Climate Data Visualization -

Atmospheric CO_2 Concentration / Temperature / Precipitation

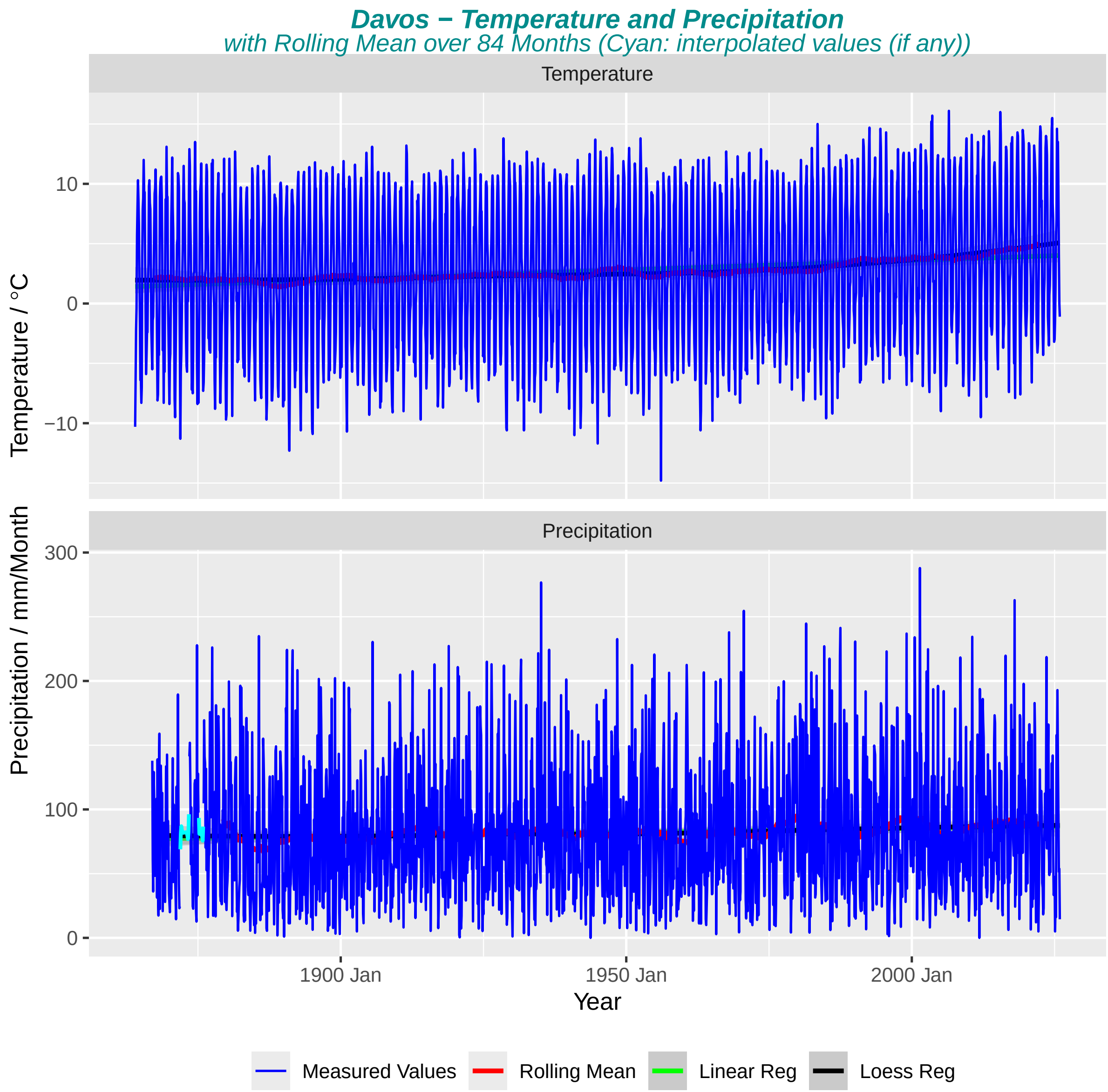
Wolfgang Vollmer

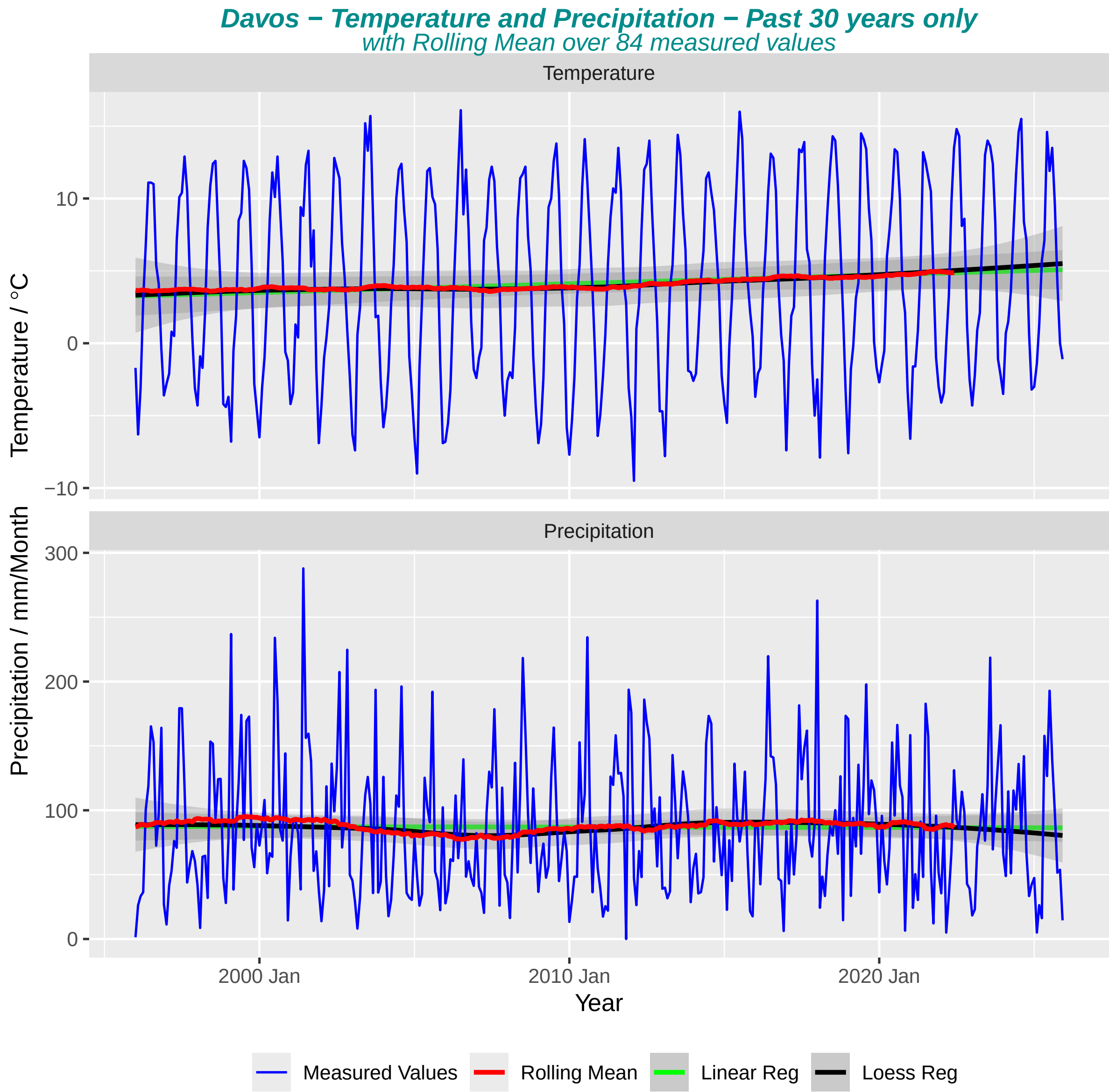
2026-01-08

Contents

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

1.1 Monthly Time Plots with Rolling Mean



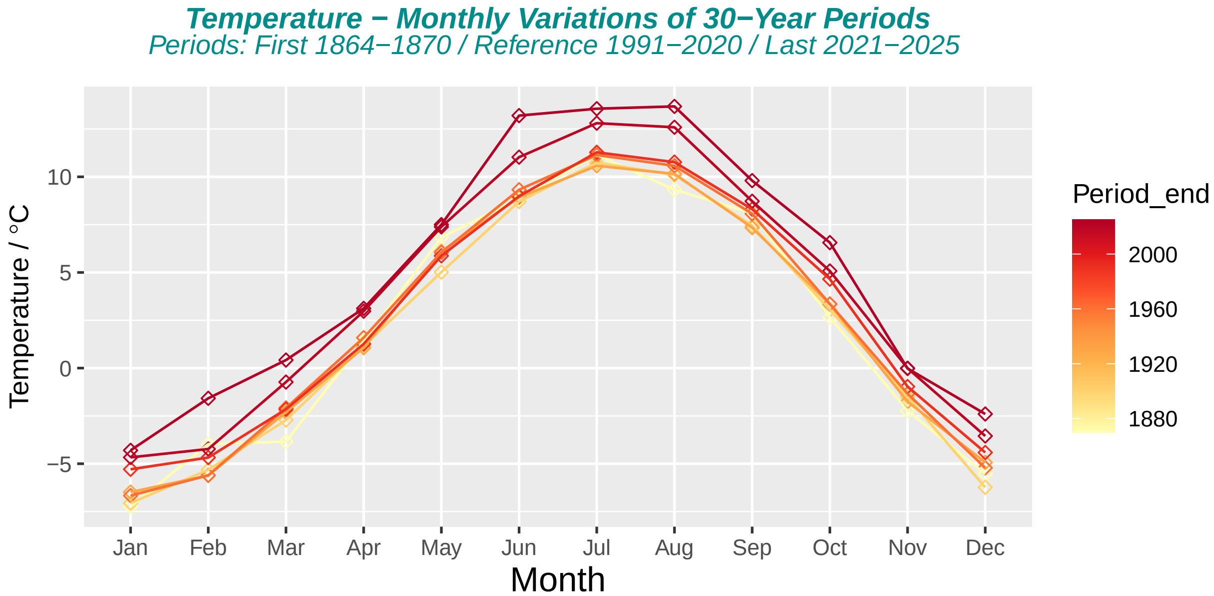


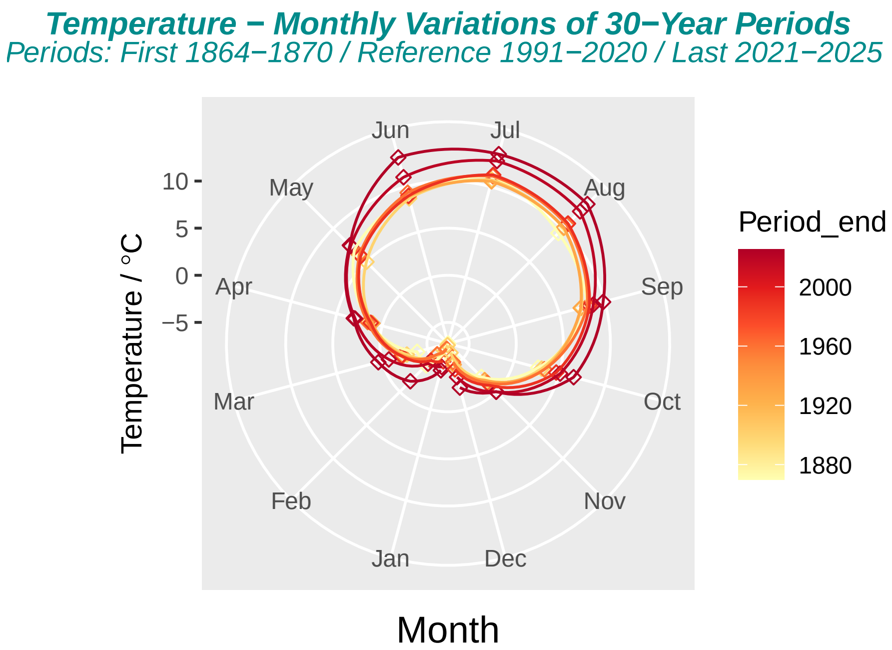
1.2 Annual seasonal plots with monthly breakdown

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

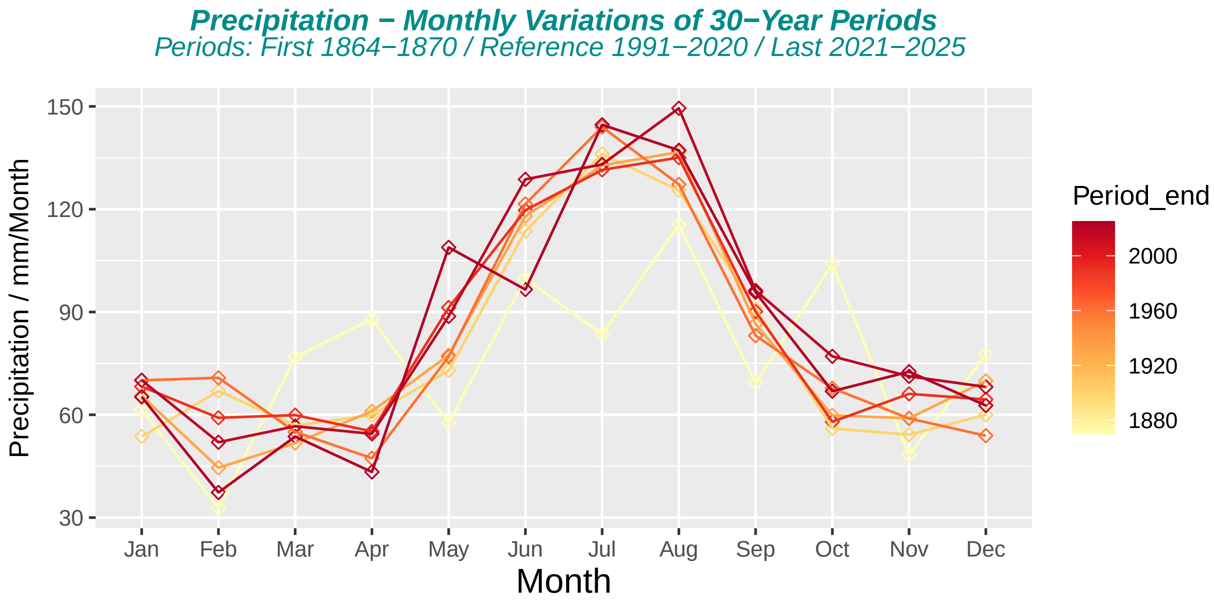
Monthly Data with Local Polynomial Regression Fitting
Davos 1864 – 2025
Temperature
Temperature / °C
10
0
−10
Precipitation
Precipitation / mm/Month
300
200
100
0
1900 Jan
1950 Jan
2000 Jan
Year
Month
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

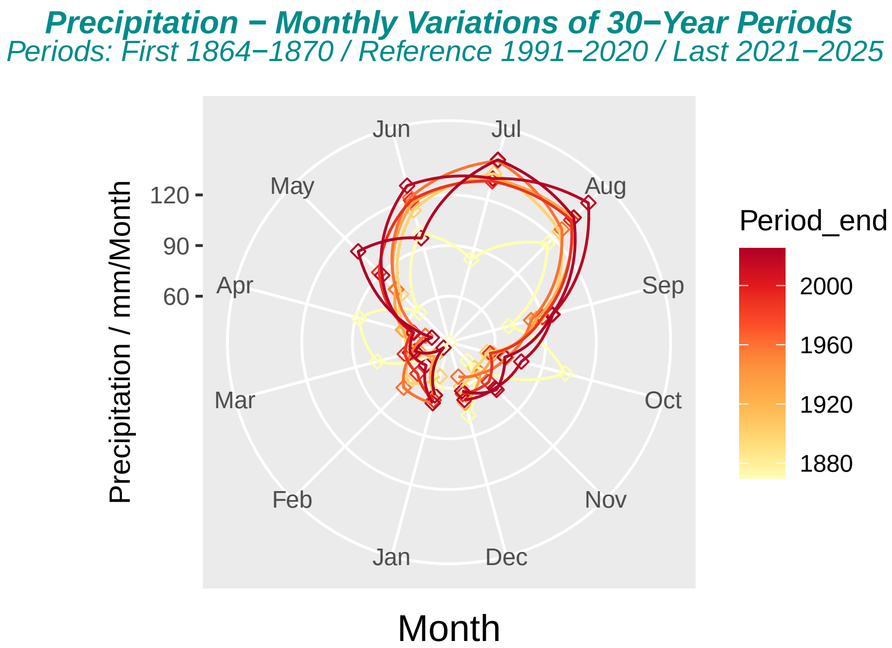
1.2.1 30-year period plots with monthly breakdown - Cartesian and Polar Coordinates





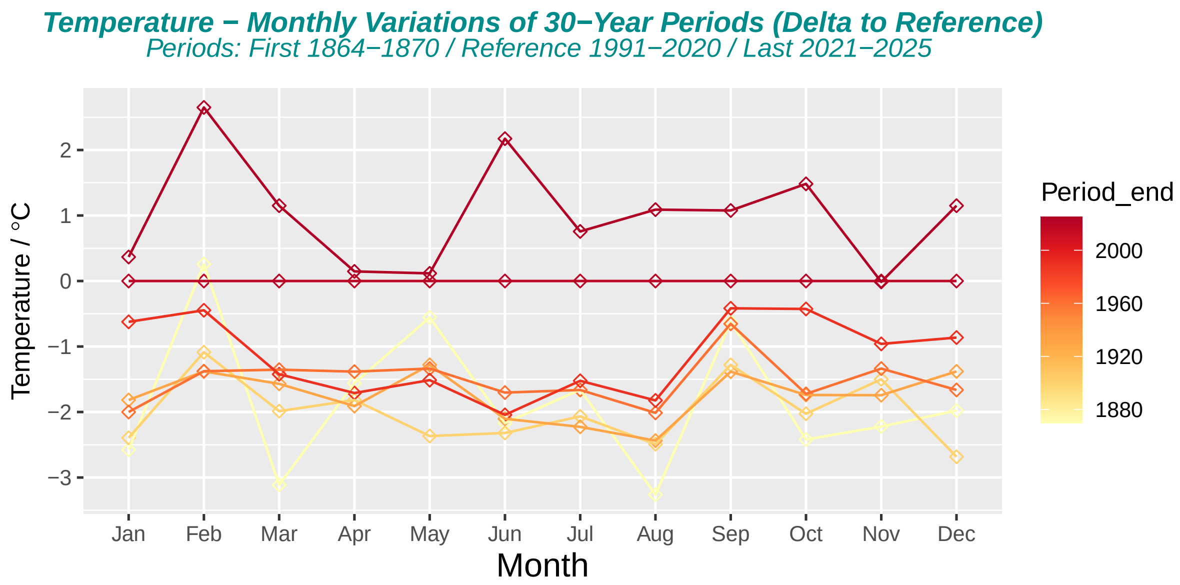

```
#>
#> _
```

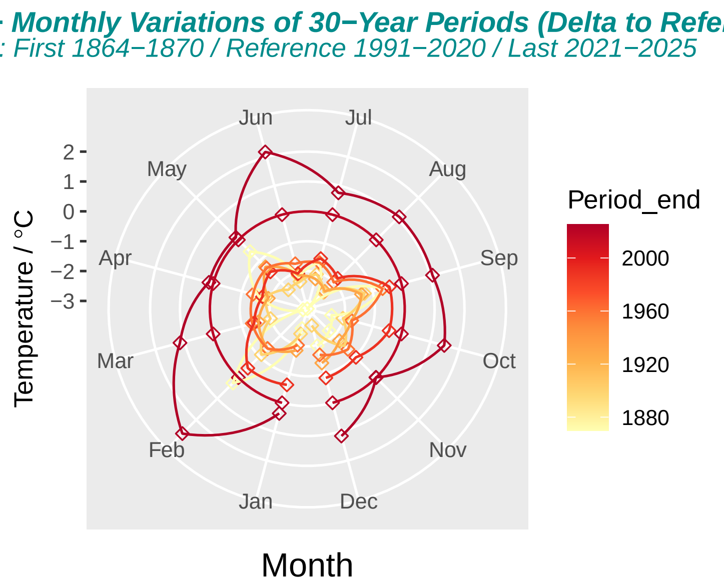

Precipitation − Monthly Variations of 30−Year Periods
Periods: First 1864−1870 / Reference 1991−2020 / Last 2021−2025
Precipitation / mm/Month
150
120
90
60
30
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month
Period_end
2000
1960
1920
1880

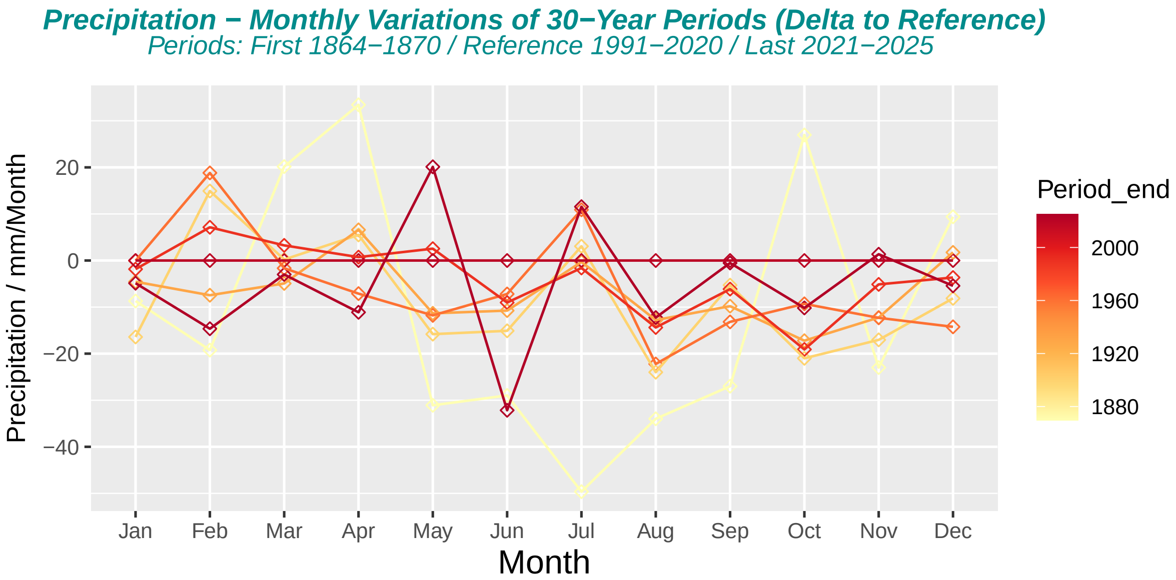

Precipitation − Monthly Variations of 30−Year Periods
Periods: First 1864−1870 / Reference 1991−2020 / Last 2021−2025
Precipitation / mm/Month
120
90
60
Jun
Jul
May
Aug
Apr
Sep
Mar
Oct
Feb
Nov
Jan
Dec
Month
Period_end
2000
1960
1920
1880

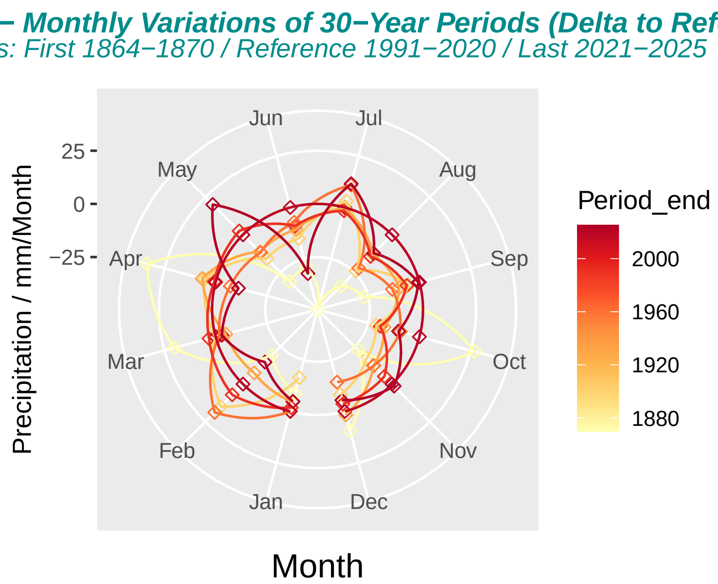
```
#>
#> _
```

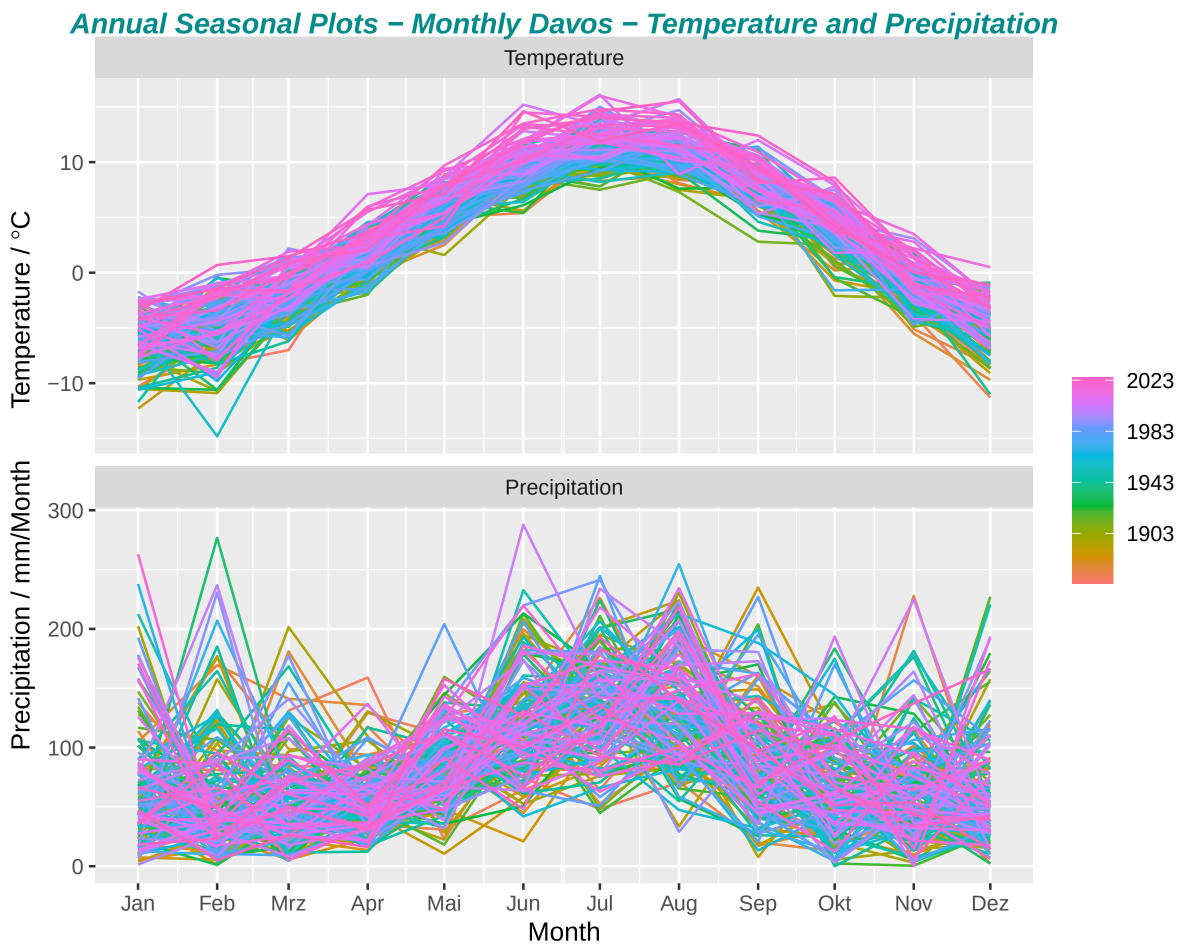
1.2.2 Plot Monthly Delta to Reference Period - Cartesian and Polar Coordinates

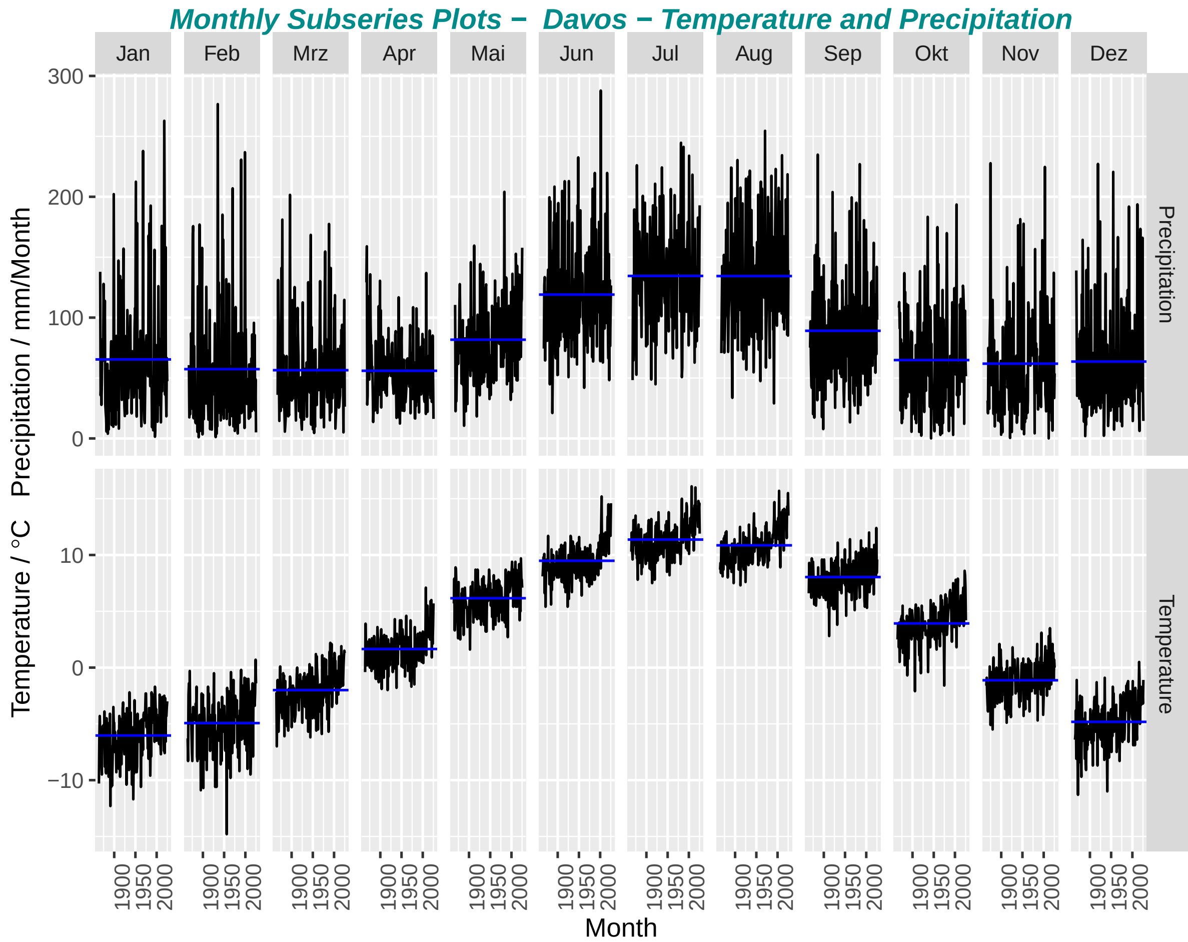





Precipitation − Monthly Variations of 30−Year Periods (Delta to Reference)
Periods: First 1864−1870 / Reference 1991−2020 / Last 2021−2025
Precipitation / mm/Month
20
0
−20
−40
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month
Period_end
2000
1960
1920
1880


Precipitation − Monthly Variations of 30−Year Periods (Delta to Reference)
Periods: First 1864−1870 / Reference 1991−2020 / Last 2021−2025
Precipitation / mm/Month
25
0
−25
Jun
Jul
May
Aug
Apr
Sep
Mar
Oct
Feb
Nov
Jan
Dec
Month
Period_end
2000
1960
1920
1880

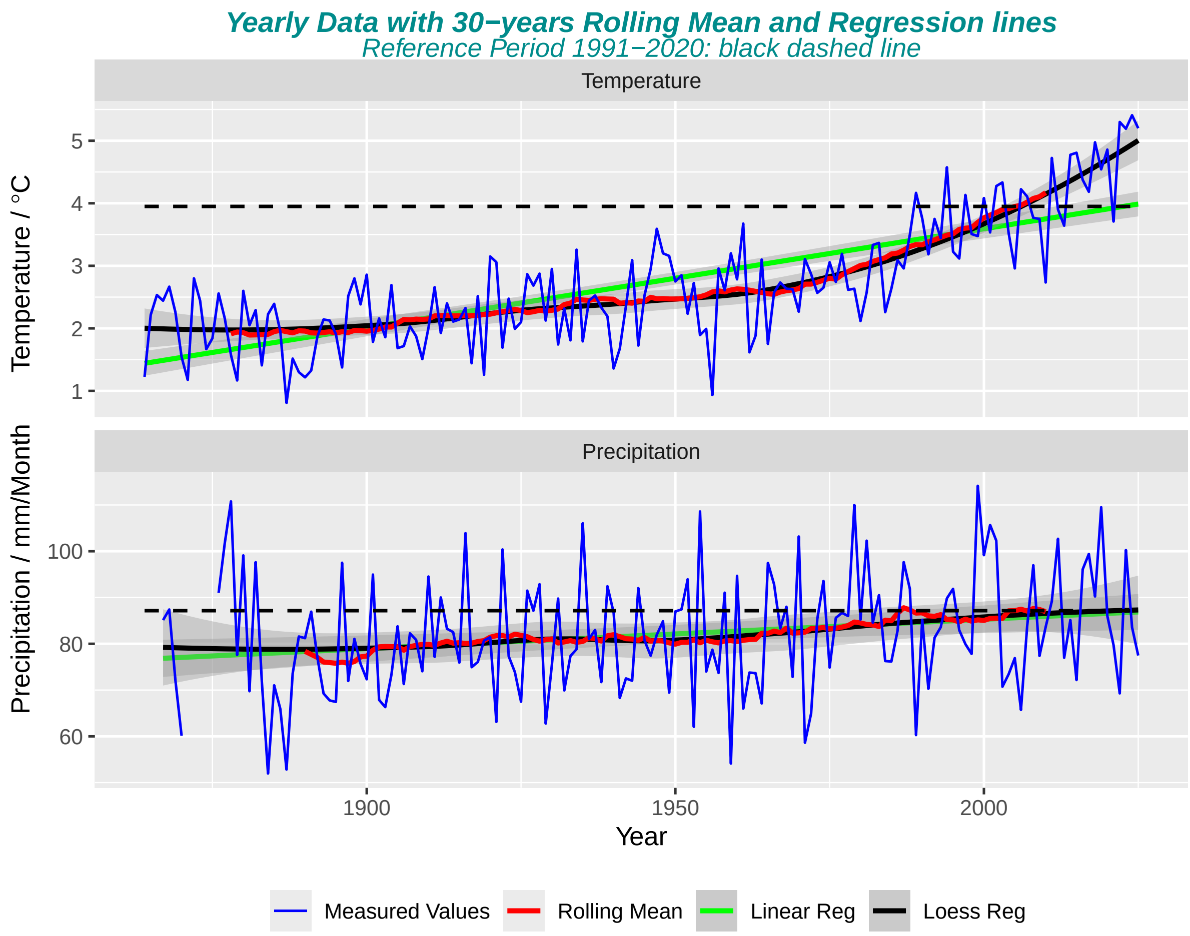

Annual Seasonal Plots − Monthly Davos − Temperature and Precipitation
Temperature
Temperature / °C
10
0
−10
Precipitation
Precipitation / mm/Month
300
200
100
0
Jan
Feb
Mrz
Apr
Mai
Jun
Jul
Aug
Sep
Okt
Nov
Dez
Month
2023
1983
1943
1903



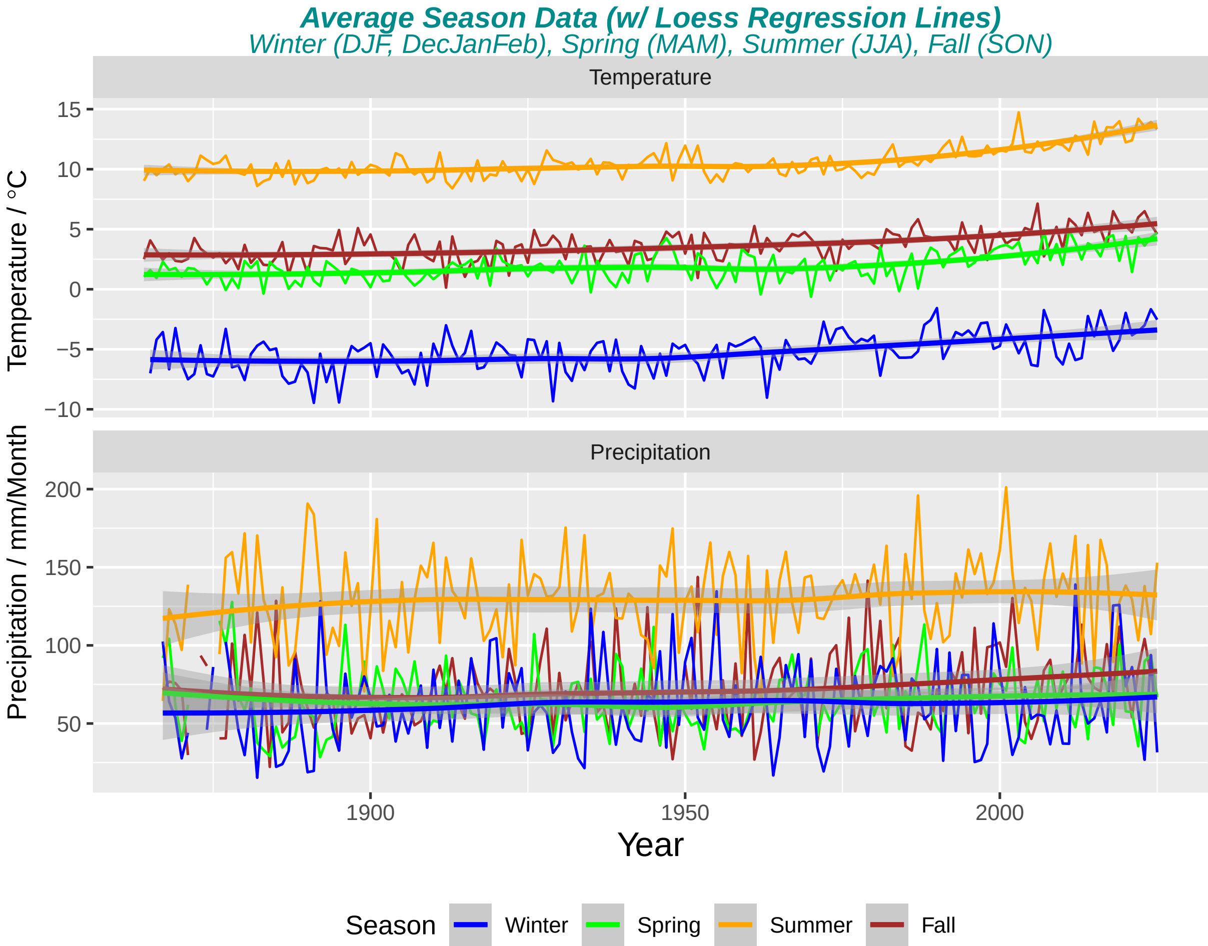
The blue horizontal lines within the seasonal subseries plot indicate the means for each month.

1.3 Annual Davos - 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

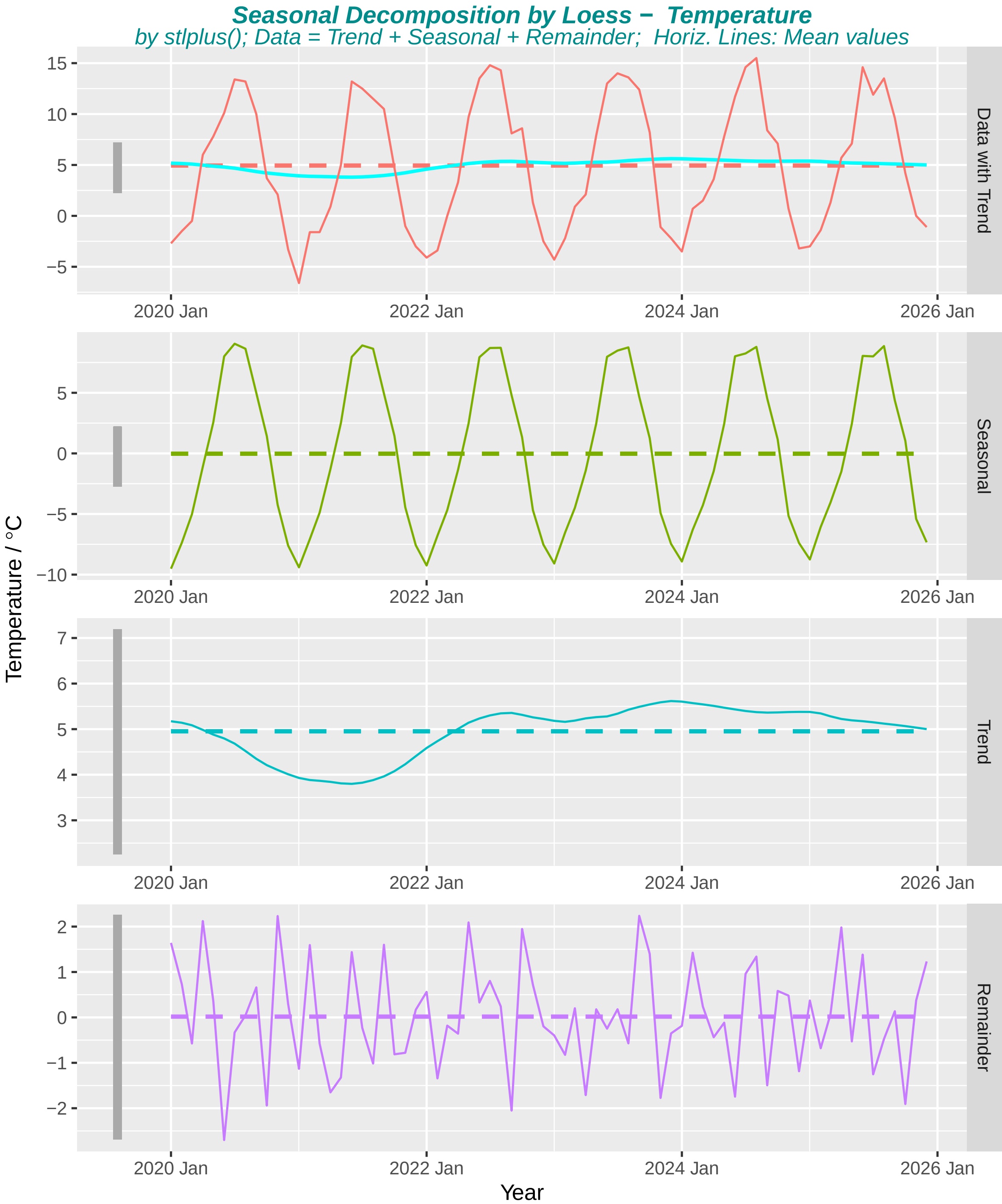
An *additive model* would be used when the variations around the trend do not vary with the level of the time series whereas a *multiplicative model* would be appropriate if the trend is proportional to the level of the time series.

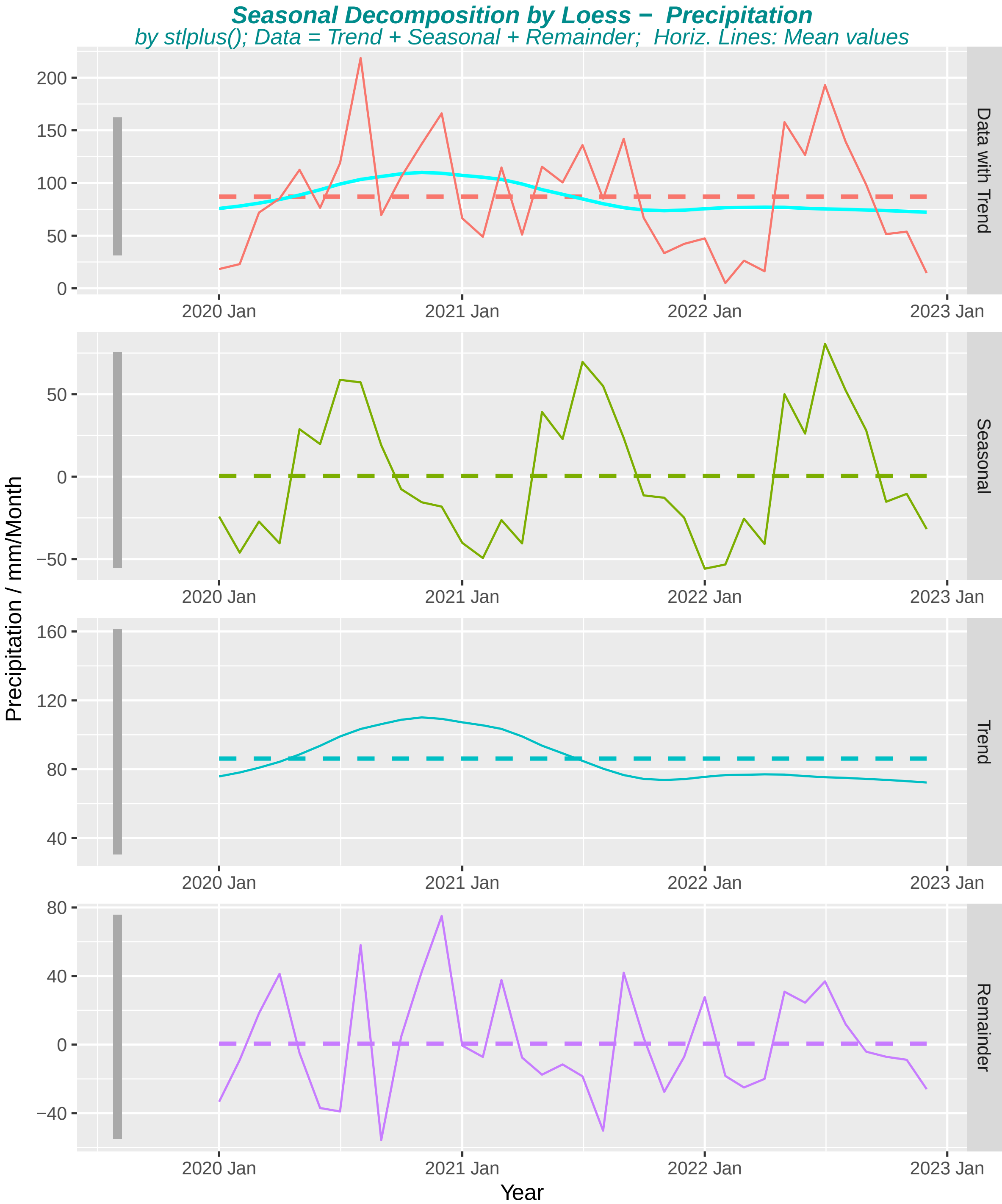
Time series using an

- 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.

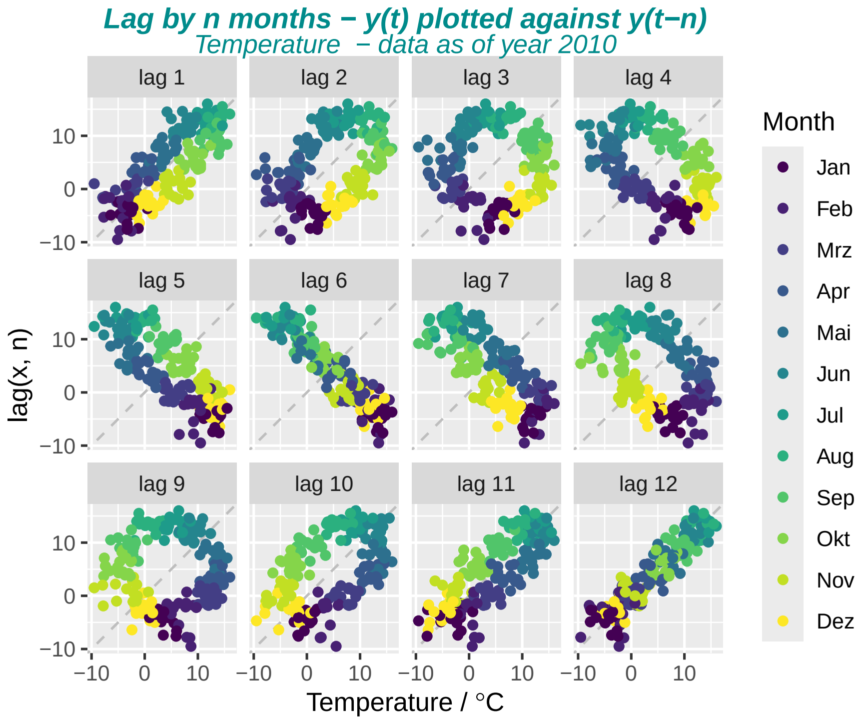

Seasonal Decomposition by Loess − Temperature
by stlplus(); Data = Trend + Seasonal + Remainder; Horiz. Lines: Mean values
Data with Trend
Seasonal
Trend
Remainder
Temperature / °C
Year
2020 Jan
2022 Jan
2024 Jan
2026 Jan



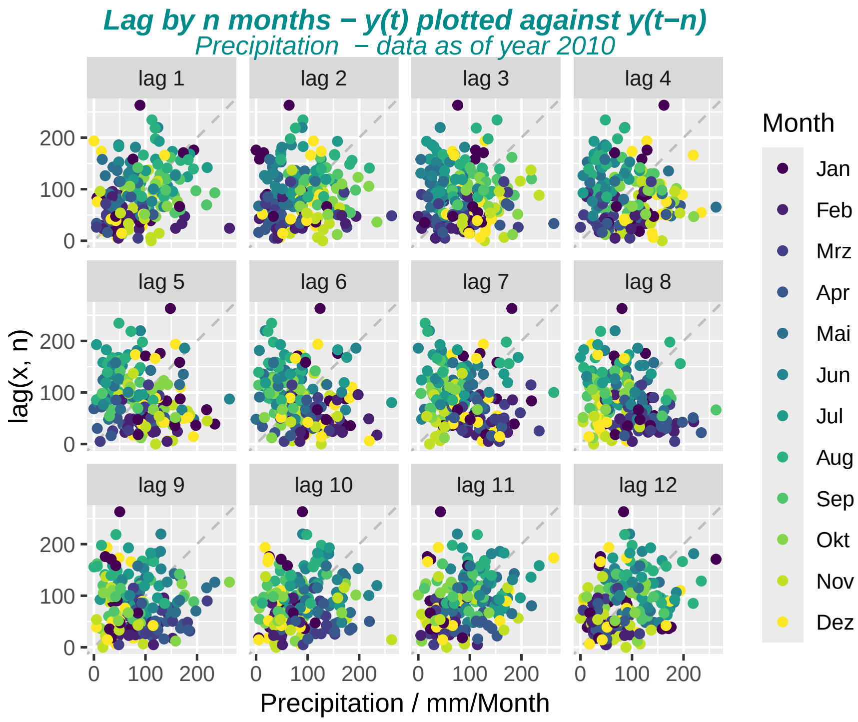
2.2 Periodicities - Season Frequency

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

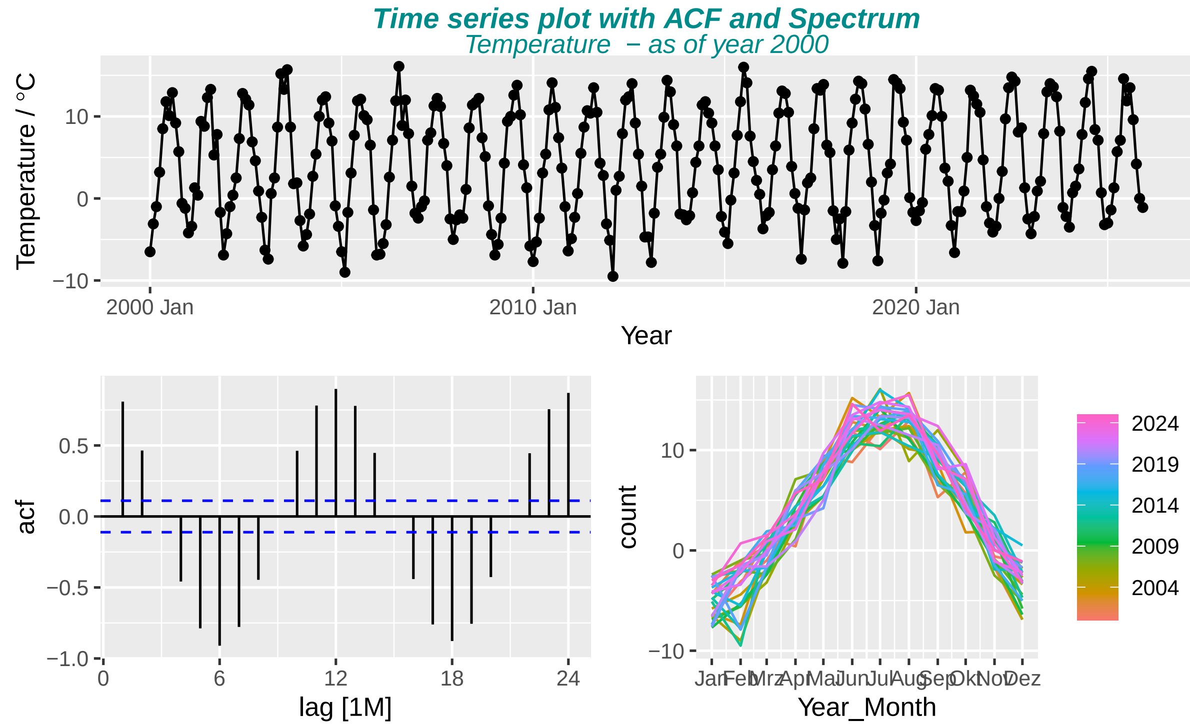
2.2.2 Periodogram - Spectral Density Estimation of a Time Series

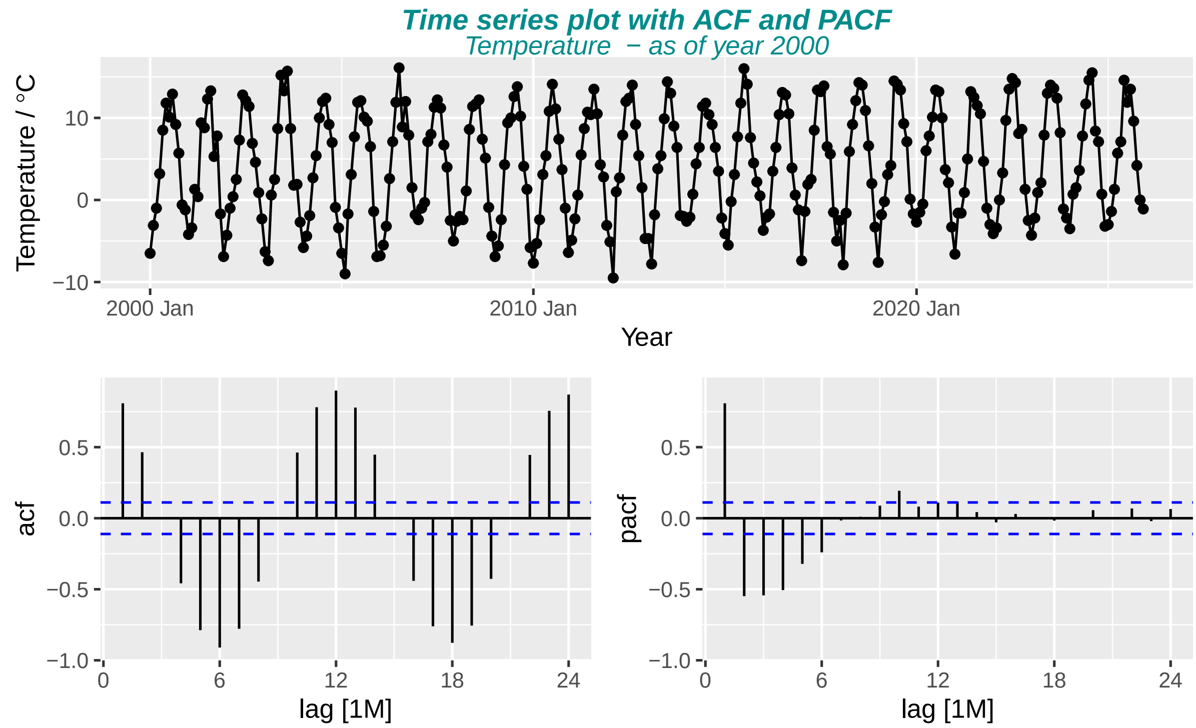
The spectral density characterizes the frequency content of the signal. One purpose of estimating the spectral density is to detect any periodicities in the data, by observing peaks at the frequencies corresponding to these periodicities.

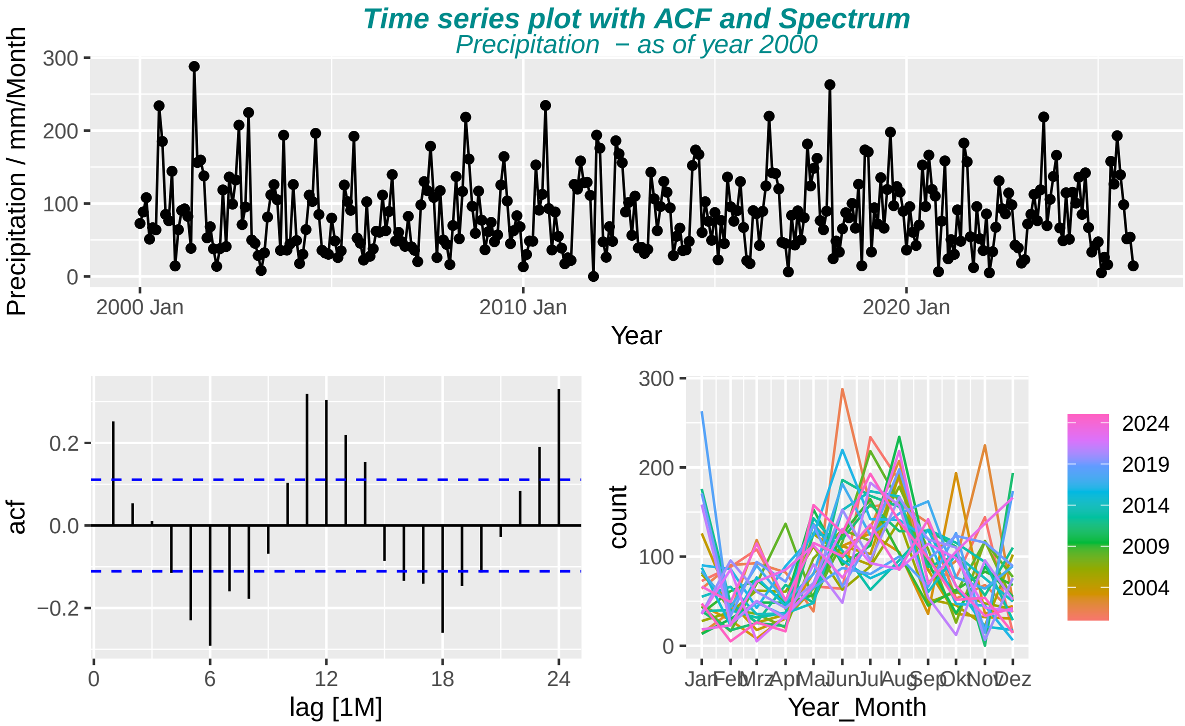
At frequency $\lambda = 1/12$ there is a significant peak => This pattern repeats every full frequency = every 12 months / every year

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

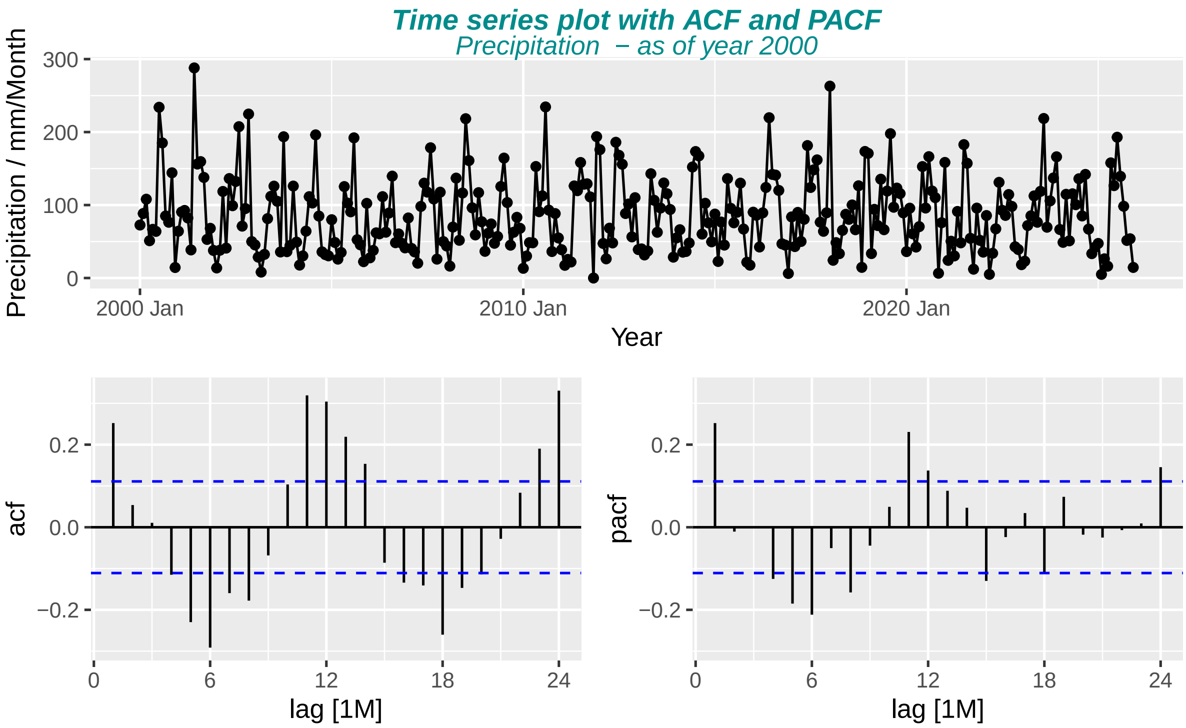
Note: The blue dashed lines in the (P)ACF plots ((Partial) Autocorrelation Function) indicate white noise series limits. In that case 95% of the spikes lie within the dashed lines.







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



Time series plot with ACF and PACF
Precipitation − as of year 2000
Precipitation / mm/Month
Year
2000 Jan
2010 Jan
2020 Jan
acf
pacf
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.

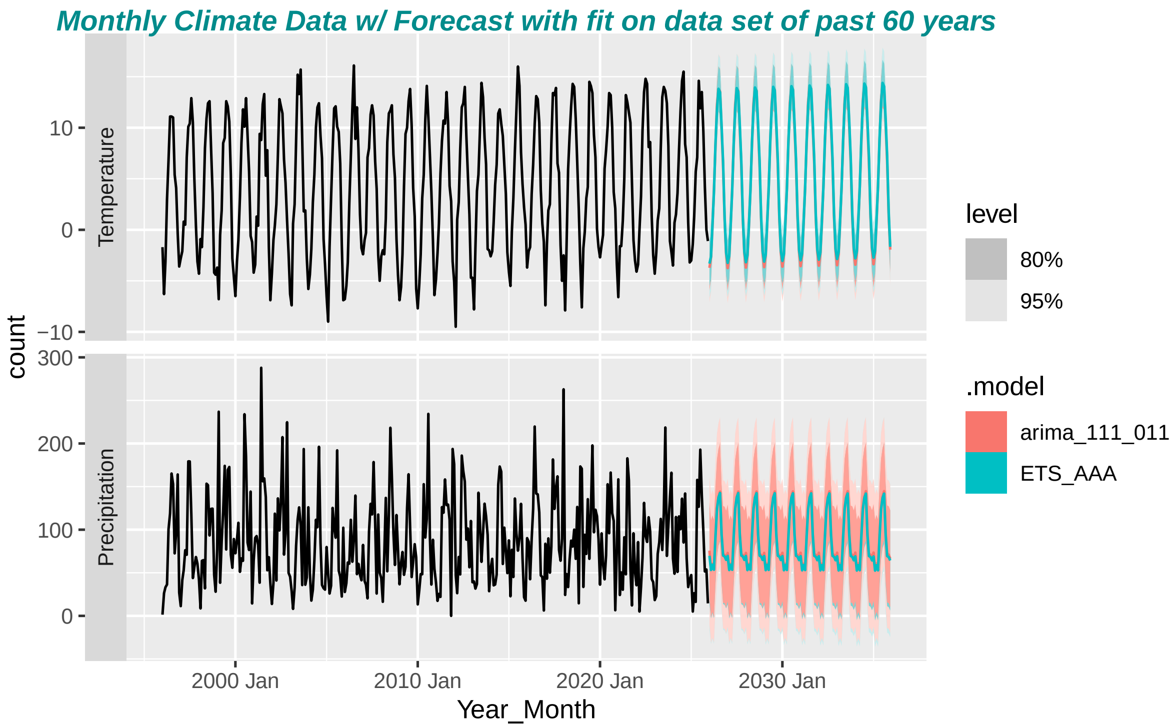
Forecasts produced using **ETS** methods are weighted averages of past observations, with the weights decaying exponentially as the observations get older.

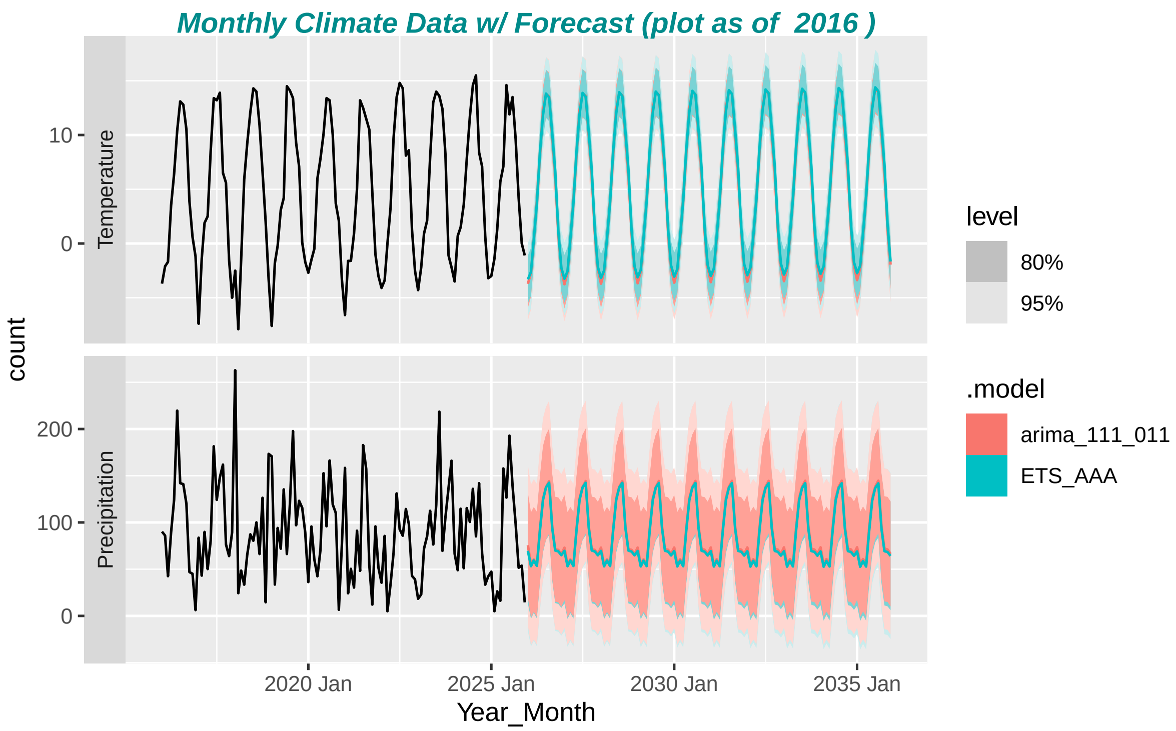
Here a $ETS(A, A|A)$ **model** with additive ("A") *Error term*, *Trend term* and *Seasonal term* was chosen.

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 Davos Temperature   <ETS(A,A,A)> <ARIMA(1,1,1)(0,1,1)[12]>
#> 2 Davos Precipitation <ETS(A,A,A)> <ARIMA(1,1,1)(0,1,1)[12]>
```

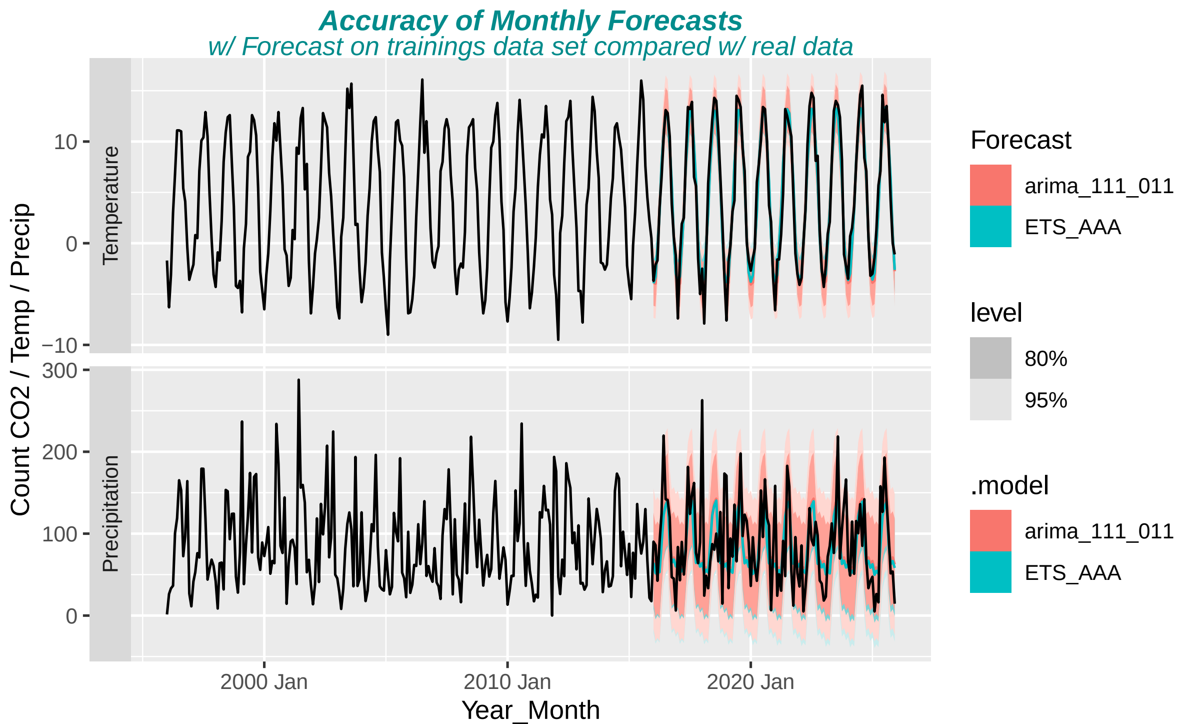




Monthly Climate Data w/ Forecast (plot as of 2016)
count
Temperature
Precipitation
10
0
200
100
0
2020 Jan
2025 Jan
2030 Jan
2035 Jan
Year_Month
level
80%
95%
.model
arima_111_011
ETS_AAA

3.2 Forecast Accuracy Evaluation

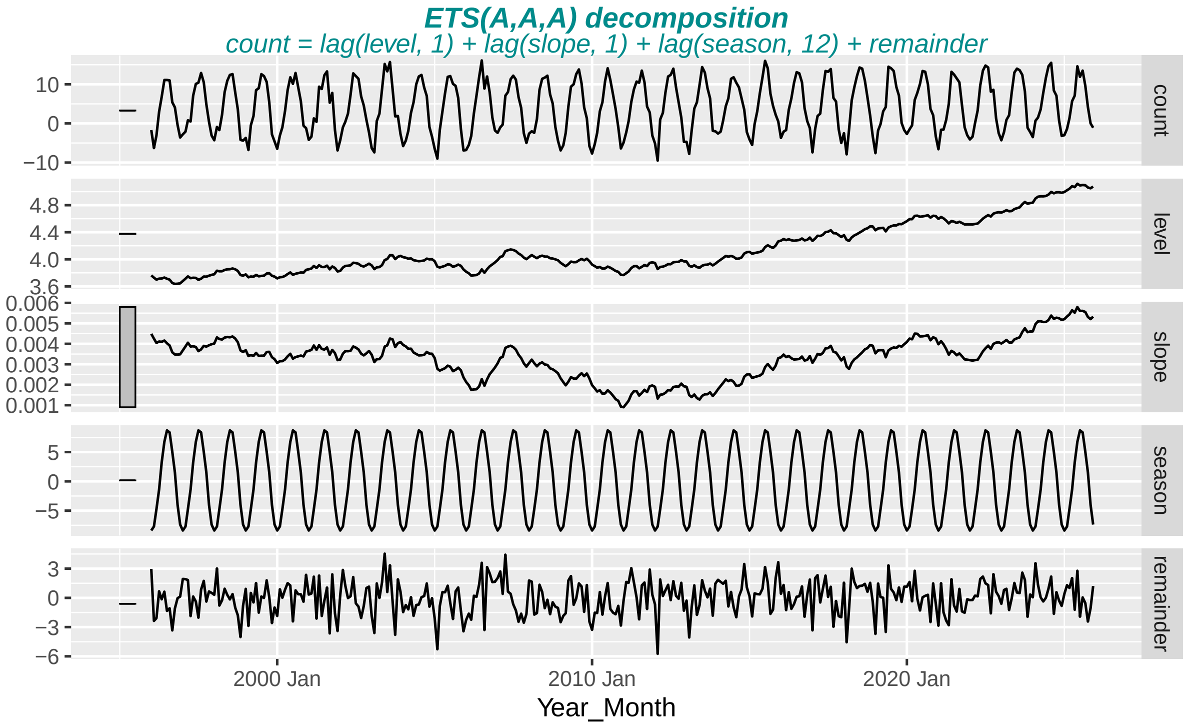
- Forecast Accuracy Evaluation w/ training data “data_train” & test data “data_test”
  - “data” : complete dataset includes the forecasted (future) data range on top of data_train
  - “data_train” = “data” - forecast_range (“data_test”)
    - data used to train the model (~80% of “data)
  - “data_test”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



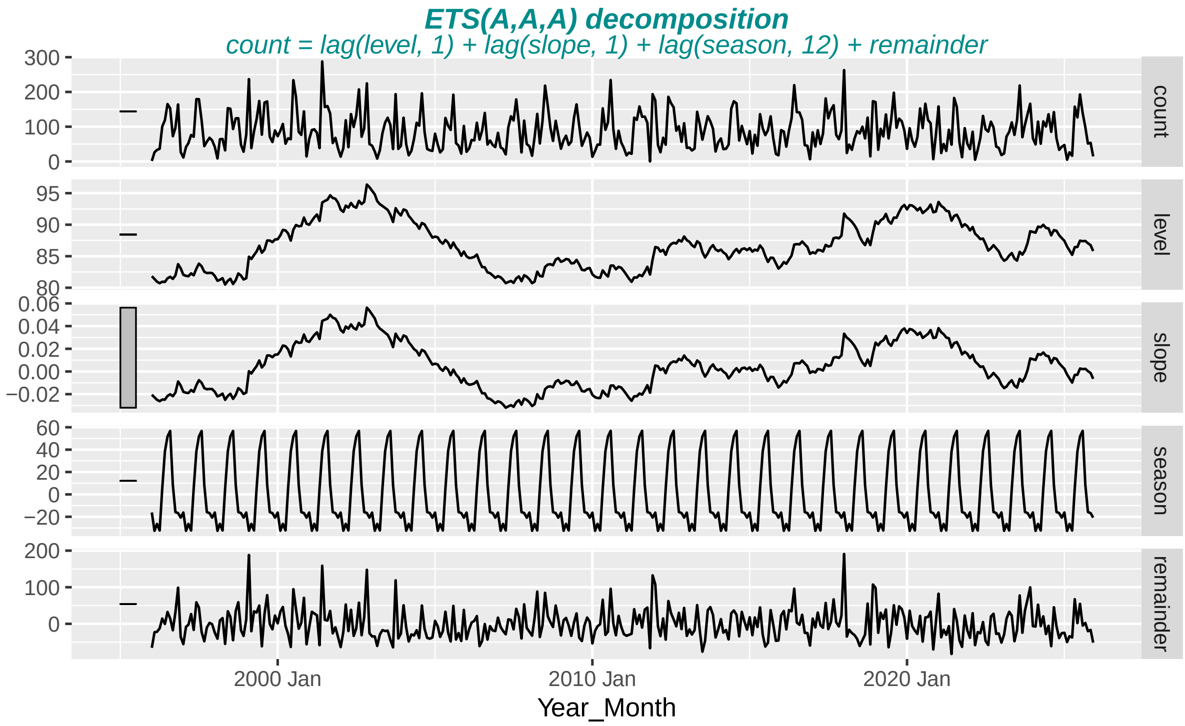
3.2.1 components(fit_ets) - plot of the decomposition of the fitted ETS model

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

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

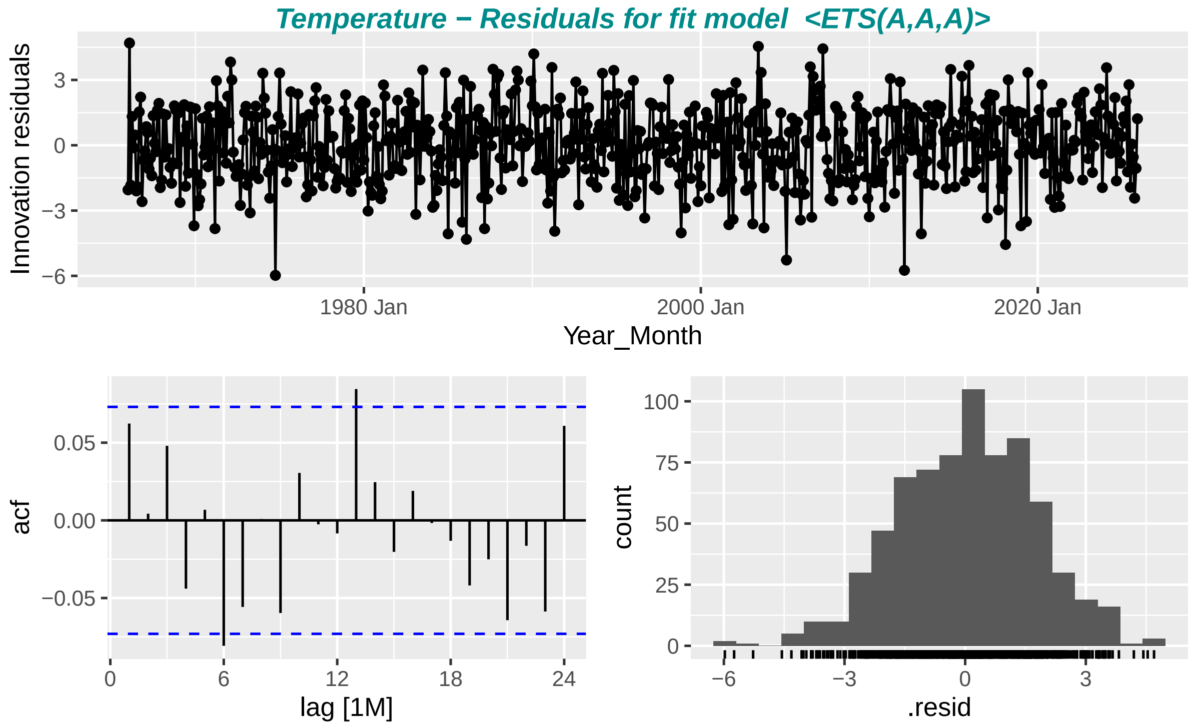


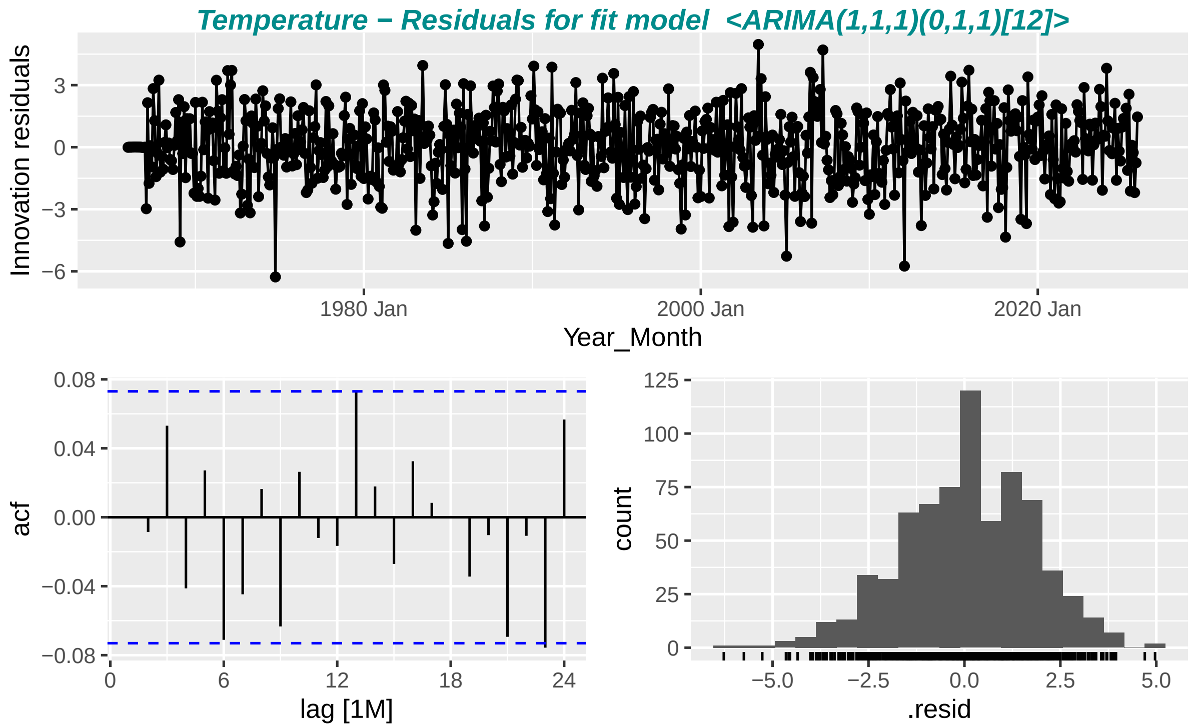

```
#> [1] "Precipitation"
```

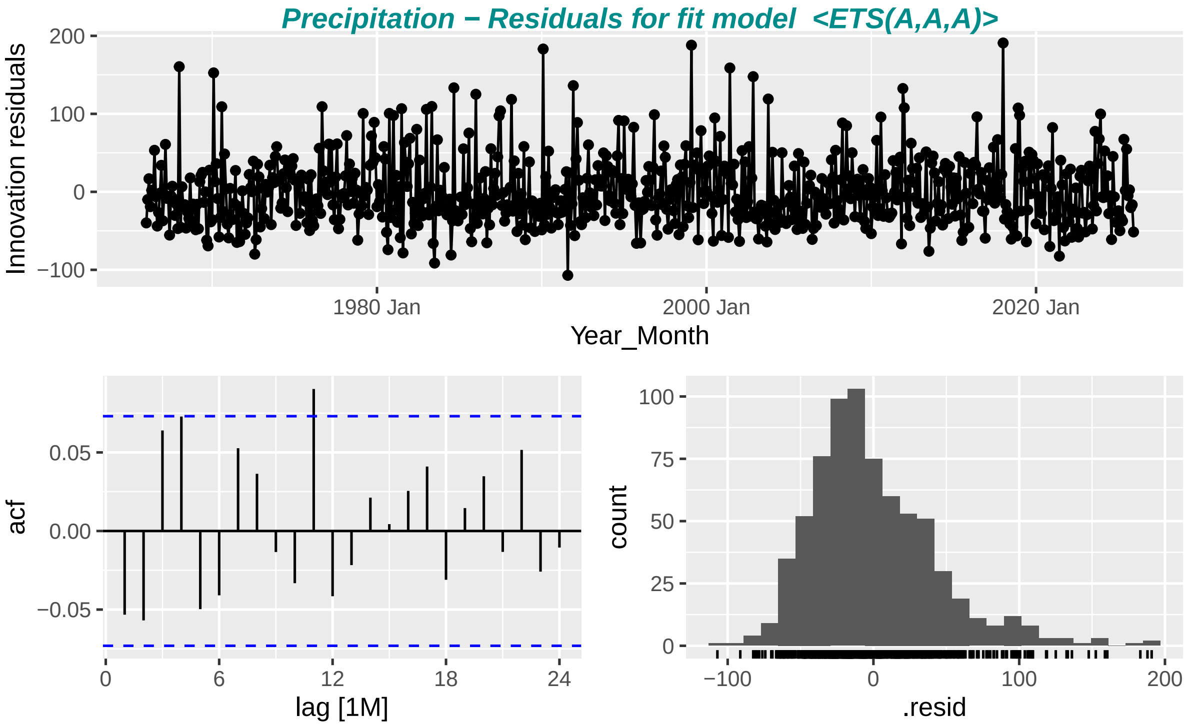


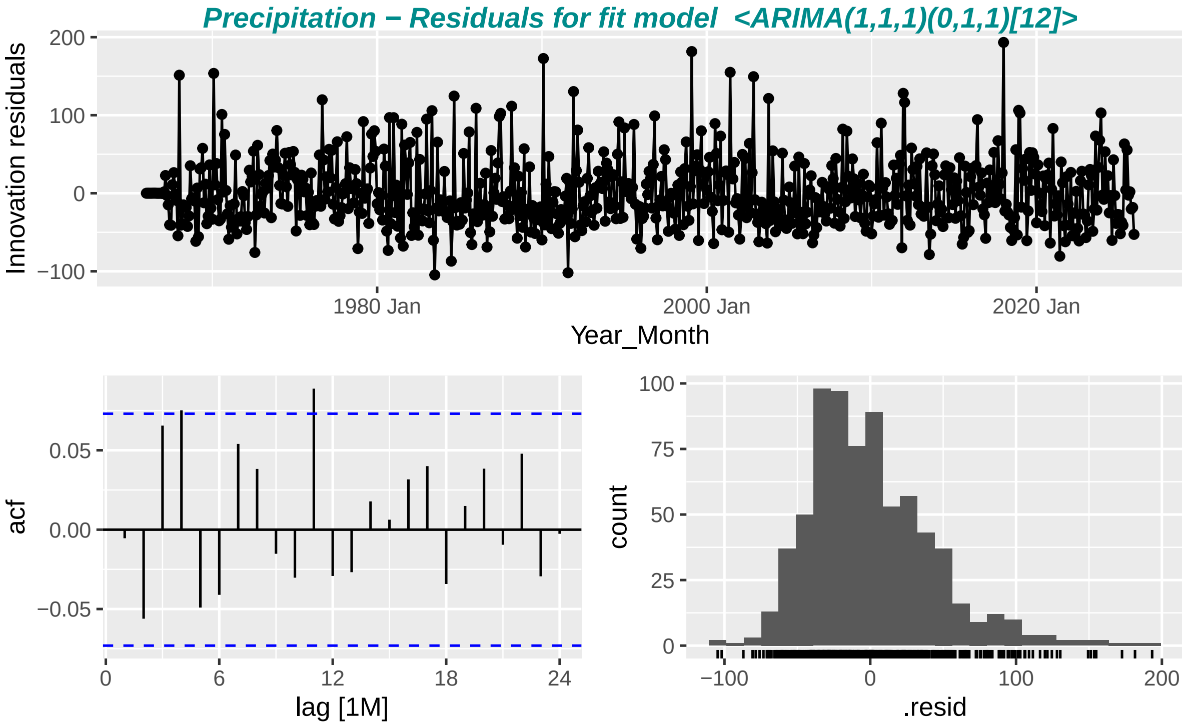
3.2.2 gg_tsresiduals(fit) - plot of innovation residuals, acf and histogram

- 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
200
100
0
−100
1980 Jan
2000 Jan
2020 Jan
Year_Month
acf
0.05
0.00
−0.05
0
6
12
18
24
lag [1M]
count
100
75
50
25
0
−100
0
100
200
.resid


Precipitation − Residuals for fit model <ARIMA(1,1,1)(0,1,1)[12]>
Innovation residuals
200
100
0
−100
1980 Jan
2000 Jan
2020 Jan
Year_Month
acf
0.05
0.00
−0.05
0
6
12
18
24
lag [1M]
count
100
75
50
25
0
−100
0
100
200
.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
1864-1870	2.1	76.2
1871-1900	1.9	78.9
1901-1930	2.2	80.2
1931-1960	2.4	81.4
1961-1990	2.8	83.2
1991-2020	3.9	87.2
2021-2025	5.0	82.1

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
Davos	Temperature	2026	5.11	5.01
Davos	Temperature	2030	5.37	5.20
Davos	Temperature	2035	5.69	5.43
Davos	Temperature	2040	6.00	5.67
Davos	Temperature	2045	6.32	5.91
Davos	Temperature	2050	6.64	6.15
Davos	Precipitation	2026	85.77	87.55
Davos	Precipitation	2030	85.46	87.55
Davos	Precipitation	2035	85.07	87.81
Davos	Precipitation	2040	84.68	88.07
Davos	Precipitation	2045	84.29	88.34
Davos	Precipitation	2050	83.90	88.60

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	5.11	5.01	6.64	6.15	1.53	1.14
Precipitation	2026	2050	85.77	87.55	83.90	88.60	-1.87	1.05

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	-3.31	-3.72	-1.78	-2.66	1.53	1.06
Temperature	Feb	2026	2050	-2.62	-2.70	-1.08	-1.56	1.53	1.14
Temperature	Mar	2026	2050	0.34	0.27	1.88	1.41	1.53	1.14
Temperature	Apr	2026	2050	3.72	3.89	5.25	5.04	1.53	1.14
Temperature	May	2026	2050	8.33	8.07	9.87	9.22	1.53	1.14

Measure	Month	Year.x	Year.y	Mean.x_ETS	Mean.x_ARIMA	Mean.y_ETS	Mean.y_ARIMA	Delta_ETS	Delta_ARIMA
Temperature	Jun	2026	2050	11.85	12.27	13.39	13.41	1.53	1.14
Temperature	Jul	2026	2050	13.82	13.78	15.35	14.92	1.53	1.14
Temperature	Aug	2026	2050	13.47	13.56	15.00	14.70	1.53	1.14
Temperature	Sep	2026	2050	10.16	9.88	11.69	11.02	1.53	1.14
Temperature	Oct	2026	2050	6.66	6.33	8.19	7.47	1.53	1.14
Temperature	Nov	2026	2050	1.12	0.90	2.66	2.04	1.53	1.14
Temperature	Dec	2026	2050	-2.23	-2.37	-0.70	-1.23	1.53	1.14
Precipitation	Jan	2026	2050	69.67	75.65	67.80	74.25	-1.87	-1.40
Precipitation	Feb	2026	2050	53.19	54.70	51.32	56.10	-1.87	1.40
Precipitation	Mar	2026	2050	59.38	60.38	57.51	61.63	-1.87	1.26
Precipitation	Apr	2026	2050	53.48	55.24	51.62	56.50	-1.87	1.26
Precipitation	May	2026	2050	91.10	93.14	89.24	94.40	-1.87	1.26
Precipitation	Jun	2026	2050	124.22	125.76	122.36	127.02	-1.87	1.26
Precipitation	Jul	2026	2050	137.51	137.75	135.64	139.01	-1.87	1.26
Precipitation	Aug	2026	2050	142.54	144.25	140.67	145.52	-1.87	1.26
Precipitation	Sep	2026	2050	94.12	95.87	92.26	97.13	-1.87	1.26
Precipitation	Oct	2026	2050	70.00	71.34	68.13	72.61	-1.87	1.26
Precipitation	Nov	2026	2050	69.04	70.62	67.17	71.88	-1.87	1.26
Precipitation	Dec	2026	2050	64.95	65.87	63.09	67.13	-1.87	1.26

5 Backup

5.1 Davos - 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
Davos	Temperature	1864	NA	1.0	9.0	2.5	1.2
Davos	Temperature	1865	-7.0	1.6	10.0	4.1	2.2
Davos	Temperature	1866	-4.2	0.9	9.5	3.2	2.5
Davos	Temperature	1867	-3.6	2.3	10.0	2.5	2.4
Davos	Temperature	1868	-6.7	1.6	10.4	3.0	2.7
Davos	Temperature	1869	-3.2	1.8	9.6	2.4	2.3
Davos	Temperature	1870	-6.2	1.0	9.9	2.3	1.5
Davos	Temperature	1871	-7.5	1.8	9.0	2.5	1.2
Davos	Temperature	1872	-7.1	1.7	9.6	4.3	2.8
Davos	Temperature	1873	-4.7	1.3	11.1	3.4	2.4
Davos	Temperature	2016	-1.8	2.7	12.1	5.0	4.4
Davos	Temperature	2017	-3.3	4.3	13.5	3.5	4.2
Davos	Temperature	2018	-5.1	4.5	13.5	6.5	5.0
Davos	Temperature	2019	-4.2	2.4	14.0	5.5	4.5
Davos	Temperature	2020	-2.0	4.4	12.2	5.3	4.9
Davos	Temperature	2021	-3.8	1.4	12.4	4.7	3.7
Davos	Temperature	2022	-3.5	4.3	14.2	6.0	5.3
Davos	Temperature	2023	-3.0	3.6	13.5	6.5	5.2
Davos	Temperature	2024	-1.7	4.3	13.9	5.4	5.4
Davos	Temperature	2025	-2.5	4.7	13.3	4.6	5.2

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

City	Measure	Year	Winter_avg	Spring_avg	Summer_avg	Fall_avg	Year_avg
Davos	Precipitation	1864	NA	NA	NA	NA	NA
Davos	Precipitation	1865	NA	NA	NA	NA	NA
Davos	Precipitation	1866	NA	NA	NA	NA	NA
Davos	Precipitation	1867	102.5	91.9	64.4	71.6	85.1
Davos	Precipitation	1868	64.0	104.2	123.1	76.8	87.4
Davos	Precipitation	1869	53.5	61.5	113.6	75.9	72.1
Davos	Precipitation	1870	27.7	38.8	97.1	71.1	60.1
Davos	Precipitation	1871	44.1	62.1	138.9	29.8	NA
Davos	Precipitation	1872	NA	NA	NA	NA	NA
Davos	Precipitation	1873	NA	NA	NA	93.4	NA
Davos	Precipitation	2016	64.6	85.3	167.6	70.7	96.1
Davos	Precipitation	2017	44.3	73.5	151.3	100.8	99.4
Davos	Precipitation	2018	125.5	49.1	89.3	69.1	90.2
Davos	Precipitation	2019	125.9	100.5	127.7	112.0	109.5
Davos	Precipitation	2020	73.7	57.8	138.3	78.6	86.0
Davos	Precipitation	2021	86.1	57.3	129.4	54.1	79.7
Davos	Precipitation	2022	57.6	35.4	103.2	85.1	69.3
Davos	Precipitation	2023	26.8	89.9	137.9	104.1	100.3
Davos	Precipitation	2024	93.8	93.7	107.2	80.8	83.6
Davos	Precipitation	2025	31.5	66.8	152.9	67.9	77.5

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

City	Month	Temperature	Precipitation
Davos	Jan	-6.0	65.4
Davos	Feb	-4.9	57.4
Davos	Mar	-2.0	56.5
Davos	Apr	1.6	56.0
Davos	May	6.2	81.7
Davos	Jun	9.5	119.0
Davos	Jul	11.4	134.5
Davos	Aug	10.9	134.4
Davos	Sep	8.0	89.1
Davos	Oct	3.9	64.9
Davos	Nov	-1.1	61.9
Davos	Dec	-4.8	63.6

5.2 Davos - 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 Davos Temperature   1864 Jan 1864-1870   -10.3
#> 2 Davos Temperature   1864 Feb 1864-1870    -6.3
#> 3 Davos Temperature   1864 Mrz 1864-1870    -2.2
#> 4 Davos Temperature   2025 Okt 2021-2025     4.2
#> 5 Davos Temperature   2025 Nov 2021-2025     0
#> 6 Davos Temperature   2025 Dez 2021-2025    -1.1
#> # 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 Davos Precipitation   1867 Jan 1864-1870   138.
#> 2 Davos Precipitation   1867 Feb 1864-1870    60.7
#> 3 Davos Precipitation   1867 Mrz 1864-1870    36.1
#> 4 Davos Precipitation   2025 Okt 2021-2025    51.5
#> 5 Davos Precipitation   2025 Nov 2021-2025    53.8
#> 6 Davos Precipitation   2025 Dez 2021-2025    14.5
```

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