THE TRAMONTANE WIND: DYNAMIC DIAGNOSIS AND HIRLAM SIMULATIONS

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1. Introduction: the Tramontane wind and the PYREX Experiment

The Tramontane wind is the wind from north-west or north that blows at the north-western edge of the Pyrenees and spreads into the Mediterranean, reaching, sometimes, the eastern part of the Balearic Islands. From a climatological point of view (Reiter, 1975) it is the most frequent and the strongest wind of the Western Mediterranean. It could be characterised by a wind maximum in the Gulf of Lyon; a shear line, which separates two different zones, one with strong wind (Tramontane area) and other with weak wind (sheltered area); and a secondary maximum near the Balearic Islands.

The PYREX Experiment (Bougeault et al., 1990 and 1993) was a major field study of the dynamical influence of the Pyrenees on the atmospheric circulation. The main objective was the quantification of the retardation of the cross mountain flow by the range. But, other meso-scale phenomena had been reported as the generation of local winds (Tramontane, Cierzo and Autan). During the PYREX field phase, October and November of 1990, a large number of experimental means had been deployed in the area: additional radiosoundings, automatic stations, constant level balloons, research airplanes...There were 10 IOPs (Intensive Observation Periods), 5 of them with northern synoptic flow, and therefore favourable to the Tramontane generation.

Next a short description of the principal characteristics of the Tramontane wind during PYREX is presented (Campins et. al. 1995):

a) Wind maximum: from the analysis of the constant level balloons and flight data during the Tramontane cases, a wind maximum was observed, offshore, in the Gulf of Lyon (100 km from the coast). The intensity of this maximum depended on the case, but up to 33 ms^{-1} was observed in the strongest case. Then, the wind was accelerated in the north-eastern edge of the Pyrenees and the Gulf of Lyon, reaching a maximum, and then decreasing. Related to the wind maximum there was a tangential acceleration maximum (around $10*10^{-4}$ ms^{-2}).

b) Shear line: as it was commented from the climatological point of view, the existence of a narrow area, which separates a strong wind zone of a sheltered area with weak wind, can be inferred. In fact this area is very sharp, as it could be deduced from the plane data. During PYREX, several planes flew into the Tramontane area, and some of them crossed the shear line. Even variations of the wind intensity up to 20 ms^{-1} in 10-20 km were observed. A rolling of the wind was observed too. This shear line was not always located at the same place, it could change even during the same Tramontane event. During PYREX, two different orientations were observed: NW-SE and NNE-SSW. As it will be seen later, each one was related to the spread of the wind into the Mediterranean.

c) The spread into the Mediterranean: as we commented before, the Tramontane wind starts at the south-west of France, spreads into the Mediterranean and reaches the maximum at the Gulf of Lyon. Sometimes this accelerated wind does not reach the Balearic

Islands, but when it does, it can even be strong. In general, the first case occurs when the wind in the Gulf of Lyon is from the north-west, and the second one when it is from the north. Both Tramontane cases have a close relation with the position of the shear line: the NW-SE orientation corresponds to the NW Tramontane situation and the NNE-SSW orientation to the N situation. So, from PYREX observations two different Tramontane patterns could be inferred.

d) Vertical structure: it has been studied from radiosoundings at different stations, and from a flight over the sea, where the Tramontane was well developed. From the temperature observations, the Tramontane was seen as a cold entrance at low levels separated from upper levels by an inversion layer located between 1200-1500 meters. The wind analysis showed the Tramontane confined in a thin layer, below the inversion, with the maximum around 500-1000 meters.

2. The Tramontane as an orographic effect and HIRLAM simulations

2.1. The Tramontane as an orographic effect

As it has been mentioned, the Tramontane wind is closely related to the generation of a pressure anomaly produced by the interaction of the atmospheric flow with the Pyrenees. This pressure configuration has a dipolar shape, with a high pressure centre windward and a low pressure centre in the lee of the Pyrenees (Bessemoulin et al., 1993). A measurement of the strength of the orographic interaction is the pressure drag, which measures the loss of momentum of the atmospheric flow when crossing the range. During PYREX, the pressure drag was highly correlated with the pressure dipole (Bessemoulin et al., 1993), and it was also quite correlated with the wind observed at surface stations (Campins et al., 1995).

From a different point of view, increasing the horizontal resolution, from 0.91 to 0.455 degrees latitude/longitude, in a numerical simulation with the former INM operational model LAM (and so increasing the height of the mountains) produced a better Tramontane representation (García-Moya et al. 1992). With both versions, a dynamic diagnosis of the contribution of the horizontal momentum equation terms was made. It revealed a close relation between the tangential acceleration maximum (i.e. the wind maximum) and the acceleration due to the dipolar pressure structure (due to the orographic forcing). The higher resolution gave results closer to the observations (Campins et al., 1995).

2.2. HIRLAM simulations

In the present study we try to confirm the contribution of the Pyrenees to the Tramontane wind. So, three different simulations of the IOPs 1 and 9 were made with the same numerical model. The model used is the INM operational model HIRLAM described in Gustafsson (1991), which is a three-dimensional hydrostatic model with hybrid coordinates in the vertical and spherical coordinates in the horizontal. The vertical diffusion parameterization follows Louis (1979). The clouds and precipitation schemes are based on Sundqvist (1989). A mean orography is used together with a roughness length depending on the subgrid scale variation of the topography. The horizontal grid is regular in latitude and longitude. Two versions are used in the simulations: 0.5 and 0.2 degrees, which roughly correspond to 50 and 20 km resolutions. The vertical grid has 31 levels with the lowest level around 90 m and with the separation between levels slowly growing upwards from 150 m in the lowest levels. The initial and boundary conditions are ECMWF reanalyses performed at T213 truncation with the observations disseminated operationally (it does not use the special observations performed for PYREX). In order to evaluate the impact of the Pyrenean mountains, the simulations at 0.2 resolutions are also carried out removing this mountains in the orography of the model.

We have performed simulations departing from three different initial times: 5 October at 12 UTC for IOP 1, and 15 and 16 November at 12 UTC for IOP 9. All the integrations have been carried out at both resolutions, 0.5 and 0.2 degrees, and for the 0.2 one the simulations have been also done removing the Pyrenees from the model orography. We use the 24 hour forecast for the comparison with observations. The surface measurements and the data from constant level balloons and research flights at 950 hPa were used in the comparisons. It must be taken into account that the Piper Aztec flights under-measured the wind intensity. For this reason the wind intensity of the constant level balloons is always higher than the measured by these flights.

2.2.1. IOP 1: 5 October 1990 at 12 UTC

a) Observations

The IOP 1, extended from 4 October at 18 UTC to 5 October at 18 UTC, was a quite strong Tramontane event. At surface (Fig. 1), strong winds were observed at the Gulf of Lyon (Perpignan 13 ms^{-1}) and into the Mediterranean (the Island of Minorca 12 ms^{-1}). At higher levels a wind maximum of 23 ms^{-1} was observed by the constant level balloons and the Piper Aztec Plane (P11) at the edge of the Pyrenees, just reaching the Gulf of Lyon. The P11 flight crossed the shear line, measuring more than 15 ms^{-1} from north-west at the eastern side and less than 5 ms^{-1} from west at the western side (Fig. 6).

b) HIRLAM-0.5

At lowest levels (up to 925 hPa) a slight dipolar pressure structure around the Pyrenees is obtained, decreasing with hight. The surface wind is lower than the observed wind (e.g., while Perpignan was reading 13 ms^{-1}, the model gives 8 ms^{-1}; and at the Island of Minorca, 12 ms^{-1} were observed against the 9 ms^{-1} of the model). At the north side of the Pyrenees the observed wind is more deviated to the west than the simulated one, and at the south side, the observed wind turns around the low pressure centre while the simulated wind does not.

Also at higher levels, and below the inversion, this simulation underestimates the wind maximum at the Gulf of Lyon, where the constant level balloons and the flight (P11) observed 23 ms^{-1}. The model maximum reaches 17 ms^{-1} and it is located downstream of the observed one. Concerning to the shear line, the simulation reproduces a transition zone between a strong and a weak wind areas, but it is not sharp enough and the involved circulations are not obtained.

c) HIRLAM-0.2

The dipolar pressure structure is closer to the reality and the isobars are more packed over the Pyrenees than in the 0.5 simulation (Fig. 3). At the same time, the low pressure centre at the lee of the Pyrenees seems to fit better with the observations. The surface wind is blocked at the north side and turns around the low pressure centre at the south side of the range. The wind at surface is slight closer to the observed in Perpignan (9 ms^{-1} simulated and 13 ms^{-1} observed) and nearly the same in Minorca (11 ms^{-1} simulated and 12 ms^{-1} observed).

The wind at 950 hPa shows a good agreement with the observed one: the wind maximum reaches 23 ms^{-1} and 20 ms^{-1} are given by the model, and its position, just at the eastern edge of the Pyrenees, is correctly located. The shear line is better reproduced than in the 0.5 simulation: it is sharper and even it presents the rolling of the wind from north to west when crossing the line (Fig. 6).

d) HIRLAM-0.2 without Pyrenees

As it could be expected, with the simulation done without the Pyrenees, the dipolar pressure structure around the Pyrenees is not reproduced and the isobars cross the range perpendicularly. The same occurs with the wind: it is not deviated by the mountains. In the Tramontane zone, the wind spreads from the northeast in a wide area with values around 12 ms^{-1}. But there is neither a maximum zone nor a shear line. At higher levels, the same structure for pressure and wind is observed, being stronger increasing the height.

Subtracting from the 0.2 simulation with the whole orography the 0.2 simulation without the Pyrenees, the effect of the range will be obtained. For the sea level pressure an over-pressure up to +5 hPa at the northern side of the Pyrenees and a sub-pressure up to -3 hPa at the lee side are detected. On the other hand the intensity of the wind is +7 ms^{-1} stronger at the Gulf of Lyon and up to -12 ms^{-1} lower at the lee of the range when the Pyrenees are present. At 950 hPa more or less the same is obtained: an over-pressure of +30 mgp and a sub-pressure of -20 mgp on the geopotential, and +10 and -15 ms^{-1} on the wind intensity.

2.2.2. IOP 9: 15 and 16 November 1990 at 12 UTC

a) Observations

The IOP 9 started at 6 UTC on 14 November 1990 and finished at 18 UTC on the 16 November 1990, and it was the strongest Tramontane event.

On the 15 November at 12 UTC strong winds from NW on surface were observed at the Gulf of Lyon (Perpignan 10 ms^{-1}), but not in the Island of Minorca (6 ms^{-1}). The Piper Aztec flight (P23) measured up to 23 ms^{-1} and the constant level balloons up to 29 ms^{-1}. The shear line had NW-SE orientation, corresponding to a NW Tramontane event (Fig. 7).

On the 16 November at 12 UTC the Tramontane increased and rolled to N direction. On surface strong winds were observed at the Gulf of Lyon (Perpignan 15 ms^{-1}) and in this case, they reached the Island of Minorca (15 ms^{-1}). The Piper Aztec flight (P25), which flew over the Gulf of Lyon around 9 UTC, measured a wind maximum of 28 ms^{-1}. On the other hand, some constant level balloons were launched on the 16th at 960 hPa pressure level. From them, it was found that the wind decreased with time, reading a wind maximum around 8 UTC of 33 ms^{-1}, 28 ms^{-1} at 11 UTC and around 14 UTC 26 ms^{-1}. The shear line had NNE-SSW orientation, related to a N Tramontane event (Fig. 8).

The reason for the wind rolling (from NW to N-NNE) could be the movement of a deep cyclone from the Gulf of Genoa to the Tyrrhenian Sea.

b) HIRLAM-0.5

On the 15 November the wind maximum at the Gulf of Lyon is well simulated (25 ms^{-1} for the simulations against the 29 ms^{-1} observed), but the shear line is not present. At surface, the wind speed in Perpignan is slightly higher than the observed (11 ms^{-1} simulated versus 10 ms^{-1} observed) and clearly over-estimated in Minorca (11 ms^{-1} simulated versus 6 ms^{-1} observed). The NW direction of the wind is well reproduced by this simulation.

Worse results are obtained on the 16 November: i) the simulated wind maximum in the Gulf of Lyon is only 17 ms^{-1} (28 ms^{-1} were observed), and ii) the simulated wind spreads into it with moderate (bigger than 10 ms^{-1}) wind from NE, and the shear line is not present. At surface the wind speed is under-estimated at the Gulf of Lyon (i.e. Perpignan 7 ms^{-1} simulated in front of 15 ms^{-1} observed) but better in Minorca (12 ms^{-1} simulated in front 15 ms^{-1} observed). Again the rolling of the wind to NE is well reproduced.

c) HIRLAM-0.2

In both simulations the dipolar pressure structure is better reproduced than the 0.5 version, but weaker than the observed one, specially on the 16th (Figs. 4 and 5).

Concerning to the wind, on the 15th the maximum (23 ms^{-1}) is slightly lower than with the 0.5 version, so, lower than the observed (29 ms^{-1}). The shear line is not well reproduced, but present (Fig. 7). At the surface the wind speed in Perpignan and Minorca is nearly the same as with the 0.5 simulation (11 ms^{-1} at both stations), and so this simulation overestimates the wind speed (specially in Minorca). The wind direction is from NW, as the observed.

On the 16th, the 0.2 simulation improves the 0.5 simulation: the wind maximum at the Gulf of Lyon is 19 ms^{-1} (28 ms^{-1} were observed); the wind, from NE spreads into the Mediterranean and the shear line is not present (Fig. 8). At surface the wind in Perpignan is again lower than the observed (8 ms^{-1} simulated vs. 15 ms^{-1} observed), but nearly the same in Minorca (12 ms^{-1} vs. 15 ms^{-1} observed). The rolling of the wind from NW (on the 15th) to N-NE (on the 16th) is again well reproduced.

d) HIRLAM-0.2 without Pyrenees

On the 15th and 16th November, subtracting the 0.2 simulation without Pyrenees from the 0.2 simulation with the whole orography, we obtain similar (but less clear) results than for the IOP 1:

i) On the 15th, a dipolar structure around the Pyrenees for the sea level pressure (+3 and -3 hPa) and at 950 hPa (+20 and -15 mgp); and a maximum and a minimum around the shear line for the wind (+5 and -12 ms^{-1} on surface and +9 and -15 ms^{-1} at 950 hPa) are detected.

ii) On the 16th, the results are very close to the 15th (+3 and -2 hPa on surface and +20 and -10 mgp at 950 hPa; and +5 and -7 ms^{-1} on surface and +9 and -11 ms^{-1} at 950 hPa). But the observed pressure dipole and the wind is stronger than on the 15th. So, in this case, as we said before, the 0.2 simulations is not able to simulate the strengthness of the flow-range interaction.

2.2.3. General trends of the sea level pressure

The favourable situations for Tramontane generation are characterised by a northern synoptic flow, which crosses the Pyrenees. Usually, this flow crosses the Alps too, and the well-known Genoa cyclogenesis is formed. So, during the Tramontane events frequently a cyclone at the Gulf of Genoa is present, or, if it has moved towards the southeast, at the Tyrrhenian Sea. The presence and intensity of that cyclone has a great importance on the observed wind in the Western Mediterranean, and it can add a new acceleration to the Tramontane wind, which coming from the Gulf of Lyon spreads into the Mediterranean (Campins et al., 1995). Then, the simulation of the Tramontane wind depends not only on the orographic disturbance due to the Pyrenees but also on the Genoa cyclogenesis evolution. In order to known the accuracy of the present simulations, a broad comparison between the sea level pressure of some surface stations and the nearest grid point to them is made for the 0.5 and 0.2 HIRLAM versions.

In both of them there is an over-estimation of the surface pressure, mainly at the lee of the Pyrenees and in the Mediterranean, but not at the windward side of the range. In general this difference is not high (1-2 hPa) for the IOP 1 and for the 15th of IOP 9. But on the 16 November (IOP 9) there exists a big difference between the simulated surface pressure and the observed one, specially at the lee of the Pyrenees and into the Mediterranean (up to 4 hPa), but not at the northern side of the range. Concerning to the pressure gradients there exists a sub-estimation of it at the Mediterranean Sea in the IOP 1 (i.e. the observed cyclone was deeper than the simulated one), an over-estimation on the 15th (IOP 9) for the 0.5 version (so, and over-estimation of the wind speed in that area) and a sub-estimation of the pressure gradient around the Pyrenees on the 16th of IOP 9. In the last case it could be the reason why the simulated wind was too much weaker than the observed one. In fact, the pressure gradient, i.e. the wind, was greater than the simulated

3. Conclusions

Three different simulations of two Tramontane events (IOP 1 and 9 of PYREX Experiment) were performed with the same numerical model (HIRLAM) in order to study the principal characteristics of the Tramontane wind.

In general, the 0.2 simulation is closer to the observations than the 0.5 one. The degree of concordance depends on the IOP. So, for IOP 1 the 0.2 simulation results improves the 0.5 one, and they are very close to the observations (both the wind maximum and the shear line). Concerning the first day of IOP 9 (15 November at 12 UTC) the two simulations underestimate the wind maximum and fail in the location and orientation of the shear line (0.2 simulation is slight better than 0.5 simulation). And finally, concerning to the second day of the IOP 9 (16 November at 12 UTC) both simulations underestimate the wind maximum too much and do not reproduce the shear line (although the 0.2 simulation again performed better than the 0.5 one).

In short, the 0.5 simulation almost reproduces the wind maximum (intensity and position) and it does not the shear line. On the other hand the 0.2 simulation improves the wind maximum (intensity and position) and in some cases it reproduces quite well the shear line.

Comparing the 0.2 simulations with and without Pyrenees the involved orographic mechanisms can be stressed: i) the formation of a dipolar pressure structure at both sides of the Pyrenees, ii) the deviation of the wind to west and north-west and the increasing of its speed and iii) a shelter effect of the Pyrenees, which separates the Tramontane area with a sharp zone of transition (the shear line).

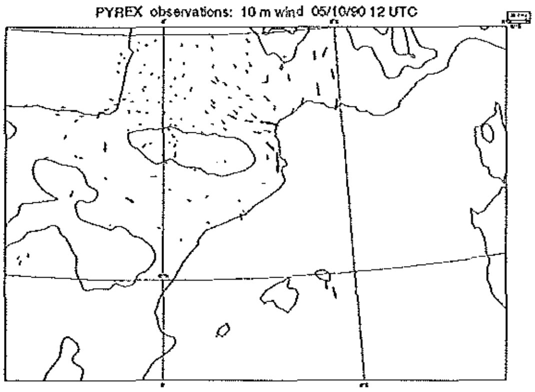

Figure 1. 10 m wind observations (ms-1). 5 October 1990 at 12 UTC (IOP 1).

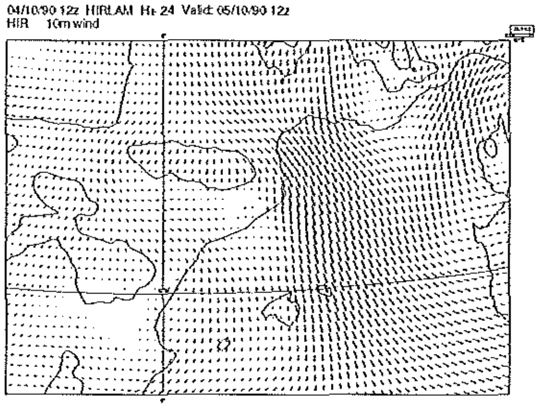

Figure 2. 10 m wind (ms-1) for HIRLAM-0.2 simulation. 5 October 1990 at 12 UTC (IOP 1).

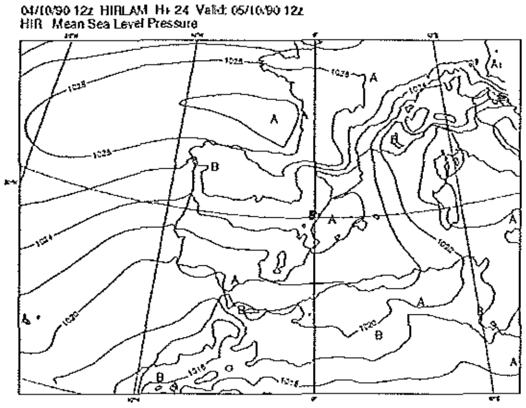

Figure 3. Mean sea level pressure (hPa) for HIRLAM-0.2 simulation. 5 October 1990 at 12 UTC (IOP 1). Contour interval 2 hPa.

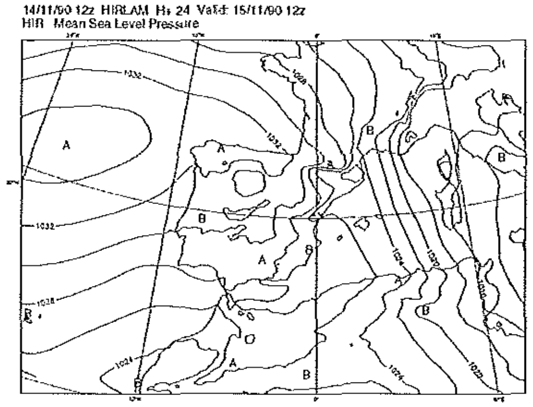

Figure 4. Mean sea level pressure (hPa) for HIRLAM-0.2 simulation. 15 November 1990 at 12 UTC (IOP 9). Contour interval 2 hPa.

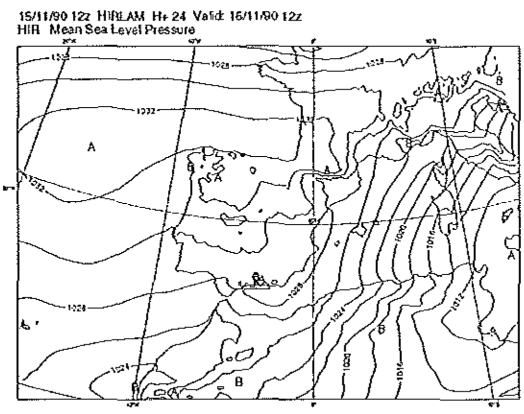

Figure 5. Mean sea level pressure (hPa) for HIRLAM-0.2 simulation. 16 November 1990 at 12 UTC (IOP 9). Contour interval 2 hPa.

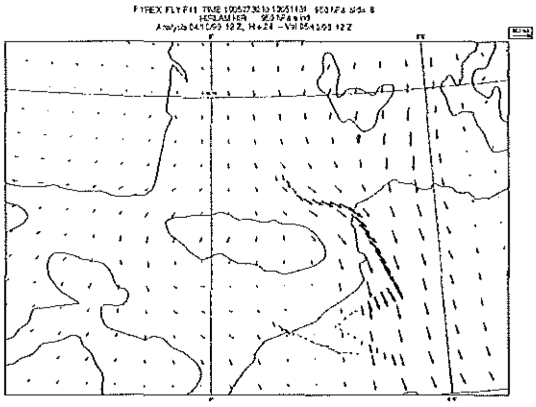

Figure 6. 950 hPa wind (ms-1) for HIRLAM-0.2 simulation and measured by the Piper Aztec flight P11. 5 October 1990 around 12 UTC (IOP 1).

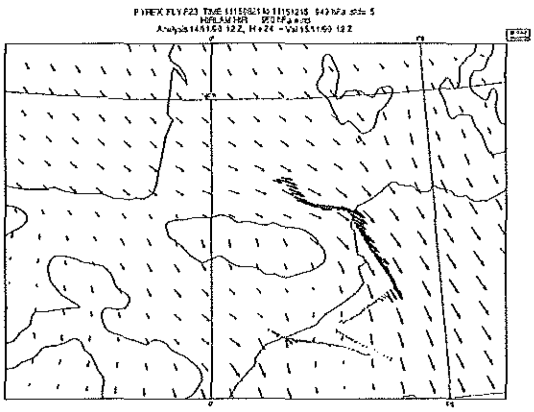

Figure 7. 950 hPa wind (ms-1) for HIRLAM-0.2 simulation and measured by the Piper Aztec flight P23. 15 November 1990 around 12 UTC (IOP 9).

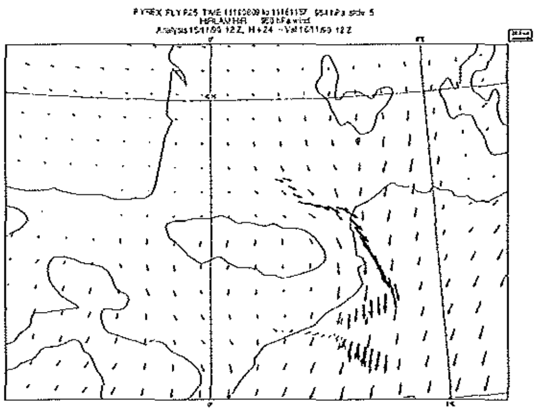

Figure 8. 950 hPa wind (ms-1) for HIRLAM-0.2 simulation and measured by the Piper Aztec flight P25. 16 November 1990 around 12 UTC (IOP 9).

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