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Spatial relationship between the atmospheric circulation and the precipitation measured in the western Swiss Alps by means of the analogue method

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Abstract. An adaptation technique based on the synoptic atmospheric circulation to forecast local precipitation, namely the analogue method, has been implemented for the western Swiss Alps. During the calibration procedure, relevance maps were established for the geopotential height data. These maps highlight the locations where the synoptic circulation was found of interest for the precipitation forecasting at two rain gauge stations (Binn and Les Marécottes) that are located both in the alpine Rhône catchment, at a distance of about 100 km from each other. These two stations are sensitive to different atmospheric circulations.

We have observed that the most relevant data for the analogue method can be found where specific atmospheric circulation patterns appear concomitantly with heavy precipitation events. Those skilled regions are coherent with the atmospheric flows illustrated, for example, by means of the back trajectories of air masses. Indeed, the circulation recurrently diverges from the climatology during days with strong precipitation on the southern part of the alpine Rhône catchment. We have found that for over 152 days with precipitation amount above 50 mm at the Binn station, only 3 did not show a trajectory of a southerly flow, meaning that such a circulation was present for 98 % of the events.

Time evolution of the relevance maps confirms that the atmospheric circulation variables have significantly better forecasting skills close to the precipitation period, and that it seems pointless for the analogue method to consider circulation information days before a precipitation event as a primary predictor. Even though the occurrence of some critical circulation patterns leading to heavy precipitation events can be detected by precursors at remote locations and 1 week ahead (Grazzini, 2007; Martius et al., 2008), time extrapolation by the analogue method seems to be rather poor. This

would suggest, in accordance with previous studies (Obled et al., 2002; Bontron and Obled, 2005), that time extrapolation should be done by the Global Circulation Model, which can process atmospheric variables that can be used by the adaptation method.

1 Introduction

Some major precipitation events recently occurred in the Swiss alpine Rhône catchment (1987, 1993 and 2000). October 2000 is the last to date with precipitation amounts above 500 mm in 7 days in the south-eastern part of the catchment (Petrascheck and Hegg, 2002). According to present statistics, this event has a return period of more than 1000 years for different rain gauges. This created a 100 to 300-yr flood on the Rhône, depending on the location (Petrascheck and Hegg, 2002).

This work is part of the MINERVE (Modélisation des Intempéries de Nature Extrême sur les Rivières Valaisannes et de leurs Effets) project that aims at providing a real-time flood management on the upper Rhône catchment (García Hernández et al., 2009). The main idea is to use dams to store water during an extreme event. This means that a certain storage volume must be made available before the precipitation begins. This requires the precipitation and the discharge to be predicted several days in advance. At present, MeteoSwiss provides the COSMO (Consortium for Small-scale Modeling, see Steppeler et al., 2003) and COSMO-LEPS (Limited Area Ensemble Prediction System, see Montani et al., 2003; Marsigli et al., 2005) forecasts. Our work aims at providing a parallel forecast based on a statistical approach, namely the analogue method, in order to

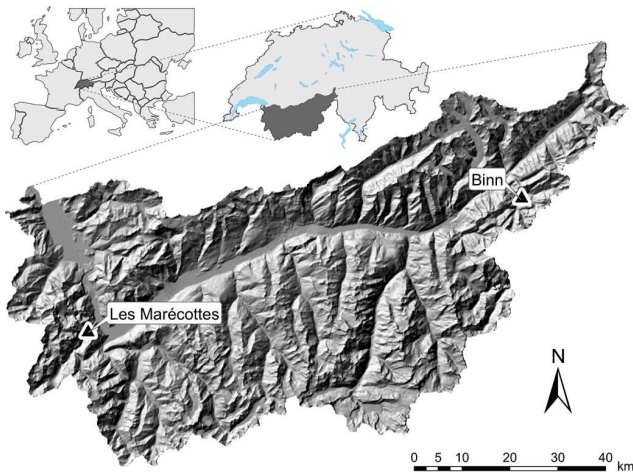


Fig. 1. Location of the alpine Rhône catchment in Switzerland and the two rain gauge stations of interest (source: Swisstopo).

better assess the meteorological uncertainties. It will also give an overview of the synoptic atmospheric circulation and its identified determining elements, and offer the possibility to refer to historical events.

The analogue method is an adaptation technique that allows forecasting daily (and possible subdaily) precipitation by means of identification of analogue past situations in terms of synoptic circulation. The chosen method is similar to the one developed by Obled et al. (2002), Bontron and Obled (2005), Ben Daoud et al. (2009) and Marty et al. (2012). This study covers part of the method calibration for the Swiss Alps. The parameters' space is highly multi-dimensional, which means that the calibration process cannot be easily automatised. The purpose of this study is to perform diagnostic analyses that could help the calibration and provide guidelines for the selection of predictor variables.

Strong southerly flows, which are critical for precipitation on the eastern part of the Rhône catchment, have been the subject of many studies. These show the presence of upper-level precursors in potential vorticity fields and in geopotential heights (e.g. Massacand et al., 1998; Martius et al., 2006, 2008; Grazzini, 2007, etc.). We will show similar analyses by means of backward trajectories of air masses, and set these in perspective with the regions of the geopotential levels having the highest skill for precipitation forecasting at gauging stations of interest.

2 Data and methodology

The study area is the alpine upper Rhône catchment in Switzerland (Fig. 1). The altitude ranges from 372 to 4634 m a.s.l. and the area is 5524 km².

Our calibration is illustrated in 2 locations (Fig. 1) that are sensitive to different atmospheric circulations. Les Marécottes is sensitive to strong westerlies, while Binn is

extremely sensitive to the southerly circulation. This last one was actually the circulation pattern of October 2000 and it is the most critical situation for the catchment. It can generate large amounts of precipitation on the eastern or southern part of the catchment by strong orographic effects.

2.1 Datasets and tools

The chosen dataset is the NCEP/NCAR reanalysis (6-hourly, 17 atmospheric levels at a resolution of 2.5°; see Kalnay et al., 1996), as predictor variables and the daily precipitation measured at the MeteoSwiss stations network as predictand (which is to be predicted), for the period 1962–2007. Other authors usually consider a precipitation averaged over a basin or a region as the predictand in order to smooth local effects (Obled et al., 2002; Marty et al., 2012), which is not the case in the present study.

We developed the model used for this study, which is called ATMOSWING (Analogue Technique MOdel for Statistical Weather forecastING), and is written in C++ with an object-oriented architecture. It allows us to process calibration and real-time forecasting and to visualize the outputs. This model has been intensively tested against the model developed at the Grenoble Institute of Technology (Bontron and Obled, 2005; Marty et al., 2012) to ensure that the processing is correct.

2.2 The analogue adaptation technique

The analogue method is a downscaling technique based on the idea expressed by Lorenz (1969). It aims at forecasting a predictand, often the daily precipitation, on the basis of predictor variables describing the synoptic atmospheric circulation. Its main hypothesis is that similar situations in terms of atmospheric circulation are likely to lead to similar local weather (Bontron and Obled, 2005). This has been observed for the Alpine region in various studies (Massacand et al., 1998; Grazzini, 2007; Martius et al., 2006, 2008; Fehlmann et al., 2000).

The approach consists of the following steps. The method summarized hereafter is similar to the approach of Obled et al. (2002), Bontron and Obled (2005), Ben Daoud et al. (2009) and Marty et al. (2012). Numerous variations of the method are possible, and some aspects and parameters will not be detailed hereafter. In the following procedure, we are interested in forecasting the cumulated daily rainfall (6 a.m. to 6 a.m. the next day) for the 7 coming days, D_1 to D_7 .

1. We collect some predictors (geopotential heights and humidity variables) for our 7 lead times (D_1 to D_7) from the Global Circulation Model (GCM) outputs in the case of real-time forecasting or from the reanalysis dataset (Kalnay et al., 1996) in the case of the calibration procedure. The predictor data are thus already extrapolated over time.

- Then, we process the first level of analogy on the synoptic circulation. Bontron and Obled (2005) showed that the geopotential heights at 500 hPa and 1000 hPa are the best first predictors of the NCEP/NCAR reanalysis dataset. Thus, these fields are extracted over a certain spatial window for every target date D_j to be compared to the reanalysis archive. To cope with seasonal effects, candidate data are extracted for every year from the archive within a period of 4 months centred around the target date D_j . The similarity criterion is the S1 score given in Eq. (1), which is a comparison of gradients (Teweles and Wobus, 1954; Drosowsky and Zhang, 2003).

$$S1 = 100 \frac{\sum_i |\Delta \hat{z}_i - \Delta z_i|}{\sum_i \max\{|\Delta \hat{z}_i|, |\Delta z_i|\}} \quad (1)$$

where $\Delta \hat{z}_i$ is the forecast geopotential height difference between the i -th pair of adjacent points in the target situation, and Δz_i is the corresponding observed geopotential height difference in the candidate situation. The differences are processed separately in both directions, and then averaged. The smaller the S1 values are, the more similar the pressure fields.

The S1 score has been compared against other criteria by Bontron and Obled (2005). The RMSE is better to compare most variables, except the geopotential heights. In this case, S1 shows improved forecasting skills. The reason for such better results is that the S1 criteria allows comparing the circulation pattern, by means of the gradients, rather than the absolute value of the geopotential heights.

- The N_j dates with the lowest values of S1 are considered as analogues to the target day D_j . The number of analogues, N_j , is a parameter to calibrate that varies with the lead time j in the forecast usage. It has an optimum clearly identifiable that is often around 30 dates for the first lead time ($j = 1$) if we consider only one level of analogy, and that is increasing for subsequent lead times.
- We may next add new subsampling levels based on other variables, such as the humidity fluxes, to pick out a lower number of analogues N'_j amongst the previous selection. If we consider a second level of analogy, the first number of analogues, N_j , needs to be higher than in the case of a single level approach. Naturally, $N'_j < N_j$.
- Finally, the daily observed precipitation amount of the N'_j resulting dates provides the empirical conditional distribution, considered as the probabilistic forecast for the target day D_j .

2.3 Calibration

For every level of analogy, a parameter one has to calibrate is the analogues number. In each of these levels, for every atmospheric variable, we also need to calibrate:

- The best atmospheric levels to select
- The spatial windows (their location and size)
- The temporal windows (hour of the day)

To calibrate the method, we need to reforecast the past and to assess the performance of our model by comparing the results to observed precipitation. As the GCM outputs are not available in a forecasting mode for the past, the calibration is performed in a perfect prognosis framework with the reanalysis dataset. This means that the predictors are analysed fields and not output forecasts from a meteorological model, and thus have a smaller and constant uncertainty when model forecasts show an increasing uncertainty with the lead time.

The calibration is done by means of a trial and error approach: we choose an initial parameters set, run the model over a long calibration period (1962–2007) and assess the result. The model accuracy is rated by means of the CRPS (Continuous Ranked Probability Score) (Brown, 1974; Matheson and Winkler, 1976; Hersbach, 2000). Let the precipitation variable be denoted x with x^0 the observed value, and $F(x)$ the predicted cumulative distribution functions (cdf). The mean CRPS of a forecast series of length n can be written as:

$$CRPS = \frac{1}{n} \sum_{i=1}^n \left(\int_{-\infty}^{+\infty} [F_i(x) - H_i(x - x_i^0)]^2 dx \right) \quad (2)$$

where $H(x - x_i^0)$ is the Heaviside function that is null when $x - x_i^0 < 0$, and is equal to 1 otherwise.

The mean CRPS is processed on the calibration period. The best parameters are selected according to the optimal (i.e. lowest) score.

2.4 Relevance mapping

The relevance map is a spatial representation of the forecasting skill of every grid cell of the predictor dataset. This map is processed by fixing every parameter except the location of a unitary sized spatial window that moves across the whole map (Bontron and Obled, 2005). By iterating the position of this small window, we get the CRPS score corresponding to every spatial unit. It allows us to see where the synoptic circulation information is relevant to explain the precipitation time series at our rain gauge station. The relevance mapping was processed on the whole time series (including days without precipitation).

The predictors' best locations are not expected to be the same for different stations or sub-catchments, but to match

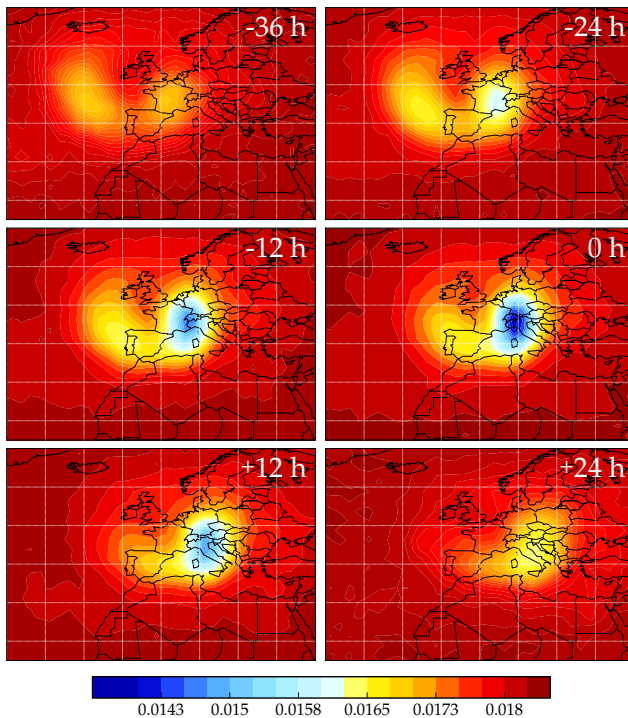


Fig. 2. Time evolution of the relevance map on the 500 hPa atmospheric pressure level for the Binn station. The values are the CRPS scores.

the meteorological characteristics of the region. The predictors' best locations should indeed be consistent with the meteorological phenomena that influence the region's weather.

2.5 Isobaric back trajectories

We processed isobaric back trajectories (Danielsen, 1961) of air masses on the wind field of the NCEP/NCAR reanalysis dataset (Kalnay et al., 1996) for days above a certain amount of precipitation at the station of interest. The starting location is the central point of the Rhône catchment. As the resolution of the dataset is rather coarse compared to the catchment size, the hypothesis is made that there is no significant variation of the synoptic circulation information for distances of about 50 km, which are subgrid scales.

3 Results for the Rhône catchment

3.1 Relevance maps evolution

As the NCEP/NCAR reanalysis has higher time resolution than the rainfall series, we had to choose the best temporal window to compare the predictor variables. To illustrate the effect of the hour selection, as well as the time extrapolation influence for the method, some relevance maps (Sect. 2.4) were established for various hours around the precipitation period. This was made by considering the predictor at a time $h + \Delta t$ to predict the precipitation at time h with Δt varying

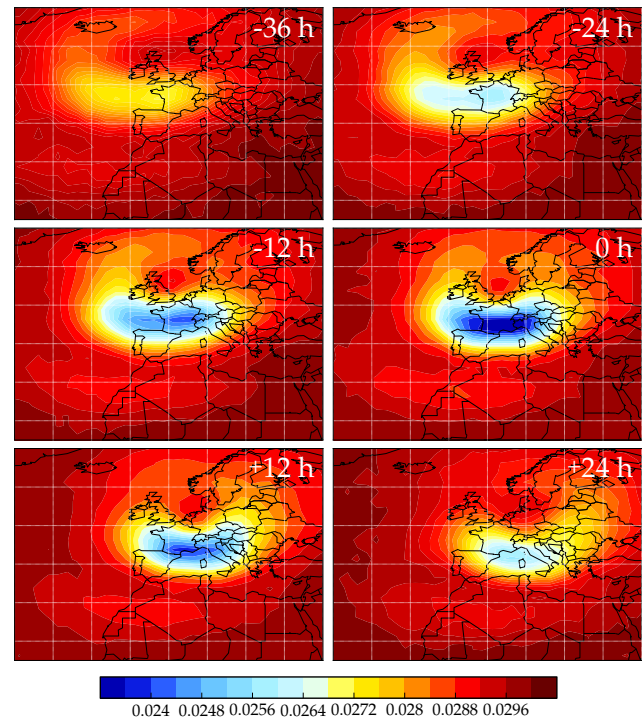


Fig. 3. Time evolution of the relevance map on the 500 hPa atmospheric pressure level for the Marécottes station. The values are the CRPS scores.

in between -36 h and $+24$ h. Precipitation time h is 6 p.m., being the center of the measuring period (6 a.m. to 6 a.m. the next day).

The evolution on the 500 hPa level for the Binn (Fig. 2) and Marécottes stations (Fig. 3) illustrates the formation of the patterns where the atmospheric circulation is determining the whole precipitation time series. One can see the patterns being formed at some remote distance some hours before the precipitation period. These patterns evolve and move over the catchment, where they reach their strongest relevance, before continuing to travel eastward and losing their predictability skill. These patterns characterize the relevant regions in terms of atmospheric circulation, by means of the geopotential field gradients.

3.2 Relevance maps optimums

The relevance maps were processed for both the Binn and Marécottes stations at 500 hPa and 1000 hPa, each with its optimal temporal window (Fig. 4). The hour is expressed relatively to the center (6:00 p.m.) of the precipitation measuring period (6:00 a.m.–6:00 a.m. the next day), resulting in a time difference Δt . One can see that if the time matches the precipitation period for both stations on the 500 hPa, it varies from -6 h at Binn to $+6$ h at Les Marécottes on the 1000 hPa.

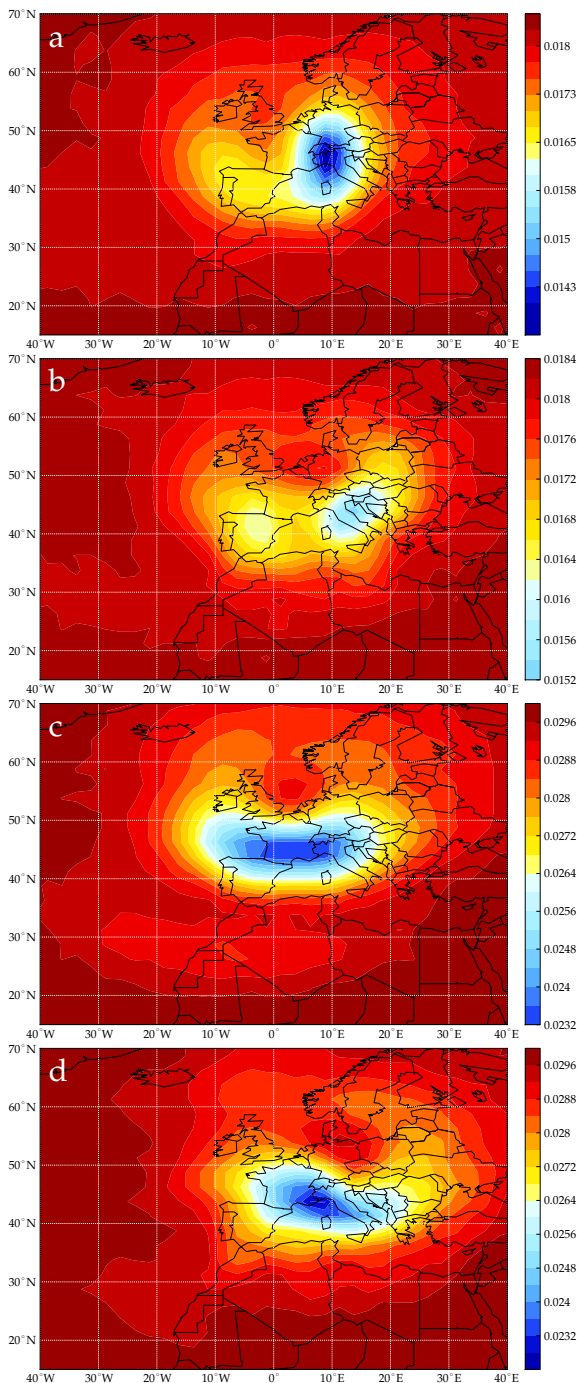


Fig. 4. Relevance map (a) on the 500 hPa at $\Delta t = 0$ h and (b) on the 1000 hPa at $\Delta t = -6$ h for the Binn station, and (c) on the 500 hPa at $\Delta t = 0$ h and (d) on the 1000 hPa at $\Delta t = +6$ h for the Marécottes station. The values are the CRPS scores.

The CRPS score cannot be compared between the stations, but it can be compared between atmospheric levels for one station. The reduced range of values for any map is due to the fact that we consider spatial windows with size of a grid cell to search for analogues, which is clearly not the optimal

extent. Adaptation of the spatial window size, which is the next step following the relevance map in the calibration process, greatly increases the forecasting skills of the method.

As one can see on the two relevance maps for Binn (Fig. 4a and 4b), the 500 hPa level explains the precipitation in that region better than the 1000 hPa. The difference is significant and may be explained by the heterogeneity on the 1000 hPa level. Indeed, this level shows a first optimal location in the Adriatic Sea and over Italy and a second minor over Spain. Another potential reason for the importance of the 500 hPa level is the need of a strong upper-level current for the precipitation to reach the other side of the orographic barrier with a remarkable intensity (Massacand et al., 1998).

On the opposite, the relevance maps for the Marécottes station (Fig. 4c and d) show a better score for the 1000 hPa level than for the 500 hPa.

For both stations, the most relevant areas include the catchment on the 500 hPa level, but not on the 1000 hPa on which they are located further south. By the way, it makes us more confident to consider the 1000 hPa level above the sea rather than in the Alps, where its significance is debatable.

4 Meteorological analyses

We will first discuss the meteorological situations leading to heavy precipitation events at the Binn station. It is well known that southerly circulations are critical for this location, particularly in autumn. Such a flow may trigger high precipitation events on the Alpine southern slopes by orographic lifting (Massacand et al., 1998). Sometimes, but not always, high precipitation amounts may reach the Rhône catchment. When this happens, the Binn region is concerned most of the time.

Analyses of some events of extreme precipitation on the Alpine south side indicate the presence of an upper-level precursor on the potential vorticity distribution (Massacand et al., 1998). These events could be characterized by similar potential vorticity patterns taking the form of a meridionally elongated deep intrusion of stratospheric air. Martius et al. (2006) found a strong correlation between this potential vorticity streamer and extreme precipitation on the southern slopes of the Alps (streamers are present for 73 % of extreme precipitation days). The upper-level circulation was accordingly characterized by a deep trough at 500 hPa extending from the British Isles towards the Iberian Peninsula at the time of the precipitation (Fehlmann et al., 2000; Plaut et al., 2001). This trough was accompanied by an upper-level ridge to the west ensuring air advection, and another one to the east, which contributed to blocking the perturbation (Fehlmann et al., 2000; Plaut et al., 2001). The consequences of such a system are a moisture-laden strong southerly flow at low levels that extends from the Mediterranean to the Alps, a reduction of the static stability, and an enhancement of the convection (Massacand et al., 1998).

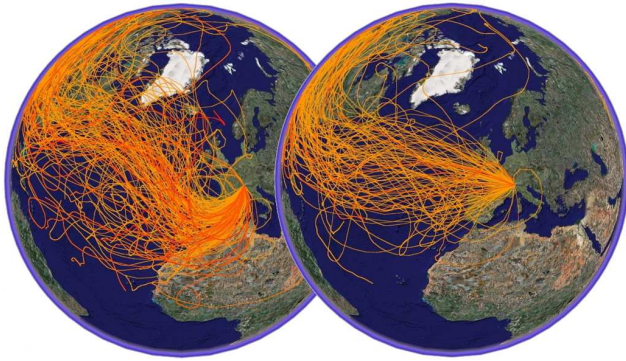


Fig. 5. Isobaric back trajectories at 500 hPa of the days with precipitation above 50 mm (left) at the Binn and (right) the Marécottes station (source: GoogleEarth).

Grazzini (2007) states that “since the incident airflow is mostly controlled by the large-scale pressure gradient we assume that strong southerly flow conditions can be broadly described in terms of the 500 hPa height field”. He calculated a reference pattern and its associated anomaly for the most intense events on Alpine southern slopes and the Rhône catchment by averaging the 500 hPa height fields. It revealed the elongated meridional trough and a sharp pressure gradient on its east side.

These troughs may result from amplification of Rossby waves (Grazzini, 2007; Martius et al., 2008), and thus are generated by an evolving system that finds its origin at remote locations. The wave-packet at high levels is propagating from the Pacific region for autumn and winter cases, and can be traced back to approximately 1 week ahead (Grazzini, 2007; Martius et al., 2008). The onset of strong southerly flow is more predictable than its decay (Grazzini, 2007). This may be due to satisfactory modelling of the strong dynamical forcing associated with Rossby-wave propagation (Grazzini, 2007), while the dissipation stage characterized by wave-breaking phenomena and local processes does imply the less robust physical part of the model.

Plaut et al. (2001) worked on clustering large-scale circulation patterns of many heavy precipitation days ($\geq 50 \text{ mm d}^{-1}$) for different sub-regions. Two of the three clusters he obtained for Ticino and the eastern part of the Rhône catchment are coherent with the circulation we observed. These are composed of anomalies on the 700 hPa level that reveal the location of the troughs, around which air masses flow. However, we won't go into details, as Martius et al. (2006) showed that Ticino and the eastern Rhône catchment present some differences in the location and the orientation of their associated streamers. High precipitation days coincide only in about 50 % of the cases for the eastern Rhône catchment, Ticino and Grisons, and are exclusively in one of the three regions otherwise.

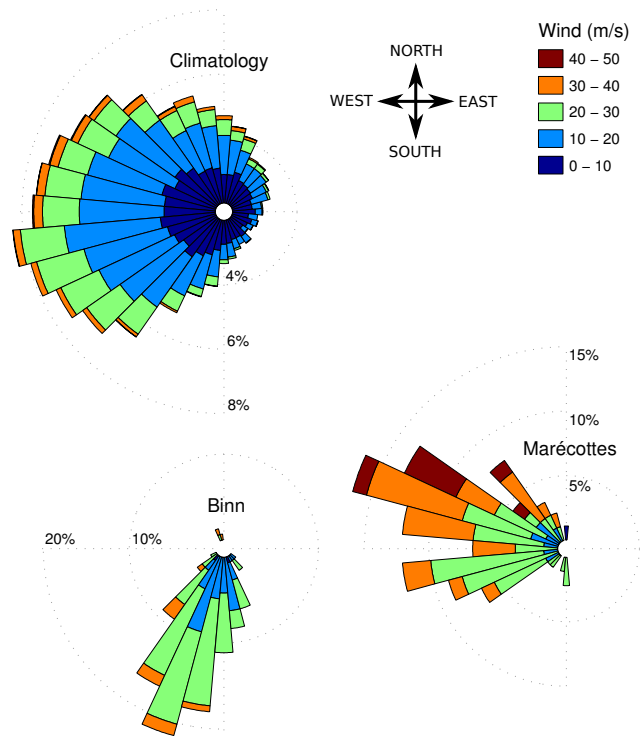


Fig. 6. Wind roses made with the NCEP/NCAR reanalysis dataset at the central point of the catchment on the 500 hPa level; wind roses of the climatology and of the days with precipitation above 50 mm at the Binn and Marécottes stations.

A strong southerly flow seems to be necessary for extreme precipitation events on Alpine southern slopes, but other factors also need to be taken into account, as the occurrence of this flow is greater than that of extreme precipitation (Martius et al., 2006; Grazzini, 2007). Streamers are frequent over Western Europe and heavy precipitation is not always observed (Martius et al., 2006).

The back trajectories of air masses (Sect. 2.5) at 500 hPa for the days with more than 50 mm of precipitation at the Binn station (Fig. 5 left) show a clear tendency that diverges from the climatology characterized by the zonal flow (Horton et al., 2009). Their atmospheric circulation has a strong southerly component close to the station, which is consistent with the presence of the trough previously described. While such circulations were observed only for a part of large sample of events in previous studies, it appears here to be almost a constant rule for daily precipitation amounts $\geq 50 \text{ mm}$ at the Binn station. We found indeed that of over 152 days with precipitation above 50 mm at the Binn station, only 3 (in late November and December) did not show a trajectory with a southerly flow, meaning that such a circulation was present for 98 % of the events.

Another illustration of this same information is the wind rose for Binn (Fig. 6 left). The wind roses were also established on the NCEP/NCAR reanalysis dataset at the central

point of the catchment. We can see that the days with strong precipitation at the Binn station have an important southerly flow at 500 hPa that diverges from the average climatology. It is information that exists in the reanalysis dataset and that can be useful in a downscaling approach.

Doing the same for the Marécottes station, we can see on the back trajectories (Fig. 5 right) and the wind rose (Fig. 6) that the west component is dominating. This corresponds to the westerlies, and thus makes the direction information relatively useless to discriminate the critical situations. However, the wind intensity is much more important than the average climatology, and thus represents a discrimination potential in a downscaling model.

When we compare the back trajectories for severe rainfall events and the relevance maps at 500 hPa, processed on the whole series, the similarities are obvious. For Binn, the relevance map shows the curvy circulation patterns characterizing the southerly flow that produces heavy precipitation at the station. The same analysis can be made on the Marécottes station, with a prevailing west circulation during heavy precipitation events.

These analyses confirm that the most relevant data for the analogue method can be found where specific atmospheric circulation patterns appear concomitantly with heavy precipitation events.

5 Conclusions

The analysis of the back trajectories and the wind roses reveals first that the reanalysis dataset contains valuable information for a statistical downscaling method despite of its resolution (2.5°). It also reveals that the atmospheric circulation diverges from the average climatology during heavy precipitation events and that a strong recurrence of the conditions is visible for those days. We have found that of over 152 days with heavy precipitation at the Binn station, only 3 do not show a trajectory of a southerly flow. This reveals a strong precursor that can be used in an adaptation method such as the analogue method.

Events in the Binn region require a special configuration of the circulation at the global scale to produce heavy precipitation for several days (Buzzi et al., 1998). Complex local phenomena such as topographic enhancement, convection or moisture fluxes have an influence over the precipitation amount, but large-scale flow is equally important in producing the necessary conditions (Grazzini, 2007). The analogue method aims at bypassing these local phenomena by using the global circulation information to forecast local precipitation. The basis for such an approach is the presumption that most of the effects of the local processes are already embedded in the precipitation series.

The relevance maps established for the analogue method calibration at two locations in the alpine Rhône catchment show a good coherence with known atmospheric circulation

characteristics. More specifically, the most relevant data for the analogue method are located where the atmospheric circulation is dominant during heavy precipitation events (Horton et al., 2010, 2011). As one can see in Fig. 4, the most skilled areas do not include the troughs or lows, but the resulting flow. This is a consequence of the S1 criteria we use, which is a comparison of the gradient. As far as the authors know, this is the first analysis that sets in perspective the relevance maps and climatology.

The time evolution of the relevance maps confirms that the atmospheric variables have significantly better forecasting skills close to the precipitation period, and that it seems pointless for the analogue method to consider circulation information days before the predictand as a primary predictor. Even though the occurrence of a southerly flow can be detected by precursors at remote locations and one week ahead (Grazzini, 2007; Martius et al., 2008), time extrapolation by the analogue method seems to be rather poor. This may be easily explained by the fact that two similar synoptic situations at a given time are unlikely to evolve analogously over several days, and that other analogous situations will become more relevant. This would suggest that time extrapolation should be done by the GCM and not by the adaptation method. This is consistent with previous studies (Obled et al., 2002; Bontron and Obled, 2005; Marty et al., 2012), as they consider circulation predictors at the day of the precipitation.

Plaut et al. (2001) states that “the presently available operational models provide more accurate forecasts of air mass circulation than of precipitation, especially over mountainous areas”. This is also true for specific conditions leading to heavy precipitation events. Grazzini (2007) demonstrated that the GCM of the European Centre for Medium-Range Weather Forecast (ECMWF) performs even better under the specific conditions linked with high precipitation events in the Alpine region than the average conditions. The assertion that synoptic circulations conducive to major events have a superior predictive skill does not imply that precipitation is also more predictable by numerical weather prediction models (Fehlmann and Quadri, 2000; Grazzini, 2007). This is where a statistical approach becomes very interesting: trying to link the well-forecasted atmospheric circulation with local precipitation without the use of complex and error-prone physical processes modelling and parametrizations.

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