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Monthly resolved biannual precipitation oxygen isoscape for Switzerland

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Abstract

Stable oxygen isotope composition of atmospheric precipitation ($\delta^{18}O_p$) was scrutinized from 39 stations distributed over Switzerland and its border zone. Monthly amount-weighted $\delta^{18}O_p$ values averaged over the 1995–2000 period showed the expected strong linear altitude dependence (−0.15–−0.22 ‰/100 m) only during the summer season (May–September). Steeper gradients (∼ −0.51–−0.59 ‰/100 m) were observed for winter months over a low elevation belt, while hardly any altitudinal difference was seen for high elevation stations. This dichotomy could be explained by the characteristically shallower vertical atmospheric mixing height during winter season. Grids and isotope distribution maps of the monthly $\delta^{18}O_p$ have been calculated for 1995–1996 when the station network was the densest. The adopted interpolation method took into account both the variable mixing heights and the seasonal differences in isotopic lapse rates and combined them with residual kriging. The presented dataset allow point estimation of $\delta^{18}O_p$ with monthly resolution. According to the test calculations this biannual dataset can be extended to recent years and back to 1992 with maintained fidelity and with a reduced station-set even back to 1983 at the expense of faded reliability over some parts of Switzerland. There is even a good chance to reach back to the seventies for the Swiss Plateau.

1 Introduction

Stable isotopes of past and present precipitation are important natural tracers in the hydrological cycle on global, regional and local scales and are permanently in the focus of environmental isotopic studies. Owing to the growing number of monitoring stations for isotopic composition of atmospheric precipitation worldwide and the great technical advance in geostatistical treatment of geochemical data via geographic information system (GIS) – based spatial modelling tools (Bowen, 2010a) precipitation isotope mapping revolutionized over the past decade.

Precipitation isoscape (isotopic landscape) is a map of isotopic variation produced by iteratively applied predictive model to estimate the local isotopic composition of precipitation as a function of observed local and/or extralocal environmental variables across regions of space using gridded environmental data sets (Bowen, 2010a; West et al., 2010). The first isoscape of global precipitation was derived by Bowen and Wilkinson (2002). Later on Bowen and Revenaugh (2003) proved that geostatistical approach undeniably outperform simple interpolation techniques. These advances fertilized numerous studies on regional precipitation isoscapes (Meehan et al., 2004; Leibminger et al., 2006; Lykoudis and Argiriou, 2007; Lykoudis et al., 2010; Vachon et al., 2010; Holko et al., 2012; Welker, 2012) and it is not surprising that stable water isotopes of precipitation became the prime substance of isoscape development. Nowadays, geostatistical approach became a popular technique for the mapping of precipitation water isotope ratios (Bowen, 2010b).

Although these studies have dominantly pictured the long-term mean isotopic landscape of the region, recently and occasionally the average seasonal cycle is also tracked (Vachon et al., 2010; Welker, 2012). Only one study made an attempt to generate monthly resolved gridded dataset employing geostatistical method over the Eastern Mediterranean region (Lykoudis et al., 2010). However, the application fields (ecology, hydrology or forensic applications) that motivated the evolution of precipitation isoscapes would surely benefit more if the temporal differences could be followed as well. This will open up new perspective in isoscape applications, i.e. dynamic applications. This recognition inspired the present study focussed stable oxygen isotope composition of atmospheric precipitation (hereafter $\delta^{18}O_p$).

The Alps host the oldest and densest network monitoring stable isotopes of atmospheric precipitation compared to any other mountainous area of the world owing to the good representation of international (GNIP) and national (Switzerland and Austria) networks. Detailed assessments conducted on these data substantially contributed to our knowledge about isotopic processes acting and interacting at various spatial and

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temporal scales in the atmosphere, or more generally in geospheres (e.g. Siegenthaler and Oeschger, 1980; Leibminger et al., 2007; Fröchlich et al., 2008).

The relative wealth of long and regular monitoring data offer a great opportunity to initiate a kind of time-series approach of $\delta^{18}O_p$ isoscapes in this region. The motivation of the research was to develop a gridded data set of monthly $\delta^{18}O_p$ over Switzerland and adjacent areas with high spatial resolution back to the early 1970s. In the present paper only the methodological background will be discussed and test interpolations on $\delta^{18}O_p$ are provided for 1995 and 1996, when the station network was the densest, in order to check whether a reduced number of station-set could reproduce the same spatial patterns captured by the full dataset. Furthermore we hoped that this exceptional station collection would improve the understanding of stable isotope spatial pattern over a complex terrain.

2 Material and methods

2.1 Stable oxygen isotope ratios from precipitation

Measurements of oxygen isotope ratios in precipitation started as early as 1965 at Thonon des Bains (France) and 1971 at Bern in the Alpine region. However, the network was very sparse during the first years. Station density significantly improved only from 1973 when more Swiss and Austrian stations were involved into the network (Fig. 1).

We gathered 43 monthly resolved $\delta^{18}O_p$ records from the region. This collection constituted from the following sources:

Swiss National Network for Isotopes in the Water Cycle (NISOT) (Schürch et al., 2003) represented by 6 + 5 stations. The +5 stations are included also in the GNIP global network. Global Network of Isotopes in Precipitation (GNIP) (IAEA, 2010) is represented by 5 stations from Germany and one station from France. Austrian Network of Isotopes in Precipitation (ANIP) (Kralik et al., 2003) represented by 9 stations from Vorarlberg and Tyrol.

Eight relatively shorter records were available from Northern Italy (Longinelli and Selmo, 2003, 2006). Last but not least, the Division of Climate and Environmental Physics, University of Bern ran an extended network with 9 stations, until 2010. It is worth emphasizing that this is the first publication of these invaluable multidecadal monitoring records.

Spatial and temporal distribution of the records is presented in Fig. 1. We note that available station records frequently suffer from gaps, Bern and Grimsel are the only stations that provide continuous records. Hence, as an accidental benefit, these gaps may be filled with the retrieved information from neighbouring stations based on the proposed interpolation employing advanced geostatistical tools.

Station density was the highest (0.17–0.18 station/100 km^2, $n = 39$) in 1995–96, while the period (> 5 yr) when amount weighted isotope values could be calculated using the widest subset was 1995–2000. This population of 39 stations correspond to almost twice as many as were available for the much more expanded domain of the eastern Mediterraneum during the best represented period of the Mediterranean isoscape (Lykoudis et al., 2010).

Two steeper increases can be discerned in the temporal station density curve (Fig. 1). These are linked to a significant expansion in the network, (i) the early 1980s when the network of the Division of Climate and Environmental Physics was initiated and the station density exceeded 0.10 station/100 km^2, and (ii) in the early 1990s when NISOT and the two earliest N Italian stations were launched and the station density exceeded 0.14 station/100 km^2. The longest 12 records have been (almost) continuously available since 1973 providing a station density of 0.06 station/100 km^2. These key periods were regarded when reduced subsets were designated. The 12 and 24 longest station records would allow extending the mapping back to 1973 and 1984 (Fig. 1). The entire network offers the early 1990s as the starting date for isoscape generation.

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2.2 Planetary boundary layer

Monthly average maximum daytime PBL height above the region (data derived from a $1^\circ \times 1^\circ$ GRID, von Engeln and Teixeira, 2013) was corrected for the corresponding grid-cell reference surface (derived from the hypsometric data of the same $1^\circ \times 1^\circ$ cell). Corresponding subset of SRTM database (Farr et al., 2007) was used as reference terrain. Due to the further GRID manipulations the coarse spatial resolution of the original PBL dataset was equalized to the 100 m resolution of the SRTM digital elevation model (DEM) applying ordinary kriging interpolation (Cressie, 1993). Graphical illustration of the PBL derivation can be found in the Supplement.

2.3 Interpolation and mapping

Our primary intension was to adopt a method designed for the global isoscape (Bowen and Wilkinson, 2002). Regarding the relatively small spatial domain and the accompanied large orographic complexity, however, the consensus opinion in the Alps is that height effect dominates the Alpine $\delta^{18}O_p$ (Siegenthaler and Oeschger, 1980; Schürch et al., 2003). Our experience agreed with this opinion as residuals after the removal of the height effect did not showed any significant correlation with either latitude or longitude. Therefore only the altitude was employed as predictor. Though the south–north contrast was discernible in the residuals, in line with expectations (Sodemann and Zubler, 2010), meaning that the northern Italian sites and Locarno from Ticino tended to define a separate cluster with characteristically less depleted values compared to the rest of the domain. It surely mirrors the combined effect of the characteristically drier air and the, closely linked, isotopically distinct moisture source of these Mediterranean exposed region.

This regional difference in vapour source effect or relative humidity was decided to be treated in the residual field by spatial interpolation similarly to Bowen and Revenaugh (2003) or Lykoudis et al. (2010).

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Regarding the seasonally variable vertical $\delta^{18}O_p$ structure (see Sect. 3.1) a 4-steps approach was designed for interpolation taking into consideration the monthly PBL. Interpolation was calculated in Golden software Surfer 9 (Golden software INC. 2010) using ordinary kriging. Since interpolation was calculated for three sets of stations (All, 24 and 12) for each month of the 2 yr period (24 months) over the same domain, a Visual Basic command was written in Scripter to facilitate the process. Obtained GRIDs (with 100 m resolution) were exported to.asc format and further GRID and raster manipulation were managed in ArcGIS 10 (ESRI INC. 2010) using the Spatial Analyst module.

Step 1 – PBL truncated DEM: to get the PBL truncated DEM surface of the actual month (Z^t, t = January 1995, ..., December 1996) a conditional structure was used from the Spatial Analyst Raster Calculator:

$$Z^t_{i,j} = \mathrm{Con}\left(\mathrm{PBL}^t_{i,j} > \mathrm{DEM}_{i,j}, \mathrm{DEM}_{i,j}, \mathrm{PBL}^t_{i,j}\right) \quad (1)$$

Meaning that: if the PBL value is higher than the DEM at the i,j GRID point, then the point in the new GRID gets the value of the DEM otherwise it gets the value of the PBL.

Step 2 – monthly initial GRIDs: computed from this surface using the regression equations obtained from the below-PBL stations (1995–2000) as follows

$$\delta^{18}O^t_{\mathrm{ini}} = S_m \cdot Z^t_{i,j} + b_m \quad (2)$$

where S_m and b_m (m = January, ..., December) are the slope and offset of the corresponding monthly regression equation, respectively. The operation was carried out with the Spatial Analyst Raster Calculator tool.

Step 3 – residual kriging: GRID values corresponding to the stations' coordinates were extracted from each initial GRIDs using ExtractMultiValuesToPoints extension of the Spatial Analyst collected in a table and exported to.txt format. Values from the monthly initial GRIDs were subtracted from the corresponding raw monthly station data in a separate spreadsheet. Assumed that only the horizontal dependencies are

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retained in the obtained residuals they were interpolated in the same GRID using ordinary kriging (Cressie, 1993).

Step4 – final map: corresponding initial and residual GRIDs were summed

$$\delta^{18}O_p^t = \delta^{18}O_{ini}^t + \delta^{18}O_{res}^t \quad (3)$$

The operation was carried out again with the Spatial Analyst Raster Calculator tool.

3 Results and discussion

3.1 Seasonal pattern in the oxygen isotopic lapse rate

The expected strong altitude dependence (Siegenthaler and Oeschger, 1980) was evident only for summer months (–0.15––0.22 ‰/100 m). Steeper gradients (–0.51––0.59 ‰/100 m) were observed for winter months over a low elevation belt, while hardly any altitudinal difference is seen for high elevation stations. This dichotomy can be also observed, though to a lesser degree, during spring and autumn (Fig. 2).

Similar deviation for summit stations have already been observed in the Alps even at the dawn of atmospheric isotopic studies (Ambach et al., 1968; Siegenthaler and Oeschger, 1980) and was reported very recently from other European mountain range (Holko et al., 2012) but proper explanation is still missing. Owing to the relatively great number of stations collected in the present dataset and their relatively well coverage throughout the full Alpine elevation range monthly plots allowed to capture the seasonal pattern of this elevational decoupling.

Our working hypothesis was that the lower atmospheric mixing height is mirrored in this pattern. It is well-known that atmospheric mixing height is low during winter and significantly higher during summer over Europe (Seidel et al., 2012; von Engeln and Teixeira, 2013).

To test this hypothesis planetary boundary layer (PBL) levels were approximated (see Sect. 2.2). Afterwards stations grouped considering their relative position to the PBL

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(i.e. above or below PBL). This comparison nicely confirmed our suspect as visually placed breakpoints of the scatterplots are regularly corresponded to the PBL separated station groups (Fig. 2).

The different atmospheric conditions/processes above and below the PBL could be the plausible physical explanation for the observed pattern. High wind speeds, for instance, prevailing above the PBL (Seidel et al., 2012) could probably maintain well mixed conditions above PBL and cause the large scale isotopic homogeneity over high elevations. Alternatively, or as an additional factor, a certain portion of high elevation winter precipitation seems to fall from clouds formed well before the air parcel arrives to the high elevation Alpine region, therefore corresponding to a "site-alien" isotopic signature.

PBL is usually situated at, or above the Alpine summits (Nyeki et al., 2000; Henne et al., 2004) during summer, hence does not affect the vertical isotopic pattern.

3.2 Monthly $\delta^{18}O_p$ isoscapes for 1995–1996 and experience with dataset reduction tests

The full set of maps and the derived dataset can be found in the Supplement. The major findings are illustrated by the following maps.

The twelve longest stations, unfortunately, are usually not enough to reproduce the maps derived from the full dataset, except for a few summer months like July 1995, or June 1996 (Fig. 3).

A critical region where regional pattern frequently occurred is Valais. These more depleted (e.g. May 1996) or enriched (e.g. July 1996) patterns cannot be reproduced with the 12 longest station records, but relatively well captured when at least one station is included, as Visp in the 24 group (Fig. 4).

Another critical region is the eastern sector of Switzerland. Maps calculated from reduced dataset often fail to capture the right values in this region (Fig. 5). It is clear from the difference maps that this is not a station error, because the anomaly field usually shows a dipole structure Pontresina and Vaduz are situating at the poles. It was surprising that in certain months the map calculated from 24 stations showed larger differences over this sector than the map based on 12 stations. The error can be as large as 2 to 4 ‰.

Finally we remark that mountain stations from the north Italian network (Graniga and Presolana) frequently define some local anomaly pattern. This occurs in any seasons so we are quite confident that it is not an artefact due to PBL sorting of the stations. These mountain stations tend to diverge from their nearby low elevation neighbour while the lowland station agrees well with the next nearest one. This suggests that Graniga and Presolana might own locally restricted isotopic pattern at those months. In the presented interpolation approach it is unfeasible to reduce the radius of influence only for these two stations therefore we have to face the risk that their anomalies are probably extended over a larger domain. However, as seen from the "bull eye" patterns of the difference maps the anomaly fields practically fade out even in this present stage before the border hence do not exert significant bias in the interpolation over the Swiss territory.

3.3 Further implications

Presented results might have significant implications to other related fields using stable precipitation isotopes. The central assumption of palaeoaltimetry based on δ^{18}O measured from authigenic minerals is the general observation of decreasing δ^{18}O values in rainfall as elevation increases (Rowley and Garzione, 2007). In Fig. 6 one can easily observe as the wintertime lack of altitude dependence inherited also to the multiannual mean $\delta^{18}O_p$ values of the high elevation stations. Projected values based on the station records below 1200 m a.s.l. are doubtlessly more negative above ~2000 m a.s.l. than the measured values. This fact might introduce an additional uncertainty to the methodological background of palaeoaltimetry (Blisniuk and Stern, 2005; Rowley and Garzione, 2007). First, when the uplifted terrain penetrated the regional PBL, the precipitation stable isotope most probably deviated from the normal altitude dependence leading to a dampened estimate, i.e. altitudes would be underestimated. On the contrary, if the PBL height is increased due to better mixing (warming) the correspondent $\delta^{18}O_p$ change would be misinterpreted as an uplift without any real orogene activity. This concern tends to strengthen the view of Ehlers and Poulsen (2009) in as much as past climate changes could significantly influence palaeoaltimetry interpretations due to the overwhelming signal from palaeoclimate changes.

The observed below vs. above PBL regime is an additional explanation for the lower $\delta^{18}O_{ice}$-tempearture scaling observed in Greenland based on air bubble $\delta^{15}N$ (Huber et al., 2006) compared to the spatial dependence (Dansgaard, 1964) besides source condition and seasonal precipitation distribution.

A Lagrangian moisture diagnostic model provided solid evidence for significant variability of effective moisture source for winter precipitation across the Greenland ice sheet (Sodemann et al., 2008a,b). Sodemann et al. (2008a, Fig. 5c) found that temperatures difference between first and arrival (over Greenland) condensation documents a clear contrast for central Greenland the ice sheet margin. This pattern is in good agreement with the source latitude distribution over Greenland (Sodemann et al. (2008b), Fig. 9b) suggesting more distant vapour sources for central Greenland. The presented Alpine $\delta^{18}O_p$ data provide a solid experimental hint that this long-range vapour transport is plausible. Using the winter season Alpine analogy height-independent and less negative $\delta^{18}O_p$ can be expected under these conditions (low PBL heights) over central Greenland. Consequently, isotope based temperature estimates inevitably underestimate real surface temperature changes.

This mechanism might help explaining the lower $\delta^{18}O_{ice}$-tempearture scaling observed in Greenland.

4 Conclusions

The 12 longest records are usually insufficient to map the regional $\delta^{18}O$ patterns.

Valais and the eastern sector often has unique $\delta^{18}O$ signature, which can be captured only when at least one station from these regions is used.

The presented dataset allow point estimation of $\delta^{18}O_p$ with monthly resolution. It will definitely be excellent auxiliary material for future hydrological modelling or climatological applications. According to our test calculations with reduced station-set this biannual dataset will be possible to extended back to 1992 with maintained fidelity and limited by the earliest monitoring data from the Graubünden–Liechtenstein region, namely July of 1992 (Vaduz) and even a decade before at the expense of faded reliability over the eastern sector especially east from the Upper Rhine Valley.

Decoupled regimes below and above PBL received little attention in spatial precipitation isotope modelling efforts. Present results point out that PBL location is recommended to be taken into account for future models developed for stable isotope composition of precipitation.

The presented dataset, and more particularly the extended record to be developed using the present approach, will be a useful input data for the Alpine hydrological modelling efforts, provide a basis for regional ecological modelling (e.g. migratory studies), provide the crucial local isotopic target throughout practically the entire western Alpine region for calibration of palaeoclimate proxy records (e.g. from tree rings, ice cores or speleothems) and could be employed as a reference dataset for regional isotope enabled circulation models. Combination with Lagrangian moisture source diagnostics (Sodemann and Zubler, 2010), for instance, offer an advanced interpretation of Alpine subregional moisture regime.

Supplementary material related to this article is available online at: http://www.atmos-chem-phys-discuss.net/13/9895/2013/acpd-13-9895-2013-supplement.zip.

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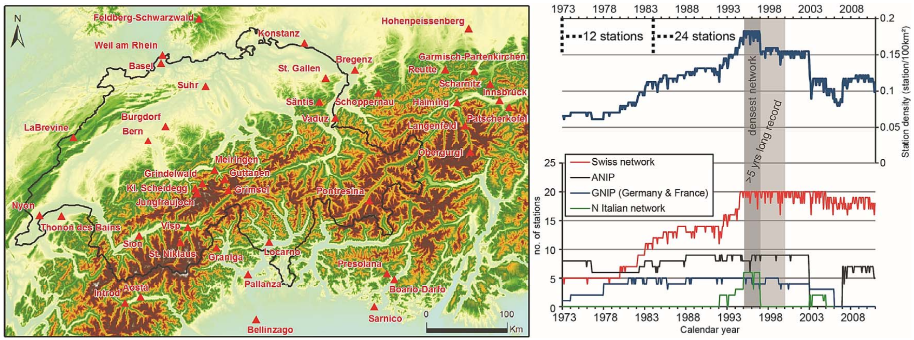

Fig. 1. Spatial and temporal distribution of the 43 stations with available record of monthly stable oxygen isotope ratio of precipitation over Switzerland and its border region. Temporal distribution is shown between 1973 and 2010. Before 1973 practically only Thonon des Bains (France) and Bern (Switzerland) provide record. (Data sources: NISOT, Schürch et al., 2003, ANIP, Kralik et al., 2003, GNIP, IAEA, 2010, N-Italy, Longinelli and Selmo, 2006, 2003, and the private network run by the Division of Climate and Environmental Physics, University of Bern.)

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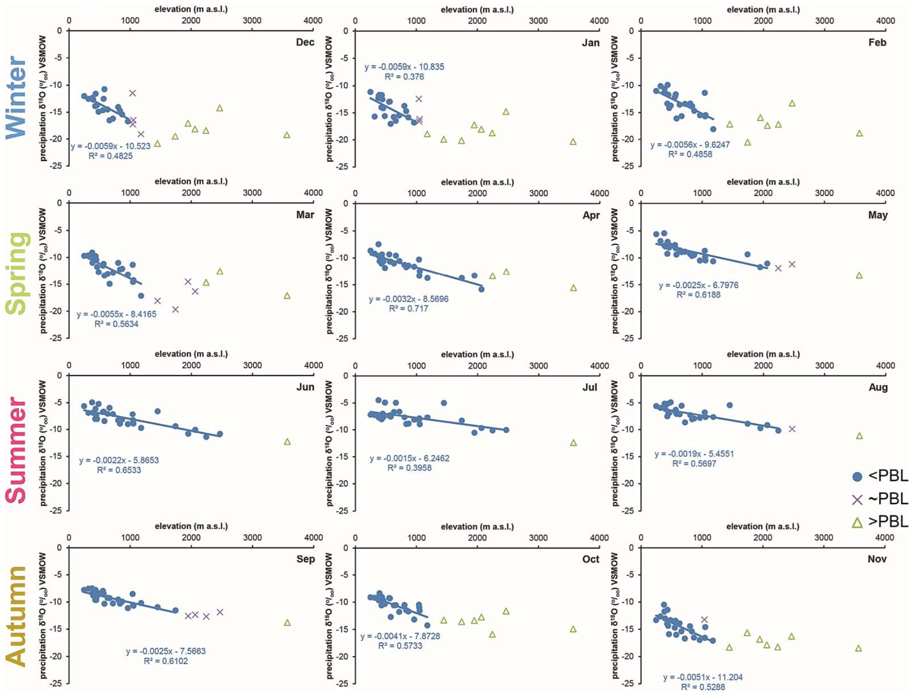

Fig. 2. Monthly amount weighted stable oxygen isotope composition of precipitation over Switzerland and its border zone. Blue dots represent stations that were always below the planetary boundary layer (PBL), green triangles represent stations that were always above the PBL while purple crosses represent stations that were occasionally above the PBL during the 1995–2000 period. Regression equations fitted to the stations below the PBL are given for each month.

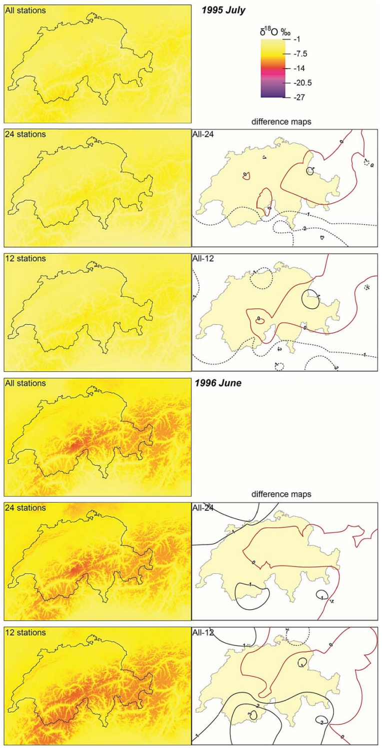

Fig. 3. Precipitation oxygen isoscapes for Switzerland derived for 1995 July and 1996 June. The top maps show the isoscapes obtained using all available stations, whereas the middle and bottom maps show isocapes for the longest 24 and 12 stations, respectively. The difference maps obtained after substraction of the GRID computed with the reduced dataset from the full one are shown at the right. Isolines are marked by a solid line (positive values), a dashed line (negative values) and a red line (zero).

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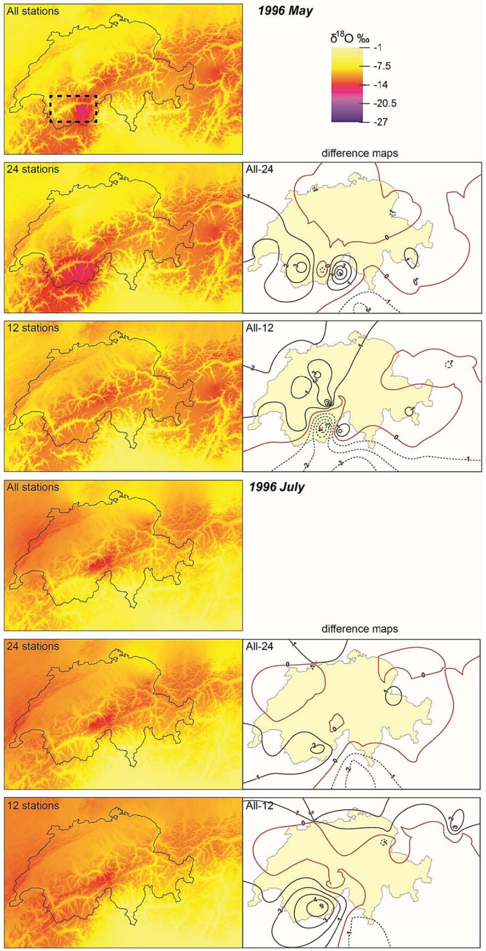

Fig. 4. Precipitation oxygen isoscapes for Switzerland derived for May 1996 and July 1996. Dashed rectangle frames Valais. For further explanation see the caption of Fig. 3.

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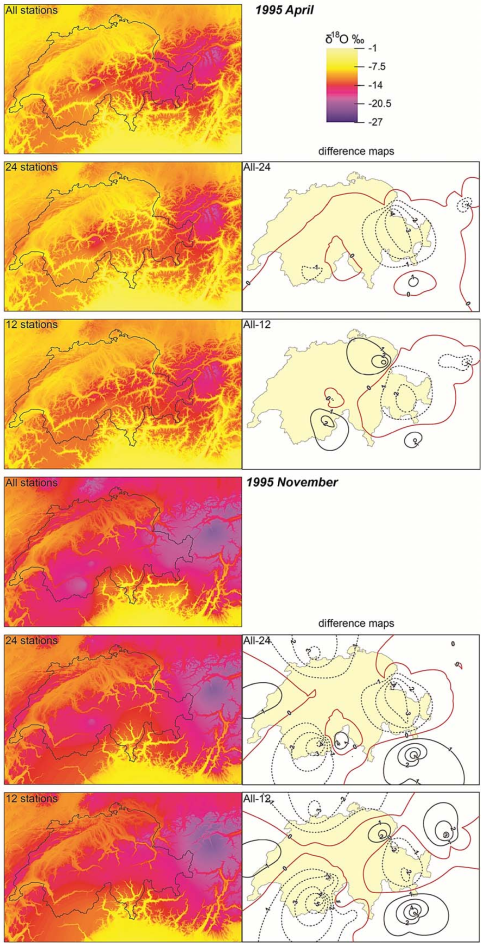

Fig. 5. Precipitation oxygen isoscapes for Switzerland derived for April 1995 and November 1995. For further explanation see the caption of Fig. 3.

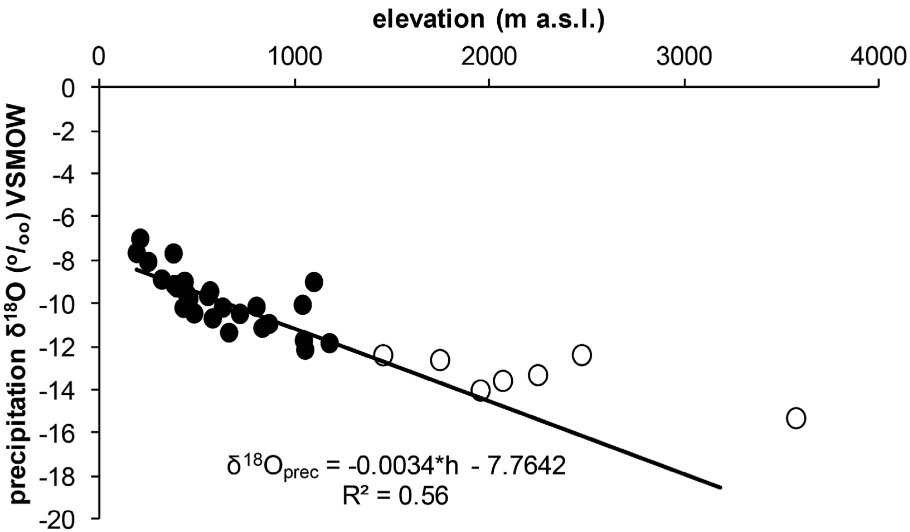

Fig. 6. Multiannual (1995–2000) amount weighted mean stable oxygen isotope ratios from the Alpine region as a function of stations' elevation. Regression is fitted to the subset (filled circles) below 1200 m a.s.l.

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