Weather regimes as a proxy for extremes in the power system

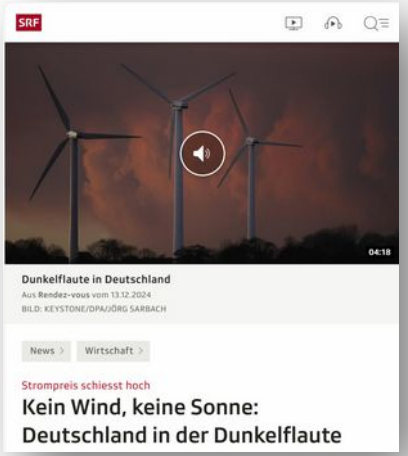
Christian M. Grams[1], Dominik Büeler[1], Fabian Mockert[2]

[1]MeteoSwiss, Zurich-Airport, Switzerland

[2]IMKTRO, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

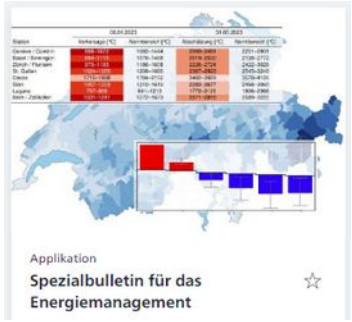
Keystone

Axpo Holding AG

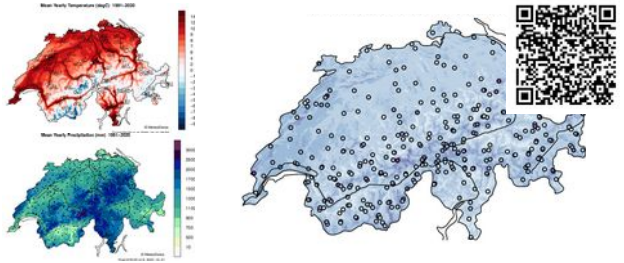


MeteoSwiss climate services in support of the energy transition

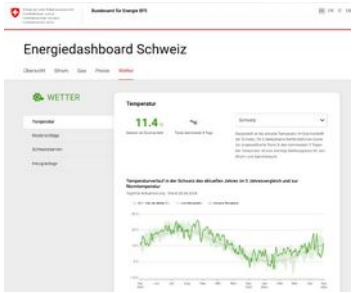
Energy Bulletin



Seamless Weather and Climate Data

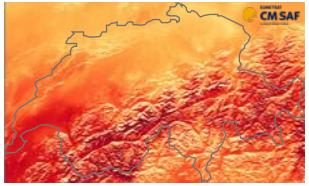


Energy Dashboard

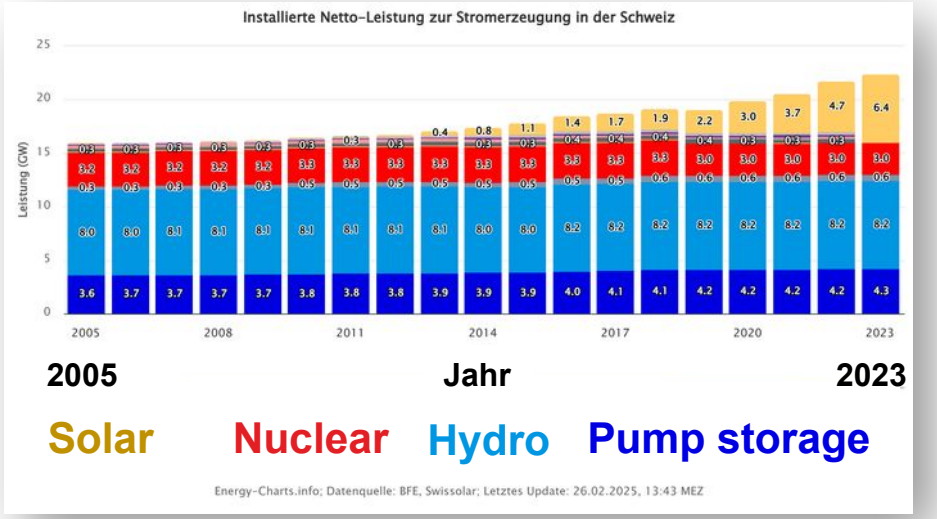


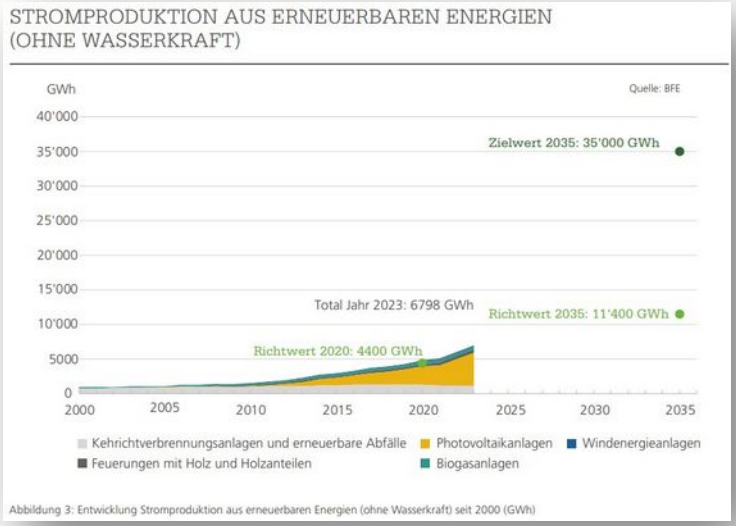
Solar potential

www.sonnenfassade.ch
www.sonnendach.ch



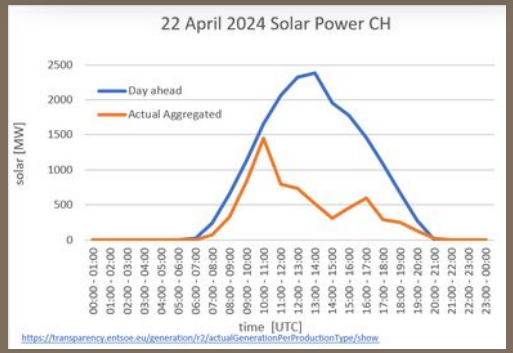
The Swiss energy transition

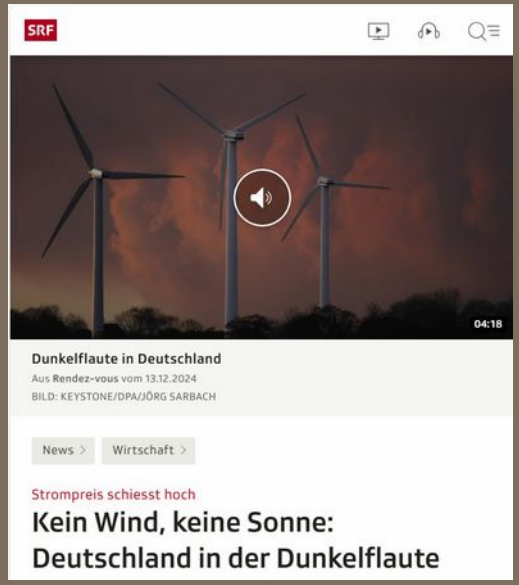




Quelle: Swiss Energy-charts / Energie Schweiz / BFE / Swisssolar
https://www.energy-charts.info/index.html?l=de&c=CH

Source: BFE / UVEK
Energiestrategie 2025 Monitoring Bericht 2024 Kurzfassung (abgerufen am 28.2. 2025
)

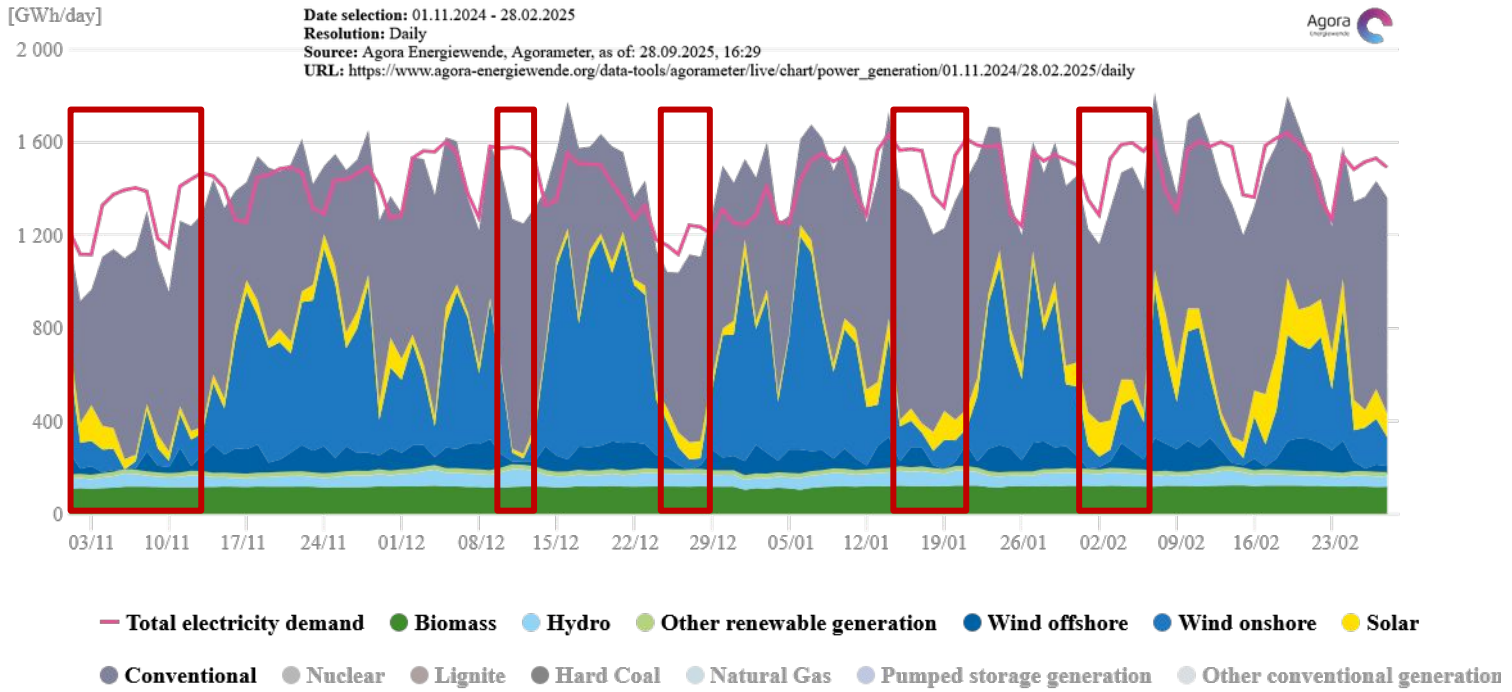




Sources: https://transparency.entsoe.eu/generation/r2/actualGenerationPerProductionType/show
NZZ 30.4.2024
https://www.nzz.ch/wirtschaft/fehlprognose-beim-solarstrom-ploetzlich-fehlte-der-schweiz-die-produktion-eines-grossen-kernkraftwerkes-ld.1828058

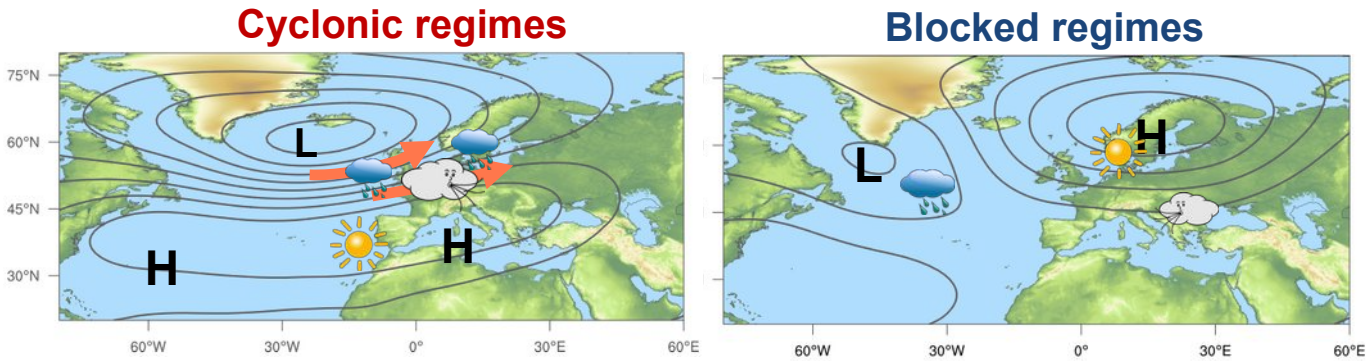
SRF 13.12.2024: https://www.srf.ch/news/wirtschaft/strompreis-schiesst-hoch-kein-wind-keine-sonne-deutschland-in-der-dunkelflaute

Multi-day variability winter 2024/25 in Germany



Weather regimes

- WR are *quasi-stationary, persistent, and recurrent* states of the large-scale flow
- WR explain *multi-day variability* of *large-scale flow* over a specific region



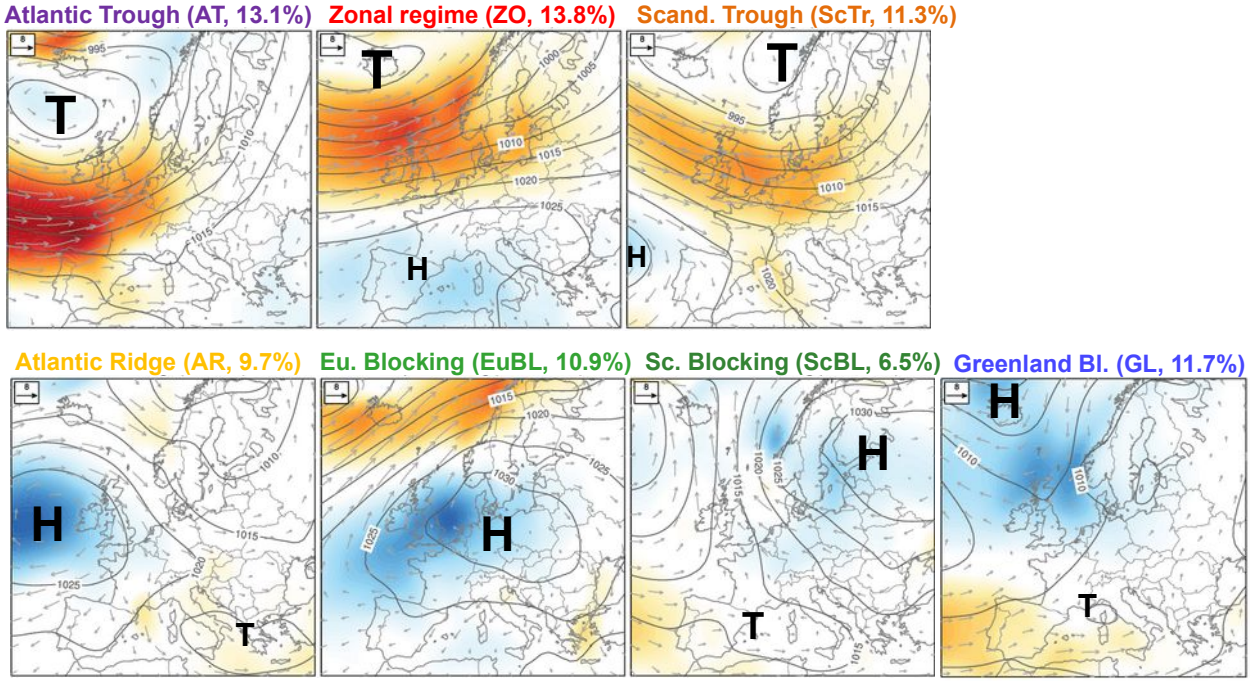
Here following Grams et al. 2017 doi:10.1038/nclimate3338 adapted to ERA5

- 10d low-pass filtered normalized Z500 anomalies from **ERA5 (1979-2019)**
- EOF analysis & k-means clustering of 7 leading EOFs (76% of variability) & objective definition of individual regime life cycles (e.g. >5 day persistence)

Slido survey

1) Have you heard of weather regimes and in which context are you using regimes?
2) For which region are using regimes?
3) How often are you using regimes?
4) From which source are you getting regime data information?

Weather regimes – 100m wind variability (winter)

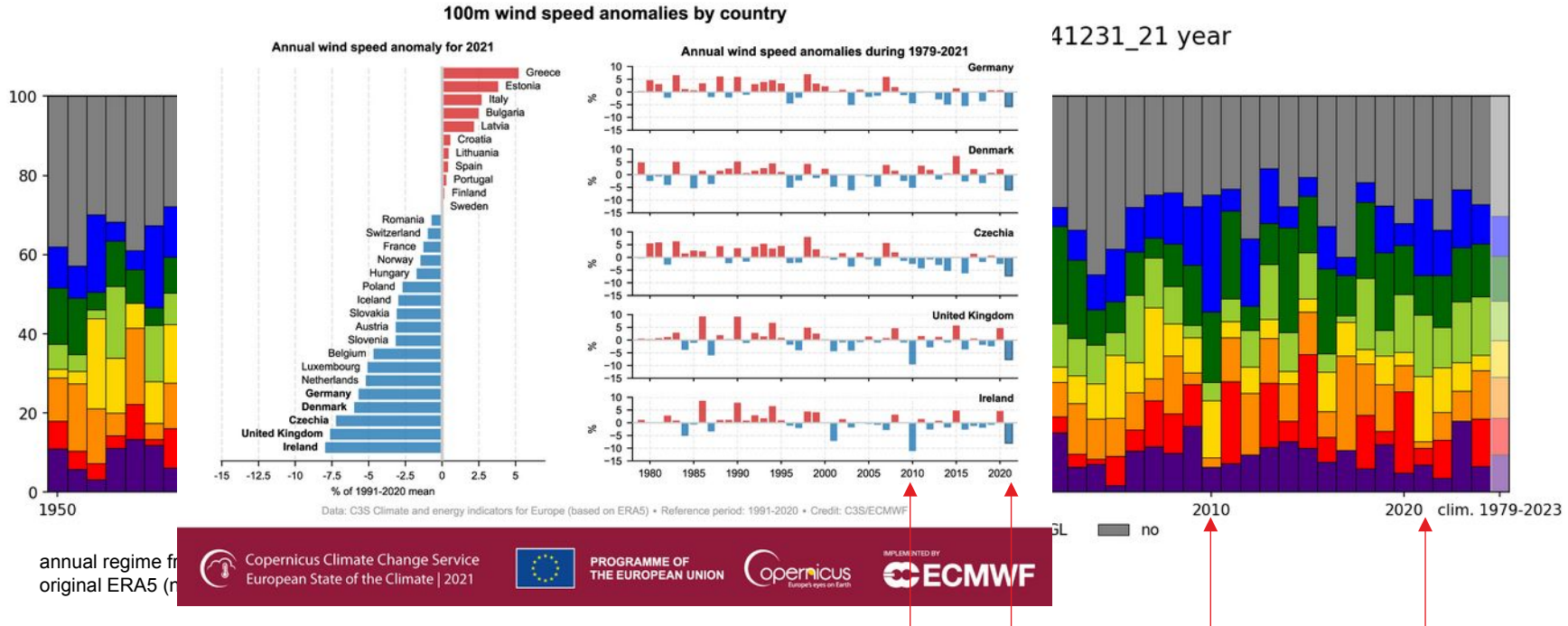


Cyclonic regimes go along with **above average wind** speed in most countries adjacent to the **North Sea**

Blocked regimes go along with **below average wind** speed in most countries adjacent to the **North Sea**

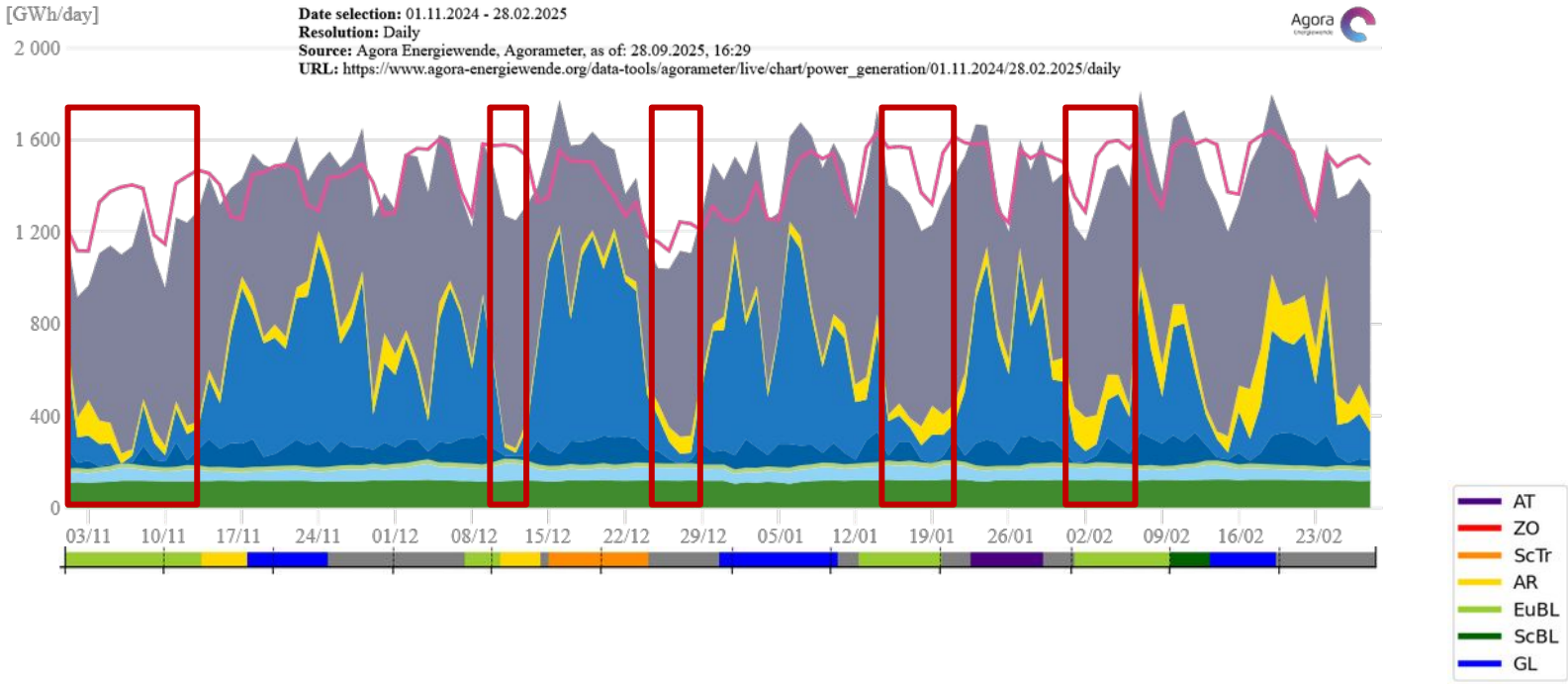
Grams, C.M., et al. (2017), doi:10.1038/nclimate3338.
Blog: https://christiangrams.wordpress.com/balancing-europes-wind-power/
see also Zubiate et al. (2017) doi:10.1002/qj.2943

Regime interannual variability



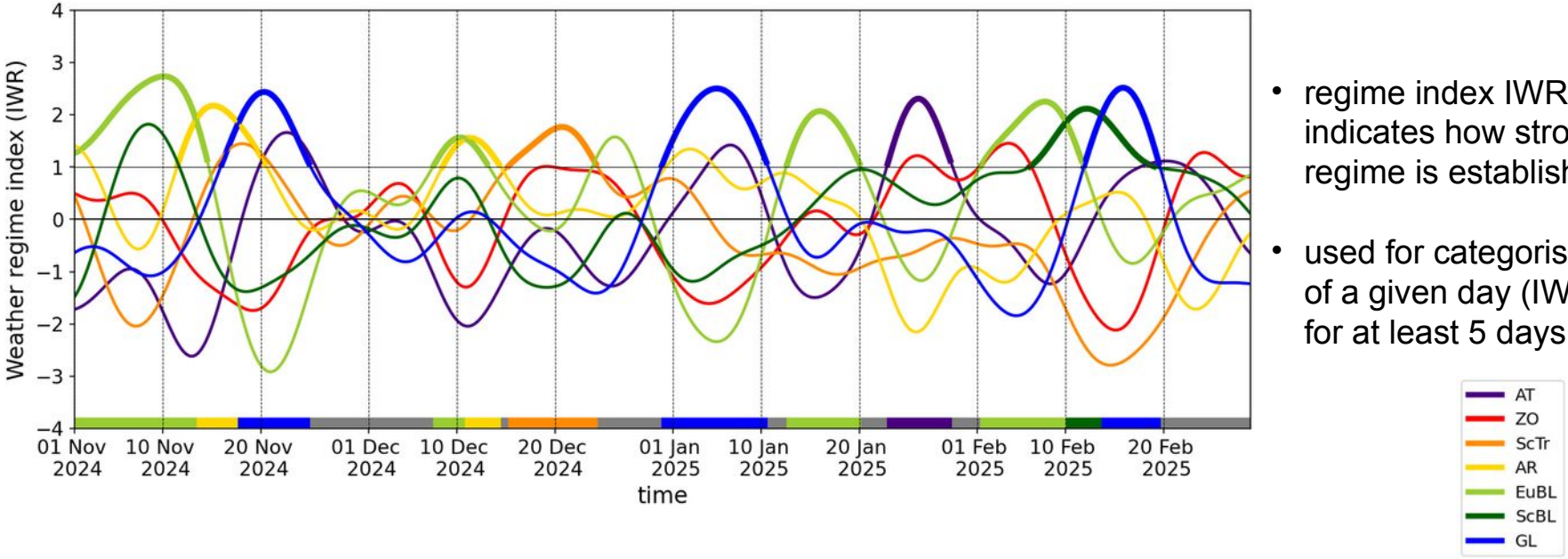
Central and NW European wind drought 2021
https://climate.copernicus.eu/esotc/2021/low-winds

Multi-day variability winter 2024/25 in Germany



Weather regimes in winter 2024/25

weather regime index time series 1.11.2024-28.2.2025



- regime index IWR indicates how strongly regime is established
- used for categorisation of a given day (IWR>1.0 for at least 5 days, …)

“Dunkelflaute” in Germany

- periods with little wind & solar power output
- often feared as „cold Dunkelflaute“
- following Drücke et al. 2021 (doi:10.1016/j.renene.2020.10.102)
- objective definition: combined capacity factor < 0.06 for at least 2 days

Meteorological Applications
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RESEARCH ARTICLE | Open Access

Meteorological conditions during periods of low wind speed and insolation in Germany: The role of weather regimes

Fabian Mockert, Christian M. Grams, Tom Brown, Fabian Neumann

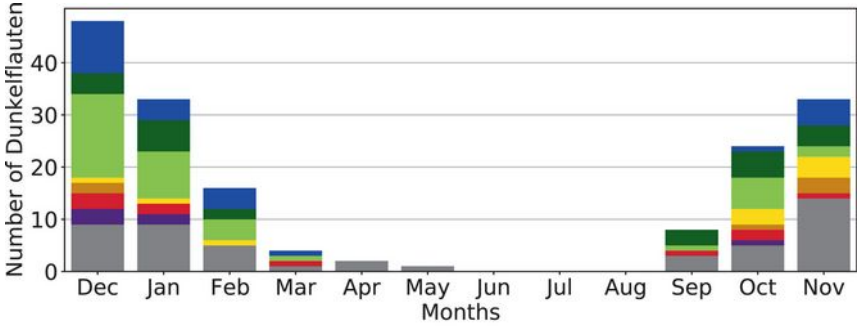
First published: 21 July 2023 | https://doi.org/10.1002/met.2141 | Citations: 1

https://doi.org/10.1002/met.2141

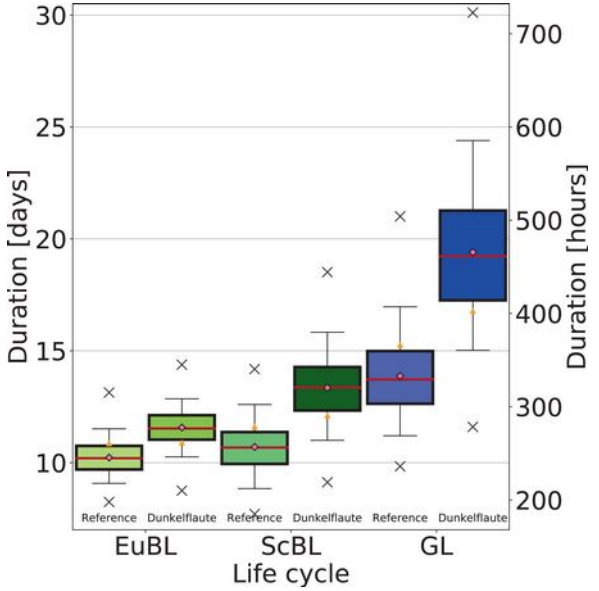
Collaboration with Prof. Dr. Tom Brown, Dr. Fabian Neumann (TU Berlin) and **Fabian Mockert** (KIT)

Mockert et al. 2023, doi:10.1002/met.2141

“Dunkelflaute” in Germany – seasonality and link to regimes



- Dunkelflauten preferentially in winter and during **European Blocking** and **Greenland Blocking**
- in autumn also **Scandinavian Blocking**



- Dunkelflauten occur in particularly long-lasting regime life cycles

Mockert et al. 2023, doi:10.1002/met.2141

“Dunkelflaute” in Germany – surface weather

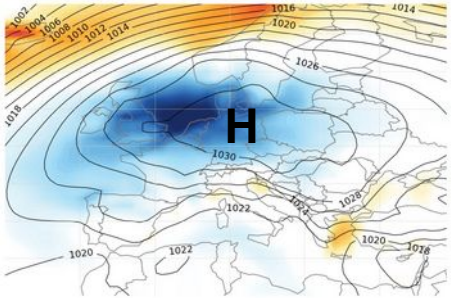
European Blocking

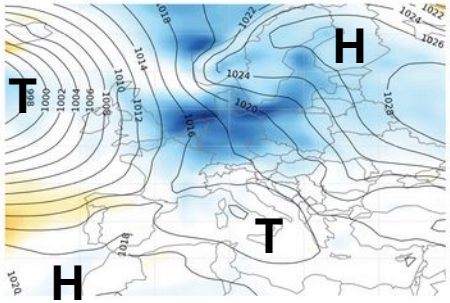
Scandinavian Blocking

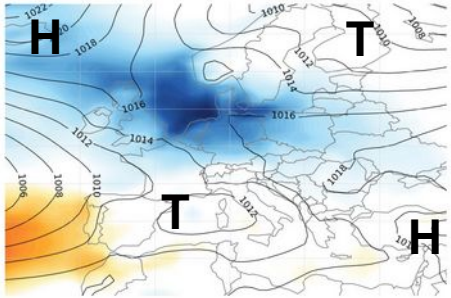
Greenland Blocking

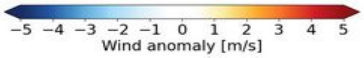
100m wind

2m temperature

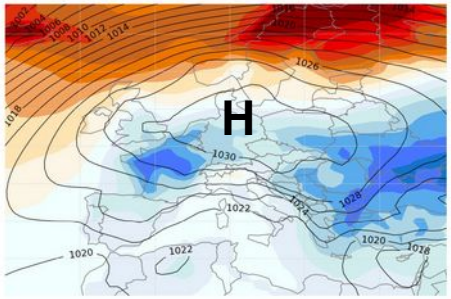


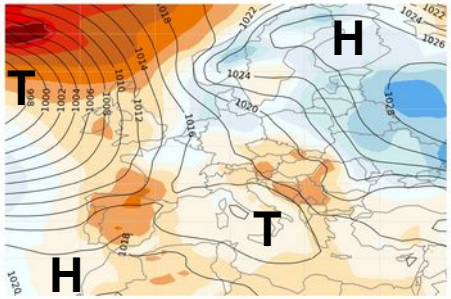


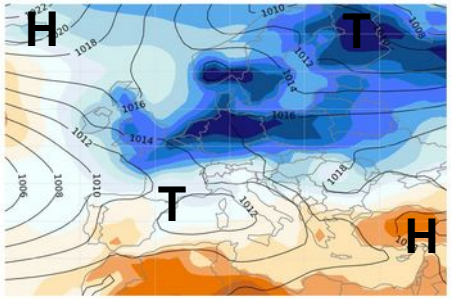


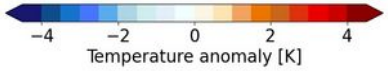


cold Dunkelflaute !

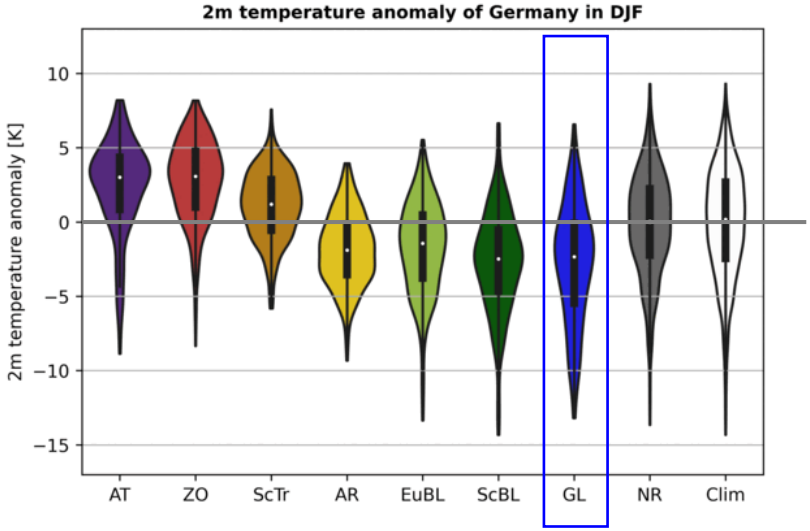








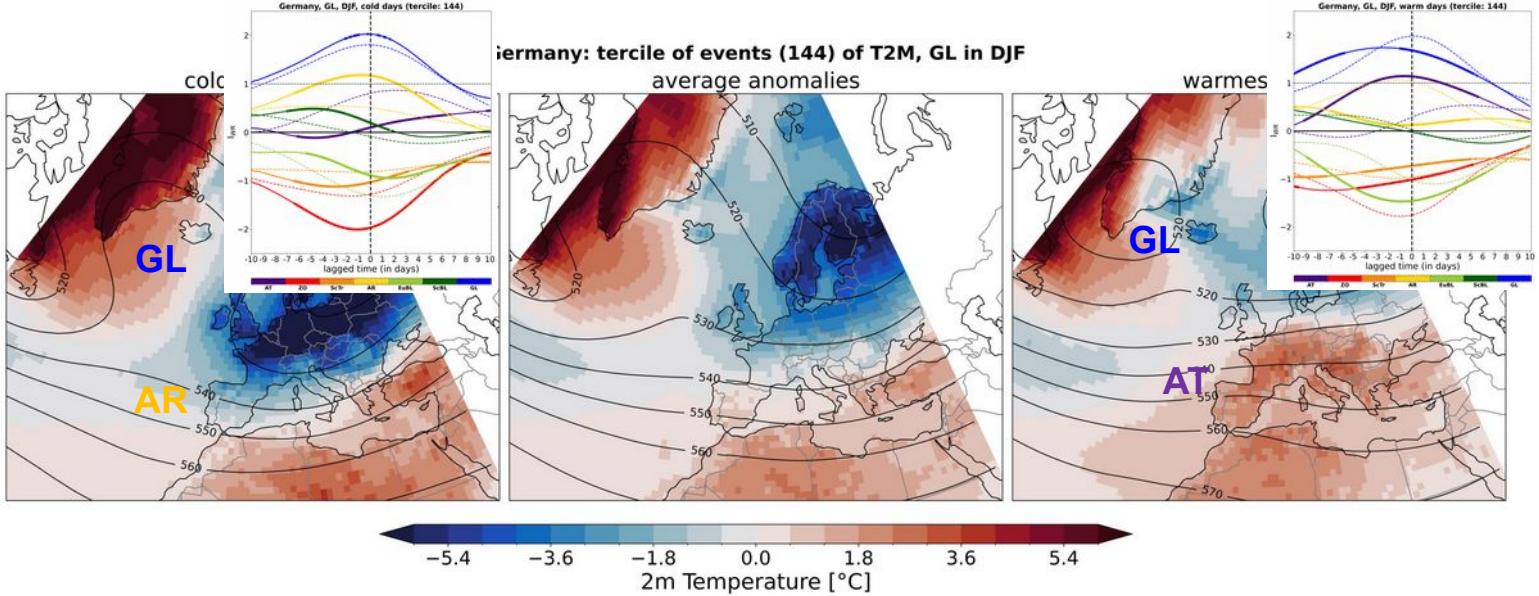
intra-regime weather variability



- country-aggregated 2mT anomaly (ERA5) Germany
- e.g. there are cold and mild GL days

Gerighausen et al. 2025 doi:10.48550/arXiv.2408.04302. *in press at Met. Apps.*

intra-regime weather variability



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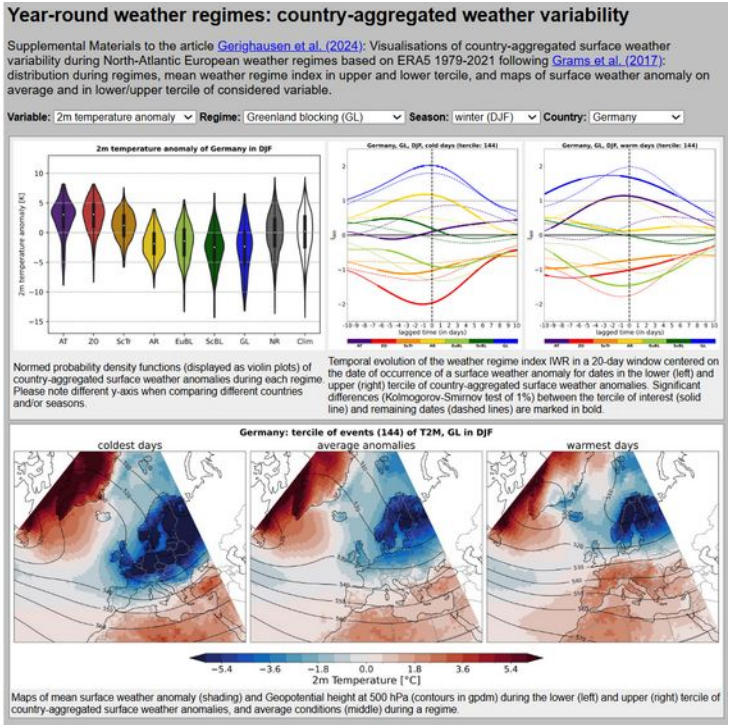
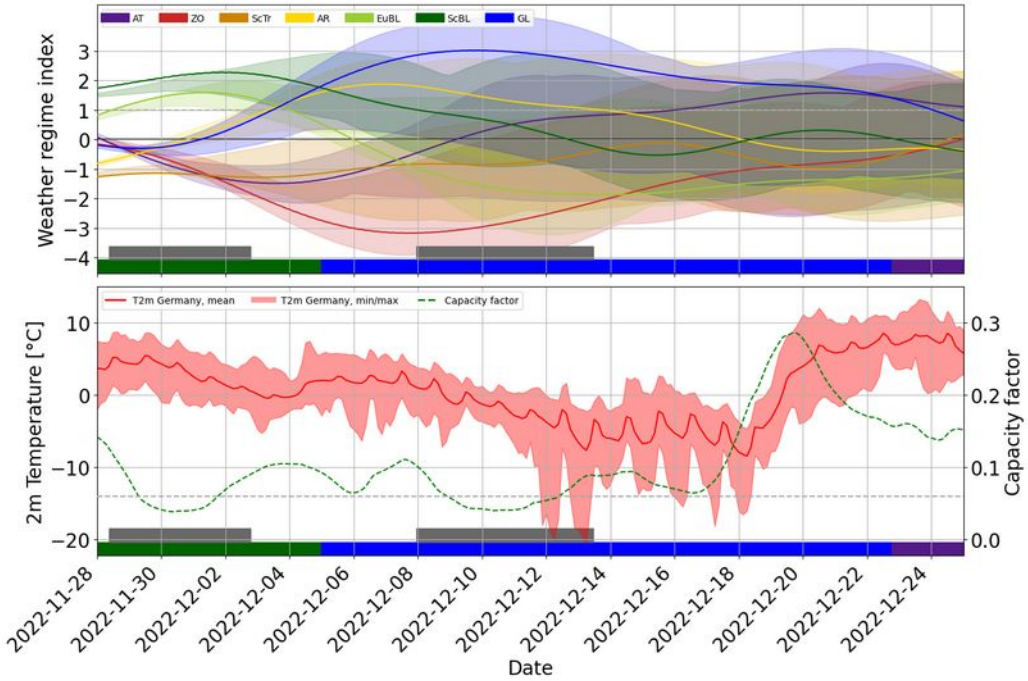
intra-regime weather variability



Gerighausen et al. 2025
doi:10.48550/arXiv.2408.04302
in press at Met. Apps.

interactive visualisations
retrievable at Zenodo:
https://zenodo.org/records/12923703
(**3 GB**!)

regime knowledge in forecasting

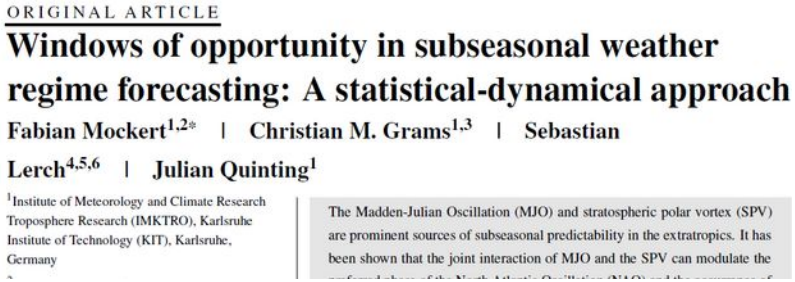


- ECMWF extended-range forecast of regime index correctly predicts GL and co-projection in AR three weeks ahead!
- this was related to a cold Dunkelflaute

Gerighausen et al. 2025
doi:10.48550/arXiv.2408.04302
in press at Met. Apps.

outlook regimes and forecasting

- MeteoSwiss together with ECMWF currently implement operational forcast products for these regimes
- Exploration of solar power gaps in Switzerland in a MSc thesis at MeteoSwiss
- Modulation by stratosphere and MJO provide „window of forecast opportunity“ (Cassou 2008, Beerli and Grams 2019, Lee et al. 2019, Spaeth et al. 2024)
- PostProcessing and ML-tuned „regime activity“ forecast very promising for improving regime prediction up to three weeks (Mockert et al. 2025 in review for QJRMS)



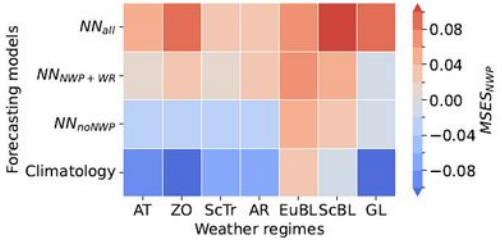
ORIGINAL ARTICLE

Windows of opportunity in subseasonal weather regime forecasting: A statistical-dynamical approach

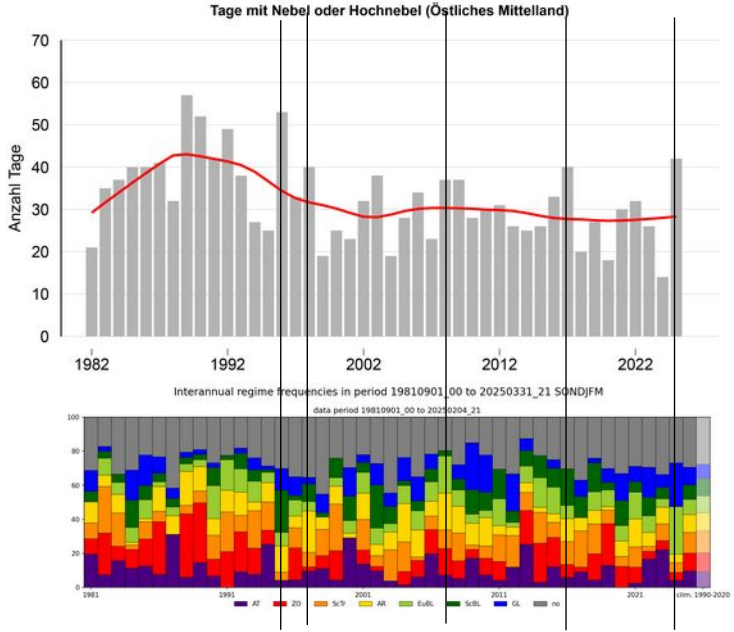
Fabian Mockert[1,2*] | Christian M. Grams[1,3] | Sebastian Lerch[4,5,6] | Julian Quinting[1]

[1]Institute of Meteorology and Climate Research Troposphere Research (IMKTRO), Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

The Madden-Julian Oscillation (MJO) and stratospheric polar vortex (SPV) are prominent sources of subseasonal predictability in the extratropics. It has been shown that the joint interaction of MJO and the SPV can modulate the

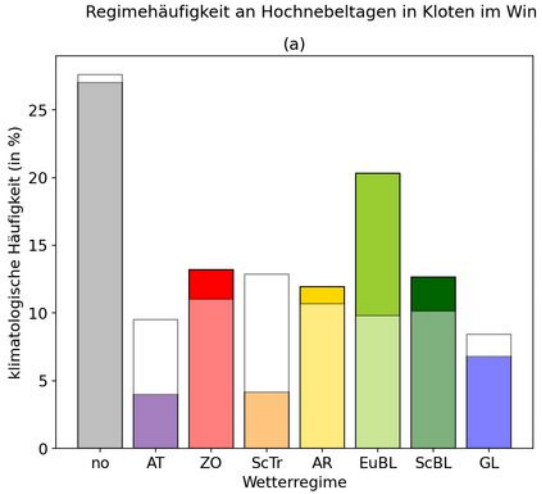


Regimes for climate monitoring: low stratus in Zurich



1995/96

2024/25

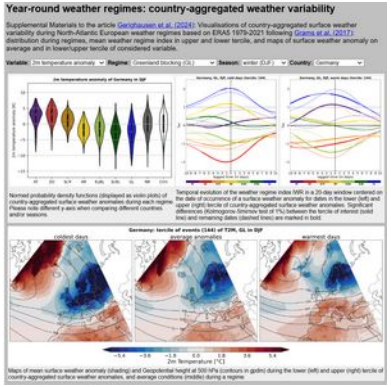


bold: regime frequency during fog days SONDJFM 1981-2025
white/pale: climatological regime frequency SONDJFM 1990/91-2020/21

Klimablog 25.2.2025
https://www.meteoschweiz.admin.ch/ueber-uns/meteoschweiz-blog/de/2025/02/nebliges-halbjahr.html

Summary

- weather regimes multi-day weather variability with relevance for wind and solar power
- Dunkelflauten related to blocked regimes
- Greenland blocking can produce cold Dunkelflaute
- regime knowledge helps understanding intra-regime weather variability and aids forecasting
- MeteoSwiss currently explores use of regimes for climate monitoring and sub-seasonal forecasting
- Solar power gaps of concern for CH energy transition



interactive visualisations
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(**3 GB**!)

christian.grams@meteoswiss.ch

Slido survey

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Literature on year-round regimes

Regimes and surface weather modulation:

Beerli, R., and C. M. Grams, 2019: Stratospheric modulation of the large-scale circulation in the Atlantic–European region and its implications for surface weather events. *Q.J.R. Meteorol. Soc.*, **145**, 3732–3750, doi:10.1002/qj.3653.

Domeisen, D. I. V., C. M. Grams, and L. Papritz, 2020: The role of North Atlantic–European weather regimes in the surface impact of sudden stratospheric warming events. *Weather and Climate Dynamics*, **1**, 373–388, doi:https://doi.org/10.5194/wcd-1-373-2020.

Gerighausen, J., J. Dorrington, F. Mockert, M. Osman, and C. M. Grams, 2024: Quantifying intra-regime weather variability for energy applications. doi:10.48550/ARXIV.2408.04302. https://arxiv.org/abs/2408.04302 (Accessed August 24, 2025, in press for Met. Apps.).

Gerighausen, J., Dorrington, J., Osman, M., & Grams, C. (2024). Collection of figures to explore intra-regime weather variability of North Atlantic-European year-round weather regimes as Supplementary Dataset for Gerighausen et al. (2024) (1.0). Zenodo. https://doi.org/10.5281/zenodo.12923703

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MeteoSchweiz
Operation Center 1
CH-8058 Zürich-Flughafen
T +41 58 460 91 11
www.meteoschweiz.ch

christian.grams@meteoswiss.ch

MeteoSvizzera
Via ai Monti 146
CH-6605 Locarno-Monti
T +41 58 460 92 22
www.meteosvizzera.ch

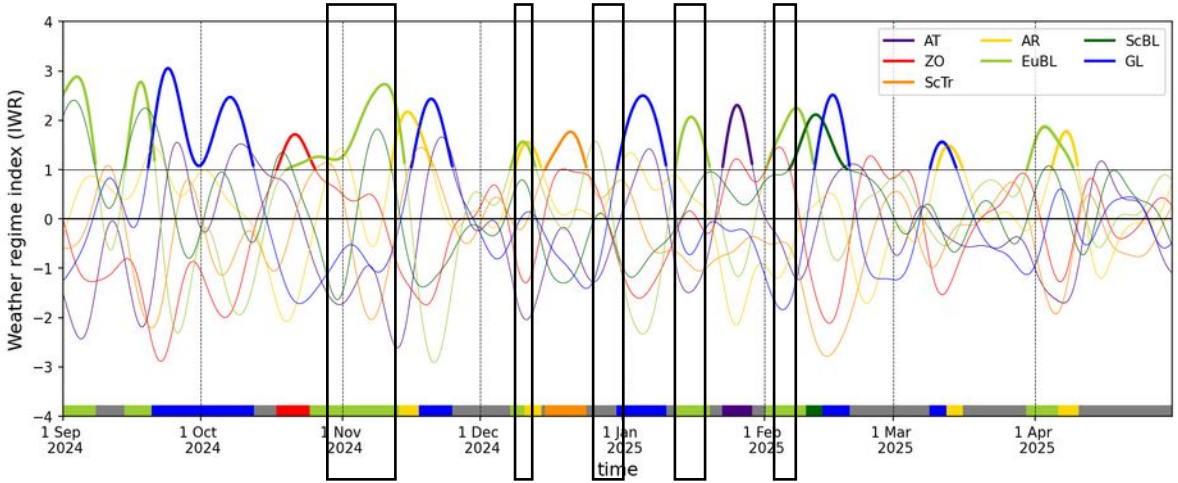
MétéoSuisse
7bis, av. de la Paix
CH-1211 Genève 2
T +41 58 460 98 88
www.meteosuisse.ch

MétéoSuisse
Chemin de l'Aérologie
CH-1530 Payerne
T +41 58 460 94 44
www.meteosuisse.ch

EXTRA SLIDES

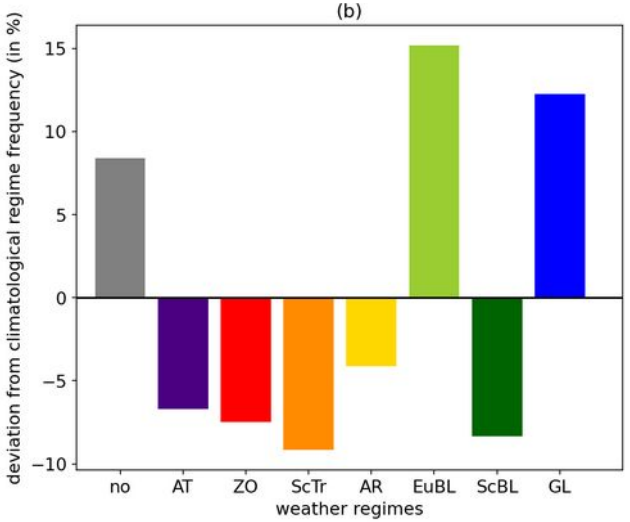
Regimes for climate monitoring

weather regime index time series 1.9.2024-30.4.2025



low stratus in ZRH (Hochnebel)

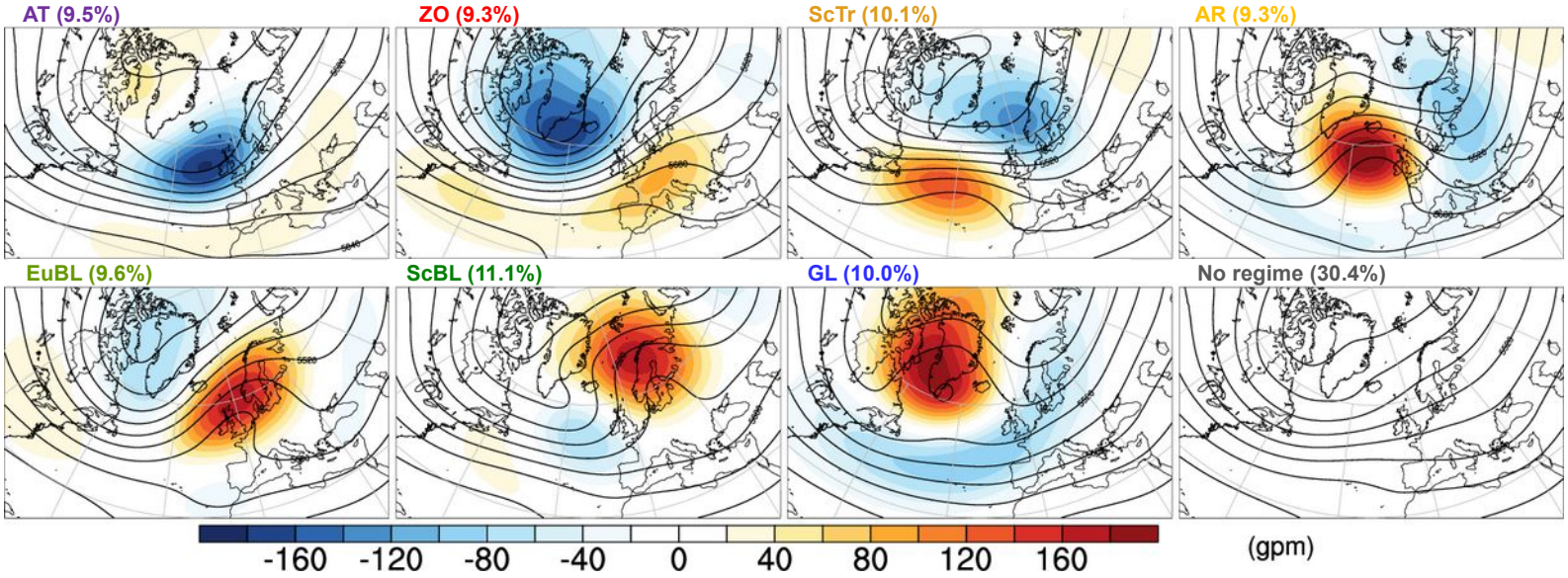
anomalous regime freq. in 2024/25



EuBL: 3x more frequent
GL: 2.5x more frequent

Weather regimes

cluster mean Z500 anomaly $\overline{\phi'(\varphi,\lambda)}_{wr}$ shading) **and absolute values** (black contours)



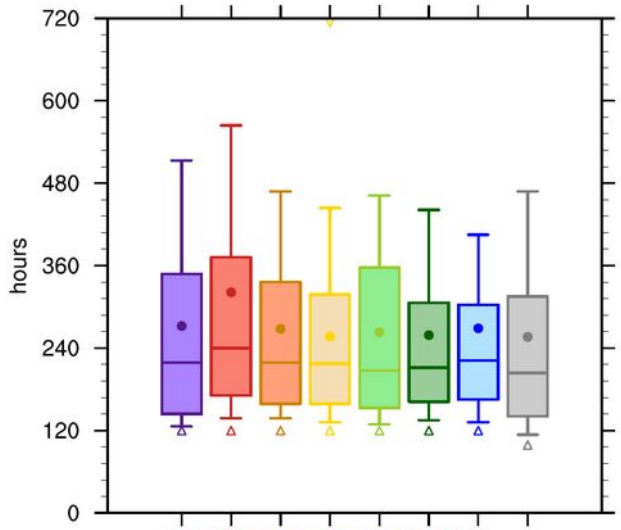
Cyclonic regimes:
- Atlantic trough
- Zonal Regime
- Scandinavian trough

Blocked regimes:
- Atlantic ridge
- European blocking
- Scandinavian blocking
- Greenland blocking

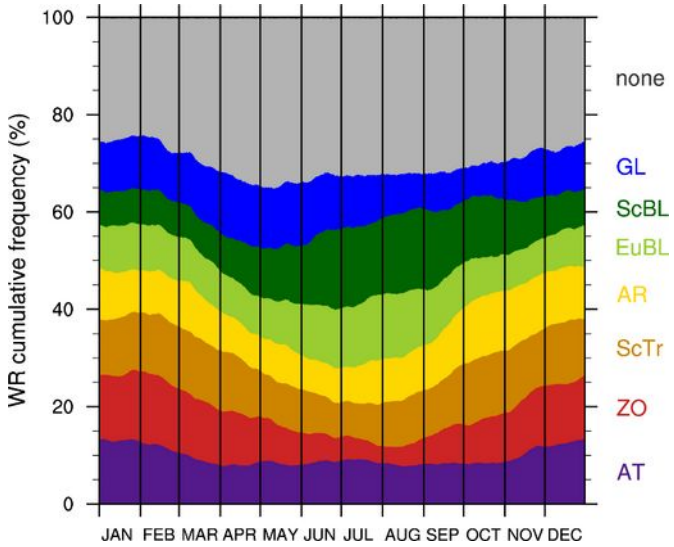
Following Grams et al. 2017 doi:10.1038/nclimate3338
updated to ERA5 (1979-2019, publication in preparation)

Regime characteristics

duration



frequency



Cyclonic regimes:

- Atlantic trough
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Blocked regimes:

- Atlantic ridge
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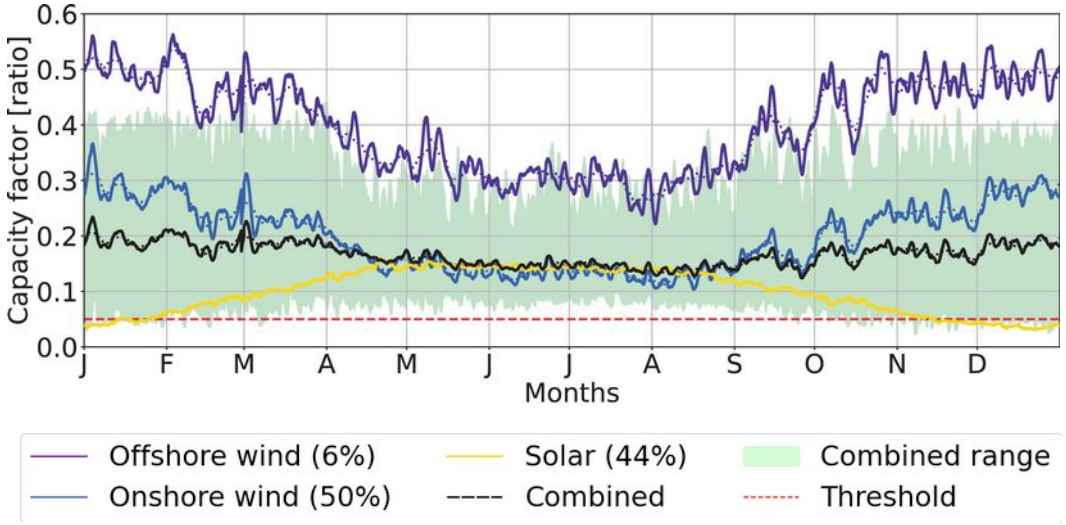
- Greenland blocking

Mockert et al. 2023, doi:10.1002/met.2141

“Dunkelflaute” in Germany

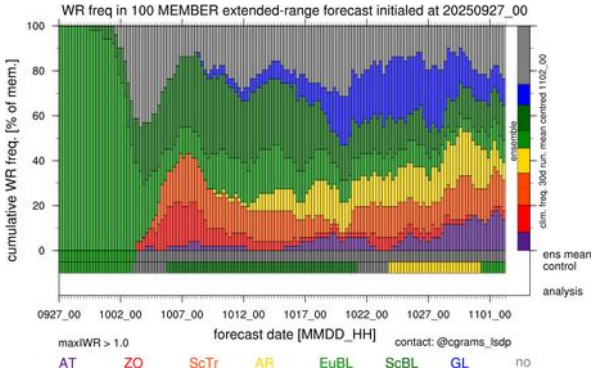
- following Drücke et al. 2021 (doi:10.1016/j.renene.2020.10.102)
- objective definition combined capacity factor < 0.06 for at least 2 days



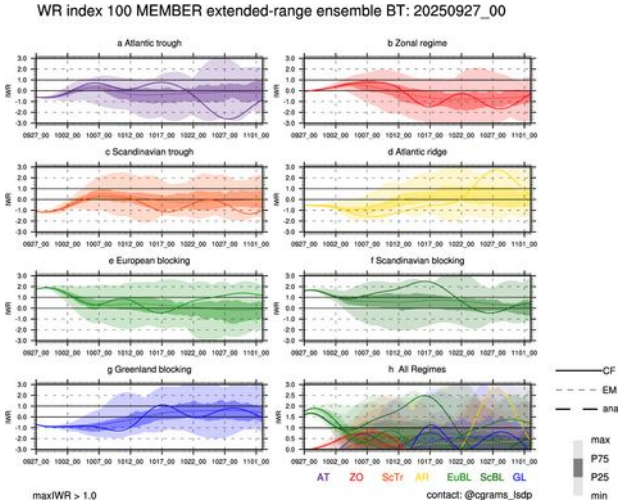
Regime forecasts in preparation

IFS ensemble **BT 20250927_00**

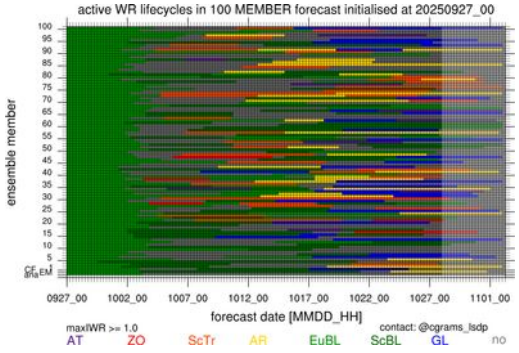
(a) overview regime forecast



(b) detailed regime forecasts



(c) details on members



daily ECMWF **extended-range 100 member ensemble** forecast – in implementation at MeteoSwiss and ECMWF