The scientific goals of the COPS working group on convection initiation are

- exploration of the complete chain of atmospheric processes leading to precipitation over complex terrain;
- detecting/removing CI-related deficiencies in QPF of numerical weather forecast models.

To accomplish these goals in an integrated effort by many groups of the science community a number of scientific questions was expressed:

CI 1: What is most relevant for the heterogeneity of the boundary layer fields of key prognostic variables (differences in soil moisture, surface parameters, vegetation, orography, etc.)?

CI 2: How are small-scale inhomogeneities of atmospheric humidity, temperature, and wind in complex terrain related to CI?

CI 3: How is the diurnal cycle of CI related to processes at the surface and in the boundary layer and why is the diurnal cycle of convection not represented adequately in the models?

CI 4: To which extent do gravity waves and mountain waves initiate or inhibit convection?

CI 5: What is the relative importance of the large-scale flow versus local orographic and surface driven processes in determining the location, timing and intensity of convection in regions of moderate orography?

CI 6: Do aerosol particles influence CI?

MECHANISMS INITIATING DEEP CONVECTION OVER COMPLEX TERRAIN DURING COPS
By Christoph Kottmeier, Volker Wulfmeyer and the COPS team

Precipitating convection in a mountain region of moderate topography is investigated, with particular emphasis on its initiation in response to boundary-layer and mid- and upper-tropospheric forcing mechanisms. It is found that the initiation of precipitating convection can be roughly classified as being due to either: (i) surface heating and low-level flow convergence; (ii) surface heating and moisture supply overcoming convective inhibition during latent and/or potential instability; or (iii) mid-tropospheric dynamical processes due to mesoscale convergence lines and forced mean vertical motion. These phenomena have to be adequately represented in models in order to improve quantitative precipitation forecast.
Selected COPS cases are analysed and classified into these initiation categories. It is shown that convective systems are captured in considerable detail by sensor synergy. Convergence lines were observed by Doppler radar in the location where deep convection is triggered several hours later. The results suggest that in many situations, observations of the location and timing of convergence lines will facilitate the nowcasting of convection. Further on, forecasting of the initiation of convection is significantly complicated if advection of potentially convective air masses over changing terrain features plays a major role. The passage of a frontal structure over the Vosges – Rhine valley – Black Forest orography was accompanied by an intermediate suppression of convection over the wide Rhine valley. Further downstream, an intensification of convection was observed over the Black Forest due to differential surface heating, a convergence line, and the flow generated by a gust front.

The Figure shows a sketch of prevailing synoptic settings and orographic effects for convection initiation processes. The blue columns represent the conditions met during IOP 9c, IOP 4b, and IOP 8b. Signatures: 500 hPa flow (solid black), surface pressure systems (Low, High, dashed), warm fronts (red), cold front (blue), positive and negative vorticity advection (PVA, NVA), warm air and cold air advection (WAA, CAA), typical vertical profiles of potential temperature ($\Theta$) and equivalent potential temperature ($\Theta_e$) downstream the trough and ridge, surface orography (brown solid), components of the surface energy balance: radiation budget (G), sensible heat flux (H), latent heat flux (L), cloud coverage ranging from blue sky (1) over single convective cells (2 and 3), organised deep convection (4) to overcast sky with embedded convection (5).

Tab.: Classification of individual IOPs in three convection classes and class combinations.

<table>
<thead>
<tr>
<th>Type</th>
<th>Type I: Locally initiated convection</th>
<th>Type II: Convection favoured by large-scale lifting</th>
<th>Type III: Convection near convergence lines or frontal zones</th>
<th>Combination of Type I and II</th>
<th>Post-frontal cold air convection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numbers of IOP-days</td>
<td>12</td>
<td>5</td>
<td>15</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

There was a total of 18 IOPs during COPS. The complete life cycle of convective systems was captured. The long observation period of three months allowed for the investigation of a wide range of convective situations with different initiation mechanisms over complex terrain.
The lower boundary condition led to the evolution of different mesoscale processes so that even under different large-scale conditions boundary-layer processes significantly triggered and/or modified deep convection.

It is shown for IOP 8b (type I, Tab) that several hours before deep convection is initiated, convergence lines were observed in that area by radar, sodar, and lidar. This is much earlier than reported in other investigations (e.g. WILSON et al., 1998). The detection and propagation of mesoscale convergence lines was only feasible due to the high temporal and spatial distribution of remote sensing systems. That means the detection of these convergence lines facilitates nowcasting to a certain extent when adequate observations are available.

If in general the conditions for CI are favourable, due to advection of warm and moist air and mid-tropospheric lifting such as during IOP 4b (typ II, Tab), the spatial distribution of these variables turns out to be indicative for the region of preferred CI even when obtained from a coarser-resolution global model (GFS). These predictors have to be properly weighted compared to boundary layer and orographic influences, which on the one hand tend to suppress convection in extended lower regions upstream of mountains such as the Rhine valley while on the other hand orographically-induced convergence triggered convection over the mountain crests on IOP 4b.

Nowcasting of convection for IOP 9c (type III, Tab) may be degraded by intermediate suppression of frontal convection-related phenomena such as clouds and precipitation, when the mesoscale front passes over a wide valley such as the Rhine valley. Secondary downstream CI may then occur due to differential surface heating near the margin of the overcast region and/or by gust fronts.

All three IOPs prove to be appropriate prototypes representing the main trigger mechanisms of deep convection over complex terrain. It can be expected that by exploitation of the full data set of each IOP even a more detailed understanding of the contributing processes for CI can be achieved. Especially, use of aircraft, GPS, and high resolution lidar data will give additional information concerning CI-related processes. Additionally, these IOPs are excellent cases for studying the performance of mesoscale models concerning convective precipitation.

**DRIVING PROCESSES FOR DEEP CONVECTION OVER COMPLEX TERRAIN: COPS OBSERVATIONS AND RESPECTIVE COSMO SIMULATIONS**

By Ulrich Corsmeier and the COPS Team

Data of COPS IOP 9c measured at July 20, 2007 were used to analyse the interaction of convection initiating processes of different scales. A weak cold front passing the COPS area in the morning from west to east was further weakened over the Rhine valley and partly strengthened by a gust front resulting from a MCS behind the front. Further convection initiation appears from a thermally driven convergence zone east of the Black Forest and valley and slope winds over the low mountain range. This leads to a series of severe convective systems in front of the former cold front. Model simulations with COSMO-DE show a not sufficient representation of the sub synoptic scale convection driving processes. Although moisture convergence and CAPE are simulated roughly at the right location, they are not strong enough to initiate deep convection und subsequent precipitation.
The Figure shows a gust front reaching the northern Black Forest. There are still easterly winds in the East. The temperature gradient is increasing (14 K). There is high cloud coverage in the West (10 UTC, left). A convergence line is developing east of the Black Forest. The wind increases up to 6 ms$^{-1}$. The gust front is locally enhanced by orography. The temperature gradient is increasing an convection is initiated (left).

COSMO-DE simulated CAPE is increasing along simulated moisture convergence and observed gust front (~2500 J kg$^{-1}$). CI is detected by radar along the high CAPE line. Weak convergence causes CAPE line moving east and CAPE maximum near Stuttgart moving west and increasing. CI is observed in reality but not in the model (right).

The Figure shows a west to east cross section of COSMO-DE simulated vertical wind speed (left) and specific humidity (right) through the COPS area at the latitude of the Hornisgrinde supersite on July 20, 2007 at 11 UTC. At 8.4 E a maximum of specific humidity combined with vertical motion is detected, leading to horizontally enlarged humidity gradients. The maximum corresponds to the simulated CAPE maximum and to the gust front measured and moves eastward. But in contrast to reality the horizontal gradients are not strong enough to trigger sufficient vertical motion for convection initiation in the model.
FORECASTING SUMMER CONVECTION OVER THE BLACK FOREST: A CASE STUDY FROM THE COPS EXPERIMENT
By Evelyne Richard and the COPS team

On 15 July 2007, in a very warm but also very dry environment, an isolated short-lived deep convective storm developed over the Black Forest in the late afternoon. Very few of the high-resolution models involved in COPS were able to capture this event. Based on various Meso-NH simulations, the conditions leading to the development of the storm have been investigated and carefully checked against a variety of observations. Although the modelled storm tends to appear a few kilometres south of the observed one, it is clear that the triggering and propagation of the storm are strongly controlled by the presence of a low-level convergence line, roughly north-south oriented, located along the crest line of the Black Forest massif and propagating eastwards.

The Meso-NH forecast of July 15 storm appears fairly realistic. The initiation time, duration, and trajectory of the storm are quite well captured. According to the model, convection is mainly triggered by the convergence which developed in the lee of the southern Black Forest. Despite these good results, the positive bias found in the humidity fields has to be further investigated. The envisaged model intercomparison exercise on this case will help to clarify this issue and to understand why others models (e.g. COSMO-DE) were not as successful.

Streamlines and convergence at 1000 m ASL. The thick black line indicates the trajectory of the storm.

COSMO MODEL SIMULATION OF CONVERGENCE ZONES IN COMPLEX TERRAIN: A CASE STUDY FROM COPS
By Christian Barthlott and the COPS team

An isolated thunderstorm in southwest Germany and east France is analysed. On July 15, 2007 deep convection developed east of the Black Forest crest, although convective available potential energy (CAPE) was only moderate and convective inhibition (CIN) was high. Data analysis revealed that convection was triggered by updrafts penetrating the capping inversion of the planetary boundary layer as a result of low-level convergence. Although the numerical weather prediction model COSMO-DE of the German Weather Service (2.8 km grid resolution) simulated a convergence line and the evolution of a line of low clouds in good agreement with radar and satellite observations, no precipitating deep convection developed from this line of clouds. For an improved representation of orographic effects, simulations with a finer grid resolution of 1 km were performed. Despite almost optimal conditions, i.e.
moderate amount of CAPE and almost vanishing CIN, the updrafts required to overcome CIN were not reached in both model configurations. Although both simulations did not initiate deep convection, the results suggest that in an air mass convection situation without mid-tropospheric forcing, the simulated location and timing of convergence lines with coexistent large values of CAPE and low values of CIN can be used as diagnostic parameters for deep convection nowcasting.

The Figure shows vertical cross-sections of horizontal convergence and vertical wind speed at 1400 UTC along 48.19° N simulated with COSMO_2.8 (left) and COSMO_1 (right).

COSMO_2.8 succeeds well in reproducing the location and timing of the observed mesoscale convergence line and the subsequent formation of shallow clouds but generates no deep convection. Although the increase of horizontal grid resolution from 2.8 km to 1 km increases the strength of the convergence zone and the vertical wind speed, the vertical extent of the updrafts remains the same and the capping inversion inhibits the breakout of deep convection in the simulation. In comparison to the measured vertical wind speeds, the simulated ones are considerably smaller and, hence, considered to be decisive for the missing initiation of deep convection. Besides an accurate specification of the thermodynamic and kinematic fields, the results highlight the role of boundary layer convergence features for QPF. It is hypothesized that the lifting depth of a convergence line must be simulated well enough to correctly account for its triggering effect on deep moist convection. Although both simulations did not initiate deep convection, the results suggest that in an air mass convection situation without mid-tropospheric forcing, the simulated location and timing of convergence lines appropriate high CAPE and low CIN can be used as nowcasting tool for deep convection.

INFLUENCE OF THE WIND PROFILE ON THE LOCATION OF HOTSPOTS OF CONVECTION IN MOUNTAINOUS TERRAIN
By Martin Hagen and the COPS team

Radar observation of the initiation and life cycle of small convective cells during the COPS field campaign in south-western Germany and eastern France show a dependence on the prevailing wind profile. Several hotspots for convective initiation were identified. Orographic features favour convergent flow. On the days when weak winds were prevailing, cells developed over the crest line, whereas on days when strong westerly winds were observed the initiation of convection took place in the lee of the mountains within convergent flow.
Observations with radar during the COPS field campaign in Central Europe of isolated shower cells show a strong dependence on the orography and the prevailing wind field. The simulations with MesoNH were able to reproduce the observations in a quite realistic manner, even reproducing “hot spots” of cell initiation in relation to orography. The X-band radar at Bischenberg allowed for observations with high temporal resolution at one of the north-eastern hot spots. Convergence along ridges favours the initiation of convection.

INFLUENCE OF OROGRAPHY AND AEROSOLS ON THE MICROPHYSICS OF CONVECTIVE CLOUDS OBSERVED DURING COPS
By Alan Blyth and the COPS team

Analysis is elaborated of microphysical data gathered on 2 days during COPS with instruments on the BAe 146 research aircraft. High concentrations of ice particles larger than 150 μm were observed in the 11 July 2007 cloud at temperatures of between -3 and -8 °C. In contrast, on 15 July 2007, large ice particles were barely detectable. However, the concentration of small ice particles was significantly higher than observed in the 11 July cloud. This is possibly due to the higher peak concentrations of aerosols that were observed on 15 July consistent with the model prediction of the presence of Saharan dust and the venting of aerosols from the Murg Valley.
The Figure presents vertical wind speed and aerosol concentration measured on board the Bae 146 research aircraft on July 15, 2007 over the Black Forest.

The concentration of large ice particles was greater than expected from primary ice nucleation in 11 July cloud. The observations suggest that the Hallett-Mossop process of secondary ice particle production was active and it is likely that the high concentrations could be explained with this mechanism. There are some issues to resolve however. Observations were also made near the ascending tops of some of the clouds that formed near the famous, much-photographed 15 July cloud. The analysis offers interesting twists to consider for modelling this cloud: mainly high concentration of aerosols probably associated with Saharan dust; and also venting of aerosols out of the Murg Valley, which likely contributes to the high concentrations. There is some support from the observations, but more modelling and data synthesis needs to be carried out. Venting from the valley was observed on a few other days during COPS suggesting that not only are the valley flows responsible for the convergence lines that help with the initiation of convection, but they may cause transport of aerosols into the clouds. Thus it is possible that the orography played a significant role in altering the microphysical behaviour of the clouds that formed or advected over the Black Forest.

OBSERVATIONS OF CONVECTION INITIATION AND DEVELOPMENT FROM THE DOPPLER ON WHEELS RADARS AND COMPARISON WITH HIGH RESOLUTION WRF SIMULATIONS
By Lindsay J. Bennett and the COPS team

Two mobile X-band Doppler on Wheels (DOW) radars were operated during COPS. Their objectives were to (1) provide high resolution wind fields in regions not covered by the operational radar network, (2) observe areas of convergence and determine their role in the initiation of convection, and (3) observe the evolution of convective cells and the influence of the terrain on their propagation. Observations from the DOWs during IOP15a, 12 August 2007 are presented and compared with simulations using the Weather and Research
Forecasting model WRF. Early results show that the model simulations of the timing and location of precipitation compare well with the observations and suggest that the clouds formed as a result of converging upslope flows.

The Figure shows examples of simulated 10 m horizontal wind vectors overlaid on orography. The WRF model runs were initialised with GFS analyses. A subsection of the inner domain is shown at (a) 0700, (b) 0900 and (c) 1000 UTC. The black dot marks the location of DOW3. At 0700 UTC down-valley and down-slope winds are occurring. The wind direction is southerly along the Murg and Nagold valleys and south-westerly along the Enz and down the eastward facing slope. By 0900 UTC, the wind direction has shifted 180 degrees to a northerly flow along the centre of the valleys and to an upslope north-easterly or northwesterly along the valley sides. These flows lead to areas of convergence that result in the development of clouds by 1000 UTC. Clouds develop widely across the northern Black Forest but those that precipitate are confined to the eastern slope (not shown).

OBSERVATIONS AND MODELLING OF FLOWS OVER COMPLEX TERRAIN - A CASE STUDY FROM THE COPS FIELD EXPERIMENT

By Victoria Smith and the COPS team

The case study of IOP 9c (20 July 2007) is characterised by forced convection embedded in surface frontal zones. The main features of that case are:

- Highly complex propagation and development of MCS over the COPS region
- Complex orography modified, organised and intensified associated cold pool gust front structure
- CI within the frontal zone, in response to orographic modification and uplift, with instability aloft, and convergence east of the Black Forest
- A squall line of convective activity develops from re-organisation of MSC outflow
- The case presents the opportunity to understand key dynamical processes associated with mesoscale convective flow over complex terrain

Observations of the COPS instrument network

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

The Figure shows the orography and the location of surface Automatic Weather Stations and the COPS supersites on the left. The stations are numbered approximately according to the time of the gust front passage. On the right, Θ for all AWS stations during MCS outflow passage is shown. It is 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 and channelling in controlling the valley flow regimes.

**Model Setup used for simulations**

- Weather Research and Forecasting (WRF)
- Initialised with ECMWF analyses and started at 00 UTC on 20 July, 2007
- Three nested grids are used, with resolutions of 2.7 km, 900 m and 300 m
- Convection explicitly resolved in middle and inner domain
- Morrison Microphysics scheme: Double-moment for ice, snow, rain and graupel for cloud-resolving simulations.
Isosurfaces of theta $\approx 300$ K and vertical wind $\approx 2$ms$^{-1}$ are shown for the Black Forest and the Rhine valley. Crosses denote the locations of the COPS supersites (from left to right) V, R, H, M and S. The black line indicates the German-French border.

**Conclusions**

- There is a good overall simulation of mesoscale features of IOP9c by WRF.
- The location of precipitation is further west than the observations. This is attributed to the analyses and simulation start time, because simulations begun at 06 UTC represented locations better.
- Longer model spin-up time resulted in higher vertical velocities aloft orography, thus precipitation was initiated earlier than observations.
- At 09 UTC, higher theta values in the Rhine valley prevent the MCS outflow from reaching the valley floor.
- The temperature of the outflow air was still warmer than the night-time residual fog layer in the Rhine Valley.
- Upon reaching the Black Forest, the orographic barrier forced a steepening and intensification of the outflow bore, resulting in a line of high vertical velocity. This initiates the development of the observed gust front ahead of the MCS frontal zone.
- The structure of the deformation of the gust front by orography is captured well by the model.
- Orographic forcing and convergence from thermally-driven easterly flows, provide a further mechanisms for the CI seen in both the model and the observations.
- Channelling of flows out of the COPS region along the valleys, not well represented by WRF
- Larger, convective and meso-scale flows govern the surface wind regimes, thus, suggesting further explanation why the precipitating cells form further upstream in WRF than in reality