Lecture for International Summer School on the Atmospheric Boundary Layer, Les Houches, France, June 17, 2008

Atmospheric Boundary Layers

Bert Holtslag

Introducing the latest developments in theoretical concepts, observations and numerical techniques

This talk:

Some background, history and challenges

WAGENINGEN UNIVERSITY
METEOROLOGY AND AIR QUALITY

Why is the boundary layer important?

Weather Forecasting: Surface temperatures, Wind, Fog needed for Agriculture, Energy use, Traffic, Wind power…

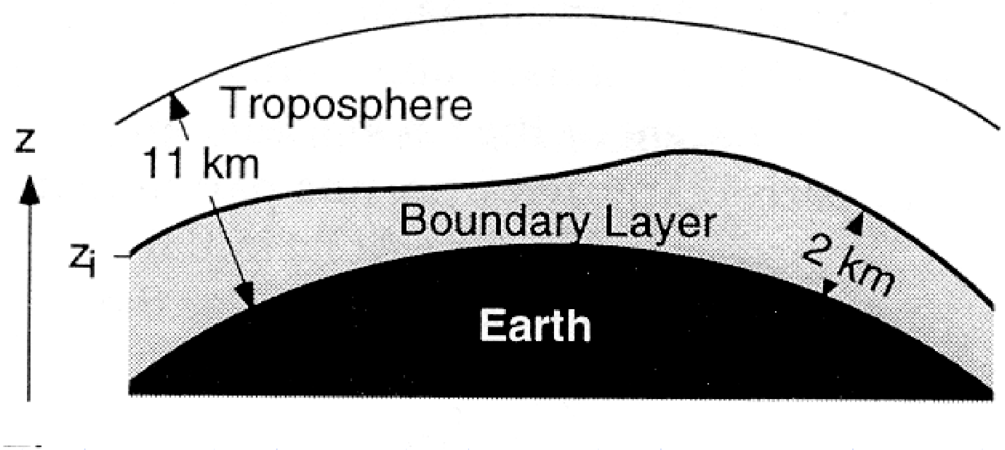
Weather and Climate Studies:
Model performance? Impact of changing conditions?

Dispersion of pollutants and greenhouse gasses

Many other subjects on variety of scales…

And we live in this layer!

Atmospheric Boundary layer (ABL)

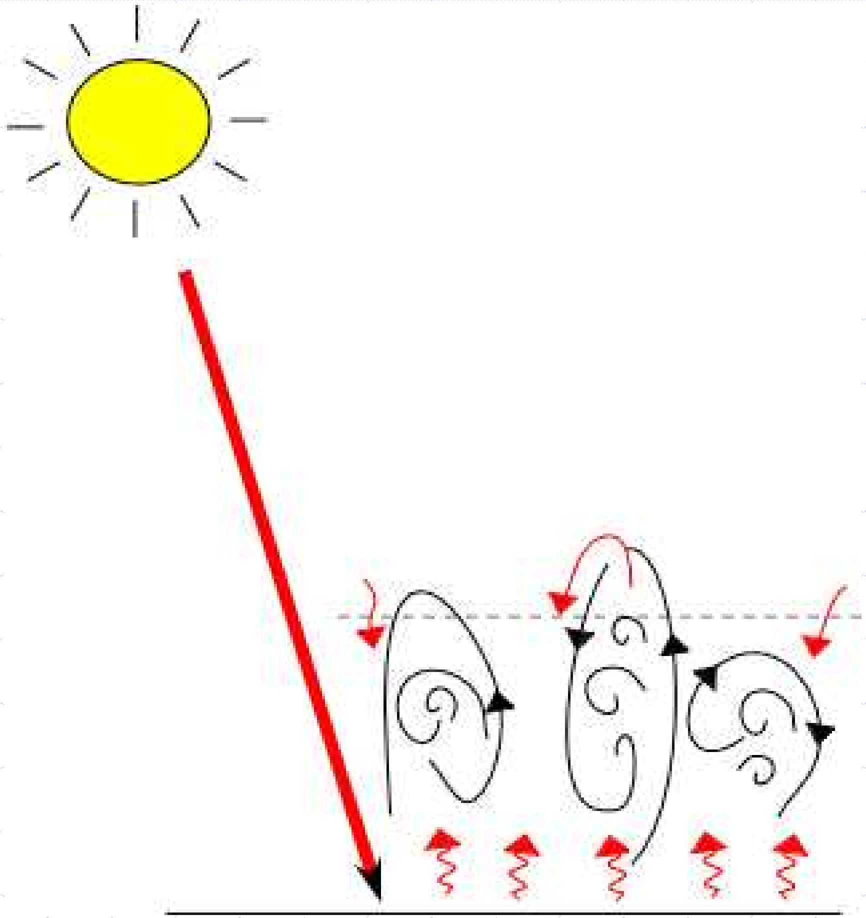


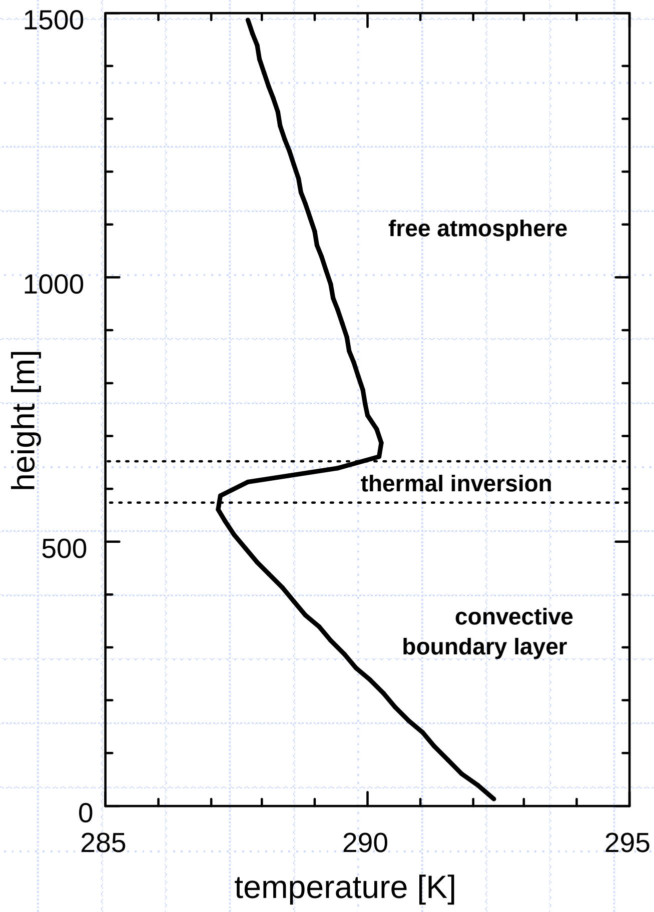
(Stull, 1988)

The lower layer of the Atmosphere influenced by the presence of the earth's surface:
Friction, Surface Heating (Convection) and Cooling

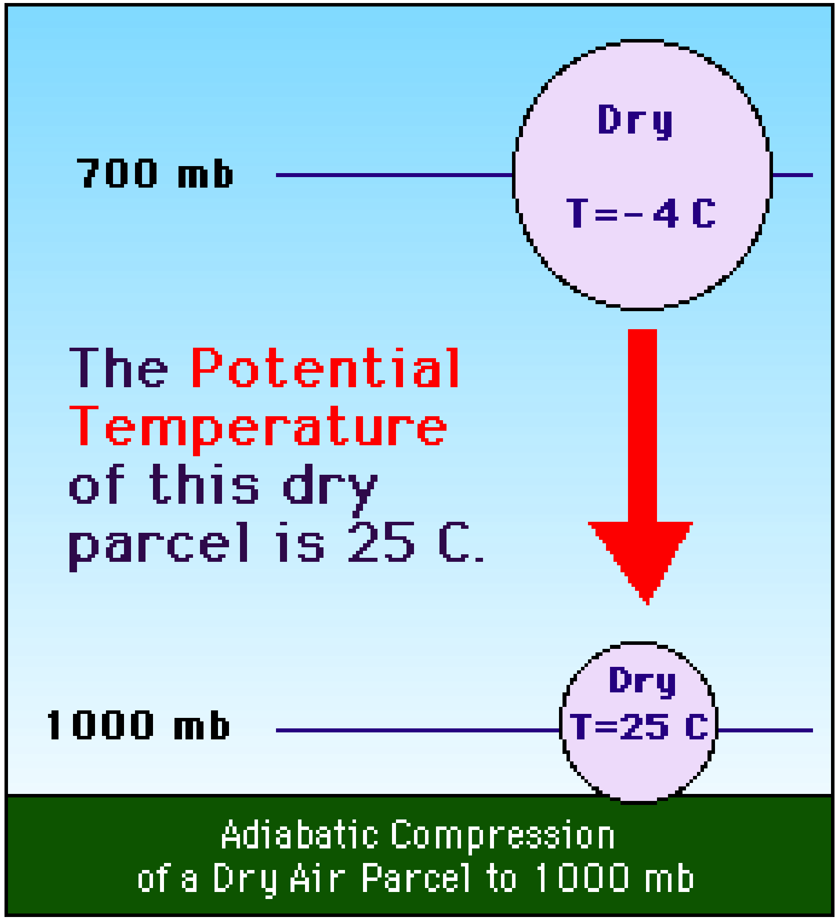
Important characteristic is Turbulence!

Daytime Clear Convective Boundary Layer over Land





Potential temperature



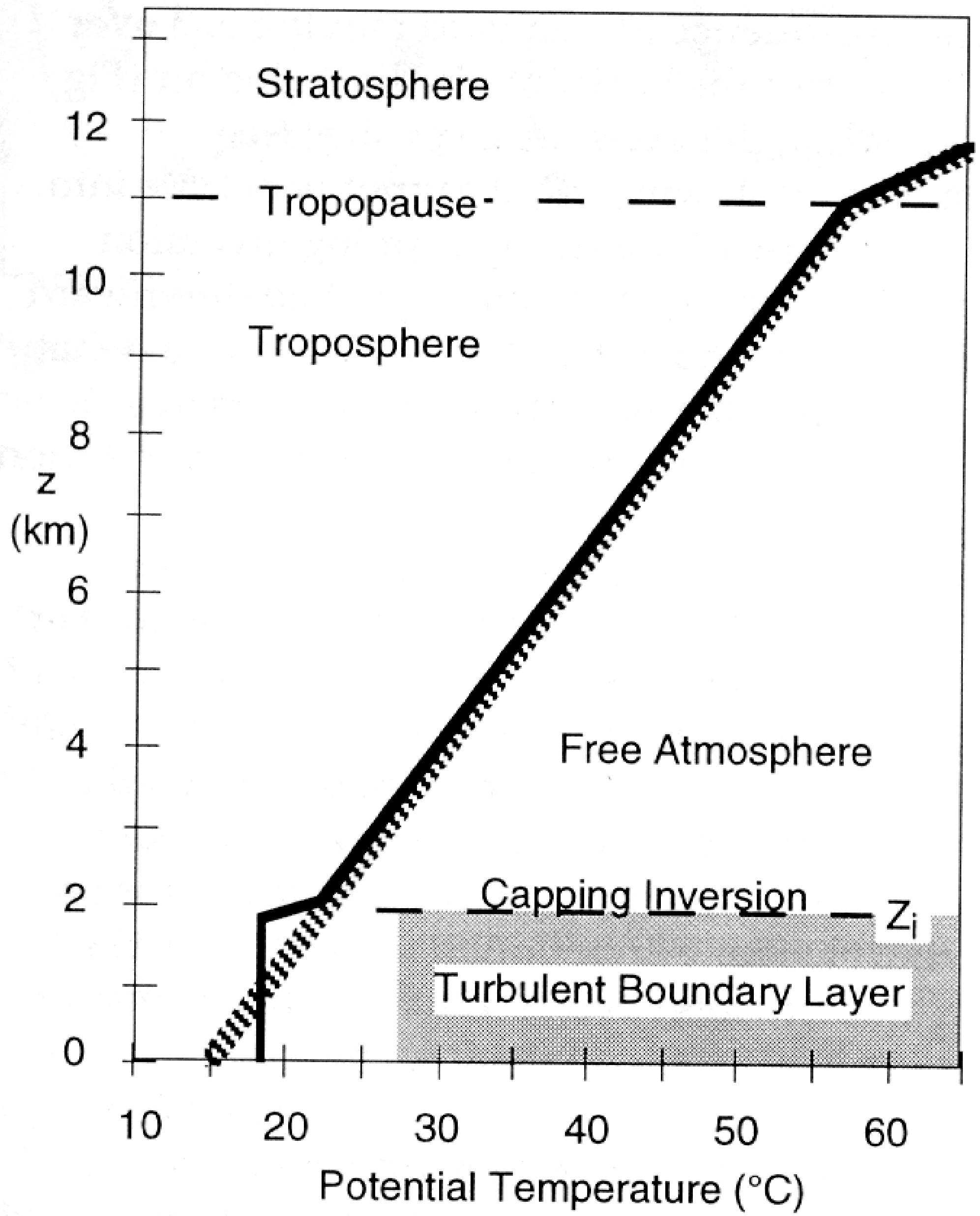
Temperature that a parcel will have if it is moved (dry) adiabatically to reference level (at P= 1000 mb or z=0)

$$\theta = T\left(\frac{P_0}{P}\right)^{R_d/C_p}$$

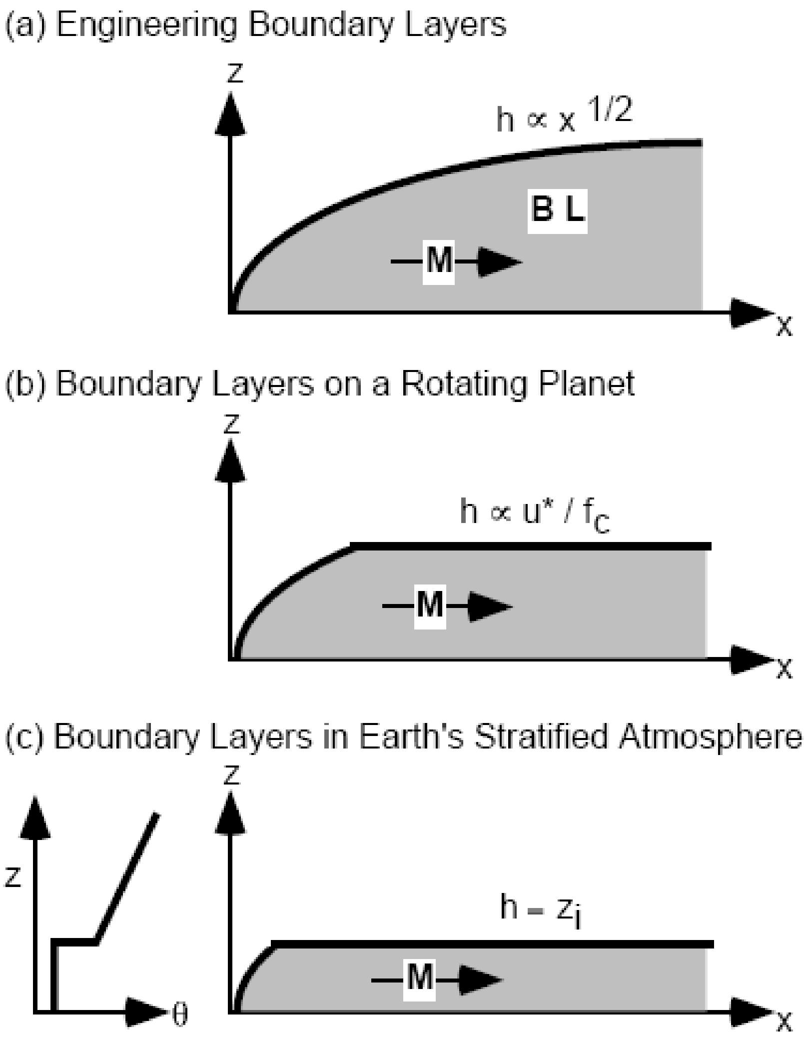
Temperature decrease (increase) for rising (sinking) parcel due to air expansion (compression)!

Temperature structure of a ‘standard’ atmosphere with turbulent ABL below

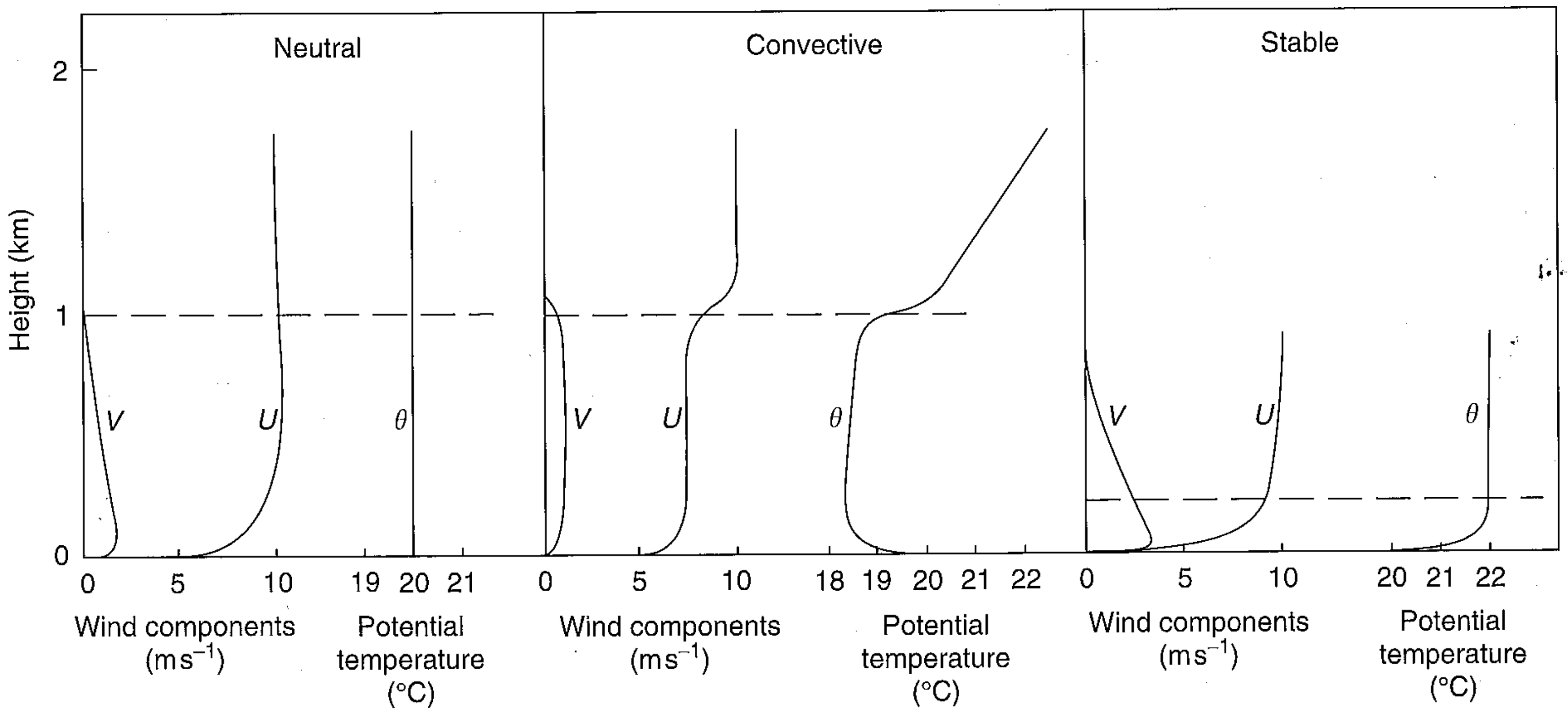
(Stull, 2001)



Variety of boundary layers

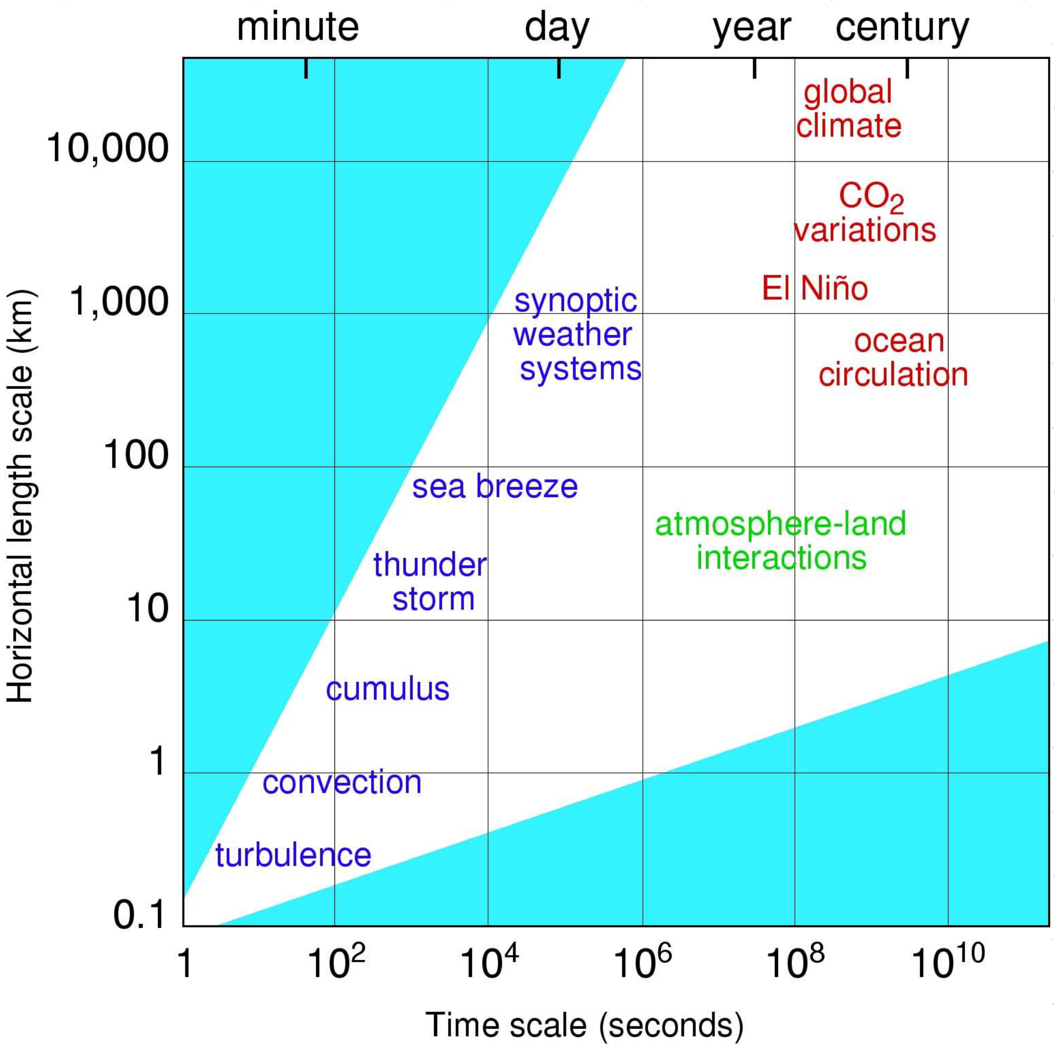


Typical distinction for clear boundary layers



Neutral Boundary layer rarely found in atmosphere!

From small to large scales…



(Holtslag, 2002)

Separation of scales: The spectral gap?

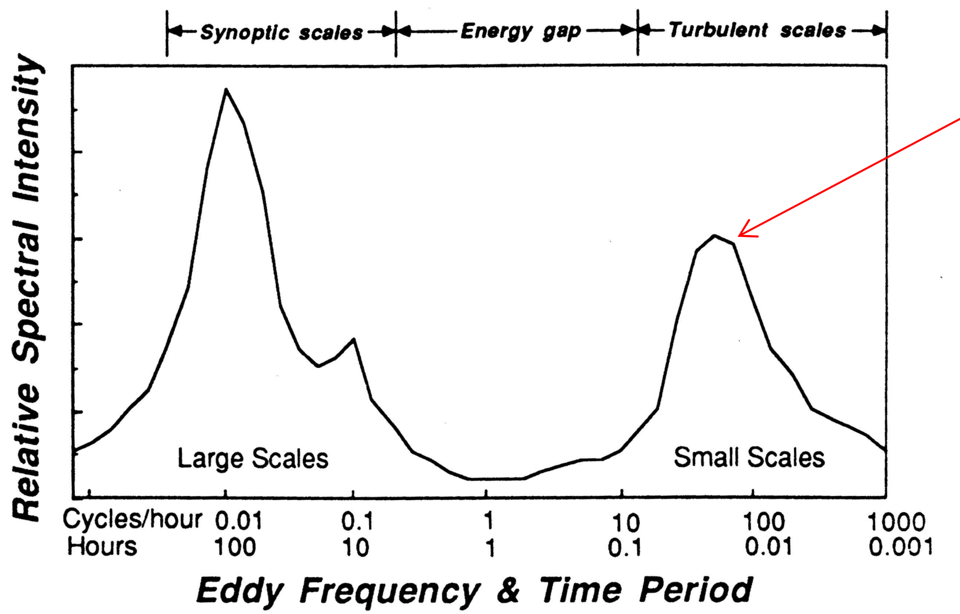


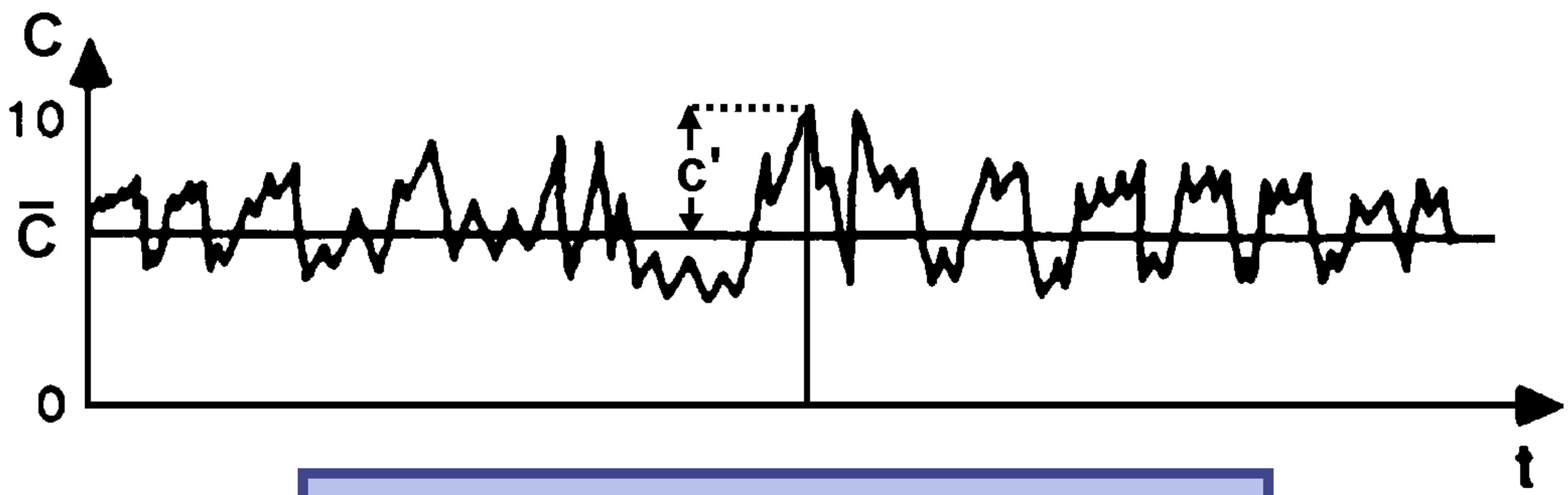
Fig. 2.2 Schematic spectrum of wind speed near the ground estimated from a study of Van der Hoven (1957).

Spectral peak: Length scale of dominant turbulent eddies

(Stull, 1988)

In general, spectral gap is rarely seen in observations **!**

Reynolds decomposition



Value = Mean + fluctuation

$$C = \overline{C} + c`$$

$$\overline{c`} \equiv 0$$

But what is the proper averaging time?

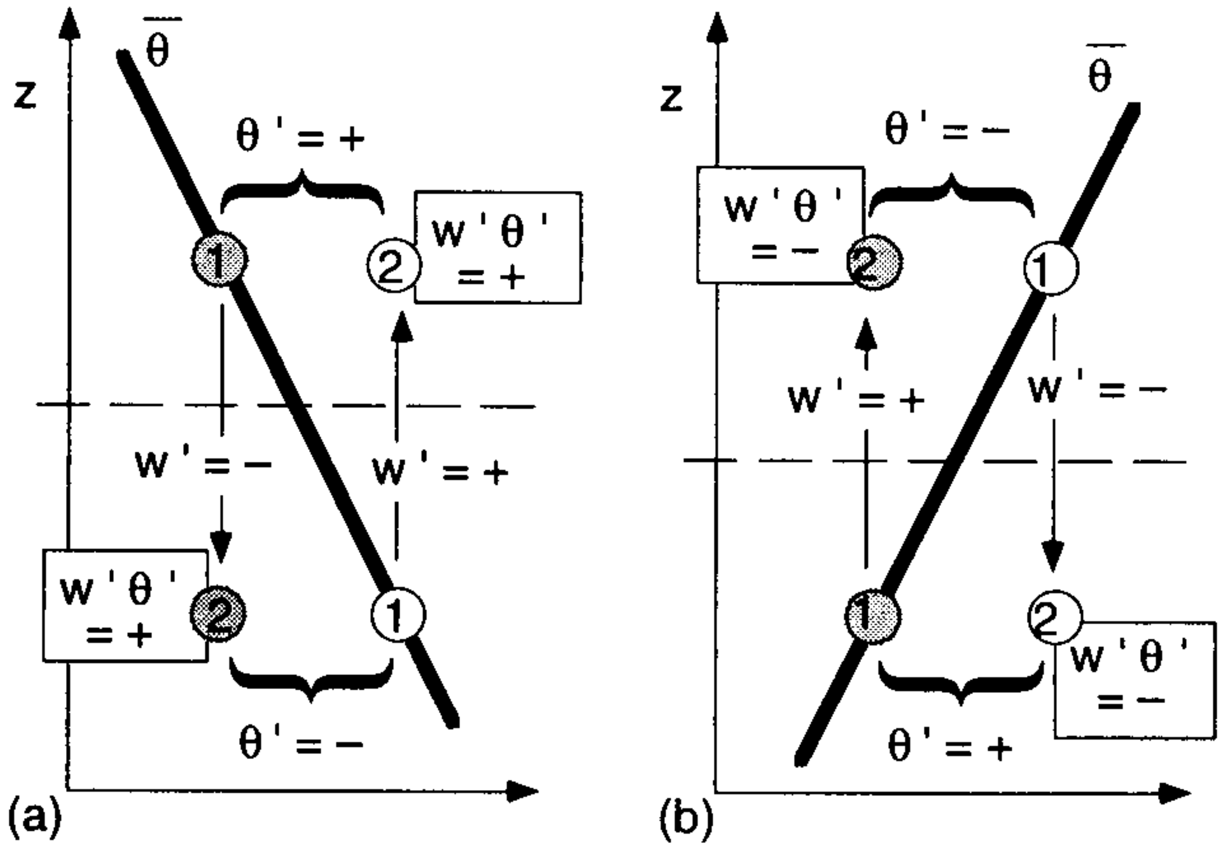
Product of fluctuating variables

$$\overline{AB} = \bar{A}\bar{B} + \overline{a`b`}$$

Total = Mean + turbulent part

If A or B reflects a wind speed component (u, v of w), then $\overline{AB}$ reflects a transport

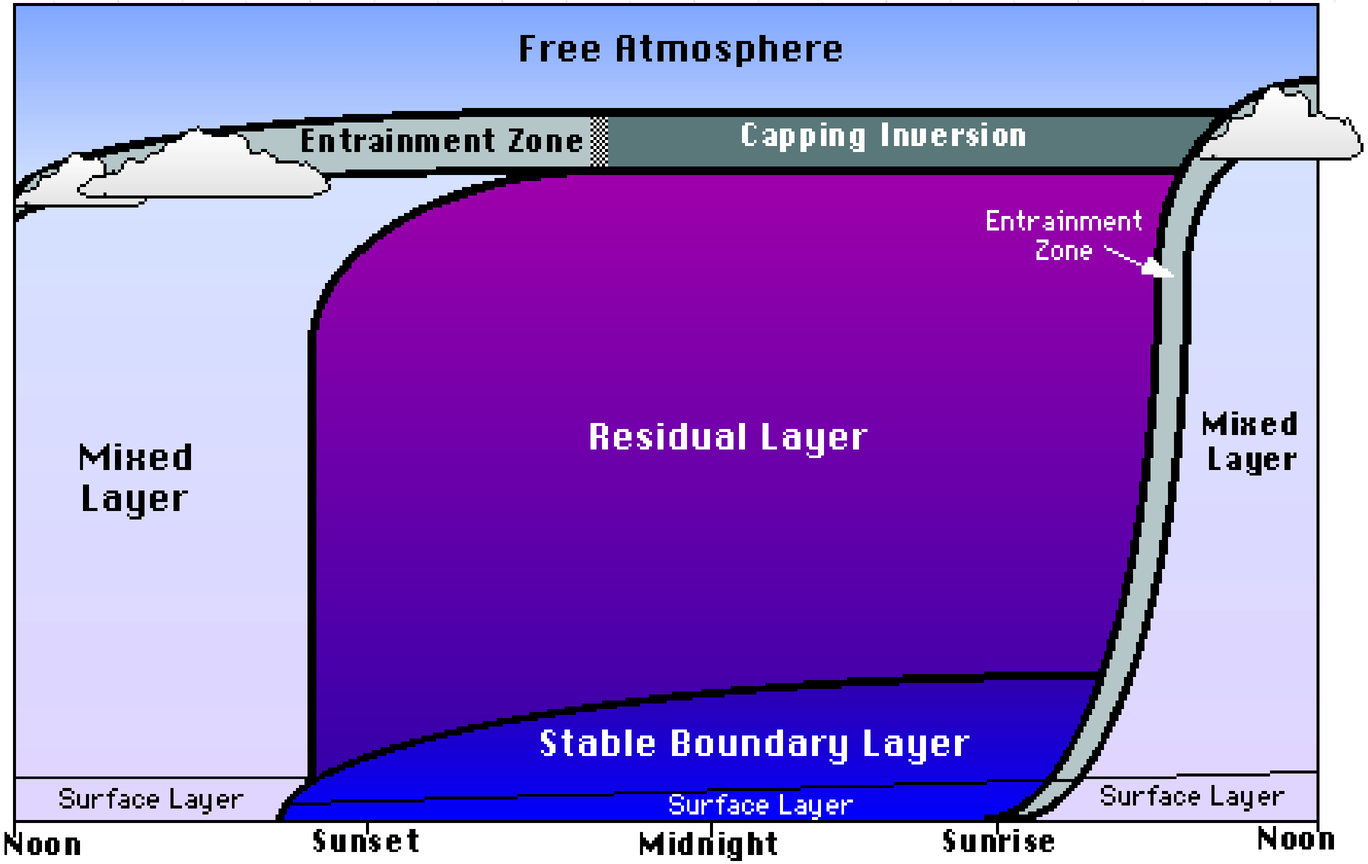
Turbulent Heat Flux $H = \rho C_p \overline{w\theta}$



Unstable

Stable

At clear skies in Spring and Summer:
Strong diurnal variation over Land (order 100 m to several kilometers)!



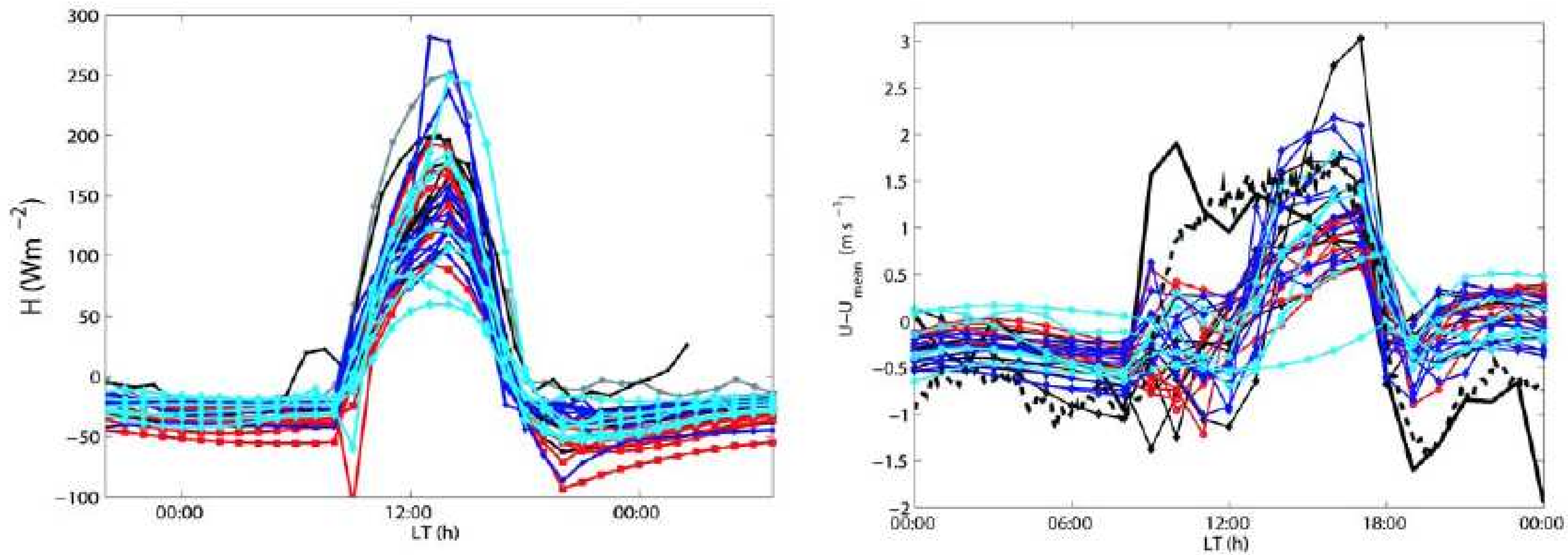
Structure of Planetary Boundary Layer

adapted from Stull, 1988.

Do we really understand?

GEWEX NEWS
WCRP
World Climate Research Programme
(A Programme of WMO, ICSU and IOC)
GABLS
GEWEX Atmospheric Boundary Layer Study
Vol. 17, No. 1 Global Energy and Water Cycle Experiment February 2007

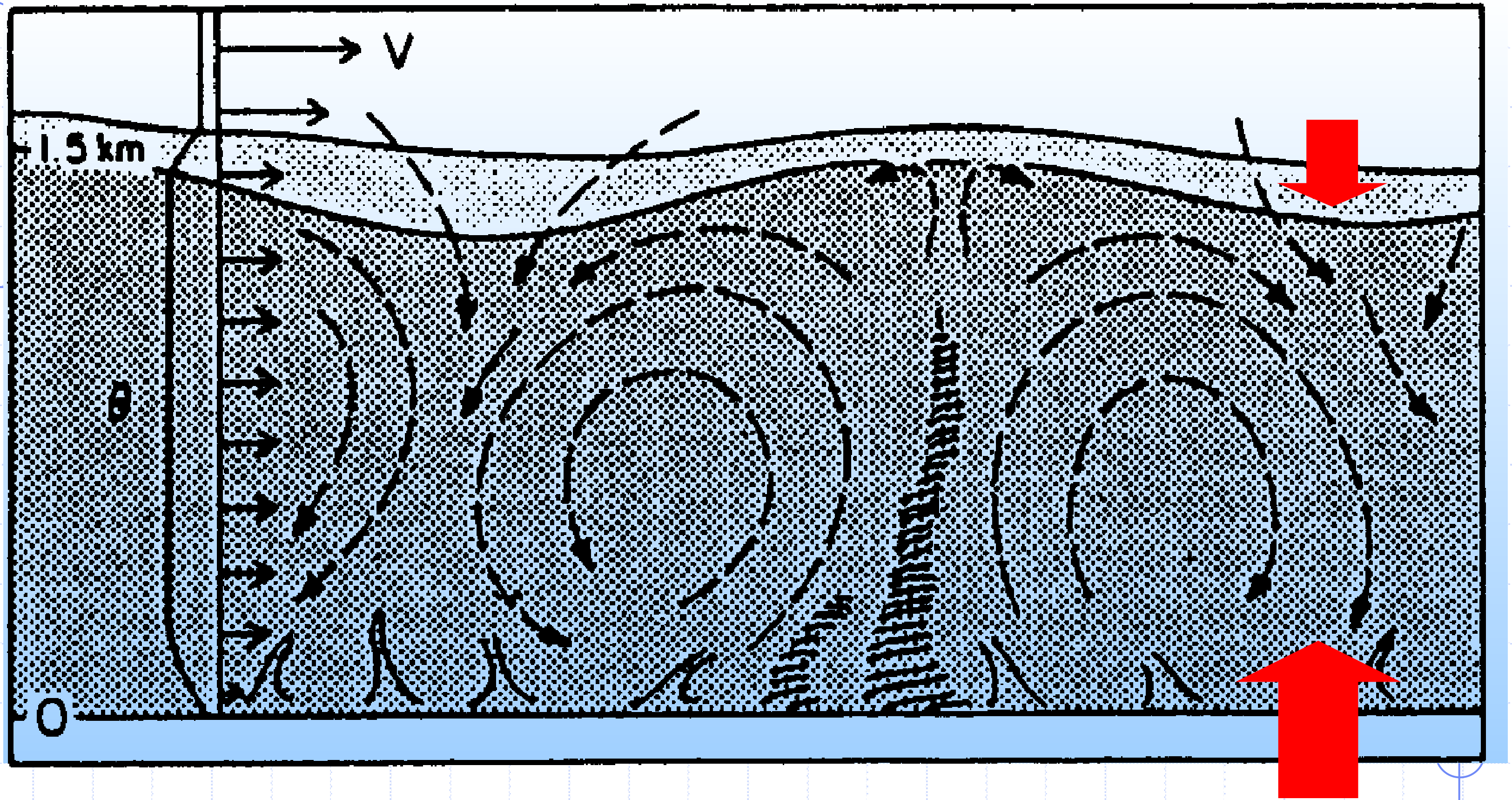
GABLS INTERCOMPARISON SHOWS THAT MODELS DIFFER CONSIDERABLY AND UNDERESTIMATE DIURNAL CYCLE OF WIND SPEED



First model results for GABLS2 using prescribed surface temperatures (Svensson and Holtslag, 2007)

Convective Boundary Layer (CBL) or Mixing Layer

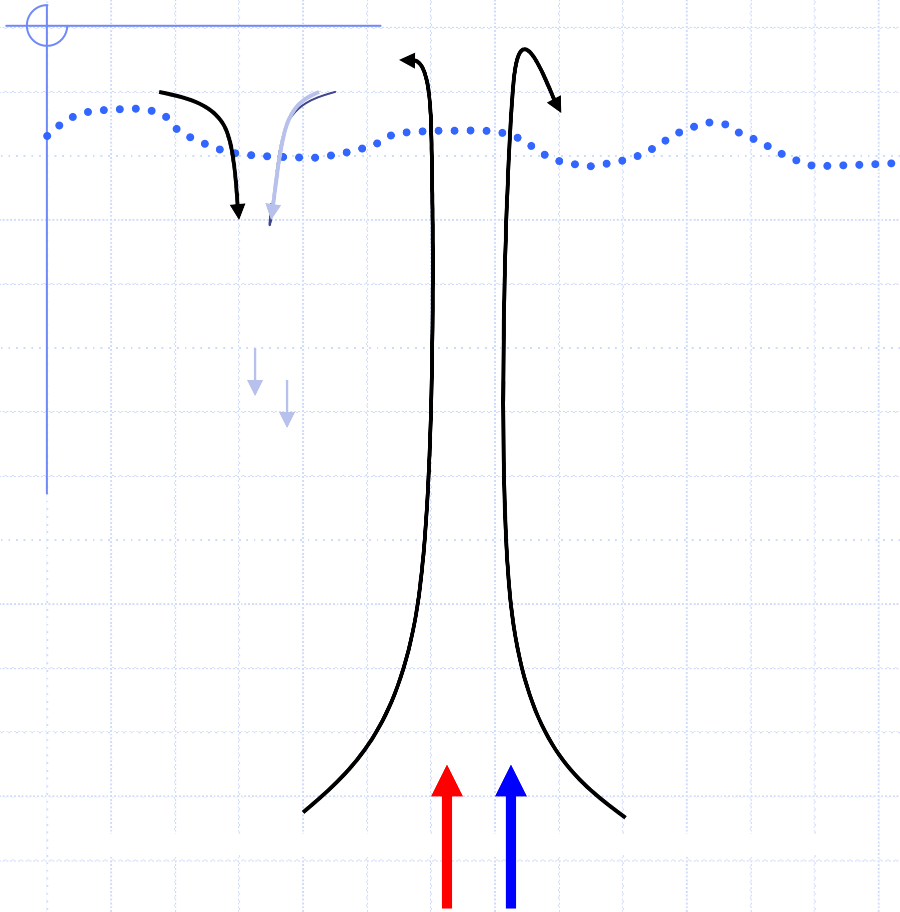
Turbulence is dominated by buoyancy



Strong mixing leads to rather uniform profiles,
in particular for potential temperature

(Figure by John Wyngaard, 1985)

Essential processes to be represented in the CBL

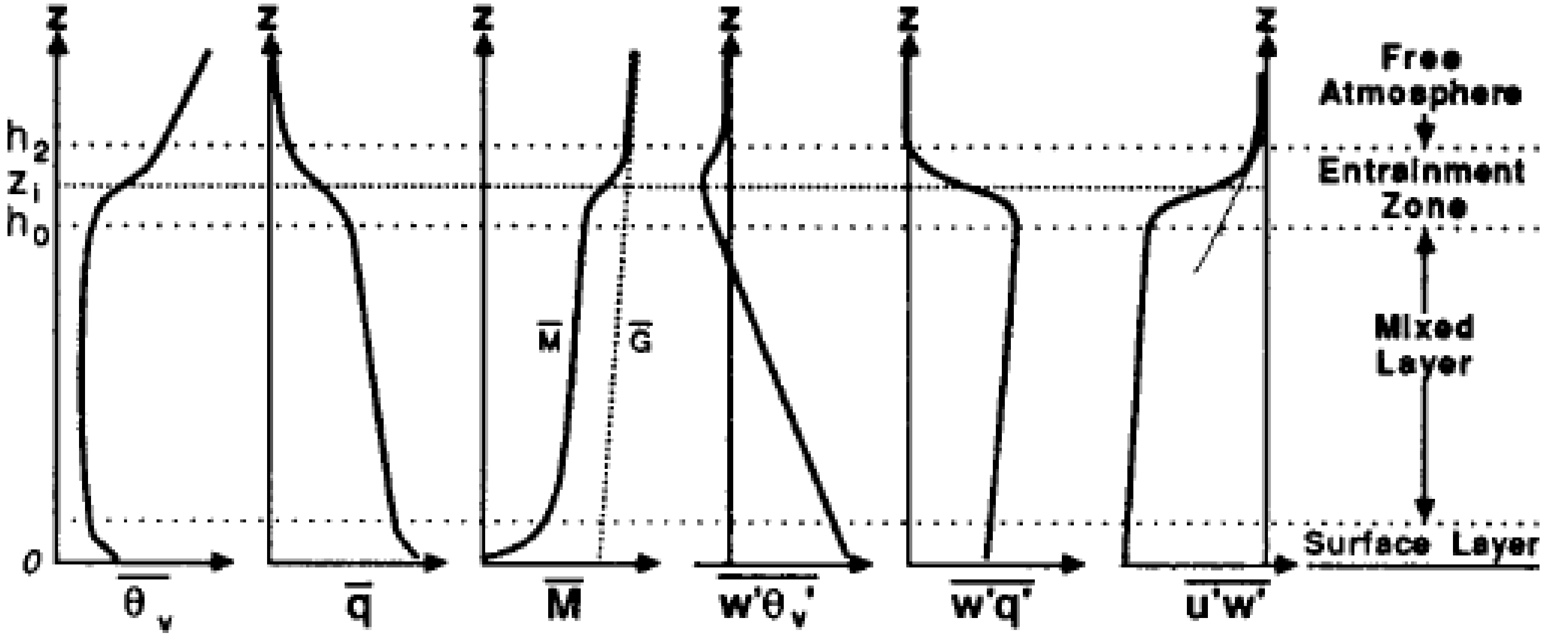


Entrainment
(exchange fluxes)

Turbulent mixing
(turbulent fluxes)

Interaction with surface
(surface fluxes)

CBL mean profiles and fluxes

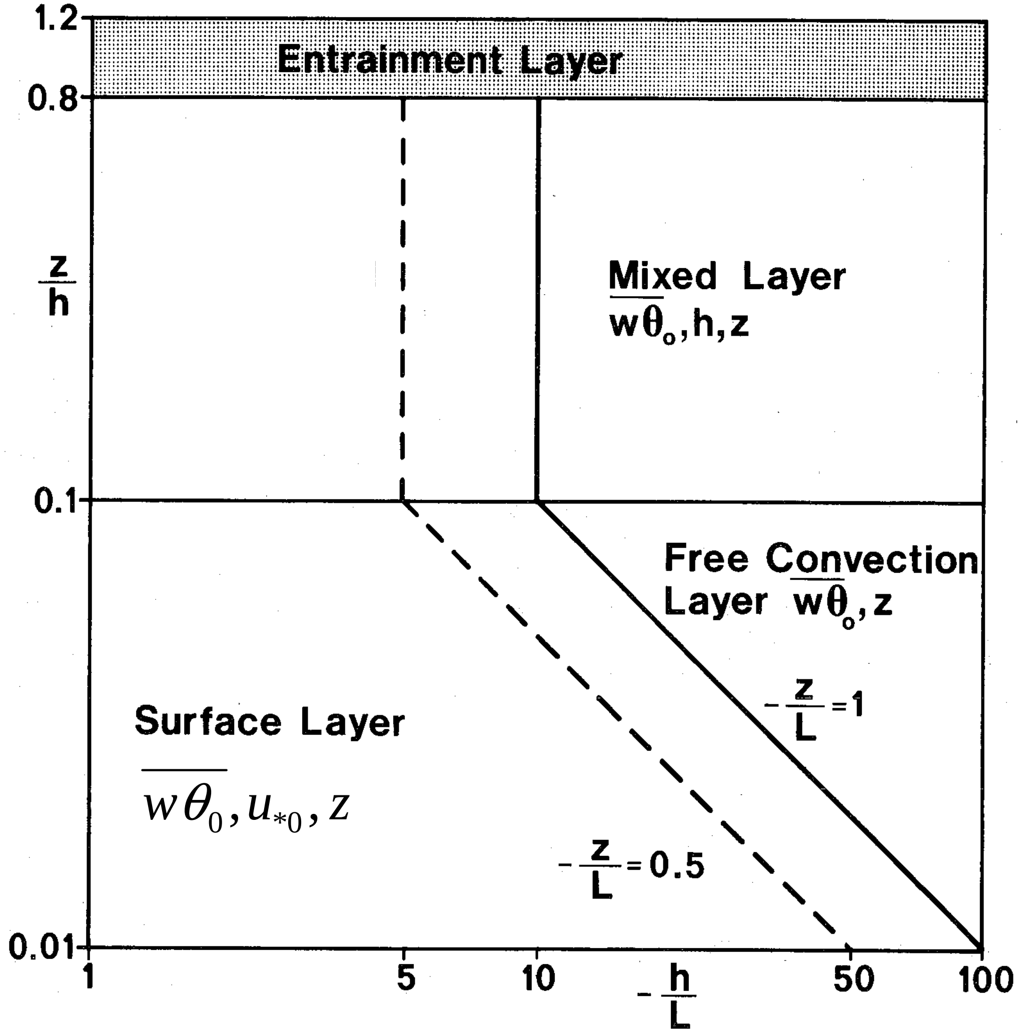


Potential temperature | Specific humidity | Wind magnitude | Fluxes of heat, water vapor, momentum

$$Friction\ velocity\ u_{*0} : u_{*0}^4 = (-\overline{uw_0})^2 + (-\overline{vw_0})^2$$

Various regions in unstable boundary layer

depending on height z, turbulent depth h and Obukhov length L



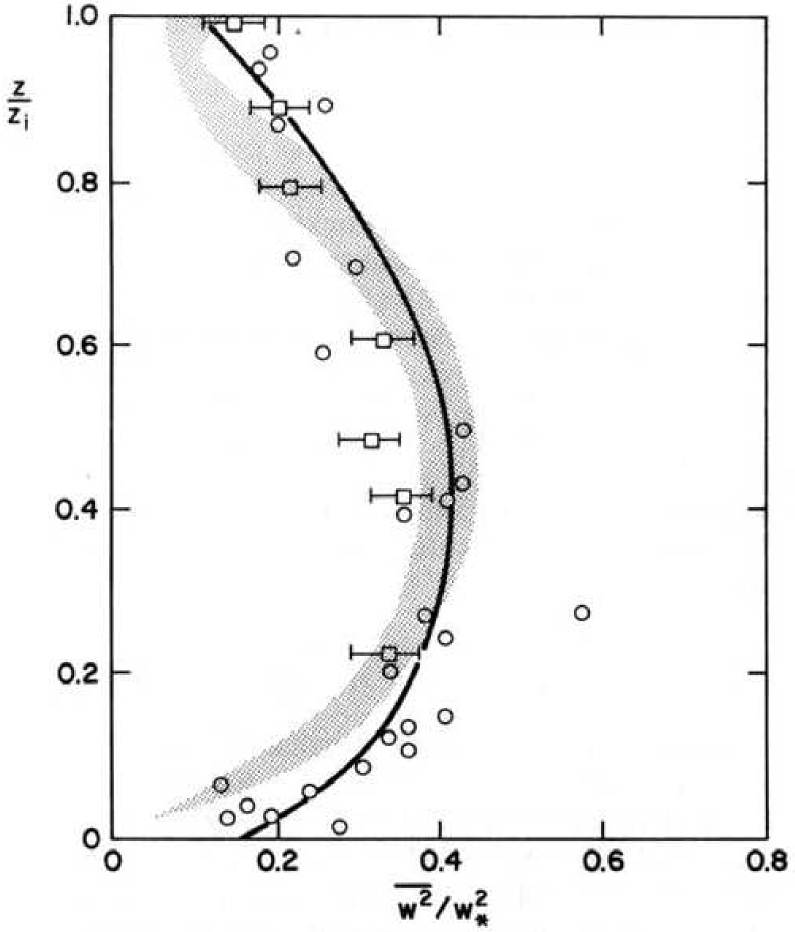
$$L \equiv -\frac{u_{*0}^3}{\kappa g \overline{w\theta_0} / \overline{\Theta}}$$

$$w_*^3 \equiv g \overline{w\theta_0} h / \overline{\Theta}$$

$$\frac{w_*^3}{u_{*0}^3} = -\frac{h}{\kappa L}$$

(after Holtslag and Nieuwstadt, 1986)

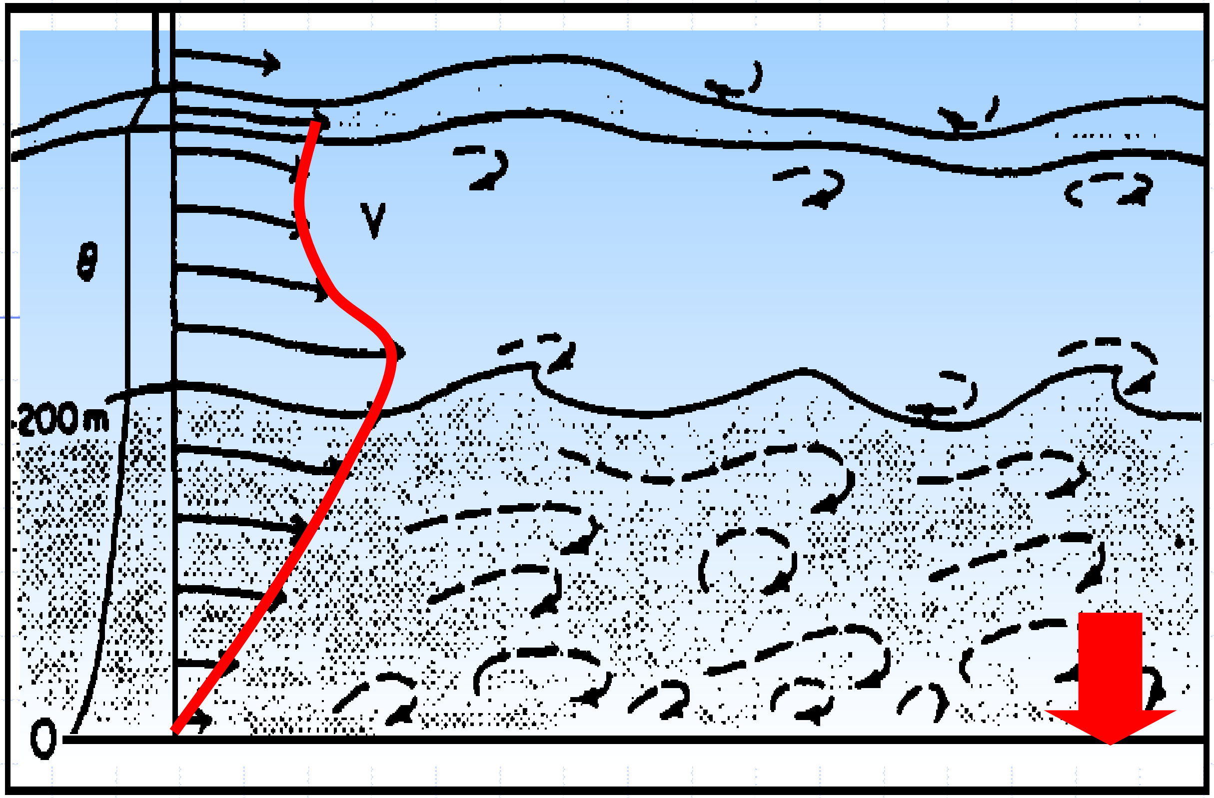
Application of CBL scaling



Vertical velocity variance versus relative height by LES, field data and convection tank data

(after Holtslag and Moeng, 1991)

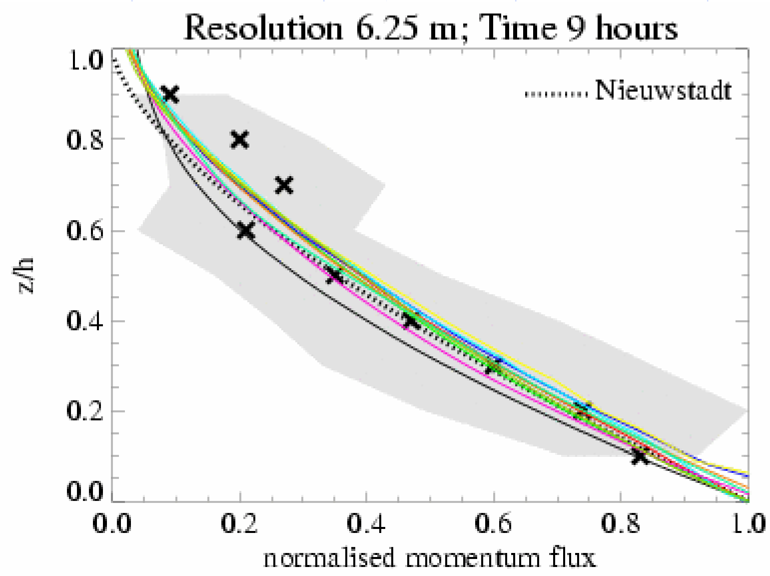
Stable boundary layer

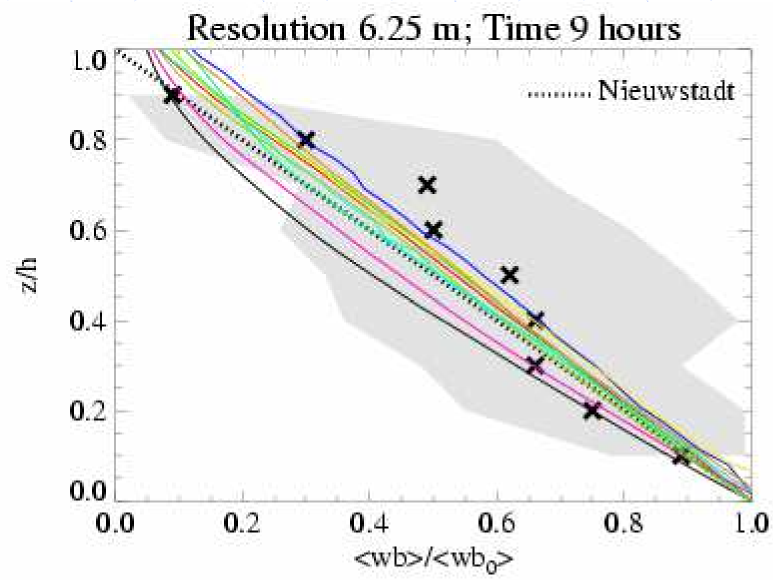


Turbulence by friction, surface cooling stabilizes
Large gradients in temperature and wind

(Figure by John Wyngaard, 1985)

Flux profiles Stable boundary layer





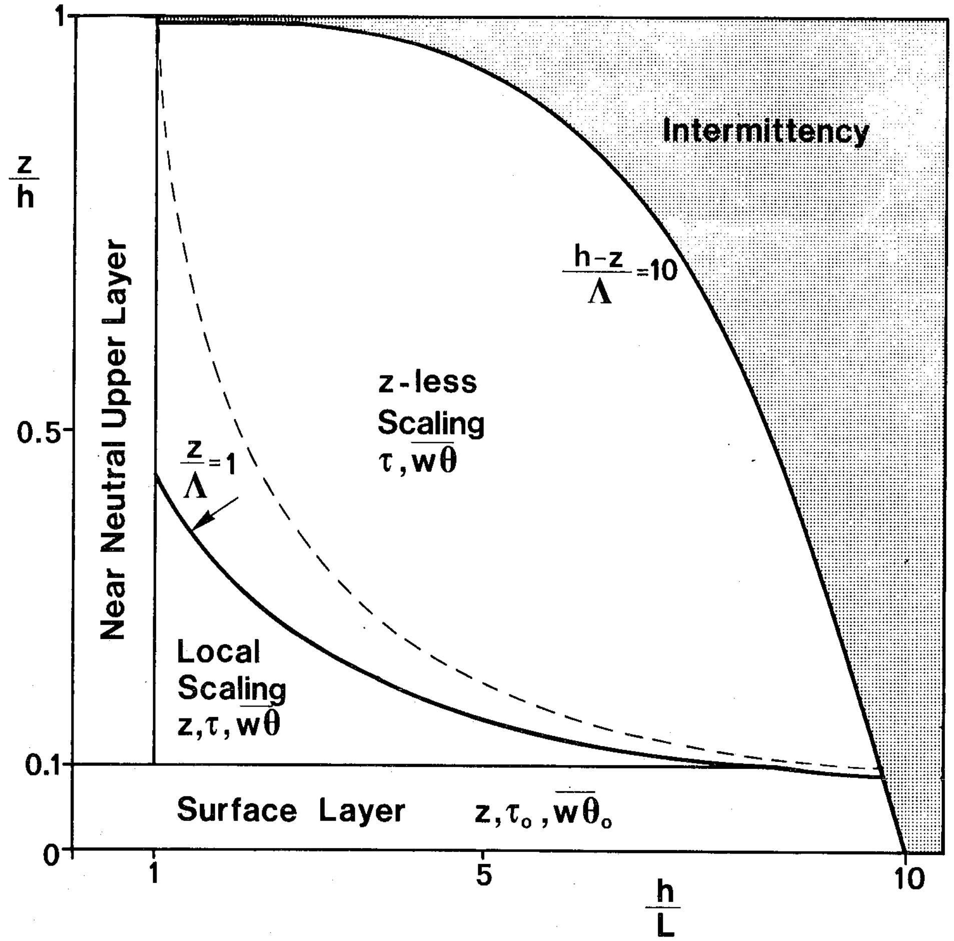
Momentum flux

Heat flux

Grey band: LES results by Beare et al (2006) for GABLS1
X: Cabauw data by Nieuwstadt (1984)

Various regions in stable boundary layer

depending on height z, turbulent depth h and Obukhov length L



$$\Lambda \equiv -\frac{u_*^3}{\kappa g \overline{w\theta} / \overline{\Theta}}$$

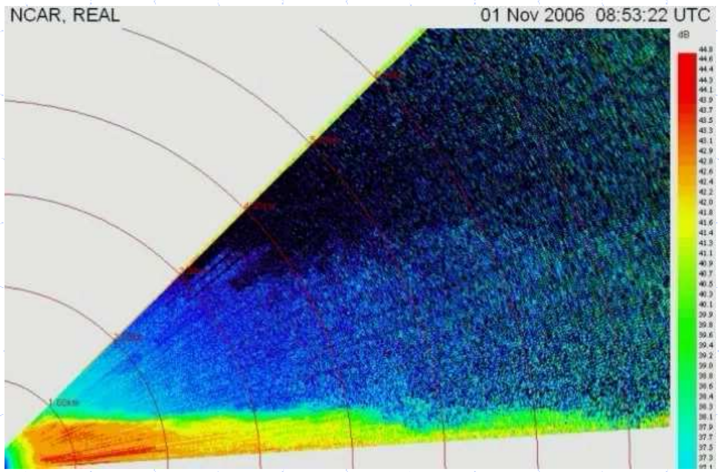
$$\tau = u_*^2$$

(after Holtslag and Nieuwstadt, 1986)

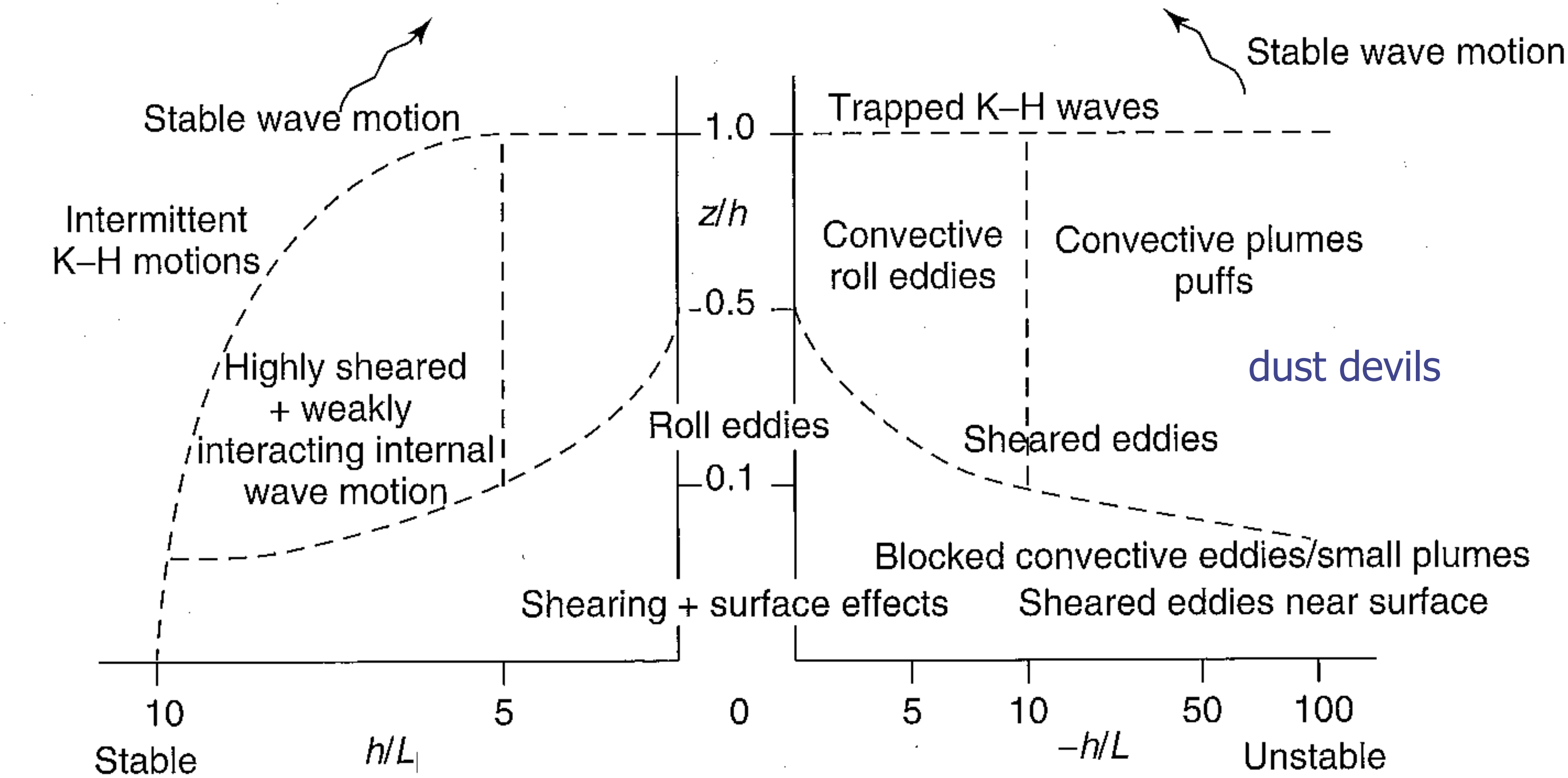
At night, besides of turbulence radiative cooling…

© Vincent van Gogh

waves



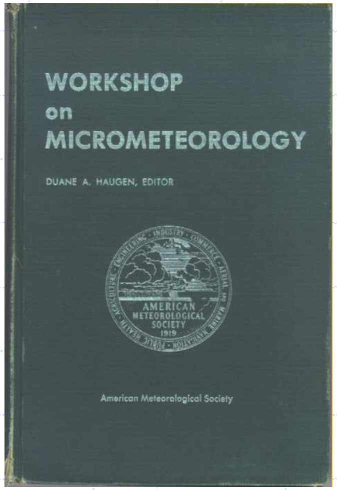
Sketch of ABL processes depending on stability



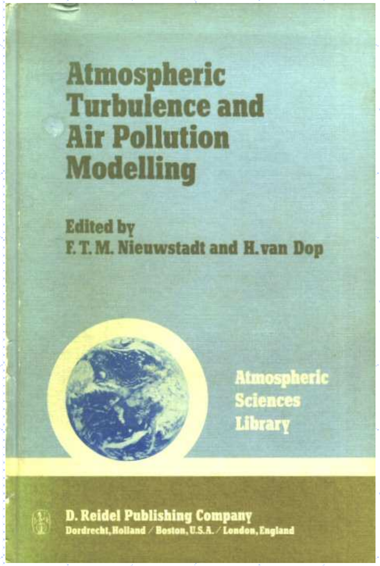
(After Holtslag and Nieuwstadt 1986 and Nieuwstadt and Hunt 2003)

Some history

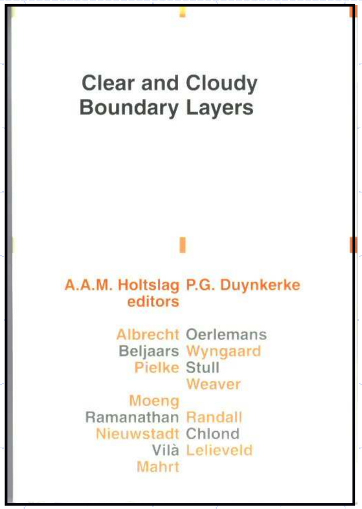
Workshop on Micrometeorology
(Haugen, 1973)



Atmospheric Turbulence and Air Pollution Modelling
(Nieuwstadt and Van Dop, 1982)



Clear and Cloudy Boundary Layers
(Holtslag and Duynkerke, 1998)



Any progress?
Challenges?

Flux profile relations in atmospheric surface layer

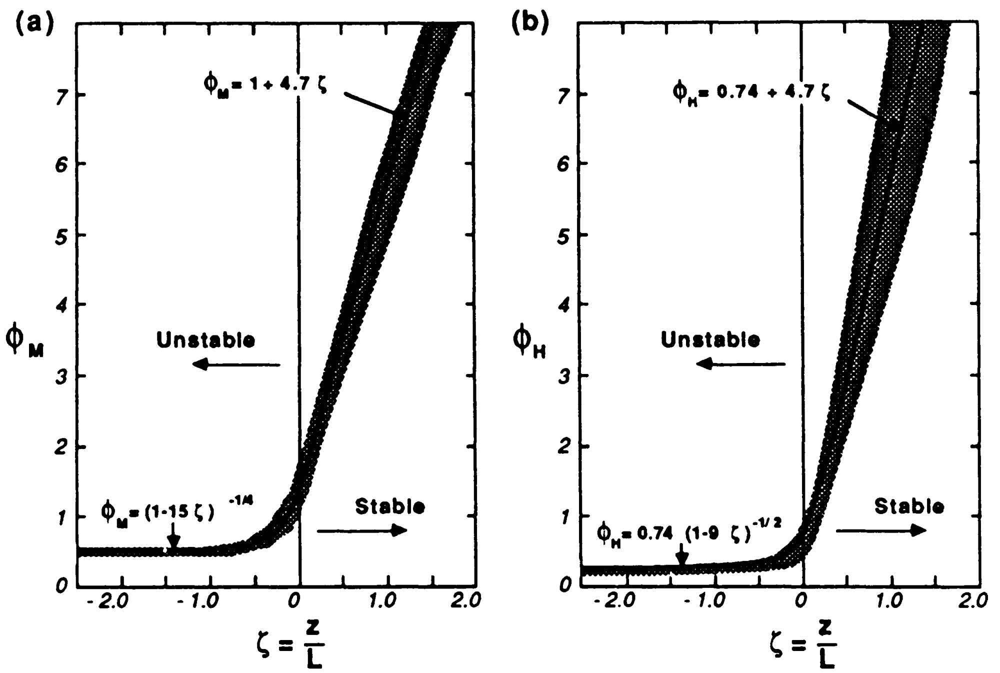


Fig. 9.9 (a) Range of dimensionless wind shear observations in the surface layer, plotted with interpolation formulas. (b) Range of dimensionless temperature gradient observations in the surface layer, plotted with interpolation formulas. After Businger, et al. (1971).

$$\phi_m \equiv \frac{\kappa z}{u_{*0}} \frac{d\overline{U}}{dz} = f(z/L)$$

$$\phi_h \equiv \frac{\kappa z}{\theta_{*0}} \frac{d\overline{\Theta}}{dz} = f(z/L)$$

$$\frac{1}{L} \equiv \frac{\kappa g \theta_{*0} / \overline{\Theta}}{u_{*0}^2}$$

$$\overline{w\theta_0} = -u_{*0}\theta_{*0}$$

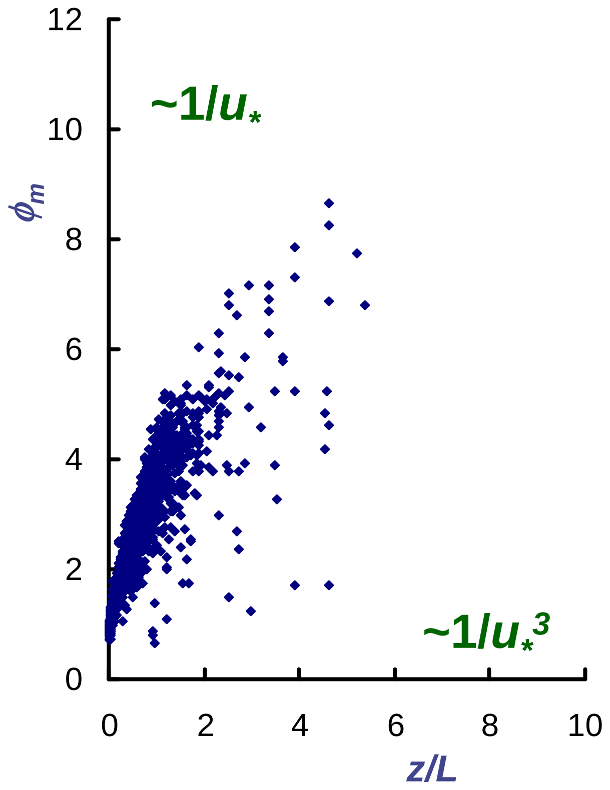
Still extremely useful in applications and modeling

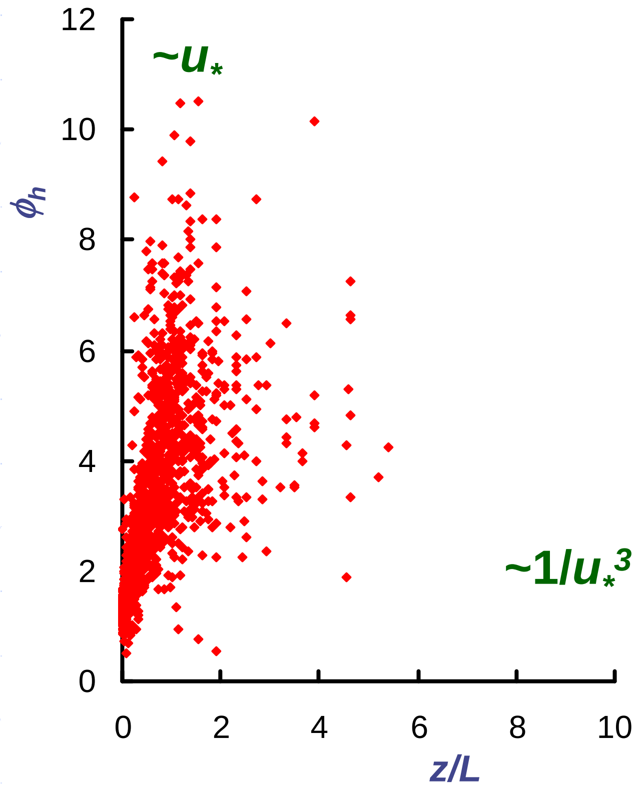
Intermezzo on self correlation: Real and randomized data

"Construct a randomized dataset by using the original observations as a pool of values to draw from at random" (Klipp & Mahrt, 2004)

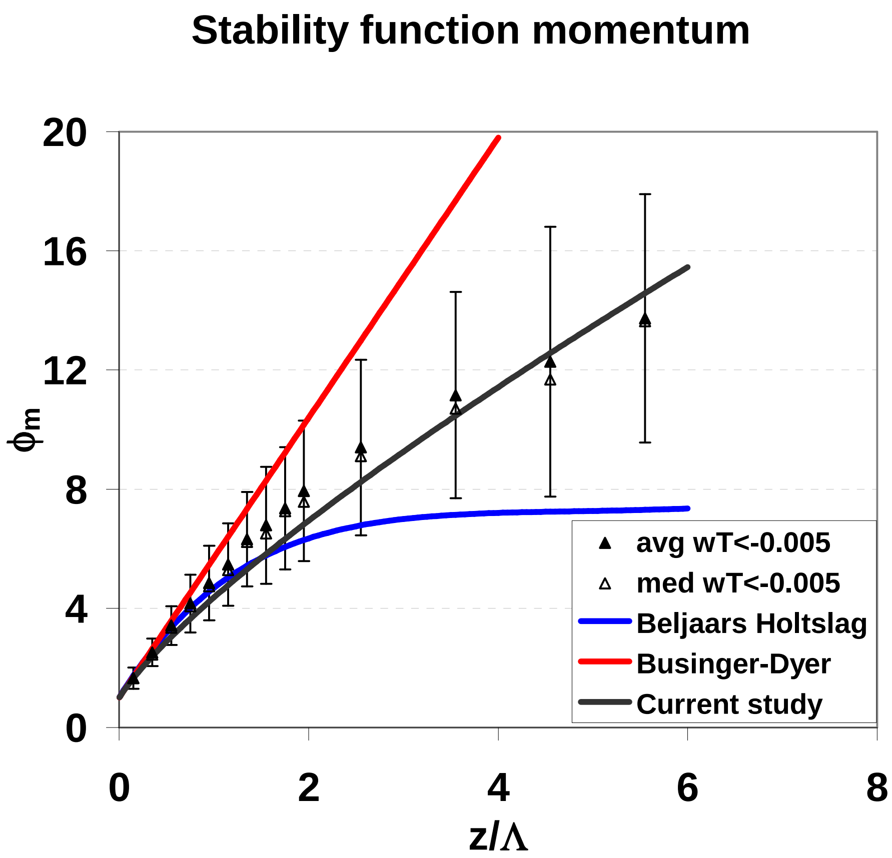
For example:

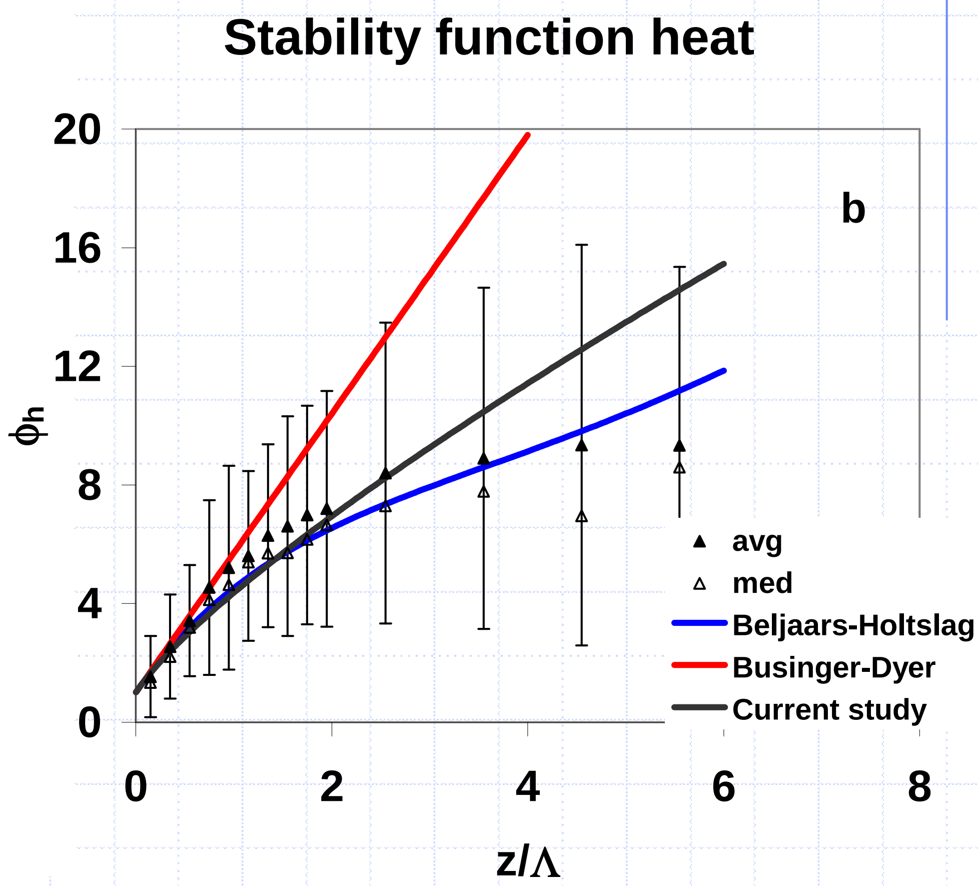
H_{real}	H_{random}
-24	-15
-20	-10
-28	-25
-30	-28
-10	-16
-12	-18
-16	-20
-18	-24
-15	-30
-25	-12



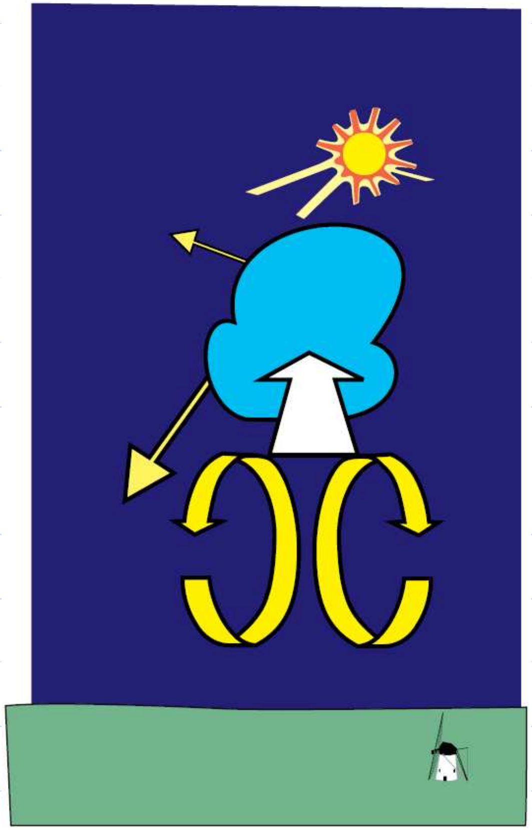


(Baas et al, 2006, J.Atmos.Sci.)



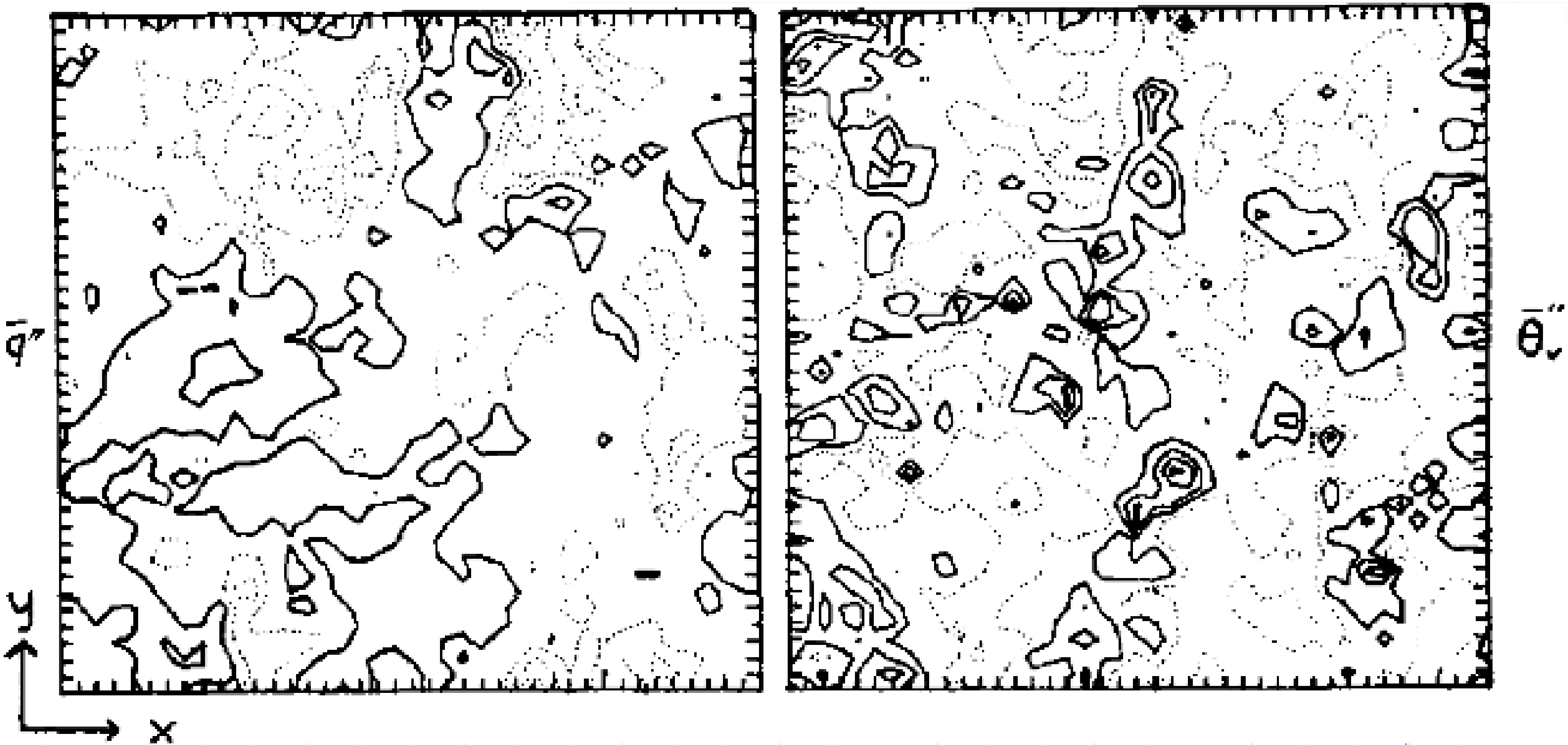


The gradients functions for momentum and heat
using local scaling for CASES99 data
(Steeneveld et al, 2006)



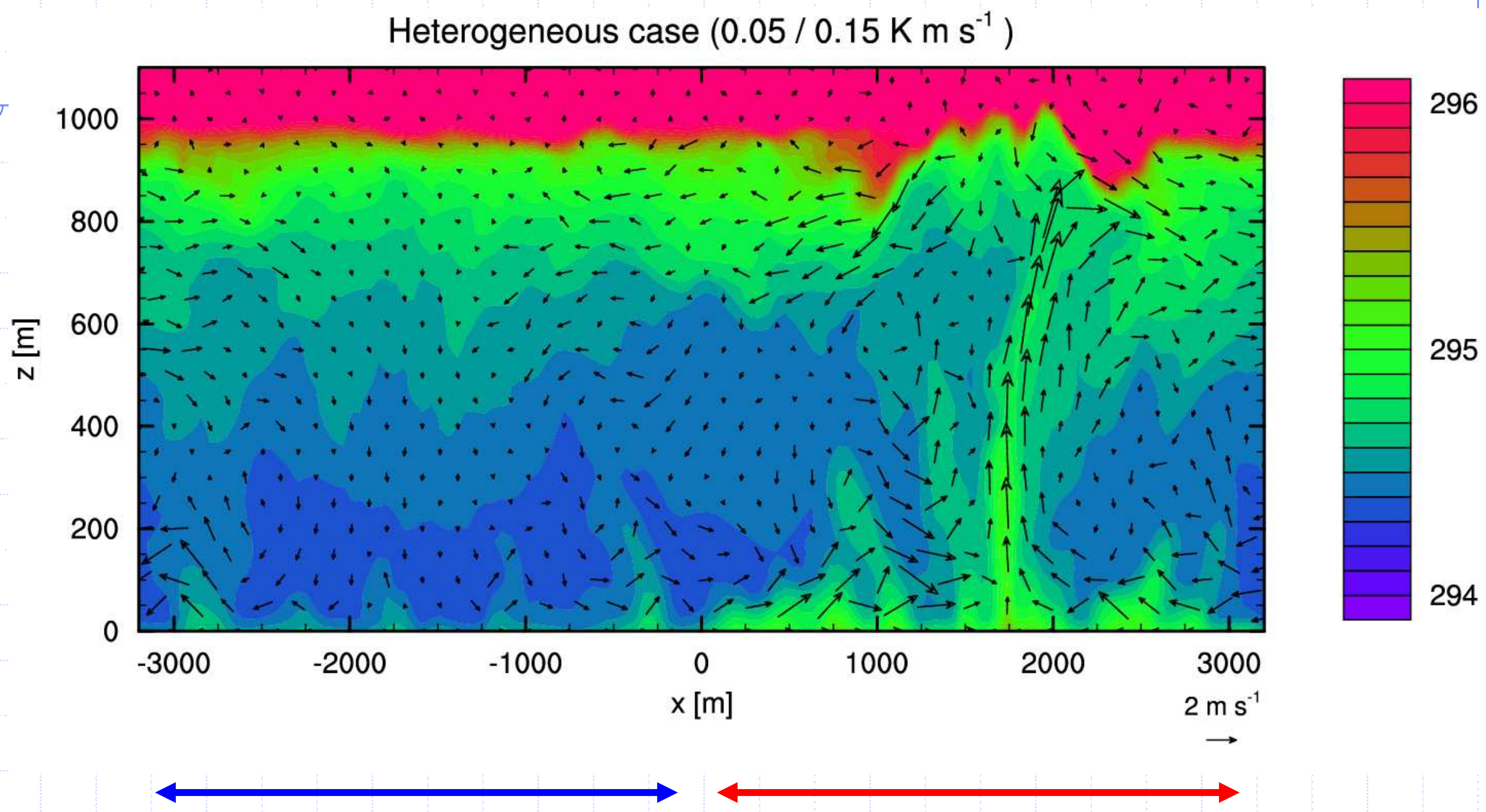
Many LES Studies after
pioneering work of Deardorff
in 1960ies and 70ies
and examples will be given
in this Summer school

Since 1980's more attention for
boundary layer clouds:
Formation, microphysics,
turbulence, radiation,
parameterization and impacts
on weather, air quality
and climate,..



Deardorff's (1974 BLM) LES of a horizontal cross-section in a convective boundary layer at 0.38 z_i with 40^3 grid points inside a volume 5 km x 5 km x 2 km showing humidity (left) and temperature (right) fluctuations.

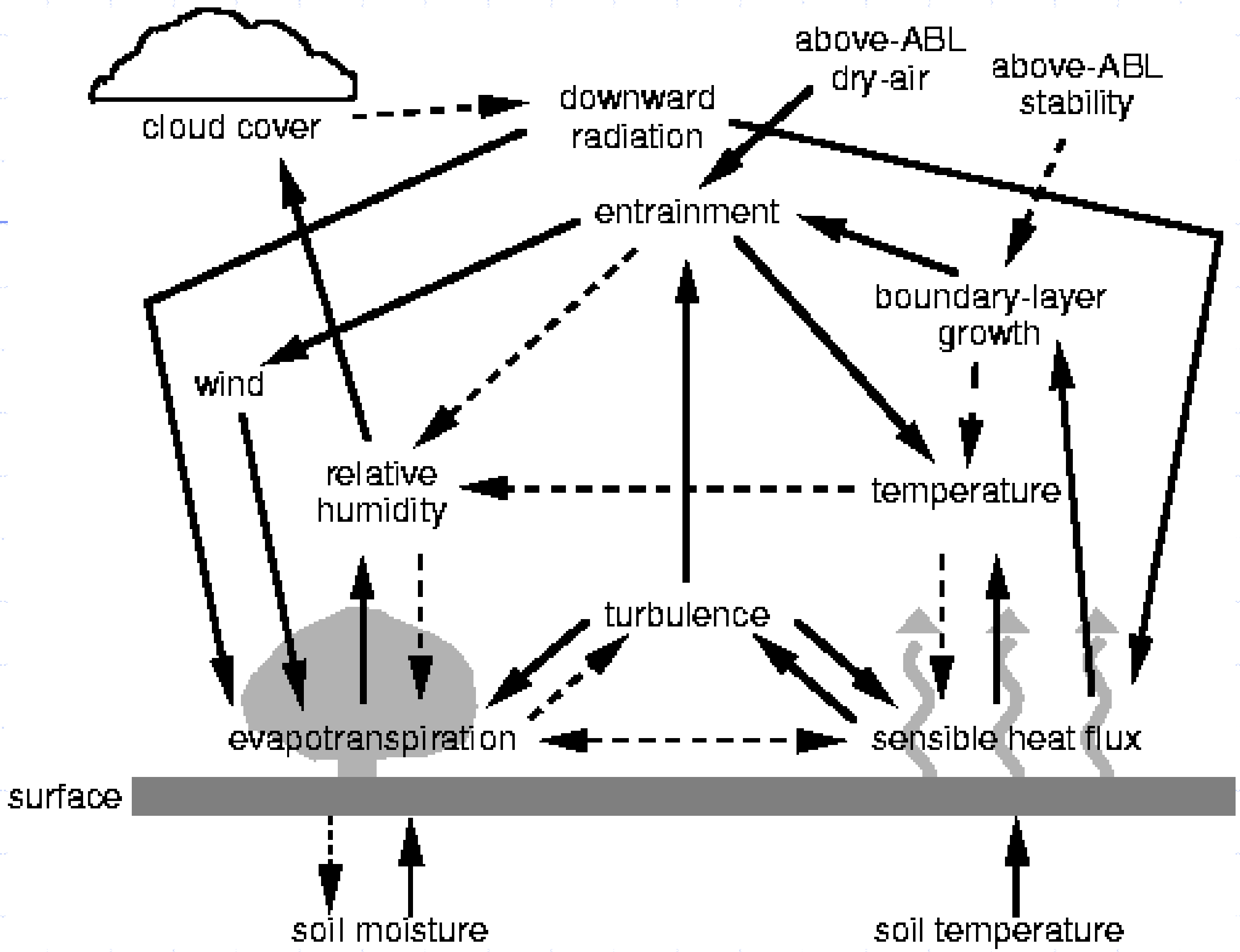
Convection above heterogeneous land



Cold and moist

Warm and dry

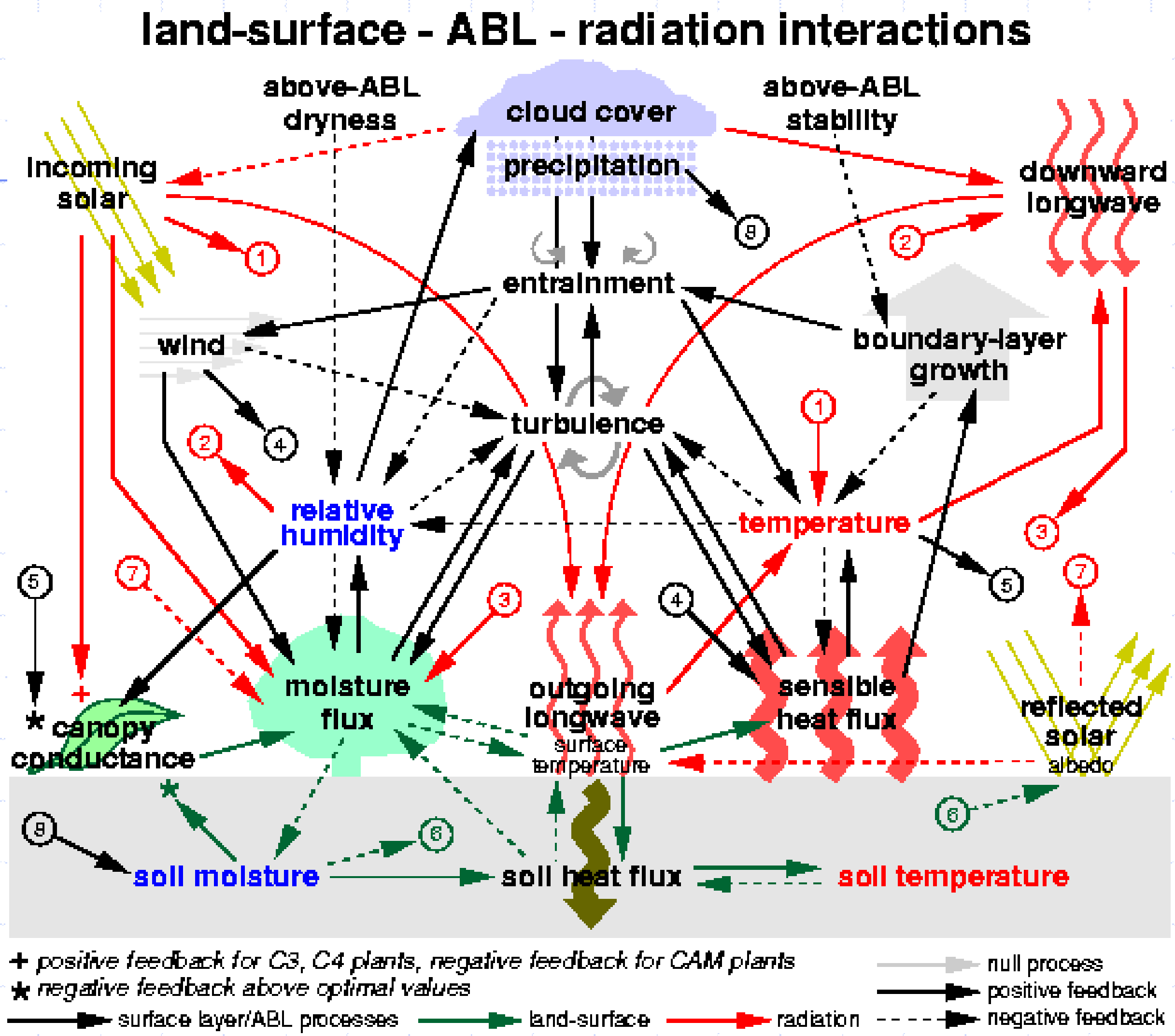
Thanks to Chiel van Heerwaarden and Jordi Vila



The interaction of the land-surface with the atmospheric boundary layer during daytime includes many processes and feedback mechanisms

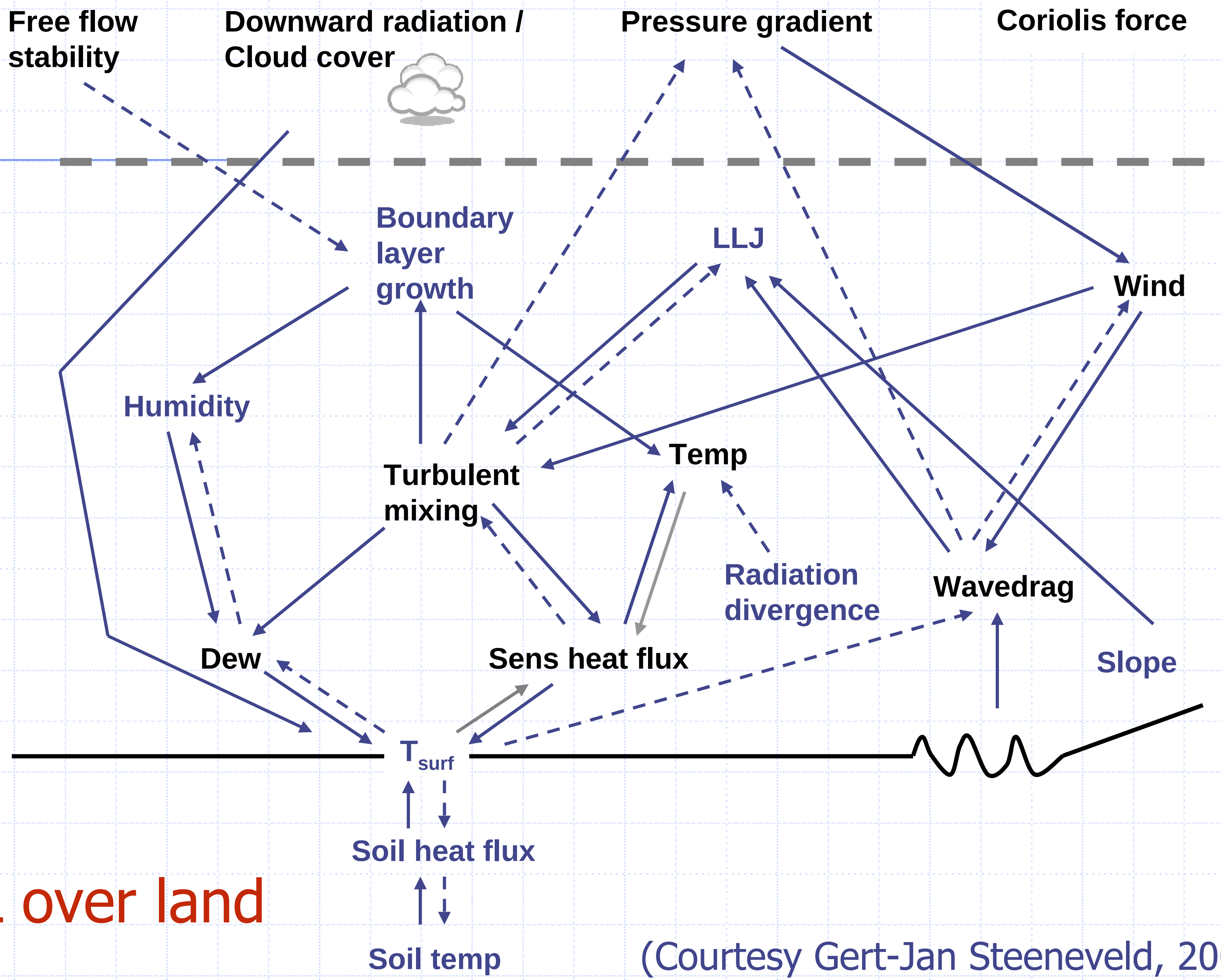
(solid arrows=positive feedback, dashed arrows=negative feedback)

(Ek, M.B., and A.A.M. Holtslag, 2004, J. Hydrometeorology, vol. 5, p. 86-99)



(Courtesy Michael Ek)

Still a big challenge to understand and represent these processes!



SBL over land

(Courtesy Gert-Jan Steeneveld, 2007)

Ten Remaining Problems

(as presented by Don Lenshow, BLT Stockholm, 2008)

- Accurate estimates of PBL height and entrainment rate
- Quantifying effects of chemical reactions on PBL flux and concentration profiles
- Growth of scalar variance and length scale
- Effects of vegetated and urban canopies and wind farms on the PBL
- PBL structure in the nocturnal PBL and during transitions
- Horizontal heterogeneity (including orography)
- Interactions of clouds with the PBL
- Effects of mesoscale structure on PBL dynamics
- Development of improved closures for LES
- Turbulence at the interfaces and over ocean waves

Parameterization of the Atmospheric Boundary Layer

A View from Just Above the Inversion

J. TEIXEIRA, B. STEVENS, C. S. BRETHERTON, R. CEDERWALL, J. D. DOYLE,
J. C. GOLAZ, A. A. M. HOLTSLAG, S. A. KLEIN, J. K. LUNDQUIST,
D. A. RANDALL, A. P. SIEBESMA, AND P. M. M. SOARES
(Bulletin American Meteorological Society (BAMS), 2008)

Some ongoing issues and challenges:

How to (better) represent sub-grid vertical fluxes?

How to represent cloud fraction and cloud water?

How to solve the equations (more) efficiently?

and

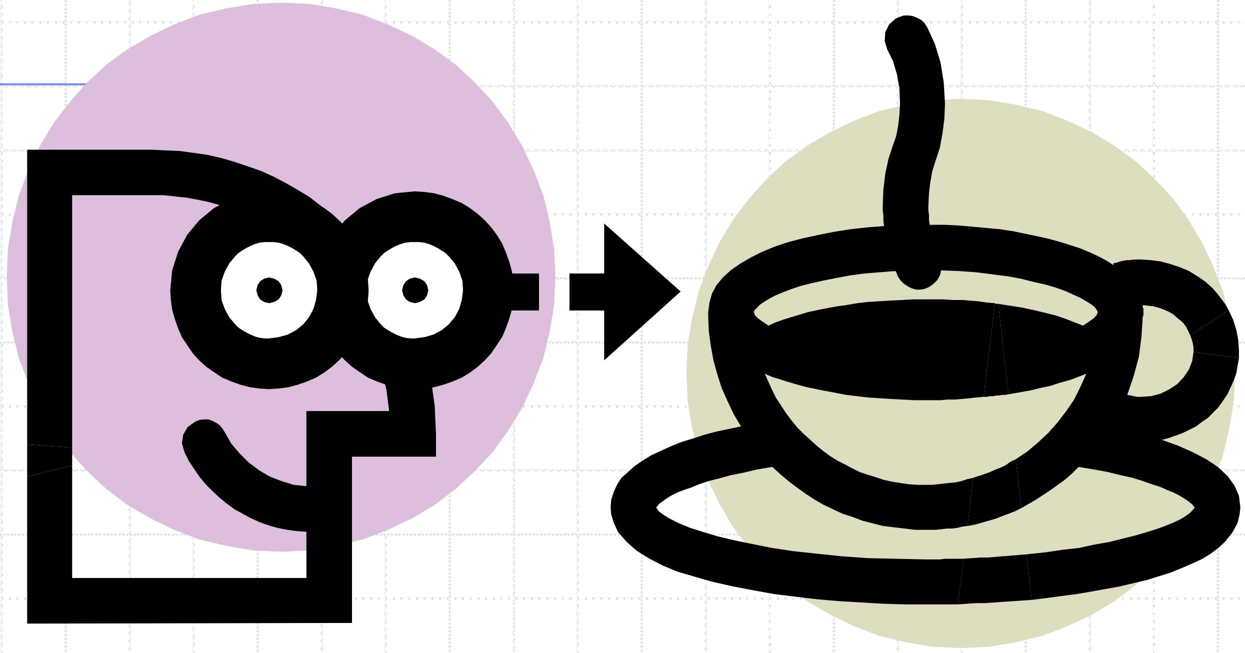
How to develop more general parameterizations that represent all types of boundary layers?

Summary

Real progress is made in understanding of Atmospheric Boundary Layers in last decades

Many issues still need attention:
Stable boundary layer
Diurnal cycle, morning and evening transition
Boundary layer clouds and fog
Interaction of ABL with the earth's surface
Heterogeneity
…

Tomorrow: talk on Modeling Atmospheric Boundary Layers!



Break