



# Chapter 4: SARIMA Models

Seasonal Time Series



# Outline

- 1 Seasonality in Time Series
- 2 Seasonal Differencing
- 3 The SARIMA Model
- 4 Seasonal ACF and PACF Patterns
- 5 Estimation and Diagnostics
- 6 Forecasting with SARIMA
- 7 Real Data Application: Airline Passengers
- 8 Summary

# What is Seasonality?

## Definition 1 (Seasonality)

A time series exhibits **seasonality** when it shows regular, periodic fluctuations that repeat over a fixed period  $s$  (the seasonal period).

## Common Seasonal Periods

- Monthly data:  $s = 12$  (annual cycle)
- Quarterly data:  $s = 4$  (annual cycle)
- Weekly data:  $s = 52$  (annual) or  $s = 7$  (weekly pattern)
- Daily data:  $s = 7$  (weekly pattern)

# Examples of Seasonal Data

## Economic Series

- Retail sales (holiday peaks)
- Tourism (summer/winter)
- Agricultural production
- Energy consumption
- Employment (hiring cycles)

## Other Domains

- Weather/temperature
- Website traffic
- Hospital admissions
- Transportation usage
- Electricity demand

## Why It Matters

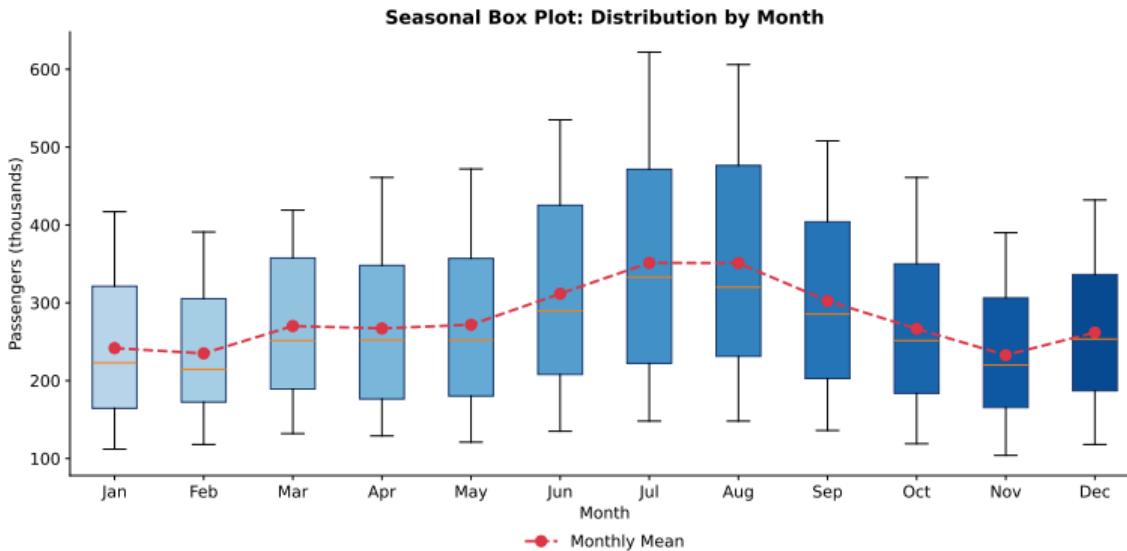
Ignoring seasonality leads to biased forecasts and invalid inference!

## Example: Airline Passengers Data



- Monthly international airline passengers (1949–1960)
- Clear **upward trend** and **growing seasonal amplitude**
- Summer peaks reflect vacation travel patterns

# Visualizing Seasonal Patterns



- Box plot reveals consistent seasonal pattern across years
- July–August show highest passenger counts (summer travel)
- November–February show lowest counts (winter months)

# Deterministic vs Stochastic Seasonality

## Deterministic Seasonality

Fixed seasonal pattern:

$$Y_t = \sum_{j=1}^s \gamma_j D_{jt} + \varepsilon_t$$

where  $D_{jt}$  are seasonal dummies.

### Properties:

- Pattern is constant over time
- Can be removed by regression

## Stochastic Seasonality

Evolving seasonal pattern:

$$\Delta_s Y_t = Y_t - Y_{t-s}$$

exhibits dependence structure.

### Properties:

- Pattern evolves over time
- Requires seasonal differencing

# Detecting Seasonality

## Visual Methods

- Time series plot – look for repeating patterns
- Seasonal subseries plot – compare same seasons across years
- ACF plot – spikes at seasonal lags ( $s, 2s, 3s, \dots$ )

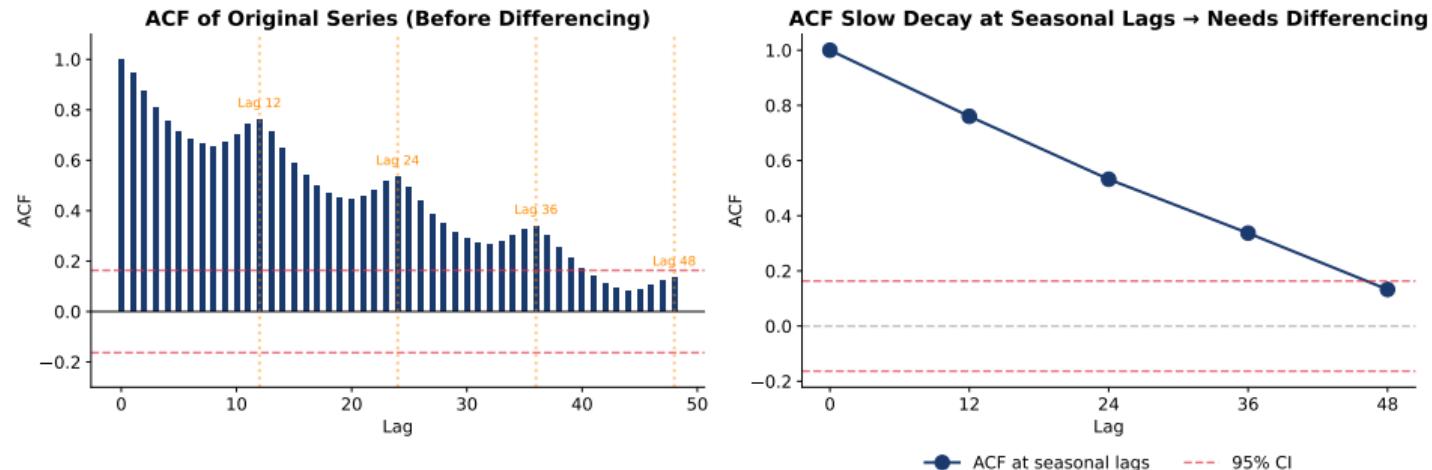
## Statistical Tests

- Seasonal unit root tests (HEGY, CH, OCSB)
- F-test for seasonal dummies
- Kruskal-Wallis test (nonparametric)

## ACF Signature

Strong seasonality: ACF shows significant spikes at lags  $s, 2s, 3s, \dots$

# ACF Reveals Seasonal Structure



- Slow decay at all lags indicates non-stationarity (trend)
- Spikes at lags 12, 24, 36 confirm seasonal pattern ( $s = 12$ )
- ACF at seasonal lags shows slow decay  $\Rightarrow$  needs seasonal differencing

## F-test for Seasonal Dummies: Intuition

### What Does This Test Do?

Tests whether the **mean values differ significantly across seasons**.

- If January mean  $\neq$  February mean  $\neq \dots \neq$  December mean  $\Rightarrow$  seasonality
- Compares a model WITH seasonal dummies vs. a model WITHOUT

### The Models Being Compared

**Restricted:**  $Y_t = \alpha + \varepsilon_t$     **Unrestricted:**  $Y_t = \alpha + \sum_{j=1}^{s-1} \gamma_j D_{jt} + \varepsilon_t$   
where  $D_{jt} = 1$  if observation  $t$  is in season  $j$ , 0 otherwise.

### Key Idea

If adding seasonal dummies **significantly reduces** prediction errors, then seasonality is present.

## F-test for Seasonal Dummies: Formula and Example

### F-statistic Formula

$$F = \frac{(SSR_R - SSR_U)/(s - 1)}{SSR_U/(n - s)} \sim F_{s-1, n-s}$$

- $SSR_R$  = Sum of Squared Residuals from restricted model (no dummies)
- $SSR_U$  = Sum of Squared Residuals from unrestricted model (with dummies)
- $s - 1$  = number of restrictions (monthly: 11, quarterly: 3)

### Numerical Example (Monthly Data, n=120)

$SSR_R = 15000$ ,  $SSR_U = 8500$ ,  $s = 12$

$$F = \frac{(15000 - 8500)/11}{8500/108} = \frac{590.9}{78.7} = 7.51$$

Critical value  $F_{0.05, 11, 108} \approx 1.87$ . Since  $7.51 > 1.87$ : **Reject  $H_0$**   $\Rightarrow$  Seasonality present!

## Kruskal-Wallis Test: Intuition

### What Does This Test Do?

A **nonparametric** test that checks if observations from different seasons come from the same distribution.

- Works by **ranking** all observations from smallest to largest
- Checks if ranks are evenly distributed across seasons
- If one season consistently has higher/lower ranks  $\Rightarrow$  seasonality

### Why Use It Instead of F-test?

- **No normality assumption** – works with any distribution
- **Robust to outliers** – extreme values don't distort results

### Limitation

Less powerful than F-test when data IS normally distributed.

## Kruskal-Wallis Test: Formula and Example

### Test Statistic

$$H = \frac{12}{N(N+1)} \sum_{j=1}^s \frac{R_j^2}{n_j} - 3(N+1)$$

where  $N$  = total observations,  $n_j$  = obs. in season  $j$ ,  $R_j$  = sum of ranks in season  $j$ .

### Example: Quarterly Sales ( $n=20$ , $s=4$ )

Data ranked 1-20. Suppose rank sums by quarter:

- Q1:  $R_1 = 15$ , Q2:  $R_2 = 35$ , Q3:  $R_3 = 70$ , Q4:  $R_4 = 90$

$$H = \frac{12}{20 \times 21} \left( \frac{15^2}{5} + \frac{35^2}{5} + \frac{70^2}{5} + \frac{90^2}{5} \right) - 3(21) = 12.6$$

Critical value  $\chi^2_{0.05,3} = 7.81$ . Since  $12.6 > 7.81$ : **Reject  $H_0$**   $\Rightarrow$  Seasonality!

### In Python

```
scipy.stats.kruskal(q1, q2, q3, q4)
```

# HEGY Test: What Problem Does It Solve?

## The Key Question

Given a seasonal time series, we need to know:

- ① Does it need **regular differencing** ( $1 - L$ )?  $\Rightarrow$  set  $d = 1$
- ② Does it need **seasonal differencing** ( $1 - L^s$ )?  $\Rightarrow$  set  $D = 1$

HEGY tests for **both** types of unit roots simultaneously!

## Why Not Just Use ADF?

ADF only tests for a **regular** unit root at frequency zero. Seasonal data can have unit roots at **seasonal frequencies** that ADF misses!

## HEGY Tests Multiple Frequencies

Quarterly: tests at  $0, \pi, \pm\pi/2$ . Monthly: tests at  $0, \pi, \pm\pi/6, \pm\pi/3, \pm\pi/2, \pm2\pi/3, \pm5\pi/6$ .

## HEGY Test: Decision Rules with Examples

### HEGY Critical Values (5%, n=100, with constant)

Test	Statistic	Critical Value	If NOT rejected...
$t_1 (\pi_1 = 0)$	t-stat	-2.88	Need $d = 1$
$t_2 (\pi_2 = 0)$	t-stat	-2.88	Need $D = 1$
$F_{34} (\pi_3 = \pi_4 = 0)$	F-stat	6.57	Need $D = 1$

### Example: Quarterly GDP

Suppose HEGY gives:  $t_1 = -1.52$ ,  $t_2 = -4.21$ ,  $F_{34} = 2.15$

- $t_1 = -1.52 > -2.88$ : Cannot reject  $\Rightarrow$  **need  $d = 1$**
- $t_2 = -4.21 < -2.88$ : Reject  $\Rightarrow$  no unit root at  $\pi$
- $F_{34} = 2.15 < 6.57$ : Cannot reject  $\Rightarrow$  **need  $D = 1$**

**Conclusion:** Use SARIMA with  $d = 1, D = 1$

## Canova-Hansen Test: The Opposite of HEGY

HEGY vs Canova-Hansen: Different Null Hypotheses!

	HEGY	Canova-Hansen
$H_0$	Seasonal unit root	No seasonal unit root
$H_1$	No seasonal unit root	Seasonal unit root
Reject $H_0$	Use seasonal dummies	Use $(1 - L^s)$ differencing
Don't reject	Use $(1 - L^s)$ differencing	Use seasonal dummies

### Why Does This Matter?

- HEGY: “Prove there’s NO unit root” (conservative toward differencing)
- CH: “Prove there IS a unit root” (conservative toward dummies)
- Use **both** tests for robust conclusions!

## Summary: Choosing the Right Seasonality Test

Test	$H_0$	If Reject	Best For
F-test	No seasonality	Seasonality exists	Normal data
Kruskal-Wallis	No seasonal diff.	Seasonality exists	Non-normal, outliers
HEGY	Unit root exists	Use dummies	Determining $d, D$
Canova-Hansen	No unit root	Use $(1 - L^s)$	Confirming stability

### Key Insight

F-test/Kruskal-Wallis: “*Is there seasonality?*”    HEGY/Canova-Hansen: “*What type?*” (deterministic vs stochastic)

## Definition 2 (Seasonal Difference)

The **seasonal difference operator**  $\Delta_s$  is defined as:

$$\Delta_s Y_t = (1 - L^s) Y_t = Y_t - Y_{t-s}$$

where  $L^s Y_t = Y_{t-s}$  is the seasonal lag operator.

## Examples

- Monthly data ( $s = 12$ ):  $\Delta_{12} Y_t = Y_t - Y_{t-12}$   
Compares each month to the same month last year
- Quarterly data ( $s = 4$ ):  $\Delta_4 Y_t = Y_t - Y_{t-4}$   
Compares each quarter to the same quarter last year

# Combining Regular and Seasonal Differencing

## Full Differencing

For series with both trend and seasonality:

$$\Delta\Delta_s Y_t = (1 - L)(1 - L^s)Y_t$$

## Expansion

$$(1 - L)(1 - L^s)Y_t = Y_t - Y_{t-1} - Y_{t-s} + Y_{t-s-1}$$

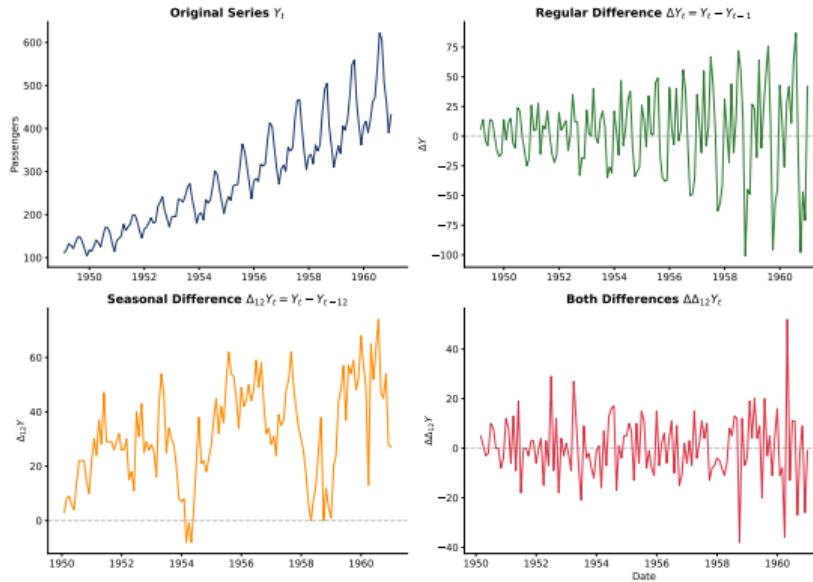
For monthly data ( $s = 12$ ):

$$\Delta\Delta_{12} Y_t = Y_t - Y_{t-1} - Y_{t-12} + Y_{t-13}$$

## Order of Differencing

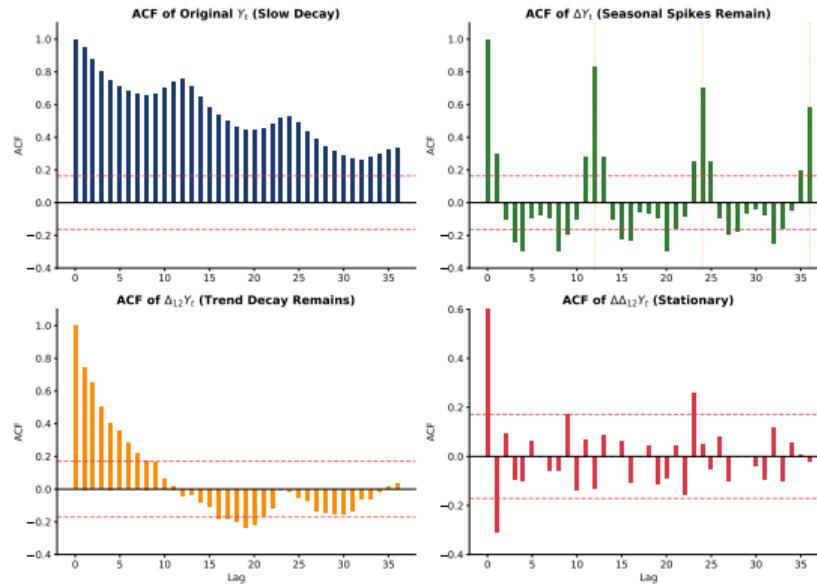
- $d$ : number of regular differences (trend removal)
- $D$ : number of seasonal differences (seasonal trend removal)

# Effect of Differencing Operations



- Regular differencing removes trend but seasonal pattern remains
- Seasonal differencing removes seasonality but trend pattern remains
- **Both differences** needed to achieve stationarity

# ACF Before and After Differencing



- Original ACF: slow decay indicates non-stationarity
- After  $\Delta$ : seasonal spikes remain at lags 12, 24, 36
- After  $\Delta_{12}$ : trend decay remains at early lags
- After  $\Delta\Delta_{12}$ : ACF cuts off  $\Rightarrow$  **stationary**

## Definition 3 (Seasonally Integrated Process)

A series  $Y_t$  is **seasonally integrated** of order  $(d, D)_s$ , written  $Y_t \sim I(d, D)_s$ , if:

$$(1 - L)^d (1 - L^s)^D Y_t$$

is stationary.

## Common Cases

- $I(1, 0)_{12}$ : Regular unit root only (monthly)
- $I(0, 1)_{12}$ : Seasonal unit root only
- $I(1, 1)_{12}$ : Both regular and seasonal unit roots

# SARIMA Model Definition

Definition 4 (SARIMA( $p, d, q$ )  $\times$  ( $P, D, Q$ ) $_s$ )

The **Seasonal ARIMA** model is:

$$\phi(L)\Phi(L^s)(1 - L)^d(1 - L^s)^D Y_t = c + \theta(L)\Theta(L^s)\varepsilon_t$$

## Components

- $\phi(L) = 1 - \phi_1L - \dots - \phi_pL^p$ : Non-seasonal AR
- $\Phi(L^s) = 1 - \Phi_1L^s - \dots - \Phi_PL^{Ps}$ : Seasonal AR
- $\theta(L) = 1 + \theta_1L + \dots + \theta_qL^q$ : Non-seasonal MA
- $\Theta(L^s) = 1 + \Theta_1L^s + \dots + \Theta_QL^{Qs}$ : Seasonal MA
- $(1 - L)^d$ : Regular differencing
- $(1 - L^s)^D$ : Seasonal differencing

# SARIMA Notation

## Full Specification

SARIMA( $p, d, q) \times (P, D, Q)_s$  has 7 parameters to specify:

Parameter	Meaning
$p$	Non-seasonal AR order
$d$	Non-seasonal differencing order
$q$	Non-seasonal MA order
$P$	Seasonal AR order
$D$	Seasonal differencing order
$Q$	Seasonal MA order
$s$	Seasonal period

## Example

SARIMA(1, 1, 1)  $\times$  (1, 1, 1)<sub>12</sub>: Monthly data with AR(1), MA(1), seasonal AR(1), seasonal MA(1), regular and seasonal differencing.

## Common SARIMA Models

Airline Model: SARIMA(0, 1, 1)  $\times$  (0, 1, 1)<sub>s</sub>

$(1 - L)(1 - L^s)Y_t = (1 + \theta L)(1 + \Theta L^s)\varepsilon_t$  – Classic model (Box & Jenkins, 1970)

SARIMA(1, 0, 0)  $\times$  (1, 0, 0)<sub>s</sub>

$(1 - \phi L)(1 - \Phi L^s)Y_t = \varepsilon_t$  – Pure seasonal and non-seasonal AR

SARIMA(0, 1, 1)  $\times$  (0, 1, 0)<sub>s</sub>

$(1 - L)(1 - L^s)Y_t = (1 + \theta L)\varepsilon_t$  – Random walk + seasonal diff + MA(1)

# The Multiplicative Structure

## Why Multiplicative?

The seasonal and non-seasonal parts **multiply**:

$$\phi(L)\Phi(L^s) \quad \text{and} \quad \theta(L)\Theta(L^s)$$

Example: SARIMA(1, 0, 0)  $\times$  (1, 0, 0)<sub>12</sub>

$$(1 - \phi L)(1 - \Phi L^{12}) Y_t = \varepsilon_t$$

$$\text{Expanding: } Y_t - \phi Y_{t-1} - \Phi Y_{t-12} + \phi\Phi Y_{t-13} = \varepsilon_t$$

The cross-term  $\phi\Phi Y_{t-13}$  captures interaction!

## Interpretation

Multiplicative structure allows parsimonious modeling of complex seasonal patterns with few parameters.

## Key Insight

Seasonal models show patterns at both:

- Non-seasonal lags:  $1, 2, 3, \dots$
- Seasonal lags:  $s, 2s, 3s, \dots$

Model	ACF	PACF
SAR( $P$ )	Decays at $s, 2s, \dots$	Cuts off after $Ps$
SMA( $Q$ )	Cuts off after $Qs$	Decays at $s, 2s, \dots$
SARMA	Decays at seasonal lags	Decays at seasonal lags

## Example: Airline Model ACF/PACF

SARIMA(0, 1, 1)  $\times$  (0, 1, 1)<sub>12</sub>

After differencing  $W_t = (1 - L)(1 - L^{12})Y_t$ :

$$W_t = (1 + \theta L)(1 + \Theta L^{12})\varepsilon_t$$

### Expected ACF Pattern

- Spike at lag 1 (from  $\theta$ )
- Spike at lag 12 (from  $\Theta$ )
- Spike at lag 13 (from  $\theta \cdot \Theta$  interaction)
- All other lags near zero

### Expected PACF Pattern

- Exponential decay at lags 1, 2, 3, ...
- Exponential decay at lags 12, 24, 36, ...

## Step-by-Step Process

- ① Examine ACF for slow decay at seasonal lags  $\Rightarrow$  seasonal differencing
- ② After differencing, check ACF/PACF patterns
- ③ Non-seasonal behavior at lags  $1, 2, \dots, s - 1$
- ④ Seasonal behavior at lags  $s, 2s, 3s, \dots$

## Practical Tips

- Start with  $d \leq 1$  and  $D \leq 1$
- Usually  $P, Q \leq 2$  is sufficient
- Use information criteria (AIC, BIC) for final selection
- Auto-SARIMA algorithms can help

## Maximum Likelihood Estimation

Standard approach for SARIMA:

- Conditional MLE (conditional on initial values)
- Exact MLE (via Kalman filter)

## Computational Considerations

- More parameters than ARIMA  $\Rightarrow$  more data needed
- Seasonal parameters estimated from lags  $s, 2s, \dots$
- Need sufficient seasonal cycles (at least 3-4 years of monthly data)

# Stationarity and Invertibility

## Stationarity Conditions

Both non-seasonal and seasonal AR polynomials must have roots outside the unit circle:

- $\phi(z) = 0 \Rightarrow |z| > 1$
- $\Phi(z^s) = 0 \Rightarrow |z| > 1$

## Invertibility Conditions

Both non-seasonal and seasonal MA polynomials must have roots outside the unit circle:

- $\theta(z) = 0 \Rightarrow |z| > 1$
- $\Theta(z^s) = 0 \Rightarrow |z| > 1$

## Residual Analysis

After fitting SARIMA, check that residuals are white noise:

- ① Plot residuals over time (no patterns)
- ② ACF of residuals (no significant spikes)
- ③ Ljung-Box test at multiple lags including seasonal
- ④ Normality tests (Q-Q plot, Jarque-Bera)

## Important

Check ACF at **both** non-seasonal and seasonal lags!

Significant ACF at lag 12 suggests inadequate seasonal modeling.

## Information Criteria

Compare competing SARIMA models using:

- $AIC = -2 \ln(L) + 2k$
- $BIC = -2 \ln(L) + k \ln(n)$
- $AICc = AIC + \frac{2k(k+1)}{n-k-1}$  (corrected for small samples)

where  $k = p + q + P + Q + 1$  (plus 1 for variance).

## Auto-SARIMA

Python's `pmdarima.auto_arima()` with `seasonal=True` automatically searches for optimal  $(p, d, q) \times (P, D, Q)_s$ .

## Forecast Computation

SARIMA forecasts are computed recursively:

- Replace future  $\varepsilon_{T+h}$  with 0
- Replace future  $Y_{T+h}$  with forecasts  $\hat{Y}_{T+h|T}$
- Use known past values  $Y_T, Y_{T-1}, \dots$

## Seasonal Pattern in Forecasts

SARIMA forecasts naturally capture seasonality:

- Short-term: influenced by recent values
- Long-term: revert to seasonal pattern

## Uncertainty Quantification

$(1 - \alpha)\%$  prediction interval:

$$\hat{Y}_{T+h|T} \pm z_{\alpha/2} \sqrt{\text{Var}(e_{T+h})}$$

Variance computed from  $\text{MA}(\infty)$  representation.

## Key Properties

- Intervals widen with forecast horizon
- For  $I(1, 1)_s$  series: intervals grow without bound
- Seasonal pattern visible in point forecasts
- Uncertainty captures both trend and seasonal variation

## Behavior as $h \rightarrow \infty$

- Point forecasts converge to deterministic seasonal pattern
- If drift present: linear trend + seasonal pattern
- Forecast intervals continue to widen

## Practical Implication

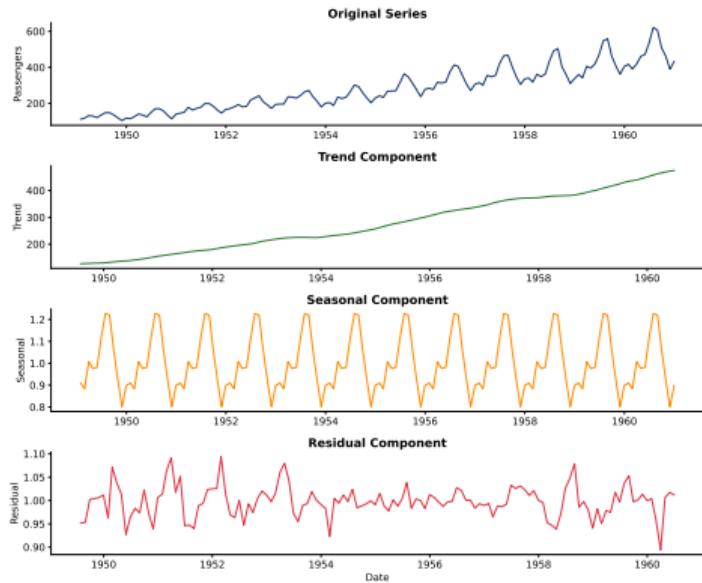
- Short-term: SARIMA captures both level and season
- Medium-term: Good seasonal forecasts, growing uncertainty
- Long-term: Mainly reflects seasonal pattern, wide intervals

## Airline Passengers Data



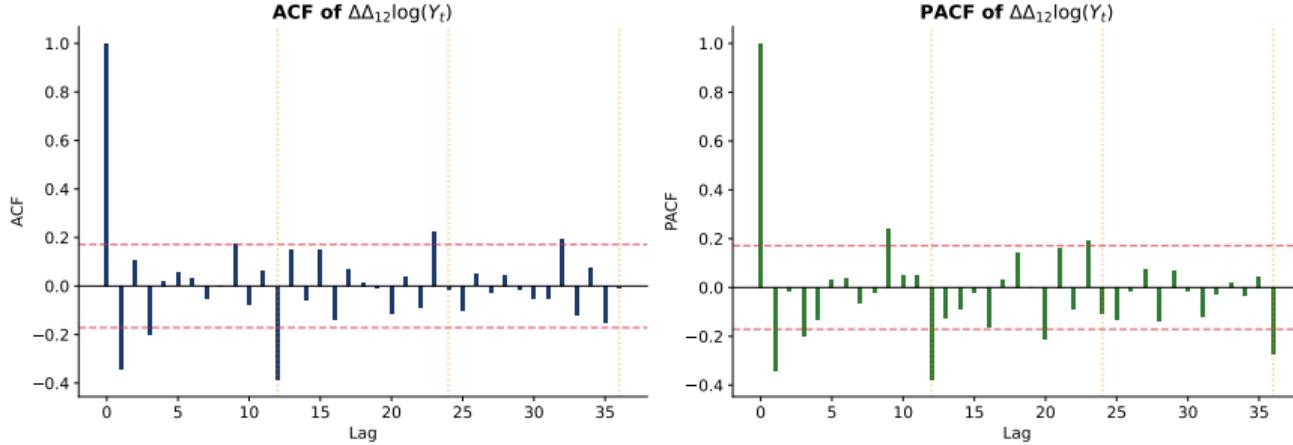
- Classic dataset: Monthly international airline passengers (1949-1960)
- Clear upward trend and growing seasonal amplitude

# Seasonal Decomposition



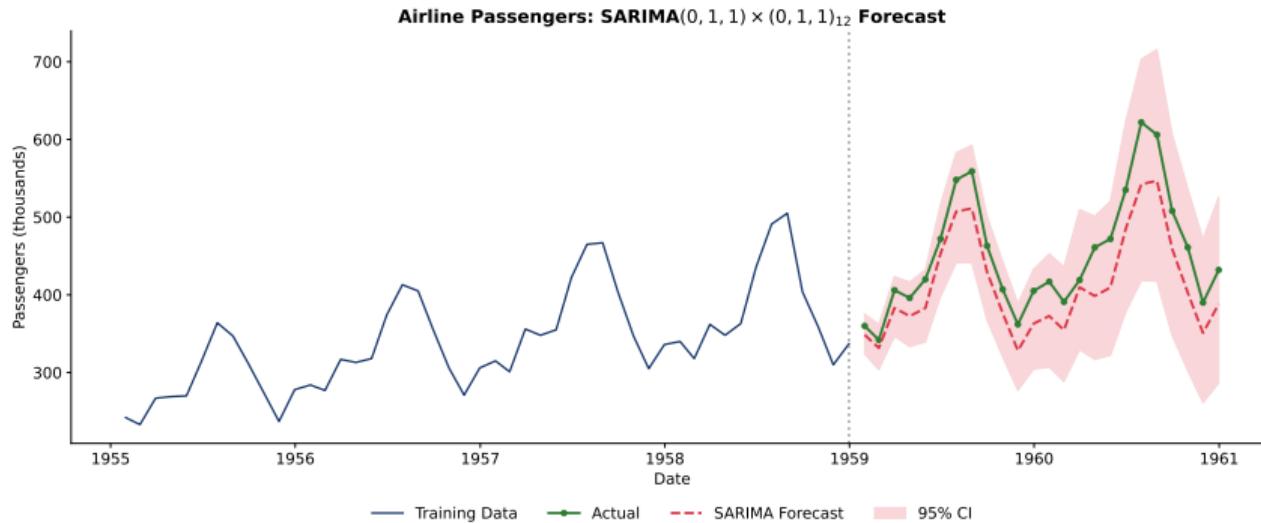
- Trend: Strong upward growth
- Seasonality: Summer peaks (vacation travel)
- Residual: Random variation after removing trend and season

# ACF/PACF Analysis



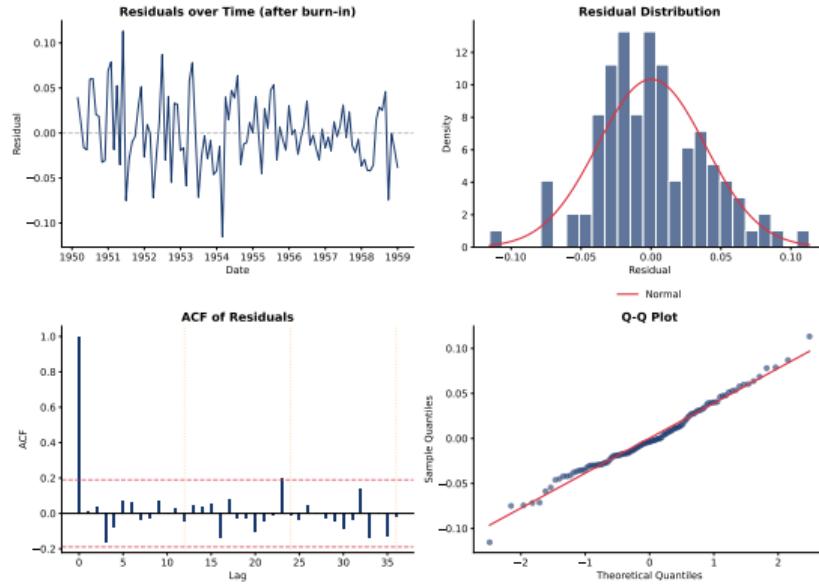
- After  $\Delta\Delta_{12}$  differencing: spikes at lags 1 and 12
- Suggests SARIMA(0, 1, 1)  $\times$  (0, 1, 1)<sub>12</sub> (Airline model)

# SARIMA Forecast Results



- SARIMA captures both trend and seasonal pattern
- Forecasts show appropriate seasonal peaks and troughs

# Model Diagnostics



- Residuals appear random; ACF within bounds at all lags
- Model adequately captures seasonal structure

## Fitting SARIMA in Python

```
from statsmodels.tsa.statespace.sarimax import SARIMAX  
  
model = SARIMAX(y, order=(0,1,1), seasonal_order=(0,1,1,12))  
results = model.fit()  
forecast = results.get_forecast(steps=24)
```

## Note

Complete Python examples with comments are provided in the Jupyter notebooks.

# Key Takeaways

## Main Points

- ① Seasonality is common in economic and business data
- ② Seasonal differencing  $(1 - L^s)$  removes stochastic seasonality
- ③ SARIMA( $p, d, q$ )  $\times$  ( $P, D, Q$ )<sub>s</sub> extends ARIMA for seasonal data
- ④ Multiplicative structure captures seasonal-trend interactions
- ⑤ ACF/PACF show patterns at both regular and seasonal lags
- ⑥ Model selection: Use AIC/BIC or auto-SARIMA algorithms

## Next Steps

Chapter 5 will cover multivariate time series: VAR models, Granger causality, and cointegration.

## References

-  Box, G.E.P., Jenkins, G.M., Reinsel, G.C., & Ljung, G.M. (2015). *Time Series Analysis: Forecasting and Control*. 5th ed. Wiley.
-  Hyndman, R.J. & Athanasopoulos, G. (2021). *Forecasting: Principles and Practice*. 3rd ed. OTexts.
-  Hamilton, J.D. (1994). *Time Series Analysis*. Princeton University Press.
-  Brockwell, P.J. & Davis, R.A. (2016). *Introduction to Time Series and Forecasting*. 3rd ed. Springer.