Climate Data Visualization -

Atmospheric CO_2 Concentration / Temperature / Precipitation

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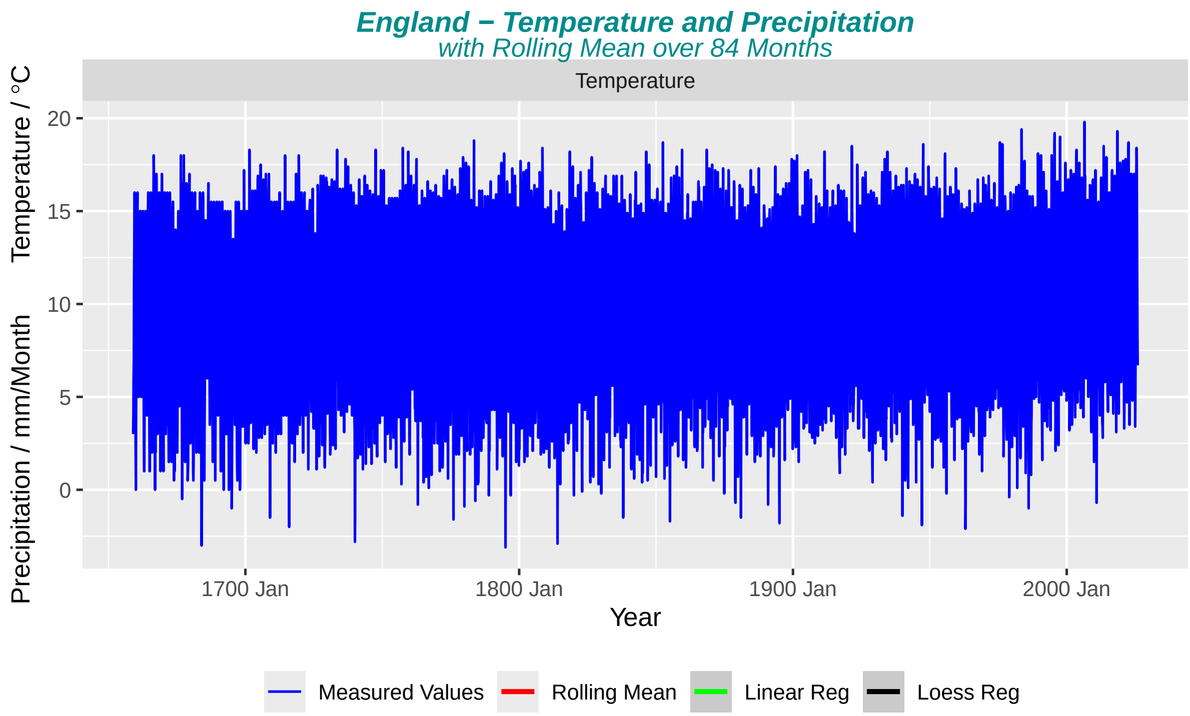
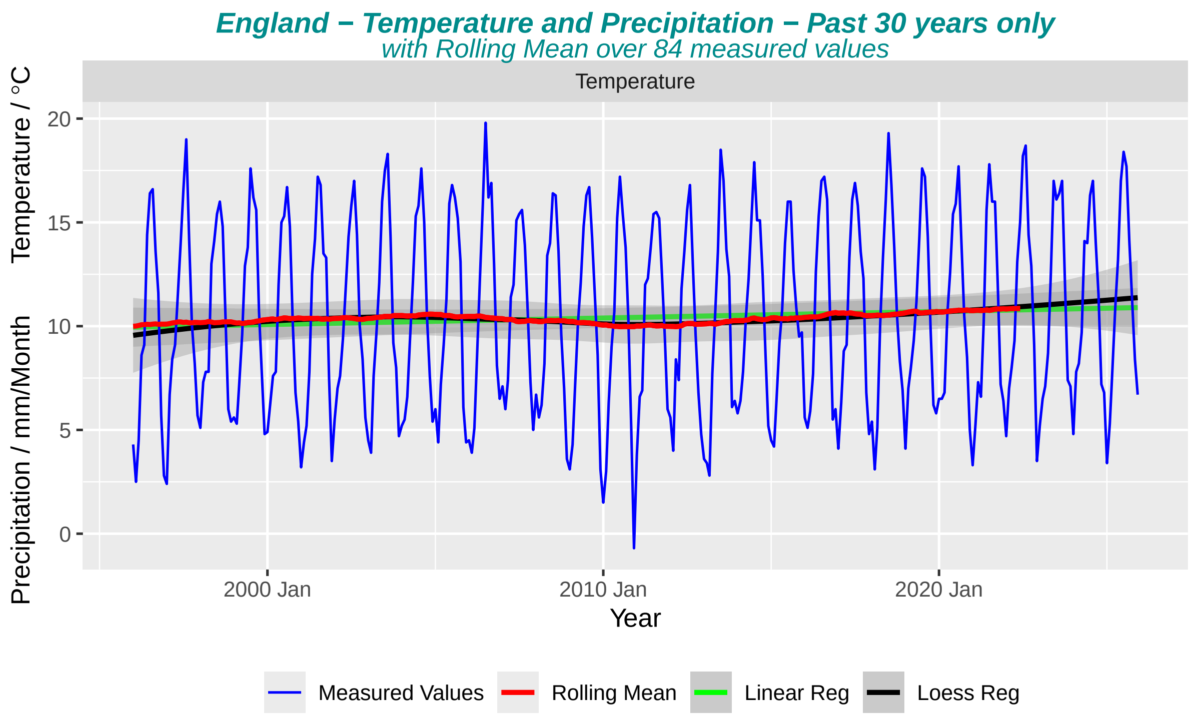
Contents

1 England - Visualization of Temperature Data 1659 - 2025

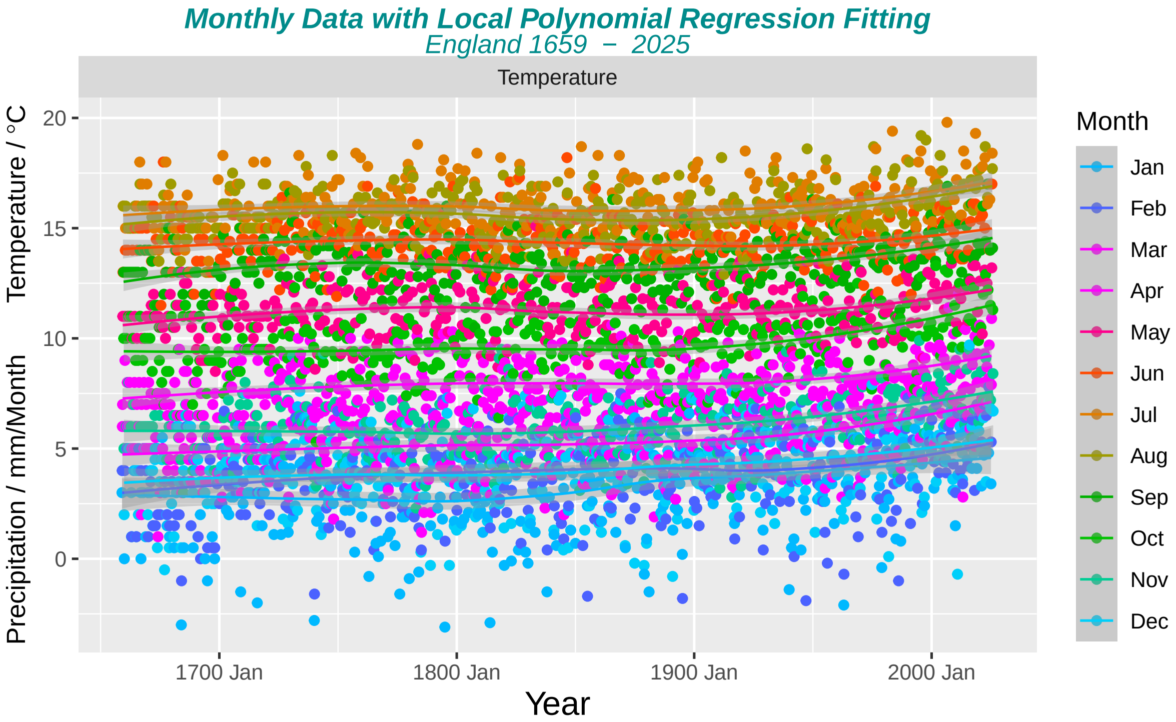
1.1 Monthly Time Plots with Rolling Mean



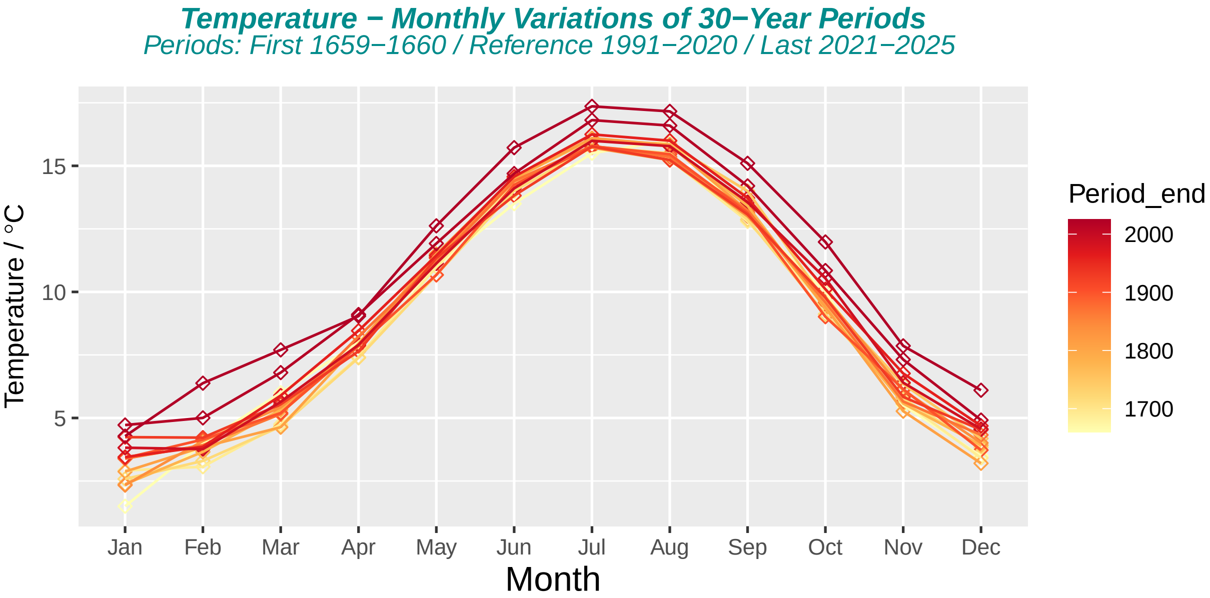


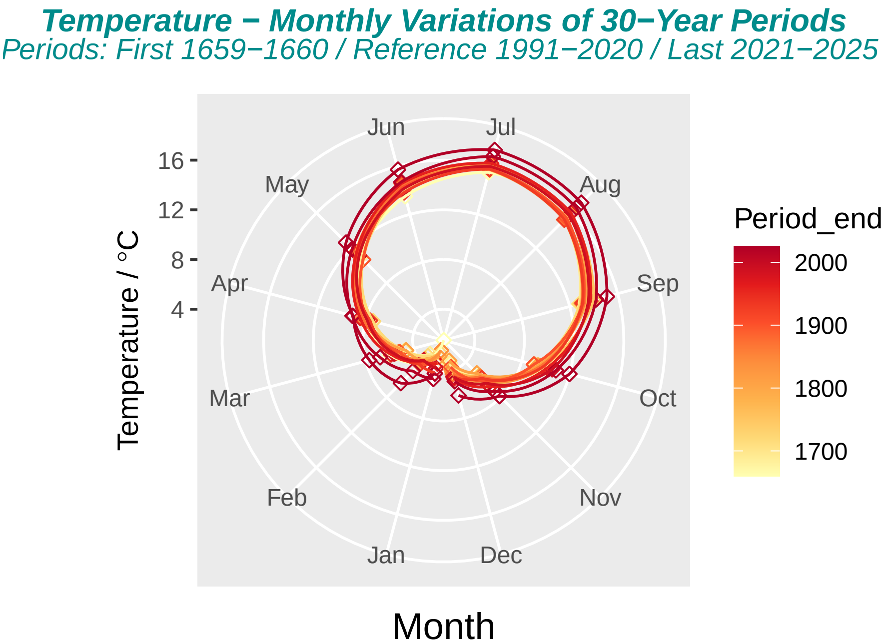
1.2 Annual seasonal plots with monthly breakdown

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


Monthly Data with Local Polynomial Regression Fitting
England 1659 – 2025
Temperature
Precipitation / mm/Month Temperature / °C
20
15
10
5
0
1700 Jan
1800 Jan
1900 Jan
2000 Jan
Year
Month
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

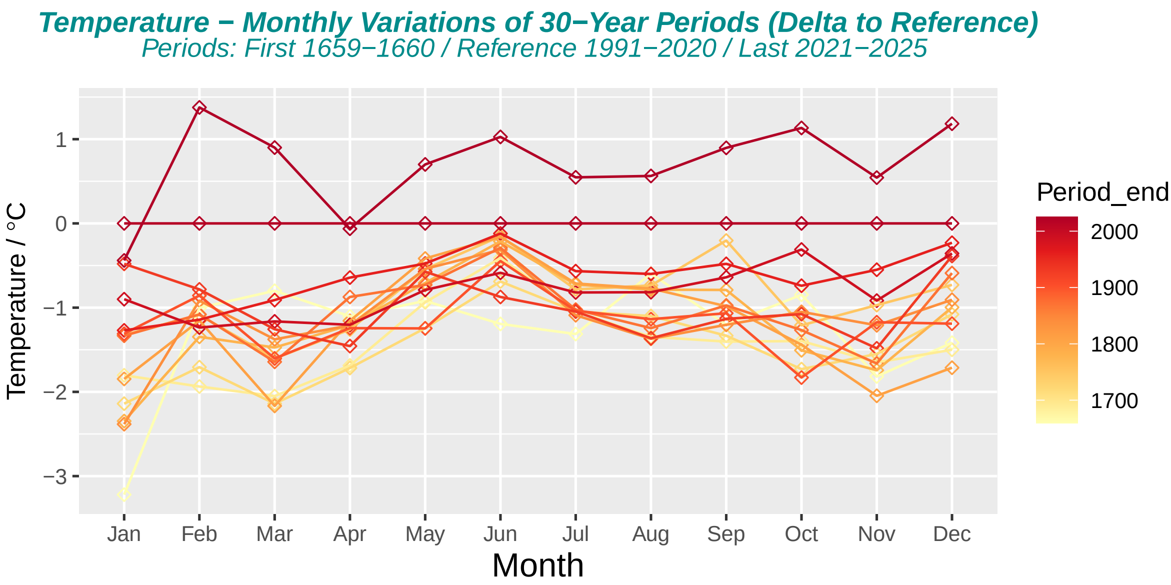
1.2.1 30-year period plots with monthly breakdown - Cartesian and Polar Coordinates

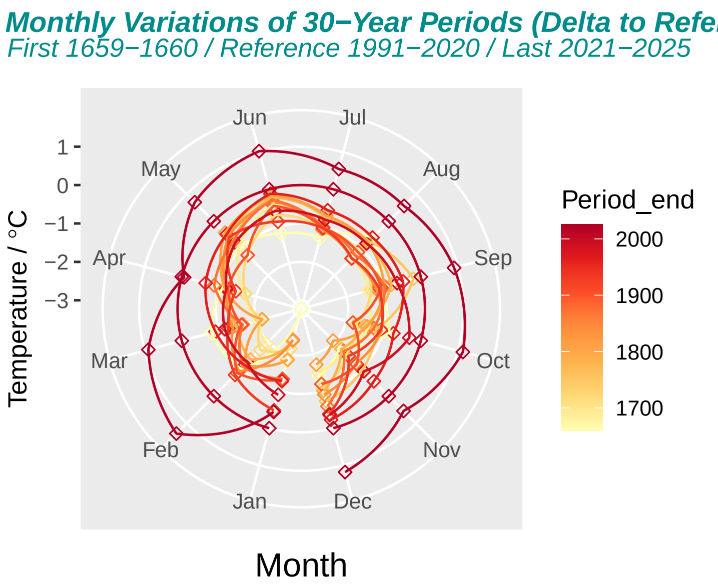


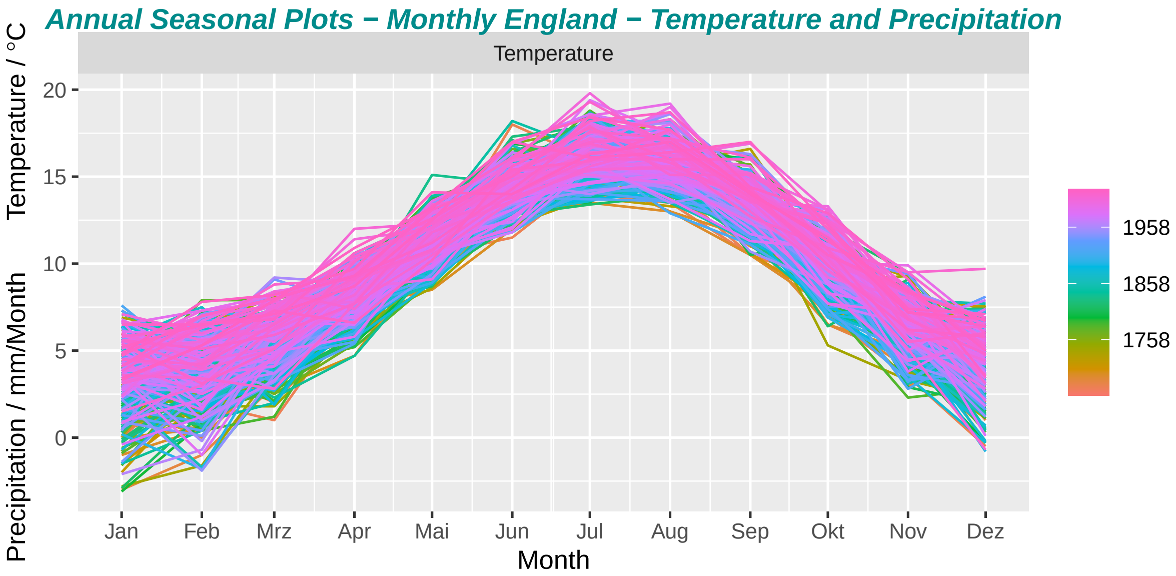


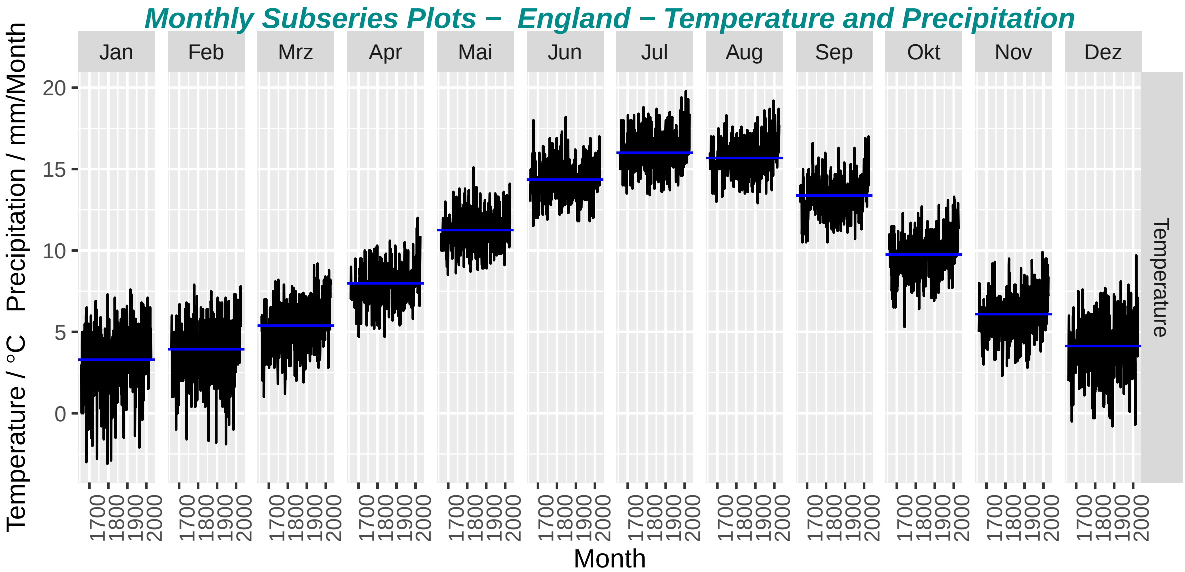

```
#>
#> _
```

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





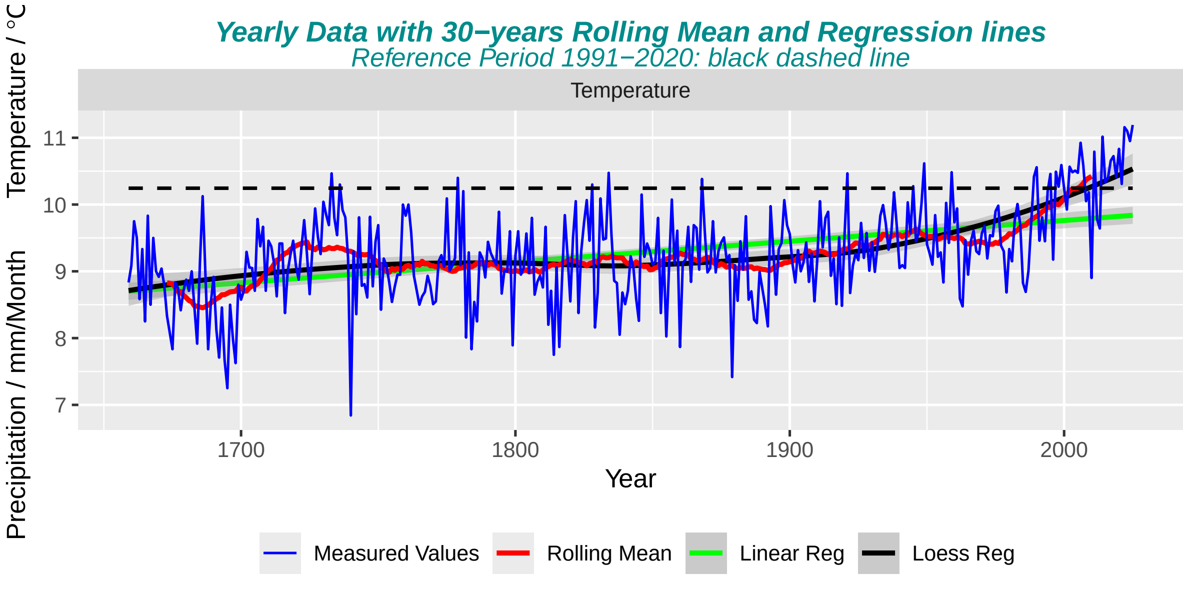




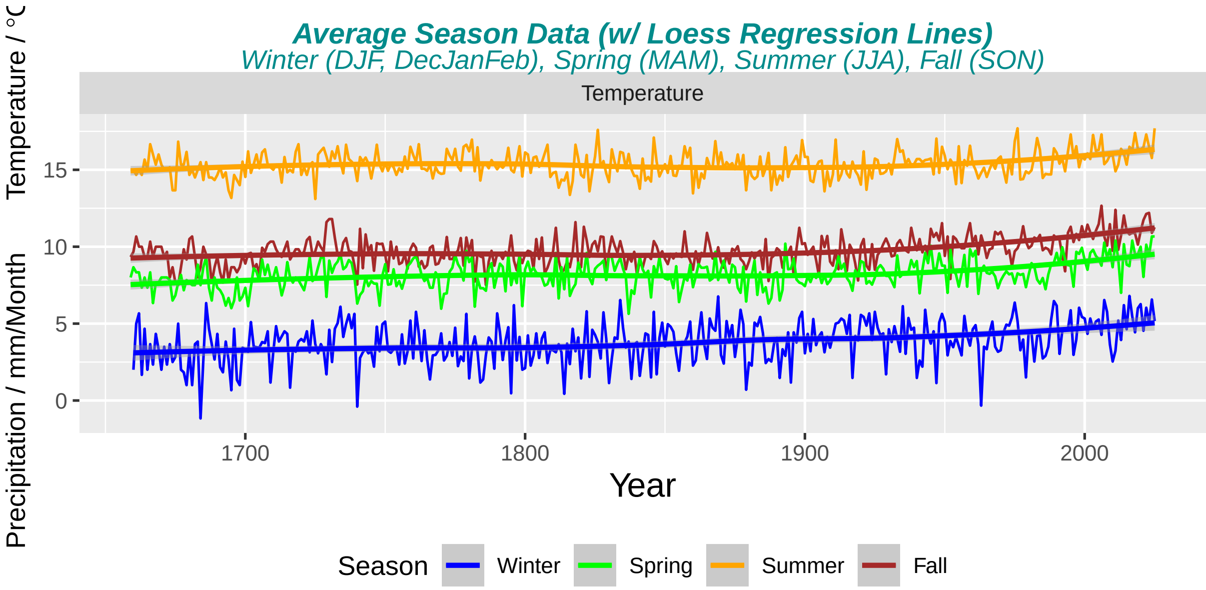
The blue horizontal lines within the seasonal subseries plot indicate the means for each month.

1.3 Annual England - Temperature and Precipitation

1.3.1 Annual Time Plot of Temperature



1.3.2 Annual Seasonal Plot of Temperature



2 Trend and Seasonal Analysis

2.1 Time Series Decomposition - Trend and Seasonal Components

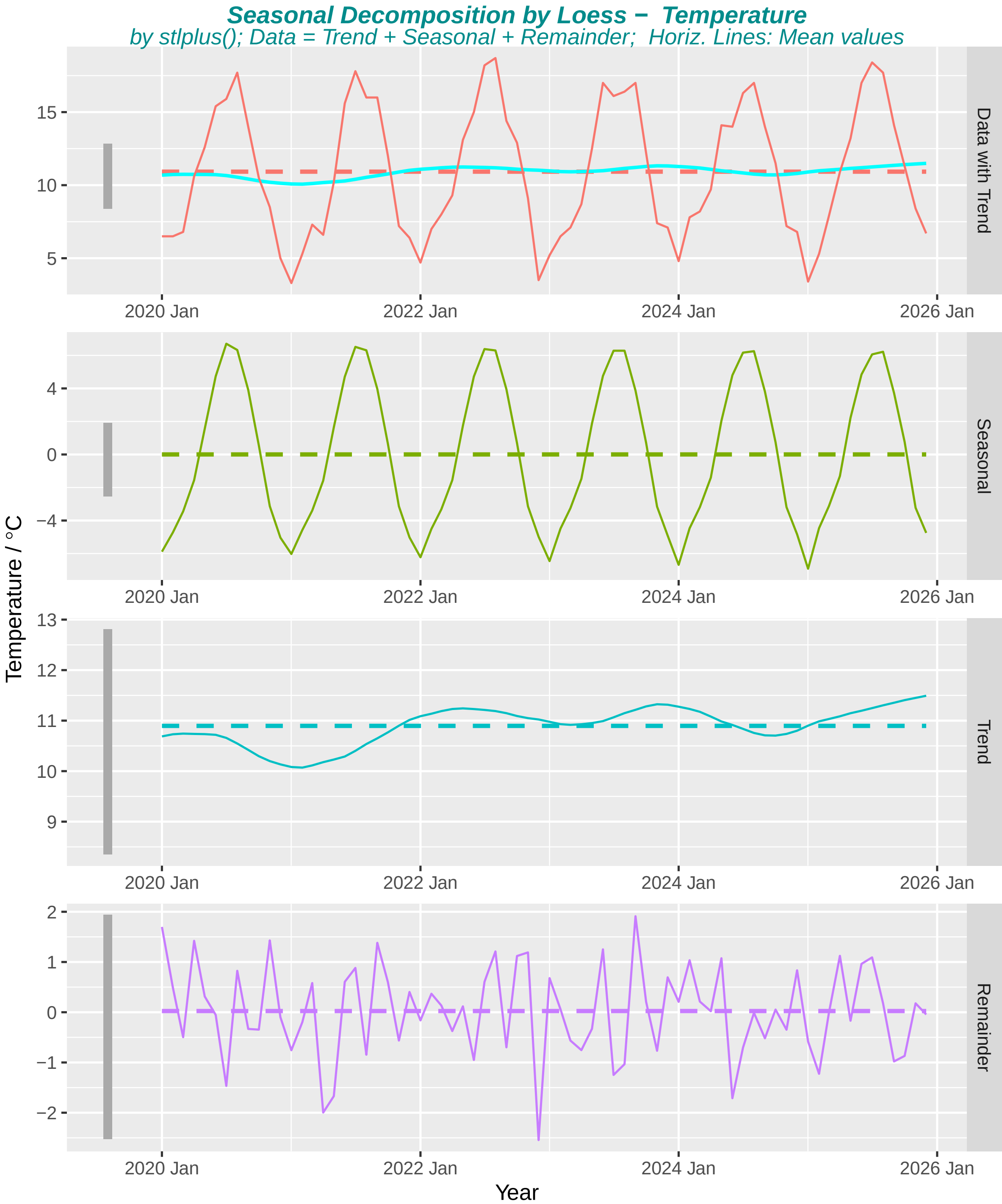
An *additive model* would be used when the variations around the trend do not vary with the level of the time series whereas a *multiplicative model* would be appropriate if the trend is proportional to the level of the time series.

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

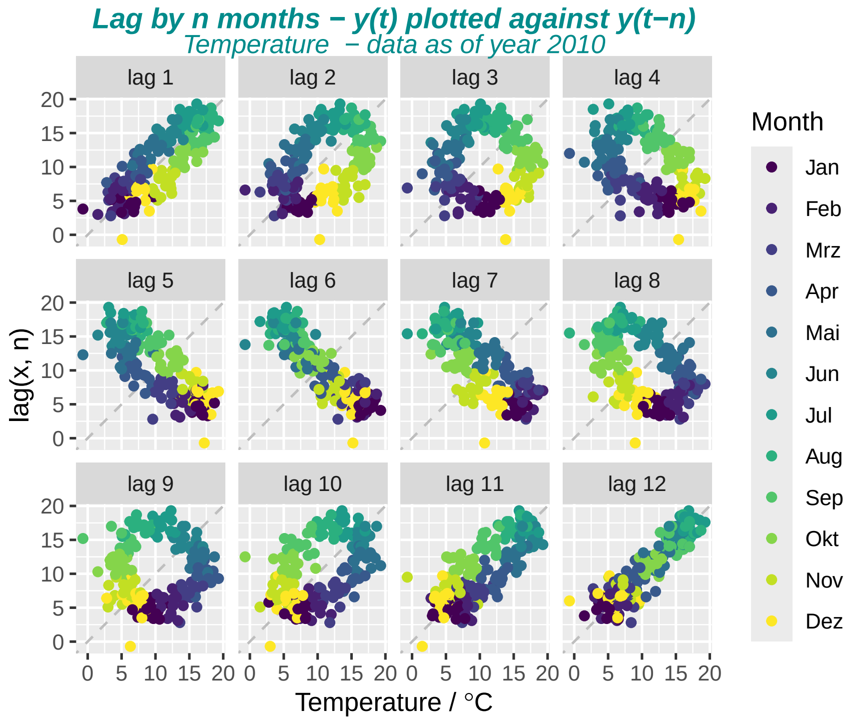
For *Seasonal decomposition of time series by Loess (stlplus)* uses in general an additive error model, it only provides facilities for additive decompositions. It is possible to obtain a multiplicative decomposition by first taking logs of the data.



2.2 Periodicities - Season Frequency

2.2.1 Lag Plot - Differences

Lagged scatterplots, where the horizontal axis shows lagged ($k = 1, .., 12$) 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
0
5
10
15
20
Month
Jan
Feb
Mrz
Apr
Mai
Jun
Jul
Aug
Sep
Okt
Nov
Dez

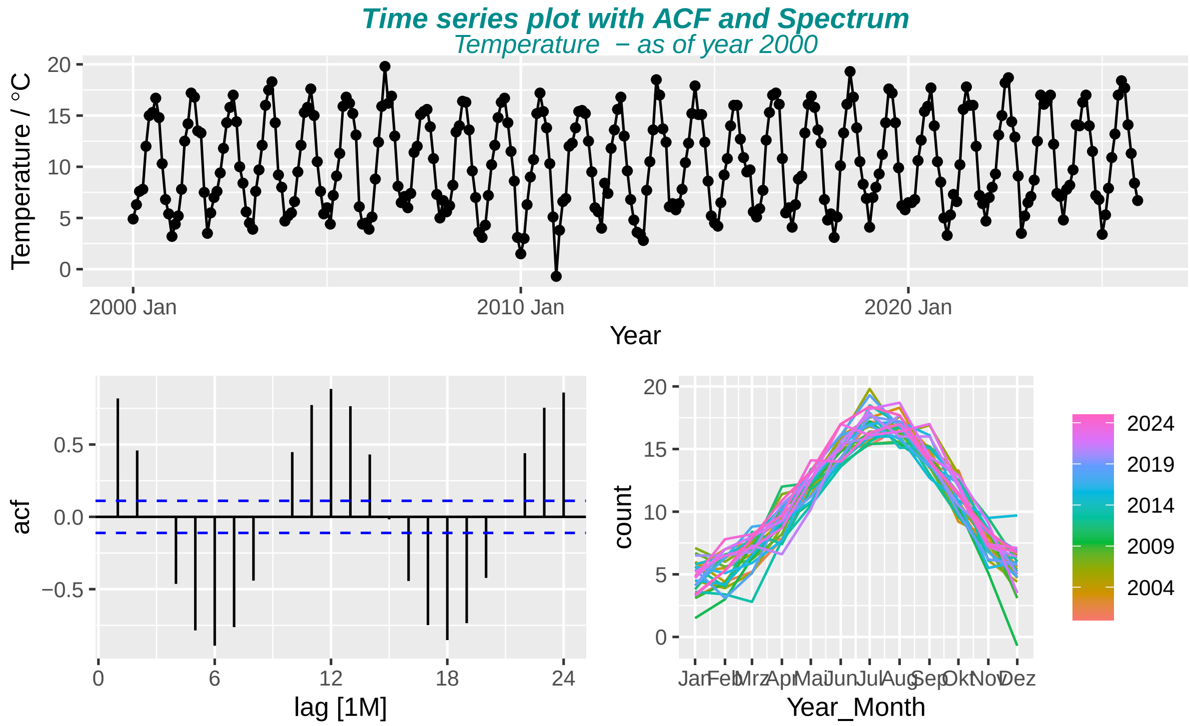
2.2.2 Periodogram - Spectral Density Estimation of a Time Series

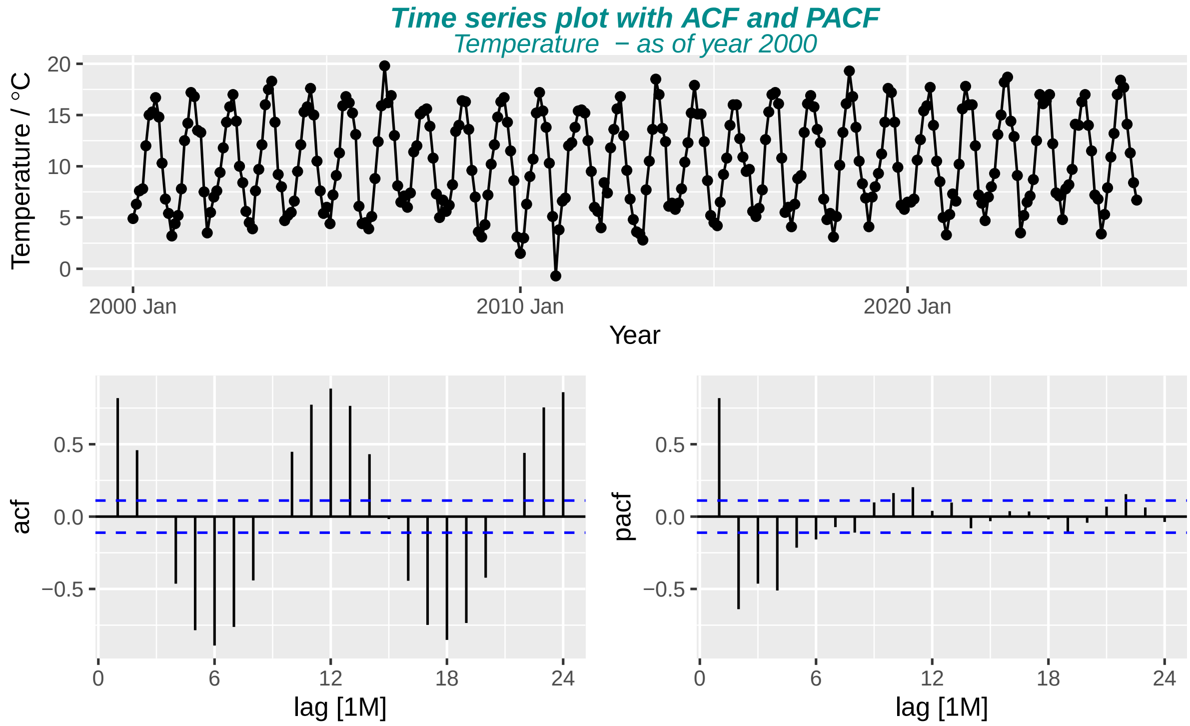
The spectral density characterizes the frequency content of the signal. One purpose of estimating the spectral density is to detect any periodicities in the data, by observing peaks at the frequencies corresponding to these periodicities.

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.





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.

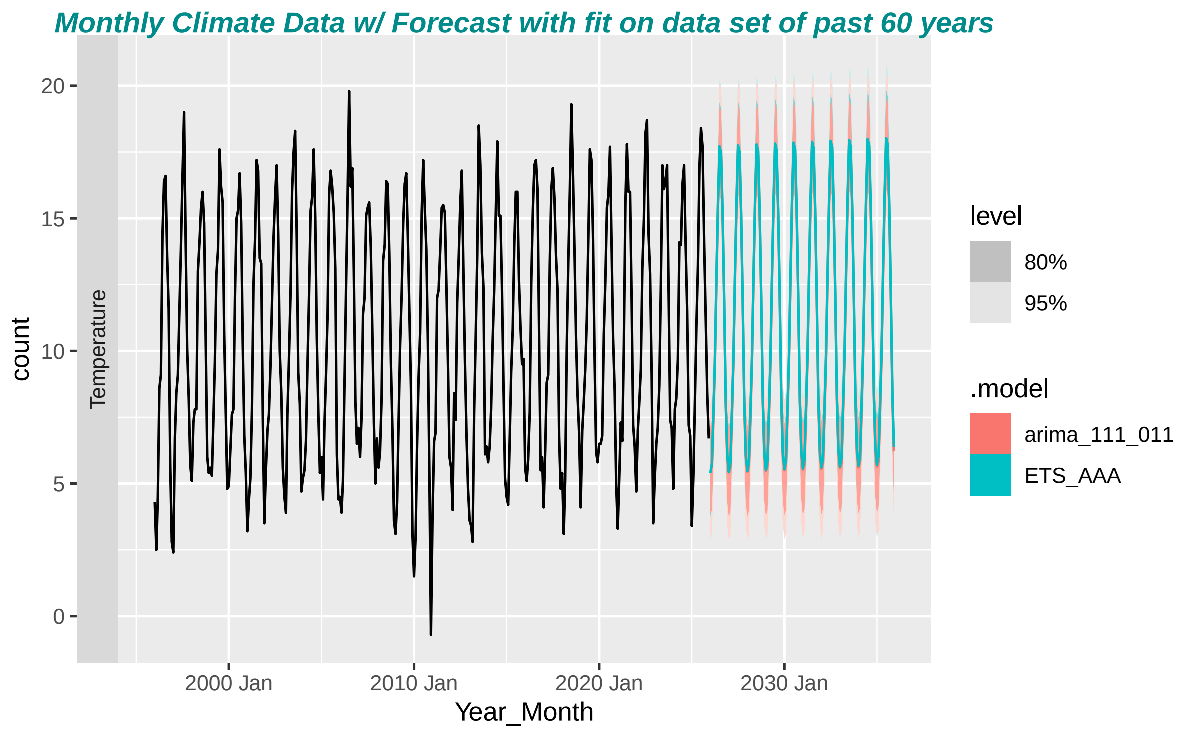
Forecasts produced using **ETS** methods are weighted averages of past observations, with the weights decaying exponentially as the observations get older.

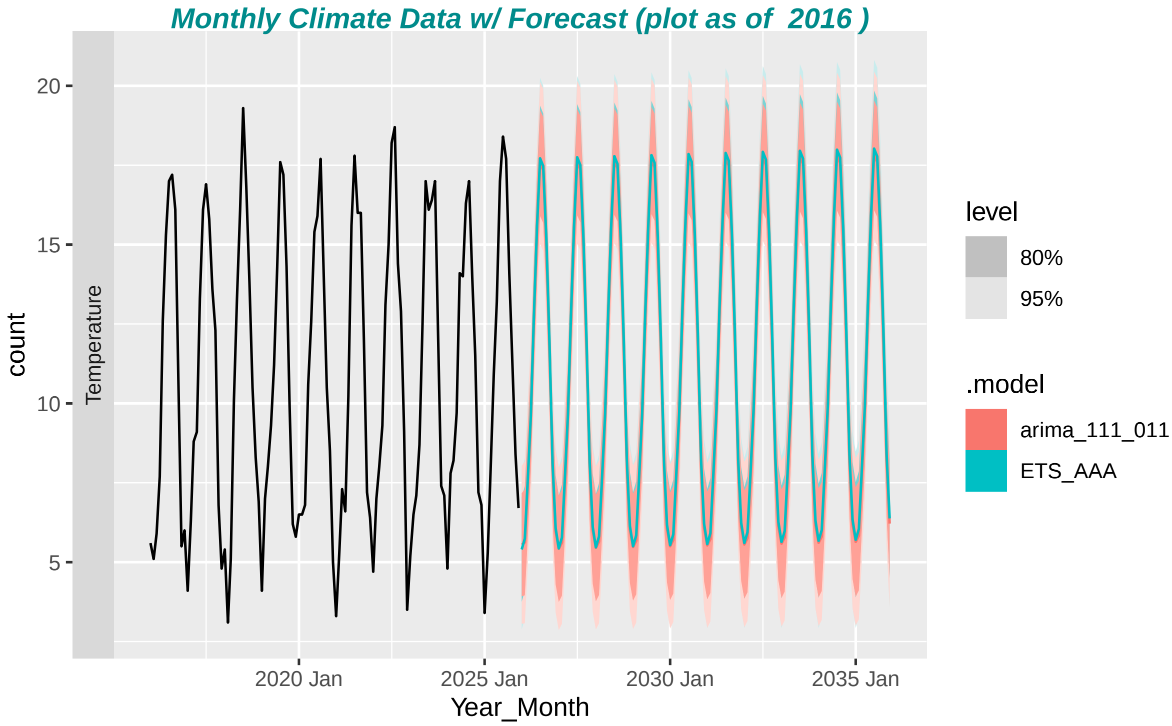
Here a $ETS(A, A|A)$ **model** with additive ("A") *Error term*, *Trend term* and *Seasonal term* was chosen.

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)

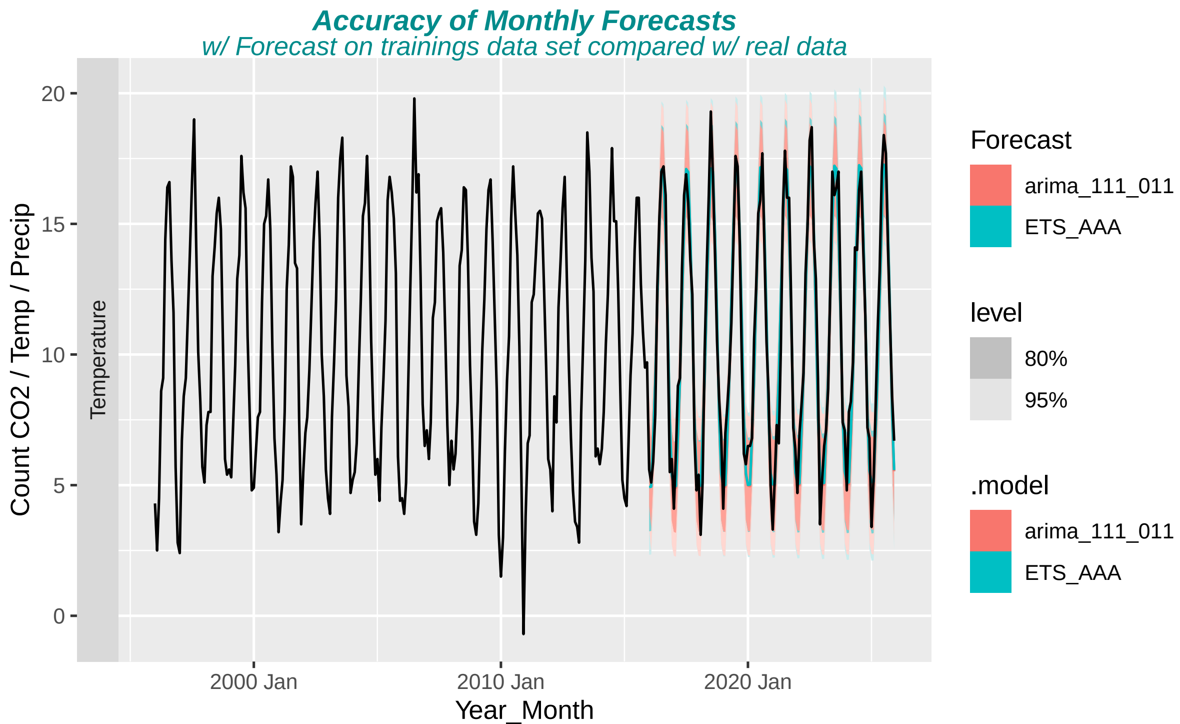
```
#> # A mable: 1 x 4
#> # Key:     City, Measure [1]
#>   City    Measure           ETS_AAA              arima_111_011
#>   <chr>   <fct>             <model>                    <model>
#> 1 England Temperature <ETS(A,A,A)> <ARIMA(1,1,1)(0,1,1)[12]>
```




Monthly Climate Data w/ Forecast (plot as of 2016)
count
Temperature
20
15
10
5
2020 Jan
2025 Jan
2030 Jan
2035 Jan
Year_Month
level
80%
95%
.model
arima_111_011
ETS_AAA

3.2 Forecast Accuracy Evaluation

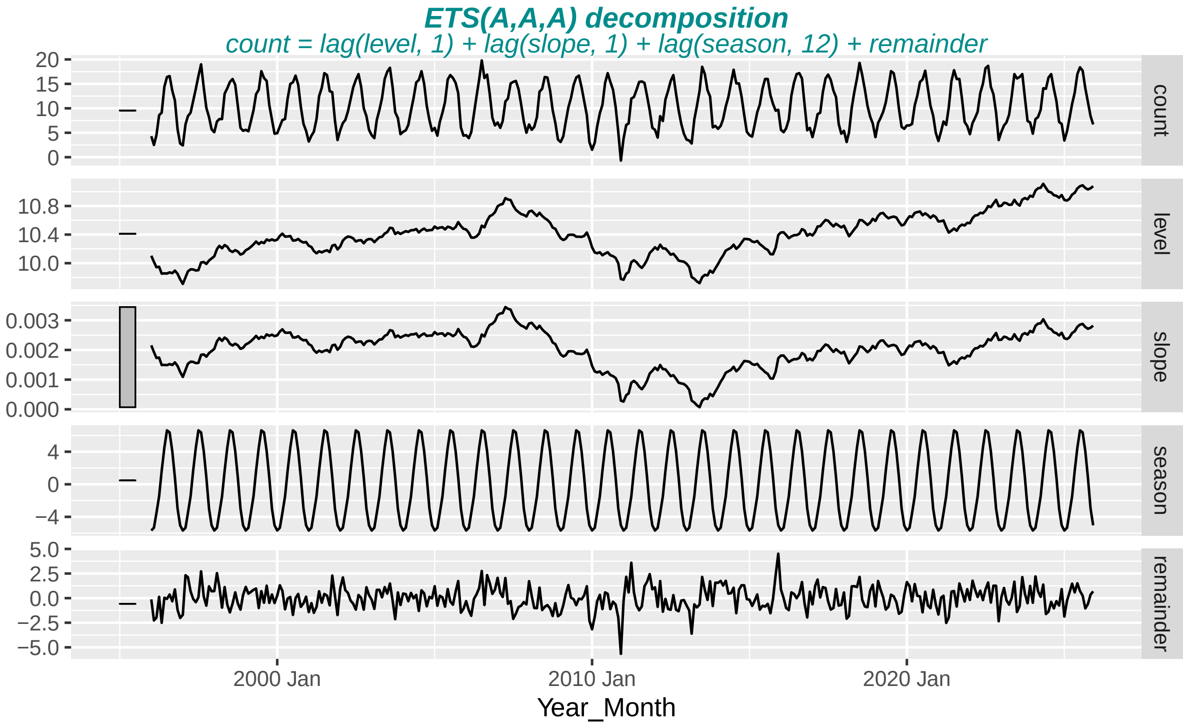
- Forecast Accuracy Evaluation w/ training data "data_train" & test data "data_test"
  - "data" : complete dataset includes the forecasted (future) data range on top of data_train
  - "data_train" = "data" - forecast_range ("data_test")
    - data used to train the model (~80% of "data)
  - "data_test"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

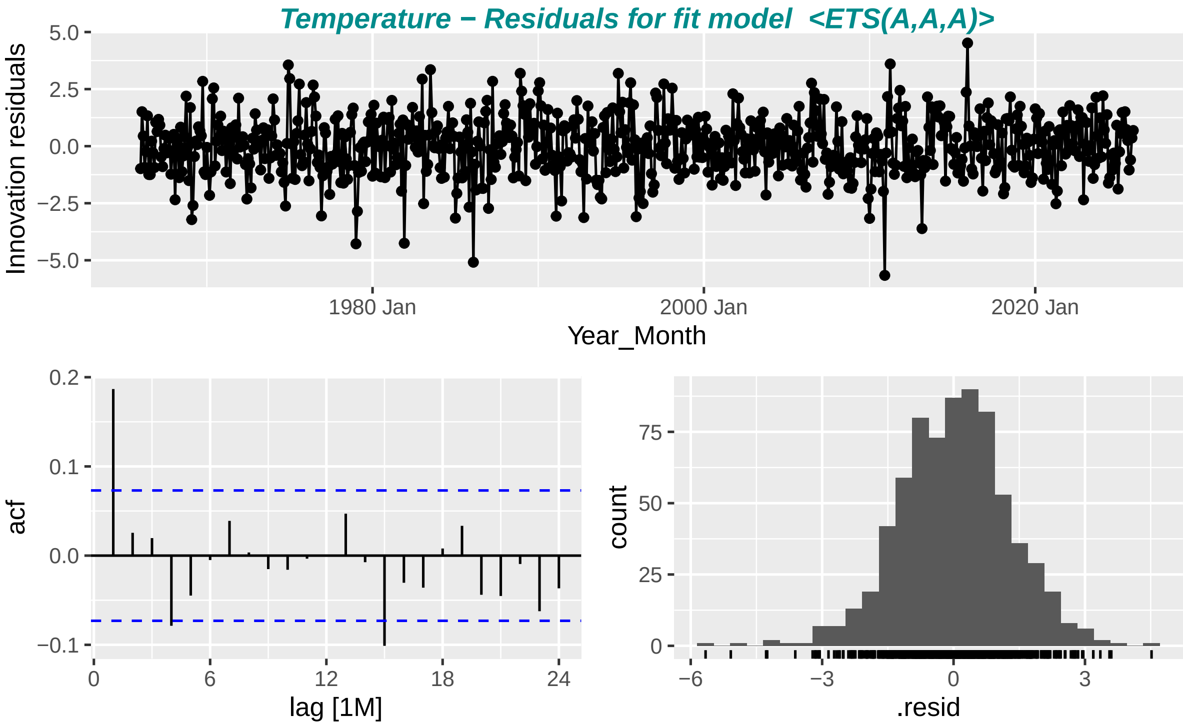
- Note: compare Time series decomposition, for ETS model is valid:
  - count = lag(level, 1) + lag(slope, 1) + lag(season, 12) + remainder

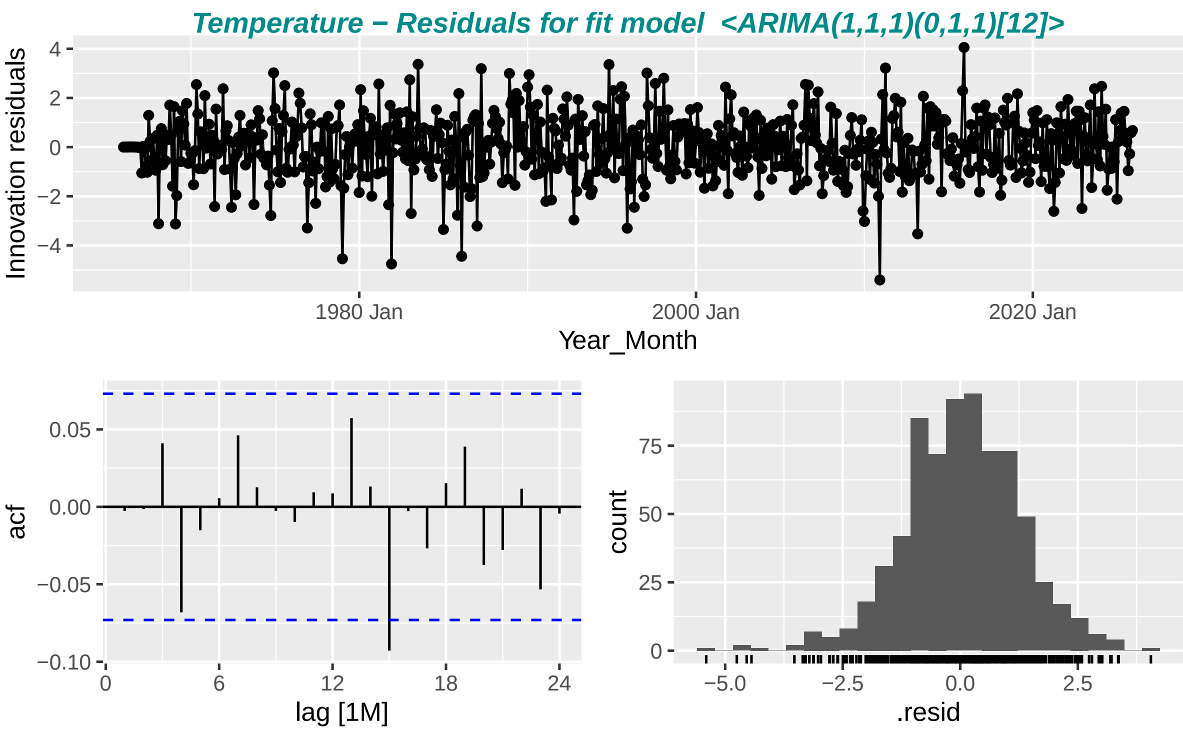
```
#> [1] "Temperature"
```



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
1659-1660	9.0
1661-1690	8.8
1691-1720	8.8
1721-1750	9.4
1751-1780	9.1
1781-1810	9.0
1811-1840	9.1
1841-1870	9.2
1871-1900	9.1
1901-1930	9.3
1931-1960	9.6
1961-1990	9.4
1991-2020	10.2
2021-2025	10.9

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
England	Temperature	2026	11.10	10.99
England	Temperature	2030	11.23	11.08
England	Temperature	2035	11.40	11.21
England	Temperature	2040	11.57	11.35
England	Temperature	2045	11.74	11.49
England	Temperature	2050	11.91	11.62

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	11.1	10.99	11.91	11.62	0.81	0.63

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	5.40	5.55	6.21	6.04	0.81	0.50
Temperature	Feb	2026	2050	5.74	5.62	6.56	6.24	0.81	0.62
Temperature	Mar	2026	2050	7.55	7.40	8.36	8.05	0.81	0.64
Temperature	Apr	2026	2050	9.61	9.52	10.42	10.16	0.81	0.65
Temperature	May	2026	2050	12.75	12.61	13.57	13.26	0.81	0.65

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	15.60	15.50	16.41	16.15	0.81	0.65
Temperature	Jul	2026	2050	17.72	17.57	18.53	18.22	0.81	0.65
Temperature	Aug	2026	2050	17.47	17.35	18.28	18.00	0.81	0.65
Temperature	Sep	2026	2050	15.15	15.00	15.97	15.65	0.81	0.65
Temperature	Oct	2026	2050	11.95	11.80	12.77	12.45	0.81	0.65
Temperature	Nov	2026	2050	8.12	7.96	8.93	8.61	0.81	0.65
Temperature	Dec	2026	2050	6.07	5.97	6.89	6.62	0.81	0.65

5 Backup

5.1 England - 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
England	Temperature	1659	NA	8.0	15.0	9.3	8.8
England	Temperature	1660	2.0	8.7	15.0	9.7	9.1
England	Temperature	1661	5.0	8.3	14.7	10.7	9.8
England	Temperature	1662	5.7	8.3	15.0	10.0	9.5
England	Temperature	1663	1.7	7.3	14.7	10.0	8.6
England	Temperature	1664	4.7	8.0	15.7	9.3	9.3
England	Temperature	1665	2.0	7.3	15.0	9.3	8.2
England	Temperature	1666	3.7	8.3	16.7	10.3	9.8
England	Temperature	1667	2.3	6.3	16.0	9.3	8.5
England	Temperature	1668	4.3	7.7	15.3	10.0	9.5
England	Temperature	2016	6.8	8.7	16.5	10.8	10.4
England	Temperature	2017	5.5	10.4	16.3	10.9	10.7
England	Temperature	2018	4.4	9.5	17.4	10.9	10.7
England	Temperature	2019	6.0	9.5	16.4	10.1	10.4
England	Temperature	2020	6.3	10.0	16.3	11.0	10.8
England	Temperature	2021	4.5	8.0	16.5	11.7	10.3
England	Temperature	2022	6.0	10.1	17.3	12.1	11.2
England	Temperature	2023	5.1	9.4	16.5	12.2	11.1
England	Temperature	2024	6.6	10.7	15.8	10.9	10.9
England	Temperature	2025	5.2	10.7	17.7	11.3	11.2

Table 6: Monthly Means over all Years (Temperature / degree C and Monthly Precipitation / mm)

City	Month	Temperature
England	Jan	3.3
England	Feb	3.9
England	Mar	5.4
England	Apr	8.0
England	May	11.3
England	Jun	14.4
England	Jul	16.0
England	Aug	15.7
England	Sep	13.4
England	Oct	9.7
England	Nov	6.1
England	Dec	4.1

5.2 England - 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 England Temperature   1659 Jan 1659-1660     3
#> 2 England Temperature   1659 Feb 1659-1660     4
```

```
#> 3 England Temperature   1659 Mrz 1659-1660     6
#> 4 England Temperature   2025 Okt 2021-2025    11.3
#> 5 England Temperature   2025 Nov 2021-2025     8.4
#> 6 England Temperature   2025 Dez 2021-2025     6.7
```

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