Boundary layer equilibrium – oceans and land

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Based on:


Why is mixed layer cooler than the ocean SST?
LW cooling = -2.5 K/day

Clouds redistribute heat and water and modify radiative balance

Equilibrium for whole layer:

\[0 = (g/C_p) \Delta R_{net} + \omega_0 \Delta \theta + \omega_T (\theta_T - \theta_M)\]

-40 \quad +10 \quad +30 \text{ W m}^{-2}

cooling \quad surface flux \quad subsidence

Surface velocity scale: \(\omega_0 = \rho V_0 C_D \approx 90\text{hPa/day}\)
Subsidence: \(\omega_T \approx 40 \text{ hPa/day}\)
Why is the mixed layer not saturated, as the air blows over ocean? Evaporation from ocean is balanced by subsidence of dry air above.

\[ 0 = \omega_0 (q_S(SST) - q_M) + \omega_T (q_T - q_M) \]

\[ q_M = \frac{[\omega_0 q_S(SST) + \omega_T q_T]}{\omega_0 + \omega_T} \]

A weighted average
\[ q_M = \frac{[90*22 + 40*5]}{130} = 16.7 \text{ g/kg} \]
so \[ \theta_{EM} \approx 346K \]
cloud-base \( \approx 960\text{hPa} \)

Can think of the two balances on a ‘conserved parameter’ diagram: “Mixing” of surface point and 850hPa point, modified by radiation.
Relate equilibrium structure to convective fluxes: \( F_q, F_\theta \)

[illustration]

Assume \( \omega = 40 \text{hPa/day} \) in cloud layer, below cloud-base decreases linearly to zero at surface.
Assume radiative cooling
\[
\frac{\partial \theta_{\text{Rad}}}{\partial t} = -2.4 \text{ K/day}
\]

Equilibrium means steady state
[assume horizontally homogeneous]

\[
0 = \frac{\partial F_q}{\partial p} + \omega \frac{\partial q^-}{\partial p}
0 = \frac{\partial F_\theta}{\partial p} + \omega \frac{\partial \theta^-}{\partial p} + \frac{\partial \theta_{\text{Rad}}}{\partial t}
\]
[where \( F_q \) and \( F_\theta \) represent the convective fluxes of total water and ‘liquid water potential temperature’ above cloud-base]

Integrate to give fluxes from \( \omega, \theta \) and \( q \) profiles, and \( \frac{\partial \theta_{\text{Rad}}}{\partial t} \).
This gives equilibrium fluxes [in units of \( \text{W m}^{-2} \)] from profiles

Simple mass-flux model [illustration]
Can couple fluxes with a mass flux transport model for shallow convection

\[
F_q = \Omega_q (q_c - q) \text{ with } q_c = q_B \text{ a cloud-base value of } 16.54 \text{ gkg}^{-1}
\]

and compute the \( \Omega_q \) shown in the figure.

Shallow clouds transport mass out of sub-cloud layer and distribute through cloud layer. Convective fluxes can be represented by this mass transport model.
Shallow Cumulus

– non-precipitating
– net LH = 0
– but transport heat because condense water, advect it upward and reevaporate it [a “refrigerator”]
– buoyant, because of condensation but still ‘cold’, because of liquid
– conserved variables: \( \theta_E = \theta + Lq/C_p \)
  \( \theta_L = \theta - L/\ell/C_p \)
  \( q_T = q + \ell \)

– represent by mass transport of air with sub-cloud properties to higher levels
– equilibrium structure over ocean is balance of convective transports, subsidence, and radiative flux divergence (cooling)
Conserved Variable diagram – 2

– Similar to other thermodynamic diagrams; just \( \theta \), q as axes

Dry virtual potential temperature
\[ \theta_v = \theta(1 + 0.608q/1000) \]
– vapor is less dense
– SP of equal density
– Slopes 1K every 6g kg\(^{-1}\)
  [Could use as axis]

Wet virtual potential temperature
– if parcels carry liquid .. Denser; \( \Delta \ell = 2 \text{ g kg}^{-1}/100\text{hPa} \)
– \( \theta_v = \theta(1 + 0.608q/1000 - \ell/1000) \)
– line of equal density
\[ (\partial\theta/\partial p)_{\theta_{sv}} \approx 0.9 (\partial\theta/\partial p)_{\theta_{es}} \]
Parameterizing shallow convection with a mixing line representation

– parameterize a cloud field: what do these simple diagnostic studies tell us?
– two approaches:

a) parameterize fluxes, and their gradients:
eg with mass flux model; say cloud-base q-flux = surface q flux
[Problem from a ‘climate perspective is that system may drift to either dry or cloudy state]

b) parameterize structure: eg ‘mixed layer’ or ‘mixing line’.

Single mixing line can represent whole BL structure of both clear and cloudy air.

Unsaturated air: find T, T_d at p by drawing lines of constant θ and q
Cloudy air: find T, T_d [for total water] at p by drawing lines of constant θ_{es} and q

A type of convective adjustment.

[example: advanced students read paper/Betts and Ridgway, 1989]
How does ocean BL and land differ?

Radiative cooling  
SH, subsidence

Evaporation and subsidence

Stays a little cooler than ocean and sub-saturated:  
surface wind and subsidence control evaporation  
[ocean store suns heat; diurnal cycle small]

**LAND: what are the essential differences??**

Sun heats surface and drives large diurnal cycle; daytime unstable;  
cools radiatively at night; at night stable BL  
Surface not saturated.. Except inside leaves.  
Sun drives evaporation through photosynthesis  
[coupled to CO₂ uptake]  
Subsidence of dry air still plays key role, averaged over 24hrs.

*Need to understand mean state and diurnal cycle*
Coupling of CO₂ and water vapor through the BL
BOREAS Northern Study area [Thompson, Manitoba]

Figure 1 Coupling of CO2 and water vapor profiles of June 8 at 1719 UTC (LST=UTC-6h)

Figure 2. Profiles through the mixed layer on four days in June, showing tight coupling between water vapor and CO₂ structure. Illustrative slope of 7 ppm CO₂ to 5 g kg⁻¹ is shown.
RH, LCL and pressure height of cloud-base are fundamental BL quantities

Fig. 19a. Relation between height of cloudbase and RH as surface temperature varies. [Note independent of surface pressure]

Fig. 19b. As Fig. 4a for ratio of $P_{LCL}$ to surface pressure $p$. [Note dependence on $T$ is weak]

– Over land, there is link to evaporative resistance

Dry soils $\rightarrow$ large resistance to evaporation

Extra resistance produces drop of saturation from inside leaf to outside leaf

Reduces relative humidity (RH) and increases BL depth
We can create an “equilibrium model” by averaging over 24hour cycle – how does mean BL depth and fluxes depend on soilwater and solar forcing?

[see Betts: *J. Hydrometeorol*. 2000]
Compare idealized model and diurnally averaged ERA40
Evaporation and photosynthesis are linked to *same* vegetative resistance

$q$ and $CO_2$ at equilibrium are functions of BL depth

$CO_2$ and water vapor are tightly coupled
Coupling between CO$_2$, water vapor, temperature and radon and their fluxes in an idealized equilibrium boundary layer over land.

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[J. Geophys. Res. in revision]
Idealized equilibrium boundary layer over land

- Extension of Betts (2000) in *J. Hydromet*.
- Idealization is to average over diurnal cycle
- **Extensions**
  - add vegetation model
  - CBL and ML equilibrium
  - Simple coupling of radiation to clouds
Purpose

• Couple mixed layer ‘equilibrium’ of potential temperature, water vapor, CO$_2$ (and radon) with the surface energy and water budgets and net ecosystem exchange (and surface radon flux)

• Suggest that regional ML budgets may give useful constraints on regional carbon budgets.
Idealized equilibrium model

- Surface energy budget: diurnal mean
- Radiative fluxes coupled through cloud cover
- Photosynthetic controlled evaporation, linked to stomatal resistance, calculated from Ball-Berry model, fitted to Wisconsin tall tower data.
- ML and CBL equilibrium

- 45 equations … read the paper
• Sensitivity of vegetative resistance and ML depth to soil water and net short-wave
Surface energy fluxes and EF as a function of soil water content

Latent and sensible heat fluxes

Evaporative fraction
Surface energy fluxes and EF as a function of ML depth: $P_{\text{LCL}}$

Latent and sensible heat fluxes  

Evaporative fraction
ML properties as a function of soil water content

ML potential temperature and mixing ratio

ML CO$_2$ and radon
ML properties as a function of ML depth: $P_{LCL}$

ML potential temperature and mixing ratio

ML CO$_2$ and radon
Photosynthesis and respiration
Coupling of CO$_{2m}$ to q$_{m}$ and NEE

Photosynthesis; respiration
CO$_{2m}$ against q$_{m}$ and NEE
Conclusions-1

• SWC is primary control on NEE and on evaporation through stomatal resistance
• Dry soil: equilibrium depth of the ML increases sharply, as reduced evaporation leads to a warmer drier equilibrium
• LCL is powerful constraint on ML depth
• Radiative impact of clouds on equilibrium
Conclusions-2

- Two different perspectives:
  - as a function of SWC
  - as function of cloud-base height
- Important coupling between ML q and CO₂, and between NEE exchange and CO₂
  - useful for carbon budget estimates

Preprint at ftp://members.aol.com/bettspapers/BHB_JGR.pdf
Take away these ideas

*Ocean equilibrium*: balance of radiative cooling, subsidence and surface fluxes
  giving a typical tradewind BL with cloud-base 50hPa above surface and a 150hPa deep shallow cumulus layer.
  [Solar heating absorbed in deep ocean mixed layer]

*Land diurnal cycle* driven by solar heating, but *equilibrium* similar to ocean, except a drier mean state because additional ‘vegetative’ resistance to evaporation at surface.

*CO₂ and water vapor coupled in BL over vegetation.*