Stable boundary layer modeling at the Met Office

Adrian Lock
with contributions from many other Met Office staff

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Outline

- Current operational configurations and performance
- “Recent” changes
- Stable boundary layers in complex terrain (COLPEX)
- Fog
- Summary

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Current operational configurations

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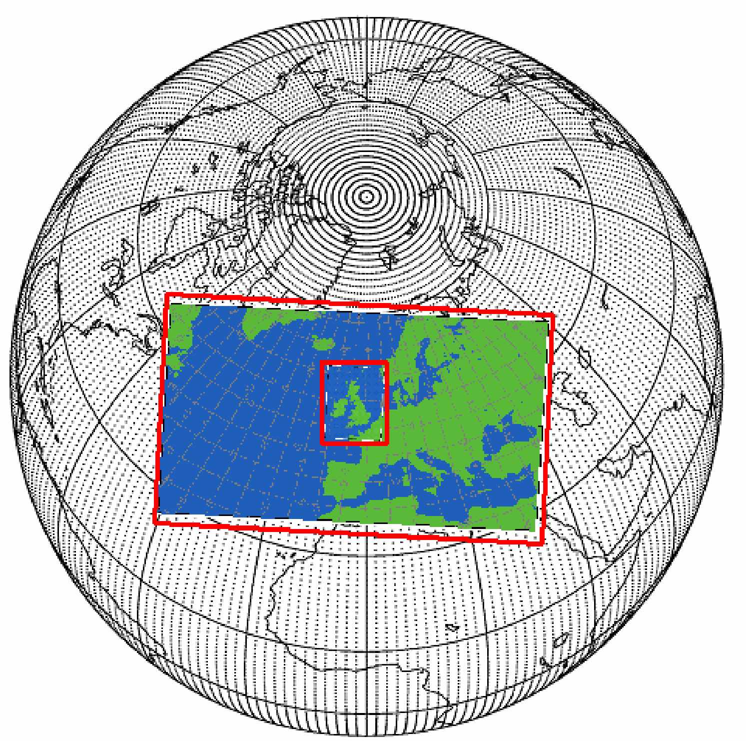
The operational forecast models

NWP horizontal grid lengths, lid:

- Global NWP: ~25 km, 80km
- Global seasonal: ~135km, 80km
- [N.Atlantic/Europe: 12 km, 80km]
- UK: 1.5km, 40km



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Operational configurations

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- Current global climate-seasonal configuration = GA3.0
  - Documented in Walters et al (Geoscientific Model Development, 2011)
  - PBL scheme = non-local K-profile + local Ri for SBLs
  - Massflux scheme for convection, PC2 prognostic cloud scheme, etc
  - N96 (~135km) and L85 (80km lid, 9 levels below 1km)
- Current global NWP = GA3.1 = GA3.0 except:
  - Enhanced SBL mixing: "long tail" stability functions over land (instead of "Mes"), λ_M doubled in PBL, no reduction of λ (to 40m) above PBL top
  - Single aggregate surface tile (cf 9 tiles)
  - N512 (~25km) and L70 (reduced stratospheric resolution)
- UK model (UKV for "variable" grid but mainly 1.5km)
  - As GA3.0 but no convection parametrization, Smith fixed pdf cloud scheme, Smagorinsky diffusion in horizontal
  - Very nearly the same PBL scheme (eg same stability functions)
  - L70_UK (40km lid, 16 levels below 1km)

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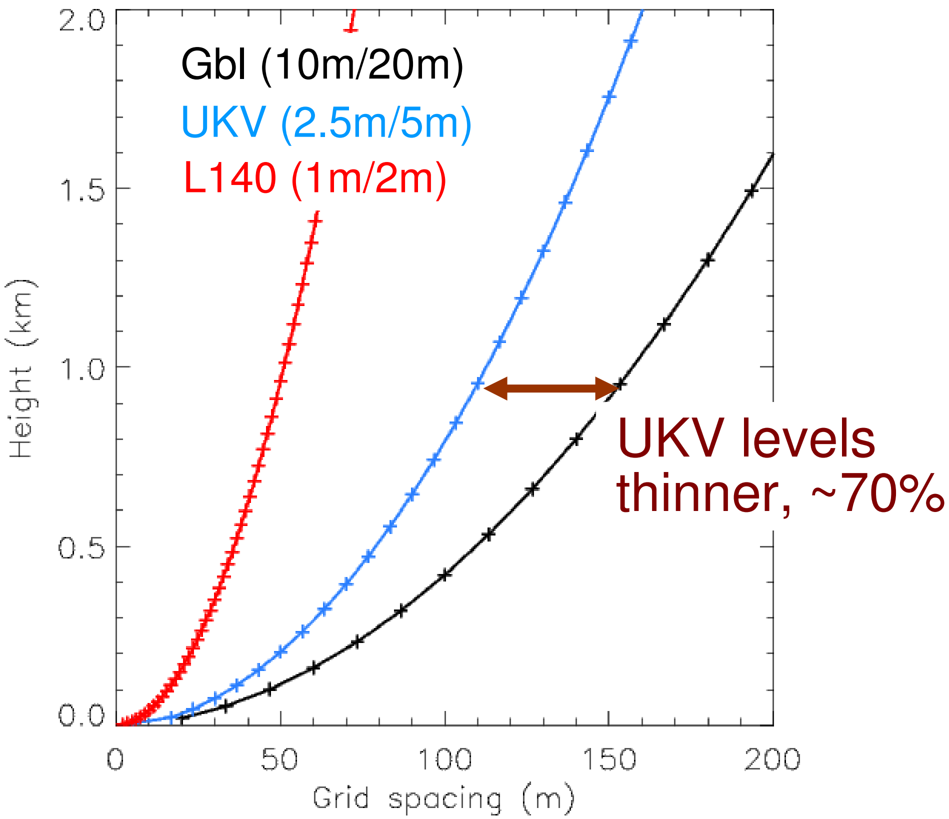
Operational vertical grids

Current vertical grids (lowest levels for U/T):



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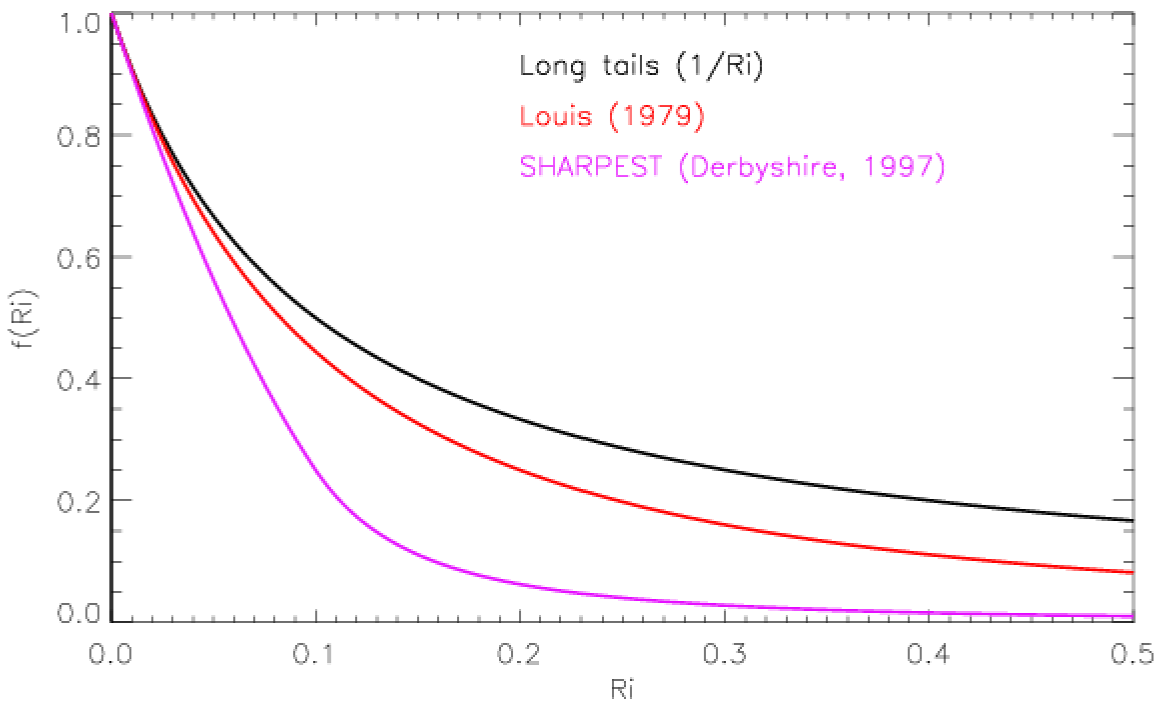
PBL Tails

- *f(Ri)* in local scheme (used for SBLs): $$K = \lambda^2 \frac{du}{dz} f(Ri)$$
- SHARPEST over sea, "Mes tail" over land (except "**long tail**" in GA3.1)
- "Mes tail" motivated by surface heterogeneity
  = linear transition between Louis at z=0 and SHARPEST at z=200m



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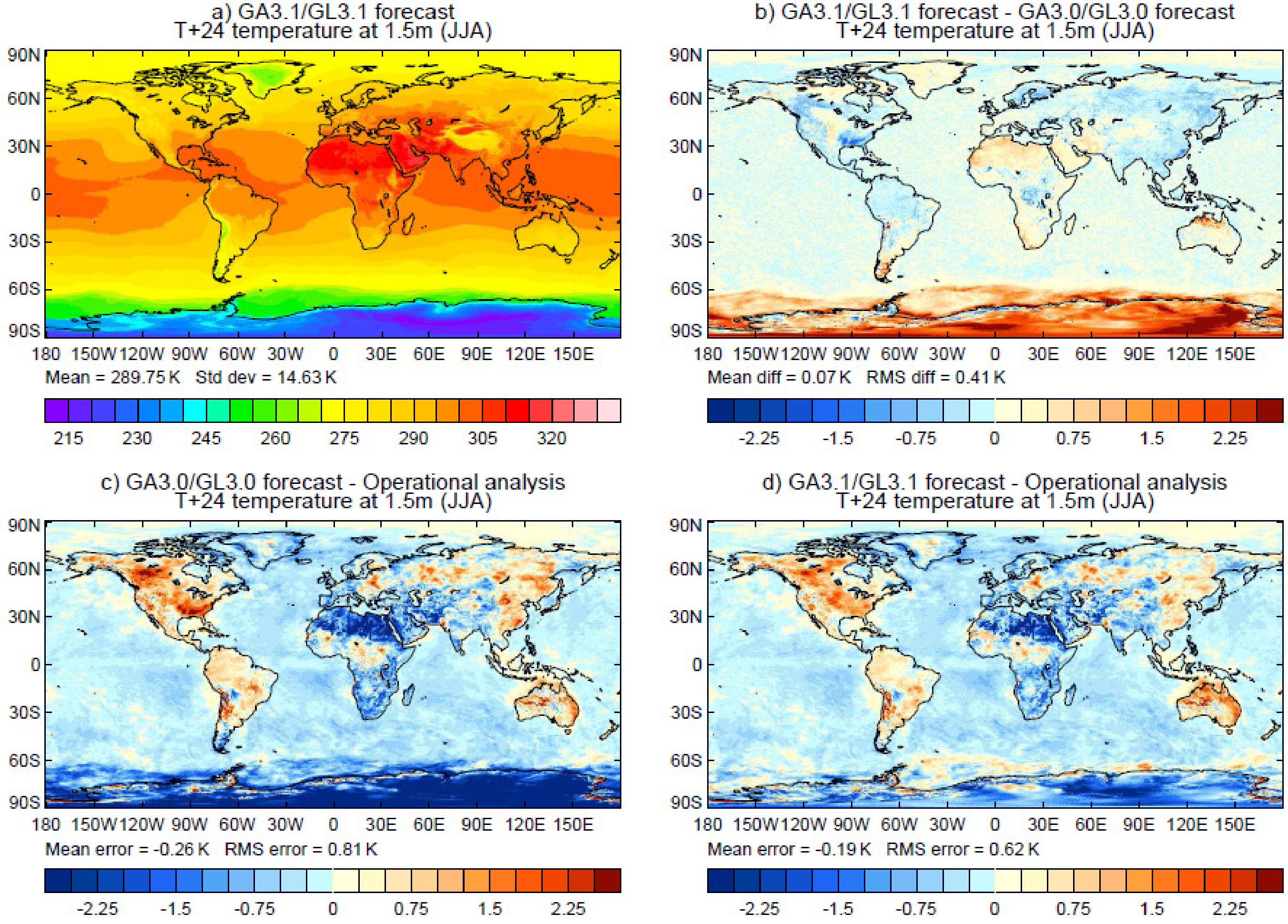
Why GA3.1 for NWP?

- Suppresses (but doesn't fix) systematic errors of GA3.0
- Single tile gives cooling especially where significant tree fraction
  - Reduces North American negative PMSL bias in particular
- Long-tail warms deserts at night (reduce emissivity instead?)



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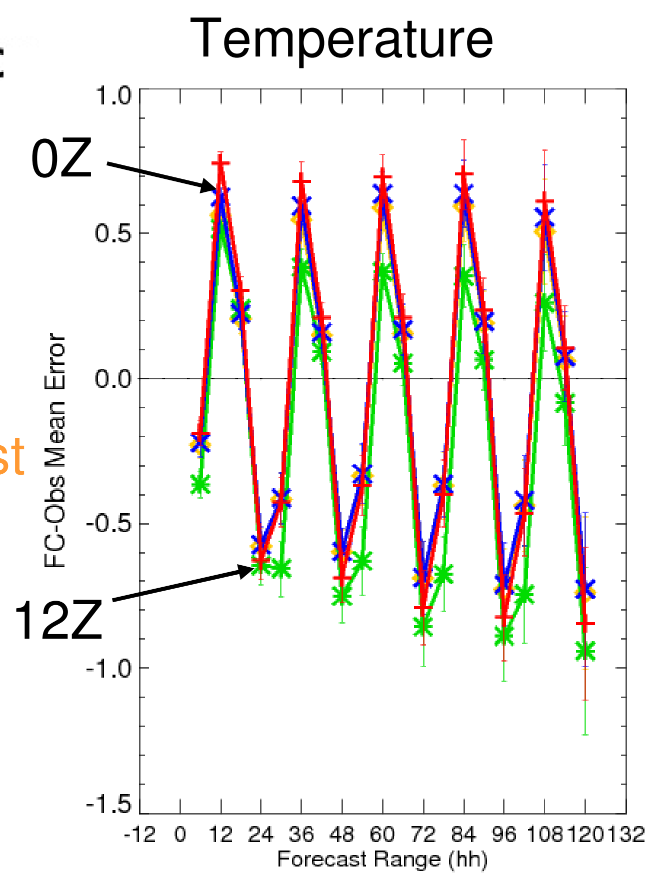
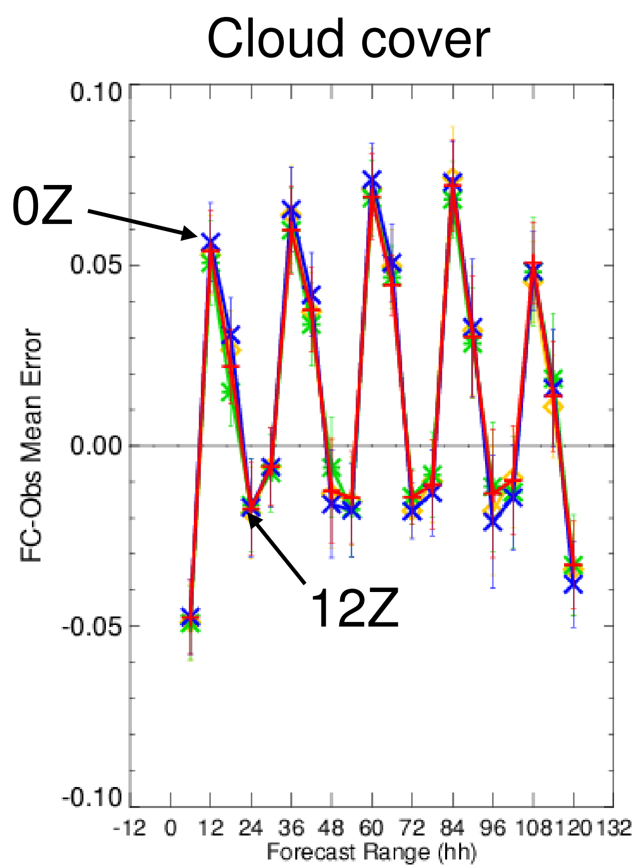
Summer diurnal cycle of biases

for Europe (global forecasts from 12Z)

GA3.0
GA3.1
GA3.0+ Sharpest





- Too warm at night (except deserts), too cold by day
  - Sharper tail only gives small (0.1-0.2K) cooling at night
- Too much cloud at night (consistent), too little by day (inconsistent!)
  - but cloud cover verification not easy to interpret

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Diurnal cycle of UK clear sky T bias

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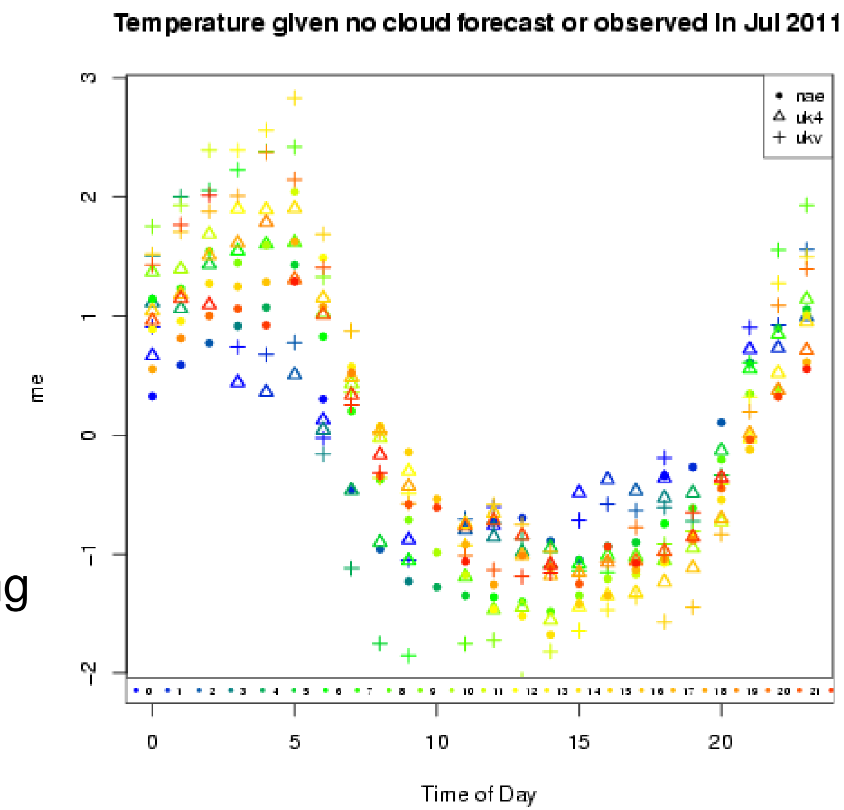
- Still too warm at night, too cold by day, even when cloud free
- Day:
  - Excessive evaporation?
  - Too well-mixed?
- Night:
  - Excessive turbulent mixing (mes tail)?
  - Grid-box mean cf grass?
- Role of ground heat flux in suppressing diurnal cycle?
- Revisit surface roughness (currently $z_{0h}=0.1z_{0m}$)
- Looks like it ought to be tractable!
  - Further analysis of SEB errors needed



Colours denote forecast range

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Relevant "recent" changes to PBL scheme

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Not so recent!

- Brown et al (2008)
  - Non-local momentum transport
    - reduces slow daytime wind bias over land
  - SHARPEST tails over the sea
  - Both improve surface drag and forecast wind direction over the sea
- John Edwards' decoupled screen T diagnostic
- Frictional heating from turbulent dissipation ($\sim\tau_i du_i/dz$)
  - Non-trivial near-surface warming (up to 1K/day)
- Monotonically damping, second-order-accurate, unconditionally-stable implicit solver of Wood et al. (2007)
  - Huge reduction of noise in near surface winds/temperatures

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UKV (1.5km) valley cooling problems

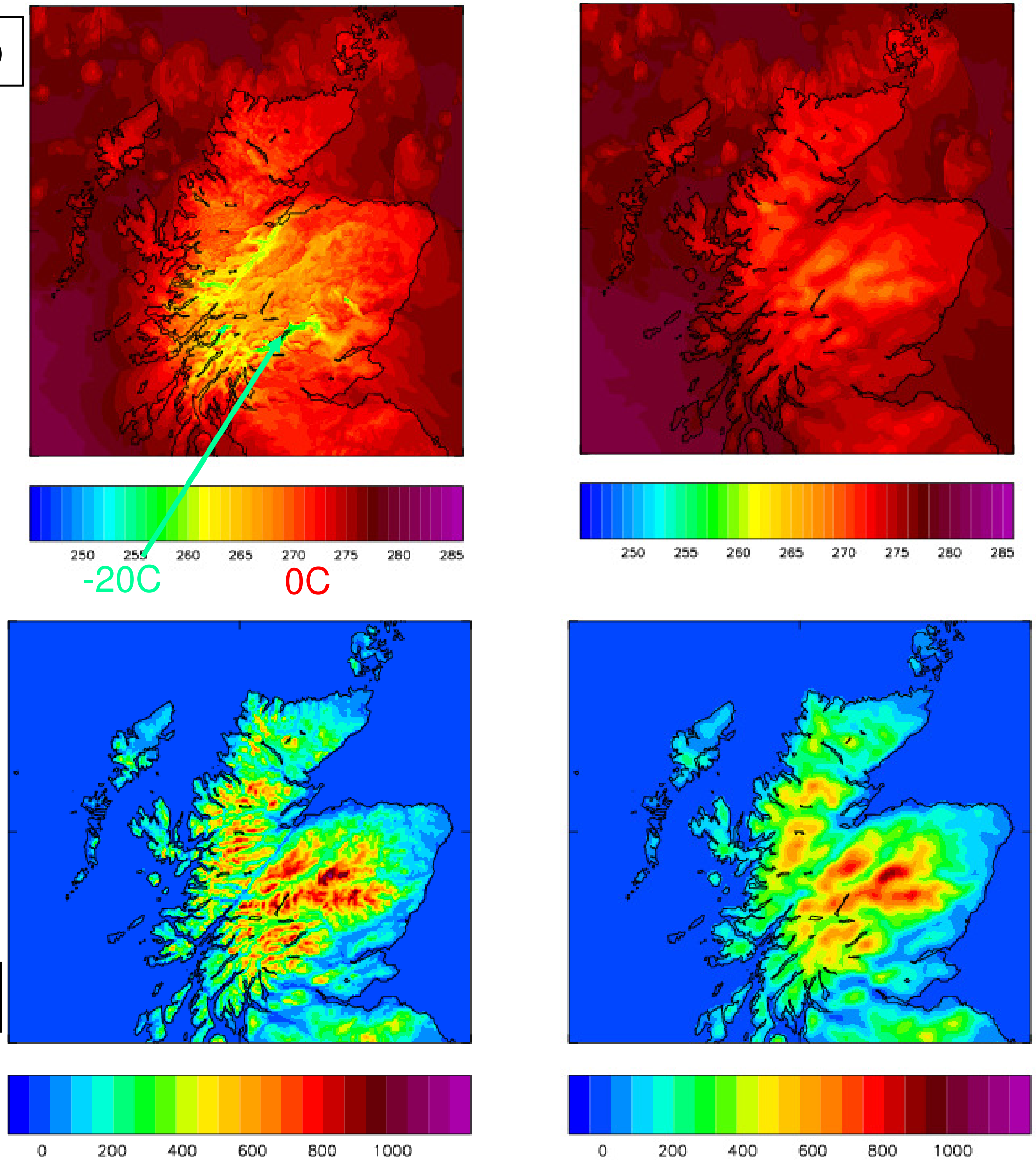
Winter 2010

$T_{1.5m}$ 12Z 2[nd] Feb

- Screen T up to 20K too cold in Scottish valleys
- Goes away if orography smoothed to 12km – not popular!
  - Standard is to use Raymond filter that suppresses 2Δ completely, 4Δ by 50% and 6Δ hardly at all
- Suggestion that flow decouples over valleys too readily (period actually quite windy)
- Similar problems seen in 12km models with steep 6Δ valleys (~70km across – ie Himalayas)

Control

Control + 12km orography



Orographic height

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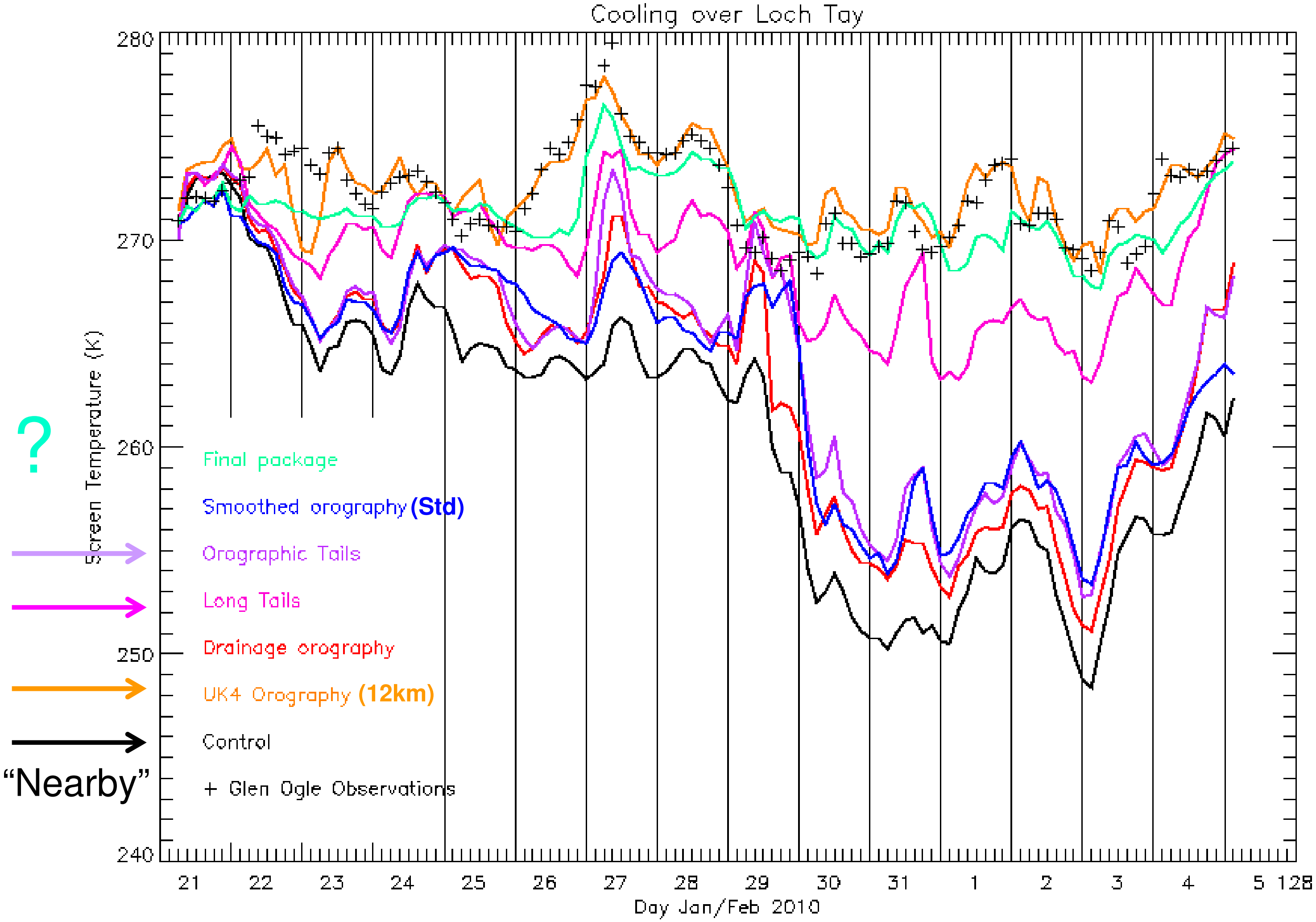
Valley cooling



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Subgrid drainage shear

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- Initial attempts to related length of tail to orography (eg McCabe and Brown, 2007) had little impact as resolved *Ri* typically large
- Instead, approximate the wind shear associated with unresolved orographic drainage flows on slopes of α as

$$S_d = N^2 \alpha t \; f\left(z / \sigma_h\right)$$

- Include this wind shear in the turbulent mixing parametrization, as an enhancement to the standard resolved scale vertical wind shear

$$K = \lambda^2 \left(S + S_d\right) f\left(Ri\right) \quad \text{with} \quad Ri = N^2 \big/ \left(S + S_d\right)^2$$

- Typical values for N^2~1K/100m, α~0.15 and t=30mins gives S_d~ 0.1s^{-1}, or a drainage flow of 2ms^{-1} at 20m.
  - This then implies *Ri*~0.04 and *K*~1 m^{2}s^{-1}

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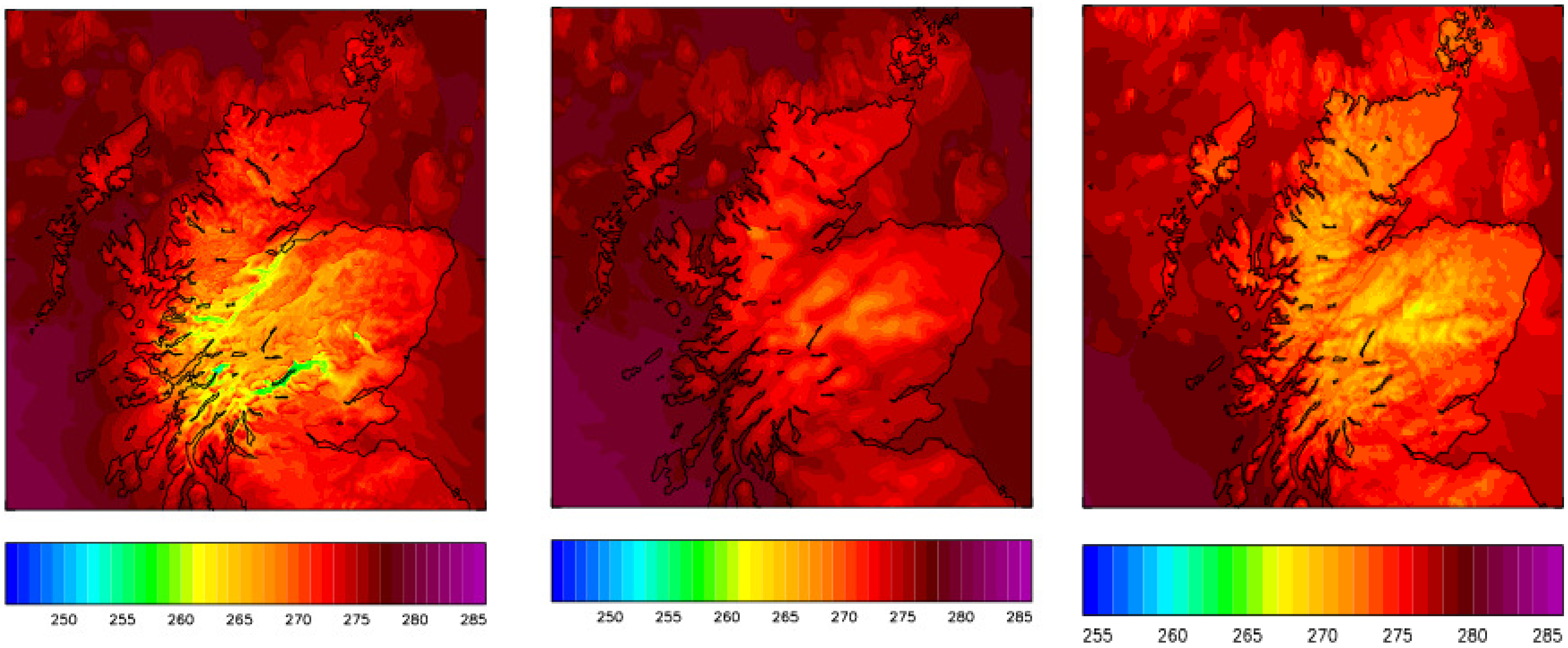
UKV valley cooling

- Including this representation of shear from unresolved drainage flows in local PBL scheme
  - Safely allows use of high res orography (~6km) in 1.5km model
  - No subsequent sign in verification of a warm bias in orographic regions

Control | Control + 12km orography | Control+drainage flow



$T_{1.5m}$ at 12Z 2/2/10

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Stable boundary layers in complex terrain

First results

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COLPEX

Met Office / NCAS

- Extensively instrumented hills and valleys in Shropshire for ~1year
- Very high resolution (100m) UM simulations
  - Provide a database which will aid interpretation of the observations
  - Inform choices about the next generation of operational forecast models
- To better understand the mechanisms leading to the formation of cold pools, drainage flows and fog in valleys
- Evaluate the performance of 1.5km operational forecasts and develop improvements:
  - Coarse-grain 100m UM to inform parametrization developments
    - eg the parametrization of shear from unresolved drainage flows
  - surface temperature downscaling

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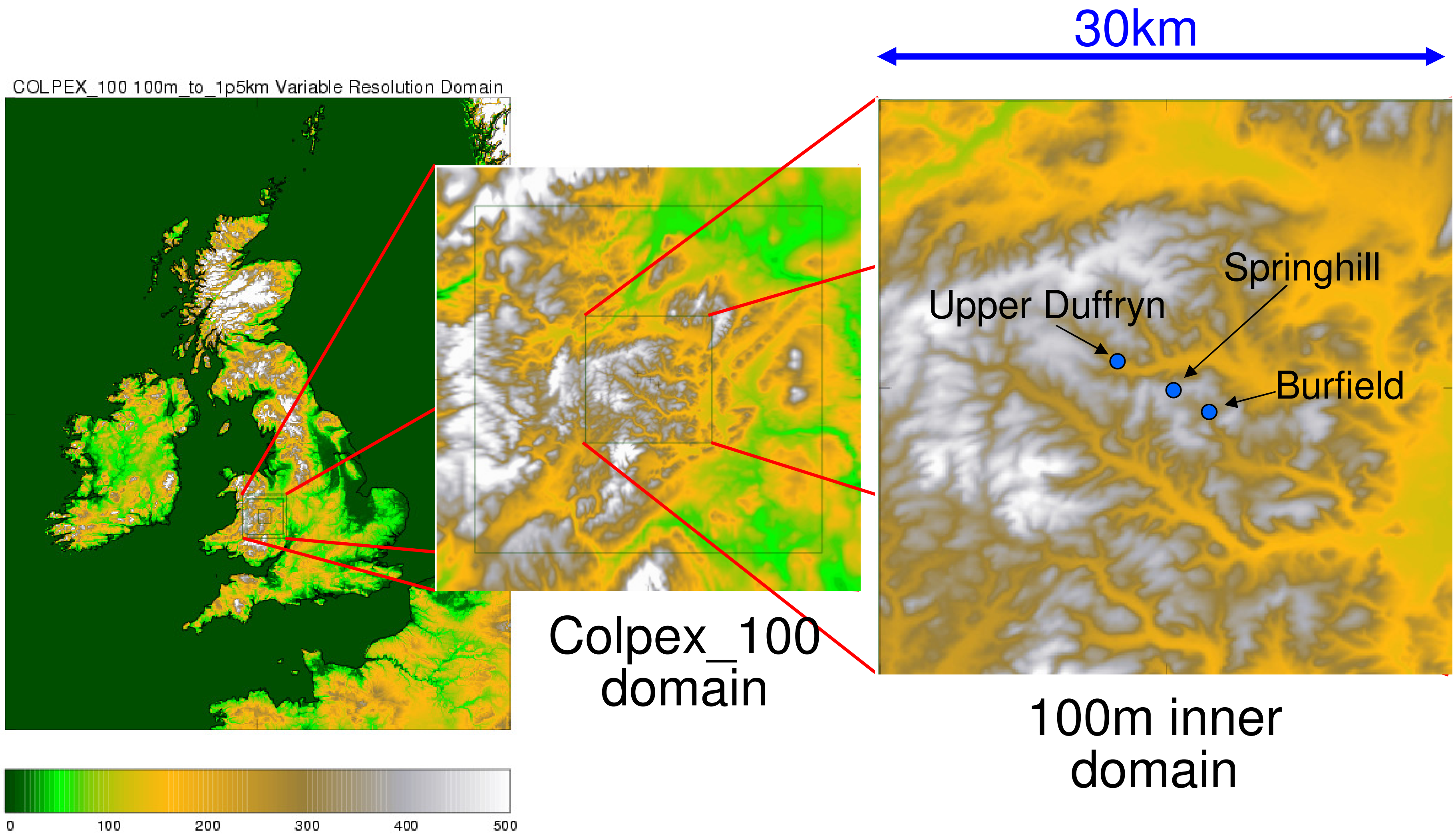
Upper Duffryn
Valley site

- 3 main sites
  - 30/50m masts with sonics, T, q; radiometers; ground heat flux and temperature; visibility measurements
  - doppler lidar
  - frequent sondes during 17 IOPs
- ~20 other AWS sites

COLPEX_100 Orography



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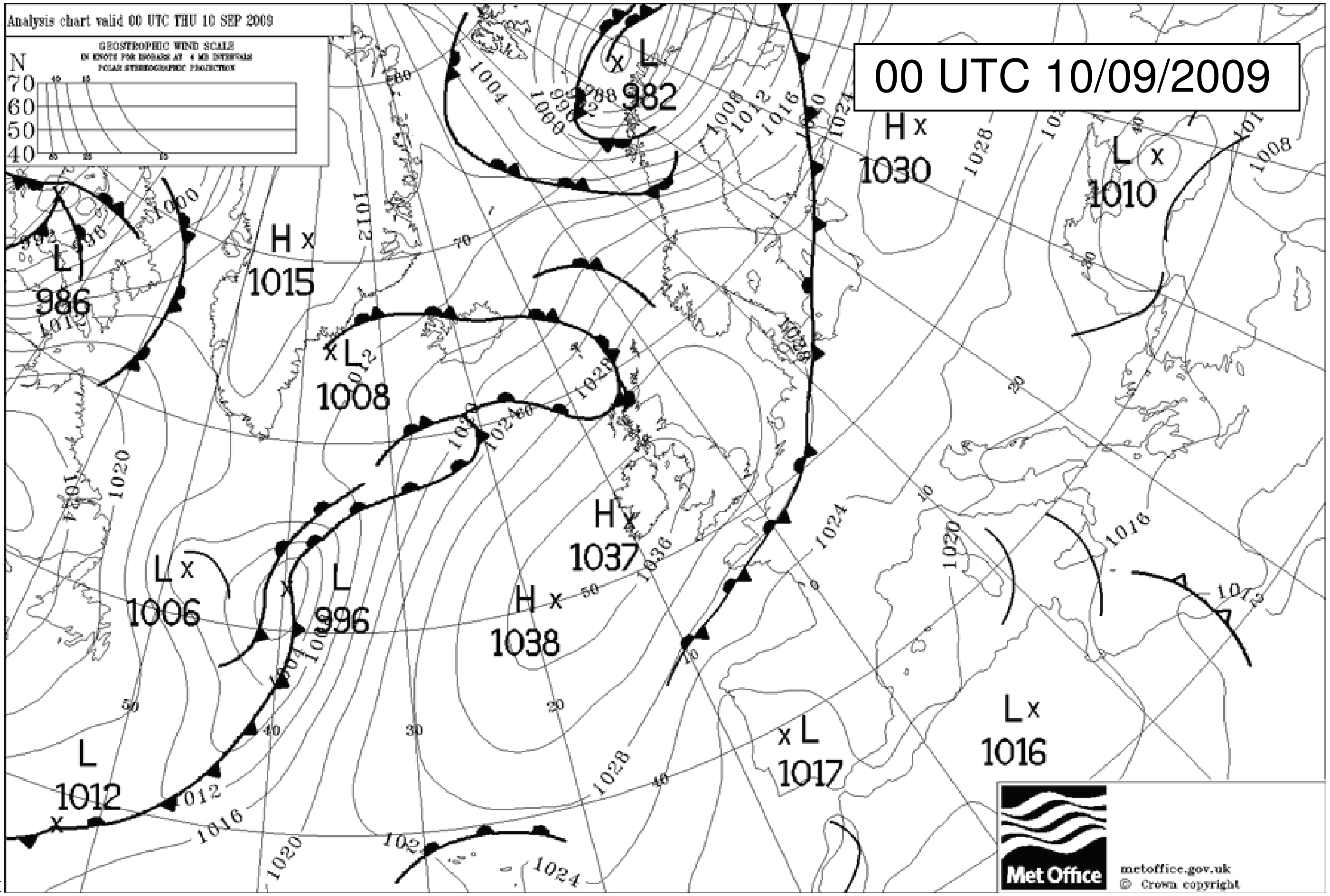
9th September 2009 IOP

- Initial focus on a clear-sky COLPEX IOP
- Simulation from 15UTC 09 to 15 UTC 13 September 2009



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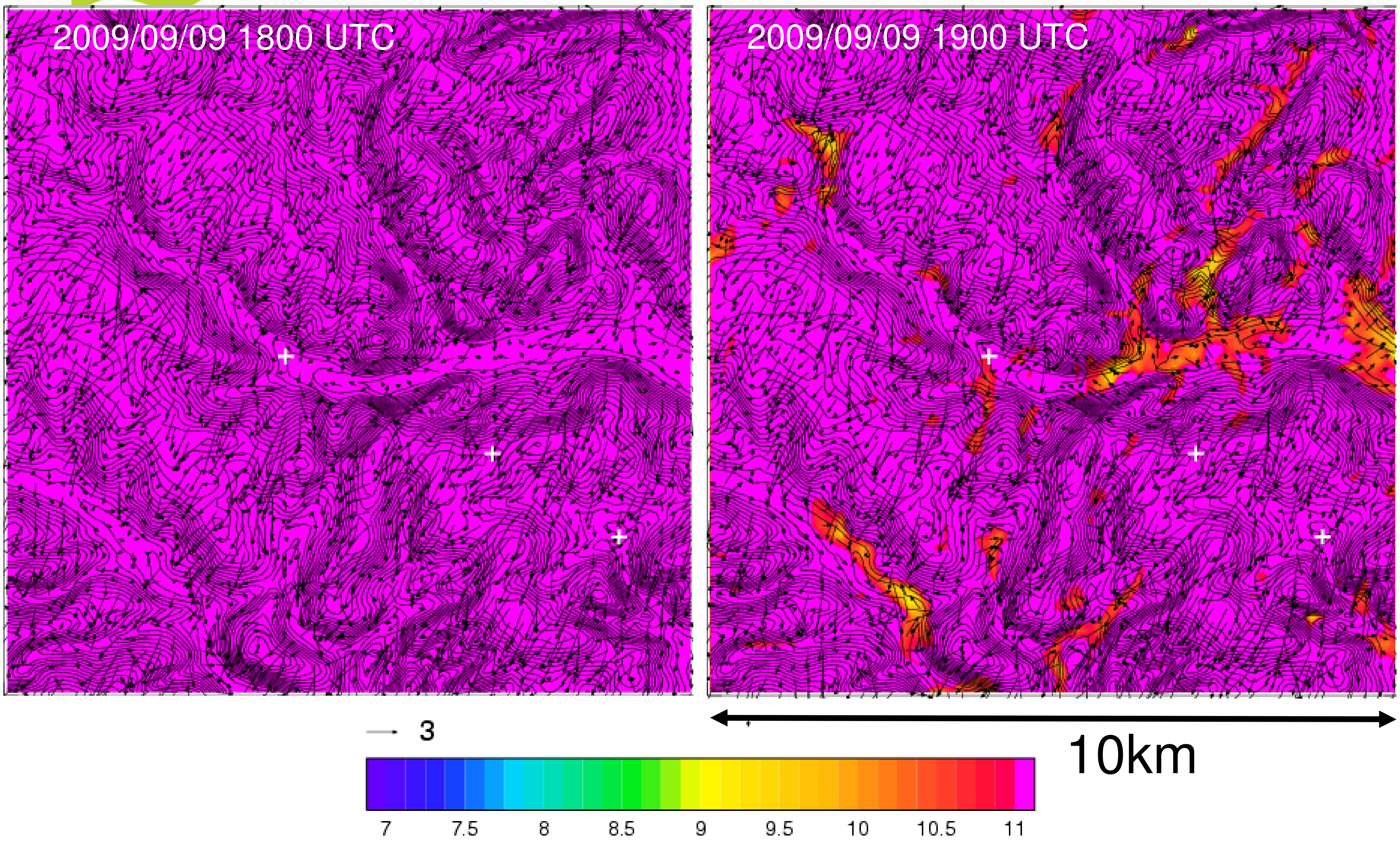
Potential temperature at 2m, winds at 1m



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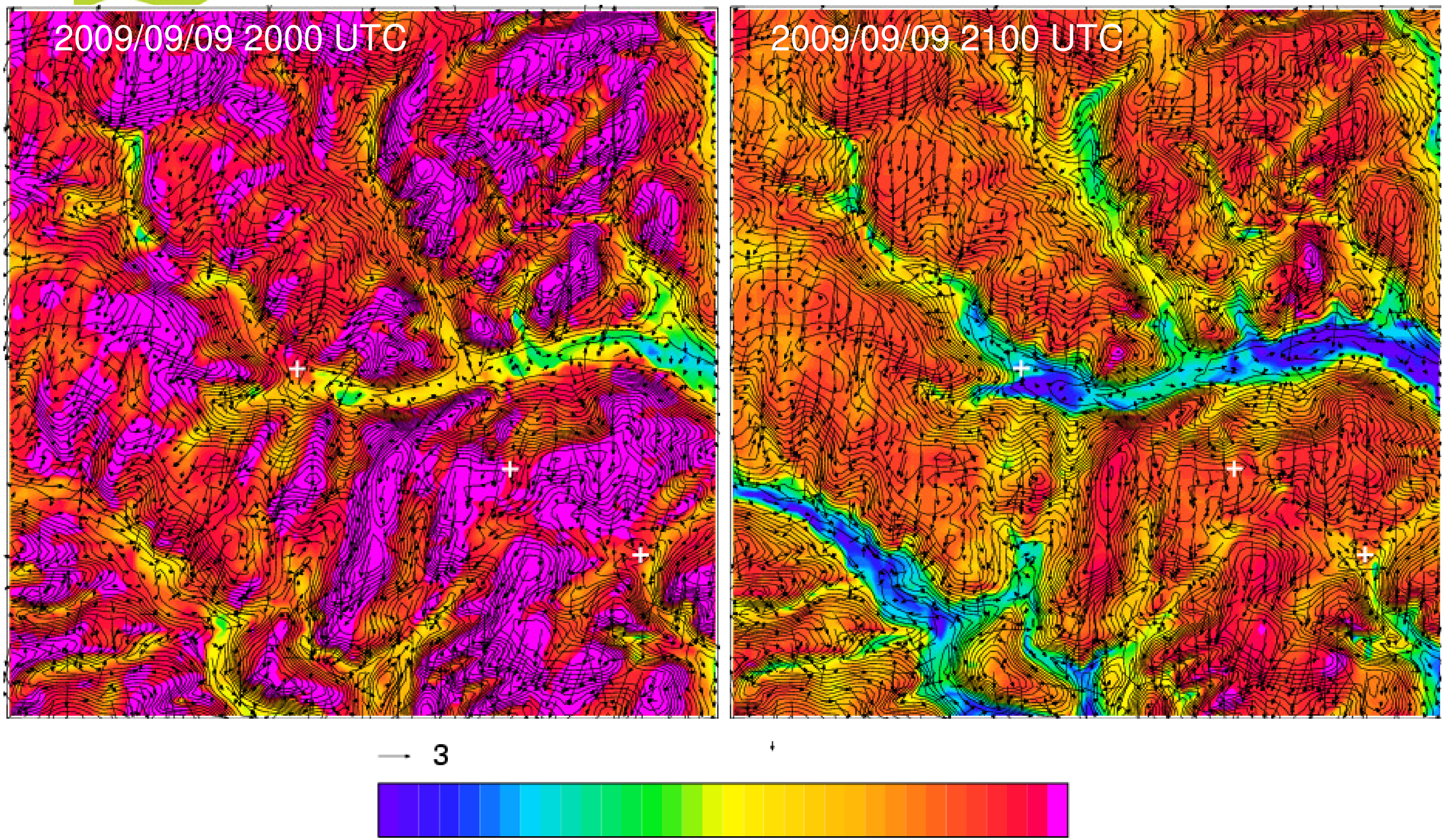
Potential temperature at 2m, winds at 1m



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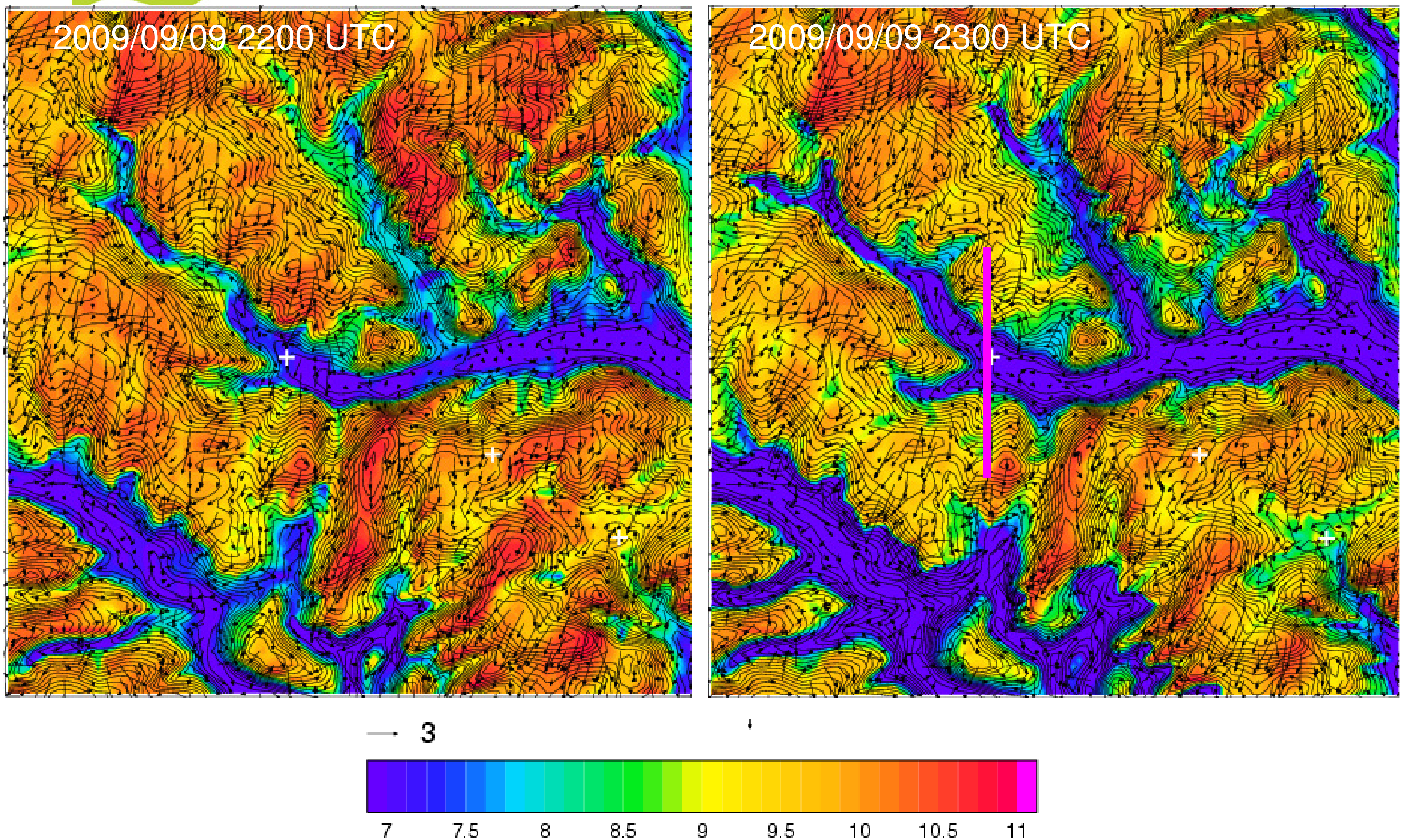
Potential temperature at 2m, winds at 1m



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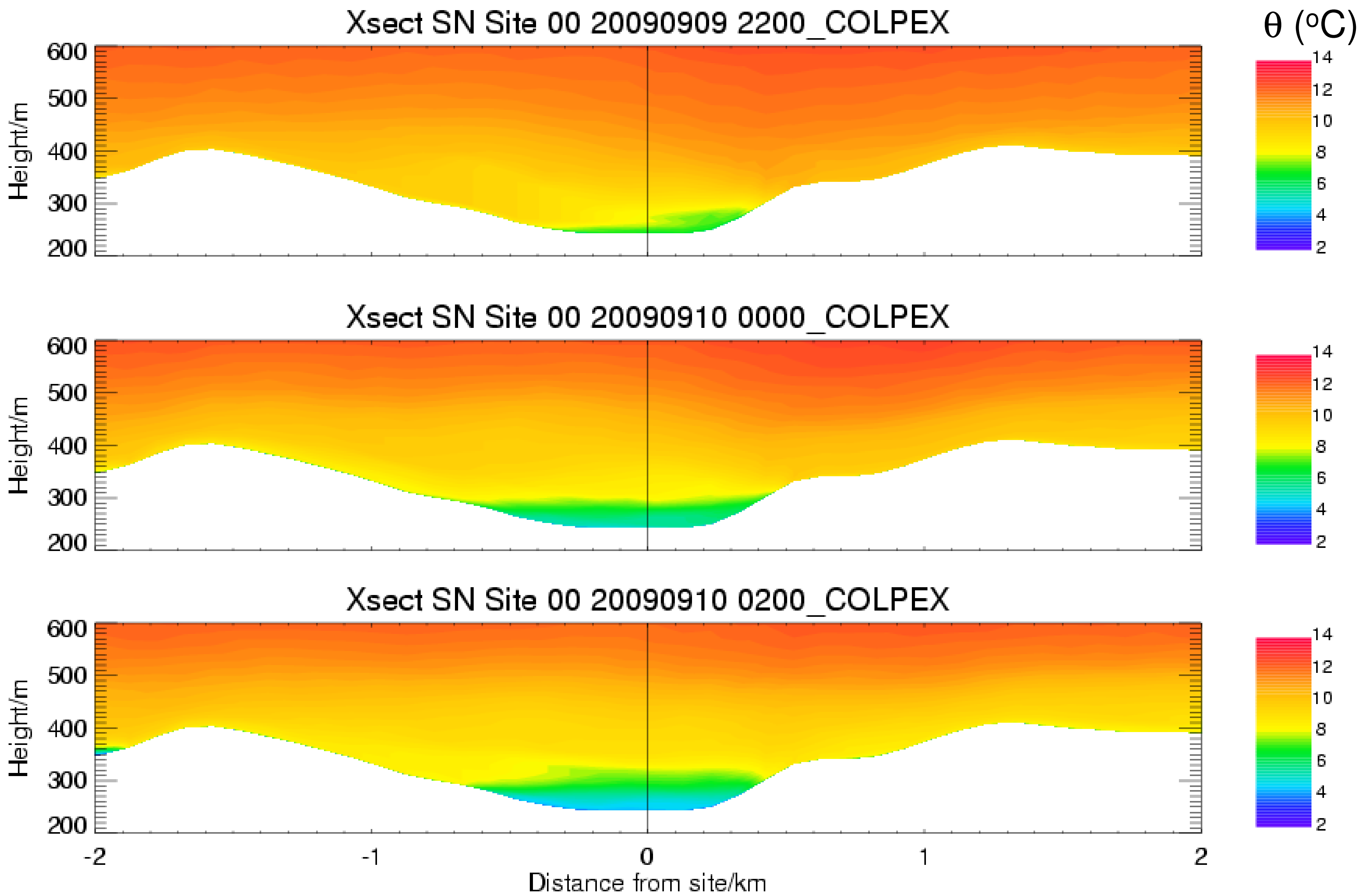
North-South section through Upper Dyffryn, Clun Valley



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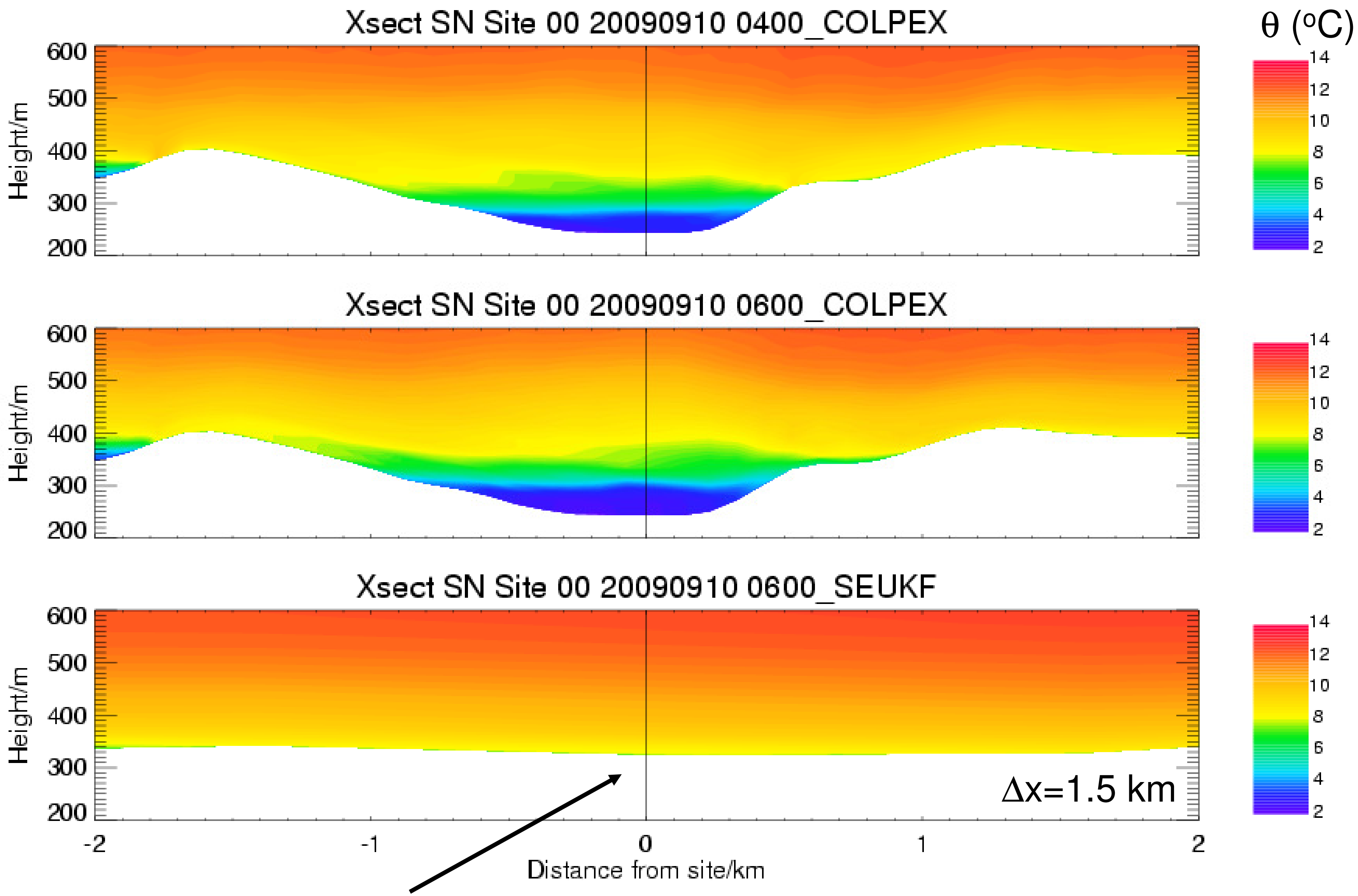
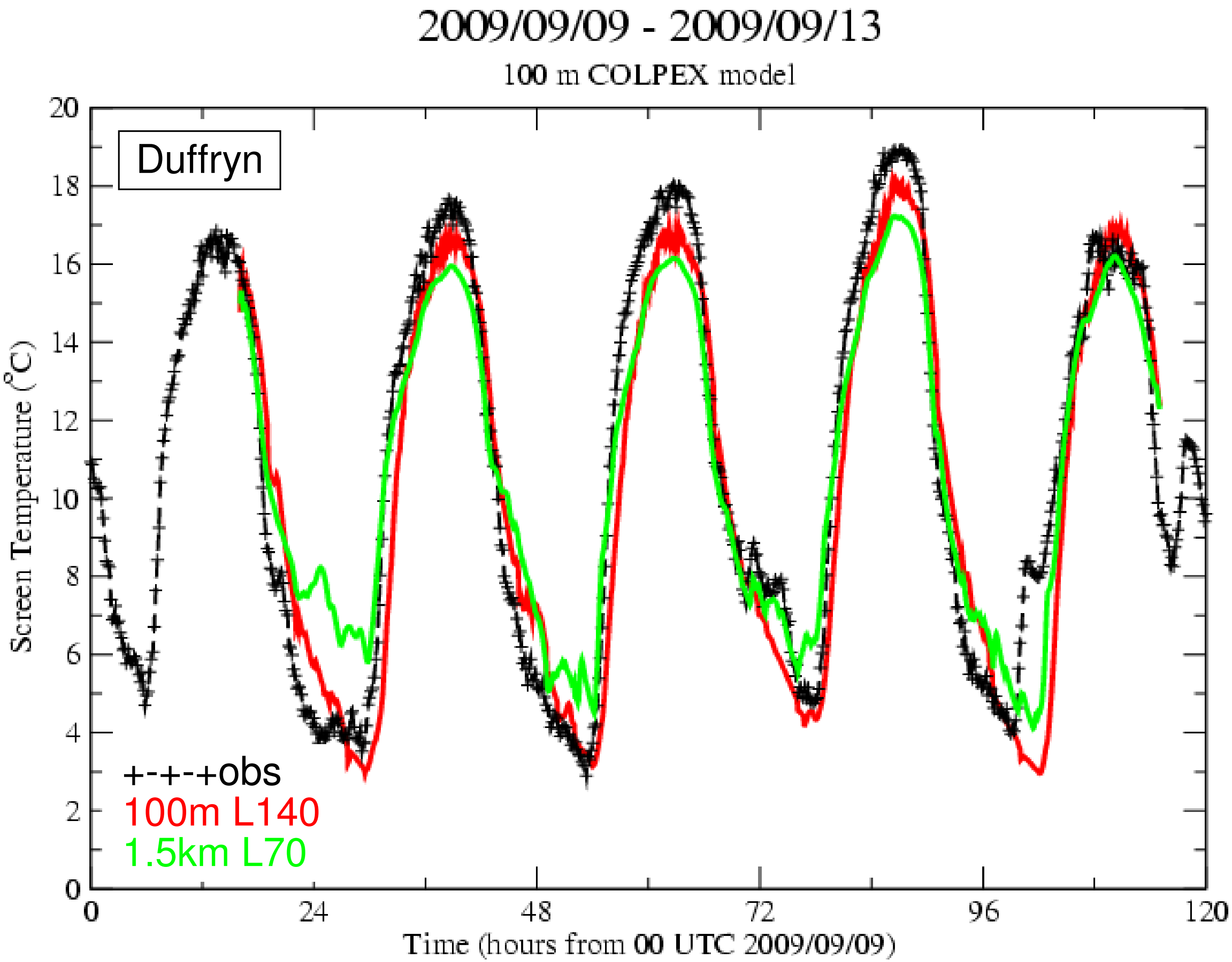
North-South section through Upper Dyffryn, Clun Valley



Clearly 1.5km resolution is inadequate!

Model screen temperature: Δ=100m L140 vs Δ=1.5km L70



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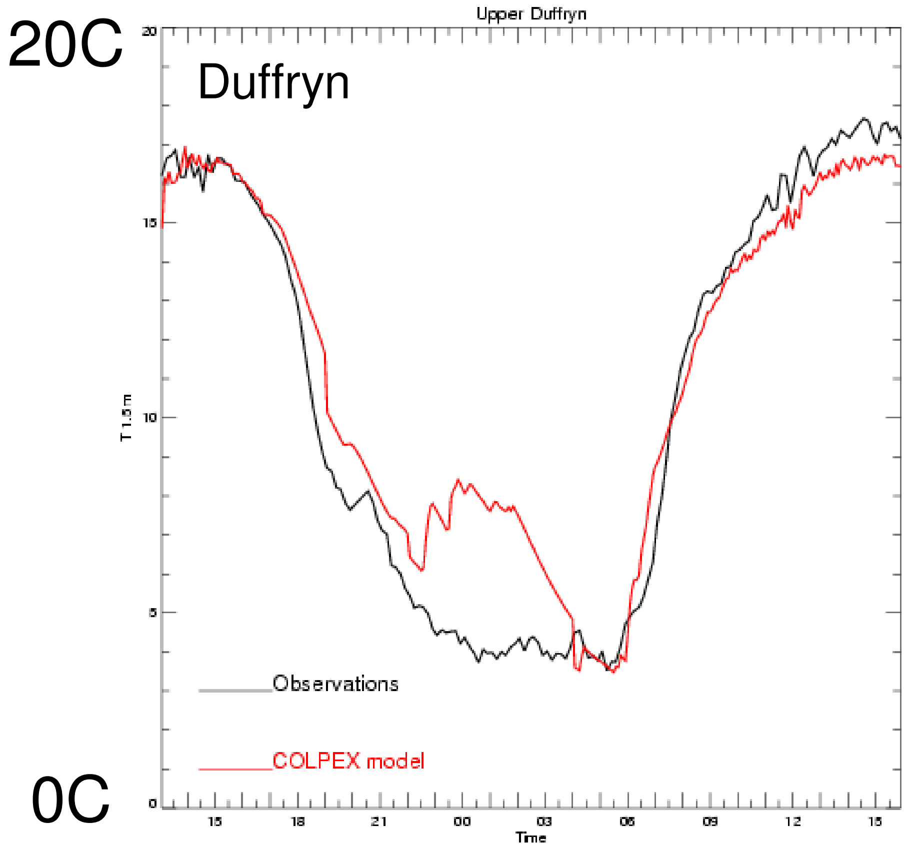
- Clear benefit of 100m resolution over 1.5km or vertical resolution?
- Temperature minima well represented in high res model
- Daytime temperatures still too cold

Impact of vertical resolution on screen temperature

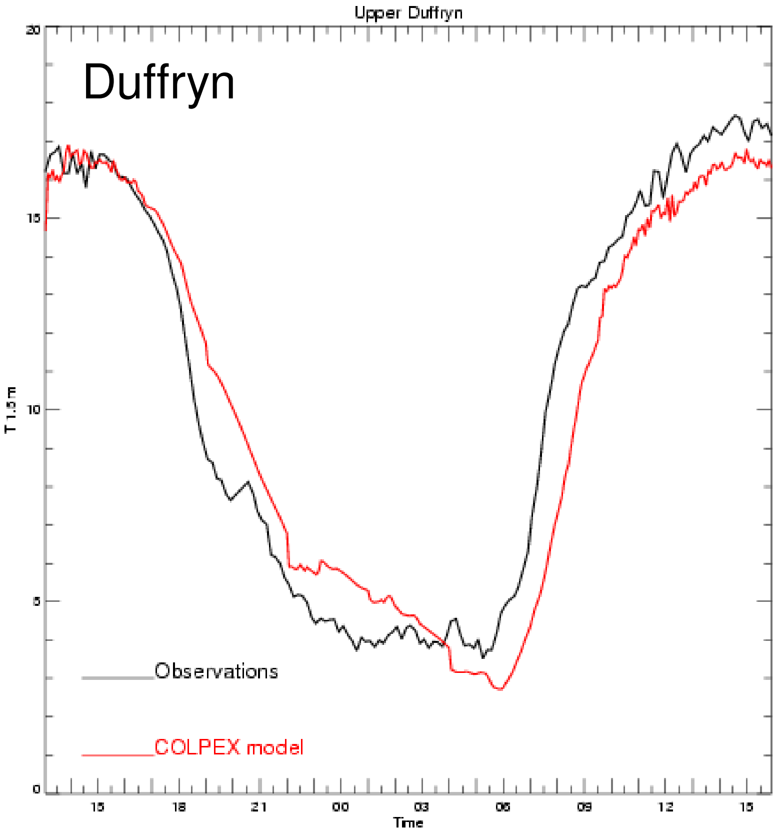
Δ=100m; L140 vs L70

- L140 also improves Springhill (also by cooling slightly) and improves Burfield by warming

L70



L140



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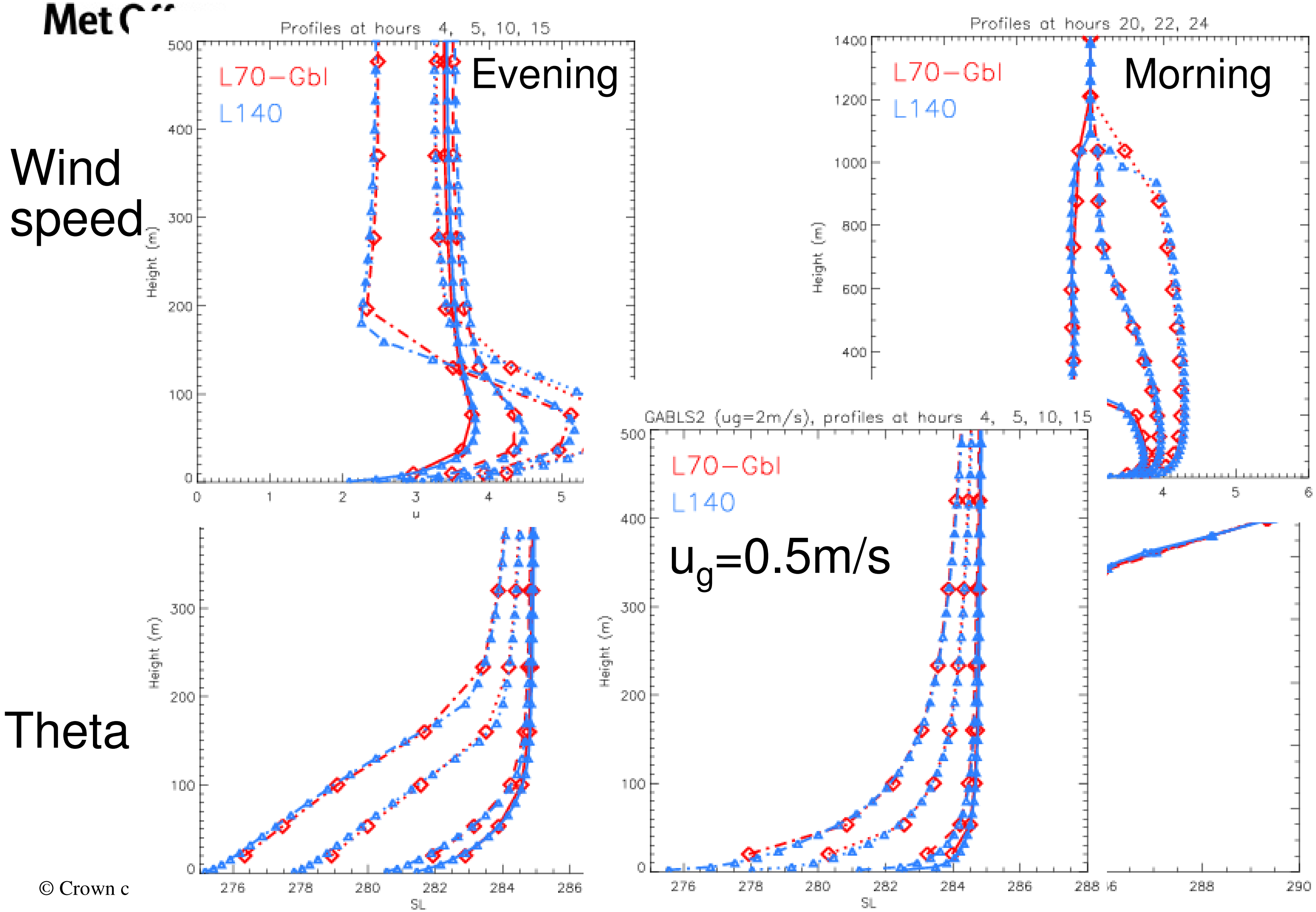
SCM impact of vertical resolution is negligible!

GABLSII: L70 vs L140



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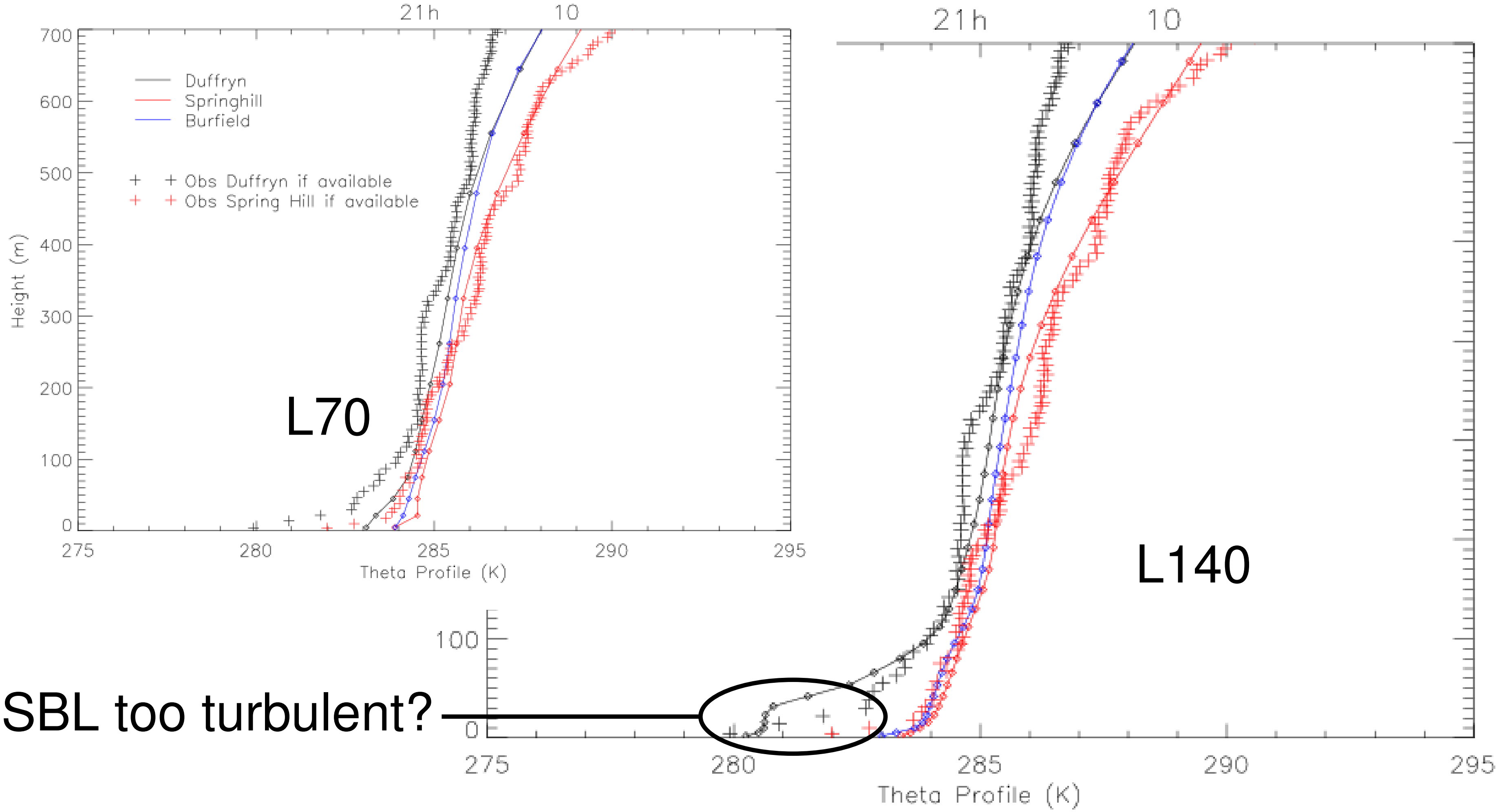
COLPEX_100m impact of vertical resolution

L70 vs L140 at 9pm

- L140 generates realistically colder shallow SBL in valley



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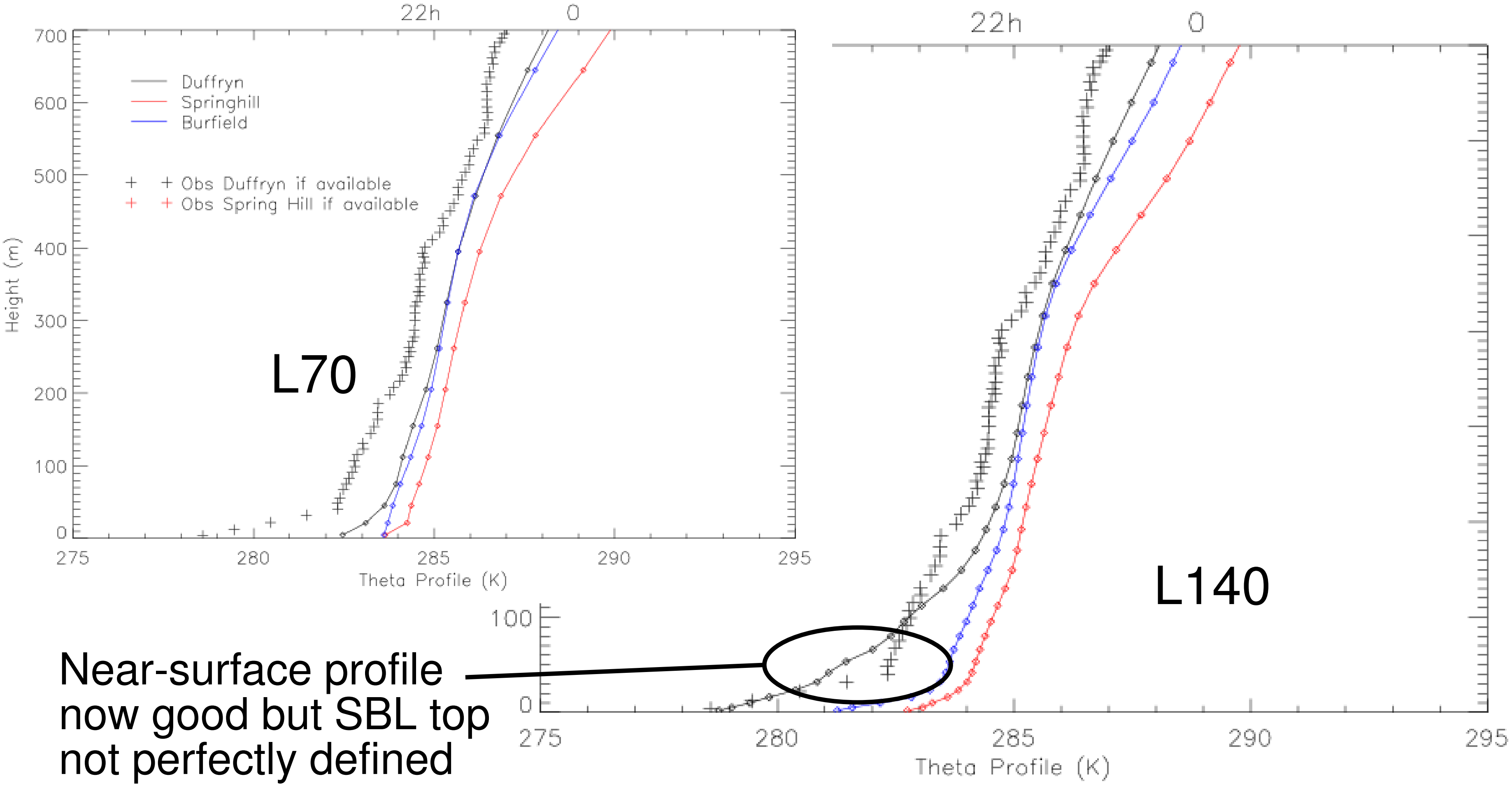
COLPEX_100m impact of vertical resolution

L70 vs L140 at 10pm



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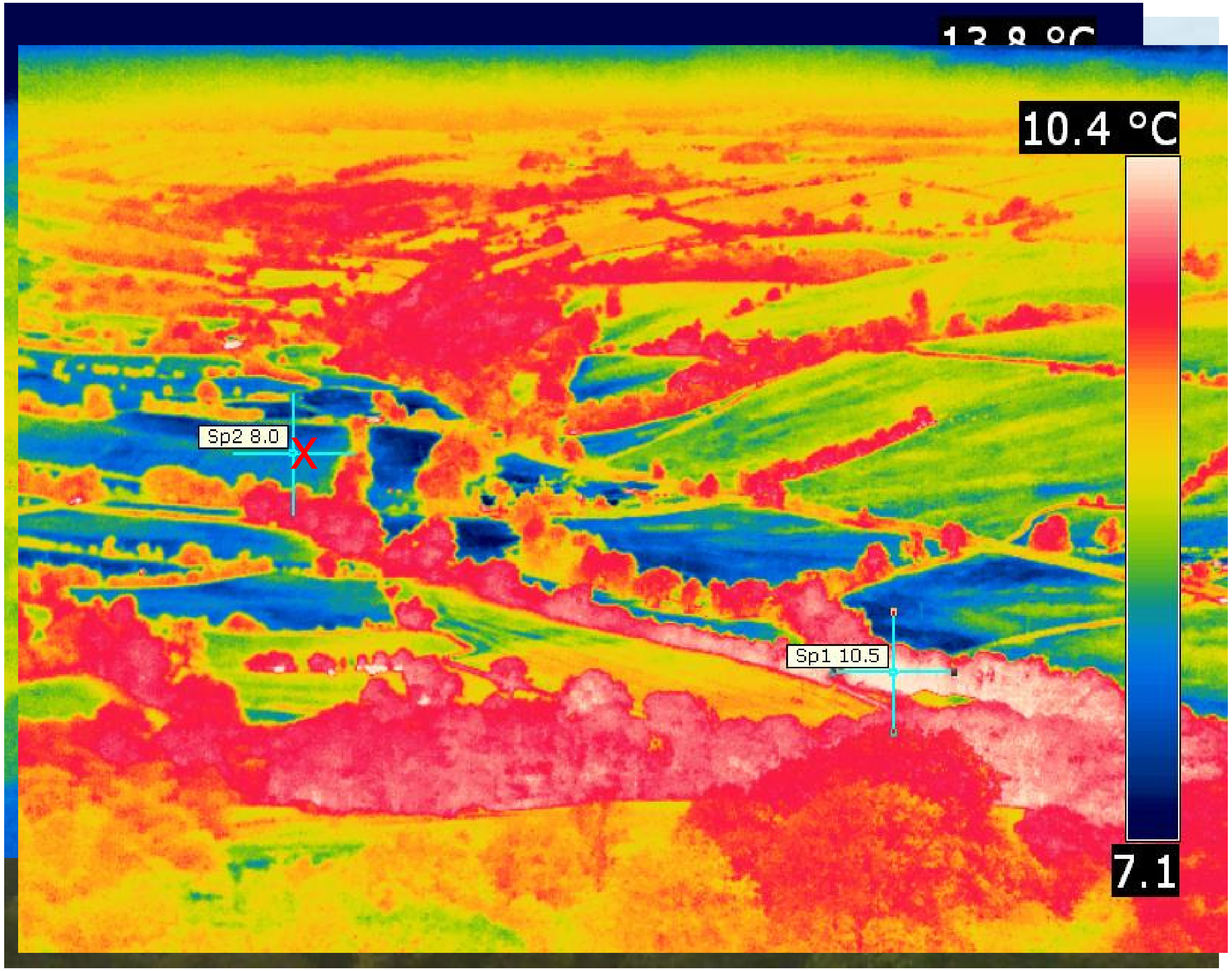
Surface heterogeneity: evening (2030)

Surface heterogeneity: daytime (1730)

Trees/hedges 2-3K warmer than fields so gridbox mean T will be biased warm



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Cold pool formation

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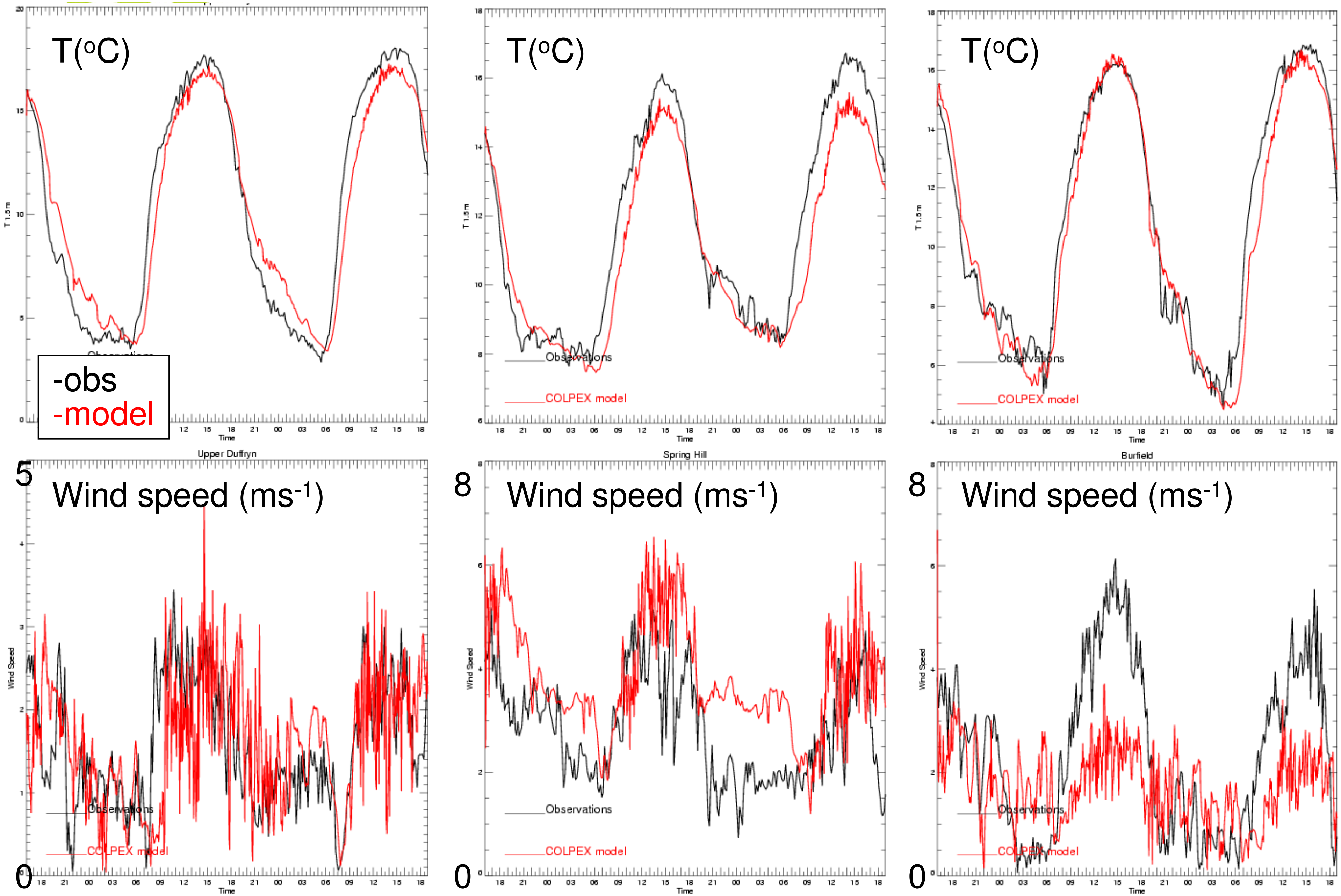
140-level 100 m model results

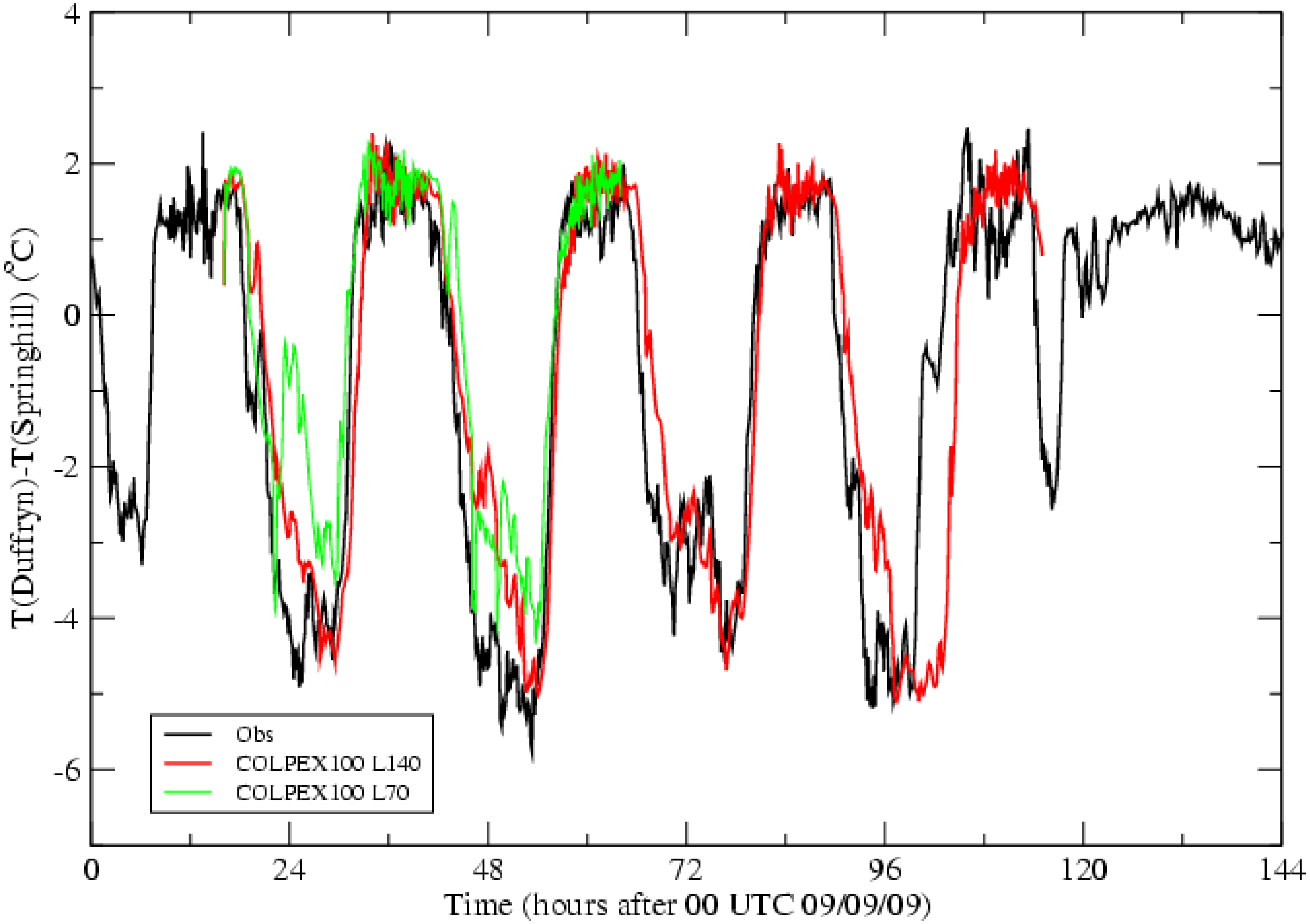
Duffryn (Clun valley) Springhill (hill-top) Burfield (valley)



Cold pool strength

- Repeatable nighttime ΔT of approx. -4 K
- 100m L140 model gives good prediction of ΔT amplitude
- Coarser vertical resolution (L70) results in weaker cold pools

Temperature differences 09-13 Sept 2009



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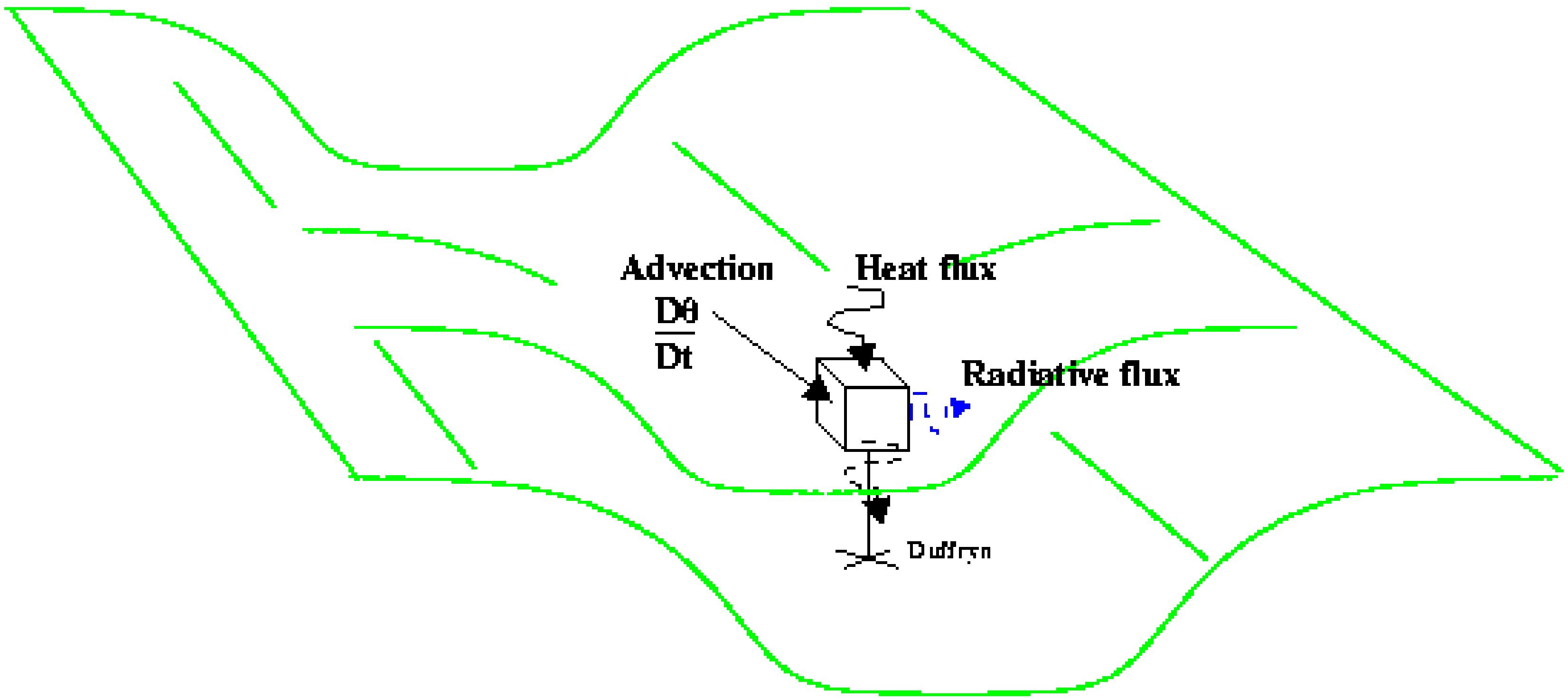
Heat budget

•Q: What are the dominant sources of cooling?

•Can use the model θ budget to identify which are the important processes at different times during the night.



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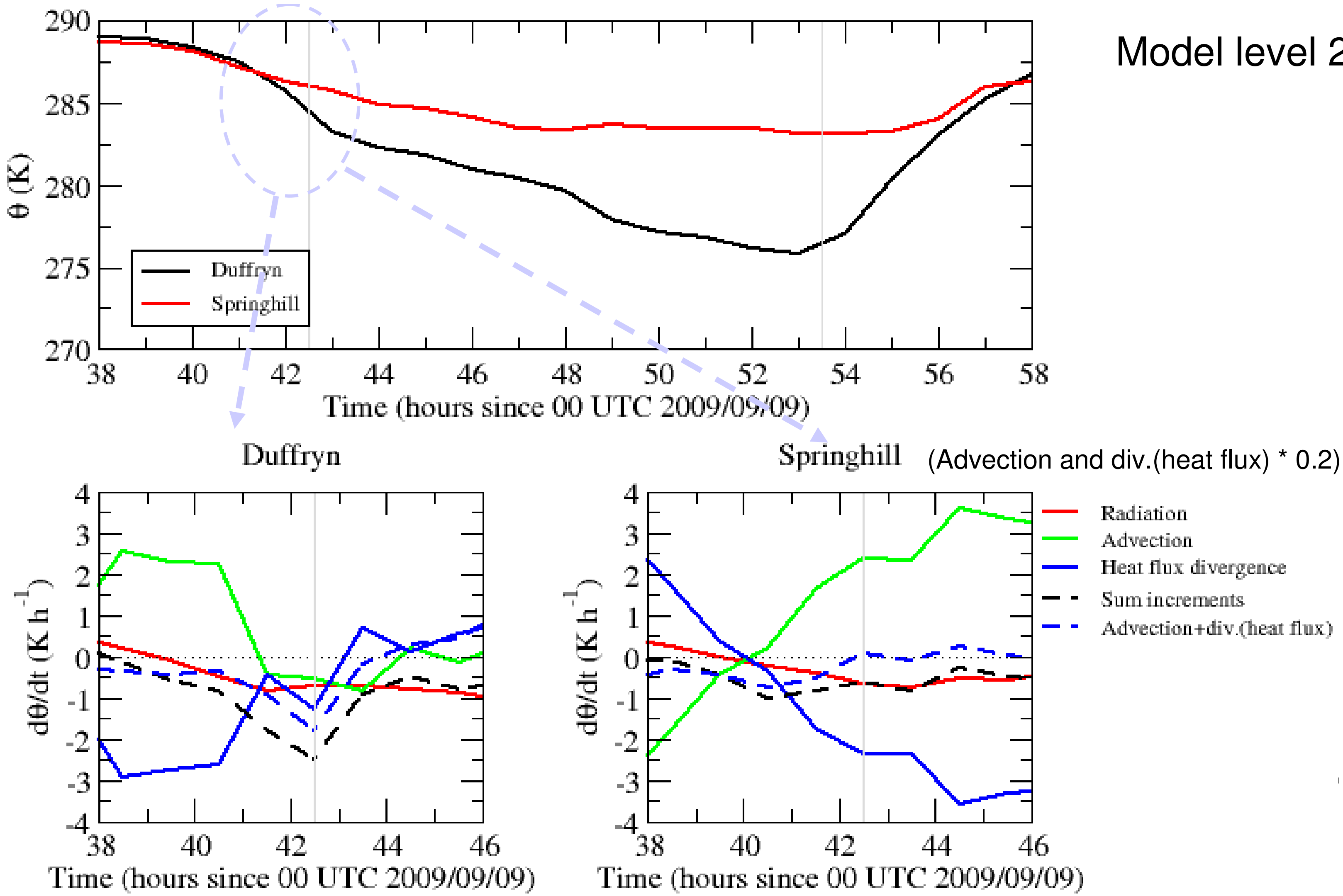
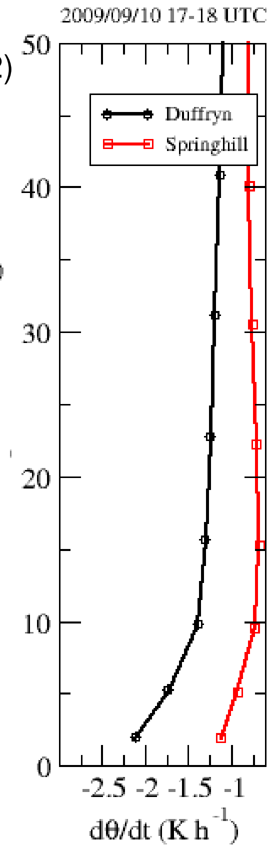
Model level 2 ~5m





- Cooling in valley is relatively rapid around sunset.
- Later on, hill-top and valley cooling rates are more similar
- Model heat budget suggests early rapid cooling in valley is largely due to greater turbulent heat flux divergence (relative to advection)

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Fog

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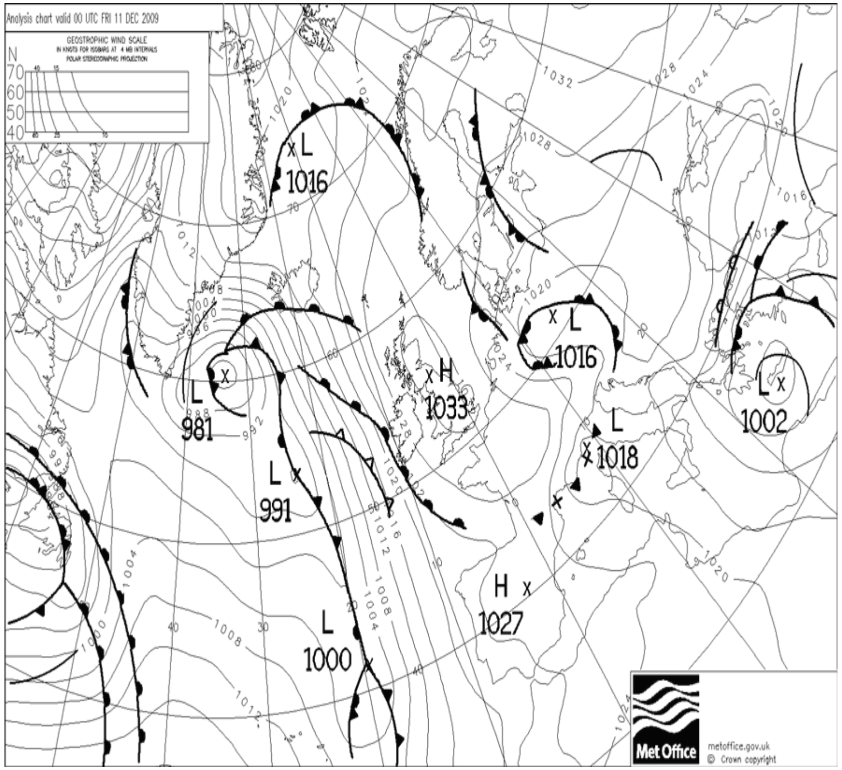
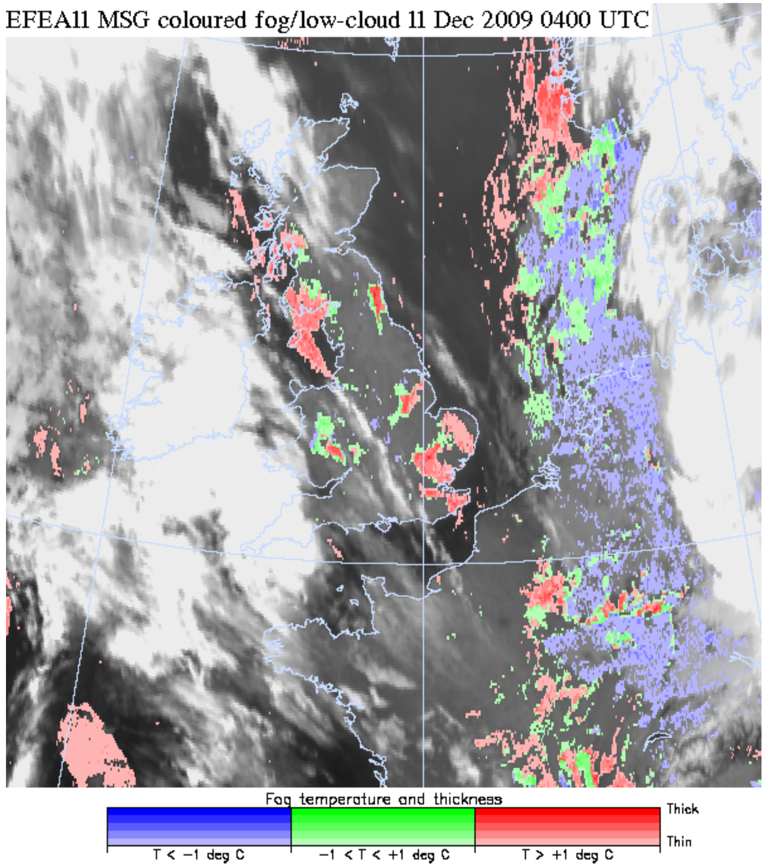
10th-11th December 2009
COLPEX IOP



11th December 00Z



Satellite fog/low-cloud product
11th December 04Z

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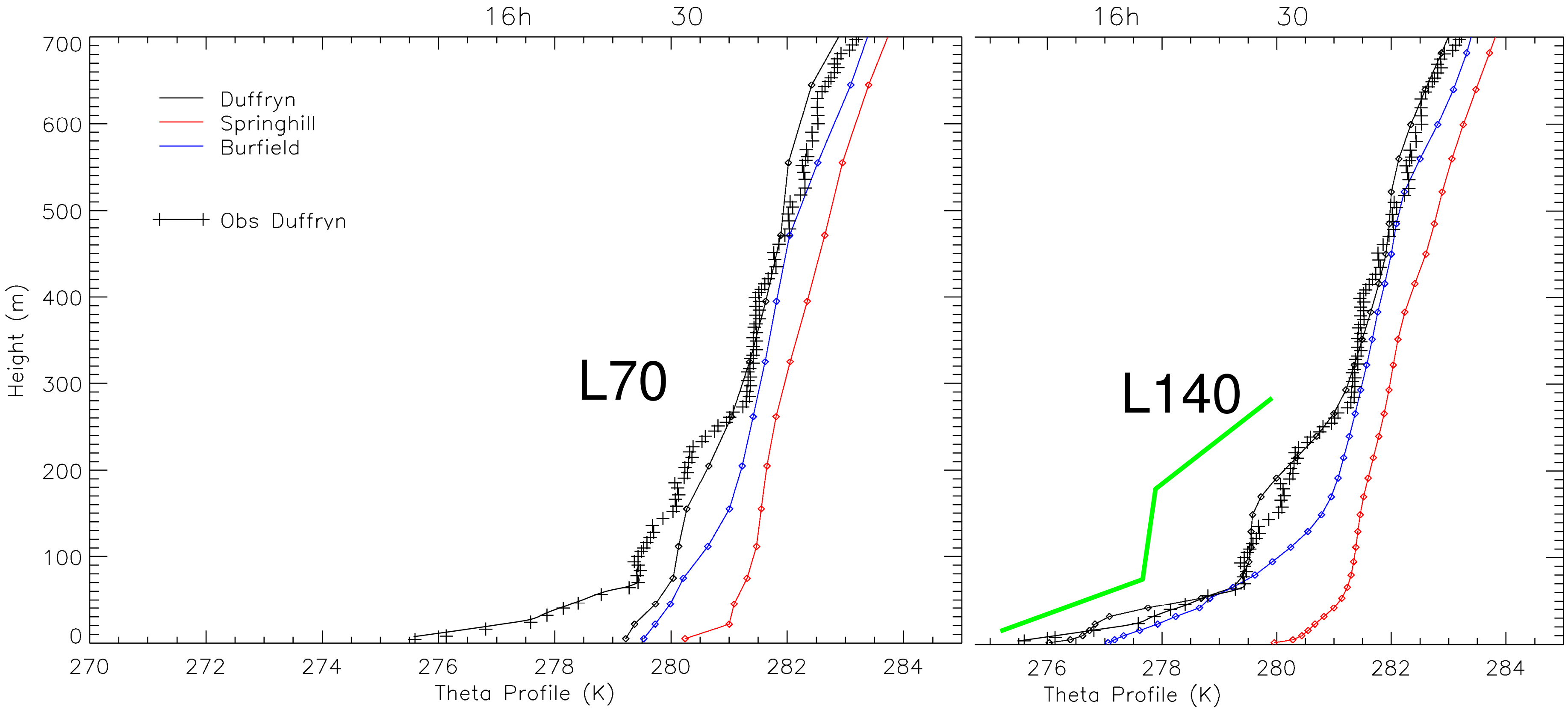
Differences in theta profiles at 1630

L70 and L140 against observations



Increasing resolution greatly improves vertical structure of theta profile:

- captures inversions at ~60m, ~250m and "mixed-layer" between
- again doesn't have linear near-surface profile – too turbulent?

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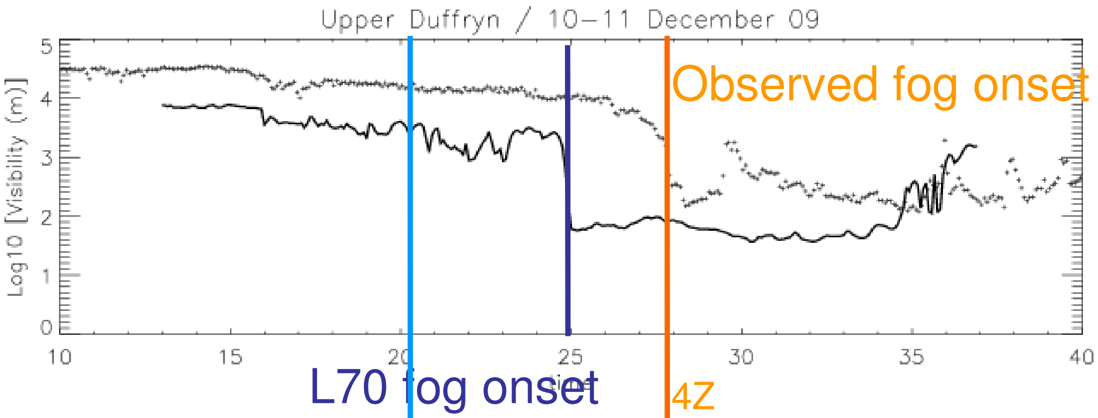
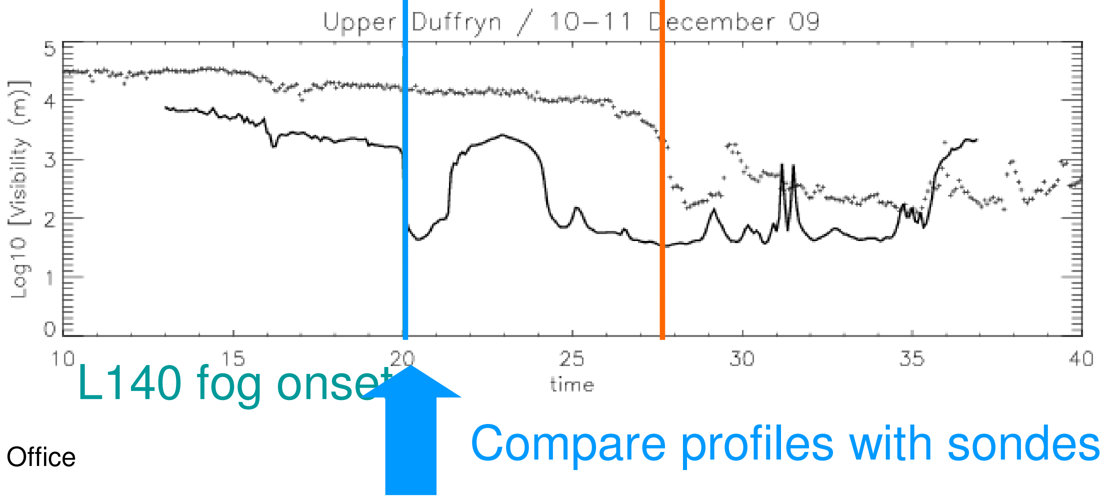
Differences in time series of visibility, L70 and L140 against observations

- Despite better vertical T structure, L140 forms fog much earlier than L70, which was already too early

L70



L140



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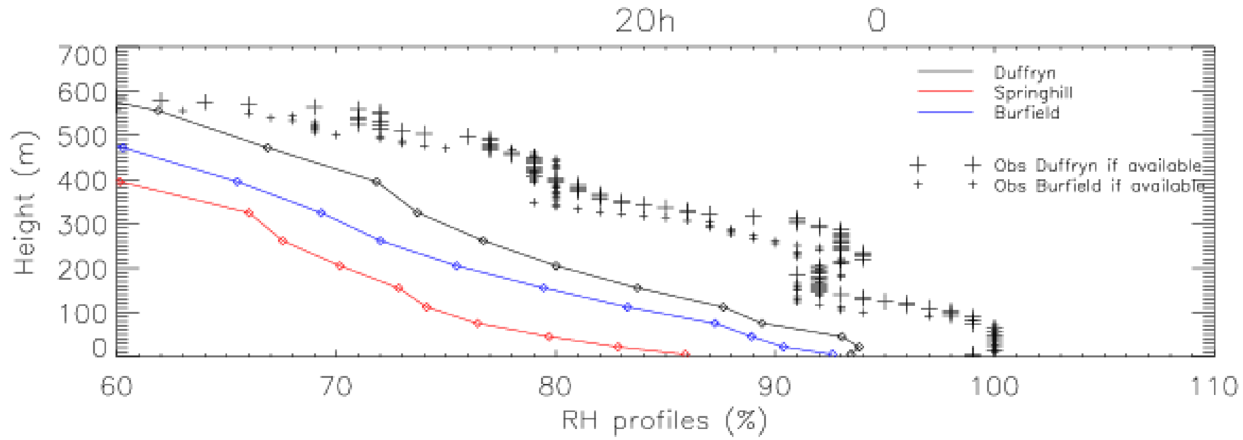
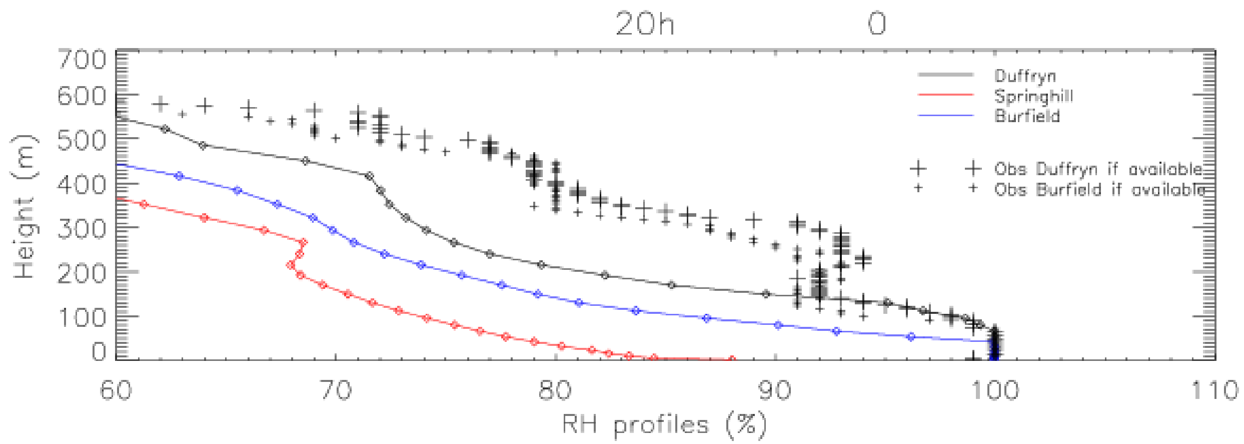
Parametrization of cloud formation

L70



L140



- RH is (correctly) high in L140 UM over a relatively deep layer
  - But there is no cloud at all in reality (from LW fluxes) despite 100% RH!
  - RHcrit already set to 99% in model

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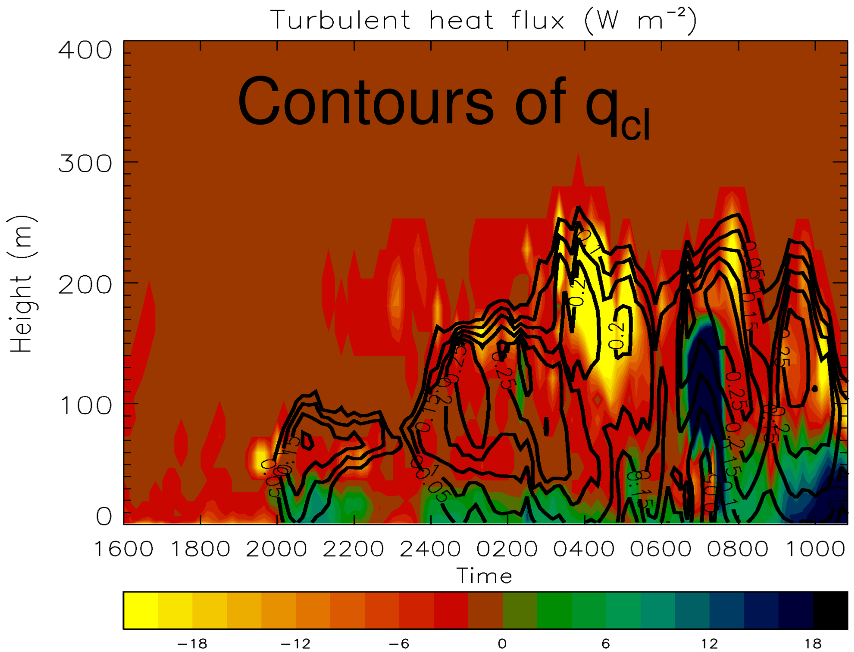
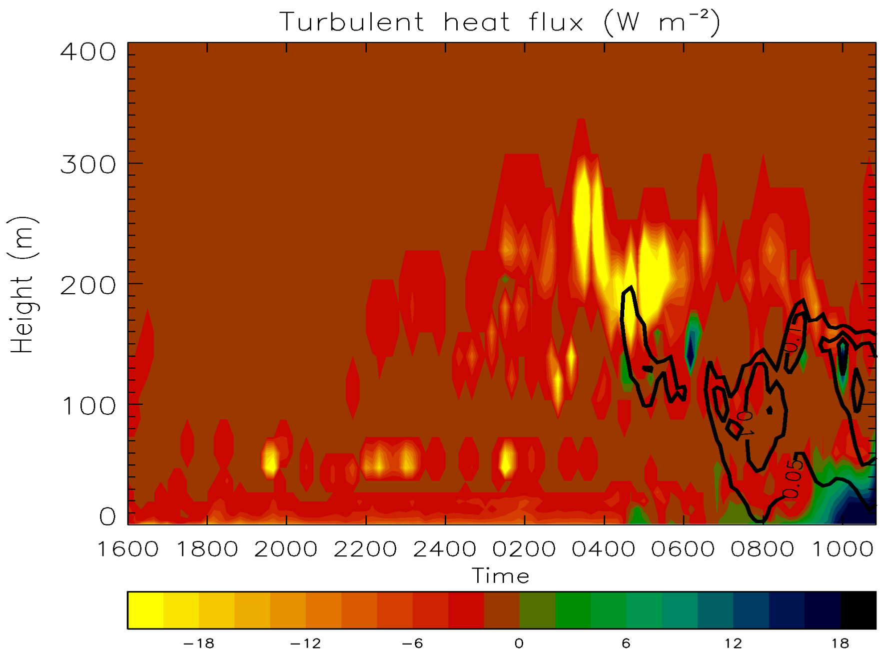
Sensitivity to microphysics

- Fog development at Duffryn also very sensitive to assumed cloud droplet number concentration
  - fewer drops are larger and so fall out faster
  - leaves RH at 97-98% so potentially too dry?

$N=300\ cm^{-3}$



$N=20\ cm^{-3}$



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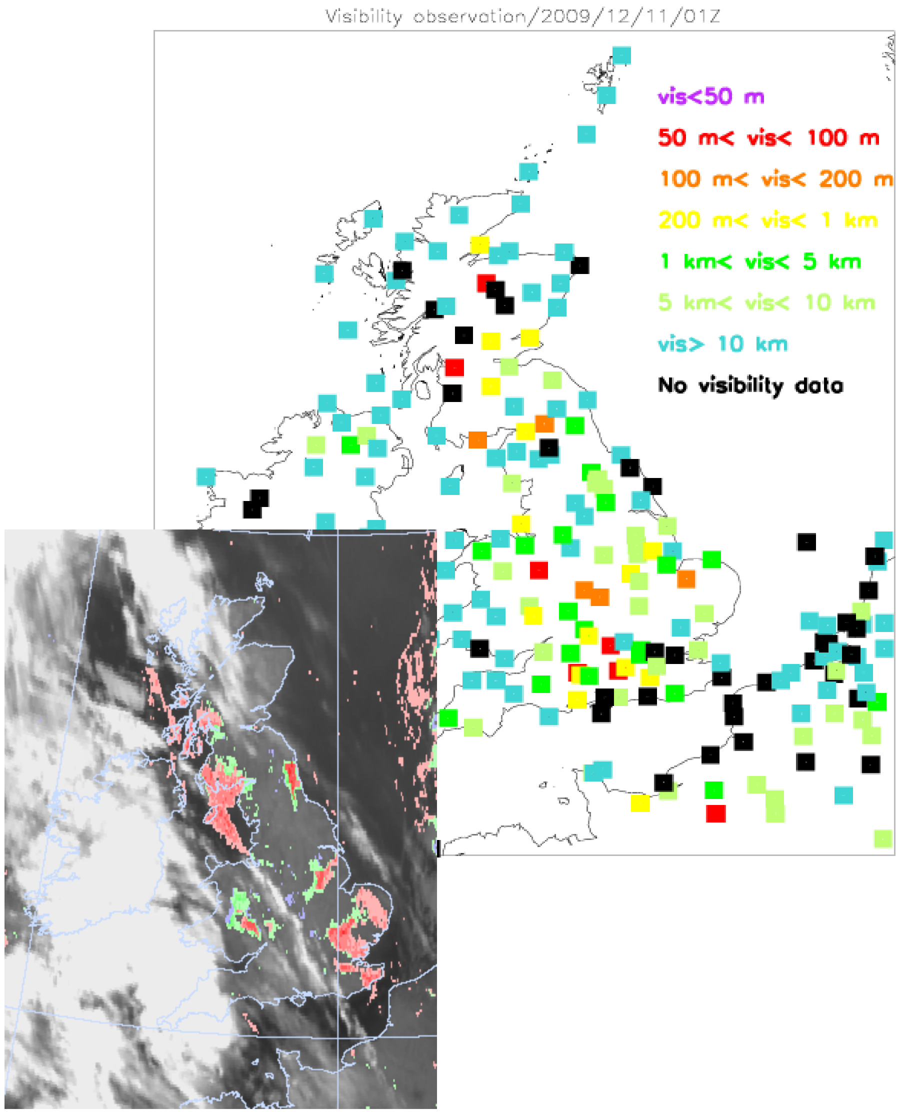
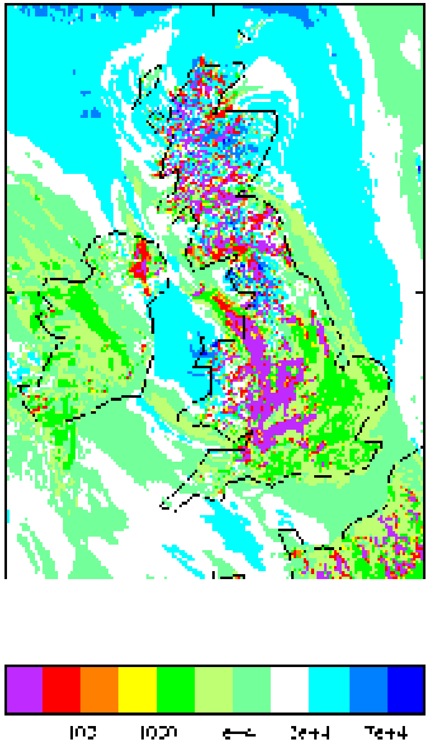
UKV sensitivity to SBL mixing

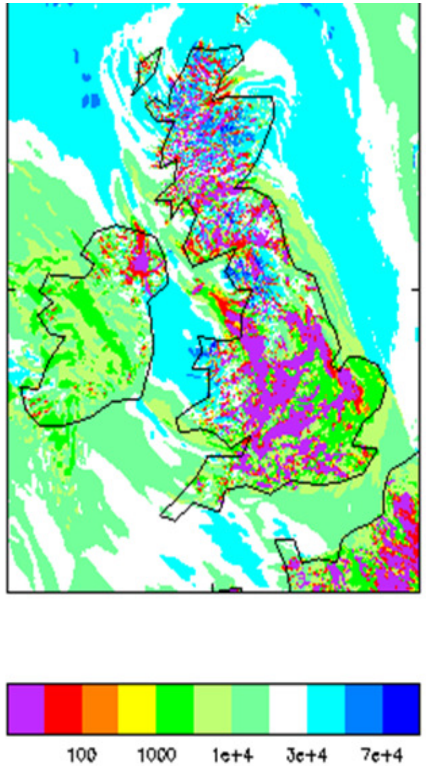
"LEM tails"

More fog (eg eastern England) but now too widespread and thick





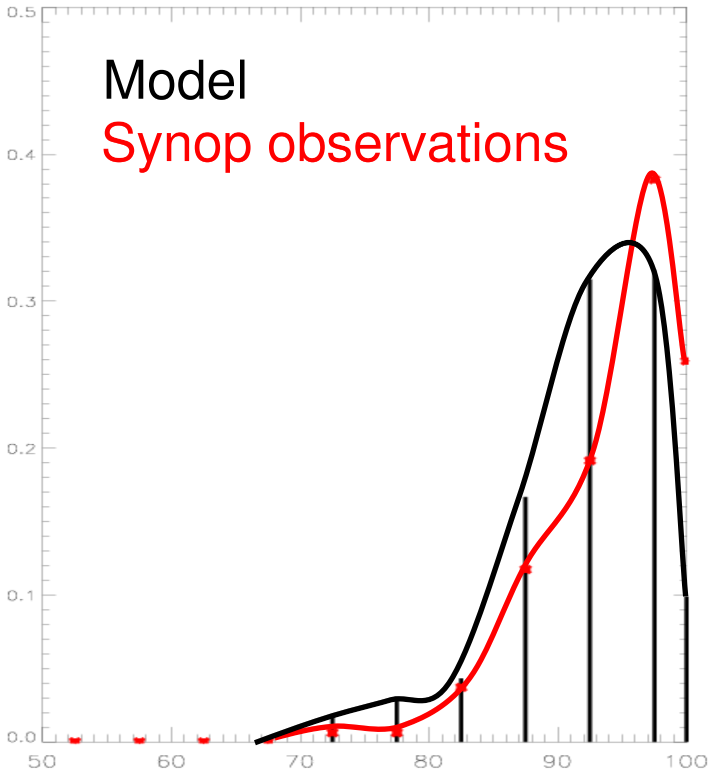
Control visibility



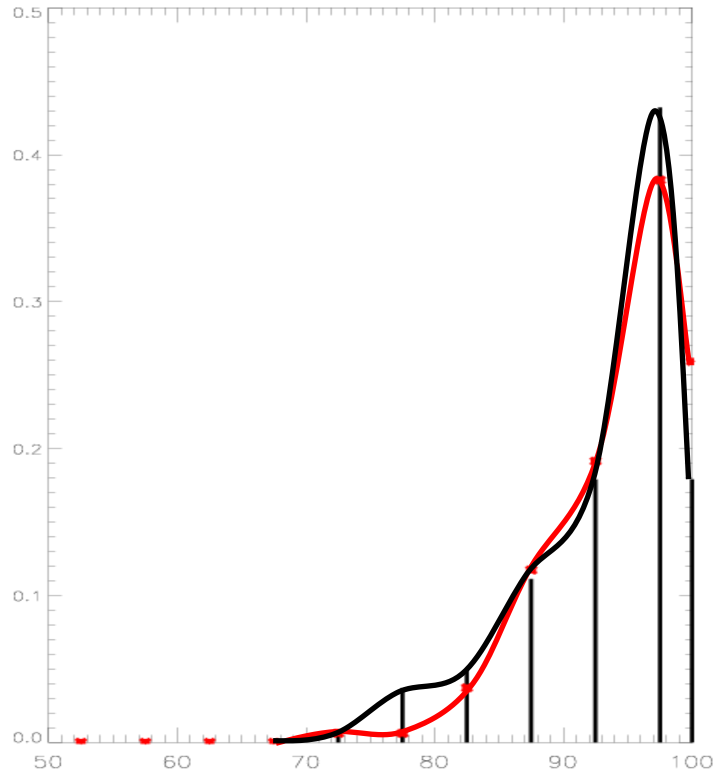
LEM tail visibility

Impact of LEM tails on RH distribution

Control: Mes tail



Test: LEM tails



- Sharper tails (less turbulent mixing) improves high end of RH distribution
- But gives too much fog
  - Revise dew deposition? Improve drop number (aerosol activation)?

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Summary

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Summary (1)

- Diurnal cycle of screen T biases is reasonably consistent across all resolutions and timescales, suggests problems are robust
- Very active area so short term progress should be possible:
  - Generally warm by night (except deserts: $\varepsilon<0.97$?), cold by day
  - Still seen under clear skies so not exclusively a cloud problem
    - Excessive nocturnal turbulent mixing (->sharper tail)
    - Higher vertical resolution helps (in 100m 3D model at least)
    - Excessive evaporation by day?
    - Overdone direct radiative effect of aerosol?
    - Surface heat capacity too large (diurnal and cloud clearing)?
      - Higher soil resolution?
  - Winter cold bias in screen T in high latitudes remains an issue (exacerbated by sharper tails)
    - Representation of snow?
    - More pronounced decoupling?
  - Further analysis of surface energy budget errors and comparison with satellite surface temperatures on-going

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Summary (2)

- Fog
  - aerosol activation and drop number (and thence size)
  - interaction with radiation (currently a fixed drop size)?
    - would this (realistically) reduce the strong feedback between initial fog formation and radiative fluxes?
  - improve fog deposition, including horizontally onto vegetation
- Stable boundary layers in complex terrain
  - COLPEX 100m/L140 UM actually doing a remarkably good job, but much more work to be done:
    - further investigation of surface temperatures and drainage flow structure
      - fine details of vertical structure are important for temperature evolution and fog formation
    - continue progress with understanding where and how cold pools form
    - coarse-graining to inform parametrization in standard NWP configurations

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Summary (3)

Unfortunately it is important to get everything right!

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