Climate Data Visualization -

Atmospheric CO_2 Concentration / Temperature / Precipitation

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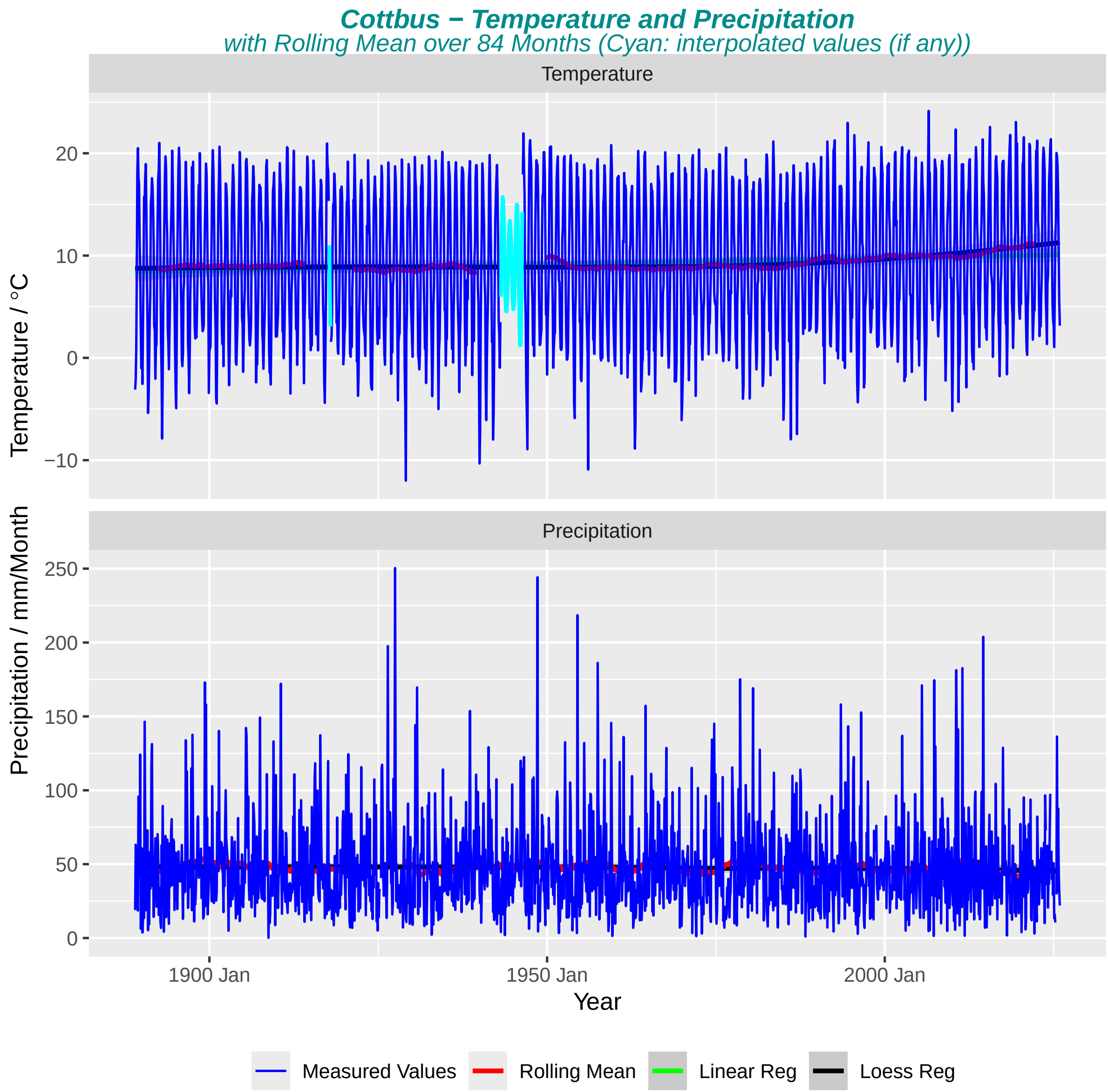
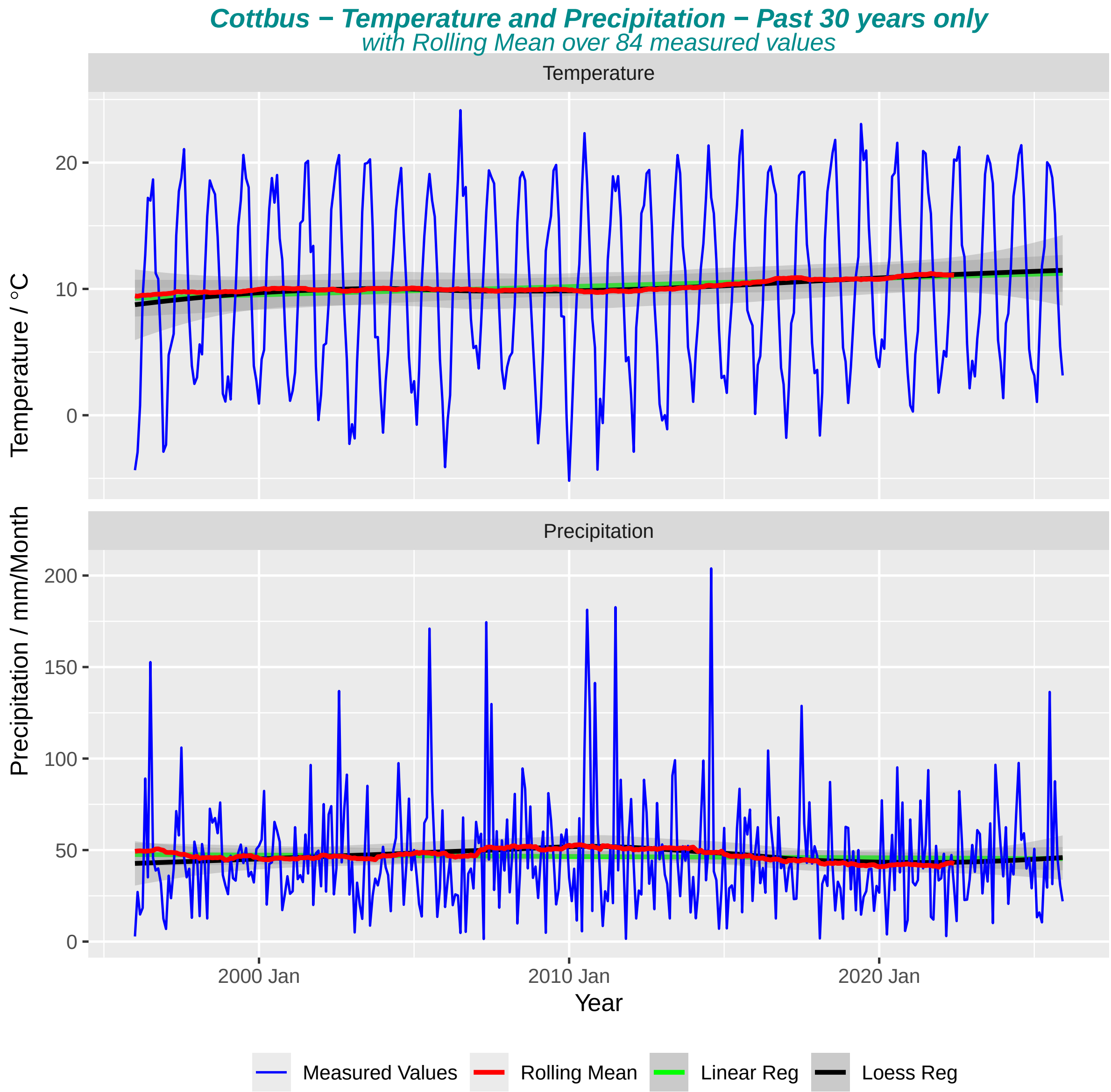
2026-01-08

Contents

1 Cottbus - Visualization of Temperature, Precipitation Data 1889 - 2025

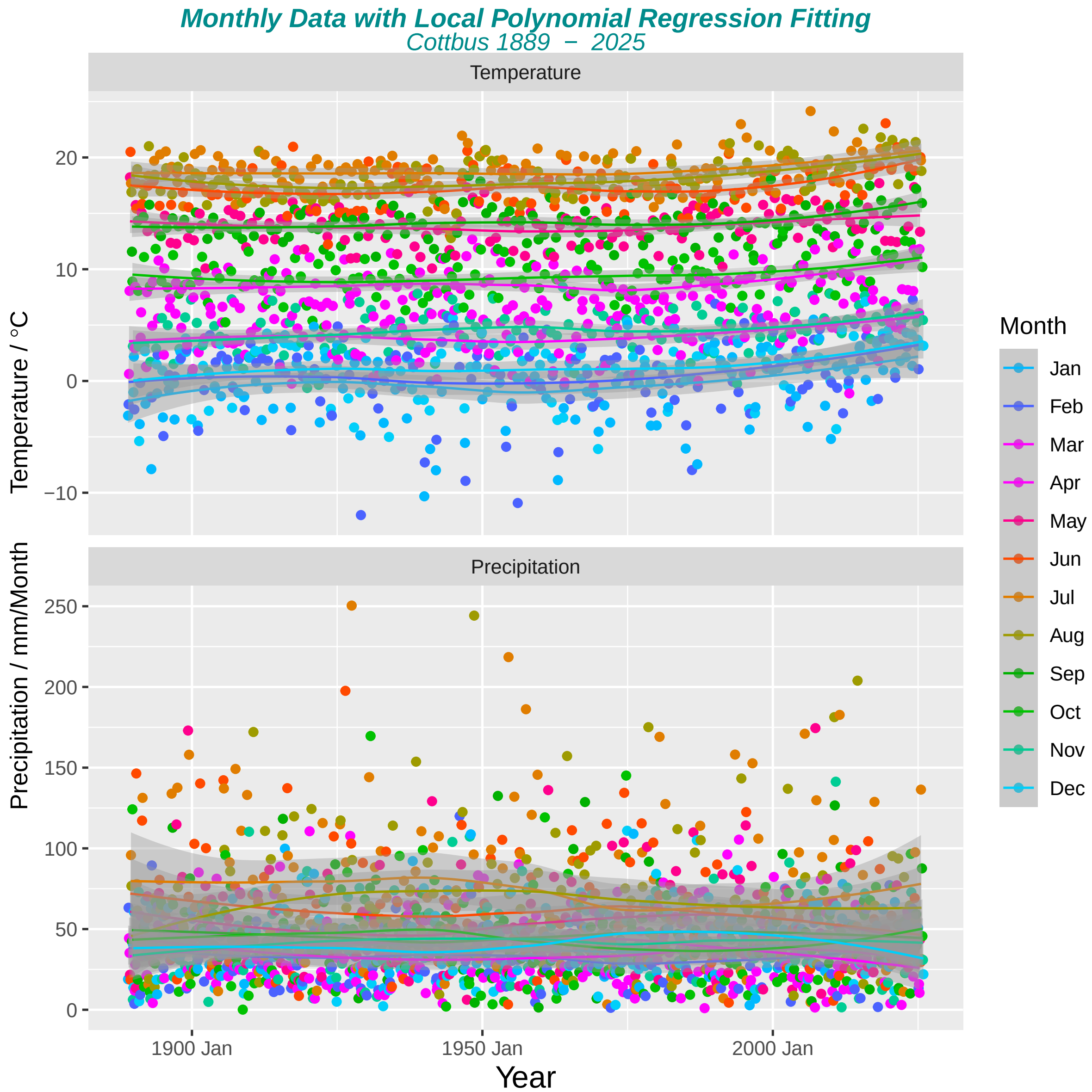
1.1 Monthly Time Plots with Rolling Mean



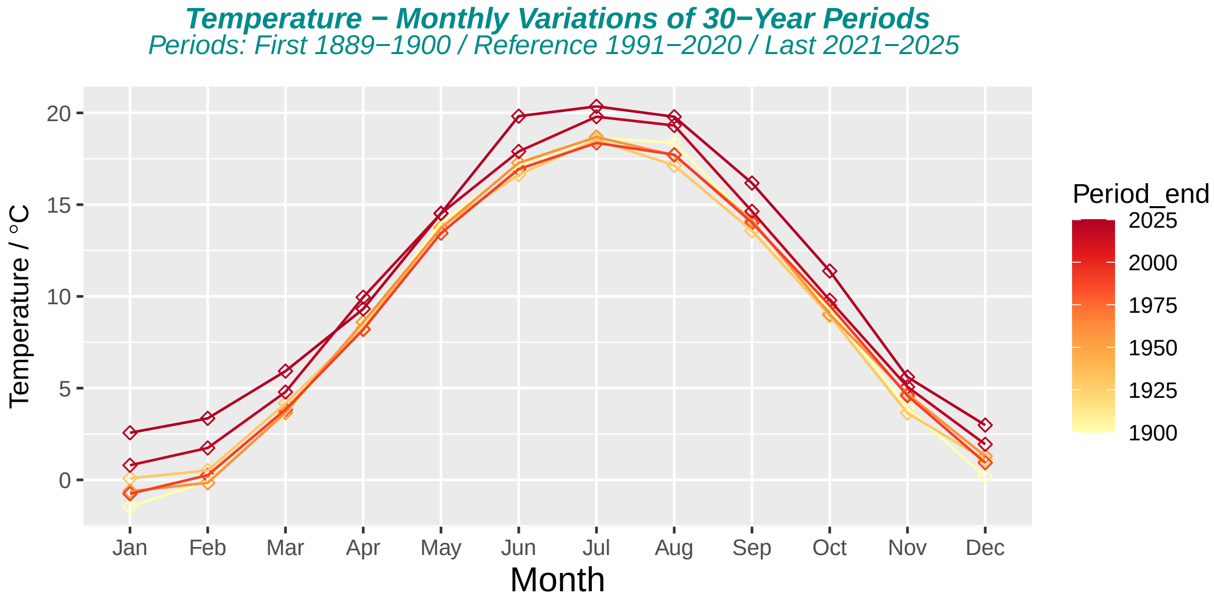


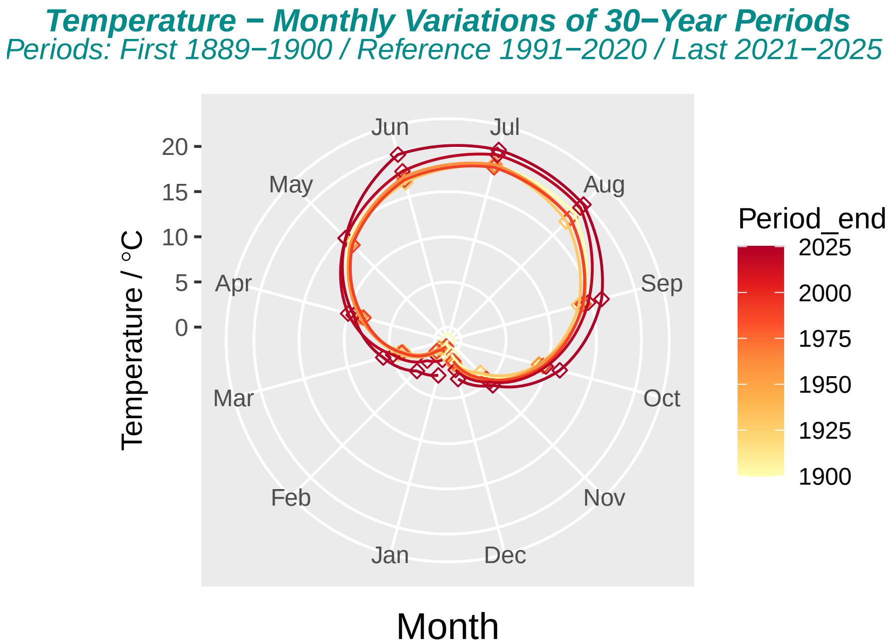
1.2 Annual seasonal plots with monthly breakdown

The seasonal charts show the monthly seasonal patterns, where available.

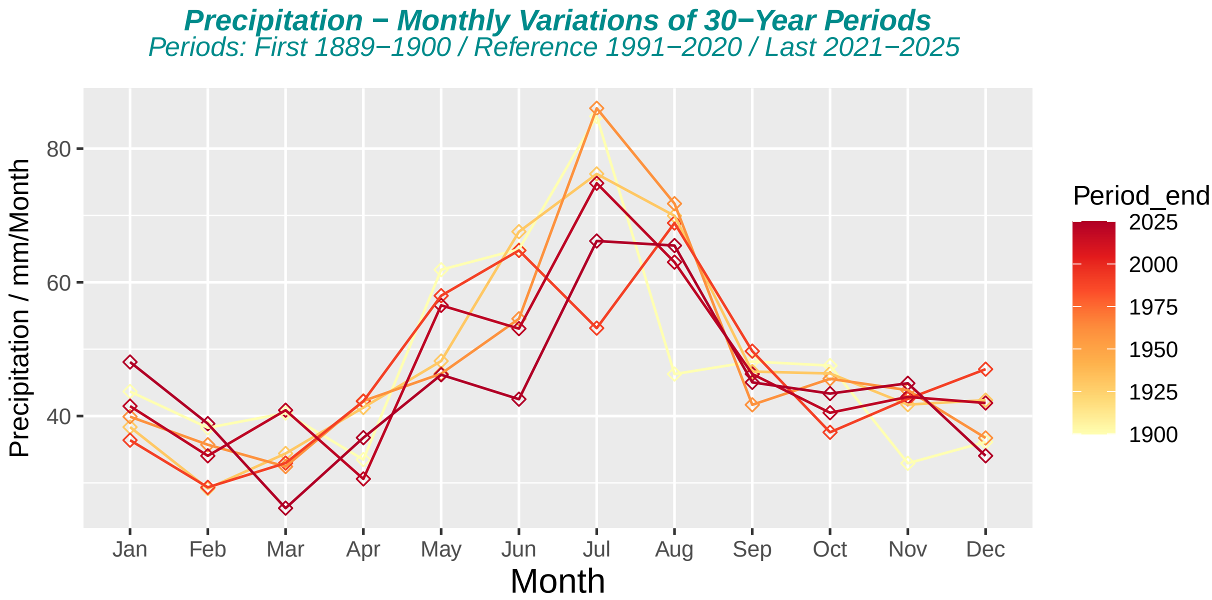

Monthly Data with Local Polynomial Regression Fitting
Cottbus 1889 − 2025
Temperature
Temperature / °C
20
10
0
−10
Precipitation
Precipitation / mm/Month
250
200
150
100
50
0
1900 Jan
1950 Jan
2000 Jan
Year
Month
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

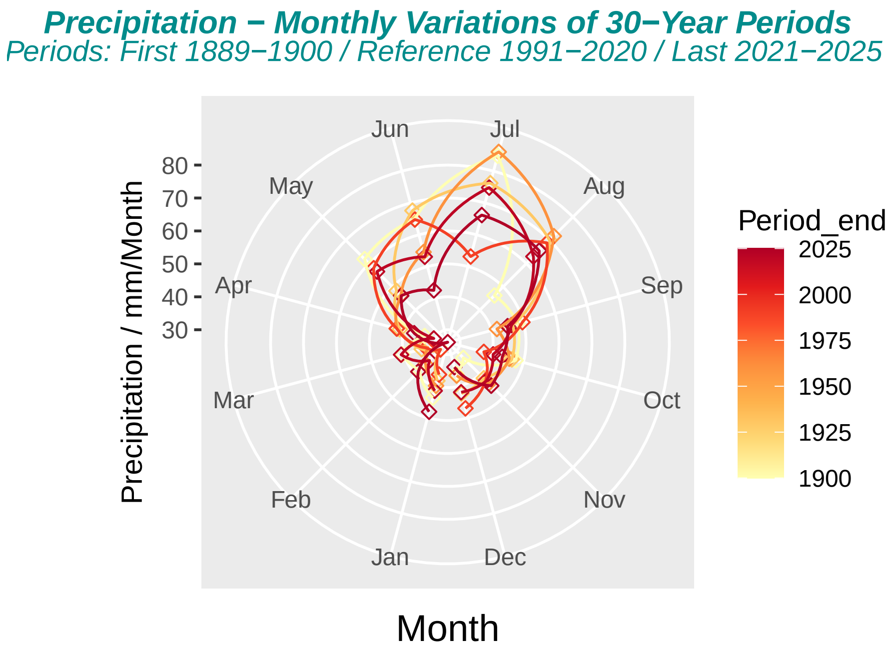
1.2.1 30-year period plots with monthly breakdown - Cartesian and Polar Coordinates





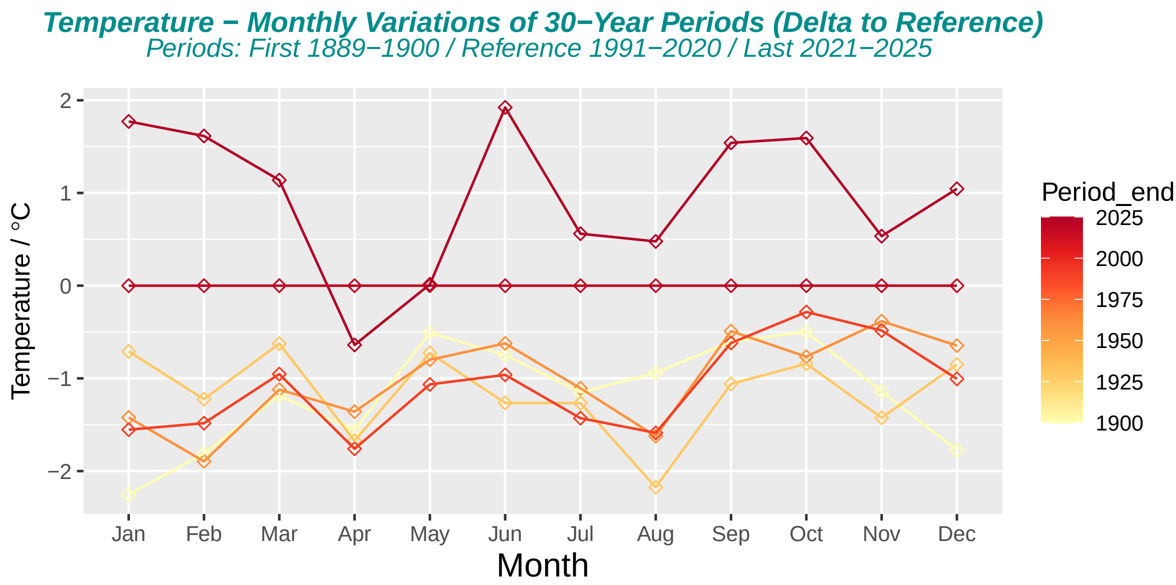

```
#>
#> _
```

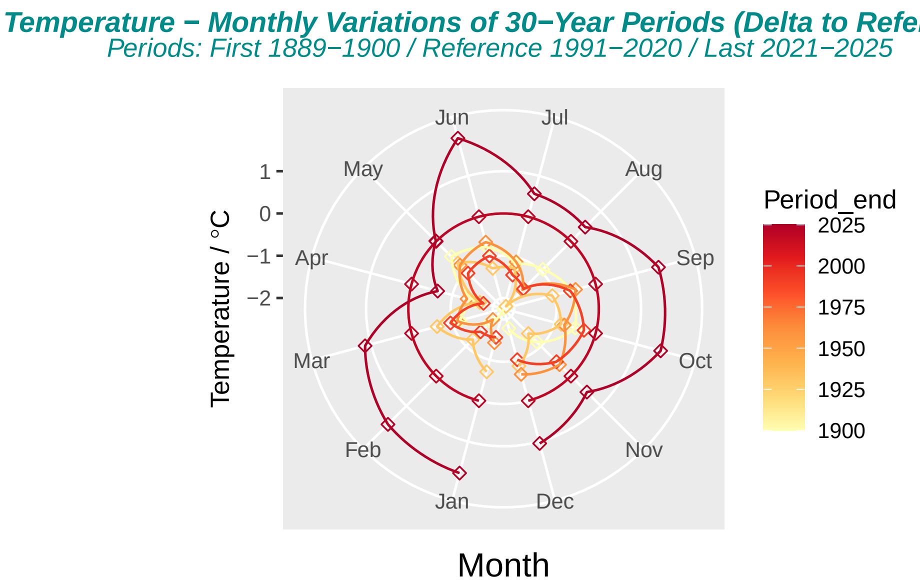

Precipitation − Monthly Variations of 30−Year Periods
Periods: First 1889−1900 / Reference 1991−2020 / Last 2021−2025
Precipitation / mm/Month
80
60
40
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month
Period_end
2025
2000
1975
1950
1925
1900


Precipitation − Monthly Variations of 30−Year Periods
Periods: First 1889−1900 / Reference 1991−2020 / Last 2021−2025
Precipitation / mm/Month
80
70
60
50
40
30
Jun
Jul
May
Aug
Apr
Sep
Mar
Oct
Feb
Nov
Jan
Dec
Month
Period_end
2025
2000
1975
1950
1925
1900

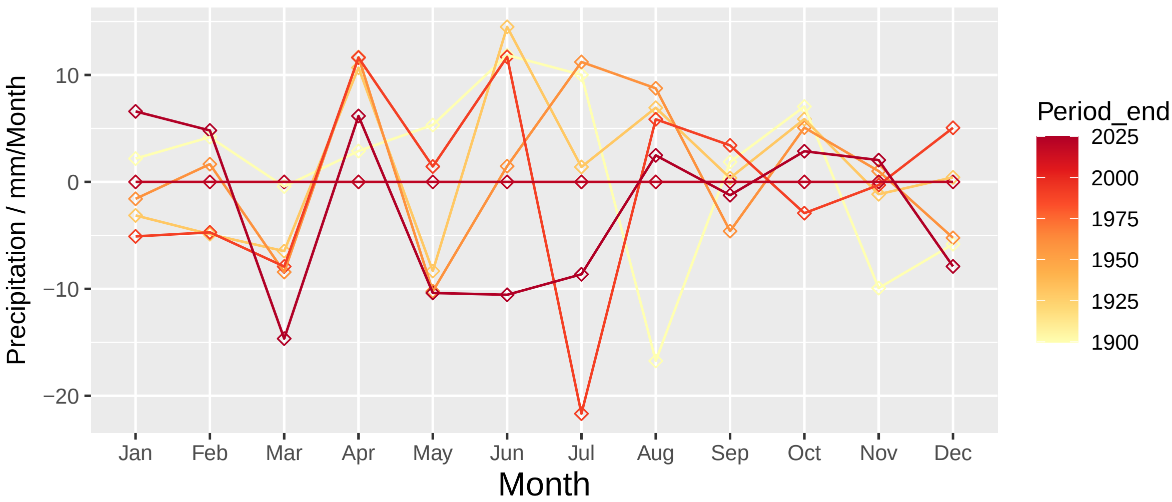
```
#>
#> _
```

1.2.2 Plot Monthly Delta to Reference Period - Cartesian and Polar Coordinates

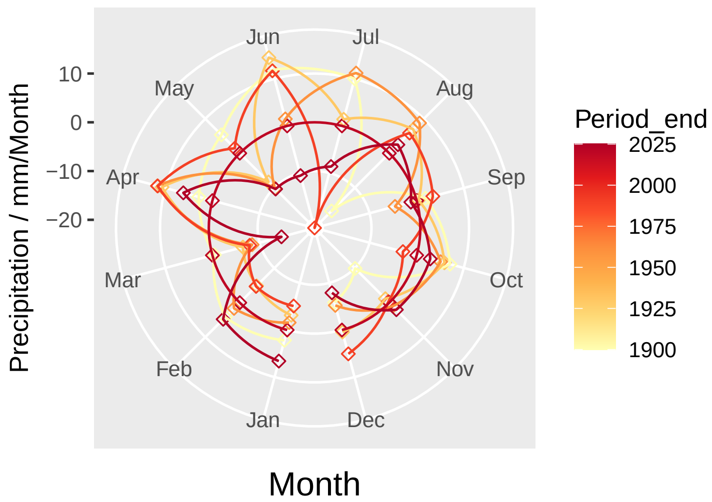


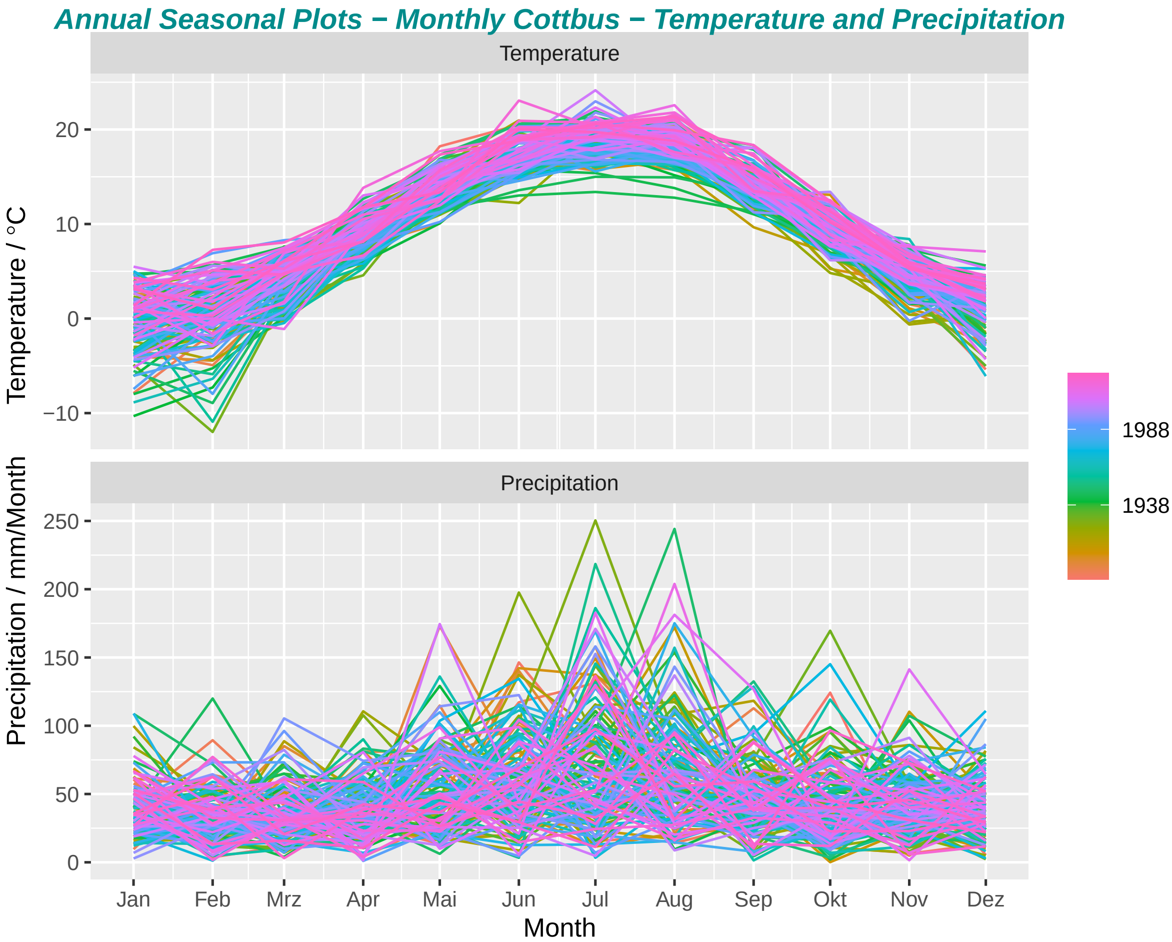


Precipitation − Monthly Variations of 30−Year Periods (Delta to Reference)
Periods: First 1889−1900 / Reference 1991−2020 / Last 2021−2025

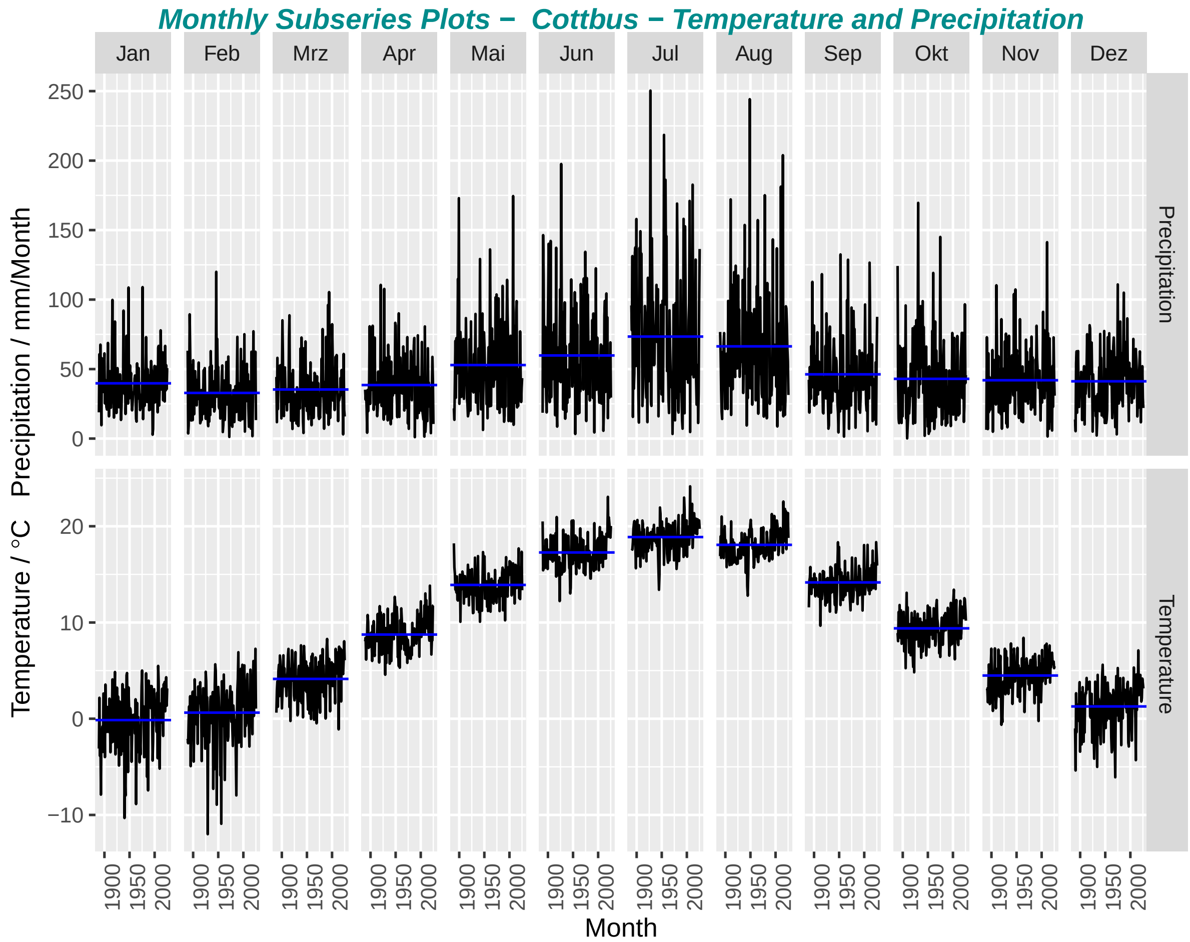


Precipitation − Monthly Variations of 30−Year Periods (Delta to Reference)
Periods: First 1889−1900 / Reference 1991−2020 / Last 2021−2025





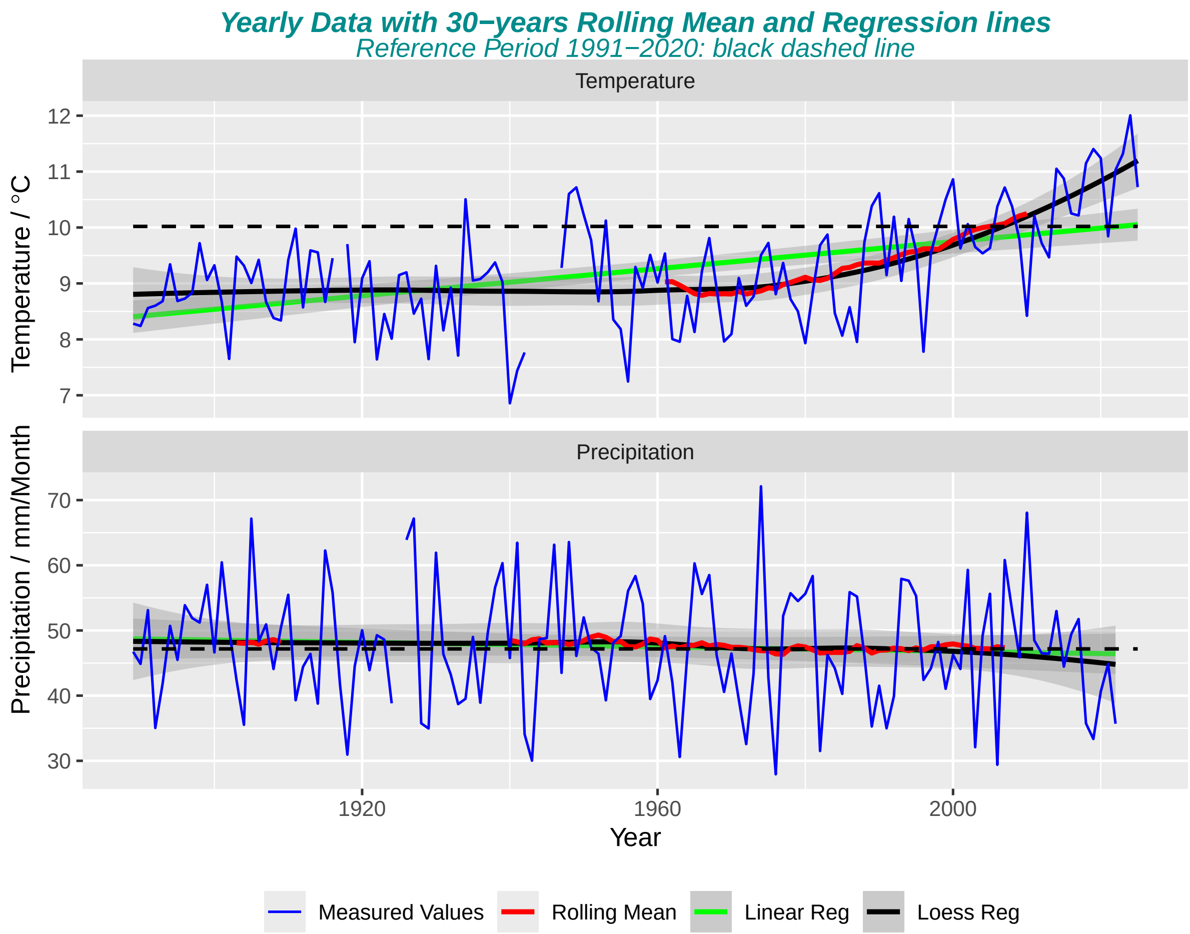
Annual Seasonal Plots − Monthly Cottbus − Temperature and Precipitation
Temperature
Temperature / °C
20
10
0
−10
Precipitation
Precipitation / mm/Month
250
200
150
100
50
0
Jan
Feb
Mrz
Apr
Mai
Jun
Jul
Aug
Sep
Okt
Nov
Dez
Month
1988
1938



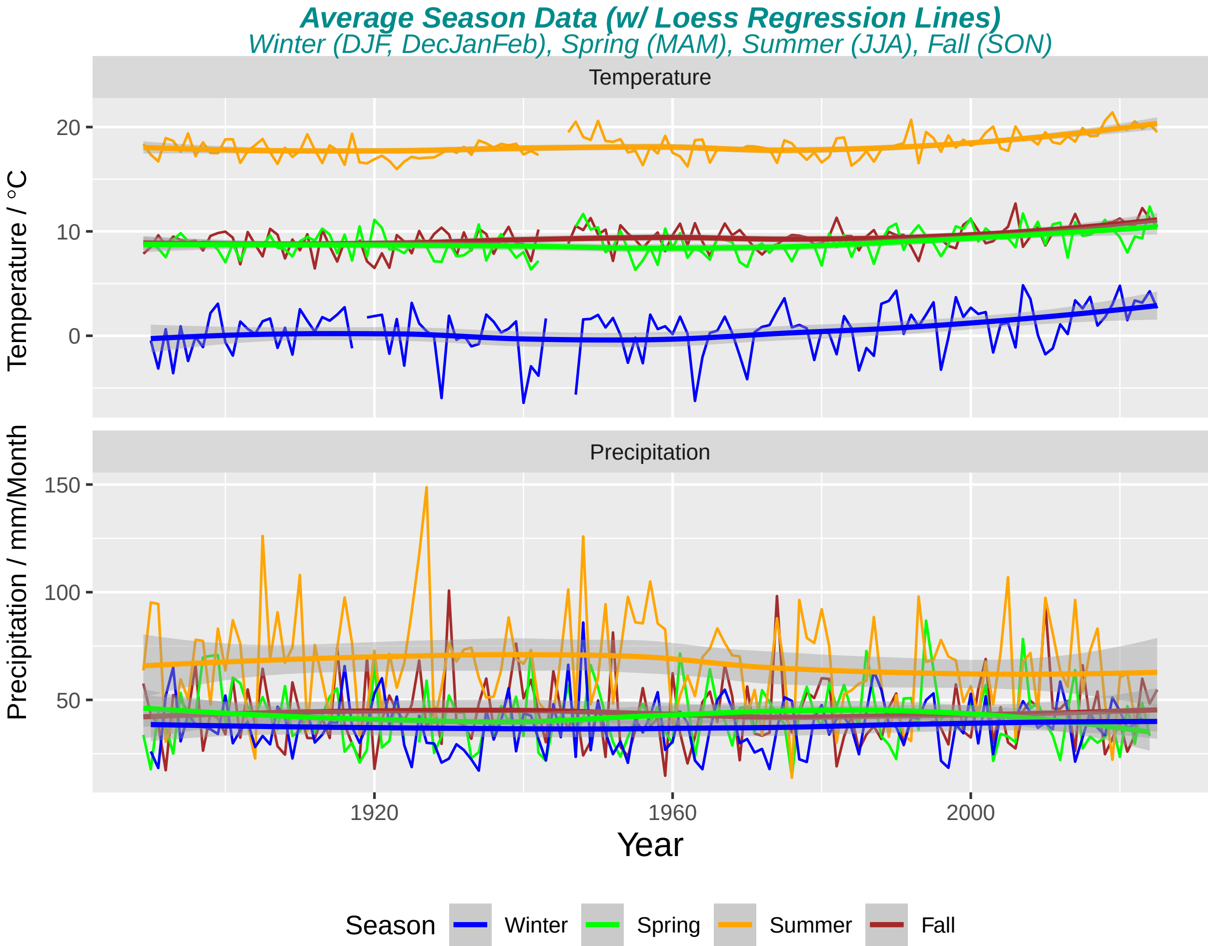
The blue horizontal lines within the seasonal subseries plot indicate the means for each month.

1.3 Annual Cottbus - Temperature and Precipitation

1.3.1 Annual Time Plot of Temperature, Precipitation



1.3.2 Annual Seasonal Plot of Temperature, Precipitation



2 Trend and Seasonal Analysis

2.1 Time Series Decomposition - Trend and Seasonal Components

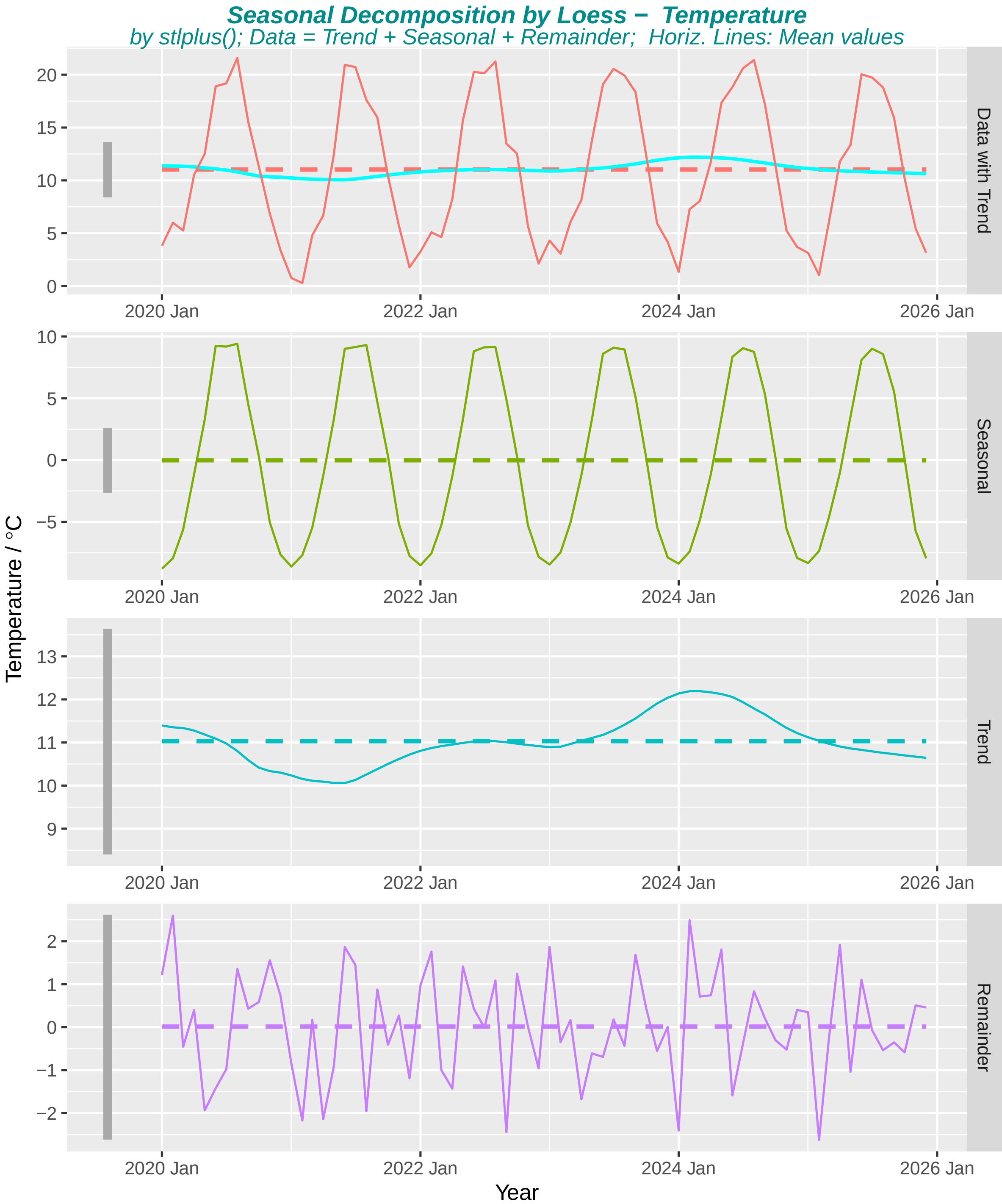
An *additive model* would be used when the variations around the trend do not vary with the level of the time series whereas a *multiplicative model* would be appropriate if the trend is proportional to the level of the time series.

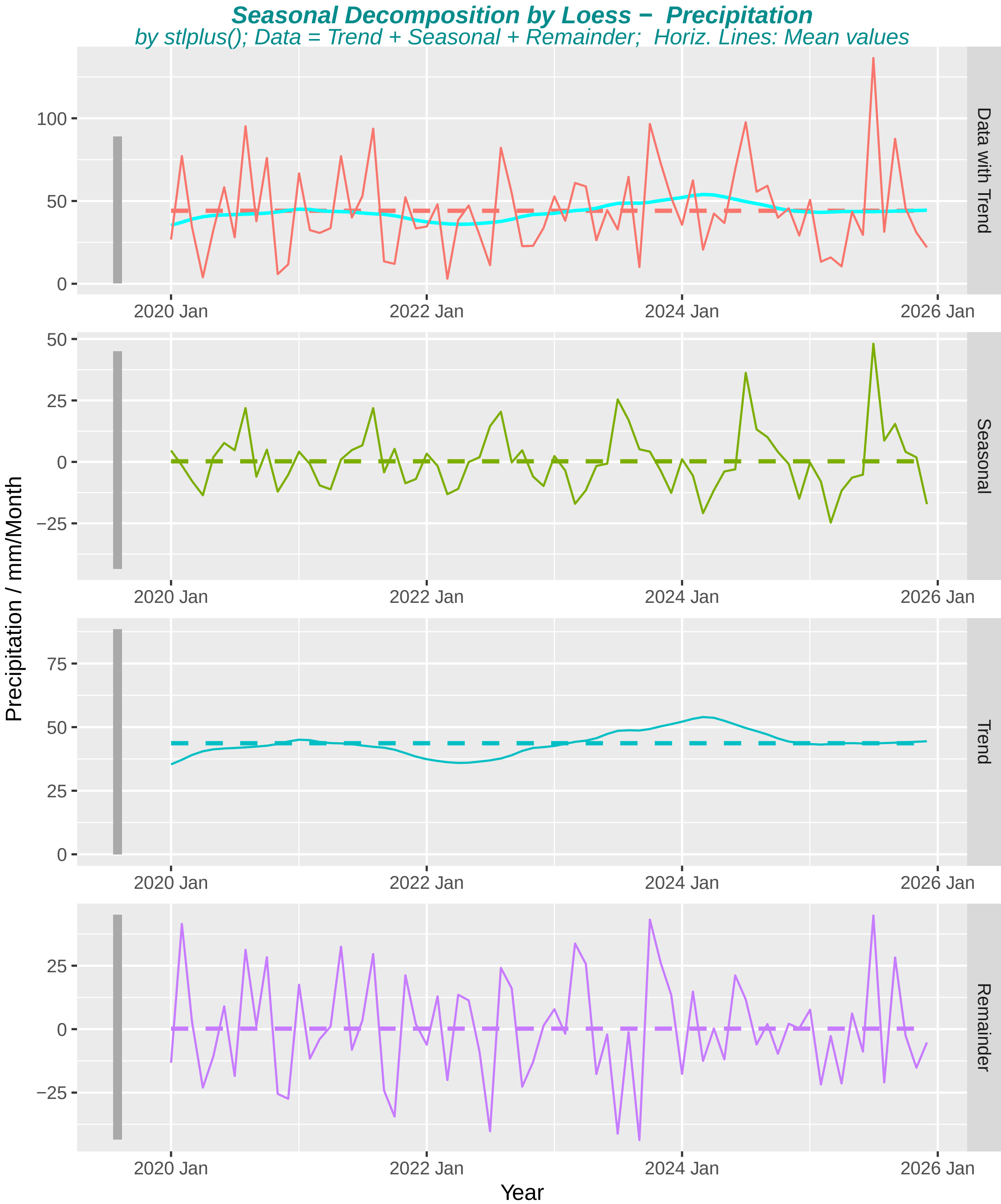
Time series using an

- additive model: $y_t = T_t + C_t + S_t + \epsilon_t$
- multiplicative model: $y_t = T_t * C_t * S_t * \epsilon_t$

Trend / Cycle / Seasonal / Noise component
Cyclical components is often grouped into the Trend component

For *Seasonal decomposition of time series by Loess (stlplus)* uses in general an additive error model, it only provides facilities for additive decompositions. It is possible to obtain a multiplicative decomposition by first taking logs of the data.

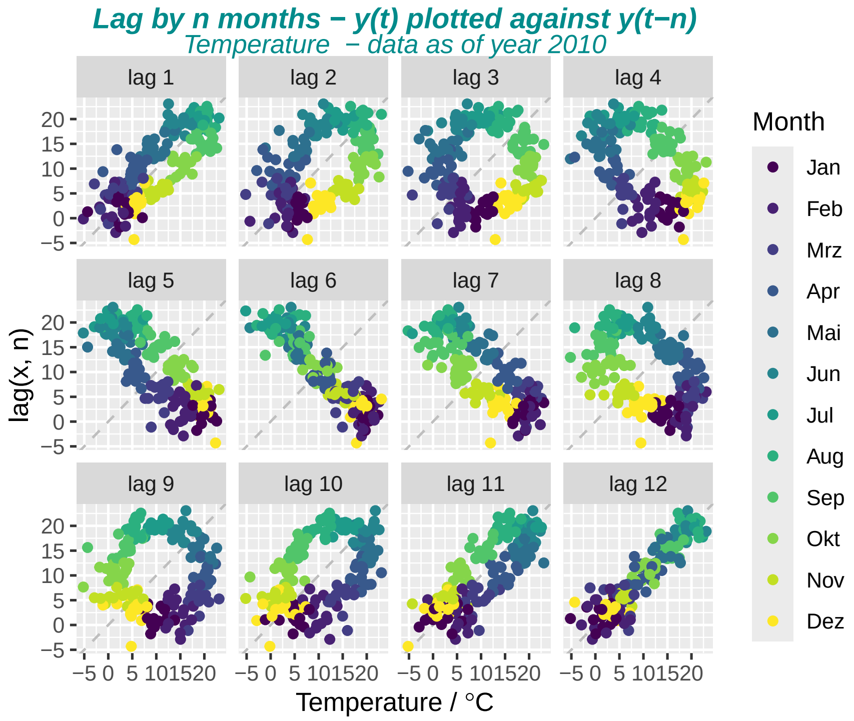

Seasonal Decomposition by Loess − Temperature
by stlplus(); Data = Trend + Seasonal + Remainder; Horiz. Lines: Mean values
Data with Trend
Seasonal
Trend
Remainder
Temperature / °C
Year
2020 Jan
2022 Jan
2024 Jan
2026 Jan



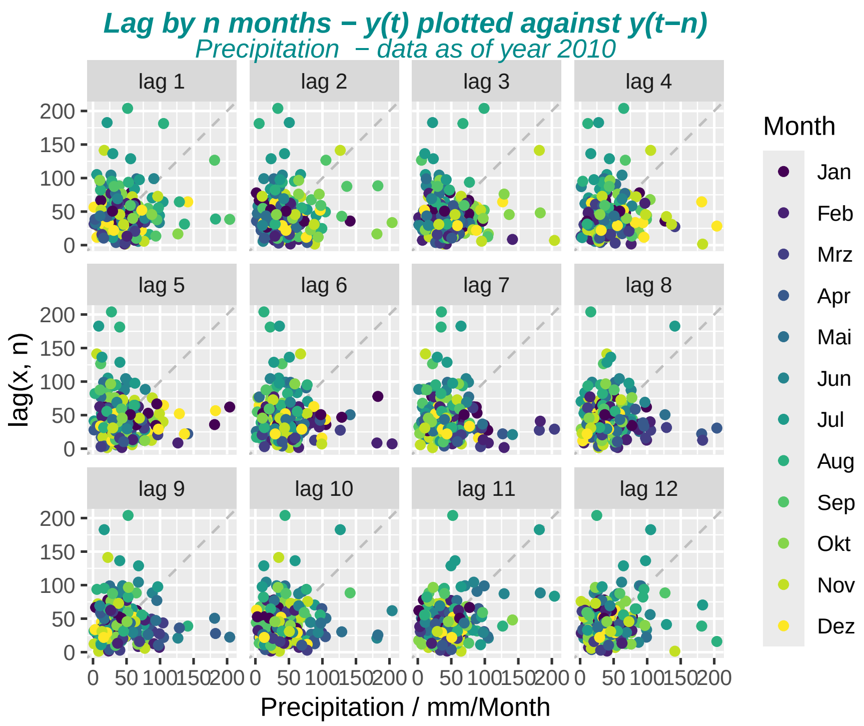
2.2 Periodicities - Season Frequency

2.2.1 Lag Plot - Differences

Lagged scatterplots, where the horizontal axis shows lagged $(k = 1, .., 12)$ values of the time series. Each graph shows y_t plotted against y_{t-k} for different values of k. For seasonal data the relationship is strongly positive at a lag $k = 12$, reflecting the strong seasonality of the data. The strongly negative relationship is evident in the case oflag $k = 6$.



Lag by n months − y(t) plotted against y(t−n)
Temperature − data as of year 2010
lag 1
lag 2
lag 3
lag 4
lag 5
lag 6
lag 7
lag 8
lag 9
lag 10
lag 11
lag 12
lag(x, n)
Temperature / °C
Month
Jan
Feb
Mrz
Apr
Mai
Jun
Jul
Aug
Sep
Okt
Nov
Dez



Lag by n months − y(t) plotted against y(t−n)
Precipitation − data as of year 2010
lag 1
lag 2
lag 3
lag 4
lag 5
lag 6
lag 7
lag 8
lag 9
lag 10
lag 11
lag 12
lag(x, n)
Precipitation / mm/Month
Month
Jan
Feb
Mrz
Apr
Mai
Jun
Jul
Aug
Sep
Okt
Nov
Dez

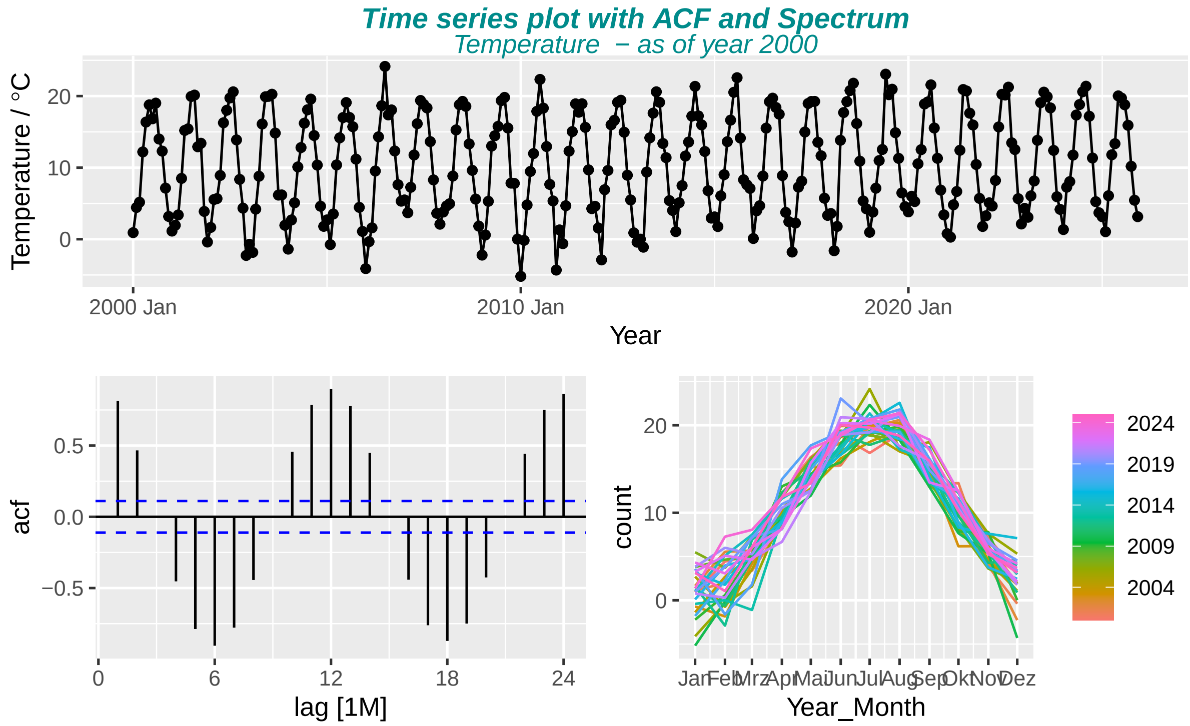
2.2.2 Periodogram - Spectral Density Estimation of a Time Series

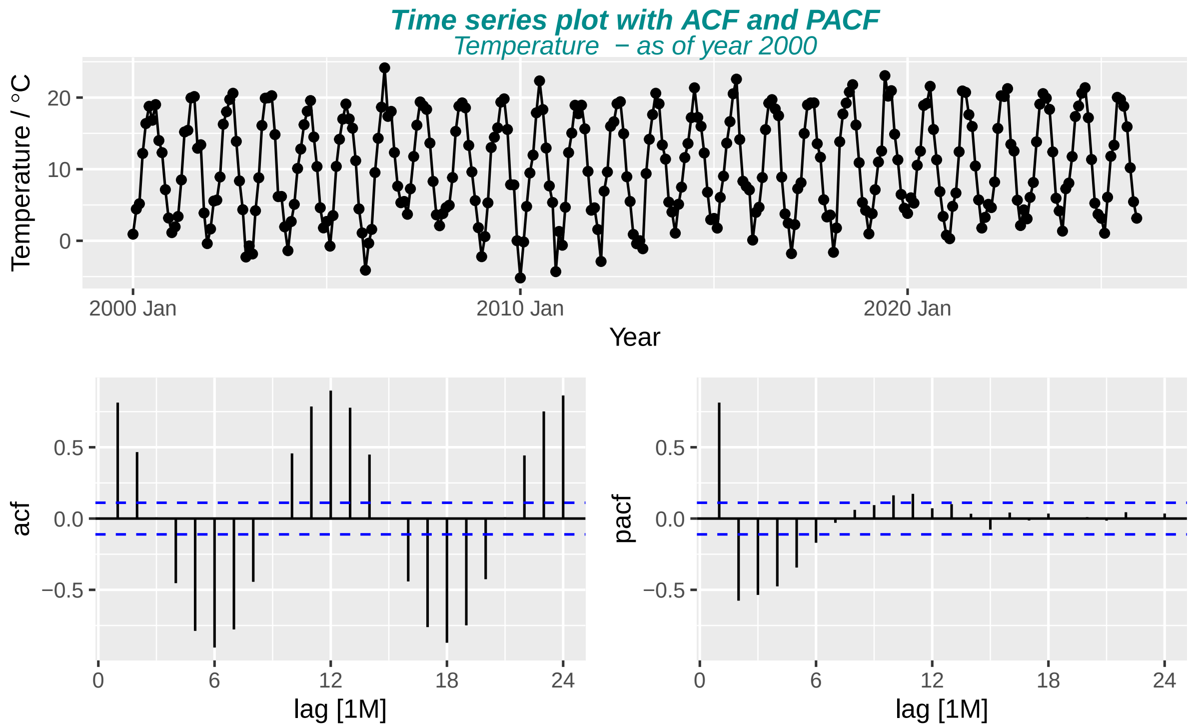
The spectral density characterizes the frequency content of the signal. One purpose of estimating the spectral density is to detect any periodicities in the data, by observing peaks at the frequencies corresponding to these periodicities.

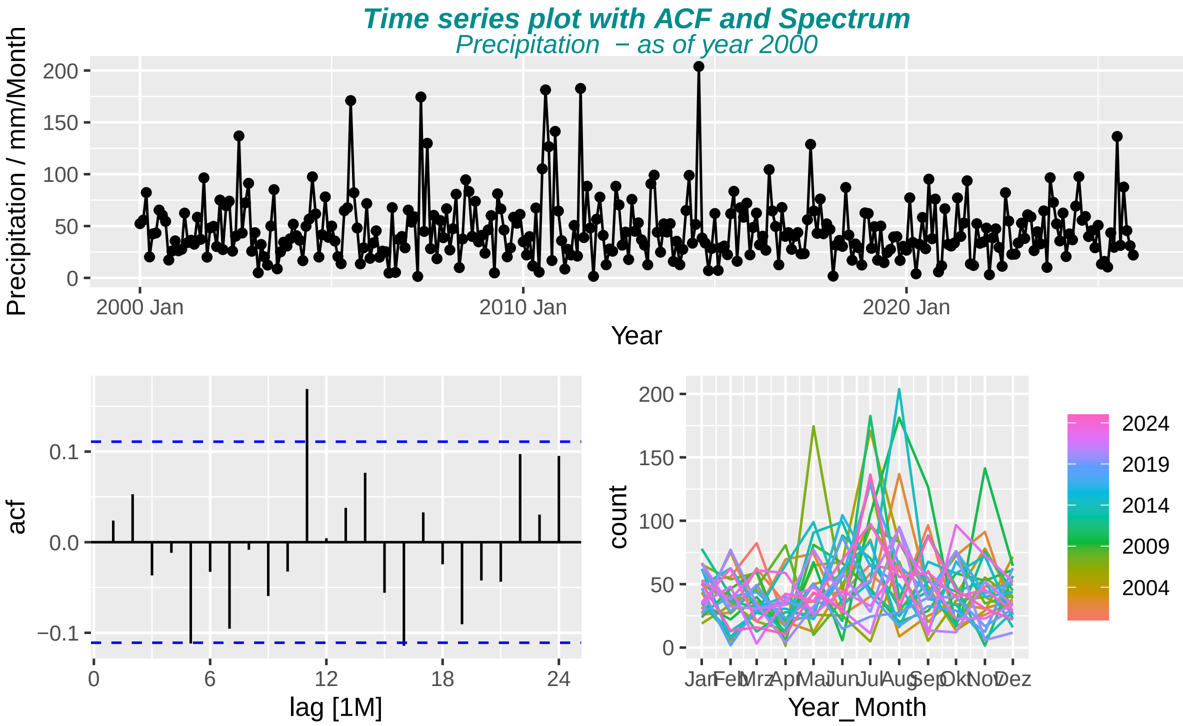
At frequency $\lambda = 1/12$ there is a significant peak => This pattern repeats every full frequency = every 12 months / every year

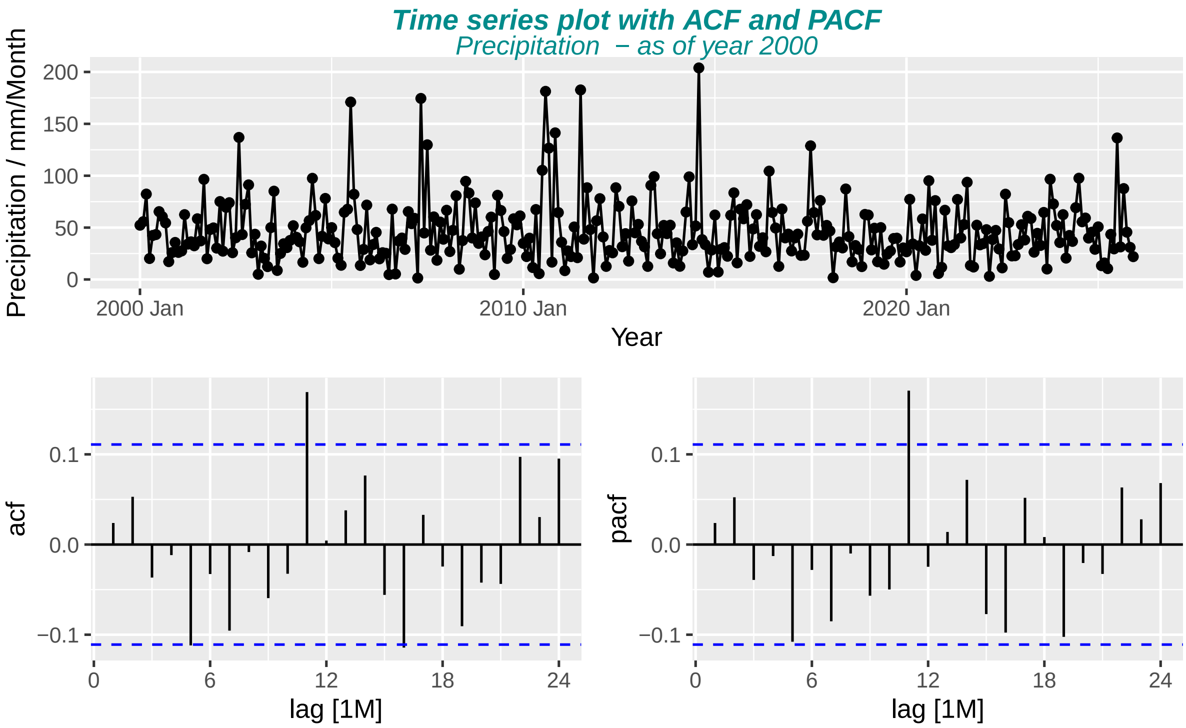
The remaining peaks are random and therefore cannot be assigned significantly.

Note: The blue dashed lines in the (P)ACF plots ((Partial) Autocorrelation Function) indicate white noise series limits. In that case 95% of the spikes lie within the dashed lines.






Time series plot with ACF and Spectrum
Precipitation − as of year 2000
Precipitation / mm/Month
200
150
100
50
0
2000 Jan
2010 Jan
2020 Jan
Year
acf
0.1
0.0
−0.1
0
6
12
18
24
lag [1M]
count
200
150
100
50
0
Jan Feb Mrz Apr Mai Jun Jul Aug Sep Okt Nov Dez
Year_Month
2024
2019
2014
2009
2004


Time series plot with ACF and PACF
Precipitation − as of year 2000
Precipitation / mm/Month
200
150
100
50
0
2000 Jan
2010 Jan
2020 Jan
Year
acf
0.1
0.0
−0.1
0
6
12
18
24
lag [1M]
pacf
0.1
0.0
−0.1
0
6
12
18
24
lag [1M]

3 Forecasting - Estimate/Train the model

3.1 Forecasting with ETS and ARIMA model

Exponen**T**ial **S**moothing (**ETS**) and **A**uto**R**egressive **I**ntegrated **M**oving **A**verage Forecasting Models **ARIMA** models are the two most widely used approaches to time series forecasting, and provide complementary approaches to the problem.

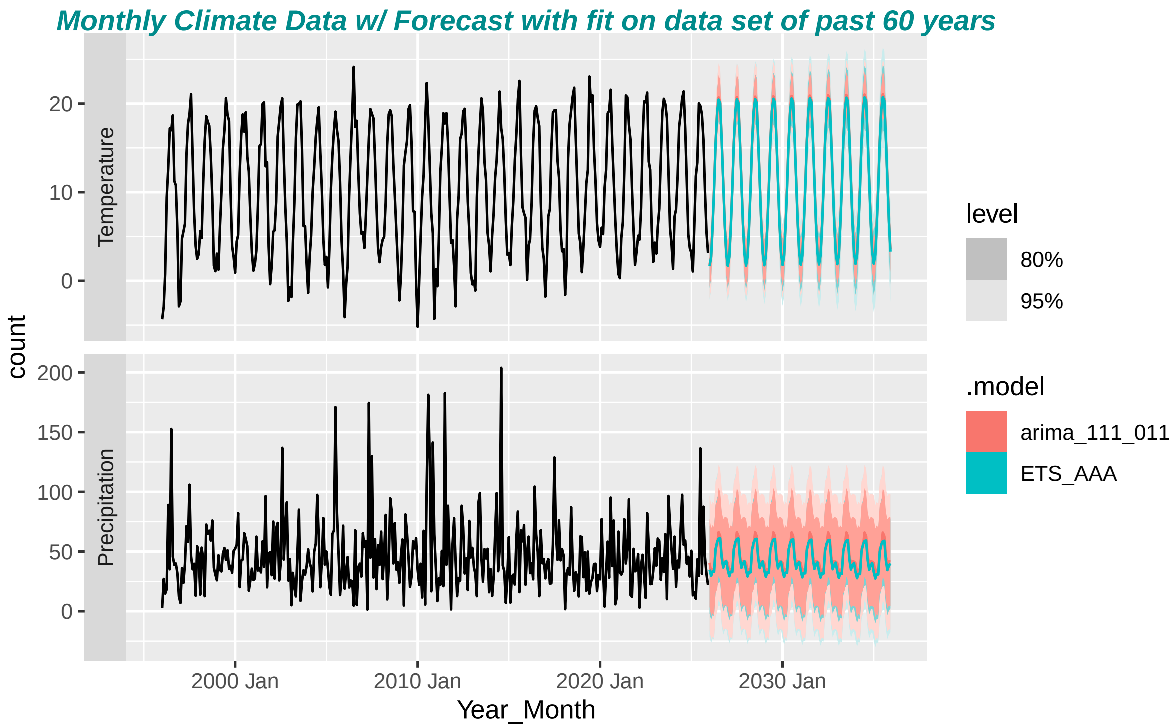
Forecasts produced using **ETS** methods are weighted averages of past observations, with the weights decaying exponentially as the observations get older.

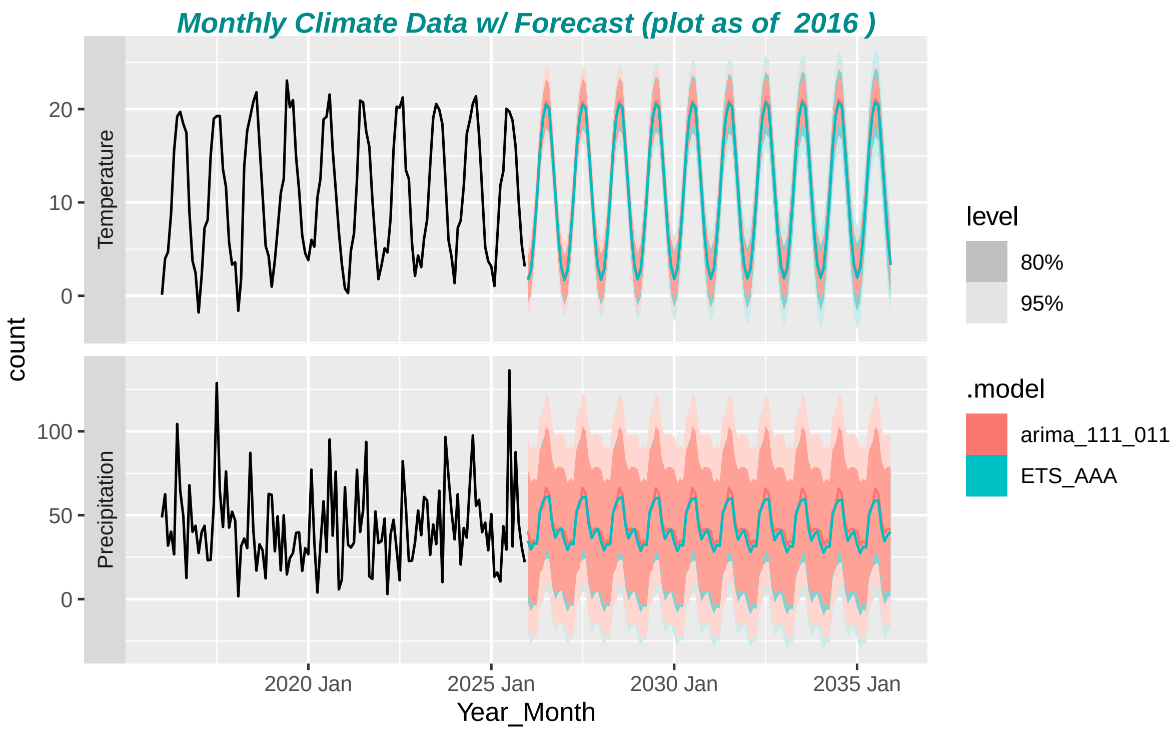
Here a $ETS(A, A|A)$ **model** with additive ("A") *Error term*, *Trend term* and *Seasonal term* was chosen.

While exponential smoothing models are based on a description of the trend and seasonality in the data, **ARIMA** models aim to describe the autocorrelations in the data.

Here a $ARIMA(111)(011)_{12}$ **model** with autoregressive, differencing, and moving average terms of (111) in the ordinary and 011 in the seasonal term with a seasonal period 12 (12 months/year)

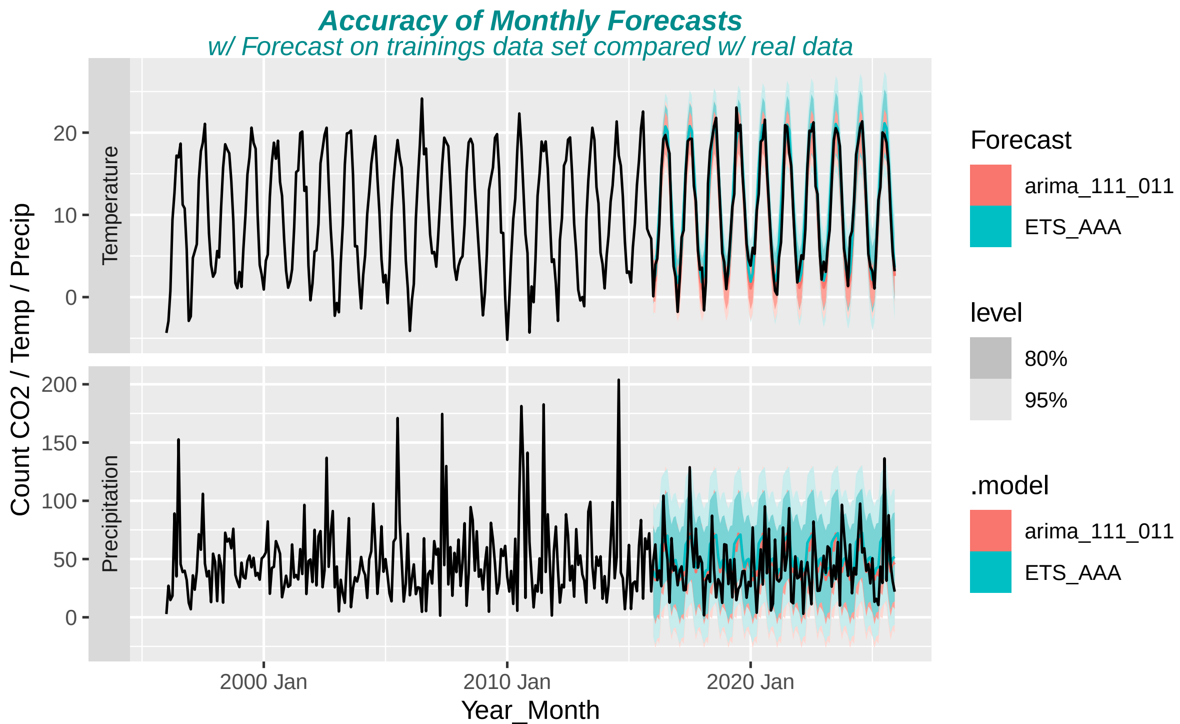
```
#> # A mable: 2 x 4
#> # Key:     City, Measure [2]
#>   City    Measure            ETS_AAA               arima_111_011
#>   <chr>   <fct>              <model>                     <model>
#> 1 Cottbus Temperature   <ETS(A,A,A)> <ARIMA(1,1,1)(0,1,1)[12]>
#> 2 Cottbus Precipitation <ETS(A,A,A)> <ARIMA(1,1,1)(0,1,1)[12]>
```




Monthly Climate Data w/ Forecast (plot as of 2016)
count
Temperature
Precipitation
20
10
0
100
50
0
2020 Jan
2025 Jan
2030 Jan
2035 Jan
Year_Month
level
80%
95%
.model
arima_111_011
ETS_AAA

3.2 Forecast Accuracy Evaluation

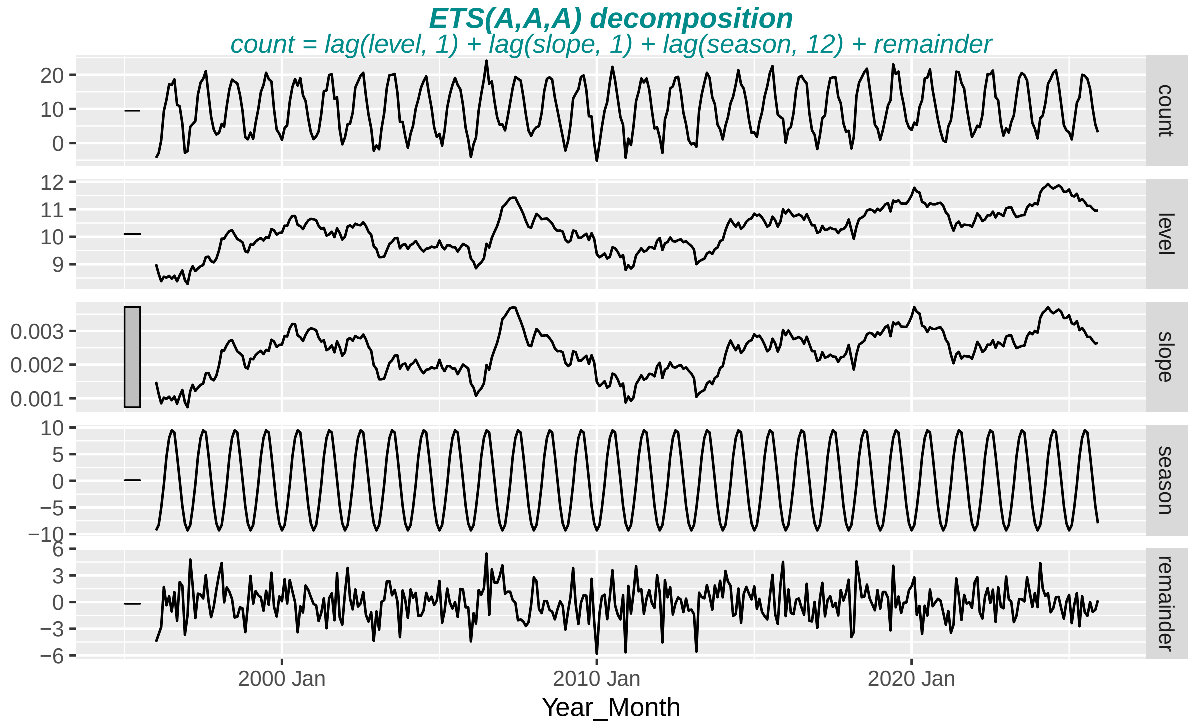
- Forecast Accuracy Evaluation w/ training data “data_train” & test data “data_test”
  - “data” : complete dataset includes the forecasted (future) data range on top of data_train
  - “data_train” = “data” - forecast_range (“data_test”)
    - data used to train the model (~80% of “data)
  - “data_test” = “data” - “data_train”
    - ~ 20% of “data”
  - e.g. for last_year = 2025:
    - data_train is selected from 1966 - 2015
    - data_test is selected from 2016 - 2025



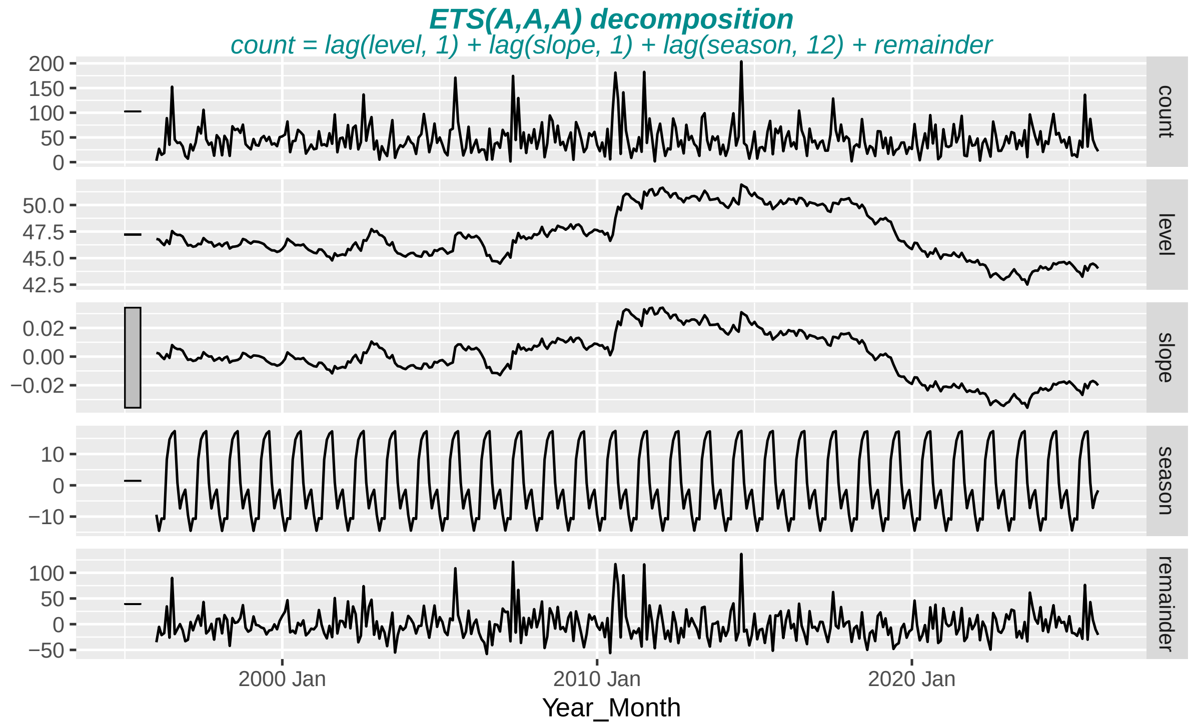
3.2.1 components(fit_ets) - plot of the decomposition of the fitted ETS model

- Note: compare Time series decomposition, for ETS model is valid:
  - count = lag(level, 1) + lag(slope, 1) + lag(season, 12) + remainder

```
#> [1] "Temperature"
```

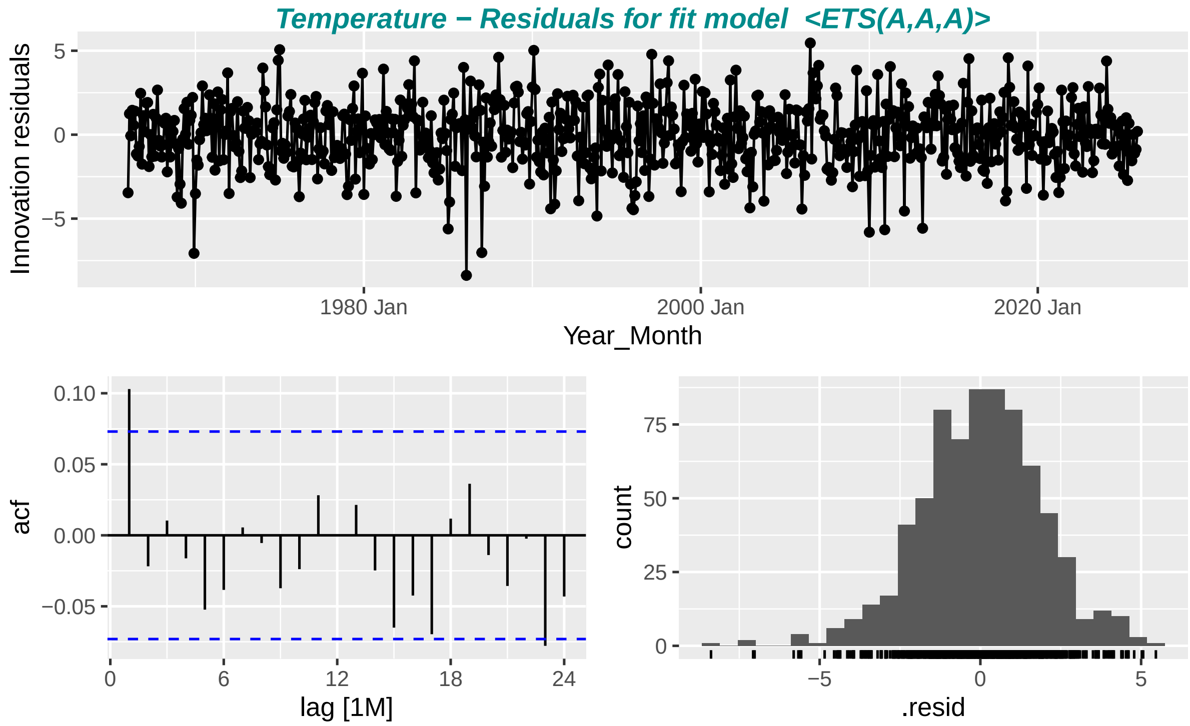


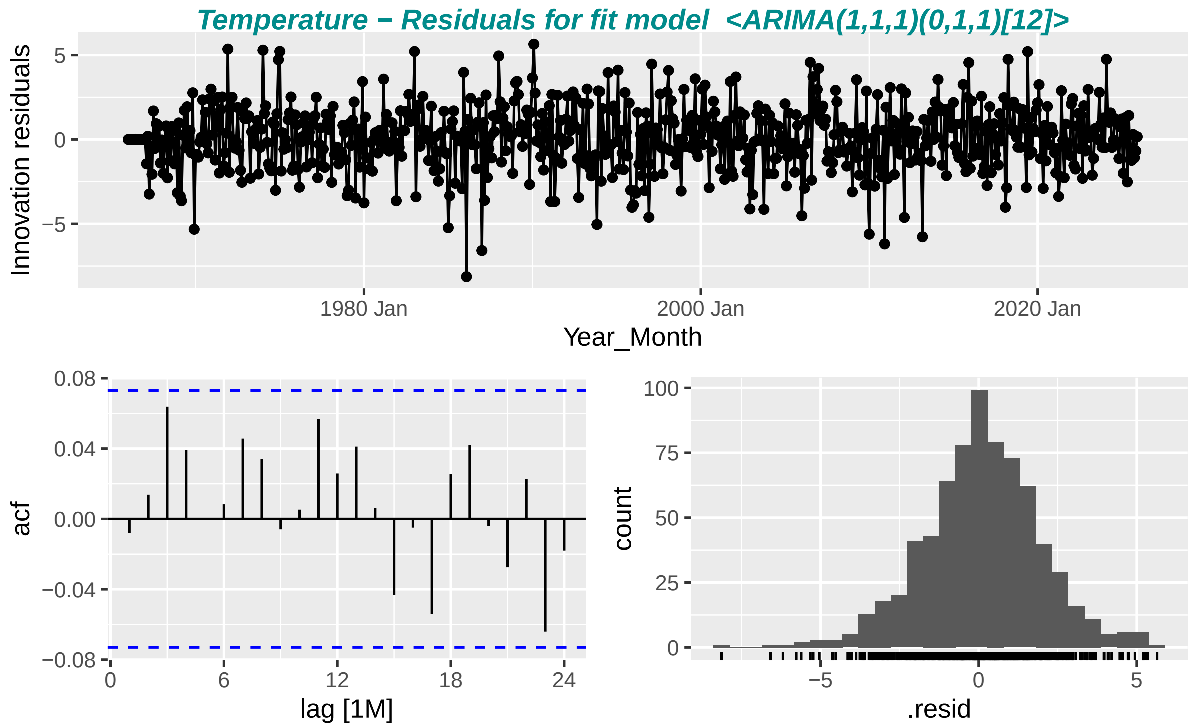

```
#> [1] "Precipitation"
```

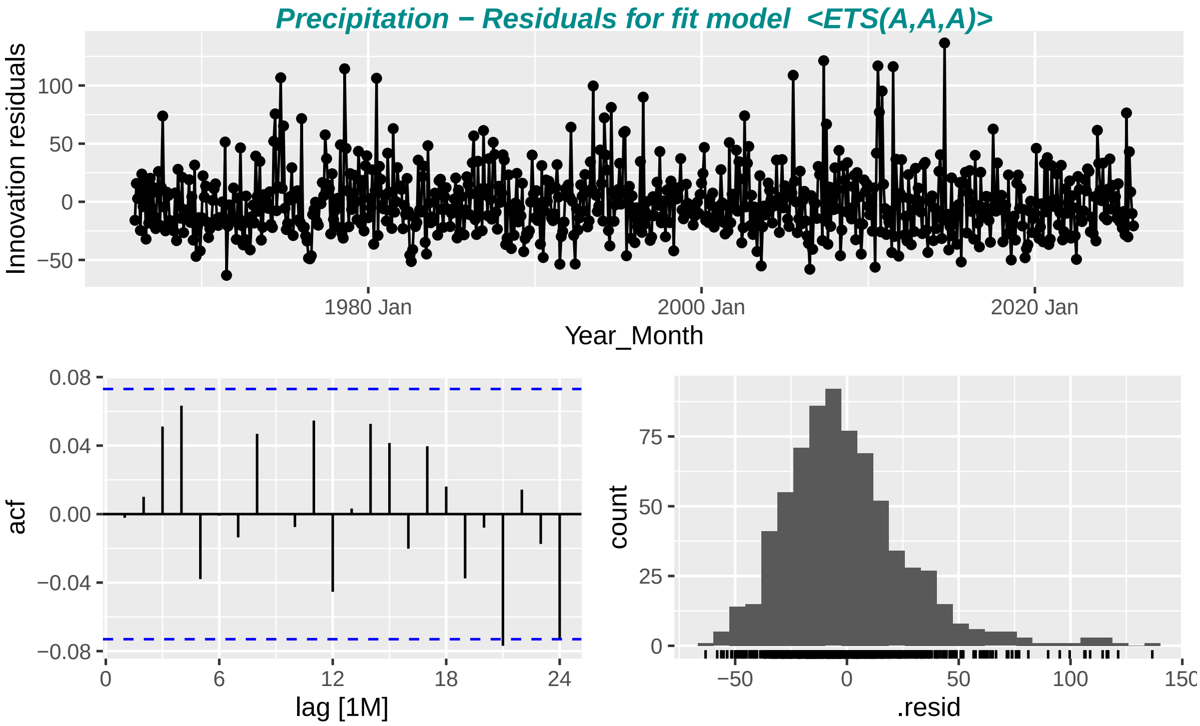


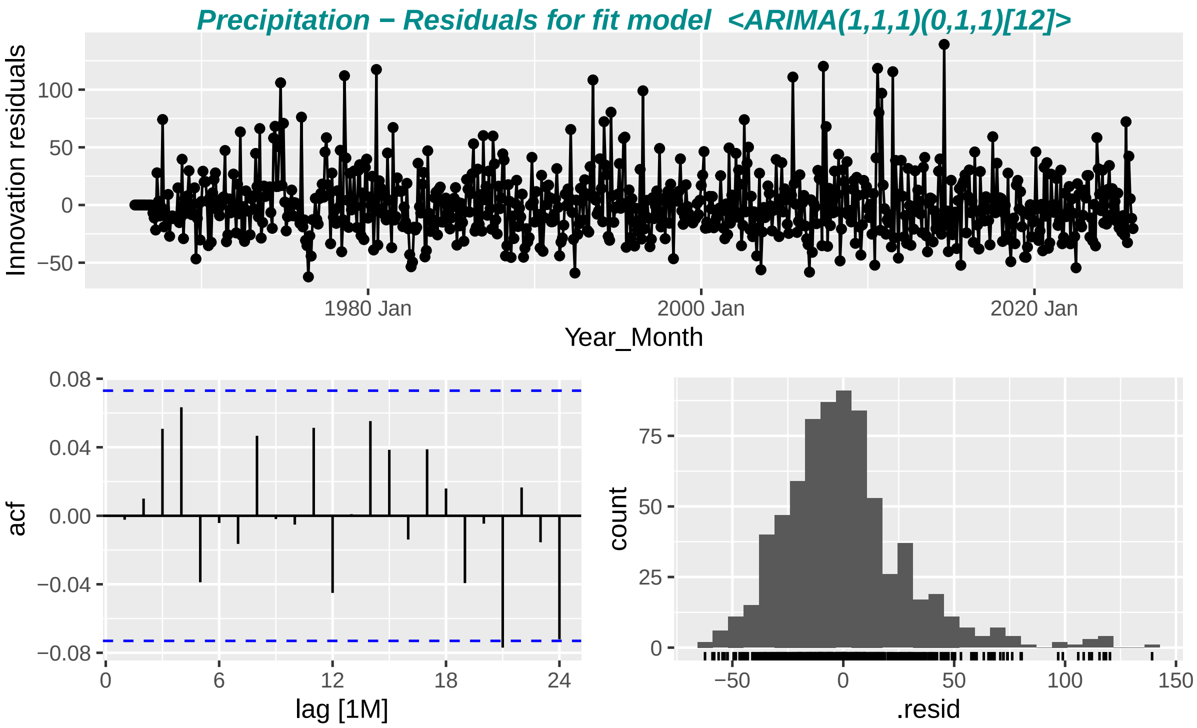
3.2.2 gg_tsresiduals(fit) - plot of innovation residuals, acf and histogram

- gg_tsresiduals(fit) (Ch 7.3 Evaluating the regression model)
  - TS of innovation residuals, acf plot, histogram of residuals | PACF (plot_type='partial')
  - innovation residuals should have constant variance ("homoscedasticity")
  - histogram of the innovation residuals: should be normally distributed






Precipitation − Residuals for fit model <ETS(A,A,A)>
Innovation residuals
Year_Month
1980 Jan
2000 Jan
2020 Jan
acf
lag [1M]
count
.resid


Precipitation − Residuals for fit model <ARIMA(1,1,1)(0,1,1)[12]>
Innovation residuals
Year_Month
1980 Jan
2000 Jan
2020 Jan
acf
lag [1M]
count
.resid

4 Forecast Tables

4.1 Yearly mean values of past time periods

Table 1: Mean values for the given time periods; Units: Temperature (degree C), Precipitation (mm/Month), CO2 (ppm)

Period_Time	Temperature	Precipitation
1889-1900	8.8	48.2
1901-1930	8.9	48.5
1931-1960	9.0	48.1
1961-1990	8.9	46.9
1991-2020	10.0	47.2
2021-2025	11.0	44.8

4.2 Yearly mean forecast values for the next 25 years

Table 2: Mean Yearly ARIMA and ETS Forecast values (next 25 years); Units: Temperature (degree C), Precipitation (mm/Month), CO2 (ppm)

City	Measure	Year	ETS_AAA	arima_111_011
Cottbus	Temperature	2026	10.98	11.11
Cottbus	Temperature	2030	11.11	11.26
Cottbus	Temperature	2035	11.26	11.46
Cottbus	Temperature	2040	11.42	11.66
Cottbus	Temperature	2045	11.58	11.86
Cottbus	Temperature	2050	11.74	12.05
Cottbus	Precipitation	2026	43.89	45.75
Cottbus	Precipitation	2030	42.92	45.60
Cottbus	Precipitation	2035	41.72	45.41
Cottbus	Precipitation	2040	40.51	45.22
Cottbus	Precipitation	2045	39.31	45.03
Cottbus	Precipitation	2050	38.11	44.84

Table 3: Forecast increase/decrease over the next 25 years; Units: Temperature (degree C), Precipitation (mm/Month), CO2 (ppm)

Measure	Year.x	Year.y	ETS.x	ARIMA.x	ETS.y	ARIMA.y	Delta_ETS	Delta_ARIMA
Temperature	2026	2050	10.98	11.11	11.74	12.05	0.76	0.95
Precipitation	2026	2050	43.89	45.75	38.11	44.84	-5.78	-0.91

Table 4: Forecast increase/decrease over the next 25 years; Units: Temperature (degree C), Precipitation (mm/Month), CO2 (ppm)

Measure	Month	Year.x	Year.y	Mean.x_ETS	Mean.x_ARIMA	Mean.y_ETS	Mean.y_ARIMA	Delta_ETS	Delta_ARIMA
Temperature	Jan	2026	2050	1.65	1.82	2.41	2.76	0.76	0.95
Temperature	Feb	2026	2050	2.67	2.76	3.43	3.71	0.76	0.95
Temperature	Mar	2026	2050	5.89	6.04	6.65	6.98	0.76	0.95
Temperature	Apr	2026	2050	10.29	10.48	11.06	11.42	0.76	0.95
Temperature	May	2026	2050	15.48	15.57	16.24	16.52	0.76	0.95
Temperature	Jun	2026	2050	19.02	19.02	19.78	19.97	0.76	0.95

Measure	Month	Year.x	Year.y	Mean.x_ETS	Mean.x_ARIMA	Mean.y_ETS	Mean.y_ARIMA	Delta_ETS	Delta_ARIMA
Temperature	Jul	2026	2050	20.45	20.71	21.22	21.65	0.76	0.95
Temperature	Aug	2026	2050	20.05	20.19	20.82	21.14	0.76	0.95
Temperature	Sep	2026	2050	15.77	15.89	16.53	16.84	0.76	0.95
Temperature	Oct	2026	2050	11.15	11.27	11.92	12.22	0.76	0.95
Temperature	Nov	2026	2050	6.29	6.35	7.06	7.29	0.76	0.95
Temperature	Dec	2026	2050	3.01	3.19	3.77	4.14	0.76	0.95
Precipitation	Jan	2026	2050	34.82	40.59	29.04	39.67	-5.78	-0.92
Precipitation	Feb	2026	2050	29.53	32.56	23.75	31.64	-5.78	-0.91
Precipitation	Mar	2026	2050	33.36	35.09	27.58	34.18	-5.78	-0.91
Precipitation	Apr	2026	2050	32.99	33.43	27.21	32.52	-5.78	-0.91
Precipitation	May	2026	2050	52.02	52.48	46.24	51.57	-5.78	-0.91
Precipitation	Jun	2026	2050	58.16	55.14	52.38	54.22	-5.78	-0.91
Precipitation	Jul	2026	2050	60.79	66.23	55.01	65.32	-5.78	-0.91
Precipitation	Aug	2026	2050	61.16	63.09	55.38	62.18	-5.78	-0.91
Precipitation	Sep	2026	2050	44.67	46.42	38.89	45.51	-5.78	-0.91
Precipitation	Oct	2026	2050	36.58	40.20	30.80	39.28	-5.78	-0.91
Precipitation	Nov	2026	2050	40.37	42.03	34.59	41.12	-5.78	-0.91
Precipitation	Dec	2026	2050	42.18	41.78	36.40	40.87	-5.78	-0.91

5 Backup

5.1 Cottbus - Average Yearly and Seasonal Data

Table 5: Annual paste(“Temperature /”, degree * C) (first and last 10 years)

City	Measure	Year	Winter_avg	Spring_avg	Summer_avg	Fall_avg	Year_avg
Cottbus	Temperature	1889	NA	9.0	18.4	7.9	8.3
Cottbus	Temperature	1890	-0.5	9.0	17.3	8.5	8.2
Cottbus	Temperature	1891	-3.1	8.4	16.7	9.6	8.6
Cottbus	Temperature	1892	0.6	7.5	18.9	8.7	8.6
Cottbus	Temperature	1893	-3.6	9.2	18.7	9.5	8.7
Cottbus	Temperature	1894	0.9	9.8	17.6	9.2	9.3
Cottbus	Temperature	1895	-2.4	9.1	19.4	9.0	8.7
Cottbus	Temperature	1896	-0.1	8.8	17.2	9.1	8.7
Cottbus	Temperature	1897	-1.1	9.0	18.5	8.2	8.8
Cottbus	Temperature	1898	2.2	9.0	17.5	9.6	9.7
Cottbus	Temperature	2016	3.7	9.7	19.1	10.0	10.2
Cottbus	Temperature	2017	1.0	10.1	19.2	10.3	10.2
Cottbus	Temperature	2018	1.8	11.1	20.6	10.8	11.1
Cottbus	Temperature	2019	3.0	10.2	21.4	10.9	11.4
Cottbus	Temperature	2020	4.8	9.4	19.9	11.2	11.2
Cottbus	Temperature	2021	1.5	8.0	19.8	10.7	9.8
Cottbus	Temperature	2022	3.4	9.5	20.6	10.6	11.0
Cottbus	Temperature	2023	3.2	9.3	19.9	12.2	11.3
Cottbus	Temperature	2024	4.3	12.4	20.3	11.3	12.0
Cottbus	Temperature	2025	2.6	10.4	19.5	10.5	10.7

Table 6: Annual Precipitation / mm/Month (first and last 10 years)

City	Measure	Year	Winter_avg	Spring_avg	Summer_avg	Fall_avg	Year_avg
Cottbus	Precipitation	1889	NA	33.7	63.7	57.6	46.7
Cottbus	Precipitation	1890	26.0	17.8	95.2	43.2	44.9
Cottbus	Precipitation	1891	18.4	44.7	94.5	38.5	53.1
Cottbus	Precipitation	1892	51.9	37.7	30.5	17.3	35.0
Cottbus	Precipitation	1893	65.0	25.1	40.2	52.2	41.9
Cottbus	Precipitation	1894	30.7	53.2	59.6	50.3	50.7
Cottbus	Precipitation	1895	43.1	38.8	50.5	43.8	45.5
Cottbus	Precipitation	1896	38.6	42.8	77.9	66.1	53.9
Cottbus	Precipitation	1897	37.5	69.7	77.4	26.4	51.9
Cottbus	Precipitation	1898	36.4	70.4	47.9	43.5	51.2
Cottbus	Precipitation	2016	44.5	32.9	72.9	40.2	49.4
Cottbus	Precipitation	2017	37.1	30.1	83.1	53.9	51.8
Cottbus	Precipitation	2018	33.5	32.7	48.5	24.7	35.7
Cottbus	Precipitation	2019	51.1	38.8	22.2	32.0	33.4
Cottbus	Precipitation	2020	44.8	23.5	60.5	39.9	40.6
Cottbus	Precipitation	2021	36.9	47.1	62.2	25.9	44.9
Cottbus	Precipitation	2022	38.7	29.6	40.9	33.5	35.7
Cottbus	Precipitation	2023	41.5	48.7	NA	59.8	NA
Cottbus	Precipitation	2024	NA	33.2	NA	48.2	NA
Cottbus	Precipitation	2025	31.0	NA	65.8	54.7	NA

Table 7: Monthly Means over all Years (Temperature / degree C and Monthly Precipitation / mm)

City	Month	Temperature	Precipitation
Cottbus	Jan	-0.1	39.8
Cottbus	Feb	0.6	32.9
Cottbus	Mar	4.1	35.3
Cottbus	Apr	8.7	38.5
Cottbus	May	13.9	52.9
Cottbus	Jun	17.3	59.8
Cottbus	Jul	18.9	73.4
Cottbus	Aug	18.1	66.4
Cottbus	Sep	14.2	46.2
Cottbus	Oct	9.4	43.0
Cottbus	Nov	4.5	42.0
Cottbus	Dec	1.3	41.2

5.2 Cottbus - Head and tail of data

```
#> # A tsibble: 6 x 5 [1M]
#> # Key:       City, Measure [1]
#> # Groups:    City, Measure [1]
#>   City    Measure     Year_Month Period_Time count
#>   <chr>   <fct>            <mth> <chr>       <dbl>
#> 1 Cottbus Temperature   1889 Jan 1889-1900   -3.1
#> 2 Cottbus Temperature   1889 Feb 1889-1900   -2.09
#> 3 Cottbus Temperature   1889 Mrz 1889-1900    0.63
#> 4 Cottbus Temperature   2025 Okt 2021-2025   10.2
#> 5 Cottbus Temperature   2025 Nov 2021-2025    5.45
#> 6 Cottbus Temperature   2025 Dez 2021-2025    3.15
#> # A tsibble: 6 x 5 [1M]
#> # Key:       City, Measure [1]
#> # Groups:    City, Measure [1]
#>   City    Measure       Year_Month Period_Time count
#>   <chr>   <fct>              <mth> <chr>       <dbl>
#> 1 Cottbus Precipitation   1889 Jan 1889-1900    18.9
#> 2 Cottbus Precipitation   1889 Feb 1889-1900    63.2
#> 3 Cottbus Precipitation   1889 Mrz 1889-1900    44.3
#> 4 Cottbus Precipitation   2025 Okt 2021-2025    45.6
#> 5 Cottbus Precipitation   2025 Nov 2021-2025    30.9
#> 6 Cottbus Precipitation   2025 Dez 2021-2025    22
```

5.3 Data Sources

5.3.1 Temperatures and Precipitation

- Basel / Davos: **Federal Office of Meteorology and Climatology MeteoSwiss**
  - https://www.meteoswiss.admin.ch/home/climate/swiss-climate-in-detail/homogeneous-data-series-since-1864.html
- Cottbus/ Giessen/ Hohenpeissenberg/ Mannheim/ Potsdam: **DWD Archiv Monats- und Tageswerte**
  - https://www.dwd.de/DE/leistungen/klimadatendeutschland/klarchivtagmonat.html
  - *Monatswerte historisch und aktuell*
  - File: produkt_klima_monat_xy.txt
    - column MO_TT (Temperature; Monatsmittel der Lufttemperatur in 2m Höhe in °C and MO_RR (Precipitation; Monatssumme der Niederschlagshoehe in mm))
- England **Met Office - National Meteorological Service for the UK**
  - https://www.metoffice.gov.uk/hadobs/hadcet/data/download.html
  - Monthly_HadCET_mean.txt, 1659 to date

5.3.2 CO2 Concentrations

- **National Oceanic & Atmospheric Administration - Earth System Research Laboratory**
  - *NOAA ESRL* https://www.esrl.noaa.gov/gmd/ccgg/trends/global.html
  - Data file: ***Mauna Loa CO2*** monthly mean data
  - https://www.esrl.noaa.gov/gmd/ccgg/trends/data.html

5.4 R code

- Source code (maybe not yet the latest version) and output files are stored on GitHub repository https://github.com/WoVollmer/R-TimesSeriesAnalysis/tree/master/Climate
- Partially based on *c't Magazin* articles by *Andreas Krause*:
  - #3/2014 p.188 http://www.ct.de/1403188 & #6/2014 p.180 http://www.ct.de/1406180
- *Forecasting: Principles and Practice (3rd ed)* https://otexts.com/fpp3
  - Rob J Hyndman and George Athanasopoulos; Monash University, Australia