

Climate Data Visualization - Atmospheric CO_2 Concentration / Temperature / Precipitation

Wolfgang Vollmer

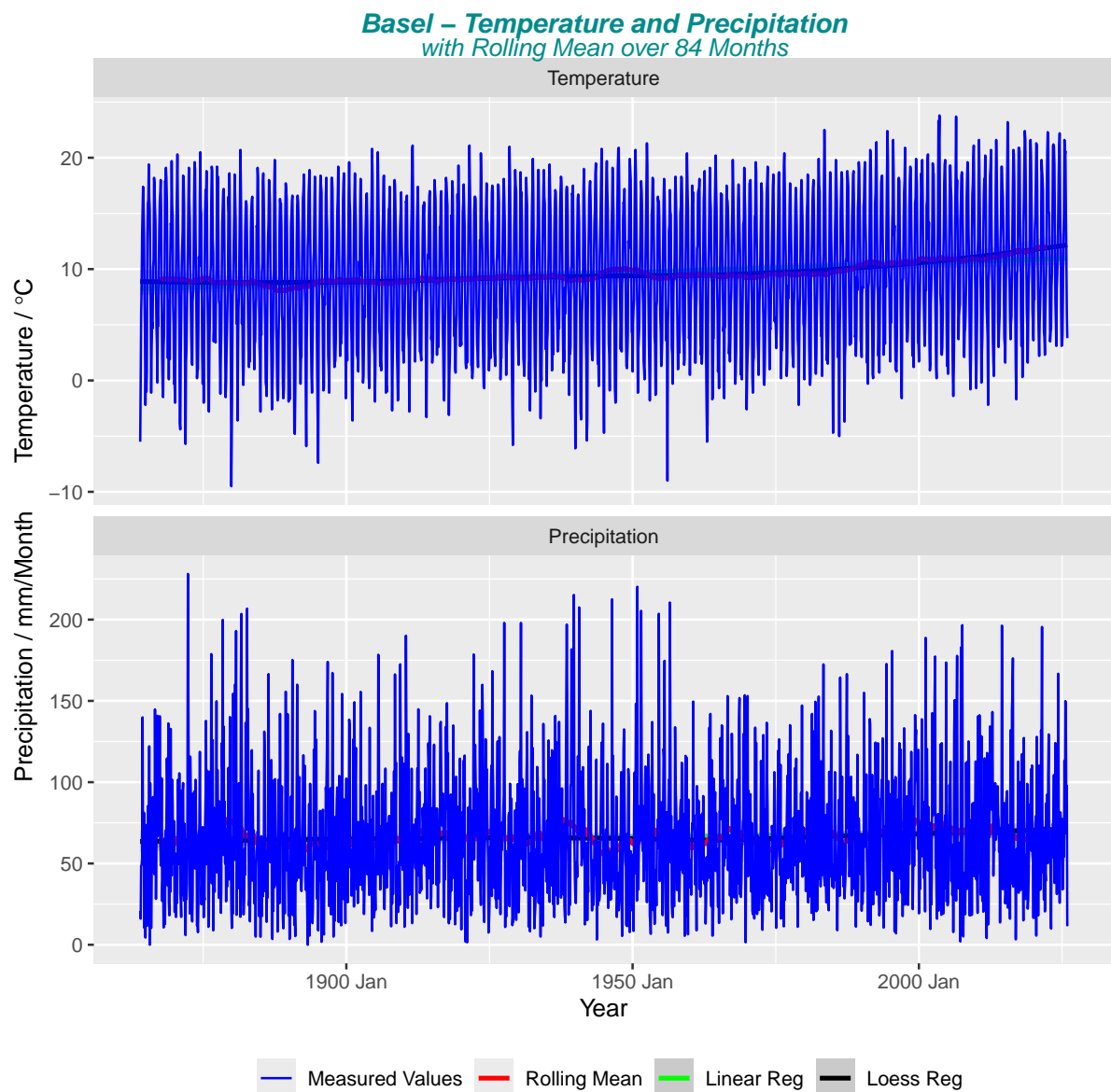
2026-01-08

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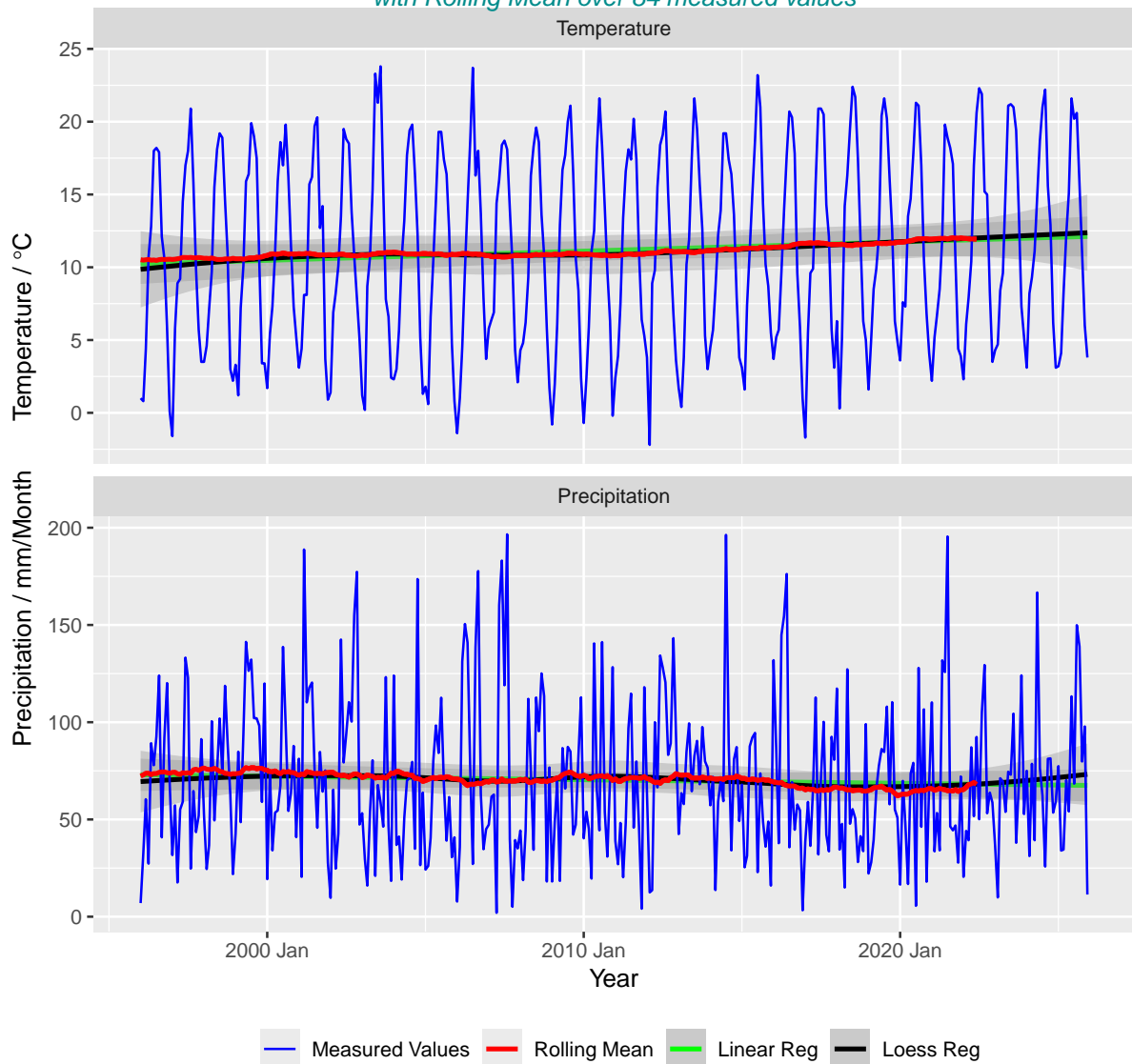
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1 Basel - Visualization of Temperature, Precipitation Data 1864 - 2025

1.1 Monthly Time Plots with Rolling Mean



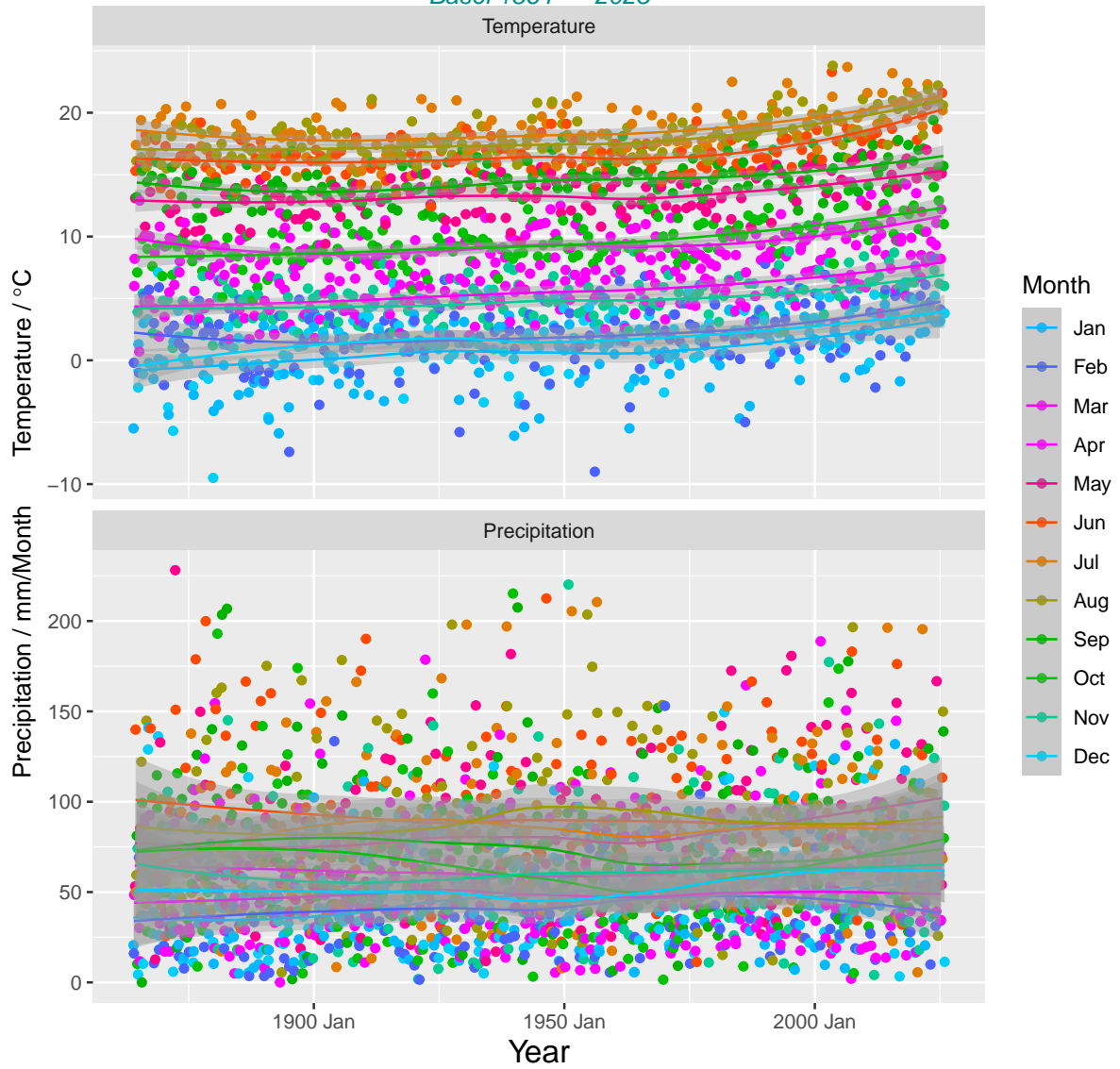
Basel – Temperature and Precipitation – Past 30 years only
with Rolling Mean over 84 measured values



1.2 Annual seasonal plots with monthly breakdown

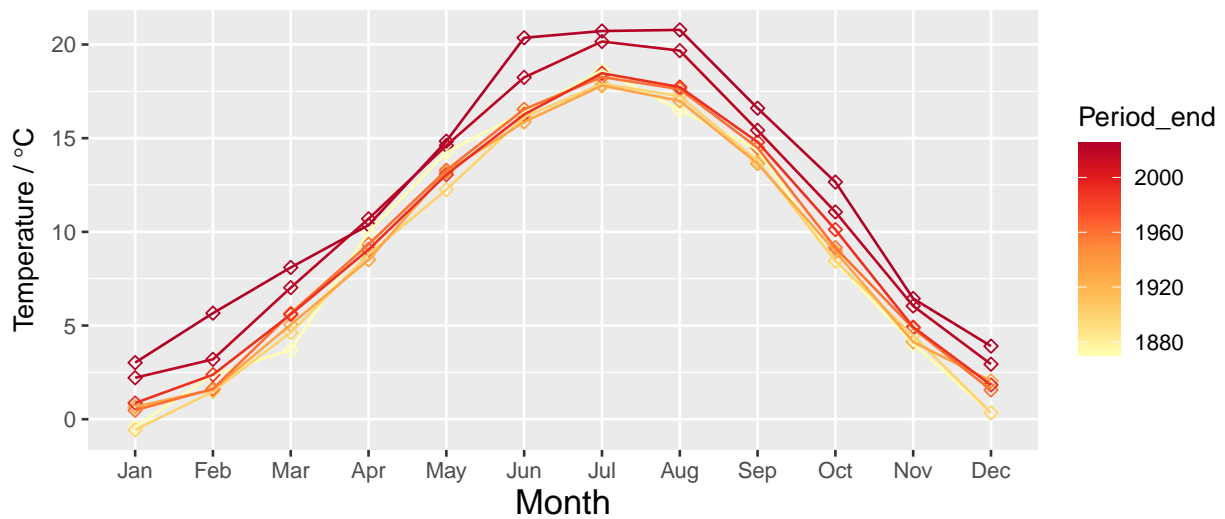
The seasonal charts show the monthly seasonal patterns, where available.

Monthly Data with Local Polynomial Regression Fitting Basel 1864 – 2025

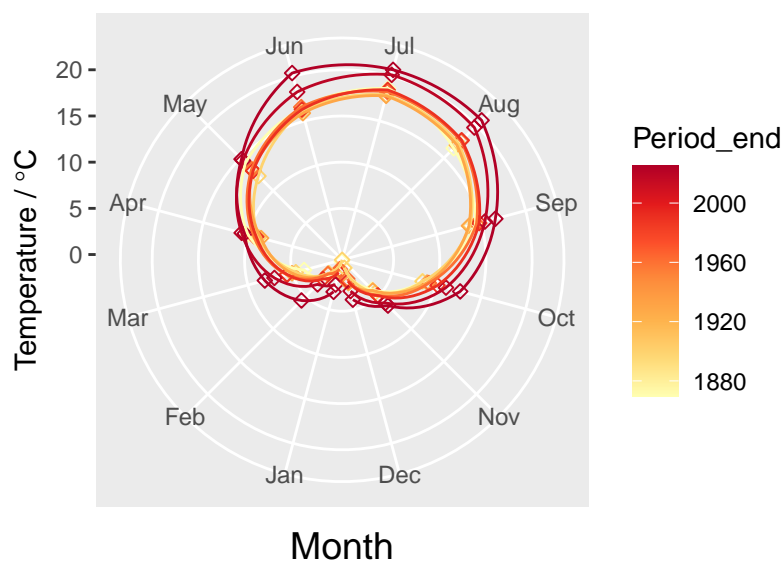


1.2.1 30-year period plots with monthly breakdown - Cartesian and Polar Coordinates

Temperature – Monthly Variations of 30-Year Periods
Periods: First 1864–1870 / Reference 1991–2020 / Last 2021–2025

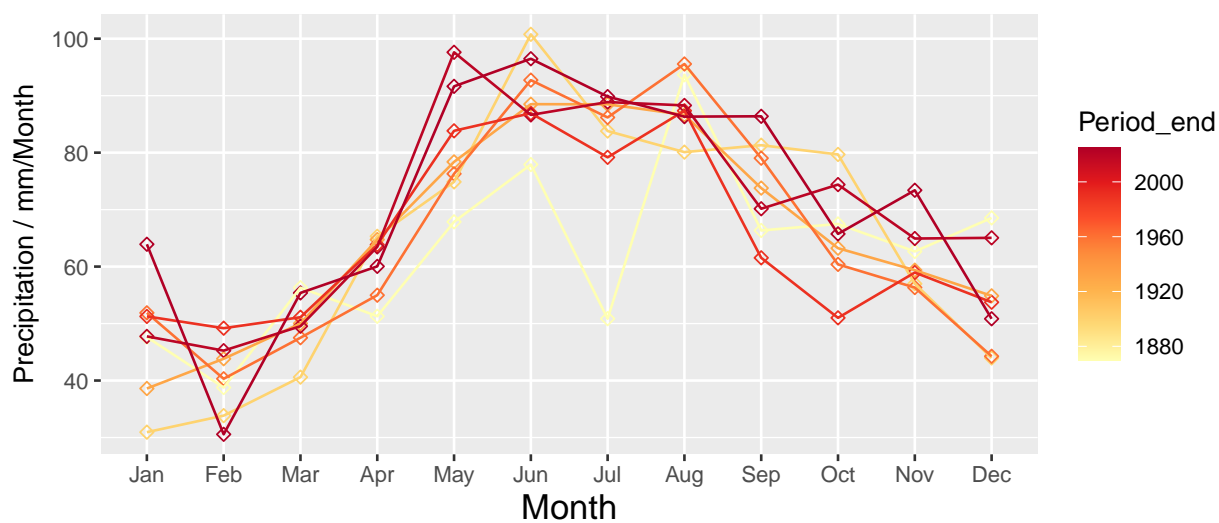


Temperature – Monthly Variations of 30-Year Periods
Periods: First 1864–1870 / Reference 1991–2020 / Last 2021–2025

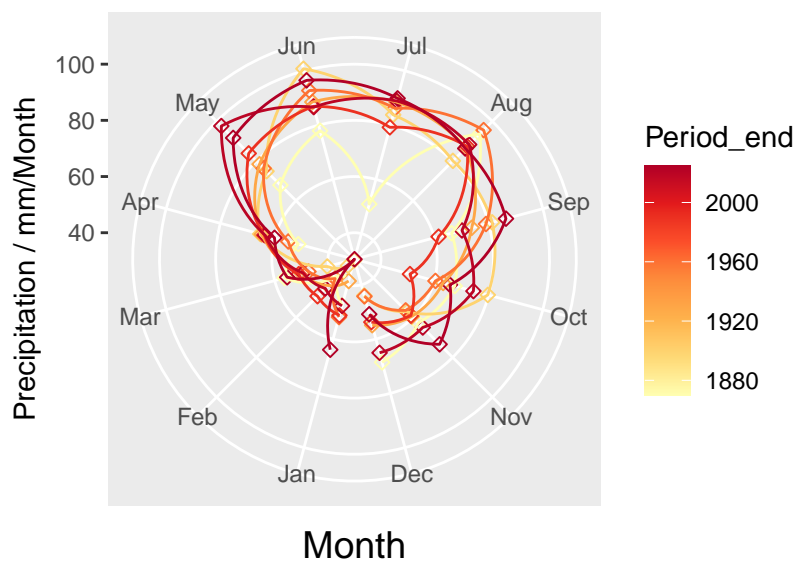


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Precipitation – Monthly Variations of 30–Year Periods
 Periods: First 1864–1870 / Reference 1991–2020 / Last 2021–2025



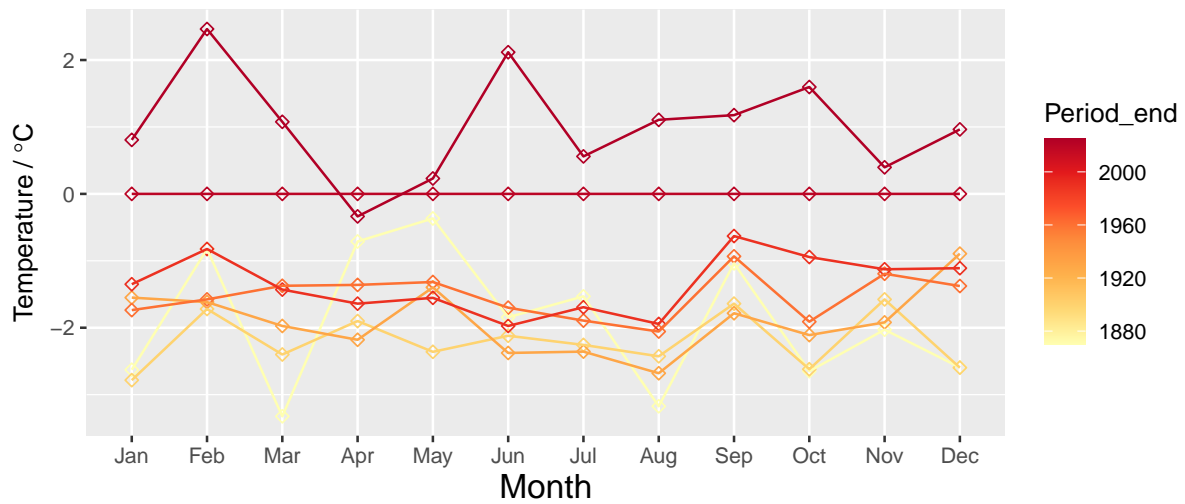
Precipitation – Monthly Variations of 30–Year Periods
 Periods: First 1864–1870 / Reference 1991–2020 / Last 2021–2025



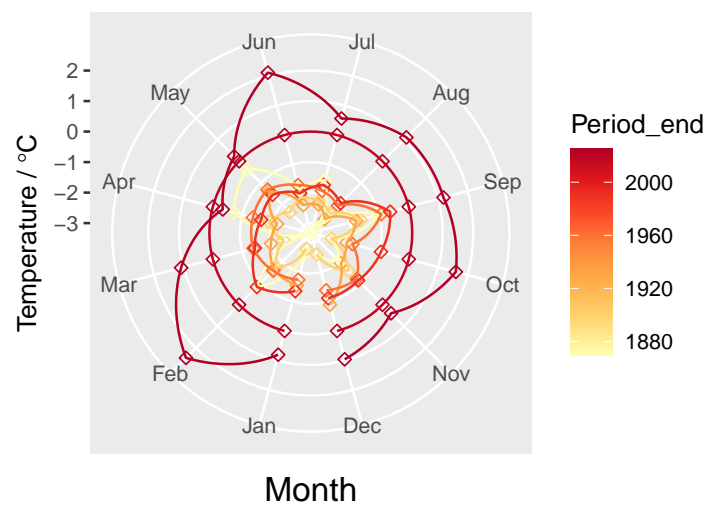
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1.2.2 Plot Monthly Delta to Reference Period - Cartesian and Polar Coordinates

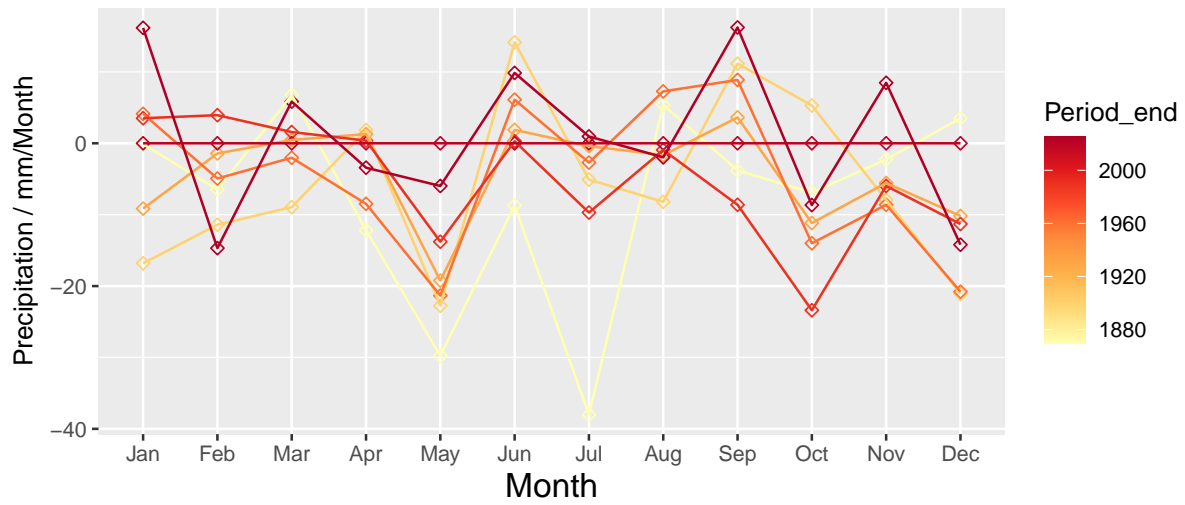
Temperature – Monthly Variations of 30–Year Periods (Delta to Reference)
Periods: First 1864–1870 / Reference 1991–2020 / Last 2021–2025



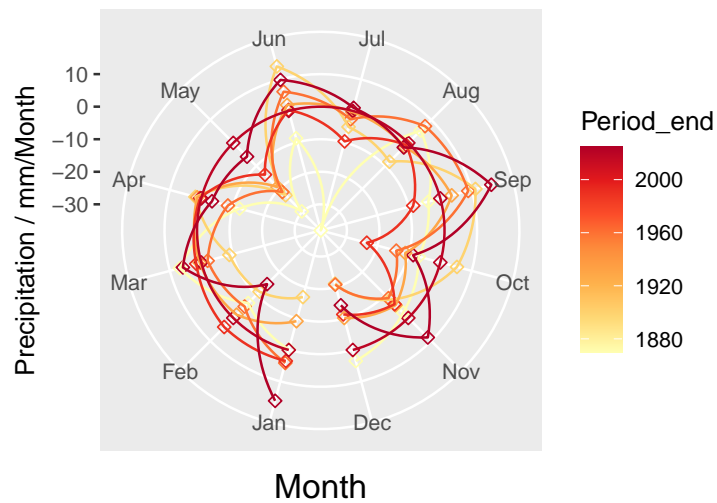
Temperature – Monthly Variations of 30–Year Periods (Delta to Reference)
Periods: First 1864–1870 / Reference 1991–2020 / Last 2021–2025



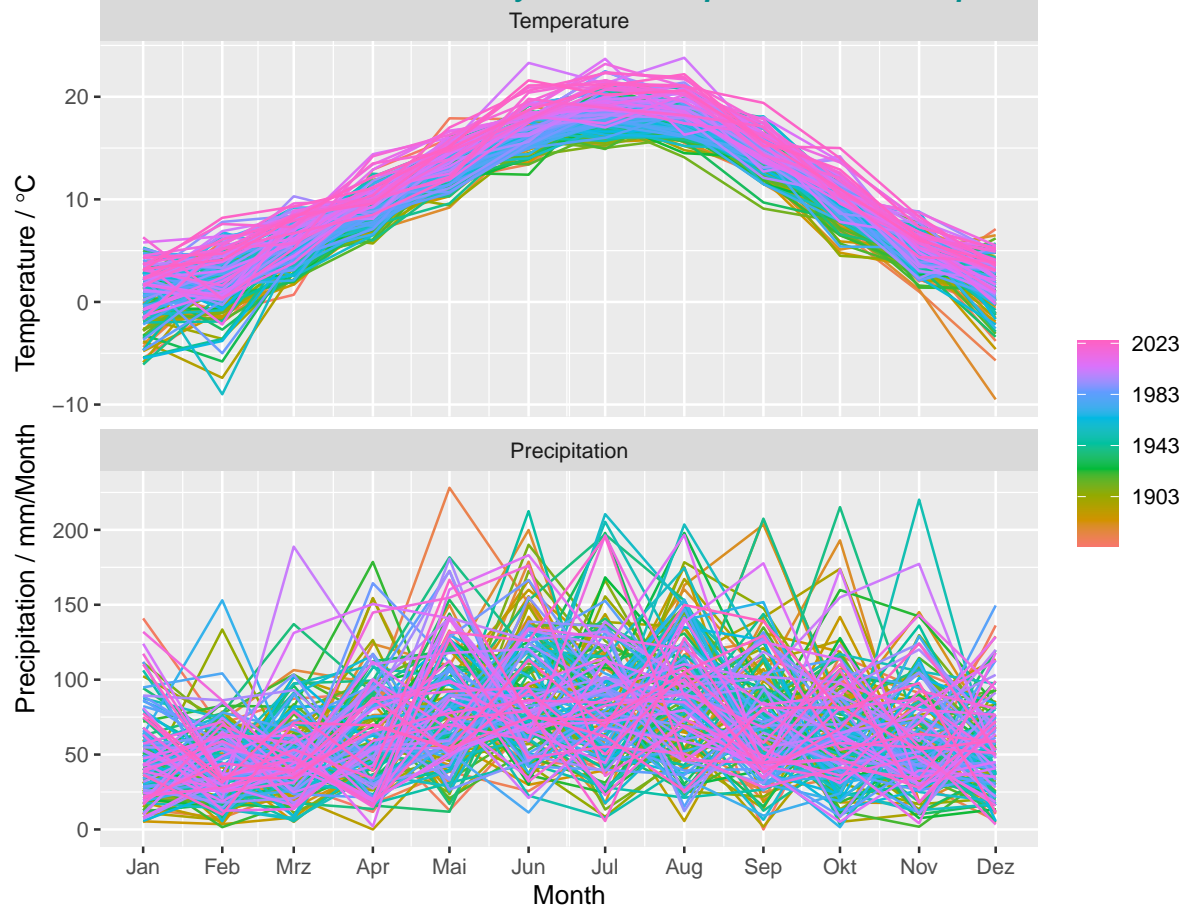
Precipitation – Monthly Variations of 30–Year Periods (Delta to Reference)
 Periods: First 1864–1870 / Reference 1991–2020 / Last 2021–2025

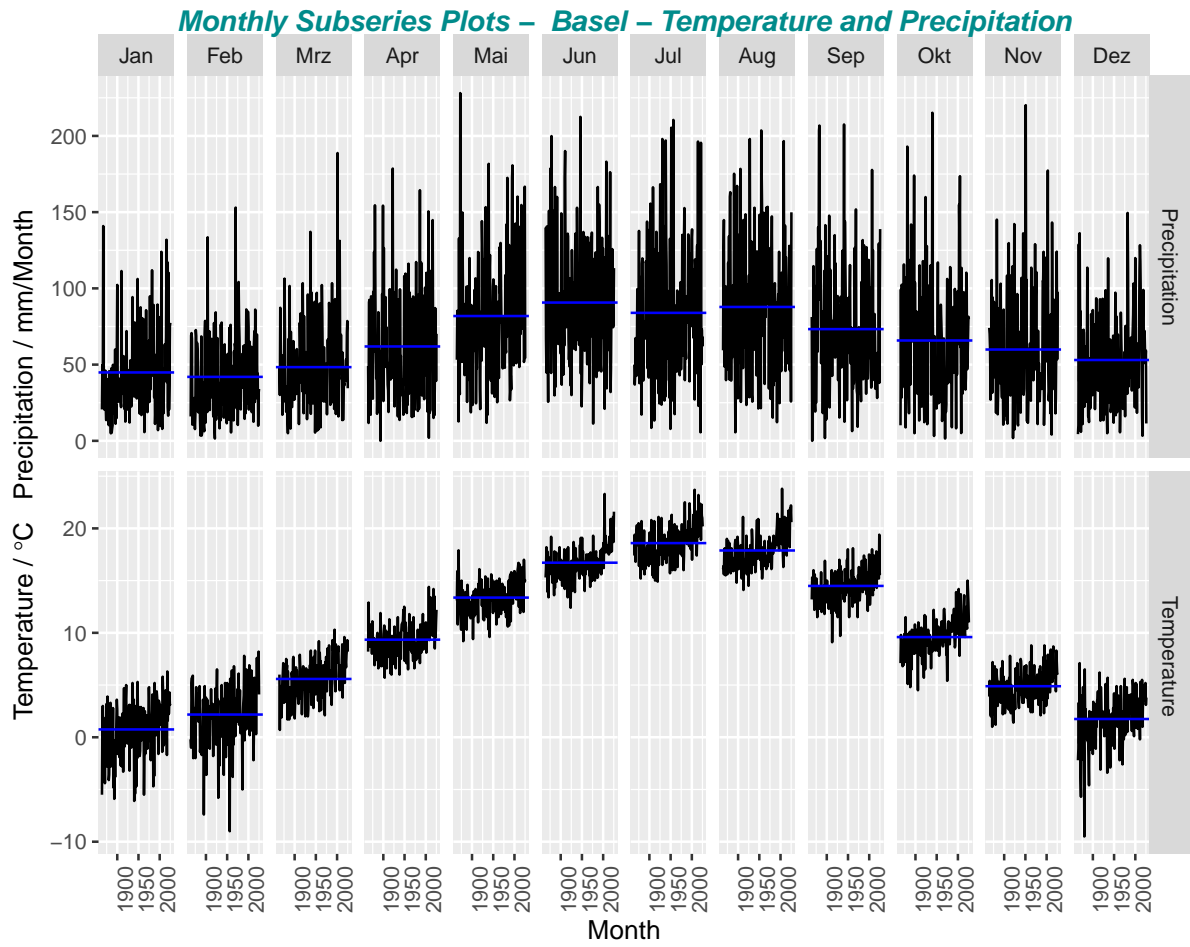


Precipitation – Monthly Variations of 30–Year Periods (Delta to Reference)
 Periods: First 1864–1870 / Reference 1991–2020 / Last 2021–2025



Annual Seasonal Plots – Monthly Basel – Temperature and Precipitation

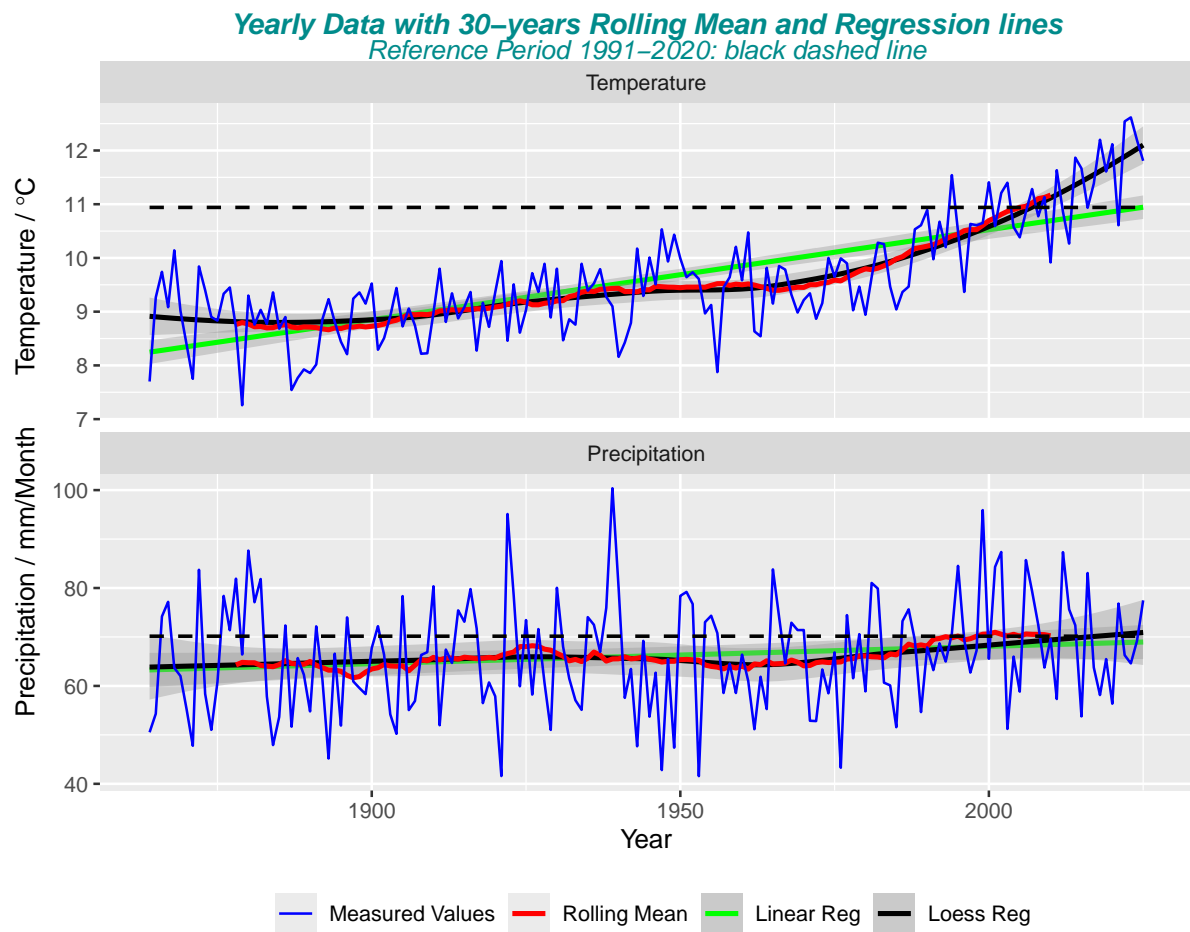




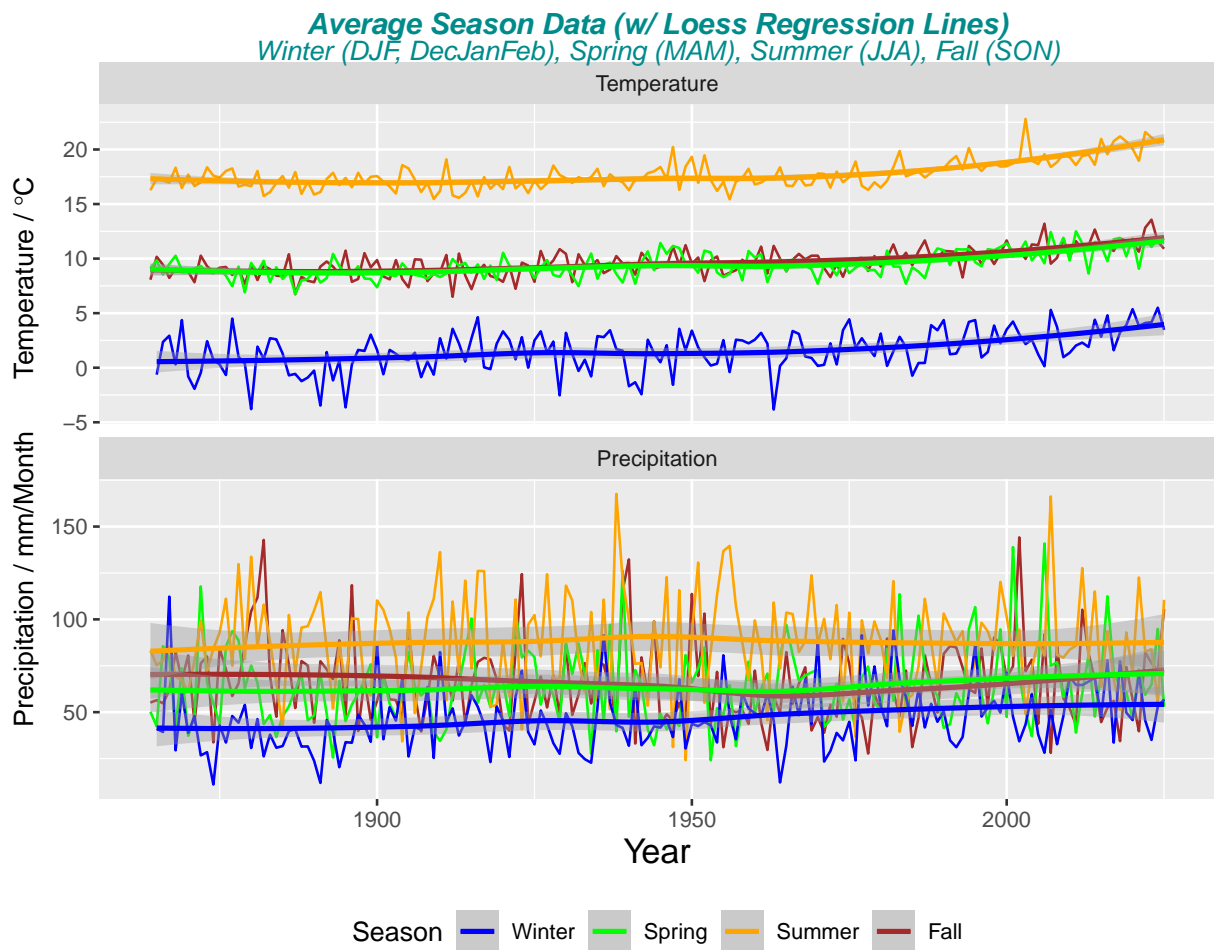
The blue horizontal lines within the seasonal subseries plot indicate the means for each month.

1.3 Annual Baseline - 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.

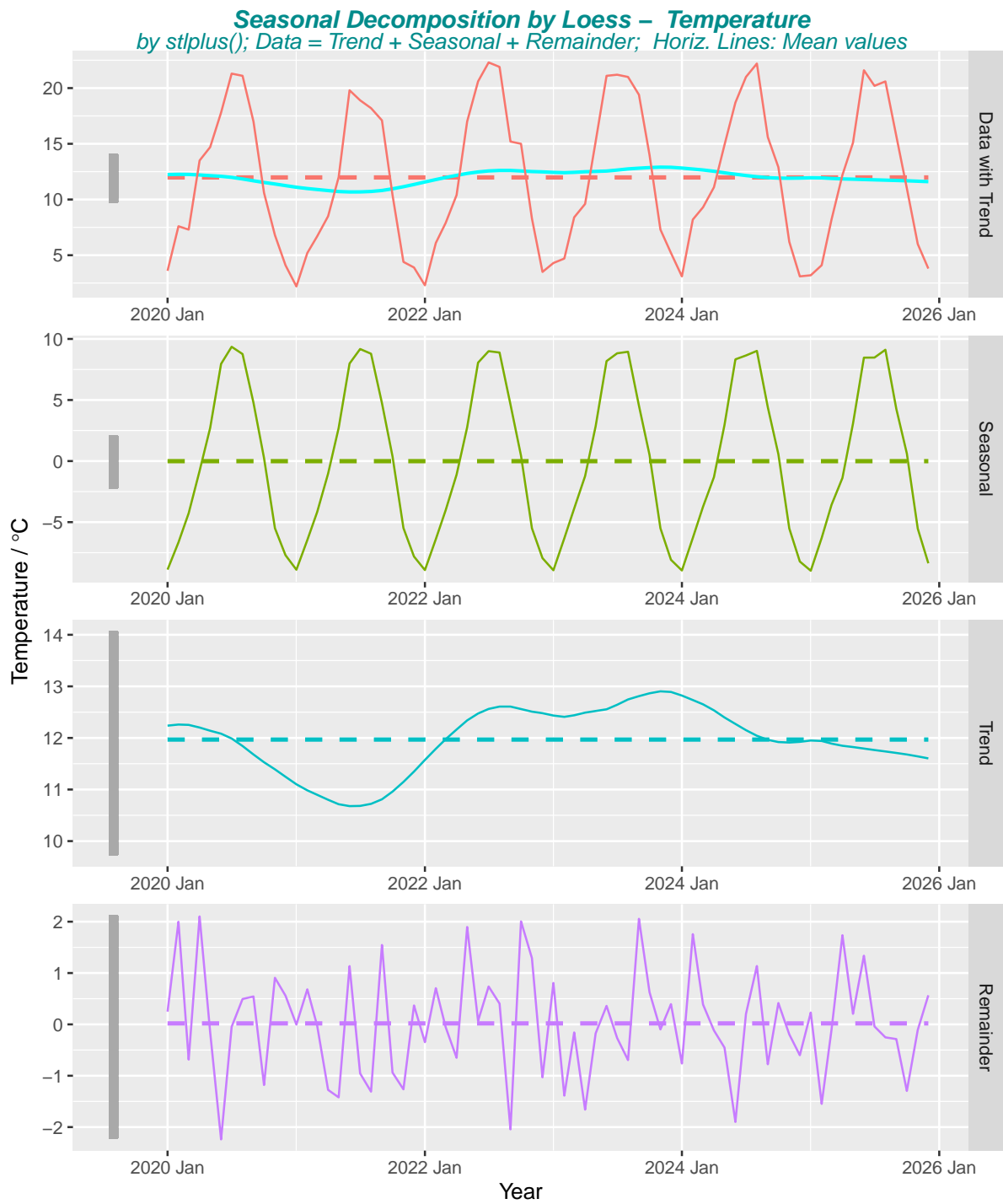
Time series using an

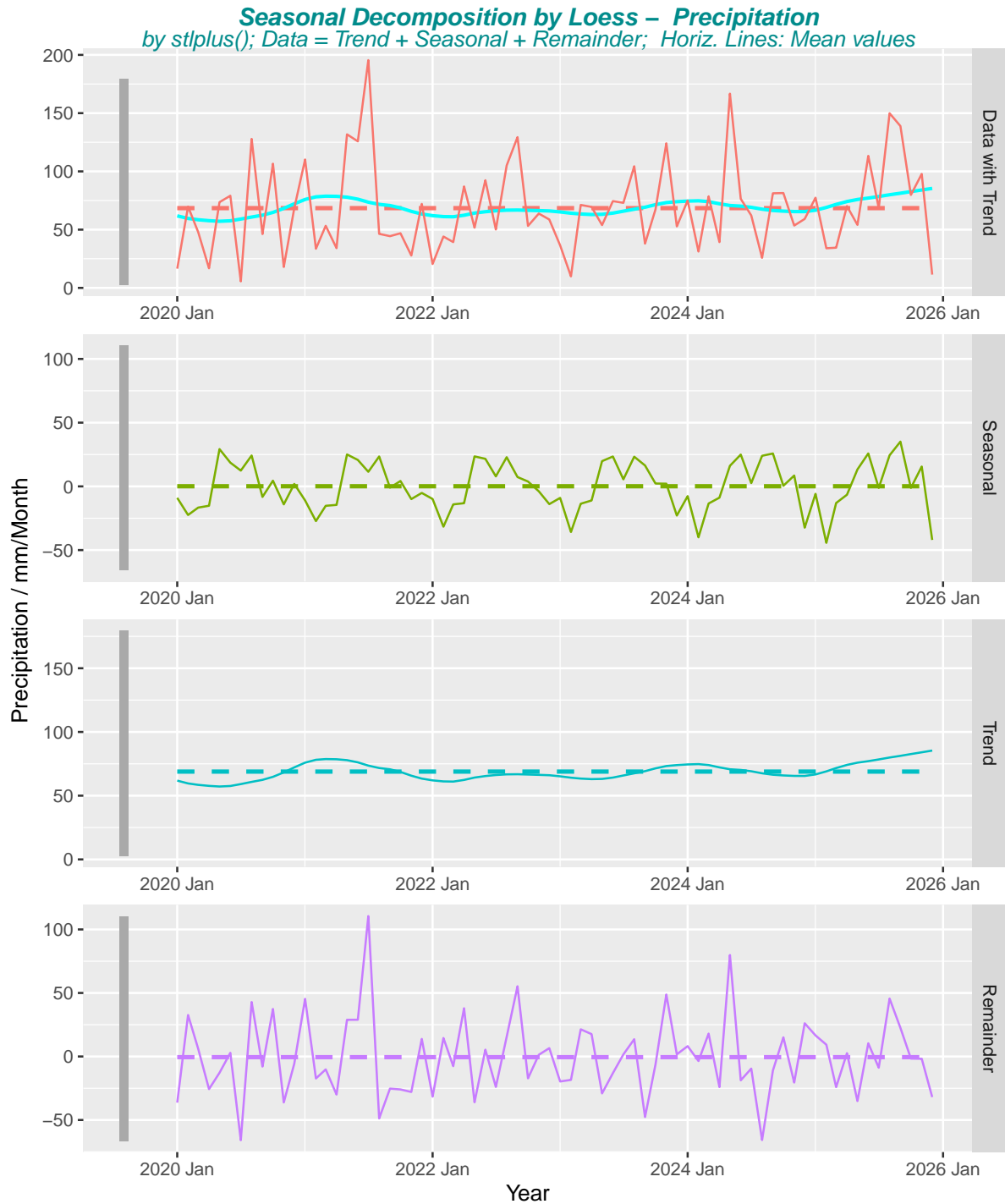
- additive model: $y_t = T_t + C_t + S_t + \epsilon_t$
- multiplicative model: $y_t = T_t * C_t * S_t * \epsilon_t$

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.



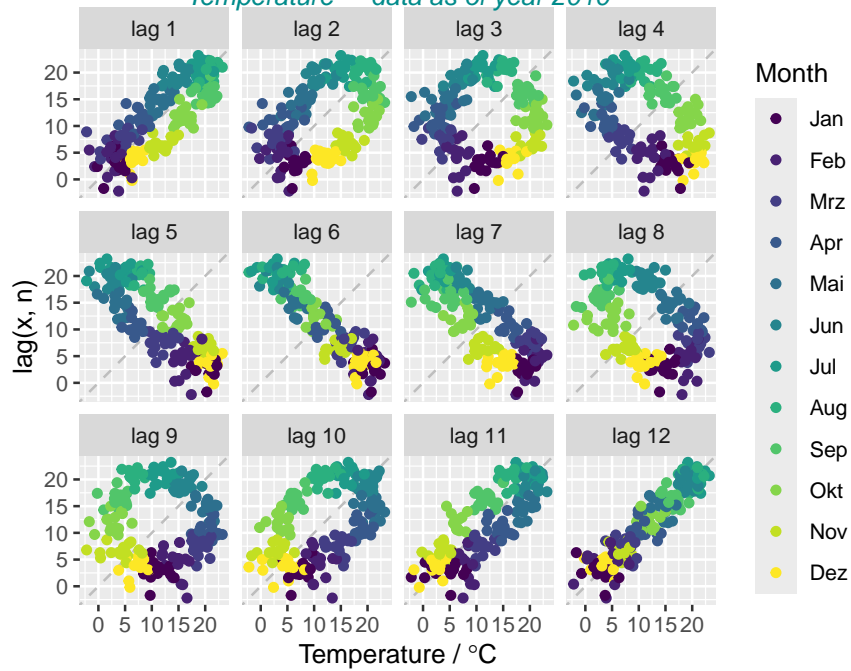


2.2 Periodicities - Season Frequency

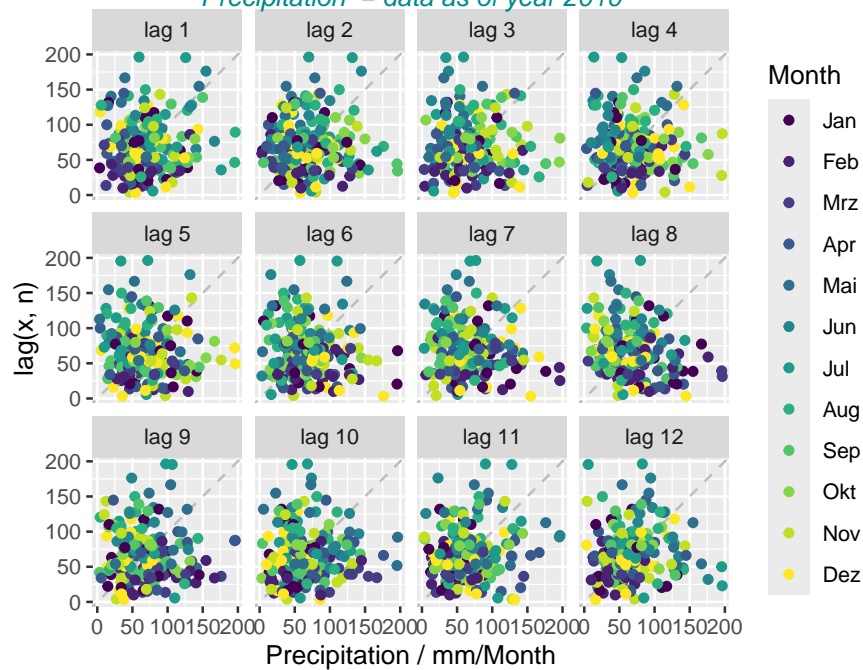
2.2.1 Lag Plot - Differences

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



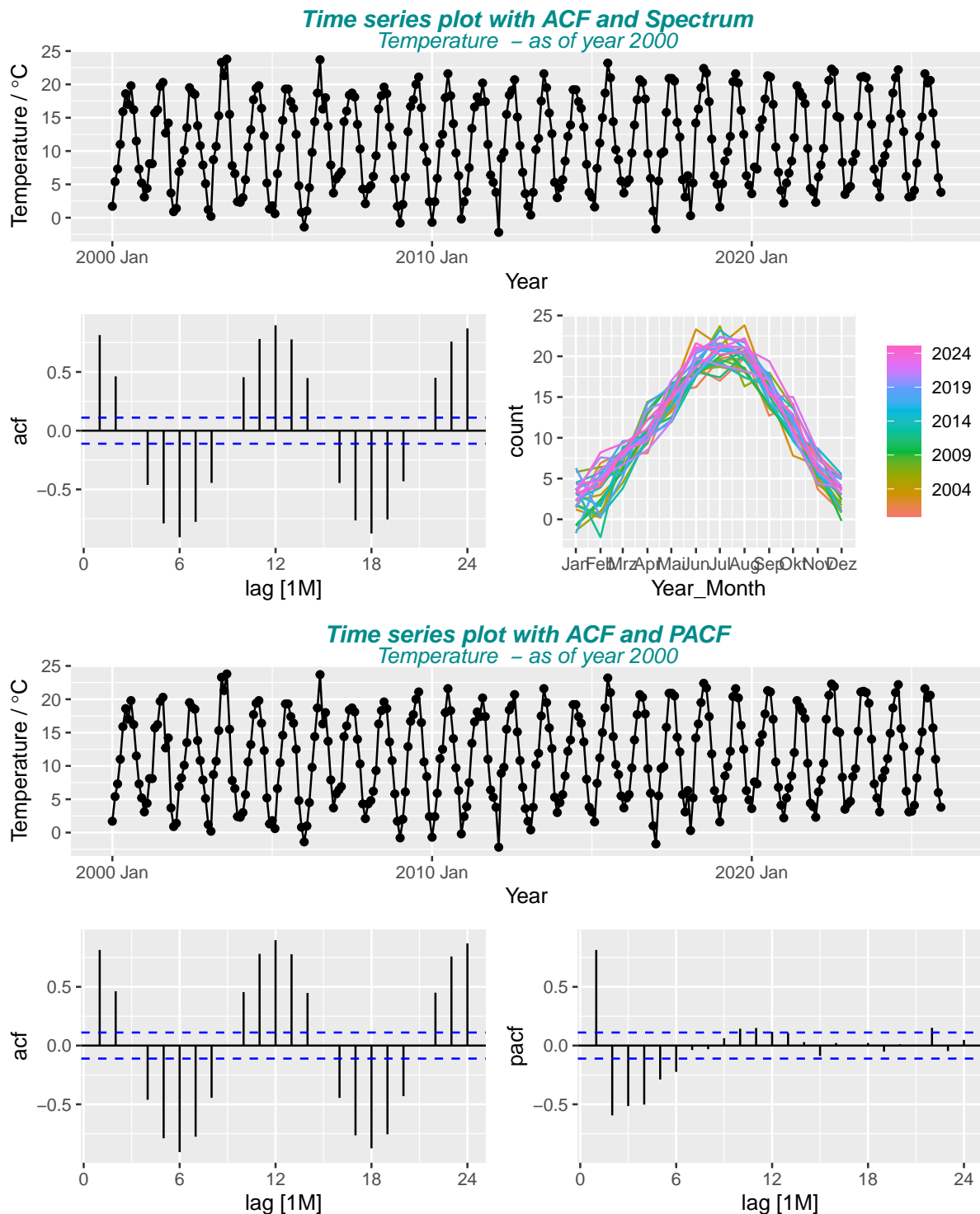
2.2.2 Periodogram - Spectral Density Estimation of a Time Series

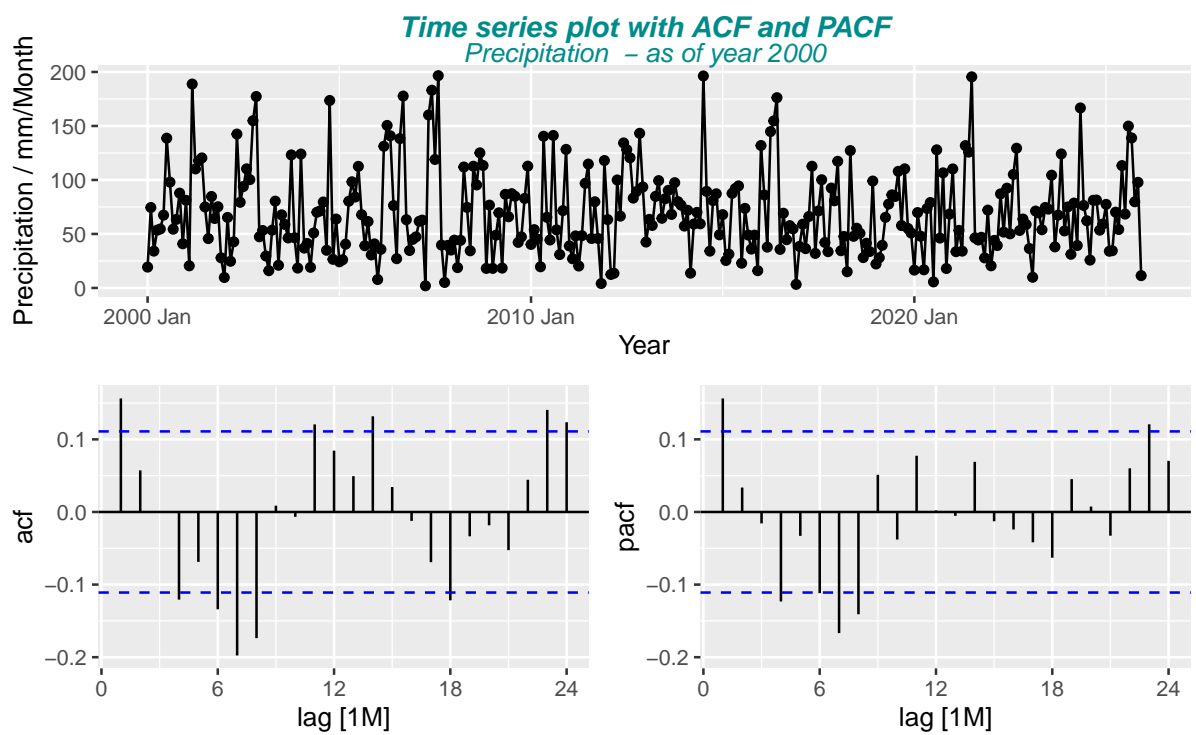
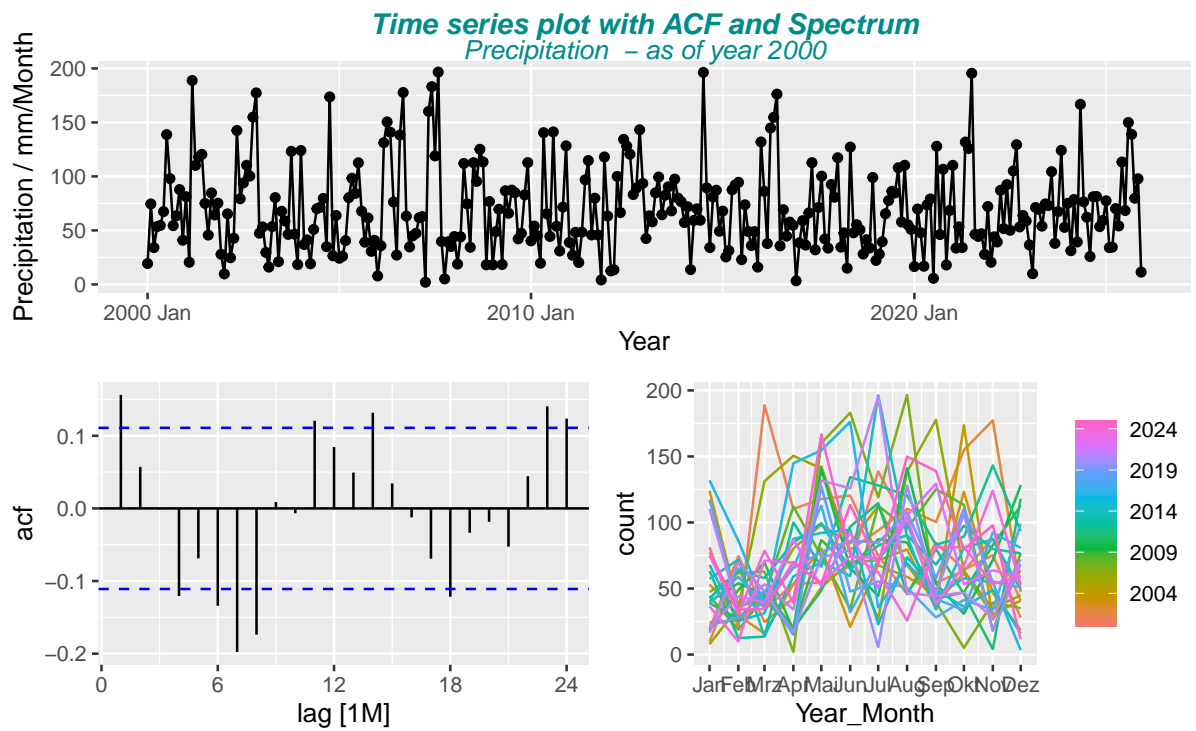
The spectral density characterizes the frequency content of the signal. One purpose of estimating the spectral density is to detect any periodicities in the data, by observing peaks at the frequencies corresponding to these periodicities.

At frequency $\lambda = 1/12$ there is a significant peak \Rightarrow 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.

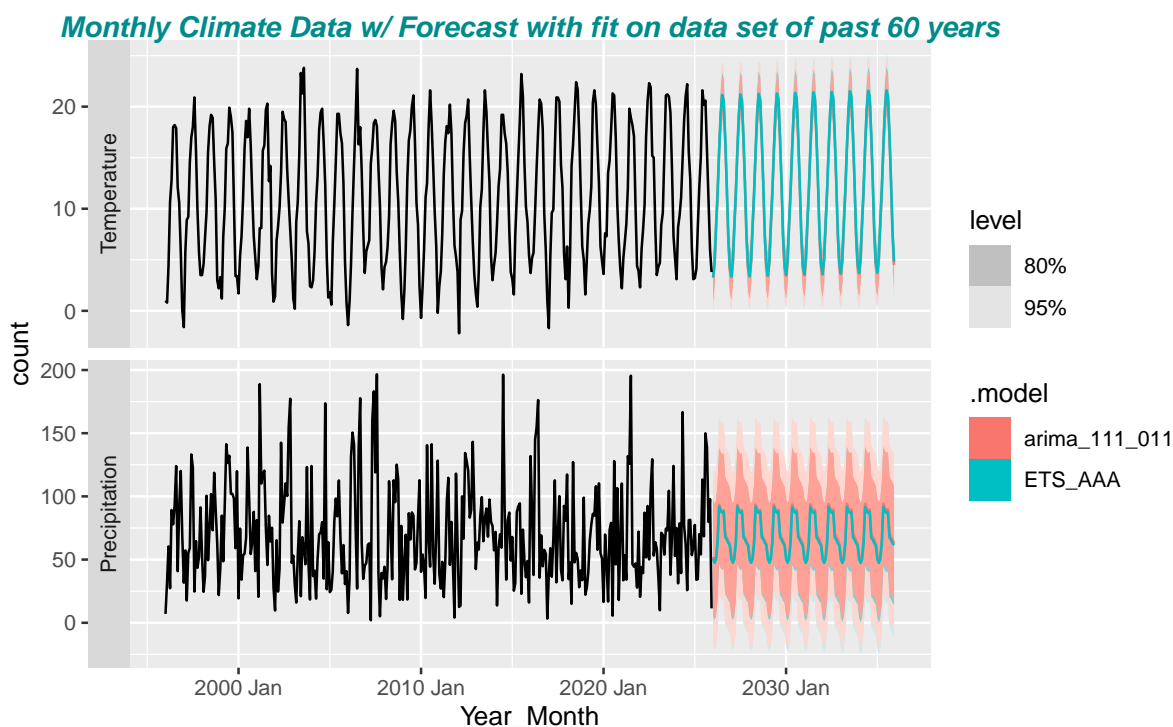
Forecasts produced using **ETS** methods are weighted averages of past observations, with the weights decaying exponentially as the observations get older.

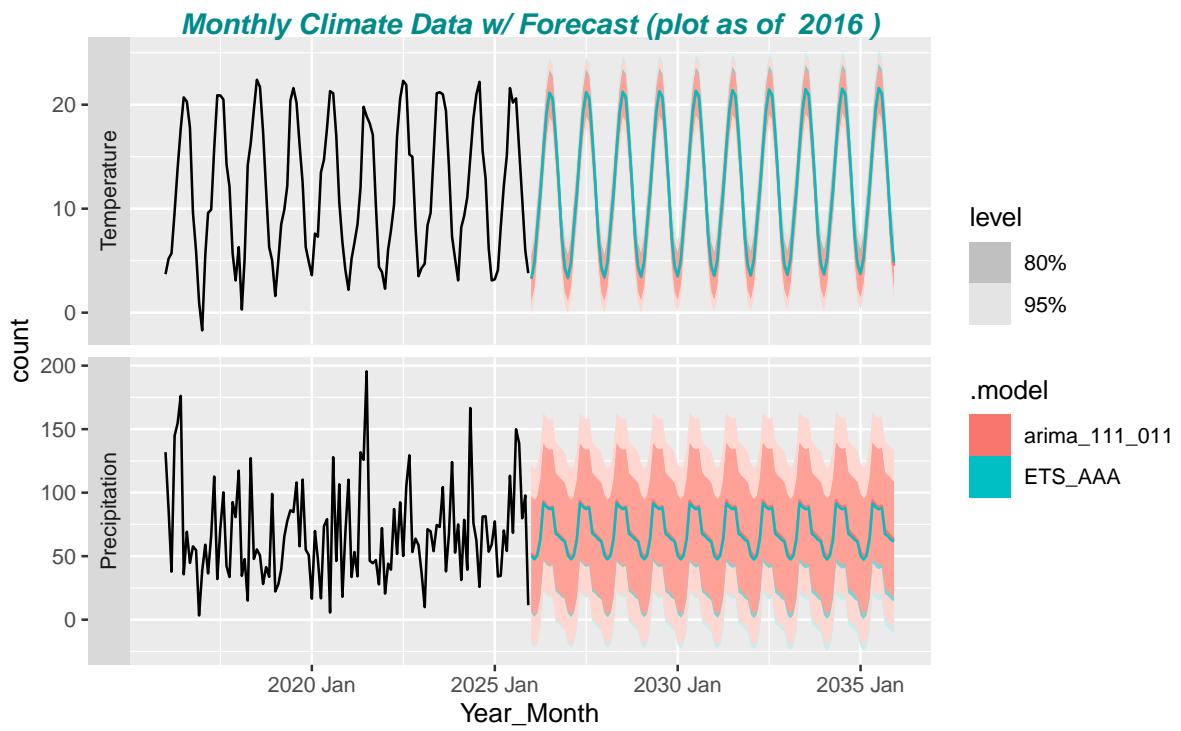
Here a *ETS(A, A|A)* **model** with additive (“A”) *Error term*, *Trend term* and *Seasonal term* was chosen.

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)

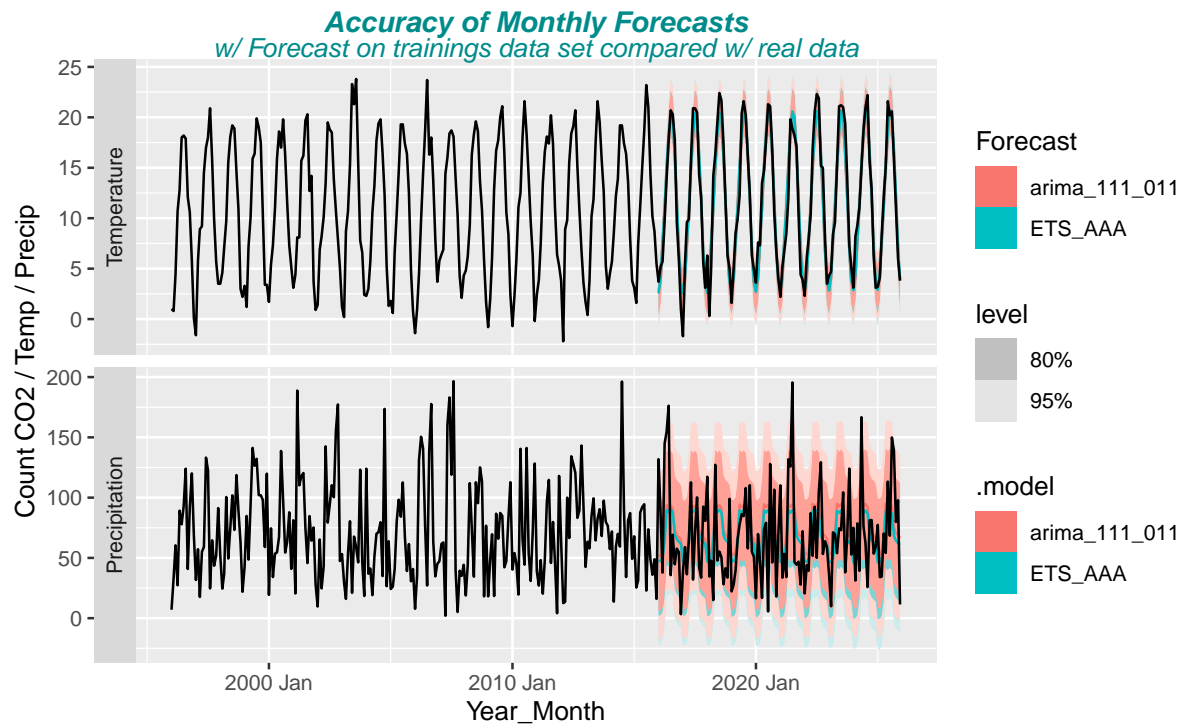
```
#> # A mable: 2 x 4
#> # Key:      City, Measure [2]
#>   City Measure      ETS_AAA      arima_111_011
#>   <chr> <fct>      <model>      <model>
#> 1 Basel Temperature <ETS(A,A,A)> <ARIMA(1,1,1)(0,1,1)[12]>
#> 2 Basel Precipitation <ETS(A,A,A)> <ARIMA(1,1,1)(0,1,1)[12]>
```





3.2 Forecast Accuracy Evaluation

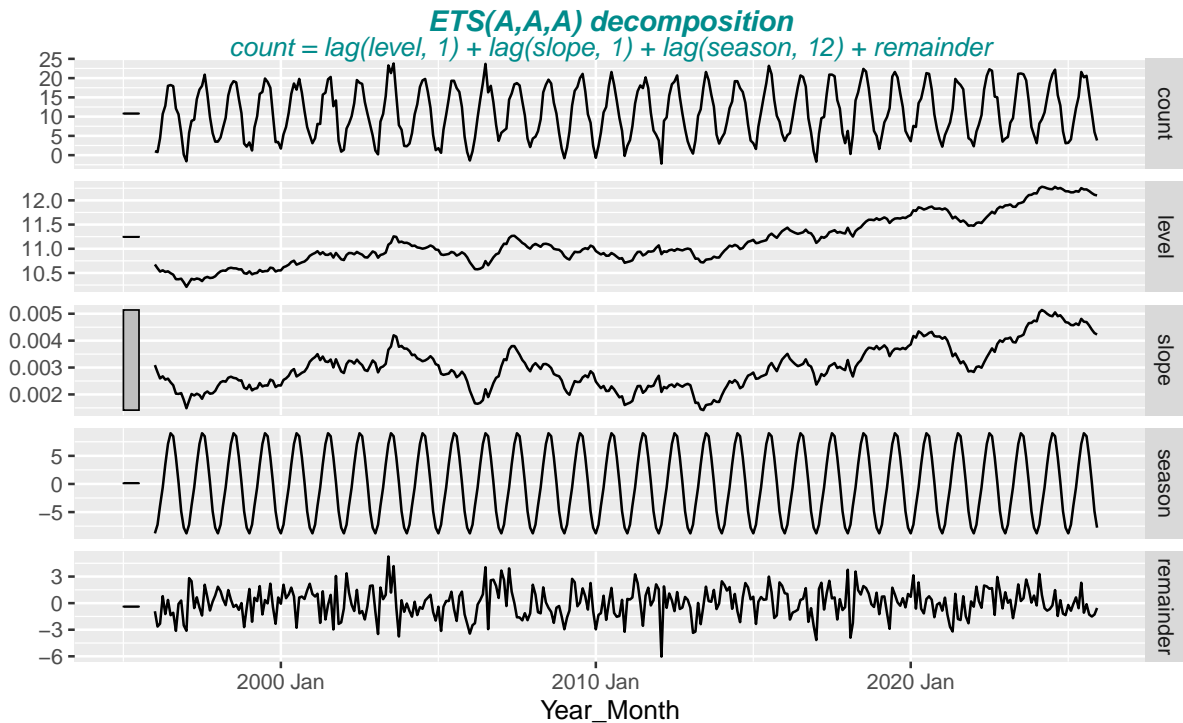
- Forecast Accuracy Evaluation w/ training data “data_train” & test data “data_test”
 - “data” : complete dataset includes the forecasted (future) data range on top of data_train
 - “data_train” = “data” - forecast_range (“data_test”)
 - * data used to train the model (~80% of “data”)
 - “data_test”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



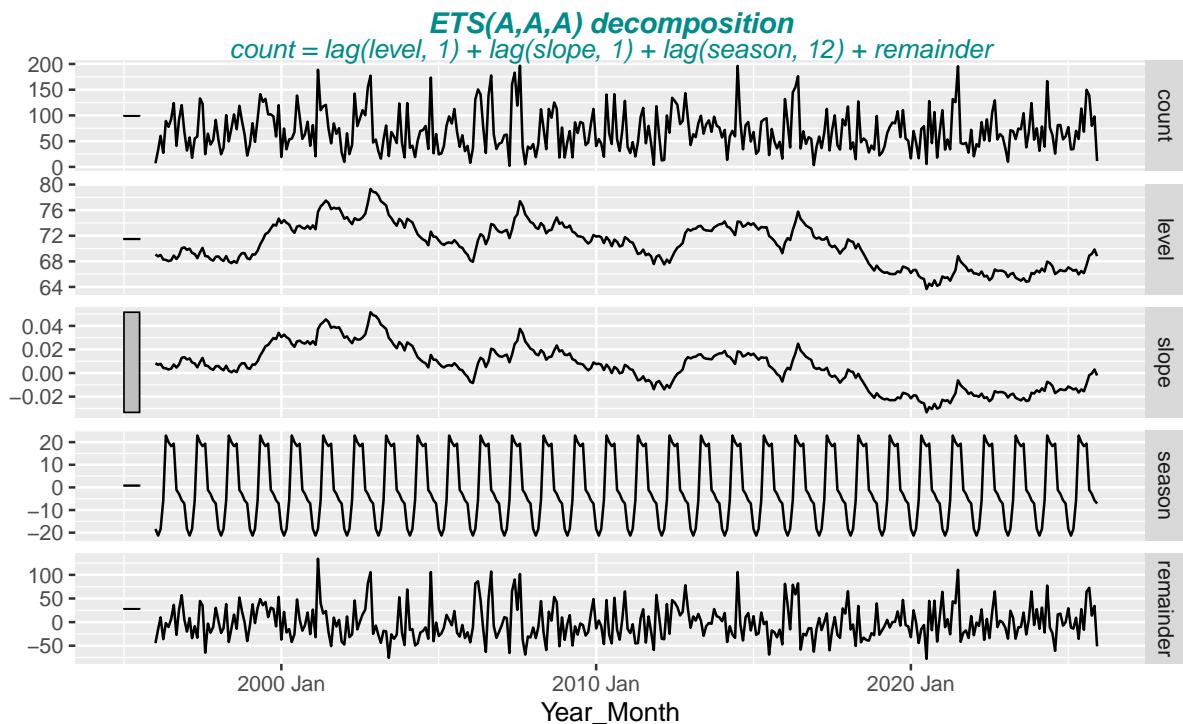
3.2.1 components(fit_ets) - plot of the decomposition of the fitted ETS model

- 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"
```

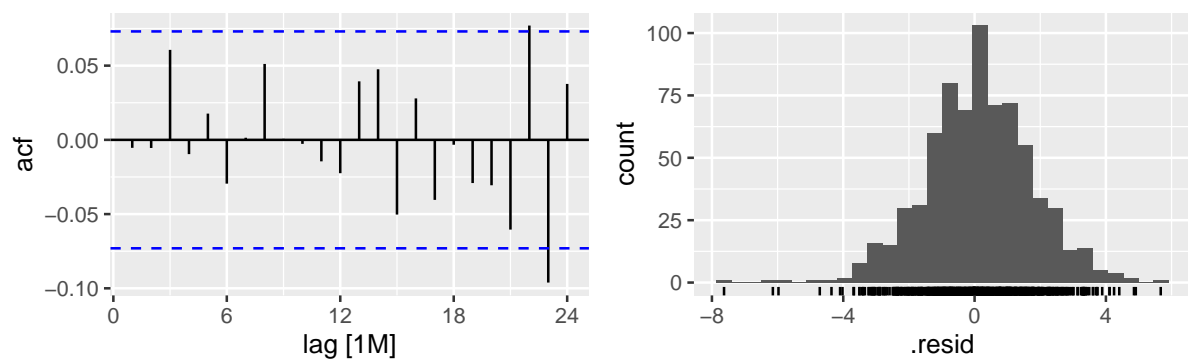
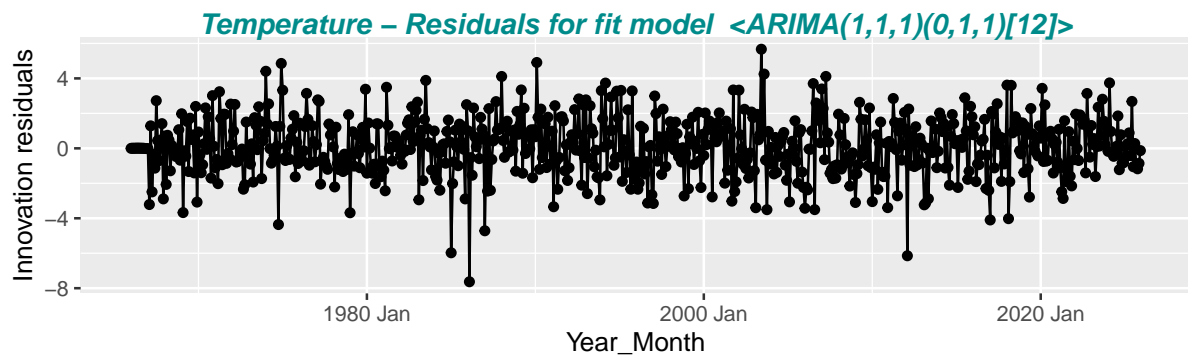
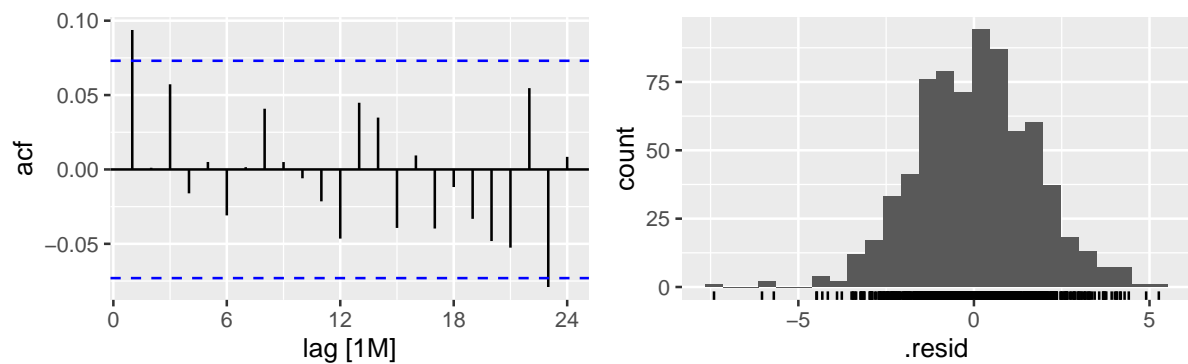
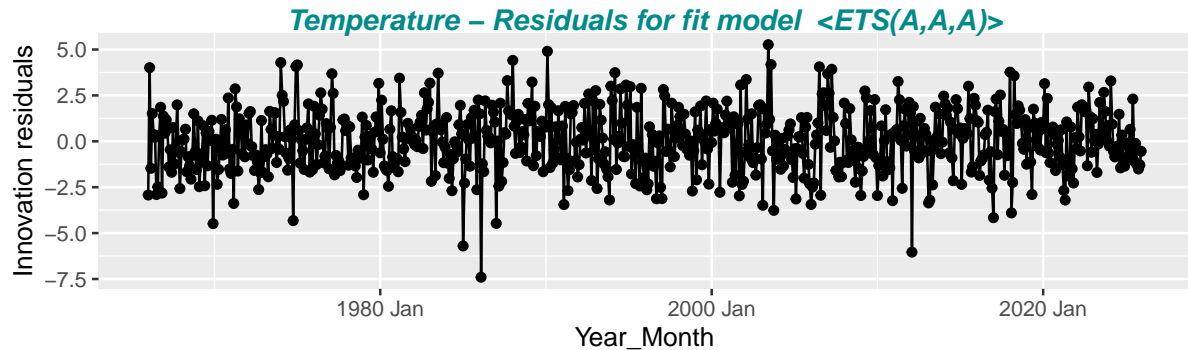


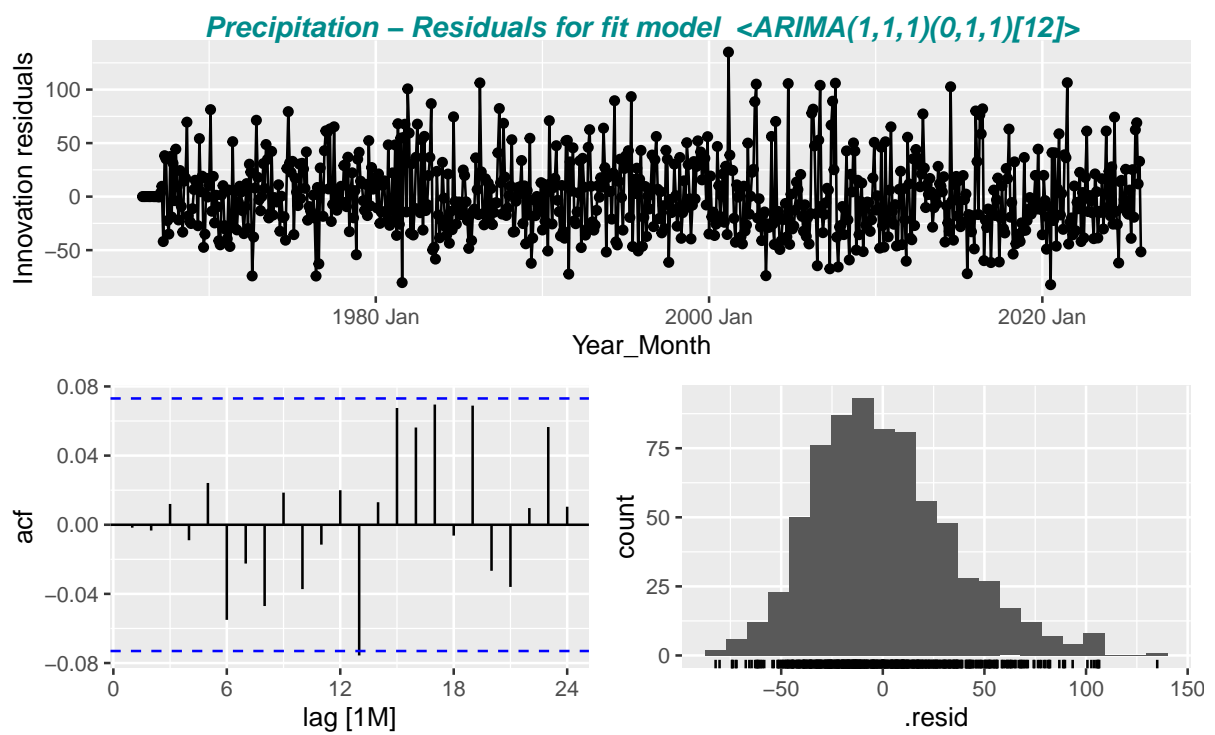
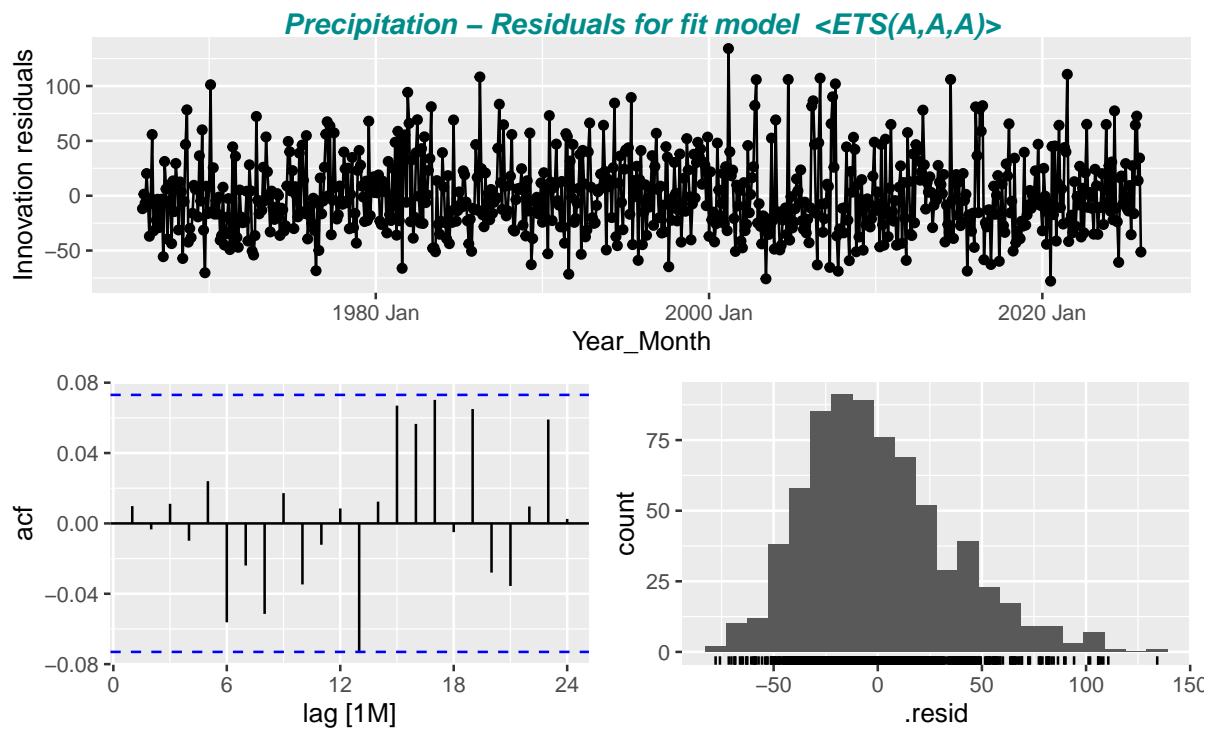
```
#> [1] "Precipitation"
```



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
1864-1870	9.0	62.4
1871-1900	8.7	64.3
1901-1930	9.0	65.9
1931-1960	9.4	65.5
1961-1990	9.6	64.8
1991-2020	10.9	70.2
2021-2025	12.0	70.9

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
Basel	Temperature	2026	12.13	11.93
Basel	Temperature	2030	12.33	12.12
Basel	Temperature	2035	12.59	12.36
Basel	Temperature	2040	12.84	12.60
Basel	Temperature	2045	13.09	12.84
Basel	Temperature	2050	13.35	13.07
Basel	Precipitation	2026	68.81	70.21
Basel	Precipitation	2030	68.71	70.59
Basel	Precipitation	2035	68.58	71.01
Basel	Precipitation	2040	68.45	71.42
Basel	Precipitation	2045	68.32	71.84
Basel	Precipitation	2050	68.20	72.25

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_ET	Delta_ARIMA
Temperature	2026	2050	12.13	11.93	13.35	13.07	1.22	1.14
Precipitation	2026	2050	68.81	70.21	68.20	72.25	-0.61	2.04

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_ET	Mean.x_ARIMA	Mean.y_ET	Mean.y_ARIMA	Delta_ET	Delta_ARIMA
Temperature	Jan	2026	2050	3.32	3.21	4.54	4.38	1.22	1.17
Temperature	Feb	2026	2050	4.87	4.58	6.09	5.73	1.22	1.14
Temperature	Mar	2026	2050	8.23	8.03	9.45	9.17	1.22	1.14
Temperature	Apr	2026	2050	11.50	11.34	12.71	12.48	1.22	1.14
Temperature	May	2026	2050	15.60	15.45	16.82	16.59	1.22	1.14

Measure	Month	Year.x	Year.y	Mean.x_ET	Sean.x_ARIMA	Mean.y_ET	Sean.y_ARIMA	Delta_ET	Delta_ARIMA
Temperature	Jun	2026	2050	19.24	19.01	20.46	20.15	1.22	1.14
Temperature	Jul	2026	2050	21.15	20.99	22.37	22.13	1.22	1.14
Temperature	Aug	2026	2050	20.63	20.44	21.84	21.58	1.22	1.14
Temperature	Sep	2026	2050	16.90	16.68	18.12	17.82	1.22	1.14
Temperature	Oct	2026	2050	12.46	12.30	13.67	13.44	1.22	1.14
Temperature	Nov	2026	2050	7.28	7.04	8.50	8.18	1.22	1.14
Temperature	Dec	2026	2050	4.38	4.08	5.60	5.22	1.22	1.14
Precipitation	Jan	2026	2050	50.46	52.19	49.85	54.79	-0.61	2.61
Precipitation	Feb	2026	2050	47.50	49.02	46.89	51.02	-0.61	2.00
Precipitation	Mar	2026	2050	50.41	51.65	49.80	53.64	-0.61	1.99
Precipitation	Apr	2026	2050	63.22	65.10	62.61	67.09	-0.61	1.99
Precipitation	May	2026	2050	91.75	93.41	91.14	95.40	-0.61	1.99
Precipitation	Jun	2026	2050	88.80	89.77	88.19	91.76	-0.61	1.99
Precipitation	Jul	2026	2050	87.03	88.04	86.42	90.03	-0.61	1.99
Precipitation	Aug	2026	2050	88.12	89.09	87.51	91.08	-0.61	1.99
Precipitation	Sep	2026	2050	67.69	70.17	67.08	72.16	-0.61	1.99
Precipitation	Oct	2026	2050	65.94	67.20	65.33	69.19	-0.61	1.99
Precipitation	Nov	2026	2050	63.09	64.92	62.48	66.92	-0.61	1.99
Precipitation	Dec	2026	2050	61.66	61.94	61.05	63.93	-0.61	1.99

5 Backup

5.1 Basel - 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
Basel	Temperature	1864	NA	9.1	16.3	8.1	7.7
Basel	Temperature	1865	-0.6	9.8	17.3	10.2	9.3
Basel	Temperature	1866	2.4	8.5	17.2	9.4	9.7
Basel	Temperature	1867	2.9	9.5	17.0	8.2	9.1
Basel	Temperature	1868	0.3	10.3	18.3	9.1	10.1
Basel	Temperature	1869	4.4	8.9	16.5	8.8	9.0
Basel	Temperature	1870	-0.8	9.0	17.7	8.8	8.4
Basel	Temperature	1871	-1.9	9.1	16.6	7.8	7.8
Basel	Temperature	1872	-0.5	9.3	17.0	10.3	9.8
Basel	Temperature	1873	2.4	8.8	18.4	9.3	9.4
Basel	Temperature	2016	4.8	9.8	19.6	11.1	10.9
Basel	Temperature	2017	1.6	11.8	20.8	10.7	11.4
Basel	Temperature	2018	3.2	11.9	21.2	11.8	12.2
Basel	Temperature	2019	3.9	10.2	20.7	11.6	11.6
Basel	Temperature	2020	5.4	11.8	20.1	11.5	12.1
Basel	Temperature	2021	3.8	9.1	19.0	10.6	10.6
Basel	Temperature	2022	4.1	11.8	21.6	12.8	12.5
Basel	Temperature	2023	4.2	11.1	21.1	13.6	12.6
Basel	Temperature	2024	5.5	11.8	20.6	11.6	12.2
Basel	Temperature	2025	3.5	11.8	20.8	10.9	11.8

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

City	Measure	Year	Winter_avg	Spring_avg	Summer_avg	Fall_avg	Year_avg
Basel	Precipitation	1864	NA	50.2	83.1	55.2	50.5
Basel	Precipitation	1865	41.1	42.4	75.4	56.5	54.3
Basel	Precipitation	1866	39.3	85.6	77.6	54.7	74.2
Basel	Precipitation	1867	112.2	79.1	85.6	61.8	77.2
Basel	Precipitation	1868	29.4	41.3	69.1	82.4	63.7
Basel	Precipitation	1869	60.2	73.6	67.1	67.4	62.0
Basel	Precipitation	1870	38.8	37.3	61.1	80.5	55.2
Basel	Precipitation	1871	47.9	47.5	77.7	44.3	47.8
Basel	Precipitation	1872	26.7	117.7	99.4	76.3	83.7
Basel	Precipitation	1873	28.4	65.5	72.3	80.0	58.4
Basel	Precipitation	2016	78.0	112.4	93.7	52.4	83.1
Basel	Precipitation	2017	33.6	71.8	67.8	56.1	63.8
Basel	Precipitation	2018	77.5	63.3	51.2	34.4	58.1
Basel	Precipitation	2019	49.7	60.9	93.0	74.4	65.5
Basel	Precipitation	2020	45.7	46.1	70.9	56.9	56.4
Basel	Precipitation	2021	70.7	73.1	122.6	39.7	76.8
Basel	Precipitation	2022	45.6	59.4	82.5	82.1	66.3
Basel	Precipitation	2023	35.0	64.9	84.0	76.5	64.6
Basel	Precipitation	2024	53.0	94.9	54.8	72.0	69.2
Basel	Precipitation	2025	56.9	52.9	110.5	105.5	77.5

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

City	Month	Temperature	Precipitation
Basel	Jan	0.8	44.9
Basel	Feb	2.2	42.0
Basel	Mar	5.6	48.4
Basel	Apr	9.3	61.9
Basel	May	13.4	81.9
Basel	Jun	16.7	90.7
Basel	Jul	18.6	84.0
Basel	Aug	17.9	87.8
Basel	Sep	14.5	73.3
Basel	Oct	9.6	65.8
Basel	Nov	4.9	59.9
Basel	Dec	1.7	53.0

5.2 Basel - 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>         <nth> <chr>      <dbl>
#> 1 Basel Temperature 1864 Jan 1864-1870   -5.5
#> 2 Basel Temperature 1864 Feb 1864-1870   -0.2
#> 3 Basel Temperature 1864 Mrz 1864-1870     6
#> 4 Basel Temperature 2025 Okt 2021-2025    11
#> 5 Basel Temperature 2025 Nov 2021-2025     6
#> 6 Basel Temperature 2025 Dez 2021-2025    3.8
#> # A tsibble: 6 x 5 [1M]
#> # Key:      City, Measure [1]
#> # Groups:   City, Measure [1]
#>   City Measure   Year_Month Period_Time count
#>   <chr> <fct>         <nth> <chr>      <dbl>
#> 1 Basel Precipitation 1864 Jan 1864-1870    20.6
#> 2 Basel Precipitation 1864 Feb 1864-1870    16
#> 3 Basel Precipitation 1864 Mrz 1864-1870    48.4
#> 4 Basel Precipitation 2025 Okt 2021-2025    79.8
#> 5 Basel Precipitation 2025 Nov 2021-2025   97.8
#> 6 Basel Precipitation 2025 Dez 2021-2025   11.4
```

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