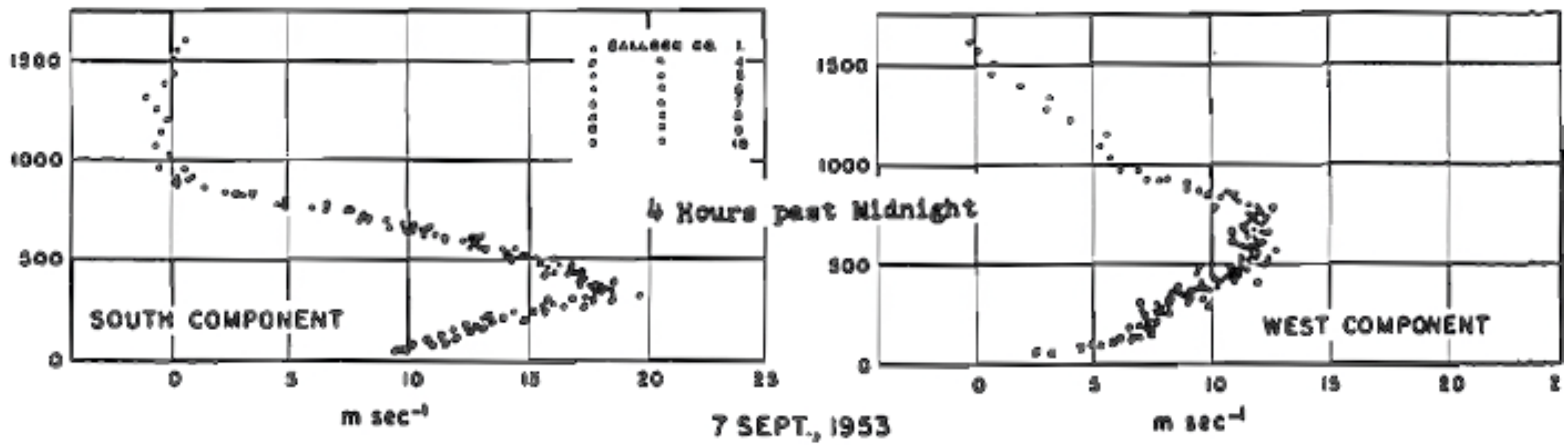
Boundary layer processes

Bjorn Stevens
Max Planck Institute for Meteorology, Hamburg

The Atmospheric Boundary Layer (ABL)

- 'An Abstraction' (Wippermann '76)
- 'The bottom 100-3000 m of the Troposphere' (Stull '94)
- 'The lower part of the troposphere where the direct influence from the surface is felt through turbulent exchange with the surface' (Beljaars '94)



A turbulent layer that emerges due to the destabilizing influence of the surface on the atmosphere, and which is characterized by lengthscales h, such that

$$z_0 << h << H, L$$

Here z_0 denotes the scale of roughness elements, H is the depth of the troposphere and L is the characteristic length scale measuring variations in surface properties

Who cares?

- Spin-down of the large-scale flow (Charney & Eliassen, 1949) --- 'It is thus noteworthy that the first incorporation of the planetary boundary layer in a numerical prediction model was done even before the first 1-day forecast was made' (A. Wiin-Nielsen, 1976)
- Conditional Instability of the Second Kind (CISK; Charney & Eliasen, 1964, Ooyama 1964)
- Diurnal Cycle: Convection/Precipitation & Nightime Minimum Temperatures.
- Air Pollution, Contaminant Dispersion.
- Ocean Coupling (wind-stress and wind-stress curl).
- Radiative balance & Hydrological Cycle.
- Modulation of local circulations: mountain-valley flows; sea breezes; katabatic flows.
- Biogeochemical Cycles (nutrient transport in upper ocean/ boundary layer transport).
- Wind Power.

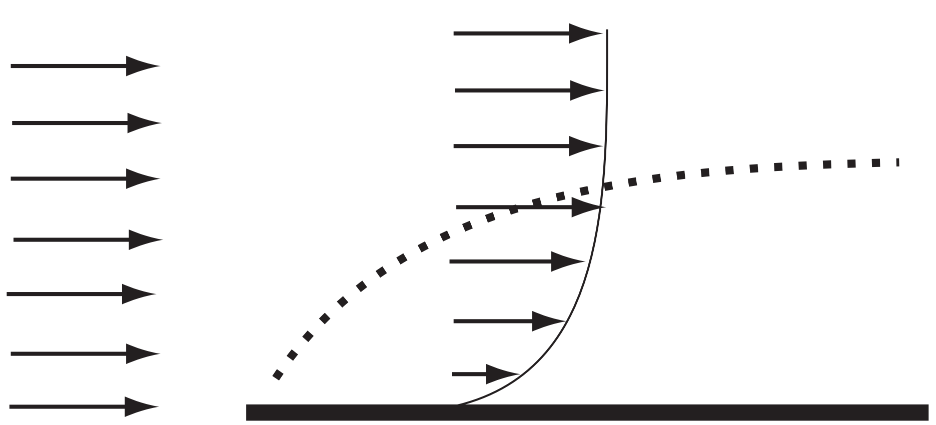
The impact of the boundary layer in models is particularly felt after a few days of integration when the accumulated surface fluxes contribute substantially to the heant, moisture and momentum balance of the atmosphere. (A. Beljaars, 1994)

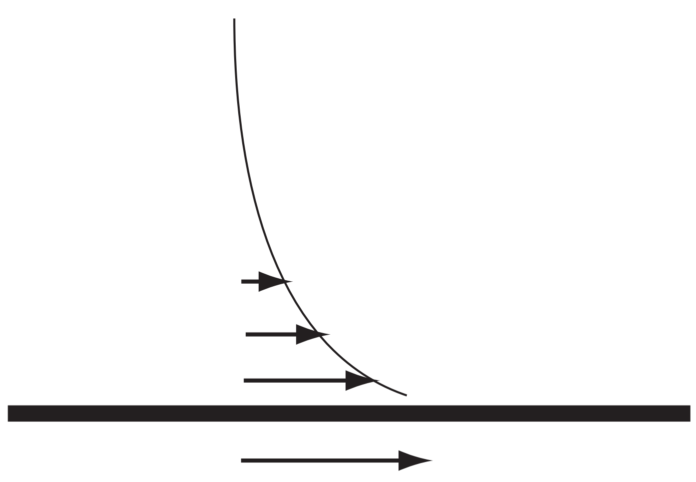
The Boundary Layer -- Prandtl/Blasius

$$\partial_t u + \mathbf{u} \cdot \nabla u = -\alpha \partial_x p + \nu \nabla^2 u \qquad (1)$$

$$H \longrightarrow (\nu x/U)^{1/2} \simeq (\nu t)^{1/2}$$

$$w \simeq (\nu U/x)^{1/2}$$



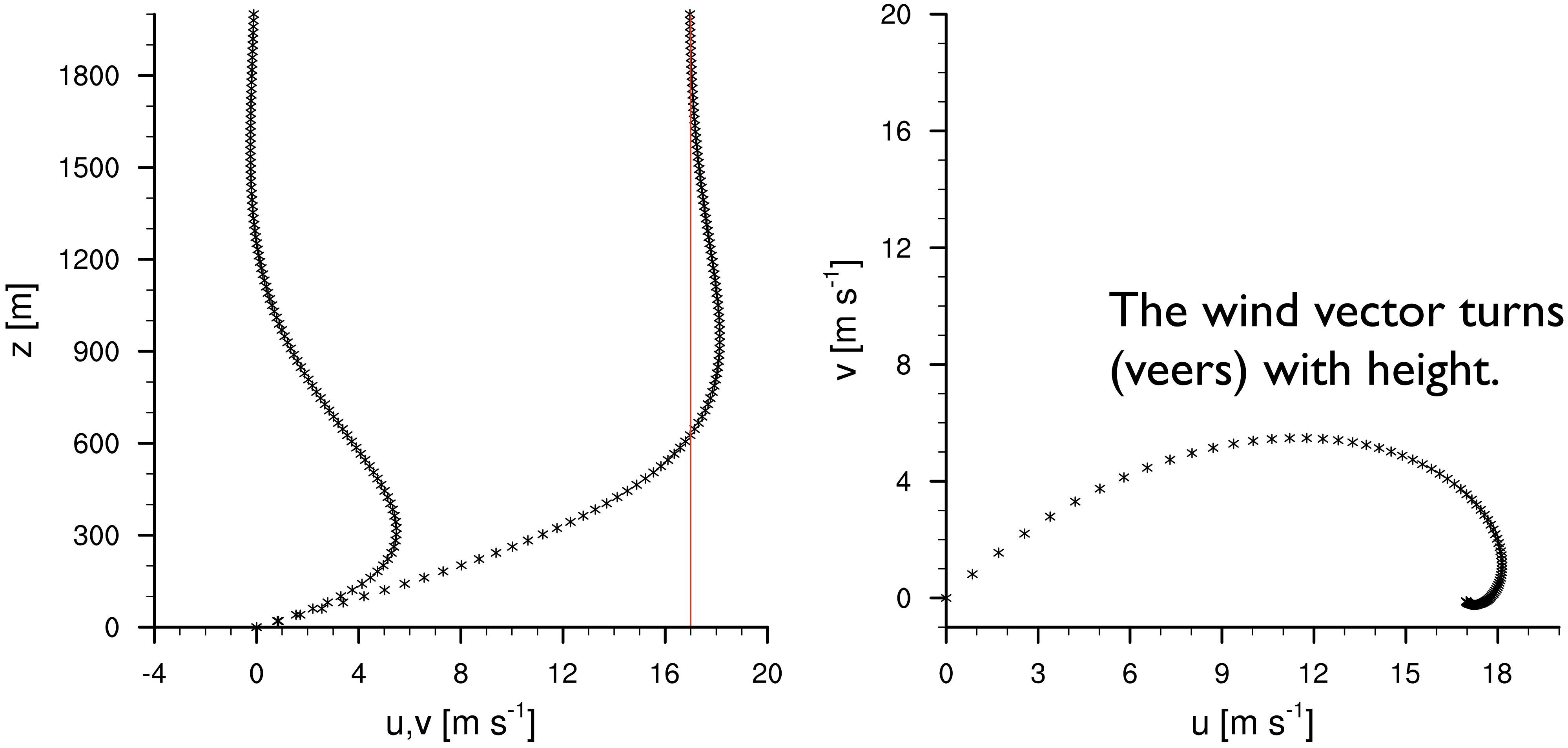


$$\partial_t \theta + \mathbf{u} \cdot \nabla \theta = \kappa \nabla^2 \theta$$

The Boundary Layer -- Ekman

$$\partial_t v + \mathbf{u} \cdot \nabla v + fu = -\alpha \partial_y p + \nu \nabla^2 v$$

$$H \longrightarrow (\nu/f)^{1/2}$$



The wind vector turns clockwise (veers) with height.

Remarks -- Momentum Boundary Layers

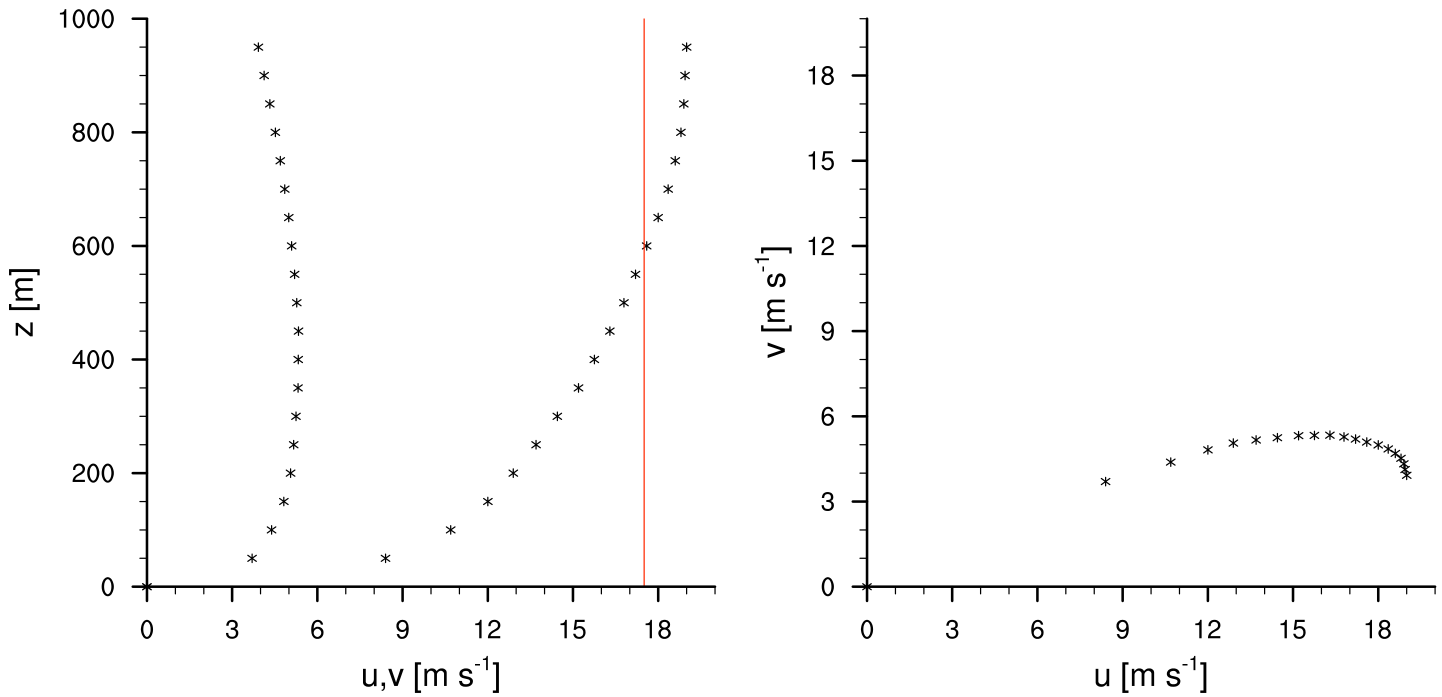
- Concepts: Boundary layer depth, *h;* Secondary Circulations, *w.*
- Viscous solutions are unstable, and the surface is not smooth, hence atmospheric boundary layers are turbulent.

$$\partial_t \overline{v} + \overline{\mathbf{u}} \cdot \nabla \overline{v} + f\overline{u} = -\alpha \partial_y \overline{p} + \nu \nabla^2 \overline{v} + \nabla \cdot (A \nabla \overline{v})$$

where

$$\overline{v' \mathbf{u}'} \equiv -A \nabla \overline{v}$$

$$\nabla \cdot (A \nabla \overline{v}) = \nabla A \cdot \nabla \overline{v} + A \nabla^2 \overline{v}$$



$$A = \ell^2 \left| \frac{du}{dz} \right|$$

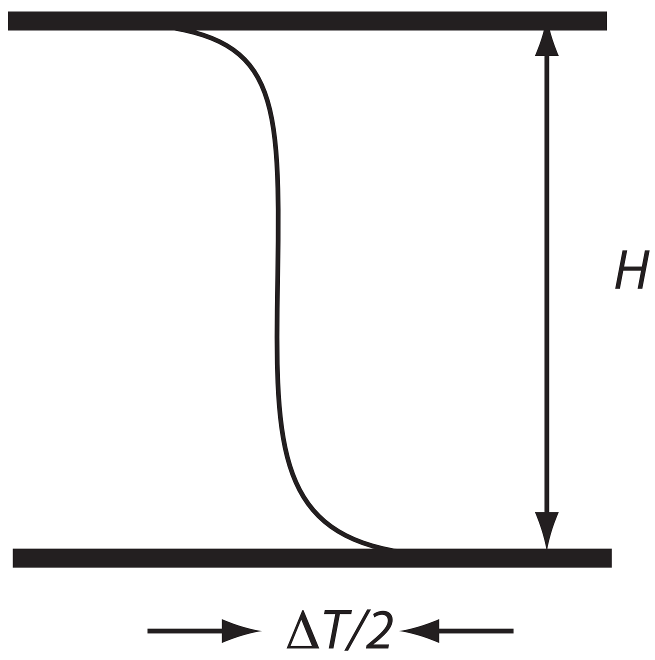
which introduces the idea of a mixing length, which is reasonable if

$$\ell \ll \left| \frac{du}{dz} \right| \left(\frac{d^2 u}{dz^2} \right)^{-1}$$

i.e., mixing is local.

Remarks -- Thermal Boundary Layers

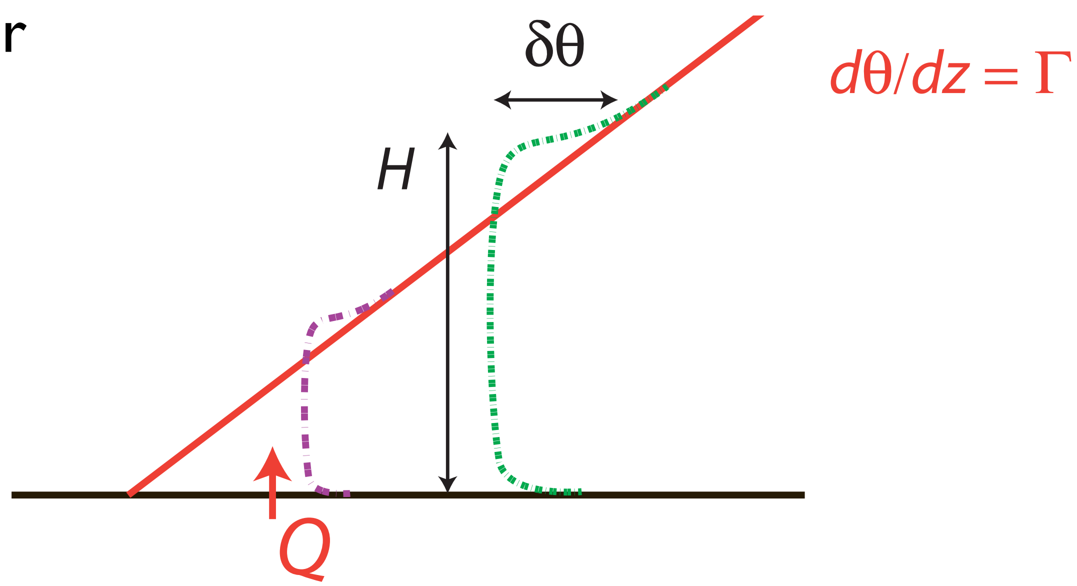
Rayleigh-Bénard is a paradigm for thermal convection



$$Ra = \frac{(g/T_0)\Delta T H^3}{\nu\kappa}$$

which suggests that a local rule will not be appropriate, although thermal atmospheric boundary layers are generally asymmetric.

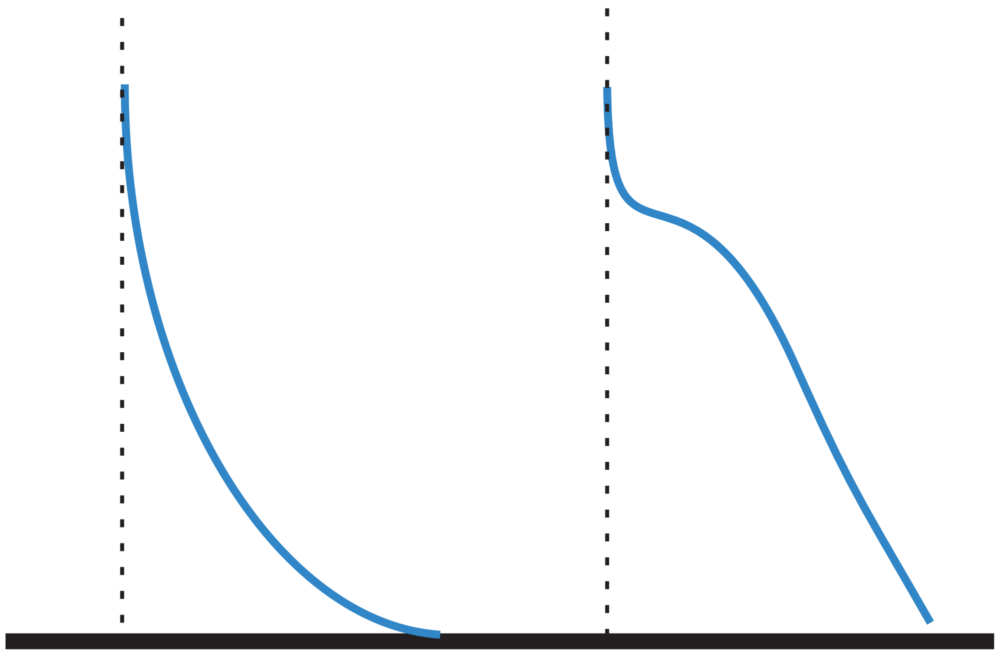
and encourages the conceptualization of the layer as a bulk entity, for which the determination of the depth of the layer is key, and within which fluxes are not necessarily proportional to local gradients



Remarks -- Concepts

Shear Dominance

- Eddy Diffusivity/Viscosity (local concept)
- Mixing Length, l
- Surface matching,

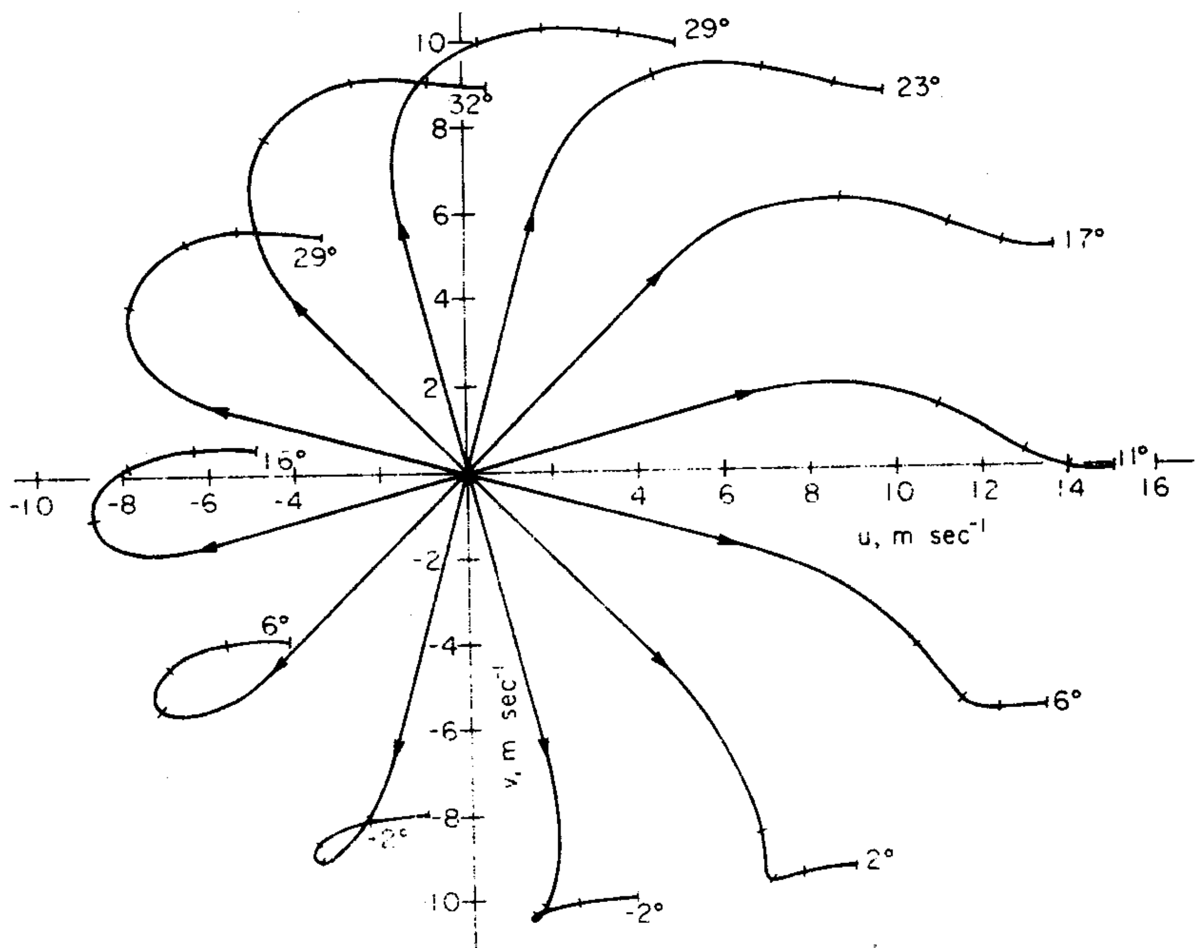


Buoyancy Dominance

- Boundary Layer Depth (integral concept)
- Surface layer ($z << h$),
- Entrainment layer

Complications -- Momentum Boundary Layers

- Momentum boundary layers that are thermally stratified can be expected to deepen less.
- Horizontal temperature gradients cause shear in the geostrophic wind which alters the expected behavior (more veering, or even backing).



These still prove to be a challenge to model

1238 A. R. BROWN *et al.*

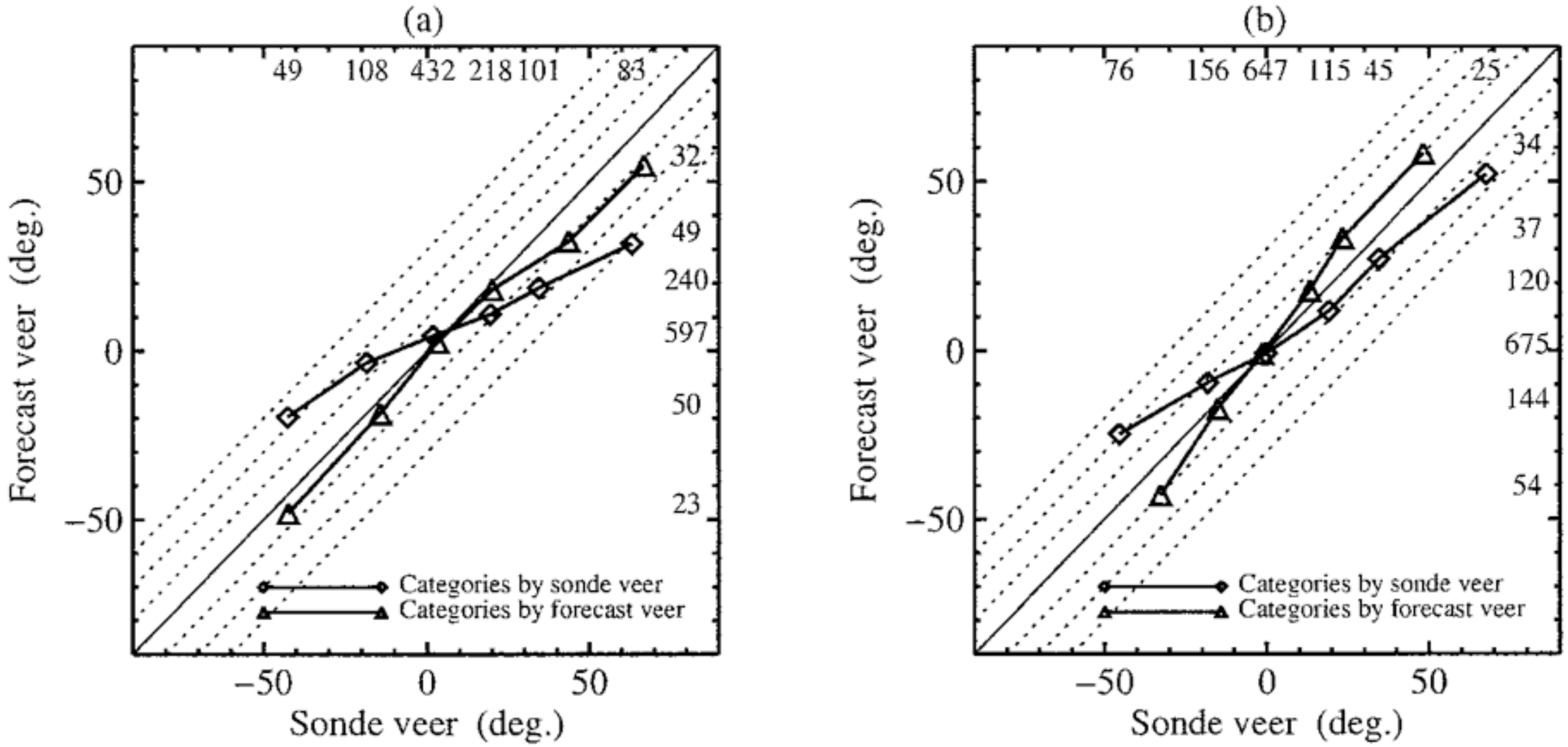


Figure 3. Composites for Sable, Charlie, Lima and Mike of ERA-40 24-hour forecast wind veer versus sonde veer for DJF8488 for (a) surface to 850 hPa and (b) 850 hPa to 700 hPa. The composites have been made based both on the sonde veer and on the forecast veer, using the categories of Hollingsworth (1994), except that the strong veer category has been split into veers between 27° and 42° and veers exceeding 42°. The numbers near the top axis indicate the number of cases in each category based on the sonde veer, while the numbers near the right axis indicate the number of cases in each category based on the forecast veer.

Baroclinic ABL (part II)

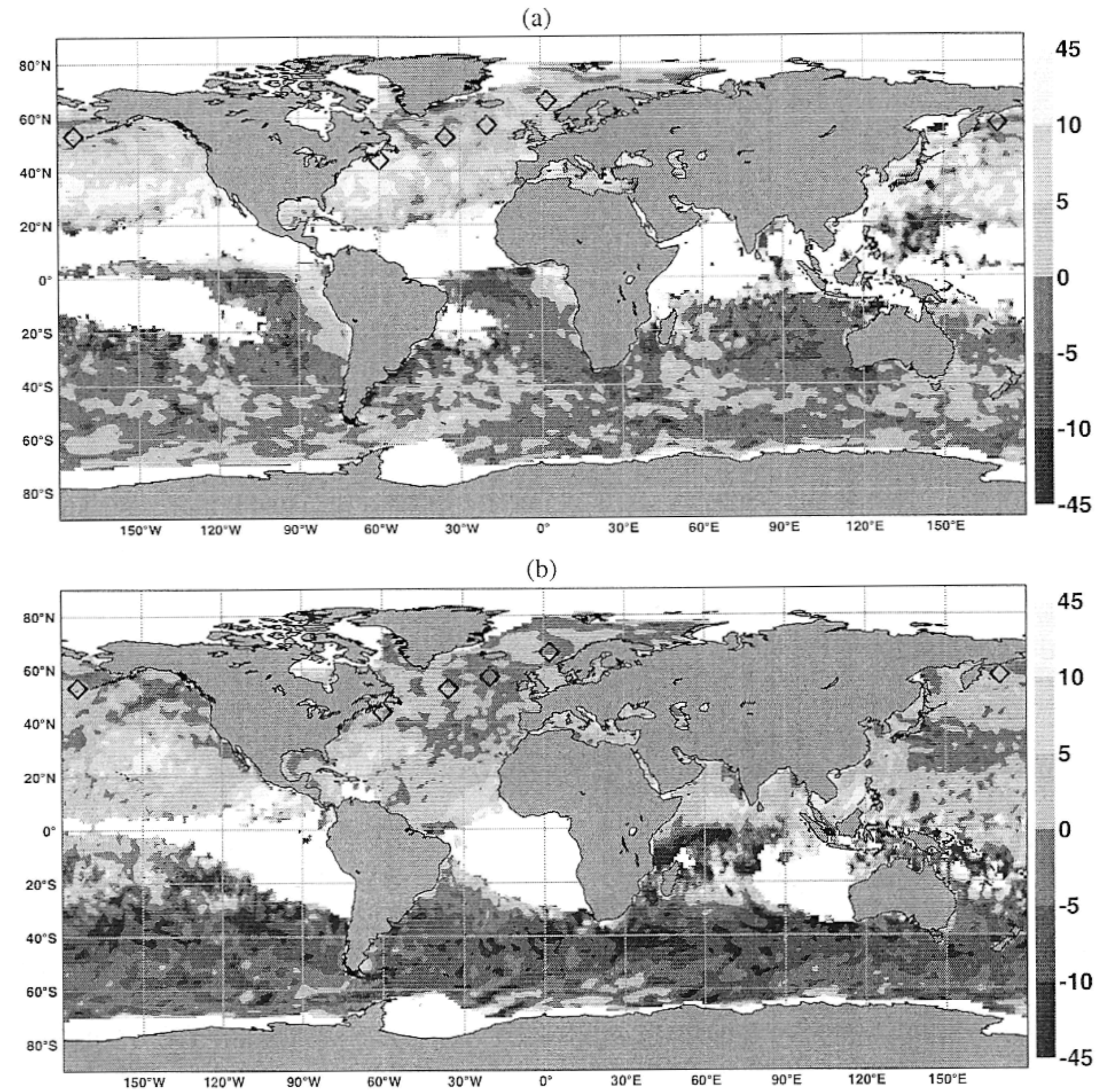
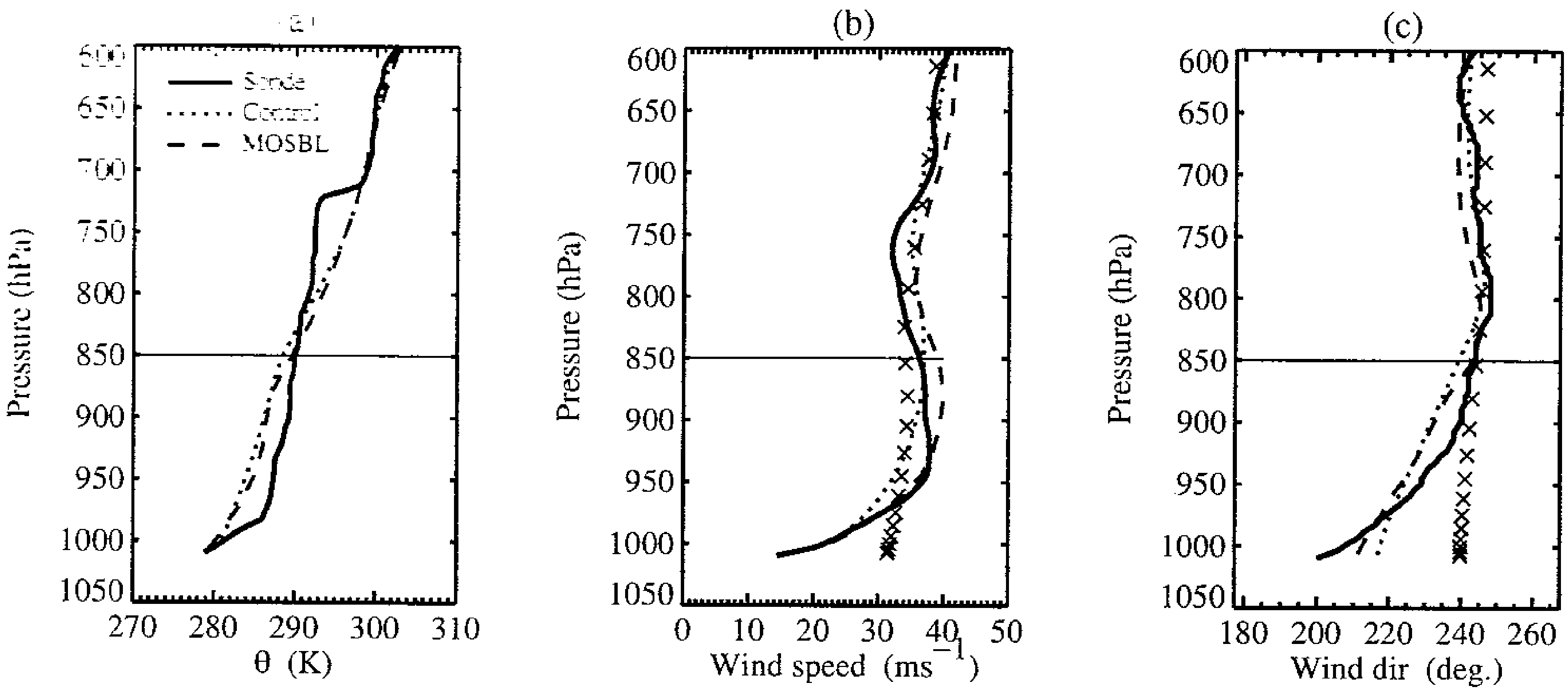


Figure 5. Wind-direction bias of ECMWF short-range forecast 10 m winds relative to QuikSCAT surface winds for DJF0001: the average for collocations in which both ECMWF and QuikSCAT wind direction are within ±60° of (a) southerly and (b) northerly directions and with wind speed of at least 4 m s^{-1}. Black diamonds indicate sonde locations of (from west to east) Shemya, Sable, Charlie, Lima, Mike and St. Paul.

TABLE 1. REGIONAL AVERAGES (DEGREES) OF WIND DIRECTION BIASES SHOWN IN FIG. 5

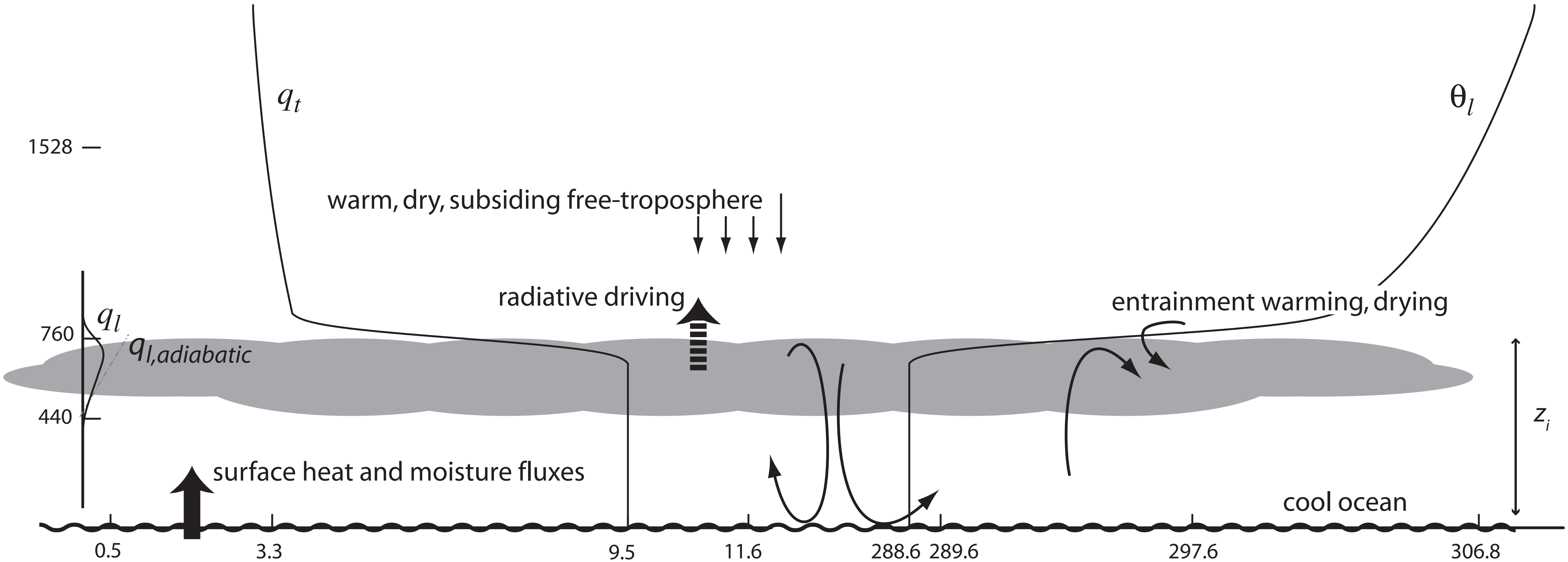
	Globe	Northern hemisphere	Tropics	Southern hemisphere
Northerly flows	−1.6	1.2	0.9	−5.7
Southerly flows	0.5	6.0	−1.0	−1.6

Baroclinic ABL (part III)



Model Changes that limit mixing leads to a globally worse model, but one that better agrees with the data locally --- A persistent problem.

Complications -- Cloudy Boundary Layers



- *Clouds are unambiguously part of the boundary layer.*
- *Order epsilon sensitivity to state has an order unity effect.*
- *History is important (t ~ 1/D)*

Stratocumulus Layers (part II)

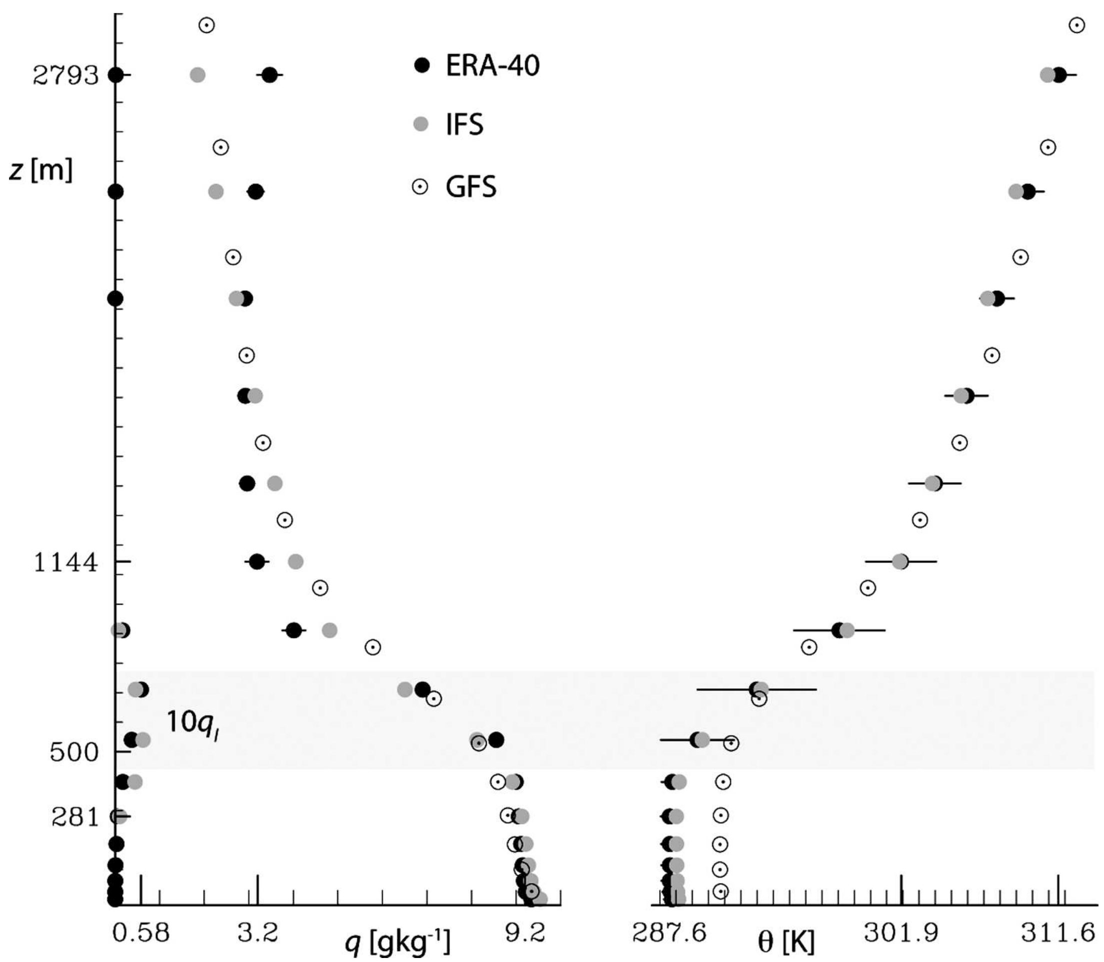


FIG. 8. Mean profile for 10–20 Jul 2001, for ERA-40, GFS, and IFS forecasts, averaged over the first 24 h of the forecast. For guidance the position of the observed cloud layer is indicated by the shading. Profiles for liquid water are multiplied by 10 and do not include GFS.

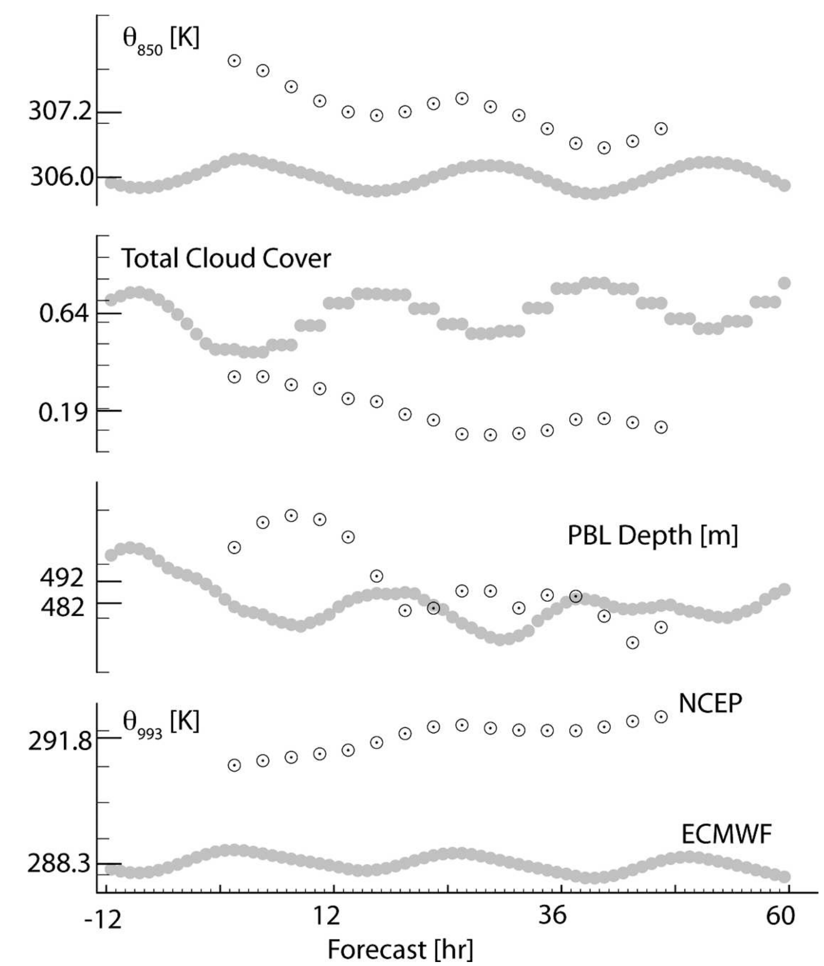
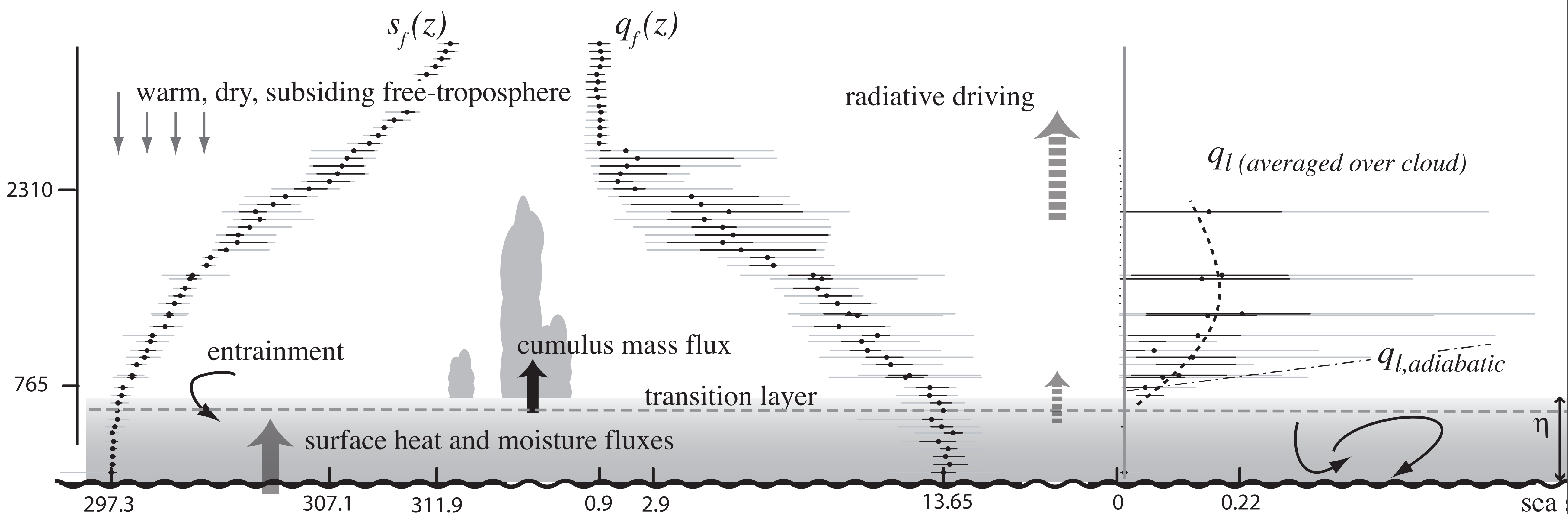


FIG. 7. July average at each forecast hour for selected fields from ECWMF (gray circles) and NCEP (open circle with center dot): (top to bottom) θ_{850}, total cloud cover, PBL depth, and θ_{993}.

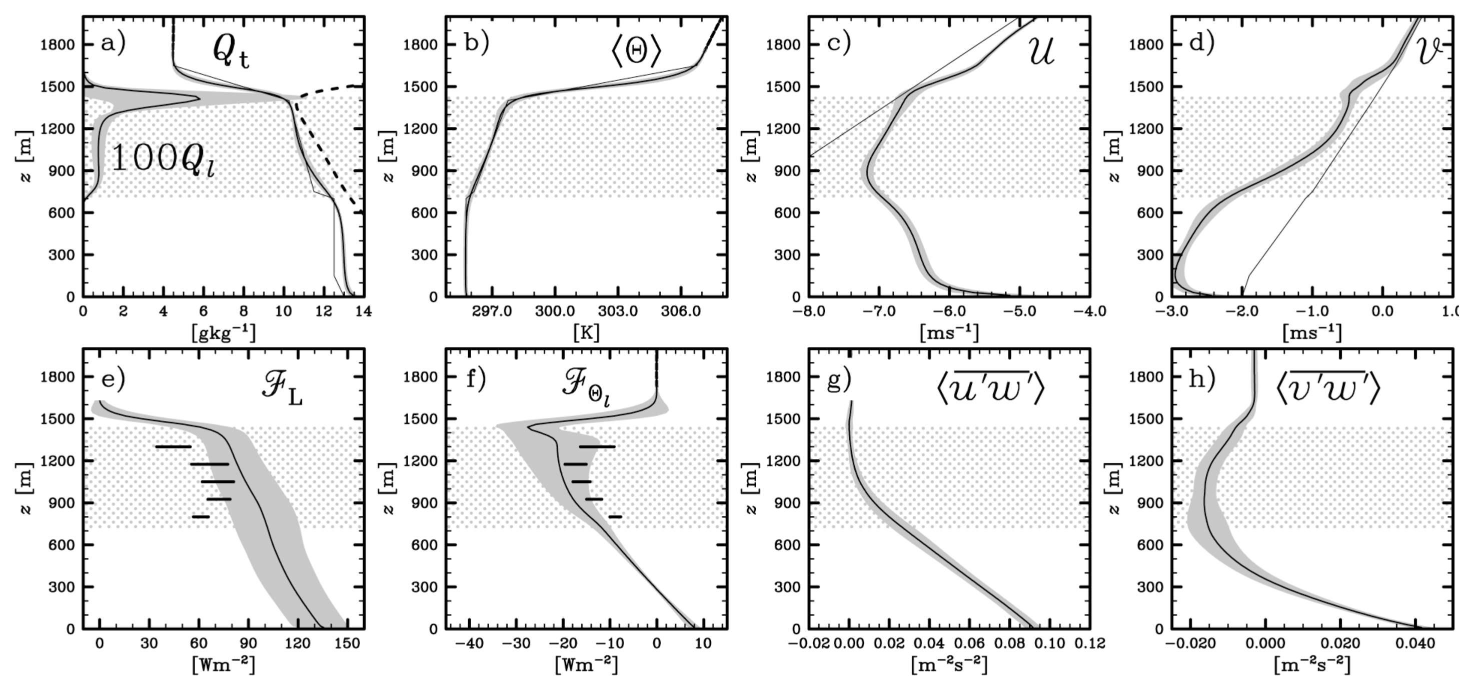
Cumulus-Topped Layers



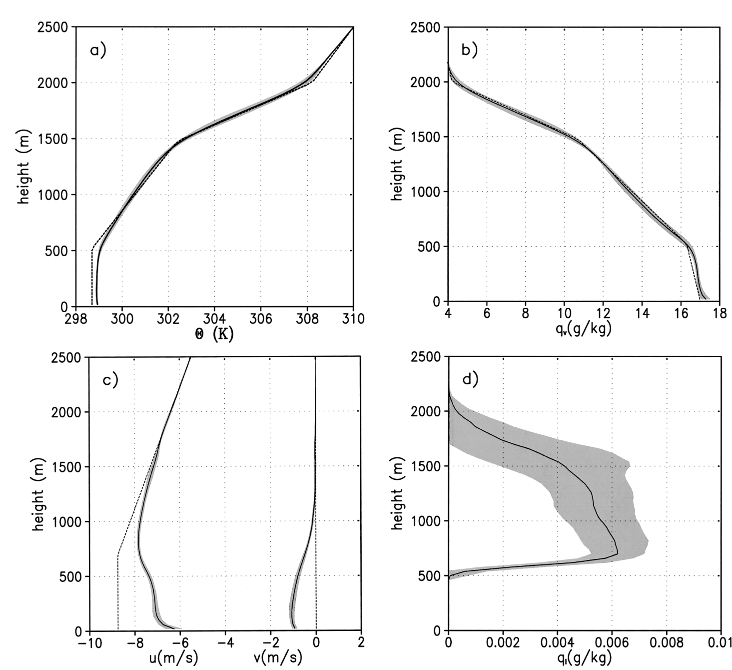
- *Thermal and momentum boundary layer are increasingly distinct.*
- *The concept of a mass flux, M*

Cumulus-Topped Layer (Part II)

1876 JOURNAL OF THE ATMOSPHERIC SCIENCES VOLUME 58



15 May 2003 SIEBESMA ET AL. 1205



Remarks

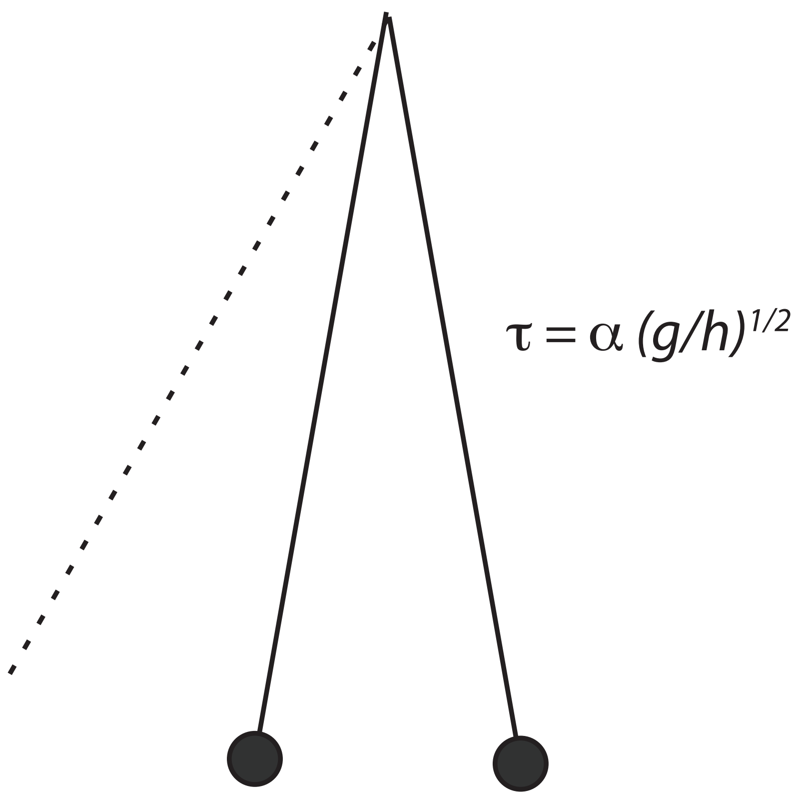
- Boundary layers are rich in processes.
- Boundary layers are thin.
- Boundary layers are turbulent.

Some words about modeling

- Similarity.
- Local rules: (L, z, q, S, N).
- Bulk rules $(h, \Delta T, \Delta U, \Delta F, D, M, B)$.
- Forgotten parameters $(\Delta x, \Delta z)$.
- Stochastic Methods.
- Hybrid approaches.
- Two scale models.

Similarity

Non-dimensional equivalence



The law of the wall (log-layer) -- intermediate asympototic

$$\partial u/\partial z = \alpha\ (u_*/z)$$

$$\partial u/\partial z = \alpha\ (u_*/z)\ f(\pi)$$

Local vs Bulk Rules

- Fluxes proportional to local TKE, *e*.
- Mixing profile scales with bulk quantities.
- The length scales are the trick in both approaches.

$$\partial_t e = -\overline{u'w'}\partial_z \overline{u} + \overline{w'b'} - \epsilon$$

$$K = \sqrt{e}\ell$$

versus

$$K(z) = v_* h g(\pi) \quad \text{where} \quad \pi = z/h$$

In practice both often combine elements of the other.

Summary

- Boundary layers are essential.
- Most ideas are built around classical concepts.
- Our task is difficult because boundary layers are rich, thin and turbulent.
- Many essential problems remain.
- Fine-scale modeling is helping to enrich the phenomenological basis for our modeling.