"It's not the heat, it's the humidity!" New Climate Indices for Europe with a Multilevel Factor Model

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Climate damages

Figure: Source: CLIMap (https://gisaction.com/)

How do we measure the climate?

Economists usually proxy climate with one or two variables: *temperature* and/or *precipitation*...

$$\Downarrow$$

Climate is a complex phenomenon in which a large number of variables are determined *jointly* (Dell et al., 2014), therefore practitioners face a trade-off:

- including many variables $\rightarrow$ *overparametrization*
- including few variables $\rightarrow$ *omitted variable bias*

A potential solution is using **indices**:

- temperature, precipitation, humidity indices;
- Niño/Niña events (*e.g.*, ONI, SOI);
- Artic Sea Ice extent (Diebold et al., 2021);
- extreme weather conditions (*e.g.*, ACI, used in Kim et al. (2022))

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- extreme weather conditions (*e.g.*, ACI, used in Kim et al. (2022))

However...

Climate indices are often naively defined: simple averages or with *ad-hoc* weights; included variables are often arbitrary; lack of capillarity.

Our contribution

We propose **global** and **local** climate indices for Europe with these features:

- "all-encompassing" $\rightarrow$ several variables;
- statistically and methodologically rigorous $\rightarrow$ Dynamic Factor Models;
- global (Europe as a whole) and local (country-specific) perspective;
- granularity $\rightarrow$ data at grid level.

Methodology & Data

Dynamic factor models in a nutshell

A very popular tool to summarize variable information into one or more series is using Dynamic Factor Models (DFM) as in Alquist et al. (2020); Delle Chiaie et al. (2022); Baumeister et al. (2022, 2024).

$$\underset{k\times 1}{x_t} = \sum_{j=0}^{p} \Lambda_j f_{t-j} + \varepsilon_t, \quad \varepsilon_t \sim N(0, \Sigma_\varepsilon)$$

$$\underset{q\times 1}{f_t} = \sum_{i=1}^{s} A_i f_{t-i} + u_t, \quad u_t \sim N(0, \Sigma_u)$$

Estimation: PC, TS (Doz et al., 2011), ML-EM (Doz et al., 2012).

Multilevel factor models: global and local factors

Suppose that some factors are common to all variables, while others only to some groups:

- *hierarchical* approach (Breitung and Eickmeier, 2015; Delle Chiaie et al., 2022);
- *multilevel* approach (Choi et al., 2018);

Multilevel approach

We exploit the second methodology since it is:

- non-parametric,
- more flexible and robust,
- computationally efficient.

Choi et al. (2018)

$$x_{mit} = \underbrace{\gamma'_{mi} G_t}_{Global} + \underbrace{\lambda'_{mi} F_{mt}}_{Local} + e_{mit},$$

where

- $m = 1, \ldots, M \rightarrow$ country index;
- $i = 1, \ldots, k_m \rightarrow$ variable (per country) index;
- $t = 1, \ldots, T \rightarrow$ time index.

The number of global factors can be **assumed** (Choi et al., 2018) or **estimated** (Choi et al., 2023); the number of local factors is then derived via common procedures (Bai and Ng, 2002).

Estimation: 4-step procedure (Choi et al., 2018) ▸ Details

Data

Data comes from **Copernicus ERA5-land** database (*grib*).

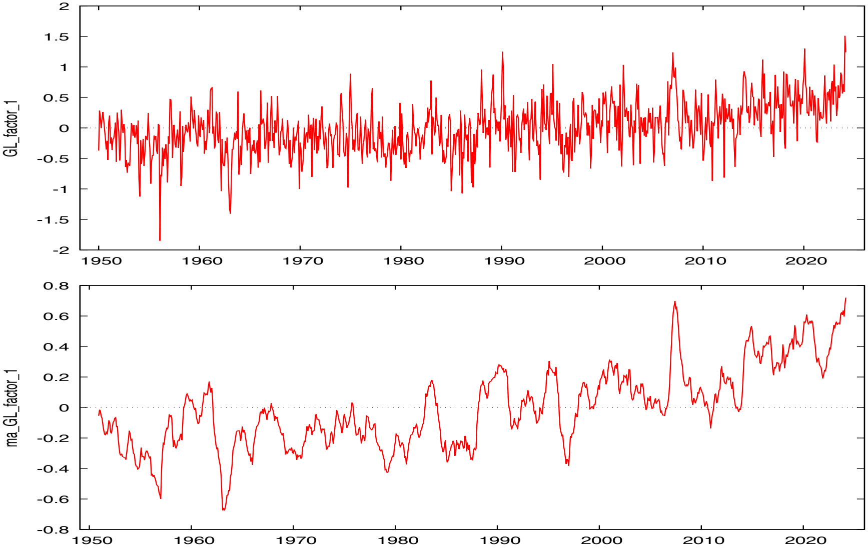
- Different level of spatial-temporal detail
  $\Rightarrow$ EU countries, monthly (1950:01-2024:04)

- Different classes of climate variables:
  - **temperature**: 2m temperature, 2m dewpoint temperature,...
  - **lakes**: lake temperatures, lake ice measures,...
  - **snow**: snow cover, snow density, snow albedo,...
  - **soil water**: volumetric soil water at different layers;
  - **radiation/heat**: solar and thermal radiation;
  - **evaporation**: potential and total evaporation, runoff;
  - **wind, precipitation**: wind speed, total precipitation,...

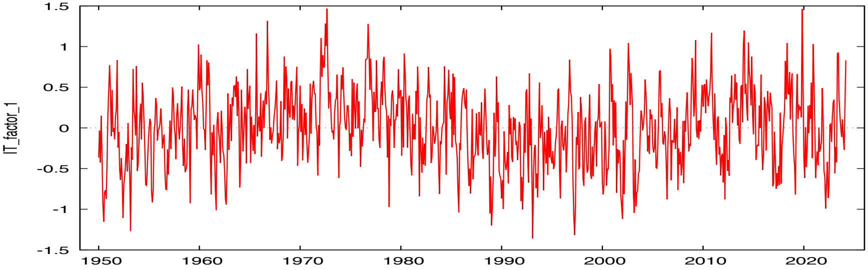
Details

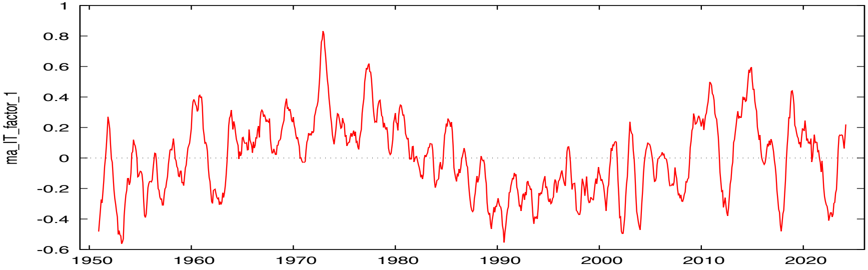
Results

The global factor

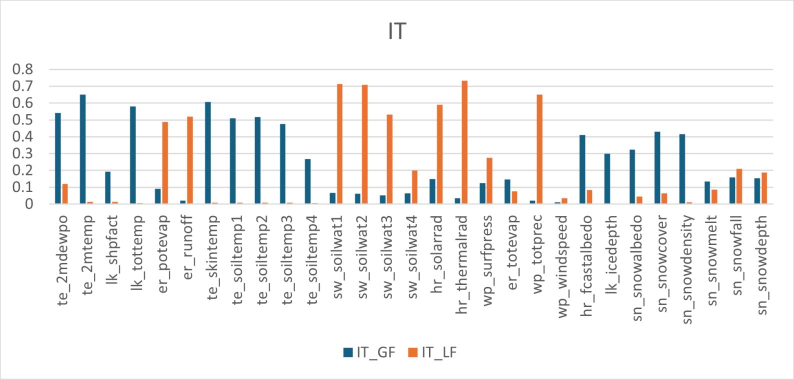


A country-specific example: Italy

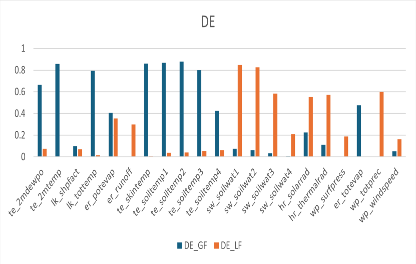




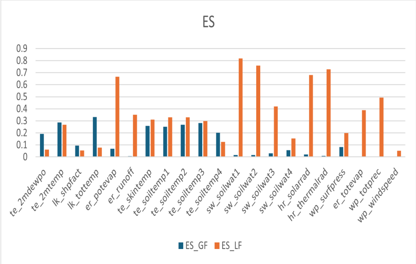
Variance contribution



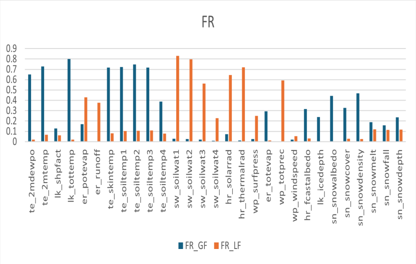
Variance contribution ratio for Italy: blue indicates the global factor, orange the local one.



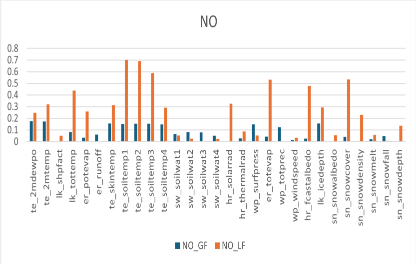
(a) Variance contribution for DE



(b) Variance contribution for ES



(c) Variance contribution for FR



(d) Variance contribution for NO

Discussion

- For temperate climate countries the global factor accounts for temperature effects; the local one for precipitation, radiation and water $\rightarrow$ valid proxies for climate change?

- For hotter/colder countries this distinction becomes less clear.

- What if...
  - more local factors?
  - different climatologies?

Application

Application

We use our indices to estimate the effect of a climate shock on European economic activity in the spirit of Bilal and Känzig (2024)'s application.

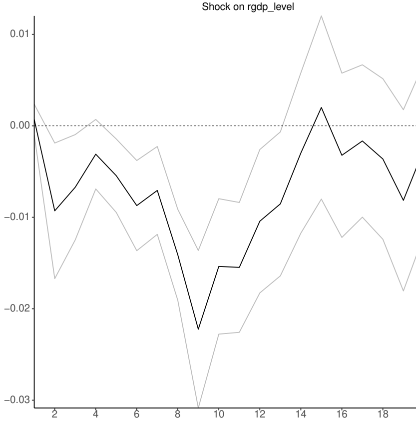
We rely on quarterly data, sourced from OECD and FRED, and *local projections* (Jordà, 2005).

$$y_{i,t+h} - y_{i,t-1} = \alpha_i + \beta_h shock_{(i),t} + w'_{i,t}\gamma + w'_t\eta + u_{i,t+h}$$

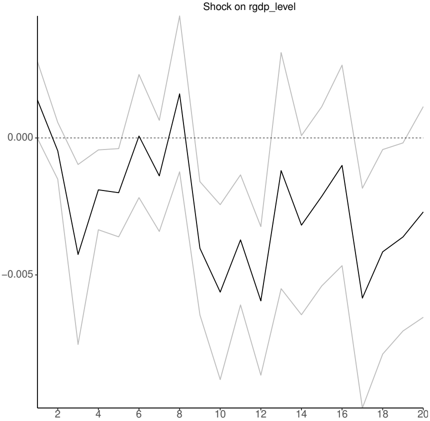
- y: log GDP;
- *shock*: global/local climate index;
- w: controls;
- u: error term.

Setup

- Countries: AUT, BEL, CHE, DEU, DNK, ESP, FIN, FRA, GBR, GRC, ISL, ITA, LUX, NLD, NOR, PRT, SWE
- Time span: ≈1982q2:2023q2
- $h = 1, \dots 20$;
- controls: local/global index, inflation, unemployment, industrial production, COVID-19 cases, EU recessions, Brent, DE interest rate, (time trend)
- lagged controls: shock, GDP growth and controls up to 8 lags;
- Driscoll-Kraay standard errors;



(a) Global index shock



(b) Local index shock

Conclusion

- we device global-local indices for EU using multilevel factor models;
- the global component catches temperature effects; the local one precipitation, radiation, water effects in most countries
- local projection: global vs local

Future developments:

- more granular data!
- what about extreme events?

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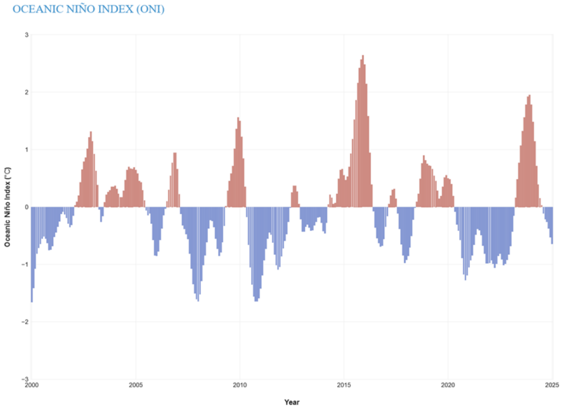
Example 1: ONI index

Used variable: average sea surface temperature

- The ONI is NOAA's primary index for tracking the ocean part of ENSO, the El Niño-Southern Oscillation climate pattern.
- Rolling 3-month average temperature *anomaly* (difference from average) in the surface waters of the east-central tropical Pacific.
- Index values of +0.5 or higher indicate El Niño. Values of -0.5 or lower indicate La Niña.



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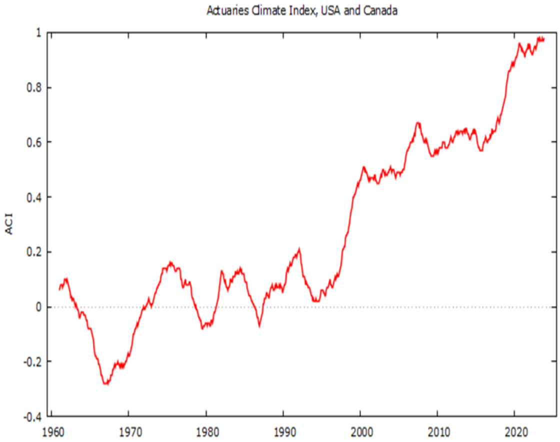
Example 2: ACI index



Reference period: 1961 – 1990
5-year moving average

Simple average of 6 components:

- High temperatures
- Low temperatures
- Heavy rain
- Drought
- High wind
- Sea level

Multilevel factor model estimation

- Step 1. Select two countries and get $\hat{G}_t$ via canonical correlation analysis;
- Step 2. Replace G_t with $\hat{G}_t$ and estimate λ_{mi} and F_{mt} via PC;
- Step 3. Replace λ_{mi} and F_{mt} with their previously obtained estimates and compute/revise $\hat{G}_t$ and $\hat{\gamma}_{mi}$ via PC;
- Step 4. Substitute the newly obtained quantities and revise $\hat{\lambda}_{mi}$ and $\hat{F}_{mt}$ again via PC

Global and local factor spaces are estimated *consistently* and are *asymptotically normal*.

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Data in details

Category	Variables
Temperature	2m dewpoint temperature 2m temperature skin temperature soil temperature (lvls 1-4)
Lakes	lake total temperature lake shape factor lake ice depth*
Snow	snow cover* snow density* snow albedo*
Soil Water	volumetric soil water (lvls. 1-4)
Heat/Radiation	forecast albedo* surface net solar radiation surface net thermal radiation
Evaporation	runoff potential evaporation total evaporation
Wind, precipitation	surface pressure total precipitation wind speed

Notes: * only for IS, LI, SE, AT, CH, NO, FI, IT, FR, ME.

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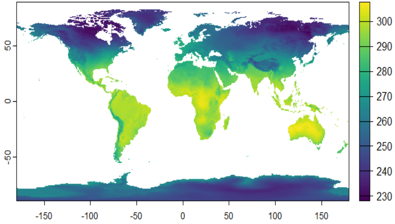
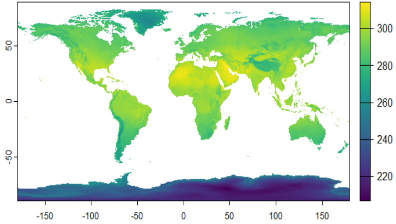
Data processing



(a) Temperature, January 1950



(b) Temperature, July 2000

Filtering: climatologies and anomalies

- Monthly climatology: averaged or filtered values for a specific month over a reference period.
- Monthly anomaly: difference between a monthly value and the climatology of that variable for that specific month.

Examples

IEA (Weather, Climate and Energy Tracker) uses a reference period 2000-2019 for climatologies, ACI uses 1961-1990. Ahmadi et al. (2022) use a 30-year rolling average. Bilal and Känzig (2024) use Hamilton filtering.

We use:

1. fixed averages: 1950-1979;
2. moving average: 20 years;
3. Hamilton filter: 2 years.

A closer look at anomalies

What is a climate anomaly?

Climate anomaly is defined as the departure from the **normal conditions** (or climatology). It is a critical concept to separate the signal of **climate change** from the **seasonal cycle**.

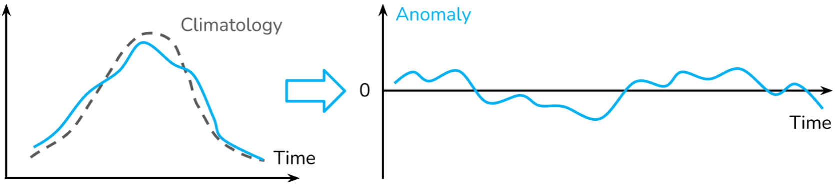


Figure: Source: `https://comptools.climatematch.io/tutorials/W1D3_RemoteSensing/student/W1D3_Tutorial5.html`

Example: constructing anomalies for precipitation

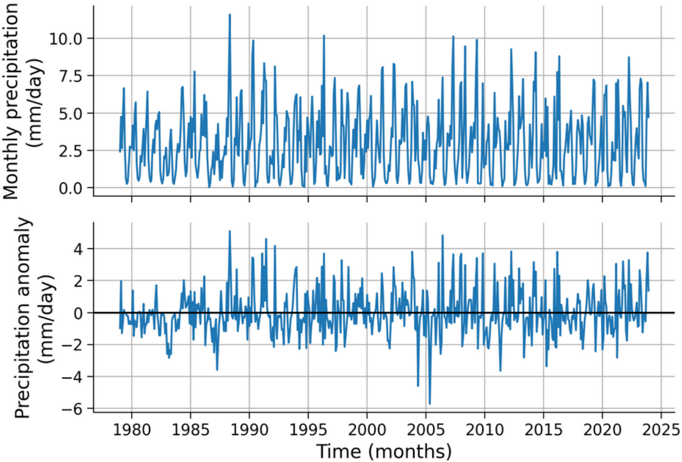


Figure: Source: `https://comptools.climatematch.io/tutorials/W1D3_RemoteSensing/student/W1D3_Tutorial5.html`

Factor contributions - country-specific DFM

	DE	ES	FR	IT	NO
2m dewpoint	**0.660**	0.318	**0.701**	**0.718**	0.489
2m temp	**0.876**	**0.966**	**0.969**	**0.983**	**0.558**
lake shape	0.128	0.228	0.202	0.240	0.021
lake temp	**0.843**	**0.640**	**0.795**	**0.768**	0.498
pot evap	0.467	**0.504**	0.423	0.294	0.195
runoff	0.031	0.016	0.027	0.033	0.045
skin temp	**0.884**	**0.989**	**0.979**	**0.992**	**0.536**
soil temp1	**0.992**	**0.998**	**0.996**	**0.947**	**0.997**
soil temp2	**0.993**	**0.994**	**0.993**	**0.943**	**0.999**
soil temp3	**0.947**	**0.951**	**0.947**	**0.914**	**0.976**
soil temp4	**0.977**	**0.828**	**0.979**	**0.966**	**0.809**
soil water1	0.154	0.213	0.186	0.206	0.020
soil water2	0.152	0.183	0.187	0.181	0.013
soil water3	0.170	0.143	0.201	0.175	0.029
soil water4	0.079	0.173	0.108	0.191	0.078
solar rad	0.279	0.203	0.245	0.179	0.197
surf press	0.011	0.052	0.018	0.048	0.006
therm rad	0.132	0.123	0.096	0.031	0.007
tot evap	0.460	0.110	0.271	0.043	0.423
tot prec	0.010	0.051	0.012	0.025	0.051
wind speed	0.020	0.040	0.003	0.086	0.063
fcast albedo	-	-	0.241	0.249	0.325
lake ice	-	-	0.160	0.266	**0.557**
snow albedo	-	-	0.361	0.356	0.077
snow cover	-	-	0.254	0.263	0.382
snow dens	-	-	0.373	0.351	0.110

Notes: variance contribution (ratio) of the common component.

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Factor contribution: IT

	Global	Local	Tot Factor
2m dewpoint	**0.539**	0.111	**0.650**
2m temp	**0.655**	0.022	**0.677**
lake shape	0.192	0.014	0.206
lake temp	**0.581**	0.001	**0.583**
pot evap	0.096	**0.572**	**0.668**
runoff	0.021	0.471	0.492
skin temp	**0.610**	0.017	**0.627**
soil temp1	**0.515**	0.025	**0.540**
soil temp2	**0.523**	0.024	**0.546**
soil temp3	0.481	0.024	**0.505**
soil temp4	0.271	0.017	0.288
soil water1	0.069	**0.784**	**0.853**
soil water2	0.065	**0.776**	**0.841**
soil water3	0.054	**0.573**	**0.626**
soil water4	0.065	0.208	0.273
solar rad	0.152	**0.604**	**0.756**
surf press	0.122	0.221	0.343
therm rad	0.036	**0.728**	**0.764**
tot evap	0.147	0.094	0.241
tot prec	0.021	**0.606**	**0.627**
wind speed	0.011	0.027	0.038
fcast albedo	0.407	0.040	0.447
lake ice	0.296	0.005	0.300
snow albedo	0.323	0.035	0.358
snow cover	0.428	0.028	0.456
snow dens	0.414	0.003	0.417

Factor contribution: other countries

	DE		ES		FR		NO	
	Global	Local	Global	Local	Global	Local	Global	Local
2m dewpoint	**0.662**	0.076	0.192	0.061	**0.638**	0.026	0.168	0.282
2m temp	**0.856**	0.003	0.289	0.264	**0.732**	0.067	0.166	0.359
lake shape	0.101	0.069	0.094	0.054	0.133	0.072	0.000	0.050
lake temp	**0.795**	0.014	0.330	0.078	**0.800**	0.018	0.081	0.442
pot evap	0.409	0.353	0.069	**0.663**	0.184	0.495	0.032	0.262
runoff	0.001	0.299	0.006	0.353	0.000	0.365	0.057	0.005
skin temp	**0.859**	0.005	0.260	0.308	**0.722**	0.081	0.150	0.350
soil temp1	**0.869**	0.036	0.253	0.326	**0.732**	0.114	0.147	**0.716**
soil temp2	**0.879**	0.040	0.270	0.324	**0.756**	0.115	0.150	**0.707**
soil temp3	**0.802**	0.053	0.285	0.295	**0.728**	0.120	0.151	**0.599**
soil temp4	0.429	0.062	0.204	0.122	0.398	0.092	0.147	0.300
soil water1	0.076	**0.847**	0.016	**0.818**	0.034	**0.872**	0.064	0.037
soil water2	0.063	**0.824**	0.016	**0.759**	0.032	**0.839**	0.080	0.014
soil water3	0.033	**0.582**	0.031	0.419	0.024	**0.588**	0.077	0.000
soil water4	0.008	0.209	0.056	0.153	0.009	0.231	0.048	0.036
solar rad	0.225	**0.551**	0.020	**0.682**	0.081	**0.679**	0.000	0.305
surf press	0.004	0.189	0.080	0.201	0.025	0.196	0.145	0.042
therm rad	0.111	**0.575**	0.008	**0.730**	0.016	**0.723**	0.028	0.078
tot evap	0.474	0.000	0.004	0.387	0.292	0.010	0.043	**0.505**
tot prec	0.001	**0.600**	0.003	0.496	0.000	**0.554**	0.119	0.004
wind speed	0.049	0.163	0.001	0.052	0.018	0.061	0.013	0.038
fcast albedo	-	-	-	-	0.299	0.003	0.024	0.459
lake ice	-	-	-	-	0.230	0.012	0.151	0.324
snow albedo	-	-	-	-	0.431	0.000	0.002	0.048
snow cover	-	-	-	-	0.310	0.002	0.039	**0.518**
snow dens	-	-	-	-	0.452	0.005	0.000	0.176

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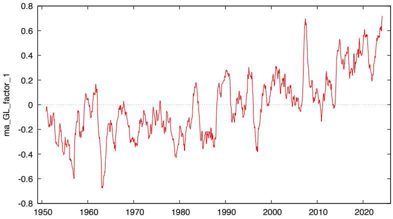
More local factors

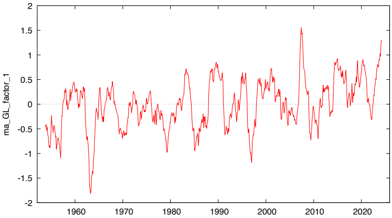
Suppose 1 Global factor - 2 local factors

- For temperate climate countries the explanatory power of the global factor shifts to the 1^{st} local factor, and the former local factor to the 2^{nd} one;
- on the other hand, the global factor starts to capture the dynamics of more continental countries (East Europe).

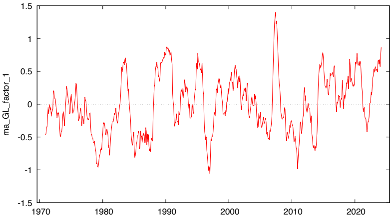
Different climatologies: global factor



(a) Fixed period: 1950-1979

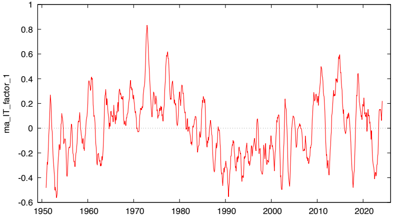


(b) Hamilton filter



(c) 20-years rolling mean

Different climatologies: IT factor



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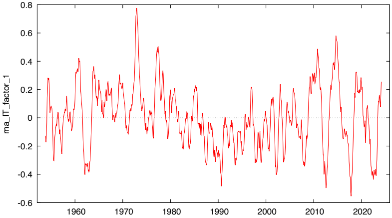
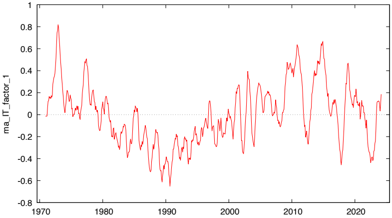


(b) Hamilton filter



(c) 20-years rolling mean