Boundary-layer processes in the MetUM

Adrian Lock, with thanks to Ian Boutle

Contents

- Need for a boundary layer parametrization
- Interior fluxes – stable boundary layers
- Interior fluxes – unstable boundary layers
  - Top fluxes – entrainment
- Surface fluxes
- Combining it all to produce a scheme

Role of the boundary layer

- Accurate representation of the BL in NWP is:
  - Crucial for forecasting near-surface weather parameters (temperature, wind, visibility, pollutant concentrations, etc)
  - Boundary layer drag important for evolution of synoptic scale features (lows, fronts, etc)
  - Vertical structure of the BL important for formation and persistence of low cloud and fog
- The BL is the interface between the surface and the atmosphere
  - Impact on global budgets by moderating the surface fluxes of heat and moisture

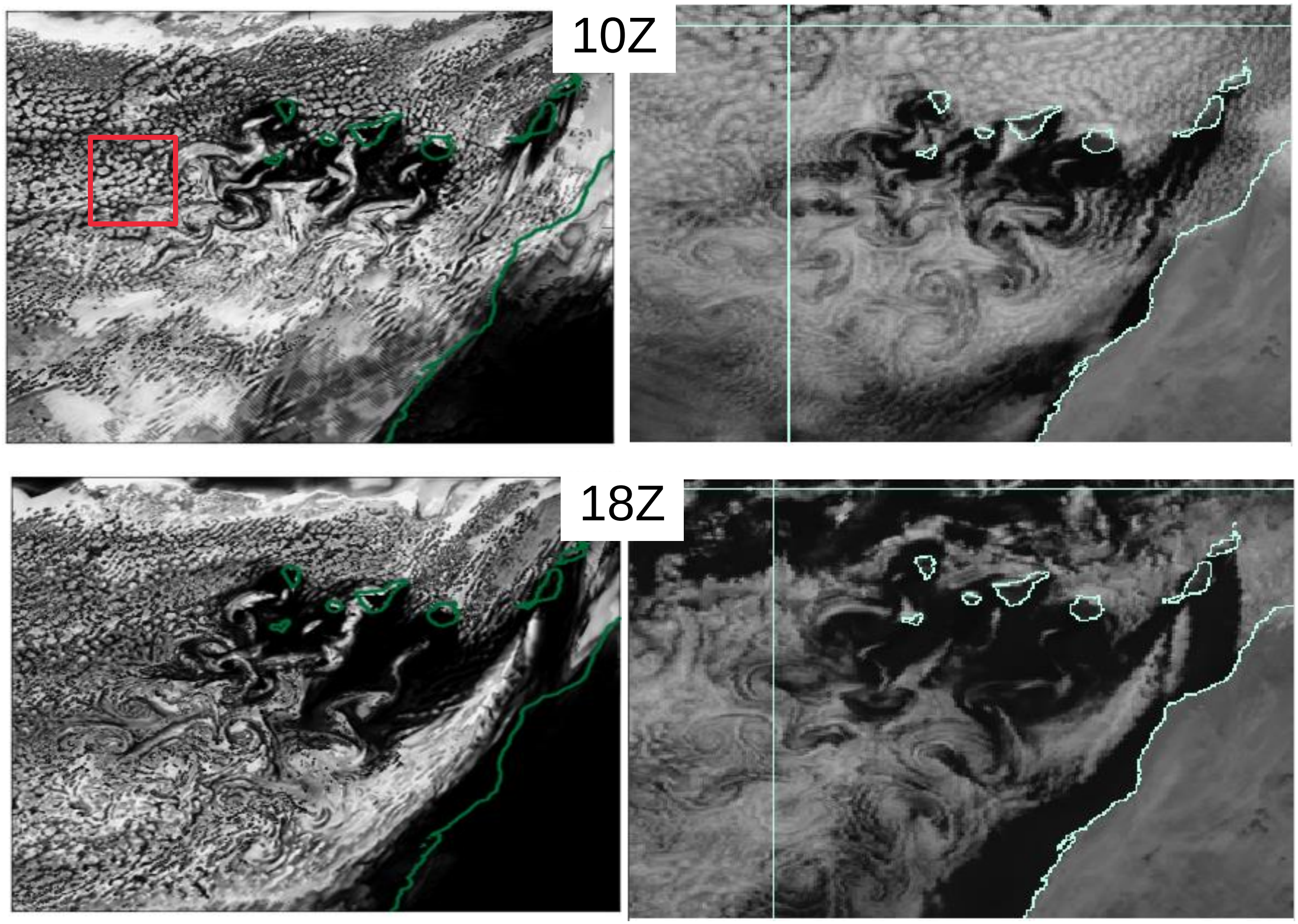
- Turbulence is a ubiquitous phenomenon on a huge range of scales
- In a GCM*, the larger, coherent turbulent eddies transport heat, moisture, momentum, aerosols, tracers, etc
- Even at high resolution some form of a scheme is needed to represent the microscale dissipation of turbulence
- The parametrization challenge is to relate these effects of turbulence (plumes/eddies) to resolved variables

*GCM=general/global circulation model

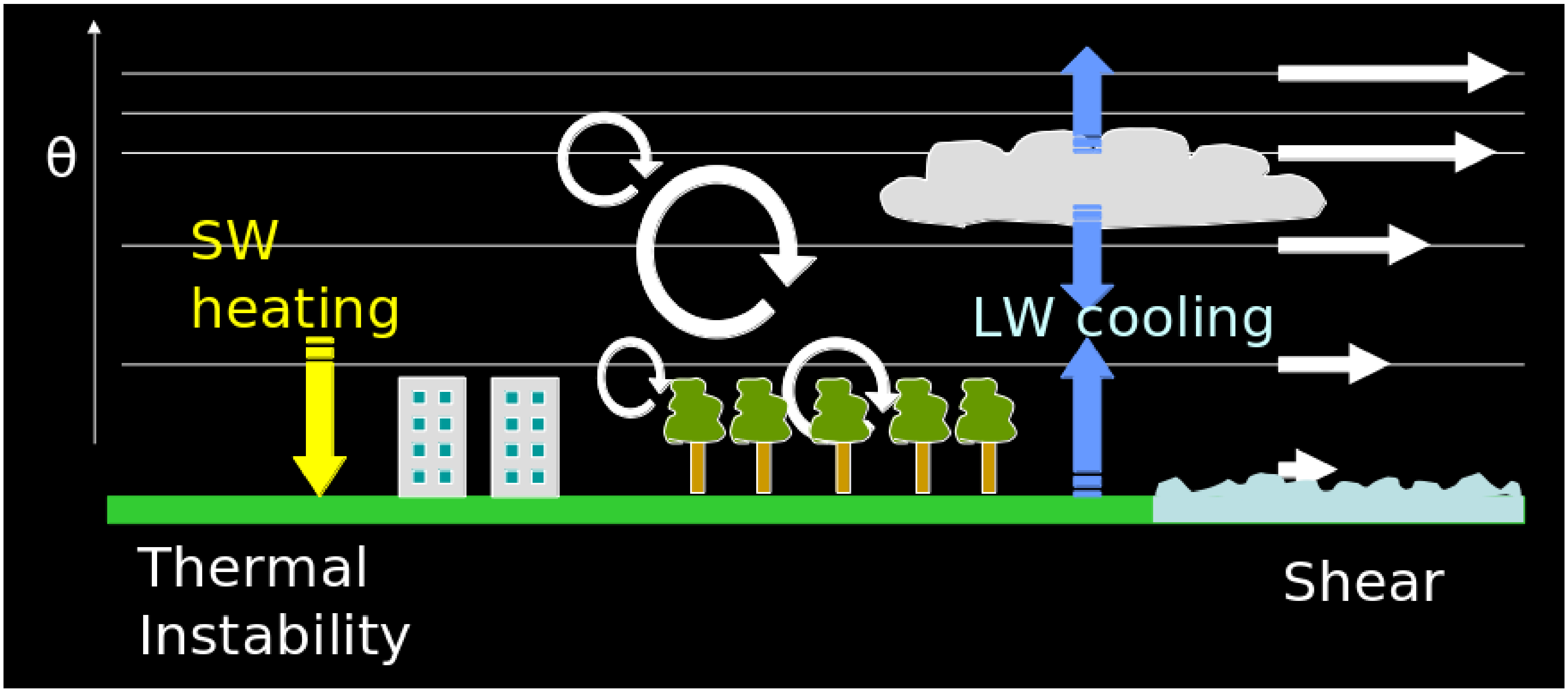
Vortex shedding and stratocumulus break-up from the Canary Islands

- Another gratuitous picture to illustrate a variety of scales of motion typically unresolved in a GCM (□ ~ 100km)

MetUM (1km) cloud | Satellite images



Processes important for turbulence generation in the boundary layer



Reynolds Averaging

Local Navier-Stokes equations:

$$\frac{\partial \varphi}{\partial t} + \nabla.(\varphi \mathbf{u}) = S_\varphi + \nu \nabla^2 \varphi$$

Molecular diffusion – this is negligible in the atmosphere

Advection

Other terms, dependant on what φ is

Grid-box average:

$$\varphi = \overline{\varphi} + \varphi'$$

Grid-box mean

Fluctuations, $\overline{\varphi'} = 0$

Average the whole equation in a similar way:

$$\frac{\partial \overline{\varphi}}{\partial t} + \nabla.\left(\overline{\varphi}\,\overline{\mathbf{u}}\right) = S_\varphi - \nabla.\left(\overline{\varphi' \mathbf{u}'}\right)$$

A covariance term or turbulent flux – the job of the BL scheme is to represent this

Covariance terms (turbulent fluxes)

$$\nabla.(\overline{\varphi'\mathbf{u}'}) = \underbrace{\frac{\partial\overline{\varphi'u'}}{\partial x} + \frac{\partial\overline{\varphi'v'}}{\partial y}}_{} + \frac{\partial\overline{\varphi'w'}}{\partial z}$$

- In higher resolution models (Δx<10km), horizontal terms are important
- So need parametrizing
- Met UM uses a Smagorinsky scheme

- In lower resolution models (Δx>10km), this term is dominant
- All turbulent transport is vertical
- Ignore others and parametrize this
- Traditional NWP 1D BL scheme

- MetUM has several combinations in use:
  - 1D BL scheme (vertical only) ← Standard global model
  - 1D BL scheme (vertical) + 2D Smagorinsky (horizontal) ← Operational UKV (1.5 km)
  - Blended 1D BL and 3D Smagorinsky schemes ← Parallel suite UKV (1.5 km)
  - 3D Smagorinsky (vertical and horizontal) ← High resolution applications (<1km)

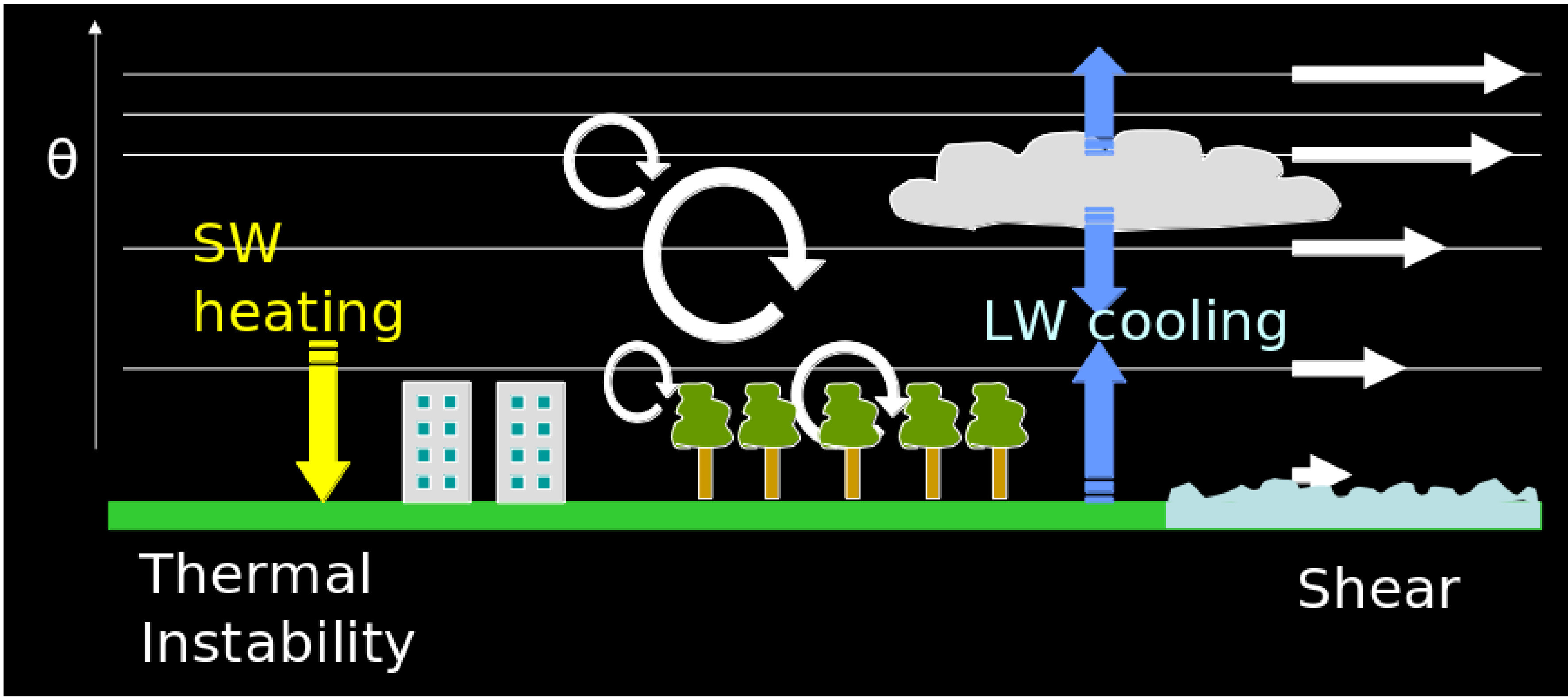
The closure problem

- How to calculate the turbulent fluxes?
- Equations can be constructed for these 2nd order terms, eg:

$$\frac{D}{Dt}\overline{u_i'u_j'} = -\overline{u_j'u_k'}\frac{\partial \overline{u_i}}{\partial x_k} - \overline{u_i'u_k'}\frac{\partial \overline{u_i}}{\partial x_k} - \frac{\partial}{\partial x_k}\overline{u_i'u_j'u_k'} + \frac{g}{\overline{\theta_{\mathrm{v}}}}(\overline{u_i'\theta_{\mathrm{v}}'}\delta_{3j} + \overline{u_j'\theta_{\mathrm{v}}'}\delta_{3i}) + \frac{1}{\rho}\left(\overline{u_j'\frac{\partial p'}{\partial x_i} + u_i'\frac{\partial p'}{\partial x_j}}\right)$$

- But those introduce 3rd order terms, and so on
- "Closure" implies replacing the higher order terms with a parametrization
  - "nth order closure" has prognostic equations for (some) nth order terms and parametrizes the n+1th order terms
- The standard MetUM PBL scheme uses a regime-dependent first order closure
  - a second order closure is also available (carries prognostic equations for up to 4 second order terms)

Processes important for turbulence generation in the boundary layer



Stability effects on turbulence

- Wind shear generates turbulence
- Buoyancy (stability) can either generate or damp
- Unstable boundary layers
  - Transports are dominated by large eddies (plumes/thermals)
  - Can be generated by wind shear ("neutral"), surface heating ("convective") or cloud-top cooling (stratocumulus)
  - Fluxes in convective BLs can be against the mean gradient
    - large eddies are insensitive to local gradients
- Stable boundary layers (SBLs)
  - Key is the ratio of stabilizing buoyancy relative to destabilizing wind shear – represented by the Richardson number (Ri).
  - Turbulent flux is entirely down gradient

Interior fluxes

Stable boundary layers and free troposphere

Interior fluxes (1)

Local closure for SBLs and free troposphere

- Simplest scheme, K-diffusion: $\overline{\varphi' w'} = -K \frac{\partial \varphi}{\partial z}$
- Assumes that mixing transports flux down-gradient – a diffusion process acting to smooth things
- Parametrize eddy diffusivity based on a mixing length, wind shear and Richardson number:

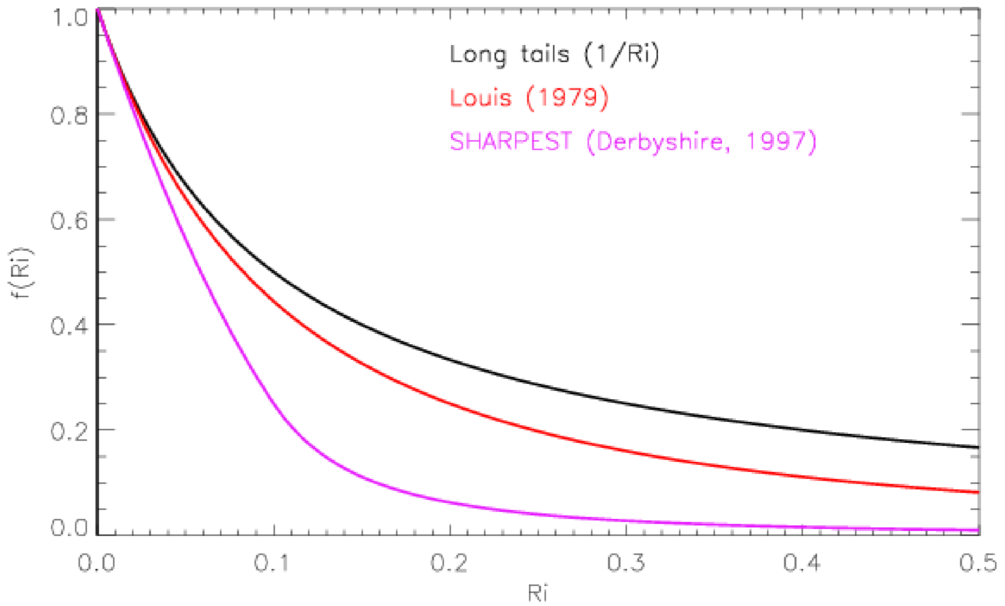
$$K = \Lambda^2 \left| \frac{\partial \mathbf{v}}{\partial z} \right| f(Ri)$$

$$\Lambda = \max\left[\lambda_{\min}, 0.15\, z_h\right] \qquad Ri = \frac{\dfrac{g}{\theta_v} \dfrac{\partial \theta_v}{\partial z}}{\left| \dfrac{\partial \mathbf{v}}{\partial z} \right|^2}$$

Stable stability functions

- Observations and LES suggest SHARPEST is best
- Practical experience means most GCMs use long/Louis
- MetUM uses SHARPEST over sea and “Mes-tail” over land – linear transition between Louis at surface and SHARPEST above 200m
- Some enhanced mixing can be motivated by surface heterogeneity (hence land-sea split) but tails are generally considered to be a useful tuning knob (ie, a compensating error)

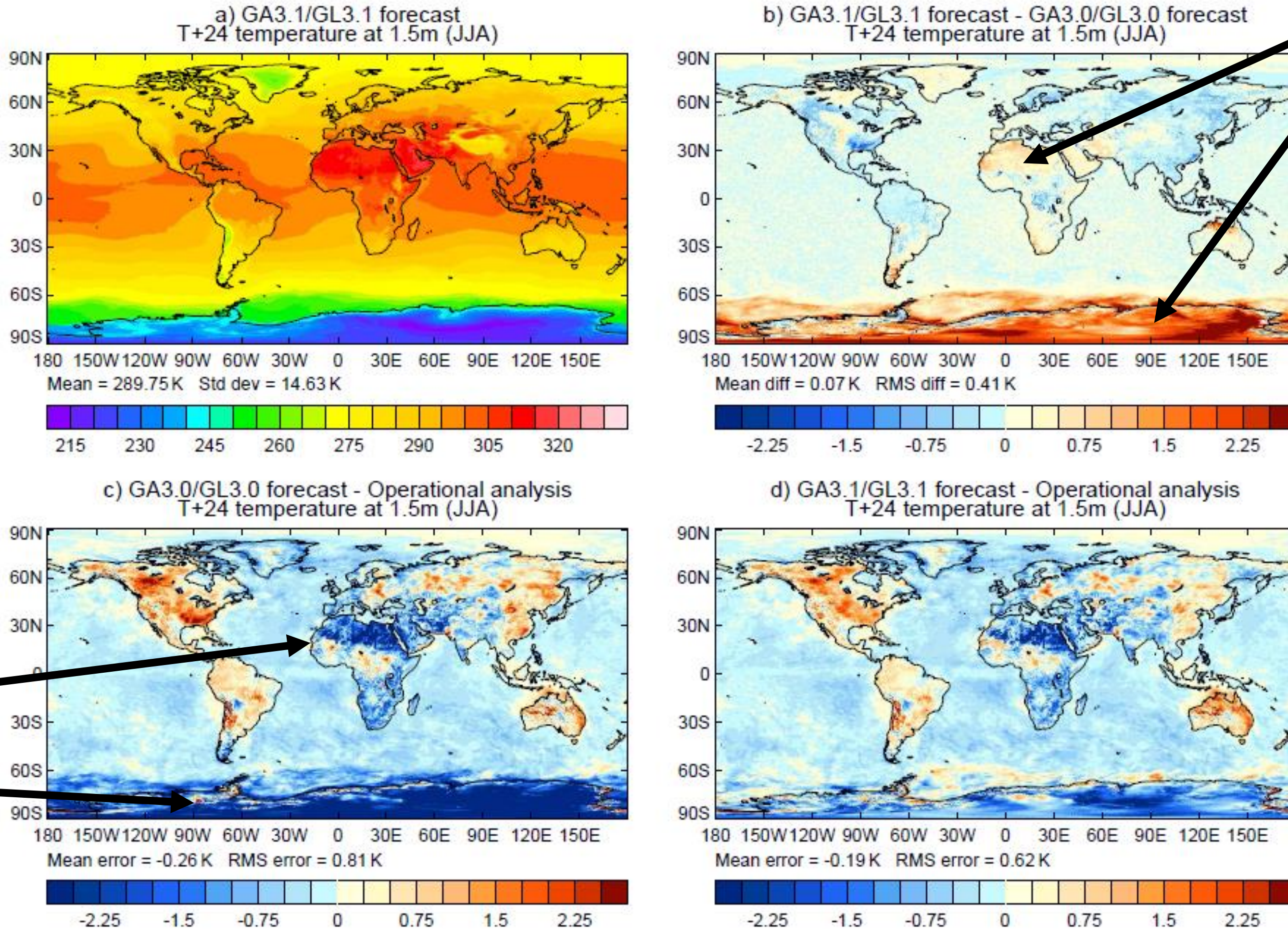
Function continues on the unstable side, for free tropospheric and neutral transition



Impact on surface temperature, JJA

Long tails (GA3.1) vs Mes tails (GA3.0)

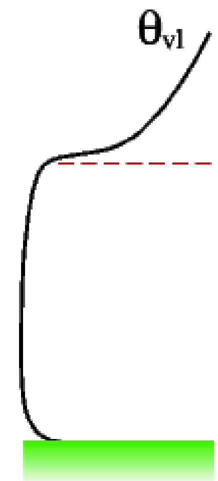
Long-tail improves here



Mes-tail too cold over desert and Antarctic

Interior fluxes
Unstable boundary layers

Interior fluxes (2)
Unstable boundary layers



- Typically have well-mixed profiles

$$\overline{\varphi' w'} = -K \frac{\partial \varphi}{\partial z} = 0 \qquad Ri = \frac{g}{\theta_v} \frac{\partial \theta_v}{\partial z} \Bigg/ \left| \frac{\partial \mathbf{v}}{\partial z} \right|^2 = ?$$

- Vertical gradients are small – would imply little turbulence
- Instead positive surface fluxes drive buoyant plumes, which rise throughout the depth of the BL
- This maintains the well-mixed profile
- Additional "non-local" flux and a "non-local" *K* profile

$$\overline{\varphi' w'} = -K \frac{d\varphi}{dz} + \overline{\varphi' w'}^{NL}$$

Surface driven mixing - heat

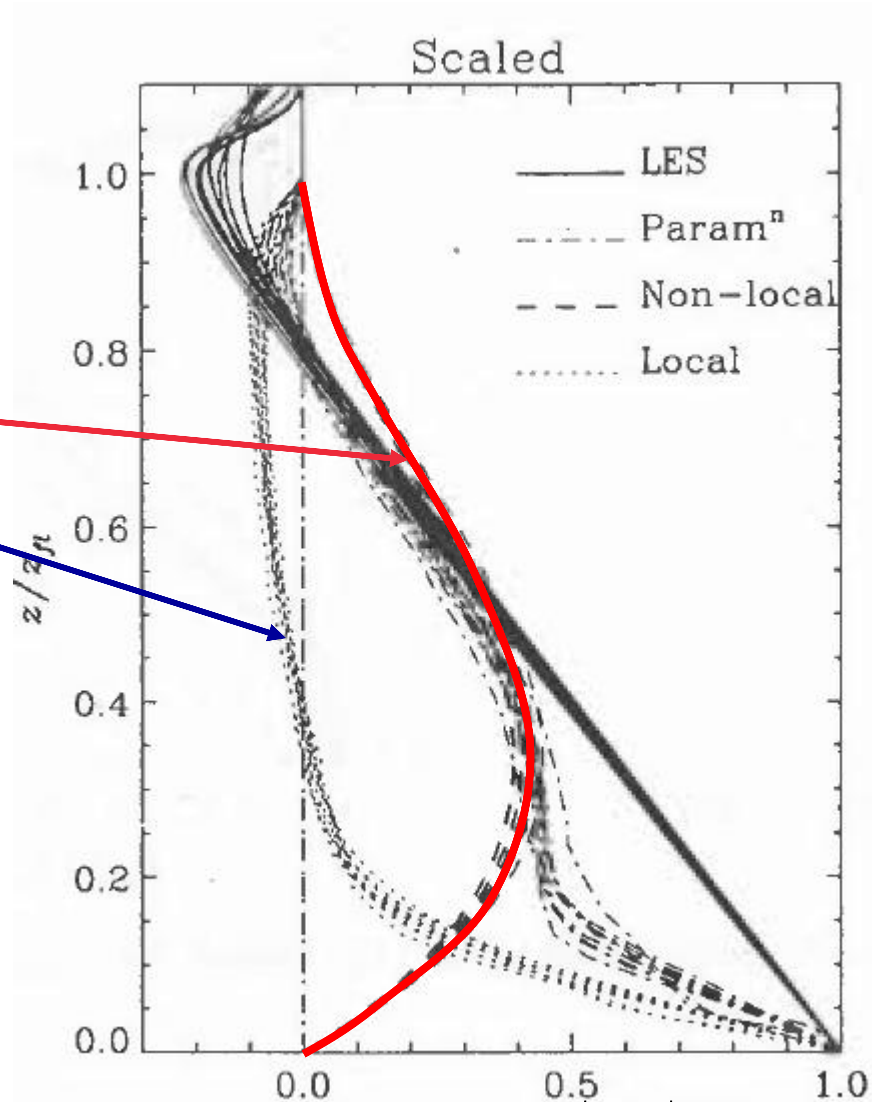
- Everything scales on the surface fluxes and PBL depth
- Parametrization based on LES

$$\overline{\theta' w'} = -K \frac{\partial \theta}{\partial z} + K\gamma$$

$$\gamma \sim \left(\overline{\theta' w'}\right)_0 \Big/ \left(w_m z_h\right)$$

- K profile formulated as a scaled shape function:

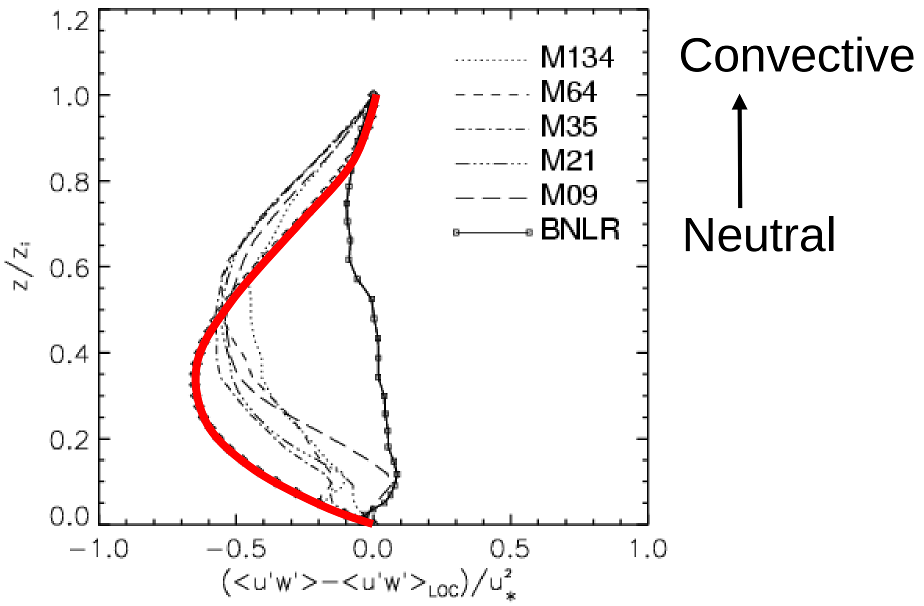
$$K_{Surf}^{NL} = f\left(\frac{z}{z_h}, \left(\overline{\theta' w'}\right)_0\right)$$



$\overline{\theta' w'} / \overline{\theta' w'}|_0$

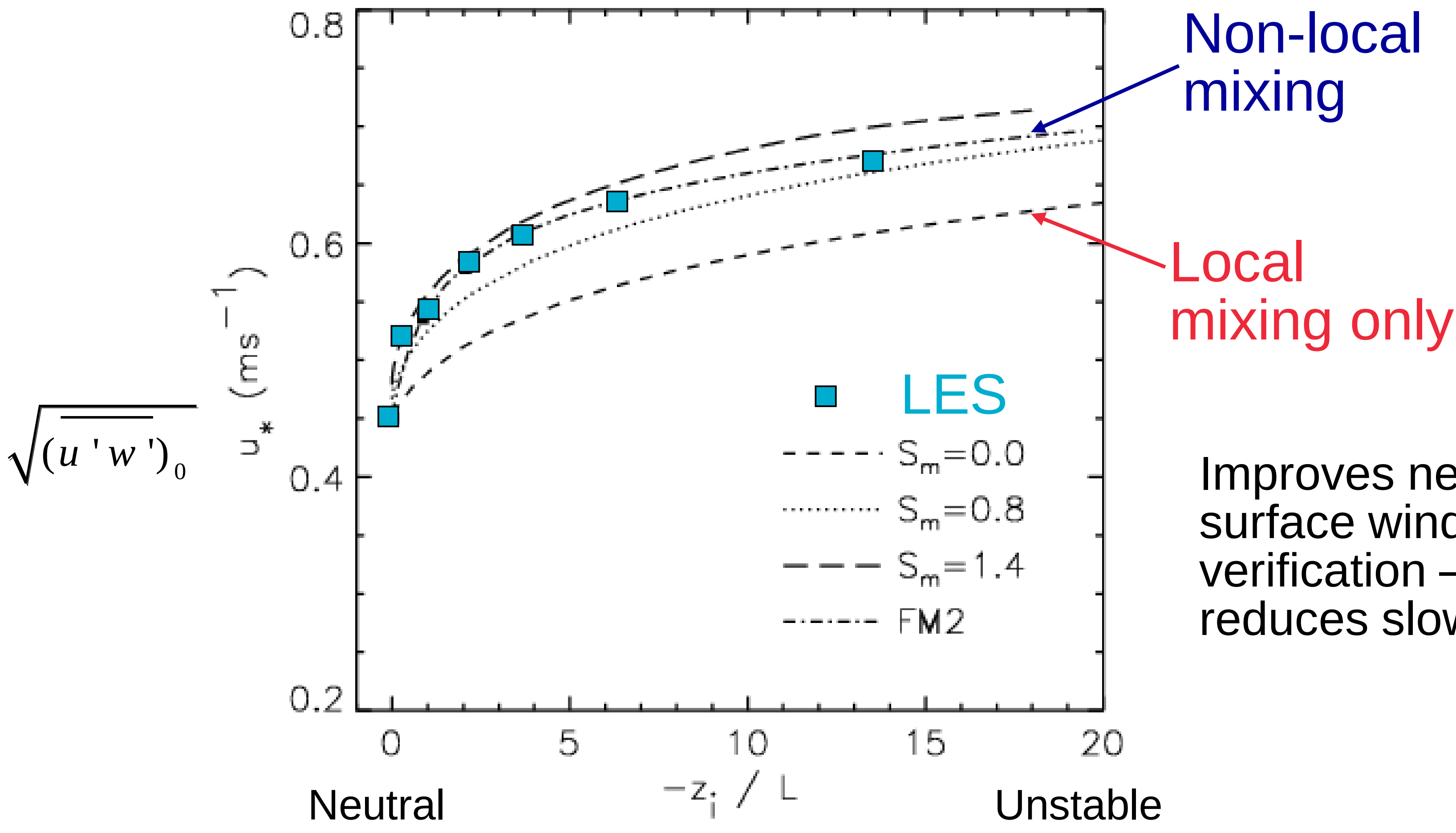
Surface driven mixing - momentum

$$\overline{u'w'} = -K\frac{\partial u}{\partial z} + \boxed{(\overline{u'w'})_{NL}}$$



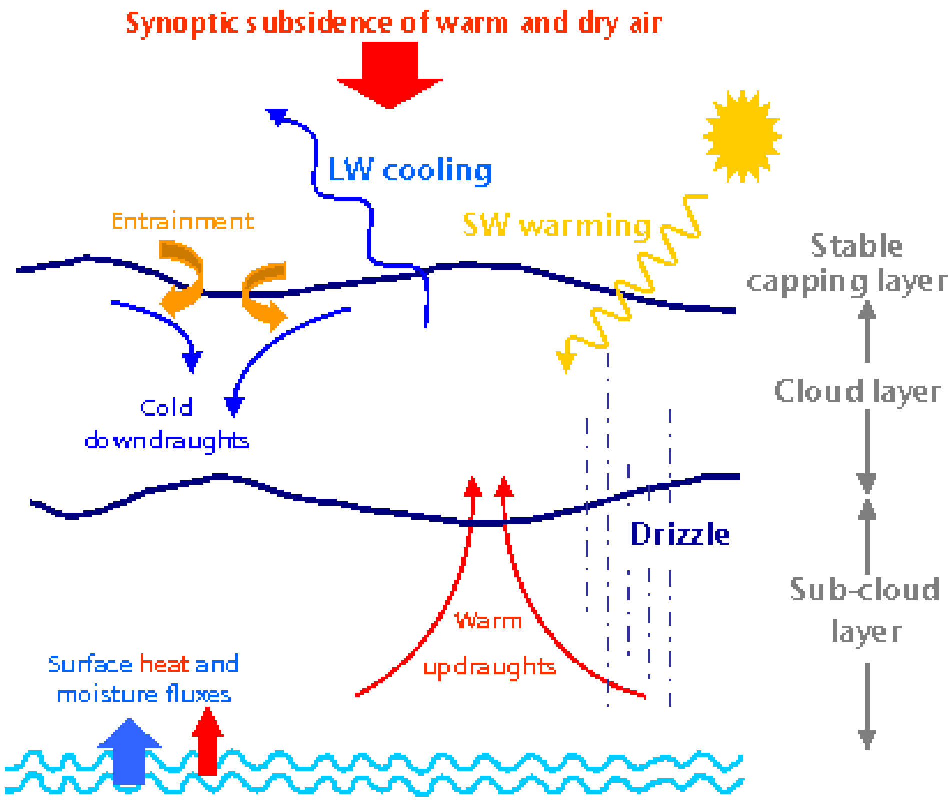
- Non-local term becomes more important in unstable BLs
- Mixes momentum towards the surface more efficiently

Stability dependence of non-local momentum fluxes



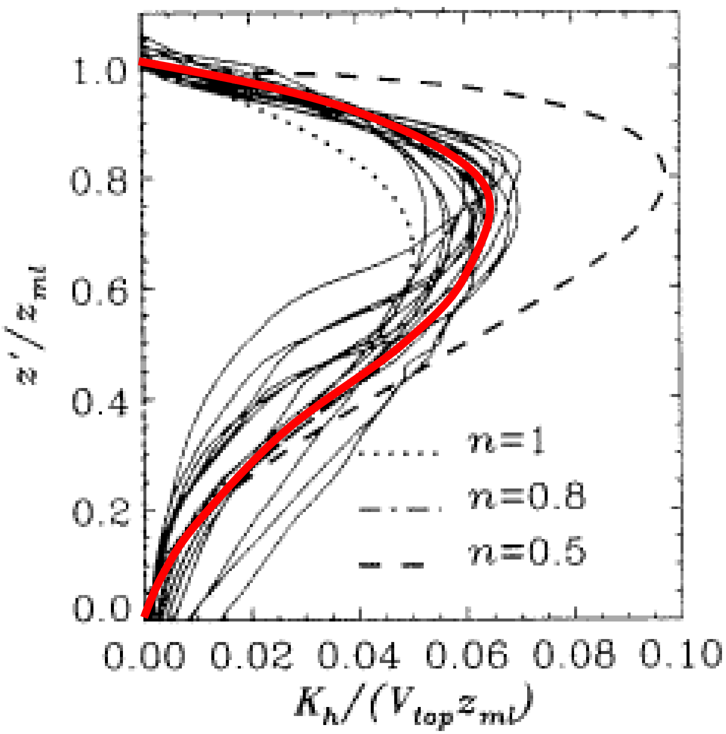
Improves near-surface windspeed verification – reduces slow bias

Cloudy boundary layers



- So far only considered "clear" boundary layers
- "Cloudy" boundary layers have many additional processes to parametrize
- Realistic interaction between cloud and turbulence is crucial for accurate evolution

Cloud top driven mixing



- Radiative & evaporative cooling at cloud top drives negatively buoyany plumes
- Like surface driven mixing upside-down!

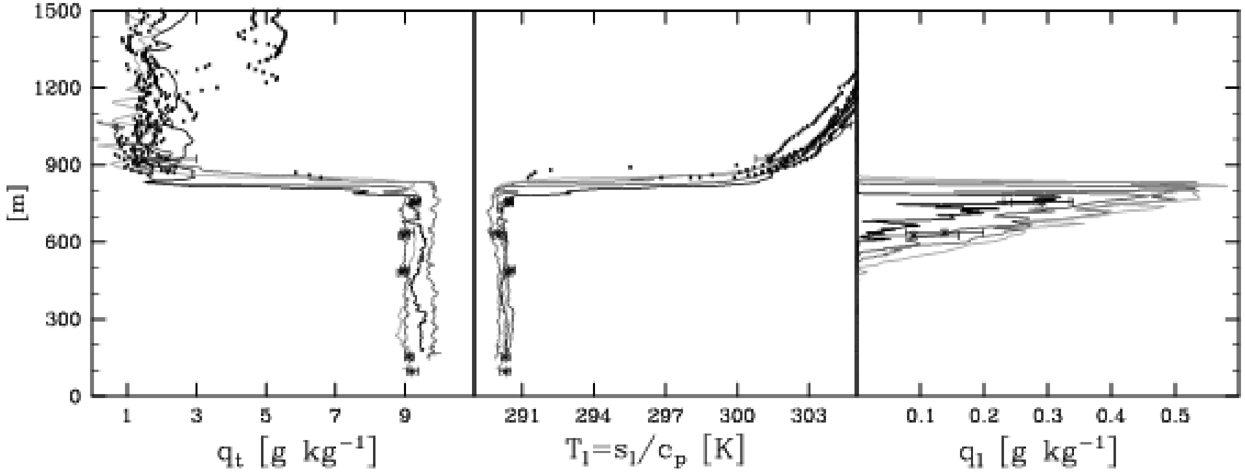
$$K_{Top}^{NL} = f\left(\frac{z'}{z_{ml}}, \left(\overline{\theta' w'}\right)_{Top}\right)$$

Turbulence generation due to radiative and buoyancy reversal (evaporation) mechanisms at cloud-top

Entrainment

Mixing across the PBL top

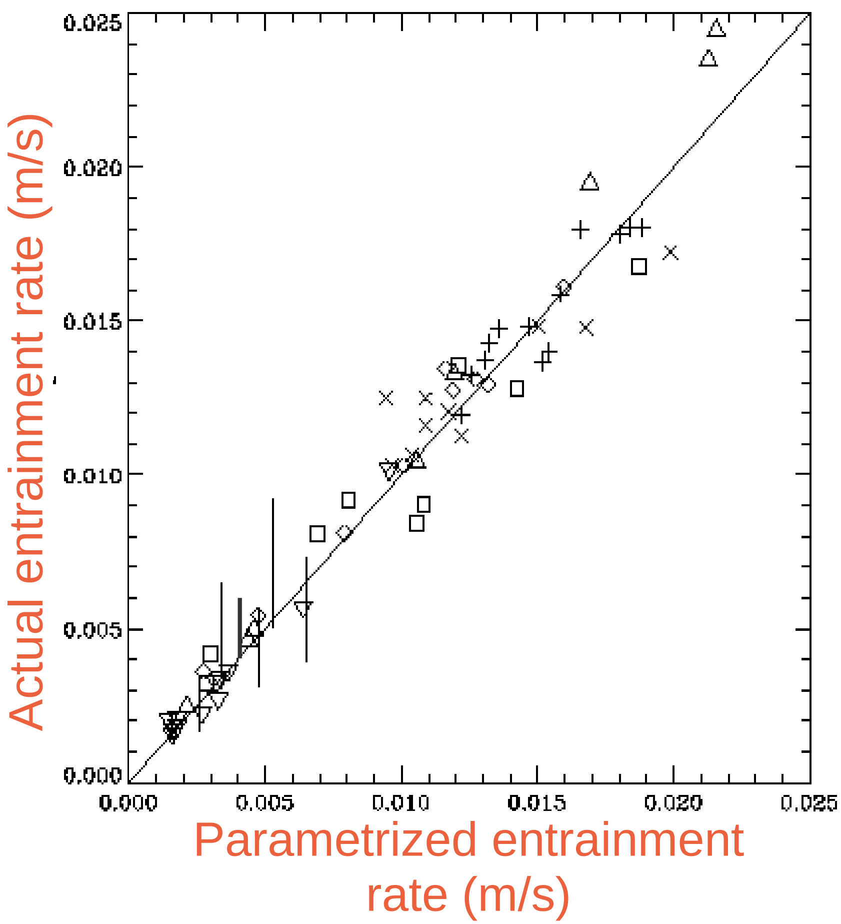
Entrainment



- The boundary layer is capped by a stable layer (“inversion”)
- Over-turning eddies in the boundary layer scour the base of the inversion, or overshoot their neutral buoyancy
- This mixes warmer, drier air down into the boundary layer
- The Met UM parametrizes fluxes in terms of an entrainment rate (w_e):

$$\overline{(\theta' w')}_h = -w_e \Delta\theta \qquad \overline{(q' w')}_h = -w_e \Delta q$$

Entrainment rate parametrization



LES

Cloud free, vary shear and buoyancy:

△ = surface heated

Smoke clouds, vary radiation:

▽ = radiatively cooled

□ = surf heat + rad cool

Water clouds, vary inversion jump and water content:

X = rad cool only

\+ = rad cool + buoy rev

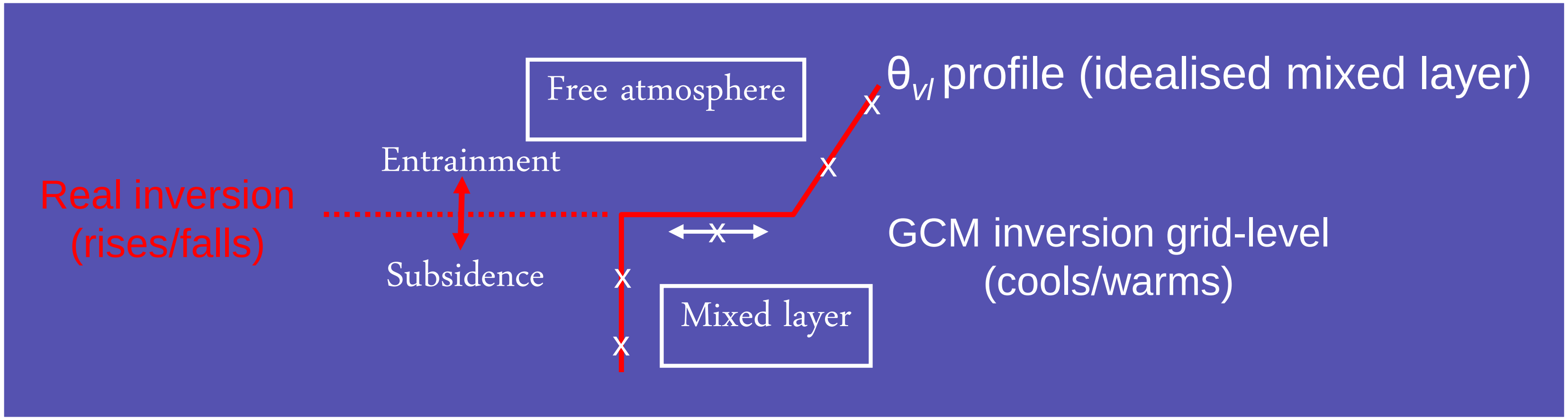
◇ = buoyancy reversal only

Observations

| = Nicholls & Leighton,1986; Price, 1999; Stevens et al 2003

Numerical handling of inversions

- In reality processes (turbulence, radiation, subsidence) are coupled
- Scheme reconstructs a “sub-grid” profile with sharp inversion
- Distributes tendencies realistically between the mixed layer and inversion grid-level
- Prevents spurious numerical mixing across inversion



Surface fluxes

Surface fluxes

Met Office

Momentum flux: $$(\overline{u'w'})_0 = C_D \left|\mathbf{v_1}\right| u_1$$

Sensible heat flux: $$(\overline{\theta'w'})_0 = C_H \left|\mathbf{v_1}\right| (\theta_s - \theta_1)$$

Evaporation / latent heat flux: $$(\overline{q'w'})_0 = C_E \left|\mathbf{v_1}\right| (q_{\mathrm{sat}}(\theta_s) - q_1)$$

- These are bulk aerodynamic formula
- Over sea-surface, θ_s prescribed or from Ocean model
- Over land-surface, need to solve for surface energy budget – JULES land surface scheme
- Need to parametrize the transfer coefficients (C_D, C_H, C_E)
- Surface deposition follows a similar bulk approach

Neutral conditions

- Near the surface, parcels mix with the air over length κz, wind shear given by:

$$\frac{\partial u}{\partial z} = \frac{\sqrt{\overline{(u'w')}_0}}{\kappa z}$$

u_*, friction velocity

- Integrate this (log wind profile), and substitute into bulk formulae:

$$\overline{(u'w')}_0 = C_D \frac{\overline{(u'w')}_0}{\kappa^2} \ln^2\left(\frac{z_1}{z_{0m}}\right)$$

- Therefore:

$$C_D = \frac{\kappa^2}{\ln^2\left(\frac{z_1}{z_{0m}}\right)}$$

Monin-Obukhov similarity theory

- Under non-neutral conditions, buoyancy effects are also important, therefore write:

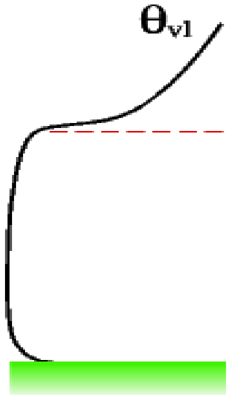
$$\frac{\partial u}{\partial z} = \frac{\sqrt{(\overline{u'w'})_0}}{\kappa z}\phi_m\left(\frac{z}{L}\right)$$

- Where:

$$L = -\frac{(\overline{u'w'})_0^{3/2}}{\kappa \dfrac{g}{\theta_1}(\overline{\theta' w'})_0}$$

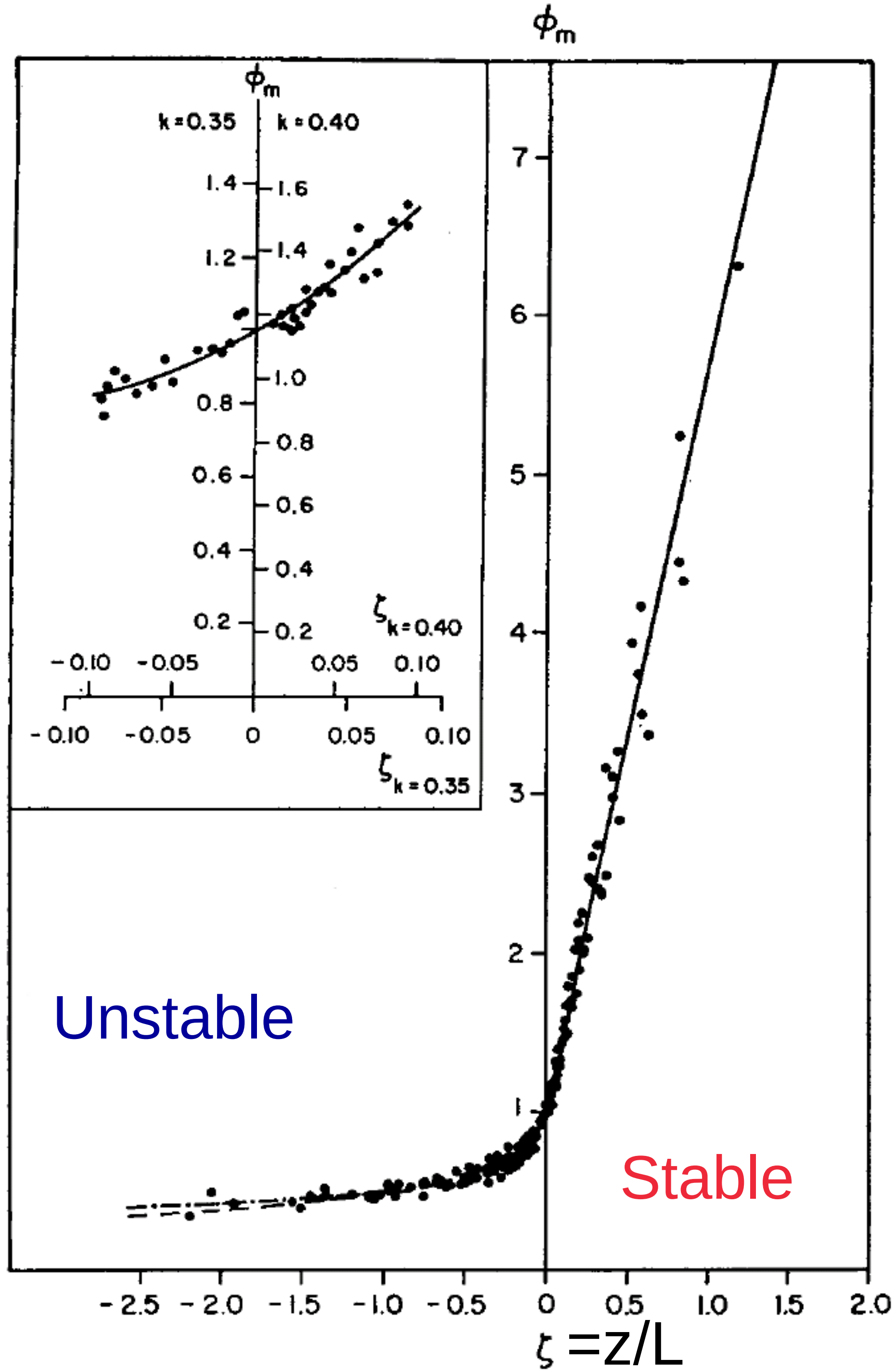
Obukhov Length

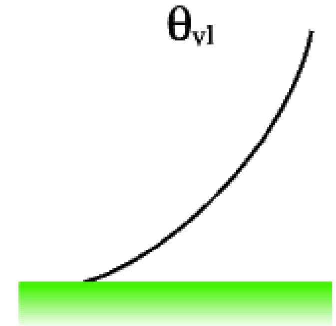
- Φ_m (and Φ_h) are the M-O stability functions (dimensionless gradients)...



Unstable BL

- Surface heat flux is positive
- Well-mixed profiles
- Buoyancy generated turbulence





Stable BL

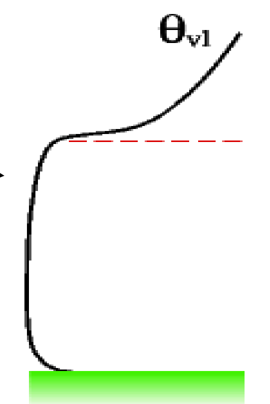
- Surface heat flux is negative
- Stratified profiles
- Shear generated turbulence

The boundary layer scheme

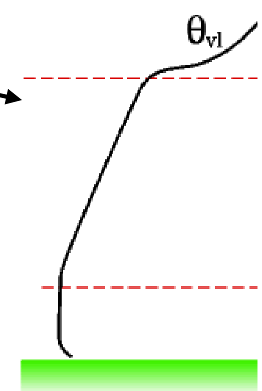
Met Office

Putting it all together…

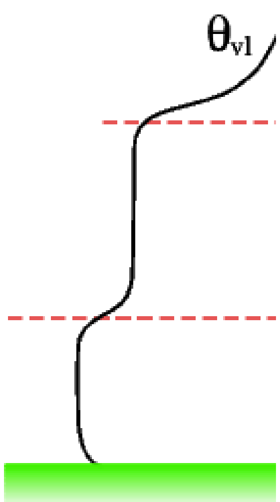
- Diagnose existence and depth of mixed layers from a moist adiabatic parcel ascent
- Test for cumulus convection, based on moisture gradient between sub-cloud and cloud layer
- If “similar” → stratocumulus
  - Surface and cloud top K profiles
  - Cloud top entrainment



- If “not similar” → cumulus
  - Surface K profile up to LCL
  - Mass-flux convection scheme above this



Decoupling and diagnosing depth of cloud-top mixing



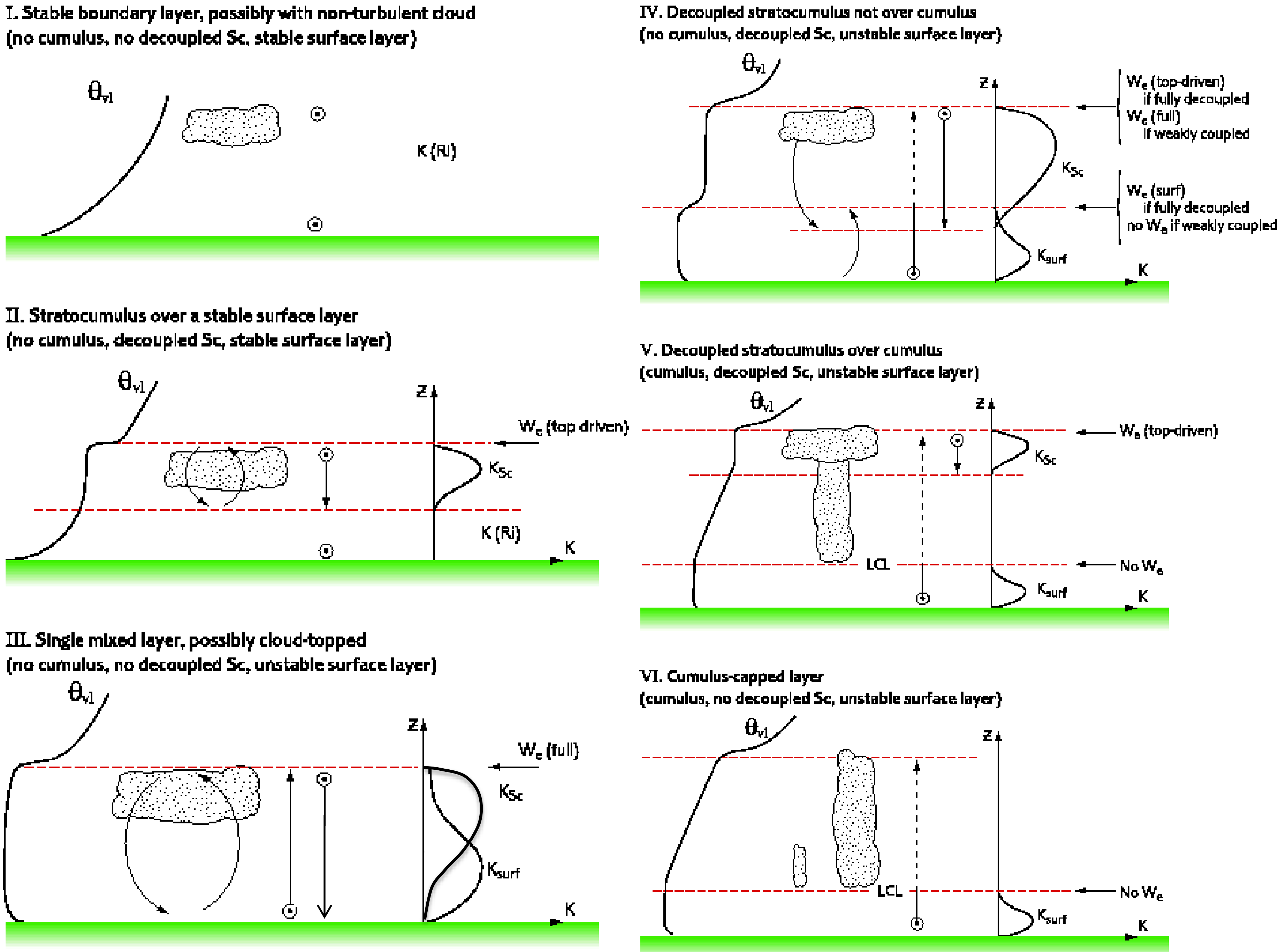
- If surface fluxes and cloud top cooling weaken, the turbulence may no longer span the whole mixed layer depth
- A stable layer can form in the middle, separating the surface mixed layer from the cloudy mixed layer
- The boundary-layer is said to be "decoupled"
- Vertical extent of surface and cloud-top K-profiles diagnosed from simple TKE budget:
    - Buoyancy consumption of TKE (ie, integrated negative buoyancy fluxes) is not allowed to exceed a small fraction (0.1) of buoyancy production

Stable to unstable transition

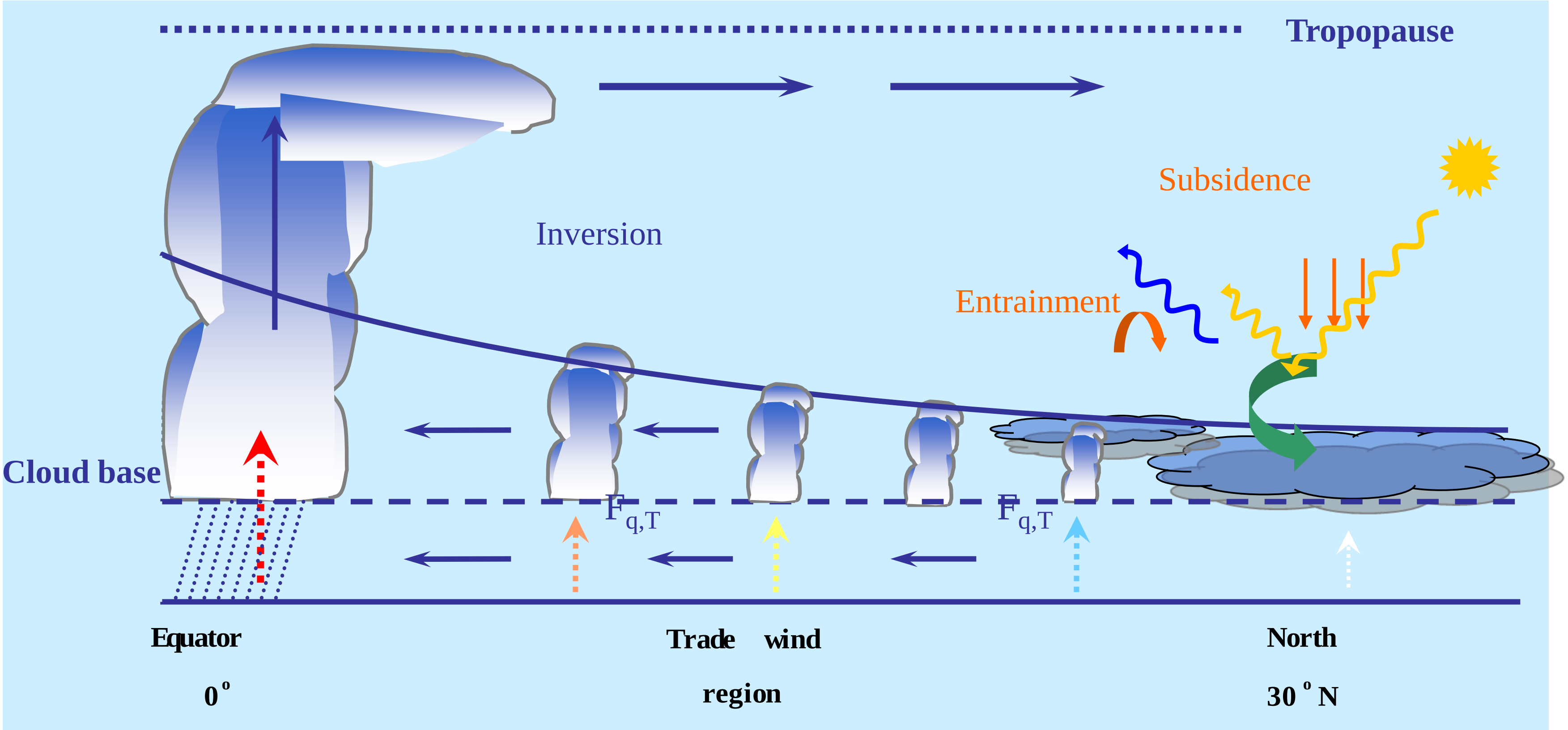
- Simply take the max of the local (Ri-based) and non-local (scaled shape profile) diffusion coefficients:

$$K = \max\left[K(Ri),\ K_{surf}^{NL} + K_{top}^{NL}\right]$$

- “Shear-dominated unstable boundary layers”
  - Motivated by cold air outbreak work
  - When $z_h(Ri) > z_{lcl} + f\, z_{cloud}$, assume there enough shear to disrupt cumulus formation (currently f=0.3)
  - Diagnose well-mixed layer to top of adiabatic parcel ascent, ie completely undo cumulus diagnosis


I. Stable boundary layer, possibly with non-turbulent cloud
(no cumulus, no decoupled Sc, stable surface layer)
θvl
K (Ri)
II. Stratocumulus over a stable surface layer
(no cumulus, decoupled Sc, stable surface layer)
θvl
z
We (top driven)
KSc
K (Ri)
K
III. Single mixed layer, possibly cloud-topped
(no cumulus, no decoupled Sc, unstable surface layer)
θvl
z
We (full)
KSc
Ksurf
K
IV. Decoupled stratocumulus not over cumulus
(no cumulus, decoupled Sc, unstable surface layer)
θvl
z
We (top-driven)
if fully decoupled
We (full)
if weakly coupled
KSc
We (surf)
if fully decoupled
no We if weakly coupled
Ksurf
K
V. Decoupled stratocumulus over cumulus
(cumulus, decoupled Sc, unstable surface layer)
θvl
z
We (top-driven)
KSc
LCL
No We
Ksurf
K
VI. Cumulus-capped layer
(cumulus, no decoupled Sc, unstable surface layer)
θvl
z
LCL
No We
Ksurf
K

Types in reality



Type 6 Type 5 Types 3 & 4

Observed cloud types vs model BL types

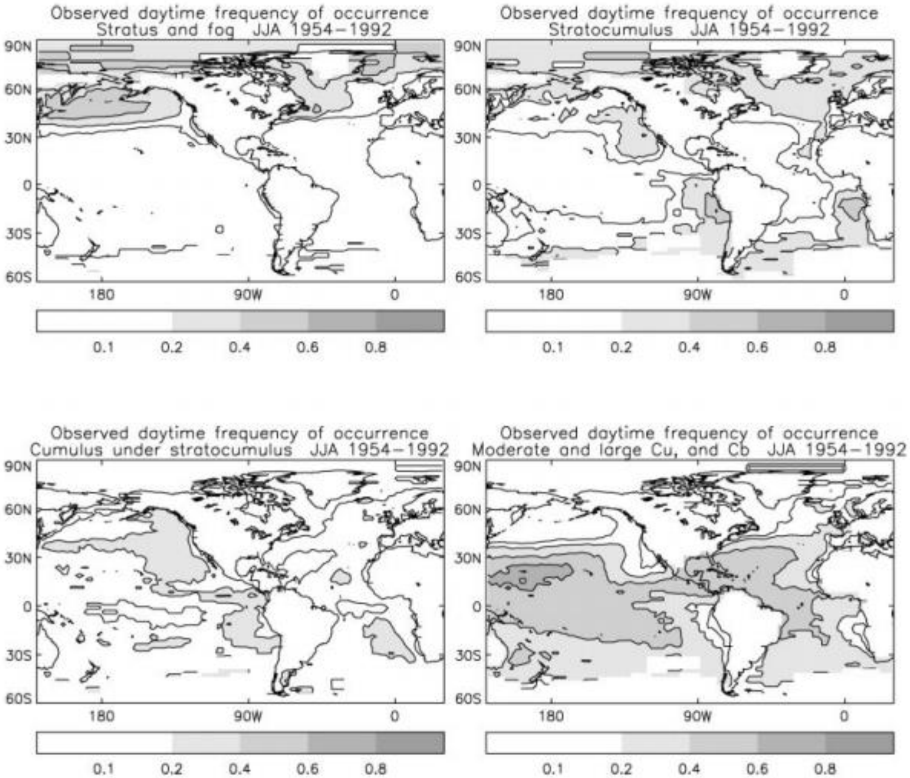


FIG. 3. Observed daytime frequency of occurrence of different cloud types, from Norris (1998). JJA mean from 1954 to 1992: (a) stratus and fog, (b) stratocumulus, (c) cumulus–stratocumulus, and (d) moderate and large cumulus, and cumulonimbus.

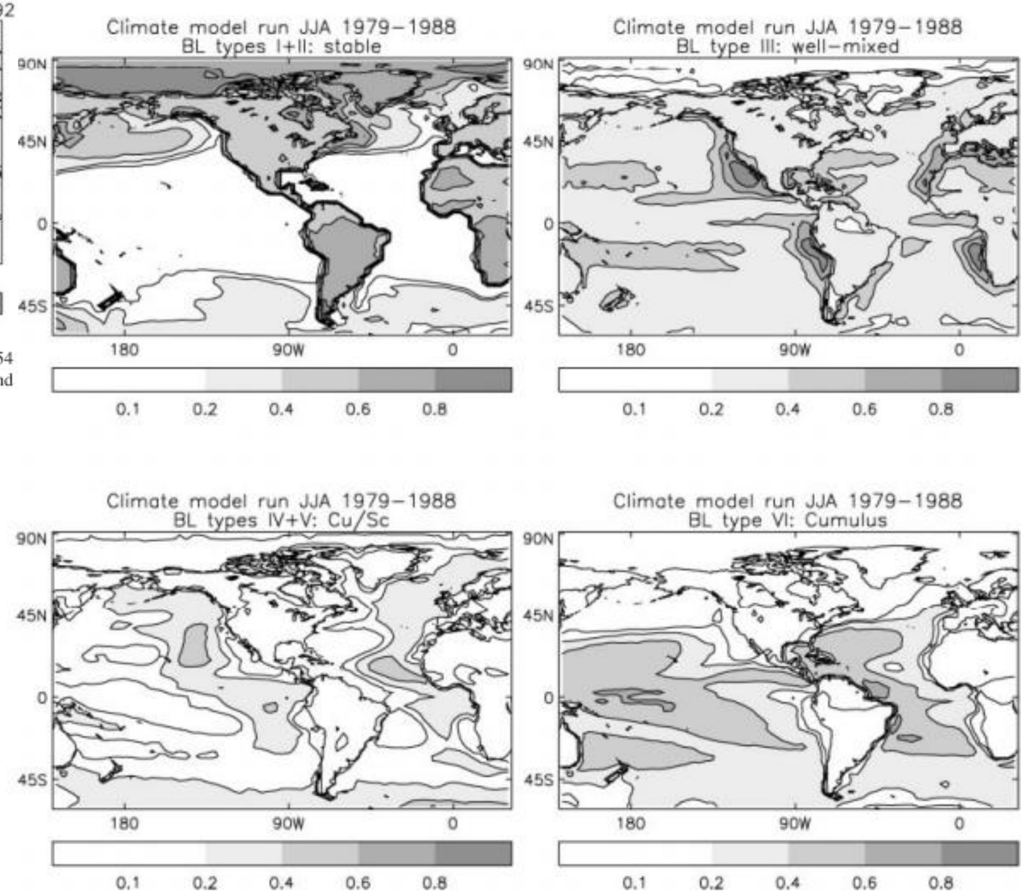


FIG. 1. The 10-yr JJA mean of the fractional occurrence of different boundary layer types diagnosed by the boundary layer scheme in Part I: (a) types I and II, stable; (b) type III, well mixed; (c) types IV and V, cumulus–stratocumulus; and (d) type VI, cumulus.

Scheme implementation

Radiation, microphysics, gravity wave drag

↓

Semi-lagrangian advection

↓

Convection diagnosis

↓

Explicit boundary layer

↓

Convection

↓

Implicit boundary layer

↓

Helmholtz solver

Talked about this so far, which gives us the K:

$$\frac{\partial \varphi}{\partial t} = \frac{\partial}{\partial z}\left(K \frac{\partial \varphi}{\partial z} \right)$$

How we obtain the LHS from this is also important, done here

Implicit solver

- Explicit calculation of diffusion terms is conditionally unstable
- For NWP timesteps must solve implicitly
- MetUM uses a two-step approach:

$$\boxed{\begin{aligned}\frac{X^* - X^n}{\Delta t} &= \mathcal{I}_1 \frac{\partial F^*}{\partial z} - \mathcal{E}_1 \frac{\partial F^n}{\partial z} + (\mathcal{I}_1 - \mathcal{E}_1)\, S \\ \frac{X^{n+1} - X^*}{\Delta t} &= \mathcal{I}_2 \frac{\partial F^{n+1}}{\partial z} - \mathcal{E}_2 \frac{\partial F^*}{\partial z} + (\mathcal{I}_2 - \mathcal{E}_2)\, S\end{aligned}}$$

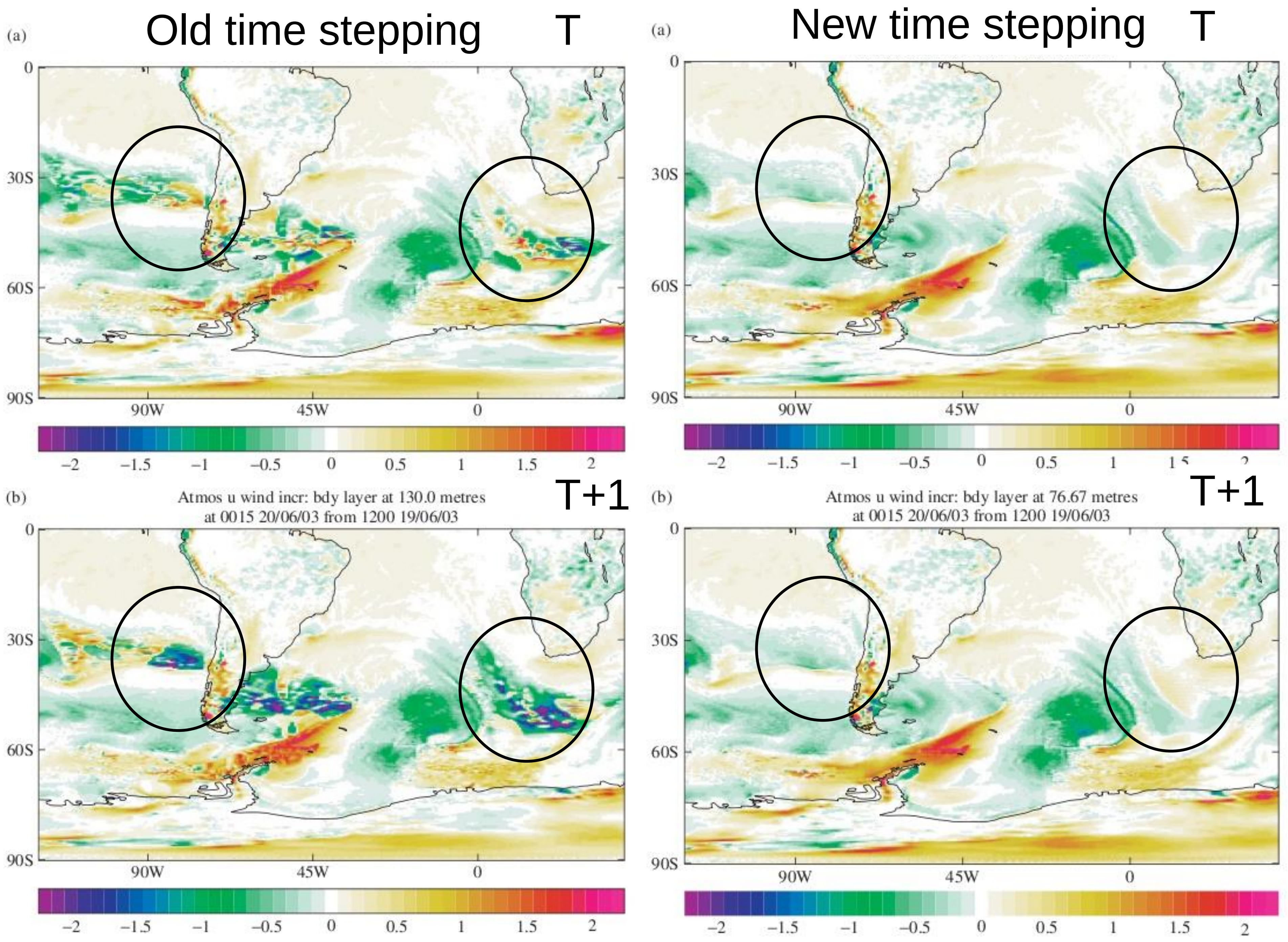
$$F^n = K_X \frac{\partial X^n}{\partial z}, \; F^* = K_X \frac{\partial X^*}{\partial z}, \; F^{n+1} = K_X \frac{\partial X^{n+1}}{\partial z}, \; K_X \equiv K(X^n)$$

$$\mathcal{I}_1 = \mathcal{I}_2 = \left(1 + \frac{1}{\sqrt{2}}\right)(1 + P)$$

$$\mathcal{E}_1 = \left(1 + \frac{1}{\sqrt{2}}\right)\left[P + \frac{1}{\sqrt{2}} \pm \sqrt{P\left(\sqrt{2} - 1\right) + \frac{1}{2}}\right]$$

$$\mathcal{E}_2 = \left(1 + \frac{1}{\sqrt{2}}\right)\left[P + \frac{1}{\sqrt{2}} \mp \sqrt{P\left(\sqrt{2} - 1\right) + \frac{1}{2}}\right]$$

P is a non-linearity measure, set to 2 in stable, 0.5 in unstable BLs



Old time stepping T
New time stepping T
(a)
(a)
0
30S
60S
90S
90W
45W
0
−2
−1.5
−1
−0.5
0
0.5
1
1.5
2
(b)
Atmos u wind incr: bdy layer at 130.0 metres
at 0015 20/06/03 from 1200 19/06/03
T+1
(b)
Atmos u wind incr: bdy layer at 76.67 metres
at 0015 20/06/03 from 1200 19/06/03
T+1

Diagnosing TKE (e)

- "Prognostic TKE" closures typically write

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

- But often l = fn(e) too, eg. $l = \sqrt{e}\,/\,N$ which implies

$$K = \tau_{turb}\, e$$

- We diagnose τ_{turb} from turbulent velocity scales and mixed layer depths, or $\tau_{turb} \sim N$ in SBL, and so can diagnose:

$$e = K \big/ \tau_{turb}$$

- TKE is used in the aerosol activation scheme

Future developments

- GA7 (UKESM1) planned to include the following enhancements
  - Resolved inversions
  - Improved parametrization of entrainment in decoupled stratocumulus
  - TKE diagnostic used to diagnose:
    - RHcrit (cloud scheme)
    - supercooled liquid water production (microphysics)
    - already used in UKCA aerosol activation scheme
- Longer term
  - Improved coupling with the convection scheme
  - Improved treatment of inhomogeneity

Questions?