Radiation and Turbulence in the SBL

GABLS Workshop

J. M. Edwards, ECMWF, 7th November 2011

Some key historical papers

- Measurements/modelling of near-surface flux divergence
  - Fleagle (1953), Funk (1960), Elliot (1964)
- Modelling studies including turbulence
  - Garratt & Brost (1981), Andre & Mahrt (1981), Tjemkes & Duynkerke (1989)
  - Radiative deepening of the NBL
- Light winds
  - Estournel & Guedalia (1985)
  - Curvature of the θ-profile

Contents

This presentation covers the following areas

- Surface Flux Budget
- LW Radiation
- Near-surface temperature profile in light winds
- Depth of SBL

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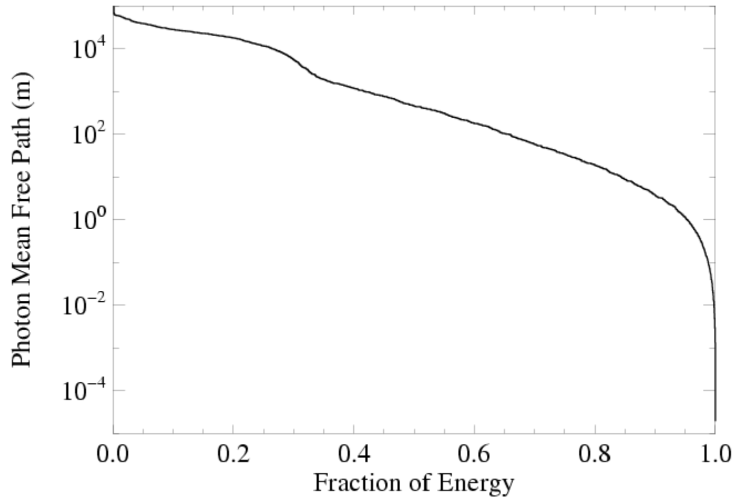
The Surface Flux Budget

- Typical nocturnal SH is O(10—20Wm^{-2}) in UK
- SH very sensitive to stratification and wind
- Downward LW at night is O(300—350Wm^{-2})
- Even if LW is relatively very accurate there is still room for compensating errors in the SH
- Storage in ground links day time and night-time behaviour
- Some evidence that UM under estimates amplitude of diurnal cycle of surface flux budget
- **Must consider SBL in context of overall surface flux budget, including surface fluxes**

LW Radiation: Spectral Variations

Spectral Variations

- Typical mid-latitude atmosphere:
  - Continuous variation of mfp
  - Photon mfp < 1m for only 5% of photons emitted from surface
  - > 100m for 2/3 of emitted photons
- Interactions dominated by water vapour and CO_2
  - Atmospheric window 8-12μm
  - Rotation and vibration rotation bands more opaque…
  - … but strong and rapid variation of gaseous absorption with frequency

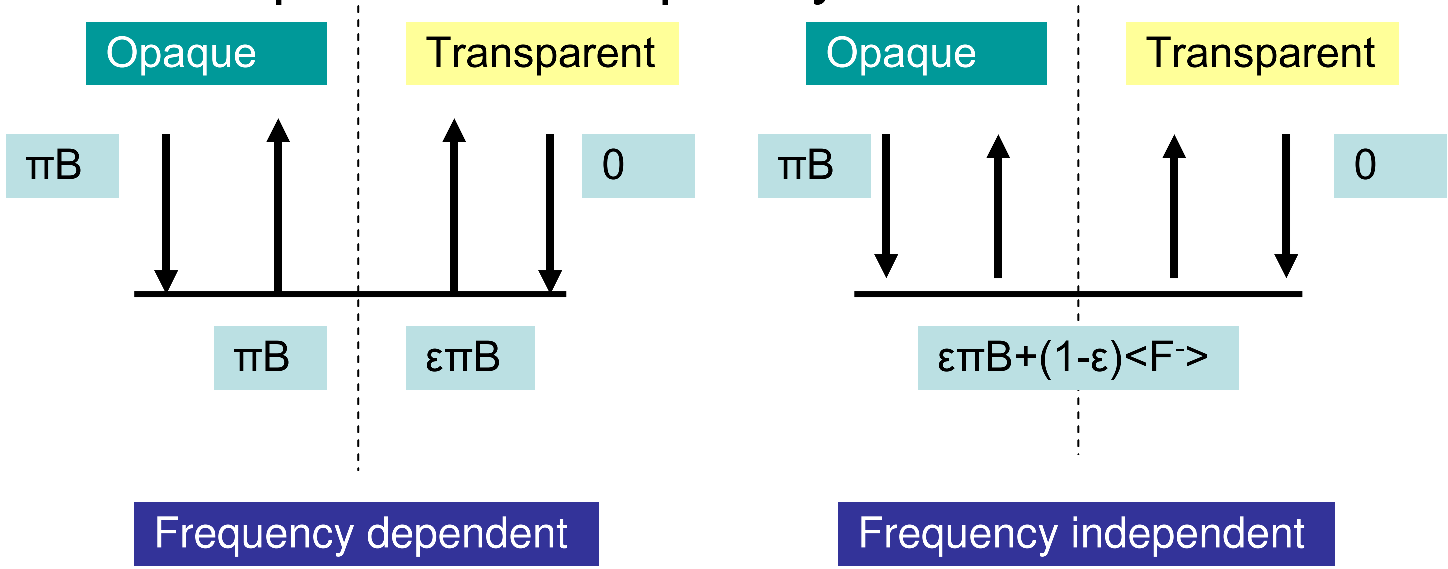


Effect of Surface Emissivity

- Emissivity of sandy soils can be < 0.9
- Because scattering is of minor importance in LW, many radiation schemes treat upward and downward radiation independently
  - Not appropriate for non-black surface
- Direct application of such schemes above non-black surface suggests strong cooling above non-black surfaces
- Cooling is spurious artefact of simplistic treatment of surface reflection.

Met Office

- Upward Flux = $\varepsilon\pi B_\nu + (1-\varepsilon)F^-_\nu$
- Broad-band flux= $\varepsilon\pi\langle B\rangle + (1-\varepsilon)\langle F^-\rangle$
- Strong and rapid variation of gaseous absorption with frequency



- With frequency dependence accounted for emission and absorption are balanced just above surface at opaque wavelengths → no net cooling
- With simple broad-band model, net redistribution of photons to transparent region, so net emission just above surface in opaque region
- Fixing requires following path of reflected photon from emission through reflection
- Actual effect of $\varepsilon<1$ is small relative warming of atmosphere

Runaway Cooling?

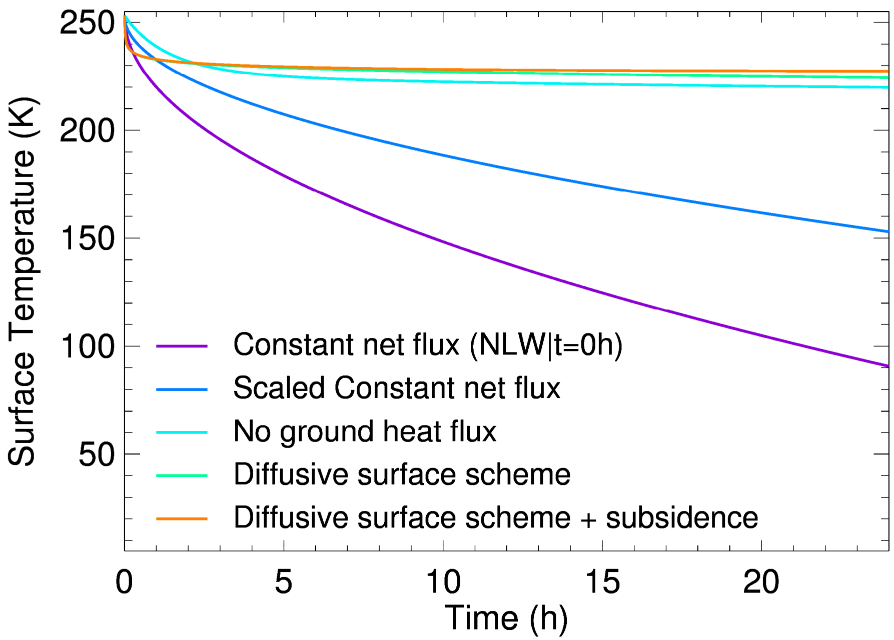
Met Office

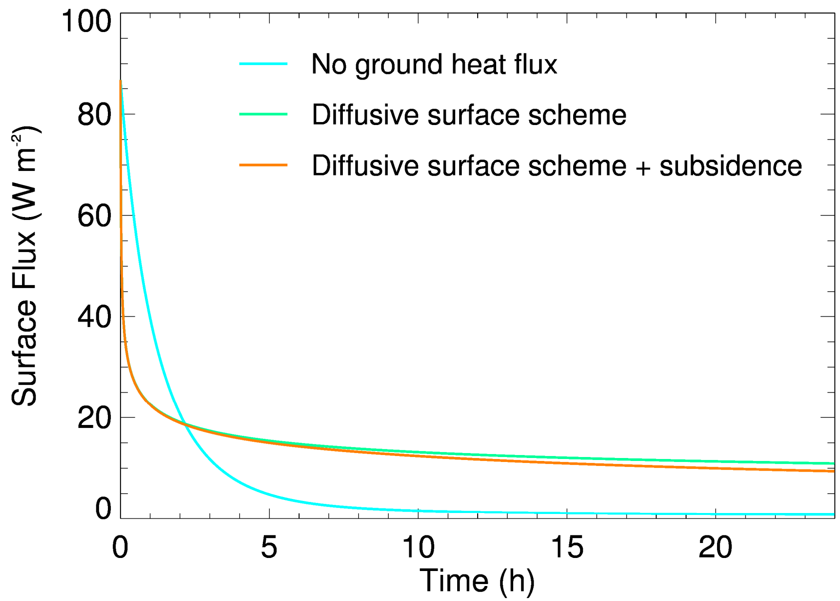
- Clear skies not uncommon in polar night
- Common perception that radiation is inefficient at arresting surface cooling, if SH ‘drops out’ of surface flux budget in light winds
- As surface and air cool, both upward and downward LW decrease: what happens to NLW?
  - If NLW stayed constant, surface temperature would decrease like $\sqrt{t}$
  - Snow would cool to 0 K in a few days

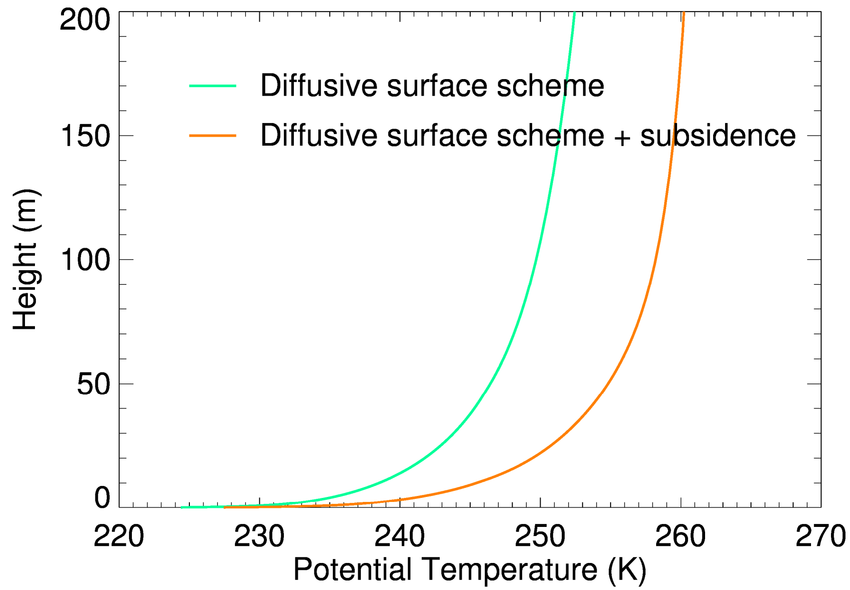
- Simple parametrizations for downward radiation: $LW\downarrow = \sigma T_{2m}^4 \cdot fnc(e_{2m})$
- Such schemes underestimate LW↓ under strong surface inversions (Niemelä et al., 2001)
  - Typical error $40Wm^{-2}$, can be over $60Wm^{-2}$
- Marty et al. (2003) suggest current radiation schemes agree with observations to about $2Wm^{-2}$ in Arctic conditions

Idealized Experiment

- Start with deep layer of fresh snow at 253K with diffusive surface scheme
- Atmosphere above T=253K, q=0.4g/kg up to 2km
- No turbulence
- Allow to cool for 24 hours


Surface Temperature (K)
250
200
150
100
50
0
5
10
15
20
Time (h)
Constant net flux (NLW|t=0h)
Scaled Constant net flux
No ground heat flux
Diffusive surface scheme
Diffusive surface scheme + subsidence


Surface Flux (W m⁻²)
100
80
60
40
20
0
5
10
15
20
Time (h)
No ground heat flux
Diffusive surface scheme
Diffusive surface scheme + subsidence


Height (m)
200
150
100
50
0
220
230
240
250
260
270
Potential Temperature (K)
Diffusive surface scheme
Diffusive surface scheme + subsidence

- Rapid reduction in NLW over first few hours of simulation, thereafter very slow cooling, even with no turbulence
- Model predicts strong near-surface inversion: strength 20—30K
- Steep near-surface temperature gradient, pronounced negative curvature
- Would be interesting to compare retrieved LST and T2m in calm winds in polar night

Transitional Decoupling

Met Office

- Clear-sky anticyclonic conditions in winter
  - Light winds (can be ~1 ms-1)
  - Forecast 1.5/2m-temperatures fall rapidly through evening transition
  - Observed 1.5/2m temperatures fall more slowly
  - Forecast cold errors can be as much as 5K
- Forecast temperatures calculated by applying surface similarity theory across bottom layer of model, O(10-20 m)

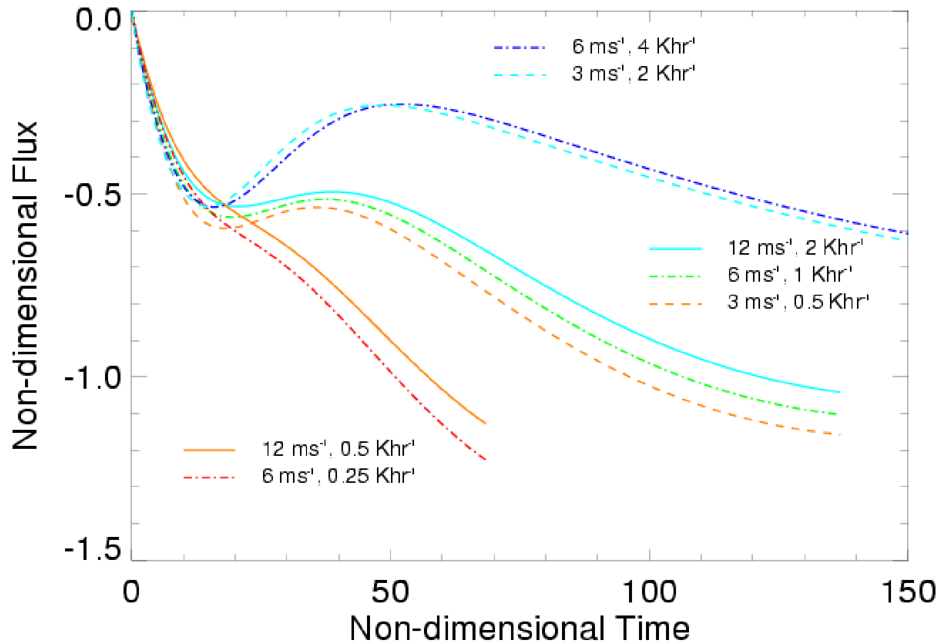
Idealized Modelling

- 1-D model with local scaling (BD/BH similarity functions)
  - High resolution – expanding grid 30 layers below 1.5 m
  - Standard treatment of roughness sub-layer -- debatable
  - Run with or without full radiation
  - Initial condition θ=const. in BL, logarithmic wind profile
  - Allow surface to cool

1. Non-radiative case

- Dimensional analysis
  - Problem characterized by u_* and $\partial\theta_s/\partial t$, but relevant variable will be $(g/\theta_0).\ (\partial\theta_s/\partial t)$
  - Time and Length scales will be $T_D=\sqrt{\{u_* /[(g/\theta_0).\ \partial\theta_s/\partial t]\}}$ and $L_D=\sqrt{\{u_*^3 /[(g/\theta_0).\ (\partial\theta_s/\partial t)]\}}$
- Physical argument
  - Time for z_s to feel surface is $O(z_s/u_*)$
  - Surface has cooled $(z_s/u_*).\ (\partial\theta_s/\partial t)$ in this time
  - Get a Richardson number $(g/\theta_0).\ (z_s/u_*)\ (\partial\theta_s/\partial t).\ z_s/\ u_*^2 = (z_s /L_D)^2$

- Turbulence decays on timescale $O(T_D)$
- Directional shear at top of SBL generates turbulence on timescale $O(f^{-1})$
- Decoupling expected for f^{-1}/T_D large



Vertical Profiles

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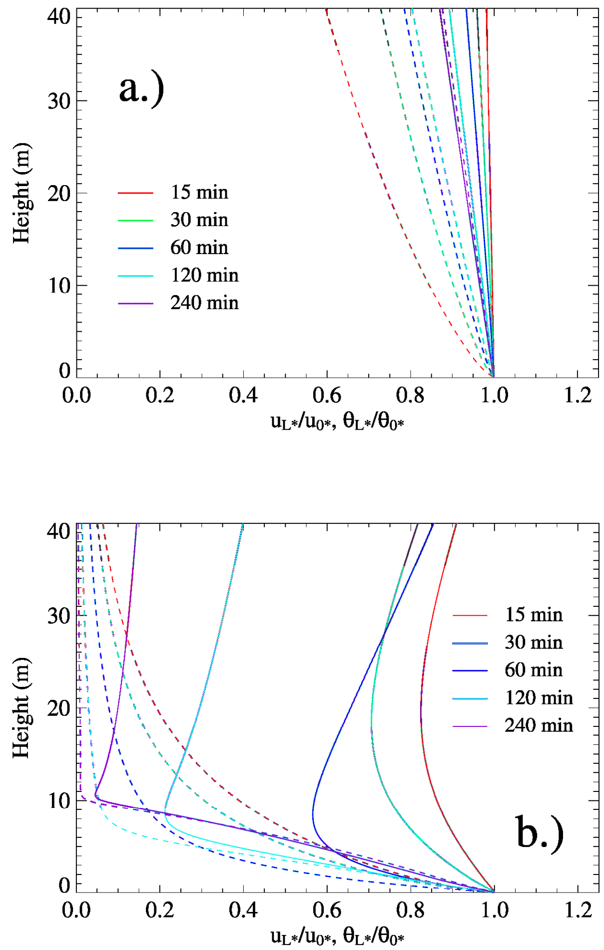
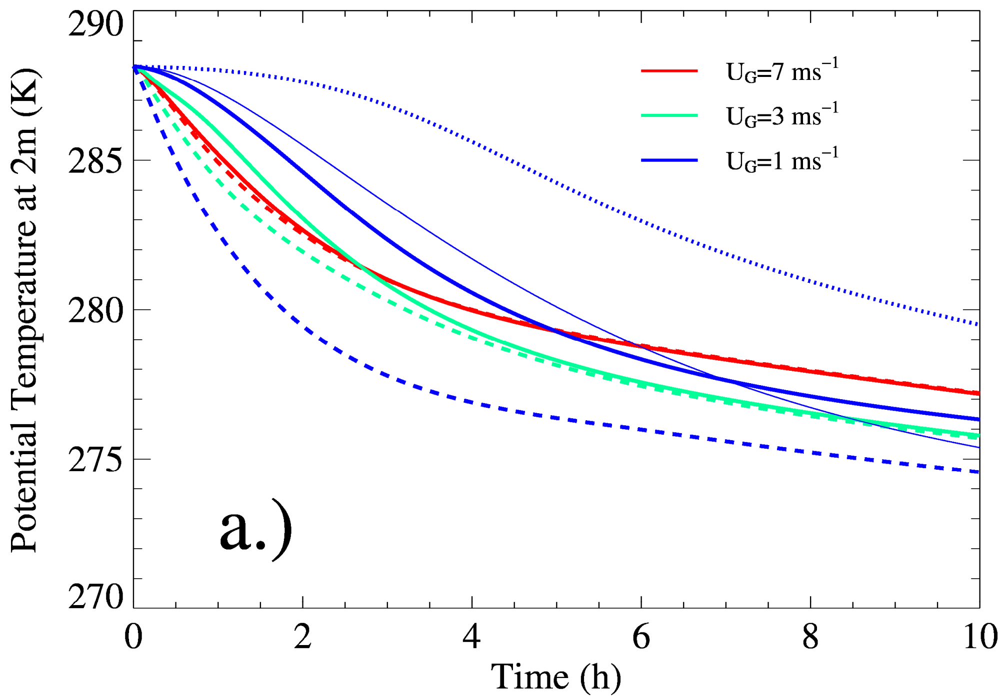
- In models T2m interpolated using surface similarity theory – gives cold biases after transition in light winds
- Delage (1997) showed that surface similarity theory works well in the developed NBL: why should the transition be different?
- Local similarity:

$$\frac{\partial \theta}{\partial z} = \theta_{L*}(z)\frac{\sigma}{kz} + \left(\frac{\theta_{L*}(z)}{u_{L*}(z)}\right)^2 \beta_h \frac{k}{g/\theta_0}$$

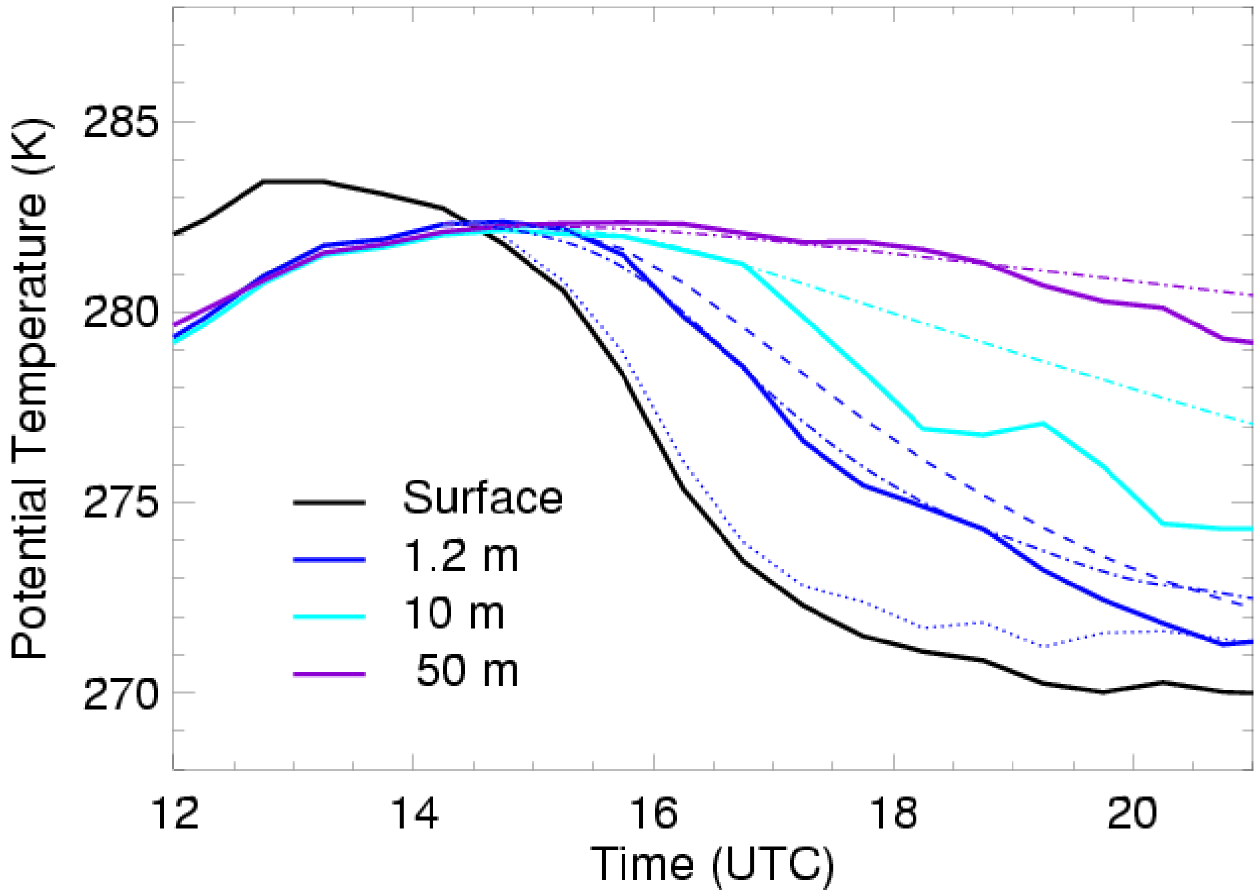


2. Radiative Effects

- If turbulence is weak (10m wind O(1ms-1)) radiative cooling dominates – at 2m mainly cooling directly to the surface

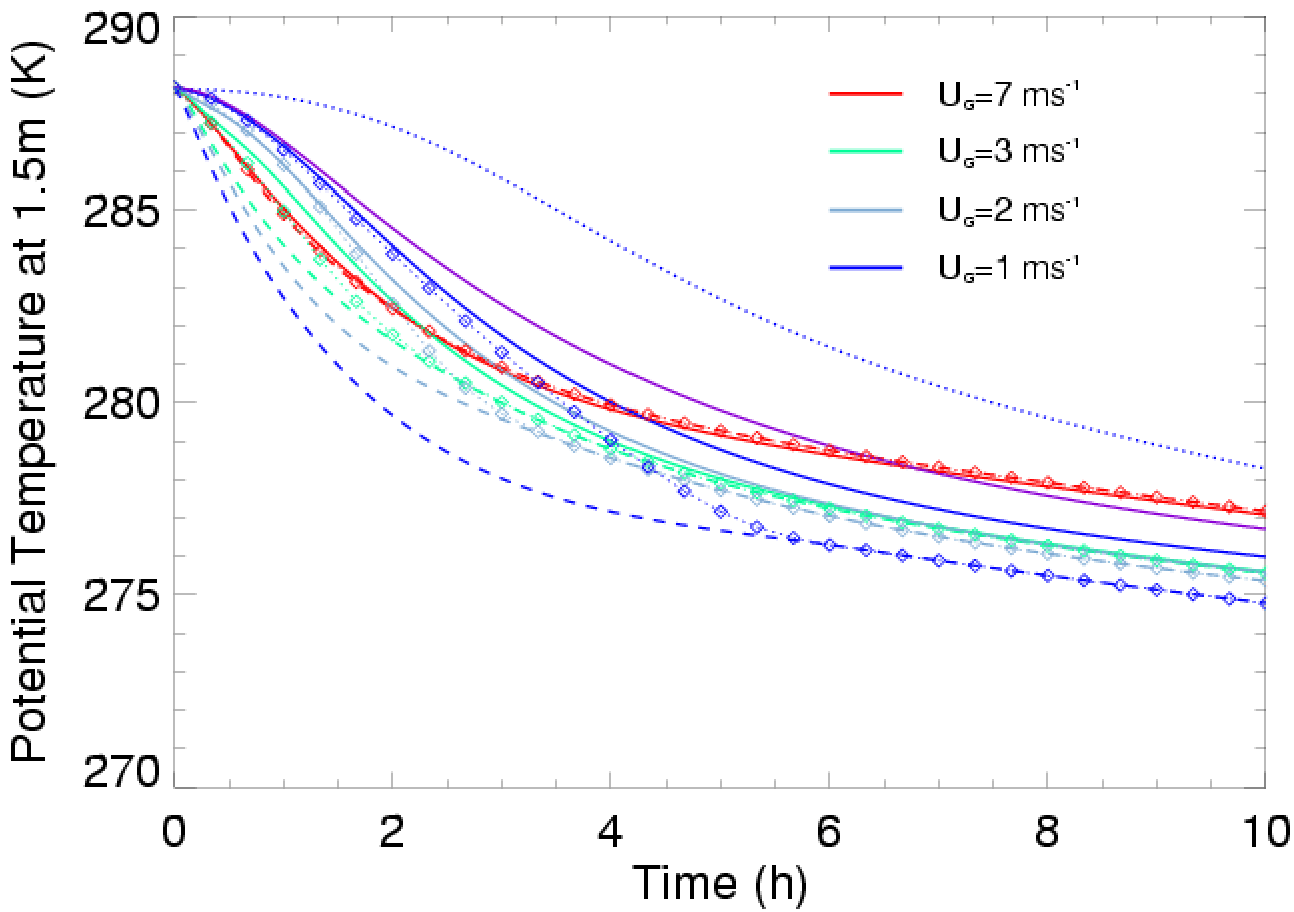


Observations: Cardington 03/02/2007

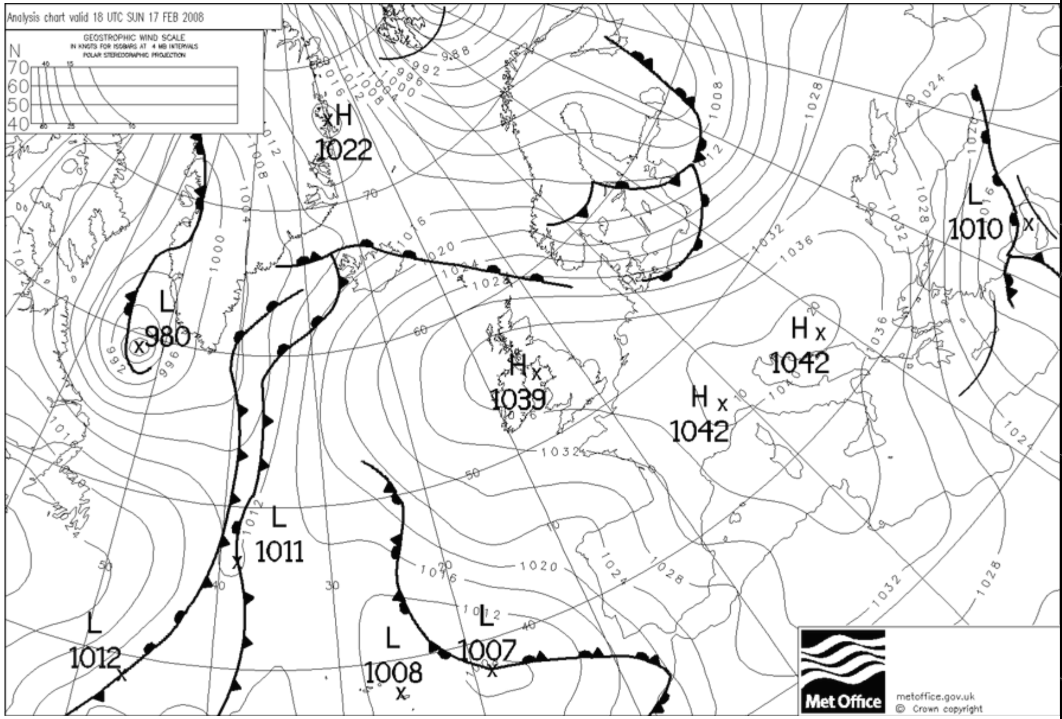


Parametrization for UM

- Diagnose transition to stability: store time since transition and T1.5m
- Evaluate cooling of T1.5m by cooling to surface
- Also diagnose T1.5m from surface similarity theory – effectively a lower limit on T1.5
- Interpolate between radiatively cooled temperature and surface similarity with weighting = fnc(z_s/L_D, $u_{*MO}\delta t/z_s$)
    - Weighting acts cumulatively at each timestep
    - L_D measures depth that feels surface



290
285
280
275
270
Potential Temperature at 1.5m (K)
0
2
4
6
8
10
Time (h)
U$_G$=7 ms^{-1}
U$_G$=3 ms^{-1}
U$_G$=2 ms^{-1}
U$_G$=1 ms^{-1}



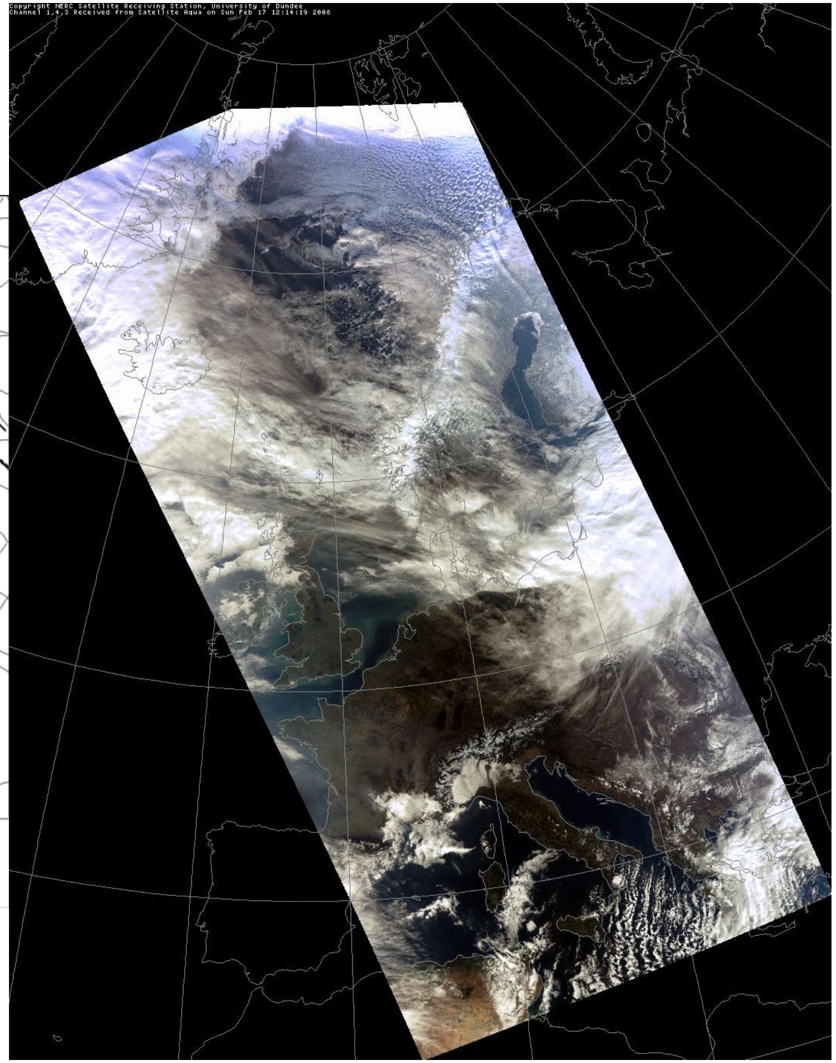
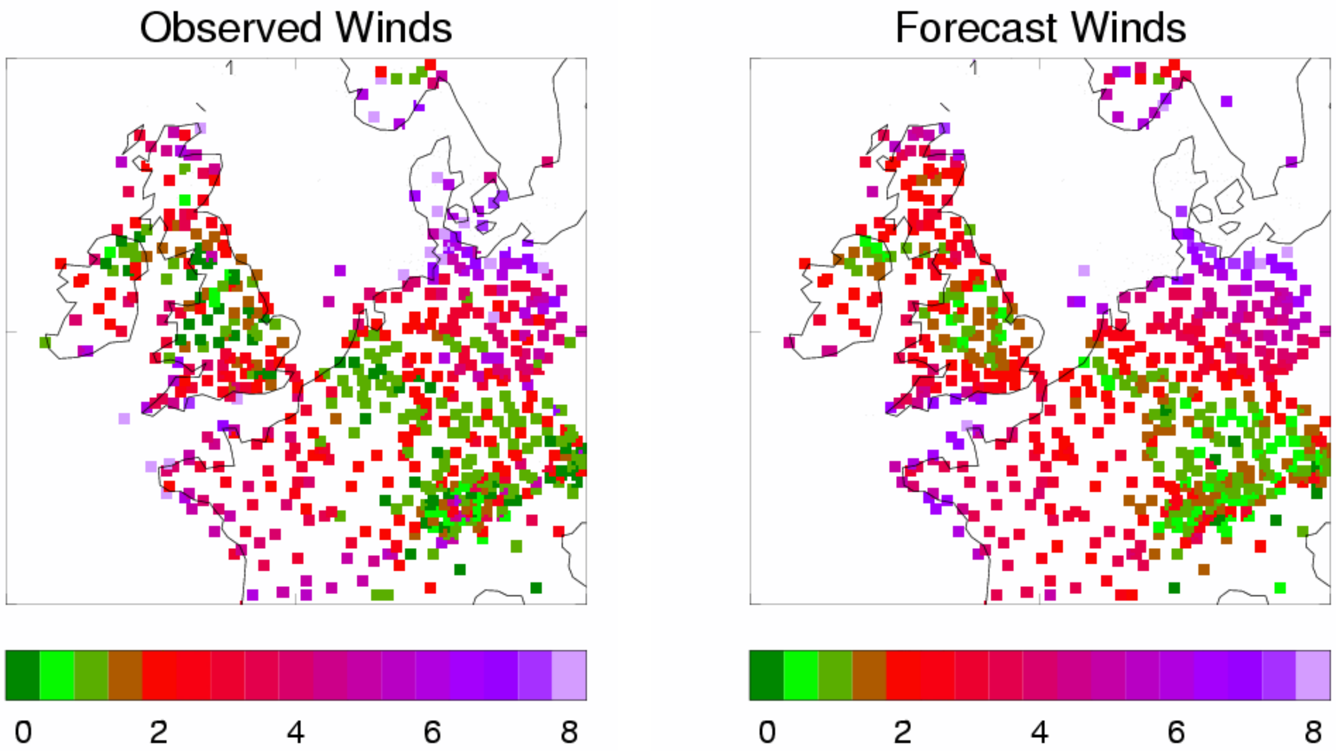
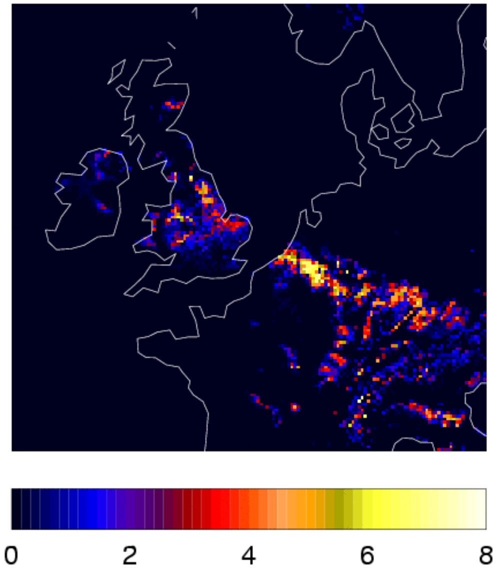


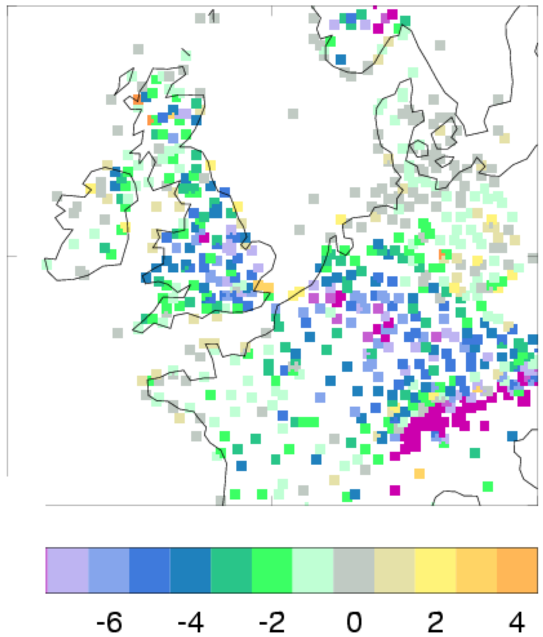
Image courtesy of NERC satellite receiving station, Dundee, Scotland

Wind speed at 17UTC



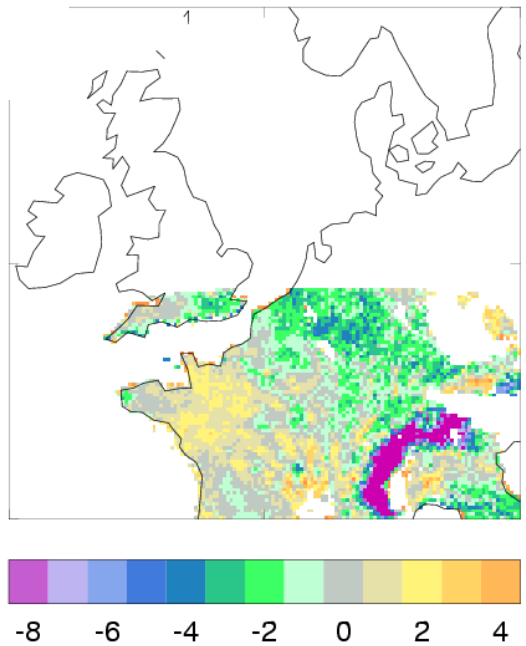


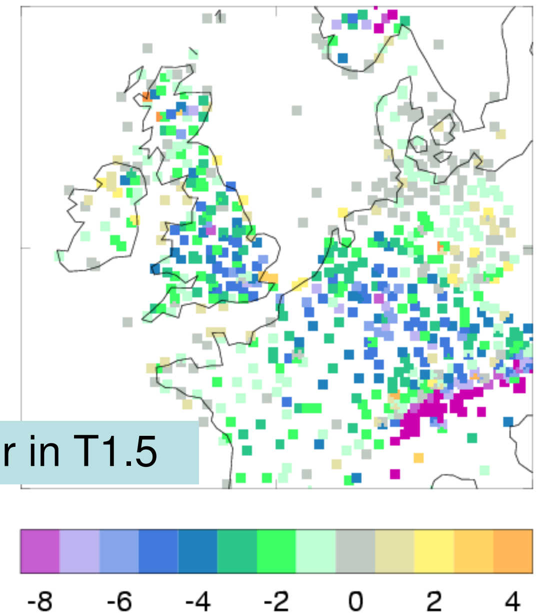
Impact on T1.5 at 17UTC



Control Error in T1.5

Error in LST

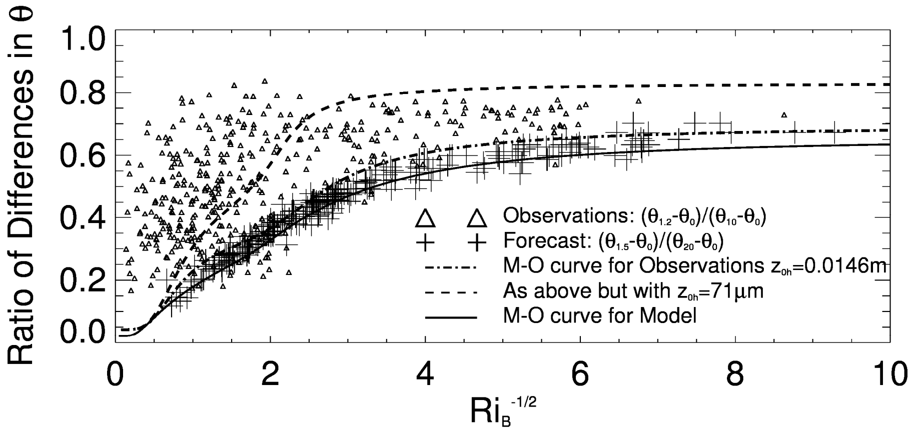




Decoupled Error in T1.5

- Gravity currents are expected later in the night
  - Time to develop will depend on slope
- Role of decaying convective turbulence not yet clear
  - LEM shows even stronger decoupling than local theory, but still questions about simulation of weak turbulence
- Air temperatures still generally warmer than forecast in light winds

Interpolating screen-level temperature at Cardington



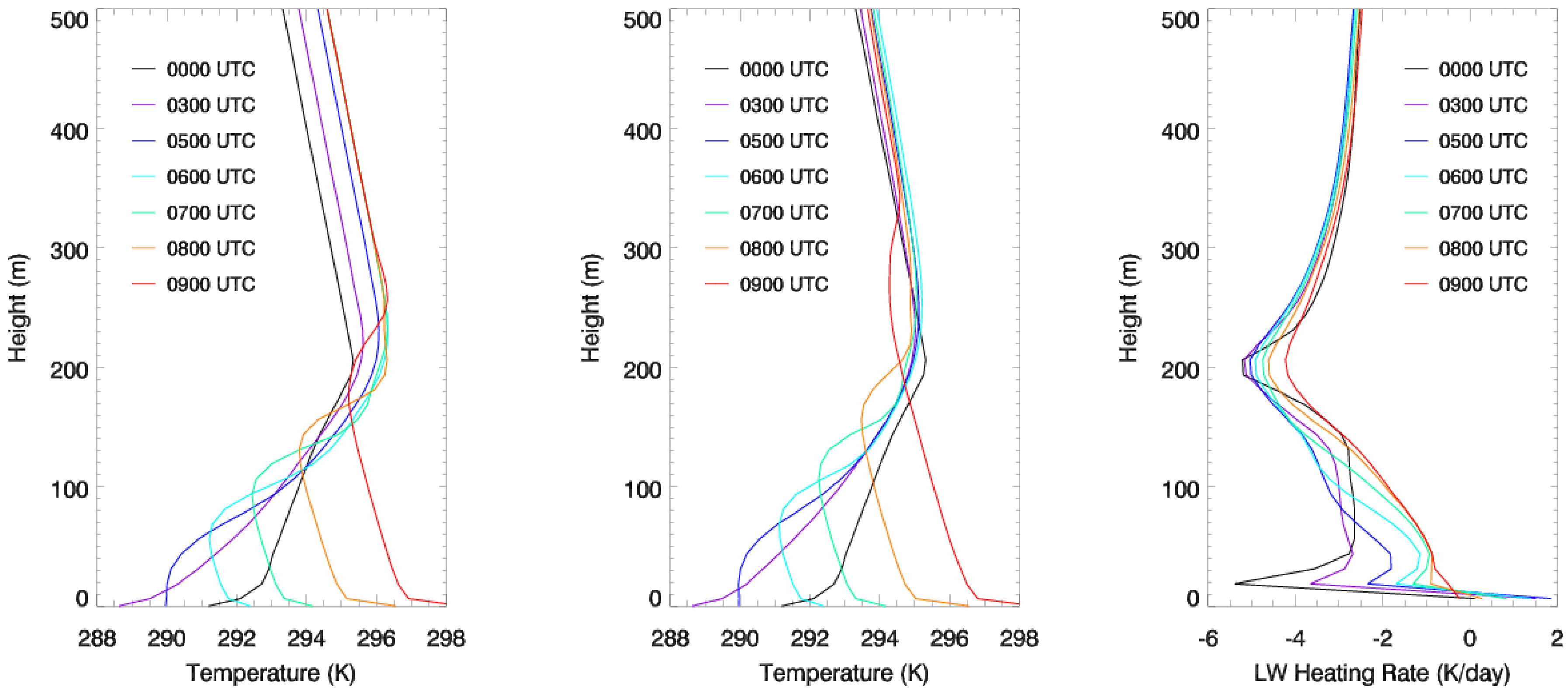
- Nocturnal observations show warmer air temperatures than surface similarity predicts when $Ri_B<1/4$
- Less bias with smaller thermal roughness, but considerable scatter and still bias in light winds

Met Office

Deepening of the SBL

- Radiative exchanges at the top of the SBL tend to deepen the SBL
    - Garratt and Brost (1981) etc.
- Effect is most pronounced around the morning transition
- GABLS3-LEM

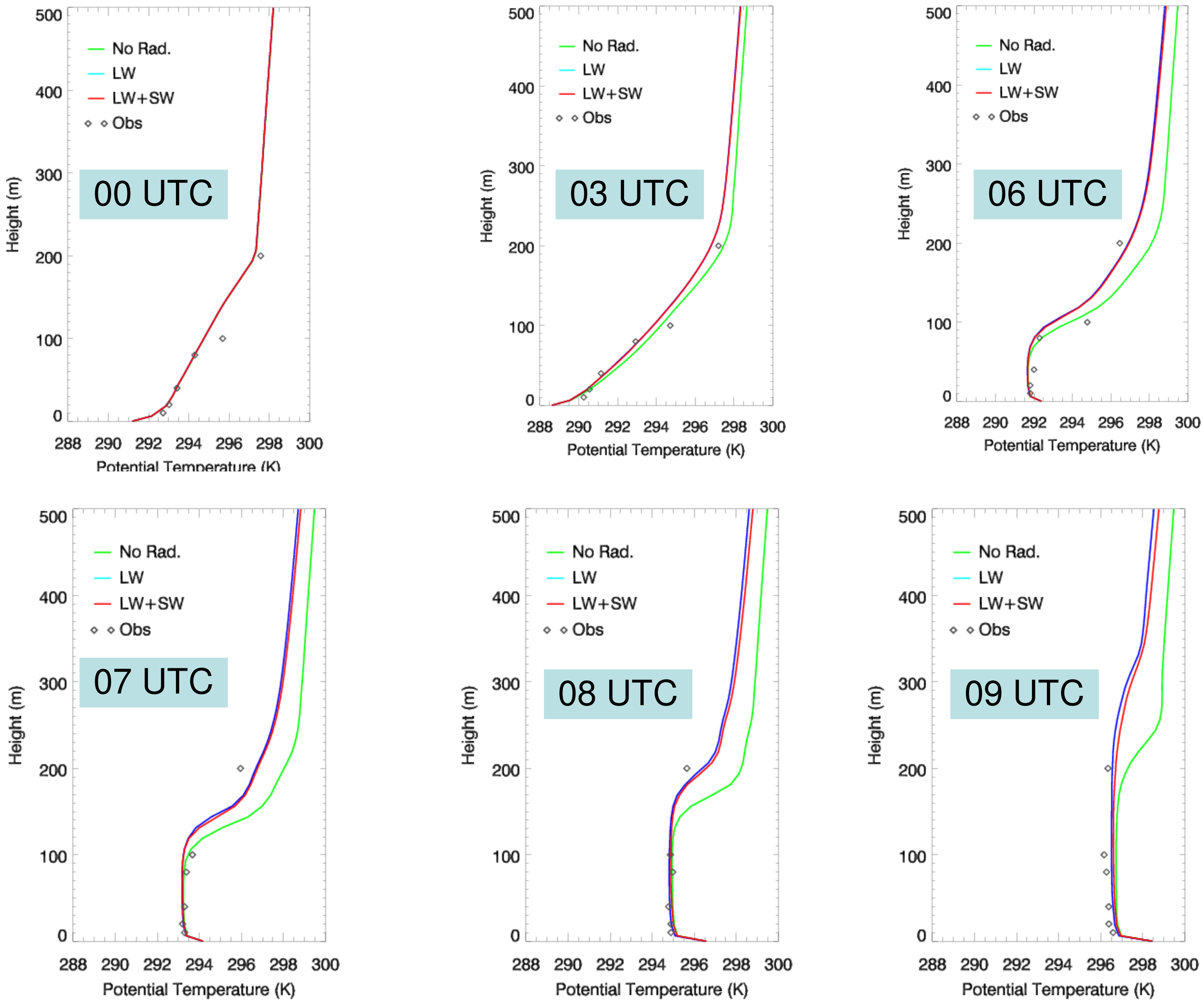
Met Office



No Radiation

With Radiation

- Mixed layer grows more quickly because radiation reduces strength of capping inversion by cooling residual layer
- Greater reduction of stability at height of top of NBL
- LEM agrees more closely with observed profile if radiation included



00 UTC
03 UTC
06 UTC
07 UTC
08 UTC
09 UTC
No Rad.
LW
LW+SW
Obs
Height (m)
Potential Temperature (K)

Key Questions

Met Office

- Need good characterization of surface flux budget and to understand whole diurnal cycle
- Better representation of near-surface temperature profile
    - Use of LST from satellite retrievals
- Winter/polar night
    - Are our problems due to the SBL, snow, the vegetative canopy or cloud cover … probably all!
    - How well do we represent subsidence?

Questions and answers