3 TRACHT Atlantic

3.1 Synoptic Conditions (8 August – 16 August 1997)

On August 8 a ridge from the Azores high extends from the Middle Atlantic over the British Isles towards Northern Scandinavia (Fig. 3.1a). A weak cut-off low is placed west of the Iberian Peninsula. A zones wit a deep tropopause containing polar air masses stretches along the northern edge of Canada.
During the following days this tongue moves southeastward and forms a large, intensive vortex over the Atlantic, which transforms into a cut-off low (Fig. 3.1b). It replaces the older and smaller one, which can be found over the Mediterranean Sea south of France. Central Europe is influenced by a high-pressure zone leading to near surface ozone concentrations up to 100 ppb in Germany (see Memmesheimer et al., 2000) and France (Tulet, 2003). A frontal system over Western Europe causes southerly winds and uplifting.

3.2 Blocking

Blocking means an interruption of the general westerly flow caused by a deformation of the pressure and temperature fields in the mid-latitudes. A description of development and structure of blocking events can be found by Berggren et al. (1949). A definition and climatology of blocking are given by Rex (1950a,b). A recent study on a blocking climatology based on potential temperature on potential vorticity surfaces is published by Pelly and Hoskins (2003). There are two common types of blocking. The first is can be described as a dipole with warmer air in the north and cold air in the south. The second type – often called Ω-pattern – has a threefold structure. Two (cold) lows n the western and eastern flank of a (warm) high-pressure ridge. Both can be found during the episode. The beginning of the episode - on August 8 gives an example of a dipole structure (Fig. 3.1a). On August 12 the meteorological situation demonstrates a fully developed Ω-pattern (Fig. 3.1b). In effect, the upper tropospheric flow patterns were disturbed during the whole episode.

The tropospheric cold tropospheric air masses (indicated by an upward deformation of the potential temperature lines in Fig. 3.8) correlate with tropopause depressions. In the stratosphere the situation reverses and the cut-off low is warmer than the surrounding areas. This surprising situation is caused by sinking air masses southward transport of air from the warm polar summer stratosphere. The compensation with relatively flat lines of potential temperature is at about 300 hPa with a potential temperature near 330 K (Fig. 3.8). The high tropopause within the region dominated by the ridge consists of warm tropospheric air from the south.

a)

b)

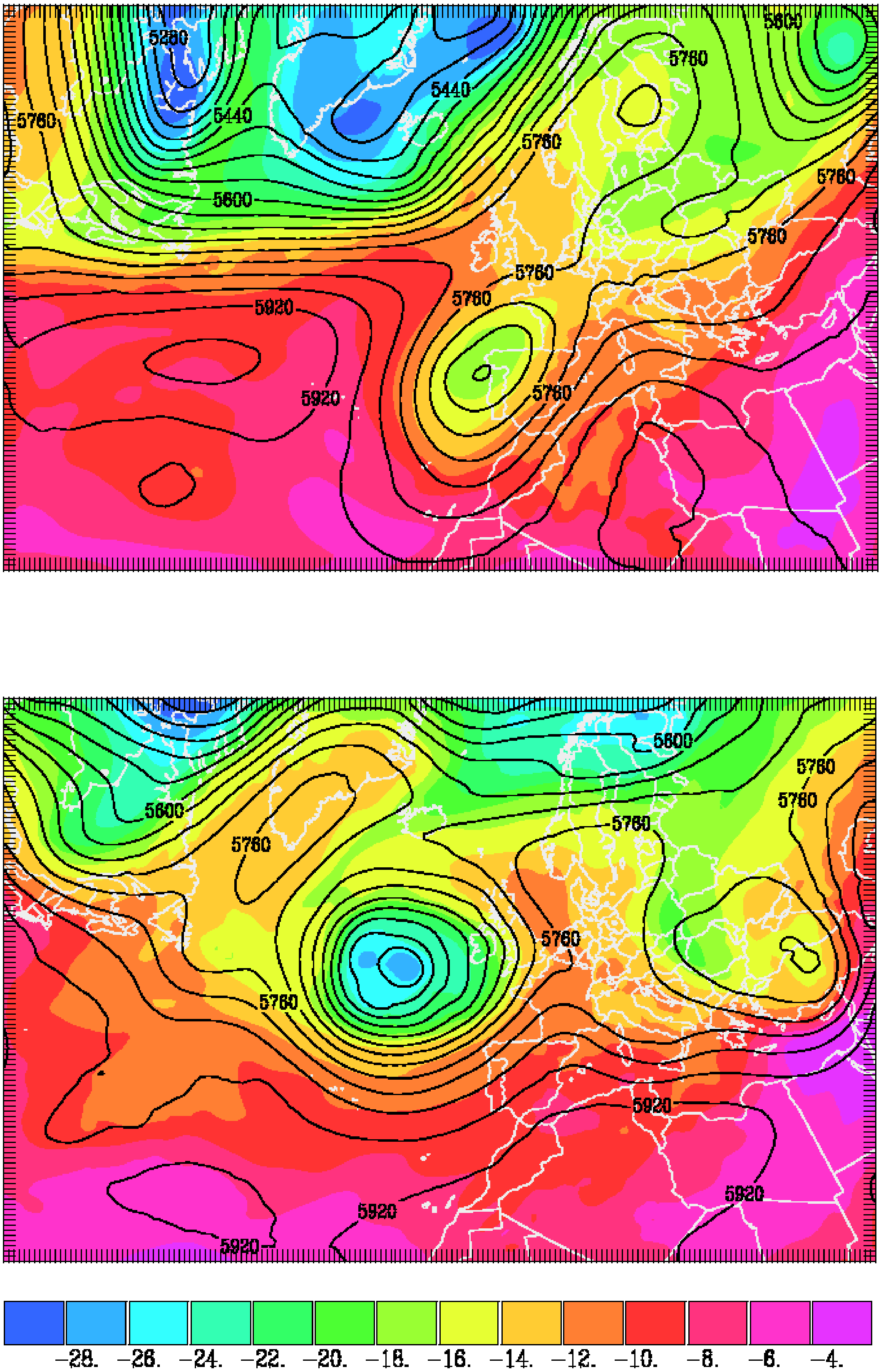


Figure 3.1: MM5 simulation: Temperature [°C] and geopotential height [gpm] at 500 hPa.
a) Upper part: 8 August, 0 UTC; b) lower part: 12 August, 0 UTC.

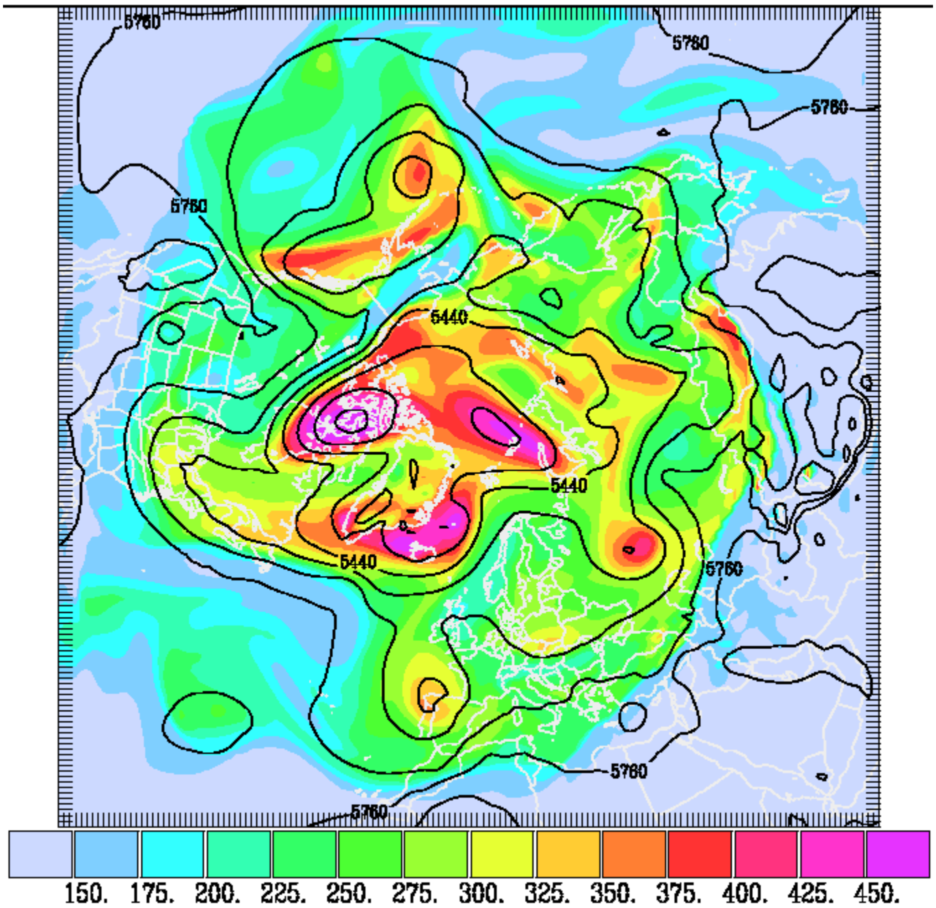


Figure 3.2: MM5 hemispheric simulation: Tropopause height [hPa] (2PVU plane) and relative topography 500/100 hPa [gpm]. Date: August 7, 0 UTC.

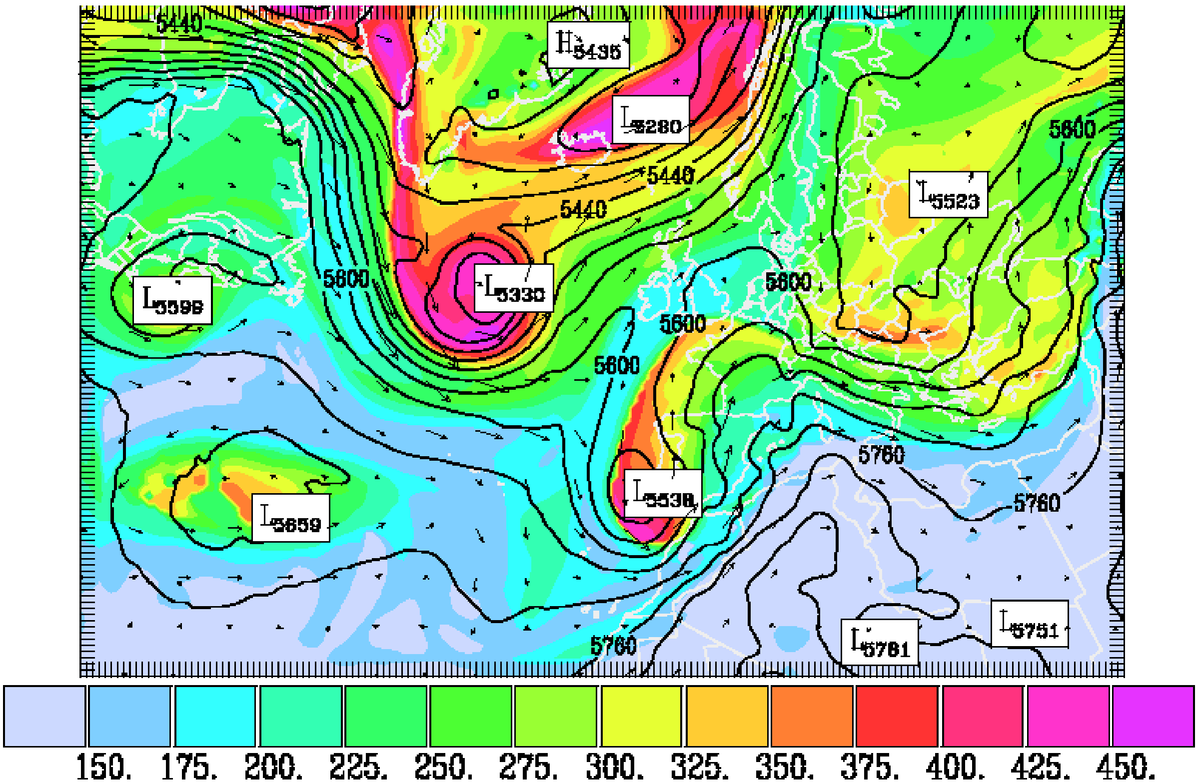


Figure 3.3: MM5 simulation TRACHT Atlantic domain: Tropopause height [hPa] (2PVU plane), relative topography 500/100 hPa [gpm] and horizontal wind at 300 hPa [m/s]. Date: August 8, 0 UTC.

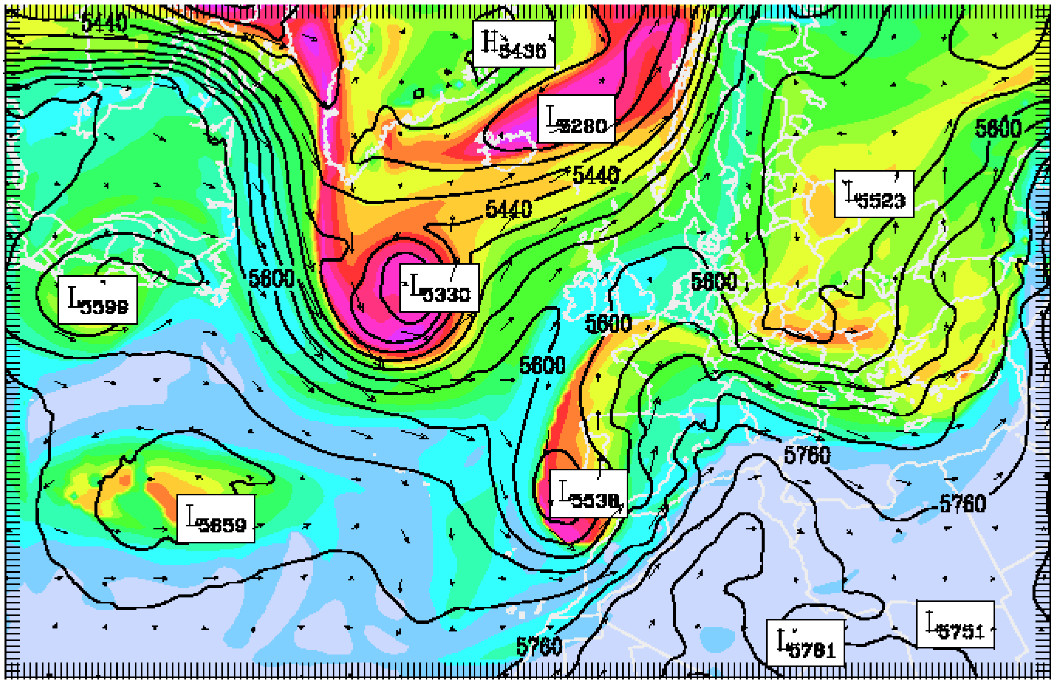


Figure 3.4: As Fig. 3.3 but for: August 10, 0 UTC.

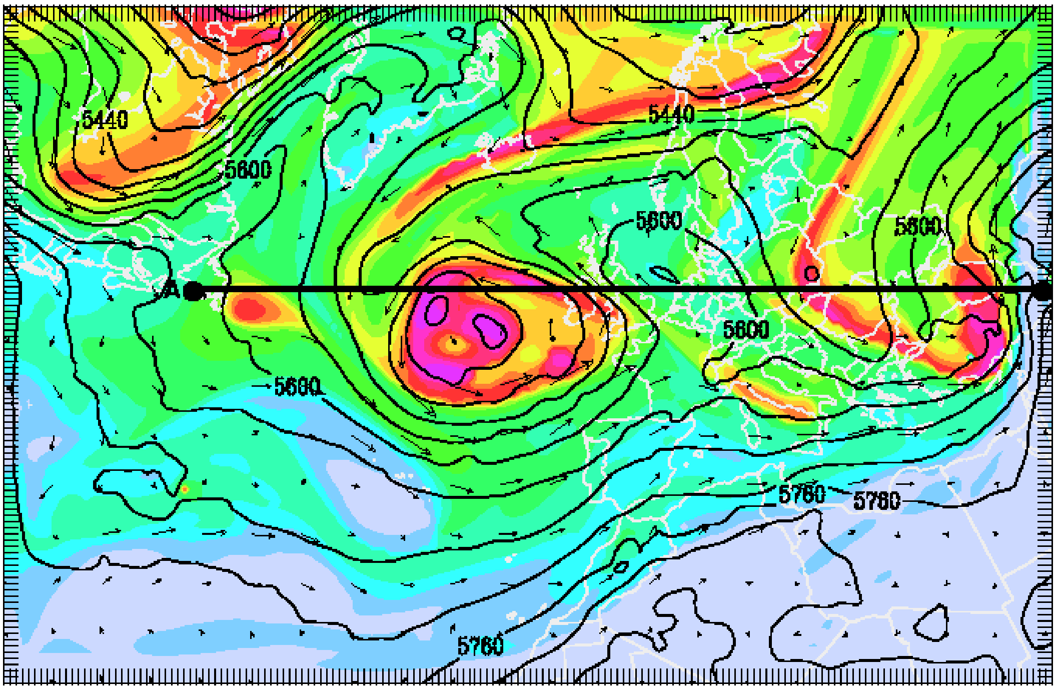


Figure 3.5: As Fig. 3.3 but for: August 12, 0 UTC. The thick line marks the location of the cross-section in section 3.

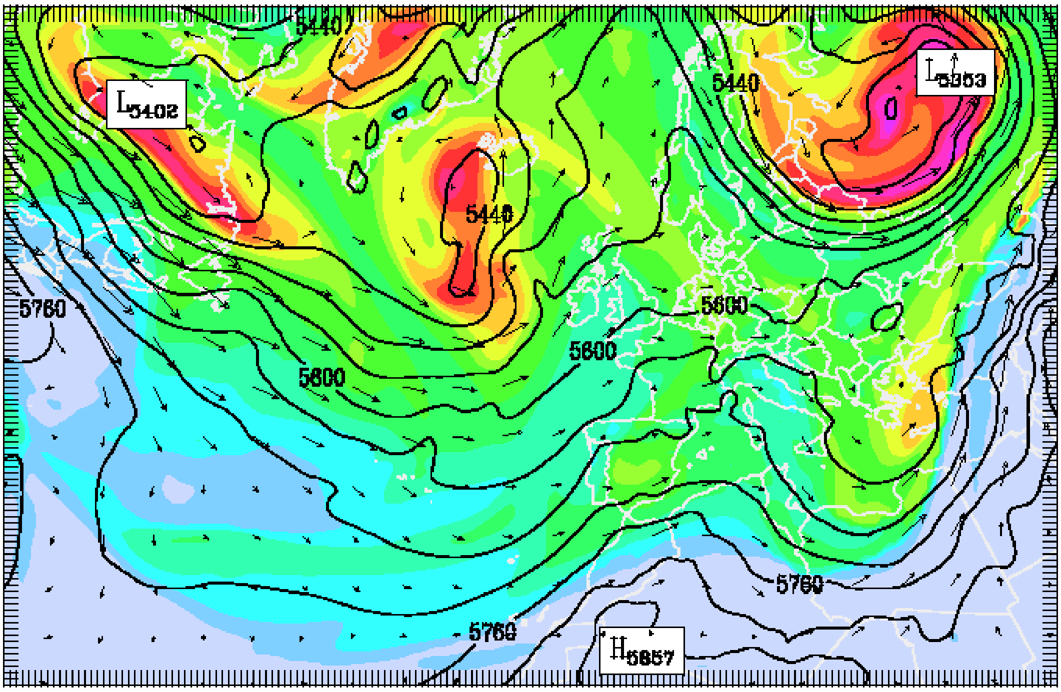


Figure 3.6: As Fig. 3.3 but for: August 14, 0 UTC.

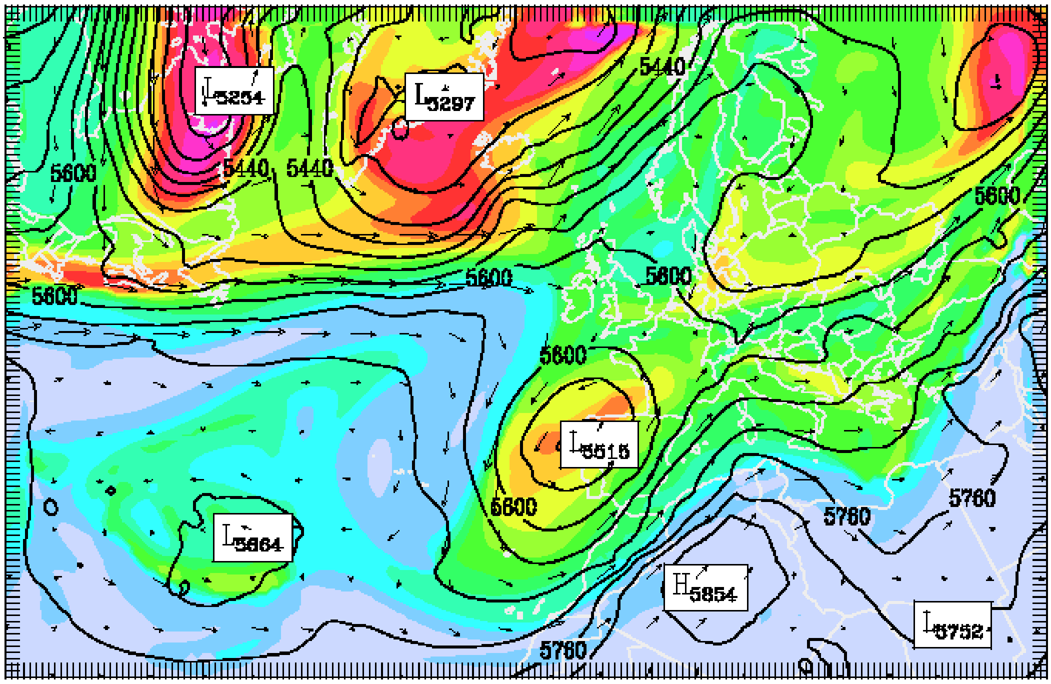


Figure 3.7: As Fig. 3.3 but for: August 16, 0 UTC.

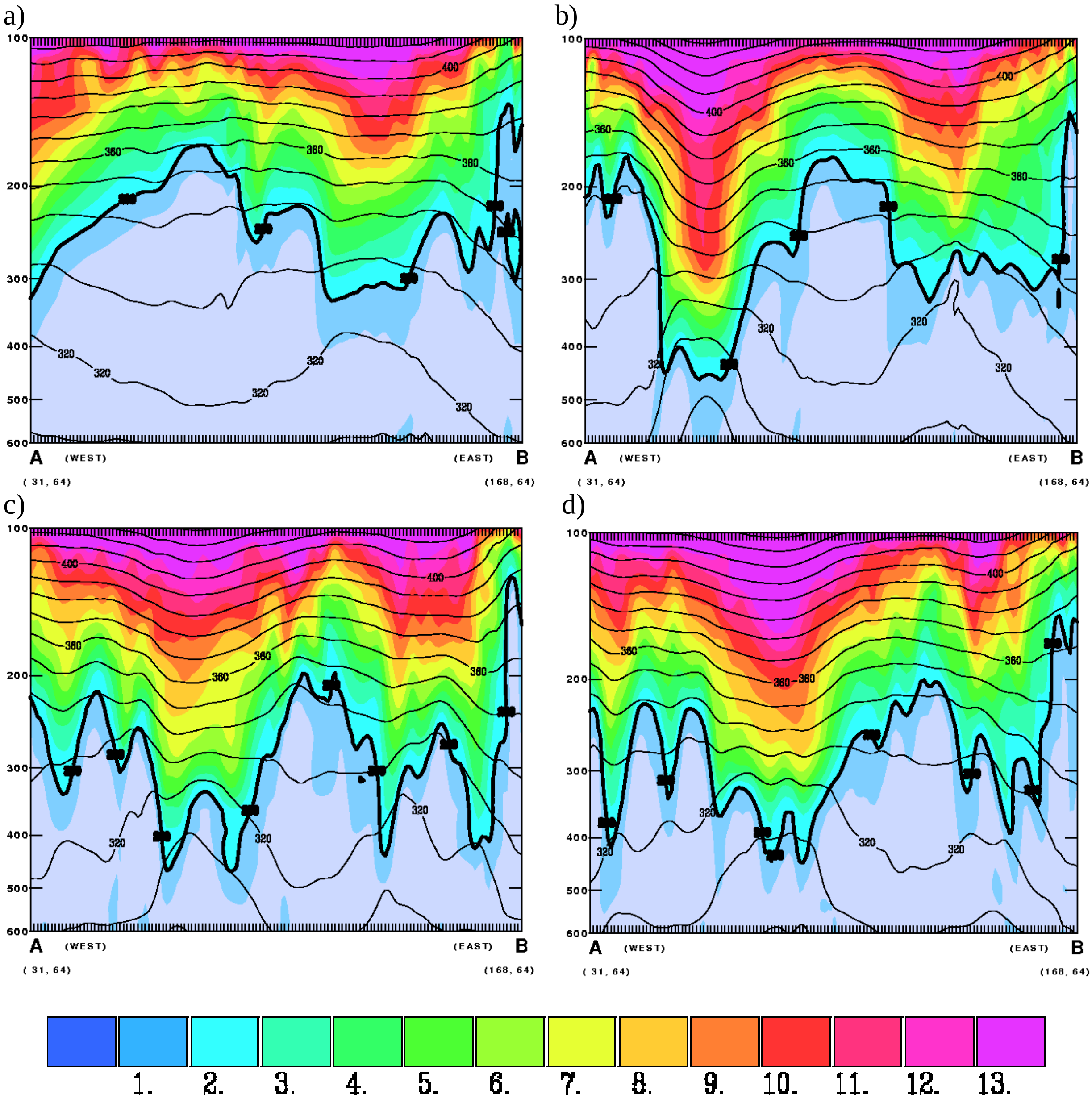


Figure 3.8: Vertical cross section: Potential vorticity [PVU] (coloured), tropopause height [hPa] (as 2 PVU-line; thick line) and potential temperature [K] (thin lines). From upper left to lower right: a) date 8 August, 0 UTC, b) 10 August, 0 UTC, c) 12 August, 0 UTC, d) 14 August, 0 UTC. The extension of the cross-section line is indicated in Fig. 3.5.

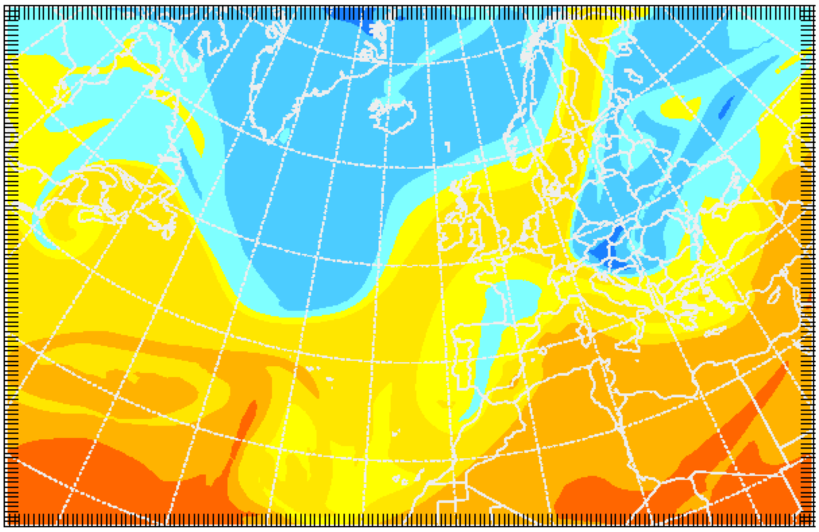
3.3 Origin of Air Masses

The cut-off low originates in polar latitudes – as the polar centric view on Fig. 3.2 indicates. Although there is a significant downward vertical advection (section 3.5 and Fig. 3.10), the horizontal transport is pre-dominant (Fig. 3.9). During the quasi-stationary phase (12. /13.August) stratospheric and tropospheric air masses are able to enter to vortex (Fig. 3.9). In addition, diabatic processes cause an erosion of the cut-off low. So, at the end of the event - after August 14 – the cut-off low contains no more pure polar stratospheric air, but a mixture of tropospheric and stratospheric contributions from polar to subtropical latitudes, from the boundary layer to the stratosphere. Air parcels from Africa and Europe (Fig. 3.9) are included as well al North-American air. The cut-off low can be regarded as a large-scale mixer for air masses. Therefore, this dynamic structure is important for stratosphere-to-troposphere exchange as well a troposphere-to-stratosphere exchange, as the vortex leaves the mid-latitudes after August 14 and re-enters the polar stratosphere.

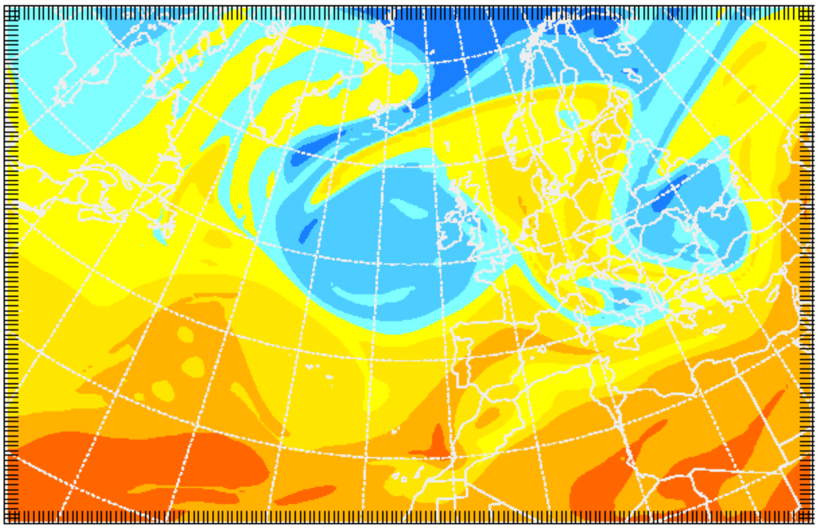
The central part of the Ω-structure is a region were upward transport takes place (Fig. 3.10). In a zone from North Africa over Western Europe to Scandinavia there is advection warm air towards the north. Ahead of a frontal system, boundary layer air is lifted up to the tropopause region. There, to branches develop: The first branch extends with a cyclonic curvature south of Iceland. It enters the vortex from the northwest. The second branch undergoes an anticyclonic motion and transports low level air in the upper troposphere southward behind the stratospheric streamer in the east of the Ω-structure.

The eastern pattern of the blocking pattern is placed over Eastern Europe and the Black Sea. A typical streamer of polar stratospheric air is formed there. It reaches downward to about 6 km causing stratosphere-to-troposphere exchange. This part the structure is more variable compared to the ridge and the cut-off low. Therefore, it is more difficult to simulate it with respect to the exact location and timing.
There are several regions were air is lifted from the lowermost troposphere to the UTLS – mainly related to ridges and frontal zones. Downward transport is related to the cut-off lows and streamers. Within these structures stratospheric air arrives at tropospheric levels, but no air from above 100 hPa could be detected in the UTLS (here 215 hPa and 300 hPa) within the model simulation. The mechanisms of fast vertical transport seem to reach not so far into the stratosphere. In the opposite direction tropospheric air could not be found above this level. This upward transport affects not only the “artificial” tracers, but can be found for typical anthropogenic pollution tracers like CO (Fig. 3.12) – which has enhanced concentrations in the upper troposphere.
No direct transport from the stratosphere to the lowermost troposphere was identified in the simulations. Although, there are regions were at least air masses from the upper troposphere arrive at the 700 hPa level (~3 km, Fig. 3.13).
The CoL-vortex and related dynamical structures of the blocking cause are active throughout the troposphere and lower stratosphere (Fig. 3.11).
The results of TRACHT demonstrate the huge importance of blocking events for the latitudinal transport. The disturbance of the usual westerly flow is coupled with a strong enhancement of the interaction between the mid-latitudes, the subtropics and the arctic regions. Stratospheric ozone reaches into the middle troposphere over the Mediterranean Sea.
In the opposite direction, polluted air from North America and Europe enters the polar latitudes as well in the troposphere and the lower stratosphere.

a) Latitude Tracer August 10, 0 UTC



b) Latitude Tracer August 12, 0 UTC



c) Latitude Tracer August 14, 0 UTC

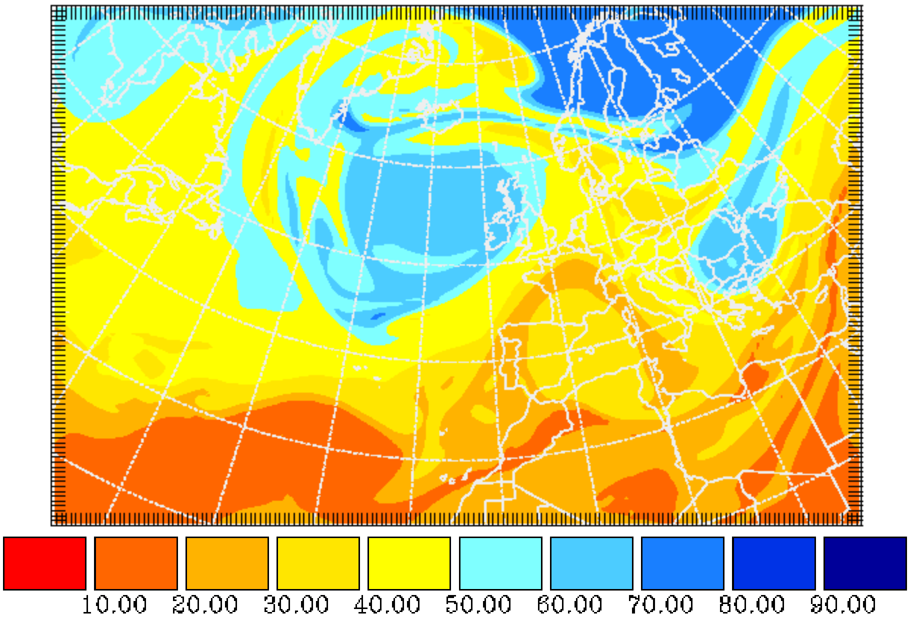
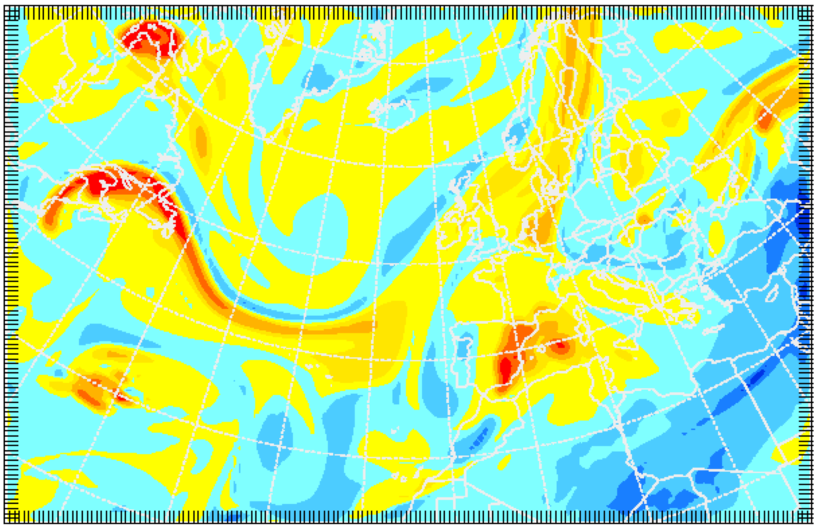
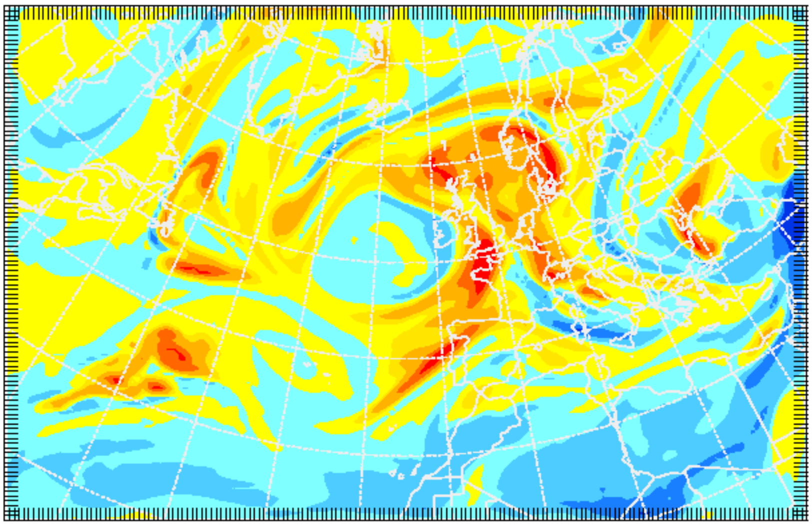


Figure 3.9: Latitude tracer at 215 hPa. a)-c) August 10/ 12/ 14 1997, 0 UTC

a) Pressure Tracer August 10, 0 UTC



b) Pressure Tracer August 12, 0 UTC



c) Pressure Tracer August 14, 0 UTC

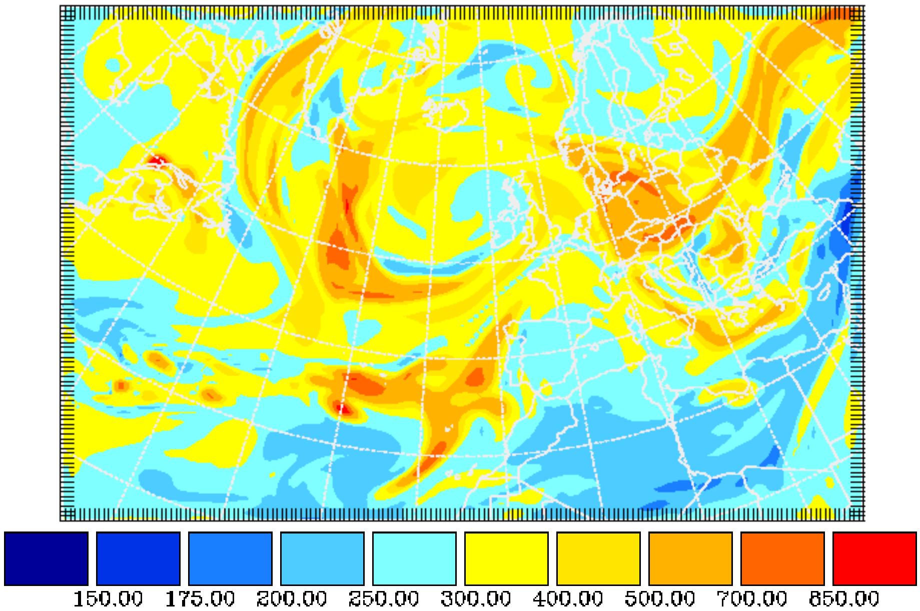


Figure 3.10: Pressure tracer at 300 hPa. a)-c) August 10/ 12/ 14 1997, 0 UTC

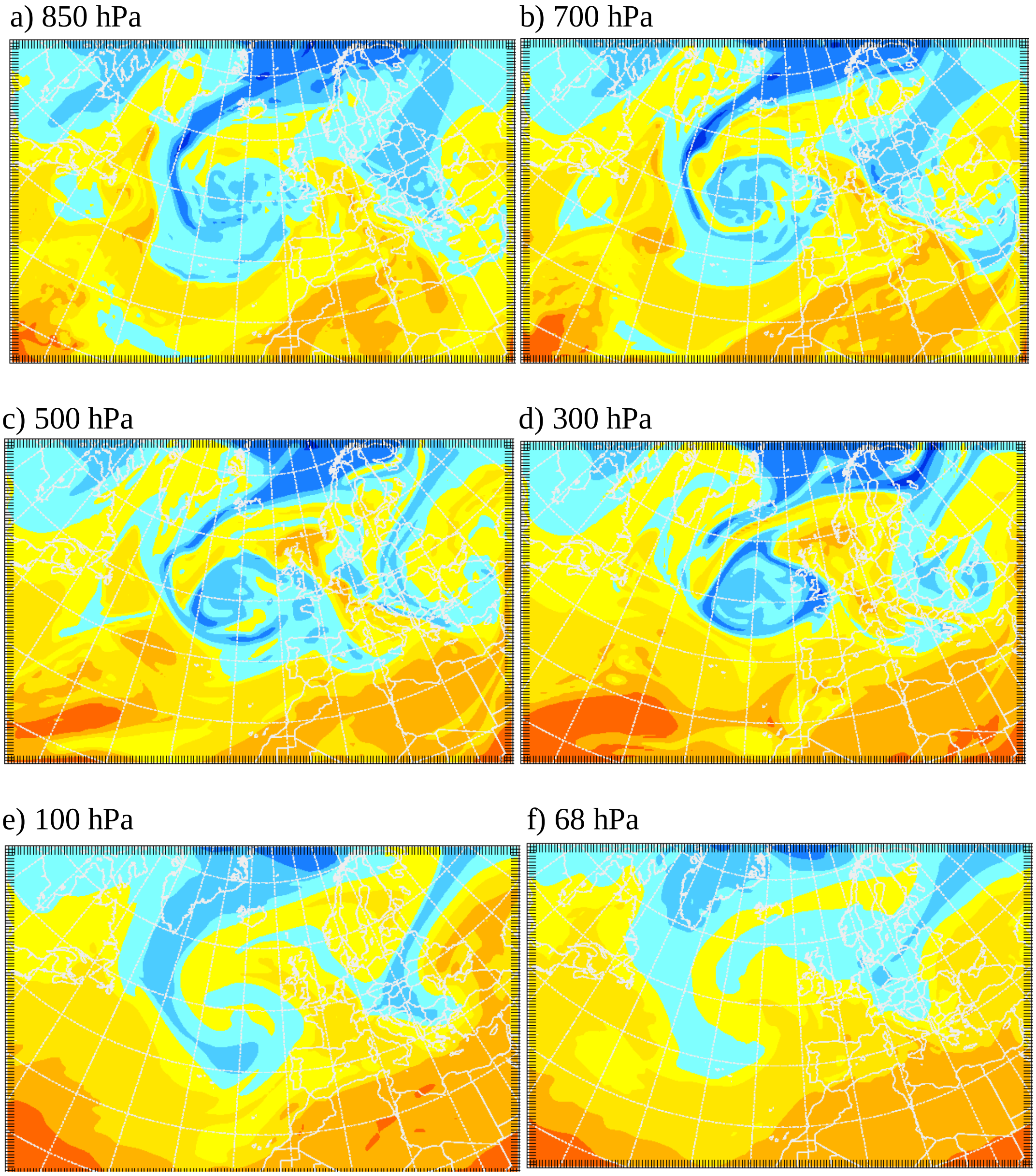


Figure 3.11: Latitude tracer 12 August 1997, 0 UTC. a) 850 hPa, b) 700 hPa, c) 500 hPa, d) 300 hPa, e) 100 hPa, f) 68 hPa.

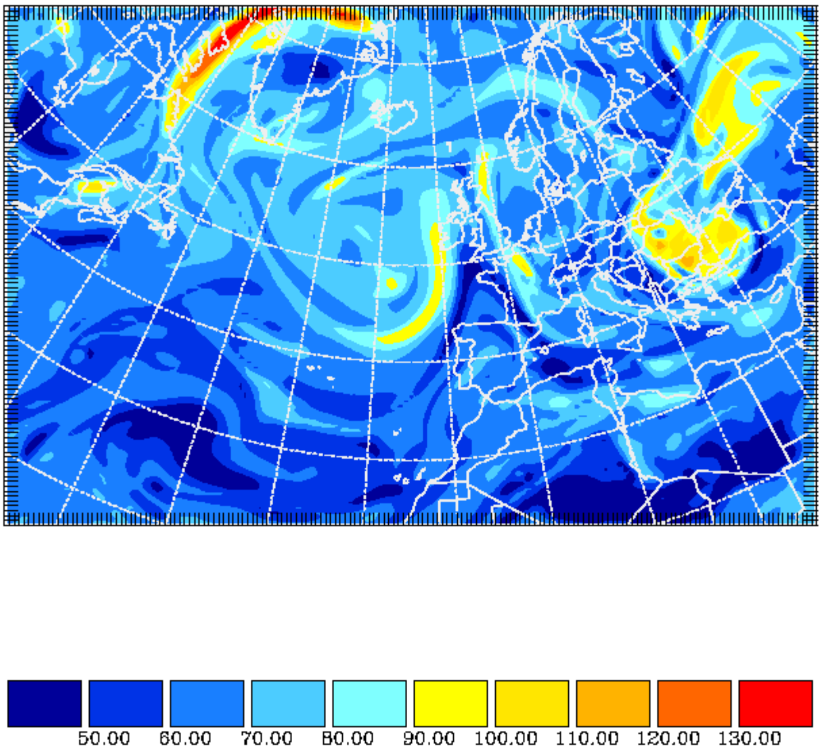


Figure 3.12: CO [ppb] at 400 hPa, 12 August 1997, 0 UTC.

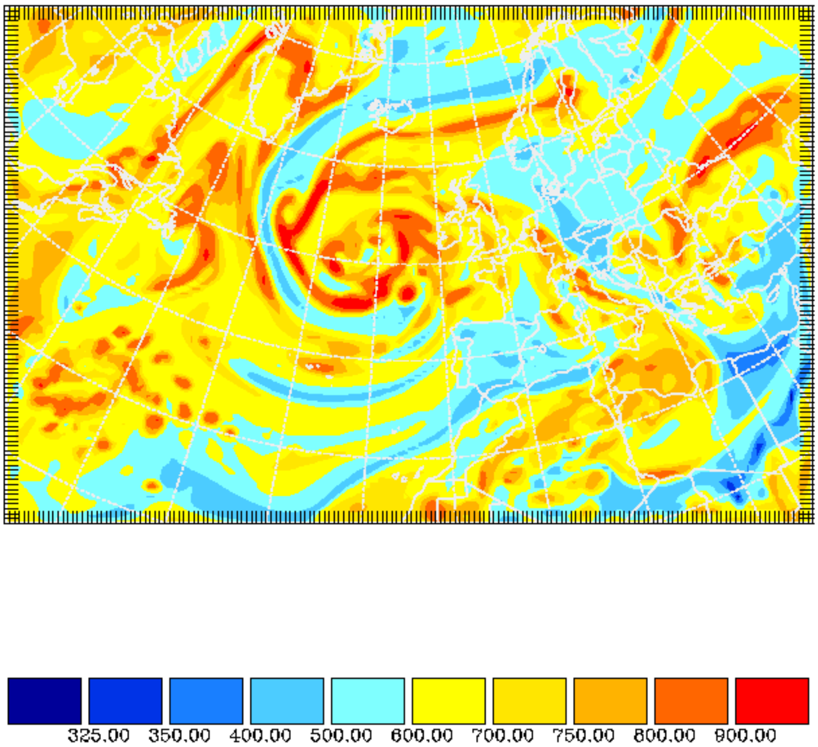


Figure 3.13: Pressure tracer at 700 hPa, August 12, 0 UTC.

3.4 Trace Gas Distributions

3.4.1 **Ozone**

Most prior studies about trace gas transport in the UTLS were upon ozone. There are many observation of ozone available – e.g. from ozone sondes, lidar or aircrafts (like MOZAIC). CRISTA is generally not able observe ozone far below the ozone layer. Therefore, within TRACHT the EURAD simulations for ozone have been compared with the MOZIC data (see TRACHT final report of Offermann et al., 2003 for details and references). The EURAD could reproduce the location and extension of the cut-off low very precise. The observed and calculated ozone concentrations reached nearly 500 ppb – which is very high for the height range of the air traffic routes (200-250 hPa). The EURAD simulations seem to have a small high bias compared to MOZAIC. The aircraft data shows more small scale variations which could not be resolved by the model. There are two possible explanations: First, the grid resolution of the model is still not fine enough to resolve small scale filaments. The second is that the aircraft emissions were missing for the simulations, which may be important on the North-Atlantic flight corridor (Shumann et al., 2000).

The CRISTA2 episode is one of the most prominent periods for high surface ozone concentrations in Europe in the year 1997 with boundary layer concentrations in the order of 100 ppb (see Fig. 3.15). The ozone production takes place in the southerly flow over Western Europe which gets partly lifted into the upper troposphere as seen from the tracer experiments described above. In addition, not only ozone is lifted, but also precursors. Therefore, additional fast photochemistry takes place in the free troposphere. The resulting “boundary layer ozone” in the UTLS has much lesser concentrations than the stratospheric ozone in the cut-off low. But such ozone plumes can be identified even the MOZAIC data (in the same way from the model calculations), were the anti-correlation between ozone and water vapour vanishes (see TRACHT final report of Offermann et al., 2003, page 70).

As several previous studies have shown, is the EURAD model able to simulate the ozone concentrations reasonably well. But the comparison with the ozone sondes at Hohenpeissenberg (TRACHT final report of Offermann et al., 2003, chapter 4.2.2) indicates that the agreement is worse for the stratosphere. It seems, that the height dependency of the ozone and potential vorticity differs from the findings obtained in other studies (for instance: Ravetta et al., 1999).

In general - due to the opposite vertical gradient - ozone is anti-correlated to water vapour or CFC11. Therefore, it is more suitable to study the downward transport. From the horizontal plots at various heights (Fig. 3.17) and the vertical cross-section (Fig. 3.18) the different behaviour of the different parts of the Ω-pattern can be seen. Near the surface the central part has the highest concentrations. Slightly increased values can also be found in the cut-off low region indicating horizontal transport from Europe and North America. The influence of the stratosphere can be seen down to about 600 hPa as well in the COL region as for the streamer in the east. In the central part relatively low concentrations (< 100 hPa) can be found up to about 150 hPa.

The cut-off low region is characterized of a mixture of tropospheric and stratospheric ozone levels up to about 300 hPa. Above that height a dominating stratospheric contribution must be stated.

3.4.2 CFC11

CFC11or Freon is an atmospheric trace gas which is chemically quasi-inert within the troposphere. The major loss process is transport to the stratosphere followed by degradation by photolysis. The photolysis of CFCs like Freon is the major source of stratospheric chlorine, which causes the depletion of the ozone layer. In addition CFCs are very efficient green house gases.
Freon has no natural sources. It was invented in 1928.The atmospheric concentrations increased steadily in the following decades
CFC11 has a very homogenous distribution throughout the troposphere. This increase has been stopped in the 90s, after the production of CFCs has been banned. Typical tropospheric concentrations during this period are about 270 ppt. Above the tropopause there is a vertical gradient, which gets steeper above 150 hPa in mid-latitudes.
The lack of sources and sinks on the short time-scale of the TRACHT episode and the availability of high quality data from CRISTA makes Freon the most suitable tracer for transport and exchange studies in the UTLS.
Within EURAD CFC11 is treated as an inert substance. The initial and boundary concentrations for the lower troposphere were derived from climatological values. Above 300 hPa the ROSE data were used. The average concentrations at the lower boundary of ROSE (at 316 hPa) were about 20-30 ppt lower than the climatological values. Vertical transport leads to an increase of the concentrations in the UTLS above the ROSE values (about +1 standard deviation), but still lower than the CRISTA data. Above that layer the average EURAD and CRISTA concentrations agree within +/- 1 standard deviation.
Due to the finer grid resolution EURAD produces finer mesoscale structures in the trace gas distributions. Horizontal and vertical transport causes steep gradients within the UTLS region. At 215 hPa (~11km) the typical concentrations are about 250 hPa in the southern half of the domain and lower Polar Regions. The trough - which forms the large vortex in the western part of the Ω-structure - reveals concentrations below 200 ppt.
On August 9 this trough enter the domain from western Greenland and forms the vortex on August 10 west of Ireland. In the following days freon-rich air from the south is advected northward and partly mixed into the vortex. On August 12 and 13 the concentrations in the vortex centre decrease to 170-180 ppt within the model simulation.
At all displayed heights strong latitudinal transport takes place, bring more polluted air towards the Arctic and cleaner air into mid-latitudes.

3.4.3 Water Vapour

Water vapour is the most important trace gas in the atmosphere. It forms clouds and precipitation. H_2O is highly relevant for climate and radiation. In addition, water vapour is a product of routine meteorological forecasts and analysis. Nevertheless the uncertainties about the H2O distribution in the UTLS are high. This is especially true for the low concentrations above the tropopause. There are large deviations between predicted fields from different sources and observations (see chapter 2.2.1).
The Nesting of the EUARD-model into the assimilated CRISTA data did enhance the abilities of the model to reproduce the concentrations of H_2O in the uppermost troposphere and lower stratosphere (see chapter 4 of the report: TRACHT-DATA) significantly.
Nevertheless the model did not adequately describe the very low concentrations in the CoL- and the streamer-region. The reasons for this are not completely clear. There may be an over prediction of the transport of water vapour into these structures from the outside. One has to keep in mind that water vapour was calculated in the meteorological model MM5 – for a correct treatment of the cloud physics – which is not a transport model.

The model performed better for regions with upward transport of moist air from below.
Water vapour is – like Freon - a tracer which decreases with height. But the gradients are much steeper. From figure 3.19 displays the distribution of H_2O at different levels. A number of high reaching bands of moist air – mostly from frontal systems - can be identified. One is located in the central part of the Ω-structure. Its vertical extension is up to the 145 hPa level. This zone splits into two branches over the northern North Sea. The first one enters the cut-off low region, the other one is transported eastward on the western side of the streamer. The cut-off low itself is indicated by very low concentrations. But the mixing process cause stronger variations within the vortex. The streamer in the east forms a sharp band of dry stratospheric air.

Ozone

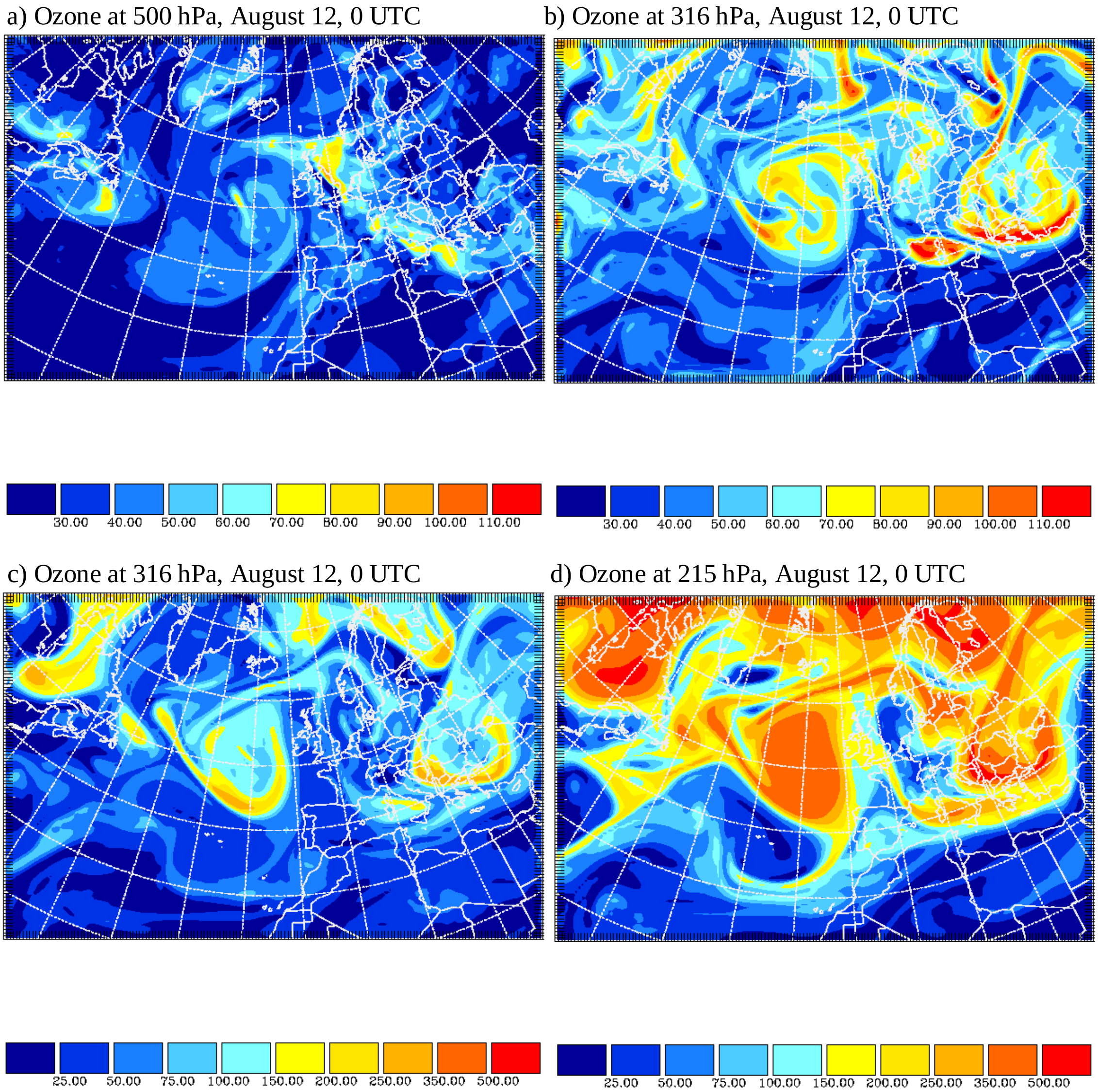


Figure 3.14: Ozone [ppb] at different heights, August 12, 0 UTC. From upper left to lower right: Near surface, 500 hPa, 316 hPa, 215 hPa.

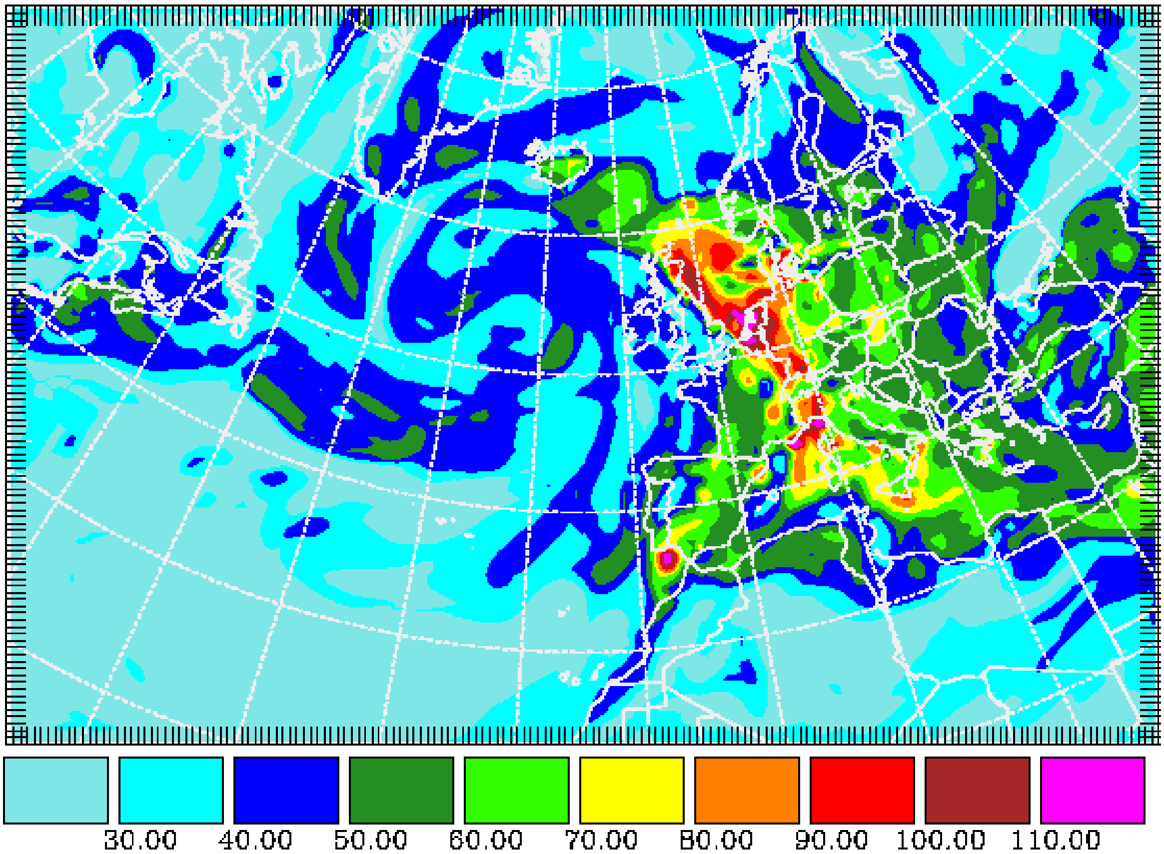


Figure 3.15: Near surface ozone concentration [ppb] 13 August, 15 UTC.

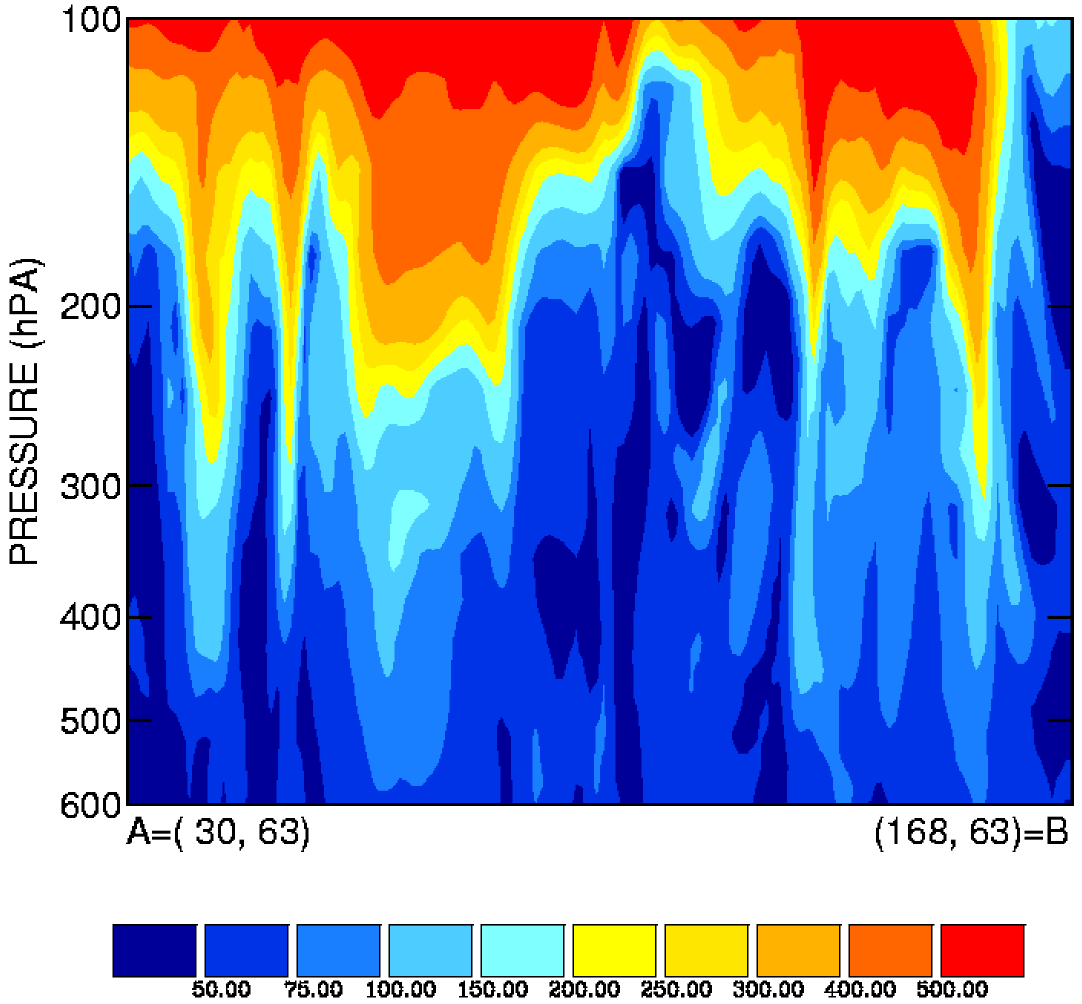
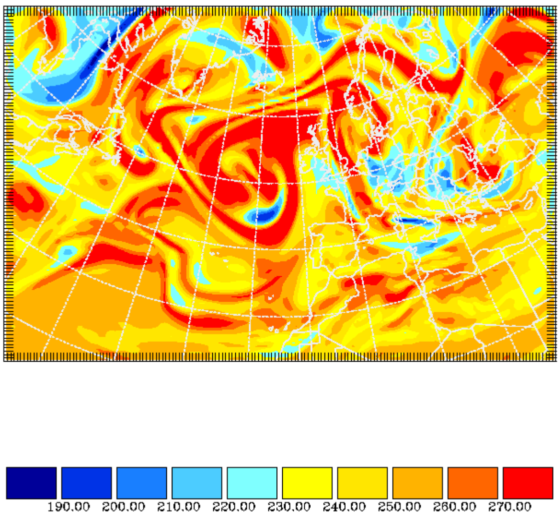


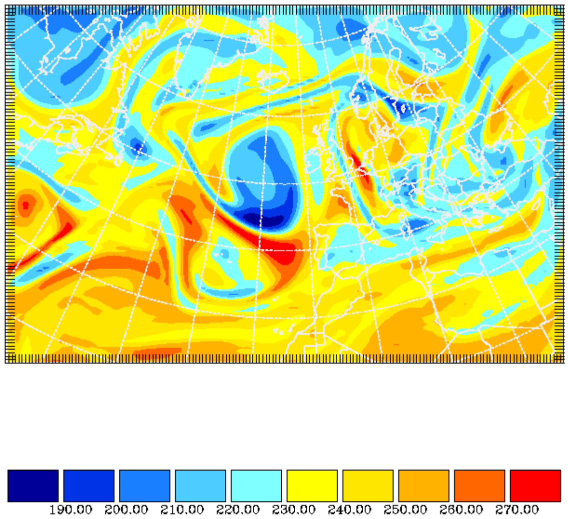
Figure 3.16: Ozone [ppt], on August 12, 0 UTC. The cross section line is indicated in Fig. 3.5.

CFC11

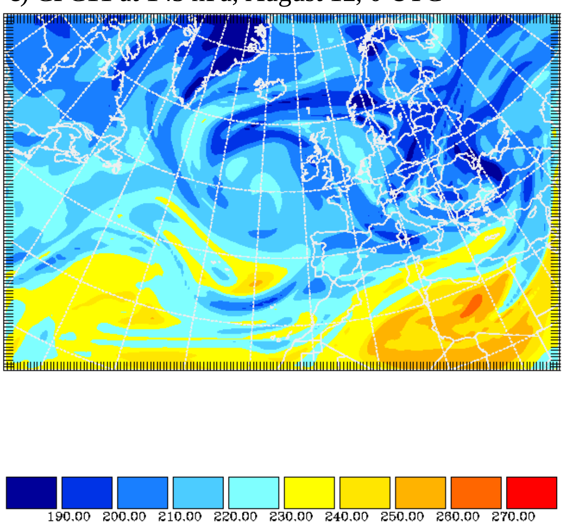
a) CFC11 at 316 hPa, August 12, 0 UTC



b) CFC11 at 215 hPa, August 12, 0 UTC



c) CFC11 at 145 hPa, August 12, 0 UTC



d) CFC11 at 115 hPa, August 12, 0 UTC

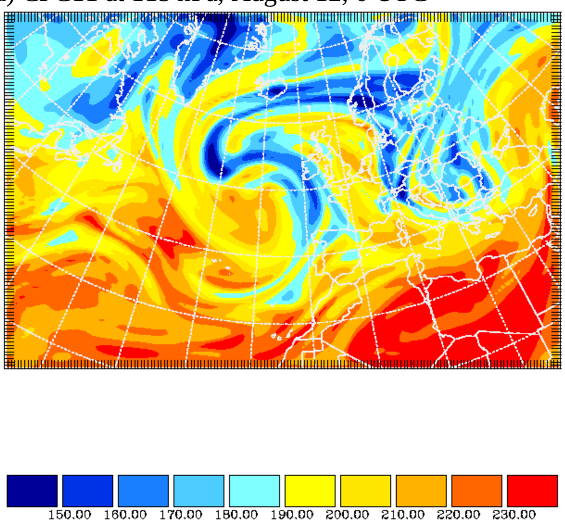


Figure 3.17: CFC11 [ppt] at different heights, August 12, 0 UTC. From upper left to lower right: 316 hPa, 215 hPa, 145 hPa, 115 hPa.

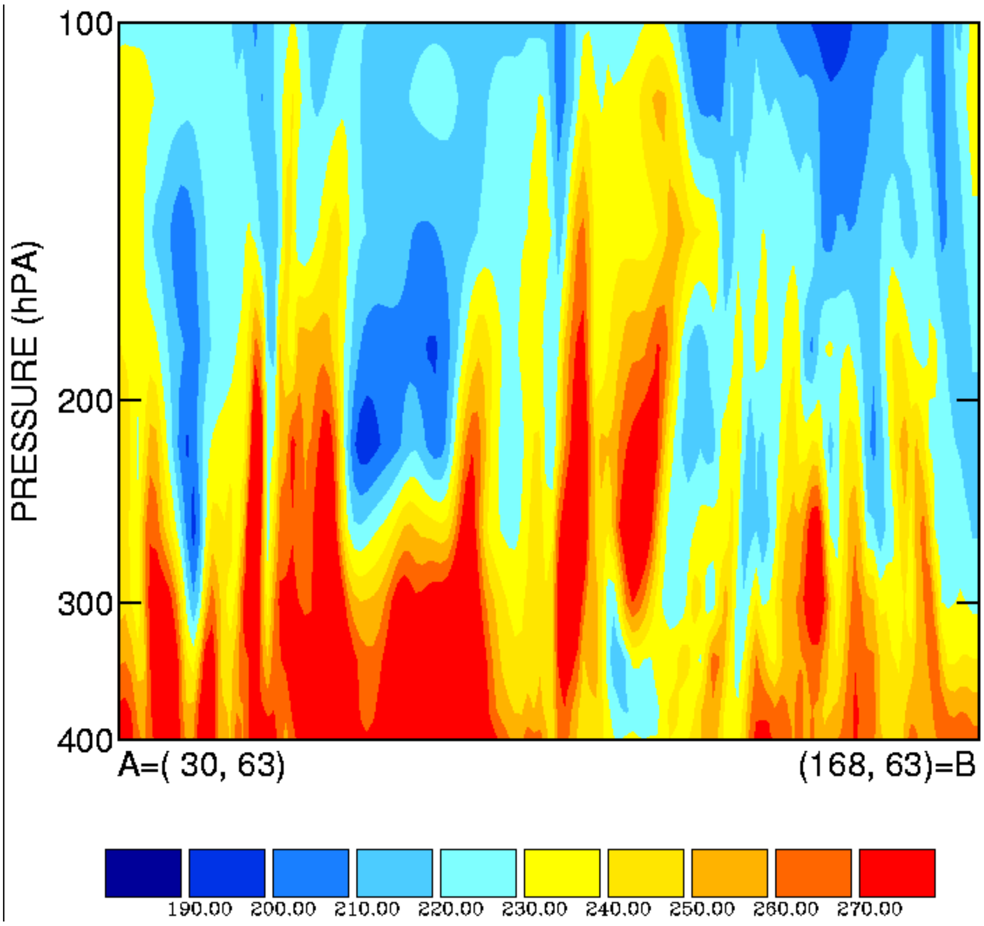
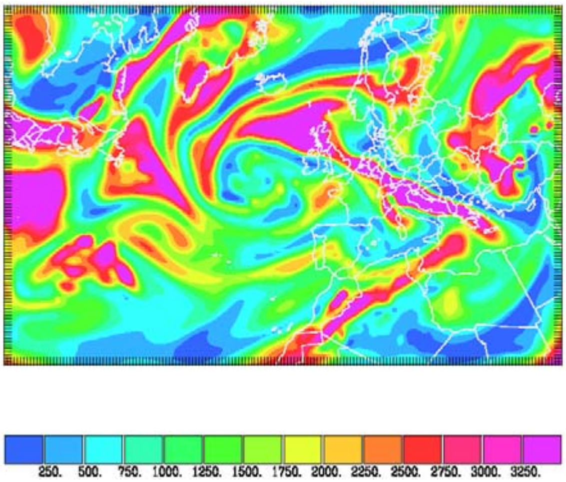


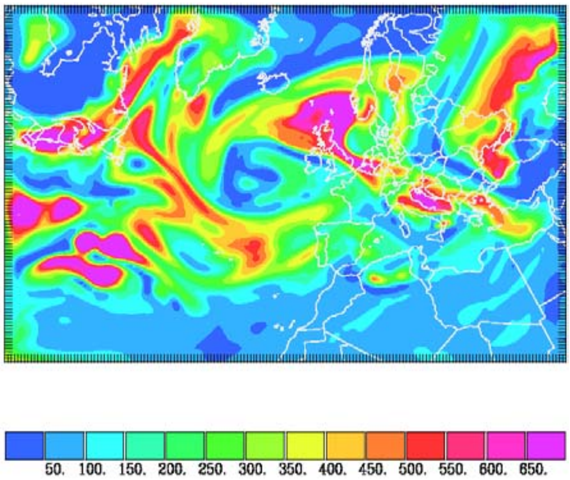
Figure 3.18: CFC11 [ppt], on August 12, 0 UTC. The cross section line is indicated in Fig. 3.5.

Water Vapour

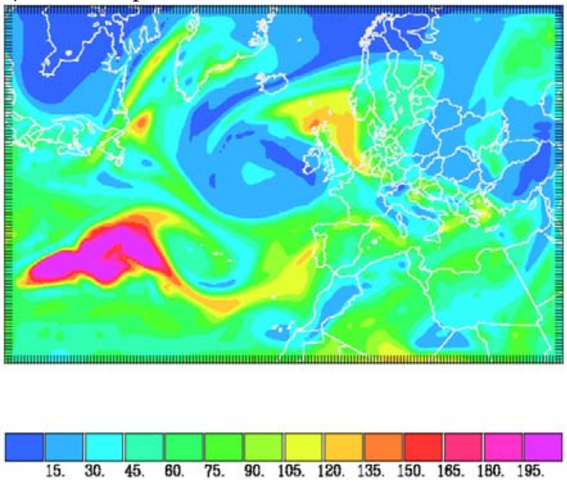
a) Water Vapour at 500 hPa



b) Water Vapour at 316 hPa



c) Water Vapour at 215 hPa



d) Water Vapour at 145 hPa

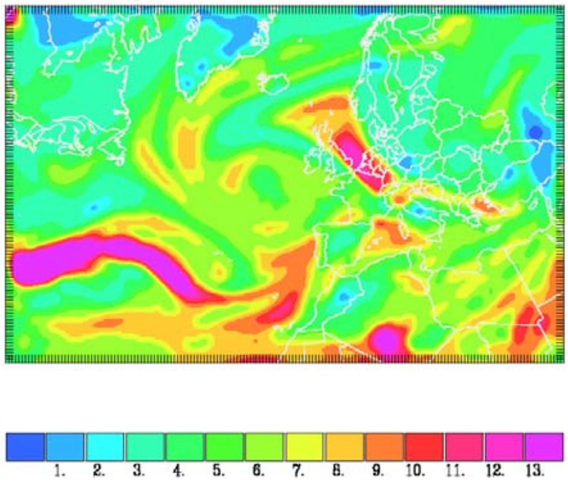


Figure 3.19: Water vapour [ppm] at different heights, August 12, 0 UTC. From upper left to lower right: 500 hPa, 316 hPa, 215 hPa, 145 hPa.

3.5 Fluxes and Budgets

The calculation of budgets or fluxes has been performed within TRACHT in two ways.
The first is used for momentum, heat and moisture (chapter 3.5.1). The approach is described in chapter 4.
The second way exploits the operator splitting technique used within the EURAD-CTM. The parameterisations of the processes are calculated separately and the effect on the concentrations can be stored. The tendencies then represent the local change rates $\partial C/\partial t|_{proc}$ due to a certain process as horizontal or vertical advection, chemistry or cloud effects.
The budgets of two chemical tracers are analysed using this second way. First ozone which has a gradient increasing with height – which is most suitable to study stratosphere-to-troposphere exchange and freon which decreases with height and therefore better suitable to study troposphere-to-stratosphere exchange.
The trace gas fluxes reveal a very complicated 4-dimensional structure – or even 6 dimensional, if you take into account the different processes and the chemistry. They are not easily accessible for integration.
For instance do the air masses in the central part of the omega structure arrive from northern Africa. The take up emissions over Europe and are lifted to the upper troposphere. There the flow splits into different pathways. Although the general situation does not change for days, the details are highly variable.
The results are shown as tendencies on pressure levels and as average changes within selected volumes.

3.5.1 Fluxes a la Indonesia

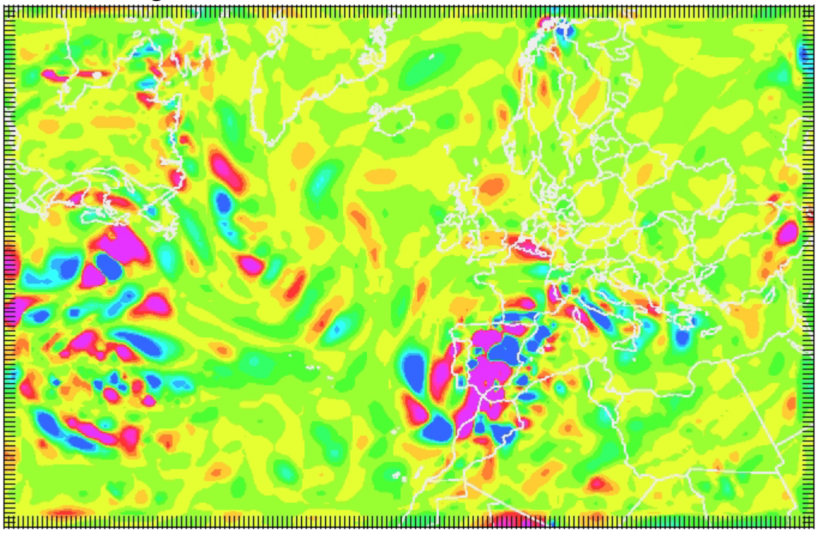
The vertical fluxes of momentum (Fig. 3.20), heat (Fig. 3.21) and moisture (Fig. 3.22) have been analysed for the TRACHT-Atlantic region using the same approach used for Indonesia (see chapter 4.4 for a detailed description). The vertical fluxes are low over most of the domain, except some regions:

Ω-Central: The fluxes are highly variable in this region from North-Africa to Scandinavia. There are large upward fluxes, which correspond with the uplifting regions of the trace gases.

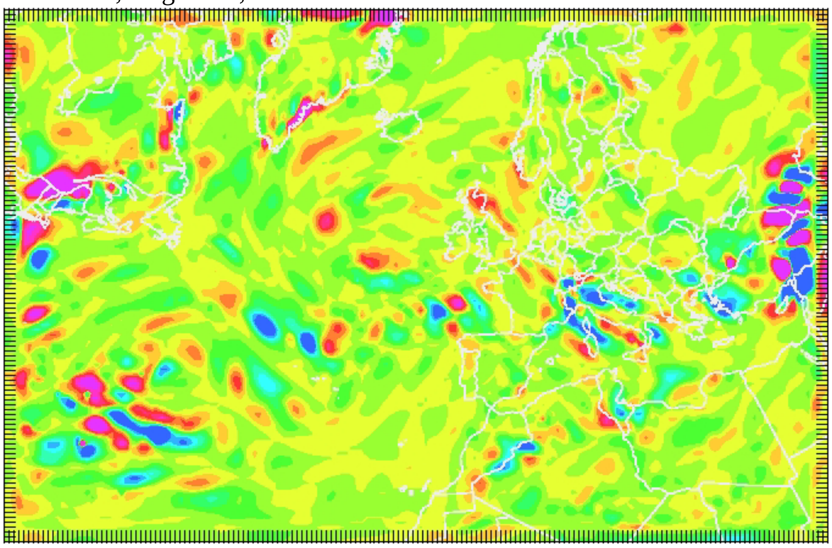
CoL-region: During the early phase (10.08.) there are downward fluxes dominating. A vortex-structure with alternating spiral-bands is visible.

Other regions in the southwest and the southeast are not analysed in detail. They correspond mostly to cloud system.
On August 14th the activity for the whole blocking structure decreases.

a) Momentum Flux 215 hPa, August 10, 0 UTC



b) Momentum Flux 215 hPa, August 12, 0 UTC



c) Momentum Flux 215 hPa, August 14, 0 UTC

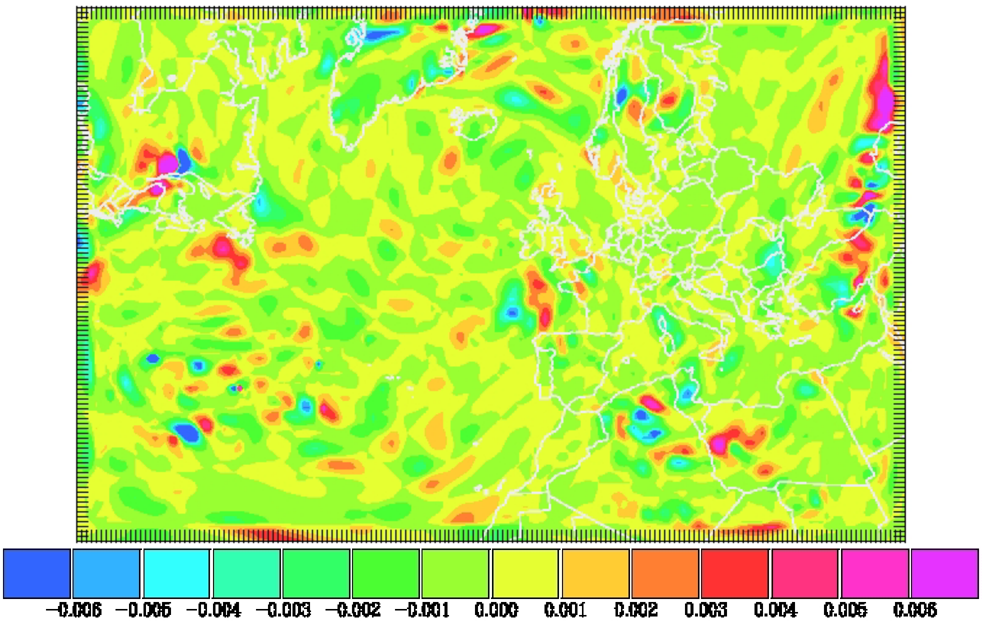
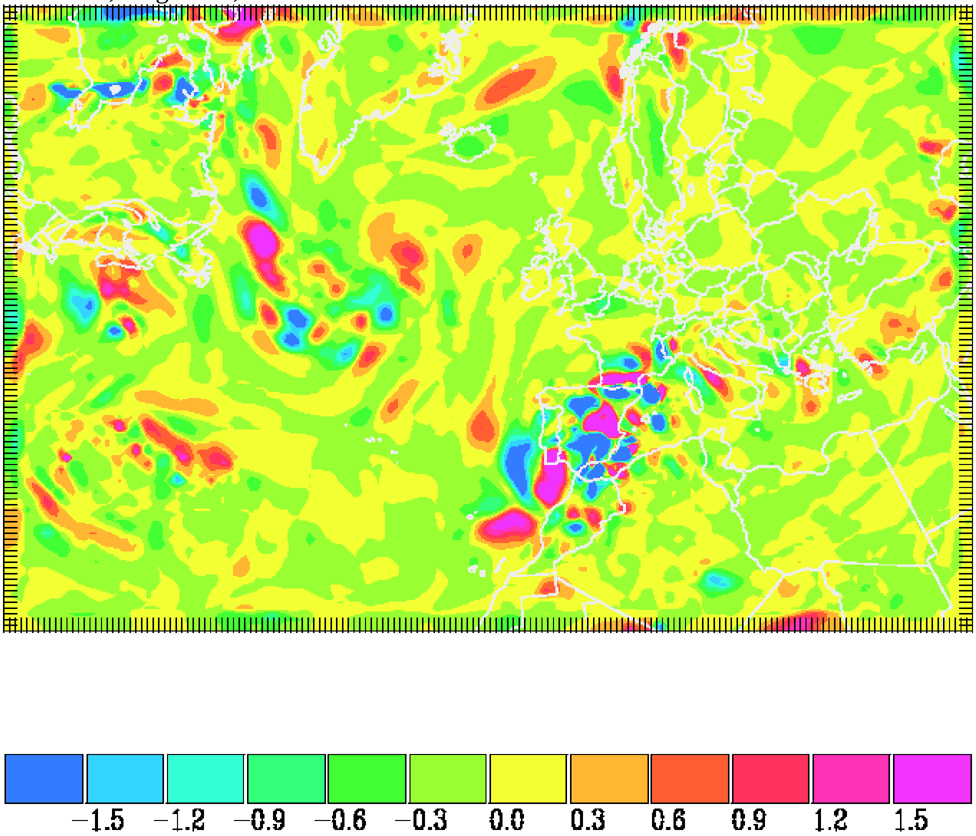


Figure 3.20: Momentum Flux [N/m^2] at 215 hPa: a) August 10 1997, 0 UTC, b) August 12 1997, 0 UTC, c) August 12 1997, 0 UTC.

a) Heat Flux 215 hPa, August 12, 0 UTC



a) Heat Flux 215 hPa, August 12, 0 UTC

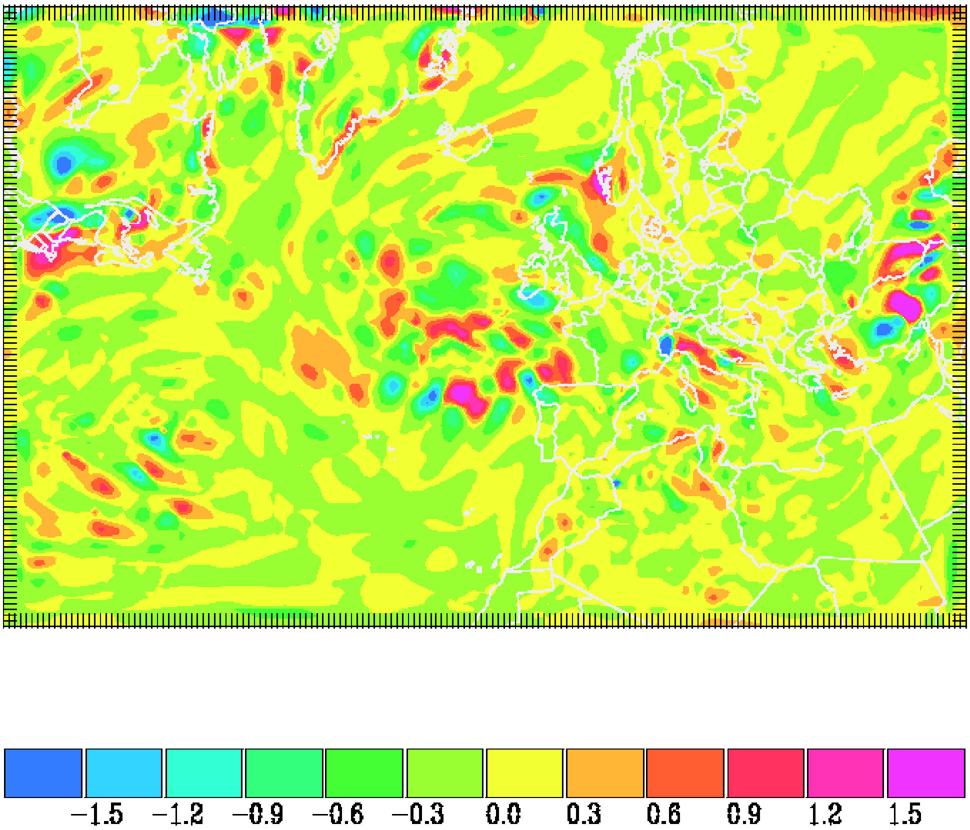
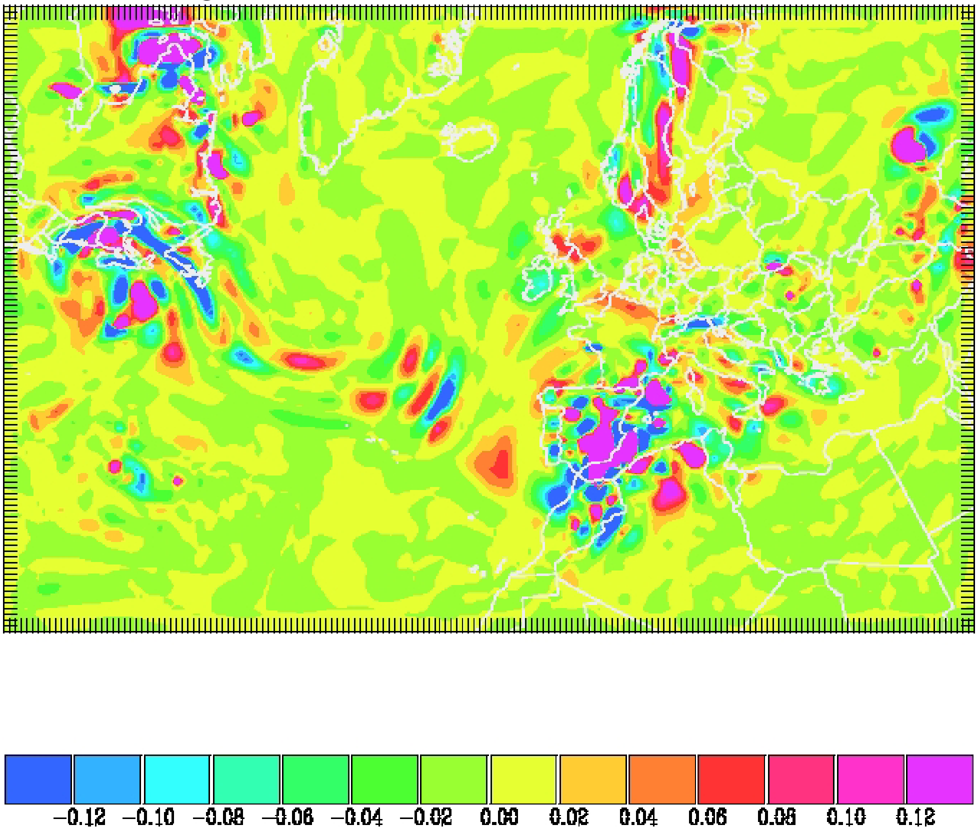


Figure 3.21: Heat Flux [W/m^2] at 215 hPa: a) August 10 1997, 0 UTC, b) August 12 1997, 0 UTC.

a) Moisture Flux 215 hPa, August 10, 0 UTC



a) Moisture Flux 215 hPa, August 12, 0 UTC

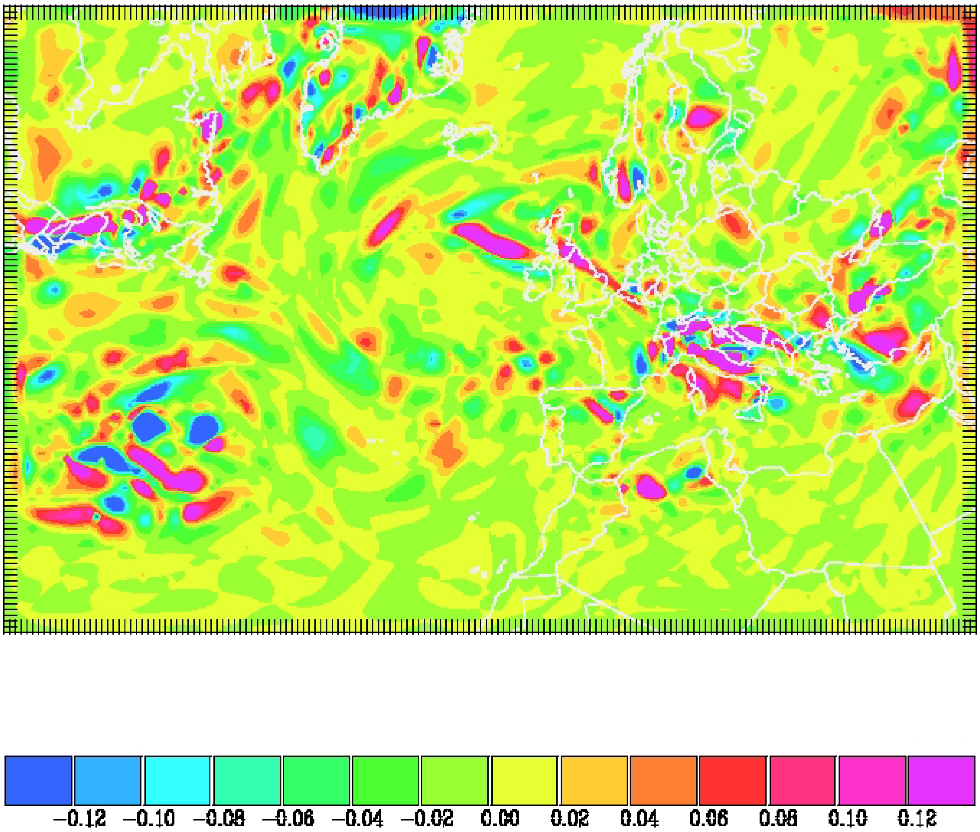


Figure 3.22: Moisture Flux [mg/m2/s] at 300 hPa: a) 10 August 1997, 0 UTC, b) 12 August 1997, 0 UTC.

3.5.2 Vertical ozone flux

The vertical ozone flux has been analysed for the region of the cut-off low over the development phase of the Ω-pattern on August 10 and 11. The concentrations for the CoL core are at stratospheric levels (well above 150 ppb in Fig. 3.23) on August 10, 0 UTC. In the south-eastern corner of the area an older and smaller cut-off low can be seen, which is replaced by the new one.

The major area with downward flux can be found in a zone which extends from the northern over the western side of the CoL to the south (Fig. 3.24). In the central part of the CoL there are compensating upward fluxes. Outside the vortices the fluxes are near neutral. The largest fluxes occur during the first day of the analysis. At the end of the period - on August 12, 0 UTC – both upward and downward flux are about 1.5-2 times smaller than at the start. Both fluxes are in a kind of equilibrium.

Figure 3.25 demonstrates that the net flux is about one magnitude smaller than the components. The net flux at 400 hPa is downward, especially on August 11. The values are in the range of cross tropopause fluxes found in the literature for cut-off lows or other types of stratospheric intrusions. 400 hPa is and average level for the tropopause height in that region during that episode (see chapter 3.1). The net vertical flux has a maximum around 300 hPa (see Fig. 3.26) and decreases with height. Above 250 hPa the flux changes its sign, so there is a small net upward transport.

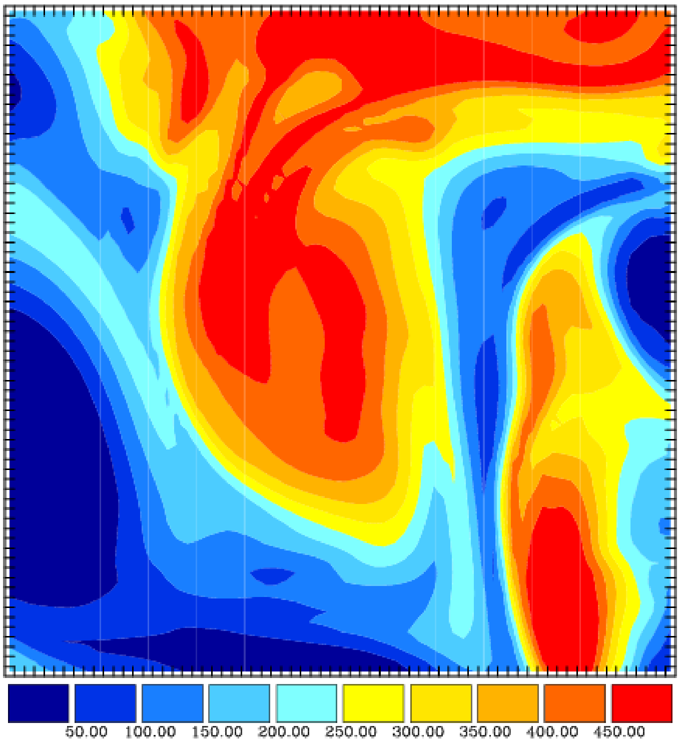


Figure 3.26: Ozone [ppb] at 300 hPa in the CoL region. Date: 10 August 1997, 12 UTC

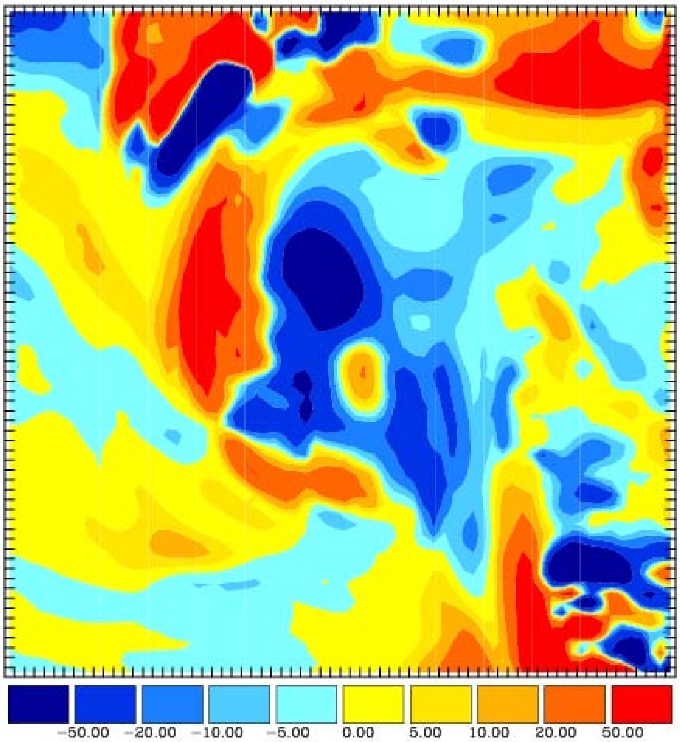


Figure 3.27: Vertical flux of ozone [10^{12} Molecules/cm^2/s] at 300 hPa for the same region and date as Fig. 3.26. Blue colours mark upward yellow to red colours downward flux.

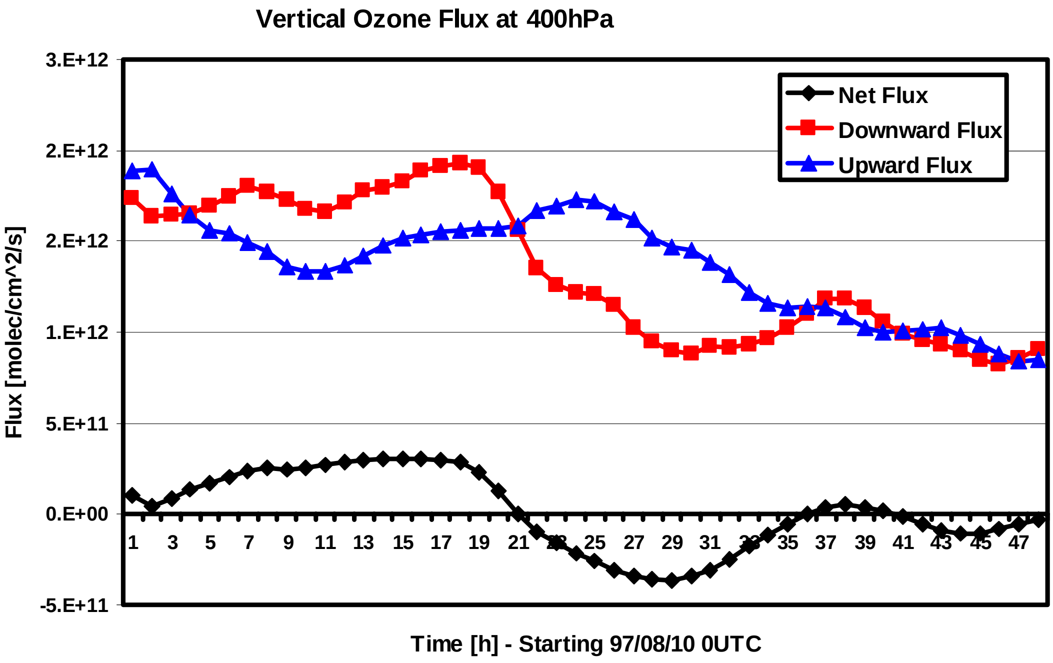


Figure 3.28: Vertical ozone flux [Molecules/cm2/s] – at 400 hPa averaged over the CoL region (of Fig. 3.23), from 10 August 1997, 0 UTC to 12 August1997, 0 UTC. Blue: Upward flux, red: Downward flux, Black: Net flux.

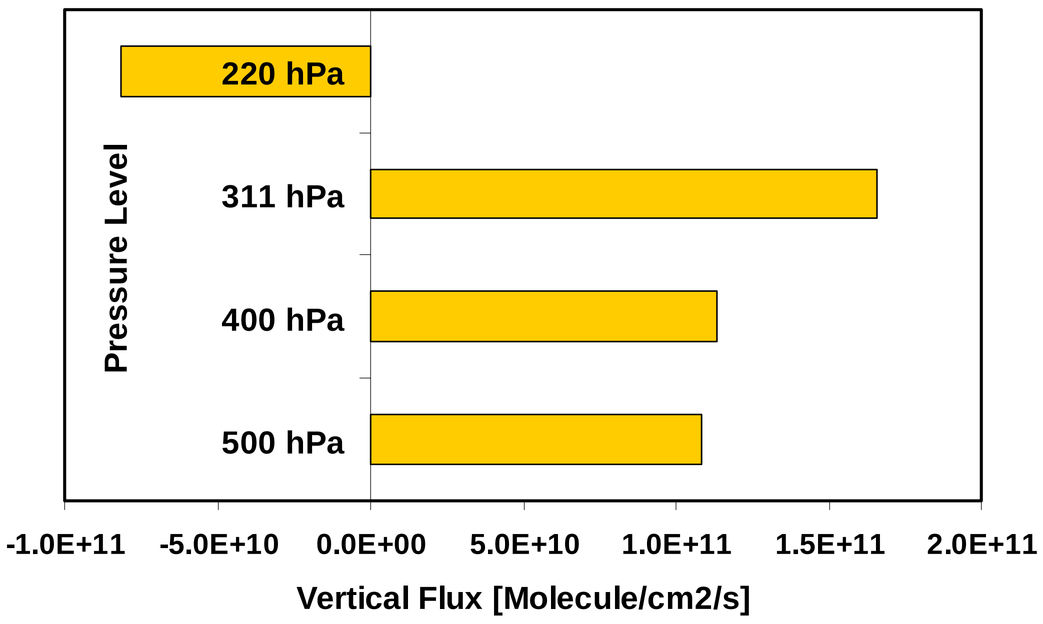


Figure 3.29: Height dependence of the net vertical ozone flux [Molecules/cm2/s].

3.5.3 CFC11 Budget

Figure 3.27 shows the tendencies due to horizontal and vertical advection of Freon at 316 hPa on August 10, 1997, 0 UTC – in the formation phase of the Ω-structure. These tendencies reveal the complex structures of the flow pattern. There is large region with generally upward transport over Western Europe and the Eastern Atlantic. A band with decreasing CFC11 mixing ratios extends from Greenland into the western part of the CoL-region. The tendency for the horizontal advection shows the vortex-like structure of the CoL with alternating bands of local gains and losses.

The vertical flux (Fig. 3.28.) is downward (negative values or blue colours) on average for the CoL-region. Western Europe is an area with general upward flux. Four regions have been defined (Fig. 3.29) to analyse the average temporal changes of the distributions in different parts of the Ω-structure. Figure 3.30 shows the tendencies for Freon in the central part of the CoL. The tendency of vertical advection gives downward transport above 12 km during the whole episode. In the period August 9 - 13 this downward transport also affects deeper layers down to the middle troposphere. After Aug. 13 the CoL leaves the chosen area and the region is filled up again. The loss by vertical transport is partly compensated by horizontal advection – mostly in the upper troposphere. The loss during the final phase of the episode is caused by the northward motion of the CoL. The total change rates are strongly variable below 12 - 14 km and much lower above. Therefore, this upper part is less affected by the transport within the blocking.

The central part of the Ω-structure has a very different behaviour (Fig. 3.31). There is a horizontal inflow from the south (mainly at lower layers), followed by uplifting (loss at lower layers increase at higher altitudes) and finally horizontal outflow in the UTLS. The height range affected by this transport pattern is larger than for the CoL region. The tropopause is moving upward in that region.

In the eastern part of the Ω-structure there is a change between decrease of Freon in the phases of stratospheric intrusions and a recovery in between. In the UTLS there is a layer with losses due to the divergence of downward flux during the whole episode. This loss is compensated by horizontal advection. The selection of a suitable integration domain is more difficult for the part of the structure than for the others. Probably the behaviour of spatially averaged tendencies is rather sensitive to the specific choice of the averaging domain so that generalisations of the results regarding advectively induced changes have to be taken with reservation.

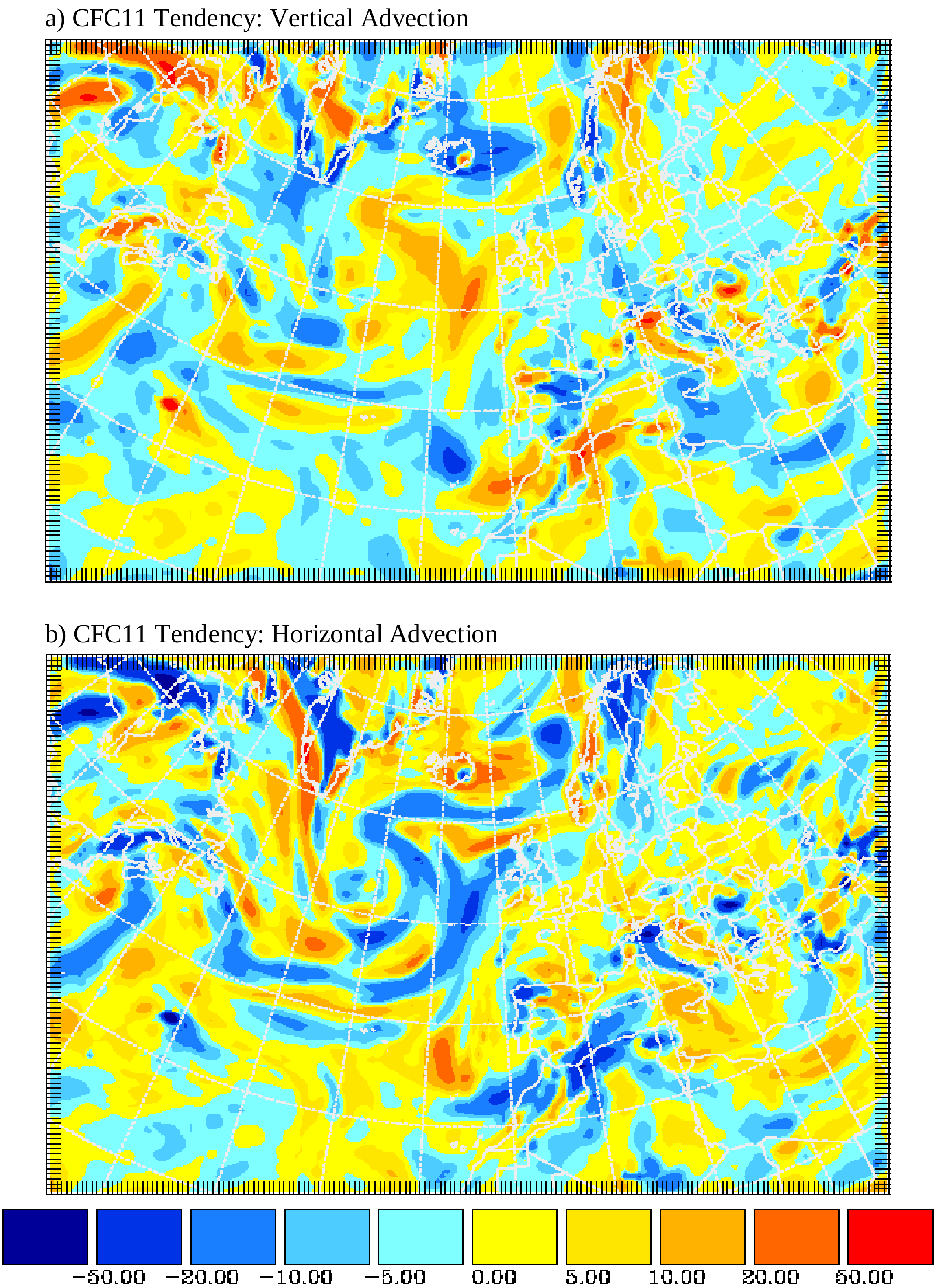


Figure 3.27: CFC11 tendencies [ppt/h] at 316 hPa on August 10, 1997, 00 UTC, resulting from a) vertical advection, b) horizontal advection.

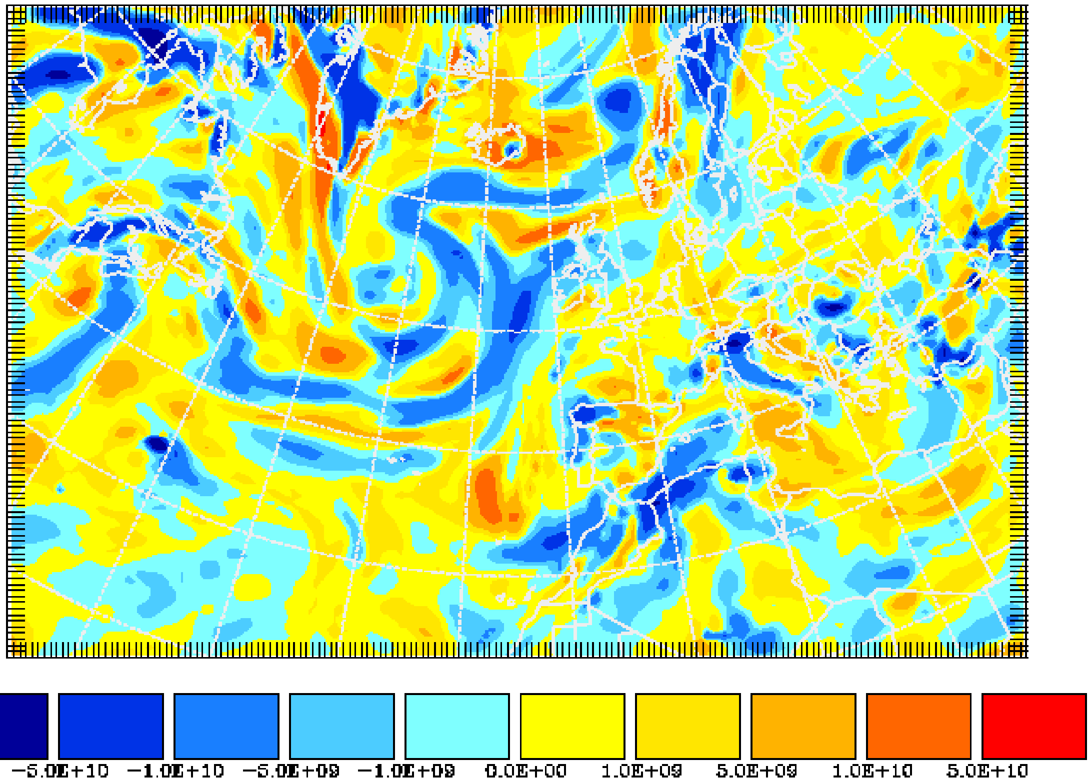


Figure 3.28: Vertical CFC11 Flux [molec./cm^2/s] at 316 hPa on 10 August 1997, 0 UTC. Negative values (blue colours) mean downward flux; positive values (yellow to red) upward flux.

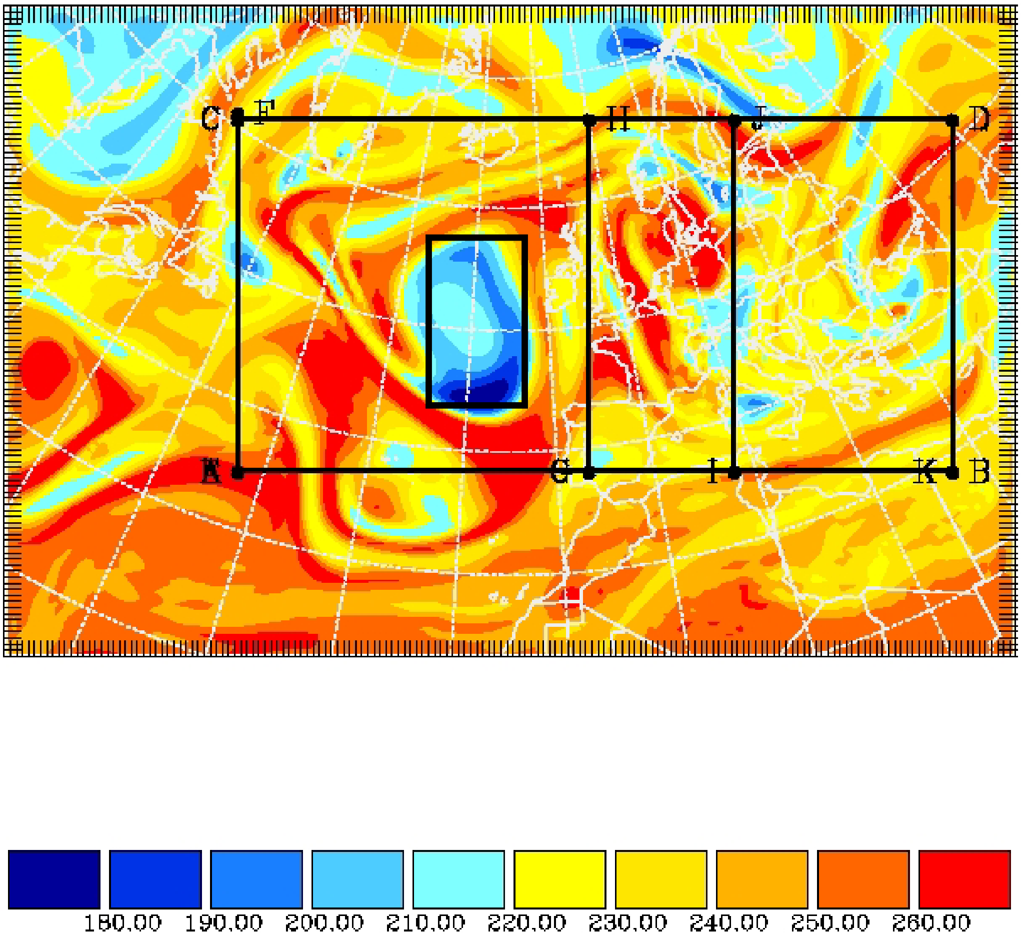


Figure 3.29: CFC11 [ppt] at 316 hPa, August 12, 1997, 00 UTC, and domains for budget calculations. Left big box Omega West, smaller box: Omega Centre, middle big box: Omega Central, right big box. Omega East.

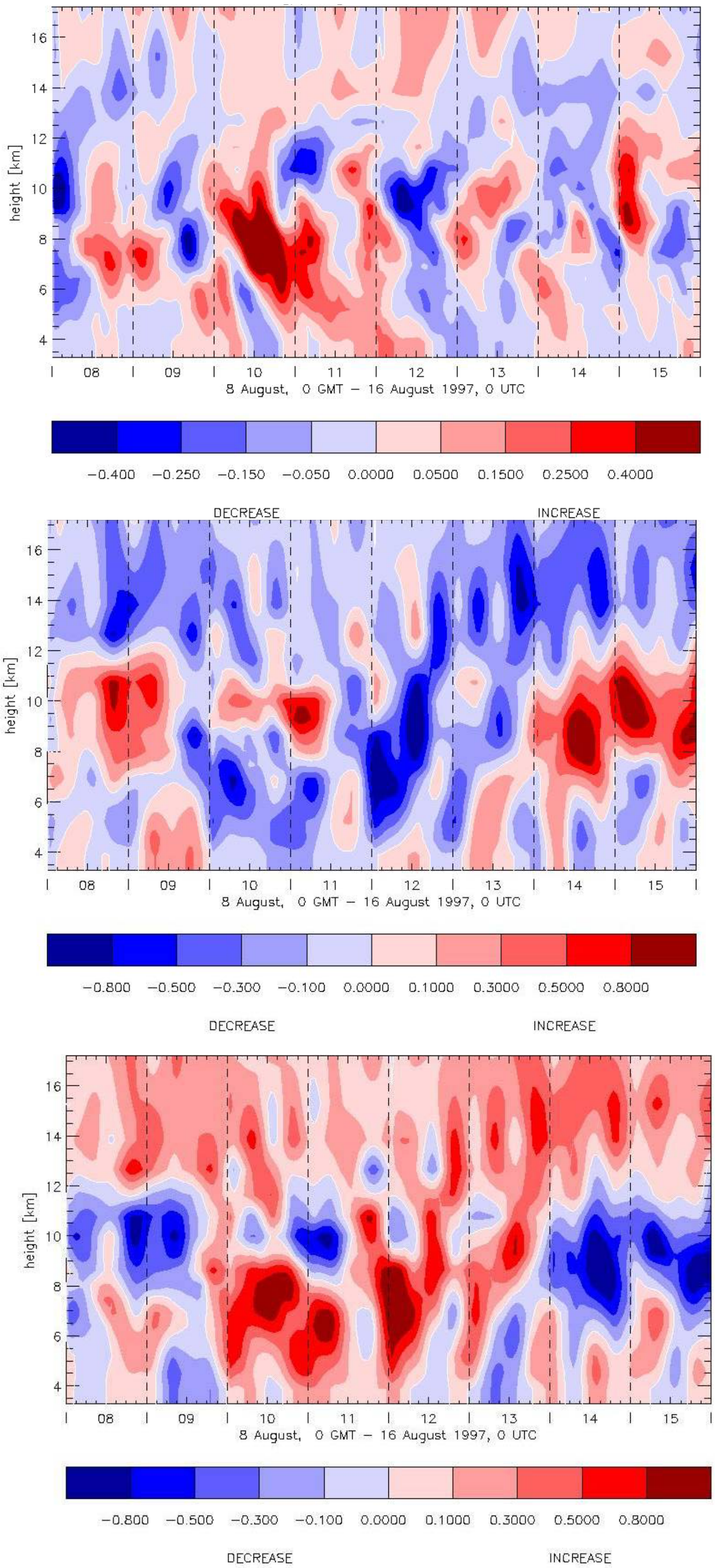


Figure 3.30: Tendency of CFC11 [ppt/h] for cut-off low centre. a) Total change, b) vertical advection, c) horizontal advection.

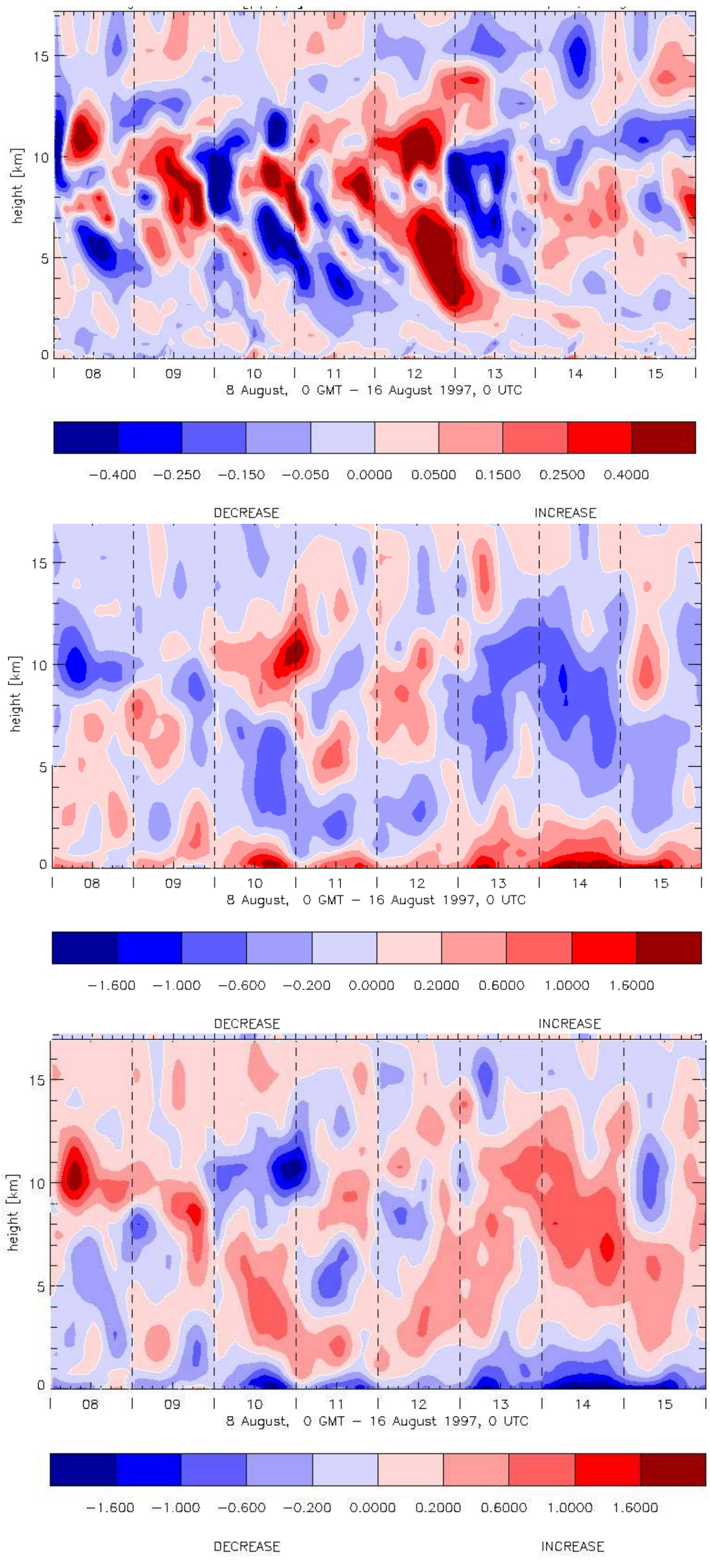


Figure 3.31: Tendency of CFC11 [ppt/h] for Central Europe. a) Total change, b) vertical advection, c) horizontal advection.

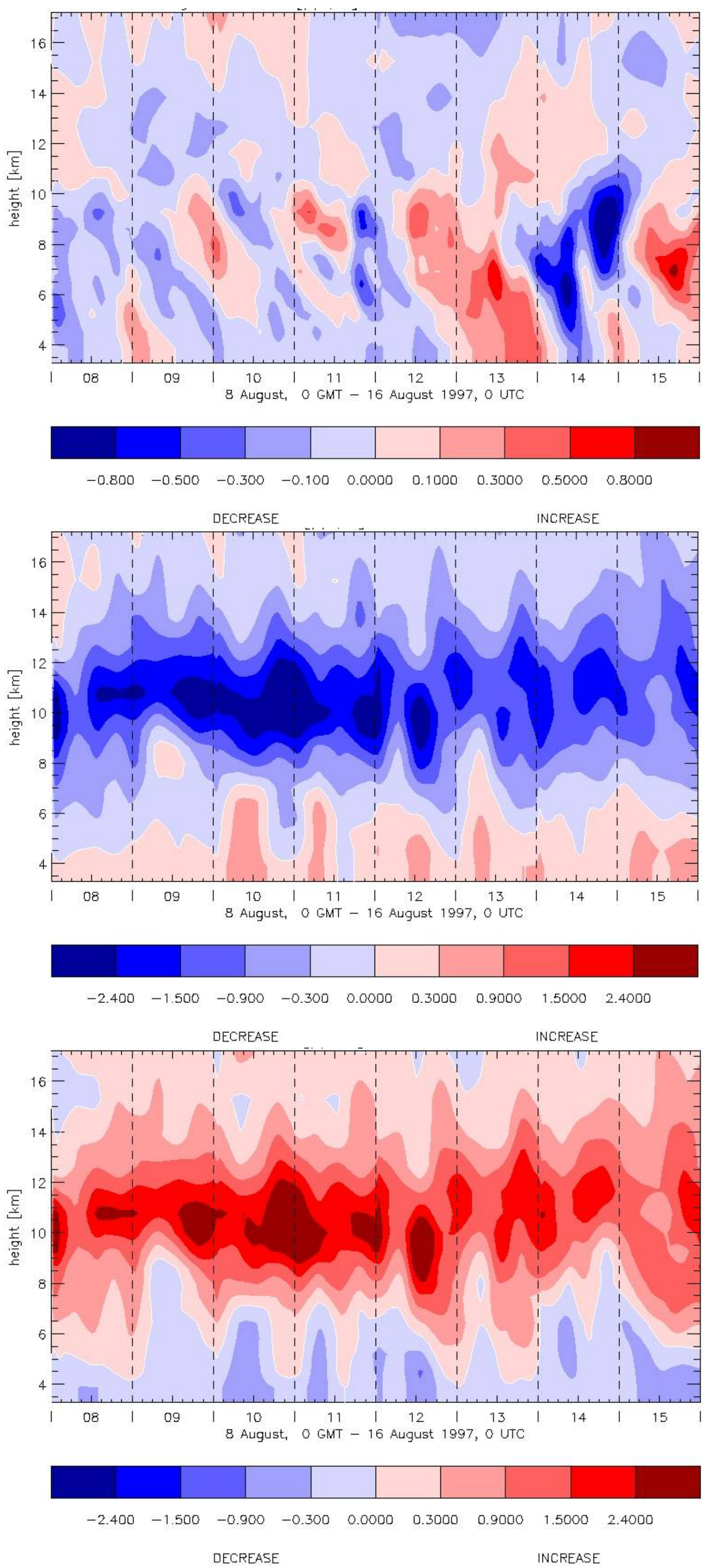


Figure 3.32: Tendency of CFC11 [ppt/h] for Eastern Europe. a) Total change, b) vertical advection, c) horizontal advection.

3.6 Conclusions

The CRISTA-2 experiment offered a unique chance to carry out meso-scale modelling of the tropopause region during an omega-type blocking event with the possibility of evaluation of the simulated results with unprecedented highly resolved remote sensing data. The simulations have been carried out with the EURAD model system. The CRISTA-2 episode lasted from Aug. 8 to 16, 1997, and the blocking event started to develop at the beginning of the observation period and lasted till its end. The blocking was characterised by a cut-off low (CoL) over the eastern North Atlantic, a high pressure ridge over Denmark stretching north-westward and a trough east of it with high dynamic variability. This dynamical pattern is clearly reflected by the CRISTA composite picture of the water vapour distribution near the tropopause for the whole episode (Fig. 1.1).

The details of the dynamics and transport pattern are extremely complex. The reduced longitudinal flow corresponds to enhanced exchange in the vertical and latitudinal direction. The EURAD model has been able to simulate the principal features of this episode quite realistically. To our knowledge, there been no such an intensive evaluation of a mesoscale chemistry-transport-model for the UTLS before.

Nevertheless some problems remain:

a) The transition in the vertical from one data source for initial and boundary values for the model to another (for instance from NNRP to ROSE for water vapour) was not completely solved and needs further studies.
b) The meteorological driver MM5 of EURAD was not able to reproduce the extremely low concentrations in the CoL and the streamer region.
c) For ozone the results were good for the UTLS (despite a slight high bias). But the deviations were higher for the stratosphere. It seems that the approach of using climatological PV-O3 initialisation did not work well in the lower stratosphere for this episode. In addition, a better adjustment of the chemical mechanism of the EURAD system to stratospheric conditions is needed in the future.
d) A (relatively small) bias was found for CFC11. This may be caused by the combination of climatological and experimental data to control initial and boundary conditions.

The simulations were able to provide new inside into the behaviour of transport in a blocking system and its role for air mass and trace substances exchange in the tropopause region (or UTLS). The observed Ω-structure consists of three main zones: A cut-off low in the west, a central ridge and a more variable region in the east, were streamers were identified. All regions have very different characteristics with respect to dynamical and chemical patterns:

<u>CoL:</u> The CoL consists primarily of polar air masses. It extends throughout the troposphere and lower stratosphere. From the upper troposphere upward stratospheric air masses dominate. But, there is considerable mixing from the sides and from below into this structure. The tropopause height is variable in space and time in this region, but the typical height is lower than on average and is found at about 400 hPa.

<u>Central ridge:</u> Advection of warm air from North Africa arrives over Western Europe. There, the uptake of emissions causes an increase of pollution and a significant boundary layer ozone production. This episode is one of the most prominent ozone episodes for Western Europe in 1997. A fast, strong uplifting brings these air masses into the upper troposphere with an elevated tropopause in the ridge. The air masses are transported

far to the north were the flow splits into two branches. One extends westward into the CoL region, the other one eastward turning south on the lee-side of the streamers.

Eastern section: The region is more variable. Sharp streamers of stratospheric intrusions extend from the north towards the Black Sea. In this region it proved difficult to reproduce the observations with the same accuracy as in the other parts of the blocking region because small spatial deviations may cause large discrepancies in a point-by-point comparison due to strong horizontal and vertical gradients in the real atmosphere.

The calculation of stratosphere-troposphere exchange fluxes is an extremely demanding task for this episode. The blocking sub-regions vary in position, time and intensity. In the same region strong upward and downward fluxes occur with a small residual transport. For the CoL and ozone this residual flux is comparable to data from the literature (Ancellet et al, 1994; Kowol-Santen et al., 2000). For the effective exchange the further fate of the air masses is important. The small cut-off low showing up in the beginning of the episode gets assimilated into the troposphere over the Mediterranean Sea after a lifetime of at least 10 days. The large cut-off low re-enters the Polar Regions with a lower tropopause. So a part of the stratospheric air processed by it gets back to the stratosphere after some days. But it is obvious that mixing of stratospheric and tropospheric air occurred so that the CoL contributes to troposphere-to-stratosphere exchange in this way.

It is emphasized that such blocking events constitute a significant mechanism for an effective exchange of air mass between different zones – like subtropics, mid- and polar latitudes - and different vertical layers from the boundary layer over the free troposphere to the lower stratosphere.