Observations & Modelling of Flows Over Complex Terrain – A Case Study from the COPS Field Experiment

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1. Convective and Orographically-induced Precipitation Study

WHAT - **Massive international field campaign – Summer 2007, Black Forest (BF), SW Germany**

WHY – Heavy orographic precipitation → flooding / flash flooding

PROBLEM – Poor skill in Quantitative Precipitation Forecasting (QPF)

- Lack of intensive observations of flow over complex orography
- Forcing mechanisms poorly understood & modelled
- Systematic error to overestimate leeward & underestimate precipitation
- Systematic error to make early prediction of precipitation

GOAL – "To advance the quality of forecasts of orographically-induced convective precipitation by 4-dimensional observations & modelling of it's life cycle"

HOW – Novel setup of multi-platform observation network to measure all spatial & temporal scales

- Allow extensive instrument intercomparisson
- Detailed observations → improved orographic flow understanding
- Verify atmospheric models, & identify key failures

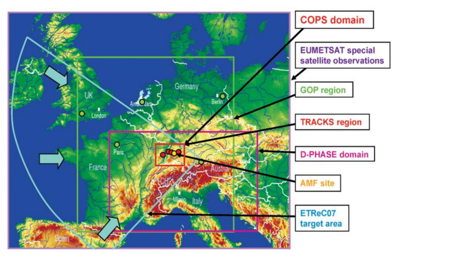
Fig. 1 Location of COPS Field Campaign

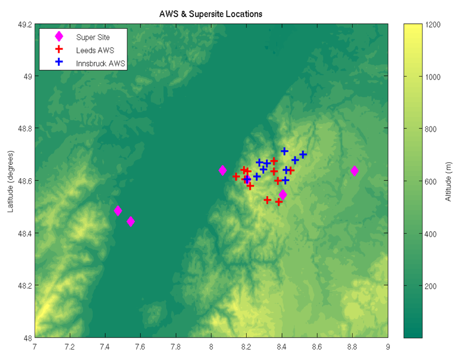
Fig. 2 Location of surface AWS stations & COPS Supersites

2. IOP9c (20/07/07) – Forced convection embedded in surface frontal zones

OVERVIEW

- Highly complex propagation & development of MCS over COPS region
- Complex orography modified, organised & intensified associated cold pool gust front structure
- CI in frontal zone, in response to orographic modification & uplift, instability aloft, & convergence east of Black Forest
- Squall line of convective activity from re-organisation of MSC outflow
- Case presents opportunity to understand key dynamical processes associated with mesoscale convective flow over complex terrain
  - Extensive instrument synergy of event, "presents an excellent case for studying the performance of mesoscale models" Wulfmeyer – Science Director Summary, 20th July 2007

OBSERVATIONS

- Weakening of MCS precipitation with passage over Rhine & re-generation east of Black Forest, ahead of the MCS
- Evidence of flow modification from Automatic Weather Stations (AWS)
  - Substantial differences in both the magnitude & direction of gust front, & of the temperature change between sites
  - Larger changes seen at mountain-top sites
  - Valley sites show their role in channelling the gust front out of BF, towards eastern region where convective cells subsequently form

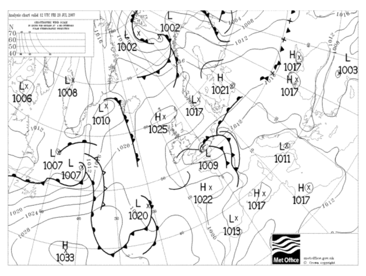
Fig.3 12Z Analyses from UK Met Office

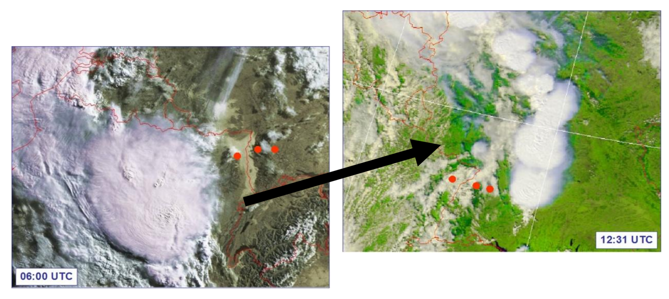

Fig. 4 Satellite images from NOAA 18

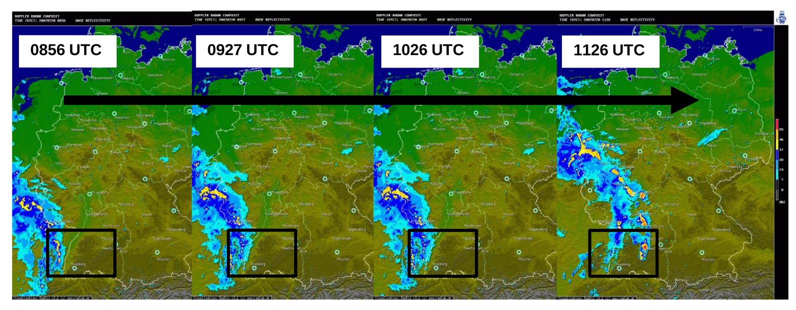

Fig.5 Rainfall radar images from DWD weather service

3. Model Setup

- Weather Research & Forecasting (WRF) version 3.0.1.1[1]
- Initialised with ECMWF analyses & started at 00Z on 20th July
- Three nested grids are used, with resolutions of 2.7km, 900m & 300m (see fig.3)
- Convection explicitly resolved in middle & inner domain
- Morrison Microphysics scheme - Double-moment ice, snow, rain and graupel for cloud-resolving simulations.

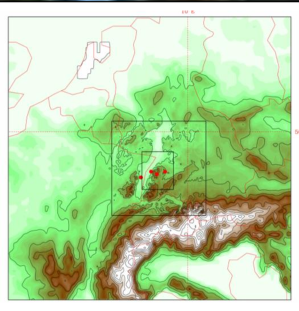
Fig. 3 WRF Domain setup

4. Observations of IOP9c

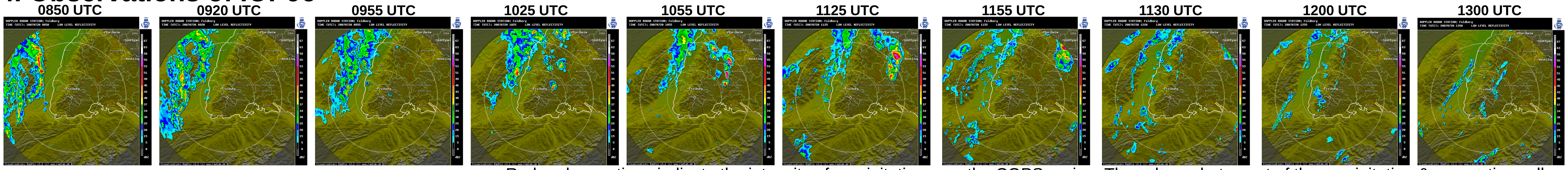

Fig. 6 Reflectivity from the DWD operated radar located at Feldberg in the Southern Black Forest. Radar observations indicate the intensity of precipitation over the COPS region. They show abatement of the precipitation & convective cells as the system descends & passes over the Rhine valley. Intense precipitation is then observed in the lee of the Black Forest at the leading edge of the MCS, after it has passed over the COPS region. It is suggested, therefore, that CI is related to the interaction of the MCS with the complex COPS orography

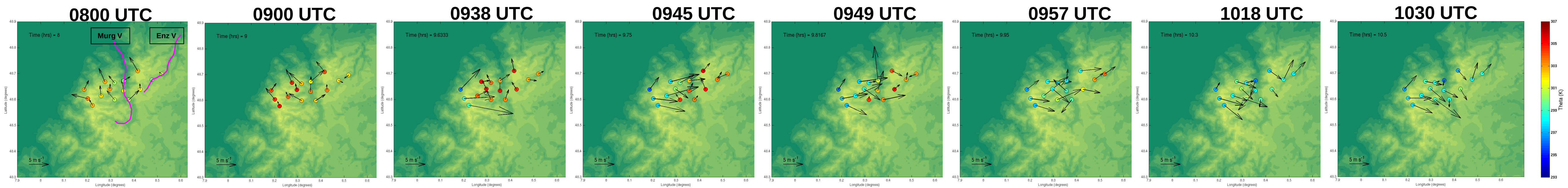

Fig. 7 Surface observations of theta (at 2m) and 2-D winds (at 2.5m) from AWS's operated by University of Innsbruck & University of Leeds. The leading edge of the MCS reaches the Western slopes of the Northern COPS region at 0938 UTC, shown by weak easterly downslope winds changing to strong westerly's & a ≈ 7K. When the gust front reaches the N-S aligned Murg valley at 0949 UTC, the valley orientation has the effect of channelling the high MCS outflow winds along the valley & out of the BF. As the main part of the MCS passes the COPS region, flow is forced around the Northern BF & into the COPS region through up-valley flow along the Murg valley. At 0957 UTC, the Murg valley winds are beginning to flip from down to up-valley, & the flow is now being forced to exit the BF along the SW-NE aligned Enz valley. By 1018 UTC, the orographic flow in the Northern BF is Westerly over the mountains then channelled out of the complex orography along the Enz valley.

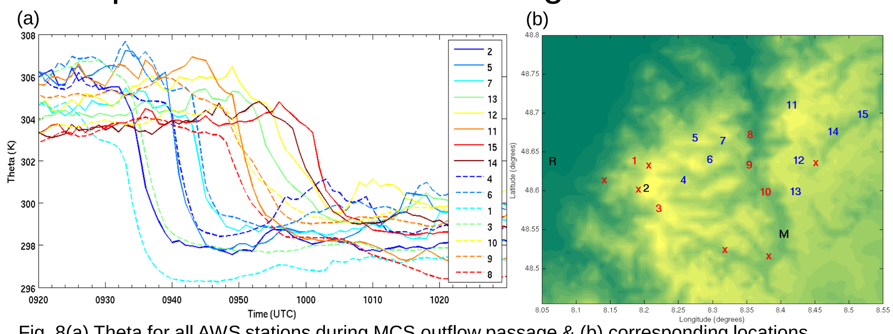

Fig. 8(a) Theta for all AWS stations during MCS outflow passage & (b) corresponding locations approximately numbered according the time of the gust front passage. Fig.(a) shows there to be large differences between the stations' response to the cold pool outflow passage. Largest $\nabla\theta$ values were observed at mountain top sites. It is also interesting to note that the valley sites observed the cooling later than the speed of the gust front passage would suggest, implying the role of turbulent mixing & channelling in controlling the valley flow regimes.

4. WRF modelling of IOP9c

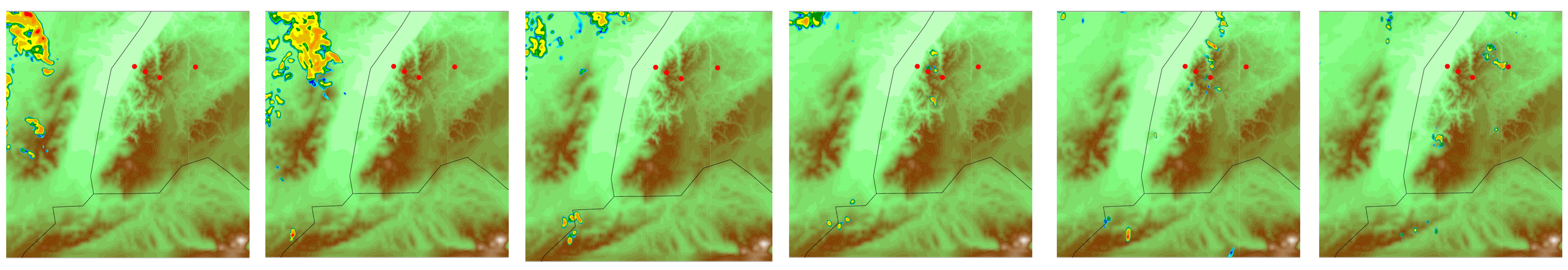

Fig. 9a Radar reflectivity, orography and COPS supersites (red dots) over similar domain to the range of the Feldberg reflectivity radar (data from the middle domain of the WRF simulation)

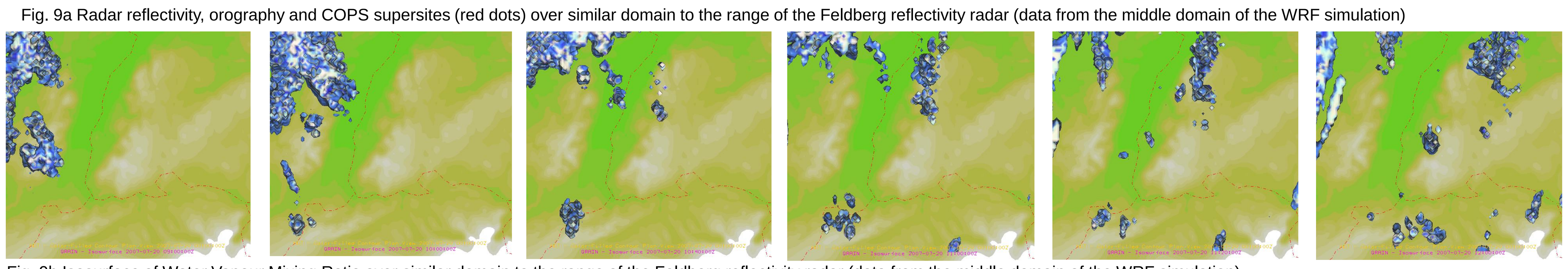
Fig. 9b Isosurface of Water Vapour Mixing Ratio over similar domain to the range of the Feldberg reflectivity radar (data from the middle domain of the WRF simulation)

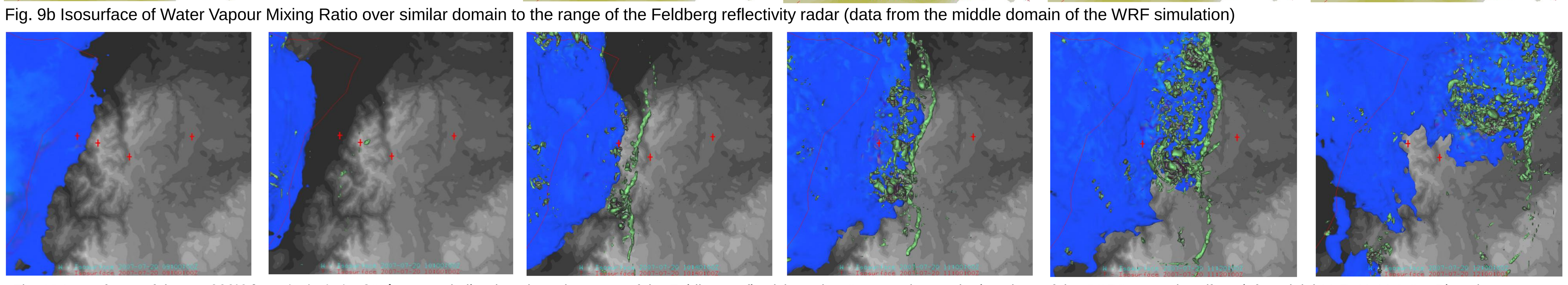
Fig. 10 Isosurfaces of theta ≈ 300K & vertical wind ≈ $2ms^{-1}$ over a similar domain to the range of the Feldberg reflectivity radar. Crosses denote the locations of the COPS supersites (from left to right) V. R, H, M & S – Plan view

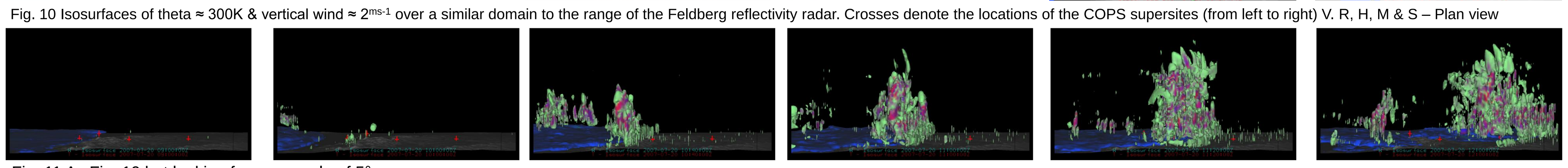
Fig. 11 As Fig. 10 but looking from an angle of 5°

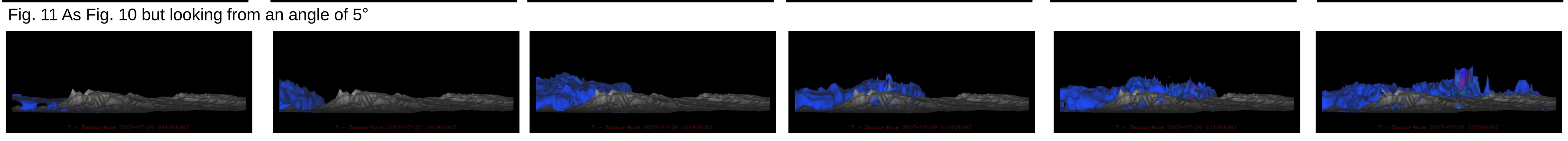
Fig. 12 Vertically zoomed in version of Fig. 1, showing the theta isosurface only, from an angle of 0°

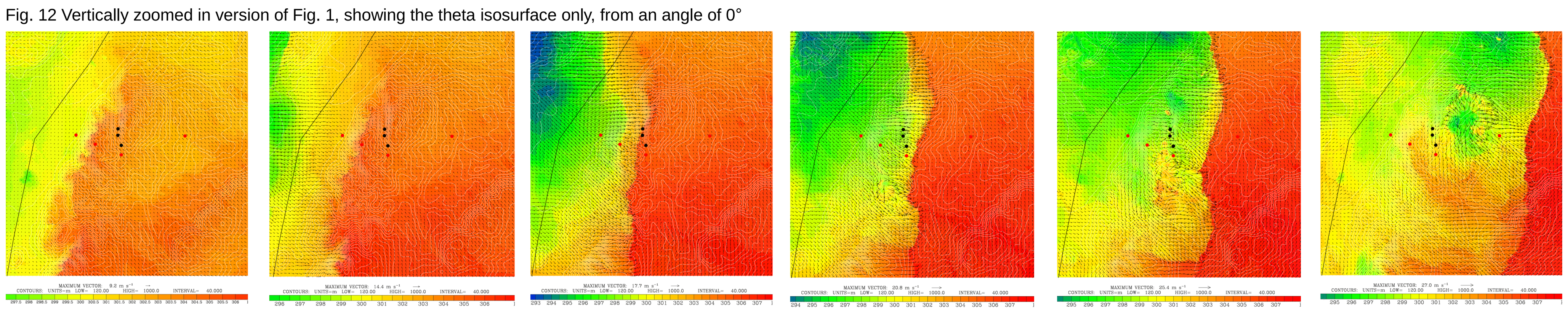
Fig. 13 Surface theta & 10m winds from domain 3 of the WRF simulation. The black line denotes the France-Germany national border, the red dots denote the COPS supersites (from left to right) R, H, M & S, and the black dots (from top to bottom) denote AWS's 8, 9 & 10.

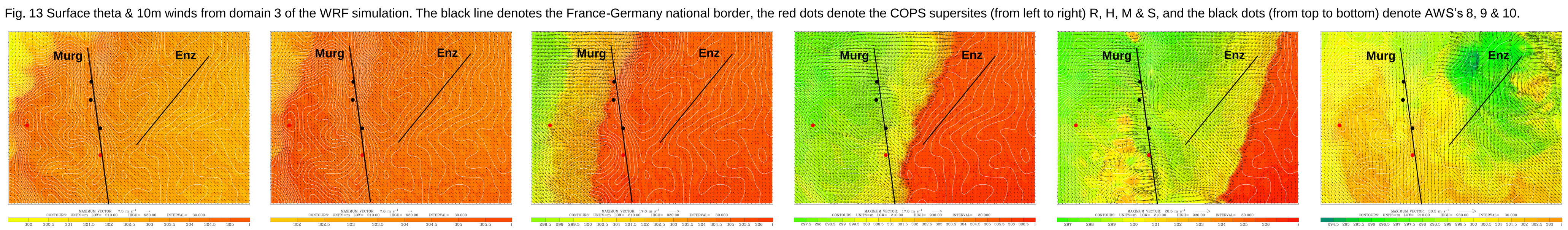

Fig. 14 As fig. 13 but zoomed into the Murg & Enz valley regions. The black line approximately denotes the axes of the Murg & Enz valley's.

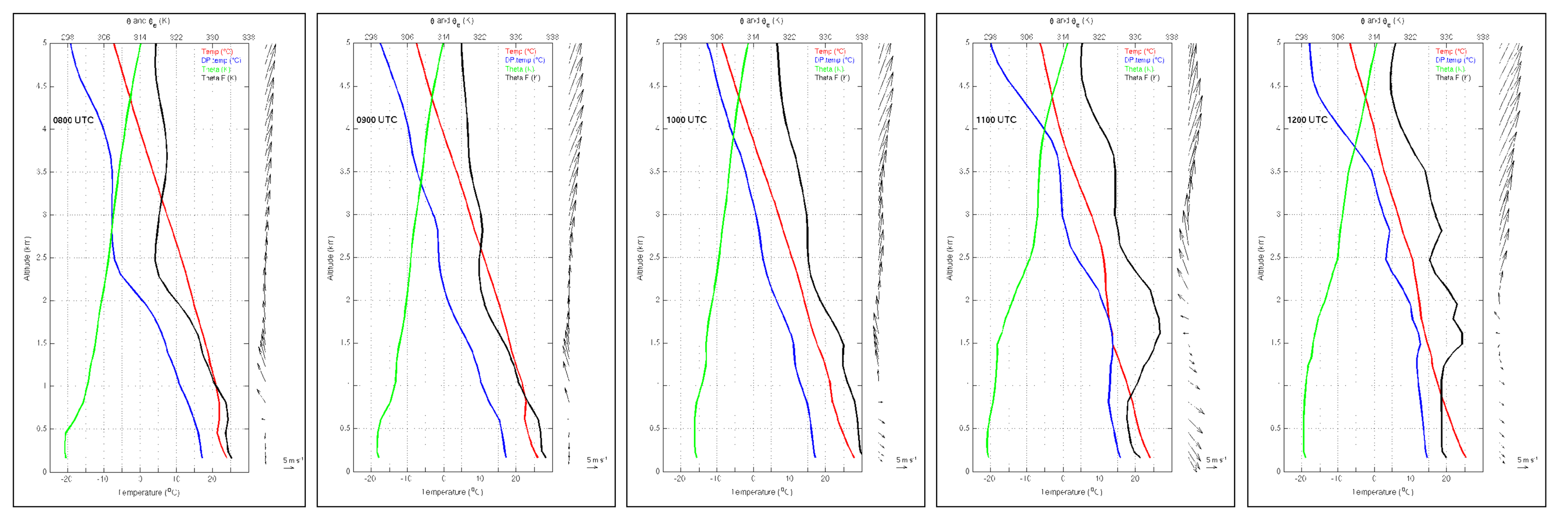

Fig. 14 Profiles of temperature, dew point temperature, theta & theta E from the location of the COPS supersite R

5. Discussion & Conclusions

- Good overall simulation of mesoscale features of IOP9c by WRF
- Location of precipitation further west than observations - attributed to analyses & simulation start time because simulations (not shown) begun at 06Z represented locations better.
  - Longer spin-up time resulted in > vertical velocities aloft orography, thus precipitation was initiated earlier than observations
- The 09Z plot from fig.12 shows high theta in the Rhine valley, preventing the MCS outflow from reaching the valley floor
  - Temperature of the outflow air was still warmer than the night-time residual fog layer in the RV
- Upon reaching the Black Forest, the orographic barrier forced a steepening & intensification of the outflow bore, resulting in a line of high vertical velocity – development of the observed gust front ahead of the MCS frontal zone.
- Structure of the deformation of the gust front by orography captured well
- The Supersite R profiles in Fig.14 show a region of high θ_e between Z = 1-2km, after the passage of the frontal zone. This instability explains one mechanism the subsequent CI aloft the COPS orography.
- Orographic forcing & convergence from thermally-drive easterly flows (from other observations not shown), provide a further 2 mechanisms for the CI seen in both the model & the observations
- Channelling of flows out of the COPS region along the valleys, not well represented by WRF
  - Larger, convective & meso-scale flows govern the surface wind regimes, thus, suggesting further explanation why the precipitating cells form further upstream in WRF than in reality.

[1] WRF Model Homepage: http://www.wrf-model.org/index.php

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