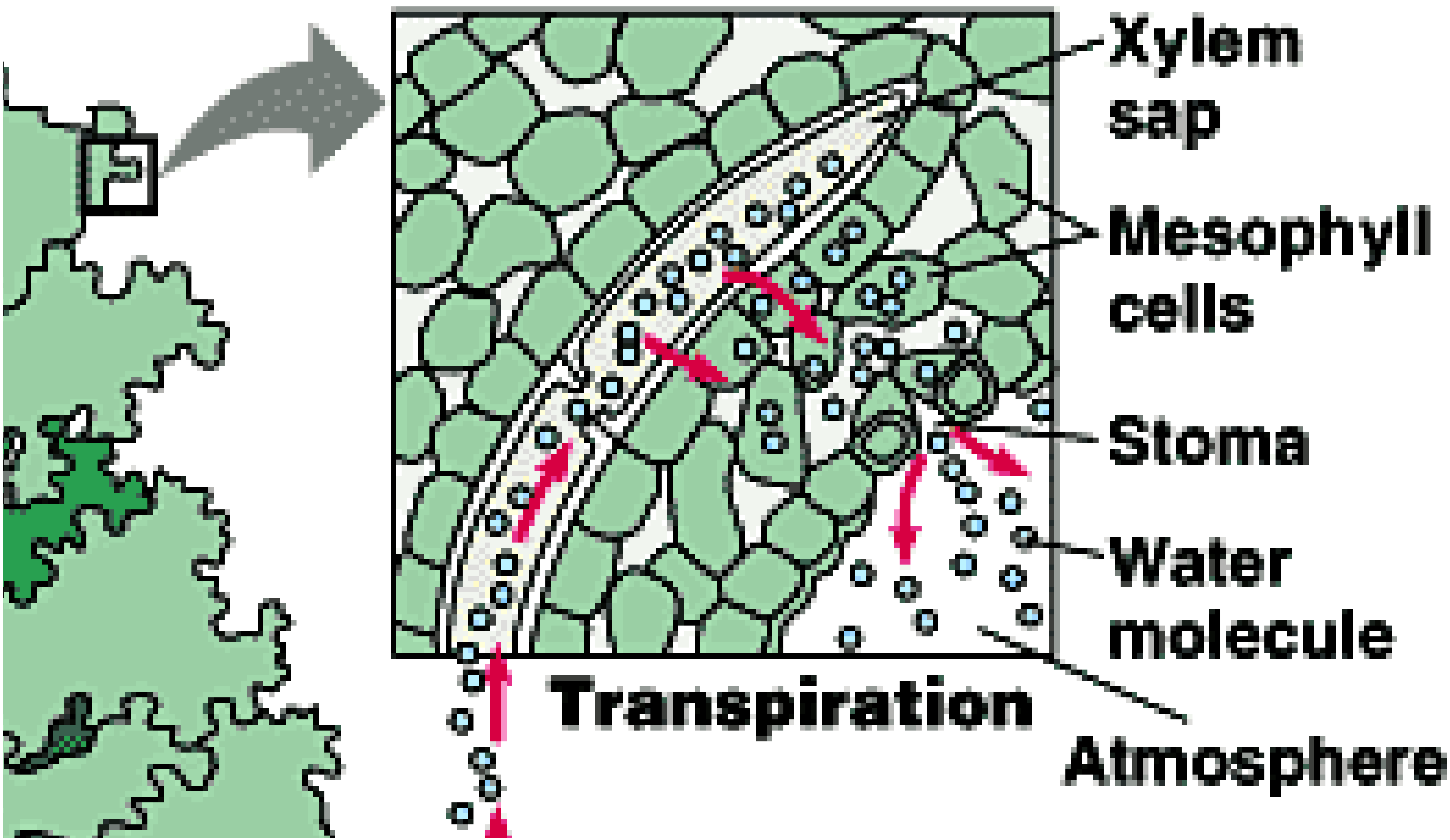
Xylem sap
Mesophyll cells
Stoma
Water molecule
Transpiration
Atmosphere

Bulk Aerodynamic Formulae

- The *bulk aerodynamic method* for momentum gives a *drag law:*

$$u_*^2 = C_D |\mathbf{V}|^2$$

where C_D is a dimensionless *drag coefficient*, $|\mathbf{V}|$ is the wind speed at 10 m, and u_*^2 is the magnitude of the downward momentum flux at the surface.

C_D varies from 10^{-3} over smooth surfaces to 2×10^{-2} over rough ones (Table 9.2).

C_D also varies with stability like C_H does.

Bulk Aerodynamic Formulae

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C_D varies from 10^{-3} over smooth surfaces to 2×10^{-2} over rough ones (Table 9.2).

From HW on turbulent fluxes:

4. The friction velocity $u_* = 0.3$ m s^{-1}.
   (a) What is the magnitude of the surface stress? Use $\rho = 1.2$ kg m^{-3}.
   (b) If $h = 500$ m, how much would the average ABL wind velocity change over 24 h due to the surface stress alone? Assume that the wind velocity and surface stress vectors are parallel. *Decreases ~15 m/s over 24 hours.*
   (c) What additional forces act to maintain the ABL wind?

Table 9.2 The Davenport classification, where z_o is aerodynamic roughness length and C_{DN} is the corresponding drag coefficient for neutral static stability[a]

z_0 (m)	Classification	Landscape	C_{DN}
0.0002	Sea	Calm sea, paved areas, snow-covered flat plain, tide flat, smooth desert.	0.0014
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C_D varies from 10^{-3} over smooth surfaces to 2×10^{-2} over rough ones (Table 9.2).

Example:
Surface wind speed = 10 m/s.
Surface classification: Open.
$z_0 = 0.03$ m, $C_{DN} = 0.0047$.
$u_*^2 = C_D |\mathbf{V}|^2 = 0.0047 \times 10^2 \text{ m}^2/\text{s}^2 = 0.47 \text{ m}^2/\text{s}^2$.
$u_* = 0.7$ m/s.

Bulk Aerodynamic Formulae

- The *bulk aerodynamic method* for momentum gives a *drag law:*

$$u_*^2 = C_D|\mathbf{V}|^2$$

where C_D is a dimensionless *drag coefficient*, $|\mathbf{V}|$ is the wind speed at 10 m, and u_*^2 is the magnitude of the downward momentum flux at the surface.

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Example:
Surface wind speed = 10 m/s.
Surface classification: Open.
$C_{DN} = 0.0047$.
$u_*^2 = C_D|\mathbf{V}|^2 = 0.0047 \times 10^2 \text{ m}^2/\text{s}^2 = 0.47 \text{ m}^2/\text{s}^2$.
$u_* = 0.7$ m/s.

How does one determine C_D?

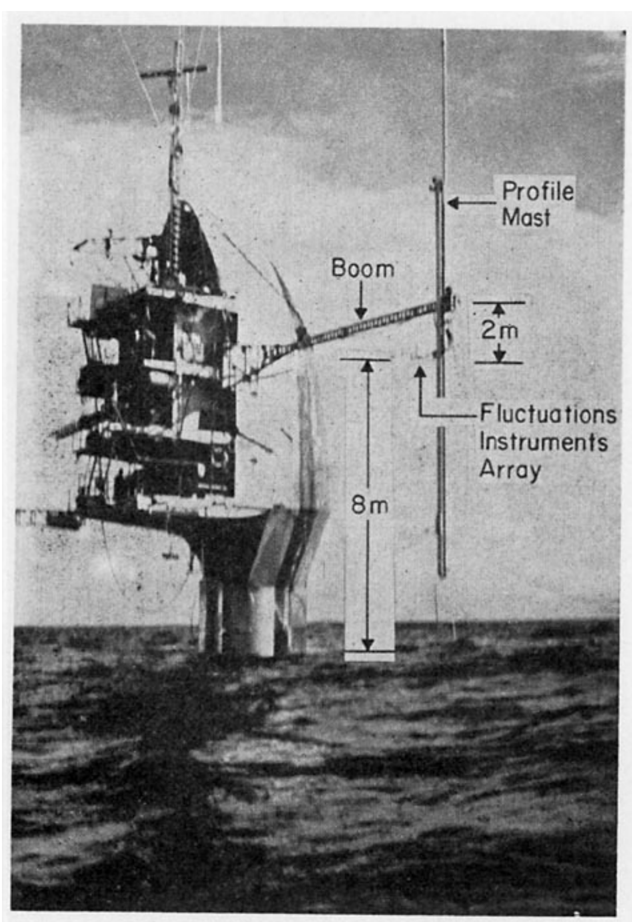
Measurements of the Turbulent Fluxes of Momentum, Moisture and Sensible Heat over the Ocean

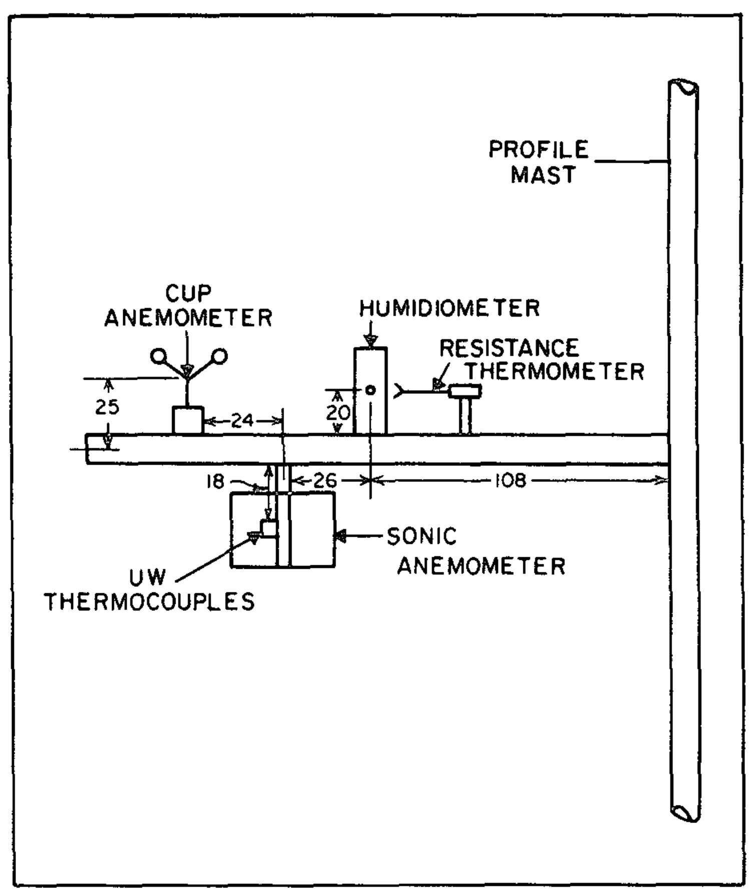
S. POND,[1] G. T. PHELPS AND J. E. PAQUIN

Dept. of Oceanography, Oregon State University, Corvallis

AND G. MCBEAN AND R. W. STEWART

Institute of Oceanography, University of British Columbia, Vancouver, Canada



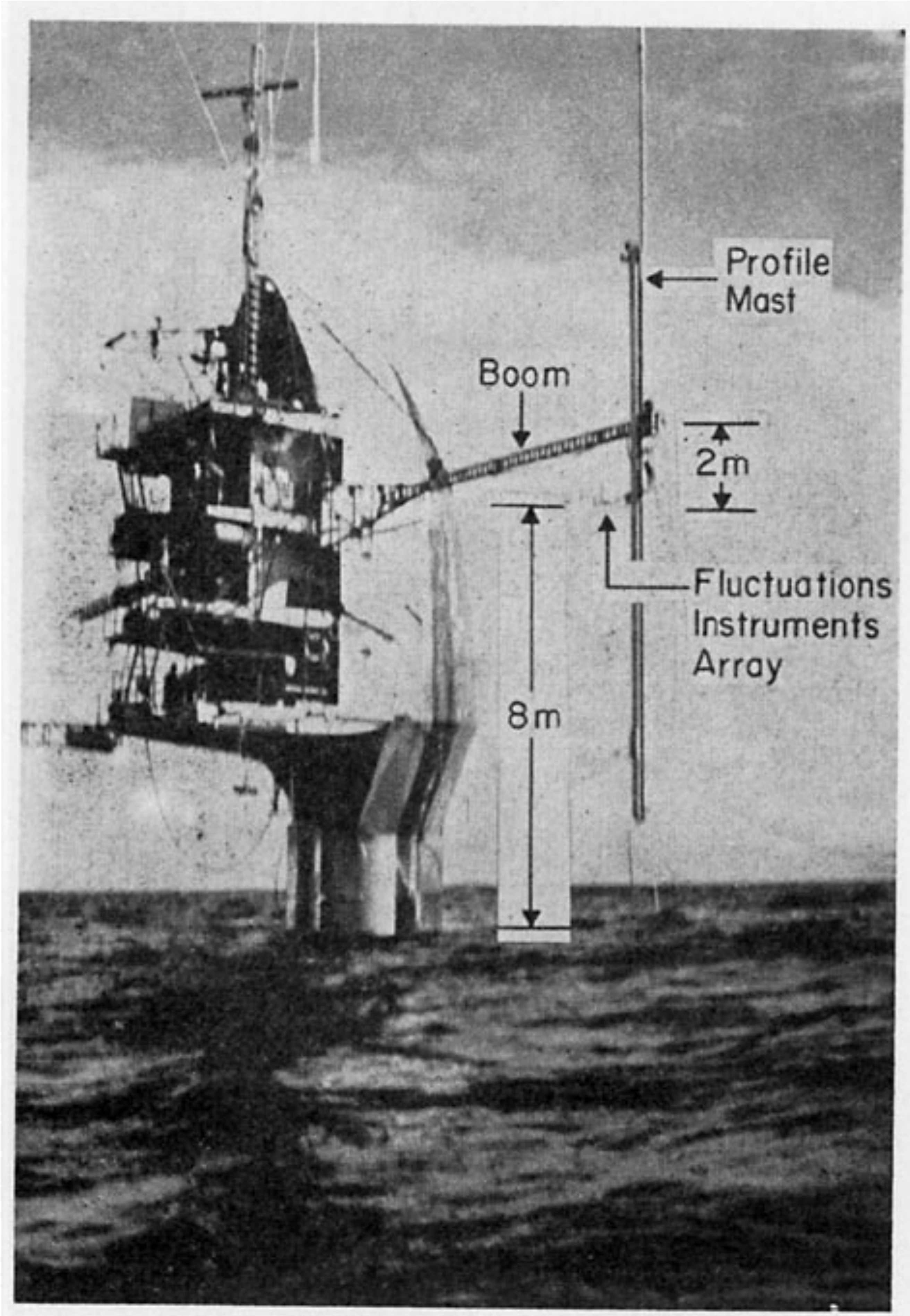


c. *Aerodynamic methods*

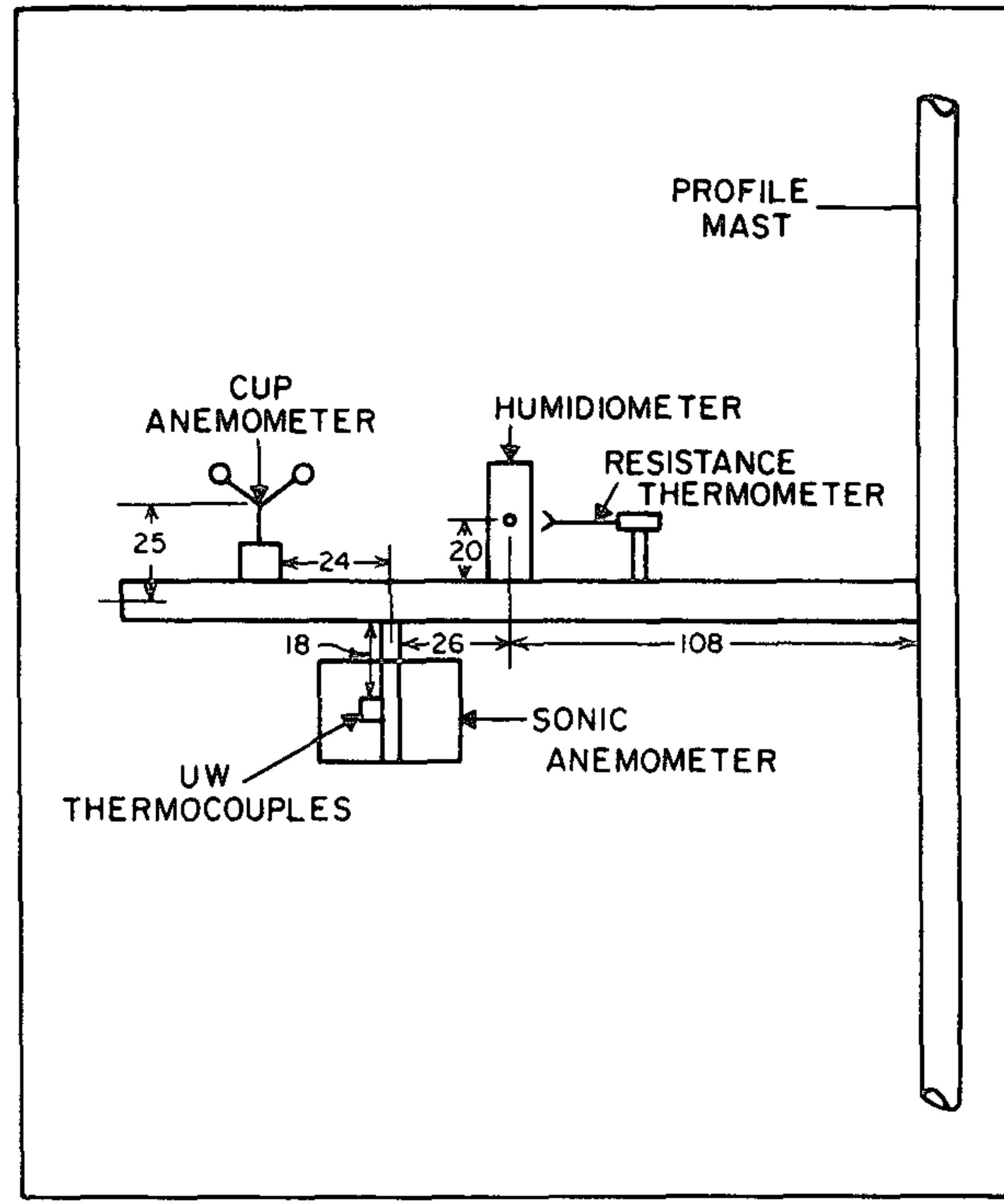
From a practical point of view it is more useful if one can relate these fluxes to more standard observations such as mean wind speed and sea-air temperature and humidity differences, i.e.,

$$\left.\begin{aligned} \tau/\rho &= -\overline{uw} = C_D U^2 \\ H_s/(\rho C_p) &= \overline{wT} = C_T U \Delta T \\ H_L/L = E &= \overline{wq} = C_q U \Delta q \end{aligned}\right\}, \qquad (14)$$

where ΔT is the difference between sea surface temperature and the air temperature at a reference height and Δq the corresponding mean moisture difference. Roll (1965) discusses the derivation of these equations and suggests that $C_D \approx C_T \approx C_q$ for conditions not too far from neutral.



R/V Flip (Floating Instrument Platform)



https://www.youtube.com/watch?v=azZIcoPI_CU *c. Aerodynamic methods*

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where ΔT is the difference between sea surface temperature and the air temperature at a reference height and Δq the corresponding mean moisture difference. Roll (1965) discusses the derivation of these equations and suggests that $C_D \approx C_T \approx C_q$ for conditions not too far from neutral.

$$u_*^2 \equiv \tau/\rho = -\overline{u'w'} = C_D U^2$$

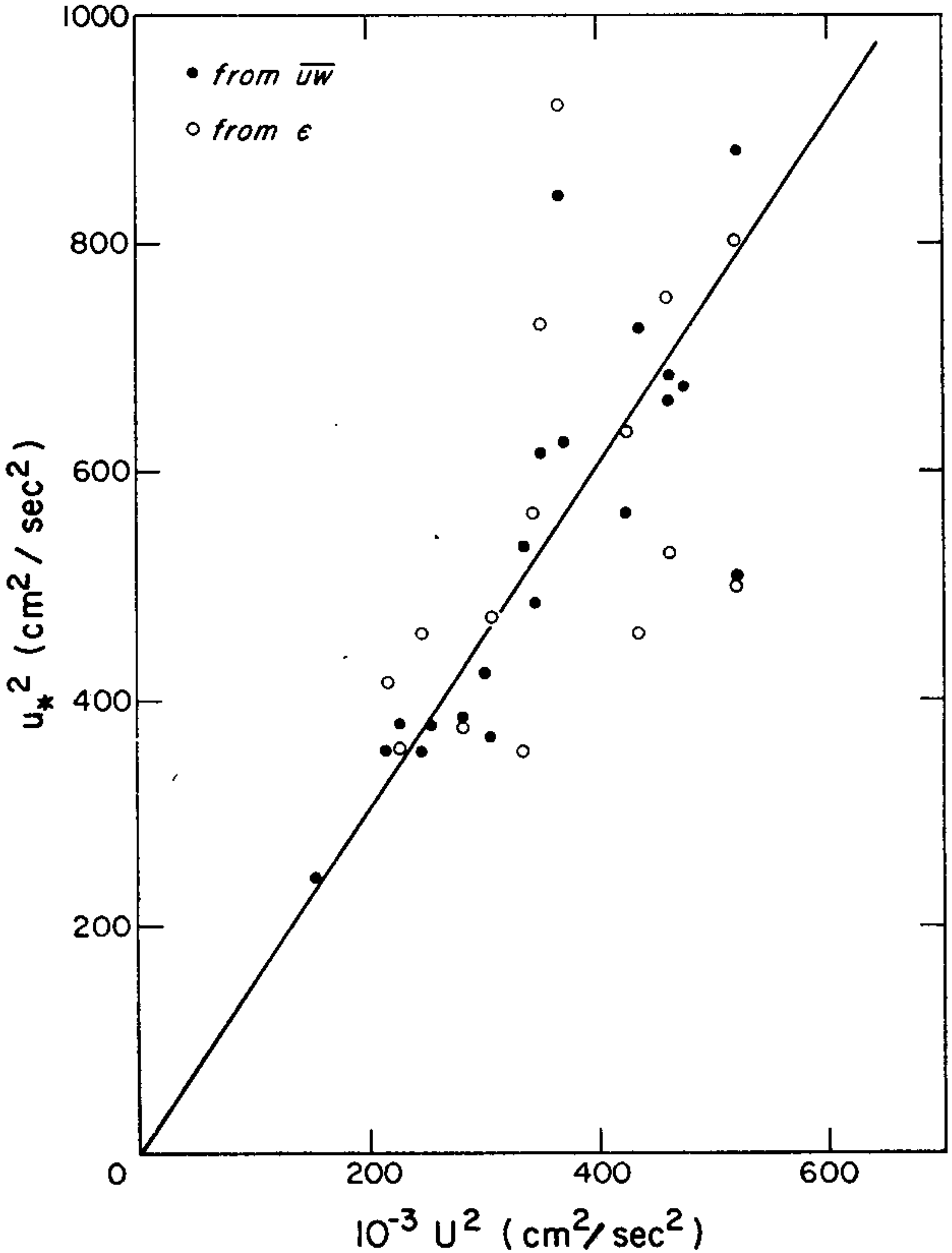


FIG. 5. u_*^2 vs $10^{-3}\,U^2$. The straight line corresponds to $C_D = 1.52 \times 10^{-3}$.

Bulk Aerodynamic Formulae

- Over the oceans, an increase in surface wind speed produces larger waves, which increases the drag.

Force 0: Wind Speed less than 1 knot
Sea: Sea like a mirror

Force 1: Wind Speed 1-3 knots
Sea: Wave height .1m (.25ft); Ripples with appearance of scales, no foam crests

Force 2: Wind Speed 4-6 knots
Sea: Wave height .2-.3m (.5-1 ft); Small wavelets, crests of glassy appearance, not breaking

Force 3: Wind Speed 7-10 knots
Sea: Wave height .6-1m (2-3 ft); Large-wavelets, crests begin to break, scattered whitecaps

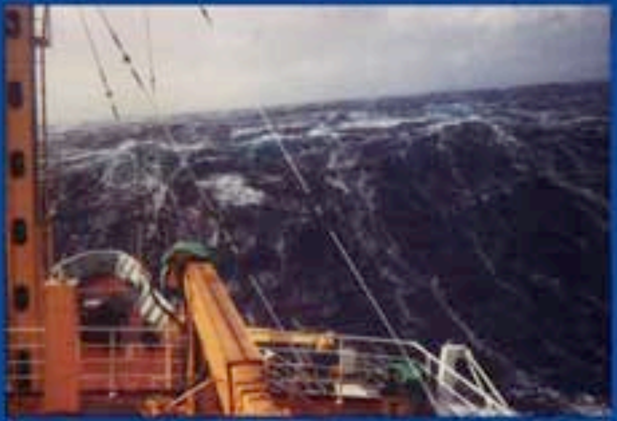
Force 4: Wind Speed 11-16 knots
Sea: Wave height 1-1.5m (3.5-5 ft); Small waves becoming longer, numerous whitecaps

Force 5: Wind Speed 17-21 knots
Sea: Wave height 2-2.5m (6-8 ft); Moderate waves, taking longer form, many whitecaps, some spray

Force 6: Wind Speed 22-27 knots
Sea: Wave height 3-4m (9.5-13 ft); Larger waves forming, whitecaps everywhere, more spray

Force 7: Wind Speed 28-33 knots
Sea: Wave height 4-5.5m (13.5-19 ft); Sea heaps up, white foam from breaking waves begins to be blown in streaks along direction of wind

Force 8: Wind Speed 34-40 knots
Sea: Wave height 5.5-7.5m (18-25 ft): Moderately high waves of greater length, edges of crests begin to break into spindrift, foam is blown in well marked streaks



Force 9: Wind Speed 41-47 knots
Sea: Wave height 7-10m (23-32 ft); High waves, sea begins to roll, dense streaks of foam along wind direction, spray may reduce visibility

Force 10: Wind Speed 48-55 knots (storm)
Sea: Wave height 9-12.5m (29-41 ft): Very high waves with overhanging crests, sea takes white appearance as foam is blown in very dense streaks, rolling is heavy and shocklike, visibility is reduced.

Force 11: Wind Speed 56-63 knots
Sea: Wave height 11.5-16m (37-52 ft): Exceptionally high waves, sea covered with white foam patches, visibility still more reduced

BEAUFORT FORCE 0
WIND SPEED: LESS THAN 1 KNOT

SEA: SEA LIKE A MIRROR

BEAUFORT FORCE 2
WIND SPEED: 4-6 KNOTS

SEA: WAVE HEIGHT .2-.3M (.5-1FT), SMALL WAVELETS,
CRESTS HAVE A GLASSY APPEARANCE AND DO NOT BREAK

BEAUFORT FORCE 4
WIND SPEED: 11-16 KNOTS

SEA: WAVE HEIGHT 1-1.5M (3.5-5FT), SMALL WAVES BECOMING LONGER, FAIRLY FREQUENT WHITE HORSES

BEAUFORT FORCE 6
WIND SPEED: 22-27 KNOTS

SEA: WAVE HEIGHT 3-4M (9.5-13 FT),
LARGER WAVES BEGIN TO FORM, SPRAY IS PRESENT,
WHITE FOAM CRESTS ARE EVERYWHERE

BEAUFORT FORCE 8
WIND SPEED: 34-40 KNOTS

SEA: WAVE HEIGHT 5.5-7.5M (18-25FT), MODERATELY HIGH WAVES OF GREATER LENGTH, EDGES OF CREST BEGIN TO BREAK INTO THE SPINDRIFT, FOAM BLOWN IN WELL MARKED STREAKS ALONG WIND DIRECTION.

BEAUFORT FORCE 10

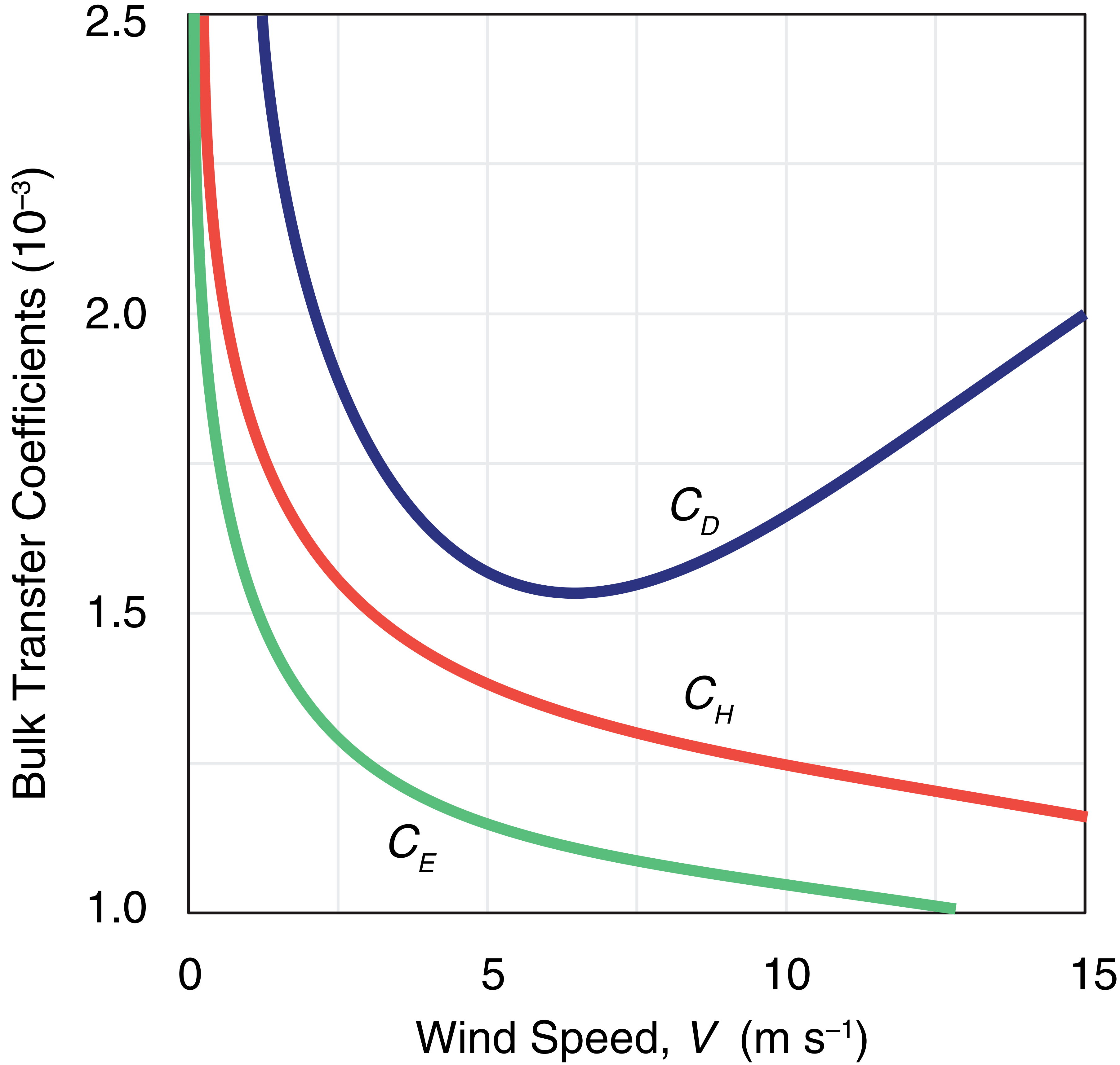
WIND SPEED: 48-55 KNOTS

SEA: WAVE HEIGHT 9-12.5M (29-41FT), VERY HIGH WAVES WITH LONG OVERHANGING CRESTS, THE RESULTING FOAM, IN GREAT PATCHES, IS BLOWN IN DENSE WHITE STREAKS ALONG WIND DIRECTION. ON THE WHOLE, SEA

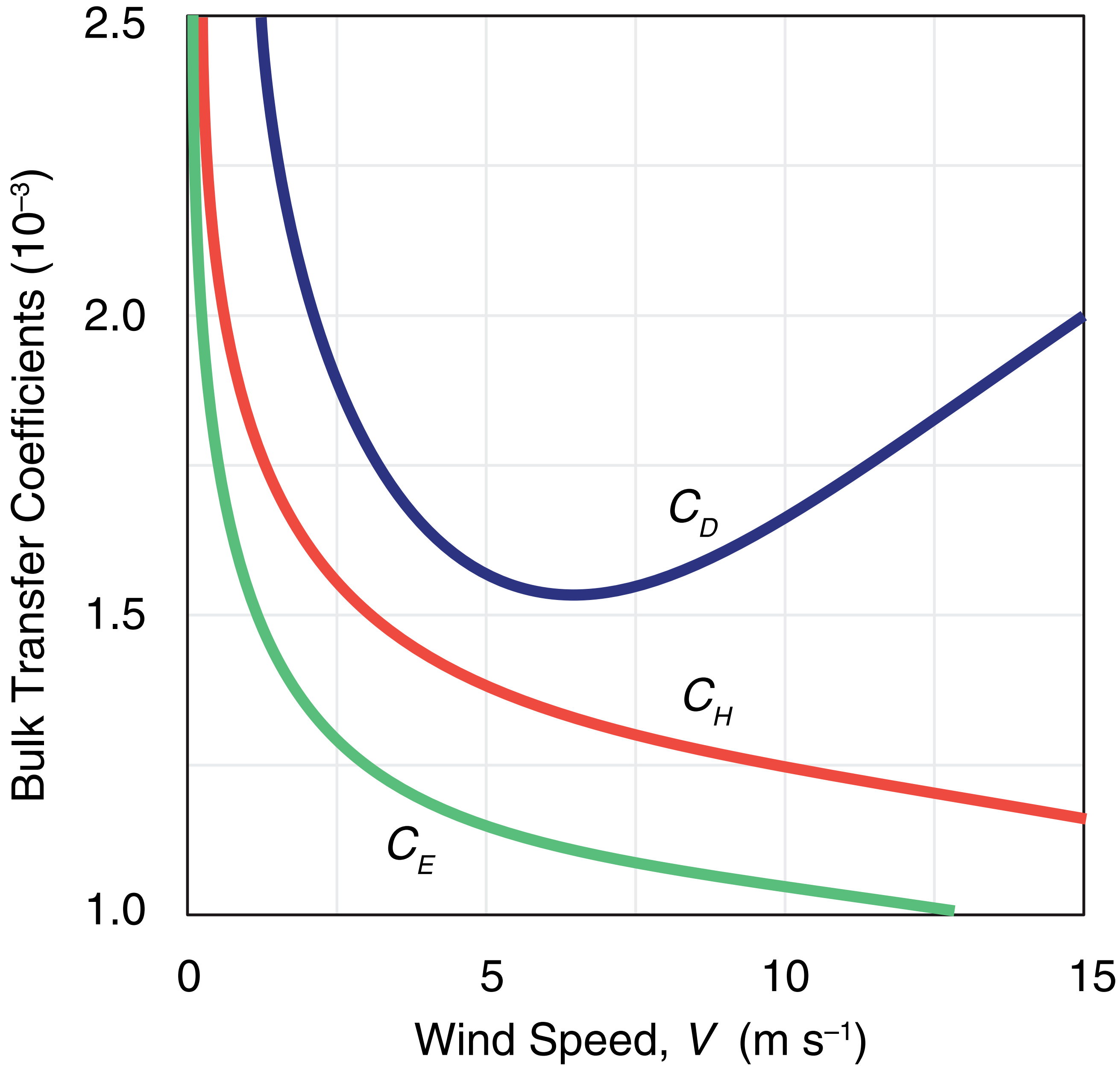
BEAUFORT FORCE 12
WIND SPEED: 64 KNOTS

SEA: SEA COMPLETELY WHITE WITH DRIVING SPRAY, VISIBILITY VERY SERIOUSLY AFFECTED. THE AIR IS FILLED WITH FOAM AND SPRAY

Bulk transfer coefficients over the ocean



Bulk transfer coefficients over the ocean

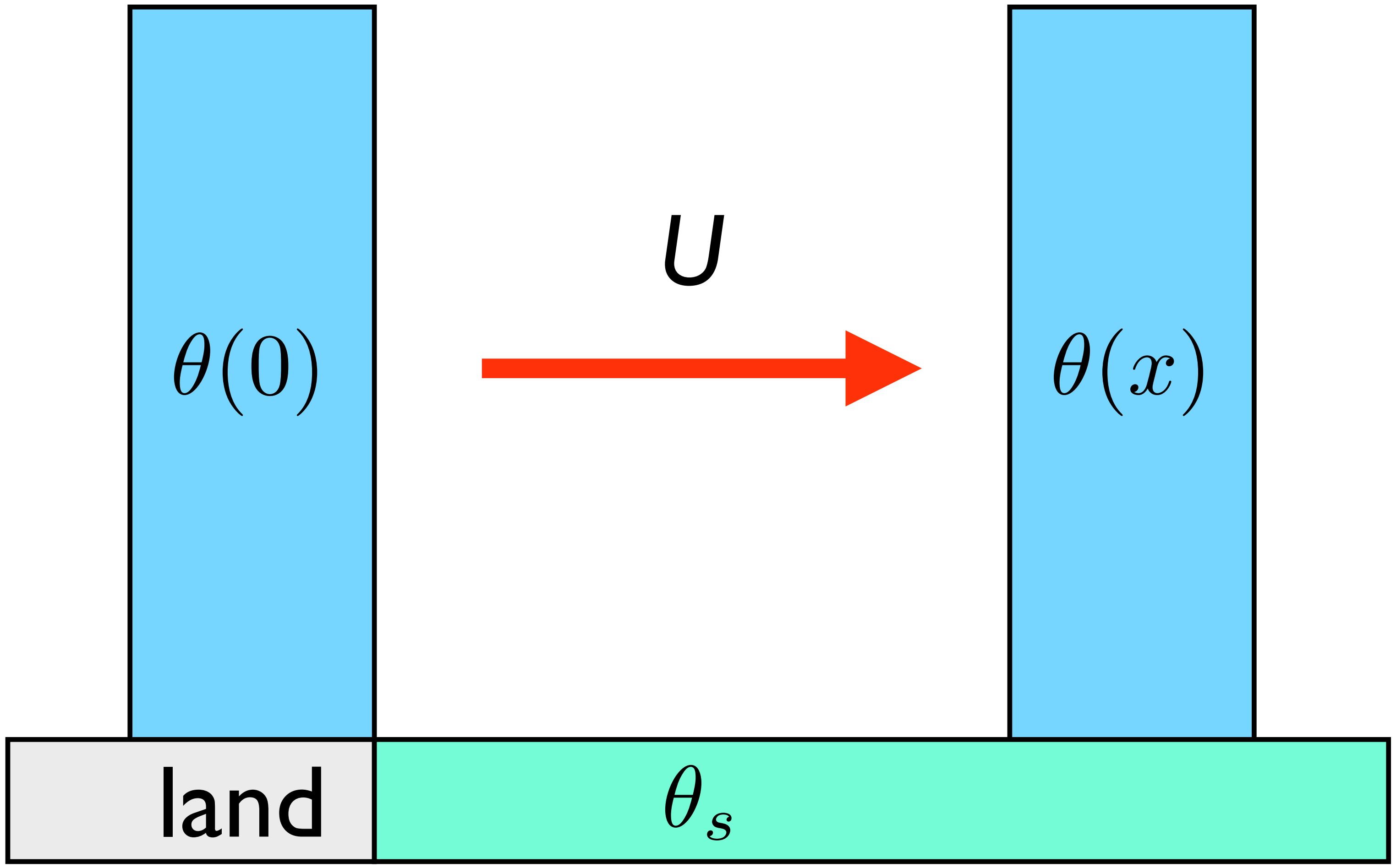


- For speeds of the mean *vector* wind < 5 m/s, the bulk formulae are not valid.
- Why not?
- How could the formulae be modified so they are valid in such situations?

Exercise 9.2: in class

Exercise 9.2 Consider a column of air initially of vertically uniform θ over cold land, capped by a very strong temperature inversion that prevents boundary layer growth. This air column advects with speed U over a warmer ocean surface with potential temperature θ_s. (a) How does temperature vary with distance x from shore? (b) At any fixed distance x from shore, how does the air temperature vary with wind speed?

[**Hint**: Use Taylor's[7] hypothesis: $\frac{\partial \theta}{\partial t} = U\frac{\partial \theta}{\partial x}$.]

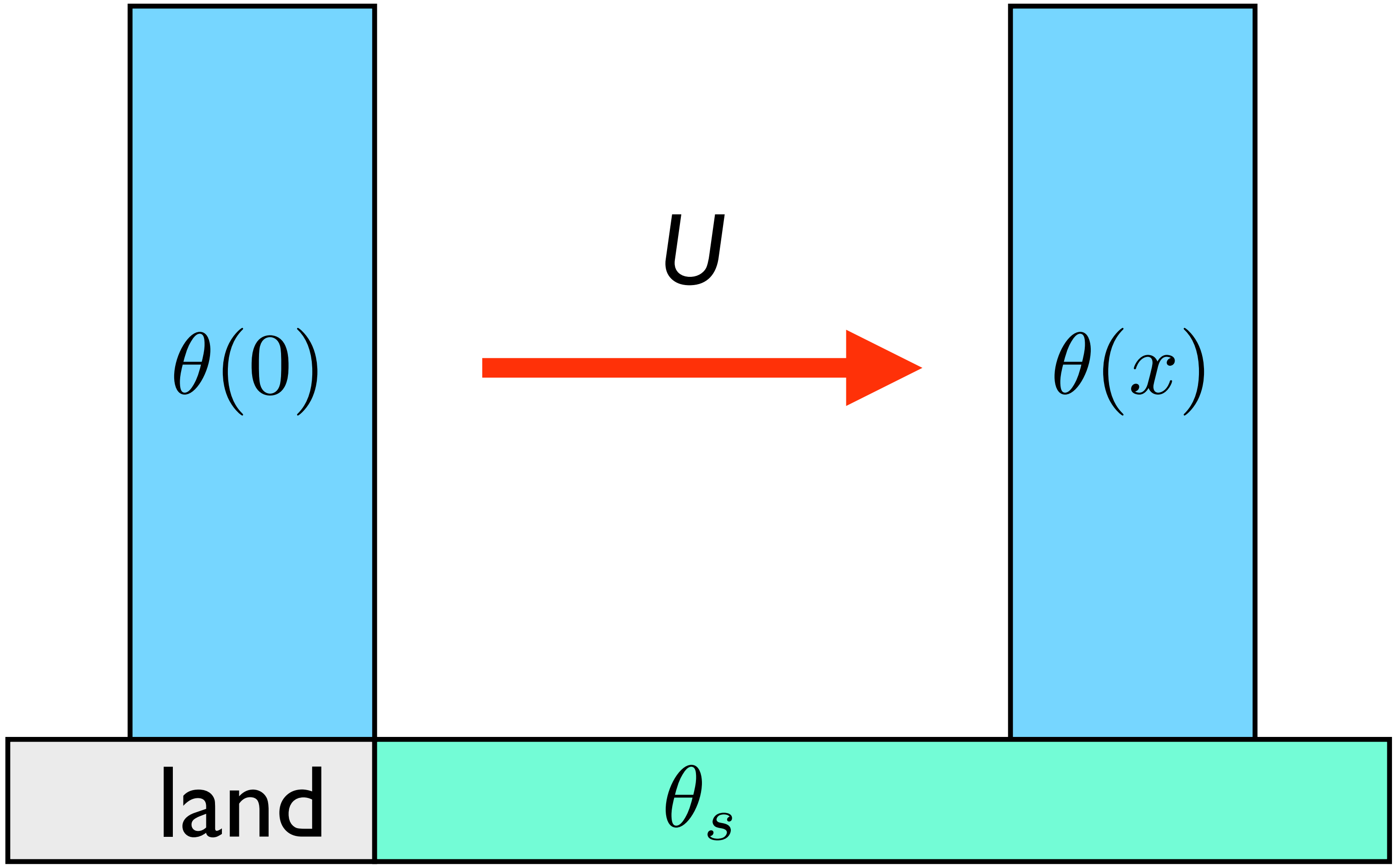


(a) What is $\theta(x)$?

(b) What is $(\partial\theta/\partial U)_x$?

$$\frac{\partial \theta}{\partial t} = \frac{F_{Hs}}{z_i}$$

$$\frac{\partial \theta}{\partial t} = U\frac{\partial \theta}{\partial x} \quad \text{(Taylor's hypothesis)}$$



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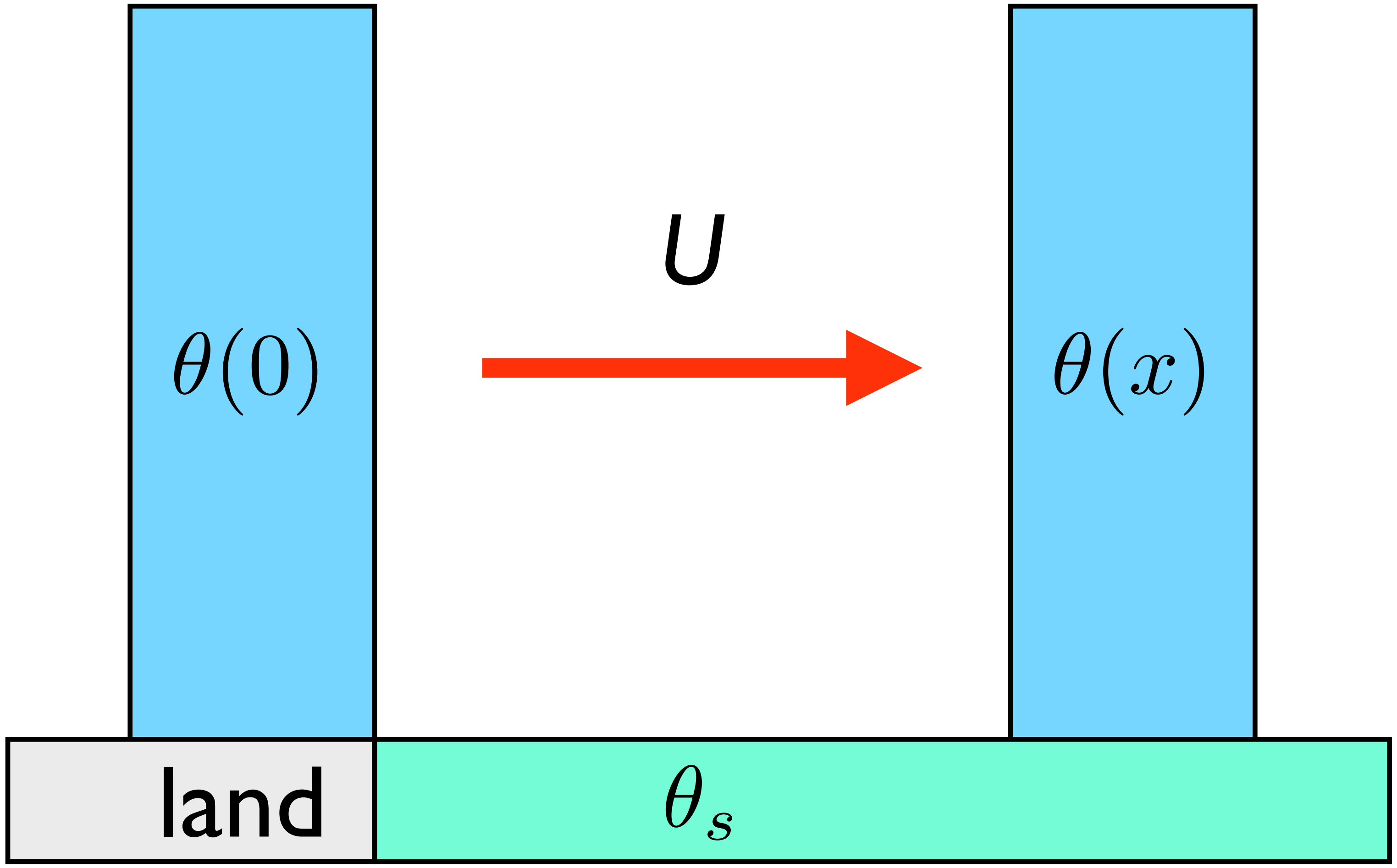
$$\frac{\partial\theta}{\partial t} = \frac{F_{Hs}}{z_i}$$

$$\frac{\partial\theta}{\partial t} = U\frac{\partial\theta}{\partial x} \quad \text{(Taylor's hypothesis)}$$

$$\frac{\partial\theta}{\partial x} = \frac{1}{U}\frac{F_{Hs}}{z_i}$$



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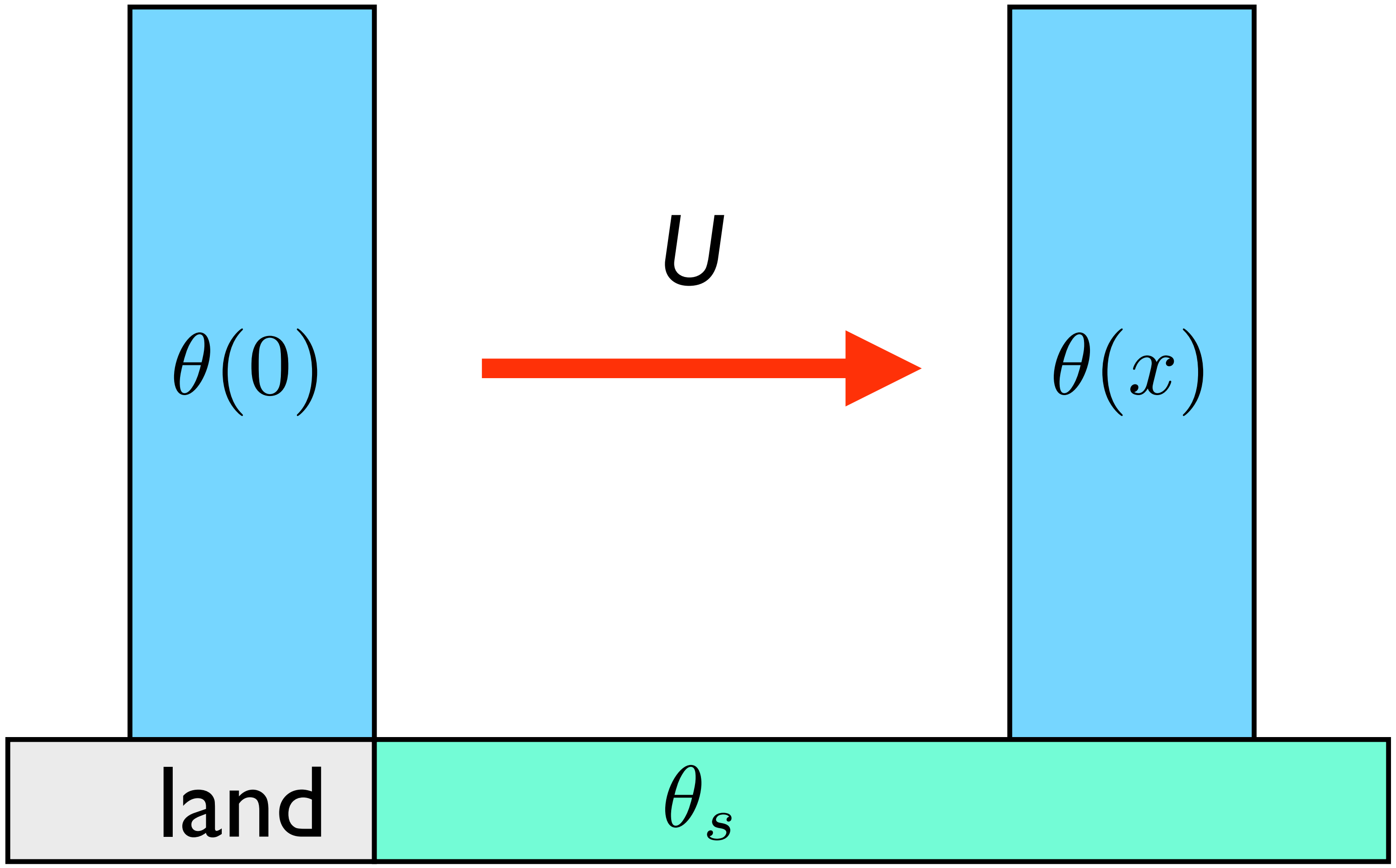
$$\frac{\partial\theta}{\partial t} = U\frac{\partial\theta}{\partial x} \quad \text{(Taylor's hypothesis)}$$

$$\frac{\partial\theta}{\partial x} = \frac{1}{U}\frac{F_{Hs}}{z_i}$$

$$F_{Hs} = C_H U(\theta_s - \theta)$$



(a) What is $\theta(x)$?

(b) What is $(\partial\theta/\partial U)_x$?

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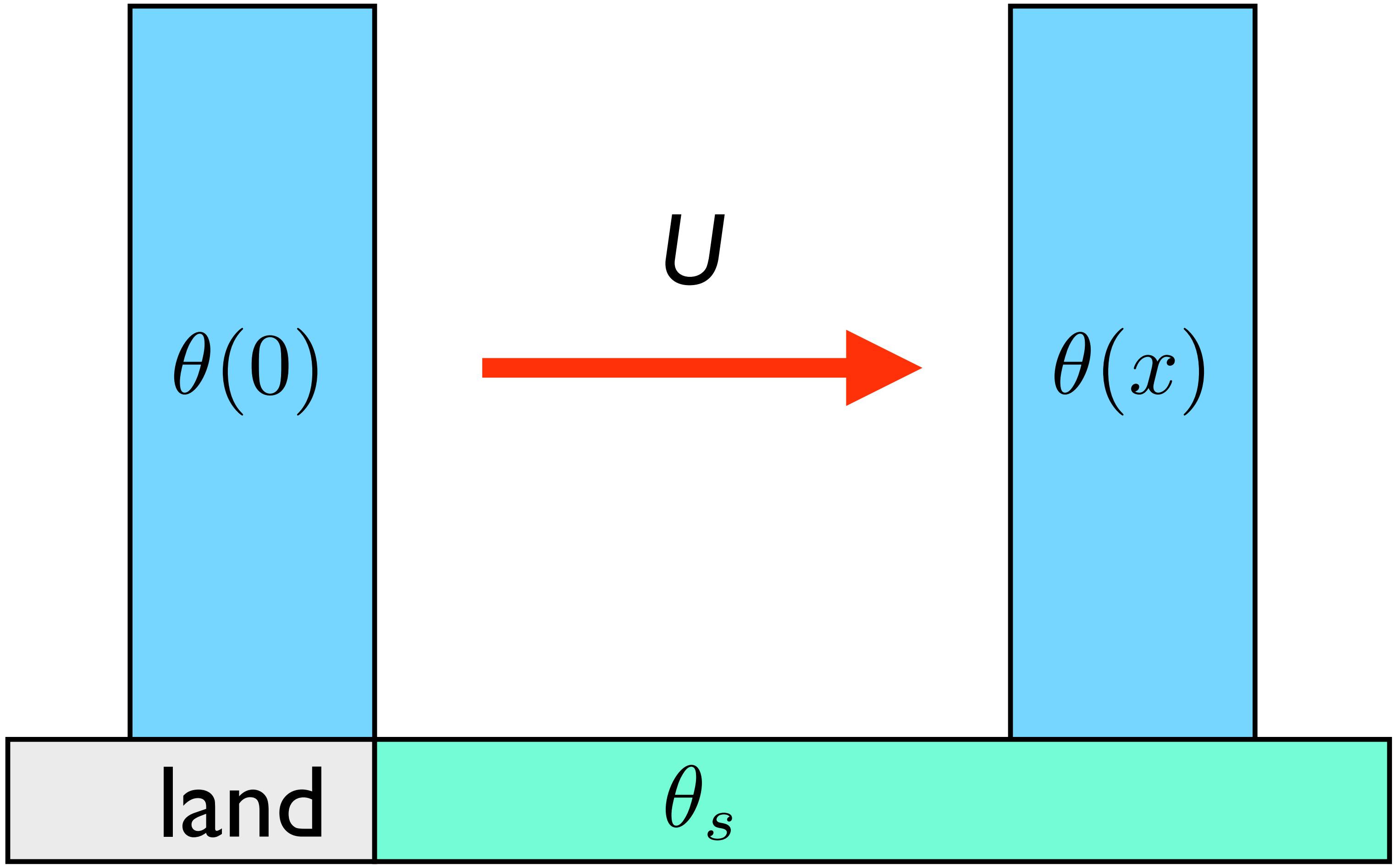

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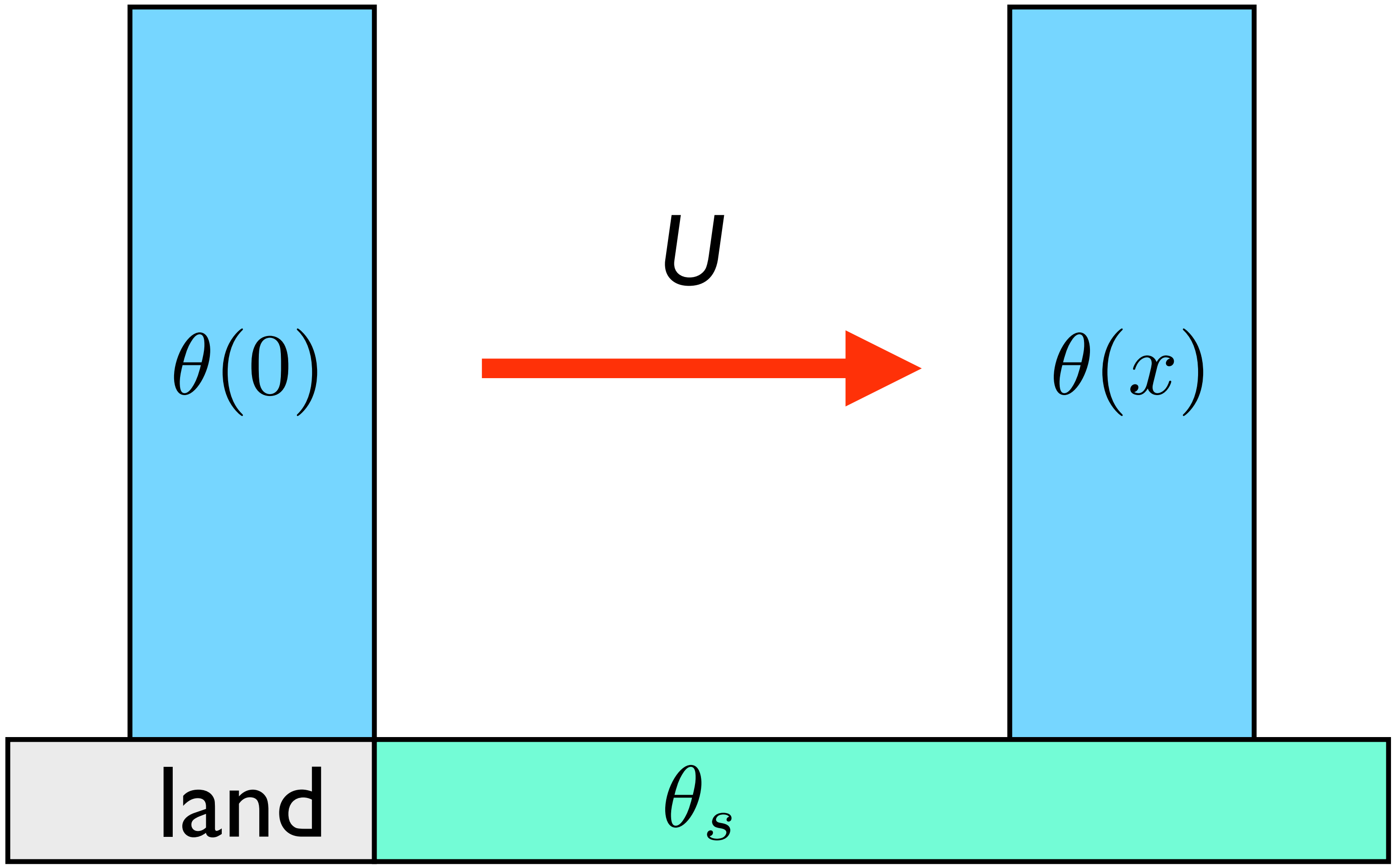

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Depends only on downstream distance.

The Global Surface Energy Balance

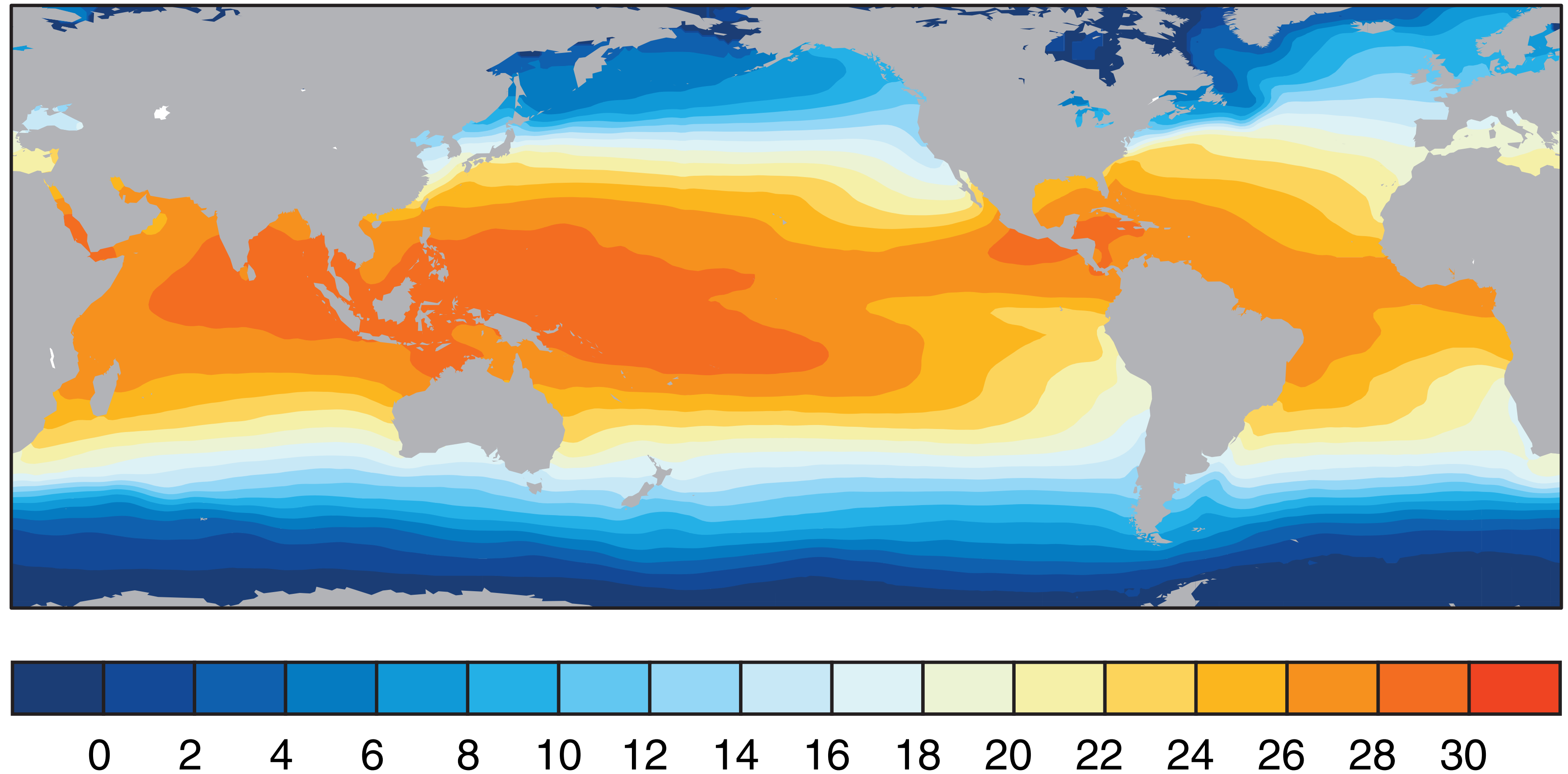
The bulk aerodynamic formulae have been used to estimate the global distribution of the terms in the surface energy balance.

The net upward transfer of energy through the Earth's surface is

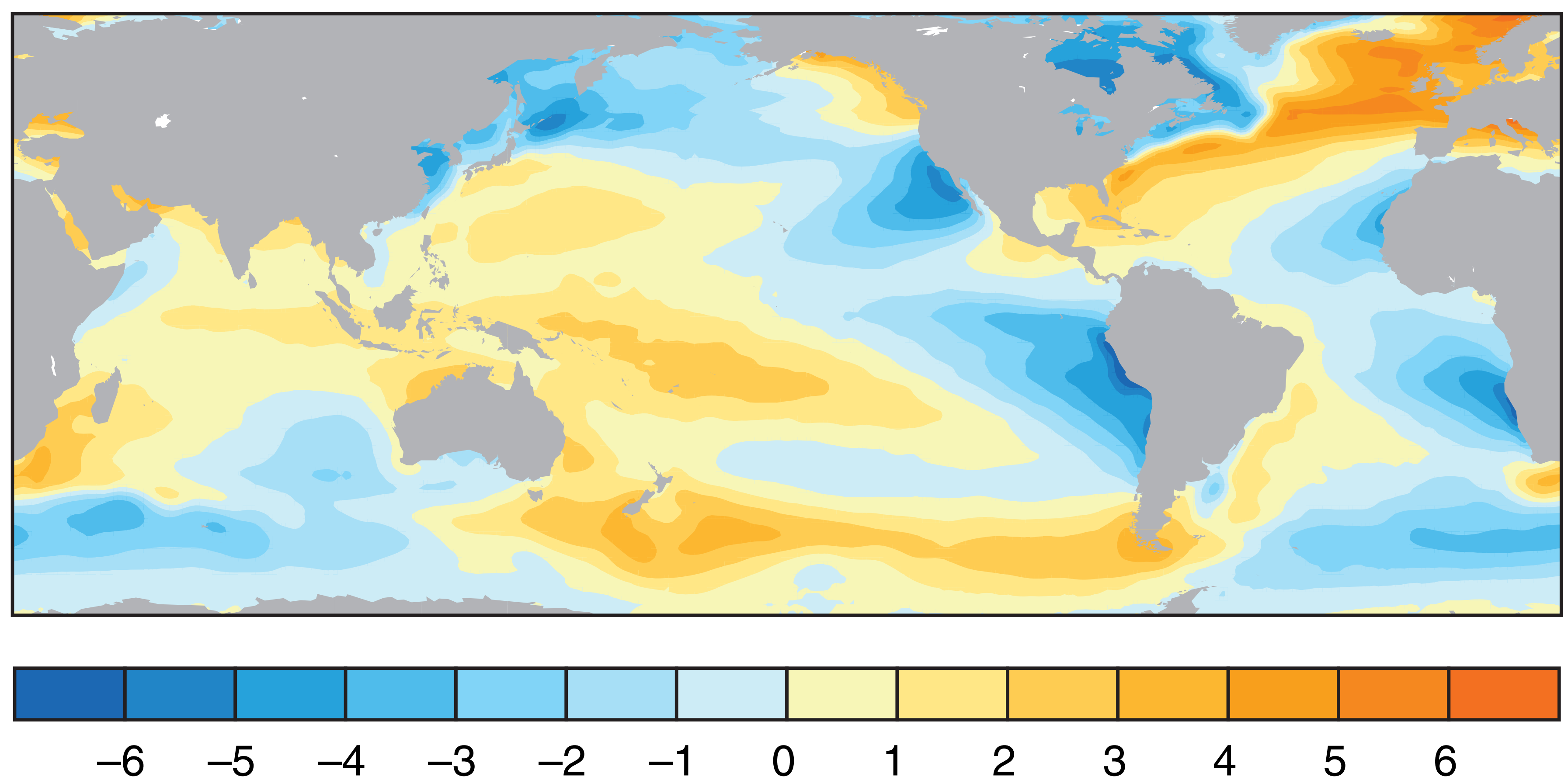
$$F_{net}^{\uparrow} = -F^* + F_{H\,s} + F_{E\,s}$$

where F^* is the net downward radiative flux, and $F_{net}^{\uparrow} = -F_G$.

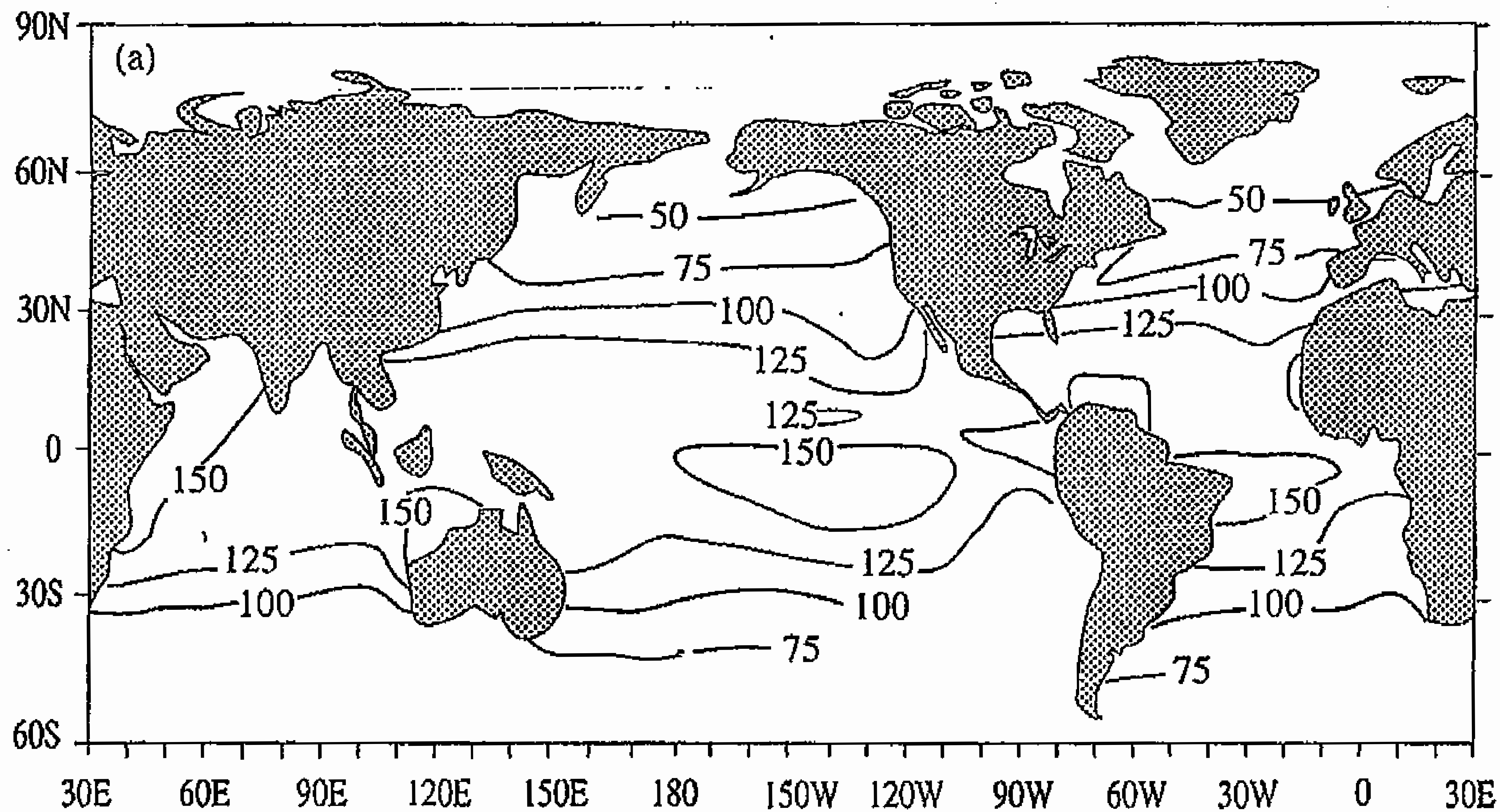
Annual mean sea surface temperature



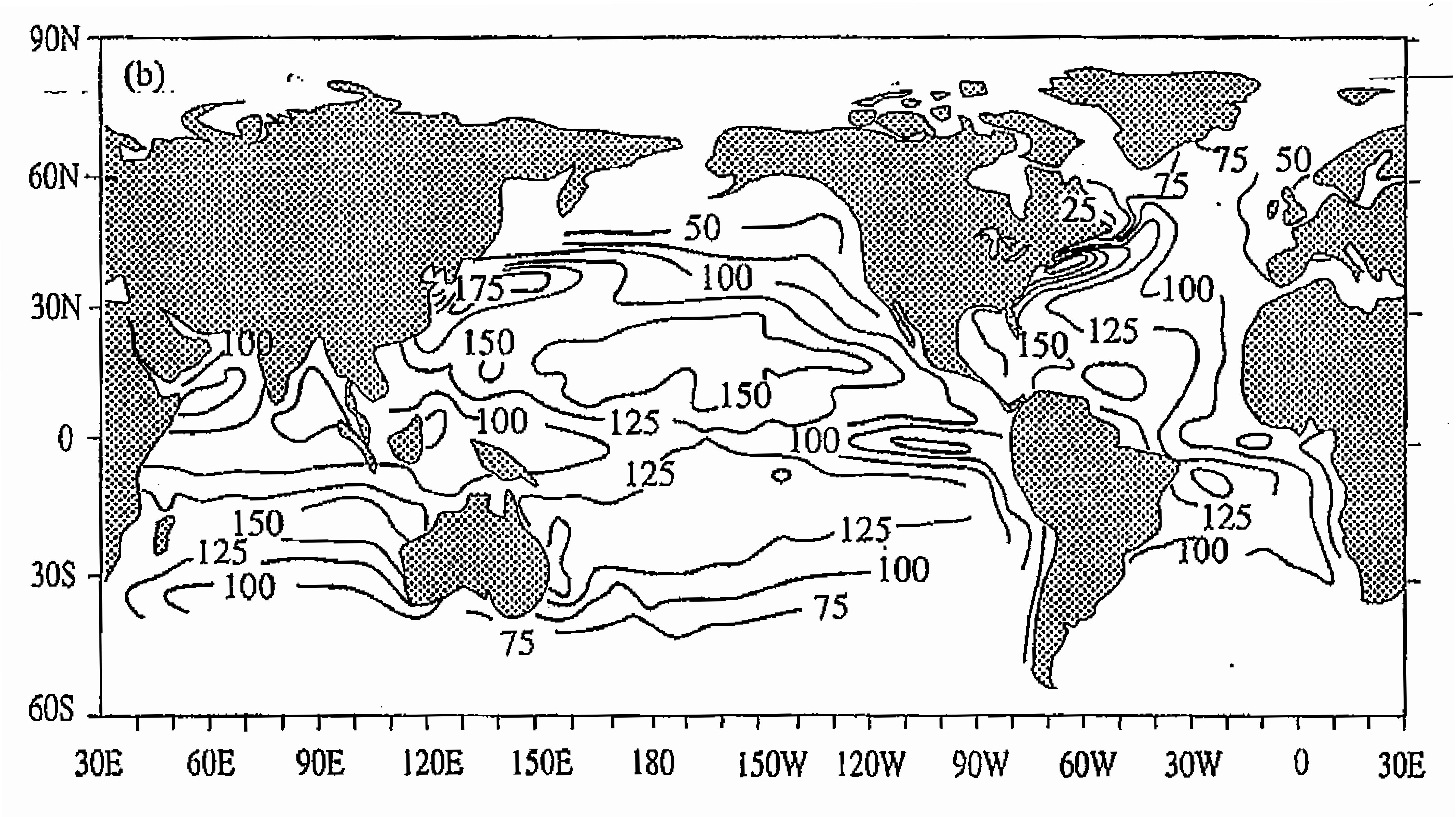
Departure of local annual mean SST from zonally averaged annual mean SST



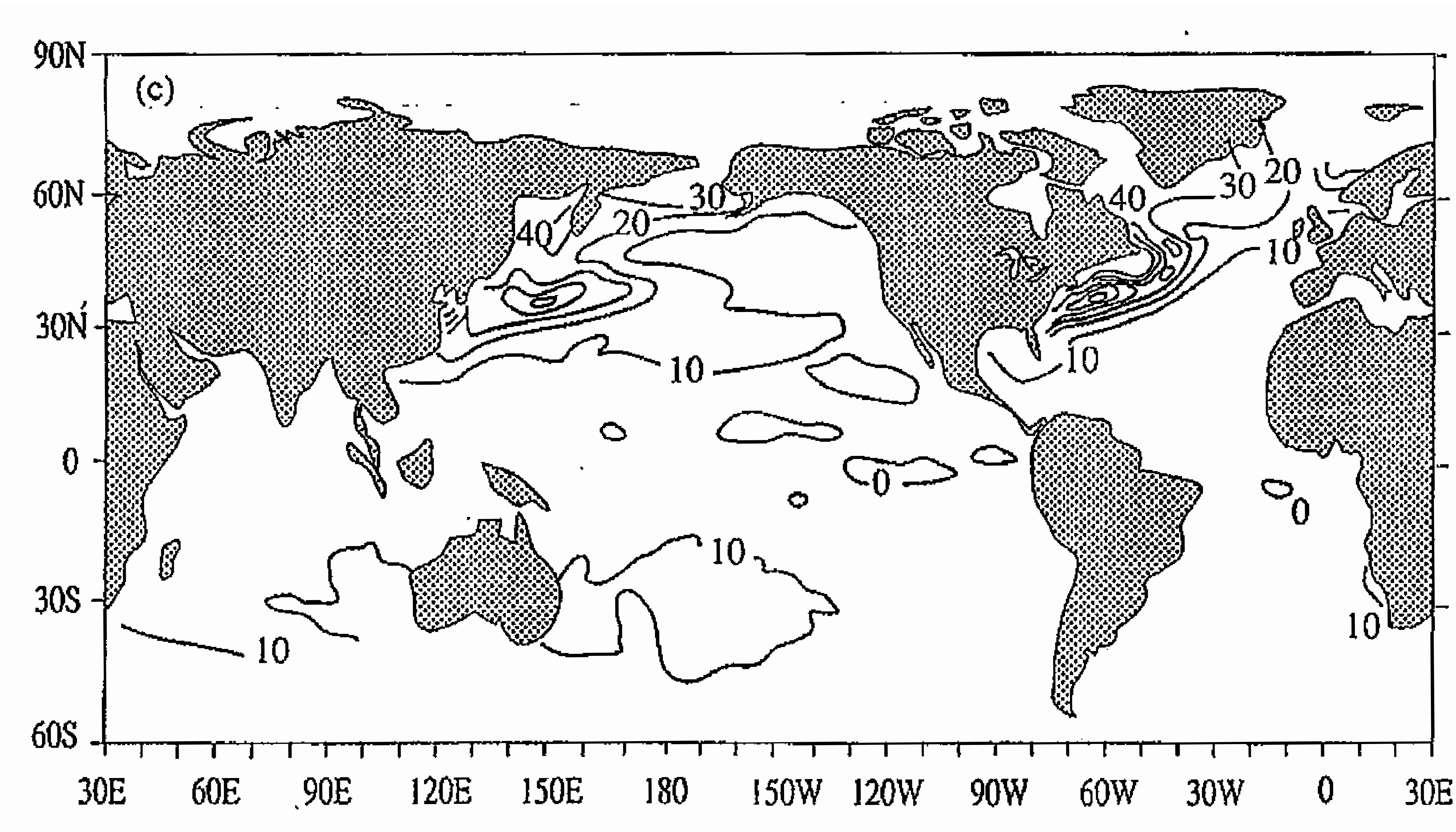
Annual mean surface net radiation



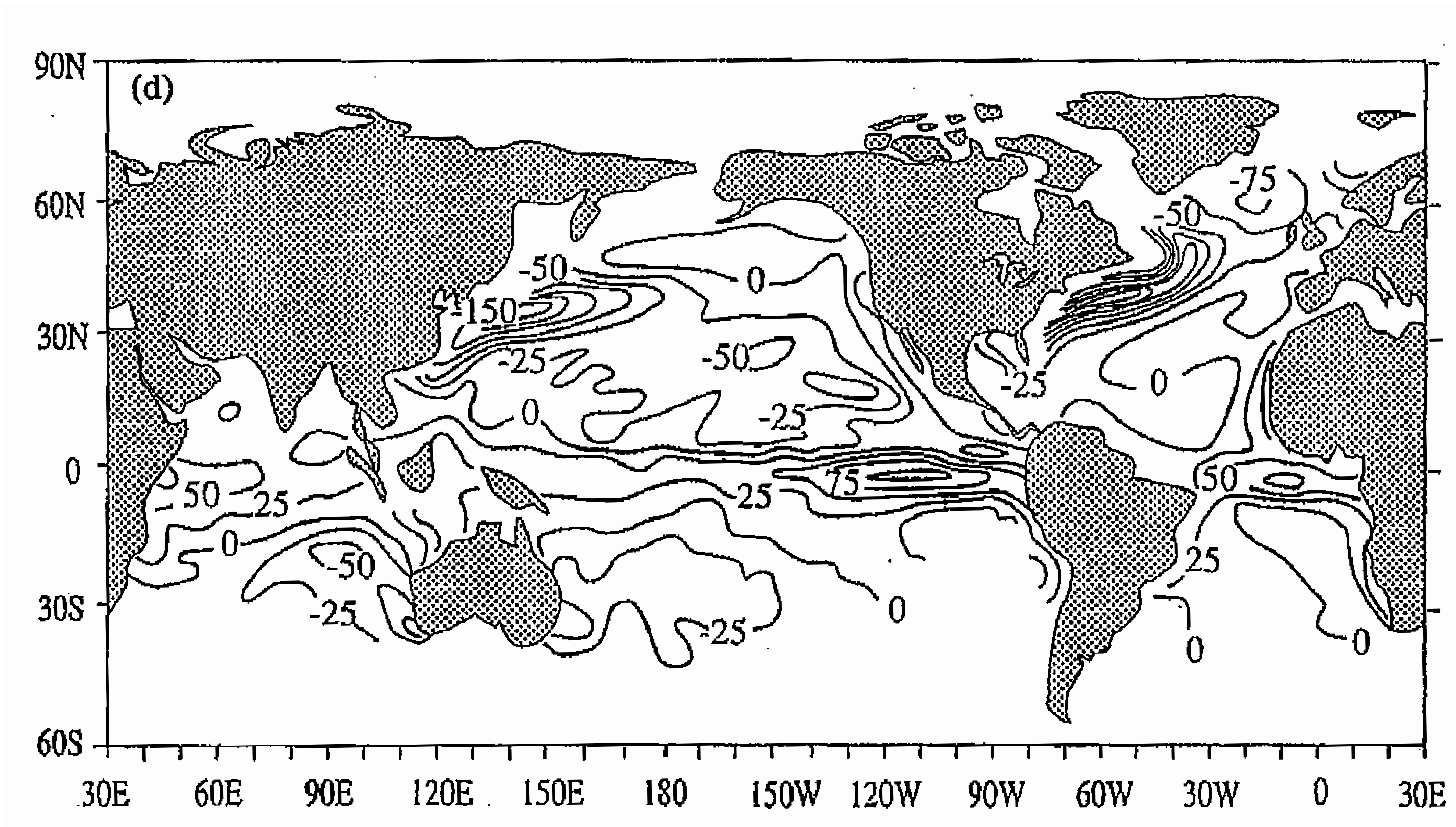
Annual mean surface latent heat flux



Annual mean surface sensible heat flux



Annual mean net downward heat flux into ocean



Annual mean net upward energy flux