

Climate Data Visualization - Atmospheric CO_2 Concentration / Temperature / Precipitation

Wolfgang Vollmer

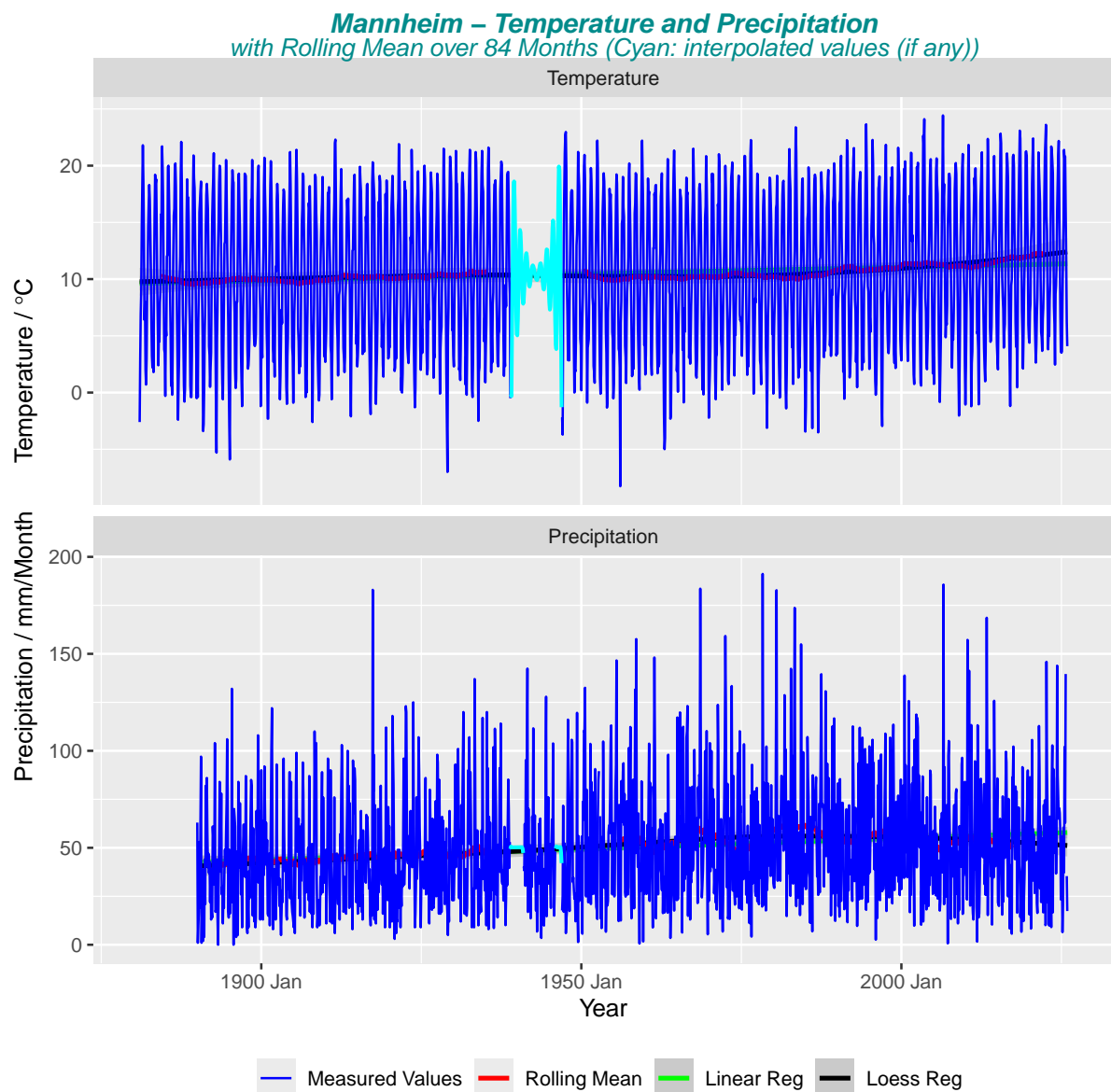
2026-01-08

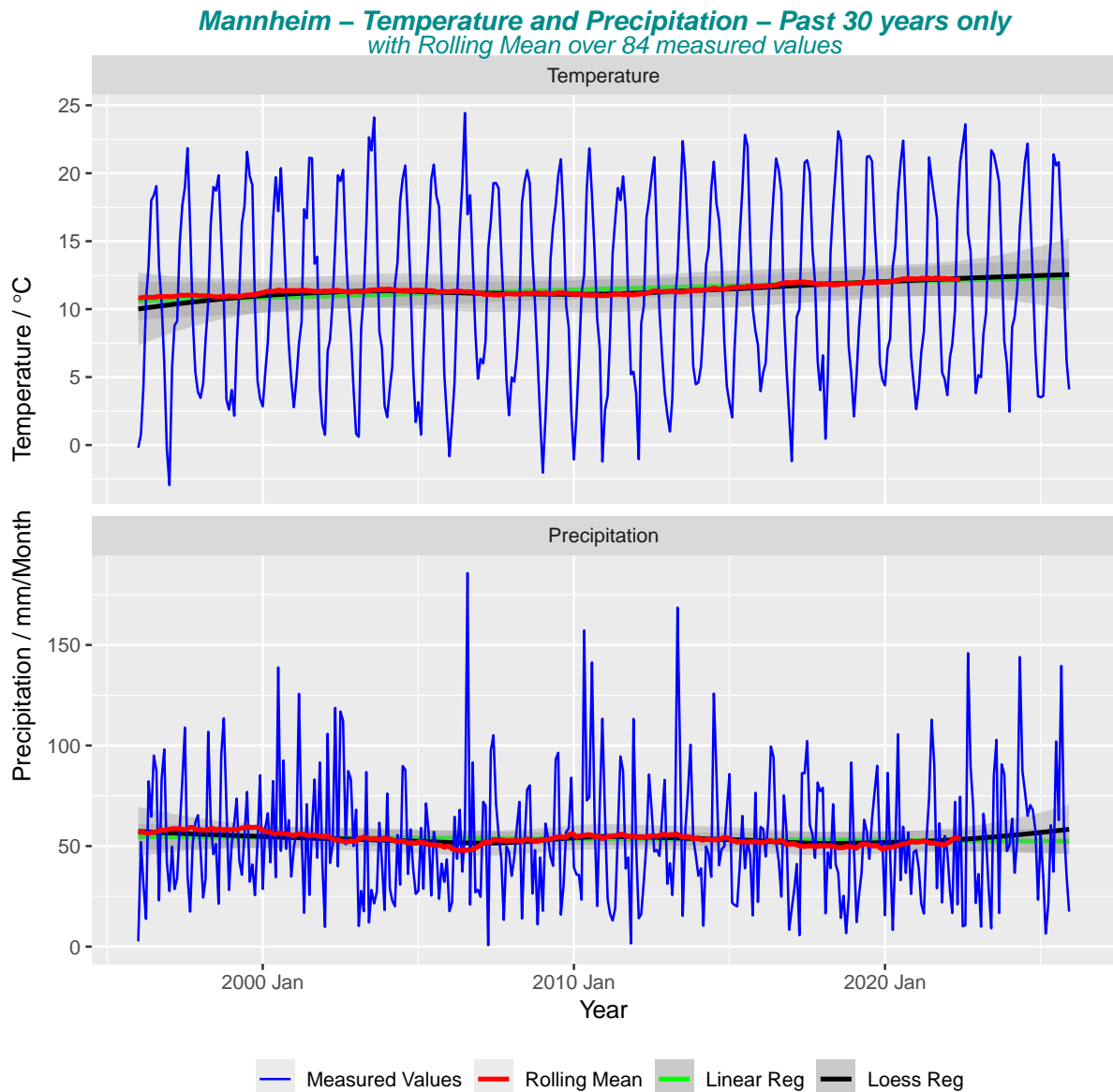
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1 Mannheim - Visualization of Temperature, Precipitation Data 1881 - 2025

1.1 Monthly Time Plots with Rolling Mean

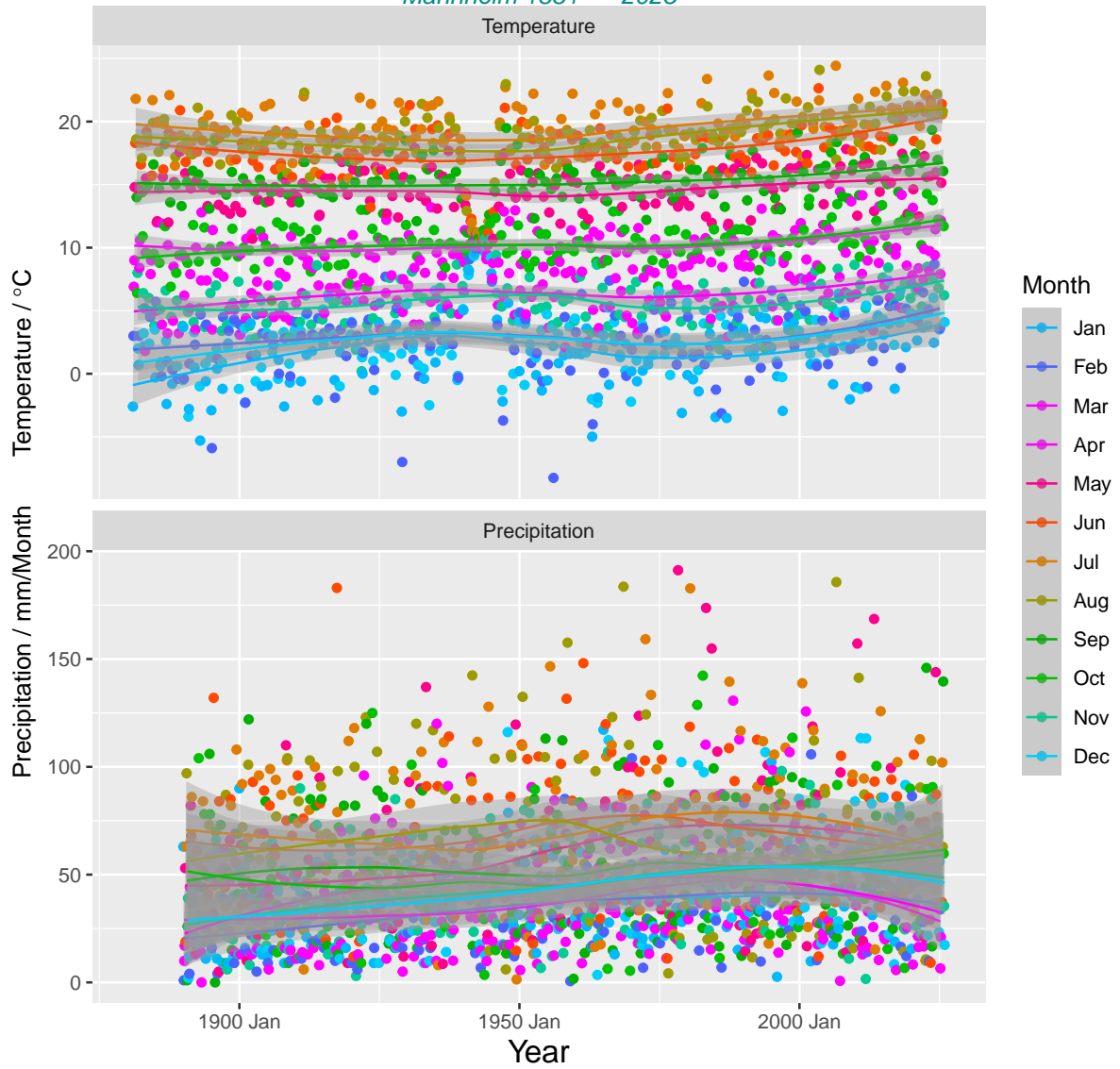




1.2 Annual seasonal plots with monthly breakdown

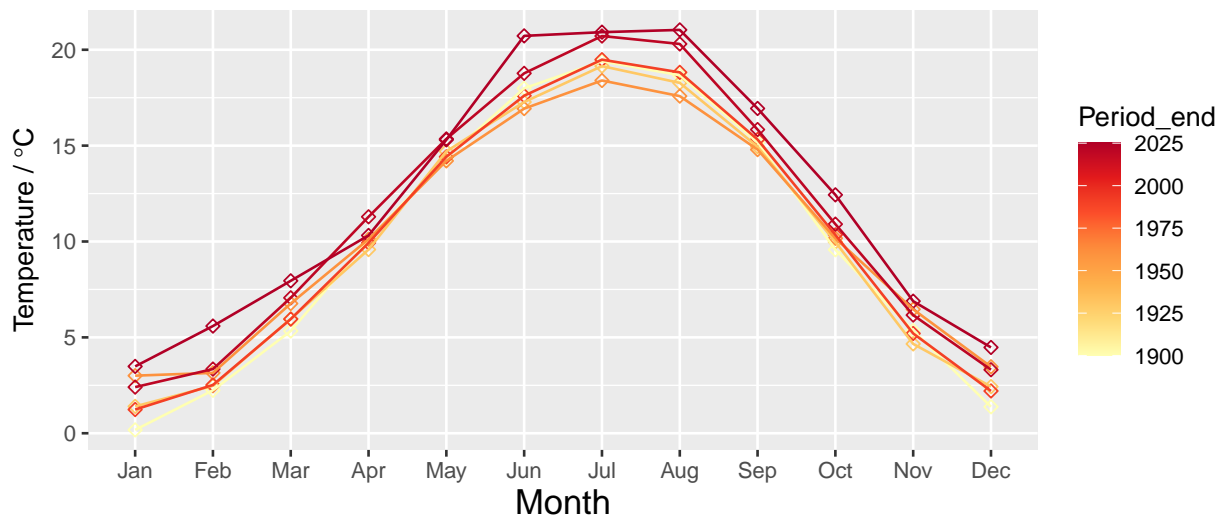
The seasonal charts show the monthly seasonal patterns, where available.

Monthly Data with Local Polynomial Regression Fitting Mannheim 1881 – 2025

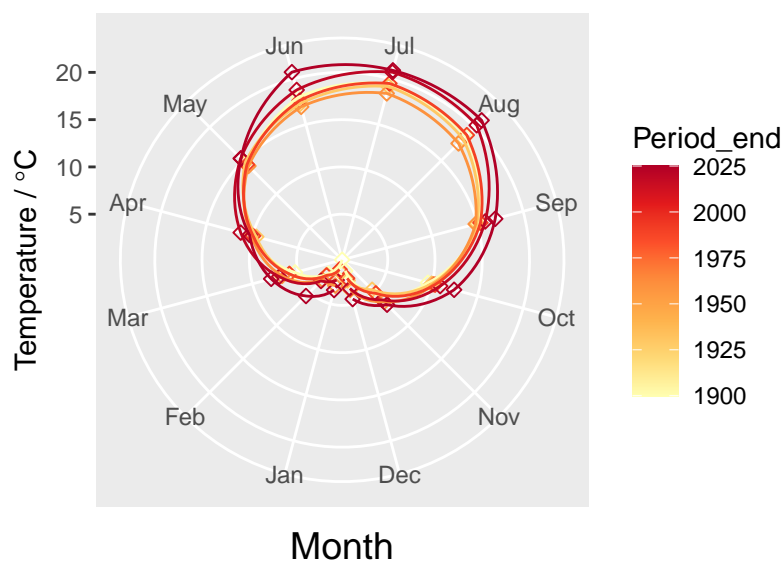


1.2.1 30-year period plots with monthly breakdown - Cartesian and Polar Coordinates

Temperature – Monthly Variations of 30-Year Periods
Periods: First 1881–1900 / Reference 1991–2020 / Last 2021–2025

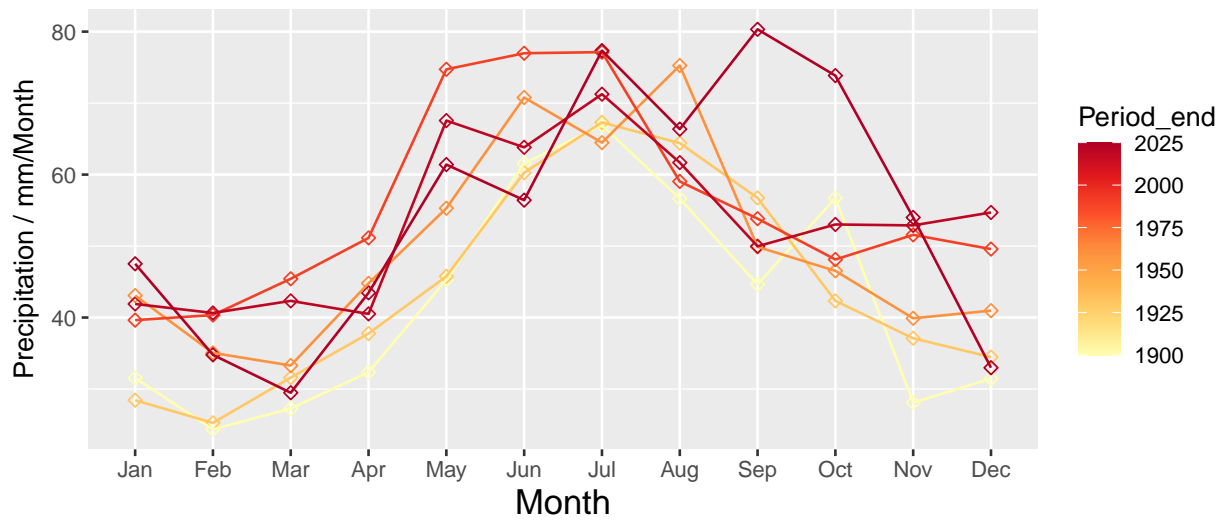


Temperature – Monthly Variations of 30-Year Periods
Periods: First 1881–1900 / Reference 1991–2020 / Last 2021–2025

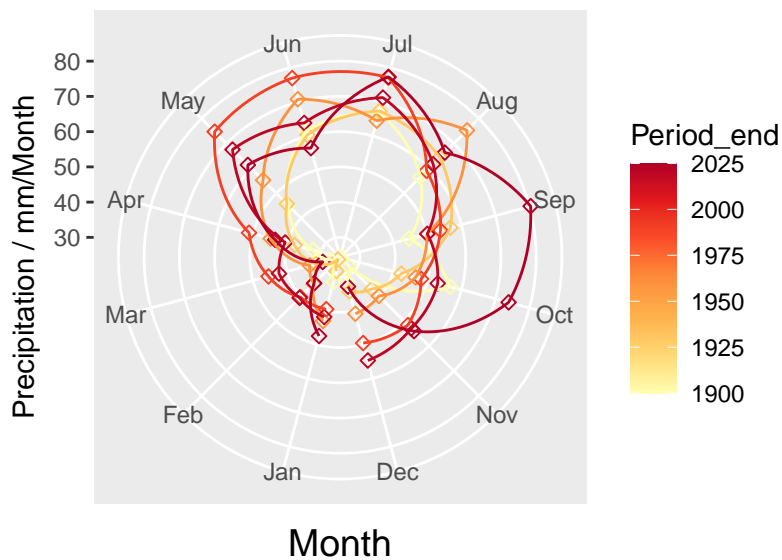


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Precipitation – Monthly Variations of 30-Year Periods
Periods: First 1881–1900 / Reference 1991–2020 / Last 2021–2025



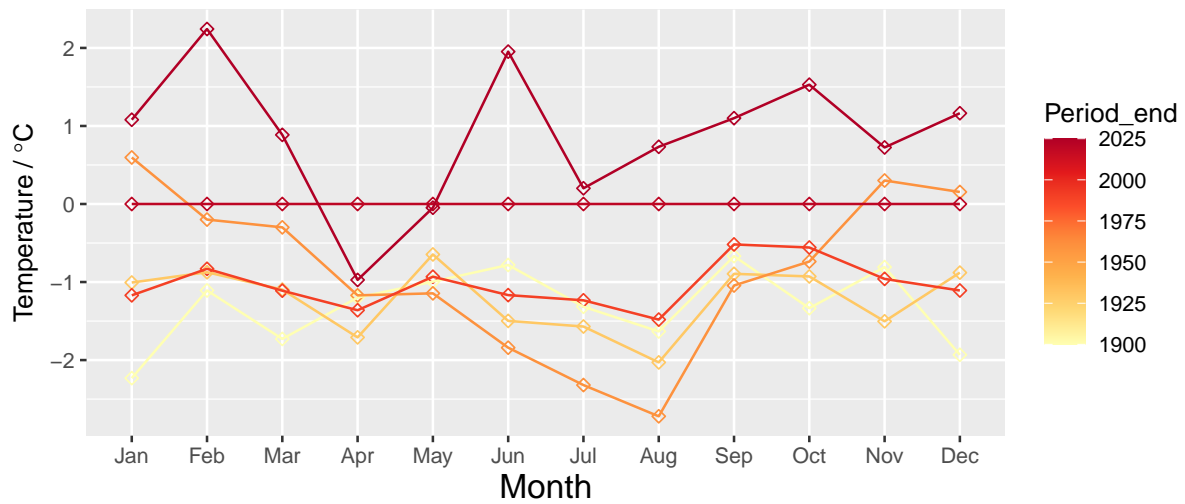
Precipitation – Monthly Variations of 30-Year Periods
Periods: First 1881–1900 / Reference 1991–2020 / Last 2021–2025



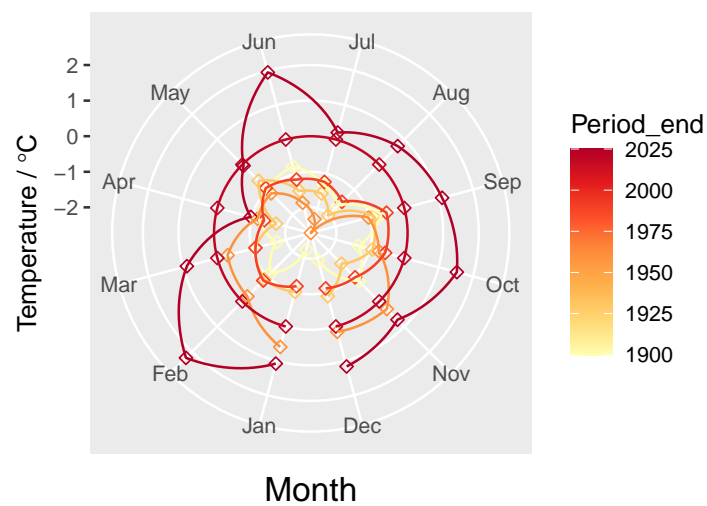
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1.2.2 Plot Monthly Delta to Reference Period - Cartesian and Polar Coordinates

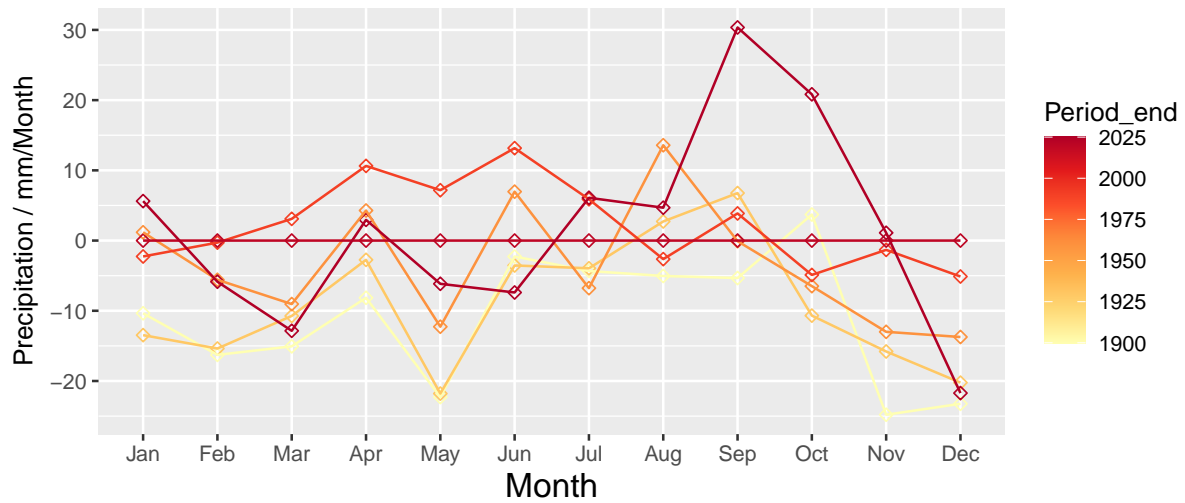
Temperature – Monthly Variations of 30–Year Periods (Delta to Reference)
Periods: First 1881–1900 / Reference 1991–2020 / Last 2021–2025



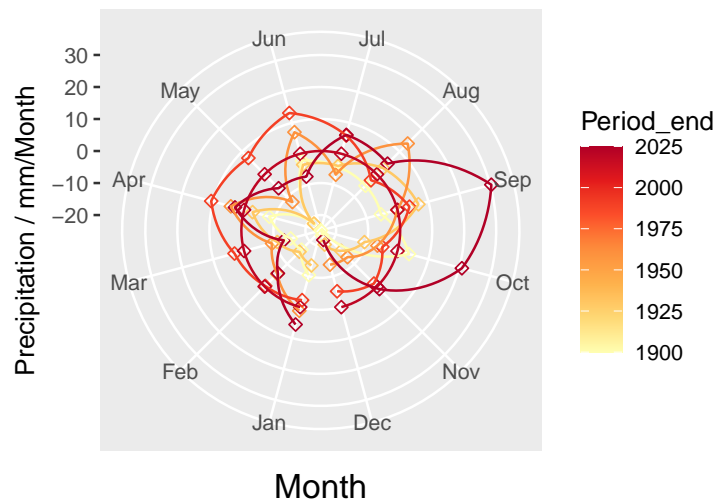
Temperature – Monthly Variations of 30–Year Periods (Delta to Reference)
Periods: First 1881–1900 / Reference 1991–2020 / Last 2021–2025



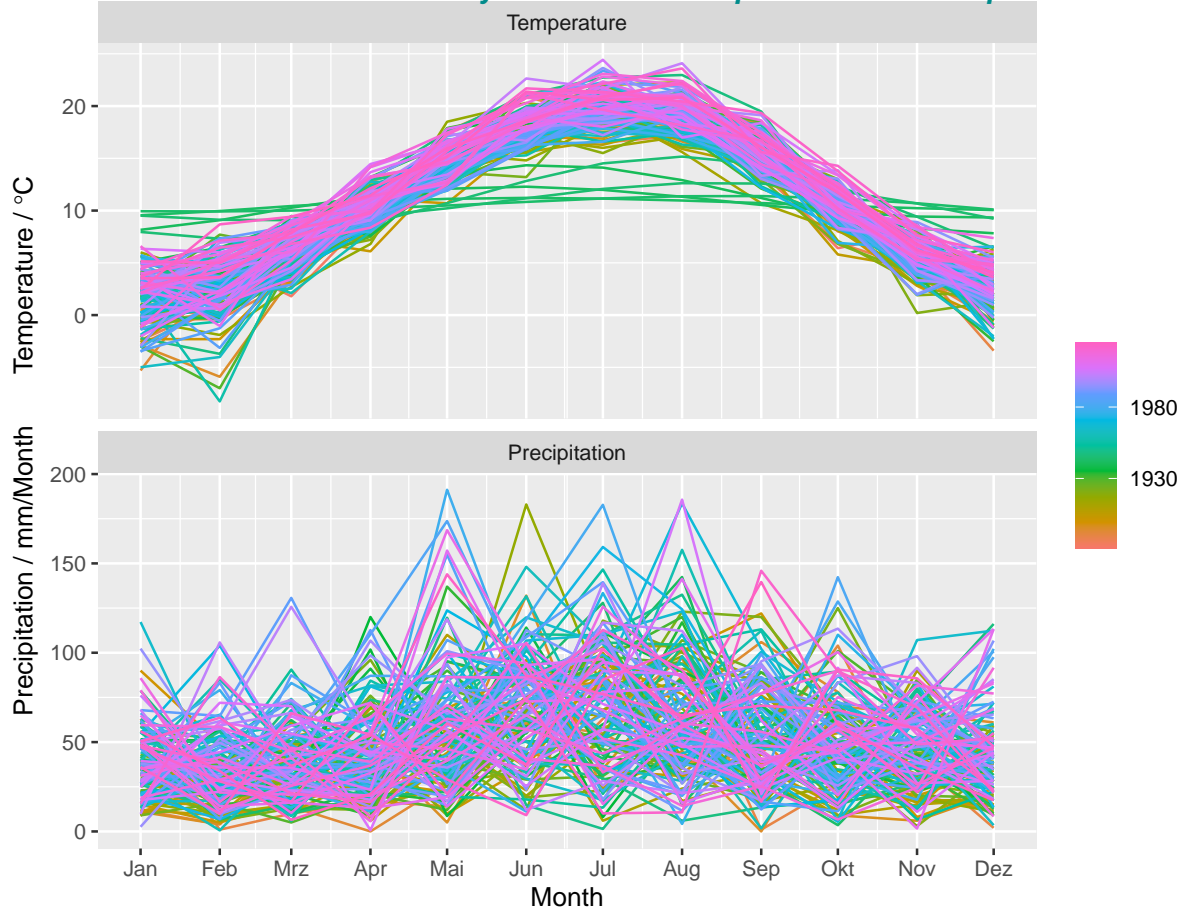
Precipitation – Monthly Variations of 30–Year Periods (Delta to Reference)
 Periods: First 1881–1900 / Reference 1991–2020 / Last 2021–2025

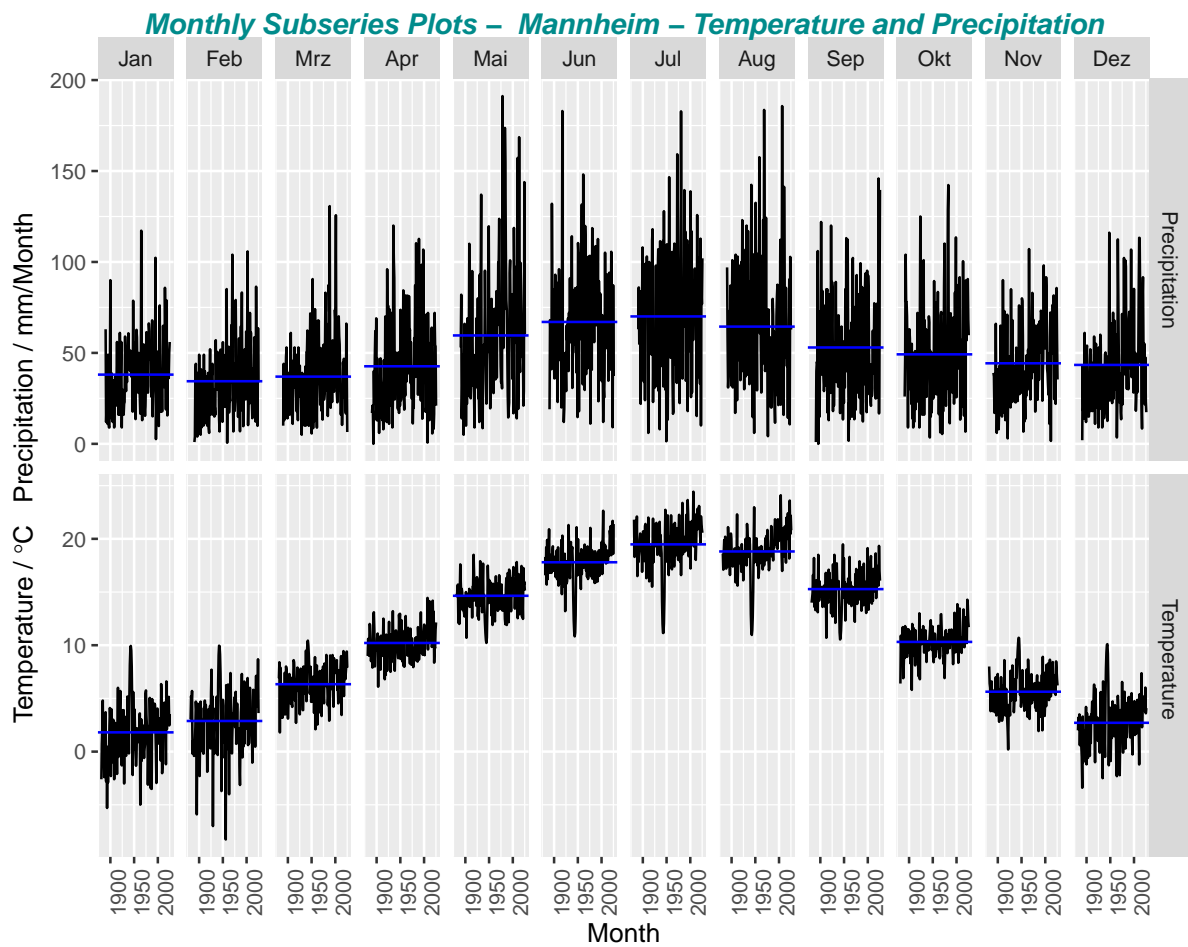


Precipitation – Monthly Variations of 30–Year Periods (Delta to Reference)
 Periods: First 1881–1900 / Reference 1991–2020 / Last 2021–2025



Annual Seasonal Plots – Monthly Mannheim – Temperature and Precipitation

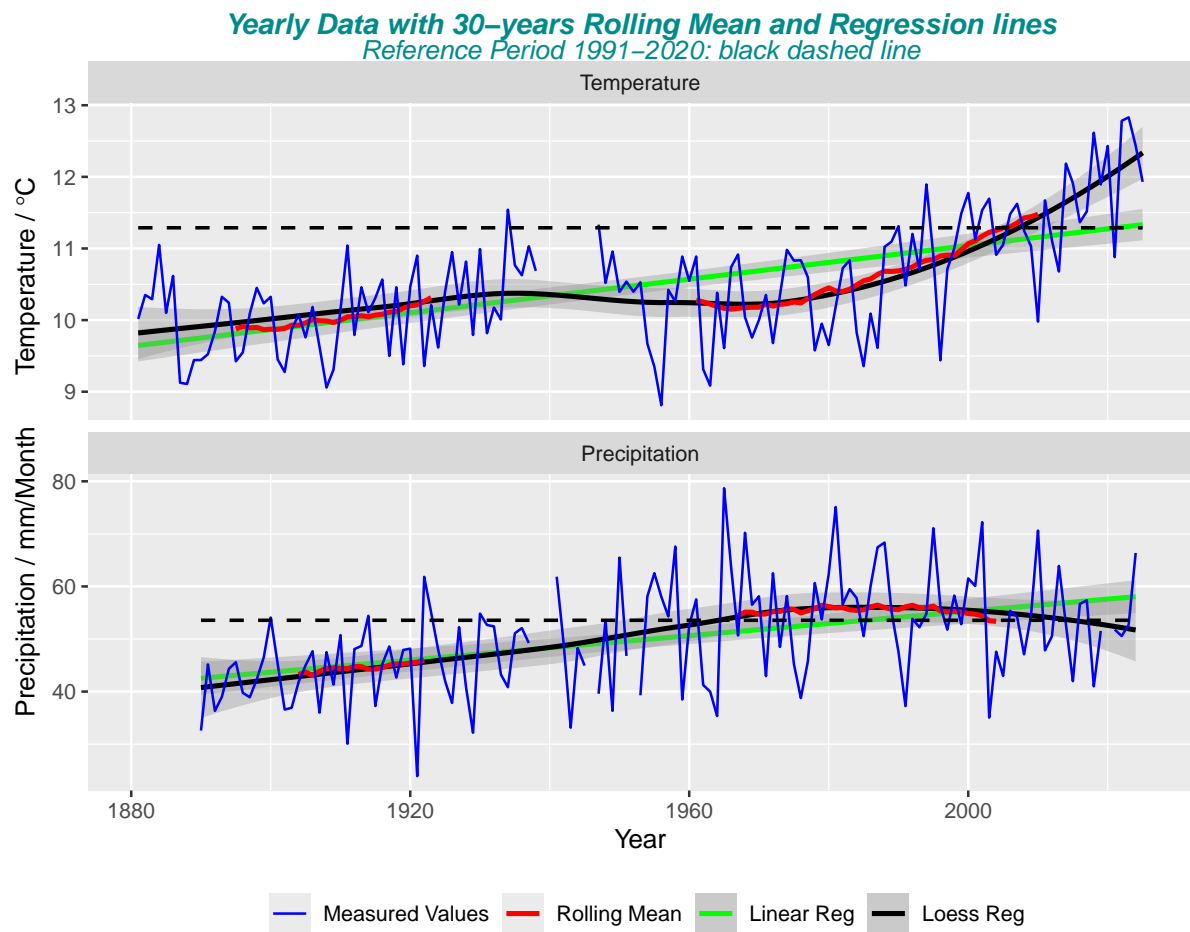




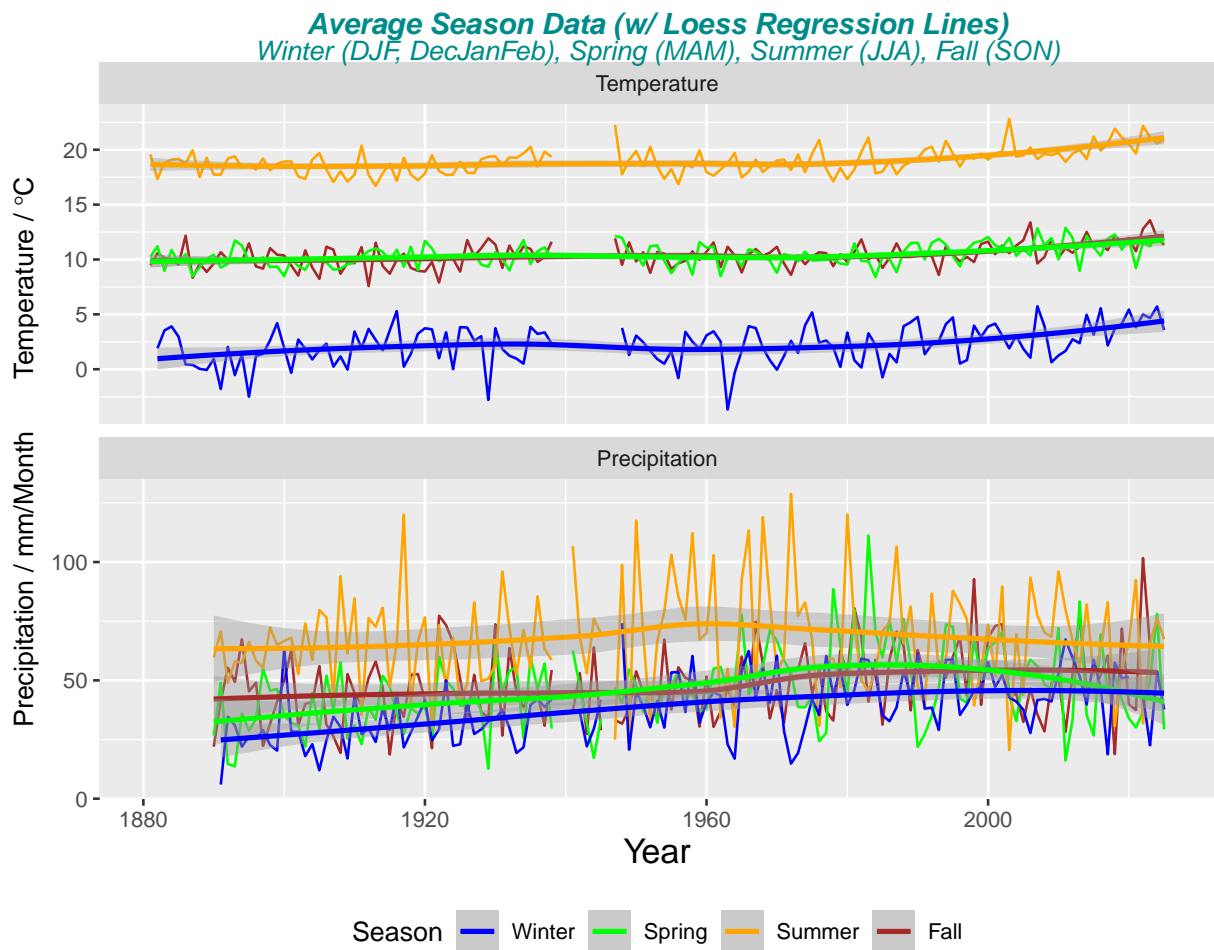
The blue horizontal lines within the seasonal subseries plot indicate the means for each month.

1.3 Annual Mannheim - 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.

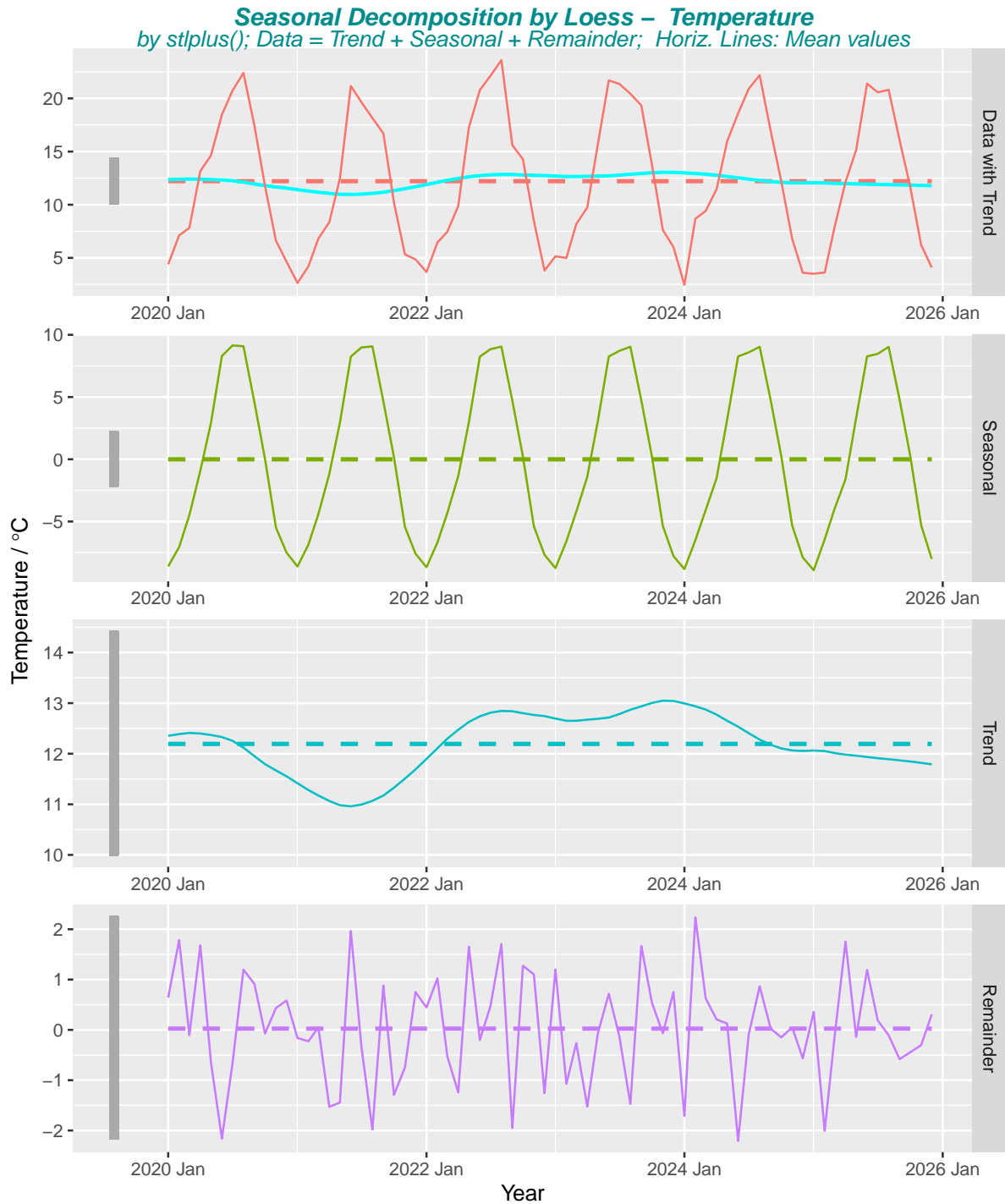
Time series using an

- 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.

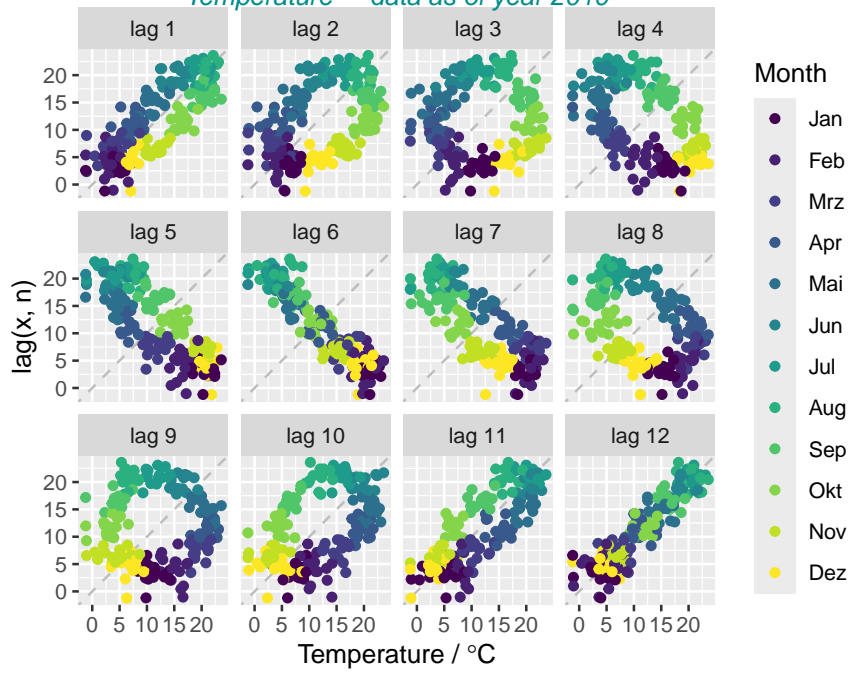


2.2 Periodicities - Season Frequency

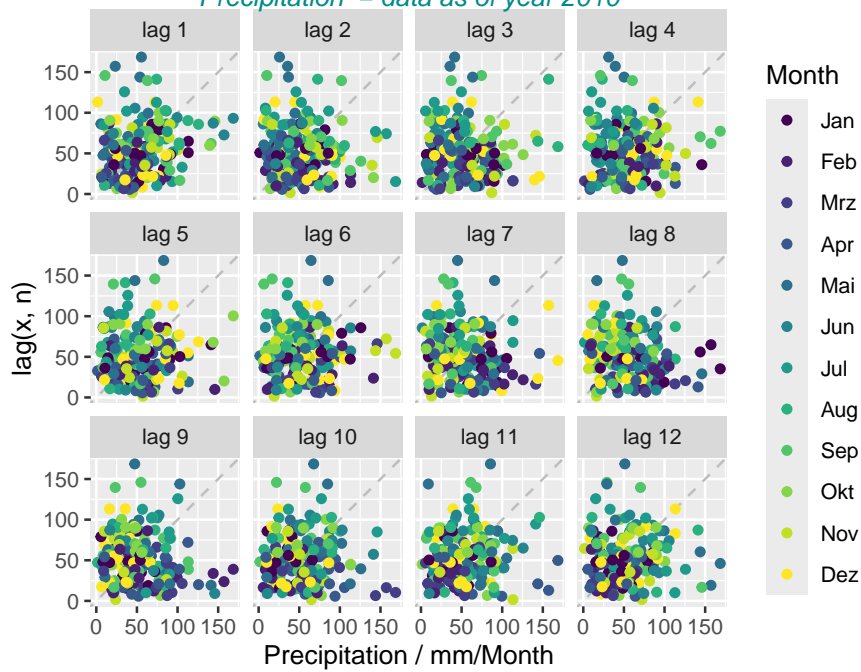
2.2.1 Lag Plot - Differences

Lagged scatterplots, where the horizontal axis shows lagged ($k = 1, \dots, 12$) 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 of lag $k = 6$.

Lag by n months – $y(t)$ plotted against $y(t-n)$
 Temperature – data as of year 2010



Lag by n months – $y(t)$ plotted against $y(t-n)$
 Precipitation – data as of year 2010



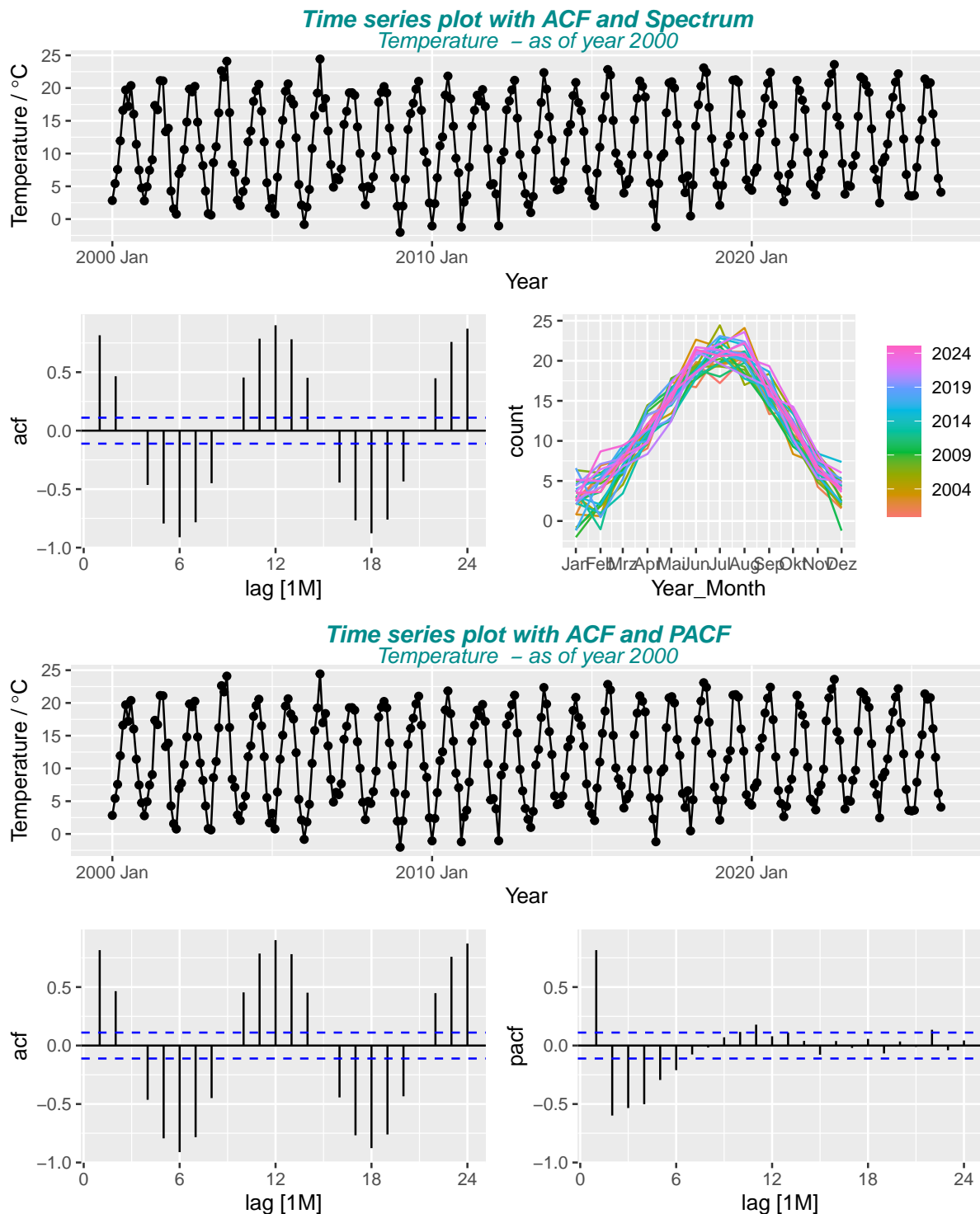
2.2.2 Periodogram - Spectral Density Estimation of a Time Series

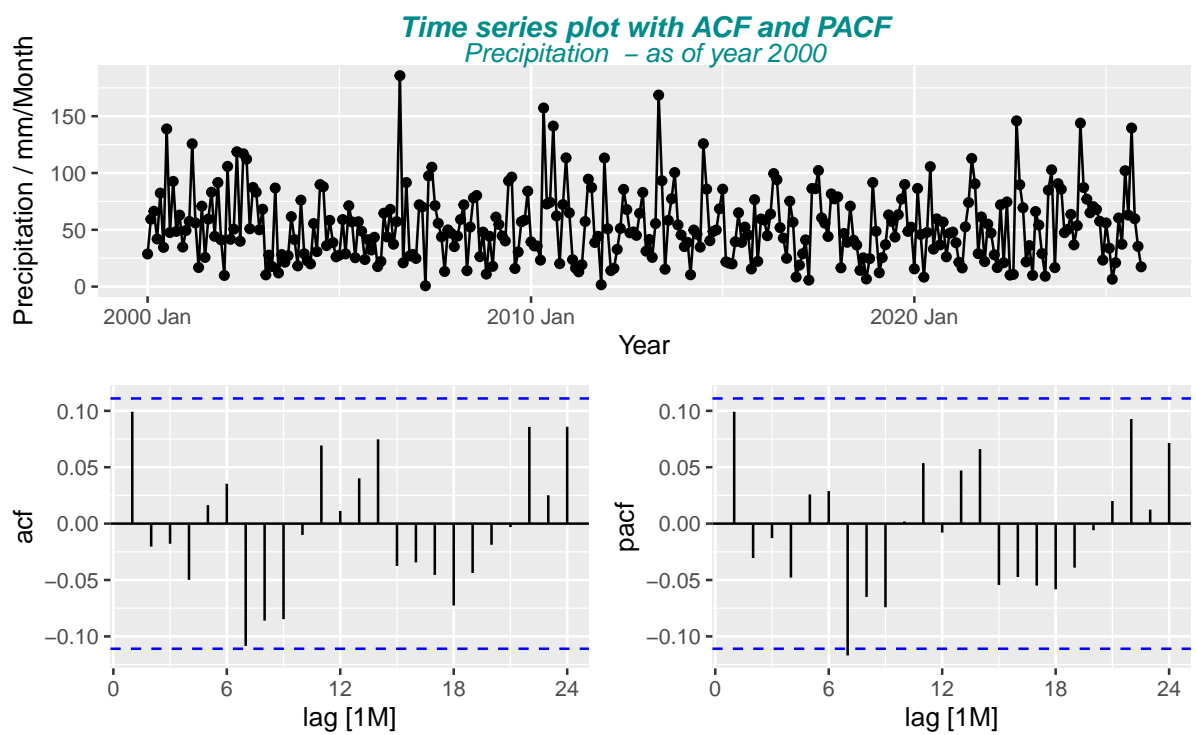
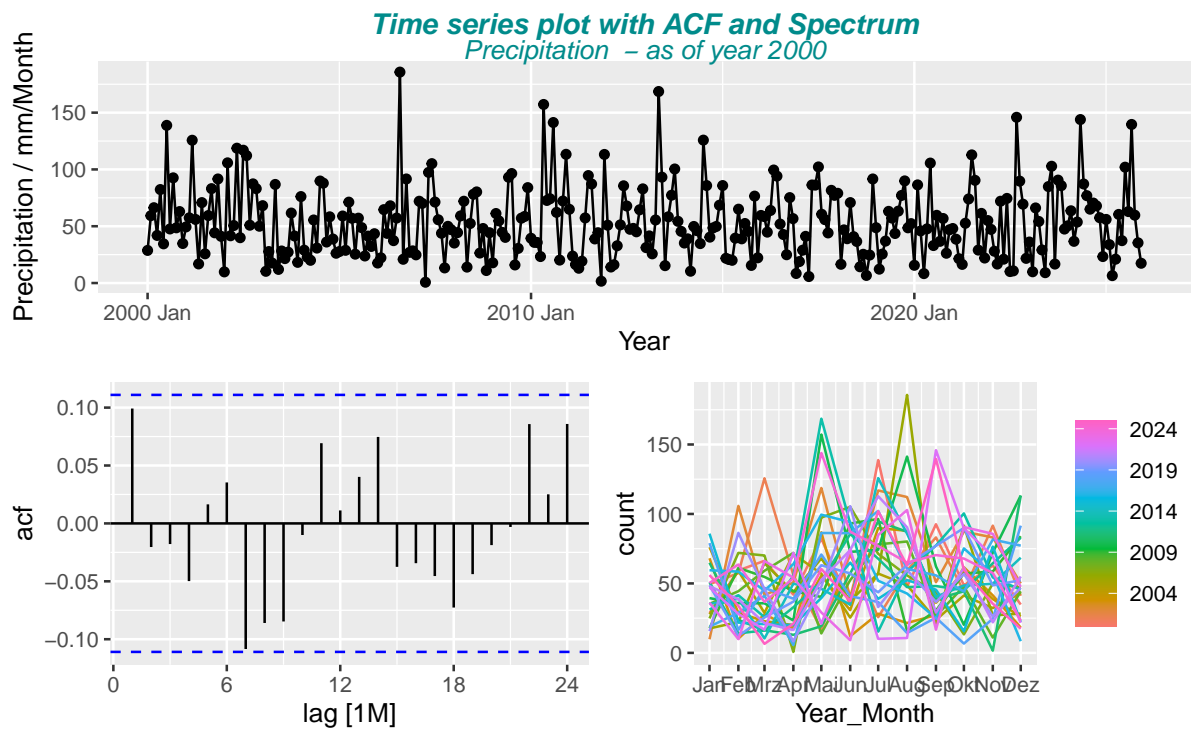
The spectral density characterizes the frequency content of the signal. One purpose of estimating the spectral density is to detect any periodicities in the data, by observing peaks at the frequencies corresponding to these periodicities.

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.





3 Forecasting - Estimate/Train the model

3.1 Forecasting with ETS and ARIMA model

Exponential Smoothing (ETS) and **AutoRegressive Integrated Moving Average Forecasting Models (ARIMA)** models are the two most widely used approaches to time series forecasting, and provide complementary approaches to the problem.

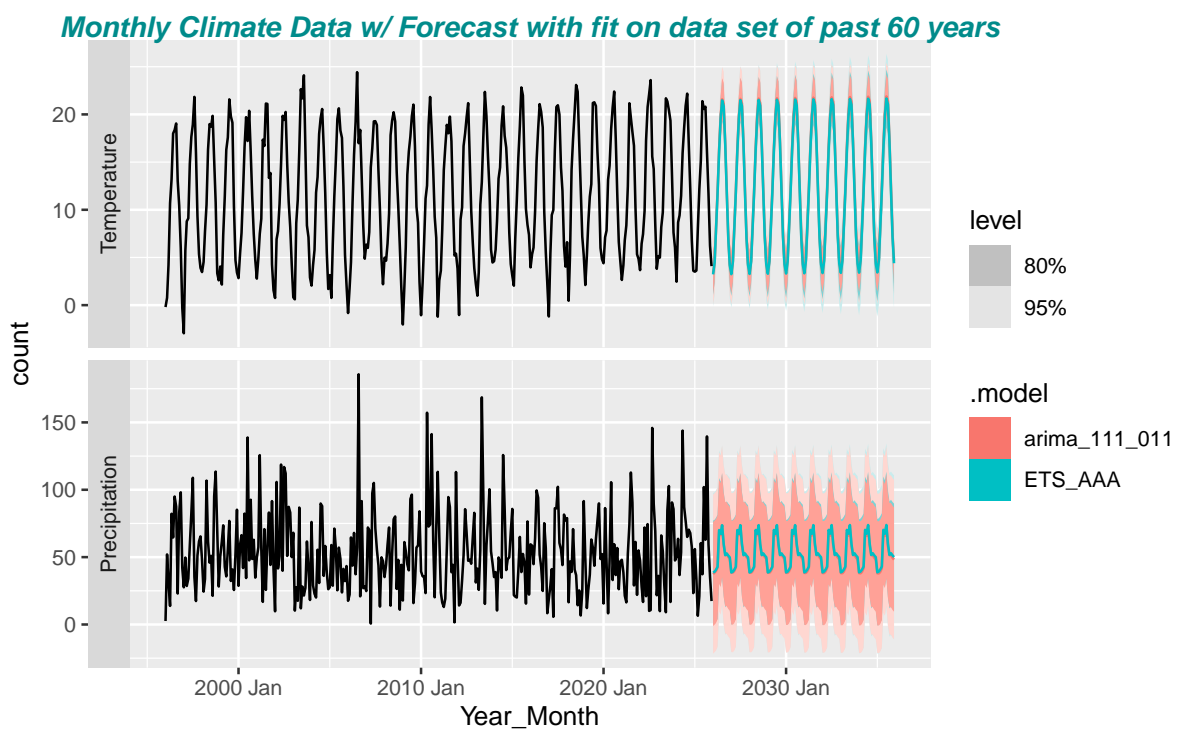
Forecasts produced using **ETS** methods are weighted averages of past observations, with the weights decaying exponentially as the observations get older.

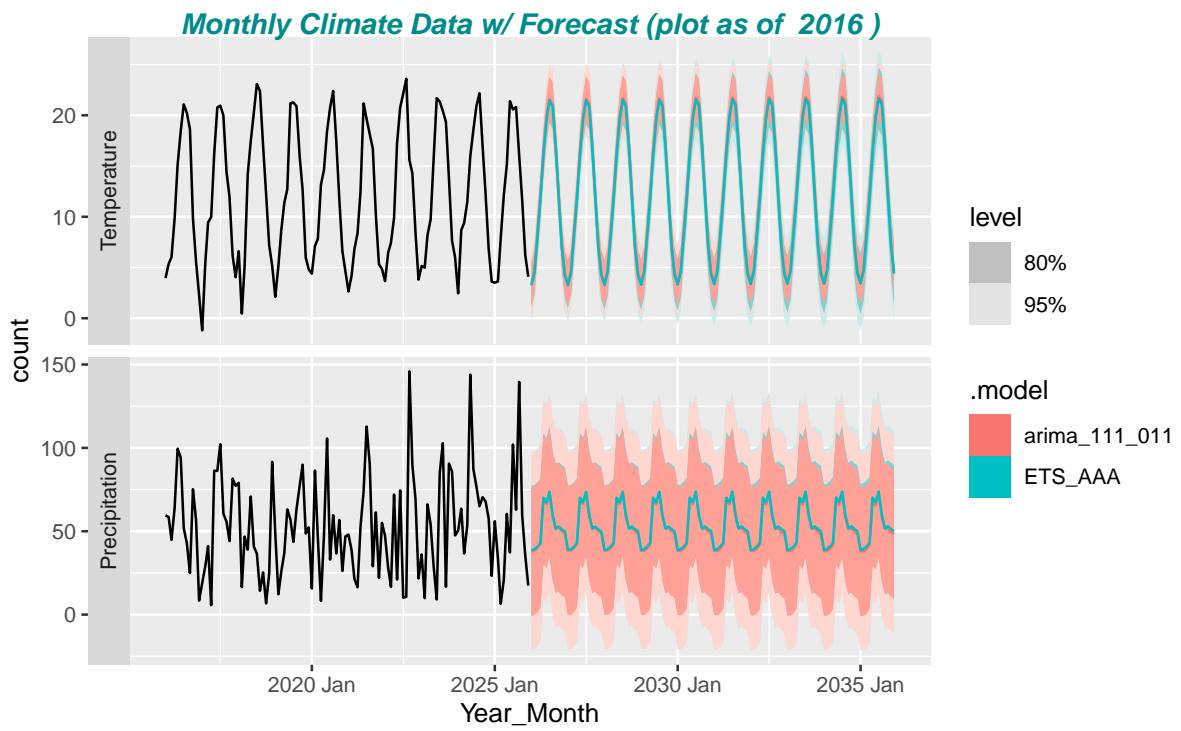
Here a **ETS(A,A,A)** model with additive ("A") *Error term*, *Trend term* and *Seasonal term* was chosen.

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)

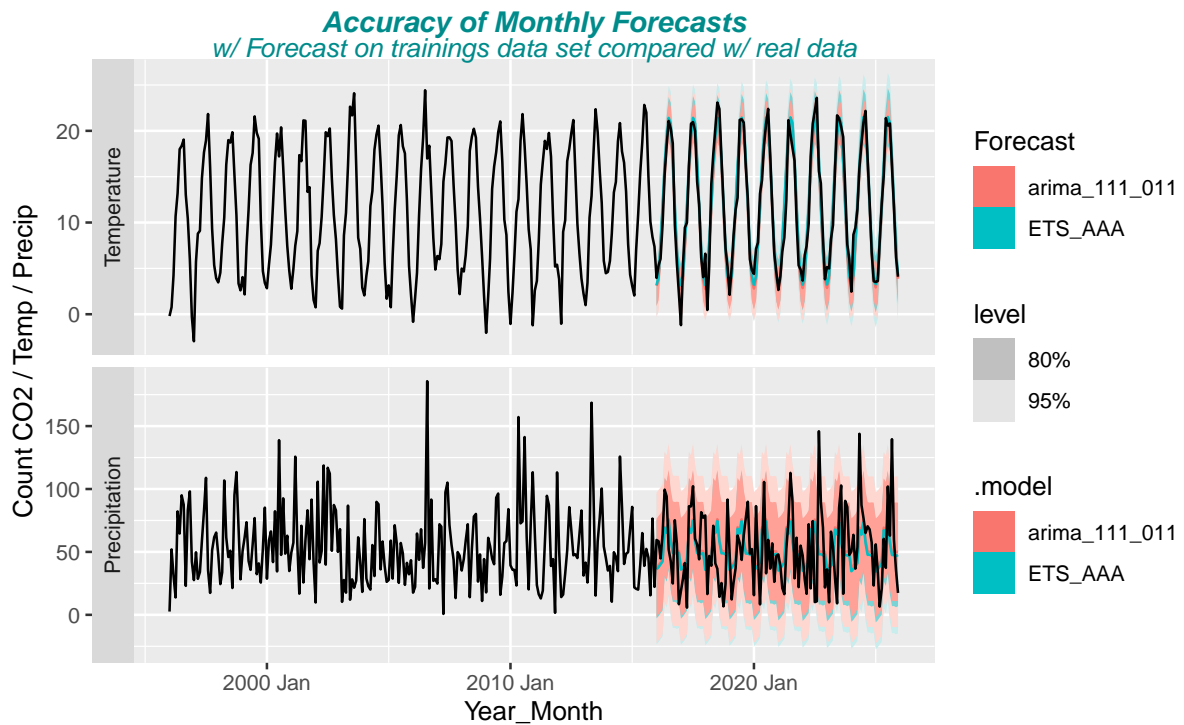
```
#> # A mable: 2 x 4
#> # Key:      City, Measure [2]
#>   City      Measure      ETS_AAA      arima_111_011
#>   <chr>     <fct>       <model>      <model>
#> 1 Mannheim Temperature <ETS(A,A,A)> <ARIMA(1,1,1)(0,1,1)[12]>
#> 2 Mannheim Precipitation <ETS(A,A,A)> <ARIMA(1,1,1)(0,1,1)[12]>
```





3.2 Forecast Accuracy Evaluation

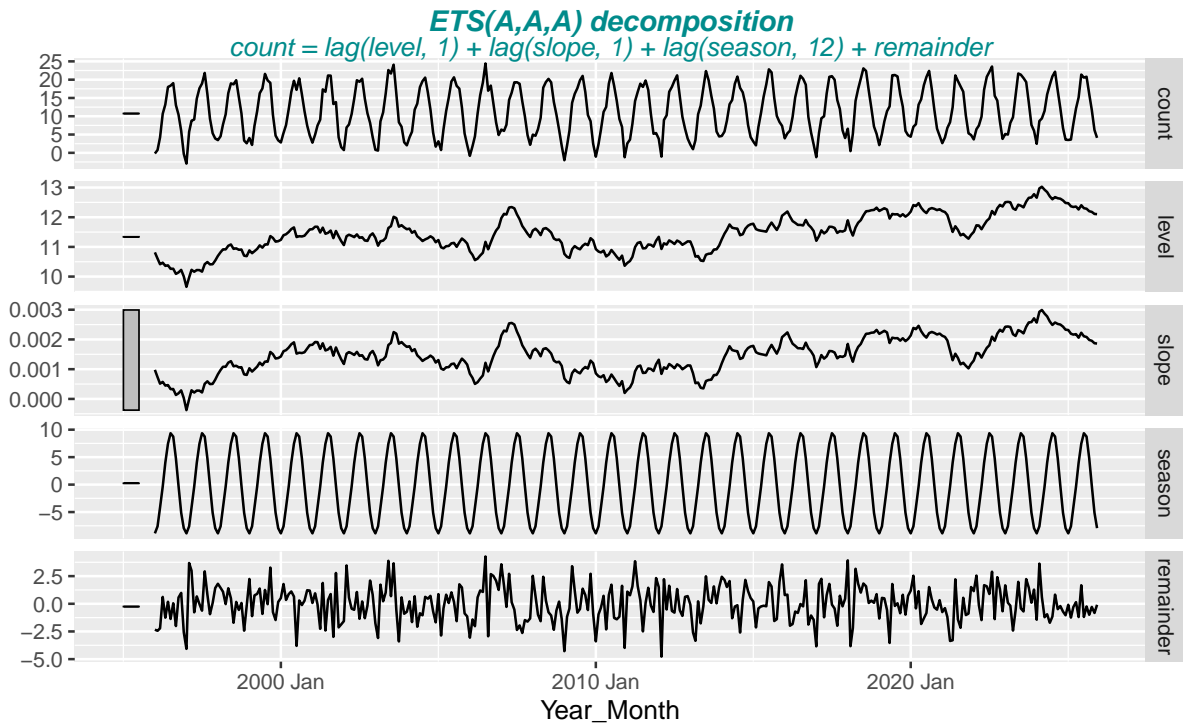
- Forecast Accuracy Evaluation w/ training data “data_train” & test data “data_test”
 - “data” : complete dataset includes the forecasted (future) data range on top of data_train
 - “data_train” = “data” - forecast_range (“data_test”)
 - * data used to train the model (~80% of “data”)
 - “data_test” = “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



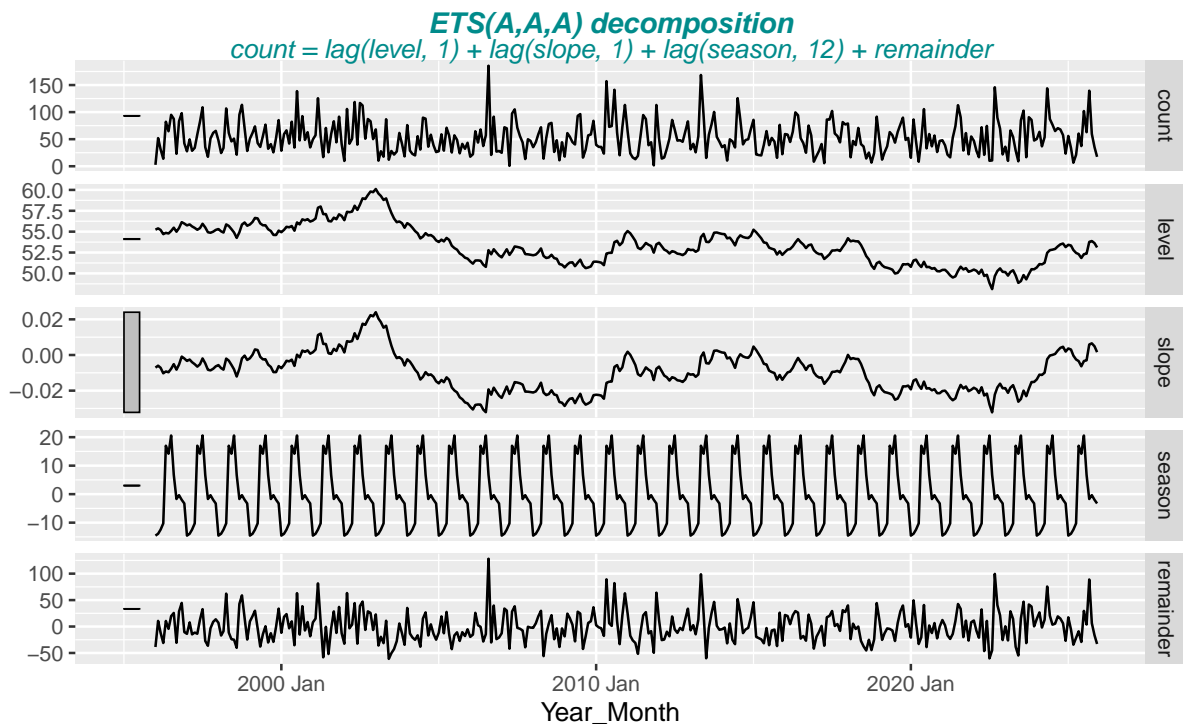
3.2.1 components(fit_ets) - plot of the decomposition of the fitted ETS model

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

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

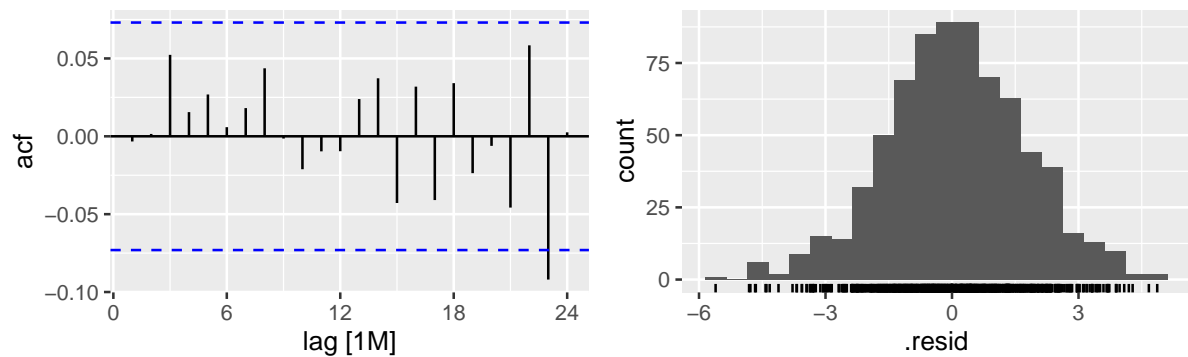
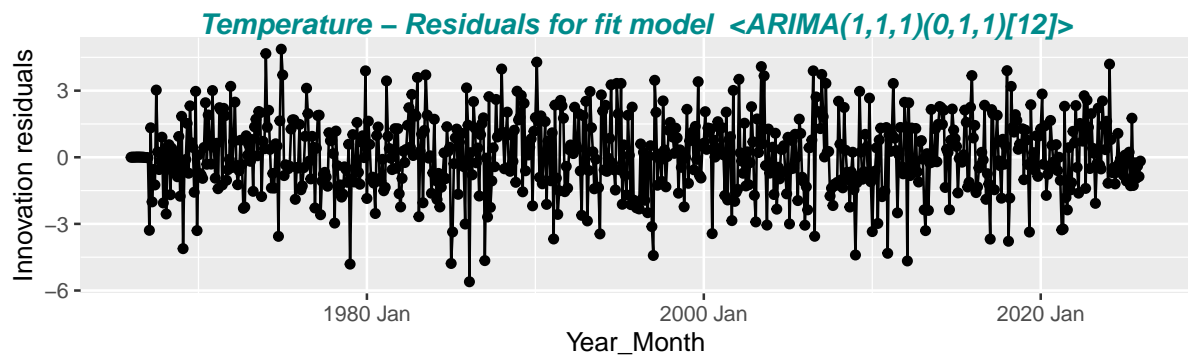
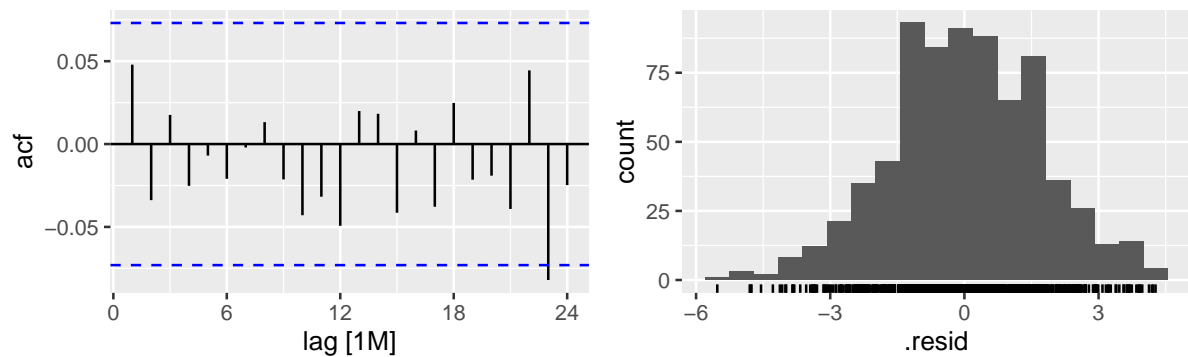
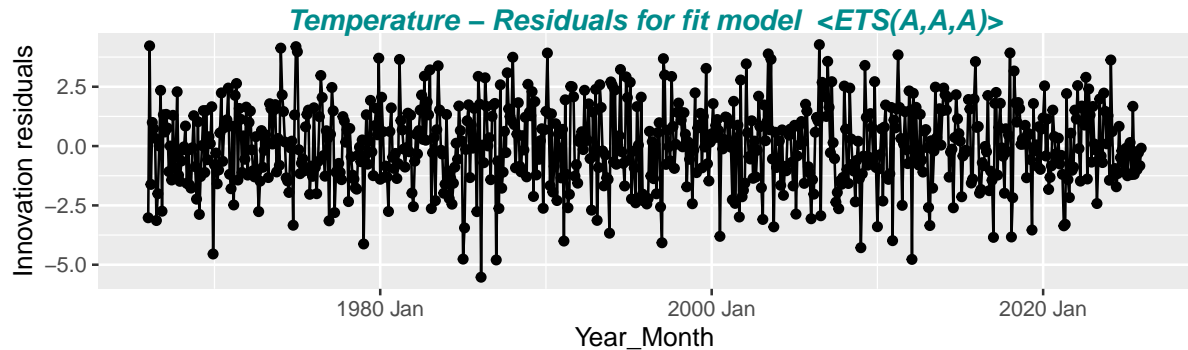


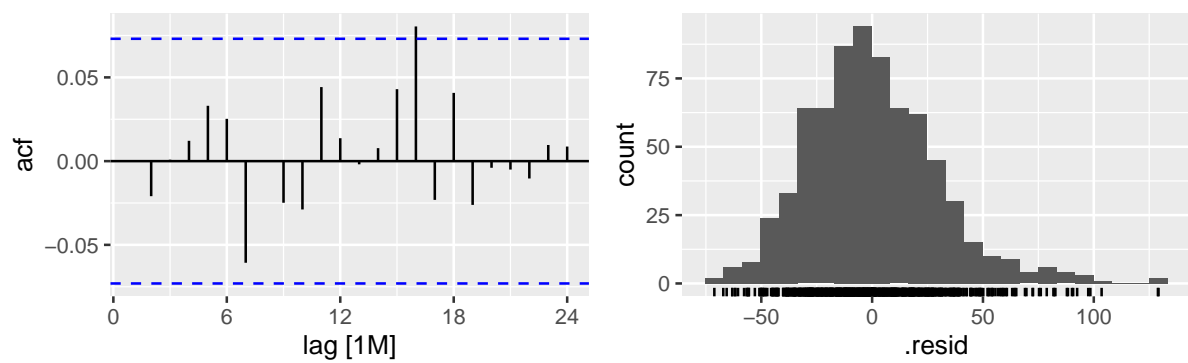
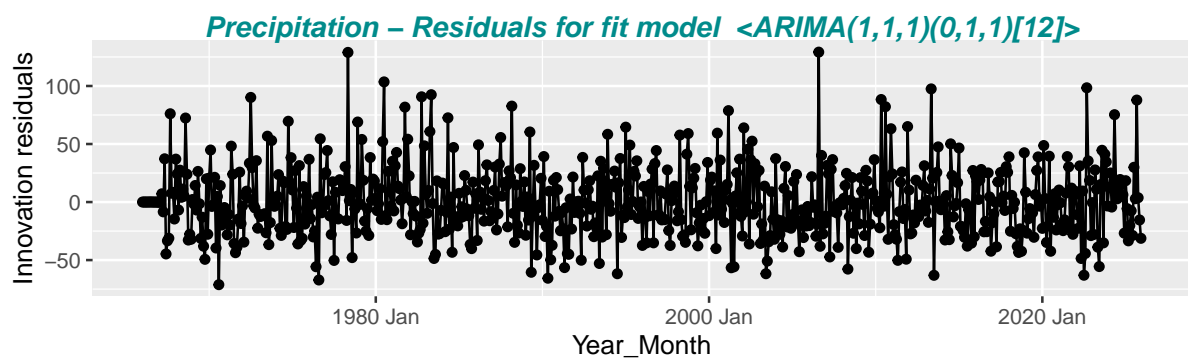
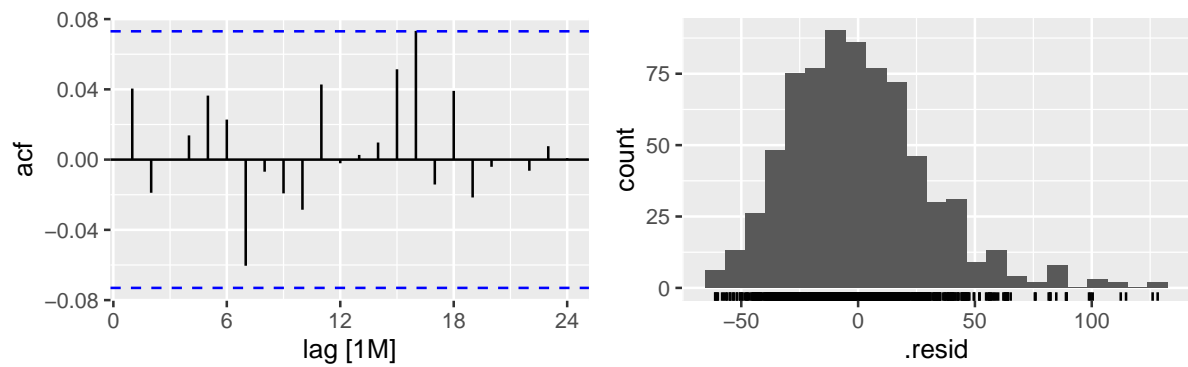
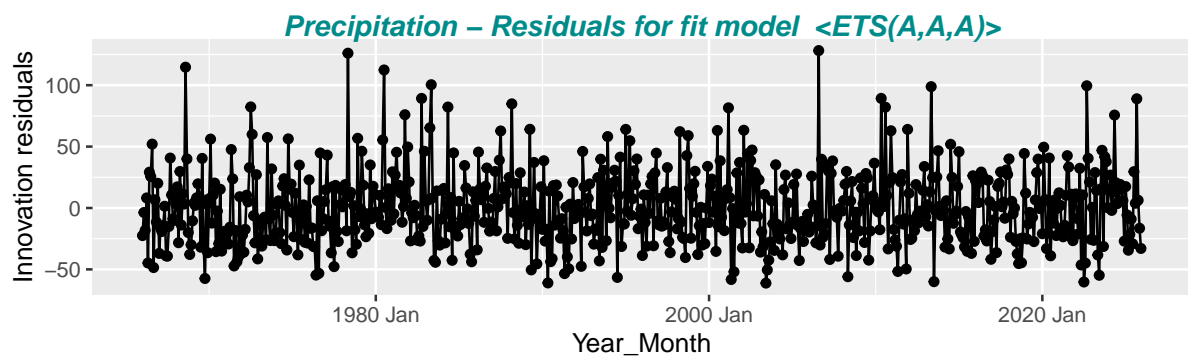
```
#> [1] "Precipitation"
```



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





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
1881-1900	10.0	42.2
1901-1930	10.1	44.3
1931-1960	10.4	49.9
1961-1990	10.3	55.6
1991-2020	11.3	53.4
2021-2025	12.2	54.8

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
Mannheim	Temperature	2026	12.12	12.29
Mannheim	Temperature	2030	12.21	12.42
Mannheim	Temperature	2035	12.32	12.58
Mannheim	Temperature	2040	12.43	12.75
Mannheim	Temperature	2045	12.54	12.91
Mannheim	Temperature	2050	12.65	13.07
Mannheim	Precipitation	2026	53.12	52.46
Mannheim	Precipitation	2030	53.19	52.28
Mannheim	Precipitation	2035	53.29	51.91
Mannheim	Precipitation	2040	53.38	51.53
Mannheim	Precipitation	2045	53.48	51.16
Mannheim	Precipitation	2050	53.57	50.79

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	12.12	12.29	12.65	13.07	0.54	0.79
Precipitation	2026	2050	53.12	52.46	53.57	50.79	0.46	-1.67

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	3.23	3.39	3.76	4.20	0.54	0.81
Temperature	Feb	2026	2050	4.50	4.59	5.04	5.38	0.54	0.79
Temperature	Mar	2026	2050	7.94	8.09	8.47	8.87	0.54	0.78
Temperature	Apr	2026	2050	11.76	11.88	12.29	12.67	0.54	0.78
Temperature	May	2026	2050	16.09	16.33	16.63	17.11	0.54	0.78
Temperature	Jun	2026	2050	19.57	19.74	20.11	20.53	0.54	0.78

Measure	Month	Year.x	Year.y	Mean.x_ET	Mean.x_ARIMA	Mean.y_ET	Mean.y_ARIMA	Delta_ET	Delta_ARIMA
Temperature	Jul	2026	2050	21.47	21.60	22.01	22.38	0.54	0.78
Temperature	Aug	2026	2050	20.86	21.13	21.40	21.91	0.54	0.78
Temperature	Sep	2026	2050	16.90	17.02	17.43	17.80	0.54	0.78
Temperature	Oct	2026	2050	11.90	12.18	12.44	12.97	0.54	0.78
Temperature	Nov	2026	2050	6.99	7.13	7.53	7.92	0.54	0.78
Temperature	Dec	2026	2050	4.20	4.38	4.73	5.16	0.54	0.78
Precipitation	Jan	2026	2050	38.56	37.40	39.02	36.91	0.46	-0.49
Precipitation	Feb	2026	2050	39.21	38.55	39.67	36.81	0.46	-1.73
Precipitation	Mar	2026	2050	40.66	39.78	41.12	37.99	0.46	-1.78
Precipitation	Apr	2026	2050	42.84	42.47	43.30	40.69	0.46	-1.79
Precipitation	May	2026	2050	70.11	68.85	70.56	67.06	0.46	-1.79
Precipitation	Jun	2026	2050	67.29	66.39	67.74	64.60	0.46	-1.79
Precipitation	Jul	2026	2050	73.69	73.68	74.15	71.89	0.46	-1.79
Precipitation	Aug	2026	2050	59.88	58.98	60.33	57.20	0.46	-1.79
Precipitation	Sep	2026	2050	51.41	52.25	51.87	50.46	0.46	-1.79
Precipitation	Oct	2026	2050	52.77	52.19	53.22	50.40	0.46	-1.79
Precipitation	Nov	2026	2050	51.13	50.16	51.59	48.38	0.46	-1.79
Precipitation	Dec	2026	2050	49.86	48.85	50.31	47.07	0.46	-1.79

5 Backup

5.1 Mannheim - 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
Mannheim	Temperature	1881	NA	10.2	19.6	9.5	10.0
Mannheim	Temperature	1882	1.9	11.2	17.3	10.6	10.3
Mannheim	Temperature	1883	3.5	9.0	18.8	10.1	10.3
Mannheim	Temperature	1884	3.9	10.9	19.1	10.0	11.1
Mannheim	Temperature	1885	3.0	9.7	19.2	9.5	10.1
Mannheim	Temperature	1886	0.4	10.5	18.7	12.2	10.6
Mannheim	Temperature	1887	0.4	8.5	20.0	8.3	9.1
Mannheim	Temperature	1888	0.0	9.3	17.5	9.6	9.1
Mannheim	Temperature	1889	-0.1	10.1	19.3	8.9	9.4
Mannheim	Temperature	1890	0.9	10.4	17.7	9.6	9.4
Mannheim	Temperature	2016	5.6	10.3	19.9	11.3	11.4
Mannheim	Temperature	2017	2.2	11.9	20.6	10.9	11.5
Mannheim	Temperature	2018	3.7	12.3	21.9	12.2	12.6
Mannheim	Temperature	2019	4.1	10.9	21.1	11.5	11.9
Mannheim	Temperature	2020	5.4	11.9	20.5	11.9	12.4
Mannheim	Temperature	2021	3.8	9.2	19.7	10.7	10.9
Mannheim	Temperature	2022	5.0	11.5	22.2	12.8	12.8
Mannheim	Temperature	2023	4.7	11.2	21.2	13.6	12.8
Mannheim	Temperature	2024	5.7	12.3	20.6	12.0	12.4
Mannheim	Temperature	2025	3.6	11.7	20.9	11.3	11.9

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

City	Measure	Year	Winter_avg	Spring_avg	Summer_avg	Fall_avg	Year_avg
Mannheim	Precipitation	1890	NA	26.7	59.7	22.0	32.6
Mannheim	Precipitation	1891	6.0	49.0	70.7	41.3	45.2
Mannheim	Precipitation	1892	34.7	14.7	49.0	55.3	36.3
Mannheim	Precipitation	1893	31.0	13.7	58.0	49.3	39.0
Mannheim	Precipitation	1894	22.0	36.0	57.3	67.3	44.3
Mannheim	Precipitation	1895	26.3	28.7	66.3	45.3	45.6
Mannheim	Precipitation	1896	25.3	33.7	58.3	49.0	39.8
Mannheim	Precipitation	1897	29.0	55.0	55.3	22.3	38.9
Mannheim	Precipitation	1898	22.7	45.7	72.3	31.7	42.3
Mannheim	Precipitation	1899	20.3	46.3	65.0	41.0	46.5
Mannheim	Precipitation	2016	46.7	69.4	62.9	52.3	56.7
Mannheim	Precipitation	2017	18.7	44.4	83.0	60.5	57.4
Mannheim	Precipitation	2018	57.6	52.2	30.6	18.9	41.0
Mannheim	Precipitation	2019	50.8	41.8	54.7	71.9	51.5
Mannheim	Precipitation	2020	51.4	34.0	66.1	39.9	NA
Mannheim	Precipitation	2021	NA	30.1	92.4	37.4	51.8
Mannheim	Precipitation	2022	43.4	36.6	31.8	101.7	50.6
Mannheim	Precipitation	2023	22.6	49.8	65.6	64.3	52.7
Mannheim	Precipitation	2024	53.8	78.1	76.4	65.3	66.4
Mannheim	Precipitation	2025	37.7	29.3	67.4	NA	NA

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

City	Month	Temperature	Precipitation
Mannheim	Jan	1.8	38.1
Mannheim	Feb	2.9	34.4
Mannheim	Mar	6.3	37.0
Mannheim	Apr	10.2	42.6
Mannheim	May	14.6	59.6
Mannheim	Jun	17.8	67.0
Mannheim	Jul	19.5	70.1
Mannheim	Aug	18.8	64.5
Mannheim	Sep	15.3	53.0
Mannheim	Oct	10.3	49.2
Mannheim	Nov	5.6	44.3
Mannheim	Dec	2.7	43.4

5.2 Mannheim - Head and tail of data

```
#> # A tibble: 6 x 5 [1M]
#> # Key:      City, Measure [1]
#> # Groups:   City, Measure [1]
#>   City      Measure      Year_Month Period_Time count
#>   <chr>    <fct>          <mt> <chr>      <dbl>
#> 1 Mannheim Temperature  1881 Jan 1881-1900  -2.6
#> 2 Mannheim Temperature  1881 Feb 1881-1900    3
#> 3 Mannheim Temperature  1881 Mrz 1881-1900   6.9
#> 4 Mannheim Temperature  2025 Okt 2021-2025  11.7
#> 5 Mannheim Temperature  2025 Nov 2021-2025   6.22
#> 6 Mannheim Temperature  2025 Dez 2021-2025   4.09
#> # A tibble: 6 x 5 [1M]
#> # Key:      City, Measure [1]
#> # Groups:   City, Measure [1]
#>   City      Measure      Year_Month Period_Time count
#>   <chr>    <fct>          <mt> <chr>      <dbl>
#> 1 Mannheim Precipitation  1890 Jan 1881-1900   63
#> 2 Mannheim Precipitation  1890 Feb 1881-1900    1
#> 3 Mannheim Precipitation  1890 Mrz 1881-1900   10
#> 4 Mannheim Precipitation  2025 Okt 2021-2025  59.7
#> 5 Mannheim Precipitation  2025 Nov 2021-2025  35.4
#> 6 Mannheim Precipitation  2025 Dez 2021-2025  17.4
```

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