Characterizing Local-ABL Coupling with a Single Column Model

Michael Ek[1] and Bert Holtslag[2]

1.*NCEP/EMC, Camp Springs, Maryland USA*

2.*Meteorology and Air Quality, Wageningen Univ.*

GLASS-WATCH/LoCo workshop

25-27 June 2008, KNMI, De Bilt, Netherlands

Outline

- Motivation
- Land-atmosphere interaction
- Theory/analytical development
- Single Column Model runs & analysis
- Summary
- Future

Motivation

- **Accumulated heat and moisture fluxes to the atmosphere on local spatial and diurnal time scales are important for weather and climate.**

- **Soil moisture is an important quantity with “memory”, similar to role of SST.**

- **As such, it is necessary to examine and understand role of soil moisture and humidity on local land-ABL interactions: theory, models/data sets.**

Land-atmosphere interaction

Betts (1996)

Diurnal timescales

Seasonal timescales

Century…

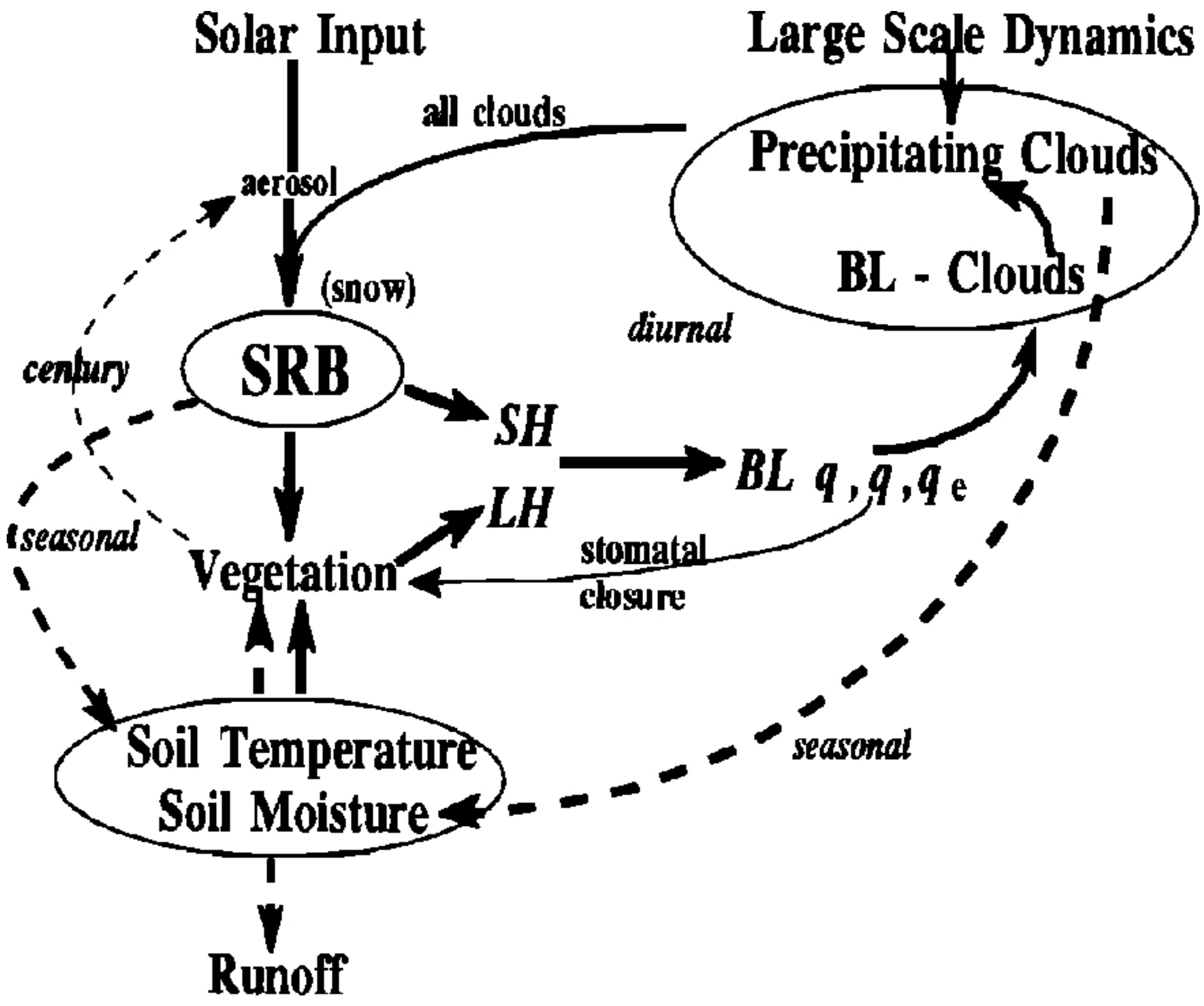


Figure 1. Schematic showing some important land surface-atmosphere interactions on different timescales.

Land-atmosphere interaction

Beljaars (2005)

EC model/ TESSEL

"We discussed including this in a recent document, but dropped it because it was too confusing."

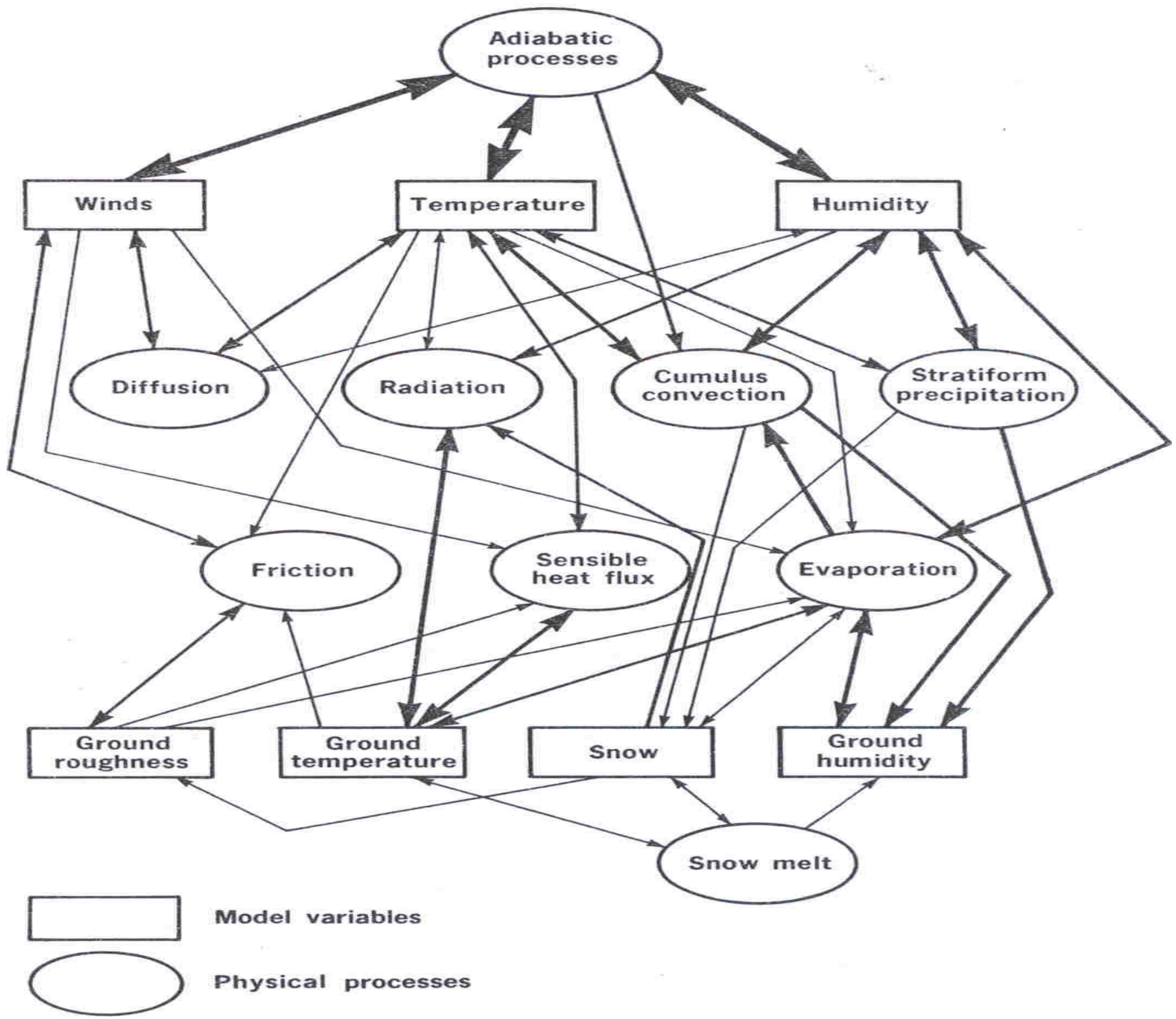
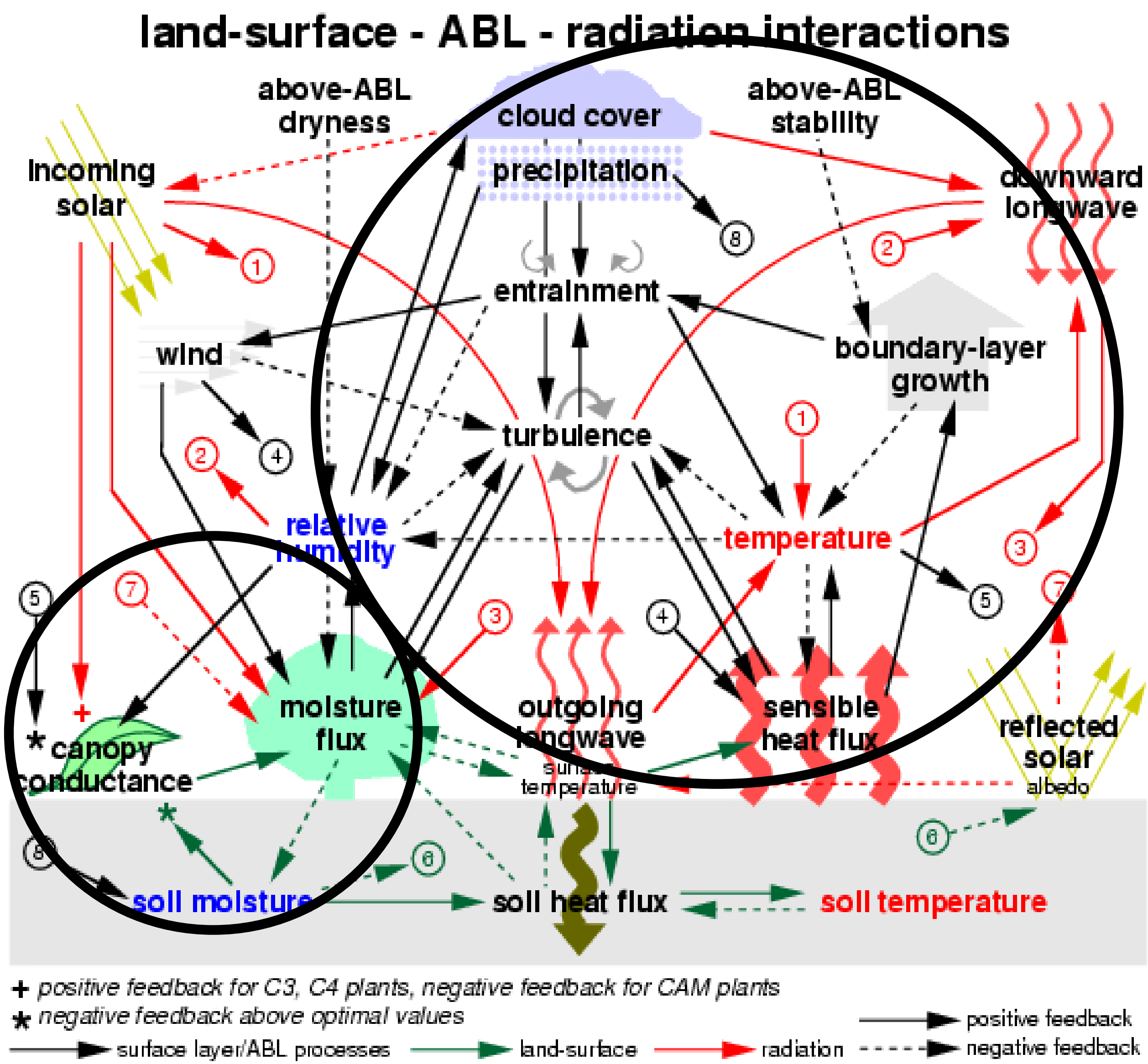


Fig. 1.1 Schematic representation of the processes included in the ECMWF model.

Land-atmosphere interaction

Ek & Holtslag (2005)

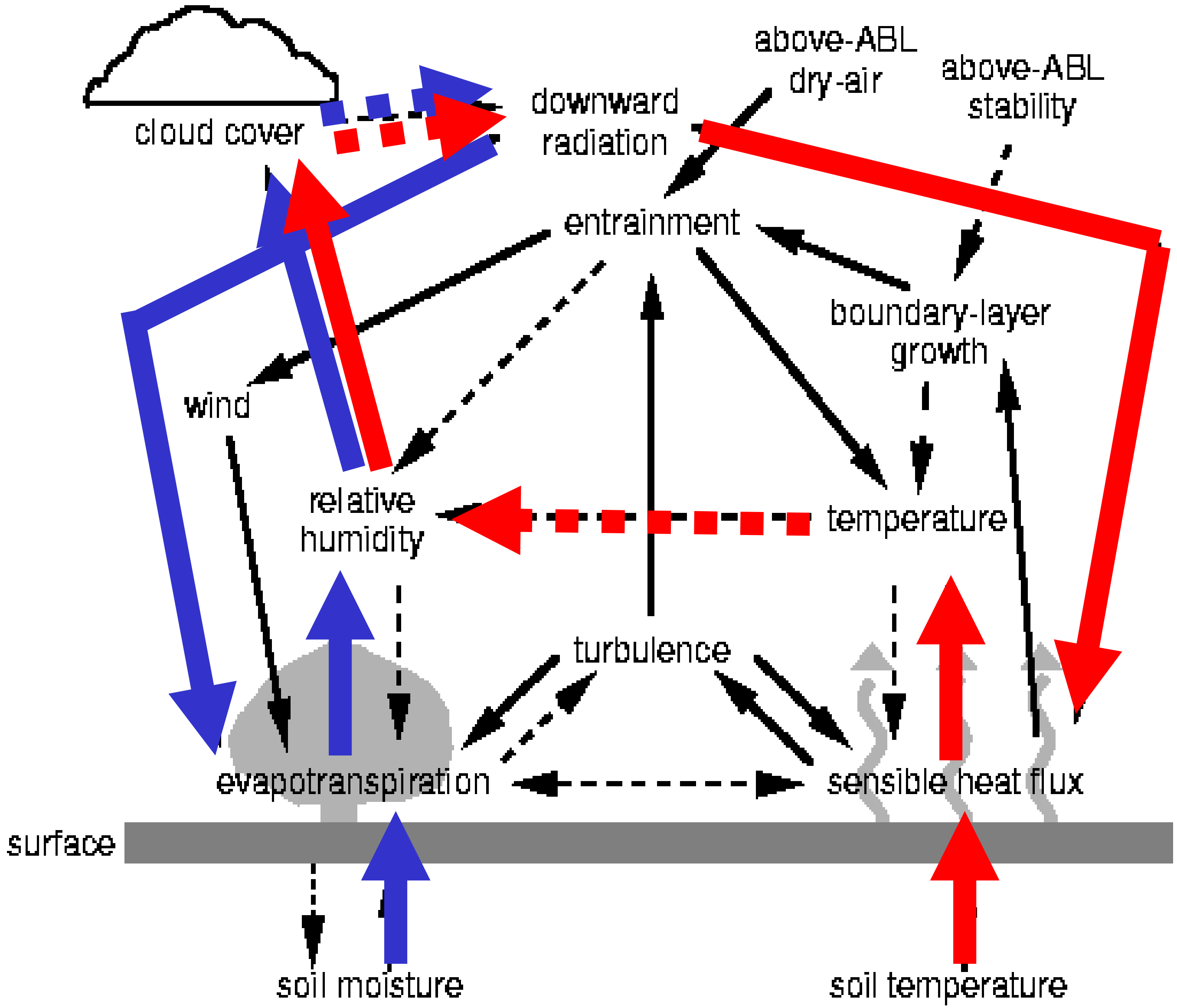
Characterized many land and atmospheric processes & feedbacks for typical daytime with focus on soil moisture vs other processes



Land-atmosphere interaction

Ek & Holtslag (2005)

Simplified.



Theory/analytical development

- Soil moisture, relative humidity, and other land-surface and boundary layer processes affect clouds and convection, and thus are important to the hydrological cycle.

- Examine a relative humidity tendency equation (at the ABL top)

Relative humidity tendency

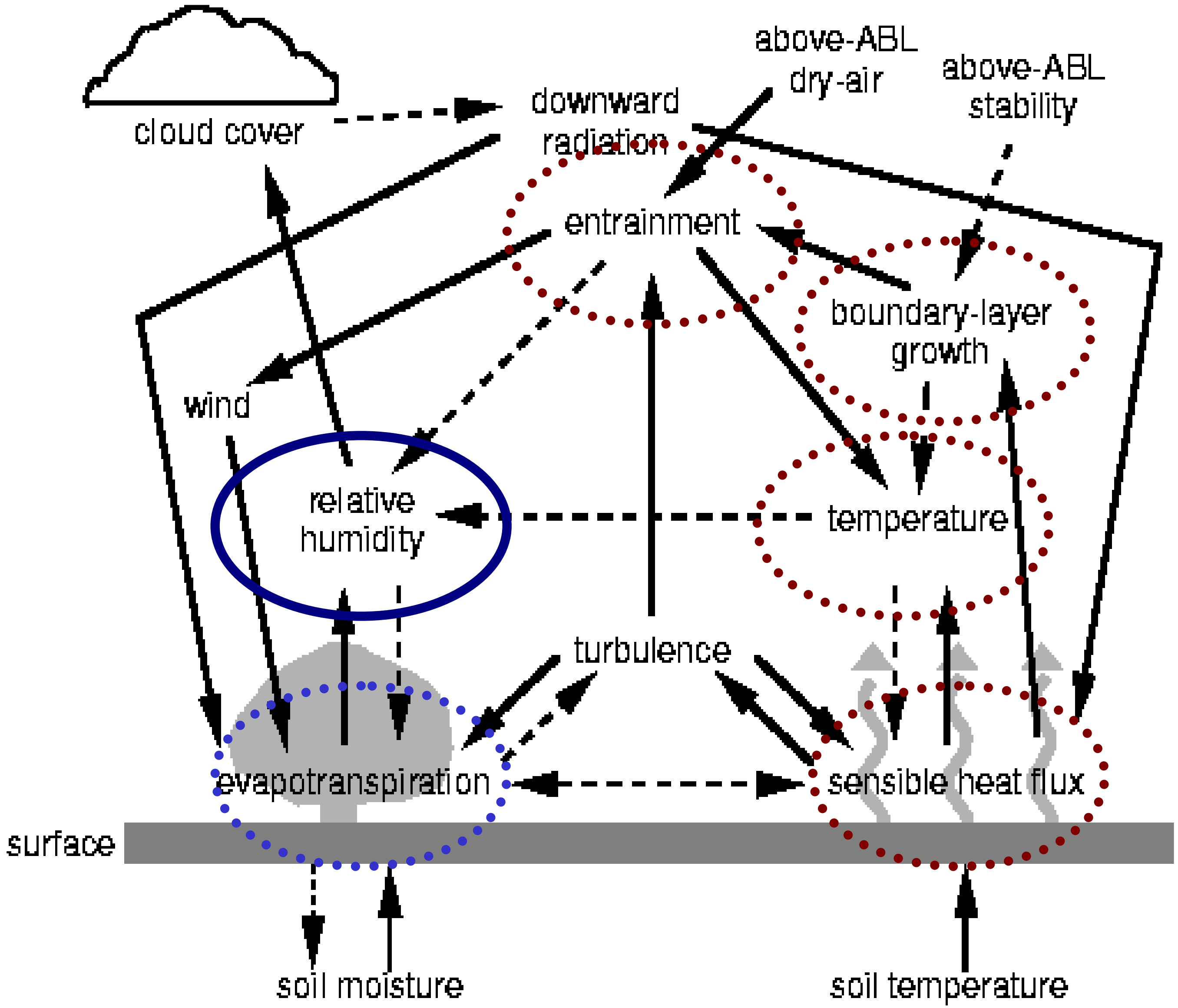
Surface evaporation

Warming due to surface sensible heat flux

ABL growth…

…ABL-top temperature decrease

…ABL-top dry-air & warm-air entrainment



RH tendency

- ABL-top relative humidity (RH) expected to control cloud formation.
- RH tendency:

surface evaporative fraction ↓ ↓

$\partial RH/\partial t = (Rn\text{-}G)/(\rho L_v h q_s)[ef + ne(1\text{-}ef)]$

↑ available energy term ↑ non-evaporative term

ne = effects of non-evaporative processes on RH tendency:

ABL growth ↓

$ne = L_v/c_p(1+C\theta)[\Delta q/(h\gamma\theta)+RH[(c_2/\gamma\theta)-c_1)]$

↑ dry-air entrainment ↑ ABL warming

$$\frac{\partial RH}{\partial t} = \frac{\partial}{\partial t}\left(\frac{q}{q_s}\right) = \frac{1}{q_s}\frac{\partial q}{\partial t} - \frac{RH}{q_s}\frac{\partial q_s}{\partial t} = \frac{1}{q_s}\frac{\partial q}{\partial t} - \frac{RH}{q_s}\frac{\partial}{\partial t}\left(\frac{\epsilon e_s}{p}\right)$$
$$= \frac{1}{q_s}\frac{\partial q}{\partial t} + RH\left(\frac{1}{p}\frac{\partial p}{\partial t} - \frac{1}{e_s}\frac{de_s}{dT}\frac{\partial T}{\partial t}\right) \quad (1)$$

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial t}\left[\theta\left(\frac{p}{p_s}\right)^{R/c_p}\right] \quad (2)$$

$$\frac{\partial T}{\partial t} = \left(\frac{p}{p_s}\right)^{R/c_p}\frac{\partial \theta}{\partial t} + \frac{R_d}{c_p}\frac{T}{p}\frac{\partial p}{\partial t} \quad (3)$$

$$\frac{\partial p}{\partial t} = \frac{\partial p}{\partial z}\frac{\partial h}{\partial t} = -\rho g\frac{\partial h}{\partial t} = -\frac{pg}{RT}\frac{\partial h}{\partial t} \quad (4)$$

$$\frac{\partial T}{\partial t} = \left(\frac{p}{p_s}\right)^{R/c_p}\frac{\partial \theta}{\partial t} - \frac{g}{c_p}\frac{\partial h}{\partial t} \quad (5)$$

$$\frac{1}{e_s}\frac{de_s}{dT} = \frac{L_v}{R_v T^2} \quad (6)$$

$$\frac{\partial RH}{\partial t} = \frac{1}{q_s}\frac{\partial q}{\partial t} + \frac{RH}{q_s}\left(c_2\frac{dh}{dt} - c_1\frac{\partial \theta}{\partial t}\right) \quad (7)$$

$$c_1 = \frac{L_v}{R_v}\frac{q_s}{T^2}\left(\frac{p}{p_s}\right)^{R_d/c_p};\ c_2 = \left(\frac{L_v}{R_v}\frac{q_s}{T^2} - \frac{c_p}{R_d}\frac{q_s}{T}\right)\frac{g}{c_p} \quad (8)$$

$$\frac{\partial q}{\partial t} = \frac{(\overline{w'q'}_s - \overline{w'q'}_h)}{h};\ \frac{\partial \theta}{\partial t} = \frac{(\overline{w'\theta'}_s - \overline{w'\theta'}_h)}{h} \quad (9)$$

$$\frac{\partial RH}{\partial t} = \frac{(\overline{w'q'}_s - \overline{w'q'}_h)}{hq_s} + \frac{RH}{q_s}\left[c_2\frac{dh}{dt} - c_1\frac{\overline{w'\theta'}_s(1+C_\theta)}{h}\right] \quad (10)$$

$$C_\theta = -\overline{w'\theta'}_h/\overline{w'\theta'}_s \quad (11)$$

$$\frac{\partial h}{\partial t} = \frac{\overline{w'\theta'}_s(1+C_\theta)}{h\gamma_\theta} \quad (12)$$

$$\overline{w'q'}_h = \Delta q\frac{\partial h}{\partial t} \quad (13)$$

$$\frac{\partial RH}{\partial t} = \left(\frac{R_n - G}{\rho L_v h q_s}\right)[e_f + x(1-e_f)] \quad (14)$$

$$e_f = \frac{LE}{R_n - G} = \frac{LE}{H + LE} \quad (15)$$

$$x = L_v/c_p(1+C_\theta)\left[\frac{\Delta q}{h\gamma_\theta} + RH\left(\frac{c_2}{\gamma_\theta} - c_1\right)\right] \quad (16)$$

Ek and Holtslag 2004

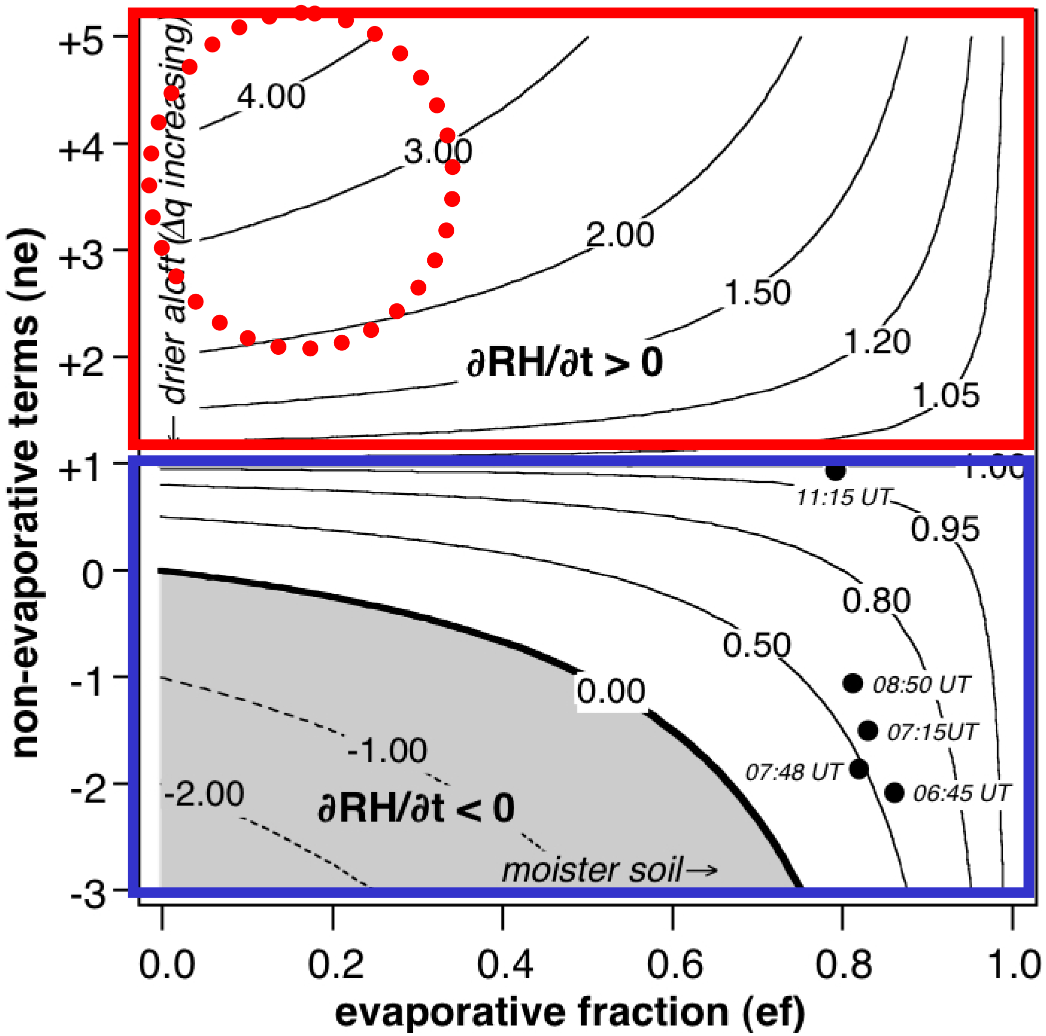
RH tendency

- ***ne>1***
(ABL-growth regime)
if Δq small, RH tendency increases as ***ef*** decreases, high surface evap limits ABL growth and limits RH increase, so probability of clouds with low sfc evap & weaker above-ABL stability

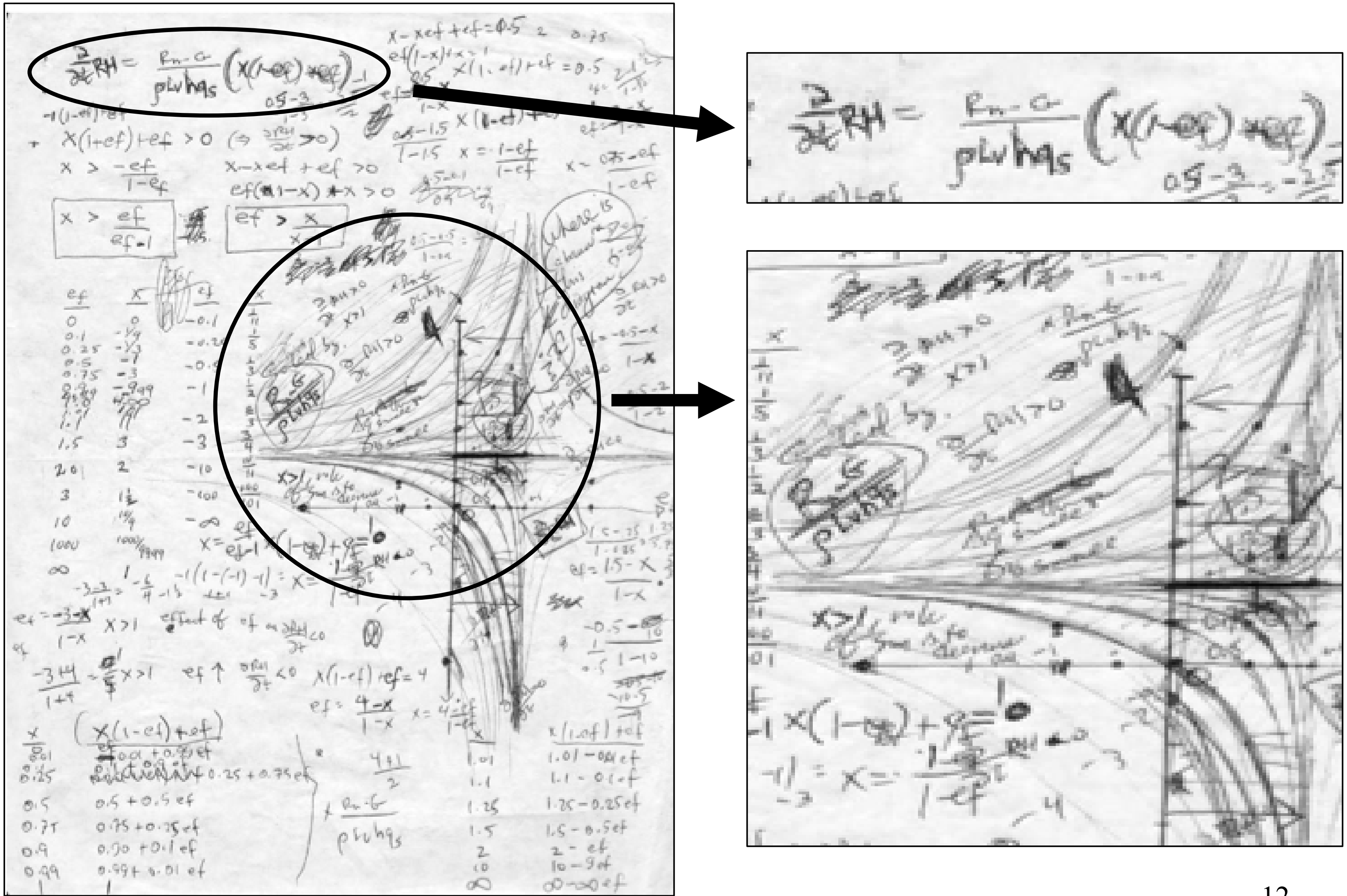
- ***ne<1***
(surface moistening regime)
RH tendency increases as ***ef*** increases, increasing probability of clouds with stronger above-ABL stab. and/or Δq large

- greatest RH tendency & ABL cloud potential: low surface evap & weak atmos. stability (ne>>1) **given sufficient B-L RH**

“Normalized” relative humidity tendency, ***ef* + *ne*(1-*ef*)**



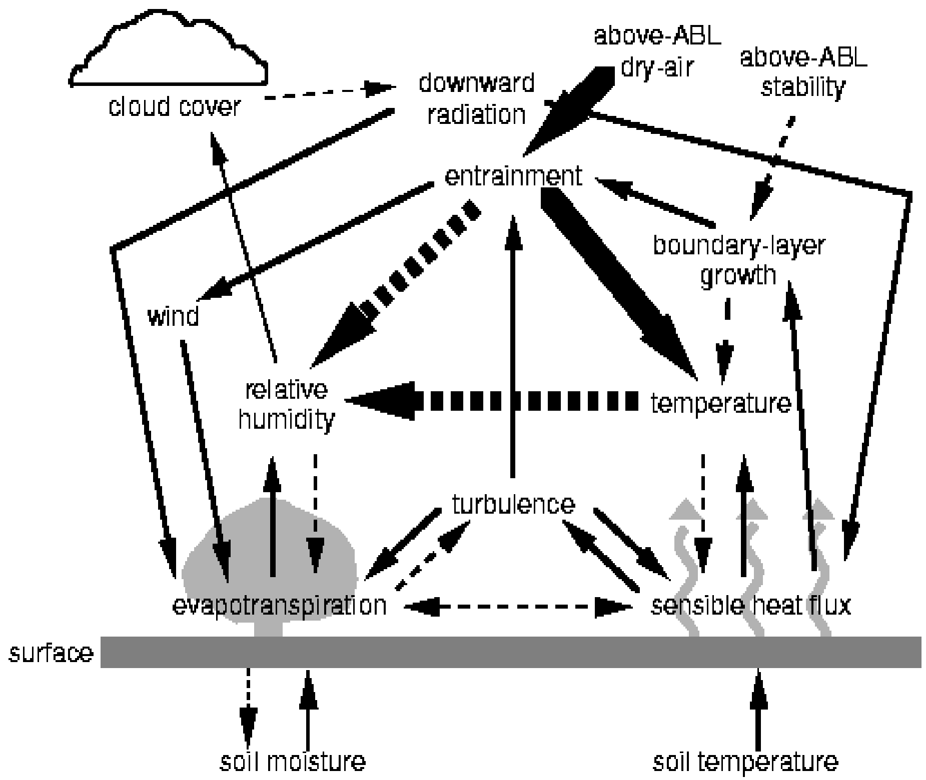
RH tendency



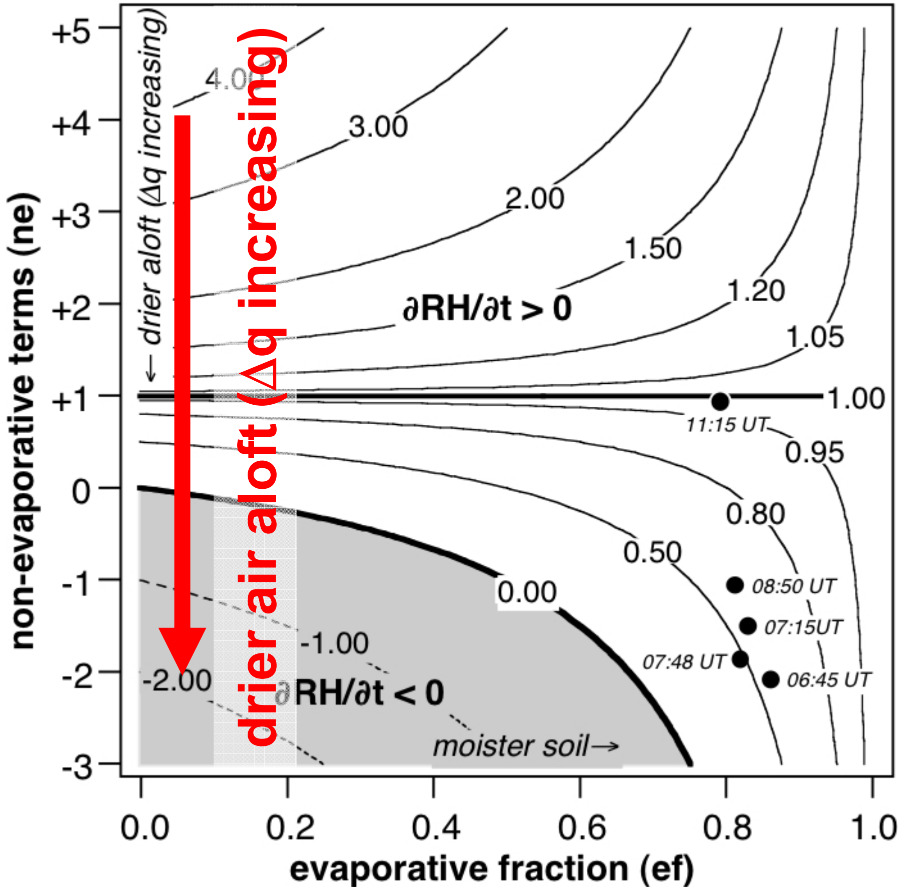
RH tendency ***dry-air entrainment***

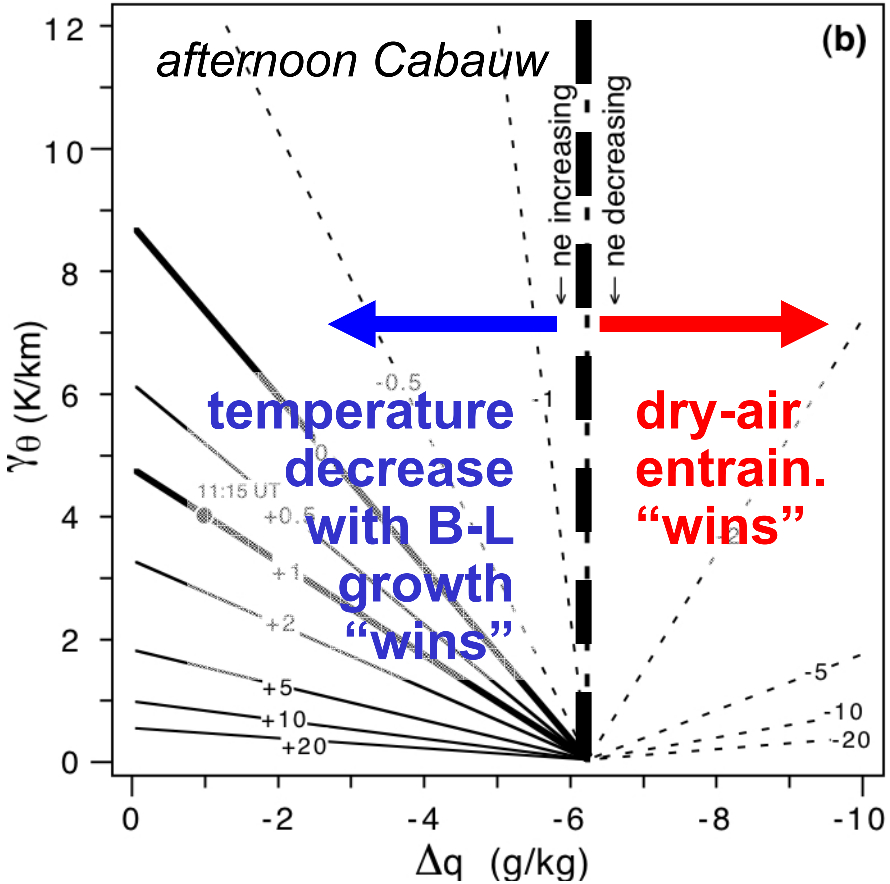
• a change in the above-ABL stability affects both dry-air entrainment and ABL growth & subsequent temperature decrease (opposing processes)

• with drier above-ABL air, *ne* decreases



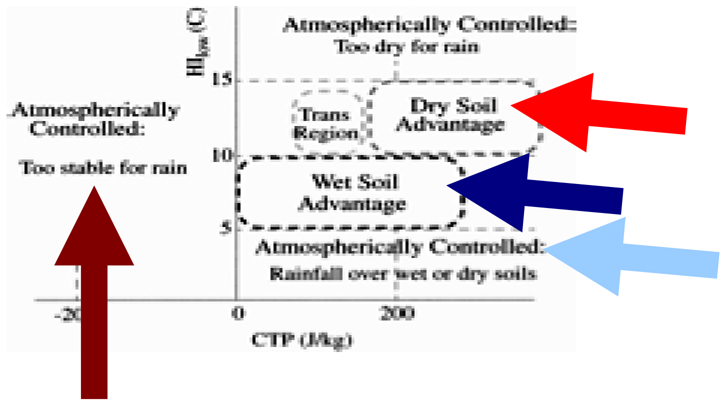
RH tendency *dry-air entrainment*

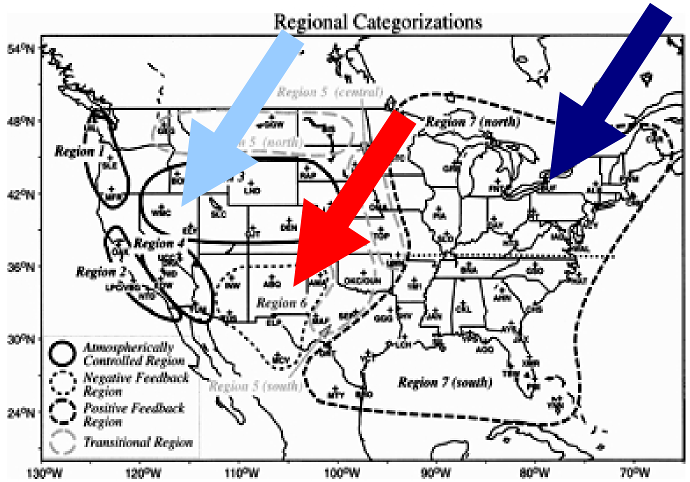


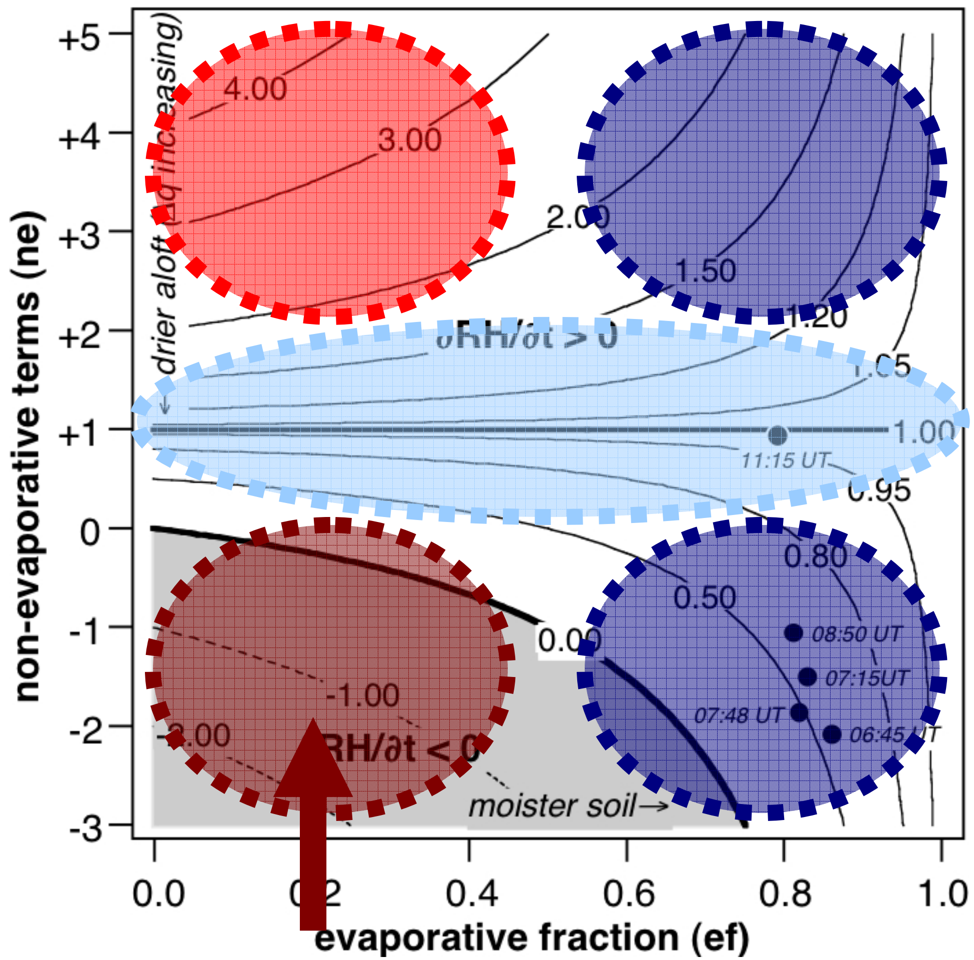


• if Δq > critical value (more negative/drier, $|\Delta q| > c_2 hRH$), then ***ne*** decreases with decreasing above-ABL stability, so dry-air entrainment "wins" over the RH increase due to ABL-top temperature decrease with increased boundary-layer growth.

RH tendency *Findell & Eltahir (2003)*





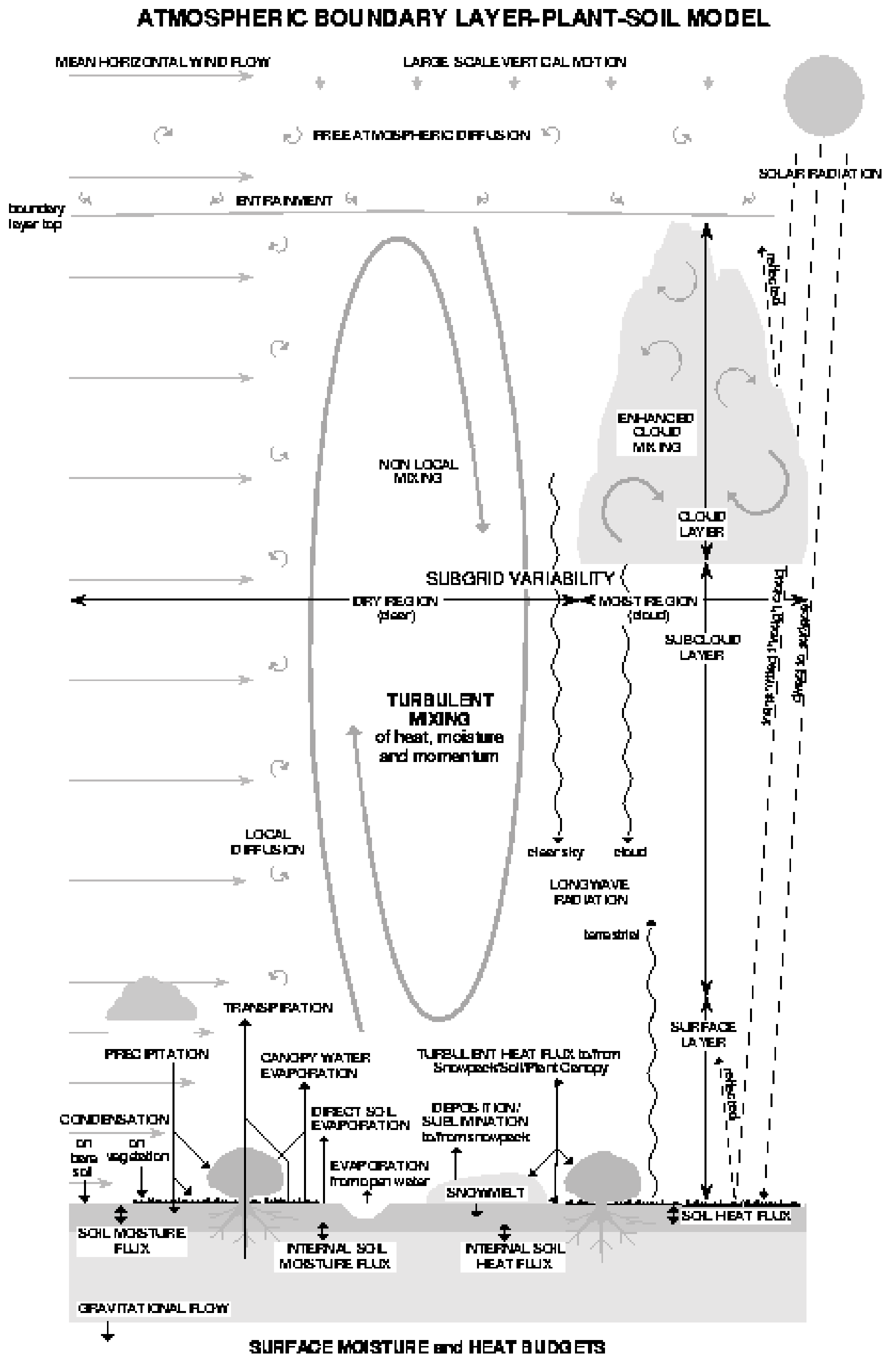


Single Column Model runs and analysis

- **Single Column Model**
- **Cabauw case**
- **HAPEX-MOBILHY cases**

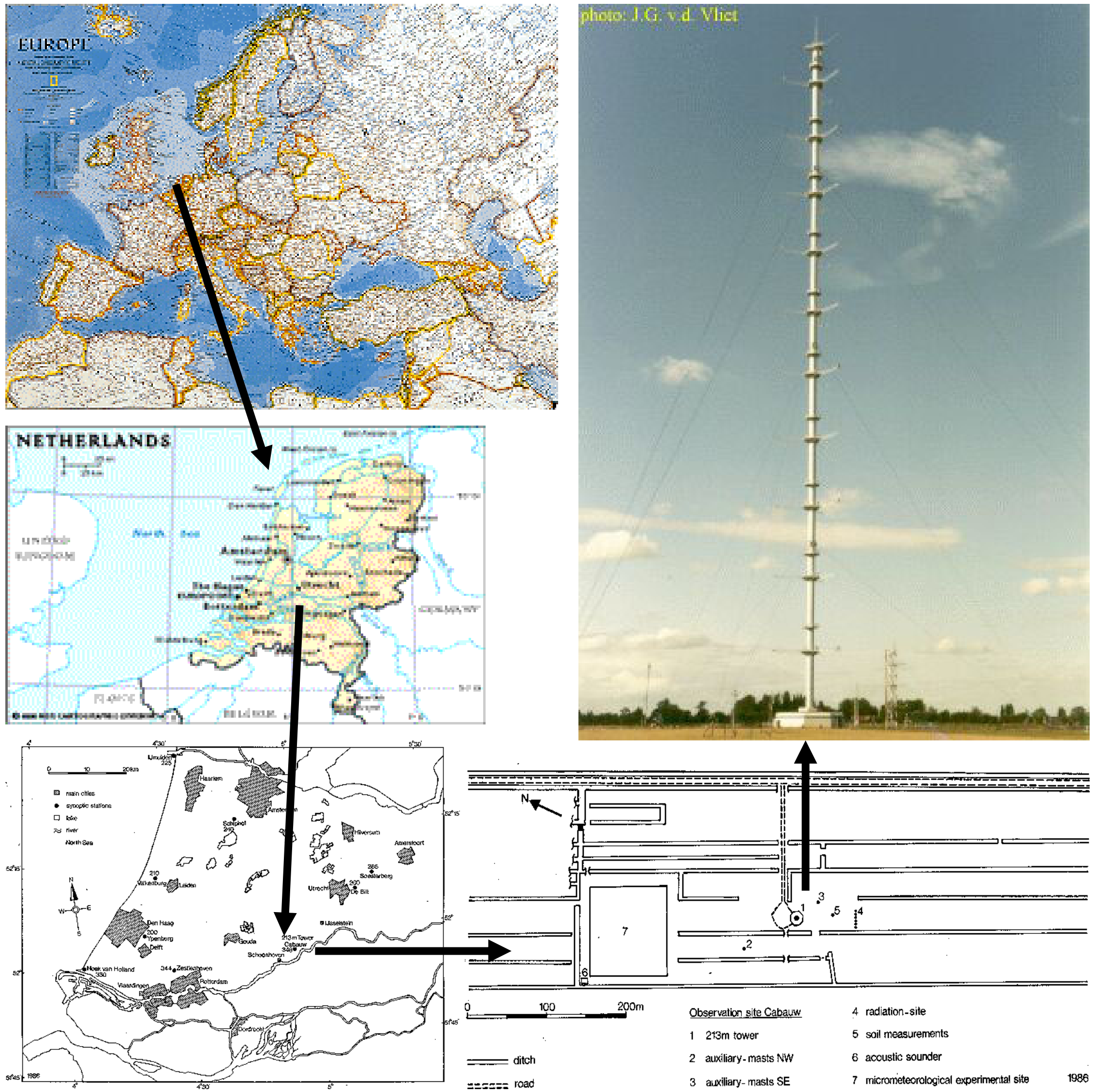
Single Column Model: coupled land-surface and ABL

- **OSU land-surface**
  multi-soil layers, simple canopy, Jarvis-Stewart conductance (evolved into “Noah” land model)
- **ABL boundary-layer**
  K-theory + nonlocal ABL mixing (Troen and Mahrt, 1986)
- **surface layer**
  M-O similarity theory
- **ABL cloud cover**
  turbulent + meso RH dist’n
- **surface radiation** simple incoming solar, longwave, albedo



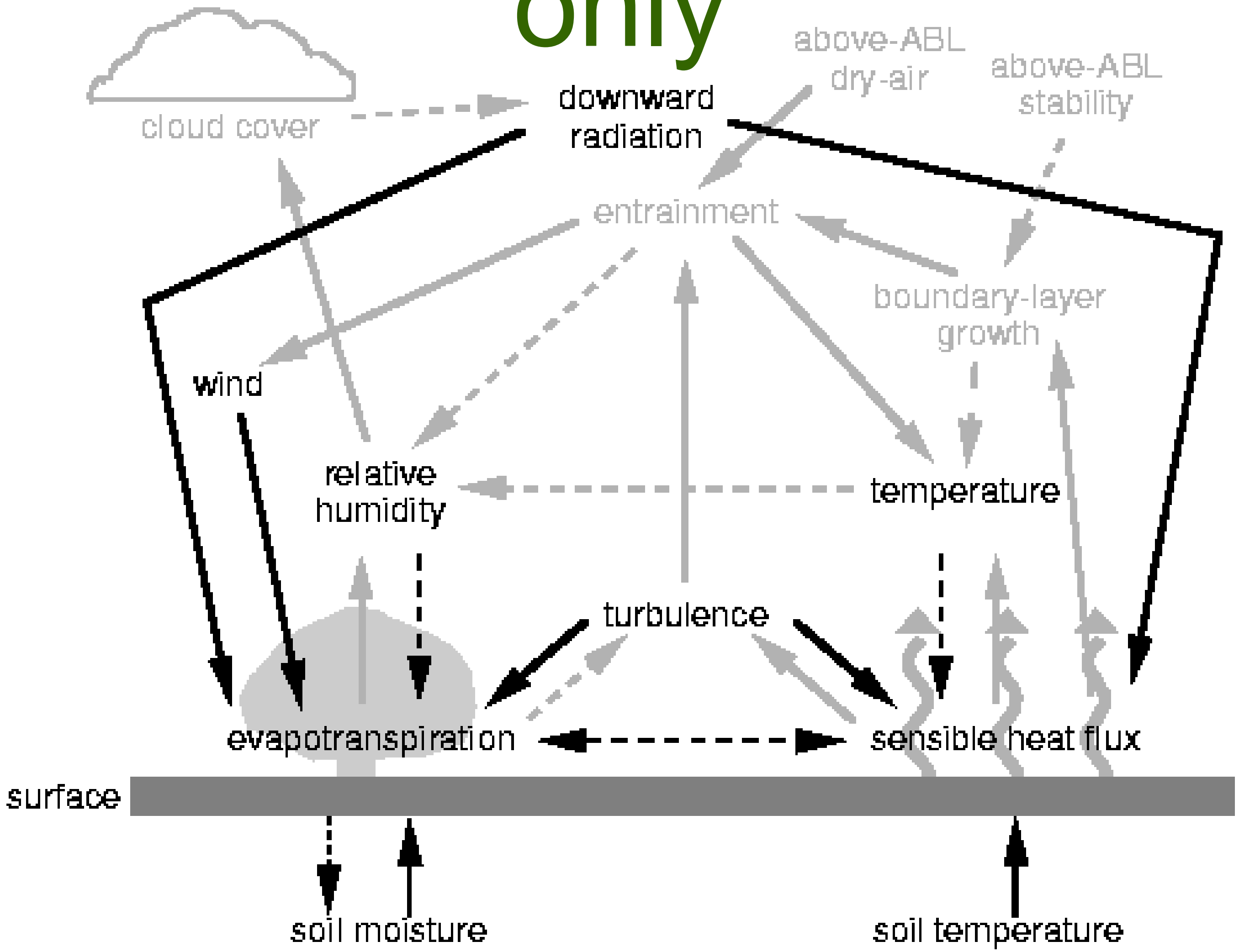
Cabauw SCM runs *31 May 1978*

- Cabauw site in central NL, 45km east of North Sea
- short grass, clay soils
- 213m tower obs
- micromet site
  surface fluxes, soil moisture & temp, radiation
- radiosondes at Cabauw & DeBilt
- fair weather day



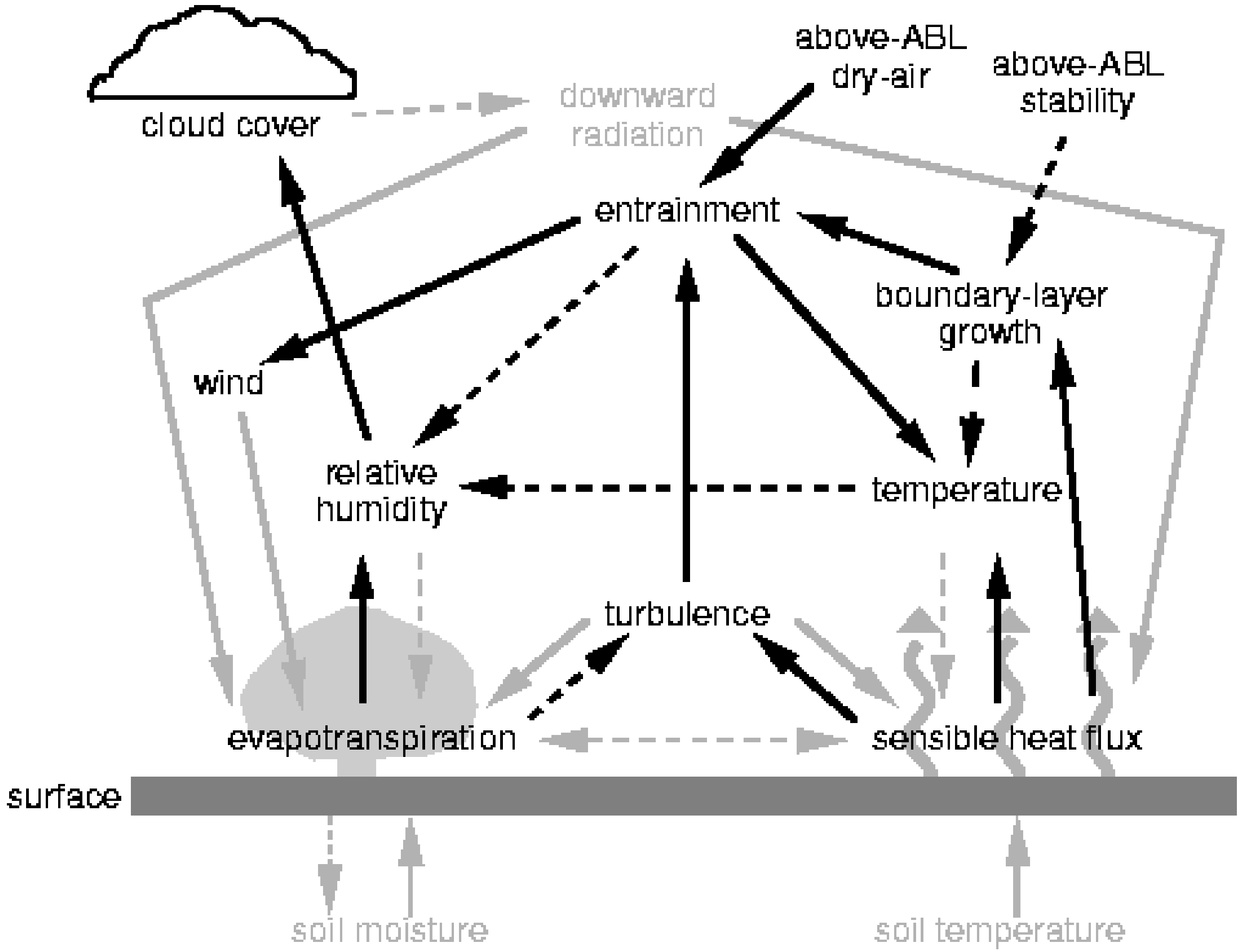
Ek and Holtslag 2004

Land-surface-only



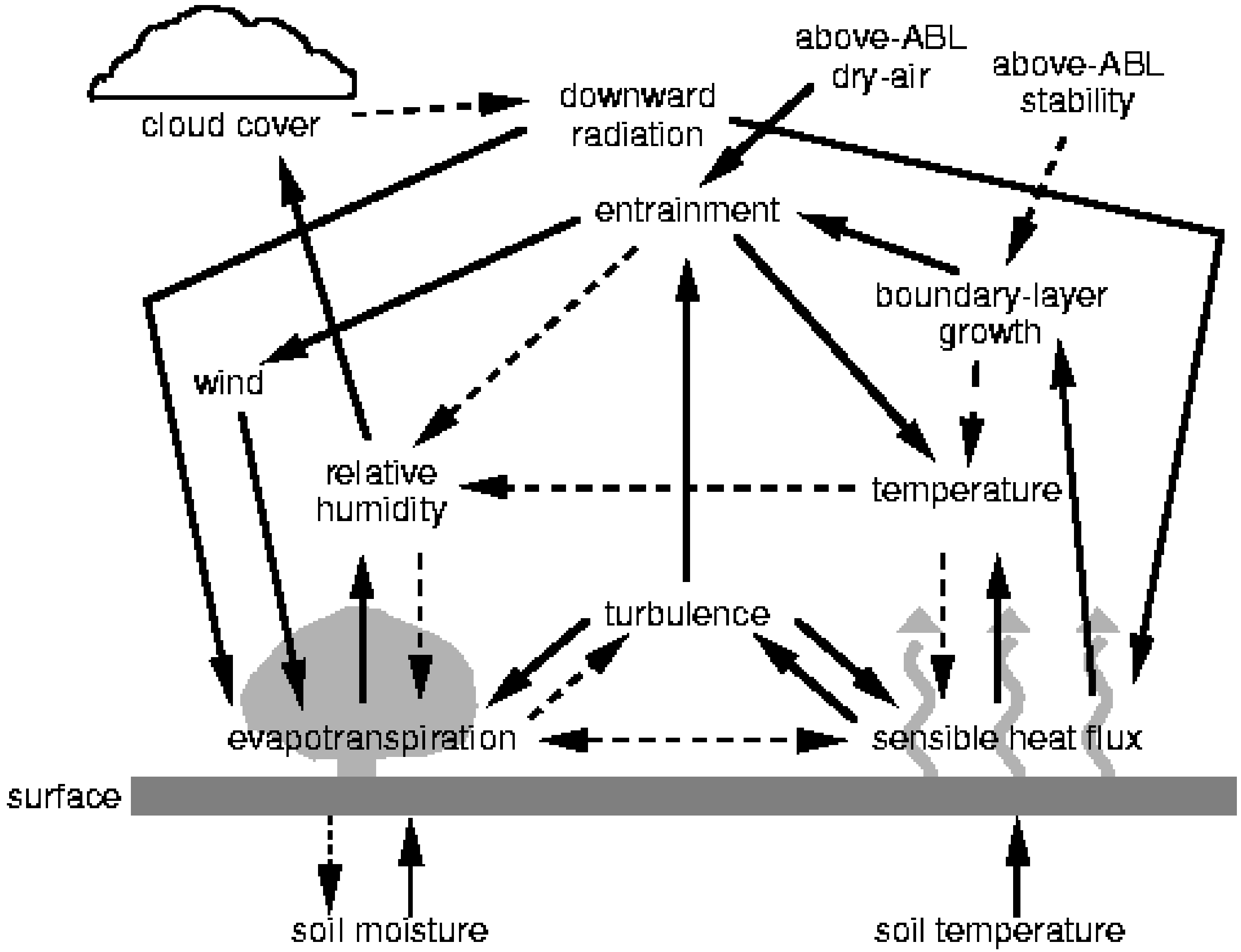
- drive land-surface model runs with observed atmospheric forcing (offline PILPS-like)

ABL-only



- drive ABL model runs with observed surface flux forcing (GABLS1,2-like)

Coupled land-surface & ABL



- coupled land-ABL model runs (GABLS3-like)

Cabauw SCM runs

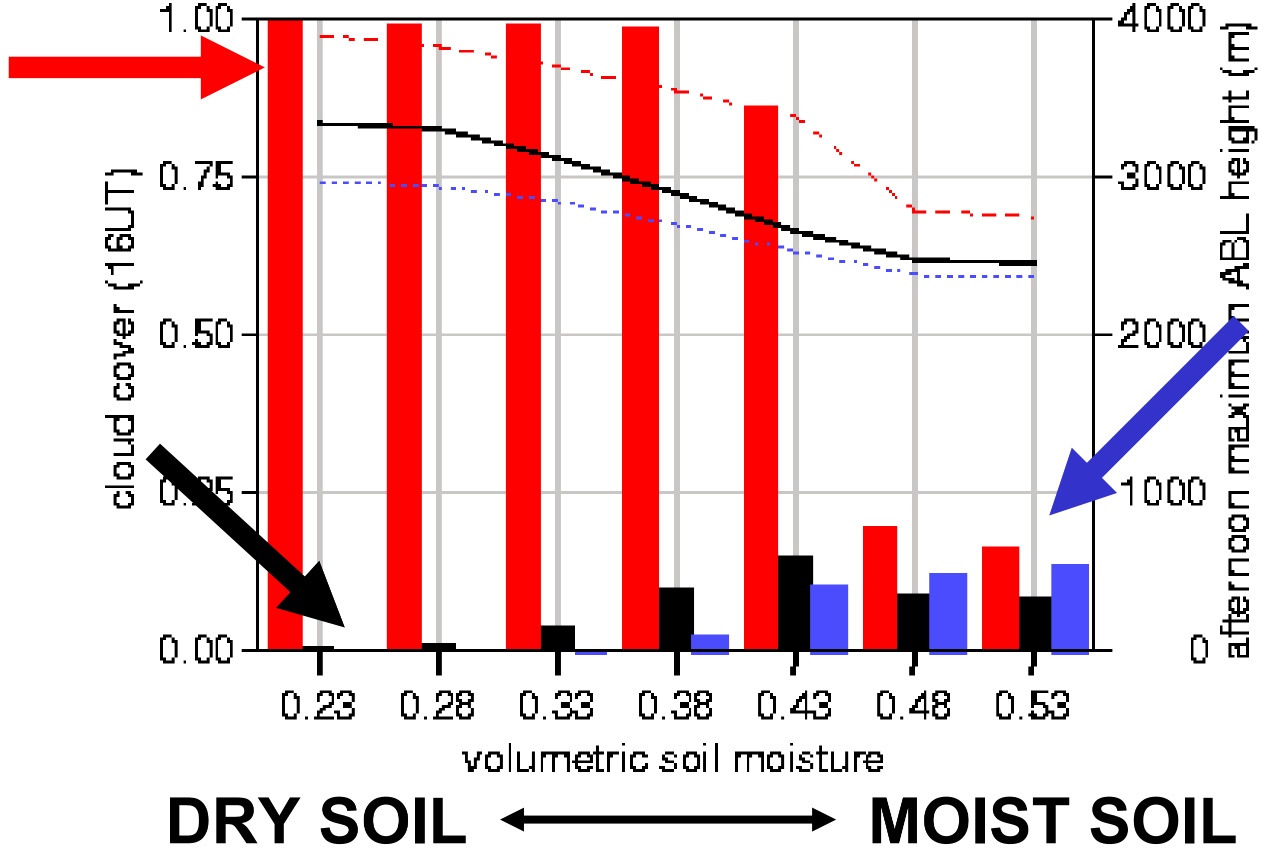
- For land-surface-only, ABL-only, and coupled land-surface-ABL column model runs…
…realistic daytime surface fluxes and atmospheric profiles & ABL clouds are produced,
…results compare well with observations using *un-tuned* surface & ABL parameterizations.

- Sensitivity tests: soil moisture, inversion strength…

Cabauw SCM runs

sensitivity to soil moisture & inversion strength

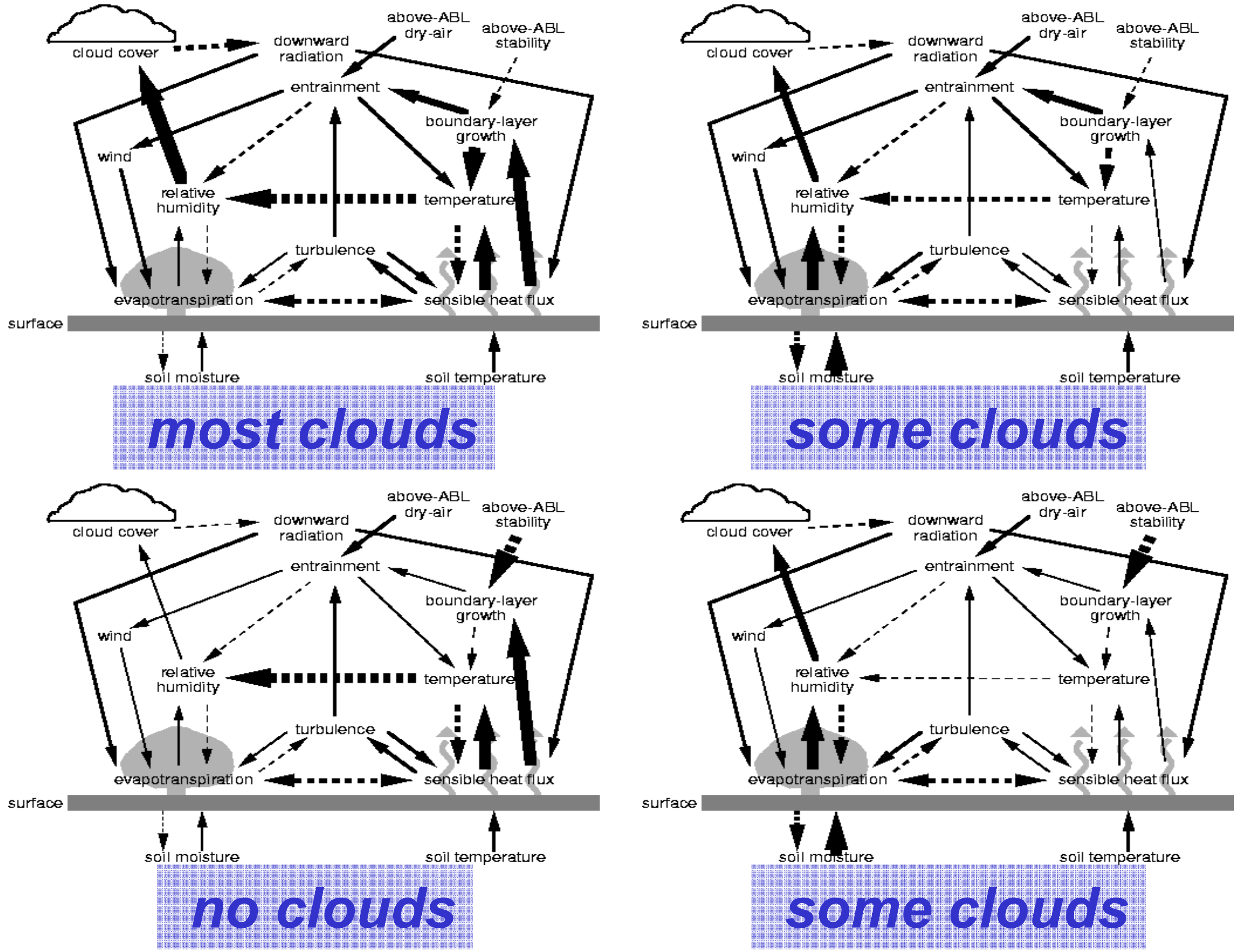
- **strong inversion -> shallow ABL, no clouds**
- **weak inversion -> deeper ABL, more clouds**
- **moist soil -> shallow ABL, similar clouds**



Cabauw SCM runs: sensitivity to soil moisture and inversion strength

WEAK ABOVE-ABL STABILITY

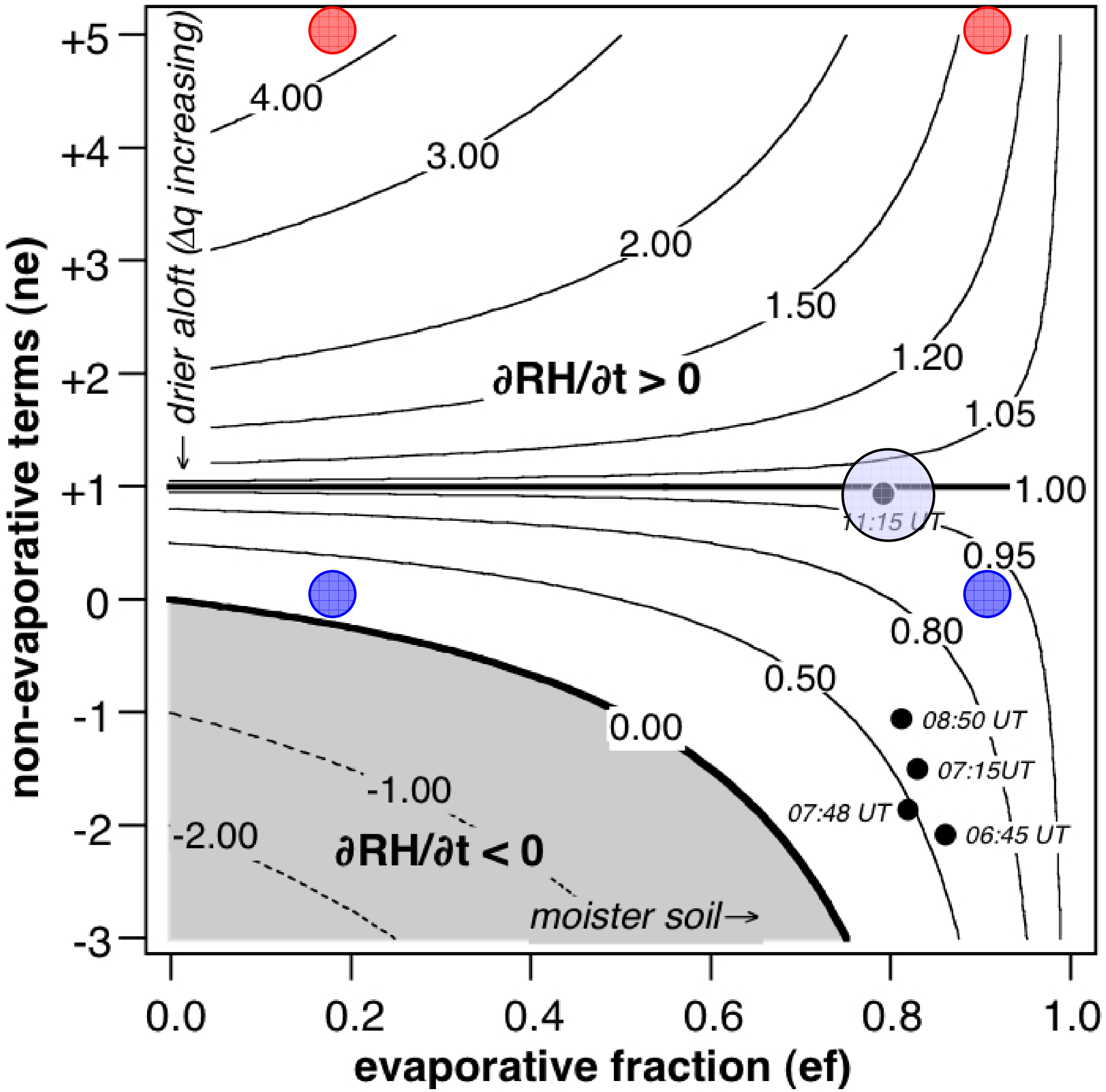
STRONG ABOVE-ABL STABILITY



DRY SOIL ⟷ MOIST SOIL

Cabauw SCM runs: sensitivity to soil moisture and inversion strength

- <u>decreased inversion strength:</u>
  ne>>1
  ABL-growth regime (with weak dry-air entrainment)
- <u>increased inversion strength:</u>
  ne<1
  surface moistening regime



"Normalized" relative humidity tendency

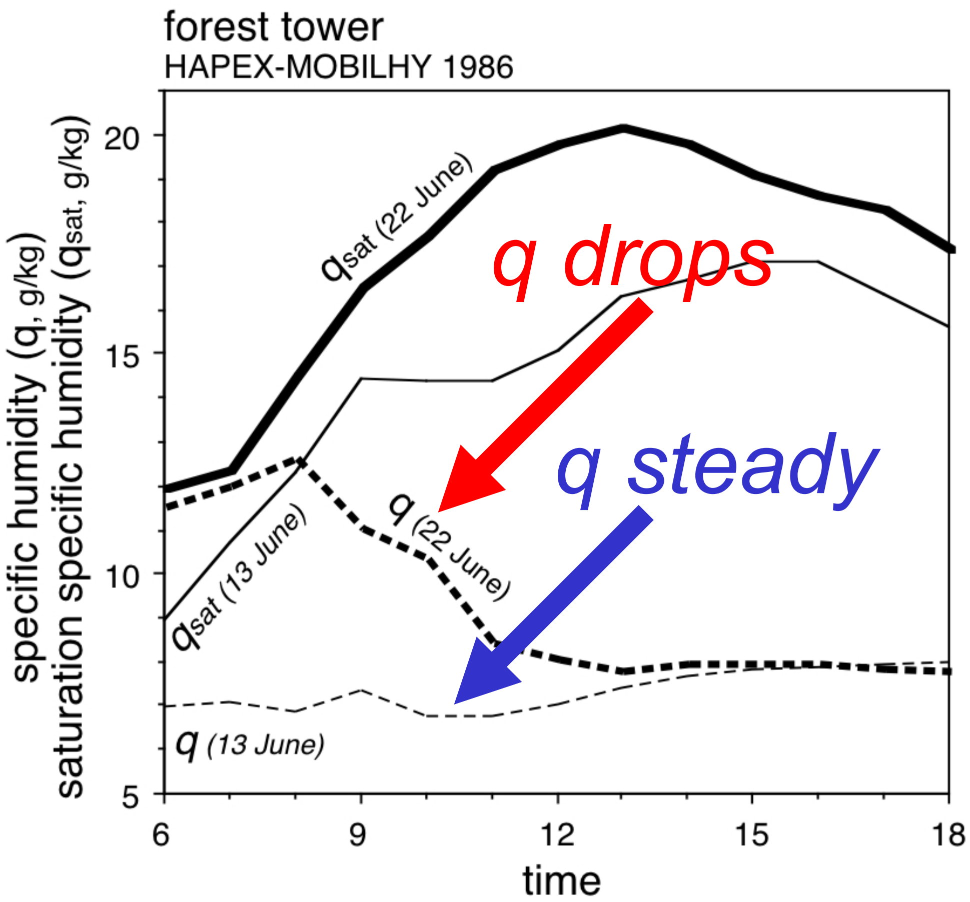
ef + ne(1-ef)

HAPEX-MOBILHY
southwest France, summer 1986

- Mahrt (1991):

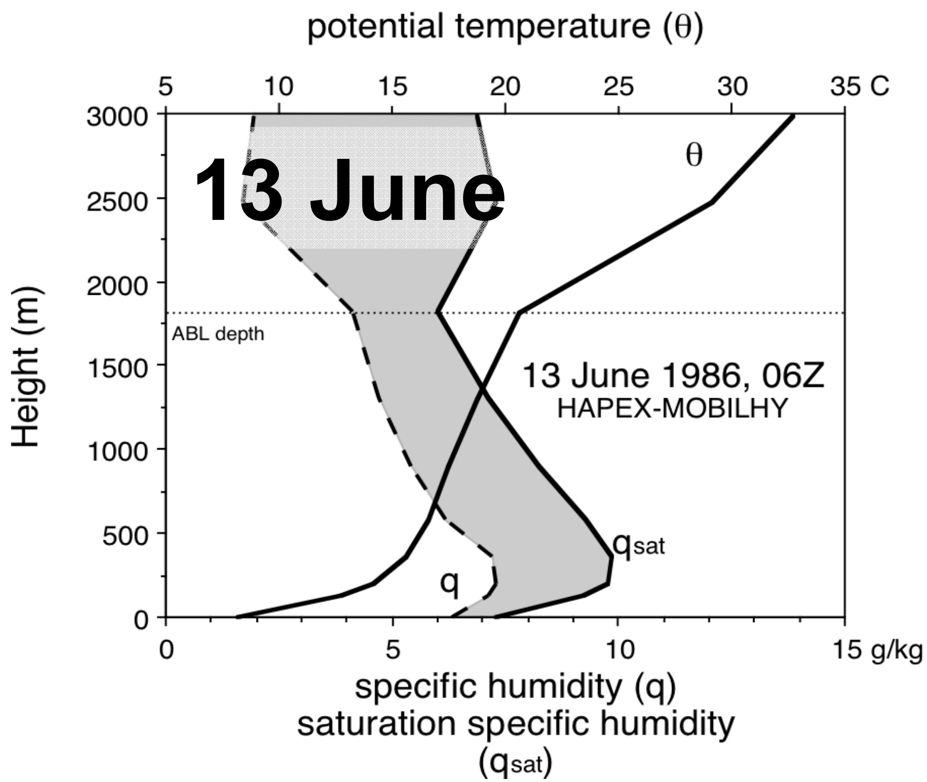
13 June: classical moistening boundary layer associated with surface evaporation

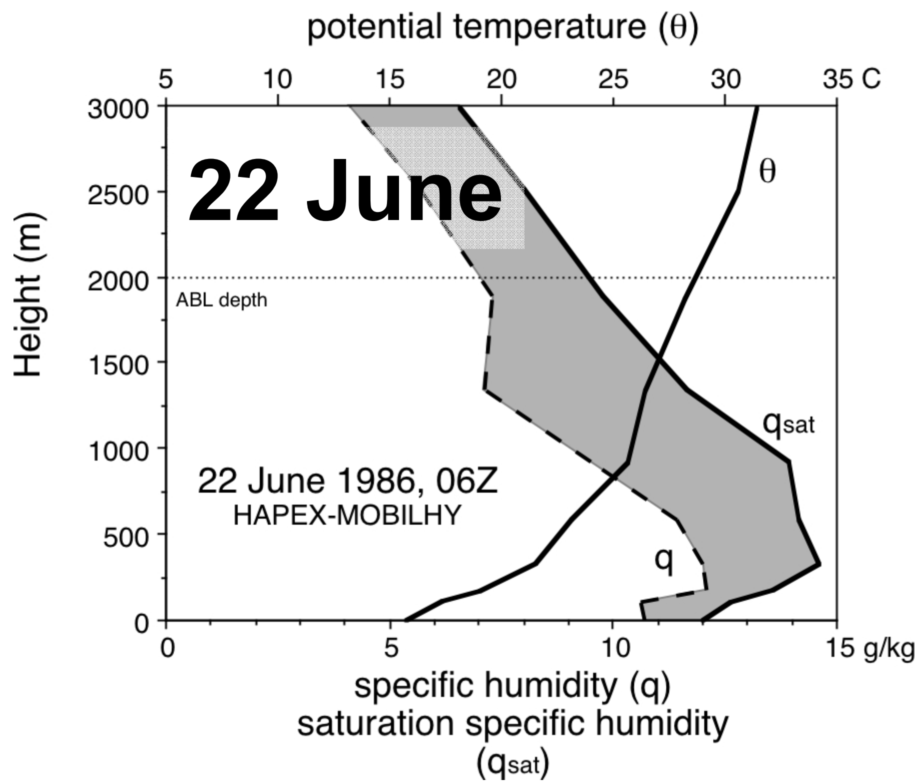
22 June: entrainment-drying boundary layer.



Ek and Mahrt 1994

HAPEX-MOBILHY

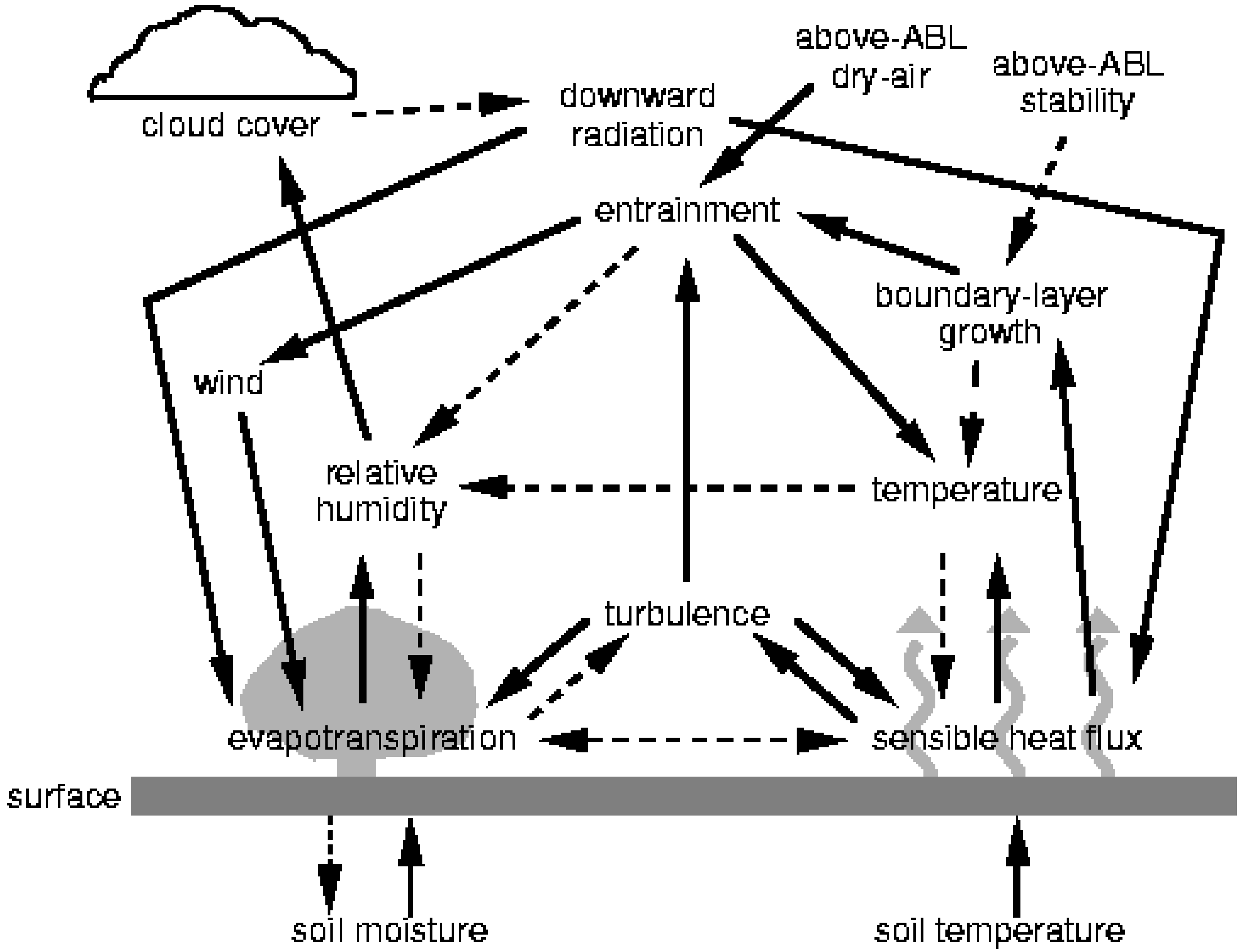




moister soil, strong above-ABL stability & moist air (but drier aloft)

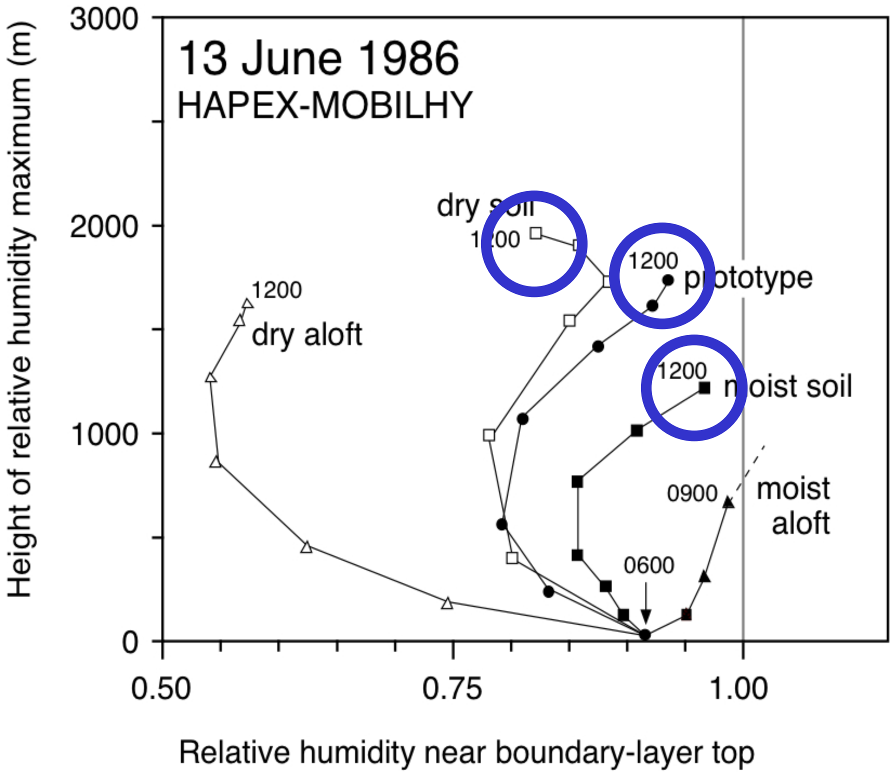
drier soil, weaker above-ABL stability & dry air (but moister aloft)

Coupled land-surface & ABL

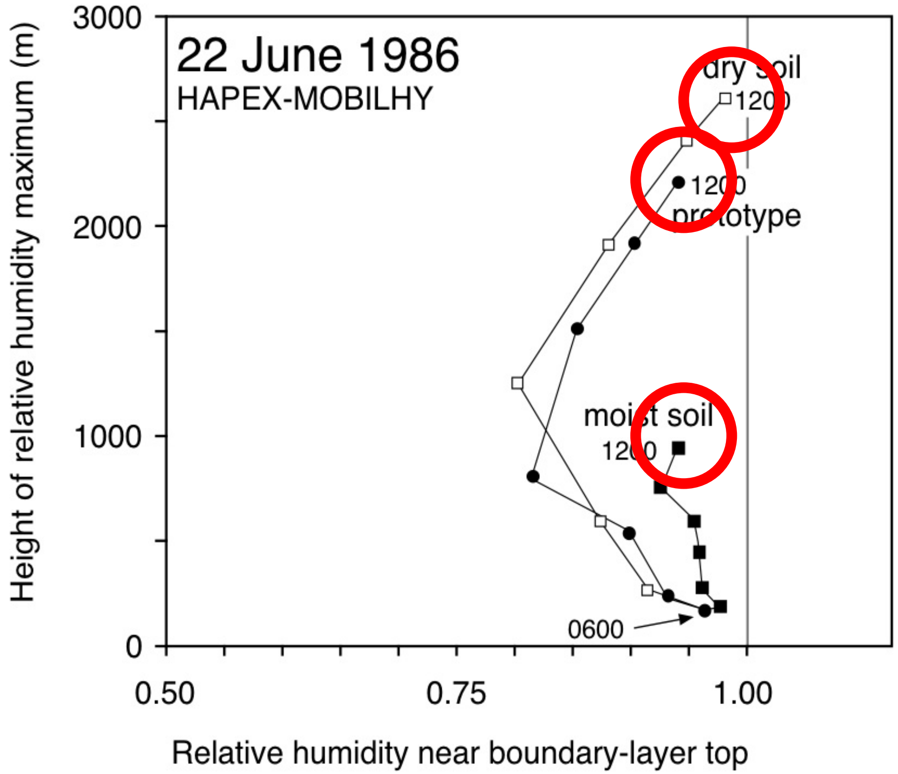


- coupled land-ABL model runs (GABLS3-like)

HAPEX-MOBILHY SCM runs



Dry-air entrainment and strong above-ABL stability dominate over temperature decrease; RH less over dry soil.



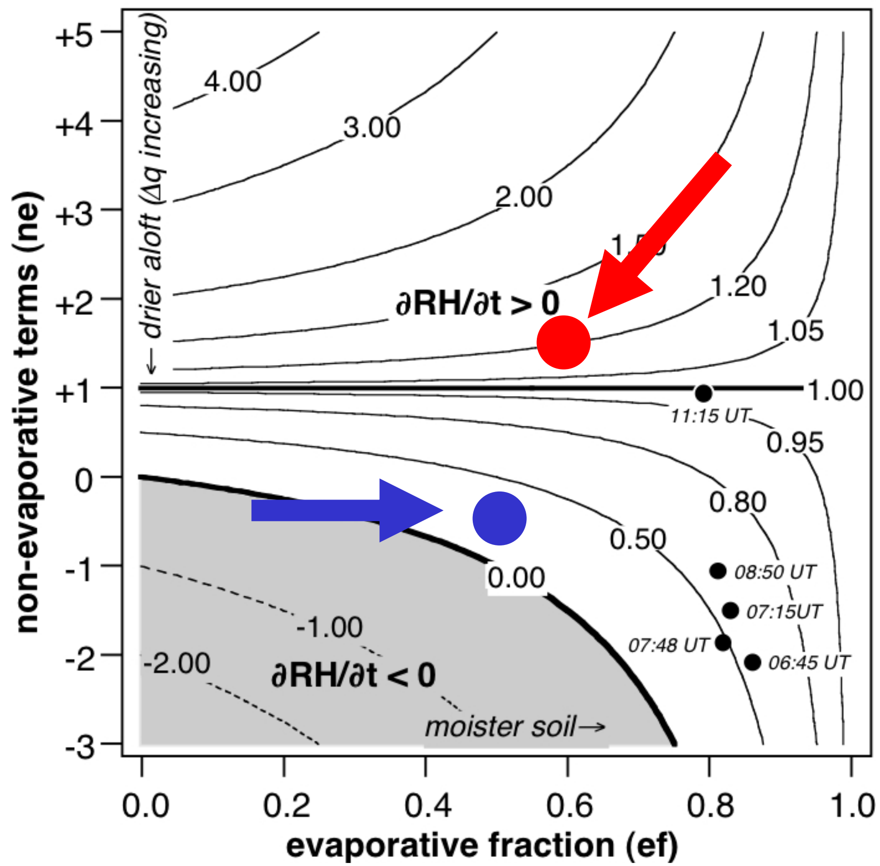
Temperature decrease dominates over dry-air entrainment; RH greater over dry soil.

HAPEX-MOBILHY SCM runs

- 13 June 1986, with strong above-ABL atmospheric stability and dry air aloft (ne<1)…

  …gave a similar mid-day ABL-top relative humidity and ABL clouds (<5%) as…

- 22 June 1986, with weaker atmospheric stability (ne~>1); similar evaporative fractions.



- Consistent with Cabauw findings.

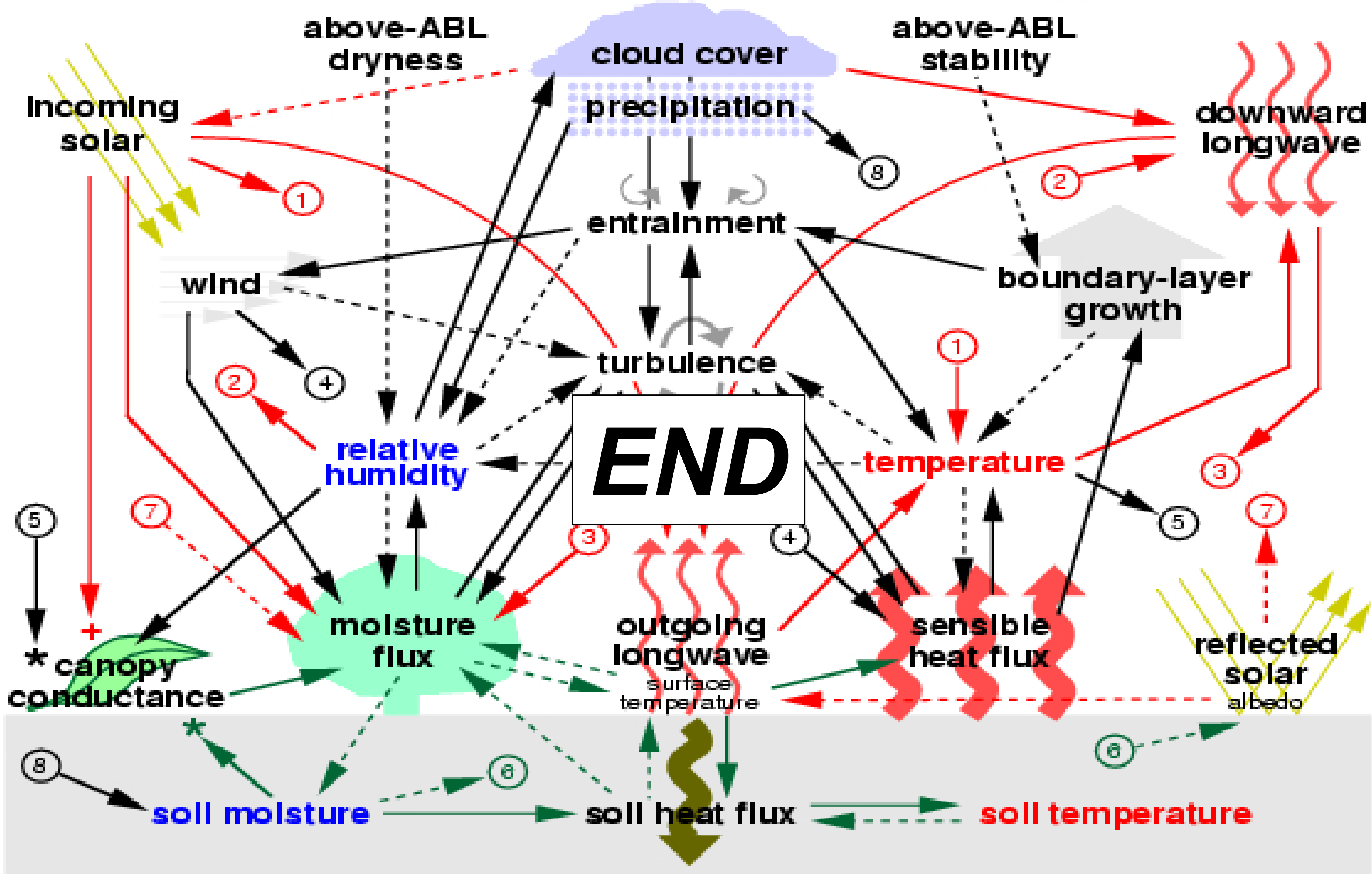
Summary

- Examined role of soil moisture, surface fluxes, and boundary layer processes on the daytime evolution of boundary layer relative humidity and clouds.
- Formulated a RH tendency equation as a method to assess land-atmosphere coupling.
- SCM runs for Cabauw and HAPEX MOBILHY demonstrate soil moisture role & interactions (e.g inversion strength).

Future

- Examine data sets from other field programs, e.g. add'l HAPEX-MOBILHY, CASES/GABLS2, Cabauw/GABLS3, etc.
- Data input: surface fluxes, B-L profiles.
- Further similar SCM tests to explore land-atmos interaction, RH tendency & clouds; use large-scale model output.
- Infer soil moisture using similar RH tendency equation applied to near surface (e.g. 2-meters), data assimil.

land-surface - ABL - radiation interactions



+ *positive feedback for C3, C4 plants, negative feedback for CAM plants*

* *negative feedback above optimal values*

surface layer/ABL processes — land-surface — radiation — positive feedback - - - negative feedback