Numerical Simulations of the 1994 Piedmont Flood: Role of Orography and Moist Processes

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ABSTRACT

The intense precipitation event that occurred between 3 and 6 November 1994 and caused extensive flooding over Piedmont in northwestern Italy is simulated and tested with respect to various physical aspects, using a meteorological mesoscale model (BOLAM).

The period when the most intense rain occurred, mainly covering the second half of 4 and all of 5 November, is examined. A control experiment, starting at 1200 UTC 4 November, simulates the two observed precipitation peaks and captures the magnitude and timing of the most intense precipitation well even at relatively low horizontal resolution (about 30 km). The European Centre for Medium-Range Weather Forecasts analyses are used to provide the initial and boundary conditions. Model output diagnostics and comparison with observations indicate that most of the precipitation is associated with a prefrontal low-level jet, ahead of the cold front, impinging upon the orography of the region (Alps and Apennines). The model simulates a multiple rainband and frontal structure whose evolution determines both intensity and location of the prefrontal warm and moist flow. Almost all of the simulated precipitation over the Alps forms in the middle-low troposphere through forced ascent, whereas part of the secondary maximum, observed over the Apennines, is of convective type.

Sensitivity experiments have been conducted to investigate the effects of orography, surface fluxes, and latent heat exchange processes in the atmosphere. The role of the orography is crucial in determining distribution and amount of precipitation, whereas sensible and latent heat fluxes from the Mediterranean Sea (over the period considered) enhanced only the convective precipitation. Distinct dynamical effects, important for the amount and the spatial distribution of precipitation, are found to be associated with warming due to condensation and cooling due to evaporation and melting of precipitation. The latter process seems to be responsible for the simulated formation of rainbands and complex evolution of the cold front over the western Mediterranean. The multiple front life cycle and propagation feeds back on the simulated precipitation distribution, affecting the location of the prefrontal moist flow. Condensation affects the atmospheric effective stratification where the flow impinges on the orography, determining the flow regime (orographic lifting vs blocking and flow around), which, in turn, has an important impact on precipitation.

1. Introduction

A major and destructive flood affected the Piedmont region in Italy in the first few days of November 1994. Piedmont is surrounded on the west and north side by the western arc of the Alps and to the south by the lower Apennines mountains that encircle the Ligurian Sea (Fig. 1). The heaviest rain fell from late 4 to early 6 November, when several mountain stations recorded accumulated values in excess of 300 mm/36 h (Buzzi et al. 1995; Lionetti 1996). The Piedmont flood cannot be classified as a flash flood, since the crucial rainfall period lasted for more than 24 h and several river basins were affected. As a consequence of the flood, 70 people died and 2000 had to be evacuated. Damage to property was extensive and estimated to exceed 20 000 billion liras (about 12 billion U.S. dollars). About one-third of the loss affected public works and agriculture: for example, 150 bridges collapsed or were seriously damaged, and more than 5000 head of livestock were lost.

The relatively large time- and space scales of the event indicate that an investigation of the synoptic- and mesoscale meteorological processes associated with the heavy precipitation can be attempted using available datasets and mesoscale meteorological modeling, with the purpose of understanding basic processes and, ultimately, of improving forecasting capabilities of rainfall in areas of complex orography. This is one of the main objectives of the Mesoscale Alpine Programme (MAP; Binder et al. 1996).

One of the most striking ways in which topography influences the weather is through its strong local control of precipitation. The problem of precipitation over mountains is very complex, especially when the topography is not simple and is located near the sea that acts as a moisture and heat source. The western Mediterranean is an area in which steep topography and sea...
strongly affect weather systems and enhance precipitation. In this region, for instance, orographic cyclogenesis is a well-known and common occurrence (see, e.g., Tibaldi et al. 1990). Lee cyclones, due to their typical position over the Gulf of Lion, Gulf of Genoa, Thyrrenian Sea, or northern Adriatic, favor precipitation mainly on the eastern part of the Alps, over the Dinaric Alps, and over the Apennines. There are, however, other weather systems that can bring intense precipitation over the southern side of the Alps, inducing moist ascending flow that undergoes additional rapid lift upstream of the barrier. Cyclones located over the Iberian Peninsula and the westernmost part of the Mediterranean are normally associated with southerly flow and precipitation over the upstream flank of the western Alps, as in the case considered in this paper.

Strong and persistent precipitation events require, in addition to a synoptic-scale meridional flow, favorable conditions at the mesoscale, like the presence of slow-moving, north–south-oriented, cold fronts whose strong
warm and moist prefrontal flow (the “warm conveyor belt”) impinges on the steep orography. In such cases, as shown below for the case considered here, the most intense orographic precipitation falls in the prefrontal sector. Moistening and heating of the meridional current is favored during late summer and autumn by the surface fluxes from the Mediterranean (which depend on air–sea temperature contrast and surface wind speed). In addition, in this season, low values of the “effective” static stability $N$ (taking into account latent heat destabilization in case of saturated ascent) and high values of the low-level wind $U$ can make the Froude number $Fr = U/NH$ (where $H$ is a measure of the mountain height) large enough to favor “flow over” in place of “flow around” the obstacle, maximizing, in this way, the uplift of the airflow as it encounters high mountains. In fact, vigorous and deep uplift of air upstream of the orography can be attained only with $Fr \gg 1$, whereas the total ascent is reduced, in case of $Fr \ll 1$, by the occurrence of upstream blocking and flow around (depending also on mountain geometry). In the case of the western Alps, $H$ is about $3 \times 10^3$ m and $U$ is of the order of $10$ m s$^{-1}$, so that, for strong ascent, the condition $N \ll 0.3 \times 10^{-2}$ s$^{-1}$ has to be met. This is easily attained only in saturated conditions, when the equivalent potential temperature replaces the potential temperature in determining the effective static stability. Nonetheless, the occurrence of saturation in a sufficiently deep layer requires the existence of upward motion, so that a feedback process governed by the flow regime upstream of the orographic obstacle is involved. This mechanism may account for the large variability of orographic precipitation in the presence of high mountains. Extensive reviews of the problem of flow over orography, also in connection with the effects on precipitation, are found in Smith (1979, 1989).

The “smooth” orographic ascent described above is not the only mechanism of precipitation, since the occurrence of convection, possibly embedded in the orographic updraft, may add further complexities and strongly enhance local precipitation rates. In fact, while the magnitude of the orographic ascending motion can be estimated from the mountain slope $H/L$ and the horizontal upstream low-level flow $U$ as $w = UH/L$ (which in the case of the Alps gives values of the order of at most a few tens of centimeters per second), intense convection is associated with values of vertical velocity two orders of magnitude larger and, usually, less coherent in space and time. Of course, the presence of complex orography can influence convection in several ways, but the interaction occurs on such a small scale (around 1 km) that its explicit modeling (as opposed to parameterization) is out of the scope of this paper, in which we analyze only processes on mesoscale and beta scales, not smaller than a few tens of kilometers.

Another diabatic process that involves latent heat and has an important influence on the mesoscale flow is associated with cooling of initially dry air due to precipitation evaporation and snow melting. For example, evaporation in a cold front and in dry air behind a cold front can enhance frontogenesis and speed up the front by increasing the secondary ageostrophic circulation (see, e.g., Huang and Emanuel 1991). Evaporation can increase the static stability near and below the saturation level, changing the Froude number and, hence, the flow regime near the topography. We show in this paper that evaporation plays an important role in determining the intensity and the distribution of precipitation, by affecting both the frontal evolution and the dynamics of the flow impinging on the orography.

In this work, we have applied the Bologna Limited Area Model (BOLAM) to simulate the atmospheric evolution in the period between 1200 UTC 4 November and 0000 UTC 6 November 1994, to study the flow features that caused the intense precipitation, and to evaluate also the effects that orography and latent heat exchange processes had on the development of the precipitation and other meteorological fields.

A description of the general aspects of the case study, including observations of precipitation, is presented in section 2. In section 3, the model and data used for the numerical experiments are presented. The reference experiment is described in section 4; sensitivity experiments are presented in section 5. In section 6, the main results are discussed.

2. Description of the case study

a. Observed precipitation

Two main areas and spells of precipitation, which contributed to the Piedmont flood, can be identified in the period 4–6 November 1994. The first spell was characterized by embedded convective activity, with peak rainfall rates of the order of 50 mm h$^{-1}$ that caused soil erosion, and affected, on 4 and early 5 November, the area between the Maritime Alps, Ligurian Apennines, and Langhe hills (see Fig. 1). This area pertains to the drainage basins of the Tanaro, Bormida, and Belbo Rivers, which caused severe and disrupting floods in the period 5–6 November.

The second period of rainfall maximum was observed on 5 and early 6 November over the eastern flank of the western Alps, north of the city of Turin, affecting the watersheds of different rivers tributaries of the Po River (the main river of the entire area south of the Alps, known as the Po Valley). However, in this second area flooding was of limited extent, partly because of the lowering of the freezing level to about 2000 m above sea level (the Alps crest in this region exceeds 3000 m) and partly because the rainfall was more uniformly distributed in time over a period of about 24 h.

Total precipitation exceeding 250 mm day$^{-1}$ was reported in several stations in both the aforementioned areas, with a peak of 314 mm accumulated on 5 November at the rain gauge station of Oropa, in the north
Portion of Piedmont. Figure 2 presents an objective analysis of the total rainfall of 5 November based on dense station networks that belong to different institutions. Station density is very high over France and high over Piedmont (average station distance of about 20 km), so that we can assume that the 24-h accumulated precipitation pattern is well resolved over the region of interest (caution is still needed, however, for the most elevated areas in the Alps, where stations are mainly located in valleys or at intermediate levels). However, the spatial filtering implied by the analysis provides a slightly smoothed field, which is better suited for a comparison with the model results (individual station values and plots can be found in the papers referenced below). Figure 2 indicates that (with the caution expressed above) the maximum to the north is close, but not coincident, with the Alpine main divide line. It actually corresponds to the upslope area in southerly to south-easterly flow. The other maximum to the south affects both sides of the (much lower) Ligurian Apennines. As shown below, the model has problems in representing the extension of the rain area to the downstream (north) side of the Apennines. It can be noted in Fig. 2 that, besides the two main maxima over Piedmont, a broad region of intense precipitation, but with values generally below 100 mm/24 h, is present also to the west of the Alps, over France. Other, more localized, secondary maxima are observed over the Corsica island. The lack of stations over the sea makes it impossible to determine whether these rainfall maxima are spatially connected with those more to the north (but numerical results indicated that this is probably not the case, the island maximum being due to local orography).

Additional figures that show precipitation amounts over Piedmont and hourly profiles, for selected stations and for the period 4–6 November, are found in Buzzi et al. (1995) and Paccagnella et al. (1995). Profiles of precipitation rates exhibit much higher time variability in the maximum over the south portion of Piedmont, indicating the presence of convection. A general description of the event, both meteorological and hydrological, is presented by Lionetti (1996), who also makes a comparison with available climatological data and with past events of heavy rain over the same area.

b. Synoptic situation

A brief description of the general structure and evolution of the case study is presented here, based mainly on European Centre for Medium-Range Forecasts (ECMWF) analyses. Some of the mesoscale aspects that will be considered in relation to the numerical simulations are also indicated.

The synoptic situation at 1200 UTC of 4 November 1994 precedes the most intense precipitation period and corresponds to the initial time of the numerical simulations. The ECMWF mean sea level pressure (MSLP), 10-m wind, 500-hPa geopotential height and wind are shown in the panels of Fig. 3. A cyclone is located west of Ireland, with a trough plunging south toward Spain and a cold front extending from the low center, across France and eastern Spain, to Morocco (Fig. 3a). The moisture content at low levels over the Mediterranean at this time is high: mixing ratio values larger than 12 g kg⁻¹, extend from the eastern Mediterranean to southern Europe.

The 500-hPa map (Fig. 3b) shows a deep trough over the eastern Atlantic and the coasts of western Europe, associated with a northwesterly jet flowing toward northwest Africa and a southwesterly one approaching the western Mediterranean. The upper trough during the period considered slowly moves to the east, while the ridge, extending from the central Mediterranean to Scandinavia and associated with an anticyclone over eastern Europe, remains almost in place. This implies an intensification of geopotential gradient and of southerly flow on the eastern side of the trough. The large amplitude attained by the upper-level trough is already associated at this time with a descent of the tropopause and a positive potential vorticity anomaly above the Bay of Biscay and the western Iberian Peninsula (Binder and Rossa 1995).

The synoptic situation one day later (Fig. 4), during the period of most intense precipitation, is characterized by a shift to the east of the low-level trough whose axis extends from central England to the Alboran Sea, crossing northwestern France and the Gulf of Lion (Fig. 4a). The MSLP along the trough has actually increased, but the pressure gradient has intensified west of Italy, where
a secondary weak trough is visible and corresponds to
a pronounced cyclonic shear in the 10-m wind. As we
shall see below, the presence of a double trough actually
corresponds to a double cloud band and, according to
the numerical simulations presented below, to a double
frontlike structure at low levels. The southerly prefrontal
flow has intensified over the Mediterranean at the lon-
gitude of the isles of Sardinia and Corsica, and is de-
flected to the west when approaching the western Alps
(Fig. 4a). At 500 hPa (Fig. 4b) the trough is more pro-
nounced than at low levels: its axis has rotated anti-
clockwise, with the most rapid advance having taken
place over North Africa. An upper region of low dy-
namic tropopause, characterized by a positive potential
vorticity anomaly, has reached at this time the western
Mediterranean, to the west of the area of high precip-
itation (Binder and Rossa 1995; see also the discussion
3. Model and data

Before introducing the numerical simulations, we describe briefly the model and data employed for the experiments. We have used BOLAM, which is a hydrostatic, primitive-equation, gridpoint meteorological model. The horizontal discretization is based on geographical coordinates on a rotated Arakawa C grid, where the rotated equator is located at the midlatitude of the domain to minimize grid anisotropy. The vertical coordinate is sigma, with vertical discretization of the Lorenz type. Potential temperature is used as a thermodynamic variable: for the advantages of this choice, see Buzzi et al. (1994), where a more complete description and a validation of the model is presented. The temporal scheme is a three-time-level leapfrog, with implicit treatment of the gravity wave components. A fourth-order horizontal diffusion term, based on the $\nabla^4$ spatial operator, is added to all prognostic equations except for the tendency of surface pressure. The boundary layer scheme is based on the mixing length theory, with exchange coefficients depending on the Richardson number as in Louis et al. (1981). Surface roughness over land is different for momentum and temperature–humidity, and is a function of orography in order to parameterize aerodynamic drag. Over the sea, Charnock’s (1955) expression is used for both roughness values. The model uses Emanuel’s convective parameterization scheme (Emanuel 1991) and Geleyn’s radiation package (Geleyn and Hollingsworth 1979; Ritter and Geleyn 1992). The water cycle (condensation, evaporation, and melting of precipitation) is parameterized in a simple way, without carrying explicitly water species but using relaxation toward equilibrium values (Buzzi et al. 1994). Land processes (vertical fluxes of heat and moisture, snow accumulation and melting, runoff, etc.) are described using a three-layer soil model. The sea surface temperature and the deep soil temperature and moisture are kept constant during each run. Lateral boundary conditions are prescribed using a relaxation scheme (Davies 1976; Lehmann 1993) that minimizes internal wave reflection.

The orography used in the model simulations is obtained by interpolating from a (slightly smoothed) one-sixth degree dataset of the U.S. Navy to the model grid. The initial and boundary condition values are obtained from ECMWF initialized, 6-hourly analyses available at 0.75° resolution on 15 standard pressure levels. The atmospheric variables are horizontally interpolated to
the model grid and vertically interpolated to the model sigma levels. Some of the surface fields composing the ECMWF analyses, such as surface temperature (including SST), moisture, and snow depth, are used to define the initial conditions, taking into account the differences in coastal profiles and orography between the ECMWF and BOLAM models.

The ECMWF data provide the initial and boundary conditions for all the numerical experiments, except those performed on a nested grid. In the latter case, a one-way nesting procedure has been implemented, in which initial and boundary values are obtained by properly interpolating from a low-resolution run to a higher-resolution inner grid.

Other meteorological standard data, including rainfall observations, obtained in the context of the ANOMALIA EU project, have been used for comparison with model results.

4. Reference simulation and mesoscale aspects

The reference simulation has been run at relatively modest resolution (about 30 km of grid distance and 24 sigma levels), since the results, as shown below, compare well with the available observations. However, runs at higher resolution (10 km and 36 levels) and in self-nested mode have been made to study the resolution dependence of precipitation amount and distribution. Apart from an expected enhancement of peaks and a more detailed spatial structure, no major differences in dynamical fields were found in this case. For this reason, we have decided to run the sensitivity experiments at 30-km resolution, and in the remainder of this paper we shall refer only to this kind of simulation.

A real mesoscale analysis of this case, in which most of the relevant structures are located over the western Mediterranean, is possible only if model output fields are used to complement the (relatively sparse) observations over the region. The good agreement between real data and model fields allows us to adopt this approach.

The east–west cross section of Fig. 5 shows the potential vorticity and relative humidity fields obtained from the reference simulation valid 2100 UTC 4 November. This section (and the following ones) is taken at a constant latitude crossing the islands of Mallorca and Sardinia. The lowest potential vorticity contour corresponds to 2.0 PV units and conventionally marks the dynamic tropopause, which lowers to almost 400 hPa over the east coast of Spain. A tongue of low values of relative humidity extends below this potential vorticity maximum, approaching the ground above the Mallorca island, slightly tilting westward with height. This particular instant corresponds to the onset of a low-level horizontal temperature gradient, to the east of the dry tongue where the maximum gradient of humidity (and hence of equivalent potential temperature) is present. The dry tongue, whose formation is favored by the orographic descent, leads the cold front that, at this time, is located near the Spanish east coast. The existence of this low-level dry air, surmounted by an almost saturated layer, is supported by the sounding of Palma de Mallorca, taken at 0000 UTC of 5 November, and shown in Fig. 6. This structure, as suggested by one of the reviewers, is reminiscent of the dryline phenomenon frequently observed over the U.S. Great Plains (see, e.g., Martin et al. 1995).

The MSLP and 10-m wind of the reference experiment after 24 h of integration, verifying 1200 UTC 5 November, are shown in Fig. 7. The main features of the MSLP field (Fig. 7a) compare well with the large-scale analysis of Fig. 4a, except that the weak low over northern France is missing and the orographic perturbation near the Alps is more pronounced.

The 10-m wind (Fig. 7b) is significantly strong, particularly over the Mediterranean where the moisture inflow into the main precipitation area takes place. Over the western Mediterranean, two distinct shear lines are clearly visible. Each line is associated, in the model solution, with wind convergence, maximum wind shear, pressure trough, temperature gradient, and rainband characterized by convective precipitation. In between the two shear lines, the model predicts a broad region of mainly stratiform precipitation, corresponding to low-level anticyclonic circulation and lower temperature. This complex structure seems also verified by the presence of multiple cloud bands, clearly visible in the satellite picture (Fig. 8). Therefore we can conclude that this feature is not a model artifact. Figure 9 shows the east–west cross section of potential temperature and meridional wind component at this time. Two areas characterized by horizontal gradient of potential temperature...
and wind shear, separated by a pool of colder air, are present at low level between the Spanish coast and Sardinia. Two relative maxima of the meridional wind are located above the Mallorca and Sardinia islands, respectively. The strong temperature gradient located along the west coast of Sardinia is the evolution of the "dryline," associated with the equivalent potential temperature gradient, mentioned above. The formation of such a strong temperature gradient is due to evaporative cooling in the dry air. This process weakens the temperature gradient to the west and intensifies it to the east, resulting in an apparent formation of a double surface front out of the original single one. This effect will appear more clearly in the comparison between the reference experiment and one without evaporation of precipitation (see the next section). By 0000 UTC 6 November the two frontlike structures merge together into a single cold front.

It can be noted in Fig. 7b that the main southeasterly warm and moist prefrontal flow is associated with the leading edge of the eastern frontal band described above, just to the west of the Sardinia island. This flow converges, over the western Alps, with a weaker current that flows along the Adriatic Sea and turns to the west along the Po Valley, south of the Alps. This low-level flow pattern is verified in surface observations over land (Buzzi et al. 1994). It can be noted that this convergence is not associated with appreciable horizontal deflection of the low-level wind, indicating that there is substantial uplift along the mountain slope.

The model-accumulated precipitation over the 24-h period from 0000 to 2400 of 5 November is shown in Fig. 10. This compares with the observed precipitation of Fig. 2. The same number of maxima, with approximately the same location and similar intensities are obtained in the simulation. The largest error seems to be associated with the maximum on southern Piedmont, which in the experiments is located about 40–50 km to the south of the observed position, too close to the coast than in reality. A detailed analysis of this precipitation maximum indicates that convection is the main contributor, in agreement with the highly irregular time and space distribution of precipitation observed in the hourly records available for that area (see, e.g., Buzzi and Tarbaglione 1995; Lionetti 1996). The model consistently attributes more than 60% of the precipitation of this area to the Emanuel convective scheme (in contrast, the other maximum to the north is almost completely attributed to explicit precipitation). We may speculate that the missed downstream extension of the area of convective precipitation could be due to the lack of an explicit representation of the convective cells that would allow simulating their northward drift during their life cycle.

5. Sensitivity experiments

Numerous sensitivity experiments have been made in order to investigate the physical and model factors associated with the abundant precipitation, and to study the dynamical evolution of the system, especially concerning the orographic effects and the double frontal structure observed during this event. The different experiments are summarized in Table 1; only experiments
no orography (NOORO), no evaporation (NOEV), and no condensation (NOCD) will be discussed in detail. Additional experiments, without the surface heat and moisture fluxes, have shown that precipitation is reduced by less than 10% over the Alps, where it seems to be mainly of stratiform type (Buzzi and Tartaglione 1995). The suppression of heat and moisture fluxes at the surface, however, hinders convection in the model, so that the convective bands over the sea are absent and the precipitation over the Ligurian Apennines is reduced by about 40%. These results indicate that, while convection is sensitive to temperature and humidity values near the surface, the main orographic uplift induces condensation in air parcels that come from levels high enough to be only marginally affected by surface fluxes. This does not imply that surface fluxes are not important to determine air humidity and temperature on timescales longer than those involved in our simulations. Surface fluxes, in fact, are important in “preconditioning” the low-level air before the start of the simulations.

In the following subsections, the effects of orography and latent heat exchanges associated with moist processes are investigated in some detail, with particular attention devoted to the impact of the above factors on precipitation distribution and associated relevant mesoscale dynamical features as, for example, the orographically induced flow and the frontal evolution. We show that both these mesoscale features have an important role in determining in the simulated precipitation fields that can be interpreted in terms of variations of atmospheric dynamical processes.

a. Orographic effects

The orography of the NOORO experiments has been defined as

\[ h[1 - \exp\{((x - x_0)^2 + (y - y_0)^2)/r_0^2\}]\]
where $h$ is the topographic height of the control experiment, $x_0$ and $y_0$ are the coordinate of the center of the Gaussian, chosen at lat = 44° and long = 7° (close to Turin), and $r_0 = 500$ km. In this way, the part of the orography (western and central Alps, Ligurian Apennines), where most of the observed orographic precipitation occurred, was strongly reduced.

An additional experiment (not shown) with completely flattened orography in the model domain has been performed for comparison. Significant differences are observed only over Spain and the western Mediterranean, where the topography of the Pyrenees and of the Iberian Peninsula induce a ridge–trough structure that increases the cyclonic circulation at low levels near the Mediterranean coast.

The pattern of the 24-h accumulated precipitation (valid for all of 5 November) over the Piedmont region for the NOORO simulation (see Fig. 11a) reveals that the maxima connected with orography have disappeared, while a precipitation band of moderate amount extends from the Ligurian coast to northern France. This rainfall configuration is consistent with the 10-m wind

### Table 1. Description of experiments.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Orography</th>
<th>Condensative latent heat</th>
<th>Evaporative latent heat</th>
<th>Surface fluxes</th>
</tr>
</thead>
<tbody>
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<td>CONTR</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>NOORO</td>
<td>No (locally)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>NOCD</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>NOEV</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>NOFLX</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>
b. Latent heat effects

The sensitivity experiments made to study the role of latent heat exchanges were conducted by eliminating the temperature tendencies due to large-scale condensation, evaporation, or both, but allowing water conversions, like the formation and fall of precipitation. Since the elimination of latent heat contributions from the moist adjustment process would make the adjustment itself meaningless, it has been decided to leave unchanged the convective parameterization scheme.

Three different sensitivity experiments have been made, by suppressing the condensational heating (NOCD), the evaporative cooling (NOEV), and all the temperature tendency contributions due to latent heat conversions (no latent heat, NOLH), respectively (see also Table 1).

The MSLP and 10-m wind of experiment NOCD, after 24 h of integration, are shown in Fig. 12. Higher MSLP values with respect to the reference experiment (see Fig. 12a) are evident in the Alpine region, particularly near the western Alps, where the pressure difference is about 4 hPa. The lower MSLP in the control run is most likely the result of the warming of the atmospheric column by the release of latent heat, as indicated also by the comparison of the 850- and 700-hPa temperature fields (not shown).

The more dramatic difference between the control experiment (Fig. 7b) and the NOCD experiment (Fig. 12b) is evident in the low-level wind fields, in the coastal area south of the western Alps. In the presence of regular warming due to latent heat release, the low-level convergence of the southeasterly flow upstream of the front is located over the Ligurian Sea and the northern Apennines, where the heaviest precipitation was observed. In the NOCD experiment, a low-level easterly flow develops south of the western Alps, representing a strong deflection of the warm low-level jet around the topographic barrier. In other words, while in the CONTR experiment there is a “flow over” regime associated with the low-level prefrontal flow impinging on the mountain, in the case of no condensation, a “flow around” regime upstream of the mountains is present at low levels. We can deduce that the latent heating contributes to increase the convergent flow in the region of heaviest precipitation, enhancing the precipitation itself. The impact of latent heat on quantitative precipitation can be appreciated by comparing Fig. 13 with Fig. 10. In the NOCD case, precipitation maxima over Piedmont and the Maritime Alps almost disappear (rainfall values are reduced to about 30% of the reference experiment). The absolute maximum appears now over...
the Ligurian Sea, upstream of the position in the CONTR experiment, while another area of strong precipitation appears off the coast of southern France, corresponding to the enhancement of the low-level wind convergence. However, the large decrease of precipitation over Piedmont cannot be ascribed entirely to the different flow regime at low levels, since the absence of latent heating reduces buoyancy and upward motion in the entire column where condensation takes place. It is interesting to note also, in Fig. 12b, that the double frontlike structure, though slightly less intense than in the reference case, is still present over the western Mediterranean.

The NOEV experiment has been set up by neglecting the temperature tendency associated only with evaporation of liquid water and snow. The MSLP and the 10-m wind for the NOEV experiment, after 24 h of simulation, are shown in Fig. 14. In this experiment, the center of the depression appears over southern France, with a minimum lower than 1000 hPa (Fig. 14a). In the 10-m wind field (Fig. 14b) only one convergence line is visible, indicating that frontal splitting has not occurred. The longitudinal cross section of Fig. 15, taken at the same latitude and time of Fig. 9, depicts the frontal structure in this experiment. A rather weak surface front is present between Mallorca and Sardinia islands, with a single maximum in the meridional wind located over Sardinia. Therefore, neither cold pool nor prefrontal intensification are present in the absence of large-scale evaporation. These changes on the mesoscale are associated with changes of the low-level prefrontal flow over the area of interest. In fact, the surface southeasterly flow to the east of the broad front is wider than in CONTR. The convergence area near the coast is more widespread, with a maximum located over southern France, near the surface pressure minimum. The precipitation field in this experiment (see Fig. 16) is consistent with these changes in the surface wind, showing a significant increase of precipitation over southern France and a slight decrease (of about 10%) over Piedmont.
The consequence of the absence of a multiple frontal-like structure is that the precipitation maxima responsible for the Piedmont flood are reduced, though not to the same extent as in the NOCD experiment. In this case, in fact, the condensational heating is preserved and can act to sustain the upward motion. It is interesting to note, however, that the removal of the evaporative cooling alone is sufficient to suppress the formation of the multiple frontal structure that contributed to direct the flow against the Ligurian Apennines and the Alps.

The third experiment, in which all the latent heat conversion terms are removed (NOLH), presents characteristics common to both NOCD and NOEV (for this reason no figures are shown here). In fact, in this case the flow over the mountains and the vertical motions are reduced and multiple frontal structures do not appear, resulting in the smallest amount of rain in the region of the observed maxima.

6. Discussion and conclusions

A case study of an intense precipitation event that affected the northwestern regions of Italy, mainly the Piedmont region, was studied with the aid of numerical simulations. The analysis, based on model output diagnostics, comparison with observations, and sensitivity experiments, shows that the remarkable amount of accumulated rainfall was strongly modulated by the mesoscale effects induced on the synoptic-scale flow by the orography and by latent heat conversions in the atmosphere. The orography of the area (western Alps and northern Apennines) played a crucial role not only on the local scale (by forcing strong upward motion) but also on the larger scale, by modifying the pressure field over the western Mediterranean and by confining the southerly prefrontal flow to the south of the Alpine region. The removal of the portion of the orography interacting with the prefrontal circulation allows the front itself, and the associated warm conveyor belt, to extend much farther to the north, preventing the concentration of precipitation in the alpine region.

Numerical simulations have been made in order to evaluate the dynamical impact of the physical processes associated with intense precipitation and to investigate the role played by orography and latent heat. A reference simulation (CONTR) has been used to compare the results with those obtained by performing several sensitivity experiments. The CONTR experiment captures location and timing of precipitation over the northwestern regions of Italy and over the southeastern regions of France. The intense orographic ascent, in the stage of heavy precipitation, is associated with a prefrontal moist low-level jet.

The most interesting effects have been found in the dynamical impact of condensational warming and evaporative cooling associated with moist processes, which, in turn, are very sensitive to the mesoscale circulation features. In the presence of considerable amounts of moisture at relatively high air temperature and steep orography forcing large vertical motions, effective feedback mechanisms are revealed by the numerical simulations.

One example of positive feedback has emerged from the comparison between the CONTR and the NOCD experiments described above, indicating that the release of latent heat of condensation on the upstream side of
the orography favors the “flow over” regime by decreasing the effective static stability of the ascending saturated flow. In this case, the orographic uplift acts as a catalyst for establishing a flow regime that is presumably maintained by the energy input of condensation. Our numerical results do not constitute a final proof, but provide hypotheses for further theoretical investigations.

The formation of a multiple front–like rainband structure is simulated in this case study. This feature is consistent with satellite images and with the surface analyses reported in the European Meteorological Bulletin of 5 November 1994. Its formation is heuristically ascribed to evaporative cooling, which is responsible for the formation of a low-level cold pool in a preexisting cold front. With NOEV, the prefrontal rainband, which assumes the character of a forerunner cold front, does not form. This prevents the steepening of the meridional flow (warm conveyor belt) that impinges upon the western Alps. Though the hypothesized feedback has, in this case, a weaker impact on the simulated precipitation, we emphasize again that a precipitation-related process (the evaporation of rain) determines the formation of a mesoscale flow structure that, in turn, affects rain rates in the flood area.

The existence of multiple rainbands, possibly associated with frontlike structures, is not uncommon in cases of depressions located over the Iberian Peninsula and the western Mediterranean. A similar situation in this respect, also associated with heavy precipitation and flooding in the Alpine area (Brig flood case), was analyzed (and simulated) by Tartaglione and Buzzi (1996).

In conclusion, from the point of view of improving our understanding of the basic mesoscale processes that induce heavy precipitation near orography, further theoretical/numerical investigations are needed to study the interaction of frontal circulation with orography and the
effects of condensation and evaporation on orographic flows and on the formation of multiple low-level fronts and rainbands. To improve the numerical modeling of such phenomena, with the ultimate scope of a better precipitation forecast, it is necessary to improve the representation of orography and, perhaps more important, of the atmospheric water cycle. An increase of model resolution probably requires a simultaneous increase in the complexity of the microphysical representation and of the convective parameterization scheme.

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