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Analysis of mountain-valley precipitation differences in the Alps

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Abstract

This paper investigates altitudinal precipitation differences in the northern Alps, based on routine observations and simulations with the MM5 model for the time period between 1991 and 2000. The analysis is performed for four station pairs, consisting of a mountain station and a nearby valley station each. The results are discussed for three different temperature levels (snow line > 2500 m, 1000 m–2500 m and < 1000 m). The climatological precipitation distribution shows that the mountain stations usually receive substantially more precipitation than the valley stations, especially for northwesterly and northerly ambient flow in 700 hPa. However, the differences are regionally variable and indicate a strong influence of the local topography. Moreover, precipitation enhancement over mountains tends to be substantially more effective for low temperatures than for high temperatures. A more detailed investigation of some parameters affecting orographic precipitation enhancement is conducted for stratiform precipitation events. We find that the magnitude of orographic precipitation enhancement markedly increases with the wind speed at 700 hPa. Moreover, precipitation enhancement increases with the depth of the moist layer in the approaching airflow.

Zusammenfassung

In diesem Paper werden Höhendifferenzen des Niederschlags in den Nordalpen untersucht. Die Studie basiert auf Wetterdaten von Beobachtungsstationen und Simulationen mit dem MM5 Modell für den Zeitraum zwischen 1991 und 2000. An Hand von vier Stationspaaren (jeweils bestehend aus einer Bergstation und einer nahegelegenen Talstation) wurde die orographische Niederschlagsverstärkung untersucht. Ferner wurde eine Unterteilung in drei verschiedene Temperaturniveaus (Schneefallgrenze > 2500 m, 1000 m–2500 m und < 1000 m) durchgeführt. Die klimatologische Niederschlagsverteilung zeigt, dass die Bergstationen üblicherweise mehr Niederschlag erhalten als die Talstationen. Die Differenz ist bei einer Nordwest- bzw. Nordanströmung in 700 hPa am größten. Es gibt jedoch sehr große regionale Unterschiede, die teilweise auf lokale topographische Effekte zurückzuführen sind. Zudem zeigt sich, dass die orographische Niederschlagsverstärkung bei niedrigen Temperaturen viel ausgeprägter ist als bei hohen Temperaturen. Für nichtkonvektive Niederschlagsereignisse wurde eine nähere Analyse einiger Parameter mit großem Einfluss auf die orographische Niederschlagsverstärkung durchgeführt. Es ergibt sich zum einen eine deutliche Zunahme der orographischen Niederschlagsverstärkung mit der 700-hPa Windgeschwindigkeit. Zum anderen nimmt die Niederschlagsverstärkung mit der Mächtigkeit der feuchten Schicht der anströmenden Luftmasse zu.

1 Introduction

Monitoring and analysis of precipitation have always been a central issue of mountain meteorology and climatology. First studies of the spatial distribution of precipitation in the Alps were made in the early 20th century (e.g. KNOCH and REICHEL, 1930). Since then many precipitation climatologies (e.g. FLIRI, 1975; FREI and SCHÄR, 1998; SCHWARB et al., 2001) were compiled to analyse the Alpine precipitation patterns. Such climatologies show that there is a high spatial and seasonal variability of precipitation in mountainous terrains like the Alps, because topography strongly influences the generation of precipitation. On the scale of the whole Alpine massif, there is a general precipitation decrease from the northern and southern Alpine rim towards the central Alps. On a smaller scale, there is often a strong correlation between precipitation amounts and orographic height (ERK, 1887; BLUMER, 1994). The differences between mountain stations and valley stations can be very large in terms of mean annual precipitation. For example, Garmisch (720 m ASL), located in the Loisach valley in the Bavarian Alps, has a mean annual precipitation amount of about 1440 mm (1991–2000), whereas the nearby mountain station Zugspitze (2960 m ASL) receives around 2090 mm/yr. However, it has to be stressed that the related height gradients may be regionally different (e.g. SCHÜEPP et al., 1978; SCHWARB, 2001). Moreover, altitudinal precipitation gradients may be misleading when the underlying stations do not only have different heights but also a significant horizontal distance from each other. The horizontal and vertical gradients can then not be separated in an unambiguous way. Moreover, the accuracy of precipitation data on mountain stations is lower because of the

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higher wind speeds and the higher fraction of solid precipitation, leading to higher drifting and thus to a general underestimation of precipitation amounts at the top of mountains.

So far, many studies have been conducted to investigate various orographic precipitation processes, such as orographic lifting, the seeder-feeder mechanism, or orographically induced convection (e.g. SMITH and BARSTAD, 2004; CARRUTHERS and CHOULARTON, 1983; KIRSHBAUM and DURRAN, 2005). There is also a large number of real-case studies of heavy precipitation events (BUZZI, et al.,1998; ASENCIO et al., 2003; ZÄNGL, 2007a,b), considering the synoptic circumstances and smaller-scale dynamical and microphysical processes leading to such extreme events. However, very little research has yet been done to analyse climatological mountain-valley precipitation differences with respect to the environmental conditions. Closing this gap will be the main goal of the present work, building on analysis techniques developed and validated in a recent study by WASTL and ZÄNGL (2007), in which the climatological precipitation gradient between the Alpine foreland and the northern Alps was investigated. As the number of suitable mountain gauge sites is small, this study will concentrate on a few mountain stations that can be compared with a nearby station in the valley. The stations selected for this investigation are required to have a large height difference but a small horizontal distance. The mountain-valley precipitation differences are examined as a function of temperature and wind direction, with additional consideration of wind speed and the vertical moisture profile for one selected station pair.

The paper is outlined as follows: The database and the methodology of the analysis are described in section 2. Section 3 provides information on the precipitation climatology of the stations under investigation, followed by a specific analysis of the parameters affecting orographic precipitation enhancement. The main findings of this work are summarised in section 4.

2 Model and precipitation data

Our climatological analysis is based on operational weather stations of Bavaria and western Austria. The data cover the time period of 1991–2000 and were provided by the DWD (Deutscher Wetterdienst), the ZAMG (Zentralanstalt für Meteorologie und Geodynamik) and the HZB (Hydrographisches Zentralbüro Österreich). The data set includes a number of mountain stations, the highest of which reach altitudes of about 3000 m ASL (Sonnblick 3105 m, Zugspitze 2960 m). Following a procedure described in WASTL and ZÄNGL (2007, hereafter WZ07), the precipitation data were brought to a common temporal resolution of 6 hours, which involved splitting the precipitation accumulations from climate stations and daily raingauge stations with the aid of the temporally higher-resolved SYNOP stations.

The second data source used for this investigation are climate-mode simulations conducted with the Penn State University – National Center for Atmospheric Research mesoscale model MM5 (GRELL et al., 1995), providing information about the environmental meteorological conditions for each 6-hour interval. The model was run on a single domain with a mesh size of 45 km, covering an area of about 3000$\times$3500 km centred in the western Alps. The simulations extend over the time period of 1991–2000 and were driven with ERA-40 reanalysis data, using continuous analysis nudging except for an area of about 1500$\times$1500 km centred in the Alpine region in order to keep the simulated evolution of the meteorological fields close to the true one. The simulations thus constitute a moderate downscaling of the ERA-40 data set with the purpose of improving the interactions between the large-scale flow and the Alpine orography. They have undergone an extensive optimisation and validation procedure and show a fairly realistic precipitation climatology (see WZ07 for more details). The synoptic conditions during each 6-hour interval are determined from three-hourly model output data using weighted averages. For example, values representing the 00–06 UTC interval are averaged from 00 UTC data (weighting 25%), 03 UTC data (50%) and 06 UTC data (25%). As in WZ07, we also take a spatial average over 2$\times$3 surrounding MM5 grid points for most variables. This is mainly motivated by reducing grid-point effects for the surface variables entering into the WZ07 precipitation type classification scheme (primarily CAPE and convective precipitation), which is used here to detect convectively dominated precipitation events. For free-atmosphere fields, we note that the spatial averaging has little impact because the advection distance within a six-hour interval is usually larger than the area covered by six MM5 grid points. A different averaging is used for moisture, for which three grid points in the Alpine foreland are taken because our analysis of the moist layer depth (see below) requires upstream moisture profiles that are unaffected by Alpine lifting. Moreover, wind direction is taken from the closest MM5 grid point only because the temporal wind shift between the beginning and the end of a 6-h interval (which would be smoothed out by spatial averaging) also enters into the above-mentioned classification scheme. For our following analysis, we focus on wind speed and direction at 700 hPa and the relative humidity at 850, 775, 700 and 600 hPa.

Since the main goal of this investigation is to analyse altitudinal precipitation differences, pairs of stations have to be chosen. We require a height difference between the mountain and valley stations of at least 1000 m but a small horizontal distance in or-

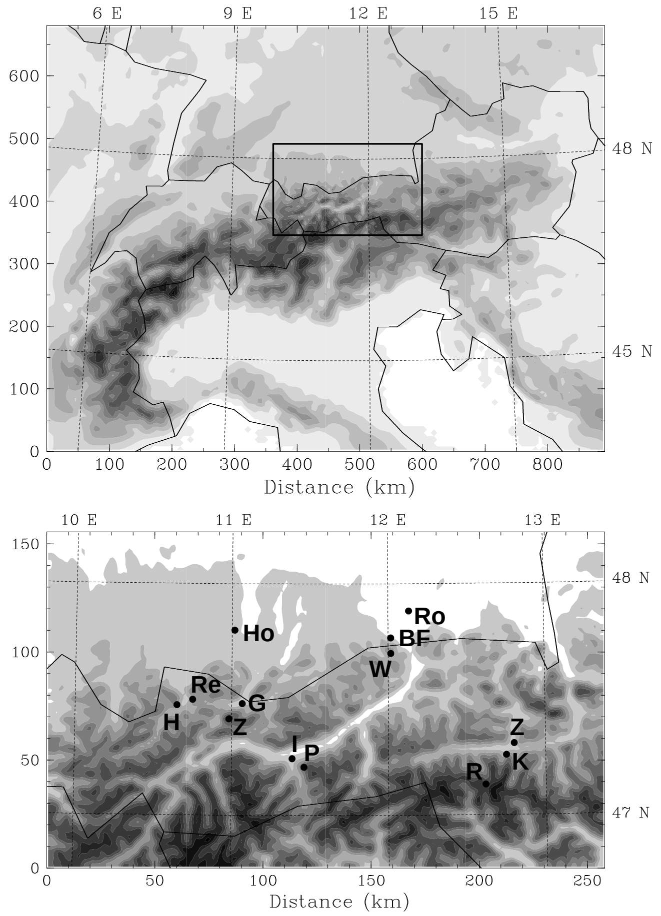

Figure 1: Location of the stations selected for the investigation. The box in (a) indicates the location of the study area (b). Each station pair consists of a mountain and a nearby valley station. The station names and altitudes are: Hahnenkamm (H, 1670 m), Reutte (Re, 870 m), Hohenpeissenberg (Ho, 977 m), Zugspitze (Z, 2960 m), Garmisch (G, 720m), Innsbruck (I, 578 m), Patscherkofel (P, 2247 m), Wendelstein (W, 1832 m), Bad Feilnbach (BF, 530 m), Rosenheim (Ro, 444 m), Zell am See (Z, 766 m), Kaprun (K, 750 m), Rudolfshütte (R, 2304 m). Shading indicates topography with an increment of 300 m, starting at sea level in (a) and at 600 m in (b).

der to avoid contamination by horizontal precipitation gradients. Moreover, we require that the valley station is not in the immediate lee of the considered mountain ridge (with respect to the prevailing wind directions) because hydrometeor drifting often extends the local orographic precipitation enhancement to such stations (e.g. ZÄNGL, 2007a). Furthermore it is important that the stations have a continuous data set over the decade. In the considered part of the Alps, there are about 15 suitable peak stations. From those we selected two station pairs in the northern Alps (Garmisch/Zugspitze and Bad Feilnbach/Wendelstein; see Fig. 1) and two in the central Alps (Innsbruck/Patscherkofel and Kaprun/Rudolfshütte), but the majority of the subsequent discussion will focus on the precipitation differences between Garmisch and the Zugspitze. The analysis of the precipitation differences starts with arranging the data according to the 700-hPa wind direction, using an interval width of 20°. The 700-hPa level is chosen because it is the lowest standard pressure level that is essentially unaffected by Alpine flow deflection, roughly corresponding to the mean Alpine crest level (3000 m). In addition, the data are subdivided into three temperature intervals using the available temperature observations. The three temperature intervals are defined by a snow line of $>$2500 m, 2500 m–1000 m and $<$1000 m, with the snow line being approximated by a temperature of +1°C. The choice of these classes was motivated by the station pair Garmisch-Zugspitze (which is investigated in most detail in this study) in order to distinguish between a snow line near or above peak level (2960 m), near or below valley level (720 m), and intermediate cases. The snow line classes are henceforth abbreviated as SL1 ($>$2500 m), SL2 (2500 m–1000 m) and SL3 ($<$1000 m). Because the available stations are usually not located at exactly these levels, a vertical temperature gradient of -0.65 K/100 m is assumed to estimate the required temperatures. This is justifiable because the vertical temperature gradient during precipitation intervals is usually close to moist adiabatic. As temperature is available only for SYNOP and climate stations, it is necessary for some stations to adopt the temperature values from nearby climate or SYNOP stations. This is the case for the stations Bad Feilnbach and Kaprun, where the temperature values are taken from the nearby stations Rosenheim and Zell am See (see Fig. 1). Moreover, for the station pair Garmisch/Zugspitze, the 1000-m temperature is taken from the station Hohenpeißenberg, which is located at 990 m ASL on an isolated hill 30 km farther north. This turned out to improve the consistency with the 1000-m temperatures derived from the other valley stations because Garmisch is frequently affected by shallow cold-air pools during wintertime warm-front passages. The detailed investigation of precipitation enhancement comprises a subdivision into four different classes of 700-hPa wind speeds. The thresholds of 7.5, 12.5 and 17.5 ms^{-1} are chosen such that the total number of precipitation events in the four wind speed classes is about the same. For the analysis of the influence of the vertical moisture profile on orographic precipitation enhancement, the relative humidity of the pressure levels between 850 hPa and 600 hPa is regarded. As already mentioned, relative humidity is taken from grid points in the Alpine foreland to exclude the effects of Alpine lifting.

3 Results and discussion

We start with considering the precipitation climatology of the four valley stations and the differences with respect to the nearby mountain stations. The precipitation climatology will be discussed depending on the

700-hPa wind direction and the above-mentioned snow line classes. Afterwards, the more detailed investigation of the main factors affecting orographic precipitation enhancement will be conducted for the station pair Garmisch/Zugspitze.

3.1 Precipitation climatology

The first station pair considered here is Garmisch/Zugspitze (see Fig. 1). Garmisch is located in the Loisach Valley in the northern Alps at an altitude of 720 m ASL, and the Zugspitze mountain station is located about 10 km southwest at 2960 m. The mean annual precipitation (1991–2000) is about 1440 mm for Garmisch and 2090 mm for the Zugspitze. The climatological precipitation distribution as a function of the 700-hPa wind direction and the snow line class (as defined above) is displayed in Fig. 2a for Garmisch. The precipitation distribution exhibits a broad peak between 240° and 300°, reaching about 200 mm/yr per 20° wind interval. This is partly related to the high climatological frequency of westerly and northwesterly winds in midlatitudes (see WZ07 for the corresponding frequency distribution of wind directions), but Alpine precipitation enhancement is also important for wind directions with a significant northerly component. Away from the peak, precipitation decreases more rapidly towards southerly than towards northerly directions, but there are still substantial precipitation amounts occurring at southwesterly directions. The latter are dominated by summertime convection, as suggested by the large fraction falling into the highest snow line class (SL1). In fact, the algorithm developed by WZ07 to distinguish between different precipitation types indicates a convective fraction of about 75% (not shown). On the other hand, precipitation at northwesterly and northerly directions primarily falls into SL2 and SL3 because northerly winds tend to be associated with cold air masses and therefore with snow lines below 2500 m except sometimes in summer. Summing up over all wind directions, SL1 and SL2 each contribute about 40% to annual precipitation, whereas about 20% fall at snow lines below 1000 m (SL3). The latter is partly because of a smaller number of precipitation events and partly because the precipitation intensity tends to be smaller at low temperatures.

Fig. 2b depicts the climatological precipitation difference between Zugspitze and Garmisch. It differs substantially from the climatology at Garmisch, both with respect to temperature and with respect to wind direction. Positive differences (i.e. higher precipitation at the mountain station) are almost entirely restricted to SL2 and SL3, whereas the differences occurring in SL1 are either negative or negligible. Moreover, significant positive differences are restricted to wind directions between west and northeast, whereas negative differences prevail at southwesterly winds. Also, the largest differences occur at more northerly directions than the climatological maximum at Garmisch, reaching values between 140 and 190 mm/yr per 20° interval for wind directions between 300° and 340°. The latter feature mainly reflects the fact that precipitation enhancement due to orographic lifting is most effective when the approaching flow is approximately normal to the mountain barrier. On the other hand, the negative differences in the SL1 class are more difficult to interpret, and further investigation is needed before final conclusions can be drawn. For southwesterly flow, the large fraction of convective precipitation (75% for Garmisch, 70% for the difference) suggests that the specific location of the Zugspitze near the western edge of the Wetterstein massif might play a role. The Wetterstein massif is known to be a preferred location for convective initiation (M. Hornsteiner, personal communication), but newly triggered convection cells need some time to reach their mature stage and so might have already passed the Zugspitze before producing intense precipitation. On the other hand, southwesterly winds advect the convection cells towards Garmisch while growing in intensity, so that Garmisch receives particularly much convective precipitation. This is supported by a comparison with other valley stations in the vicinity of Garmisch, which tend to have less precipitation at southwesterly ambient winds unless they are also located northeast of the Wetterstein massif (not shown). It is also interesting to note that a similar feature could be found for the station pair Reutte/Hahnenkamm (see Fig. 1), where the mountain station again receives substantially less precipitation than the valley station for southwesterly flow while positive differences prevail otherwise. However, a different explanation appears to be needed for westerly and northwesterly ambient flow because the convection cells then will not be advected towards Garmisch. Moreover, the WZ07 algorithm indicates a smaller fraction of convective precipitation for these wind directions. A plausible hypothesis may be based on high-resolution numerical simulations conducted by ZÄNGL (2007b) for two heavy-precipitation cases, which indicate a relative precipitation minimum at mountain crests or peaks when the melting layer is close to or slightly below the crest level. This is because the fall-speed difference between snow and rain induces divergent hydrometeor trajectories where the windward slope of a mountain intersects the melting layer, causing a reduced precipitation intensity that is then advected towards the crest line. However, a detailed investigation of this issue will be reserved for a subsequent study. It is finally mentioned that possible measurement errors due to wind-related undercatch cannot explain the negative differences in the SL1 class because the undercatch is smaller for rain than for snow and thus would induce a

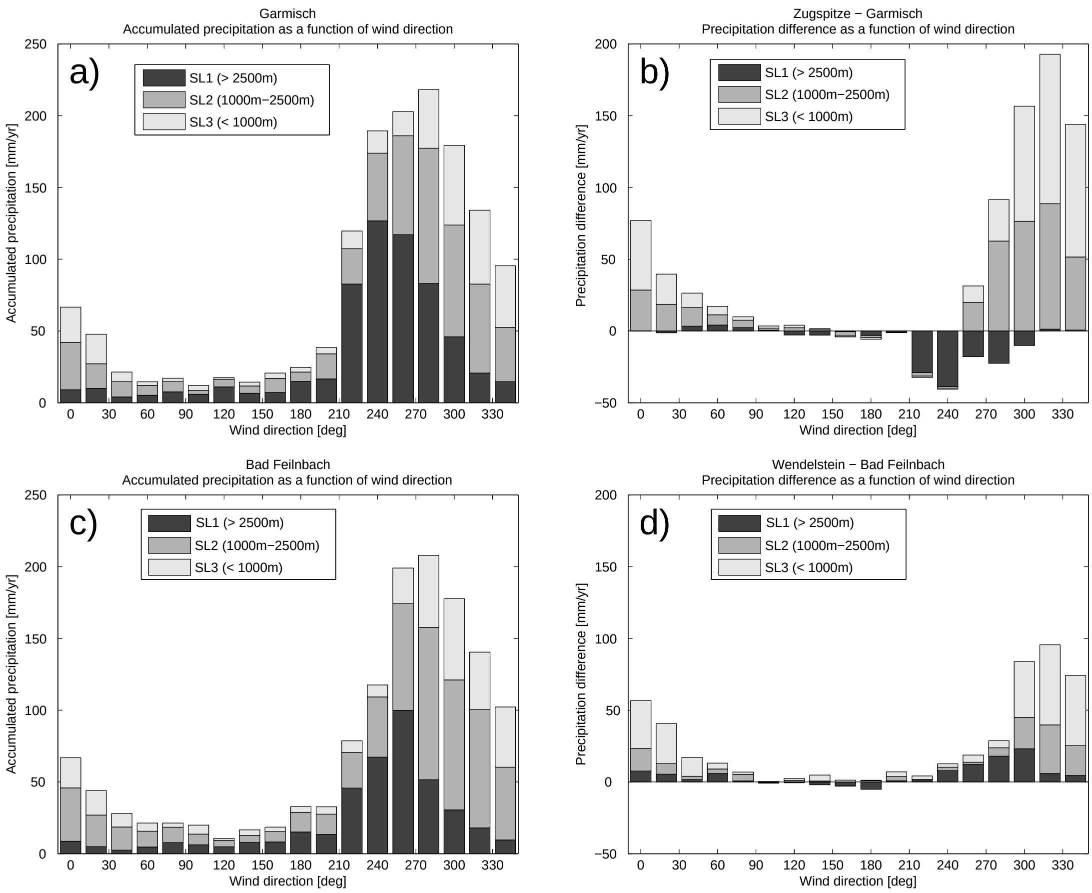

Figure 2: Accumulated annual precipitation (mm/yr) as a function of wind direction and snow line class for Garmisch (a) and differences between the Zugspitze and Garmisch (b). The lower panels show the same fields for the station pair Bad Feilnbach/Wendelstein.

signal with opposite sign. Moreover, strong winds are much less frequent in summer than in winter, which further reduces the probability of summertime undercatch.

Another station pair that is interesting to consider lies about 100 km farther east. The Wendelstein mountain (1830 m ASL) is a rather isolated peak at the northern Alpine rim, and the related valley station Bad Feilnbach (530 m ASL) is located a few kilometres farther north at the foot of the Wendelstein (see Fig. 1). The mean annual precipitation (1991–2000) is 1795 mm at the Wendelstein and 1340 mm in Bad Feilnbach. The smaller annual difference compared to Garmisch/Zugspitze might be partly related to the lower elevation of the Wendelstein, but the mountain shape might also play a role: while the Zugspitze is part of an elongated east-west oriented mountain ridge, the Wendelstein is a rather isolated peak that might be less favourable for strong precipitation enhancement. The precipitation climatology for Bad Feilnbach (Fig. 2c) shows a similar wind-direction dependence as for Garmisch except for southwesterly directions where Bad Feilnbach receives substantially less precipitation. Moreover, the fraction of precipitation falling into the SL1 class is significantly smaller. This implies that summertime convection is less than at Garmisch, suggesting that the mountains southwest of Bad Feilnbach are not as efficient in triggering convection.

This is supported by the differences between Wendelstein and Bad Feilnbach (Fig. 2d), showing positive values for nearly all wind directions including southwest. The largest precipitation enhancement is again found for northerly and northwesterly winds, for which orographic lifting is most effective, whereas negligible differences occur at easterly and southerly directions. Consistent with the smaller differences in annual precipitation, the maximum differences per 20° wind interval are considerably smaller than for Garmisch/Zugspitze (Fig. 2b). Regarding the distribution among the snow line classes, a notable difference with respect to Garmisch/Zugspitze is that even the warmest class SL1 exhibits mostly positive differences. This is partly a consequence of the above-mentioned differences in convective initiation, and it is pointed out that cells triggered over the Wendelstein do not reach Bad Feilnbach for southwesterly ambient flow. Moreover, the possible impact of divergent hydrometeor trajectories (ZÄNGL, 2007b) would affect SL2 rather than SL1 in the case of the Wendelstein. In fact, SL2 accounts for a much

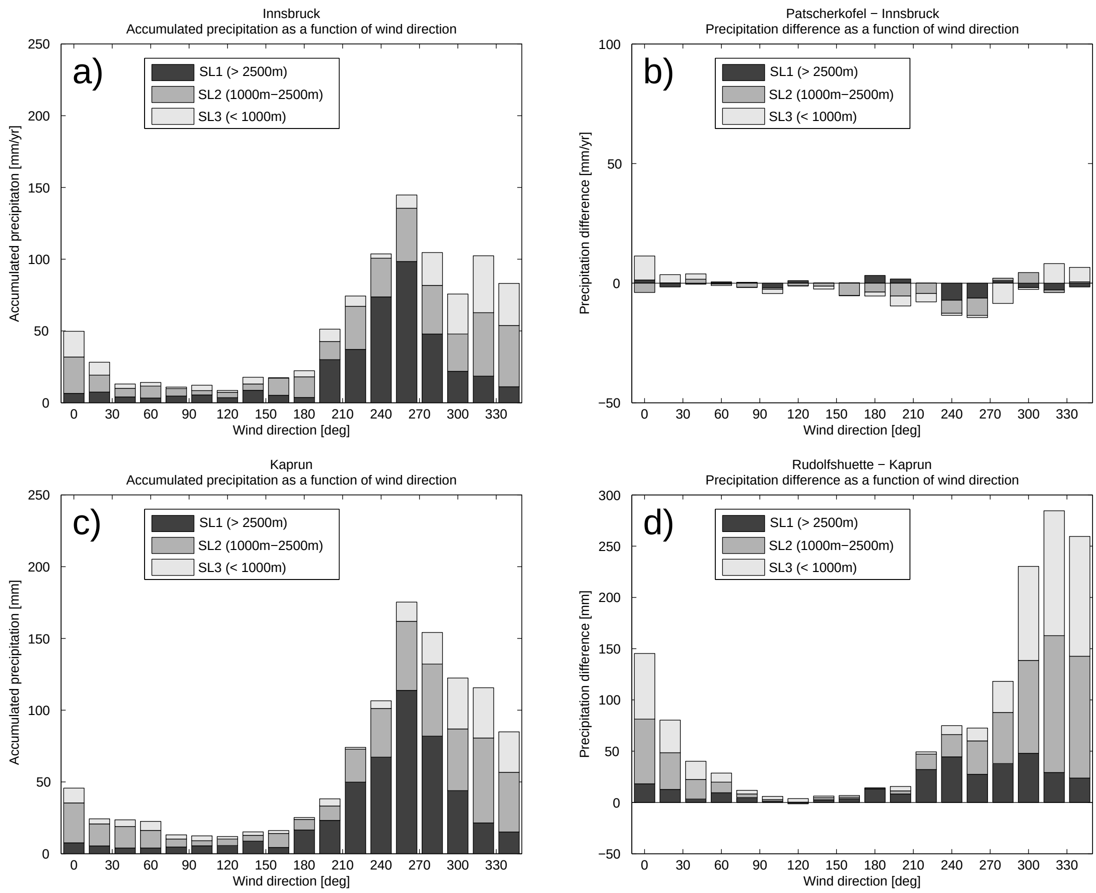

Figure 3: Accumulated annual precipitation (mm/yr) as a function of wind direction and snow line class for Innsbruck (a) and differences between the Patscherkofel and Innsbruck. The lower panels show the same fields for the station pair Kaprun/Rudolfshütte. Note that the scale of the *y*-axis is different in (b) and (d).

smaller fraction of the total precipitation difference than for Garmisch/Zugspitze, whereas the fraction of SL3 is comparable to that seen in Fig. 2b.

The station pair Innsbruck/Patscherkofel (Fig. 3a,b) is a kind of counter-example, showing that the annual precipitation amount is not necessarily correlated with orography height. Innsbruck (580 m ASL) is located in the central Alpine Inn Valley, and the nearby mountain station Patscherkofel (2250 m ASL) is located a few kilometres southeast of Innsbruck. The annual precipitation (1991–2000) is 920 mm for Innsbruck and 900 mm for the Patscherkofel, much less than for the north-Alpine stations considered so far. The precipitation climatology for Innsbruck (Fig. 3a) reveals a significantly larger fraction of summertime precipitation (snow line class SL1) than for the north-Alpine stations. Together with the dominance of southwesterly directions (260° and 240°), this suggests that summertime convection makes a large contribution to the climatological precipitation at Innsbruck. This is confirmed by the precipitation type classification developed by WZ07 (not shown). For northwesterly and northerly ambient flow, rain-shadowing from the north-Alpine mountain ridges leads to comparatively small precipitation amounts. The difference plot (Fig. 3b) shows very small values for any wind direction (even though the scale of the *y*-axis has been enlarged), indicating that there are no significant climatological precipitation differences between Innsbruck and the Patscherkofel despite an elevation difference of almost 1700 m. It needs to be mentioned, however, that substantially higher precipitation amounts ($\sim$ 1500 mm/yr) are recorded a few kilometres farther south towards the Alpine crest (Fliri, 1975). This suggests that the specific location of the Patscherkofel at the foremost edge of the Tuxer Alps is particularly unfavourable for orographic precipitation enhancement, probably because precipitation growth in orographic clouds over the Patscherkofel takes too long to reach the ground at the exposed mountain peak. It might also play a role in this context that lee effects from the northern Alps and subsidence over the Inn Valley typically tend to raise the cloud base at the Patscherkofel ridge, so that precipitation growth only becomes effective farther south where the topography is even higher.

Finally, the stations Kaprun (750 m ASL) and Rudolfshütte (2310 m ASL) are considered, which are located at the northern slope of the Alpine crest. Unlike the other mountain stations, the Rudolfshütte is not located at a peak but rather in an elevated valley at the northwestern slope of the Großglockner massif, which holds the highest peak of the eastern Alps. Nevertheless, the Rudolfshütte receives extraordinarily much precipitation (2546 mm in the 1991–2000 period), whereas Kaprun (1080 mm) is quite representative for the surrounding valley stations. The specific topographic location of the Rudolfshütte suggests several reasons for the outstanding precipitation amounts recorded there, significantly exceeding those of the surrounding mountain stations (FLIRI, 1975). First, the valley in which the station is located converges toward the south, which enforces particularly strong orographic lifting for northwesterly and northerly ambient flow. Moreover, orographic lifting above the adjacent Großglockner massif certainly also affects the Rudolfshütte station. On a larger scale, the mountain ridges of the northern Alps are not as high (except for some isolated peaks) as farther in the west and thus induce less rain-shadowing, whereas the east-west-oriented Alpine crest line in this region (the Hohe Tauern) is more conducive to strong orographic lifting than the central Alps in western Austria.

The precipitation climatology for Kaprun (Fig. 3c) has a similar characteristic as that for Innsbruck, except for generally higher amounts reflecting the larger annual precipitation. The fraction of precipitation falling in the warmest class (SL1) is even slightly higher than for Innsbruck and again dominated by convective precipitation (not shown), indicating that convective systems forming over the Alpine crest frequently reach Kaprun. The difference field (Fig. 3d) reveals that the Rudolfshütte generally receives more precipitation than Kaprun, and it is noted that the scale of the *y*-axis had to be changed because the differences reach up to 280 mm/yr per 20° wind interval. Compared to the Garmisch/Zugspitze station pair, the peak of orographic precipitation enhancement is shifted slightly more towards northerly winds. The majority of the precipitation difference again occurs at cold and medium temperatures (SL2 and SL3), but unlike the Zugspitze, differences are exclusively positive in the SL1 class. The latter is partly because convective initiation in prefrontal southwesterly flow usually takes place over the Alpine crest line south of the Rudolfshütte, so that the cells already produce substantial precipitation at the raingauge station. For northerly wind directions and a snow line close to the station height, the above argument of diverging hydrometeor trajectories does not seem to apply here because the station is not located at a mountain peak and usually has fairly low surface winds under northerly flow conditions. However, this requires further investigation before final conclusions can be drawn.

3.2 Dependence of orographic precipitation enhancement on environmental conditions

To further examine the environmental factors affecting orographic precipitation enhancement, we focus on the station pair Garmisch/Zugspitze because of its large precipitation differences and its suitable location near the northern edge of the Alps. The analysis is restricted to nonconvective precipitation events (as detected by the algorithm developed by WZ07) because convective precipitation has a different spatial variability than stable precipitation with less systematic mountain-valley differences. Moreover, we only consider the snow line classes SL2 and SL3, and wind directions between 260° and 40° because there is no significant precipitation enhancement due to stable lifting at other directions. Besides accumulated precipitation differences per year, the subsequent figures also depict normalised differences, defined as the average precipitation difference per 6-hour interval. The normalised differences have been computed by dividing the accumulated difference by the number of events, but it has to be noted that marginal events have been excluded from the computation of normalised differences. Specifically, the precipitation rate is required to be at least 0.25 mm/6h in Garmisch and at the Zugspitze, or at least 1.0 mm/6h at the Zugspitze. Note also that the ratio between accumulated and normalised differences indicates the frequency of events per year. Results are displayed only if at least 5 events fall into a certain interval of wind direction, snow line and wind speed / moist layer depth within the ten-year period of investigation.

3.2.1 Wind speed at 700-hPa

The first parameter that is expected to have an important influence on the altitudinal precipitation increase is the ambient wind speed. As the condensation rate associated with unblocked flow of saturated air over a mountain is proportional to the wind speed, one expects a systematic increase of orographic precipitation enhancement with wind speed. For our investigation, the wind speed is taken at the 700-hPa level as for wind direction. Results are shown in Fig. 4 for the snow line classes SL2 (upper panels) and SL3 (lower panels) and four wind-speed intervals separated by 700-hPa wind speeds of 7.5, 12.5 and 17.5 $\mathrm{m\,s^{-1}}$. These intervals will be denoted as WS1 ($< 7.5\ \mathrm{m\,s^{-1}}$) – WS4 ($> 17.5\ \mathrm{m\,s^{-1}}$) in the following. The criterion for selecting the thresholds was to obtain classes with approximately the same number of 6-hour intervals with nonzero precipitation. The accumulated differences (Fig. 4a,c) confirm the basic wind-direction dependence from Fig. 2b, showing that the majority of precipitation enhancement occurs at 700-hPa directions between 280° and 340° for SL2 and between

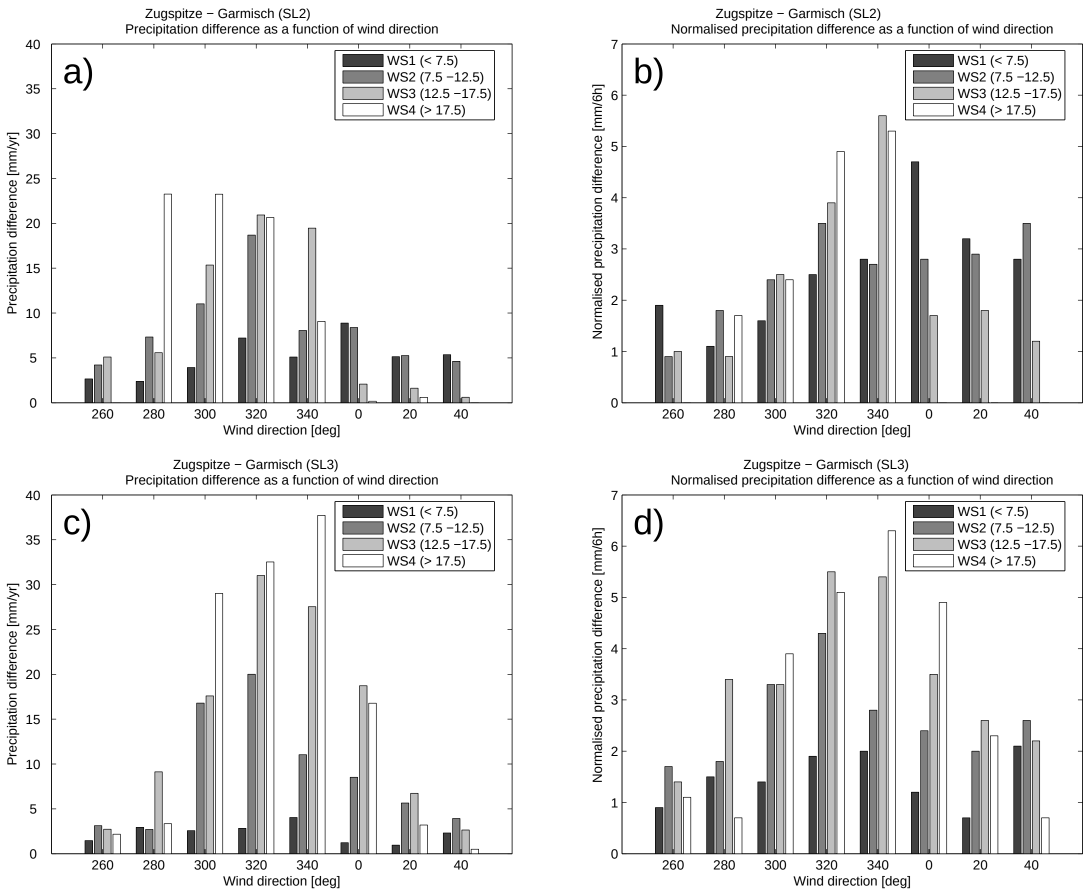

Figure 4: Left panels: Accumulated precipitation differences (mm/yr) between the Zugspitze and Garmisch as a function of wind direction and wind speed at 700 hPa for snow line classes SL2 (a) and SL3 (c). Right panels: Corresponding normalised precipitation differences (mm/6h).

300° and 0° for SL3. Apart from that, Fig. 4a indicates that the accumulated precipitation differences in SL2 increase strongly with wind speed for westerly directions (280° and 300°), reach their maximum at intermediate wind speeds (WS3) for northwesterly directions (320° and 340°) and, somewhat surprisingly, are largest at low wind speeds for northerly and northeasterly directions. Comparison with the normalised differences in Fig. 4b reveals that part of this dependence is related to different frequencies of the wind speed intervals at various wind directions. For westerly winds, the enhancement efficiency (as measured by the normalised difference) depends little on wind speed, but strong winds are much more frequent than weak winds during periods of significant precipitation. For northwesterly winds, the enhancement efficiency is generally higher and increases notably with wind speed, but the frequency distribution is shifted towards moderate wind speeds, so the accumulated differences do not maximise in the WS4 class. However, for northerly and northeasterly winds, the normalised differences decrease with increasing wind speed as do the accumulated ones. The latter is likely affected by a representativity problem, as the WS4 class does not reach the threshold of 5 events and the WS3 class is only slightly above.

The corresponding results for the SL3 class are displayed in Fig. 4c,d. For westerly winds (260° and 280°), the accumulated differences are even lower than for SL2, and the normalised precipitation differences again do not show a clear dependence on wind speed. This appears to be related to the fact that westerly winds are not quite conducive to orographic precipitation enhancement anyway because they are parallel to the orientation of the Alps. It is also important to note that the fraction of significant precipitation events is fairly small for westerly winds. Although westerly winds in general have a higher climatological frequency than northwesterly winds (see WZ07), comparing Fig. 4c and 4d indicates a smaller number of significant precipitation events for westerly than for northwesterly winds because many westerly wind events do not reach the precipitation threshold. For northwesterly and northerly winds, however, the SL3 class provides a much clearer signal of precipitation enhancement increasing with wind speed than the SL2 class. The normalised differences show a notable increase with wind speed for directions between 300° and 20°, reaching up to 6 mm/6h at 340° in the WS4 class. The accumulated differences even amplify this signal for northwesterly winds because strong northwesterly winds are more frequent in winter than in spring or autumn. It is also interesting to note that the normalised precipitation enhancement in the WS1 class shows no clear dependence on wind direction and much lower values than for the SL2 class. This suggests that weak winds in connection with low temperatures produce too small condensation rates for an effective seeder-feeder mechanism. Summing up over all wind directions and wind speeds, the accumulated precipitation difference is only slightly higher in the SL3 class than in the SL2 class, but the dependence on wind speed is much more evident. Moreover, the relative enhancement with respect to Garmisch is larger because Garmisch receives substantially less precipitation in SL3 than in SL2 (Fig. 2a).

3.2.2 Vertical moisture profile

The next environmental parameter to be investigated is the relative humidity profile. One might intuitively expect that a deep moist layer in the approaching air allows for a stronger orographic precipitation enhancement than a shallow moist layer. To investigate the influence of the moist-layer depth in a meaningful way, it is necessary to consider the relative humidity profile at a location where the approaching airmass is not yet affected by significant orographic lifting. Thus, three MM5 grid points in the Alpine foreland are taken for the subsequent investigation. Our criterion for the moist-layer depth is based on the relative humidity at 850 hPa, 775 hPa, 700 hPa and 600 hPa. These levels were subjectively chosen to distinguish between frontal zones with a deep saturated layer and postfrontal conditions with successive subsidence-induced drying. The atmosphere is considered to be moist (close to saturation) when the relative humidity at a pressure level exceeds 90%, and it is pointed out that the relative humidity with respect to ice is taken at temperatures below freezing. Four moisture classes (RH1–RH4) are defined depending on how far the moist layer extends from 850 hPa upward. While RH1 means RH$>$90% at 850 hPa only, RH2, RH3 and RH4 denote a moist layer extending from 850 hPa to 775 hPa, 700 hPa and 600 hPa, respectively. Note that in contrast to the wind speed classes defined above, a given 6-hour interval may fulfill none of these criteria because the 850-hPa humidity is below 90%. Though this happens rarely during events with significant precipitation, the sum over all RH classes is usually slightly less than the total accumulated differences shown in Fig. 2b. As for wind speed, convective events and the SL1 class are omitted, and for computing normalised precipitation differences, we again apply the precipitation thresholds of 0.25 mm/6h at both stations or 1.0 mm/6h at the Zugspitze.

Fig. 5 shows the accumulated and normalised precipitation differences between the Zugspitze and Garmisch for the snow line classes SL2 and SL3. Evidently, the basic wind-direction dependence of the accumulated difference is still consistent with Fig. 2b, confirming that the cases fulfilling none of the RH criteria make no significant contribution. Note also that the contribution of the RH1 class to the accumulated differences is very small for both snow line classes (Fig. 5a,c), which in addition indicates that the elimination of convective cases based the classification scheme developed by WZ07 was largely successful. Apart from that, the accumulated differences show a marked increase with increasing moist-layer depth, being even more pronounced for SL3 than for SL2. The RH4 class clearly dominates for westerly and northwesterly flow, but the signal is weaker for northerly and northeasterly flow. However, the normalised differences (Fig. 5b,d) show a comparatively weak tendency to increase with increasing moist layer depth. There is a notable signal for northwesterly and northerly 700-hPa winds, particularly in the SL3 class, but the spread between RH1 and RH4 is much smaller than for the accumulated differences. This appears to be partly a representativity problem, as there are very few cases in the low RH classes and the number of events falling into the RH1 class does not even reach the threshold of 5 in most wind-direction intervals of SL2. In particular, some of the few cases falling into the RH1 class may be affected by horizontal moisture gradients between the Alpine foreland (from where the moisture data are taken) and the northern Alps, leading to relatively large normalised precipitation differences because of the small overall number of cases. It is mentioned that choosing lower precipitation thresholds would increase the spread among the RH classes of the normalised precipitation differences, but it was felt that it does not make much sense to include a large number of marginal precipitation events into such a calculation. We note in addition that the mountain-valley precipitation differences were also investigated as a function of explicit MM5 precipitation in the Alpine foreland, which is an alternative measure for the strength of synoptic-scale lifting. The results basically confirmed the findings made with the saturation criterion but are not discussed here because there is a high cross-correlation between the moist-layer depth and the explicit MM5 precipitation.

4 Conclusions

Observations of operational weather stations in Bavaria and western Austria and climate-mode simulations with

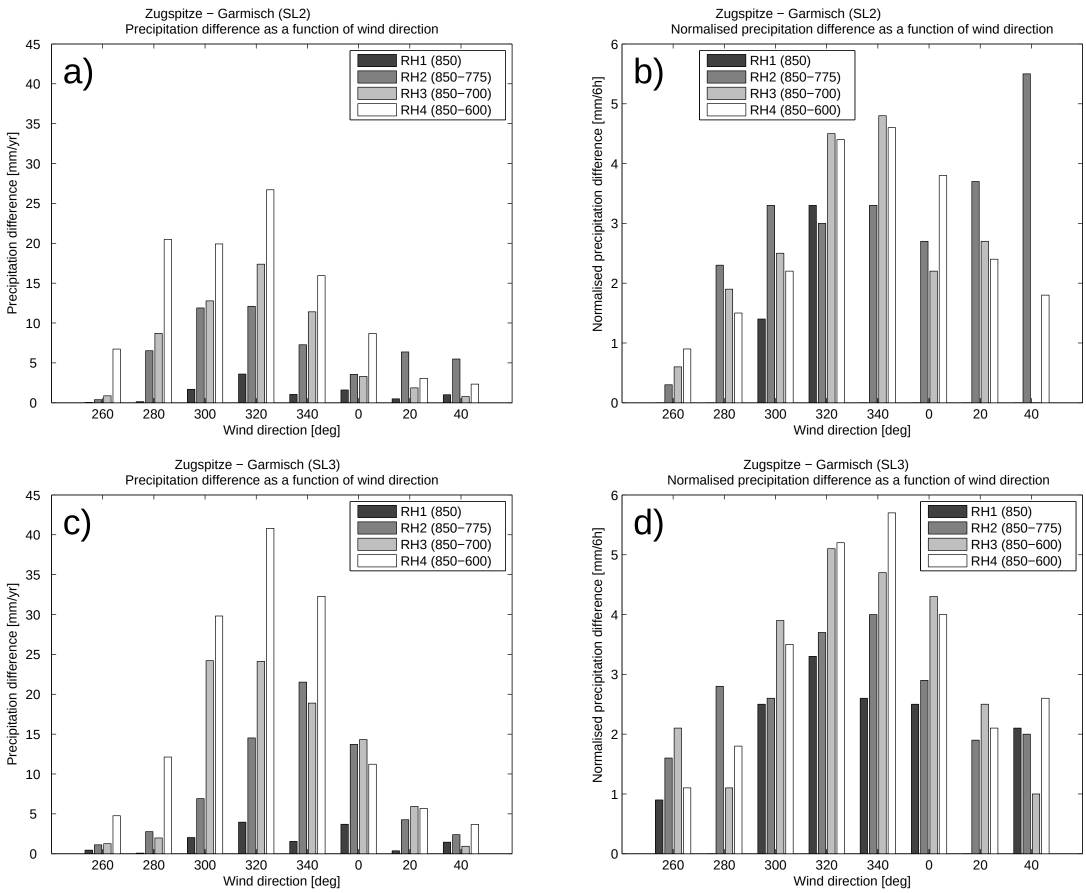

Figure 5: Left panels: Accumulated precipitation differences (mm/yr) between the Zugspitze and Garmisch as a function of 700-hPa wind direction and moist layer depth (see text for definition) for snow line classes SL2 (a) and SL3 (c). Right panels: Corresponding normalised precipitation differences (mm/6h).

the MM5 model have been used to investigate mountain-valley precipitation differences in the Alps. For this study four station pairs are selected, each consisting of a mountain and a valley station that are required to have a small horizontal distance and a substantial height difference. In addition the data set is subdivided into three temperature levels, defined by a snow line of $>$ 2500 m (SL1), 1000 m–2500 m (SL2) and $<$ 1000 m (SL3). First, the climatological precipitation distribution and the mountain-valley differences are examined as a function of the wind speed at 700 hPa. The second step is to analyse the precipitation differences depending on the wind speed and the vertical moisture profile. Convective precipitation is omitted for the latter investigation because it is usually not associated with systematic mountain-valley precipitation differences.

The results show that the increase of precipitation with height is strongly affected by the local topography. While three of the station pairs exhibit markedly higher precipitation at the mountain than in the valley, the inner-Alpine pair Innsbruck/Patscherkofel indicates essentially no precipitation increase with height. This could be traced back to the specific location of the Patscherkofel, which is not favourable for notable orographic precipitation enhancement. For the other station pairs, strong precipitation enhancement can be observed in the snow line classes SL2 and SL3 for wind directions between northwest and north, reaching more than 100 mm/yr per 20° wind interval. Westerly winds generally do not cause strong precipitation enhancement in the northern Alps because the wind then blows parallel to the Alpine ridge. For the SL1 class, the precipitation differences are comparatively small and even negative (i.e. less precipitation at the mountain) for the station pair Garmisch/Zugspitze. For southwesterly flow, the latter may again be explained by the local topography, as the Zugspitze is located at the western edge of a major mountain ridge that frequently triggers convection. For southwesterly ambient flow, the convection cells are advected towards Garmisch and there tend to produce more precipitation than at the Zugspitze where they do not yet have reached their mature stage. Otherwise, the negative differences in the SL1 class may be related to diverging hydrometeor trajectories occurring when the freezing level is at or slightly below the mountain peak, but this requires more investigation before final conclusions can be drawn.

The analysis of the precipitation differences between Garmisch and the Zugspitze as a function of the 700-hPa wind speed indicates a marked increase of precipitation enhancement with wind speed. This can be explained by the fact that the condensation rates related to orographic lifting are proportional to the wind speed for saturated ascent and a given temperature profile. The differences reach more than 5 mm/6h for northwesterly winds with more than 12.5 m/s. Climatologically, precipitation enhancement is larger for the SL3 class than for SL2 although cold air can carry less moisture than warm air, which is mainly because strong northwesterly and northerly winds are more frequent in winter than in autumn and spring. The mountain-valley precipitation differences also show a dependence on the moist-layer depth of the air approaching from the Alpine foreland because lifting a deep moist layer can cause more precipitation enhancement than lifting a shallow moist layer.

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