

The MAP Special Observing Period



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1. Objectives and context of MAP

Intense weather over major mountain ranges such as the Alps brings a high cost to society in the form of floods, windstorms, and threats to aviation. The Mesoscale Alpine Programme (MAP; see Table 1 for a list of acronyms) is a measured response of the international atmospheric and hydrologic community to the challenge of improving the understanding and prediction of these events. It relies on intense international cooperation to assemble an alpine-scale dataset suitable to advance the basic knowledge and prediction techniques.

The following scientific objectives for MAP were published in the MAP Design Proposal (Binder and Schär 1996).

- 1a) To improve the understanding of orographically influenced precipitation events and related flooding episodes involving deep convection, frontal precipitation, and runoff.
- 1b) To improve the numerical prediction of moist processes over and in the vicinity of complex topog-

raphy, including interactions with land surface processes.

- 2a) To improve the understanding and forecasting of the life cycle of Foehn-related phenomena, including their three-dimensional structure and associated boundary layer processes.
- 2b) To improve the understanding of three-dimensional gravity wave breaking and associated wave drag in order to improve the parameterization of gravity wave drag effects in numerical weather prediction and climate models.
- 3) To provide datasets for the validation and improvement of high-resolution numerical weather prediction, hydrological, and coupled models in mountainous terrain.

These statements served as the basis for planning a large field experiment, the MAP Special Observing Period (MAP-SOP), which took place from 7 September to 15 November 1999. It was indeed recognized that only a major field program could provide the measurements needed to fully validate numerical weather prediction models for the simulation of intense weather in mountain areas. The present paper reports on this experiment which was the largest field program over the Alps since ALPEX in 1982. The links between MAP and previous experiments are further discussed in section 2b.

MAP involves a large number of committees and working groups, but the main permanent structures are the MAP Data Center and the Program Office, both created in 1995 by EUMETNET, the Network of European Weather Services for research and development. Their primary missions are to maintain an archive of the relevant data, facilitate intercomparison of numerical models, prepare the SOP (completed) and make SOP data available to a wide community.

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TABLE 1. Acronyms.

AES	Atmospheric Environment Service (Canada)
ALDIS	Austrian Lightning Detection and Information System
ALPEX	Alpine Experiment
ARAT	Avion de Recherche et de Télédétection (France)
BOLAM	Bologna Limited Area Model (Italy)
CETP	Centre des Environnements Terrestres et Planétaires (France)
CIRES	Cooperative Institute for Research in Environmental Science (United States)
CNR	Consiglio Nazionale delle Ricerche (Italy)
CNRM	Centre National de Recherches Météorologiques (France)
CNRS	Centre National de la Recherche Scientifique (France)
COAMPS	Coupled Ocean Atmosphere Mesoscale Prediction System (United States)
COC	Coordination and Operations Center (Bad Ragaz, Switzerland)
CRA	Colorado Research Associates (United States)
CSIM	Centro Sperimentale per l'Idrologia e la Meteorologia (Italy)
CVB	Constant volume balloons
DIAL	Differential absorption lidar
DLR	Deutsches Zentrum für Luft und Raumfahrt (Germany)
DOW	Doppler-on-Wheels Radar (NCAR/University of Oklahoma)
DRI	Desert Research Institute (United States)
DWD	Deutscher Wetterdienst (Germany)
ECMWF	European Centre for Medium-Range Weather Forecasts
ETH	Swiss Federal Institute of Technology (Zurich, Switzerland)
EUMETNET	European Meteorological Network
GOP	General observing period
GPS	Global Positioning System
GTS	Global Transmission System
GWB	Gravity wave breaking
HERA	Heavy rain on the Alps
IGN	Institut Géographique National (France)
IMGW	Institut für Meteorologie und Geophysik, University of Vienna
IMK	Institut für Meteorologie und Klimaforschung, Forschungszentrum Karlsruhe
INSU	Institut National des Sciences de l'Univers (France)
IOP	Intensive observing period
ISAO	Istituto di Scienze dell'Atmosfera e dell'Oceano (Bologna, Italy)
JOSS	Joint Office for Science Support (United States)
LA	Laboratoire d'Aérodynamique (France)
LMD	Laboratoire de Météorologie Dynamique (France)

The SOP was funded by many European and North American weather services and science agencies. A list of agencies is given in Table 2. Some additional funding for the preparation was provided by the European Union, under the HERA and RAPHAEL projects. The European Union also supported some operations of the Fokker and Falcon aircraft through the STAAARTE training program. After the creation of the World Weather Research Program by the World Meteorological Organization in 1998, MAP was incorporated in this new action as the first of a series of “research and development projects.” Finally, the MAP–SOP coincided in time with another field experiment, organized by the European Composite Observing System

(EUCOS) program of EUMETNET. This provided ample additional radiosonde measurements at selected sites and measurements by commercial airplanes from all major European airports.

2. Organization of the SOP

a. *The scientific projects*

The SOP was organized into eight scientific projects, referred to as P1 to P8, which were to some extent in competition for access to the main facilities. We will give here a brief outline of these projects. A complete list of detailed scientific questions can be

TABLE 1. *Continued.*

LMTA	Lago Maggiore Target Area
LSEET	Laboratoire de Sondage de l'Environnement Electromagnétique Terrestre (Toulon, France)
MAP	Mesoscale Alpine Programme
MC2	Modèle Mésoéchelle Compressible Communautaire (Canada)
MDC	MAP Data Center (Zurich, Switzerland)
MeteoSwiss	Swiss Meteorological Service
Météo-France	French Meteorological Service
MIM	Meteorologisches Institut, Universität München
MM5	Mesoscale Model Version 5 (United States)
MNC	MAP Network Center (Zurich, Switzerland)
MOC	MAP Operations Center (Innsbruck, Austria)
MPO	MAP Project Office (Zurich, Switzerland)
MST	Mission selection team
NASA	National Aeronautics and Space Administration (United States)
NCAR	National Center for Atmospheric Research (United States)
NOAA	National Oceanic and Atmospheric Administration (United States)
NRL	Naval Research Laboratory (United States)
NSF	National Science Foundation (United States)
OPRA	Orographic Precipitation Radar (United States)
PBL	Planetary Boundary Layer
PNNL	Pacific Northwest National Laboratory (United States)
POC	Project Operations Center (Milan, Italy)
PSI	Paul Scherrer Institute (Switzerland)
PV	Potential vorticity
PYREX	The Pyrenean Experiment
RAPHAEL	Runoff and Atmospheric Processes for Flood Hazard Forecasting and Control
RHI	Range–height indicator, radar vertical cross section
SMR	Servizio Meteorologico Regionale (Bologna, Italy)
SOP	Special observing period
STAAARTE	Scientific Training and Access to Aircraft for Atmospheric Research Throughout Europe
TWL	Transportable Wind Lidar (France)
UCAR	University Corporation for Atmospheric Research (United States)
UGM	Ufficio Generale per la Meteorologia (Italy)
UIV	Umwelt Institut, Vorarlberg
UKMO	The Met. Office (United Kingdom)
WMO	World Meteorological Society
ZAMG	Zentralanstalt für Meteorologie und Geodynamik, Vienna

found in the MAP Science Plan (Bougeault et al. 1998).

Project P1: *Orographic precipitation mechanisms*. This project addressed the basic mechanisms of production or enhancement of precipitation by topography. It involved studies of the small-scale dynamics of precipitating systems, including convective systems and their interaction with the topography, and studies of the detailed growth mechanisms of precipitation particles.

Project P2: *Incident upper-tropospheric PV anomalies*. This project focused on the dynamics of the large potential vorticity anomalies approaching the Alps from the west at the tropopause level, also called PV streamers. The role of these anomalies as precursors

of severe precipitation in the Alps was investigated, along with their modification by the diabatic heating due to the Alpine precipitation and the significance of small-scale structures seen on water vapor satellite images.

Project P3: *Hydrological measurements and flood forecasting*. This project explored the near-real-time forecasting capabilities of hydrological flood models, forced by special precipitation measurements or by mesoscale meteorological models. The testing of soil moisture monitoring techniques, the significance of soil moisture initial conditions, and the impact of information on water storage in power company reservoirs were particularly examined.

TABLE 2. Funding agencies for the MAP-SOP.

Austria	Federal Ministries of Science and Environment National Science Foundation Austrocontrol Central Institute for Meteorology and Geodynamics
Canada	Atmospheric Environment Service
European Union	STAAARTE Program
France	Centre National de la Recherche Scientifique Météo-France Electricité de France Centre National d'Etudes Spatiales
Germany	Deutsches Zentrum für Luft und Raumfahrt Deutscher Wetterdienst Deutsche Forschungsgemeinschaft Forschungszentrum Karlsruhe
Italy	National Research Council Ufficio Generale per la Meteorologia
Switzerland	MeteoSwiss Swiss Federal Institute of Technology Swiss National Science Foundation Swiss Army, Joint Meteorological Services Paul Scherrer Institute
United Kingdom	The Met. Office
United States	National Science Foundation National Oceanic and Atmospheric Administration Naval Research Laboratory National Aeronautics and Space Administration

Project P4: *Dynamics of gap flow*. This project investigated the three-dimensional velocity distribution at the Brenner Pass and within the Wipp valley, and its time and space variability in relation to the flow above mountaintop. The data address some key questions of stratified fluid dynamics, such as the possible formation of a hydraulic jump downstream of the gap, and the consequences of this jump.

Project P5: *Nonstationary aspects of foehn in a large valley*. This project addressed the four-dimensional variability of the foehn flow in the Rhine valley. It investigated several dynamical processes that determine the spatial extension and time variations of the foehn, such as the modification of the air mass by radiation, and the interaction with the upper-level flow.

Project P6: *Three-dimensional gravity wave breaking*. This project sought answers to the basic questions regarding the creation of clear-air turbulence by breaking gravity waves, such as the space and time distribution of GWB, the predictability of gravity waves by mesoscale models, the vertical distribution of momentum fluxes in the presence of breaking gravity waves, and the associated potential vorticity generation. It also used new experimental observational strategies, combining remote sensing and in situ techniques.

Project P7: *Potential vorticity banners*. This project investigated the high-resolution structure of the Alpine wake at or below mountaintop level. Numerical models suggest that the wake is organized in well-defined potential vorticity banners, extending downstream over several hundred kilometers. The existence and the cross-stream spatial scale of these flow structures were documented.

Finally, Project P8: *Structure of the planetary boundary layer over steep orography*. This project sought answers to a number of broad questions on the

structure of the orographic PBL, such as its depth and evolution, the three-dimensional distribution of turbulent fluxes within a steep valley, the interaction of PBL turbulence with the local winds, and the exchange of air mass and atmospheric constituents between the PBL and the free troposphere.

b. Links with ALPEX and PYREX

MAP greatly benefited from the impetus, experience, and results of previous international field programs on orographic flows, mainly ALPEX (1982) and PYREX (1990). ALPEX (e.g., Kuettner 1986) allowed fundamental advances in understanding how air flows over and around the Alps. It also provided excellent observations of lee cyclogenesis and downslope winds. PYREX, a study of the momentum

budget of the flow across and around the Pyrenees (e.g., Bougeault et al. 1997) allowed great progress of the orography representation in numerical models. Several of the scientific objectives of MAP appear as an expansion of the objectives of these previous programs: for instance the design of Projects P6, P7, and P8 was largely influenced by ALPEX and PYREX findings on gravity waves, the structure of the mistral and tramontana regional winds, and the early observations of turbulence in the vicinity of a major mountain range. But many MAP objectives had not been addressed at all in previous programs. The heavy orographic rainfall events (P1), their connection with the upper troposphere (P2), and their hydrological consequences (P3) were not part of ALPEX or PYREX objectives. The gap flow (P4) and foehn studies (P5) of MAP were developed at much finer time and space scales than could be achieved at the time of ALPEX and PYREX. New observing technologies, the progress of high-resolution numerical modeling, and a much broader international participation have made MAP a completely new program.

c. Target areas and operations centers

A list of available measurement systems during the SOP is provided in Table 3. In terms of ground systems, MAP was probably the largest field experiment ever conducted in Europe. The field activities were concentrated in three target areas (see Fig. 1). The Lago Maggiore Target Area (LMTA) was the main focus of Projects P1 and P3 (so-called Wet-MAP), as well as part of P8. The Brenner Target Area was the focus for Project P4, and the Rhine valley Target Area was the focus for Project P5 and part of P8. The remaining Projects (P2, P6, and P7) were not linked to specific geographical areas, as they relied mainly on aircraft measurements.

The MAP Operations Center (MOC), hosted jointly by Austrian scientific institutions and weather services at the Innsbruck airport, was the main center of decision, and the main concentration point of MAP scientists during the field phase. The MOC selected the intensive observation periods (IOPs) and the flight missions, and negotiated flight clearances with all air traffic control (ATC) centers involved in MAP missions. It also coordinated the activities of the Brenner Pass Target Area. The NCAR Electra, NOAA P-3, and UKMO C130 aircraft were based at the MOC, while the DLR Falcon and Dornier 228 operated from their home base in Oberpfaffenhofen, 90 km north of Innsbruck, Austria.

The activities of the Lago Maggiore Target Area were coordinated at the Project Operations Center (POC), hosted by the Italian Meteorological Service in the Regional Meteorological Center at Milano-Linate military airport. The French Merlin IV and Fokker 27 aircraft were based at the POC. The radar data from the southern side of the Alps were concentrated at the POC and used to construct a real-time composite of the precipitation areas on the southern side of the Alps. This was used by MOC scientists to guide the MAP aircraft toward areas of greatest interest, in close collaboration with the regional air traffic control center in Milan, Italy. It must be stressed that the LMTA is one of the most crowded air traffic areas in Europe. Overall, the POC played a unique role in making aircraft missions on the southern side of the Alps possible and successful.

The activities of the Rhine valley Target Area were coordinated from the Coordination and Operations Center (COC), hosted by the Swiss Army and ETH in Bad Ragaz, Switzerland. The Swiss Dimona aircraft was based in Altenrhein, near the Lake Constance at the estuary of the Rhine River.

The three operations centers remained in close contact via phone, Internet, and fax during the whole field experiment. Joint briefings were held every day for weather, flight proposals, decisions, and the preparation of joint missions. More information on the operations schedule and the decision-making process can be found in the MAP Implementation Plan (Binder et al. 1999).

d. Special meteorological products

Forecasts for MAP operations were provided by an international team of 25 forecasters working in shifts at the MOC in Innsbruck. They relied on a variety of model products, satellite, and radar pictures to issue daily forecasts tailored to the needs of mission planning. Forecasting support was also available at the POC, especially for nowcasting.

The national and regional meteorological services of the Alpine countries made an outstanding effort to respond to the data and forecast needs of MAP. This is illustrated here by the network of operational and research radars (Fig. 2) and by the network of upper air measurements by radiosondes and wind profilers (Fig. 3). Also impressive was the real-time exchange of surface data from automated stations that outnumbered normal WMO requirements by a factor of 10 or more. All these data are already available from the MDC without any restriction.

TABLE 3. Main experimental facilities available during the SOP.

Target area	Location	Facility	Institution
Aircraft	Innsbruck	Electra P-3 C-130	NCAR NOAA UKMO
	Oberpfaffenhofen	Falcon Dornier 228	DLR DLR
	Milan	Merlin IV Fokker 27 ARAT	Météo-France CNRS/IGN/CNES/Météo-France
	Locarno/Altenrhein	Dimona	Metair
Lago Maggiore	Vergiate Novarra	S-Pol Doppler radar, Ronsard Doppler radar, Disdrometer	NCAR CETP
	Monte Lema	Doppler radar	MeteoSwiss
	Toce and Ticino valleys	DOW Doppler radar OPRA Radar	University of Oklahoma, Princeton University, and University of Washington
	Macugnaga	Vertical Doppler radar, disdrometer	ETH
	Locarno Monti	Vertical Doppler radar	IMK
	Lonate Pozzolo	UHF and VHF wind profiler	Météo-France
	Pallanza	Lidar	IFA-CNR
	10 sites in Po valley	Sodars, UHF radars, PBL stations, microbarograph, radio soundings	CNR, ENEL, JRC Ispra, Universities of Alessandria, Brescia, Torino, Genova, etc.
	Riviera valley	PBL instrumentation	ETH
	Toce valley	Soil moisture and PBL	Universities of Brescia, Milan, Modena, CNR
	Ispra	CVB, atmospheric electricity	LA
	Milan (POC)	Integrated water vapor by GPS	IGN/INSU
Rhine valley	Vilters	TWL scanning lidar	LMD
	Trübbach	Vertical aerosol lidar	University of Neuchatel
	Rankwell	UHF and RASS	IMK

TABLE 3. *Continued.*

Target area	Location	Facility	Institution
	Julier Pass	VHF profiler, sodar, radio sounding, surface station	MeteoSwiss
	Hoherkasten	Video cameras	MeteoSwiss
	Several sites	PBL instrumentation, sodars	IMGW, MeteoSwiss, ZAMG, PSI, ETH, UIV MIM
	7 sites	Radio-sounding stations	Swiss army, IMGW
	Sevelen	Scintillometers, CVB tracking stations	PSI MeteoSwiss, LA
Brenner	Gedeir	Scanning lidar	NOAA/ETL
	Several sites	Surface stations	Universities of Innsbruck, Modena, München, PNNL
	Several sites	Microbarographs	University of Leeds
	Several sites	Sodars, UHF, radio soundings	ZAMG, Universities of Modena, Innsbruck, Washington

In this respect, an interesting consequence of MAP was noted in Italy, where the SOP led to the first operational cooperation (exchange of data and forecasters) among the several existing local services and the National Service operated by the Italian Air Force.

Table 4 summarizes the major sets of observations and forecasting products that were transmitted in real time (via the GTS and the Internet) to the MAP information network. In order to ease the use of the abundant mass of information, an effort was undertaken to standardize the look and feel of the products.

Several special products were also available to MAP forecasters and scientists during the SOP. Rapid scans (5 min) of the *Meteosat-6* standby satellite over the Alpine region (see Fig. 4) were activated by EUMETSAT for 24-h periods, on request from the MOC (Levizzani 1998). These covered most of the IOPs. The success of this operation led to the conclusion that a similar service could be opened on a more routine basis in the near future. A midlatitude and a tropical window are being considered. This may become an important and rapid consequence of the MAP-SOP. A special “alpine radar composite” was

produced by DLR with data from all operational radars around the Alps. It was made available through the Internet within 30 min from observations. By special agreement of most operational atmospheric electricity networks, enhanced data on lightning were transmitted in real time to ALDIS (Vienna, Austria). These were used to compute more precise locations of lightning strikes all over the Alps by combining information from the national networks. This information was displayed on the operational Austrian system in the MOC and was accessible to MAP forecasters.

Finally, a special numerical weather prediction suite was run to provide very high resolution forecasts at the Alpine scale. The mesoscale Canadian AES MC2 model was run at the horizontal resolution of 3 km and forced by initial and boundary conditions from the operational model of MeteoSwiss. The model was run every night at the Swiss Center for Scientific Computing in Manno (Switzerland) for the period 2100 UTC of the previous day to 0400 UTC (i.e., a time window of 27 h). Detailed forecasts of precipitation, wind, turbulence, and potential vorticity were

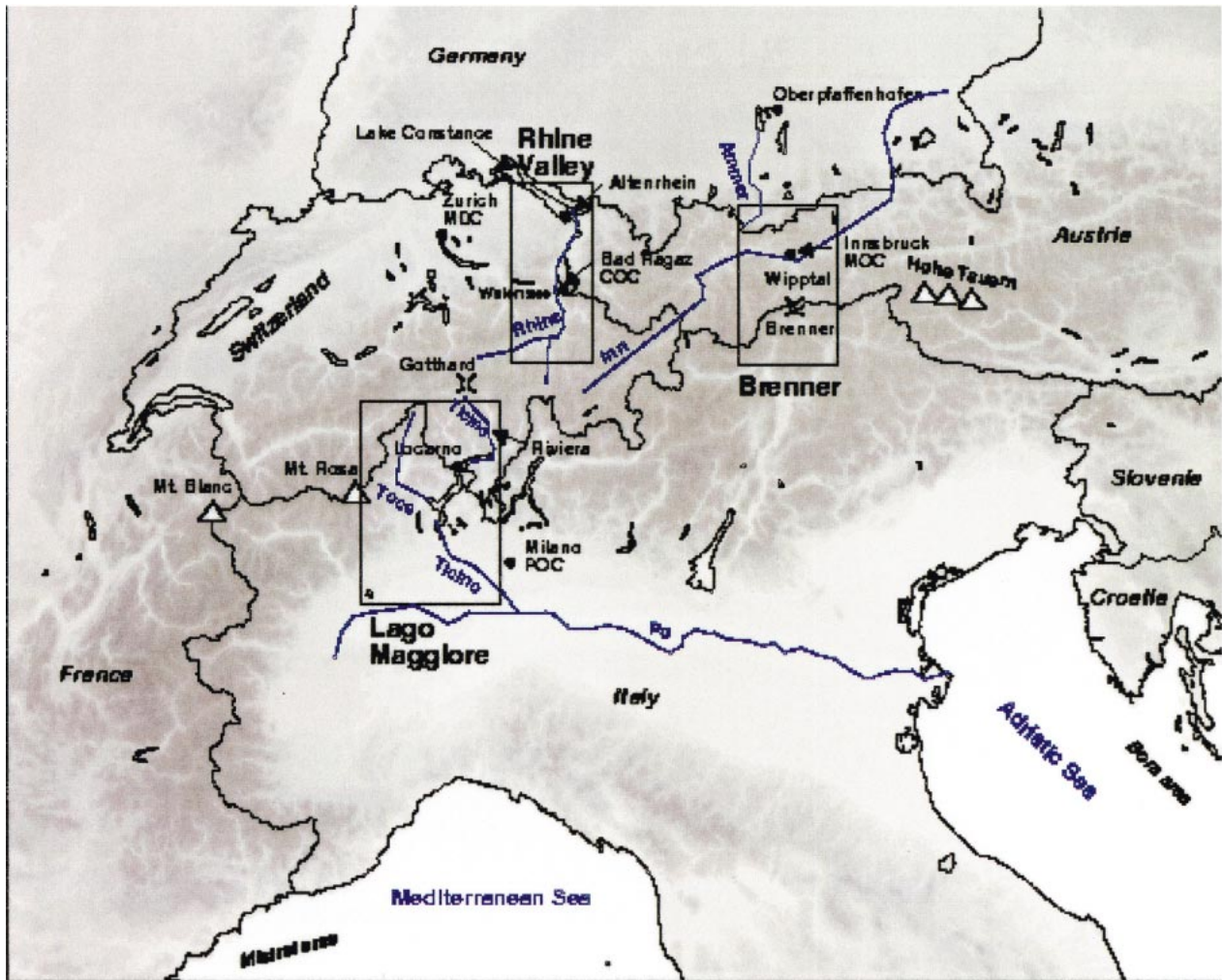


Fig. 1. Main geographic features for the SOP.

available on horizontal and vertical cross sections of interest, and were used by mission scientists to optimize the flight plans of the day. The detailed verification of MC2 forecasts was a central objective of several scientific projects. An extensive report on MC2 results has been prepared by R. Benoit et al. (2000, personal communication).

In addition, various model runs (e.g., BOLAM, COAMPS, MM5, MC2 at lower resolution, etc.) were made available to MAP forecasters and scientists through the Internet.

e. Summary of operations

The SOP benefited from excellent weather conditions. After an initial anticyclonic period from 7 to 15 September, the Alps came under the influence of a series of perturbations moving from west to east, most of them bringing active fronts and convection

into the LMTA. Following a classic pattern, the fronts were preceded by a brief period of southwesterly flow leading to foehn conditions on the northern side of the Alps, and some of them were followed by northwesterly flow, favoring the onset of PV banners. The anticyclonic conditions returned around mid-October for 10 days. The last month of the SOP had a large variety of situations, most of which were pertinent to at least one of the projects, leading to a very active schedule of IOPs. In summary, 17 IOPs were conducted, totaling 42 days of activity. All available resources (in terms of sondes, flight hours, etc.) were exhausted by the end of the SOP. The operations are summarized in Table 5. It is clear from the table that most projects fully reached their objectives. Figure 5 shows that the available aircraft resources were utilized by the various projects according to the preagreed plans.

The statistical evaluation shows that the year 1999 was a very good year relative to the frequency and distribution of MAP-relevant weather events. All phenomena occurred more frequently than expected relative to the average of the last 10 years. Foehn in the Rhine valley and gap flow events occurred 40% and 15% more frequently than the average. The PV streamers, gravity waves, and PV banners occurred at more than twice the average frequency. Only PV banner situations with a northerly flow occurred slightly less frequently than the average. The number of 17 IOPs corresponds exactly to the maximum number that would have been possible during the 10 previous years. The last equally favorable year was 1993. Hence we can state that the 1999 SOP season offered an outstanding opportunity that could be expected only once every five years.

3. Preliminary experimental results

a. Orographic precipitation mechanism

To accomplish the scientific objectives of P1, a nested observational strategy was designed. The networks of operational radars in the Alpine region provided a rich background (see Fig. 2). In the LMTA, more detailed observations were provided by seven ground-based research radars. The French Ronsard radar and the Swiss Monte-Lema radar provided dual-Doppler data, and the U.S. S-Pol radar increased the resolution of these measurements and mapped the microphysical structure within the dual-Doppler array through dual-polarization measurements. Three small specialized radars provided vertical profiles of reflectivity (the U.S. S-band OPRA, the Swiss X band, and the German K band). The U.S. Doppler-on-Wheels (DOW, Wurman et al. 1997) obtained Doppler radial velocity measurements of the winds in the Toce and Ticino River valleys to indicate how the flow is modified on the valley scale. Two French wind profilers

were installed in the LMTA and continuously monitored the wind field throughout the SOP, providing detailed upstream conditions for orographic rain events by southerly flow. Finally, many Italian PBL measurements were made in the LMTA in support of this project, including sodars, one tethered balloon, surface energy balance stations, one water vapor lidar, one special sounding station, and a microbarograph network. Whenever possible, aircraft missions were flown over this highly instrumented region in coordination with the ground-based radars. The P-3 and Electra provided airborne Doppler measurements and cloud physics sampling in specific subregions of the area covered by the radars. The Fokker, carrying the LEANDRE 2 lidar (Flamant et al. 2000), supplemented these measurements with low-level upstream temperature, moisture, wind, and PBL height data. The Merlin acquired in situ microphysical measurements in the cloud systems of the Po valley that will be very useful to check the effectiveness of the polarimetric retrieval techniques. The Merlin and Fokker also conducted two missions in the Po valley to map the surface fluxes of sensible and latent heat prior to interesting rain events.

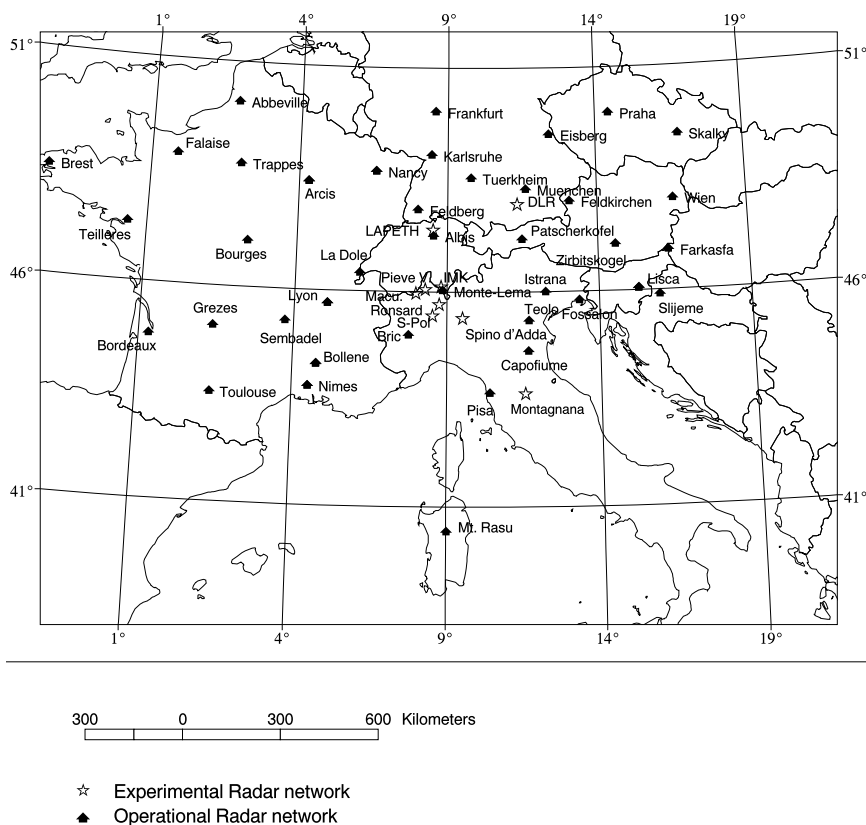


FIG. 2. Operational and research radars in the greater MAP region during the SOP.

TABLE 4. Real-time products providers during the SOP.

Service	Fcsters	RS	Surface data	Radars	NWP	other
ZAMG (Austria)	3	72	TAWES	CERAD composite	ECMWF and ALADIN-LACE models	Visualization system
Military WS (Austria)	1					
Austrocontrol (Austria)	2	102		A composite		ALDIS (lightning)
UGM (Italy)	1	280		North Italian radars		
CSIM (Italy)			Automatic stations	SINA-composite		
Regional Services (Italy)	7	280	Automatic stations	Yes		
MeteoSwiss	2	72	ANETZ, ENET	CH composite, Monte Lema	Swiss Model 14 km	Meteosat, NOAA
Météo-France	4	336	1-h synoptic	F composite		Météorage (lightning)
DWD (Germany)	2	144	1-h synoptic	D composite	Lokal Modell 7 km	
DLR (Germany)				Alpine composite		
AES/RPN (Canada)	1				MC2 3 km (run at SCSC Manno, Switzerland)	
Croatia	2	72	1-h synoptic			
Slovenia	2	102	1-h synoptic			
INM (Spain)		72	1-h synoptic	Barcelona		
UKMO (UK)						CWINDE profilers
NRL and NWS (US)	1				COAMPS	

the microphysics of the precipitation processes in the context of orographically influenced mesoscale and valley-scale airflow. Figure 7 shows results of applying the particle identification algorithm of Vivekanandan et al. (1999) to polarimetric data obtained during the IOP5 rainstorm exhibited in Fig. 6.

The various colors in Fig. 7b indicate the categories of particle type identified by the algorithm. The Vivekanandan et al. (1999) algorithm was run side by side throughout MAP with a simpler algorithm (Zeng 1999), which uses the thresholds and only a few broader but more certain particle-type categories.

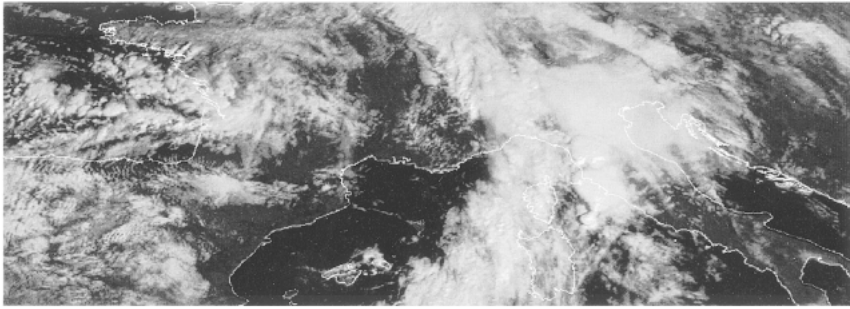


FIG. 4. Still image in the visible channel from *Meteosat-6* rapid scan sequence of 20 Sep 1999, 0942 UTC (IOP 2). Very intense convective activity with the development of several large cells over Italy was captured and closely followed by the satellite at 5-min intervals (courtesy of EUMETSAT).

Highly consistent results were obtained by the two techniques. In the case shown in Fig. 7b, the general background stratiform echo was neatly divided into a rain layer (brown colors) and an ice particle layer (pink, blue, and purple colors). The convective echo appearing in red consisted of heavy rain, graupel mixed with rain (green colors), and a few spots where hail is suggested (yellow). This cell was particularly intense, and hail may have actually been present in small amounts. The other algorithm (not shown), which tends to be more conservative, did not indicate hail. This result was rather typical: the convective cells seen in IOP 2B, 3, and 5 tended to contain a little graupel and only very occasional spots of hail. They showed maximum reflectivity and heavy rain at low levels, indicating the importance of growth by drop coalescence in the lower levels (the “warm rain” process). The relative roles of warm rain and ice processes in the orographic precipitation remains to be evaluated from the full MAP dataset.

Three aircraft in MAP had particle measuring systems on board for documenting the sizes and shapes of precipitation particles: the P-3, Electra, and Merlin. More often than not, air traffic restrictions prevented collection of an optimal microphysical dataset. Nonetheless, several flights by these aircraft collected particle samples at a range of temperatures that should be useful in evaluating the microphysical structure indicated by the S-Pol radar. In situ measurements taken at the mountain station of Macugnaga, Italy (2800 m ASL) also support the results of the particle identification algorithms (Barthazy et al. 2000).

While the ground-based radars monitored the orographically modified flow and precipitation continuously and in detail in the LMTA, the MAP research aircraft could explore the precipitation all along the

Alpine barrier. Later in IOP5, on the day following that just described, the precipitation moved eastward, and the cold front crossed northern Italy, the Adriatic, and Slovenia. The P-3 and Electra aircraft conducted an extremely successful coordinated mission documenting the frontal precipitation as it crossed the Adriatic. Figure 8 shows portions of the flight tracks of the two aircraft, while the overall radar echo pattern is supplied by the Italian operational radar at

Fossalon di Grado. This figure cannot adequately show the intricate coordination of the aircraft tracks with each other and with the radar echo pattern since the ground-based radar data were for a particular instant of time and the aircraft tracks were for the hour preceding that time. The Fossalon radar data shows that the frontal-banded precipitation extended south over the Mediterranean, yet was also evidently dynamically connected to what was happening over the Alpine slopes to the north. Analysis of the dual-Doppler radar collected on board both aircraft eventually will document the dynamics of this frontal orographic interaction in detail.

b. Incident upper-tropospheric PV anomalies

The observational strategy for P2 relied primarily on the Falcon aircraft. In support, the French network of VHF profilers provided continuous measurements of the three wind components and of the tropopause height during the passage of the anomalies. The aircraft missions were usefully guided on the basis of forecasts of the tropopause surface by the ECMWF model. During the SOP the weather was favorable in providing three cases with elongated potential vorticity streamers above central Europe: 27 October, 6–7 November, and 15 November. The Falcon performed four flights collecting in situ data and remotely sensed water vapor and backscatter data with the DIAL lidar aboard the airplane in down-looking mode. Radiosondes launched by the Swiss Army and dropsondes from the Falcon provided additional profile data.

The 6–7 November case is a good example of P2 operations. On 6 November, a trough was elongating meridionally between the North Sea and the Mediterranean Sea. The following day showed a potential vor-

TABLE 5. Summary of IOP events and operations. The overall interest of each event, combining quality of measurements and physical interest, is given in the last column: *, moderate; **, good; ***, excellent.

IOP	Day	Project	Event, location	Operations	Comments	Interest
1	15 Sep	P1	Convection, Liguria	Electra, radars	Good start!	*
2A	17 Sep	P1	Squall line, LMTA	Radars, electricity		***
	18 Sep	P1	Liguria	Radars, Fokker	Upstream flow sampling	**
2B	19 Sep	P6	Waves, Jungfrau	Electra	Weak case, one track over Rhine Valley	*
		P5	Foehn, Rhine valley	Merlin, soundings in RV, CVB	Strong case	***
	20 Sep	P1	Heavy rainfall, LMTA	Radars, Electra	Max precip. 300 mm	***
		P1	Heavy rainfall, Veneto	Teolo and Fossalon radars	Max precip. 280 mm	***
		P2	PV streamer, France	Wind profilers		
		P3	Flood, LMTA	Dense rain gauge network	368 mm (36 h) ⁻¹	***
		P4	Gap flow, Brenner Pass	Surface stations		
		P5	Foehn, Rhine valley			
		P6	Waves, Hohe Tauern	Electra	Strong w (8 m s ⁻¹), weak turbulence	***
	21 Sep	P8	PBL, Riviera	Dimona		*
	22 Sep	P8	PBL, Riviera	Dimona		*
	22 Sep	P3	Soil moisture, Toce valley	Microwave rad. on helicopter		
	23 Sep	P3	Soil moisture, Toce valley	Microwave rad. on helicopter		
3	24 Sep	P1	Surface fluxes, Po valley	Merlin, Fokker, radars	Radars in clear-air mode	**
	25 Sep	P1	Heavy rainfall, LMTA	Electra, Fokker, radars		***
	26 Sep	P1	Heavy rainfall, LMTA	Fokker, radars	Max precip. over 400 mm for the two days	
		P3	Flood, LMTA			
	28 Sep	P8	PBL, Riviera	Dimona		***
	29 Sep	P8	PBL, Riviera	Dimona, DOW radar		***
4	30 Sep	P1	Front, LMTA	Radars, Electra, P-3, Fokker CVB, electricity		**
		P2	PV streamer, France	Wind profilers		
	1 Oct	P7	Mistral, southern Alps	Electra, P-3	Clear primary banner, indication of secondary banners	***
		P8	PBL, Riviera	Dimona		***

TABLE 5. *Continued.*

IOP	Day	Project	Event, location	Operations	Comments	Interest
5	2 Oct	P4	Gap flow, Brenner	Electra, P-3, Lidar	Data from P-3 irrecoverable?	**
		P5	Foehn, Rhine valley	Merlin, Dimona, soundings, CVB, lidar	Good shallow foehn	**
	3 Oct	P1	Active front, LMTA	Radars, electricity	Max precip. 280 mm, semicircular cells	**
	4 Oct	P1	Convection, Slovenia	Electra, P-3	Fossalon di Grado available	***
		P2	Low tropopause, LMTA	Wind profilers		
6	13 Oct	P1	Stratiform rain, LMTA	Radars, Electra, P-3	Some microphysics useful	*
7	18 Oct	P1	Stratiform rain, Liguria	Radars, Electra, P-3		*
			LMTA	Merlin	Icing study	***
8	19 Oct	P5	Rhine valley	Fokker, CVB, lidar	Prefoehn flight for STAARTE	
	20 Oct	P1	Precip, LMTA	Radars		*
		P4	Gap flow, Brenner	Electra, P-3, lidar		**
		P5	Foehn, Rhine valley	Merlin, CVB, lidar	Strong foehn and turbulence	***
	21 Oct	P1	Stratiform rain, LMTA	P-3, Fokker, radars, electricity	Excellent microphysics measurements (missed approach)	**
			Heavy rain, Veneto region	Teolo and Fossalon radars	100–150 mm	
		P4	Gap flow, Brenner Pass	Doppler lidar, surface stations	Strongest case, but no aircraft	**
		P5	Foehn, Rhine valley	CVB, lidar		
		P6/7	Waves and PV banners, Ötztaler Alps	Electra		***
9	23 Oct	P1	Heavy rain, Liguria and Po valley	Electra, P-3, radars	Stratiform precip. over the slopes	**
		P2	PV streamer, France	Wind profilers		
		P5	Rhine valley	Merlin, Sfc, CVB, lidar		
10	24 Oct	P1	Rain, LMTA	P-3, Fokker, CVB		*
			LMTA	Merlin	Icing study	*
		P2	PV streamer	Profilers		
		P4	Gap flow, Brenner Pass	Electra	No SABL (clouds)	*
		P5	Foehn, Rhine valley			
	25 Oct		LMTA	Merlin, radars	Icing study	**
		P6	Waves, Grossglockner	Falcon	Good data from DIAL	***

TABLE 5. *Continued.*

IOP	Day	Project	Event, location	Operations	Comments	Interest	
11	27 Oct	P1	Surface fluxes, Po valley	Merlin, Fokker, radars	Radars in clear-air mode	***	
		P2	PV streamer, above Alps	Falcon, profilers		**	
	28 Oct	P3	Soil moisture, Toce valley	Microwave rad. on helicopter			
12	29 Oct	P3	Soil moisture, Toce valley	Microwave rad. on helicopter			
	30 Oct	P1	Weak rain, French Alps	Electra, radars, CVB	Some microphysics over LMTA	*	
		P4	Brenner, gap flow	Electra, P-3, Fokker, lidar	Hydraulic jump well documented, excellent data from LEANDRE 2	***	
		P5	Foehn, Rhine valley	Sfc			
	13	1 Nov	P4	Brenner, gap flow	Electra	Good SABL data	**
P5			Foehn, Rhine valley	Sfc			
2 Nov		P5	Foehn, Rhine valley	Merlin, CVB, lidar		*	
		P6	3D waves, Mont Blanc	C130, Electra, Fokker, Falcon	Moderate amplitude	***	
14	3 Nov	P1	Convection, Liguria	Electra, P-3, Fokker, radars	Strong case, excellent data	***	
			LMTA	Merlin	Icing study	**	
	P2	PV streamer, France	Wind profilers				
	4 Nov	P1	Stratiform rain, LMTA	Radars, Electra, P-3, Fokker	Fokker over Adriatic Sea	***	
			LMTA	Merlin, S-Pol	Icing study	***	
	5 Nov	P5	Foehn, Rhine valley	Fokker, Merlin, CVB		***	
15	6 Nov	P1	Heavy rain, LMTA	Radars, Electra (short ferry only)	Strong winds and local floods	**	
			P2	PV streamer, NE France	Falcon, wind profilers		***
	P4	P4	Gap flow, Brenner	P-3	Good evidence of the Wipptal jet	**	
			P6	Waves, Hohe Tauern	Electra, C130, Falcon	Weak waves	*
	P7	P7	Waves, Wallis Alps	C130			
			Mistral	Electra, P-3, Merlin, Fokker	Strong mistral	***	
	7 Nov	P1	P1	Heavy rain, Veneto and Northern Appennines	Teolo, Fossalon and SP Capofiume radars	Over 100 mm in 12-h, local floods	*
				P2	PV streamer, above Alps	Falcon, profilers	
P6		P6	Waves, Monte Rosa	Falcon			
			P7	Bora, Adriatic	Electra, P-3	Strong case, PV banners, Hydraulic jump	***

TABLE 5. *Continued.*

IOP	Day	Project	Event, location	Operations	Comments	Interest
	8 Nov	P6	Waves, Monte Rosa	Electra, C130, Falcon	Possibly breaking at Falcon level	**
		P7	PV banners, Po valley	P-3, Fokker, Merlin, Ronsard, CVB	Strong banners from Gotthard and Brenner, Ronsard in clear-air mode	***
	9 Nov	P7	PV banners, Po valley	Fokker, Merlin	Much weaker than previous day	*
16	11 Nov	P1	Stratiform rain, LMTA	Ronsard, Electra	One intercomparison leg with Merlin	*
			Surface fluxes, Po valley	Merlin		
		P5	Foehn, Rhine valley			
	12 Nov	P4	Gap flow, Brenner	Electra, P-3		*
		P5	Foehn, Rhine valley			
	13 Nov	P5	Foehn, Rhine valley			
		P6	Waves, French Alps	Falcon, C130, Electra	Possibly breaking below a critical level	*
17	15 Nov	P2	PV streamer, above Alps	Falcon		***

ticity streamer strongly narrowing between Denmark and northern Italy, forming a cutoff low at its south-

ern end above Italy and above the islands of Corsica and Sardinia. The ECMWF analysis depicted significant tropopause folds at the western and eastern edges of the streamer. These folds transported stratospheric air down to a height of less than 6 km. On 6 November, the Falcon performed the following flight pattern at 12 km. It flew from Munich, Germany, to Brest then to Bordeaux, France, and Venice, Italy, and finally back to Munich. This flight pattern was designed to obtain cross-streamer curtains of water vapor data at two different locations. The DIAL data obtained on the southern section along 45°N from Bordeaux to Venice are shown in Fig. 9. The determination of the low humidities (below 300 ppmv) in the lower stratosphere and upper

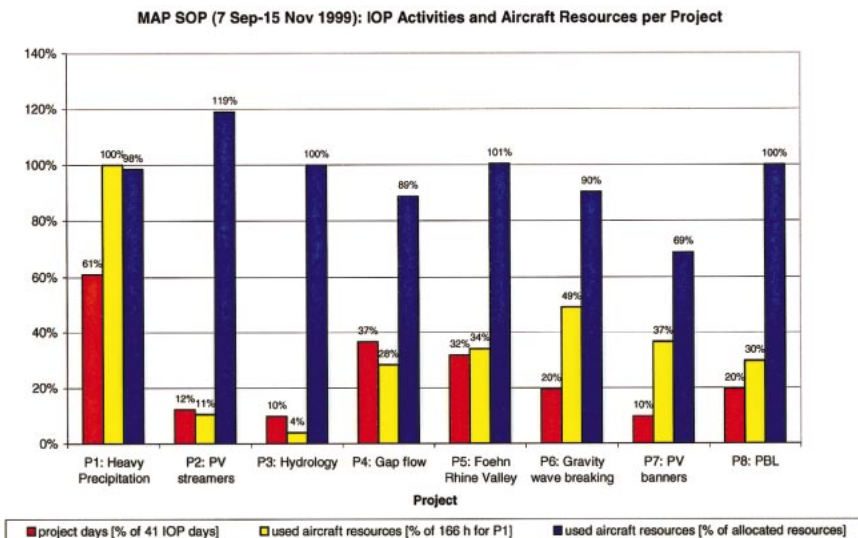


FIG. 5. Summary of resource usage by projects during the SOP. Yellow bars show the number of flight hours used by each project, the reference being the largest one (P1) (166 h). Blue bars indicate the proportion of the initially apportioned resources for each project. The red bars indicate the number of days when a major facility has been activated for each project.

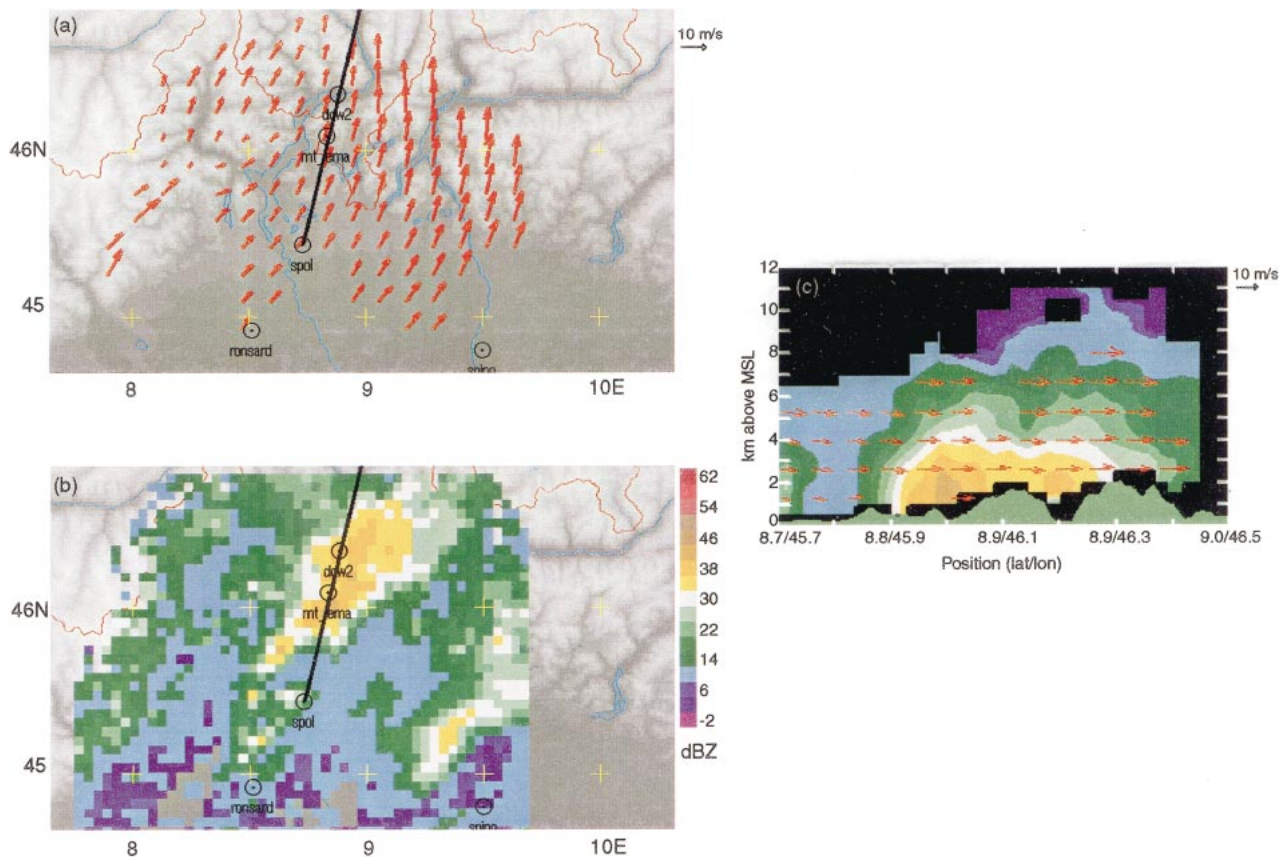


FIG. 6. (a) Dual-Doppler winds for the 2.5-km level computed from the Monte-Lema and Ronsard radars at 1814 UTC 3 Oct 1999. Topography is in gray shades with higher elevations lighter. A radial taken north-northeastward from the S-Pol radar is the black line. (b) Composite radar reflectivity corresponding to the winds in (a). (c) Vertical cross section of S-Pol radar reflectivity along the radial line shown in (a) and (b) with dual-Doppler zonal wind component superimposed.

troposphere follows the technique described in Ehret et al. (1999). The high horizontal resolution relies on the 100-Hz repetition frequency of the laser pulses, a so far unique application of an airborne DIAL system. On the following day similar measurements were obtained along five meridionally stacked zonal sections between the western and eastern borders of Germany. The data collected during this case will be very useful for the description of the mesoscale features of the streamer and its development and modification into a narrow elongated structure. The data of the last case (15 November) show a vertical cross section cutting through the entire streamer located above the Alps. During both periods, the streamers were dynamically active and the measurement systems worked perfectly.

c. Hydrological measurements and flood forecasting

Project P3 focused on the Ticino and Toce River catchments, both tributaries of the Lago Maggiore. A

special network of 14 rain gauges (13 of them property of the University of Waterloo) was deployed by the University of Brescia in two lateral valleys of the Toce valley (Val Anzasca and Val Vigezzo). In addition, several teams organized soil moisture and micrometeorological monitoring campaigns in the Toce area. Among other instruments, a time-domain reflectometry (TDR) with 14 probes was deployed by the University of Modena. Finally, a passive radiometer operating in three different microwave bands (L, C, X, the last two with horizontal and vertical polarization) was used on board a helicopter by the CNR-IROE Institute. This experiment was intended to evaluate the potential of short-distance radiometric soil moisture measurements over some selected sites, where ground and laboratory data were available for verification and antenna calibration. Two missions were performed, one after the heavy rain event of 20–21 September (IOP 2), the other during the soil drying stage after the rainfall event of 21–25 October

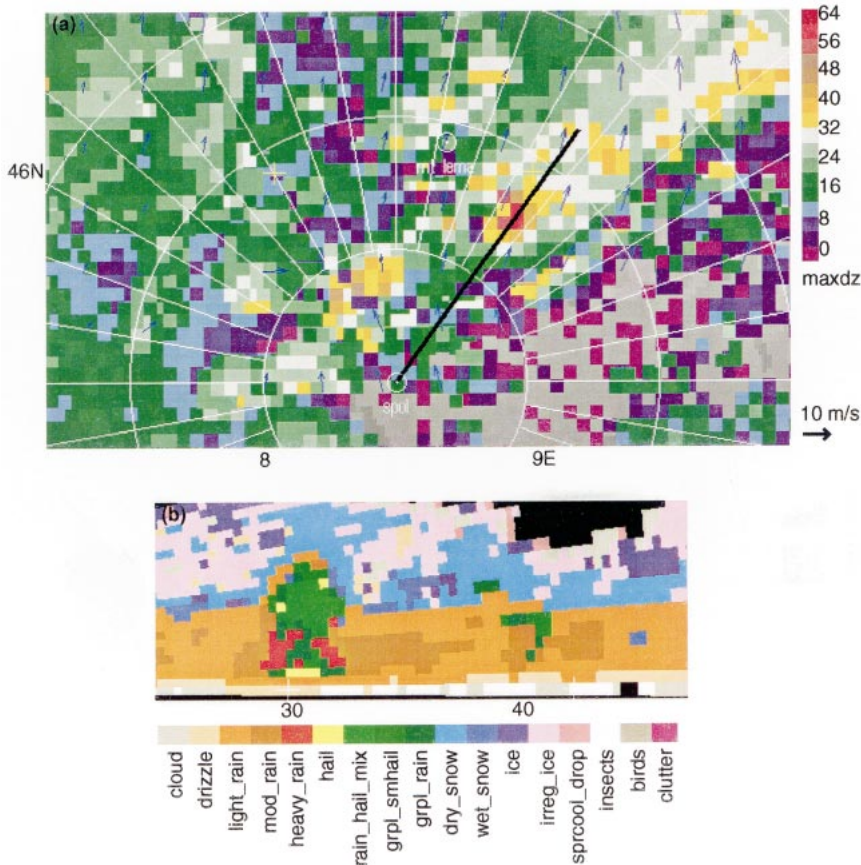


FIG. 7. (a) Radar reflectivity (composite of S-Pol, Ronsard, and Monte-Lema radars) and dual-Doppler wind (computed from Ronsard and Monte-Lema) for the 3-km level at 1541 UTC 3 Oct 1999. Range marks are at 20-km intervals from the S-Pol radar. A radial taken northeastward from the S-Pol is the black line. (b) Particle types computed by NCAR algorithm from polarimetric variables measured by S-Pol radar along this radial.

(IOPs 8, 9, 10). A first evaluation of the data indicates that meaningful results could be obtained over bare soils, or soils covered by uniform vegetation (grass or smooth crops). However, L-band measurements were hindered by external electromagnetic interferences. In situ soil measurements, complemented by boundary layer atmospheric measurements of Project P8, were also taken in the Riviera valley and other lateral valleys by ETH (Institute for Climate Research).

The numerical part of P3 consisted of two different attempts to produce real-time runoff and flood forecasts, using coupled meteorological and hydrological models. A Canadian team (University of Waterloo and AES) coupled the very fine resolution (3-km grid) MC2 model (see section 2d) to the WATFLOOD distributed hydrological model (2-km grid), in order to produce flood forecasts for both the Ticino–Toce watershed and the Ammer watershed in the Bavarian Alps. In parallel, an Italian team (Uni-

versities of Brescia, Genova, and ISAO-CNR) used the output of the BOLAM meteorological mode (run during MAP with a 6.5-km grid, starting from ECMWF analyses) for driving the Distributed Hydrological Model for the SOP (DIMOSOP) model (25-m resolution), applied to the Toce watershed. The latter is a small to midsize basin (1532 km²) characterized by very steep orography. It was probably the first time that such coupled high-resolution meteorological-hydrological deterministic models were used in quasi-real time.

The input for the hydrological models were the hourly precipitation and surface parameters predicted by the meteorological models. They benefited also from the special field observations acquired in the Toce and Riviera valleys. Moreover, the forecasting experiment used the measurements of water levels in some hydroelectric reservoirs, and the snow height and soil water content available at some representative places for the definition of the initial condi-

tions of the watershed. The DIMOSOP model included in a simplified manner a treatment of the formation and propagation of the surface runoff along the mountain slopes, of the subsurface contribution and of the flow dynamics within the river channels. The simulation of the behavior of soils required both in situ and laboratory measurements. The riverbed characteristics had been surveyed prior to the experiment along several cross sections.

The flood forecasts, provided at nine hydrometric sections and 10 hydroelectric basins, were prepared daily with a lead time of 24–30 h, based on the 36-h forecast by the mesoscale meteorological models. Figure 10 shows an example of such a forecast, made for the event of most intense precipitation (IOP 2). A 5-yr return period flood was observed in this case. The figure indicates that the forecast overestimated the peak runoff. This is probably due to an overestimation of the rainfall peak intensity in the meteorological

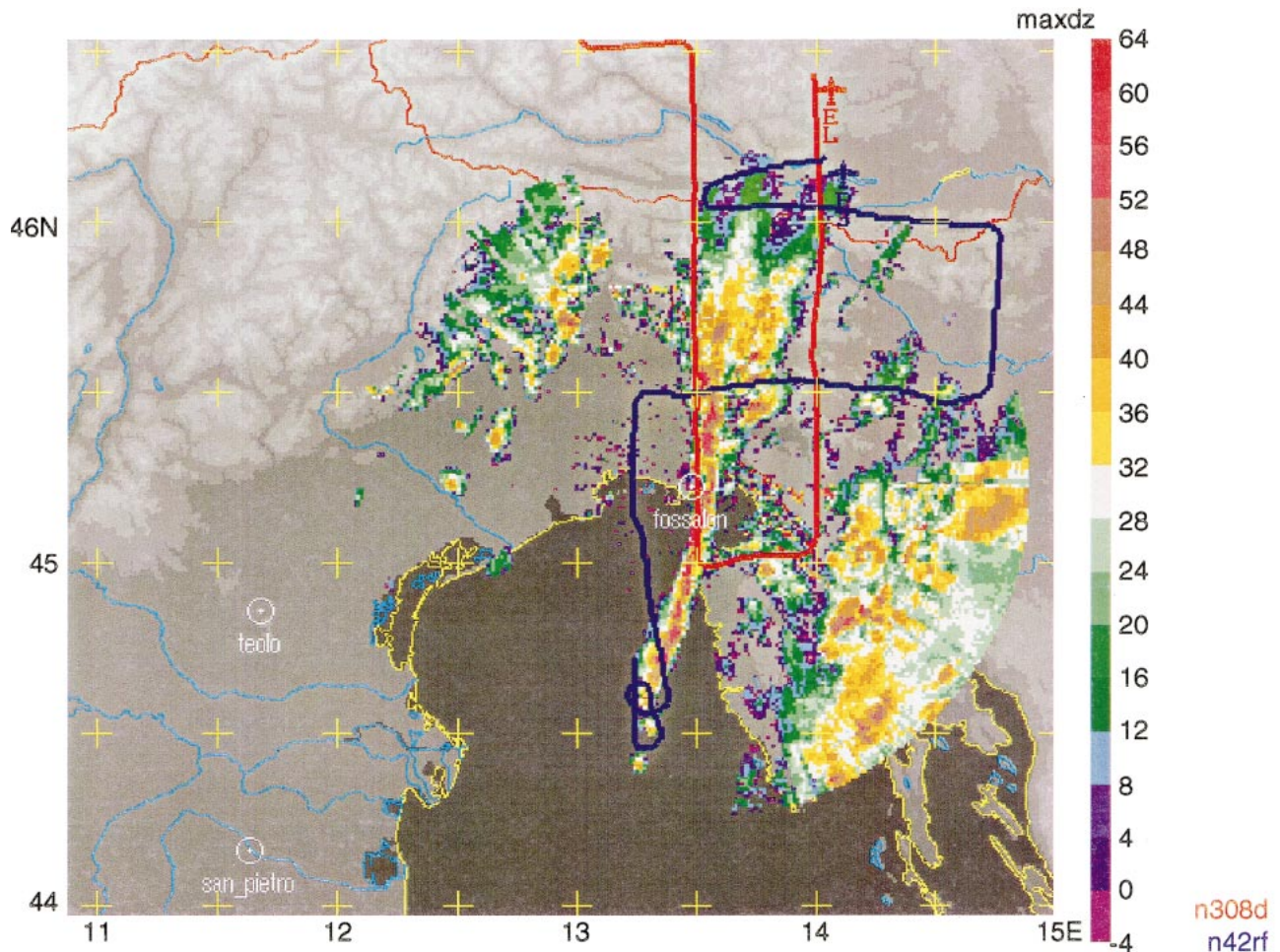


FIG. 8. Radar reflectivity (dBZ color scale) observed by the Italian operational radar at Fossalon di Grado at 0800 UTC 4 Oct 1999. One-hour flight tracks of Electra (red) and P-3 (blue) aircraft ending at 0800 UTC.

model, as shown in the upper part. However, the timing of the peak and of the rising limb of the flood were properly captured and the predicted rainfall and runoff volumes were close to the observed ones. In general, a preliminary evaluation of both flood forecasting experiments indicates useful and encouraging results. The quality of the flood forecasts mainly depends on the quality of the precipitation forecasts by meteorological models, especially the temporal and spatial localization of the intense events. No significant false alarms were issued in the Ticino–Toce watershed, although the number of flood events was very small during the SOP. The hydrological model component turned out to be sensitive also to the type of precipitation (rain or snow) as a function of height and to the melting of the snow cover.

In parallel to the above-mentioned coupled modeling efforts, a real-time precipitation forecast was issued by the University of Grenoble for different areas

in the western Alps including the Ticino–Toce watershed, based on the technique of “meteorological analog”: a series of meteorological situations analogous to the current one was searched every day, and the precipitation forecast was based on the histograms of rain observed on each watershed during the analogous situations. The comparison of the performances of this method and conventional numerical forecasts is currently under progress.

d. Dynamics of gap flow in the Wipp valley

Project P4 focused on the flow through the Brenner Pass into the Wipptal, a south–north-oriented tributary to the Inn valley close to Innsbruck. Ground-based measurements installed and operated primarily by the University of Innsbruck included several profilers, sodars, and special radio-sounding systems, a network of microbarographs, and the NOAA scanning Doppler lidar at Gedeir. Flight missions by the

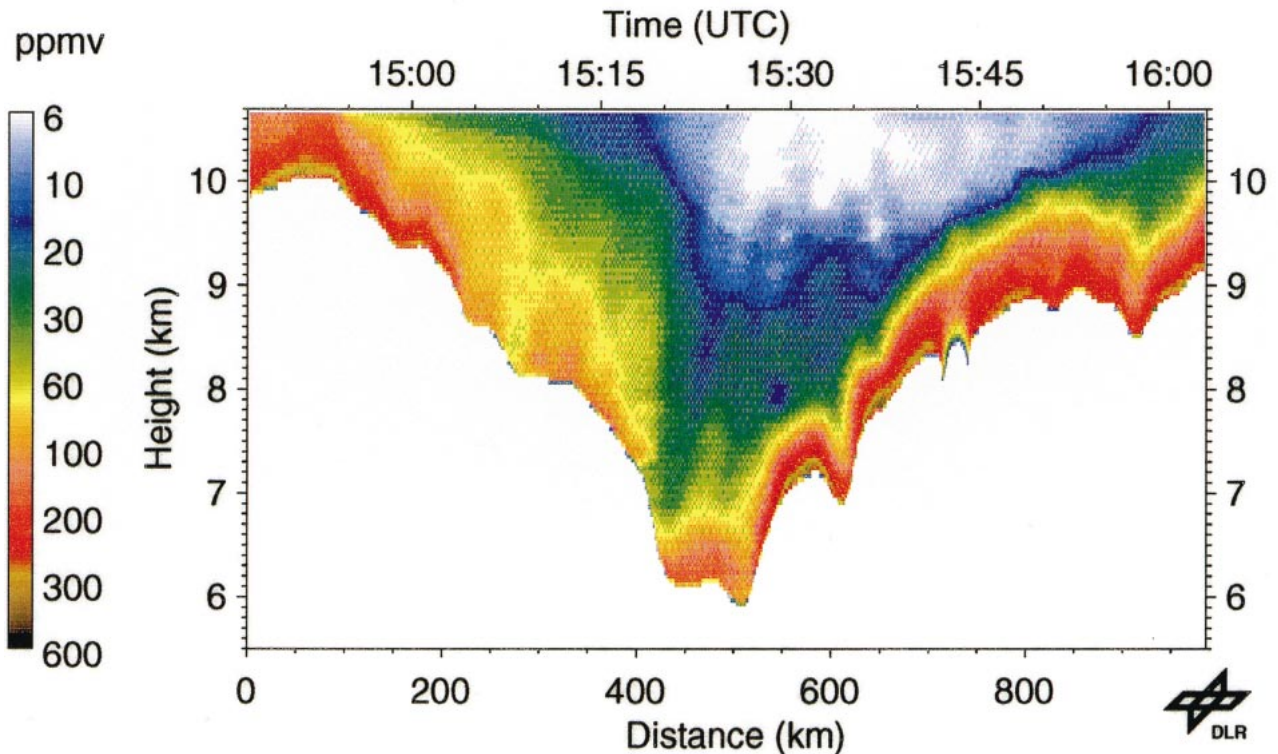


FIG. 9. Section of low water vapor concentration (< 300 ppmv) across an active potential vorticity streamer connected with a tropopause fold; data obtained on 6 Nov with an airborne H₂O-DIAL looking down from 11 km. The flight segment is along 45°N from Bordeaux (left) to Venice (right) with the western Alps in the middle (courtesy of G. Ehret).

Electra and P-3 aircraft, the Fokker, and the Dornier 228, acquired both in situ measurements of the flow and vertical cross sections by downward-looking lidars and dropsondes. The SOP was also the occasion to undertake the first scientific flights of the new WIND lidar on board the Falcon. Developed as a joint French–German project, WIND is an airborne wind Doppler lidar that implements a down-looking conical scan capability. It can map the radial wind velocity with high horizontal (vertical) resolution, and reconstruct the mesoscale wind field outside cloudy areas with a 10-km (250 m) resolution.

The large degree of cloudiness associated with foehn events came as a surprise, and prevented lidar operations on several occasions. This could be compensated for by operating the Eldora radar on some occasions when the droplet sizes were sufficient. However, interesting lidar measurements were obtained during several flight missions, and were occasionally reinforced by the presence of Saharan dust. The dropsonde operations required specific training, because the Wipptal is a narrow valley. In a couple of cases, an almost simultaneous series of three or four sondes along the valley were obtained. Low-level

flights of the P-3 in the Wipptal were not planned in advance because they were thought to be technically too difficult. However, they were made possible by the intense efforts of the mission scientists, the P-3 crew and Austrocontrol ATC.

Examples of flows observed in P4 are provided in Figs. 11 and 12. Figure 11 shows a vertical cross section along the Wipp valley observed by the downward-looking LEANDRE 2 lidar on board the Fokker, during IOP 12. The Brenner Pass is to the left and Innsbruck is at 47.25°N. The underlying topography is outlined by the transition from dark blue to cream color. The layer appearing in cream above the topography is the lidar surface echo. The region appearing in yellow/green represents the “aerosol mixed layer” while the orange is the free troposphere. The gap flow is observed between 47.1° and 47.25°N. It is evidenced by the thinning aerosol mixed layer in the region where the flow becomes supercritical. After 47.25°N, a hydraulic jump is suspected, as evidenced by the sudden rise of the mixed-layer top. Figure 12 shows cross sections of the radial velocity measured by the NOAA scanning Doppler lidar at Gedeir on the same day. It reveals the low-level jet resulting from the hydraulic

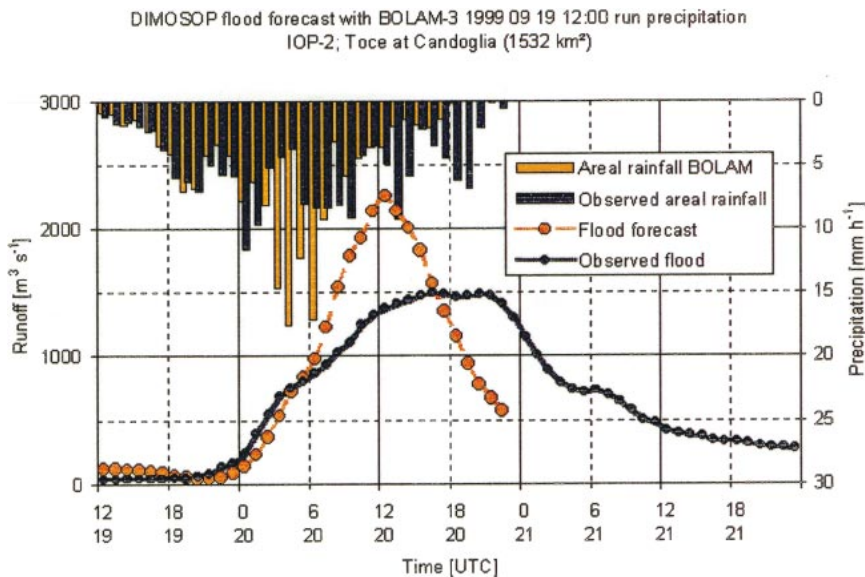


FIG. 10. Observed and forecasted flow of the Toce River at Candoglia, for 19 and 20 Sep 1999. The forecast is from the DIMOSOP model forced by the BOLAM atmospheric model for period 19 Sep 1200 UTC to 21 Sep 0000 UTC. The observed precipitation is estimated from 18 automatic rain gauges, and totals to 164 mm. The amount predicted by BOLAM is 179 mm (courtesy of R. Ranzi).

behavior of the flow. We note the wavy wind structure in the upper panels (best seen near 2-km altitude) and the near-surface jet larger than 12 m s^{-1} in the lower panel.

e. Nonstationary aspects of Foehn in the Rhine valley

The instrumentation for P5 was installed in such a way to give, for the first time, a mesogamma-scale description of the mass and wind fields in the Rhine valley and its main tributaries. Seven special radio-sounding stations, installed in a dense triangular pattern along the valley, launched 3-hourly soundings during the IOPs. Numerous automatic and micrometeorological stations were also operated, and several remote sensing instruments (wind profiler, RASS, lidars and sodars) gave quasi-continuous information on the vertical profile of the atmosphere during more than two months. The Transportable Wind Lidar (TWL) Scanning Doppler lidar allowed a three-dimensional exploration of the wind field within a part of the valley. Tethered balloons, cable cars, and even automobiles were instrumented. At one specific site, two scintil-

ometers were installed to monitor the flow along the valley at 500 m above the ground. A series of video and still cameras documented the behavior of the hazy or foggy cold air pool beneath the clear foehn air. Flight missions of the Merlin aircraft and of the Dimona light research aircraft were conducted at low altitudes during major foehn events. Finally, constant volume balloons launched from the Italian side and a wind profiler at the Julier Pass (Vogt et al. 2000) were used to construct the flow trajectory from the upstream side of the Alps toward the Rhine valley.

Close to Bad Ragaz, the Rhine valley makes a significant turn to the north toward Lake Constance, while another opening is oriented to the northwest toward the Walensee. The main flow is usually heading north or northwest. Observations suggest that the direction of the main flow is determined by the upstream profile of static stability. The TWL scanning lidar (Drobinski et al. 2000) was installed in Vilters, Switzerland, close to the bifurcation point and its measurements will allow an investigation of the dynamics of the flow in this particular area. Figure 13 shows the radial velocity

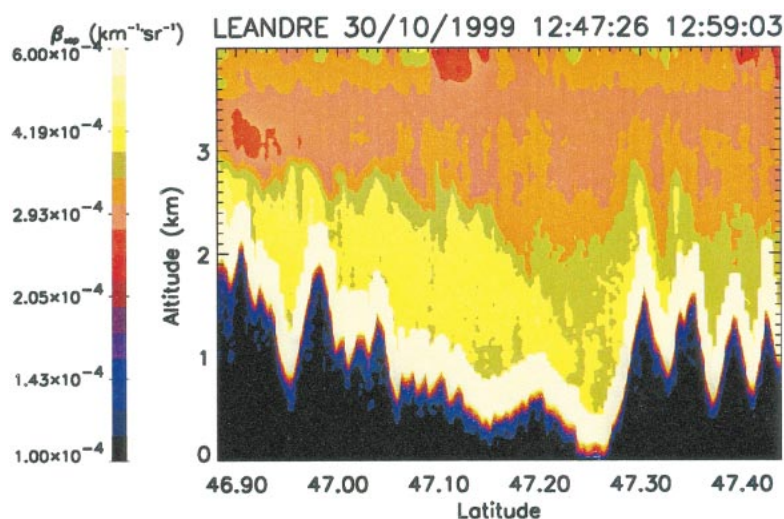


FIG. 11. Cross section along the Wipptal obtained on 30 Oct 1999 by the LEANDRE 2 downward-looking lidar, on board the Fokker 27 ARAT (courtesy of C. Flamant).

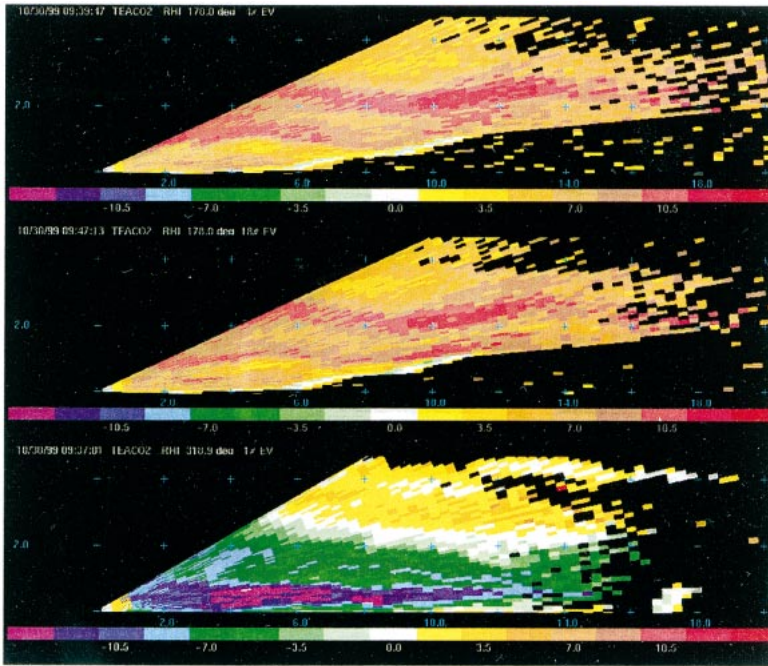


FIG. 12. Gap flow velocity measurements over Brenner Pass by the NOAA scanning Doppler lidar on the morning of 30 Oct 1999. (top two panels) Vertical cross sections of radial velocity, 8 min apart, pointing to the south along the Wipp valley, showing flow coming over the Brenner Pass. (bottom panel) Same as top panels, except looking downstream toward Innsbruck. Color bars of the velocity in m s^{-1} (white numbers) with positive values (red, brown, yellow) indicating flow toward the lidar. Blue numbers indicate distance from the lidar in km (courtesy of R. Banta and L. Darby).

field on 29 October (at about 1800 UTC) derived from the raster scan procedure.

The TWL is located at the center of the figure. The negative radial velocities correspond to a flow blowing toward the TWL, while positive radial velocities correspond to a flow blowing away from the TWL. The white area of the grid corresponds to the topography or unreliable radial velocity estimates (low signal-to-noise ratio). In the present case, the channeled flow is blowing from Walensee toward the upper Rhine valley. In the lower Rhine valley leading to Lake Constance, there is no evidence of a privileged flow direction.

A question of special importance for the air quality in the densely populated region close to Lake Constance is the behavior of the cold air pool during foehn. In the cold season the area sometimes suffers from air pollution due to a long duration of stagnant boundary layer. Foehn brings a sudden relief of pollution and is therefore welcomed by the population. The present forecasts of local foehn are poor and it is hoped that the MAP scientific investigations will improve it. Observations showed that the ability of the

foehn flow to erode the cold pools is strongly influenced by the valley orientation, meanders, and bottlenecks. Side valleys also play a major role. Aircraft observations at low levels have shown that the boundary between the cold and warm air is not forming a retarding wedge, but is rather irregular with a strong temporal and spatial variability. This may explain why the wind damage at the ground is so variable in space. The behavior of the cold air pool close to Lake Constance was observed by RASS, sodar, tethered balloons, and an instrumented cable car at Pfaender Mountain, carrying thermodynamic and ozone sensors. Several foehn events showed a wavy but rather irregular evolution of the boundary between the two air masses. Figure 14 shows the time evolution of the ozone concentration profile on 22 October. The increase of ozone during the afternoon is due to the Foehn layer eroding the surface cold air pool and penetrating down to the ground. Indeed, NO_x and other pollutants destroy the ozone under these specific conditions, and the cleaning effect of the Foehn results in an increase of ozone. The net effect is however an effective relief of pollution in the area. At the end of the period shown, a rapid descent of the boundary layer top could be observed. On that day, the foehn did not reach the ground, but was only a few decameters above ground. It was a common observation that the decrease of the depth of the cold pool was a slower process than its rebuilding by advection.

f. Three-dimensional gravity wave breaking

Project P6 arose from the need to test the ability of the new generation of mesoscale numerical models to predict mountain wave generation and breaking. It is broadly felt that the remarkable progress of numerical models in the last few years in terms of spatial resolution, nesting, data assimilation, and nonhydrostatic formulation has outstripped our progress in testing the models against observations at the proper scale. During the SOP, mesoscale models were used in real time to guide mission design toward areas offering the best chances of encountering gravity wave breaking events. Measurements were taken by the Falcon (carrying the DIAL water vapor lidar),

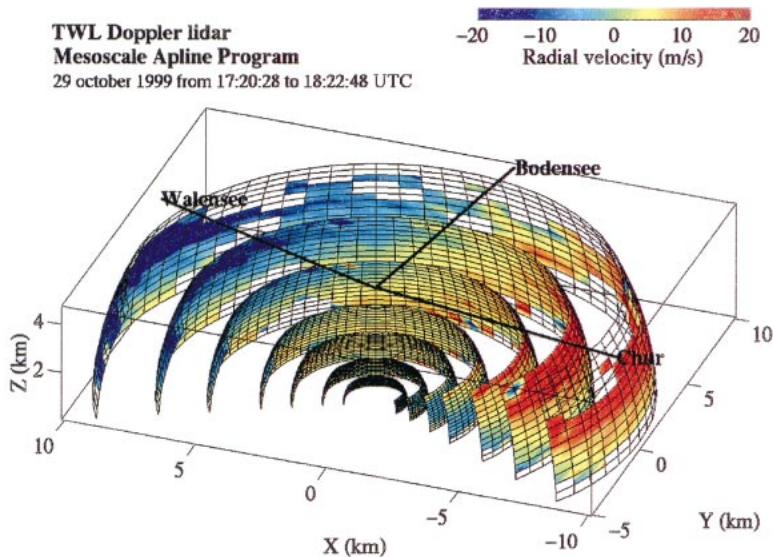


FIG. 13. Radial velocity field evaluated by the TWL Lidar at Vilters (Rhine valley). The raster scan was performed by sweeping the azimuth angle from -98° (or 262°) (in the direction of the Rhine valley toward Chur) to 142° (in the direction of Seez valley toward Walensee), and the elevation from 4 to 28 degrees after an accumulation of 10 shots used to retrieve one radial velocity profile. With increments in elevation and azimuth of 2 and 5 degrees, respectively, each velocity estimate was spaced transversely about 105 m horizontally and 262 m vertically at 3 -km range. Because the lidar is on the valley floor, this mode produces velocity estimates between portions of spherical surfaces along the valley axes and bounded laterally by the sidewalls (courtesy of P. Drobinski).

the Electra (carrying the SABL lidar) and the C130. The Fokker (carrying the LEANDRE 2 lidar) also joined them on one occasion. Dropsondes from these aircraft were also used to document extensively the wind and stability. The models used in the flight planning included the MeteoSwiss model, the Eastern European Aladin model, the German (LM) model, the Canadian MC2 model, and the U.S. Navy (COAMPS) model.

According to model predictions, the best conditions for GWB in the Alps are strong winds from the west or from the east over the western Alps, or winds from the north or south over the major east–west Alpine ridge. Unfortunately, these special conditions were not frequent during the MAP–SOP. The SOP was well endowed with events of southwest flow, giving good Wet-MAP and shallow foehn cases, but such flows run parallel to most of the primary Alpine ridges giving poor gravity waves. In spite of these conditions, 11 cases were identified and

investigated (see Table 5). These cases included various flow directions over large massifs within the Alpine regions. In each case, the aircraft were directed to the specific location for which the largest vertical velocities and lowest Richardson numbers were predicted by operational and research models. Generally, the flight tracks were designed to give repeated legs at the same altitude along a single line. This approach put highest priority on the issue of the wave’s temporal evolution. In some cases, however, the aircraft shifted to a second altitude after a few legs and this change, together with the presence of other aircraft above or below, gave reasonable vertical coverage as well. Additional vertical coverage was provided by the dropsondes and downward-pointing airborne lidars.

Preliminary evaluation of these cases has indicated that two particular scientific issues may be critical for understanding the GWB data from MAP. First, the occurrence of cold air blocking and trapping in valleys seems to be playing a controlling role in gravity wave generation over the Alps. Two blocking situations were common: (i)

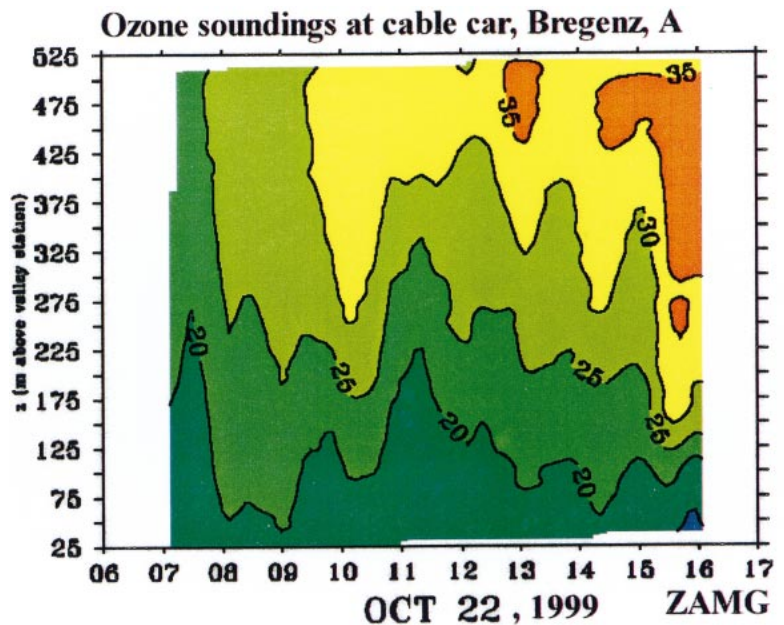


FIG. 14. Time–height cross section of the ozone concentration (ppb) on 22 Oct 1999. The data were acquired on a cable car from Bregenz to Pfänder Mountain, near Lake Constance. The time resolution corresponds to the frequency of the cable car, approximately 15 min (courtesy of K. Baumann).

When a single peak stood up above the surrounding peaks and ridges, that peak would generate waves while the other would not, immersed as they were in a stagnant blocked layer. A good example of this behavior was the Mont Blanc case on 2 November. A stagnant layer topped by a sharp shear layer extended to an altitude of about 3500 m. Only Mont Blanc, reaching to 4808 m, penetrated well into the strong airstream above, generating vertically propagating mountain waves. Monte Rosa may have done this same thing on 8 November. (ii) When several ridges lie across the flow, only the last and highest in the sequence will generate mountain waves, due to the trapped air in valleys upstream. The Hohe Tauern in the eastern Alps gave good examples of this phenomenon during southerly flow. On 25 October, the down-looking DIAL lidar on the Falcon discovered a spectacular pattern of mountain wave clouds in this region, including the arching wave cloud near the stratosphere.

The second recurring pattern was the generation of trapped lee waves, often missed by the model predictions. It has been speculated previously that nonlinear processes can transfer wave energy from vertically propagating waves to periodic lee waves. A good example was the southerly flow event on 30 September. The models predicted a deep mountain wave over the Hohe Tauern with strong descent. The Electra found some evidence of the strong descent but a clear periodic lee wave was detected as well. The models differed on their prediction of the lee wave. A second example was on 8 November. With strong

northerly flow, the airstream above the Alps was found to be nearly undisturbed while the airstream through the major passes gave strong descent and clearing. At the boundary region between the two streams, satellite images and in situ aircraft data showed periodic lee waves. On 13 November, while the disturbance at flight level was judged to be weak, the SABL found strong periodic lee waves expressed in the cloud layer below. On the Mont Blanc case (2 November), the Falcon found lee waves at its highest flight level (see Fig. 15), perhaps generated by nonlinearity in the vertically propagating waves when they reach the stratosphere.

g. Potential vorticity banners

The idea that gravity wave breaking above mountains or surface friction on mountain slopes could alter the PV in a stratified atmosphere was put forward about 10 years ago. The PV generated near mountains, being a quasi-conserved quantity, would then drift downstream forming strips or banners. In simple terms, the issue is whether the mountains produce a wake of some considerable extent. Some verification of the idea is available from numerical simulations and from small field experiments and satellite images near mountainous islands (e.g., Hawaii, St. Vincent, and the Aleutians). The goal of a PV banner project in MAP was to see whether the banners could be observed and understood in complex terrain such as the Alps and whether model predictions of banners were believable. A particular question was whether the banners would

have a single well-defined scale, or whether the downstream region would be full of chaotic disturbances of all scales. After all, the mountains themselves have a multitude of physical scales.

Project P7 had four research aircraft available for missions around the Alps. The Electra was equipped with flight-level instruments, dropsondes, the SABL lidar, and the Eldora tail doppler radar. The P-3 had flight level instruments, dropsondes, and a tail Doppler radar. The Fokker and Merlin both carried flight level instrumentation. In addition the Fokker was equipped with the down-looking LEANDRE 2 lidar.

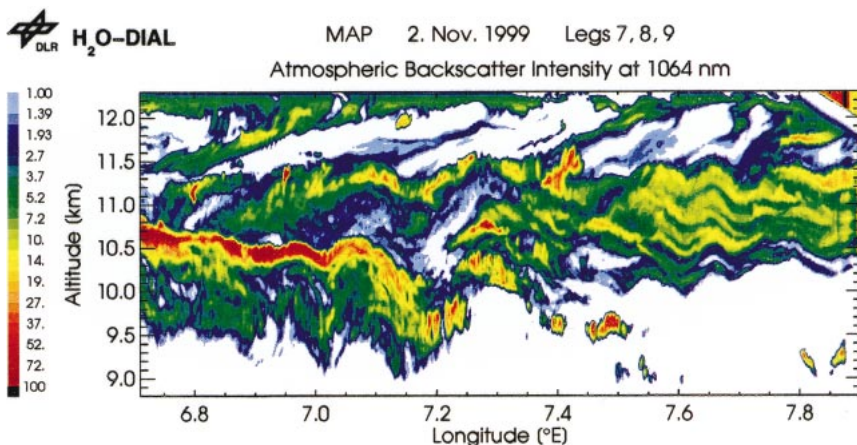


FIG. 15. Wave structures within a cirrus layer above and downstream of Mont Blanc (6.85°E) visualized by airborne backscatter DIAL data from 12.5-km altitude. The northeast (right) to southwest (left) straight flight segment covers 145 km and was executed against the ambient wind between 1102 and 1116 UTC on 2 Nov (courtesy of C. Kiemle).

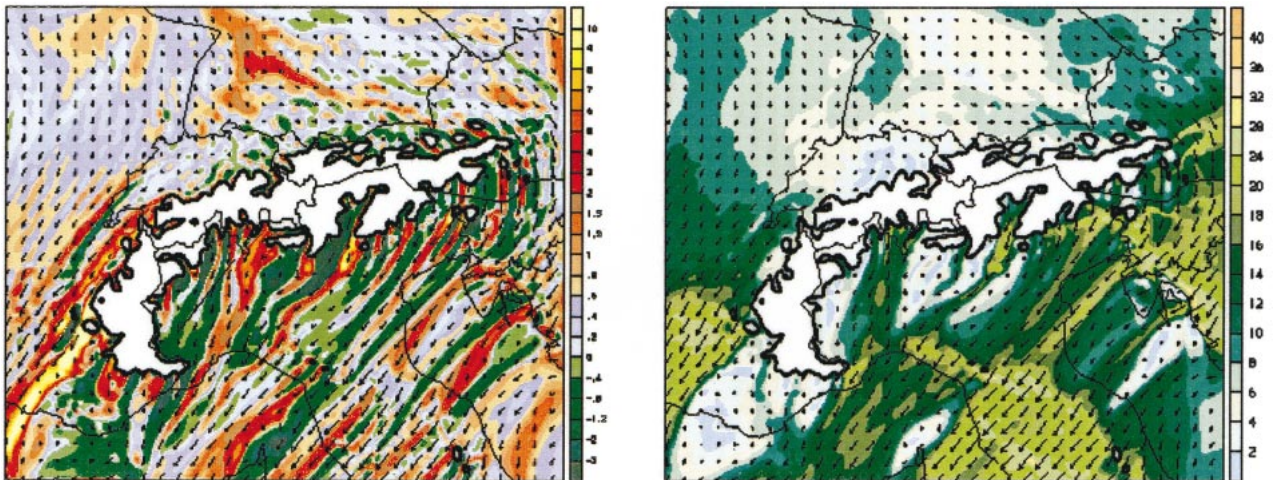


FIG. 16. MC2 numerical simulation results for IOP15, 8 Nov, 1500 UTC (18 h after model initialization). The panels show the 850-hPa distribution of (left) potential vorticity in PV units and (right) wind vectors and wind speed in m s^{-1} on the 850-hPa level. The PV banners present are associated with three Alpine wind systems, namely an atypical mistral (to the southwest of the Alps), north foehn through the Gotthard and Brenner Passes (over the Po valley) and bora (over the Adriatic Sea; courtesy of C. Schär and R. Benoit).

A useful distinction in the flight track design phase was between the primary banners coming from the eastern and western ends of the Alps and the secondary banners in between coming from individual peaks along the irregular Alpine ridge line. The primary banner was expected to be well defined, because on the western side, it coincides with the shear zone terminating famous mistral wind (a strong northerly flow off the French Riviera, originating in the Rhone valley). The secondary banners were expected to be more difficult to identify.

Successful missions were conducted during the SOP on six good cases (see Table 5). Four of these cases came during IOP 15, associated with a classic cold front/lee cyclogenesis event in early November. The two mistral cases, 1 October and 6 November, developed in the usual way. Northwestern flow, following a cold front, was split by the Alps and channeled between the Pyrenees and the western Alps. The two cases were investigated using very similar flight track strategies. The Electra and P-3 flew from Innsbruck southwest through the Milan area to a reference point over the Ligurian Sea between Genoa and Corsica. As part of this “ferry” flight, the flight tracks were modified to pass through secondary PV banners from Monte Rosa. After reaching the reference point, repeated legs to the southwest at various altitudes were flown through the eastern shear line of the mistral. Frequent dropsonde releases and the down-looking lidar helped to further define the complicated vertical structure of the shear zone. In the 6 November case, the Fokker and Merlin joined the survey, significantly

improving the observing density. Both cases had strong, well-defined shear zones.

On 7 November, a bora (a strong northeasterly wind on the Adriatic Sea, off the Croatian coast) could be documented. This case was unusually strong; perhaps one of the strongest boras in the last decade. The P-3 performed a survey some distance offshore, parallel to the coast, while the Electra flew closer to the coastal range of the Dinaric Alps. In this way, the downstream evolution of the PV banners could be ascertained. The Electra also flew a few legs along the bora flow, across the coastal range, detecting strong turbulence and collecting interesting observations in the cold air layer beneath the aircraft using the SABL lidar.

The northerly flow event on 8 November was well surveyed with research aircraft. The wealth of PV banners forecast by MC2 on this case is shown in Fig. 16. On that day the P-3, Fokker, and Merlin flew an east-west cross section south of the Alps. They found two broad stable northerly jets, associated with the flow through the two main gaps in the Alpine ridge (the Gotthard and Brenner Passes), and therefore confirming the model simulation. Flights by the Fokker and Merlin on the following day (9 November) showed the same jets but with weaker amplitude.

h. Structure of the planetary boundary layer over steep orography

The observational strategy for P8 relied on a mixture of surface-based and airborne measurements, taken in the “Riviera” section of the Ticino valley (see

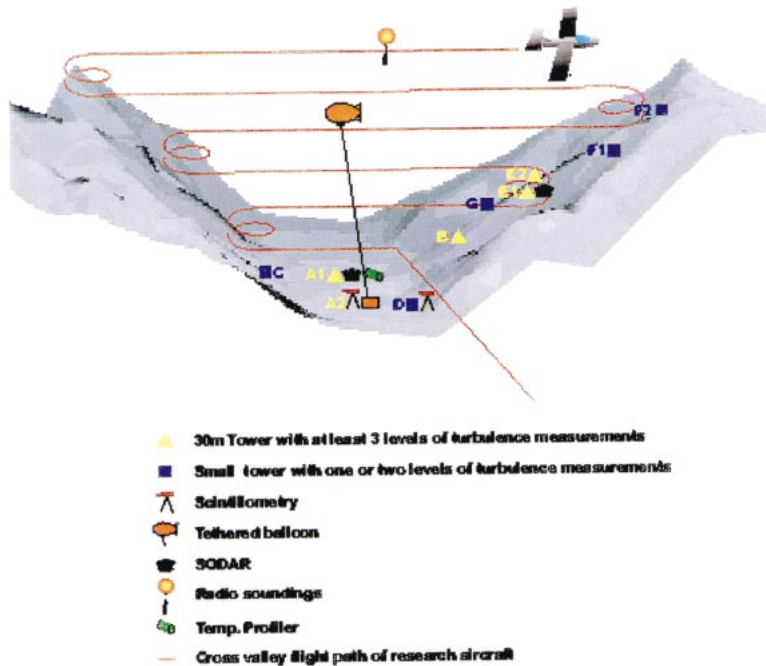


FIG. 17. A sketch of the instrumentation in the Riviera valley during the SOP (courtesy of M. Rotach).

Fig. 17). A series of towers installed across the valley floor documented the flow at various levels up to 30 m above the ground, along with sodars and a microwave temperature profiler. Turbulent fluxes were deduced from scintillometers and 20 sonic anemometers. High temporal resolution measurements at low altitude with the Dimona light research aircraft, a tethered balloon, and a radio sounding system were also performed. On one occasion (29 September) the DOW radar realized measurements inside the Riviera. PBL-related investigations were also carried out in the Rhine valley with similar instrumentation.

Research flights with the light research aircraft were carried out on eight days in August and September. On four days the development of the valley atmosphere was convectively dominated (three of them prior to the official SOP). On two days the forcing for the turbulence was clearly of mechanical nature. The two days following the heavy precipitation event of IOP 3 were used to investigate the mixed convective–mechanically driven boundary layer and the transition from a convective to a convective–mechanical forcing of the turbulence structure. Weather conditions and data collection were excellent on at least four days.

The outstanding feature of P8 was the extraordinarily dense and complete instrumental setup for turbulence measurements. This will allow questions of

spatial inhomogeneity and slope effects to be investigated in much more detail than in former studies. It will be possible to reconstruct a three-dimensional turbulence structure information for the valley, using vertically stacked and horizontally staggered tracks by the airplane along and across the instrumented cross section. Because flights were carried out in the morning and in the afternoon of most days, the diurnal evolution of the valley boundary layer can be explored as well.

The unprecedented number of instruments, in particular the 20 sonic anemometers and the 2 scintillometers in the valley transect along with the aircraft data, will allow an investigation of the turbulent exchange processes in steep topography and the exchange processes between the valley atmosphere and the free atmosphere above. There were occasions with surprisingly little interaction between the valley atmosphere and the

lower troposphere above. For example, on days with strong synoptic forcing above crest height there can be almost no wind in the valley below.

Boundary layer measurements were also taken in the LMTA, mainly over the Po valley close to the Alpine foothills, in coordination with those in the Riviera valley (section 3a) and in the Rhine valley (section 3e).

4. Outlook

Additional information including reports and quick look plots are available to anyone through the Joint Office for Science Support (JOSS) Field Data Catalog, produced during the SOP. A CD-ROM has been prepared by JOSS and the MDC to allow easy access to this information. But the main source of data will be the MAP Data Center in Zurich. According to the MAP Data Policy agreed upon by all partners, *all data from the SOP will be provided by the MAP Data Center on the basis of free and unrestricted access for non-commercial research and educational activities*. This will, of course, require that all groups having acquired data during the SOP deliver these data to the MDC in an appropriate time frame, after quality control. During the coming months, most of the work will therefore be devoted to the collection of those data and their

preparation in a proper format. Several datasets are already available from the MDC through the Internet (<http://www.map.ethz.ch>).

Despite the efforts of data producers to check the quality of the data, it is well known that format and measurement errors always remain, and a lot of time and energy can be lost if proper actions are not taken at the right time. Before the MAP–SOP, it was decided to delegate some of these actions to partners, on the basis of clear proposals and shared funding. The quality control of all surface network data was assigned to the University of Vienna, Austria, through their Data Quality for MAP (DAQUAMAP) Project (see Steinacker et al. 2000). Similar actions will be undertaken for upper air soundings and other datasets. The reanalysis of MAP IOPs by modern assimilation systems will be organized in a similar way. This is needed to provide all numerical modeling groups involved in MAP with the best possible large-scale description of the meteorological situation during MAP IOPs.

The advancement of the scientific achievements of MAP will continue to be reviewed in the annual MAP meetings, hosted alternatively by participating countries. Announcements will be posted regularly on the

MDC Internet site. It is also expected that a wealth of MAP results will be presented in all major mountain meteorology conferences for the next few years. A quarterly MAP newsletter will keep participants abreast of all developments.

The MAP–SOP demonstrated a high degree of synergy between the eight projects, and an unprecedented level of collaboration between modelers and experimentalists. Never before had so much information been exchanged in real time between alpine meteorologists. It will remain in our memories as a time of great expectations and achievements.

Acknowledgments. We are deeply indebted to many colleagues who contributed to this overview paper by providing texts, figures and all kinds of input. We kept the authorship of this paper small because there was no obvious criterion to decide who would best qualify in addition to a minimal, nationally balanced list of authors. A list of MAP PIs and officials is provided in the appendix, but many more were involved: all deserve our grateful thanks. A special mention is due for Thomas Gutermann, former director of MeteoSwiss, chairman of the MAP International Governing Panel, for his outstanding leadership in making MAP a reality. Special thanks also to François Gérard for agreeing to synchronize the EUCOS soundings with the MAP–SOP.

Appendix: A list of PIs and officials during the MAP–SOP

Name	Affiliation	Main contribution
Domenico Anfossi	CNR	P1, special sounding station Genova
Laurence Armi	University of California	P4, P-3, and Dornier missions, MST
Baldassare Bacchi	University of Brescia	P3
Robert Banta	NOAA	P4, NOAA/ETL lidar
Eszter Barthazy	ETH	P1, ETH radar and disdrometers
Kathrin Baumann	ZAMG	P5, PBL in Rhine valley
Klaus Beheng	IMK	P1, microphysics
Bruno Benech	LA	P5, CVB and Merlin missions
Robert Benoit	AES	MC2 numerical model, MST
Heinz Berger	MeteoSwiss	P5, CVB and cameras, sodars
Peter Binder	MeteoSwiss	Operations director
Philippe Bougeault	CNRM	Science director
Jean-Louis Brenguier	CNRM	In flight icing, Merlin missions
Adrian Broad	UKMO	P6, C-130 missions, MST
Reinhold Busen	DLR	P2, P6, meteorology on Falcon
Andrea Buzzi	CNR	P1, Italian coordination, MST
Jean-Luc Caccia	LSEET	P2, P7, French wind profilers
Carlo Cacciamani	SMR-ER	Climatology
Carlo Capsoni	CNR	P1, Radar in Spino d'Adda
Claudio Cassardo	University of Alessandria	P8, PBL over Po valley, MST
Serge Chauzy	LA	P1, electricity
Michel Chong	CNRM	P1, Ronsard radar, dual-Doppler retrievals

Fernandino Congeduti	CNR	P1, lidar in LMTA
Alain Dabas	CNRM	P5, TWL lidar in Rhine valley
Huw C. Davies	ETH	P2, MST
Richard Dirks	UCAR	Operations director
Manfred Dorninger	IMGW	P5, Lightning composite
Eric Dörflinger	CNRS	GPS water vapor measurements in POC
James D. Doyle	NRL	P6, COAMPS model, Electra missions
Dale R. Durran	University of Washington	P4, Electra missions, MST
Philippe Drobinski	LMD	P5, P8, TWL Lidar in Rhine valley
Aimé Druilhet	LA	P8, Merlin missions
Gerhard Ehret	DLR	P2, P6, H20-DIAL on Falcon
Heinz Finkenzeller	DLR	Air traffic coordination
Andreas Fix	DLR	P2, P6, H20-DIAL on Falcon
Cyrille Flamant	SA	P1, P4, P5, P7, Fokker missions
Pierre Flamant	LMD	P6, WIND lidar on Falcon, TWL
David C. Fritts	CRA	P6, SABL lidar on Electra
Guiseppe Frustaci	Italian Meteorological Service	POC director
Markus Furger	PSI	P5, scintillometers in Rhine valley
Nimal Gamage	UCAR	Field catalog
Teodoro Georgiadis	CNR	P1, P8, PBL measurements LMTA
Umberto Giostra	CNR	P8, PBL measurements in LMTA
Eugenio Gorgucci	CNR	P1, radar in Montagnana
Giovanni Graziani	JRC Ispra	P8, Riviera tracer experiment
Vanda Grubišić	DRI	P7, Electra missions
Sabine Göke	ETH	P1, microphysics
Joachim Gurtz	ETH	P3, Riviera hydrology
Christian Häberli	MeteoSwiss	P5, Rhine valley coordination, military soundings
Martin Hagen	DLR	P1, Alpine radar composite
Michael Hardesty	NOAA	P4, NOAA/ETL lidar
Hans Hirter	ETH	MDC and network manager
Klaus-Peter Hoinka	DLR	P2, Falcon missions, MST
Robert Houze	University of Washington	P1, S-Pol, POC science coordinator, MST
David P. Jorgensen	NOAA	P1, P-3 Missions, MST
Jürg Joss	MeteoSwiss	P1, Monte-Lema radar
Vladislav Klaus	CNRM	Wind profiler Lonate Pozzolo
Nick Kouwen	University of Waterloo	P3, precipitation monitoring and flood forecasting
Joachim Kuettner	UCAR	P6, MST
Vincenzo Levizzani	CNR	P1, P8, Meteosat rapid scans
Martin Löffler-Mang	IMK	P1, vertical Doppler radar
Piero Malguzzi	CNR	P1, MST
Guiseppe Mastrantonio	CNR	P1, P8, PBL measurements LMTA
Georg Mayr	University of Innsbruck	P4, Brenner Pass instrumentation, MST
Jose Meitin	UCAR	POC operations coordinator
Marilena Menziani	University of Modena	P3, soil moisture measurements
Valentin Mitev	Obs Neuchatel	P5, lidar
Stephen Mobbs	University of Leeds	P4, microbarographs
Marco Monai	CSIM	P1, radars in northeastern Italy
James Moore	UCAR	POC operations coordinator

Louisa Nance	CIRES	P4, P7, P-3 missions
Simonetta Paloscia	CNR	P3, microwave soil moisture measurements
Peter Parson	ZAMG	Head of MOC forecasting center
Jacques Pelon	SA	P1, P4, P5, P7, Fokker missions
Greg Poulos	CRA	P6, Electra missions
Herbert Pümpel	Austrocontrol	MOC director
F. Martin Ralph	NOAA	P4, P7, P-3 missions
Roberto Ranzi	University of Brescia	P3, hydrology coordinator
Gabriele Rau	ZAMG	P5, STAAARTE investigator
Oliver Reitebuch	DLR	P6, WIND lidar on Falcon
Evelyne Richard	LA	P1, P5, modeling coordinator, MST
Renzo Richiardone	University of Torino	P1, P6, microbarograph network LMTA
Hans Richner	ETH	P5, FORM master coordinator
Andrea Rossa	MeteoSwiss	Facility status coordinator
Mathias Rotach	ETH	P8, Riviera coordinator
Richard Rotunno	NCAR	P1, POC science coordinator, MST
Frank Roux	LA	P1, Electra missions, MST
Dominique Ruffieux	MeteoSwiss	P5, wind profilers Rhine valley
Renato Santangelo	University of Modena	P1, P4, P8 special sounding station Verona
Christoph Schär	ETH	P6, P7, Electra missions, MST
Georges Scialom	CETP	P1, Ronsard radar
Steven Skubis	Yale University	Facility status coordinator
Ronald Smith	Yale University	Science director
Bradley Smull	University of Washington	P1, DOW radar and P-3 missions, MST
Joel Stein	CNRM	P1, P5 Mesoscale modeling
Douw Steyn	University of British Columbia	P8, Riviera PBL
Ingo Steinacker	Innsbruck	Facility status coordinator
Reinhold Steinacker	University of Vienna	P4, P5, MST, Austrian coordination
Matthias Steiner	Princeton University	P1, DOW radar
Joel Van Baelen	CNRM	P2, Wind profiler network
Roland Vogt	University of Basle	P8, Riviera PBL
Siegfried Vogt	IMK	P5, Wind profiler, RASS
Hans Volkert	DLR	P6, Falcon missions, German coordination, MST
Christian Werner	DLR	WIND lidar
Charles D. Whiteman	PNNL	P4, Surface logger network
Jim Wilson	NCAR	P1, S-Pol operations
Volkmar Wirth	University of München	P2, Falcon missions
Joshua Wurman	University of Oklahoma	P1, DOW operations

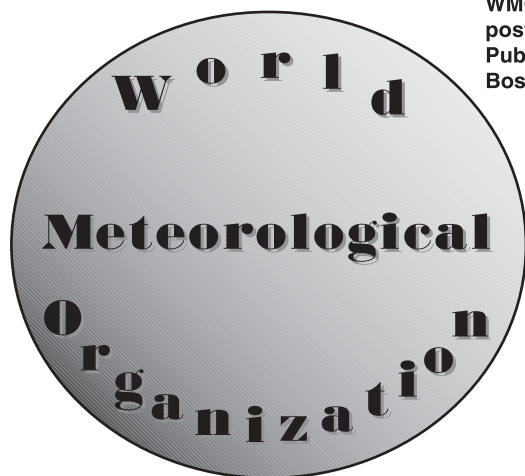
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With the development of meteorological science and the continual refinement of the technologies used in its practical application, the need to produce a new edition of the *International Meteorological Vocabulary* (IMV) became evident (the original edition was published in 1966). This volume is made up of a multilingual list of over 3500 terms arranged in English alphabetical order, accompanied by definitions in each of the languages (English, French, Russian, and Spanish) and an index for each language. This new edition has been augmented with numerous concepts relating to new meteorological knowledge, techniques, and concerns. It should help to standardize the terminology used in this field, facilitate communication between specialists speaking different languages, and aid translators in their work.

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