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SATELLITE- AND GROUND-BASED STEREO ANALYSIS OF CLOUDS DURING MAP

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ABSTRACT

This paper describes the results obtained in cloud-top and cloud-base height and motion estimation from coincident satellite- (ATSR2, Meteosat) and ground-based stereo images with various spatial resolutions. The data acquisition took place within the target area "Rhine Valley" in Switzerland during the MAP-SOP in October 1999.

It is shown which matching difficulties have to be considered with low resolution satellite images especially at cloud borders and in land areas near clouds. The 13/10/1999 case study presents the possibility of detecting multiple cloud layers by analysing different spectral channels. Furthermore, the coincident ground measurements with a stereo camera system showed to be an interesting technique to map smaller scale features and to validate satellite-based cloud-top heights of vertically thin clouds. The motion analysis from the first alpine rapid scans is consistent with the wind measurements from wind profilers and radiosondes and with regional model forecasts. As the motion is directly extracted from the cloud motion, the amounts can be directly applied to correct the along-track cloud wind error in the height determination of slightly asynchronous stereo images like ATSR2. The cloud-adapted matching algorithm can be applied to other stereo pairs from the various new satellite sensors which are designed for atmospheric studies.

1. INTRODUCTION

This study is part of the EU-project CLOUDMAP which focuses on the detection and mapping of cirrus clouds and airplane contrails using satellite sensors. The scientific objectives of the project are to provide new cloud products (height, type, optical thickness, fraction etc.), compare different techniques for the extraction of some of these products (brightness temperature, stereoscopy and Oxygen A-band) and to validate them using airborne sensor underflights and ground-based remote sensing instruments.

Clouds are a major contributor to our uncertainty concerning the nature of climate and climate change. The datasets from satellites and surface eye-observations describe both only limited aspects of natural cloud fields and have uncertainties that are difficult to fully quantify (Weare, 1999). The combined use of satellite- and ground-based sensors for the examination of cloud systems and structures has been realized in a few recent investigations (Feijt and van Lammeren, 1996; Weare, 1999).

Stereoscopy of clouds has a long tradition in meteorology (Hasler, 1981). From satellites, both geostationary and polar-orbiting sensors can be used, if the time difference between the two images is not too large. The method of Campbell (1998) shows the possibilities and limits of asynchronous stereo height analysis. Stereo measurements have the advantage that they depend only on basic geometric relationships of observations of cloud features from two different viewing angles, while other cloud top height estimation methods are dependent on the knowledge of other cloud/atmosphere parameters like cloud emissivity, ambient temperature or lapse rate.

Our combined satellite- and ground-based stereo analysis of clouds was carried out within the field campaign of the programme MAP. MAP (Mesoscale Alpine Programme) is an international research initiative devoted to the study of atmospheric and hydrological processes over mountainous terrain. It aims towards expanding our knowledge of weather and climate over complex topography (MAP Science Plan, 1998). The Special Observation Period (SOP) took place at three target areas "Lago Maggiore"(CH/I), "Rhine Valley"(CH) and "Brennerpass/ Wipp Valley"(A) from September, 7 to November, 15, 1999 (MAP Implementation Plan, 1999). As a special support to the composite observing system which was operated by numerous principal investigators during the SOP, EUMETSAT reactivated the Meteosat-6 satellite to provide the first ever seen rapid scans of the alpine region. The rapid scan periods were restricted to the short Intensive Observation Periods (IOP) of 2-5 days which took place if "Foehn" events North of the Alps (Rhine Valley, Brennerpass) or heavy precipitation events South of the Alps occurred.

2. ATSR2

The ATSR2 instrument is part of the ERS-2 satellite system which was launched in April 1995. The successor sensor, AATSR, will be part of Envisat which is currently scheduled for June 2001. ERS-2 is in a near-circular, sun-synchronous orbit at a mean height of 780km, an inclination of 98.5° and a sub-satellite velocity of 6.7 km/s. The spacecraft is positioned to operate with a descending equator crossing of around 10:30 local solar time and of a ascending equator crossing of 22:30 local solar time. The repeat cycle is about 3 days. First, the ATSR2 views the surface along the direction of the orbit track at an incidence angle of 55° as it flies toward the scene. Then, some 120s later, ATSR2 records a second observation of the scene at an angle close to the nadir (Mutlow, 1999). ATSR2's field of view comprises two 500 km-wide curved swaths, with 555 pixels across the nadir swath and 371 pixels across the forward swath. The pixel size is 1x1 km at the center of the nadir scan and 1.5 x 2 km at the center of the forward scan. The sensor records in 7 spectral channels: 0.55µm, 0.67 µm, 0.87 µm, 1.6 µm, 3.7 µm, 10.8 µm, 12.0 µm, which is comparable to the channels of the new SEVIRI instrument on MSG. The geolocation for the rectified (GBT) products proceeds by mapping the acquired pixels onto a 512x512 grid with 1km pixel size whose axes are the ERS-2 satellite ground-track and great circles orthogonal to the ground-track.

2.1 Cloud-top height retrieval

The ATSR2 GBT data were reduced to 8-bit and linearly stretched between the minimum and maximum value, cutting 0.5% on both sides of the histogram (excluding the pixels assigned with an error code). As no a priori values of the cloud heights are given to the matching algorithm, a hierarchical matching procedure with 3 pyramid levels is applied so that the maximum possible parallax at the highest level is only 1-2 pixels. Every pyramid level is enhanced and radiometrically equalized with a Wallis filter (Wallis, 1976). Points with good texture are selected with an interest operator (Förstner and Gülch, 1987) in the first pyramid level because it is likely that the same points are well detectable also in the other levels.

The matching was done with the unconstrained mode of the Multi-Photo Geometrically Constrained Matching Software package developed at our institute (Baltsavias, 1991), which is based on Least-Squares-Matching (Grün, 1985). Due to the different looking angle of the two images, matching can be very difficult, especially with thin differently looking clouds. It is therefore necessary to work with different matching parameters as every version can be good for some areas but unsuccessful in other regions. The matching solutions are quality-controlled with absolute and relative tests on the matching statistics.

The resulting y-parallaxes are a function of the height, the along-track wind component (for moving objects) and of the nadir and forward zenith angle. The nadir and forward zenith angle are known at 11 equally distributed points of the first and last scan line from the GBT header and can be linearly interpolated for all pixels (Bailey, 1995). The cloud height h is calculated from the y-parallax y_p after (Prata and Turner, 1997).

The height values of the successfully matched points are interpolated to the 512x512 grid. Three cloud tests are applied on the ATSR2 data to separate cloud, land and mixed pixels: 1) 0.87µm/11.0µm-ratio test, 2) 11.0µm-3.7µm difference test and 3) 3.7µm-12.0µm difference test. If a pixel fulfilled all tests, it was classified as cloudy; if none of the tests were fulfilled, the pixel was marked as land; all other pixels were classified as mixed. Only the cloudy pixels were then selected for the further investigations. Statistics of the results of the mixed and land pixels showed that many blunders could not be detected by the quality control within these areas. This is caused by multiple solutions within the land surface at this spatial resolution and by the problem that the matching result – especially at higher pyramid levels – is strongly affected by the near cloud borders.

2.2 Across-track wind retrieval and along-track wind error

The forward and nadir ATSR2 images are acquired with a mean time delay of 120 seconds so that significant cloud motion is observable between the two scans. In a ungridded product, the x-parallax is a function of the across-track wind component while the y-parallax is a function of both the along-track wind and the cloud height. Strong along-track winds therefore directly influence the above described cloud-top height retrieval and can theoretically lead to height errors of up to a few kilometers. At most meteorological situations however, the main wind component is west-east oriented which mainly influences the across-track wind amount and which results in height errors of only a few hundred meters. Nevertheless, it is recommended to correct the cloud-top heights by the along-track wind error whenever the cloud wind vectors are available from another source (e.g. Meteosat cloud winds). For the across-track wind retrieval and along-track wind correction, the exact time difference between the same two pixels in the forward and the nadir scan has to be calculated from the along-track distance on the ground and the satellite velocity after (Lorenz, 1985). It has to be noted that any regridding errors can additionally influence the x- and y-parallaxes; in a future study, the accuracy of this regridding for the MAP cases will be evaluated.

3. METEOSAT-6 AND METEOSAT-7

EUMETSAT supported the MAP experiment by 5min rapid scans of the Alpine region (Fig. 2) with the in-orbit stand-by Meteosat-6 positioned at 9° W (EUMETSAT, 1999). The limited scan starts at line 4218 (or line 2109 for IR/WV) of the operational Meteosat-7 scan which results in a time difference between the two scans of 21:05 minutes.

3.1 Tracking

The cloud motion from one rapid scan image to the next is in the range of 0-5 pixels. As the features – even clouds – are very self-similar within these 5 minutes, the tracking of cloud points is much easier compared to tracking of the operational 30min Meteosat-7 series where it can be difficult to select good cloud tracers (Schmetz et al., 1993). Distinct cloud points were again selected with an interest operator and then, the corresponding points in the image sequence were determined with the matching algorithm. Before matching, the images were enhanced with a Wallis filter. It is also possible to track the same points through multiple images to get cloud trajectories of a requested length.

3.2 Wind correction for ATSR2

For every ATSR2 cloud pixel, the nearest 9 Meteosat-6 pixel are calculated with an affine transformation which was previously determined with tie points. The mean of the wind components of these 9 pixels is then assigned as the correction vector of the ATSR2 pixel. North winds lead to an underestimation of the heights so that the along-track wind component has to be added to the y-parallax while southerly winds result in too high cloud-top heights.

3.3 Stereo view

The rapid scans together with the images from the operational Meteosat-7 satellite additionally provide the possibility to stereo-view clouds over Europe with a geostationary satellite for the first time (Fig. 2). As the Meteosat satellites have a reversed scan mode (south-north) with respect to all other meteorological satellites, their images cannot be used for stereo mapping with other geostationary satellites.

The stereoscopic effect is not so extended due to the low resolution of the images and due to the small longitude difference of the two satellites, 0° and 9° W, compared to the satellite height.

4. GROUND-BASED IMAGER SYSTEM (SKYCAM)

Our ground-based stereo camera system was part of the MAP Rhine Valley observing system (MAP-FORM) and was operated during three weeks in October 1999. The two camera locations were situated at Mels with a horizontal distance of 850 meters. The relatively short distance was chosen to be able to stereo analyse also low clouds. The choice of an appropriate base length for cloud mapping is difficult because of the wide height range of clouds. Each camera system consisted of a colour digital CCD camera with wide-angle lens which was mounted on a adapted theodolite tripod with a moving sun occultator device (which can be used against image blooming caused by the sun). The shutter release was controlled from a laptop with precise time information. A detailed description of the camera system and calibration process is given in (Seiz and Baltsavias, 2000).

The matching was done with the unconstrained mode of the Multi-Photo Geometrically Constrained Matching Software package (Baltsavias, 1991). In a next step, the constrained mode will be used which means that the search space is limited through the geometric constraints from the precise orientation parameters of the cameras. In addition, the cloud motion between subsequent images was estimated with manual measurements (when the time difference was too long between two images).

5. RESULTS

All the above described methods were applied to the dataset of 13th October 1999 where coincident images of ATSR2, Meteosat-6, Meteosat-7 and the ground-based imager system were taken. Table 1 shows the exact acquisition periods of the four systems.

Sensor	Start	End	Approximate Time at Rhine Valley	Frequency
ATSR2	forward: 10:15:58 nadir: 10:18:12	forward: 10:17:12 nadir: 10:19:26	forward: 10:16:30 nadir: 10:18:45	About 3 days
Meteosat-6	10:15/ 10:20	10:17/ 10:22	10:16/ 10:21	5 min
Meteosat-7	10:00	10:25	10:22	30 min
Skycam	10:00	11:00	10:16/ 10:18/ etc.	2 min

Table 1. Acquisition times of the different sensors on 13th October 1999.

A description of synoptic situation on the 13/10/1999 with forecast reports and a hindcast summary can be found at (http://www.map.ethz.ch; IOP-06).

In the cloud-top height maps from the 0.87µm and 11.0 µm ATSR2 channels (Fig. 3), significant differences can be seen at the upper left part of the image (Southern Germany/ Austria) and in the Adria region (lower right part). At both locations, thin cirrus layers are not visible enough in the 0.87µm channels so that the retrieved height is dominated by the underlying cloud layer or the land/ sea surface. In Southern Germany, an optically thick fog layer is mapped this way, while in the Adria, the heights are around the null-level which indicates that no second cloud layer exists in this area next to the cirrus layer at about 10 km.

The field of view of the ground-based imager at the Rhine Valley corresponds to about 14 x 9 ATSR2 pixels. The retrieved mean height in this area is 12.0 km above sea-level from the 11µm channel and 13.0 km from the 0.87 µm channel. The matching of the cirrus clouds in this area was much more accurate with the 11µm channel (less blunders).

Fig. 1 presents the wind field as derived from the Meteosat-6 rapid scan. Strong westerly flow is extracted in the center and right part of the Meteosat-6 data area while at the left part, circular cyclonic flow is clearly visible.

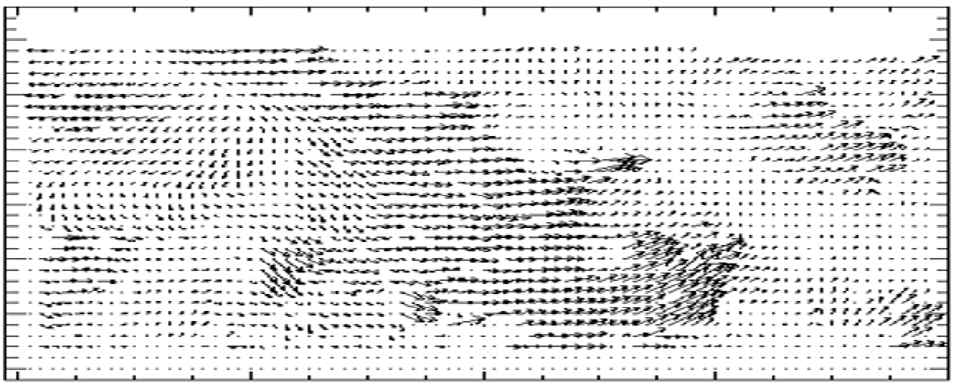

Fig. 1. Wind field as extracted from the Meteosat-6 rapid scan.

The wind correction for the ATSR2 cloud-top heights which is then derived from this Meteosat-6 wind field, is summarized in Table 2. As the main cloud motion direction in the ATSR2 image area is west-east directed, the height correction amounts are quite small. The calculated maximum x-shift of 3.5 pixels is much less than the matching result of the ATSR2 x-parallax which goes up to 7 pixels (verified with manual measurements within cirrus layer northwest of Rhine Valley). Comparison of the ungridded and the used gridded ATSR2 images have to be made to check whether any regridding errors can explain this difference. As the cloud motion was extracted from the VIS channel of Meteosat-6, it is also possible that not all cirrus clouds have been correctly detected and tracked and that their wind speeds have been underestimated.

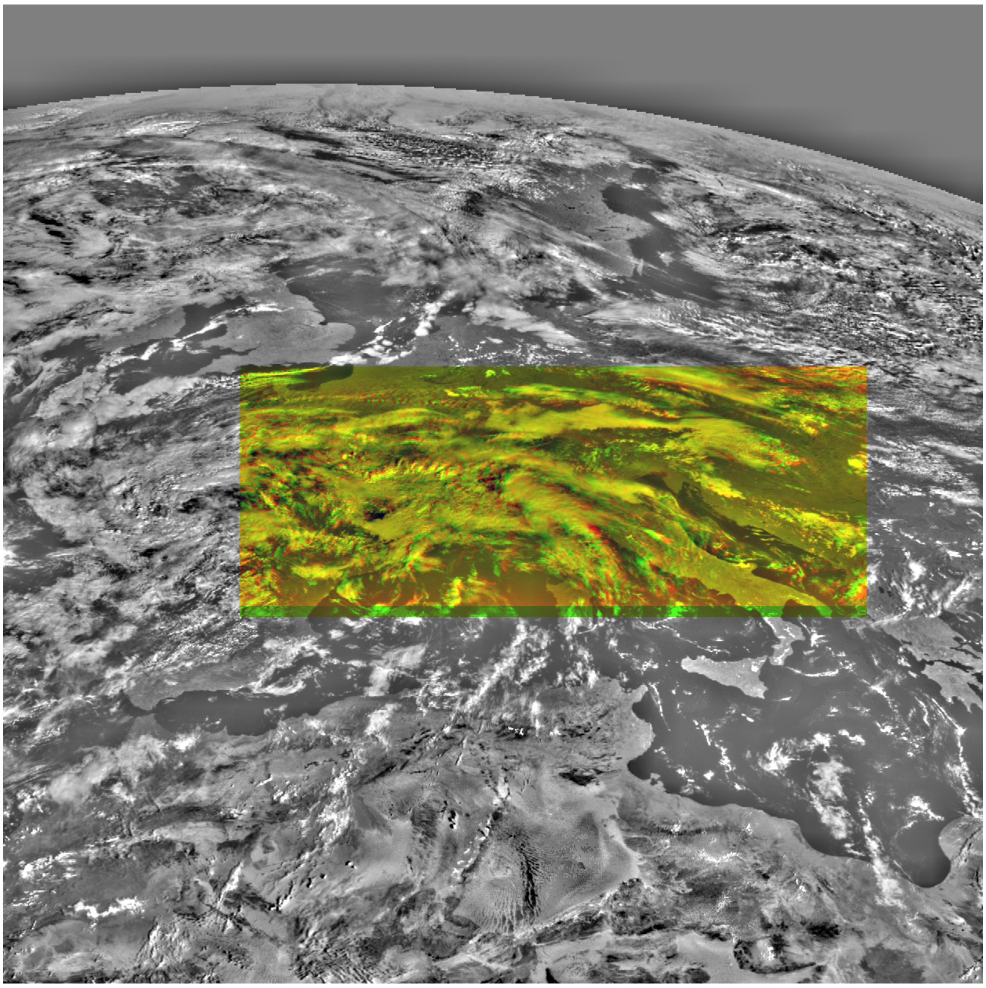

Fig. 2. Overlay of the full-globe image of Meteosat-7 (13/10/1999, 10:00) with the limited rapid scan of Meteosat-6 (13/10/1999, 10:20). The overlapping region can be stereo viewed with red-green glasses.

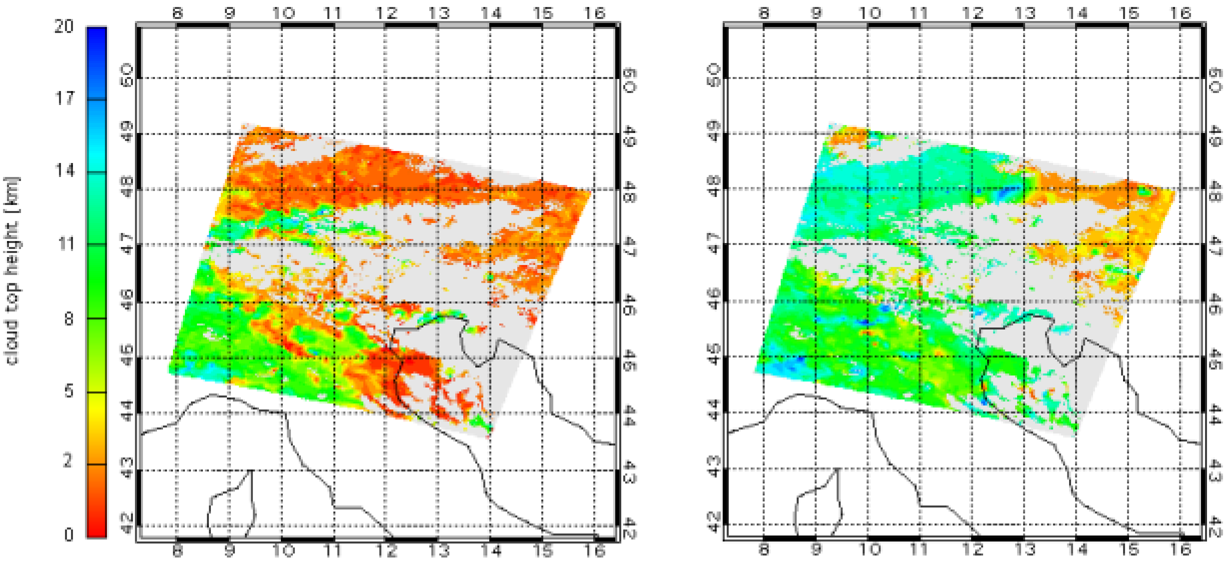

Fig. 3. Cloud-top heights from ATSR2, 13/10/1999 (grey regions: cloud mask). Left: 0.87µm channel, right: 11µm channel.

	Mean	Min	Max
x wind component [m/s]	3.5 ± 4.7	-2.2	25.7
y wind component [m/s]	1.0 ± 1.1	-2.8	7.2
x-shift [m]	433.6 ± 603.3	-227.3	3356.1
y-shift [m]	128.4 ± 147.7	-357.3	957.6
Height correction [m]	108.1 ± 117.3	-313.0	726.1

Table 2. Statistics of the ATSR2 wind correction.

In the ground-based images, two layers of clouds are visible. The stereo analysis gives the following height and motion results (Table 3):

	Date, Time	Lower layer	Upper layer
Height [km]	13/10/1999, 10:16	8.0±0.11	10.9±0.13
Motion [m/s]	13/10/1999, 10:14-10:16	17.8	25.8
Motion direction[°]	13/10/1999, 10:14-10:16	274	276

Table 3. Mean cloud parameters from the ground-based imager system.

6. COMPARISON WITH OTHER MAP DATA

A special composite observing system for the MAP-SOP was set up at the region of the Rhine Valley. Fig. 4 shows the location of our two cameras and of the lidar, radiosonde and surface climate stations which can be used for data comparison. Most of the systems were operated more or less continuously during the whole SOP; some were only switched on during IOPs. For the case described in this paper, no lidar measurements were available. The eye-observations of the surface climate stations are not listed here as the height of cirrus clouds cannot be estimated with a reliable accuracy by an observer.

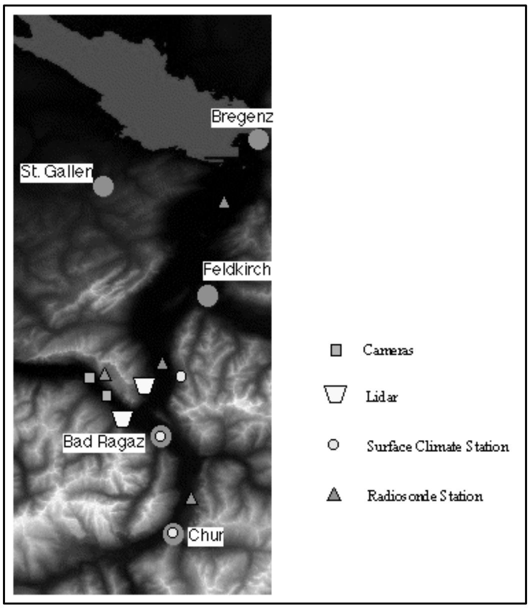

Fig. 4. Location of MAP-FORM stations which measured or observed cloud parameters during MAP.

6.1 Radiosondes

In addition to the operational radiosonde network, 6 temporary radiosonde stations were operated by the Swiss Army during the MAP-SOP in the greater Rhine Valley area. They consist of two types of sondes:

- Low-level sondes, measuring temperature and wind.
- High-level sondes, measuring pressure, temperature, humidity and wind.

A method for estimating cloud heights and amount from radiosonde data is described in (Chernykh and Eskridge, 1996).

Table 4 shows wind measurements and cloud layer estimation from the soundings of Diepoldsau, Masein and Milano-Linate which were launched at 11:00 on the 13/10/1999. The data of Diepoldsau validates the fog layer and the lower cirrus layer; humidity measurements are not available above about 250hPa so that cirrus layers higher than 10km are not detectable. The cloud height in the soundings of Masein and Milano-Linate is not as well defined as in the sounding of Diepoldsau; nevertheless, it shows that the middle cloud layer North of the Alps is much higher than South of the Alps. The windspeed in all soundings increases towards the tropopause, the wind direction is slightly north-west at the Northern side of the Alps and south-west at the Southern side.

Station	Cloud height [hPa]	Cloud height [m]	Windspeed [m/s]	Wind direction [°]
Diepoldsau	890 – 900	1200 – 1300	-	-
	370	8000	17.5	285
	-	-	at 11 km: 27.5	275
Masein	380 – 440	6750 – 7800	15.0	270
	-	-	at 11 km: 25.0	260
Milano-Linate	440 – 590	4450 – 6750	10.0	255
	200	12000	30.0	265

Table 4. Cloud height and wind information as extracted from the soundings of Diepoldsau, Masein and Milano-Linate.

6.2 Wind profilers

The data of the C.W.I.N.D.E. network (http://www.meto.gov.uk/sec5/CWINDED/cwinde99/cwindemape.html) stations Clermont-Ferrand, La Ferte Vidame, Julierpass and Lonate Pozzolo were studied. For the MAP-SOP, the Payerne wind profiler measured at the more Inner Alpine location of Julierpass (CH) and the Toulouse wind profiler at Lonate Pozzolo (I) near Milano. The wind plots at the stations in France report smaller windspeeds (8km: 10-15m/s, 12km: 15-20 m/s) and southerly flow, while the Alpine stations show west to southwest wind directions with speeds up to 40m/s.

6.3 High-resolution regional weather models

During the MAP-SOP, the non-hydrostatic, limited-area MC2 (Mesoscale Compressible Community; http://www.geo.umnw.ethz.ch/research/map_mc2/) model was run continuously. The integration was done every day at 21:00 for the next 24h. The MC2 model has an area of 1050x900 km^2 which covers the whole Alpine region and a spatial resolution of 3 km. The initialization of the model is done within the model chain of the GM global model (DWD, 125km resolution) via the EM Europe model (DWD, 56 km) via the SM Swiss Model (SMI, 14 km). The 13h forecast from 12/10/1999 for 13/10/1999 10:00 presents a southerly flow South of the Alps with a mean speed of 10 m/s on the 700hPa level and SW to W to NW flow with a mean speed of 25-30 m/s at the 300hPa level.

7. CONCLUSIONS

The measurements with the coincident satellite- and ground-based sensors during the MAP-SOP have shown the capacity of mapping cloud fields at different scales. The accurate determination of satellite cloud-top heights depends on the time difference of the stereo images, the base/height-ratio, a precise sensor model (or regridding algorithm) and a robust matching technique. Our hierarchical approach with the own matching software showed to be usable for the task of cloud matching. A special effort will be taken to improve the quality control scheme during and at the end of the matching process. The use of cloud motion wind information from geostationary satellites is a reliable technique to correct wind-induced stereo height errors due to asynchronous acquisition of the stereo images and is recommended for operational applications. The motion analysis from the first alpine rapid scans is consistent with the wind measurements from wind profilers and radiosondes and with regional model forecasts.

The case study showed the validation possibility of satellite-based cloud-top heights of vertically thin clouds with ground-based imagers. Such ground-based stereo camera systems are also an interesting technique to map smaller scale features which can be important for more regional weather nowcasting. Further MAP cases with coincident ground and satellite data will be analysed.

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