Interreg Alpine Space

Co-funded by the European Union

X-RISK-CC

WebGIS index description

X-RISK-CC

How to adapt to changing weather e**X**tremes and associated compound and cascading **RISK**s in the context of **C**limate **C**hange

This project is co-funded by the European Union through the Interreg Alpine Space programme.
www.alpine-space.eu/project/x-risk-cc/

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Extreme Precipitation

1. Maximum 1-day precipitation – Rx1d

DEFINITION

The maximum 1-day precipitation represents the intensity of daily precipitation extremes. It considers the maximum value of daily precipitation in a year or a season. Unit: mm/day.

STRENGHTS

- Rx1d can be easily interpreted as directly linked to the intensity of 1-day precipitation extremes.

LIMITATIONS

- Rx1d identifies only the most intense precipitation event per year or season, thus overlooks the occurrence of multiple extreme events of comparable intensity within the same year or season.
- The spatial resolution of data used for the index calculation affects the ability to capture small-scale processes.
- Rx1d is based on daily precipitation values, which, together with limitations in spatial resolution, hampers the representation of intense precipitation events with sub-daily durations, such as those associated with convective storms.

REFERENCES

- Brugnara, Y., and Maugeri, M. (2019). Daily precipitation variability in the southern Alps since the late 19th century, Int. J. Climatol., 39, 3492-3504. https://dx.doi.org/10.1002/joc.6034
- Ménégoz, M., Valla, E., Jourdain, N. C., Blanchet, J., Beaumet, J., Wilhelm, B., Gallée, H., Fettweis, X., Morin, S., and Anquetin, S. (2020). Contrasting seasonal changes in total and intense precipitation in the European Alps from 1903 to 2010, Hydrol. Earth Syst. Sci., 24, 5355–5377. https://doi.org/10.5194/hess-24-5355-2020
- Scherrer, S. C., Fischer, E. M., Posselt, R., Liniger, M. A., Croci-Maspoli, M., and Knutti, R. (2016). Emerging trends in heavy precipitation and hot temperature extremes in Switzerland, J. Geophys. Res. Atmos., 121, 2626–2637. https://doi.org/10.1002/2015JD024634

2. Maximum 3-day precipitation – Rx3d

DEFINITION

The maximum 3-day precipitation represents the intensity of extreme precipitation accumulated

over multiple days. It considers the maximum value of precipitation accumulated over three consecutive days in a year or a season. Unit: mm/3-days.

STRENGHTS

- Rx3d is designed to account for the intensity of extreme precipitation events extending over multiple days.

LIMITATIONS

- Rx3d identifies only the most intense 3-day precipitation episode per year or season, thus overlooks the occurrence of other 3-day events of comparable intensity within the same year or season.
- Rx3d does not describe the timing or distribution of rainfall intensity within the 3-day event, which can be critical for analysing specific impacts.

REFERENCES

- Brugnara, Y., and Maugeri, M. (2019). Daily precipitation variability in the southern Alps since the late 19th century, Int. J. Climatol., 39, 3492–3504. https://dx.doi.org/10.1002/joc.6034
- Zeder, J., and Fischer, E. M. (2020). Observed extreme precipitation trends and scaling in Central Europe. Weather Clim. Extremes, 29, 100266. https://doi.org/10.1016/j.wace.2020.100266

3. Number of days with 1-day precipitation exceeding the 97th percentile – R97pN_1d

DEFINITION

R97pN_1d represents the frequency, in a year or a season, of days recording 1-day precipitation extremes. Extreme precipitation occurrences are defined as 1-day precipitation records above the 97th percentile of all daily precipitation values in the reference period (1991-2020) considering wet days only (i.e., days with precipitation above 1 mm). Unit: days.

STRENGHTS

- R97pN_1d can be easily interpreted as directly linked to the frequency of 1-day precipitation extremes and complement the extreme intensity measured by Rx1d.
- By applying a percentile threshold, R97pN_1d accounts for local climate conditions, making it suitable for comparing regions with different rainfall regimes.

LIMITATIONS

- R97pN_1d results depend on the percentile threshold and reference period used for its calculation. A preliminary evaluation is recommended to properly interpret or adapt the index

definition to the specific goal and application.

- The spatial resolution of data used for the index calculation affects the ability to capture small-scale processes.
- R97pN_1d is based on daily precipitation, which, together with limitations in spatial resolution, hampers the representation of intense precipitation events with sub-daily durations, such as those associated with convective storms.

REFERENCES

- Scherrer, S. C., Fischer, E. M., Posselt, R., Liniger, M. A., Croci-Maspoli, M., and Knutti, R. (2016). Emerging trends in heavy precipitation and hot temperature extremes in Switzerland, J. Geophys. Res. Atmos., 121, 2626–2637. https://doi.org/10.1002/2015JD024634

4. Number of days with 3-day precipitation exceeding the 97th percentile – R97pN_3d

DEFINITION

R97pN_3d represents the frequency, in a year or a season, of 3-day precipitation extremes. Extreme values are defined as 3-day precipitation sums above the 97th percentile of 3-day accumulated values in the reference period (1991-2020) considering wet 3-day periods only (i.e., days with 3-day precipitation above 1 mm). Unit: days.

STRENGHTS

- R97pN_3d can be easily interpreted as directly linked to the frequency of 3-day precipitation extremes and complement the extreme intensity measured by Rx3d.
- By applying a percentile threshold, R97pN_3d accounts for local climate conditions, making it suitable for comparing regions with different rainfall regimes.

LIMITATIONS

- R97pN_3d results depend on the percentile threshold and reference period used for its calculation. A preliminary evaluation is recommended to properly interpret or adapt the index definition to the specific goal and application.

REFERENCES

- Scherrer, S. C., Fischer, E. M., Posselt, R., Liniger, M. A., Croci-Maspoli, M., and Knutti, R. (2016). Emerging trends in heavy precipitation and hot temperature extremes in Switzerland, J. Geophys. Res. Atmos., 121, 2626–2637. https://doi.org/10.1002/2015JD024634

5. Sum of 1-day precipitation exceeding the 97th percentile – R97pTOT_1d

DEFINITION

R97pTOT_1d represents the accumulated precipitation, over a year or a season, on days recording 1-day precipitation extremes. Extreme values are defined as 1-day precipitation records above the 97th percentile of daily precipitation values in the reference period (1991-2020) considering wet days only (i.e., days with precipitation above 1 mm). The index thus integrates information on both frequency and intensity of 1-day extremes. Unit: mm.

STRENGHTS

- The index provides a measure of the total intensity of 1-day precipitation extremes occurring in a year or season, which complements the information about maximum intensity and frequency described by Rx1d and R97pN_1d, respectively.

- By applying a percentile threshold, R97pTOT_1d accounts for local climate conditions, making it suitable for comparing regions with different rainfall regimes.

LIMITATIONS

- R97pTOT_1d results depend on the percentile threshold and reference period used for its calculation. A preliminary evaluation is recommended to properly interpret or adapt the index definition to the specific goal and application.
- The spatial resolution of data used for the index calculation affects the ability to capture small-scale processes.
- R97pTOT_1d is based on daily precipitation values, which, together with limitations in spatial resolution, hampers the representation of intense precipitation events with sub-daily durations, such as those associated with convective storms.
- The index describes the accumulated intensity while it does not account for the actual distribution of the extreme precipitation events over considered period.

REFERENCES

- Myhre, G., Alterskjær, K., Stjern, C. W., et al. (2019). Frequency of extreme precipitation increases extensively with event rareness under global warming, Sci. Rep., 9, 16063. https://doi.org/10.1038/s41598-019-52277-4

6. Sum of 3-day precipitation exceeding the 97th percentile – R97pTOT_3d

DEFINITION

R97pTOT_3d represents extreme 3-day accumulated precipitation, over a year or a season. Extreme values are defined as 3-day precipitation sums above the 97th percentile of 3-day accumulated precipitation values in the reference period (1991-2020) considering wet 3-day

periods only (i.e., days with 3-day precipitation above 1 mm). The index thus integrates information about both frequency and intensity of 3-day extremes. Unit: mm

STRENGHTS

- R97pTOT_3d is specifically designed to identify heavy precipitation events that span multiple days, making it more appropriate to account for prolonged storms or successive heavy rainfall episodes.

- The index provides a measure of the total intensity of 3-day precipitation extremes occurring in a year or season, which complements the information about maximum intensity and frequency described by Rx3d and R97pN_3d, respectively.
- By applying a percentile threshold, R97pTOT_3d accounts for local climate conditions. By normalizing the index values, the results for regions with different rainfall regimes can be compared.

LIMITATIONS

- R97pTOT_3d results depend on the percentile threshold and reference period used for its calculation. A preliminary evaluation is recommended to properly interpret or adapt the index definition to the specific goal and application.
- R97pTOT_3d is based on daily precipitation values, which limits the representation of intense precipitation events with sub-daily durations, such as those associated with convective storms.
- The index describes the accumulated intensity while it does not account for the actual distribution of the extreme precipitation events over the considered period.

REFERENCES

- Myhre, G., Alterskjær, K., Stjern, C. W., et al. (2019). Frequency of extreme precipitation increases extensively with event rareness under global warming, Sci. Rep., 9, 16063. https://doi.org/10.1038/s41598-019-52277-4

7. Convective indicator orange warning – conv_ind_orange

DEFINITION

The convective indicator orange warning estimates the expected number of thunderstorm occurrences in a year with intensity corresponding to an orange warning. The intensity classes correspond to the three commonly used warning colours in operational weather forecasting: yellow = remarkable weather, orange = severe weather, red = extreme weather. The indicator is calculated on a central European domain and includes all sub-processes related to thunderstorms (i.e., large hail, excessive rain, severe wind gusts and tornadoes).
The indicator is calculated by applying an additive logistic regression which blends the occurrence/non-occurrence of thunderstorms with a set of predictors representing key ingredients for thunderstorms (i.e., instability, moisture, lift, vertical wind shear). Thunderstorm

occurrences used to develop the statistical model are derived by merging information from fire brigade reports, eyewitnesses and meteorological measurements and categorized based on elaborated criteria catalogues. Unit: 1.

STRENGHTS

- Conv_ind_orange can be used to represent the frequency of severe thunderstorms in a year and complements the information on extreme thunderstorm occurrence reported by conv_ind_red. By aligning the thunderstorm intensity classification with operational warning levels, it offers a more straightforward interpretability of results.
- Being explicitly designed to describe convective, small-scale intense phenomena, it complements other index definitions whose ability to capture such events is more constrained by spatial and temporal resolutions of input data.
- It can be used to link spatial and temporal patterns of thunderstorm occurrences with the behavior of individual atmospheric predictors.

LIMITATIONS

- Due to the volatile, short-lived and small-scale characters of thunderstorms, the results of the indicator can be still affected by limitations of the climate data to represent the state of the atmosphere associated to thunderstorm conditions.
- The current version of the indicator does not cover the whole Alpine region, and the thunderstorm data used to build the model are limited to Austria only.

REFERENCES

- Battaglioli, F., Groenemeijer, P., Púčik, T., Taszarek, M., Ulbrich, U., and Rust, H. (2023). Modeled Multidecadal Trends of Lightning and (Very) Large Hail in Europe and North America (1950–2021). J. Appl. Meteorol. Climatol., 62, 1627-1653. https://doi.org/10.1175/JAMC-D-22-0195.1
- Rädler, A. T., Groenemeijer, P. H., Faust, E., Sausen, R., and Púčik, T. (2019). Frequency of severe thunderstorms across Europe expected to increase in the 21st century due to rising instability. npj Clim. Atmos. Sci., 2, 30. https://doi.org/10.1038/s41612-019-0083-7
- Wilks, D.S., 2006: Statistical Methods in the Atmospheric Sciences. Academic Press, New York, 2nd edition.

8. Convective indicator red warning – conv_ind_red

DEFINITION

The convective indicator red warning estimates the expected number of thunderstorm occurrences in a year with intensity corresponding to a red warning. The intensity classes are synchronized with the three commonly used warning colours in operational weather forecasting: yellow = remarkable weather, orange = severe weather, red = extreme weather. The indicator is calculated on a central European domain and includes all sub-processes related to thunderstorms

(i.e., large hail, excessive rain, severe wind gusts and tornadoes).
The indicator is calculated by applying an additive logistic regression which blends the occurrence/non-occurrence of thunderstorms with a set of predictors representing key ingredients for thunderstorms (i.e., instability, moisture, lift, vertical wind shear). Thunderstorm occurrences used to develop the statistical model are derived by merging information from fire brigade reports, eyewitnesses and meteorological measurements and categorized based on elaborated criteria catalogues. Unit: 1.

STRENGHTS

- Conv_ind_red can be used to represent the frequency of extreme thunderstorms in a year and complements the information on severe thunderstorm occurrence reported by conv_ind_red. By aligning the thunderstorm intensity classification with operational warning levels, it offers a more straightforward interpretability of results.
- Being explicitly designed to describe convective, small-scale intense phenomena, it complements other index definitions whose ability to capture such events is more constrained by spatial and temporal resolutions of input data.
- It can be used to link spatial and temporal patterns of thunderstorm occurrences with the behavior of individual atmospheric predictors.

LIMITATIONS

- Due to the volatile, short-lived and small-scale characters of thunderstorms, the results of the indicator can be still affected by limitations of the climate data to represent the state of the atmosphere associated to thunderstorm conditions.
- The current version of the indicator does not cover the whole Alpine region, and the thunderstorm data used to build the model are limited to Austria only.

REFERENCES

- Battaglioli, F., Groenemeijer, P., Púčik, T., Taszarek, M., Ulbrich, U., and Rust, H. (2023). Modeled Multidecadal Trends of Lightning and (Very) Large Hail in Europe and North America (1950–2021). J. Appl. Meteorol. Climatol., 62, 1627-1653. https://doi.org/10.1175/JAMC-D-22-0195.1
- Rädler, A. T., Groenemeijer, P. H., Faust, E., Sausen, R., and Púčik, T. (2019). Frequency of severe thunderstorms across Europe expected to increase in the 21st century due to rising instability. npj Clim. Atmos. Sci., 2, 30. https://doi.org/10.1038/s41612-019-0083-7
- Wilks, D.S., 2006: Statistical Methods in the Atmospheric Sciences. Academic Press, New York, 2nd edition.

Extreme Wind

9. Maximum 1-day wind speed – WSx1d

DEFINITION

WSx1d represents the intensity of daily wind speed extremes. It reports the highest daily wind speed maximum recorded in a year or in a season. Unit: m/s

STRENGHTS

- WSx1d can be easily interpreted as directly linked to the intensity of 1-day wind speed extremes.

LIMITATIONS

- WSx1d values do not account for very localized and short-duration wind speed extremes (i.e., wind gusts).
- WSx1d identifies only the most intense wind speed event per year or season, thus overlooks the occurrence of other extreme events of comparable intensity within the same year or season.

REFERENCES

- Kumar, D., Mishra, V., and Ganguly, A. R. (2015). Evaluating wind extremes in CMIP5 climate models, Clim. Dyn., 45, 441–453. https://doi.org/10.1007/s00382-014-2306-2
- Pryor, S. C., Barthelmie, R. J., Clausen, N. E., et al. (2012). Analyses of possible changes in intense and extreme wind speeds over northern Europe under climate change scenarios, Clim. Dyn., 38, 189–208. https://doi.org/10.1007/s00382-010-0955-3

10. Number of days with 1-day wind speed exceeding the 97th percentile – WS97pN_1d

DEFINITION

WS97pN_1d describes the frequency of extreme wind speed conditions. It is defined as the number of days in a year or in a season with daily wind speed maximum exceeding the 97th percentile threshold in the reference period (1991-2020). Unit: days

STRENGHTS

- WS97pN_1d can be easily interpreted as directly linked to the frequency of 1-day wind speed extremes and complement the extreme intensity represented by WSx1d.
- By applying a percentile threshold, WS97pN_1d accounts for local climate conditions, making it suitable for comparing regions with different wind regimes.

LIMITATIONS

- WS97pN_1d values do not account for very localized and short-duration wind speed extremes (i.e., wind gusts).
- WS97pN_1d results depend on the percentile threshold and reference period used for its calculation. A preliminary evaluation is recommended to properly interpret or adapt the index definition to the specific goal and application.

REFERENCES

- Martius, O., Pfahl, S., and Chevalier, C. (2016). A global quantification of compound precipitation and wind extremes, Geophys. Res. Lett., 43, 7709–7717. https://doi.org/10.1002/2016GL070017

11. Mean of daily wind speed maxima exceeding the 97th percentile – WS97pMEAN_1d

DEFINITION

WS97pMEAN_1d represents the average intensity of daily wind speed extremes. It is defined by averaging all daily wind speed maxima in a year or a season exceeding the corresponding 97th percentile of daily wind speed maxima in the reference period (1991-2020). Unit: m/s

STRENGHTS

- WS97pMEAN_1d complements WSx1d by providing a measure of the mean intensity of extreme daily wind speed which accounts for all exceedances in a year or a season.
- Depending on how the 1-day wind speed maximum is defined, WS97pMEAN_1d can be used to account for short-duration wind speed extremes, e.g., wind gusts.
- By applying a percentile threshold, WS97pMEAN_1d accounts for local climate conditions. By normalizing the index values, the results for regions with different wind regimes can be compared.

LIMITATIONS

- WS97pMEAN_1d values do not account for very localized and short-duration wind speed extremes (i.e., wind gusts).
- WS97pMEAN_1d results depend on the percentile threshold and reference period used for its calculation. A preliminary evaluation is recommended to properly interpret or adapt the index definition to the specific goal and application.

REFERENCES

- Martius, O., Pfahl, S., and Chevalier, C. (2016). A global quantification of compound precipitation and wind extremes, Geophys. Res. Lett., 43, 7709–7717.

https://doi.org/10.1002/2016GL070017

Extreme Heat

12. Heatwave days – HWD

DEFINITION

HWD reports the total number of days in a year experiencing heatwave conditions. A heatwave event corresponds to a period of at least three consecutive days with maximum daily temperature exceeding the 95th percentile of all daily maximum temperatures recorded over the reference period (1991-2020). Unit: days

STRENGHTS

- HWD can be directly interpreted as a measure of the frequency of days under extreme heat conditions.
- By applying a percentile threshold, HWD accounts for local climate conditions, which makes it suitable for comparing areas with different climatic regimes.

LIMITATIONS

- HWD accounts only for frequency of heatwave conditions, but it does not report anything about their intensity and duration, which requires the integration of complementary indices.
- Results depend on the percentile threshold and reference period used for the percentile calculation. A preliminary evaluation is recommended to properly interpret or adapt the index definition to the specific goal and application.
- Since the percentile is derived from all daily temperatures in the reference period and applied as fixed threshold for detecting temperature exceedances over all year, HWD is expected to capture heatwaves mostly occurring in summer, when temperatures exceeding the calculated threshold are more likely.

REFERENCES

- Ruosteenoja, K., and Jylhä, K. (2023). Average and extreme heatwaves in Europe at 0.5–2.0 °C global warming levels in CMIP6 model simulations, Clim. Dyn., 61, 4259–4281. https://doi.org/10.1007/s00382-023-06798-4
- Russo, E., and Domeisen, D. I. V. (2023). Increasing intensity of extreme heatwaves: The crucial role of metrics, Geophys. Res. Lett., 50, e2023GL103540. https://doi.org/10.1029/2023GL103540

13. Heatwave magnitude – HWM

DEFINITION

HWM represents the maximum magnitude of heatwaves occurring in a year. The heatwave magnitude is a measure of the accumulated temperature excess, and it is defined as the sum over heatwave days of the difference between the daily maximum temperature and the temperature threshold (i.e., the 95th percentile) used for heatwave detection. A heatwave event corresponds to a period of at least three consecutive days with maximum daily temperature exceeding the 95th percentile of all daily maximum temperatures recorded over the reference period (1991-2020). Unit: °C

STRENGHTS

- By adopting a percentile-based threshold, HWM accounts for local climate conditions, which makes it suitable for comparing areas with different climatic regimes.
- HWM captures both the total intensity and overall duration of heatwave conditions.

LIMITATIONS

- By considering only the maximum magnitude over all heatwaves in a year, HWM does not account for the frequency of heatwaves and the occurrence of multiple episodes with similar magnitude.
- Results depend on the percentile threshold and reference period used for the percentile calculation. A preliminary evaluation is recommended to properly interpret or adapt the index definition to the specific goal and application.
- Since the percentile is derived from all daily temperatures in the reference period and applied as fixed threshold for detecting temperature exceedances over all year, HWM is expected to capture heatwaves mostly occurring in summer, when temperatures exceeding the calculated threshold are more likely.

REFERENCES

- Perkins-Kirkpatrick, S. E., and Lewis, S. C. (2020). Increasing trends in regional heatwaves, Nat. Commun., 11, 3357. https://doi.org/10.1038/s41467-020-16970-7
- Russo, E., and Domeisen, D. I. V. (2023). Increasing intensity of extreme heatwaves: The crucial role of metrics, Geophys. Res. Lett., 50, e2023GL103540. https://doi.org/10.1029/2023GL103540
- Russo, S., Sillmann, J., and Fischer, E. M. (2015). Top ten European heatwaves since 1950 and their occurrence in the coming decades, Environ. Res. Lett., 10, 124003. https://dx.doi.org/10.1088/1748-9326/10/12/124003

Drought

14. One-month drought peak intensity – SPEI1_int

DEFINITION

SPEI1_int describes the peak intensity of 1-month drought conditions. It is defined as the minimum SPEI1 value over a year or a season.
SPEI1 gives a measure of the surface water balance (i.e., the difference between precipitation and potential evapotranspiration) over a period of one month relative to the long-term average. SPEI1 values around 0 indicate normal conditions, while values below -1 indicate deficit conditions (e.g., -1 corresponds to a deficit of one standard deviation). SPEI1 values for the current period are derived from the daily SPEI dataset produced by the ADO project (https://www.alpine-space.eu/project/ado/) adopting 1981-2020 as calibration period and Penman-Monteith equation for the potential evapotranspiration calculation. The monthly SPEI1 values are derived by retaining the last SPEI1 entry of each month. For future projections, the potential evapotranspiration used for SPEI calculation is estimated from minimum and maximum temperature based on the Hargreaves equation, while the calibration period is based on GWL 0.61 °C. Further details on data and SPEI calculation are available in “About the data”. Unit: 1

STRENGHTS

- SPEI1_int can be interpreted directly as a measure of the peak intensity of 1-month drought extremes.
- By adopting a standardized index, SPEI1_int accounts for local climate conditions, which makes it suitable for comparing areas with different climatic regimes.

LIMITATIONS

- SPEI1_int accounts only for the most extreme 1-month drought over a certain period, while it does not report anything about event duration or the occurrence of other drought events in the considered period, for which complementary definitions are needed.
- SPEI1_int is based on monthly SPEI values, which limits the representation of extreme drought conditions of shorter durations (e.g., flash drought).
- Results depend on the evapotranspiration definition and the reference period used for SPEI1 calculation. A preliminary evaluation is recommended to properly interpret or adapt the index definition to the specific goal and application.

REFERENCES

- Venturi, S., Dunea, D., Mateescu, E., et al. (2025). SPEI and SPI correlation in the study of drought phenomena in Umbria region (central Italy), Environ. Sci. Pollut. Res., 32, 168–188. https://doi.org/10.1007/s11356-024-35740-2
- Hosseinzadehtalaei, P., Van Schaeybroeck, B., Termonia, P., and Tabari, H. (2023). Identical hierarchy of physical drought types for climate change signals and uncertainty, Weather Clim. Extrem. 41, 100573. https://doi.org/10.1016/j.wace.2023.100573

15. One-month drought frequency – SPEI1_freq

DEFINITION

SPEI1_freq describes the frequency of severe 1-month drought conditions. It counts all months in a year or a season with SPEI1 < -1.5.
SPEI1 gives a measure of the surface water balance (i.e., the difference between precipitation and potential evapotranspiration) over a period of one month relative to the long-term average. SPEI1 values around 0 indicate normal conditions, while values below -1 indicate deficit conditions (e.g., -1 corresponds to a deficit of one standard deviation).
SPEI1 values for the current period are derived from the daily SPEI dataset produced by the ADO project (https://www.alpine-space.eu/project/ado/) adopting 1981-2020 as calibration period and Penman-Monteith equation for the potential evapotranspiration calculation. The monthly SPEI1 values are derived by retaining the last SPEI1 entry of each month. For future projections, the potential evapotranspiration used for SPEI calculation is estimated from minimum and maximum temperature based on the Hargreaves equation, while the calibration period is based on GWL 0.61 °C. Further details on data and SPEI calculation are available in “About the data”.
Unit: months

STRENGHTS

- SPEI1_freq can be interpreted directly as a measure of the frequency of severe 1-month drought extremes and complements drought intensity reported by SPEI1_int.
- By adopting a standardized index, SPEI1_freq accounts for local climate conditions, which makes it suitable for comparing areas with different climatic regimes.

LIMITATIONS

- SPEI1_freq does not report anything about event duration, so that consecutive months belonging to the same drought spell are counted as independent drought occurrences.
- SPEI1_freq is based on monthly SPEI values, which limits the representation of extreme drought conditions of shorter durations (e.g., flash drought).
- Results depend on the evapotranspiration definition and the reference period used for SPEI1 calculation. A preliminary evaluation is recommended to properly interpret or adapt the index definition to the specific goal and application.

REFERENCES

- Chiang, F., Mazdiyasni, O., and AghaKouchak, A. (2021). Evidence of anthropogenic impacts on global drought frequency, duration, and intensity, Nat. Commun., 12, 2754. https://doi.org/10.1038/s41467-021-22314-w
- Potopová, V., Stepanek, P., Zahradníček, P., Farda, A., Türkott, L., and Soukup, J. (2018). Projected changes in the evolution of drought on various timescales over the Czech Republic according to Euro-CORDEX models, Int. J. Climatol, 38, e939–e954. https://doi.org/10.1002/joc.5421
- Spinoni, J., Vogt, J. V., Naumann, G., Barbosa, P., and Dosio, A. (2018). Will drought events

become more frequent and severe in Europe?, Int. J. Climatol., 38, 1718–1736. https://doi.org/10.1002/joc.5291

16. Three-month drought peak intensity – SPEI3_int

DEFINITION

SPEI3_int describes the peak intensity of 3-month drought conditions. It is defined as the minimum SPEI3 value over a year or a season.
SPEI3 gives a measure of the surface water balance (i.e., the difference between precipitation and potential evapotranspiration) over a period of three months relative to the long-term average. SPEI3 values around 0 indicate normal conditions, while values below -1 indicate deficit conditions (e.g., -1 corresponds to a deficit of one standard deviation).
SPEI3 values for the current period are derived from the daily SPEI dataset produced by the ADO project (https://www.alpine-space.eu/project/ado/) adopting 1981-2020 as calibration period and Penman-Monteith equation for the potential evapotranspiration calculation. The monthly SPEI3 values are derived by retaining the last SPEI3 entry of each month. For future projections, the potential evapotranspiration used for SPEI calculation is estimated from minimum and maximum temperature based on the Hargreaves equation, while the calibration period corresponds to GWL 0.61 °C. Further details on data and SPEI calculation are available in “About the data”. Unit: 1

STRENGHTS

- SPEI3_int can be interpreted directly as a measure of the peak intensity of 3-month drought extremes.
- By adopting a standardized index, SPEI3_int accounts for local climate conditions, which makes it suitable for comparing areas with different climatic regimes.

LIMITATIONS

- SPEI3_int accounts only for the most extreme monthly SPEI3 value over a certain period, while it does not report anything about event duration or drought frequency, for which complementary definitions are needed.
- Results depend on the evapotranspiration definition and the reference period used for SPEI3 calculation. A preliminary evaluation is recommended to properly interpret or adapt the index definition to the specific goal and application.

REFERENCES

- Venturi, S., Dunea, D., Mateescu, E., et al. (2025). SPEI and SPI correlation in the study of drought phenomena in Umbria region (central Italy), Environ. Sci. Pollut. Res., 32, 168–188. https://doi.org/10.1007/s11356-024-35740-2
- Hosseinzadehtalaei, P., Van Schaeybroeck, B., Termonia, P., and Tabari, H. (2023). Identical hierarchy of physical drought types for climate change signals and uncertainty, Weather Clim. Extrem. 41, 100573. https://doi.org/10.1016/j.wace.2023.100573

17. Three-month drought frequency – SPEI3_freq

DEFINITION

SPEI3_freq describes the frequency of severe 3-month drought conditions. It counts all months in a year or a season with SPEI3 < -1.5.
SPEI3 gives a measure of the surface water balance (i.e., the difference between precipitation and potential evapotranspiration) over a period of three months relative to the long-term average. SPEI3 values around 0 indicate normal conditions, while values below -1 indicate deficit conditions (e.g., -1 corresponds to a deficit of one standard deviation).
SPEI3 values for the current period are derived from the daily SPEI dataset produced by the ADO project (https://www.alpine-space.eu/project/ado/) adopting 1981-2020 as calibration period and Penman-Monteith equation for the potential evapotranspiration calculation. The monthly SPEI3 values are derived by retaining the last SPEI3 entry of each month. For future projections, the potential evapotranspiration used for SPEI calculation is estimated from minimum and maximum temperature based on the Hargreaves equation, while the calibration period corresponds to GWL 0.61 °C. Further details on data and SPEI calculation are available in “About the data”. Unit: months

STRENGHTS

- SPEI3_freq can be interpreted directly as a measure of the frequency of severe 3-month drought extremes and complement the 3-month drought intensity reported by SPEI3_int.
- By adopting a standardized index, SPEI3_freq accounts for local climate conditions, which makes it suitable for comparing areas with different climatic regimes.

LIMITATIONS

- SPEI3_freq does not report anything about event duration, so that consecutive months belonging to the same drought spell are counted as independent drought occurrences.
- Results depend on the evapotranspiration definition and the reference period used for SPEI3 calculation. A preliminary evaluation is recommended to properly interpret or adapt the index definition to the specific goal and application.

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Compound extremes

18. Number of days with extreme 3-day precipitation and 1-day wind speed maximum – RWS97pN_3d

DEFINITION

RWS97pN_3d describes the frequency of compound precipitation and wind speed extremes in a year or in a season. It is defined as the number of days in a year or in a season when both 3-day precipitation total and daily maximum wind speed are above their respective 97th percentile threshold calculated over the reference period (1991-2020). Unit: days

STRENGHTS

- Since compound extremes are detected over a 3-day window, RWS97pN_3d accounts for possible mismatches in the timing of occurrence of wind and precipitation extremes associated to the same meteorological episode.
- By adopting a percentile threshold, RWS97pN_3d accounts for local climate conditions, making it suitable for comparing regions with different climatic regimes.
- RWS97pN_3d is designed to represent extreme events with multi-day duration.

LIMITATIONS

- Since RWS97pN_3d requires that extreme wind speed and precipitation occur exactly in the same location/grid point, co-occurrent extreme conditions recorded at close but not identical locations are not included.
- The spatial resolution of data used for the index calculation affects the ability to capture small-scale processes.
- RWS97pN_3d results depend on the percentile threshold and reference period used for its calculation. A preliminary evaluation is recommended to properly interpret or adapt the index definition to the specific goal and application.

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19. Magnitude of compound one-month drought and heatwave events – CDHW_1

DEFINITION

CDHW_1 represents the maximum magnitude of compound heatwave and 1-month drought events in a year. A compound event is detected when heatwave days are included in a month experiencing short-term drought, i.e., with SPEI1 < -1. The compound magnitude for each drought-heatwave event is described by multiplying the heatwave magnitude (HWM) normalized by the heatwave duration times the absolute value of SPEI1 in the corresponding month.
A heatwave event corresponds to a period of at least three consecutive days with maximum daily temperature exceeding the 95th percentile of all daily maximum temperatures recorded during the reference period (1991-2020).
SPEI1 gives a measure of the surface water balance (i.e., the difference between precipitation and potential evapotranspiration) over a period of one month relative to the long-term average. SPEI1 values around 0 indicate normal conditions, while values below -1 indicate deficit conditions (e.g., -1 corresponds to a deficit of one standard deviation).
SPEI1 values for the current period are derived from the daily SPEI dataset produced by the ADO project (https://www.alpine-space.eu/project/ado/) adopting 1981-2020 as calibration period and Penman-Monteith equation for the potential evapotranspiration calculation. The monthly SPEI1 values are derived by retaining the last SPEI1 entry of each month. To ensure consistency, maximum temperature used for calculating the heatwave magnitude in the historical period was retrieved from the same ADO dataset. For future projections, the potential evapotranspiration used for SPEI calculation is estimated from minimum and maximum temperature based on the Hargreaves equation, while the calibration period is based on GWL 0.61 °C. Further details on data and SPEI calculation are available in “About the data”. Unit: °C

STRENGHTS

- By adopting a percentile-based threshold for heatwave definition and a standardized index (SPEI1) for drought description, CDHW_1 accounts for local climate conditions, making it suitable for comparing regions with different climatic regimes.
- Since compound occurrences are identified over a monthly window, the index considers the different timing of the two combined extreme phenomena.

LIMITATIONS

- By considering only the maximum magnitude over all compound events in a year, CDHW_1 does not account for their frequency and the occurrence of multiple episodes with similar magnitude.
- Results depend on the percentile threshold and reference period used for the heatwave detection and SPEI1 calculation. A preliminary evaluation is recommended to properly interpret or adapt the index definition to the specific goal and application.
- Since the heatwave percentile is derived from all daily temperatures in the reference period

and applied as fixed threshold for detecting temperature exceedances over all year, CDHW_1 is expected to capture compound events mostly occurring in summer, when temperatures exceeding the calculated threshold are more likely.

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20. Magnitude of compound three-month and heatwave events - CDHW_3

DEFINITION

CDHW_3 represents the maximum magnitude of compound heatwave and 3-month drought events in a year. A compound event is detected when heatwave days are included in a month experiencing long-term drought, i.e., with SPEI3 < -1. The compound magnitude for each drought-heatwave event is described by multiplying the heatwave magnitude (HWM) normalized by the heatwave duration times the absolute value of SPEI3 in the corresponding month.
A heatwave event corresponds to a period of at least three consecutive days with maximum daily temperature exceeding the 95th percentile of all daily maximum temperatures recorded during the reference period (1991-2020).
SPEI3 values for the current period are derived from the daily SPEI dataset produced by the ADO project (https://www.alpine-space.eu/project/ado/) adopting 1981-2020 as calibration period and Penman-Monteith equation for the potential evapotranspiration calculation. The monthly SPEI3 values are derived by retaining the last SPEI3 entry of each month. To ensure consistency, maximum temperature used for calculating the heatwave magnitude in the historical period was retrieved from the same ADO dataset. For future projections, the potential evapotranspiration used for SPEI calculation is estimated from minimum and maximum temperature based on the Hargreaves equation, while the calibration period is based on GWL 0.61 °C. Further details on data and SPEI calculation are available in "About the data". Unit: °C

STRENGHTS

- By adopting a percentile-based threshold for heatwave definition and a standardized index (SPEI3) for drought description, CDHW_3 accounts for local climate conditions, making it suitable for comparing regions with different climatic regimes.
- Since compound occurrences are identified over a monthly window, the index considers the different timing of the two combined extreme phenomena.

LIMITATIONS

- By considering only the maximum magnitude over all compound events in a year, CDHW_3 does not account for their frequency and the occurrence of multiple episodes with similar

magnitude.

- Results depend on the percentile threshold and reference period used for the heatwave detection and SPEI3 calculation. A preliminary evaluation is recommended to properly interpret or adapt the index definition to the specific goal and application.
- Since the heatwave percentile is derived from all daily temperatures in the reference period and applied as fixed threshold for detecting temperature exceedances over all year, CDHW_3 is expected to capture compound events mostly occurring in summer, when temperatures exceeding the calculated threshold are more likely.

REFERENCES

- Zhang, Q., She, D., Zhang, L., Wang, G., Chen, J., and Hao, Z. (2022). High sensitivity of compound drought and heatwave events to global warming in the future, Earth's Future, 10, e2022EF002833. https://doi.org/10.1029/2022EF002833