Planetary boundary layers: our habitat and coupling parts of climate machine

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PBLs in Earth system

Atmospheric planetary boundary layers (PBLs) are strongly turbulent layers immediately affected by dynamic, thermal and other interactions with Earth's surface

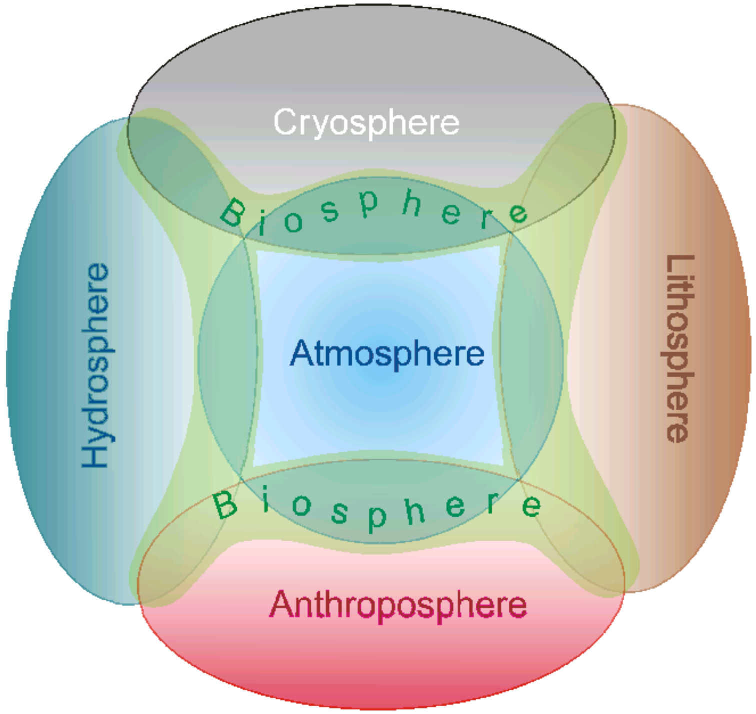
PBSs subject to diurnal variations

Absorb surface emissions

Control microclimate, extreme colds and heats, air pollution

Are sensitive to human impacts

Have dozens to thousands *m* heights



Atmospheric and hydrospheric PBLs couple geospheres and include 90% biosphere and 100% anthroposphere

Content

<u>**STABLE AND NEUTRAL stratification**</u> – comparatively shallow PBLs affected by Earth's rotation and stratification

•Free-flow stratification

•Equilibrium PBL height regimes

•Non-steady regimes → prognostic PBL height equation

<u>**UNSTABLE stratification**</u> – deep, non-rotational, well-mixed, ever-growing convective layers

•PBL growth-rate

Buoyancy-budget models: <u>prescribed</u> entrainment

•Variable entrainment (PBL ventilation)

Buoyancy- and energy-budget models: <u>modelled</u> entrainment

Different types of PBL

Self-organisation and non-local nature

Modern classification accounting for N distinguishes between

nocturnal ⇔ long-lived truly ⇔ conventionally shear-free ⇔ sheared

NS $N = 0$ ⇔ **LS** $N > 0$ **TN** $N = 0$ ⇔ **CN** $N > 0$ **cells** ⇔ **rolls**

STABLE $B_s < 0$ **NEUTRAL** $B_s = 0$ **CONVECTIVE** $B_s > 0$

Traditional classification of **PBLs** by sign of surface buoyancy flux B_s disregarded **free-flow Brunt-Väisälä frequency** N (at $z > h$)

Ekman (1905) set up a concept of planetary boundary layer (PBL) to explain physics of Polar ice drift ue to Earth’s rotation

Different types of PBL

classification by **sign of surface buoyancy flux** B_s

Stable $B_s < 0$

Neutral $B_s = 0$

Unstable (convective) $B_s > 0$

disregards **free-flow Brunt-Väisälä frequency** N (at $z > h$).

We account for N and distinguish

Stable nocturnal stable (NS) $N = 0$

long-lived stable (LS) $N > 0$

Neutral truly neutral (TN) $N = 0$

conventionally neutral (CN) $N > 0$

Unstable shear-free (convective cells) in two-layer fluid $N = 0$

in stratified fluid $N > 0$

Unstable sheared (convective rolls) in two-layer fluid $N = 0$

in stratified fluid $N > 0$

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Stable and neutral PBLs

Ekman (1905) **rotational** PBL height scale $h_* = (K_* / |f|)^{1/2}$

$f = 2\Omega \sin\varphi$ is Coriolis parameter, K_* is eddy viscosity

L I M I T S

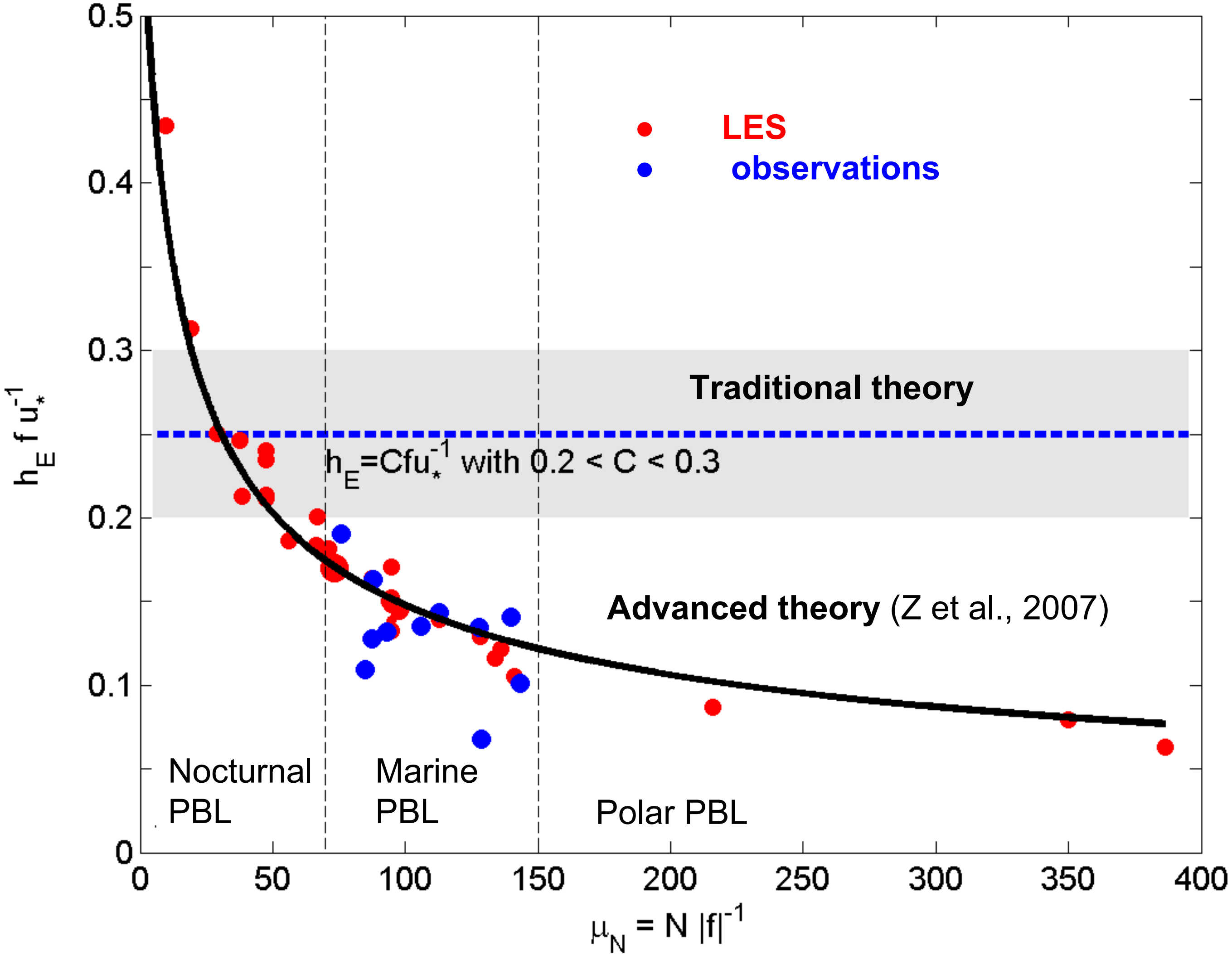
$$h_E = \begin{cases} C_R u_* |f|^{-1} & \text{TN PBL Earth rotation } (C_R = 0.6) \\ C_{CN} u_T |fN|^{-1/2} & \text{CN PBL free flow impact } (C_{CN} = 1.4) \\ C_{NS} u_*^2 |fB_s|^{-1/2} & \text{NS PBL surface-flux impact } (C_{NS} = 0.5) \end{cases}$$

Baroclinic deepening (Z&E-2003) $u_T = u_*(1 + C_0 S_g / N)^{1/2}$

$S = dU_g/dz$ is geostrophic shear, $C_0 = 0.67$ (Z& Esau, 2003)

- CN and TN (R-M, 1935) were confused: strongly variable ratio $|f| h_E / u_* = C_N (f/N)^{1/2}$ was treated as constant (see Figure)
- NS (Z, 1972) widely accepted (data: over land at mid latitudes)

PBL shallowing due to free-flow stability



Dashed line – traditional TN PBL model

Heavy curve – CN PBL model

Red points – LES

Blue points – atmospheric data

The effect of free-flow Brunt-Väisälä frequency N on the equilibrium CN PBL height h_E

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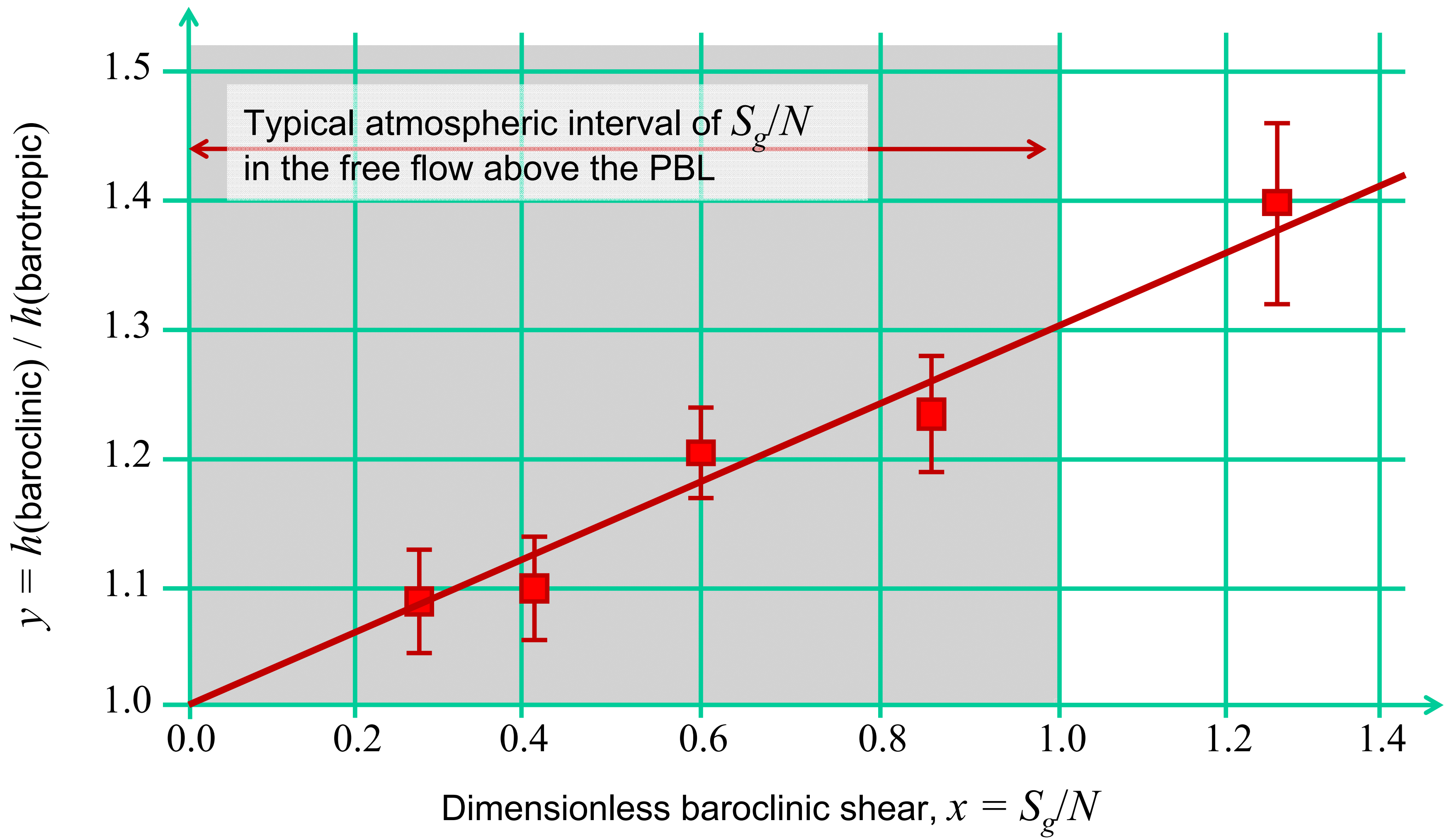
PBL deepening due to baroclinic shear

Theoretical model $y = (1 + 0.67x)^{1/2}$ against LES (Zilitinkevich & Esau, 2003)



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Diagnostic and prognostic formulations

The <u>equilibrium</u> height h_E of stable or neutral PBL is controlled by rotation (f) and stratification – at the bottom (B_s) and on top (N)

$$\boxed{\frac{1}{h_E^2} = \frac{f^2}{(C_R u_*)^2} + \frac{N|f|}{(C_{CN} u_*)^2} + \frac{|fB_s|}{(C_{NS} u_*^2)^2}}$$

Given h_E <u>real</u> PBL height h is determined by relaxation equation

$$\frac{dh}{dt} - w = -\frac{h - h_E}{t_E}$$

<u>Relaxation time scale</u> $t_E = \dfrac{h_E}{C_E u_*}$ includes empirical constant C_E

<u>Further work</u>: extend to Equator → ultimate CN PBL limit $h_E \sim U/N$
verify against LES atmospheric and oceanic data

Long-lived stable PBL

Very shallow long-lived stable PBL visualised by smoke in warm summer day over cold Lake Teletskoe, Altay, Russia, 28.08.2010

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“Long-lived” stable PBL

Rising smoke in Lochcarron (Scottish Highlands) blocked within shallow PBL capped by strong temperature inversion. Photo by S/V Moonrise (Wikimedia).

Convective boundary layers

Turbulent kinetic energy (TKE) budget equation

Kinetic energy is generated convectively and mechanically

Shear-free regime:
when convective generation is much stronger than mechanical

Deardorff (1972) governing parameters: B_s and h

convective velocity scale: $W_* = (B_s h)^{1/3}$

similarity theory: $E_K / W_*^2 = \Phi_{EK}(z/h)$, …

Eddy-viscosity scale $K_* = W_* h$ substituted into Ekman height scale $h_* = (K_* / |f|)^{1/2}$ yields $h_* \sim B_s^{1/2} / f^{3/2} \sim 30\ \mathrm{km}$ much higher than atmospheric PBL height → **hence**
ROTATION NEGLIGIBLE → convective PBL $\neq$ Ekman layer

Convective boundary layers

TKE-budget
$$\frac{dE_K}{dt} = \boldsymbol{\tau} \cdot \frac{\partial \mathbf{u}}{\partial z} + B - \frac{\partial F}{\partial z} - \varepsilon$$

Kinetic energy is generated convectively and mechanically with generation rates $B > 0$ and $\boldsymbol{\tau} \cdot \partial \mathbf{u} / \partial z$, respectively

<u>Shear-free regime</u>: when convective generation >> mechanical

Deardorff (1972) governing parameters: B_s and h

convective velocity scale: $W_* = (B_s h)^{1/3}$

similarity theory: $E_K / W_*^2 = \Phi_{EK}(z/h)$, …

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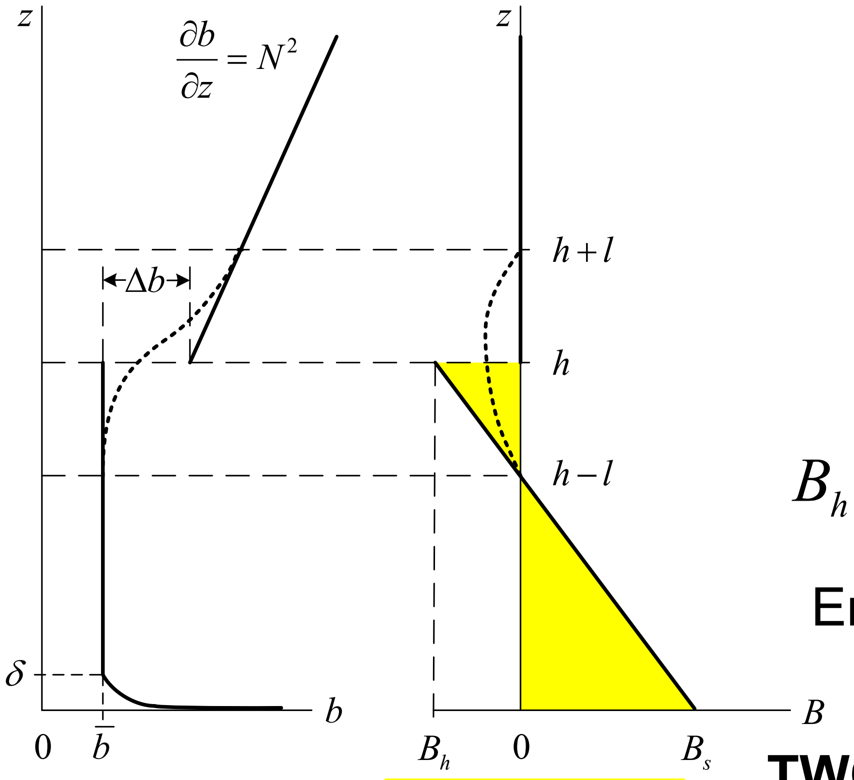
The concept of well-mixed layer

Typically $B_s \sim 10^{-3}\ \mathrm{m^2 s^{-3}}$ → strong mixing → buoyancy (b), velocity (u,v), etc. are z-independent, except near-surface ($0 < z < \delta$) and entrainment ($h - l < z < h + l$) layers → almost linear vertical profiles of turbulent fluxes (B τ and)



$$b = \begin{cases} \bar{b} & \text{at } \delta < z < h \\ \bar{b} + \Delta b + N^2 (z-h) & \text{at } z > h \end{cases}$$

$$B = \begin{cases} B_s(1 - z/h) + B_h z/h & \text{at } 0 < z < h \\ 0 & \text{at } z > h \end{cases}$$

$$B_h = -\Delta b \dot{h} < 0 \ \text{ caused by } \ \Delta b = b_{h+0} - b_{h-0}$$

Entrainment depth-scale (l) from similarity of triangles

$$\frac{l}{h-l} = -\frac{B_h}{B_s}$$

TWO PROBLEMS

1. Growth rate (PBL height)

$$\dot{h} = \frac{dh}{dt} - w$$

2. Entrainment coefficient (VENTILATION & CLOUDS)

$$A = \frac{-B_h}{B_s} = \frac{\dot{h}\Delta b}{B_s}$$

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PBL-height buoyancy-budget models

Budget equation for mean buoyancy $b = (g/T)\theta + 0.61gq$ is composed of the potential temperature (θ) and specific humidity (q) equations: $\dfrac{db}{dt} = -\dfrac{\partial B}{\partial z}$

Taking the well-mixed-layer $b(z)$ and $B(z)$ and integrating over the PBL, yields bulk buoyancy equation with **TWO UNKNOWNS** h and Δb (or $B_h = -\Delta b \dot{h}$):

$$\boxed{\frac{d}{dt}\left(\frac{1}{2}N^2h^2 - h\Delta b\right) = B_s}$$

No entrainment (Zubov, 1945; $B_h = 0$) → encroachment model: $\boxed{\dot{h} = \dfrac{B_s}{N^2 h}}$

Given entrainment (Betts/Carson/Tennekes, 1973: $A = -B_h/B_s = \text{constant}$) →

$$\boxed{\dot{h} = (1 + 2A)\frac{B_s}{N^2 h}}$$

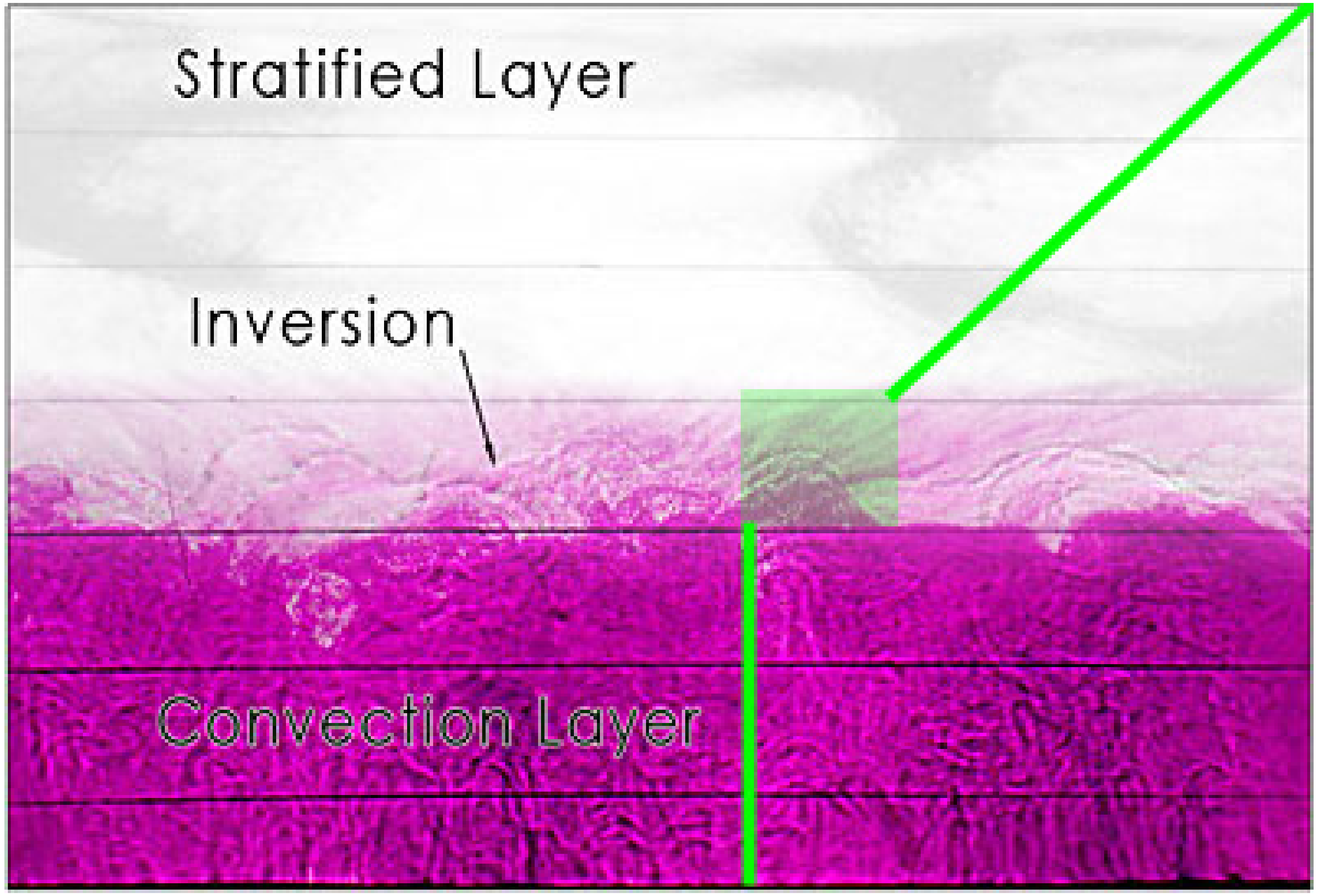
irrelevant at N=0 (in lab experiments $\dot{h} \approx 0.24W_*$)

used in Gryning-Batchvarova (1990,…) with $A = 0.2$

Empirical data on $A = B_h / B_s$ (from Z, 1991)

Atmosphere	Laboratory	Lake	$A=B_h/B_s$
Koprov, Zwang 1965			0.35
Deardorff 1967			0.1 – 0.3
Lenschow , Johnson 1968			0.9
	Deardorff et al. 1969		0.12
Lenschow 1970			0.1
Deardorff 1972			0.1
Lenschow 1973			0 – 0.17
Stull 1976			< 0.1
Deardorff 1973			0.2
Carson 1973			0.25
Betts 1973			0.25
Cattle, Weston 1973			0.25
Lenschow 1974			< 0.12
Pennel, Le Mone			< 0.1
Rayment, Readings 1974			0.25
	Deardorff et al. 1974		0.23
Betts 1974			0.3
	Willis, Deardorff 1974		0.11 – 0.23
Cattle, Weston 1975			0.29 – 0.32
		Farmer 1975	0.2
	Heidt 1977		0.18
Yamamoto et al. 1077			0.2
	Kantha 1979		0.2
Coulman 1980			0.25
Dubosklard 1980			0.9
	Denton Wood 1981		0.2 – 0.5
Driedonks, Tennekes 1984			0.2

Shear-free convection in laboratory



A snapshot of the convection layer in laboratory experiment
Earth, Atmospheric & Planetary Sciences Project, MIT, 2008
http://paoc.mit.edu/labguide/convect_atm.html

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Lab entrainment TKE-budget model (Z-91)

Two unknowns in bulk buoyancy-budget equation: $\boxed{\frac{d}{dt}\left(\frac{1}{2}N^2h^2 - h\Delta b\right) = B_s}$

PBL **height** h, and the buoyancy increment due

to entrainment Δb or **entrainment coefficient** $\boxed{A = \frac{\dot{h}\Delta b}{B_s}}$

Z (1975) closed the problem employing **bulk TKE-budget** equation and solved it (1987) for **"laboratory" shear-free** PBL growing against linear stratification accounting for energy consumption for exciting internal gravity waves at $z > h$

$$\boxed{A + C_3 \mathrm{Ri}^{3/2}\left(\frac{A}{1+A}\right)^3 = C_1 - C_2 E}$$

$\boxed{E = \dot{h}/W_*}$ and $\boxed{\mathrm{Ri} = \tfrac{1}{2}(Nh/W_*)^2}$ are Richardson number

$C_1 = 0.2,\ C_2 = 0.8,\ C_3 = 0.1$ are empirical constants (Z, 1991)

Lab entrainment TKE-budget model (Z-91)

TKE-budget in **shear-free convection** (laboratory) $\frac{dE_K}{dt} = B - \frac{\partial F}{\partial z} - \varepsilon$

Deardorff similarity: $E_K = W_*^2 \Phi_{EK}(\varsigma)$, $\varepsilon = (W_*^3 / h)\Phi_\varepsilon(\varsigma)$ where $\varsigma = z / h$

Well-mixed layer buoyancy-flux profile: $B = B_s(1-\zeta) + B_h \zeta$

Integration over PBL→ Internal-Gravity-Wave energy flux: $F_{h+0} \propto \lambda^2 \Lambda N^3$

IGW length and amplitude: $\Lambda \sim \lambda \sim l = \frac{A}{1+A} h$, l entrainment-layer depth

SOLUTION $\boxed{\frac{d}{dt}\left[W_*^2\left(\mathrm{Ri} - \frac{A}{E}\right)\right] = B_s}$ $\boxed{A + C_3 \mathrm{Ri}^{3/2}\left(\frac{A}{1+A}\right)^3 = C_1 - C_2 E}$

Entrainment coefficient $\boxed{A = \frac{\dot{h}\Delta b}{B_h}}$ Expansion rate $\boxed{E = \dot{h} / W_*}$ Ri number $\boxed{\mathrm{Ri} = \frac{1}{2}(Nh / W_*)^2}$

Empirical constants from lab experiments: $C_1 = 0.2,\ C_2 = 0.8,\ C_3 = 0.1$

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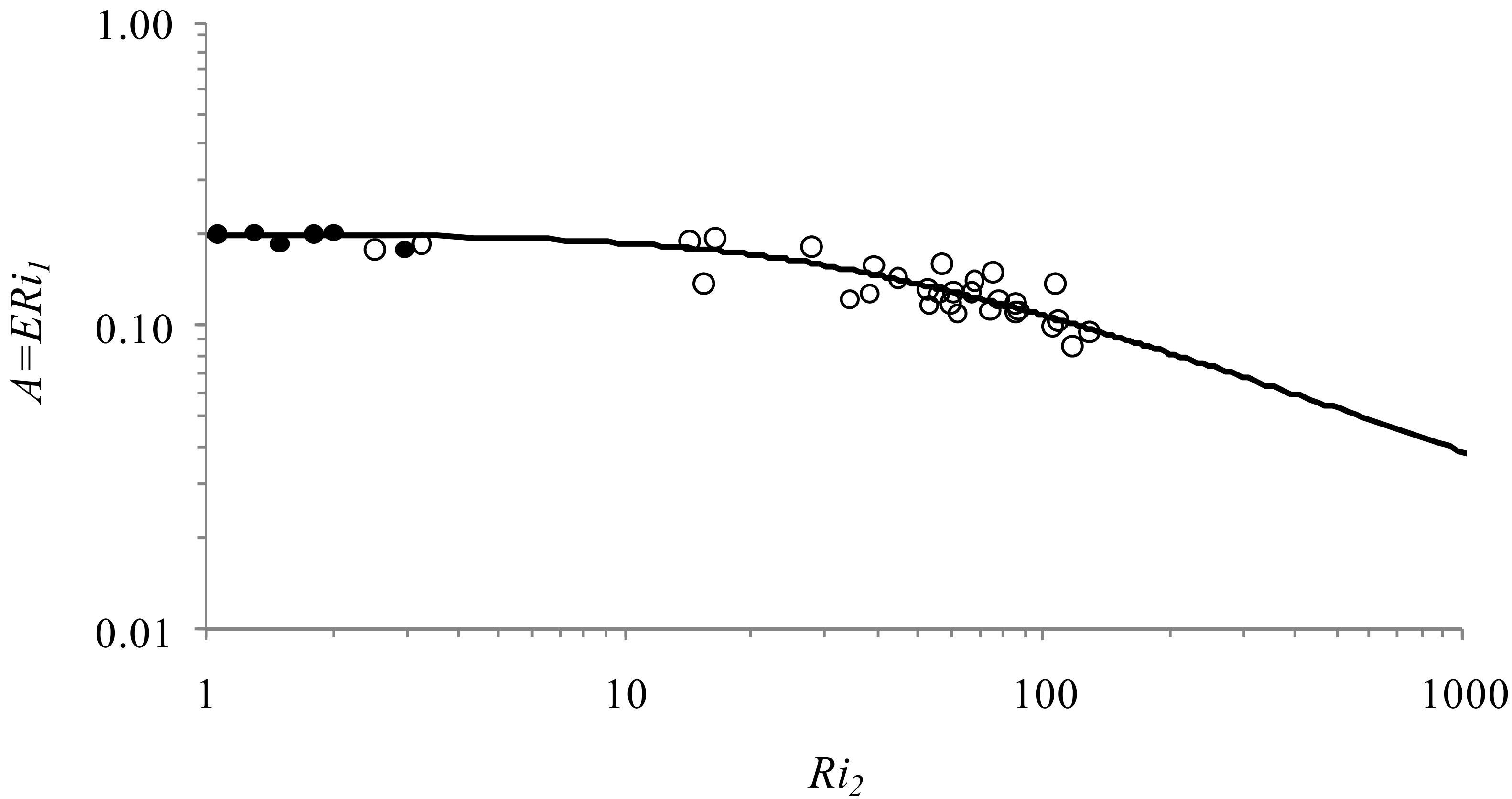
Validation against lab-experiment data



Entrainment coefficient $A = B_h/B_s$ versus $Ri_2 = \frac{1}{2}(Nh/W_*)^2$ in Deardorff et al. (1980) laboratory experiments with shear-free convective layers evolving against linearly stratified fluid (black circles) and two-layer fluid (open circles). Theoretical curve shows TKE-budget entrainment model Z (1987, 1991) with $C_1 = 0.2$, $C_2 = 0.8$, $C_3 = 0.1$.

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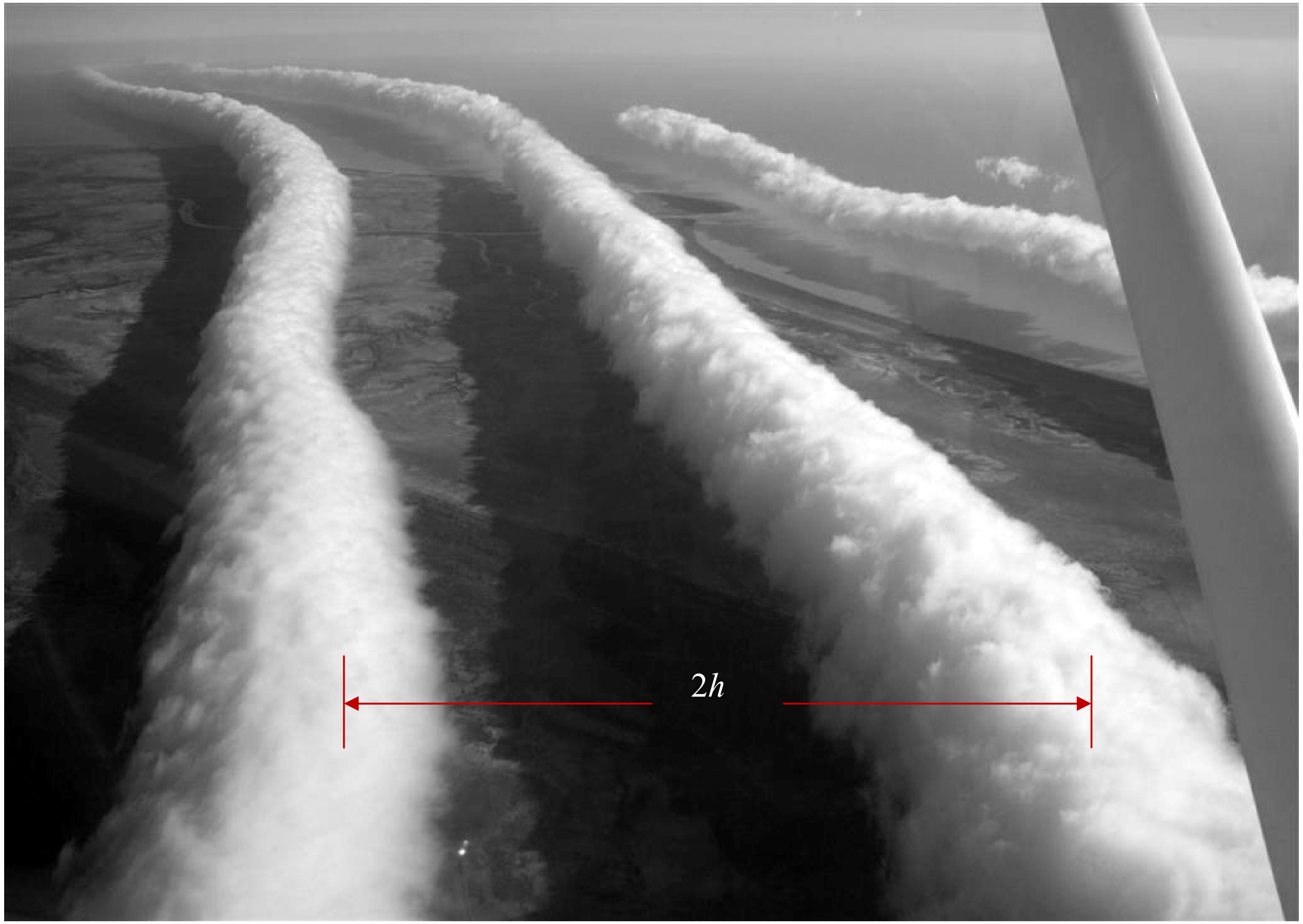
Organised rolls in sheared convection



Self-organised rolls stretched along mean wind occupy the entire PBL $(0 < z < h)$ with distance between rolls of order $2h$.

<u>Updraughts excite IGW with wave length typically</u> $\sim 2h$ <u>in the stably stratified free atmosphere</u>

Cloud streets visualise updraughts in convective rolls

Photo by Mick Petroff, Queensland, North Coast, Australia (Wikimedia Commons)

Atmospheric entrainment model (Z, 2011)

TKE-budget in sheared convection $$\frac{dE_K}{dt} = \boldsymbol{\tau} \cdot \frac{\partial \mathbf{u}}{\partial z} + B - \frac{\partial F}{\partial z} - \varepsilon$$

Generalised similarity: $W_*^3 = 2\int_0^h B dz \approx hB_s$, $V_*^3 = \int_0^h (\boldsymbol{\tau} \cdot \partial \mathbf{u} / \partial z) dz \approx \bar{U} u_*^2$

For TKE $E_K = W_*^2 \Phi_{EK}^{(c)}(\zeta) + V_*^2 \Phi_{EK}^{m}(\zeta)$ and similarly for dissipation ε

IGW energy flux: $F_{h+0} \propto \lambda^2 \Lambda N^3$

IGW amplitude: $\lambda \sim l = \frac{A}{1+A} h$ but wave-length (**the above photo**) $\Lambda \sim h$

Entrainment equation accounts for shear and IGW caused by rolls

$$\boxed{A + C_4 \mathrm{Ri}^{3/2} \left(\frac{A}{1+A} \right)^2 = C_1 - C_2 E + C_5 \left(\frac{V_*}{W_*} \right)^3}$$

$$\boxed{A = \frac{\Delta b \dot{h}}{B_h}} \quad \boxed{E = \frac{\dot{h}}{W_*}} \quad \boxed{\mathrm{Ri} = \frac{1}{2} \left(\frac{Nh}{W_*} \right)^2}$$

$C_1 = 0.2$, $C_2 = 0.8$ **lab exp.**

C_4, C_5 **to be determined**

Conclusions

Stable / neutral layers Heights from dozens to hundreds m

Weakly mixed, strongly affected by the free-flow stratification

LS and CN layers typical of Polar, marine, coastal atmosphere

Shallow Polar and sub-Polar PBLs AMPLIFY GLOBAL WARMING

Shallow LS PBLs control heavy air-pollution episodes

Convective layers **Heights** up to 3-5 *km*, **variable entrainment**

Organised cells/rolls $\boxed{W_* = (B_s h)^{1/3}}$ **ENHANCE HEAT/MASS TRANSFER**

Over open waters in Polar Ocean (especially polynias and leads)

In Tropics, e.g. over "Warm Pool Area"

Strongly variable turbulent entrainment $\boxed{0 < A = -B_h / B_s < 1}$

A **controls cumulus clouds (Knight et al., 2007), which causes strong climate sensitivity to** A **(currently given constant** $= 0{,}2$**)**

Challenge **Operational modelling and monitoring PBL height**

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PBL height and air quality

Project "Information System for Management of Air Quality", ENEA, Italy, 2008-2010

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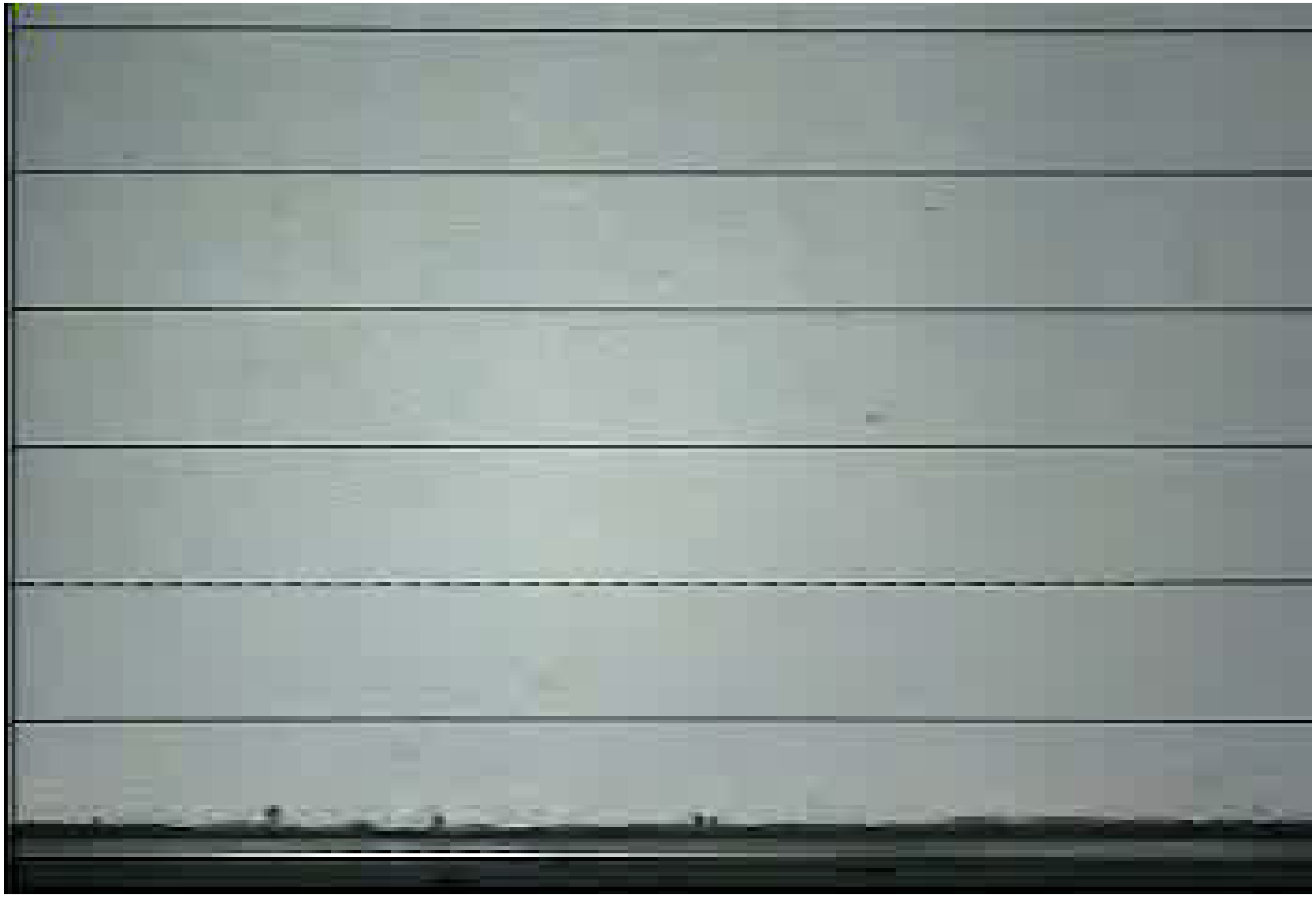
The evolution of convective boundary layer



Earth, Atmospheric and Planetary Sciences Project, MIT, 2008

http://paoc.mit.edu/labguide/convect_atm.html

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