Modelling marine boundary layer clouds

Adrian Lock

Met Office / RPN

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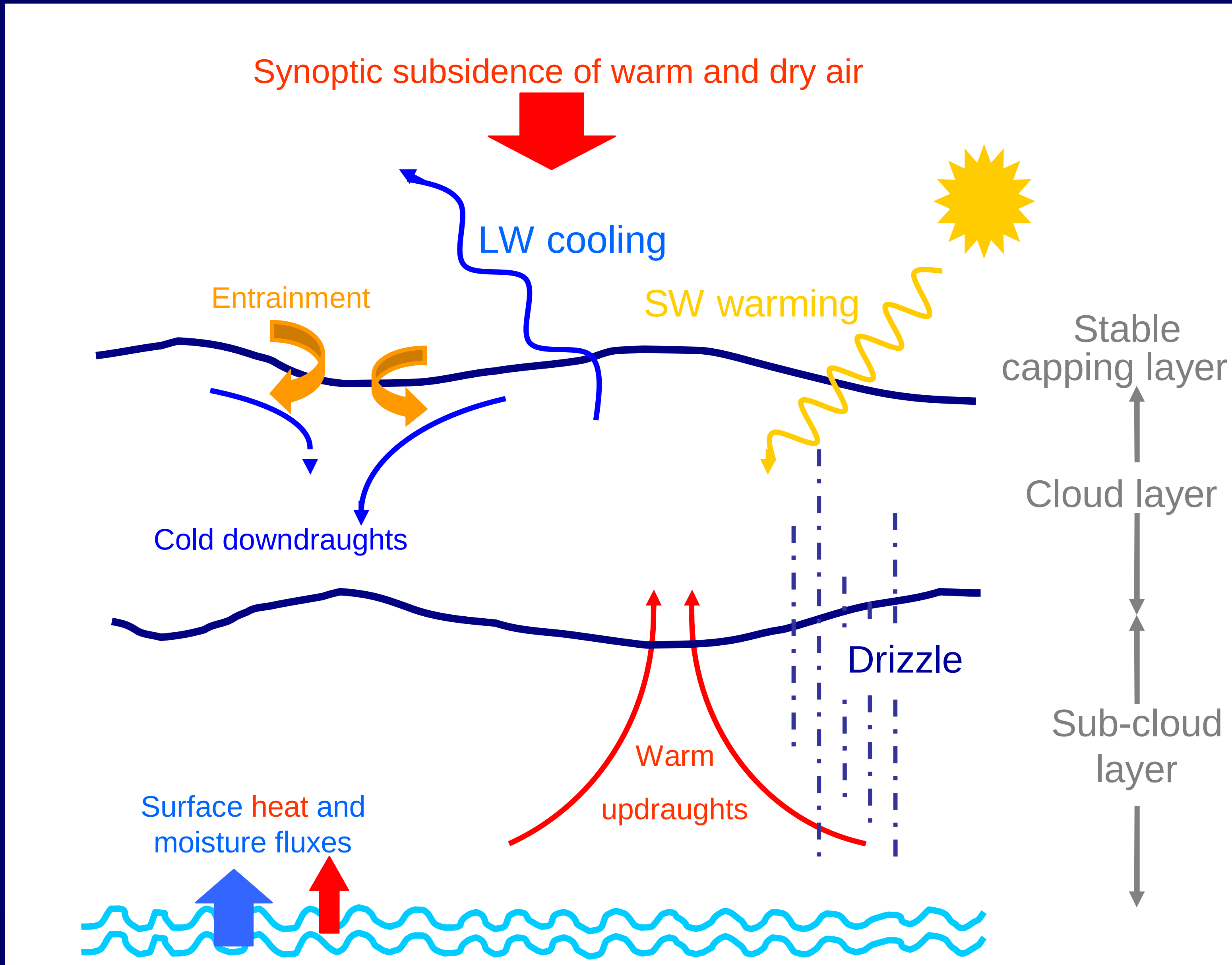
Outline

- Introduction to stratocumulus
- Met Office boundary layer parametrization
- Validation of marine subtropical Sc in Met Office GCM
- Stratocumulus single column model intercomparison
  - RPN boundary layer parametrization


Synoptic subsidence of warm and dry air
LW cooling
Entrainment
SW warming
Stable capping layer
Cloud layer
Cold downdraughts
Drizzle
Sub-cloud layer
Warm updraughts
Surface heat and moisture fluxes

Stratocumulus – complex yet simple

- Marine stratocumulus is often a stable equilibrium state arising from complicated interactions between many processes that are parametrized in NWP
- Need to replicate this balance within NWP parametrizations, often using schemes that work independently
- Simple conceptual framework: mixed layer model
  - turbulent mixing generally ensures that variables conserved under moist adiabatic ascent are close to uniform in the vertical. For example:

$$q_t = q_v + q_l \qquad \theta_e = \theta + \frac{L}{c_p \pi} q_v$$

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Observed profiles from stratocumulus

Nicholls (QJ, 1984)

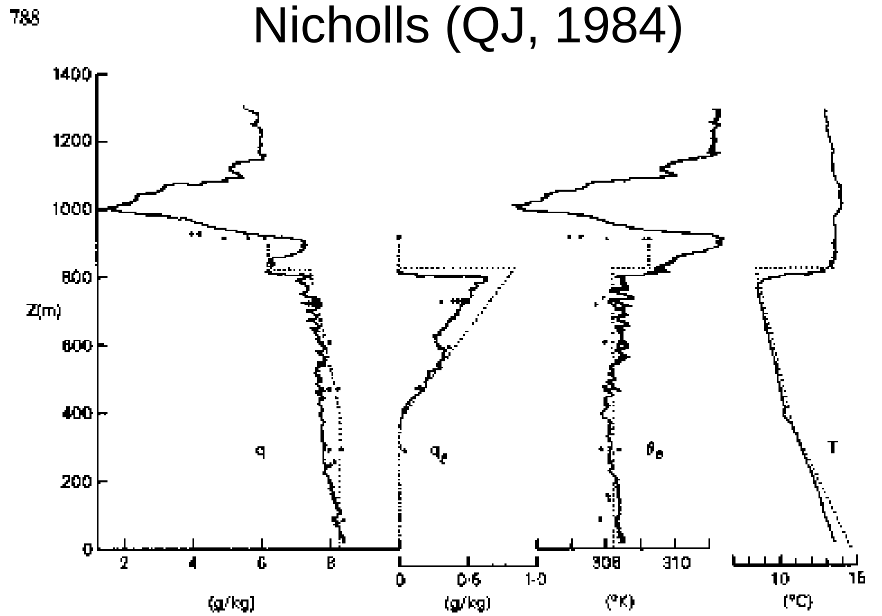
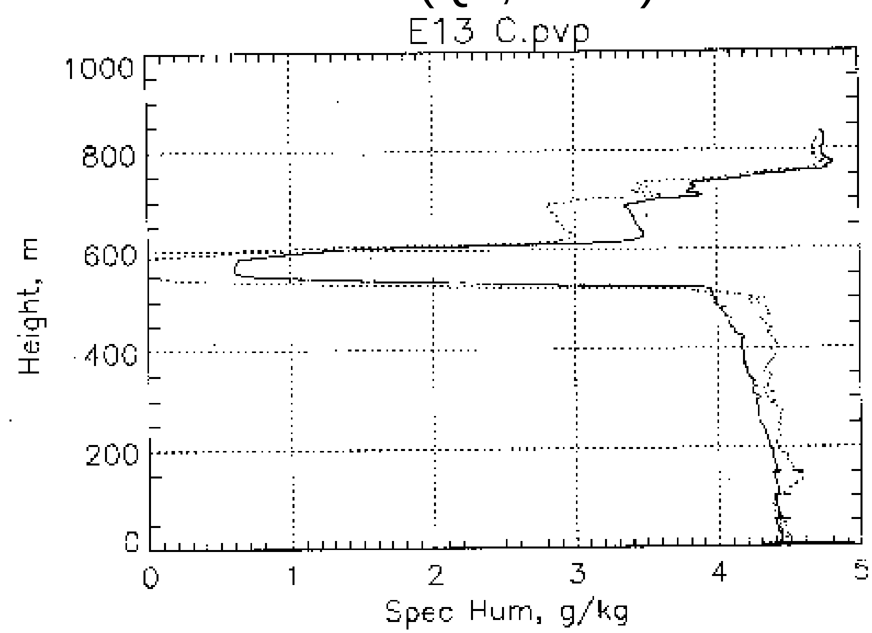


Figure 3. The vertical thermodynamic structure measured during the descent at 11 GMT together with the horizontal run-averaged values (●) and the representation used as initial data for the model (...).

Price (QJ, 1999)



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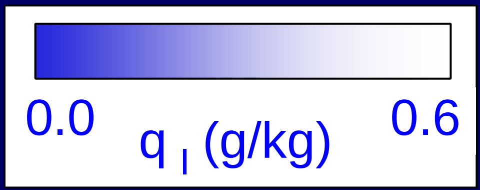
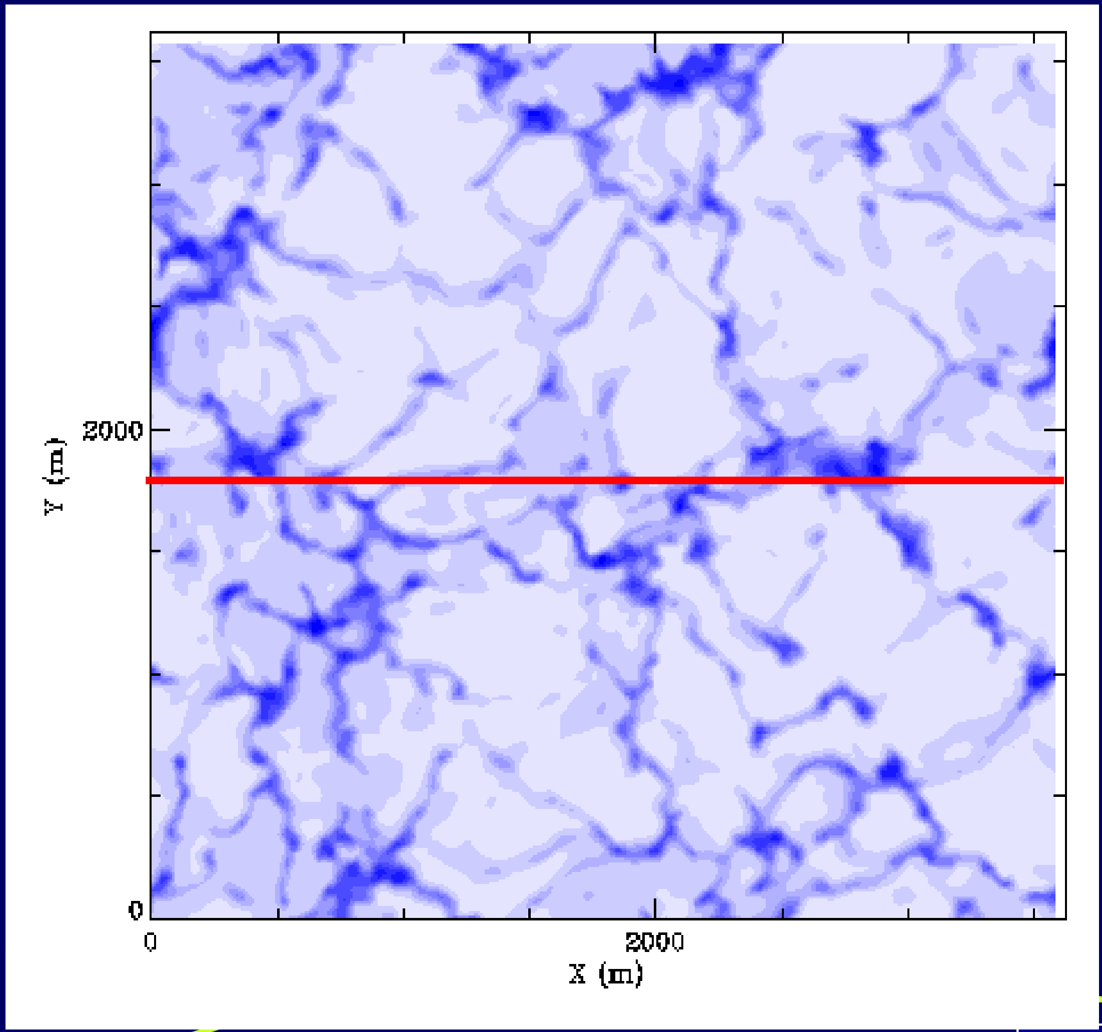
Large-eddy simulation

- 3D turbulence simulation at high resolution:
  - Sufficient to resolve the 'larger' eddies that are responsible for the bulk of the turbulent transport
  - Tend to use Δx ~ 20-100m, Δz ~ 5m-40m
- Able to explore parameter space (vary surface heating, radiative cooling, inversion strength, layer depth, etc.)
- A clean environment (no advection or representivity problems)
- But only a numerical model

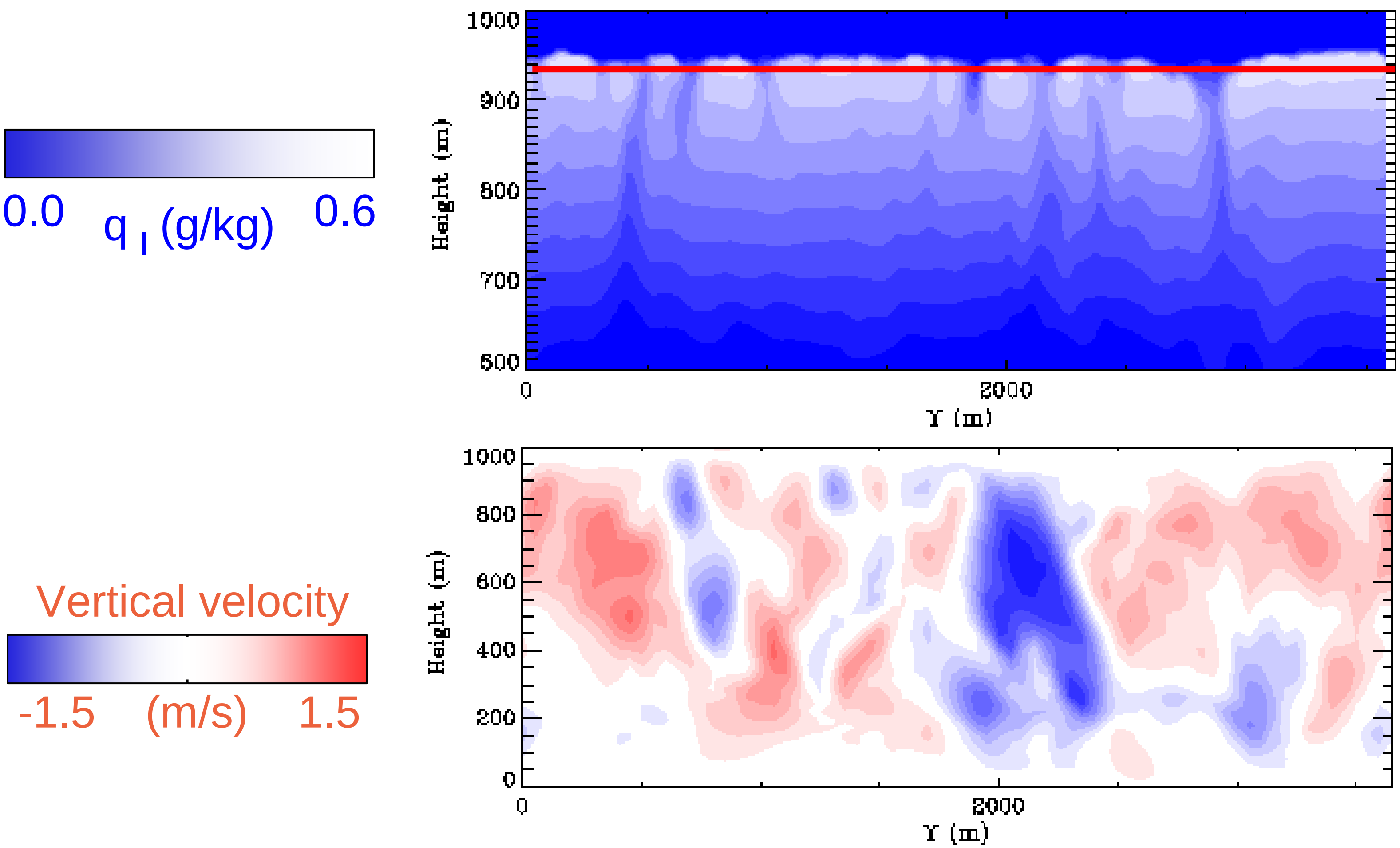
LES of Stratocumulus

- Δx =20m, Δz =5m
- Instantaneous slice through the liquid water field near cloud-top:





LES: vertical slices



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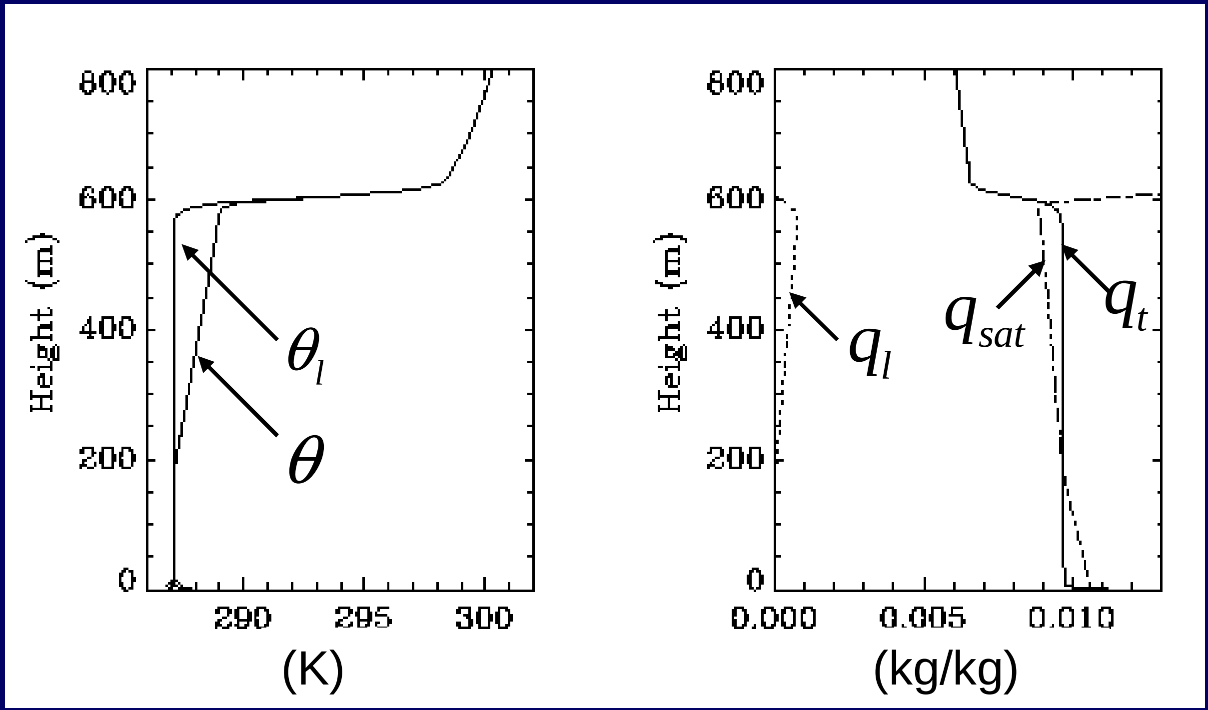
Mean profiles from LES



- Continuous turbulent mixing over the depth of the boundary layer ensures $\theta_l = \theta - (L/c_p)q_l$ and $q_t = q_v + q_l$ are constant with height

Simple framework:
Lilly's mixed layer model (1968)

- Standard equations (ignoring resolved scale advection and precipitation)

$$\frac{\partial q_t}{\partial t} = -\frac{\partial}{\partial z}\left(\overline{w'q_t'}\right)$$

$$\frac{\partial \theta_l}{\partial t} = -\frac{\partial}{\partial z}\left(\overline{w'\theta_l'} + F_{net}\right) = -\frac{\partial}{\partial z}(H)$$

where F_{net} is the net radiative heat flux and H the total heat flux

- Mixed layer model assumes θ_l and q_t are constant with height

Mixed layer model (continued)

- Integrating over the boundary layer gives the mixed layer model equations:

$$\frac{\partial q_t^{ML}}{\partial t} = -\frac{\overline{w'q_t'}\Big|_{z_i} - \overline{w'q_t'}\Big|_{surf}}{z_i}$$

$$\frac{\partial \theta_l^{ML}}{\partial t} = -\frac{H\Big|_{z_i} - H\Big|_{surf}}{\partial z}$$

- Discontinuous inversion implies $\overline{w'q_t'}\Big|_{z_i} = -w_e \Delta q_t$

$$H\Big|_{z_i} = -w_e \Delta \theta_l + \Delta_{ML} F_{net}$$

where $w_e = \frac{\partial z_i}{\partial t} - w_{LS}$ is the entrainment rate.

- Implies stratocumulus is a simple system where entrainment is a key process

Difficulties with parametrizing entrainment

- Process is non-local (mixing at inversion is driven by eddies impinging from below)
- Hard to parametrize on GCM grids. For traditional first order closures, $\overline{w'\chi'}_k = -K_k \frac{\Delta_k \chi}{\Delta_k z}$, gradients are large and
  - for K(Ri) local stability dependence is not relevant
  - for K(TKE) accurate TKE evolution hard to resolve
  - $K(z/z_i)$ is very sensitive to the definition of z_i
- So the Met Office scheme uses an explicit parametrization of entrainment fluxes, using w_e from Lock (1998)

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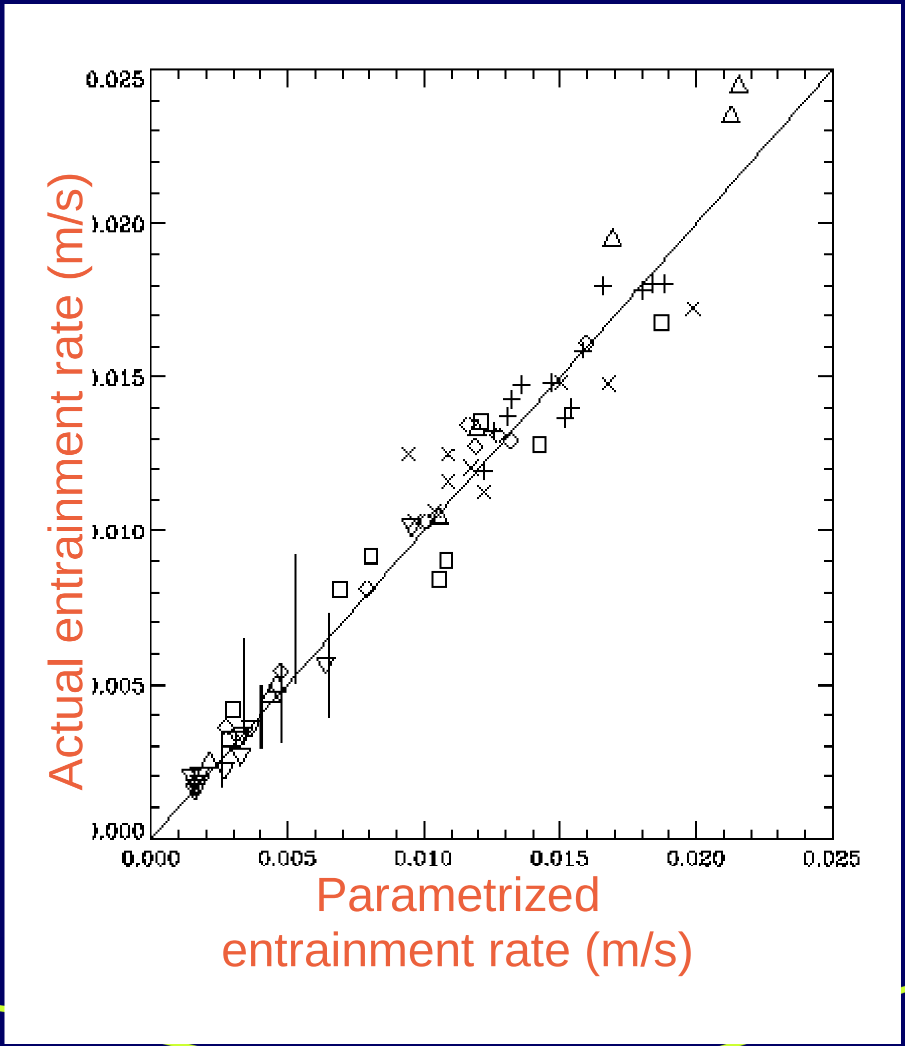
Verification of entrainment parametrization against LES and observations



LES

Cloud free:

△ = surface heated

Smoke clouds:

▽ = radiatively cooled

□ = surf heat + rad cool

Water clouds:

X = rad cool (no b.r.)

+ = rad cool + buoy rev

◇ = buoyancy reversal only

Observations

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

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Difficulties with parametrizing entrainment (continued)

- All model processes (turbulence, radiation, LS advection) should be coupled to preserve mixed layer budgets
  - i.e., no spurious numerical transport across inversion

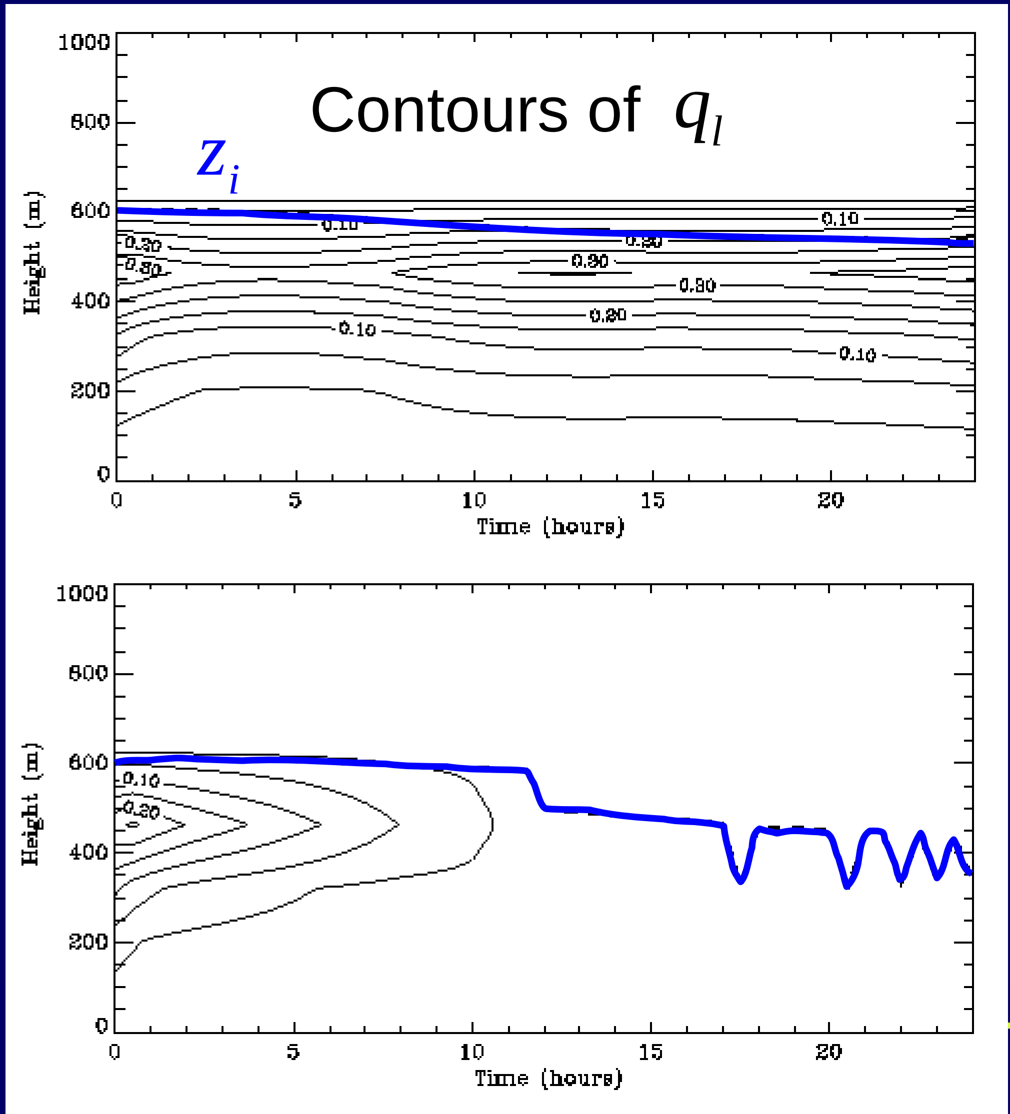
    (Stevens et al 1999, Lenderink and Holtslag 2000,

    Lock 2001, Grenier and Bretherton 2001)
- So the Met Office scheme uses a subgrid inversion diagnosis to couple the entrainment, radiative and vertical advection fluxes across the inversion

Impact of coupling inversion fluxes in SCM for nocturnal subsiding stratocumulus ($|w_{subs}| > w_e$)

Coupled fluxes:

Uncoupled fluxes:



Limitations of the mixed layer model

- The mixed layer model framework allows a realistic treatment of the inversion and the transports across it
- It is possible to use a mixed layer model as the boundary layer scheme in your GCM with z_i as a coordinate surface

  (Suarez et al, 1983: UCLA GCM) but this is:

  - technically hard to implement and
  - stratocumulus often decouples into two mixed layers

    (see Turton and Nicholls, 1987, for example)

‘K-profile’ scheme for interior mixing

- Based on a cloud-free scheme by Holtslag and Boville (1993)

For $\chi = \theta_l, q_t, u, v$ need to solve: $$\frac{\partial \chi}{\partial t} = -\frac{\partial}{\partial z}\left(\overline{w'\chi'}\right)$$

Use a 1st order closure: $$\overline{w'\chi'} = -K\frac{\partial \chi}{\partial z} + \overline{w'\chi'}^{ng}$$

§ Where K, $\overline{w'\chi'}^{ng}$ are empirically determined functions of height within the mixed layer and velocity scales representative of the turbulence forcing (separate K-profiles are used for surface and cloud-top driven turbulence)

GCSS Working Group 1: Boundary layer clouds

- Unfunded (!) international group performing intercomparisons of LES, observations and SCM
- 8 cases examined to date: stratocumulus (FIRE 1, DYCOMS II), smoke cloud, Sc to Cu transition (ASTEX), trade-cumulus (BOMEX), Cu rising into Sc (ATEX), diurnal cycles of Cu over land (ARM-SGP) and marine Sc (FIRE 1)
- Conclusions:
  - With care, LES tend to be similar to each other and observations (particularly for Cu)
  - SCMs are improving
  - many productive lines of research have been inspired by WG1
- Future cases to include microphysics (drizzling/not drizzling Sc, Cu)

EUROCS GCM intercomparison

Christian Jacob, Pier Sibesma, Roel Neggers

- Traditional GCSS/EURCREM intercomparisons have limitations
  - only a few cases
  - we know little about their representivity
- EUROCS included a GCM intercomparison of the NE Pacific
- Model output requested:
  - Along two cross-sections from California to the central Pacific, representing the Sc to Cu to ITCZ transition
  - JJA 1998, every 3 hours through the day to give the diurnal cycle

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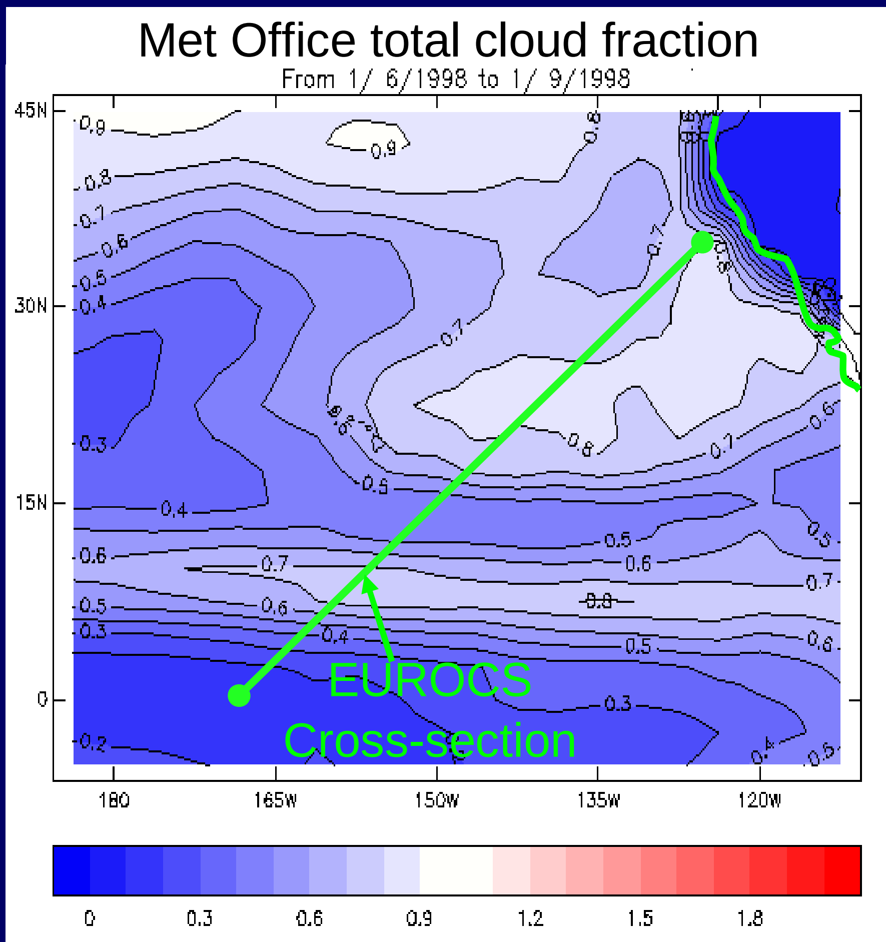
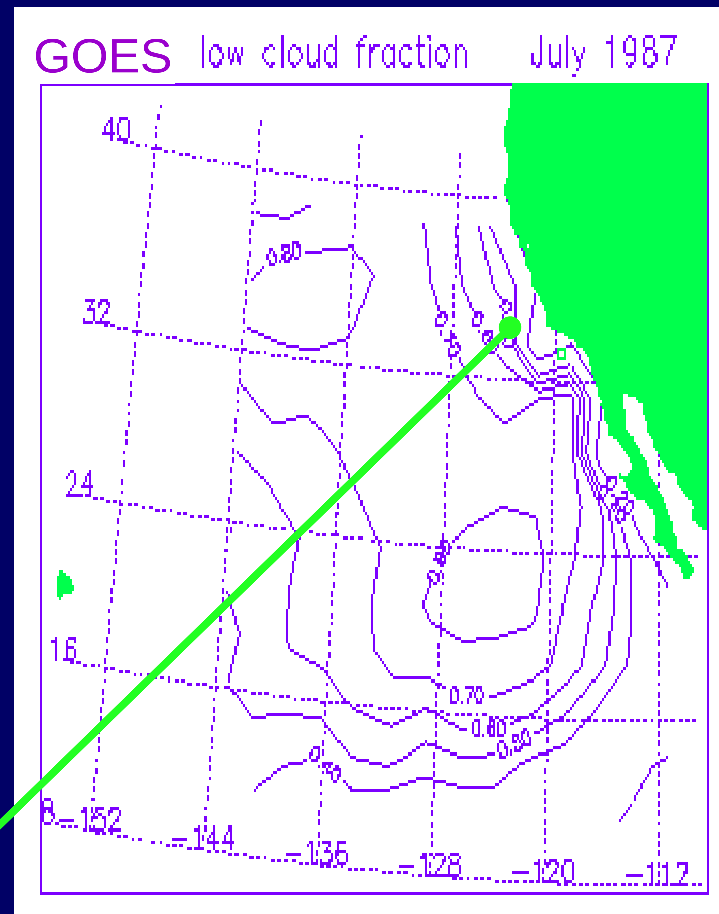
Met Office GCM

- Met Office ‘Climate’ model simulation
  - AMIP-style, prescribed SST
  - N48L38 resolution = 2.5 latitude by 3.75 longitude (~300km in tropics) with 38 levels (~250m at 1km)
- 7 other centres contributed similar climate simulations with global or regional models
- ECMWF contributed averaged short-range forecasts

Met Office GCM cloud cover climatology





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Observed daytime cloud types (Norris, 1998)
JJA mean

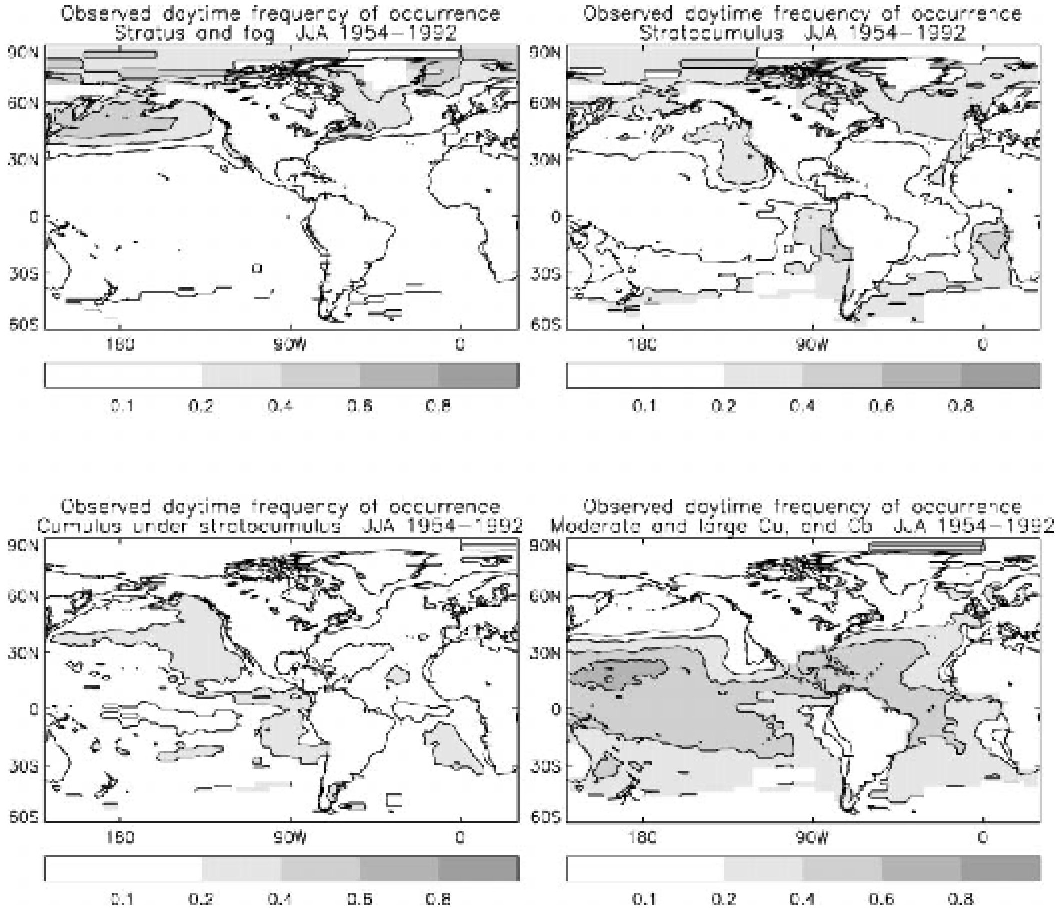

FIG. 3. Observed daytime frequency of occurrence of different cloud types, from Norris (1998). JJA mean from 1954 to 1992: (a) stratus and fog, (b) stratocumulus, (c) cumulus–stratocumulus, and (d) moderate and large cumulus, and cumulonimbus.

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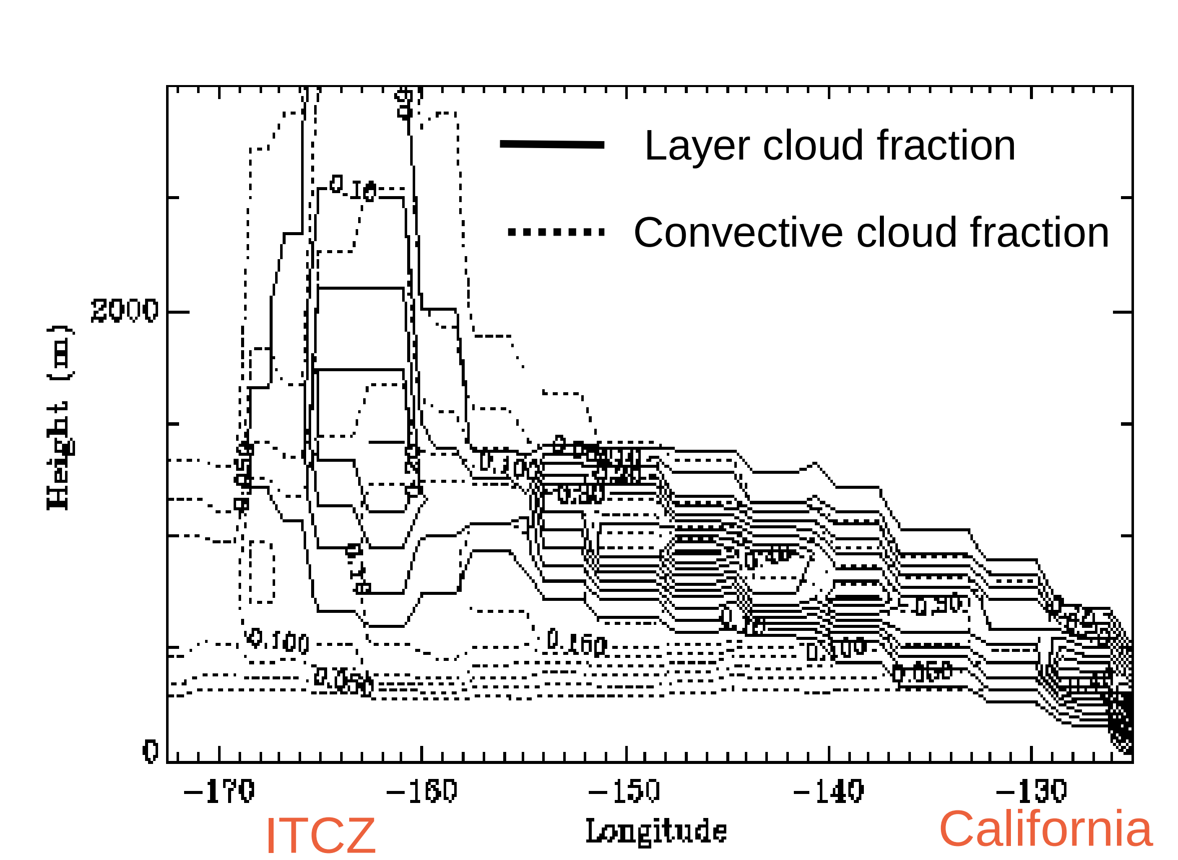
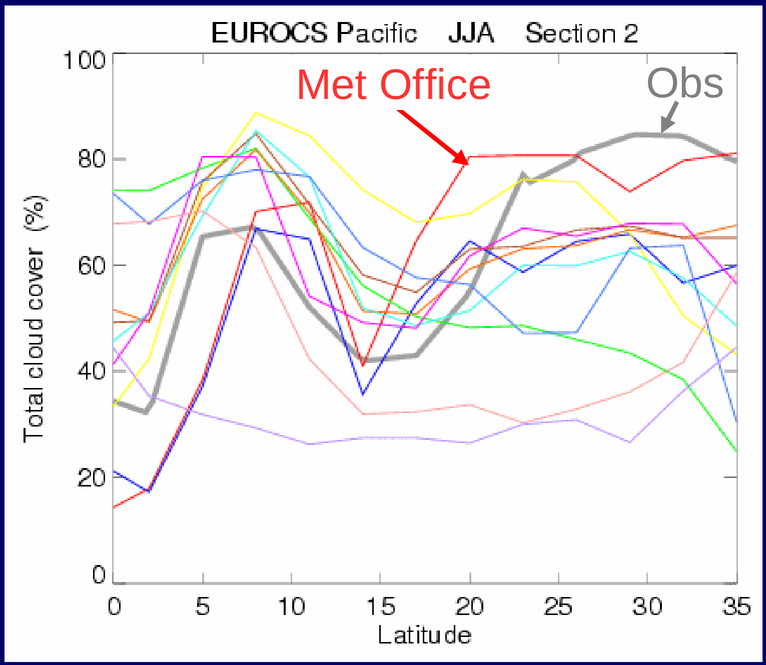
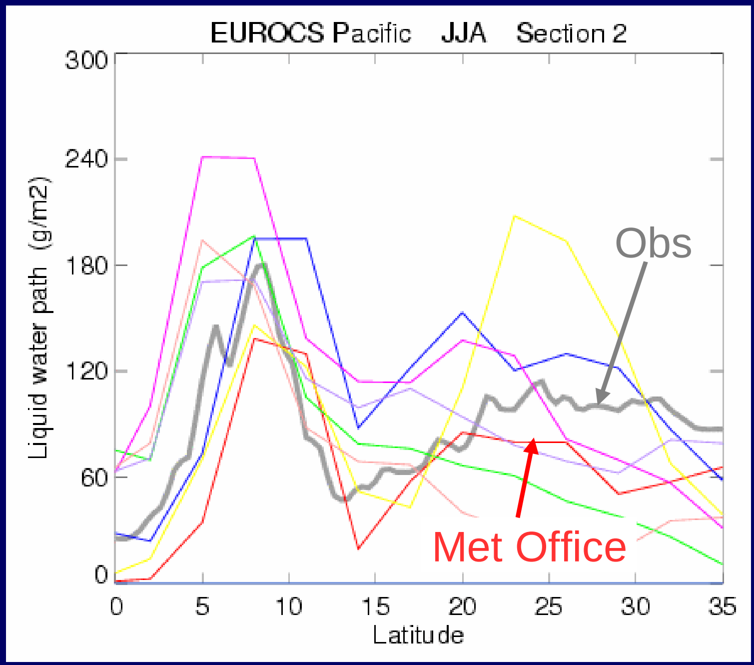
Met Office GCM cloud fractions

EUROCS cross-section – 1998 JJA mean



EUROCS GCM intercomparison
Total cloud cover and LWP

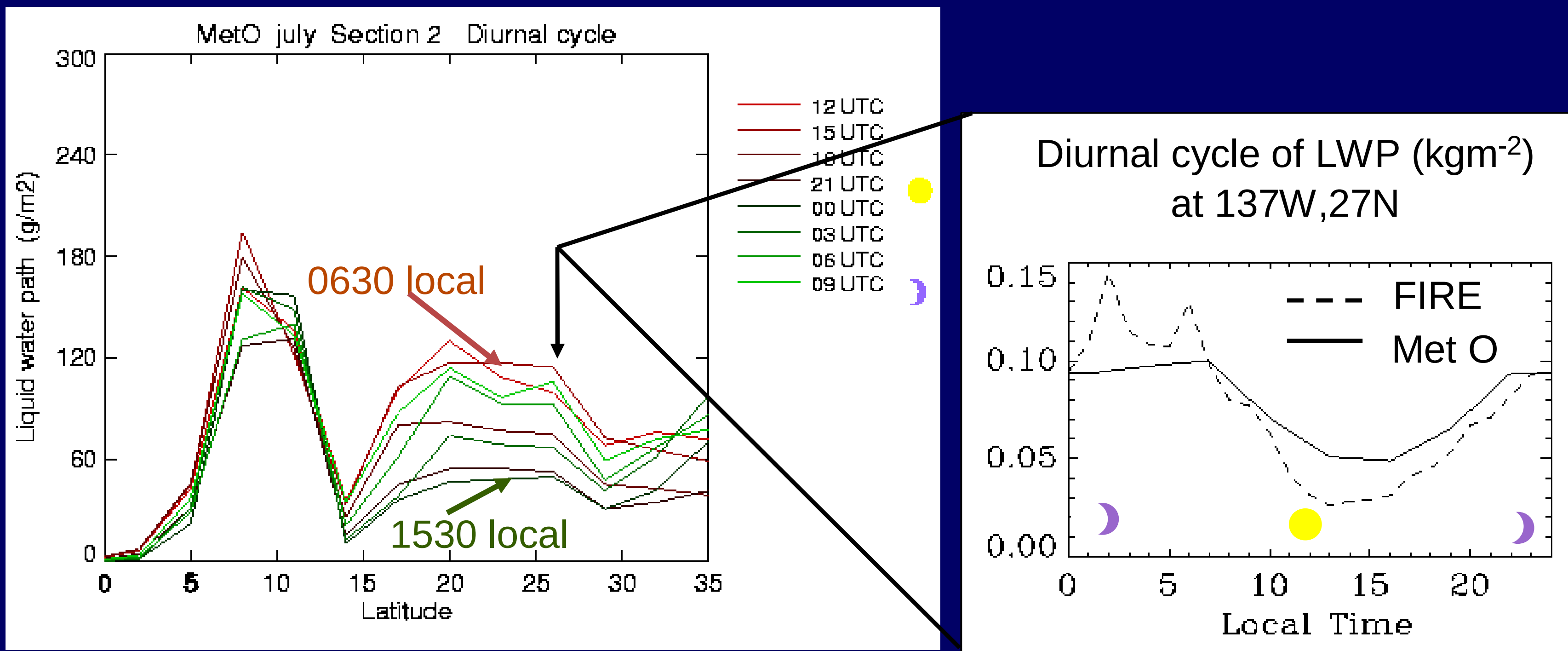




ITCZ California ITCZ California

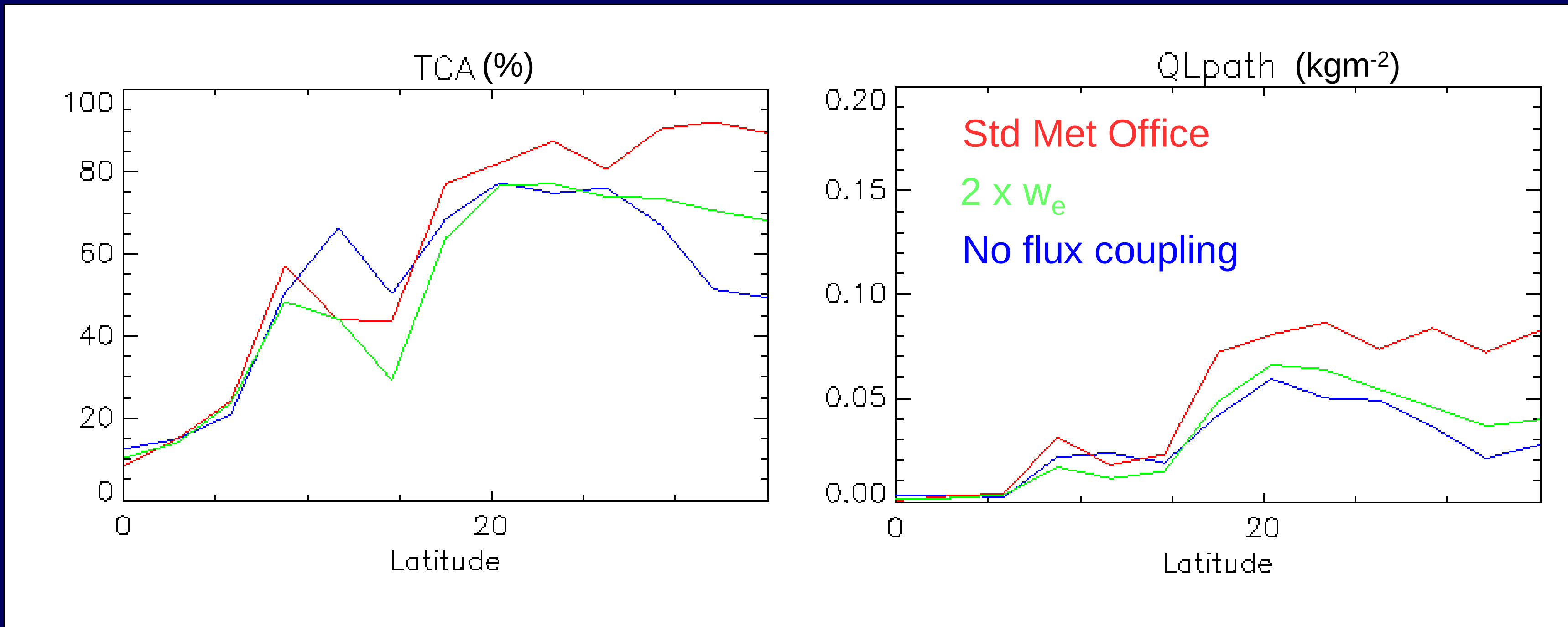
- Cloud cover too high where Sc overlies Cu
- LWP somewhat low in Sc area

Diurnal cycle of stratocumulus in GCM



- Time lag in LWP relative to solar cycle well represented away from coast
- But FIRE observations were at San Nicolas Island!

Cloud sensitivity to entrainment



- So, more active entrainment (either explicit or numerical) gives a boundary layer with less stratocumulus
- Numerical errors (no flux coupling) would be more serious than a factor of two in the parametrized entrainment

Summary

- The Met Office GCM produces a reasonably realistic marine stratocumulus sheet over the NE Pacific:
  - Good cloud cover and LWP diurnal cycle
- Close to coast LWP is too small and diurnal cycle does not lag the solar cycle
  - Lack of resolution?
    - Horizontal: noise from the coastline?
    - Vertical: cloud-top at 500m gives ~4 levels in the boundary layer so decoupling is hard and cloud layer hard to resolve

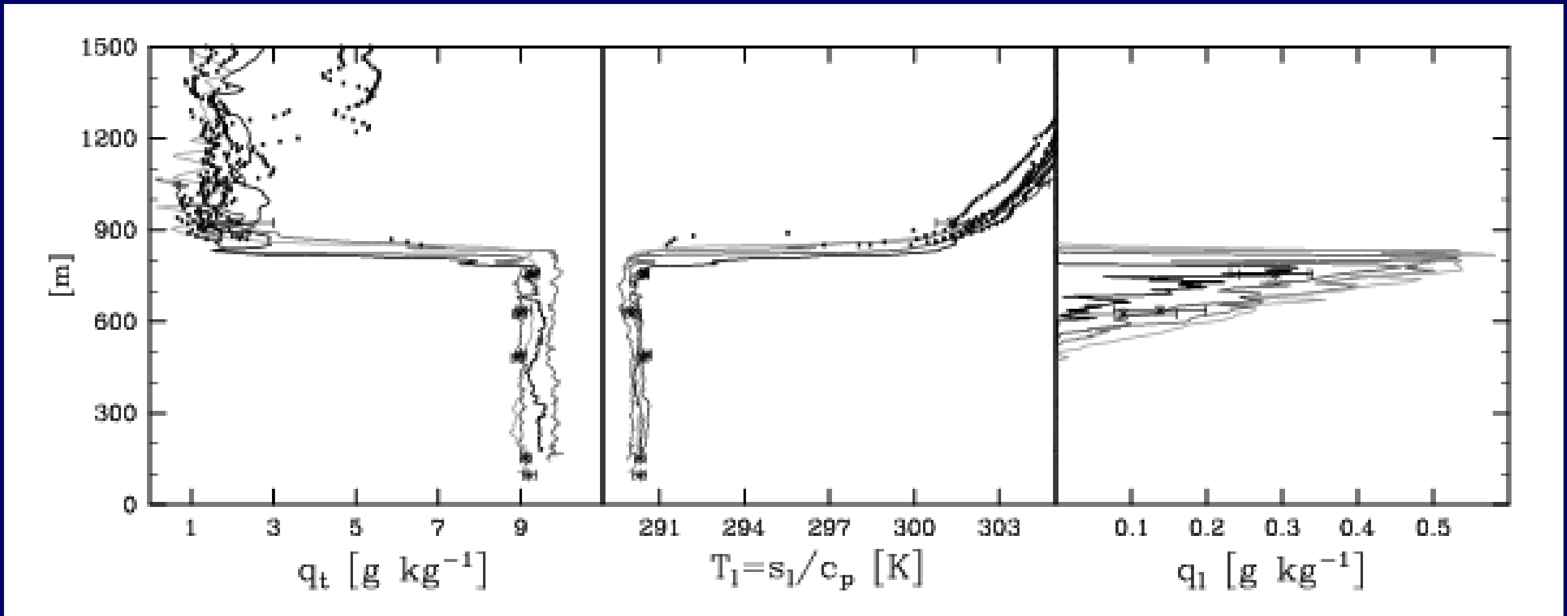
Summary (continued)

- GCM has too much cloud, particularly when stratocumulus is over shallow cumulus
  - Problem has been alleviated with change to Cu cloud fraction
  - Possible problem with Sc/Cu interaction (or with Cu/inversion interaction in general)?
  - Radiative impact of cloud inhomogeneity?
- Erroneous numerical entrainment can be a serious problem in GCMs

GCSS WG1 Case 8: simulations of RF01 from DYCOMS II

- Nocturnal stratocumulus off California (July 2001)
- Well-mixed boundary layer with cloud base at 600m, top at 850m
  - both were approximately constant over 8 hours of aircraft observations following the airmass ➡ ~equilibrium
- Case specifications
  - Initial profiles
  - Forcing: fixed geostrophic winds, large-scale divergence and fixed SST (or surface fluxes)
  - Simplified LW radiation scheme
- No drizzle was observed

Observed profiles for RF01



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Single-column model simulations of GCSS-DYCOMS

- Step 4 (fixed SST, subsidence, full idealised radiation code)
- Run for “at least 48 hours”

Resolution (Δz)	Timestep (‘standard’)	
	RPN	Met Office
10 m	10s, 60s	60s, 300s
50 m	60s, 180s	450s
“Operational”	60s, 300s, 600s	300s, 600s, 1800s

- “Operational” is a stretched grid with 13 levels below 1500m (Δz~150m at cloud-top)

RPN single-column model

- Only interfaces to the boundary layer turbulence and cloudiness schemes
  - TKE closure with mixing of θ_l and q_t
  - Bougeault-Lacarrere (1989) mixing lengths (but no condensation in parcels ➡ 'small' *l* in Sc)
  - Bechtold and Siebesma (1998) statistical cloud scheme for shallow Cu and Sc
- So, as yet, no "grid-scale" cloud, precipitation, radiation, deep convection…

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Bechtold et al cloud scheme

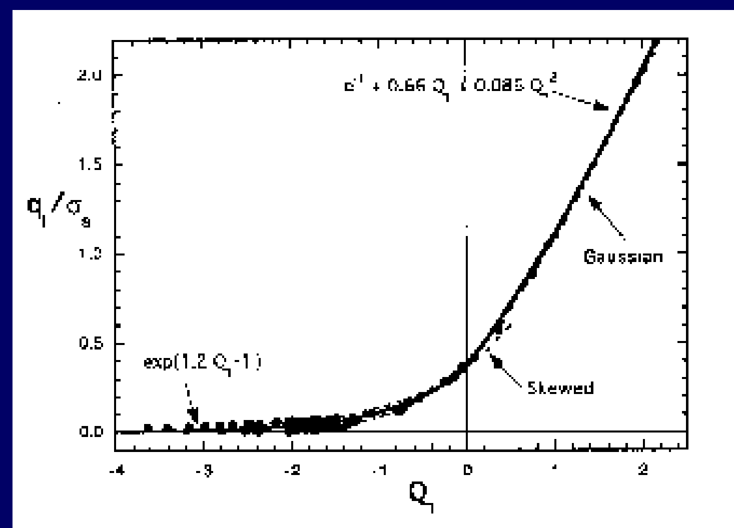
- Statistical / empirical scheme based on observations and LES
- Cloud properties are empirical functions of $Q_1 \propto \dfrac{\overline{q_t} - \overline{q_{sat}(T_l)}}{\sigma_s}$

  with $$\sigma_s \propto (l_h l_\varepsilon)^{1/2} \left(a \frac{\partial \overline{q_t}}{\partial z} - b \frac{\partial \overline{\theta_l}}{\partial z} \right)^2$$

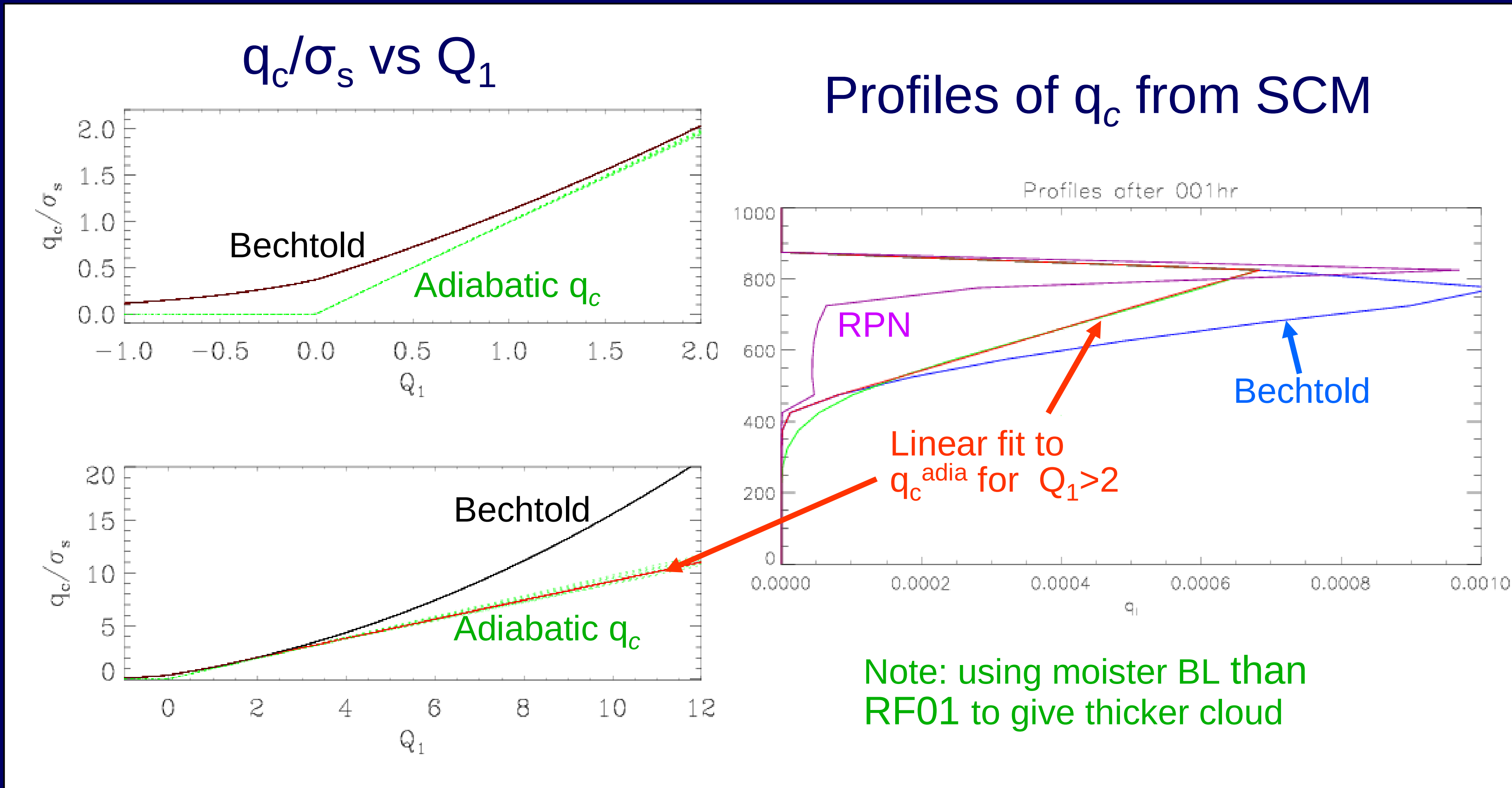
- E.g., for $Q_1 > 0$

  $$q_l = \sigma_s \left(e^{-1} + 0.66\, Q_1 + 0.086\, Q_1^2 \right)$$

- But in SCM of Sc, find σ_s is small
  - ➡ $Q_1 >> 1$
  - ➡ $q_l \sim 0.086\, \sigma_s Q_1^2 \sim {}^{1}\!/_{\sigma_s}$ is large
- RPN therefore limits $-6 < Q_1 < 4$



Using scheme outside original parameter space

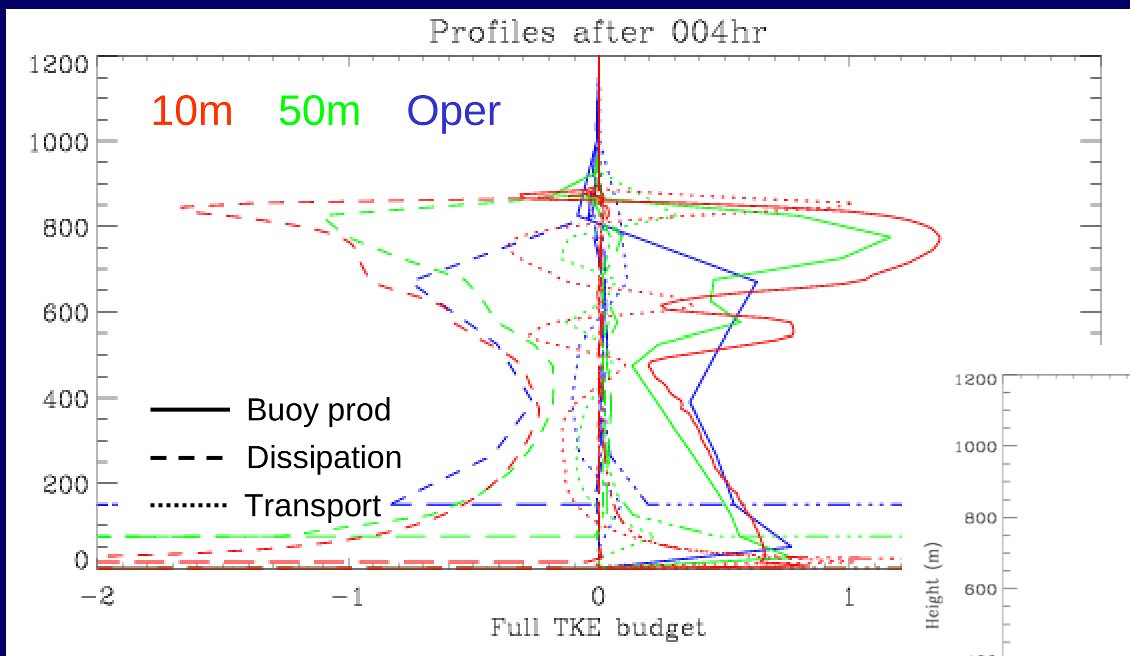


Bechtold: $q_c = \sigma_s\left(e^{-1} + 0.66\,Q_1 + 0.086\,Q_1^2\right)$

Revised: $q_c = \sigma_s\left(0.23 + 0.9\,Q_1\right)$ for $Q_1 > 2$

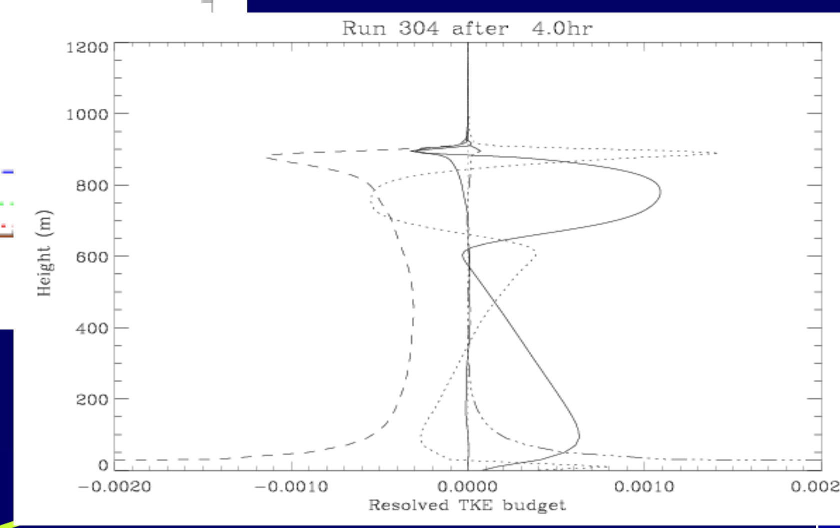
TKE budgets

- TKE budgets similar to Met Office LEM (except for strange double peak in $\overline{w'b'}$ at higher resolution)



SCM

LEM



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Bechtold et al buoyancy flux enhancement

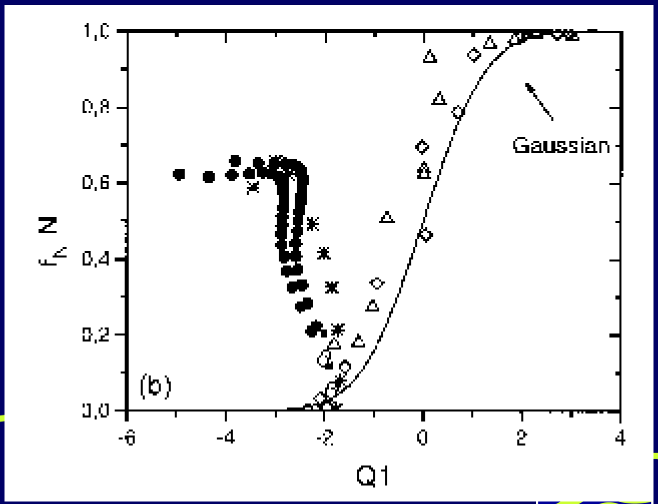
- Write buoyancy production as the weighted sum of fluxes in saturated and unsaturated air

$$\overline{w'b'} = (1 - f_N N)\,\overline{w'b'}\Big|_{clear} + f_N N\,\overline{w'b'}\Big|_{cloud}$$

where

$$\overline{w'b'}\Big|_{cloud/clear} = g\left(\beta_T^{cloud/clear}\,\overline{w'\theta_l'} + \beta_Q^{cloud/clear}\,\overline{w'q_t'}\right)$$

- For a Gaussian distribution of Q_1 about the grid-box mean (i.e. Sc), $f_N N = N$, the cloud fraction
- For a skewed distribution (i.e. Cu), $f_N >> 1$



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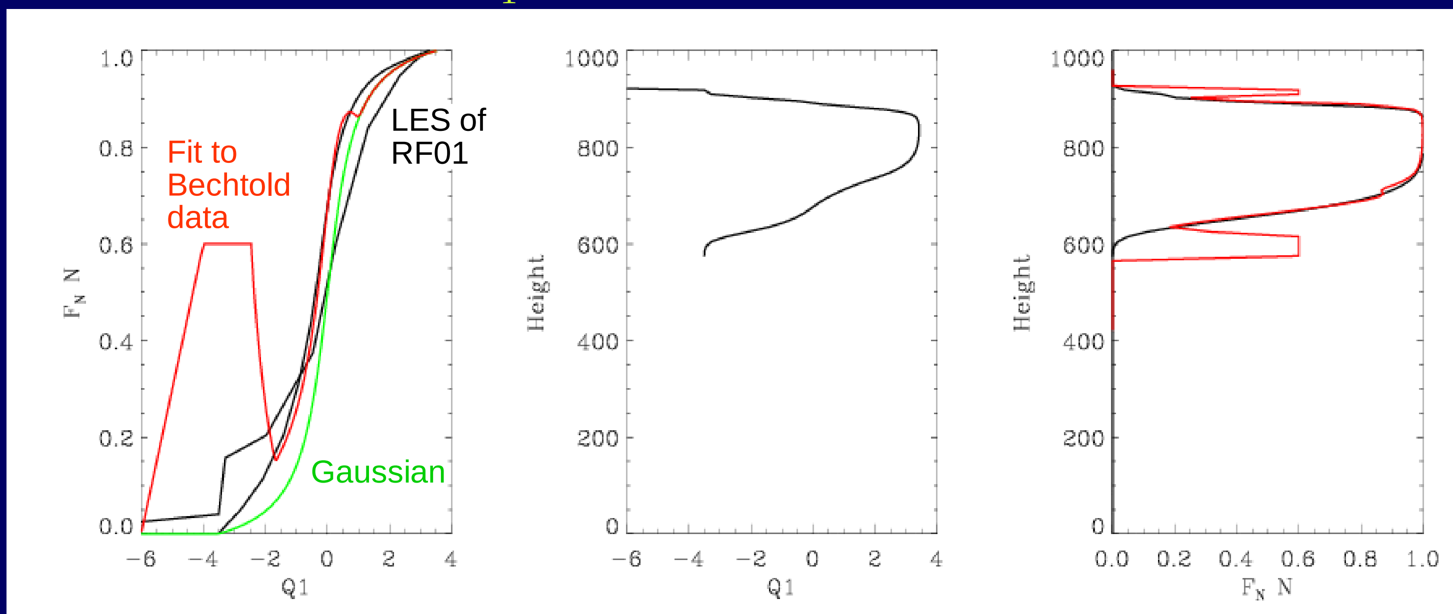
Bechtold et al buoyancy flux enhancement (continued)

- But the air just above and below stratocumulus sheets is slightly unsaturated too ($Q_1 \leq 0$, e.g. RF01):



- Hence Bechtold et al suggest imposing a Gaussian distribution at the top and base of cloud layers

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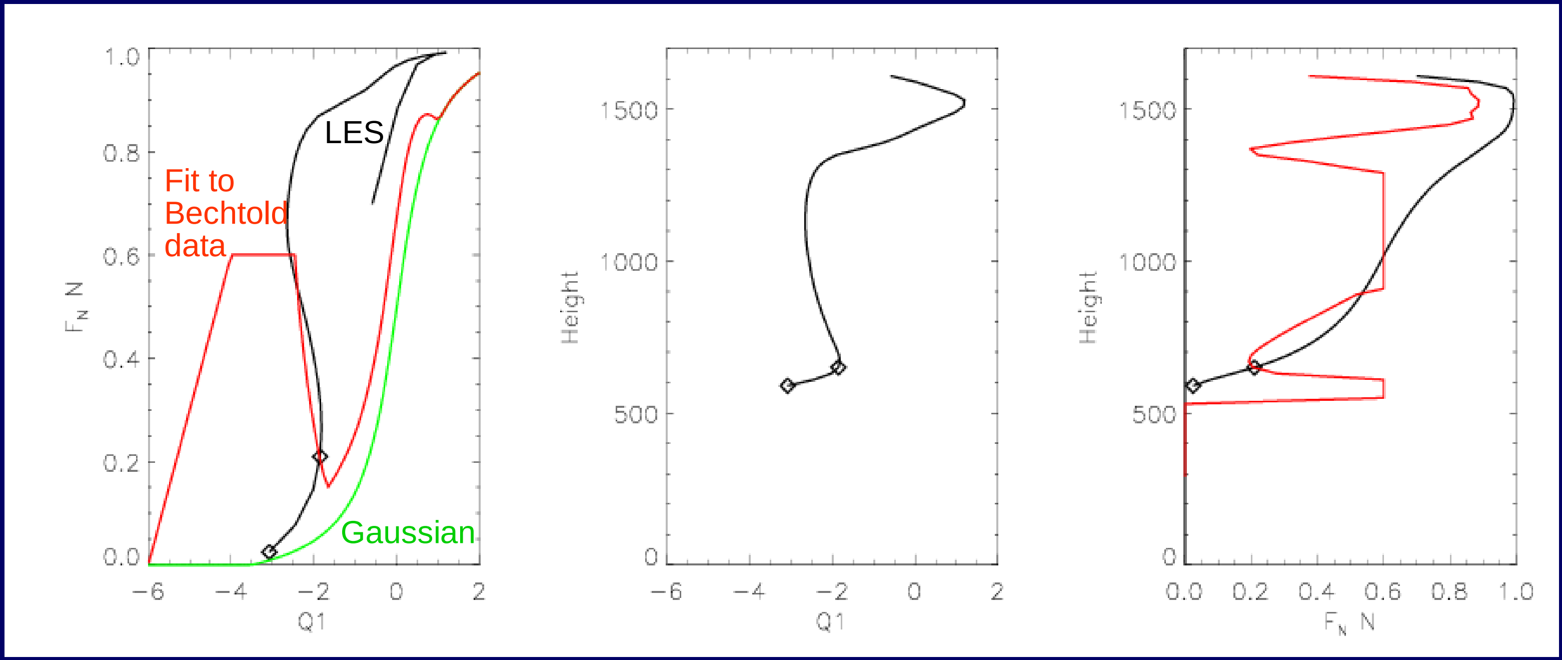
Bechtold et al buoyancy flux enhancement (continued)

- But what about Cumulus rising into stratocumulus?
  - Is Q_1 really the appropriate variable?



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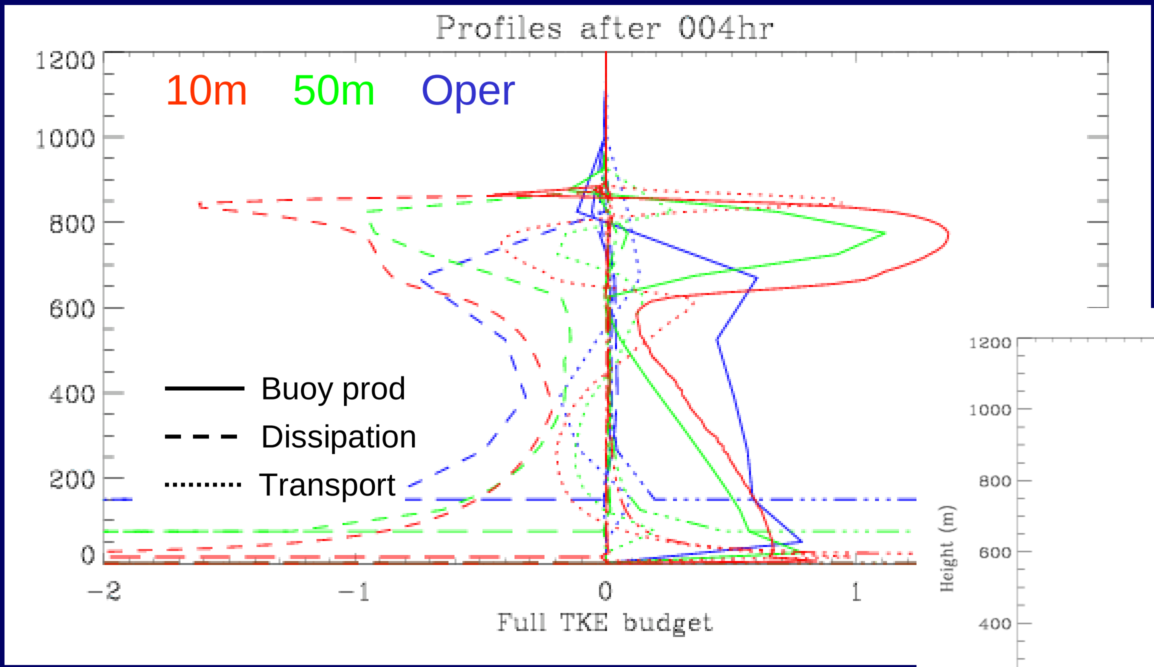
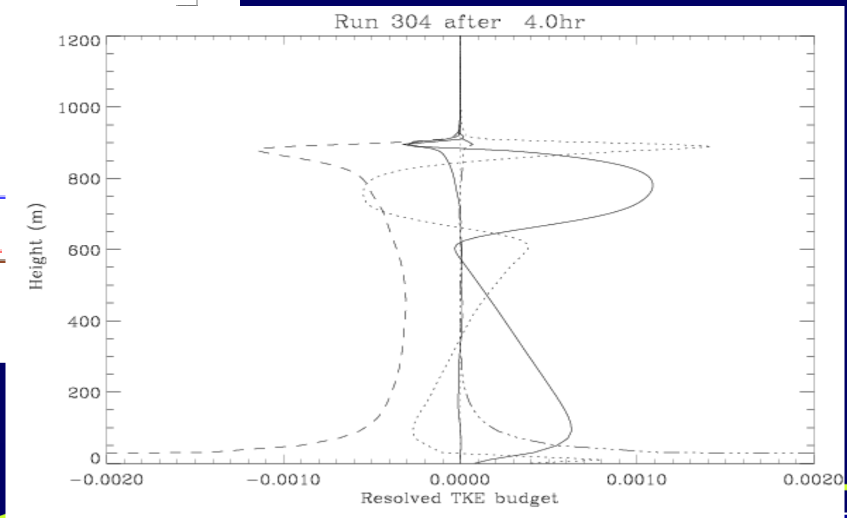
Revised TKE budgets

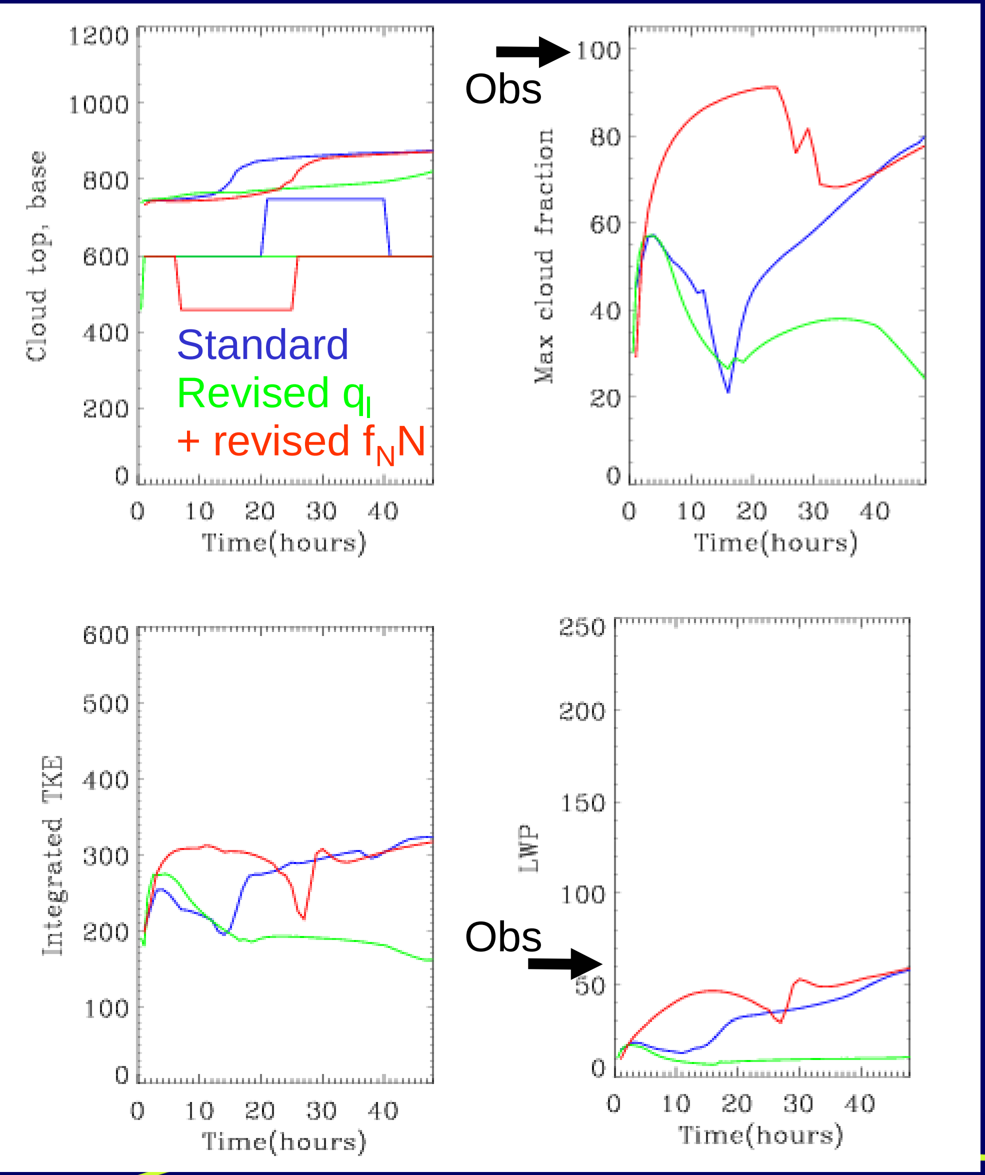
- TKE budgets very similar but without double peak in buoyancy production
- Good agreement with LES at high resolution – lack of resolution near cloud-top evident at 'Oper' resolution



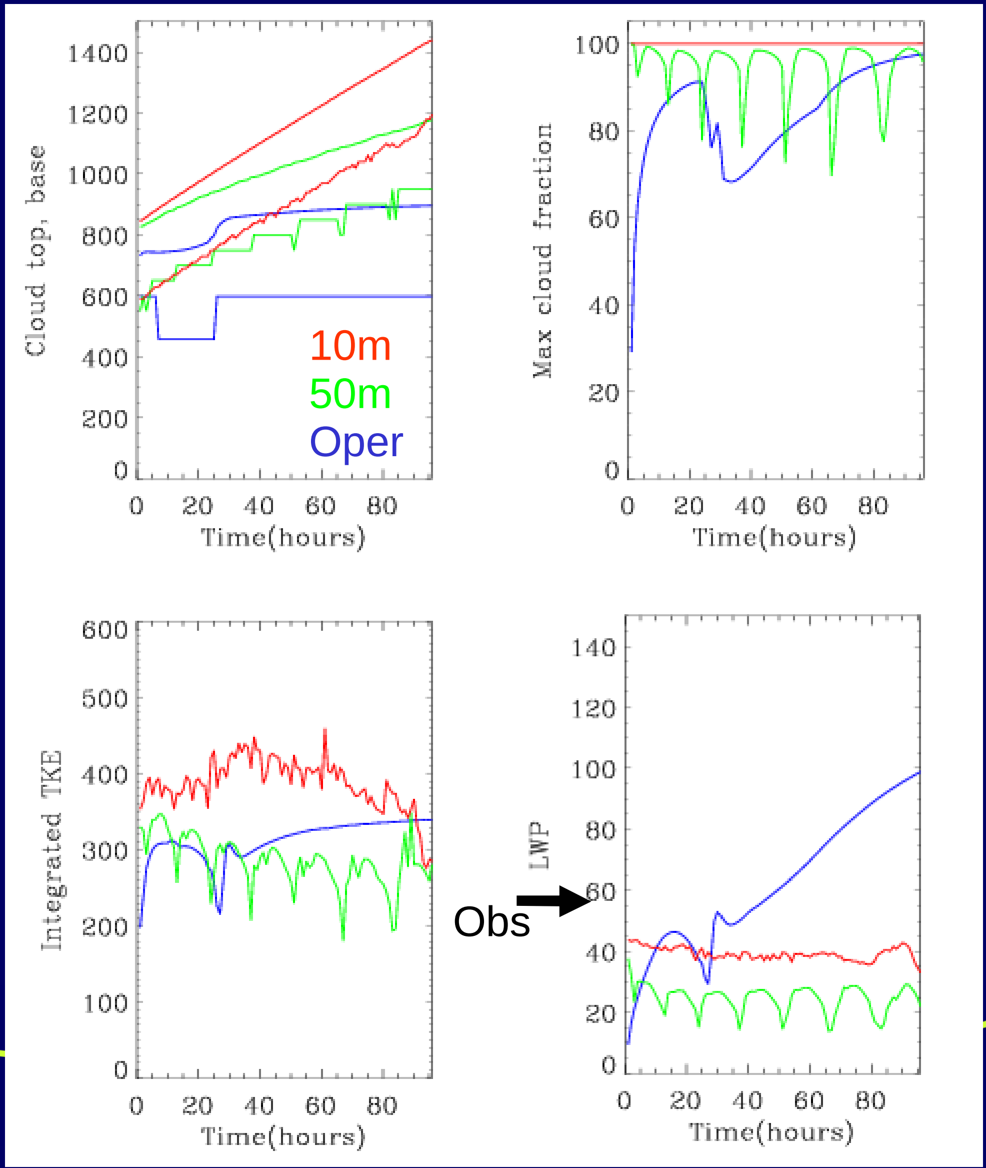


RPN time series (48 hours) Oper resolution: Impact of changes to q_l and $f_N N$ formulations

- Changes apparently beneficial (give more cloud)
- Actually the result of somewhat complex changes in TKE production and entrainment

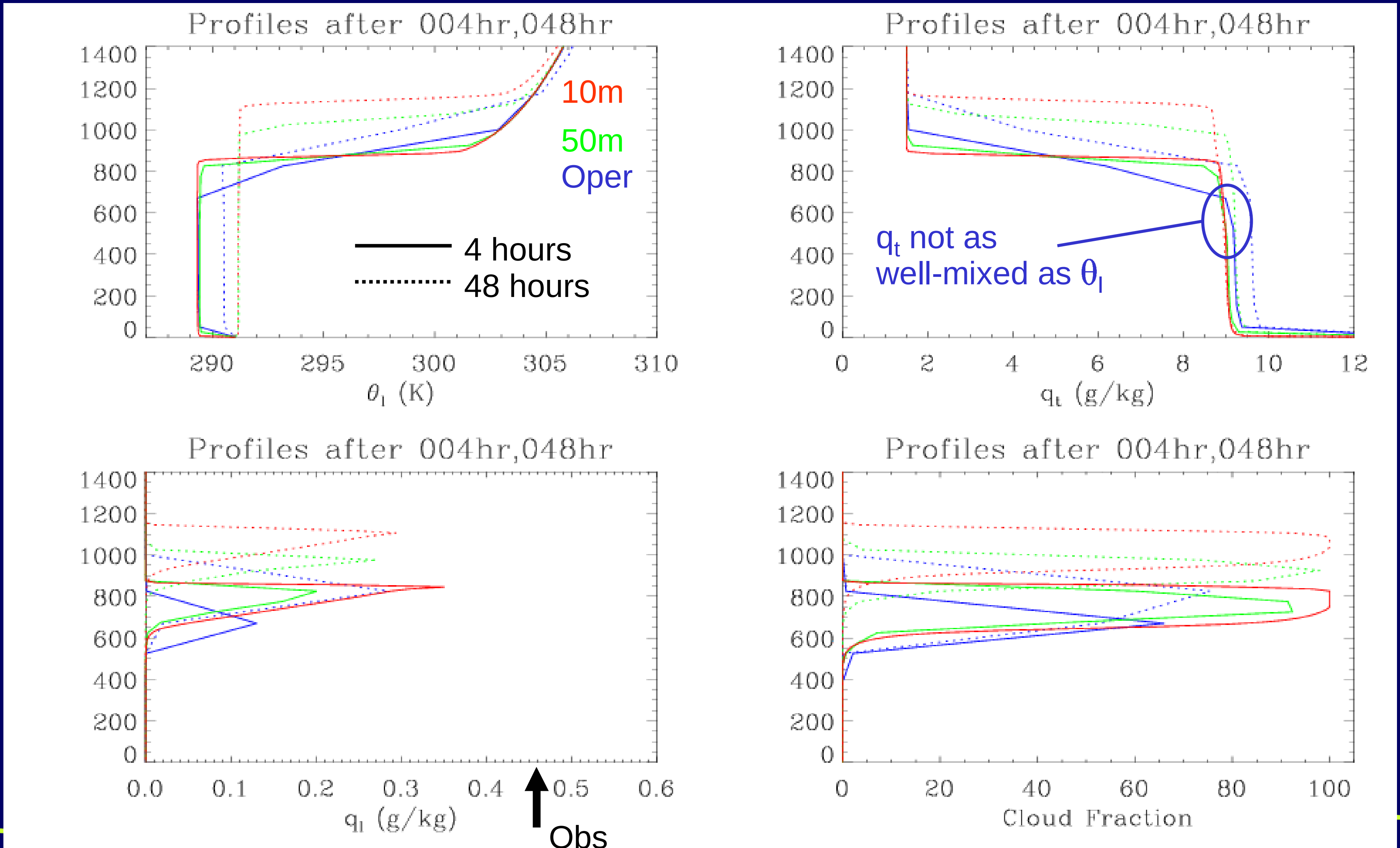


Revised RPN resolution senstivity: time series, standard timesteps (96 hours)



- Remember observations were only for 8 hours
- Lack of convergence probably reflects inadequate resolution of the TKE equation

Revised RPN profiles



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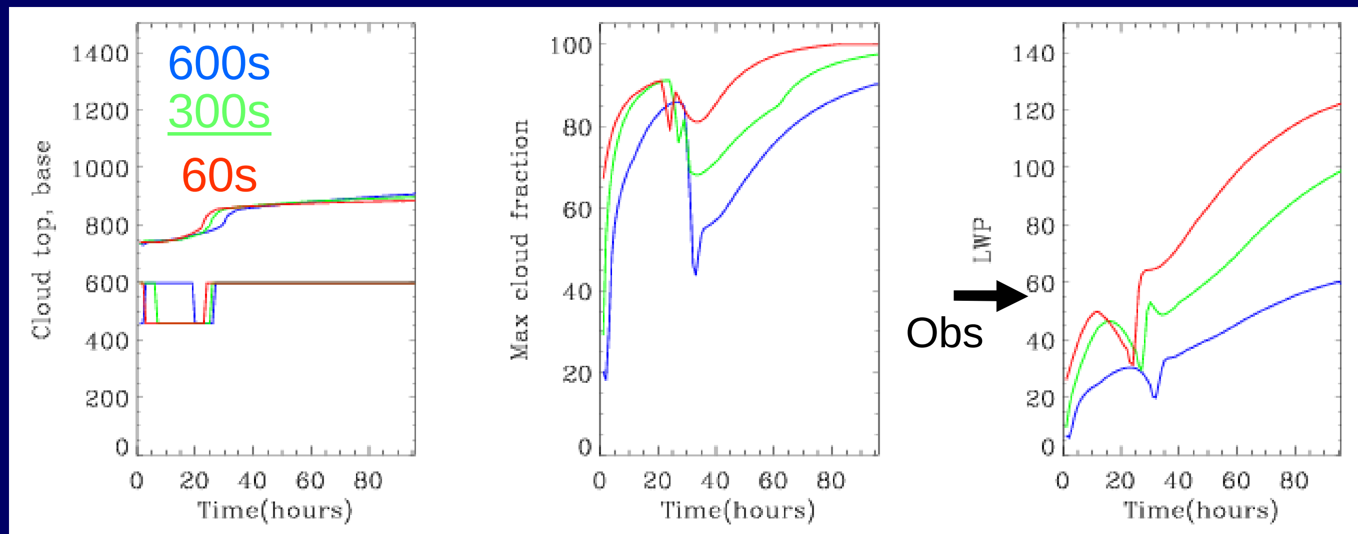
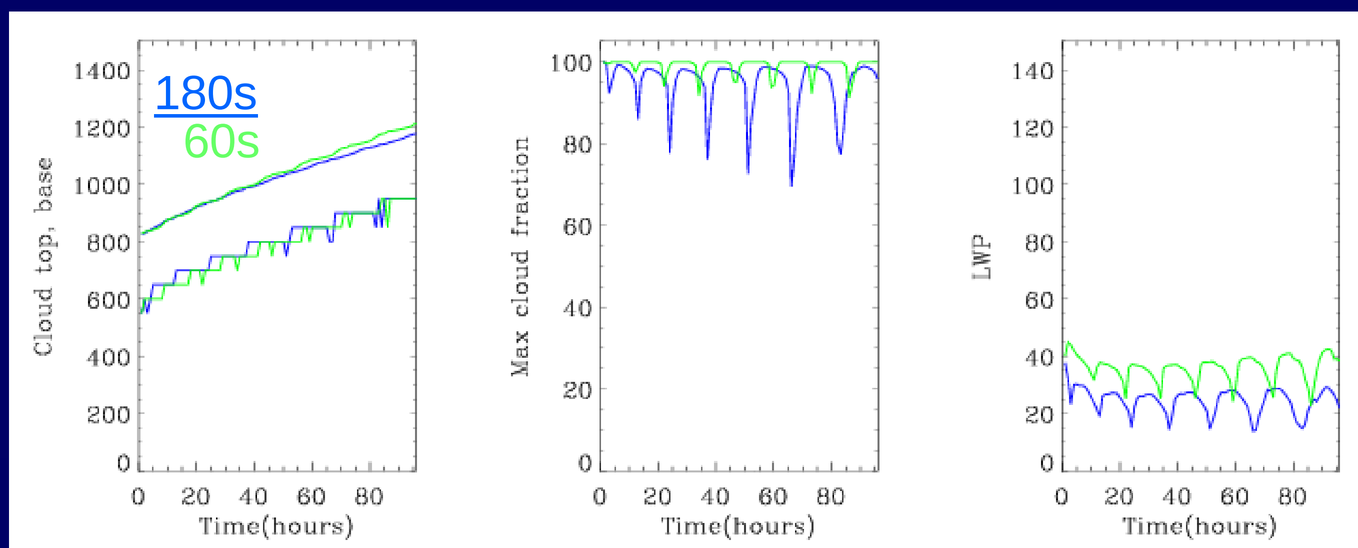
Revised RPN timestep dependence (96 hours)

‘Operational’



50m



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RPN summary

- Problems identified with the Bechtold et al scheme
  - serious errors for q_l in well-mixed boundary layers
  - strange buoyancy flux profile, particularly at higher resolution – a ‘feature’ intended for shallow cumulus that requires diagnostic removal
- Good simulation of RF01, particularly at 50m resolution or less.
- Resolution dependence:
  - “Operational” resolution too coarse properly to resolve cloud layer (hence low (~0.5) cloud fraction)
  - Higher resolution gives more entrainment
- Timestep dependence:
  - Tendency to have less cloud at larger timestep

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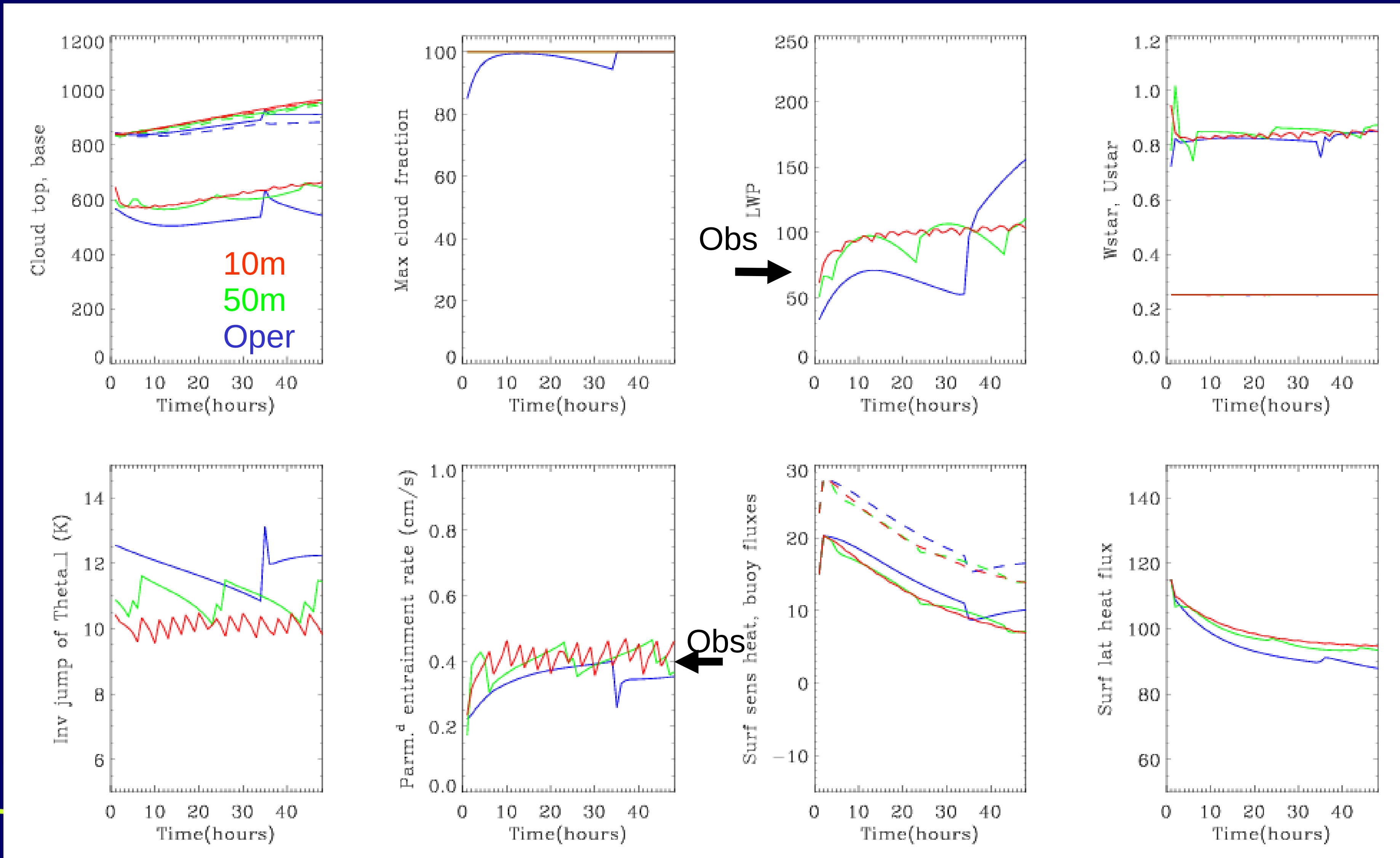
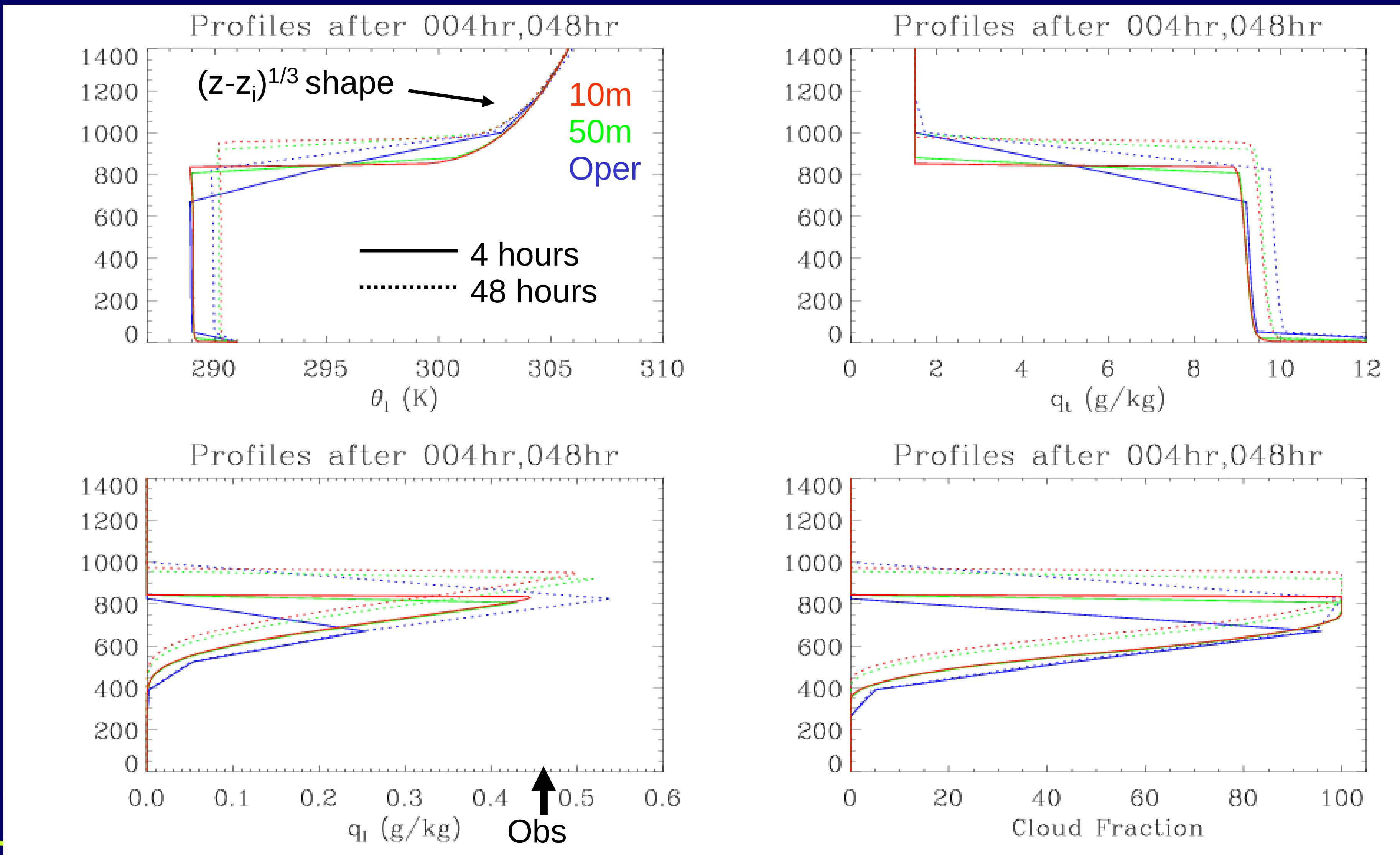
Met Office time series (48 hours)



Met Office profiles



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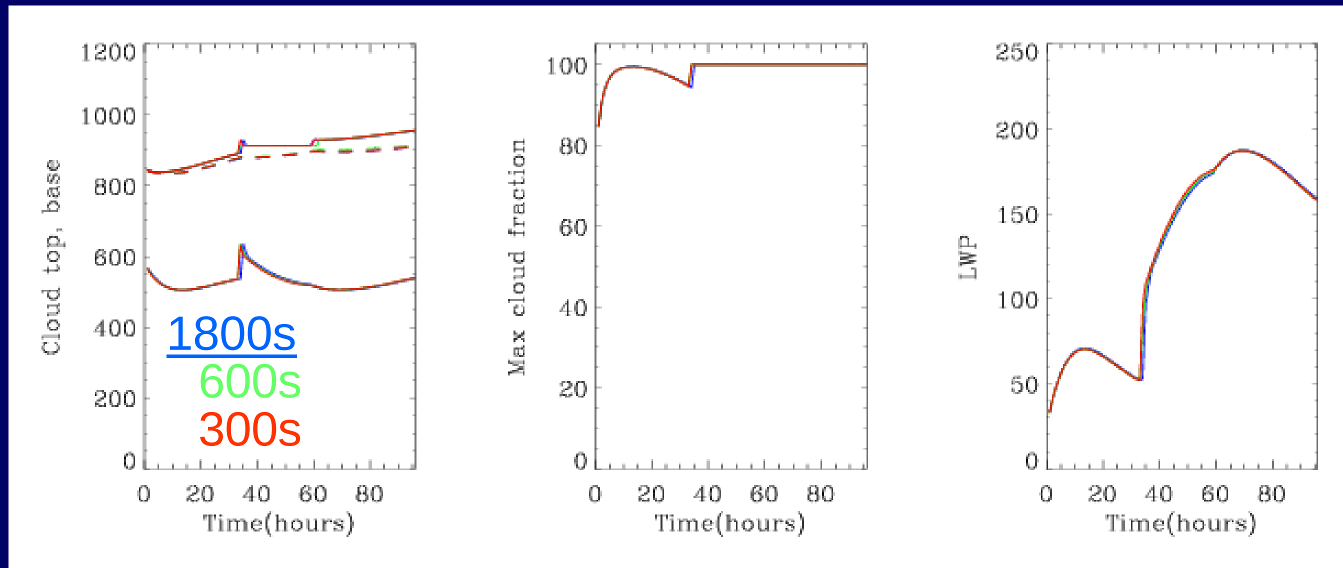
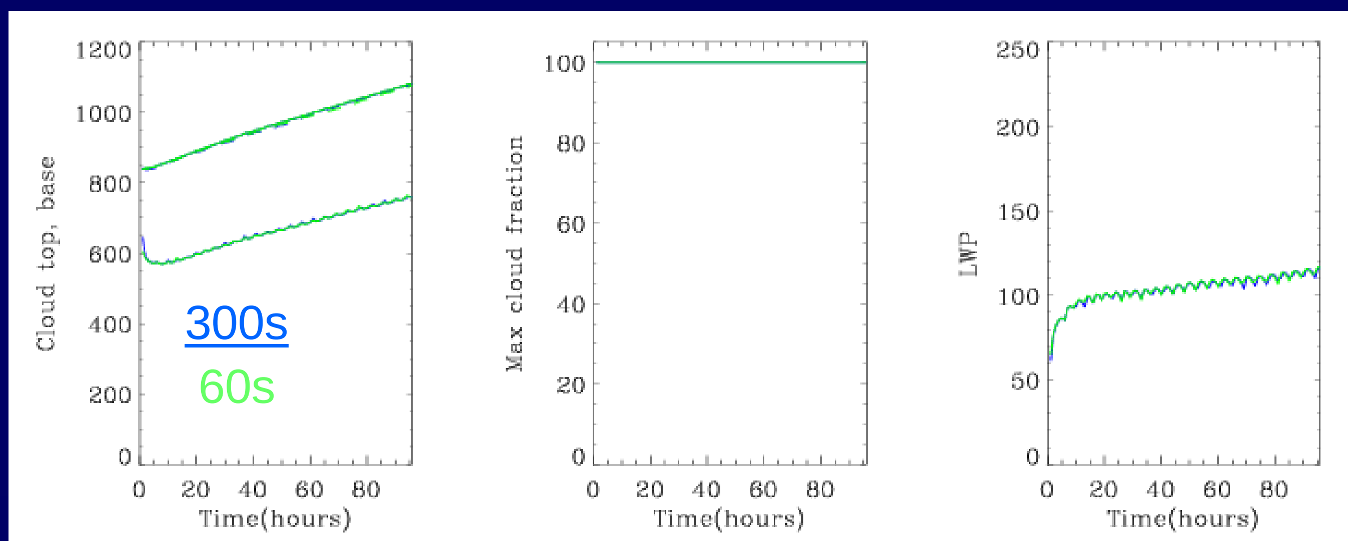
Met Office timestep dependence (96 hours)

Operational



10m



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Met Office summary

- Good simulation of RF01
- Resolution dependence:
  - the $(z-z_i)^{1/3}$ shape to the θ profile makes the inversion appear stronger as the grid size increases, giving a weaker entrainment rate.
- No timestep dependence

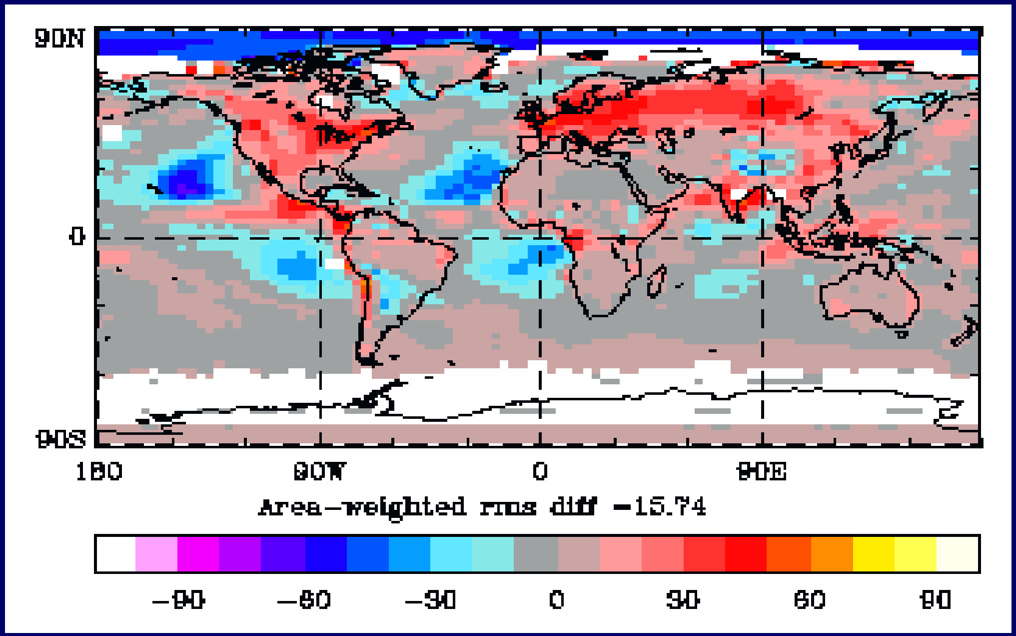
Further investigation of RPN model

- If condensation is included in the Bougeault-Lacarrere mixing length diagnosis, does that improve the mixing of q_t within the cloud layer and thence the cloud fraction in shallow cloud layers at coarse resolution?
  - How does that affect the entrainment rate?
  - How does that affect the simulation of shallow cumulus?
- Would other mixing length formulations work better?
- What controls the entrainment rate in the RPN model?
- Include an explicit entrainment parametrization, as in Met Office scheme?
- Is there an alternative formulation for the buoyancy flux enhancement?

Further simulations

- Include other physics schemes:
  - Precipitation: what effect does drizzle have?
- Test on other GCSS cases (BOMEX = shallow Cu; ATEX = shallow Cu rising into Sc)

SW forcing climatology: 5 year JJA mean (Met O - ERBE)



- Negative implies ‘too much’ cloud so:
  - Do ‘need’ less cloud towards trade Cu regions
  - No more cloud ‘needed’ close to coast