

Demographic Forecasting

*Lecture 2: Direct extrapolation
by time-series methods*

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March 5, 2024

European Doctoral School of Demography 2023/2024 · INED, Aubervilliers



Course overview

- Lecture 1: direct extrapolation by (generalized) linear models
- Lecture 2: direct extrapolation by time-series methods
- Lecture 3: parametric approaches
- Lecture 4: Lee-Carter method



Time-series analysis: intro

- A *time-series* is a collection of observations made sequentially through time. Let us focus on discrete time series recorded at equal intervals of time
- Suppose we have an observed time series y_1, y_2, \dots, y_T and we wish to forecast future values such as y_{T+h} . The integer h is called *forecasting horizon*, and we denote by \hat{y}_{T+h} the forecast made at time T for h steps ahead
- Forecasting methods may be broadly identified into three types:
 - *Judgemental forecasts* : based on subjective judgement and intuition
 - *Univariate methods* : forecasts depend on present and past values of a single series
 - *Multivariate methods* : forecasts depend, at least partly, on values of one or more additional variables (predictors)

⇒ here univariate time-series methods



Descriptive techniques

- In order to *forecast*, description and modelling of data is a prerequisite
- Always start from plotting your data!
- This can help to identify two main sources of variation in many time series: i) trend, and ii) seasonal variation
- These variations are typically removed before time-series modelling via differencing \Rightarrow helps to stabilize the **mean**
- The time plot may also help to decide whether a variable needs to be transformed \Rightarrow helps to stabilize the **variance** (e.g. log-transformation)



Stationary stochastic processes

- A *stochastic* time series is one where future values can only partly be determined by past values
- A process is defined stationary_ if its properties do not change through time
- More formally, let y_t be the realization of the underlying random variable Y_t , and the observed time-series $\mathbf{y} = [y_1, y_2, \dots, y_T]$ be a realization of the stochastic process
- A stochastic process is second-order stationary if its first and second moments are finite and do not change over time, i.e.:

$$\begin{aligned}\mathbb{E}[Y_t] &= \mu \\ \text{COV}[Y_t, Y_{t+k}] &= \mathbb{E}[(Y_t - \mu)(Y_{t+k} - \mu)] = \gamma_k\end{aligned}$$

for all t and for $k = 0, 1, 2, \dots$ (note, for $k = 0$, $\gamma_0 = \sigma^2$)

- In simpler words, a stationary series has constant mean, constant variance and no predictable patterns in the long-term



The ACF

- The set of coefficients γ_k constitutes the autocovariance function, which is standardized to give the autocorrelation function (ACF) $\rho_k = \gamma_k / \gamma_0$
- The sample autocovariance coefficient at lag k is given by

$$c_k = \sum_{t=1}^{T-k} (y_t - \bar{y}) (y_{t+k} - \bar{y}) / T$$

for $k = 0, 1, 2, \dots$,

- The sample autocorrelation coefficient at lag k is computed as $r_k = c_k / c_0$
- r_k is an estimate of the theoretical ρ_k

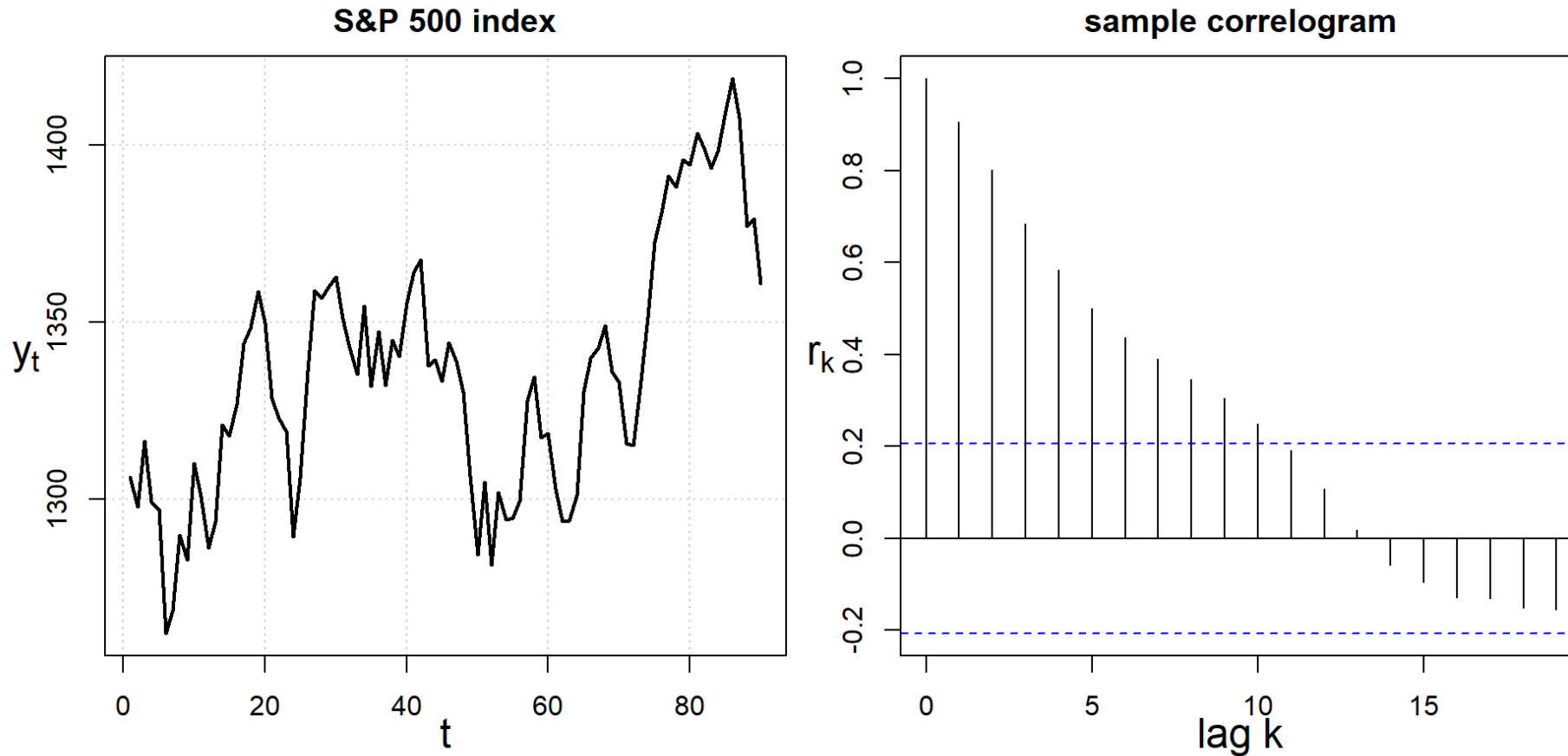


The correlogram & partial ACF

- The **correlogram** is the graph of r_k against k
- Plotting the correlogram is very useful:
 - the ACF of non-stationary data decreases slowly, with r_1 often large and positive (see example in next slide)
 - the ACF of stationary data drops to zero relatively quickly
 - useful to identify orders of $AR(p)$ and $MA(q)$ models
- The **partial** ACF (PACF) measures the excess correlation at lag k which has not already been accounted for by autocorrelations at lower lags



Non-stationary TS: an example



Note: i) non-constant mean, and ii) sample correlogram decreases slowly, with r_1 large and positive (Source: S&P data for 90 trading days from March 16, 1999, Chatfield (2000))

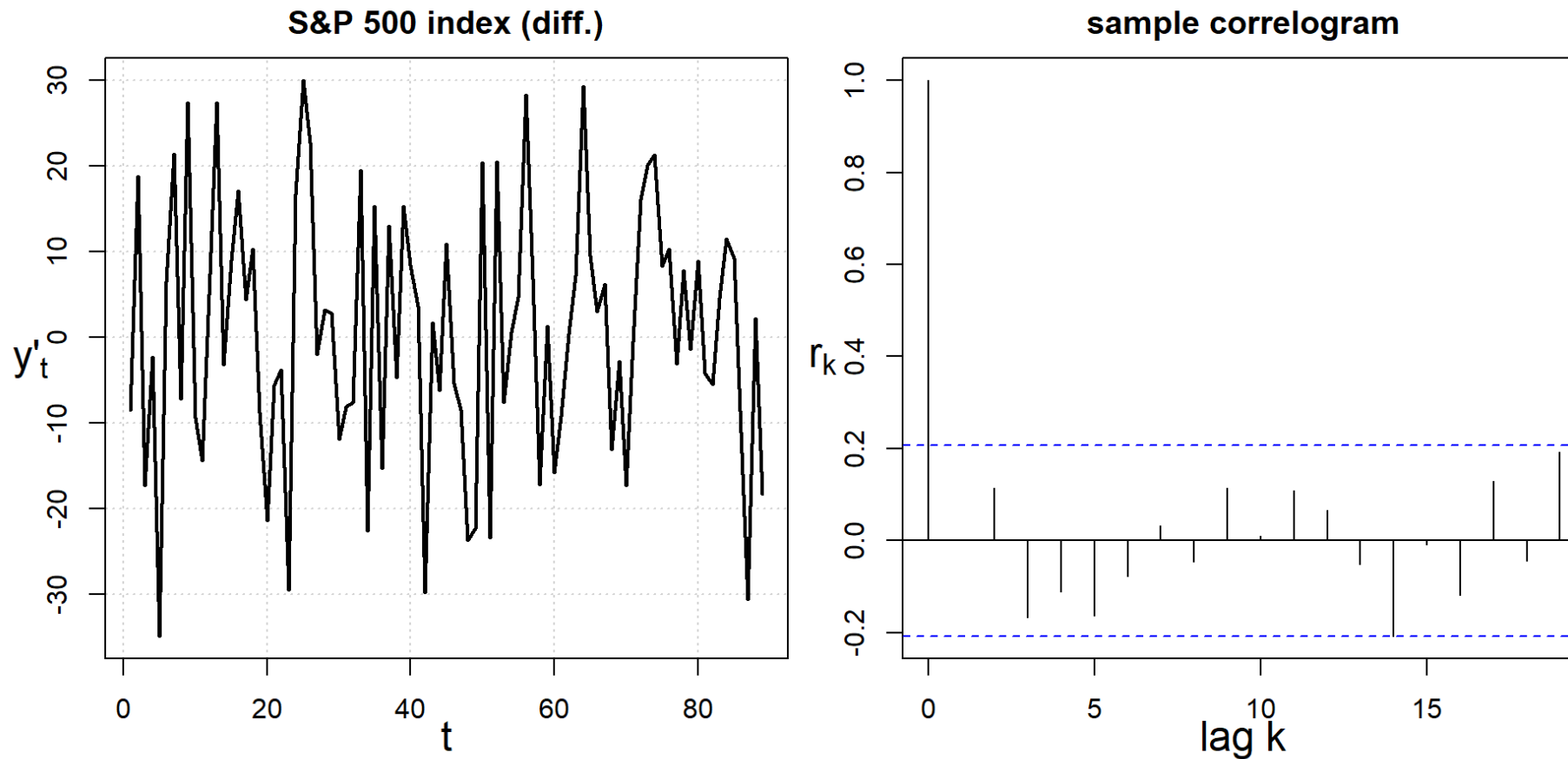


Differencing

- Powerful tool to stabilize the mean and obtain stationary time-series
 - First-order differencing: $y'_t = y_t - y_{t-1}$, y'_t is the *change* between observations of y_t (composed by $T - 1$ values)
 - If y'_t still non-stationary, second-order differencing:
 $y''_t = y'_t - y'_{t-1} = y_t - 2y_{t-1} + y_{t-2}$ (composed by $T - 2$ values)
 - Almost never necessary to go beyond y''_t
- For seasonal data, seasonal differencing: $y'_t = y_t - y_{t-m}$, where m is the number of seasons, y'_t is the change between one year to the next
- In addition to correlogram, two main tests for determining the required order of differencing:
 - Augmented Dickey Fuller test: H_0 data are non-stationary and non-seasonal
 - Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test : H_0 data are stationary and non-seasonal



Differencing in practice



Note: i) approx. constant mean and variance, no predictable patterns; ii) ACF drops to zero quickly, tiny value of KPSS test-statistics (cannot reject H_0) \Rightarrow stationary time-series



Purely random process (white noise)

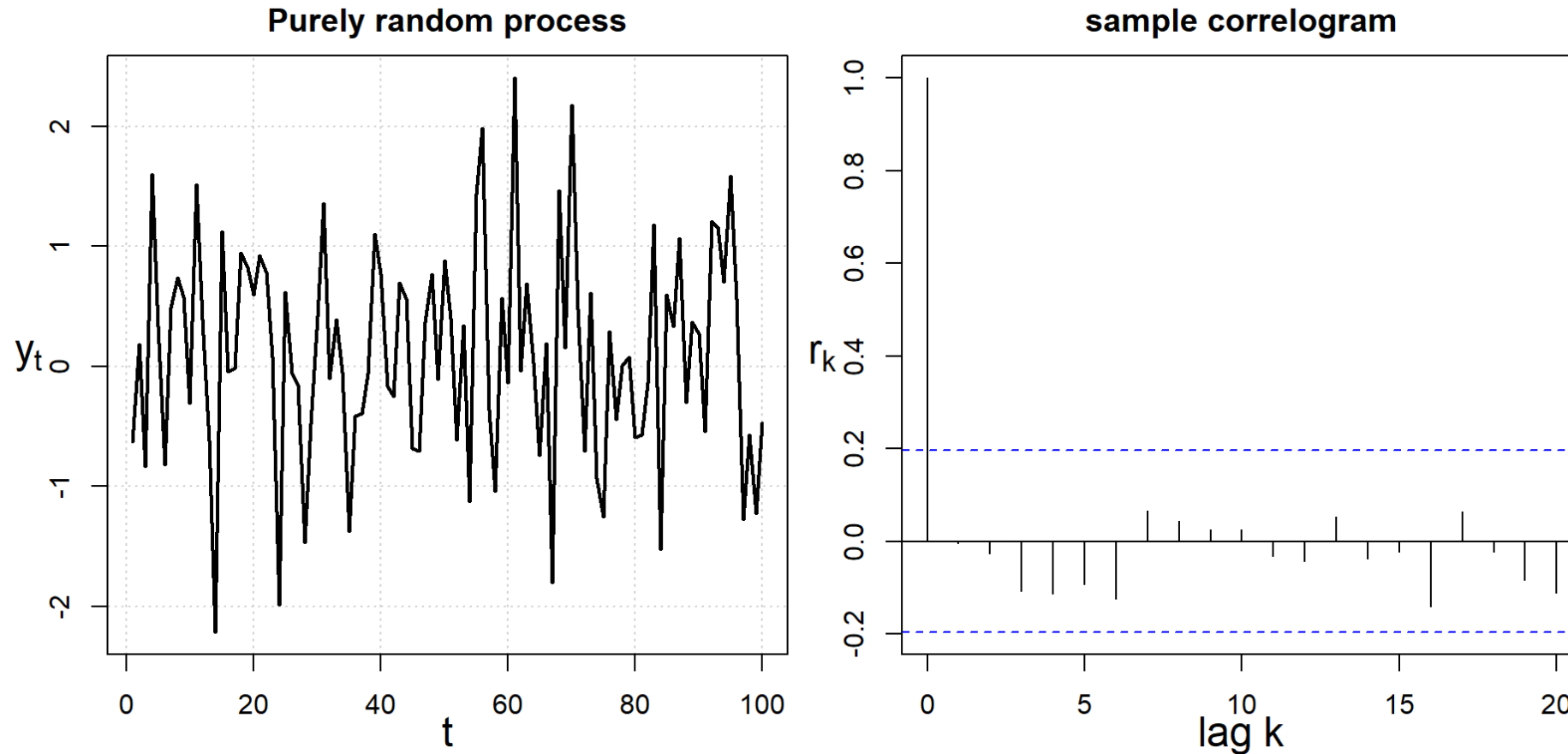
- A sequence of uncorrelated, identically distributed random variables Z_t with zero mean and constant variance σ_z^2
- A stationary process with ACF equal to:

$$\rho_k = \begin{cases} 1 & k = 0 \\ 0 & k \neq 0 \end{cases}$$

- Often used to model the random disturbances in more complicated processes



Purely random process: an example



Simulated time series of purely random process (note how it mimicks the differenced TS and correlogram of S&P)



Random walk model

- Random walk models are widely used for non-stationary data (e.g.~economic and financial data):

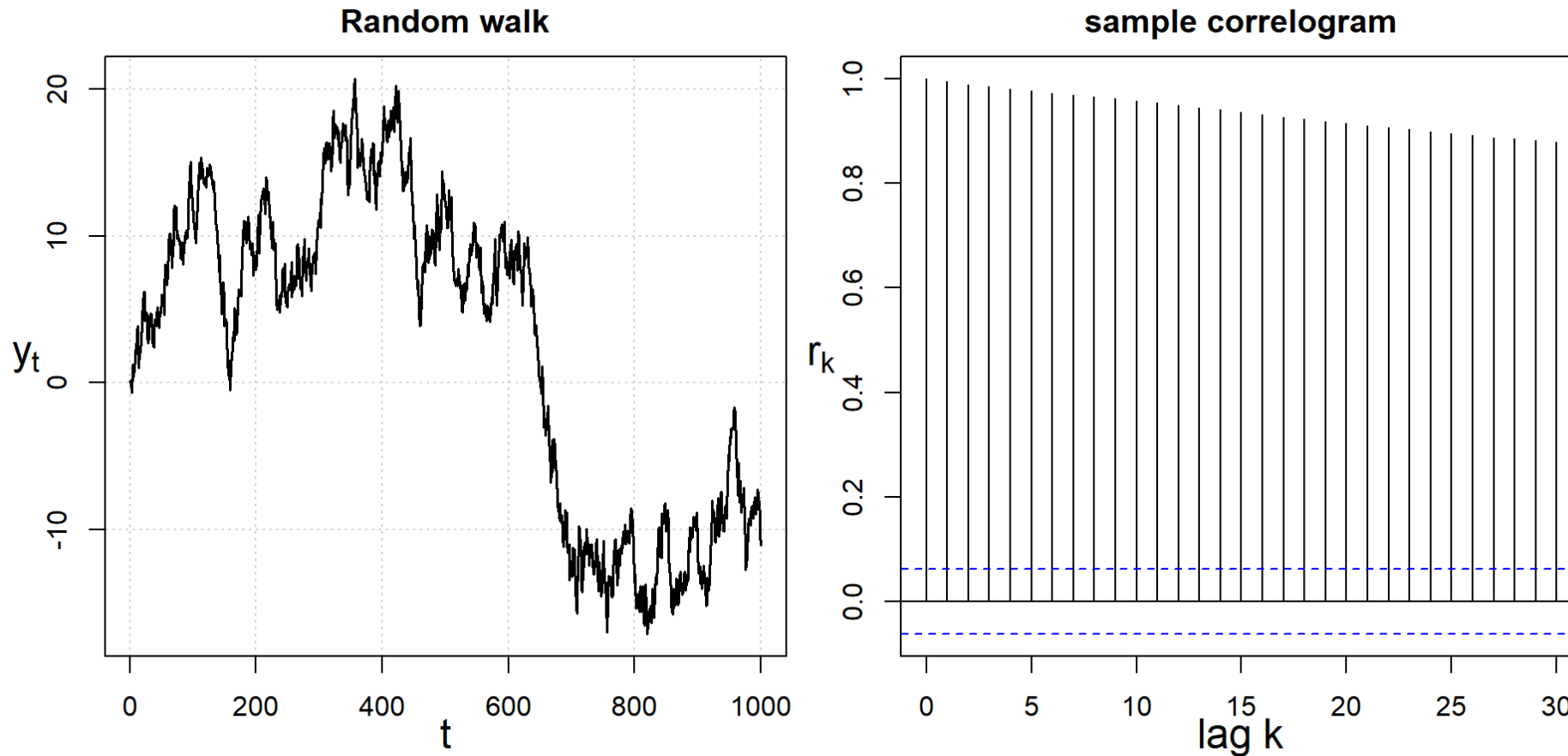
$$Y_t = Y_{t-1} + Z_t$$

where Z_t is a purely random process

- Random walk is non-stationary (variance increases through time), but first-order differences (purely random process) is stationary
- Typical features:
 - sudden and unpredictable changes of direction
 - long periods of apparent trends up/down
- Forecasts for the random walk model are simply given by the value of the last observation (i.e.~naïve forecast): $\hat{y}_{T+h|T} = y_T$



Random walk process: an example



Simulated time-series of a random walk process. Note the non-constant mean and the ACF slowly decreasing (indicating non-stationarity)



Random walk with drift model

- A closely related model that allows first differences to have non-zero mean is the **random walk with drift (RWD)**:

$$Y_t = c + Y_{t-1} + Z_t$$

where Z_t is a purely random process, and c is a constant. If $c > 0$ ($c < 0$), y_t will tend to drift upwards (downwards)

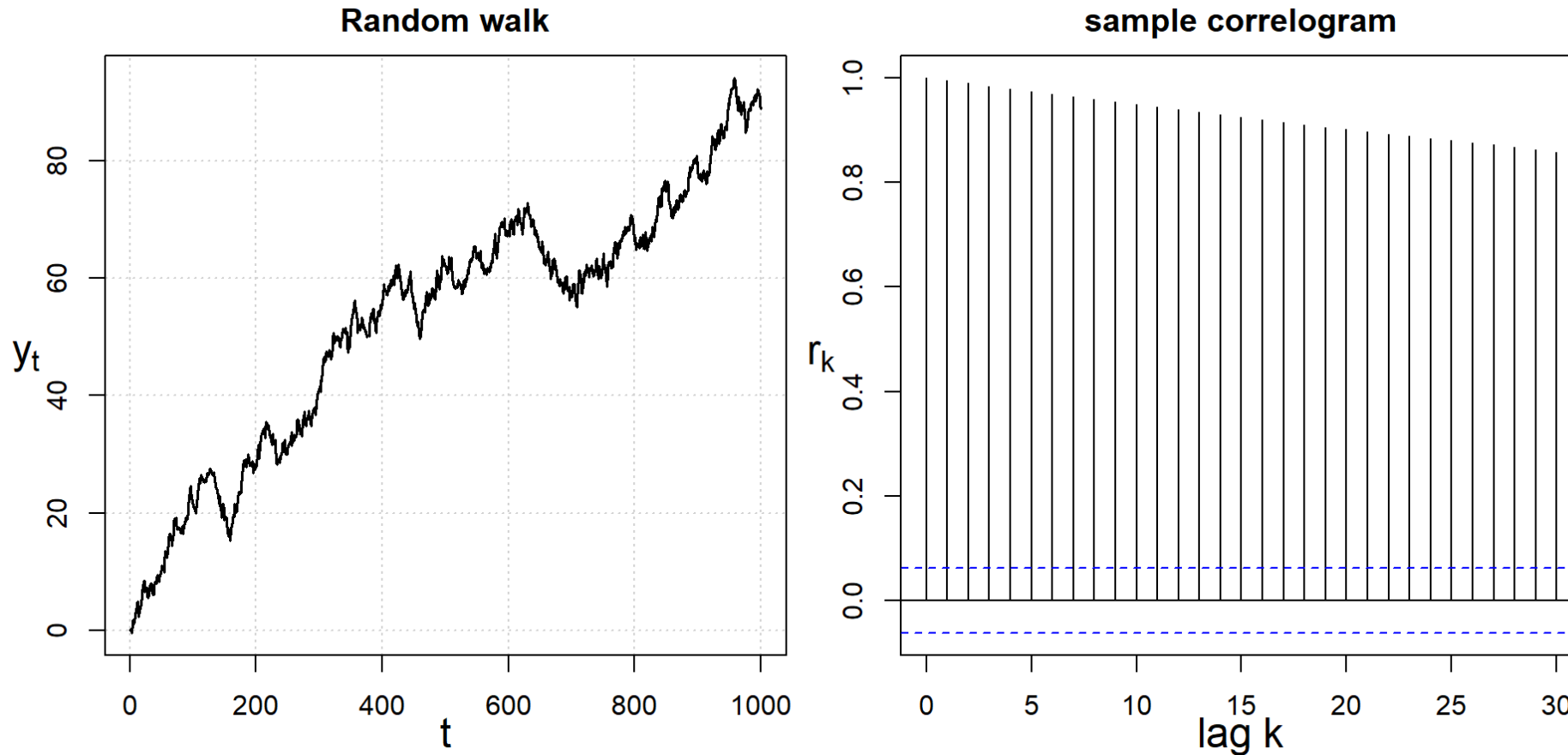
- The estimate of the drift c is given by the average of the changes between consecutive observations:

$$c = \frac{1}{T-1} \sum_{t=2}^T (y_t - y_{t-1}) = \frac{y_T - y_1}{T-1}$$

- Forecasts for the random walk model with drift are given by $\hat{y}_{T+h|T} = y_T + c h \Rightarrow$ equivalent to drawing a line between the first and last observations, and extrapolating it into the future



RWD process: an example



Simulated time-series of a random walk process with drift. Note the non-constant mean and the ACF slowly decreasing (indicating non-stationarity)



Exercise

Exercise

Load the `TimeSeries.Rdata` data in R, and consider the first 200 trading days (i.e. the first 200 observations) from January 1st, 1990. Plot the data and correlogram, and decide whether the time series is stationary. Then (after possibly appropriate transformations) fit two models :

- a RW model (without drift)
- a RWD model

In both cases, plot forecasts for the next 50 trading days, and compare the two forecasts against the observed data.

Hints:

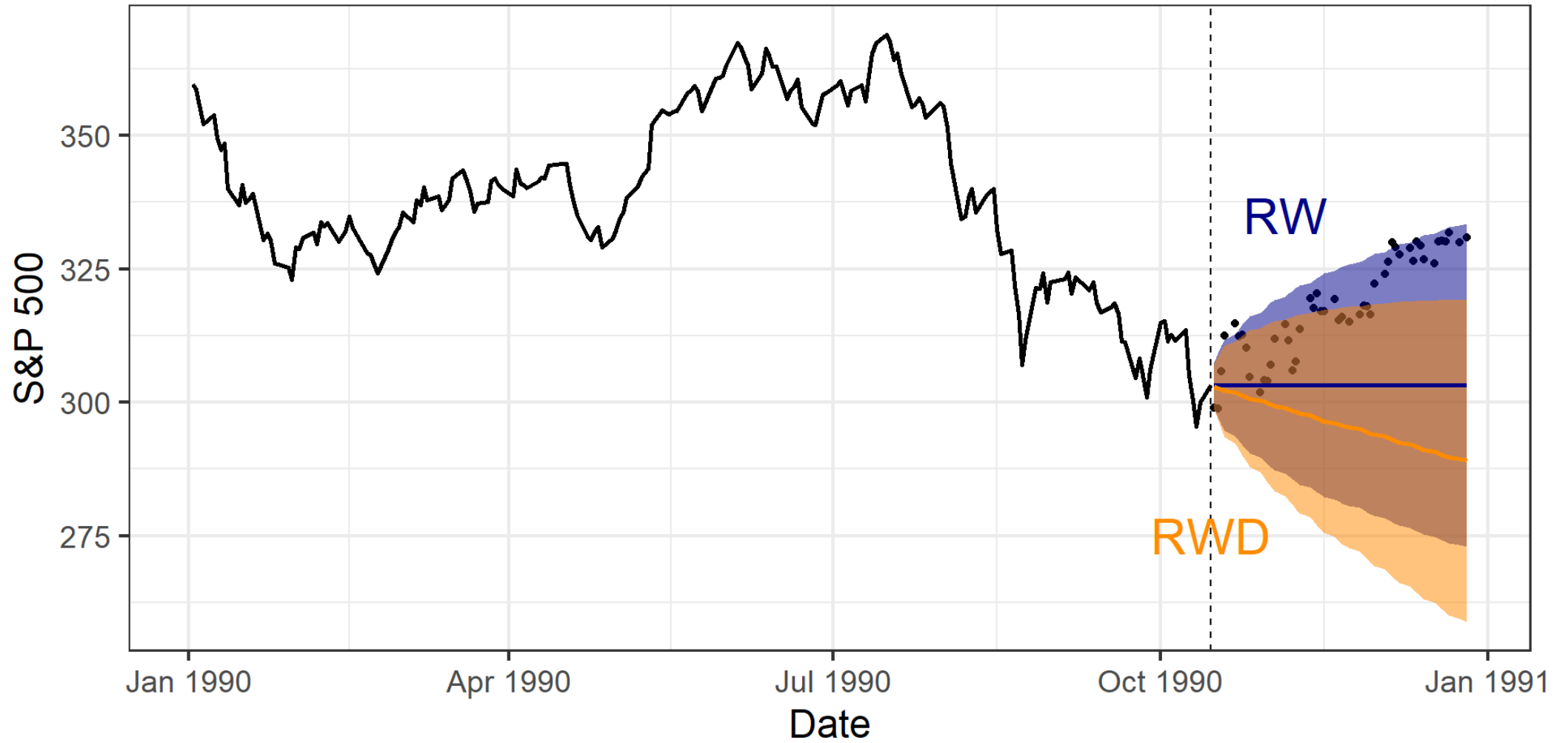
1. The correlogram is given by the `acf` function (automatically loaded in R)
2. To fit the RW models, use the package `forecast` and the function `Arima(y = ., order = c(0, 1, 0), include.drift = .)` [we will shortly see that the RW model is an ARIMA(0,1,0) model]
3. Use the command `forecast(object=., h=.)` to produce forecasts



One possible solution



RW models



Autoregressive processes

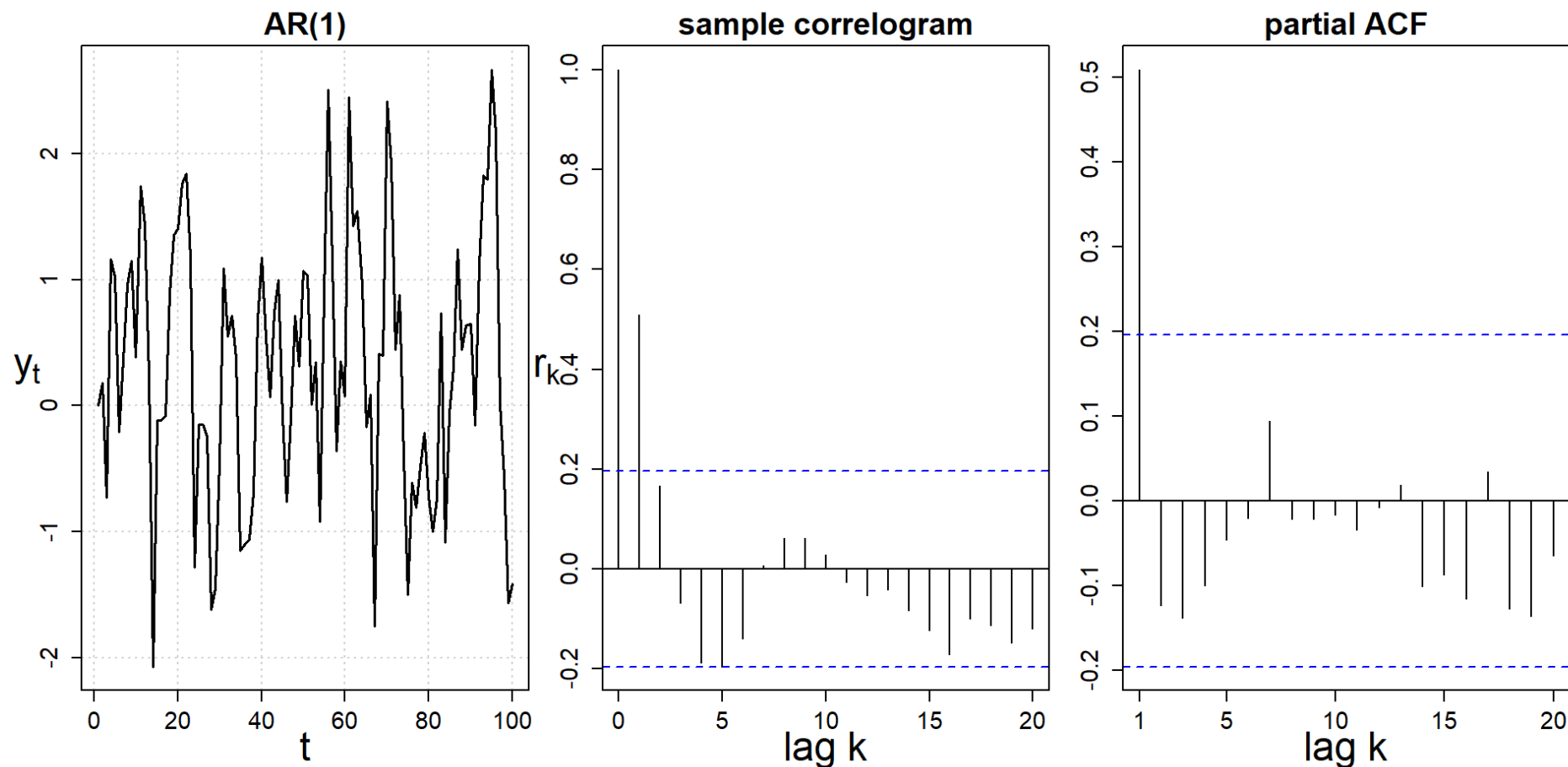
- A process Y_t is autoregressive of order p (denoted $AR(p)$) if

$$Y_t = c + \phi_1 Y_{t-1} + \phi_2 Y_{t-2} + \cdots + \phi_p Y_{t-p} + Z_t$$

where Z_t is a purely random process and c is a constant



AR(1) process: an example



Simulated time-series of an AR(1) process $y_t = 0.6y_{t-1} + z_t$. Note the ACF dies out in a sine-wave manner, PACF has all zero spikes beyond the 1st spike

Moving average processes

- A process Y_t is moving average of order q (denoted $MA(q)$) if

$$Y_t = c + Z_t + \theta_1 Z_{t-1} + \theta_2 Z_{t-2} + \cdots + \theta_q Z_{t-q}$$

where Z_t is a purely random process and c is a constant



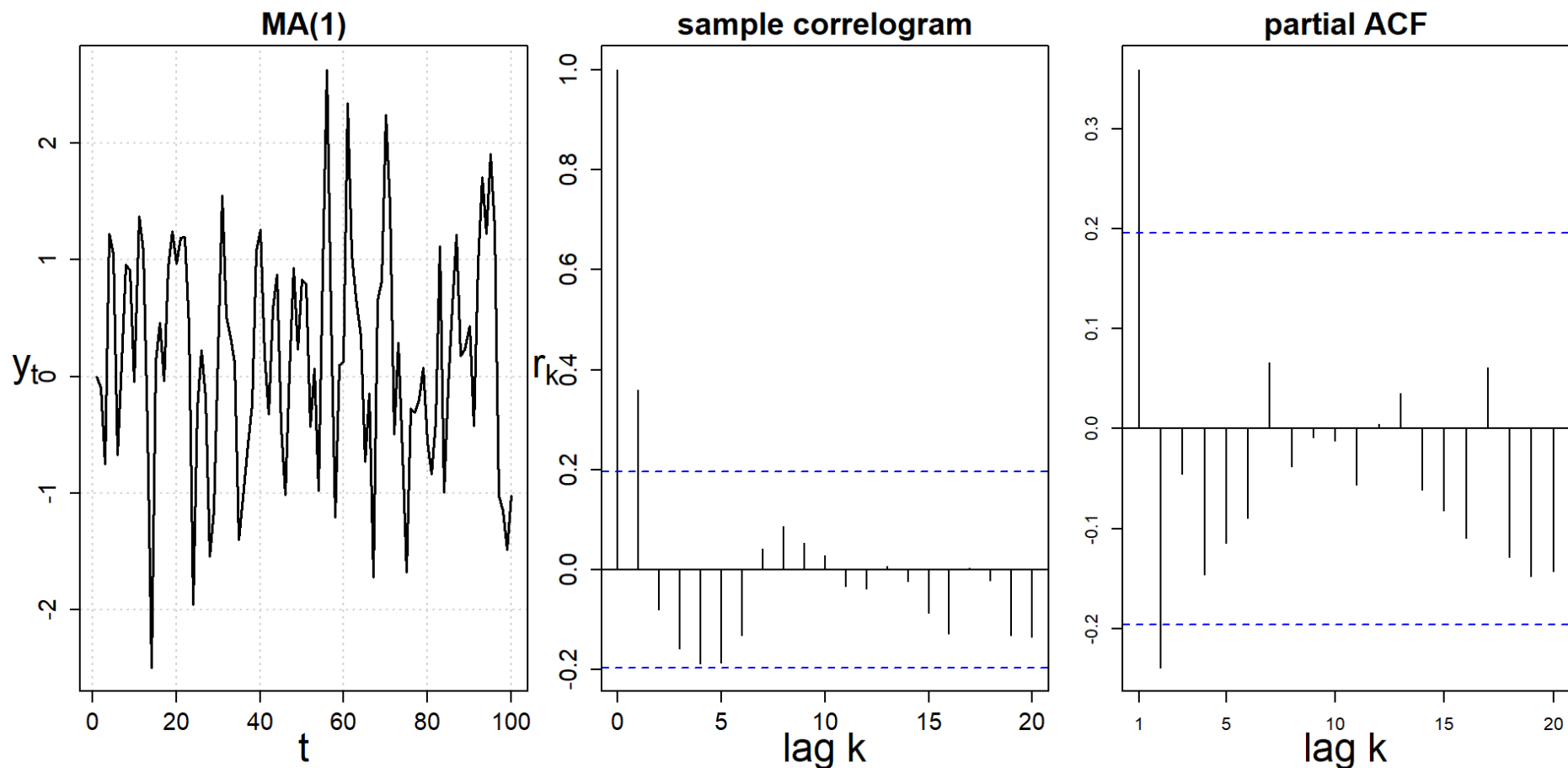
- A multiple regression with past errors as predictors; finite-order MA process is stationary for any values of θ
- Simplest example: first-order case (MA(1)), where $Y_t = Z_t + \theta Z_{t-1}$, is stationary $\forall \theta$ with ACF given by:

$$\rho_k = \begin{cases} 1 & k = 0 \\ \theta / (1 + \theta^2) & k = 1 \\ 0 & k > 1 \end{cases}$$

- An useful property of an MA(q) process is that the ACF is zero at all lags greater than q
 \Rightarrow useful for model selection



MA(1) process: an example



Simulated time-series of an MA(1) process $y_t = z_t + 0.45z_{t-1}$. Note the ACF is zero at all lags greater than 1, while the PACF dies out in a sine-wave manner

ARMA & ARIMA processes

Putting together $AR(p)$ and $MA(q)$, a process Y_t is autoregressive moving average (denoted $ARMA(p,q)$) if

$$Y_t = c + \phi_1 Y_{t-1} + \cdots + \phi_p Y_{t-p} + Z_t + \theta_1 Z_{t-1} + \cdots + \theta_q Z_{t-q}$$

where Z_t is a purely random process and c is a constant

- Moreover, most time-series are not stationary, and we cannot apply stationary AR, MA or ARMA processes \Rightarrow $ARIMA(p, d, q)$ models combine ARMA with **differencing** of order d , employed to make series stationary
- Autoregressive Integrated Moving Average ($ARIMA(p, d, q)$) is a very general class of time-series models:
 - purely random process: $ARIMA(0,0,0)$
 - random walk: $ARIMA(0,1,0)$ without constant
 - random walk with drift: $ARIMA(0,1,0)$ with constant
 - $AR(p)$: $ARIMA(p,0,0)$; $MA(q)$: $ARIMA(0,0,q)$



Modelling procedure with ARIMA

1. Plot the data and identify unusual observations
2. If necessary, transform the data to stabilize the variance
3. If data non-stationary: take first-order differences until data are stationary
4. Examine ACF/PACF: is an $AR(p)$ or $MA(q)$ model appropriate?
5. Try chosen model(s) and employ AICc to search for a better one 6 Check residuals of the model \Rightarrow they should look like a purely random process
6. Forecast

Interpreting the ACF/PACF can be very challenging, and not suitable for ARMA processes
 \Rightarrow points 3–5 with `auto.arima` function from `forecast` package



Exercise

Exercise

Now load the `FERT.SWE.Rdata` dataset, and consider again only data from 1950 onward for women aged 20. Fit and compare forecast up to 2050 of log-fertility rates using three approaches:

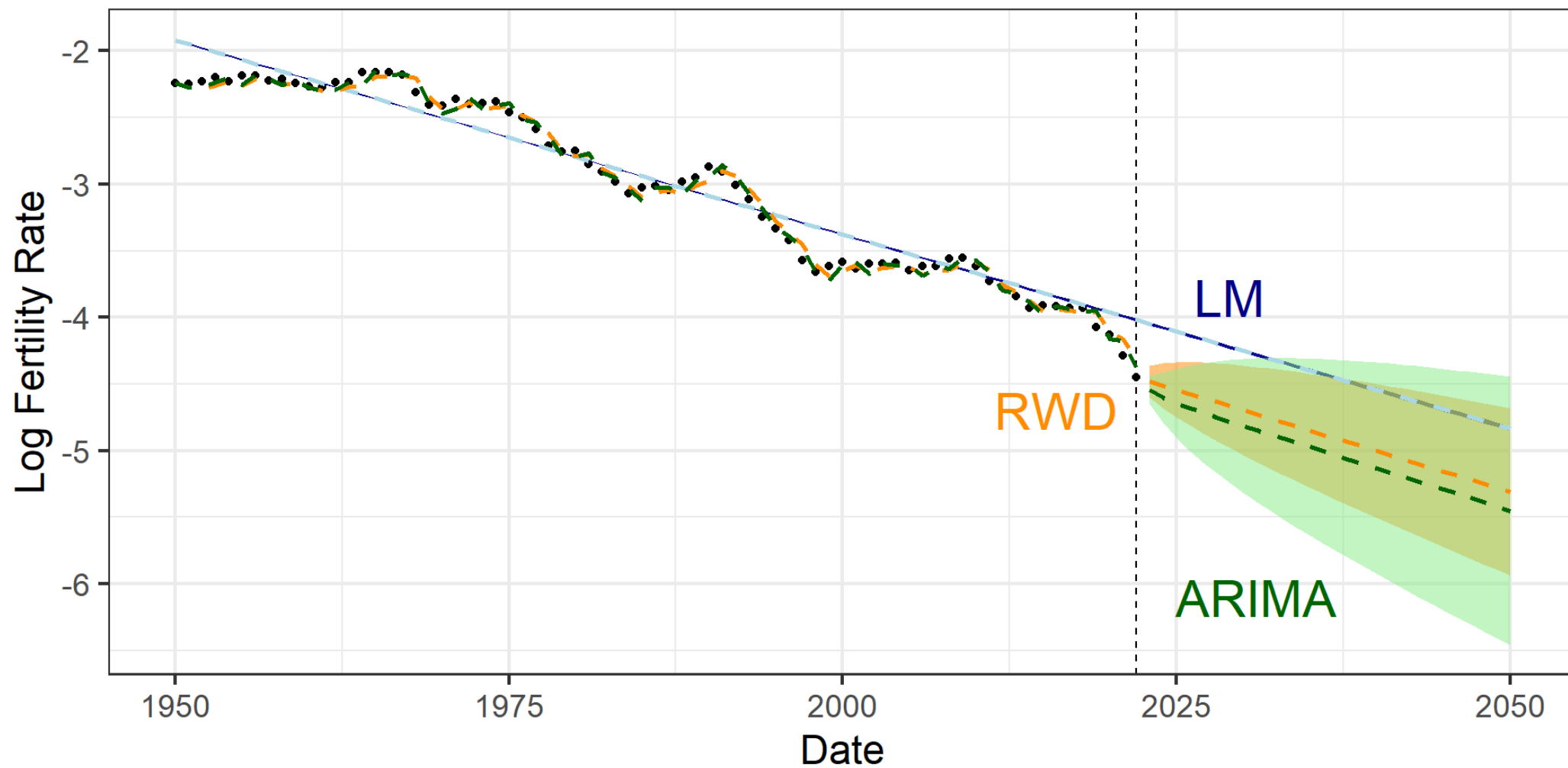
- a GLM for births with exposures as an offset (Day 1)
- a RWD model for log-fertility rates
- the most suitable ARIMA model (use the `auto.arima` function) for log-fertility rates



One possible solution



TS vs GLM



Forecasting with time-series methods

Advantages:

- much better goodness-of-fit
- almost absent jump-off bias
- wider prediction intervals

What about summary measures? Can we try to incorporate uncertainty from m different models together?



ARIMA PIs

- The computation of ARIMA prediction intervals is rather complex (and beyond the scope of this course)
- A simple example: if $\hat{\sigma}$ is the standard deviation of the residuals, then for any ARIMA model, the 95% PI for the first point forecast is given by $\hat{y}_{T+1|T} \pm 1.96\hat{\sigma}$
- Advantage: in addition to theoretical PIs, we can simulate future paths of the time-series based on the estimated model

⇒ we can combine simulations from the different models in a bootstrapping framework



Exercise

Exercise

Consider again the best ARIMA model for the log-fertility time series seen before. Compare the analytical PIs derived earlier with those we could obtain from simulating future paths of the time series. Repeat this exercise for different number of simulations. When do the PIs between the two approaches get more similar?

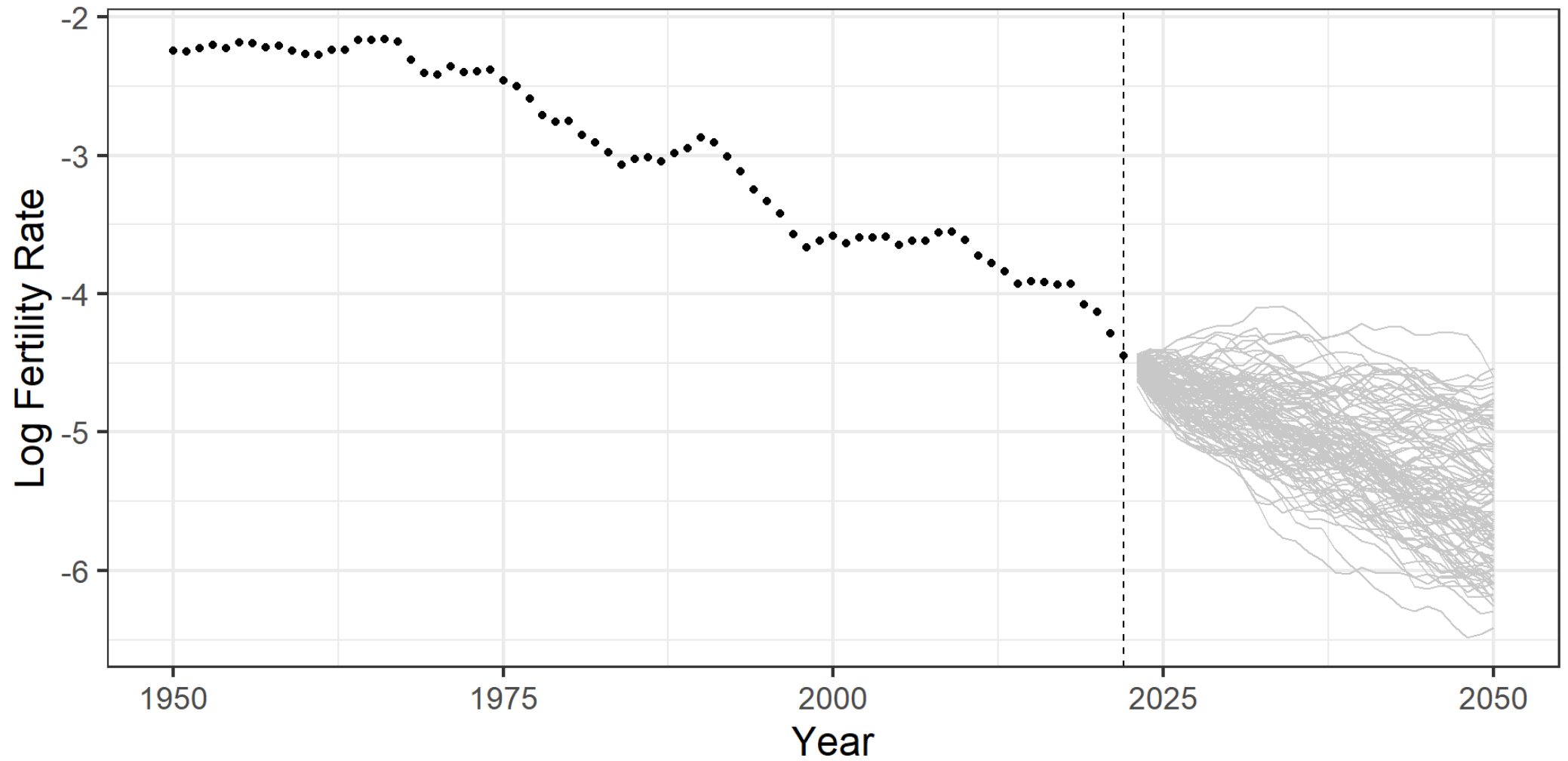
Hint: use the function `simulate(object=., nsim=., future=TRUE, bootstrap=TRUE)` to produce future paths of your estimated model



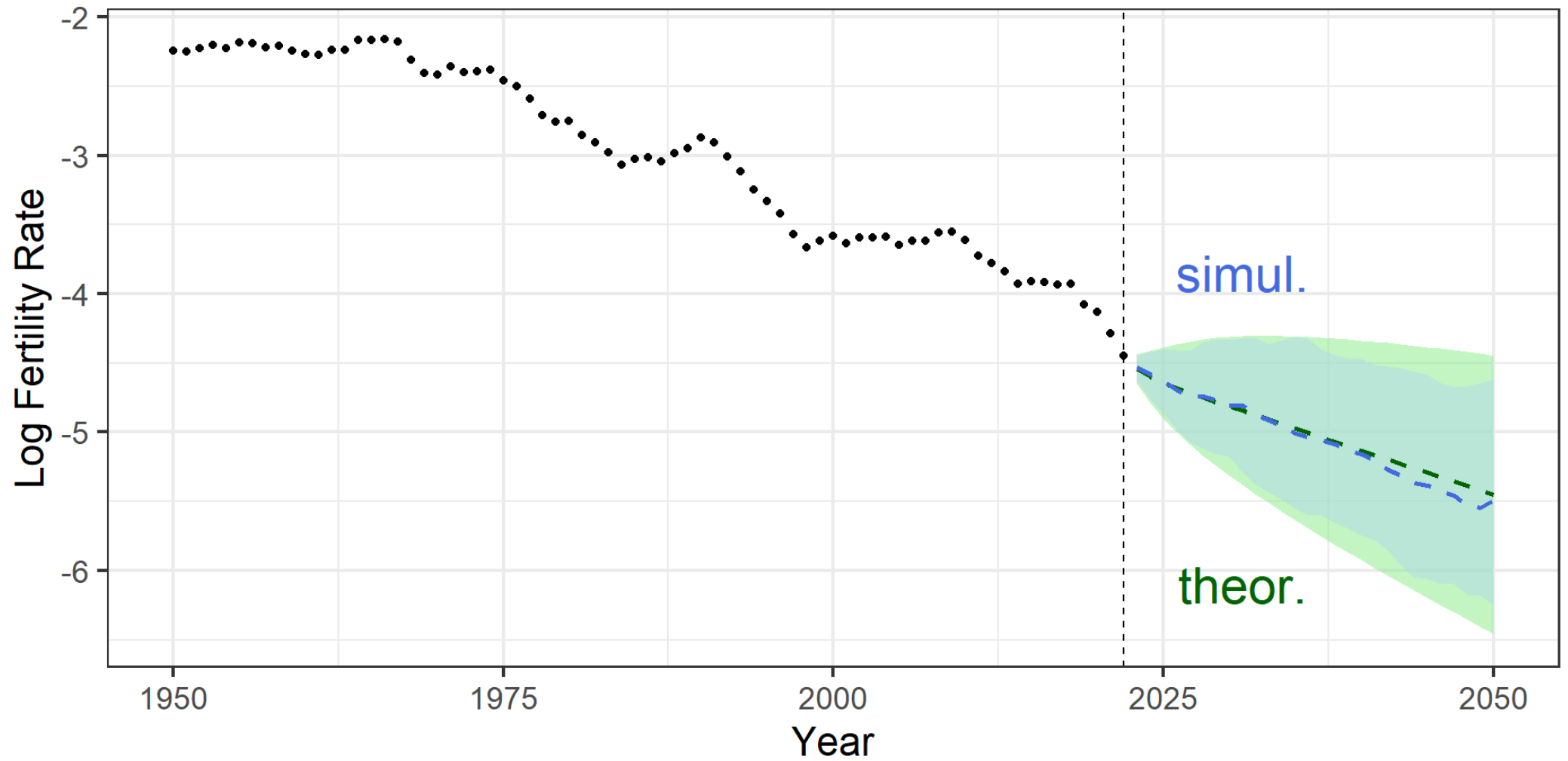
One possible solution



ARIMA simulations



ARIMA PIs

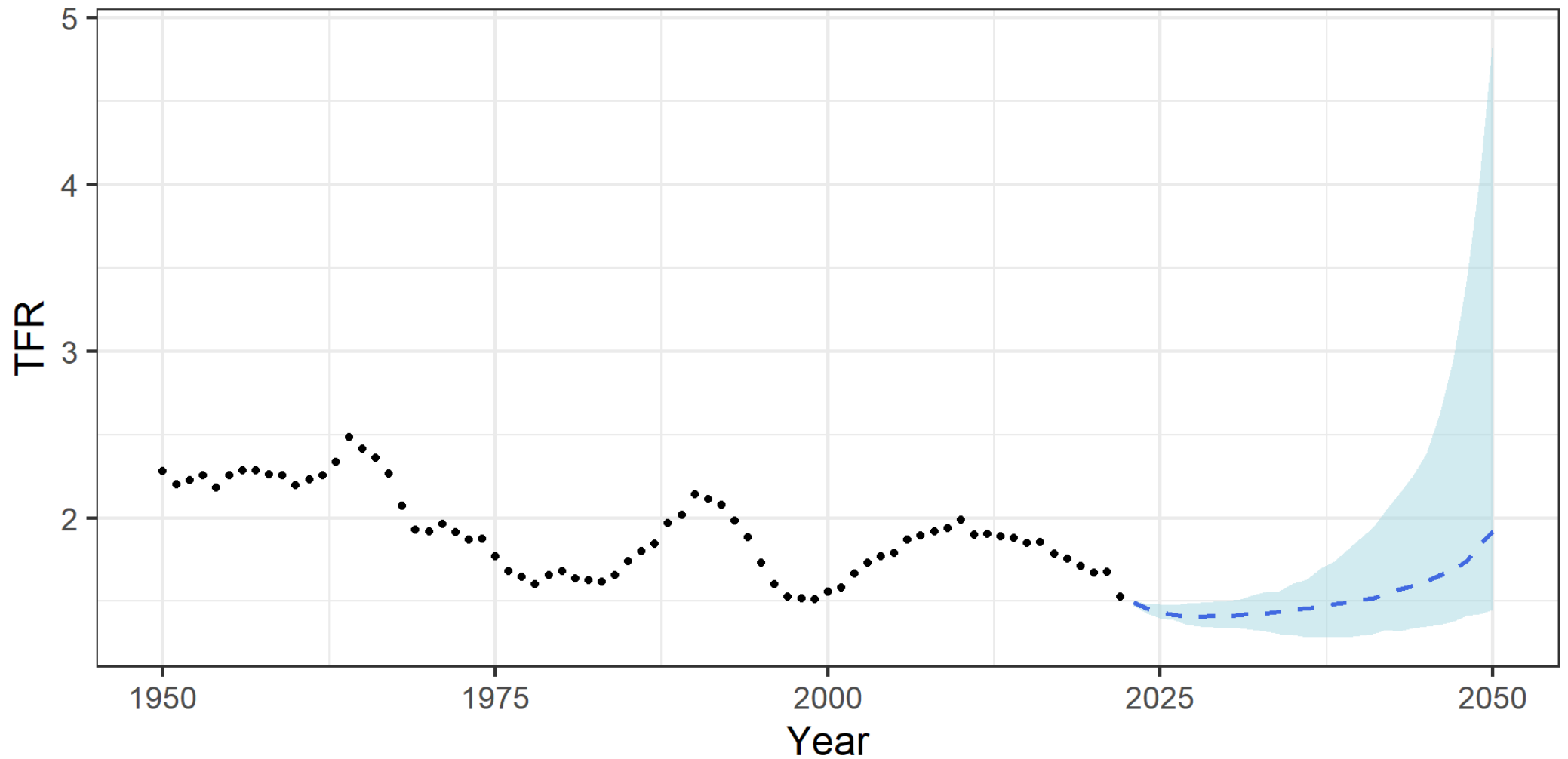


Summary measures

Combining simulations from m different models...



ARIMA TFR with 80% PI

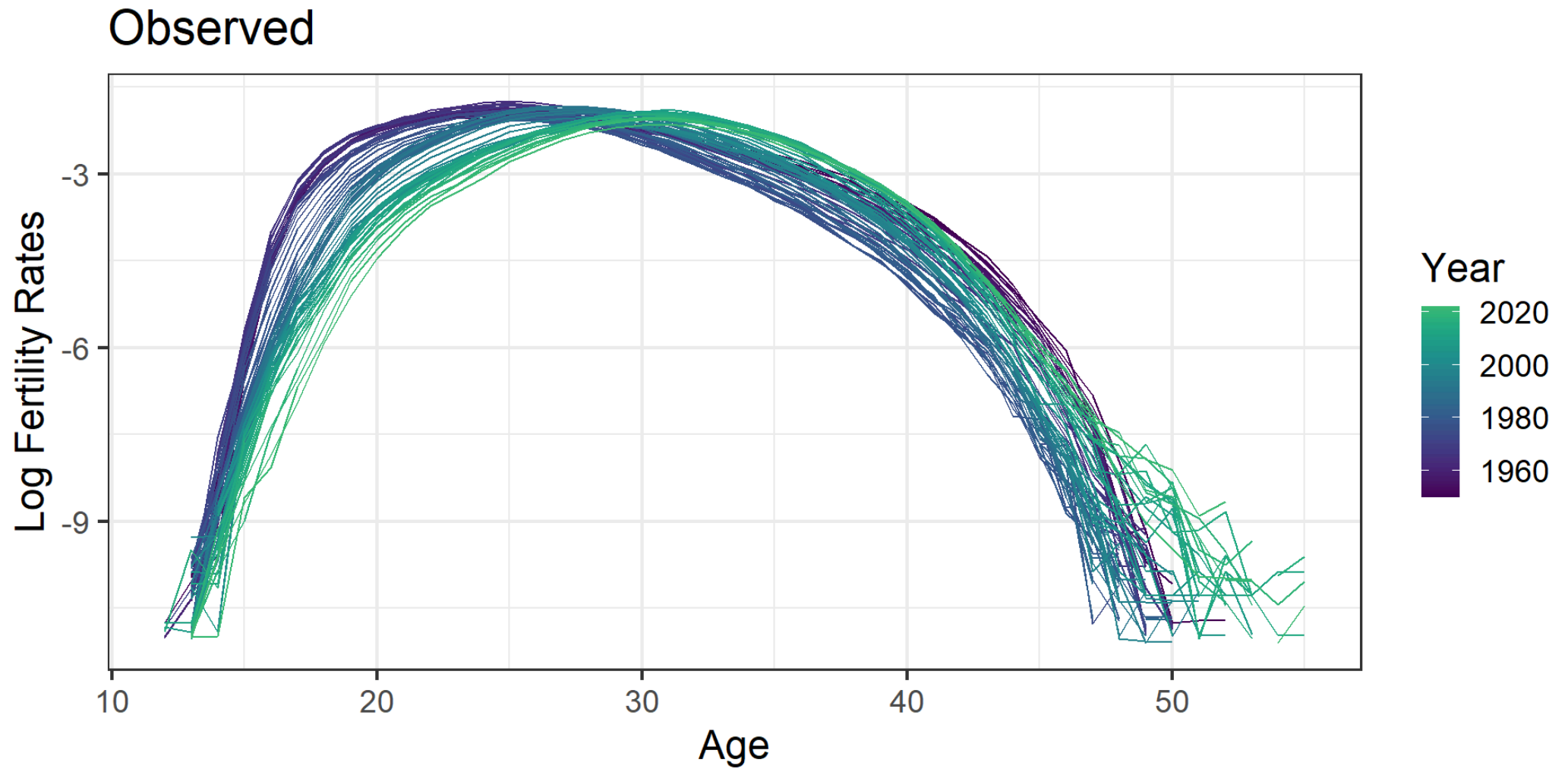


Age-specific fertility pattern

What about the age-specific shape of fertility?

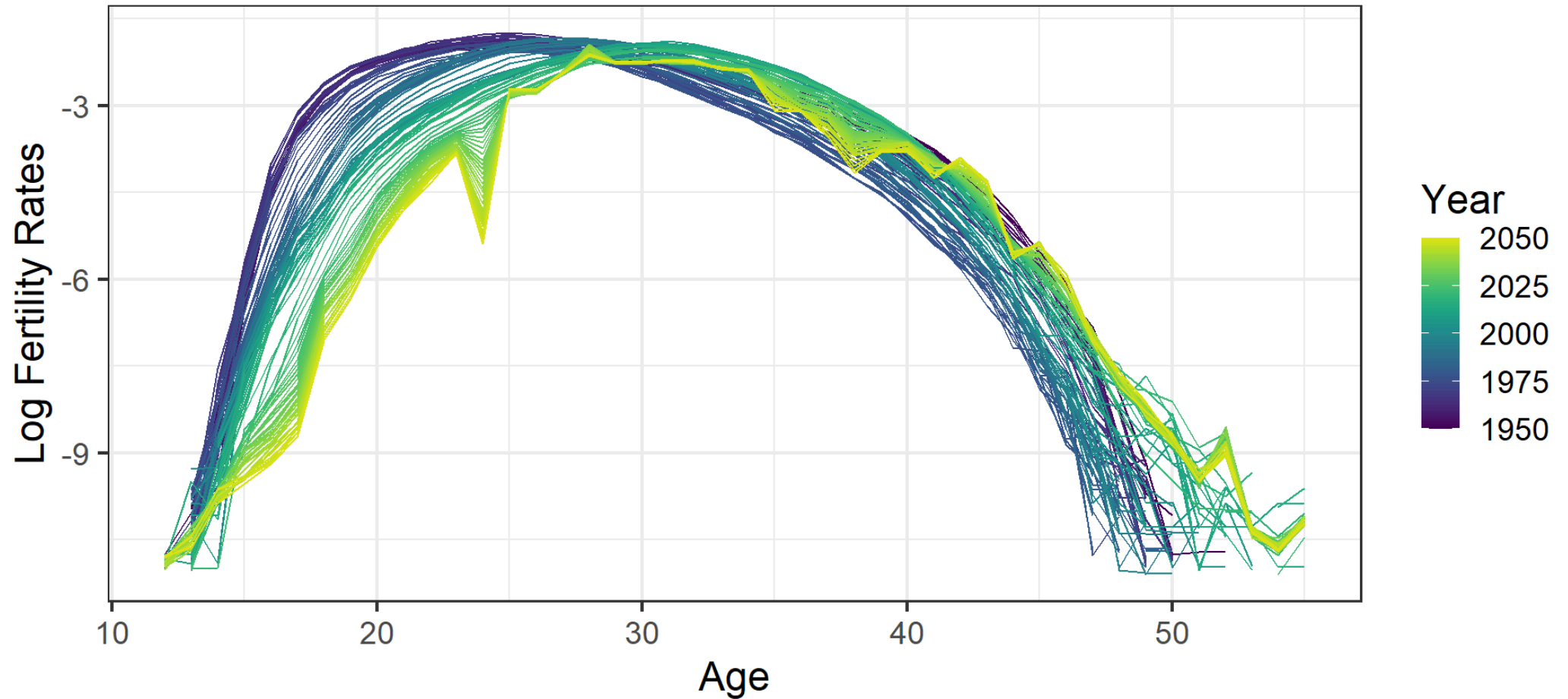


ARIMA age-pattern



ARIMA age-pattern

Observed + Forecast



Forecasting with time-series methods

Advantages:

- much better goodness-of-fit
- almost absent jump-off bias
- larger prediction intervals

Disadvantages:

- strange wiggling behaviour over ages
- too large prediction intervals?



Day 2 assignment

Assignment

3. Load the mortality data [MORTSWE.Rdata](#), and focus on mortality from 1950 to 2000 for males aged 20 years. Fit and forecast mortality up to 2022 using two separate models:

- a random walk with drift model for log-rates
- the best possible ARIMA model for log-rates

Plot the forecast rates against the subsequently observed data in 2001-2022. Which model seems to forecast mortality better?

4. Load the mortality data [MORTSWE.Rdata](#), and focus on male mortality from 1950 onwards for those aged 0-100 (i.e. exclude the 101-110+ age groups). Fit and forecast mortality up to 2050 using the best possible ARIMA model for log-rates for all age groups available (a [for](#) loop is a convenient way to do so). Compare the observed age-pattern of mortality against the forecast one. Does it seem like a reasonable pattern of mortality? [Hint: you will need to replace minus infinite values of $\ln(m_{x,t})$ with [NA](#) for some age groups]

5. Following up on Exercise 4, compute simulations for the future paths of all $\ln(m_{x,t})$, and combine them together to compute a forecast of life expectancy. Use the provided function [LifetableMX.R](#) to construct a life table from your (log) rates. [Hint: you will need to create an array, rather than a matrix, where to store your simulations of $\ln(m_{x,t})$]



