

Multiscale Testing for Equality of Nonparametric Trend Curves

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We develop multiscale methods to test qualitative hypotheses about nonparametric time trends in the presence of covariates. In many applications, practitioners are interested whether the observed time series all have the same time trend. Moreover, when some of the trends are different, it may be useful to know exactly which of the time trends are different. In addition, when two trends are not the same, it may also be relevant to know in which time regions they differ from each other. We design multiscale tests to formally approach these questions. We derive asymptotic theory for the proposed tests and show that the proposed test has asymptotic power of one against a certain class of local alternatives.

Key words: Multiscale statistics; nonparametric regression; time series errors; shape constraints; strong approximations; anti-concentration bounds.

AMS 2010 subject classifications: 62E20; 62G10; 62G20; 62M10.

1 Introduction

Comparison of several regression curves is a classical topic in econometrics and statistics. In many cases of practical interest, the functional forms of the objective regression curves are unknown, hence, the parametric approach is not applicable. In this paper, we propose a novel approach that addresses this particular problem in a nonparametric context. Specifically, we present a new testing procedure for detecting differences between the nonparametric trends curves.

In what follows, we consider a general panel framework with heterogeneous trends. Suppose we observe a panel of n time series $\mathcal{W}_i = \{(Y_{it}, \mathbf{X}_{it}) : 1 \leq t \leq T\}$ for $1 \leq i \leq n$, where Y_{it} are real-valued random variables and $\mathbf{X}_{it} = (X_{it,1}, \dots, X_{it,d})^\top$ are d -dimensional random vectors. Each time series \mathcal{W}_i is modelled by the equation

$$Y_{it} = m_i\left(\frac{t}{T}\right) + \beta_i^\top \mathbf{X}_{it} + \alpha_i + \varepsilon_{it} \quad (1.1)$$

for $1 \leq t \leq T$, where β_i is a $d \times 1$ vector of unknown parameters, \mathbf{X}_{it} is a $d \times 1$ vector of individual covariates or controls, m_i is an unknown nonparametric (deterministic) trend function defined on $[0, 1]$, α_i are so-called fixed effect error terms and $\mathcal{E}_i = \{\varepsilon_{it} : 1 \leq t \leq T\}$ is a zero-mean stationary error process.

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An important question in many applications is whether the observed time series have a common trend. In other words, the researchers would like to know if m_i are the same for all i . Moreover, when there is evidence that this is not the case, one of the major related statistical problems is to determine which of the trends are different. In addition, when two trends m_i and m_j are not the same, it may also be relevant to know in which time regions they differ from each other. In this paper, we introduce new statistical methods to approach these questions. In particular, we develop a test of the hypothesis that all time trends in model (1.1) are the same. In this setting, the null hypothesis is formulated as

$$H_0 : m_1 = m_2 = \dots = m_n, \quad (1.2)$$

whereas the alternative hypothesis is

$$H_1 : \text{there exists } x \in [0, 1] \text{ such that } m_i(x) \neq m_j(x) \text{ for some } 1 \leq i < j \leq n.$$

The method that we propose does not only allow to test whether the null hypothesis is violated. It also allows to detect, with a given statistical confidence, which time trends are different and in which time regions they differ. More specifically, for any given interval $[u - h, u + h] \subseteq [0, 1]$, consider the hypothesis

$$H_0^{[i,j]}(u, h) : m_i(w) = m_j(w) \text{ for all } w \in [u - h, u + h].$$

Here, we can regard h as a bandwidth, a common tuning parameter in nonparametric estimation. The given interval $\mathcal{I}_{(u,h)} = [u - h, u + h] \subseteq [0, 1]$ is then fully characterized by u , its center (a location parameter), and h , the bandwidth. In order to determine the regions where the time trends are different, we consider a broad range of pairs (u, h) with the property that they fully cover the unit interval $[0, 1]$. Formally, let $\mathcal{G} := \{(u, h) : \mathcal{I}_{(u,h)} = [u - h, u + h] \subseteq [0, 1]\}$ be a grid of location-bandwidth points such that

$$\bigcup_{(u,h) \in \mathcal{G}} \mathcal{I}_{(u,h)} = [0, 1].$$

We then reformulate our null hypothesis (1.2) as

$$H_0 : \text{The hypotheses } H_0^{[i,j]}(u, h) \text{ hold true for all intervals } \mathcal{I}_{(u,h)}, (u, h) \in \mathcal{G}, \\ \text{and for all } 1 \leq i < j \leq n.$$

$H_0^{[i,j]}(u, h)$ can thus be viewed as a local null hypothesis that characterizes the behavior of two trend functions only locally, whereas H_0 specified in (1.2) is the global null hypothesis that is concerned with the comparison of all of the trends on the whole unit interval.

In this paper, we introduce a method that allows us to test the hypotheses $H_0^{[i,j]}(u, h)$ simultaneously for all pairs (i, j) and for all intervals $\mathcal{I}_{(u, h)}$ under consideration. Specifically, we develop a multiscale test for the model (1.1). The underlying idea of any multiscale test is to consider a number of test statistics (each corresponding to a different set of values of some tuning parameters) all at once rather than to perform a separate test for each single test statistics. In our case, this means testing many local null hypotheses $H_0^{[i,j]}(u, h)$ simultaneously which leads to a well-known multiple testing problem. Our method accounts for this problem by using appropriate critical values that depend on the scale of the problem, i.e. on the number of hypotheses tested simultaneously and the relationship between them. In the paper, we show that the suggested procedure for obtaining critical values leads to good theoretical properties of the proposed test: it has the correct (asymptotic) level and an (asymptotic) power of one against a certain class of local alternatives.

Trend comparison is a common statistical problem that arises in various contexts. For example, in economics the researchers compare trends in real gross domestic product across several countries (Grier and Tullock, 1989), in yield over time of US Treasury bills at different maturities (Park et al., 2009), or the evolution of long-term interest rates in a number of countries (Christiansen and Pigott, 1997). In finance, comparison and subsequent classification of the trends of market fragmentation can be used to assess the market quality in the European stock market (Vogt and Linton, 2017, 2020). In climatology, the temperature time series in different geographical areas are investigated in the context of the regional and global warming trends (Károly and Wu, 2005). Finally, in industry, mobile phone providers are interested in finding the differences between the cell phone download activity in various locations (Degras et al., 2012).

In the statistical literature, the problem of testing whether the observed time series all have the same trend has been widely studied, and tests for equality of trends or regression curves have been developed in Härdle and Marron (1990), Hall and Hart (1990), Delgado (1993) and Degras et al. (2012) among many others. Versions of model (1.1) with a parametric trend are considered in Vogelsang and Franses (2005), Sun (2011) and Xu (2012) among others. In the nonparametric context, Li et al. (2010), Atak et al. (2011), Robinson (2012) and Chen et al. (2012) studied panel models under the assumption that the observed time series have a common time trend. However, in many applications the restriction of including a common time trend in the model is questionable at best. For instance, when we observe a large number of time series it is reasonable to expect that at least some of the trends are different from the others. Consequently, it often makes sense to relax the assumption of a common trend, which leads to more flexible panel settings with heterogeneous trends. Such models have been studied, for example, in Degras et al. (2012), Zhang et al. (2012) and Hidalgo and Lee (2014). Degras et al. (2012) consider the problem of testing H_0 in a model that is a special case of (1.1) and does not include additional regressors. Chen and Wu (2018) develop theory for

a very similar model framework but under more general conditions on the error terms. Zhang et al. (2012) investigate the problem of testing the hypothesis H_0 in a slightly restricted version of model (1.1), where $\beta_i = \beta$ for all i . All of these tests have an important drawback: they involve classical nonparametric estimation of the trend functions that depends on one or several bandwidth parameters, which imposes a certain limit on the applicability of such tests since in most cases it is far from clear how to choose bandwidth parameters in an appropriate way. Contrary to the aforementioned methods, our multiscale testing procedure allows us to consider a large collection of bandwidths simultaneously avoiding the problem of choosing only one bandwidth altogether.

Recently, Khismatullina and Vogt (2021) proposed a new inference method that allows researchers to detect differences between epidemic time trends in the context of the COVID-19 pandemic. In their paper, the authors present a statistically rigorous procedure that, similarly to ours, not only allows to compare trends across different countries, but to pinpoint the time intervals where the differences occur as well. Moreover, they also circumvent the need to pick a bandwidth parameter by using a multiscale testing approach. However, the model in Khismatullina and Vogt (2021) is only a special case of the model (1.1) which includes neither the covariates \mathbf{X}_{it} , nor the fixed effects α_i . Furthermore, the authors place major restriction on the error terms: in their model, ε_{it} are independent across t . In contrast, our model (1.1) can be regarded as a generalized version of theirs that allows for a wider range of economic and financial applications.

To sum up, the main theoretical contribution of the current paper is the multiscale testing method that allows to make simultaneous confidence statements about which of the time trends are distinct and the regions where they differ. We believe that currently there are no equivalent statistical methods. Even though tests for equality of the trends have been developed already for a while, most existing procedures allow only to test whether the trend curves are all the same or not, but they almost never allow to infer which curves are different and where. To the best of our knowledge, the only two exceptions are Khismatullina and Vogt (2021), whose contribution is briefly discussed above, and Park et al. (2009) who developed SiZer methods for the comparison of nonparametric trend curves in a significantly simplified version of the model (1.1). In addition to restricted model, Park et al. (2009) derive theoretical results for their analysis only for the special case of observing only two time series, whereas in other cases, the algorithm is provided without detailed proof.

The structure of the paper is as follows. Section 2 introduces the model setting and the necessary technical assumptions that are required for the theory. The multiscale test is developed step by step in Section 3. The main theoretical results are presented in Section 4. Section 5 deals with estimating the unknown parameters necessary for construction of the test statistics. To keep the discussion as clear as possible, we include in the main text of the paper only the essential parts of the theoretical arguments, and the technical details and extended proofs are deferred to the Appendix. Section 7

concludes.

2 The model

Throughout the paper, we adopt the following notation. For a real-valued vector $\mathbf{v} = (v_1, \dots, v_m) \in \mathbb{R}^m$, we write $|\mathbf{v}| = (\sum_{i=1}^m v_i^2)^{1/2}$ and $|\mathbf{v}|_q = (\sum_{i=1}^m v_i^q)^{1/q}$ respectively. For a random vector \mathbf{V} , we define its $\mathcal{L}^q, q > 1$ norm as $\|\mathbf{V}\|_q = (\mathbb{E}|\mathbf{V}|^q)^{1/q}$. For the particular case $q = 2$, we write $\|\mathbf{V}\| := \|\mathbf{V}\|_2$.

Let $\epsilon_t, t \in \mathbb{Z}$, be independent and identically distributed (i.i.d.) random variables and let \mathbf{L} be a measurable real-valued vector function such that $\mathbf{L}(\dots, \epsilon_{t-1}, \epsilon_t)$ is a properly defined random variable. Denote $\mathcal{F}_t = (\dots, \epsilon_{t-1}, \epsilon_t)$. Following Wu (2005), we define the *physical dependence measure* for the process $\mathbf{L}(\mathcal{F}_t)$ as the following:

$$\delta_q(\mathbf{L}, t) = \|\mathbf{L}(\mathcal{F}_t) - \mathbf{L}(\mathcal{F}'_t)\|_q, \quad (2.1)$$

where $\mathcal{F}'_t = (\dots, \epsilon_{-1}, \epsilon'_0, \epsilon_1, \dots, \epsilon_{t-1}, \epsilon_t)$ is a coupled process of \mathcal{F}_t with ϵ'_0 being an i.i.d. copy of ϵ_0 . Intuitively, $\delta_q(\mathbf{L}, t)$ measures the dependency of $\mathbf{L}(\mathcal{F}_t)$ on ϵ_0 , i.e., how replacing ϵ_0 by an i.i.d. copy while keeping all other innovations in place affects the output $\mathbf{L}(\mathcal{F}_t)$.

2.1 Setting

As was already briefly discussed in Section 1, the model setting is as follows. We observe a panel of n time series $\mathcal{W}_i = \{(Y_{it}, \mathbf{X}_{it}) : 1 \leq t \leq T\}$ of length T for $1 \leq i \leq n$. Each time series \mathcal{W}_i satisfies the model equation

$$Y_{it} = \boldsymbol{\beta}_i^\top \mathbf{X}_{it} + m_i\left(\frac{t}{T}\right) + \alpha_i + \varepsilon_{it} \quad (2.2)$$

for $1 \leq t \leq T$, where $\boldsymbol{\beta}_i$ is a $d \times 1$ vector of unknown parameters, \mathbf{X}_{it} is a $d \times 1$ vector of individual covariates, m_i is an unknown nonparametric trend function defined on $[0, 1]$ with $\int_0^1 m_i(u) du = 0$ for all i , α_i is a (deterministic or random) intercept term and $\mathcal{E}_i = \{\varepsilon_{it} : 1 \leq t \leq T\}$ is a zero-mean stationary error process. As common in nonparametric regression, the trend functions m_i in model (2.2) depend on rescaled time t/T rather than on real time t . Using rescaled time is equivalent to restricting the domain of the functions to the unit interval which in turn allows us to apply the usual asymptotic arguments. Discussion about the application of the rescaled time in the context of nonparametric estimation can be found in Robinson (1989), Dahlhaus (1997) and Vogt and Linton (2014). The condition $\int_0^1 m_i(u) du = 0$ for all i is a necessary identification condition due the presence of α_i . Without imposing this condition, we can freely increase the functions m_i by any (positive or negative) constant c_i while simultaneously subtract the same constant from the intercept term α_i :

$$Y_{it} = [m_i(t/T) + c_i] + \boldsymbol{\beta}_i^\top \mathbf{X}_{it} + [\alpha_i - c_i] + \varepsilon_{it}.$$

The term α_i can be regarded as an additional error component. In the econometrics literature, it is commonly called a fixed effect and is often interpreted as the term which captures unobserved characteristics of the time series \mathcal{W}_i that remain constant over time. We allow the error terms α_i to be dependent across i in an arbitrary way. Hence, by including them in model equation (2.2), we allow the n time series \mathcal{W}_i in our panel to be correlated with each other. Whereas the terms α_i may be correlated, the error processes \mathcal{E}_i are assumed to be independent across i . As usual in nonparametric estimation, we also assume that all the trend functions $m_i(\cdot)$ are continuously differentiable on $[0, 1]$. Technical conditions regarding the model are discussed further in this section.

Finally, throughout the paper we restrict attention to the case where the number of time series n in model (2.2) is fixed. Extending our theoretical results to the case where n slowly grows with the sample size T is a possible topic for further research.

2.2 Assumptions

Each process \mathcal{E}_i is supposed to satisfy the following conditions:

- (C1) **The variables ε_{it} are independent across i** and for each i the variables ε_{it} allow for the representation $\varepsilon_{it} = G_i(\dots, \eta_{it-1}, \eta_{it})$, where η_{it} are i.i.d. random variables across t and $G_i : \mathbb{R}^{\mathbb{Z}} \rightarrow \mathbb{R}$ is a measurable function. Denote $\mathcal{J}_{it} = (\dots, \eta_{it-2}, \eta_{it-1}, \eta_{it})$.
- (C2) For all i it holds that $\mathbb{E}[\varepsilon_{it}] = 0$ and $\|\varepsilon_{it}\|_q < \infty$ for some $q > 4$ **(uncorrelatedness from (C9) is enough, we do not use $\mathbb{E}[\varepsilon_{it}|\mathbf{X}_{it}] = 0$ in the proofs)**.

Assumption (C1) can be translated as the restriction on the error process \mathcal{E}_i to be stationary and causal (in the sense that ε_{it} does not depend on the future innovations η_{is} , $s > t$). The class of error processes that satisfies the condition (C1) is massive, and includes linear processes, their nonlinear transformation, as well as a large variety of nonlinear processes such as Markov chain models and nonlinear autoregressive models (Wu and Wu, 2016). Assumption (C2) is a standard moment condition.

Following Wu (2005), we impose conditions on the dependence structure of the error processes \mathcal{E}_i in terms of the physical dependence measure $\delta_q(G_i, t)$ defined in (2.1). In particular, we assume the following:

- (C3) Define $\Theta_{i,t,q} = \sum_{s \geq t} \delta_q(G_i, s)$ for $t \geq 0$. For each i it holds that $\Theta_{i,t,q} = O(t^{-\tau_q}(\log t)^{-A})$, where $A > \frac{2}{3}(1/q + 1 + \tau_q)$ and $\tau_q = \{q^2 - 4 + (q - 2)\sqrt{q^2 + 20q + 4}\}/8q$.

For fixed i and t , $\Theta_{i,t,q}$ measures the cumulative effect of η_0 on $(\varepsilon_{is})_{s \geq t}$ in terms of \mathcal{L}^q -norm. Condition (C3) assumes that the overall cumulative effect is finite and puts

some restrictions on the rate of decay of $\Theta_{i,t,q}$. Assumption (C3) is fulfilled by a wide range of stationary processes \mathcal{E}_i . For a detailed discussion of assumption (C3), as well as assumptions (C1)–(C2) and some examples of the error processes that satisfy these conditions, see Khismatullina and Vogt (2020).

Regarding the independent variables \mathbf{X}_{it} , we assume the following for each i :

- (C4) The covariates \mathbf{X}_{it} allow for the representation $\mathbf{X}_{it} = \mathbf{H}_i(\dots, u_{it-1}, u_{it})$ with u_{it} being i.i.d. across t (I do not think that we need independence across i , can you have a look?) random variables and $\mathbf{H}_i := (H_{i1}, H_{i2}, \dots, H_{id})^\top : \mathbb{R}^{\mathbb{Z}} \rightarrow \mathbb{R}^d$ being a measurable function such that $\mathbf{H}_i(\mathcal{U}_{it})$ is well defined. We denote $\mathcal{U}_{it} = (\dots, u_{it-1}, u_{it})$.
- (C5) Let \mathbf{N}_i be the $d \times d$ matrix with kl -th entry $n_{i,kl} = \mathbb{E}[H_{ik}(\mathcal{U}_{i0})H_{il}(\mathcal{U}_{i0})]$. We assume that the smallest eigenvalue of \mathbf{N}_i is strictly bigger than 0.
- (C6) Let $\mathbb{E}[\mathbf{H}_i(\mathcal{U}_{i0})] = \mathbf{0}$ and $\|\mathbf{H}_i(\mathcal{U}_{it})\|_{q'} < \infty$ for some $q' > \max\{2\theta, 4\}$, where θ will be introduced further in Assumption (C12).
- (C7) $\sum_{s=0}^{\infty} \delta_{q'}(\mathbf{H}_i, s) < \infty$ for q' from Assumption (C6).
- (C8) For each i it holds that $\sum_{s=t}^{\infty} \delta_{q'}(\mathbf{H}_i, s) = O(t^{-\alpha})$ for q' from Assumption (C6) and for some $\alpha > 1/2 - 1/q'$.

As with the error processes \mathcal{E}_i , \mathbf{X}_i is guaranteed to be stationary and causal by Assumption (C4). Assumptions (C5) and (C6) are technical conditions that prevent asymptotic multicollinearity and ensure that all the necessary moments exist, respectively. Moreover, similarly to the restriction on the error processes, we also employ the definition of the physical dependence measure $\delta_q(\cdot, \cdot)$ in Assumptions (C7) - (C8), thus, making certain that the cumulative effect of the innovation u_0 on $(\mathbf{X}_{it})_{t \geq 0}$ is finite.

To be able to prove the main theorems in Section 3, we need additional assumptions on the relationship between the covariates and the error process.

- (C9) \mathbf{X}_{it} (elementwise) and ε_{is} are uncorrelated for each $t, s \in \{1, \dots, T\}$.
- (C10) Let $\zeta_{i,t} = (u_{it}, \eta_{it})^\top$. Define $\mathcal{I}_{it} = (\dots, \zeta_{i,t-1}, \zeta_{i,t})$ and $\mathbf{U}_i(\mathcal{I}_{it}) = \mathbf{H}_i(\mathcal{U}_{it})G_i(\mathcal{J}_{it})$. With this notation at hand, we assume that $\sum_{s=0}^{\infty} \delta_2(\mathbf{U}_i, s) < \infty$.

Assumption (C9) is a slightly relaxed independence assumption: even though we do not require the covariates \mathbf{X}_{it} to be completely independent with the error terms ε_{it} , our theoretical results depend upon them being uncorrelated. We in particular need this restriction in order to prove asymptotic consistency for the differencing estimator $\hat{\beta}_i$ of β_i proposed in Section 5.1. In principle, it would be possible to relax this assumption even further, but that would involve much more complicated estimation procedure

of β_i and more arduous technical arguments. Assumption (C10) ensures short-range dependence among the variables in our model. Again, we can interpret this as the fact that the cumulative effect of a single error on all future values is bounded.

We employ these assumptions to prove the main theoretical results in our paper. For detailed proofs, we refer the reader to the Appendix.

Remark 2.1. *The conditions (C4)–(C10) can be relaxed to cover nonstationary regressors as well as stationary ones. For example, (C4) may then be replaced by*

(C4) The covariates \mathbf{X}_{it} allow for the representation $\mathbf{X}_{it} = \mathbf{H}_i(t; \dots, u_{it-1}, u_{it})$ with u_{it} being i.i.d. random variables and $\mathbf{H}_i := (H_{i1}, H_{i2}, \dots, H_{id})^\top : \mathbb{R}^{\mathbb{Z}} \rightarrow \mathbb{R}^d$ is a measurable function such that $\mathbf{H}_i(t; \mathcal{U}_{it})$ is well defined.*

The other assumptions can be adjusted accordingly. Our main theoretical results will in principle still hold in this case, however, the complexity of the technical arguments will increase drastically. Hence, for the sake of clarity, we restrict our attention only to stationary covariates \mathbf{X}_{it} .

3 Testing procedure

In this section, we develop a multiscale testing procedure for the problem of comparison of the trend curves m_i in model (2.2). As we will see, the proposed multiscale method does not only allow to test whether the null hypothesis is violated. It also provides information on where violations occur. More specifically, it allows to identify, with a pre-specified confidence, (i) trend functions which are different from each other and (ii) time intervals where these trend functions differ.

3.1 Preliminary steps

Testing the null hypothesis $H_0 : m_1 = m_2 = \dots = m_n$ in model (2.2) is a challenging task not only because it involves nonparametric estimation of the functions $m_i(\cdot)$, but also due to the presence of an unknown fixed term α_i and a vector of unknown parameters β_i . It is clear that if α_i and β_i are known, the problem of testing for the common time trend would be greatly simplified. That is, we would test $H_0 : m_1 = m_2 = \dots = m_n$ in the model

$$\begin{aligned} Y_{it} - \alpha_i - \beta_i^\top \mathbf{X}_{it} &=: Y_{it}^\circ \\ &= m_i\left(\frac{t}{T}\right) + \varepsilon_{it}, \end{aligned}$$

which is a standard nonparametric regression equation. However, in reality the variables Y_{it}° are not observed since the intercept α_i and the coefficients β_i are not known.

Nevertheless, given appropriate estimators $\hat{\alpha}_i$ and $\hat{\beta}_i$, we can consider

$$\hat{Y}_{it} := Y_{it} - \hat{\alpha}_i - \hat{\beta}_i^\top \mathbf{X}_{it} = (\beta_i - \hat{\beta}_i)^\top \mathbf{X}_{it} + m_i\left(\frac{t}{T}\right) + (\alpha_i - \hat{\alpha}_i) + \varepsilon_{it}.$$

Thus, the unobserved variables Y_{it}° can be approximated by \hat{Y}_{it} , and in what follows we show that under some mild conditions on $\hat{\alpha}_i$ and $\hat{\beta}_i$, this approximation is indeed sufficient for our analysis.

But before we proceed further, we show how to construct consistent estimates $\hat{\alpha}_i$ and $\hat{\beta}_i$. To begin with, we focus on the estimation of the vector of unknown parameters β_i . We construct the estimator $\hat{\beta}_i$ in the following way.

For each i , we consider the time series $\{\Delta Y_{it} : 2 \leq t \leq T\}$ of the differences $\Delta Y_{it} = Y_{it} - Y_{it-1}$. We can write

$$\Delta Y_{it} = Y_{it} - Y_{it-1} = \beta_i^\top \Delta \mathbf{X}_{it} + \left(m_i\left(\frac{t}{T}\right) - m_i\left(\frac{t-1}{T}\right) \right) + \Delta \varepsilon_{it},$$

where $\Delta \mathbf{X}_{it} = \mathbf{X}_{it} - \mathbf{X}_{it-1}$ and $\Delta \varepsilon_{it} = \varepsilon_{it} - \varepsilon_{it-1}$. Since $m_i(\cdot)$ is Lipschitz (by our assumption that $m_i(\cdot)$ is continuously differentiable on $[0, 1]$), we can use the fact that $|m_i(\frac{t}{T}) - m_i(\frac{t-1}{T})| = O(\frac{1}{T})$ and rewrite

$$\Delta Y_{it} = \beta_i^\top \Delta \mathbf{X}_{it} + \Delta \varepsilon_{it} + O\left(\frac{1}{T}\right). \quad (3.1)$$

Now, for each i we employ the least squares estimation method to estimate β_i in (3.1), treating $\Delta \mathbf{X}_{it}$ as the regressors and ΔY_{it} as the response variable. That is, we propose the following differencing estimator:

$$\hat{\beta}_i = \left(\sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta \mathbf{X}_{it}^\top \right)^{-1} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta Y_{it} \quad (3.2)$$

We will show in Section 5.1 that $\hat{\beta}_i$ is a consistent estimator of β_i with the property $\beta_i - \hat{\beta}_i = O_P(T^{-1/2})$.

Next, given $\hat{\beta}_i$, consider an appropriate estimator $\hat{\alpha}_i$ for the intercept α_i calculated by

$$\begin{aligned} \hat{\alpha}_i &= \frac{1}{T} \sum_{t=1}^T (Y_{it} - \hat{\beta}_i^\top \mathbf{X}_{it}) = \frac{1}{T} \sum_{t=1}^T (\beta_i^\top \mathbf{X}_{it} - \hat{\beta}_i^\top \mathbf{X}_{it} + \alpha_i + m_i(t/T) + \varepsilon_{it}) = \\ &= (\beta_i - \hat{\beta}_i)^\top \frac{1}{T} \sum_{t=1}^T \mathbf{X}_{it} + \alpha_i + \frac{1}{T} \sum_{i=1}^T m_i(t/T) + \frac{1}{T} \sum_{i=1}^T \varepsilon_{it}. \end{aligned} \quad (3.3)$$

Note that $\frac{1}{T} \sum_{i=1}^T \varepsilon_{it} = O_P(T^{-1/2})$ and $\frac{1}{T} \sum_{i=1}^T m_i(t/T) = O(T^{-1})$ due to Lipschitz continuity of m_i and normalization $\int_0^1 m_i(u) du = 0$. Furthermore, $\frac{1}{T} \sum_{t=1}^T \mathbf{X}_{it} = O_P(1)$ by Chebyshev's inequality and $\hat{\beta}_i - \beta_i = O_P(T^{-1/2})$. Plugging all these results together in (3.3), we get that $\hat{\alpha}_i - \alpha_i = O_P(T^{-1/2})$. Thus, the unobserved variables $Y_{it}^\circ := Y_{it} - \beta_i^\top \mathbf{X}_{it} - \alpha_i = m_i(t/T) + \varepsilon_{it}$ can be well approximated by \hat{Y}_{it} since $\hat{Y}_{it} = Y_{it} - \hat{\alpha}_i - \hat{\beta}_i^\top \mathbf{X}_{it} = Y_{it}^\circ + O_P(T^{-1/2})$.

We now turn to the estimator of the long-run error variance $\sigma_i^2 = \sum_{\ell=-\infty}^{\infty} \text{Cov}(\varepsilon_{i0}, \varepsilon_{i\ell})$ which is necessary for the construction of the test statistics later on. For the moment, we assume that the long-run variance does not depend on i , that is $\sigma_i^2 = \sigma^2$ for all i . We will need this further for conducting the testing procedure properly. Nevertheless, we keep the indices throughout the paper in order to be congruous in notation. We further let $\hat{\sigma}_i^2$ be an estimator of σ_i^2 which is computed from the constructed sample $\{\hat{Y}_{it} : 1 \leq t \leq T\}$. We thus regard $\hat{\sigma}_i^2 = \hat{\sigma}_i^2(\hat{Y}_{i1}, \dots, \hat{Y}_{iT})$ as a function of the variables \hat{Y}_{it} for $1 \leq t \leq T$. Hence, whereas the true long-run variance is the same for all time series, the estimators are different. Throughout the section, we assume that $\hat{\sigma}_i^2 = \sigma_i^2 + o_p(\rho_T)$ where the conditions on ρ_T will be provided further in Section 4. Details on how to construct $\hat{\sigma}_i^2$ are deferred to Section 5.2.

3.2 Construction of the test statistics

We are now ready to introduce the multiscale statistic for testing the hypothesis $H_0 : m_1 = m_2 = \dots = m_n$. For any pair of time series i and j and for any location-bandwidth pair (u, h) , we define the kernel averages

$$\hat{\psi}_{ij,T}(u, h) = \sum_{t=1}^T w_{t,T}(u, h)(\hat{Y}_{it} - \hat{Y}_{jt}), \quad (3.4)$$

where $w_{t,T}(u, h)$ are the local linear kernel weights calculated by the following formula:

$$w_{t,T}(u, h) = \frac{\Lambda_{t,T}(u, h)}{\{\sum_{t=1}^T \Lambda_{t,T}(u, h)^2\}^{1/2}}, \quad (3.5)$$

where

$$\Lambda_{t,T}(u, h) = K\left(\frac{\frac{t}{T} - u}{h}\right) \left[S_{T,2}(u, h) - \left(\frac{\frac{t}{T} - u}{h}\right) S_{T,1}(u, h) \right],$$

$S_{T,\ell}(u, h) = (Th)^{-1} \sum_{t=1}^T K\left(\frac{\frac{t}{T} - u}{h}\right) \left(\frac{\frac{t}{T} - u}{h}\right)^\ell$ for $\ell = 1, 2$ and K is a kernel function. As common in the nonparametric estimation, we assume that K has the following properties:

- (C11) The kernel K is non-negative, symmetric about zero and integrates to one. Moreover, it has compact support $[-1, 1]$ and is Lipschitz continuous, that is, $|K(v) - K(w)| \leq C|v - w|$ for any $v, w \in \mathbb{R}$ and some constant $C > 0$.

Assumption (C11) allows us to use the usual kernel functions such as rectangular, Epanechnikov and Gaussian kernels.

We regard the kernel average $\hat{\psi}_{ij,T}(u, h)$ as a measure of the distance between the two trend curves m_i and m_j on the interval $\mathcal{I}_{(u,h)} = [u-h, u+h]$. However, instead of working directly with the kernel averages $\hat{\psi}_{ij,T}(u, h)$, we replace them by their normalized and corrected version:

$$\hat{\psi}_{ij,T}^0(u, h) = \left| \frac{\hat{\psi}_{ij,T}(u, h)}{(\hat{\sigma}_i^2 + \hat{\sigma}_j^2)^{1/2}} \right| - \lambda(h). \quad (3.6)$$

Here, $\lambda(h) = \sqrt{2 \log\{1/(2h)\}}$ is an additive correction term that balances the significance of many test statistics that correspond to different values of bandwidth parameters (see the discussion on this topic and comparison between multiscale testing procedures with and without this correction term in Khismatullina and Vogt (2020)).

We now aggregate the test statistics $\hat{\psi}_{ij,T}^0(u, h)$ for all i and j and a wide range of different locations u and bandwidths (scales) h :

$$\hat{\Psi}_{n,T} = \max_{1 \leq i < j \leq n} \max_{(u,h) \in \mathcal{G}_T} \hat{\psi}_{ij,T}^0(u, h), \quad (3.7)$$

In (3.7), \mathcal{G}_T stands for the set of location-bandwidth pairs (u, h) that was mentioned in Section 1. We use the subscript T in \mathcal{G}_T to point out that the choice of the grid depends on the sample size T . Specifically, throughout the paper, we suppose that \mathcal{G}_T is some subset of $\mathcal{G}_T^{\text{full}} = \{(u, h) : u = t/T \text{ and } h = s/T \text{ for some } 1 \leq t, s \leq T \text{ such that } h \in [h_{\min}, h_{\max}]\}$, where h_{\min} and h_{\max} denote some minimal and maximal bandwidth value, respectively. As was already discussed in Section 1, we assume that the set of intervals $\{\mathcal{I}_{(u,h)} = [u - h, u + h] : (u, h) \in \mathcal{G}_T\}$ covers the whole unit interval. Furthermore, for our theoretical results, we require the following additional conditions to hold:

(C12) $|\mathcal{G}_T| = O(T^\theta)$ for some arbitrarily large but fixed constant $\theta > 0$, where $|\mathcal{G}_T|$ denotes the cardinality of \mathcal{G}_T .

(C13) $h_{\min} \gg T^{-(1-\frac{2}{q})} \log T$, that is, $h_{\min}/\{T^{-(1-\frac{2}{q})} \log T\} \rightarrow \infty$ with $q > 4$ defined in (C2) and $h_{\max} < 1/2$.

Assumption (C12) places relatively mild restrictions on the grid \mathcal{G}_T : we allow the grid to grow with the sample size but only at a polynomial rate T^θ with fixed θ . This is not a severe constraint because under this limitation, we can still work with the full set of location-bandwidth points $\mathcal{G}_T = \mathcal{G}_T^{\text{full}}$ which is more than enough for most applied problems. Assumption (C13) is concerned with the minimal and the maximal bandwidths that we use for our analysis. Specifically, according to Assumption (C13), we can choose the minimal bandwidth h_{\min} that converges to zero slower than $T^{-(1-\frac{2}{q})} \log T$ as the sample size T goes to infinity. The maximal bandwidth h_{\max} can be picked very large.

Note that the value $\max_{(u,h) \in \mathcal{G}_T} \hat{\psi}_{ij,T}^0(u, h)$ simultaneously takes into account all intervals $\mathcal{I}_{(u,h)} = [u - h, u + h]$ with $(u, h) \in \mathcal{G}_T$. Thus, it can be interpreted as a global distance measure between the two curves m_i and m_j , and the test statistics $\hat{\Psi}_{n,T}$ is then defined as the maximal distance between any pair of curves m_i and m_j with $i \neq j$.

In Section 3.3, we show how to test the null hypothesis $H_0 : m_1 = m_2 = \dots = m_n$ using the multiscale test statistics $\hat{\Psi}_{n,T}$.

3.3 The testing procedure

Let Z_{it} for $1 \leq t \leq T$ and $1 \leq i \leq n$ be independent standard normal random variables which are independent of the error terms ε_{js} and the covariates \mathbf{X}_{js} for all $1 \leq s \leq T$ and $1 \leq j \leq n$. Denote the empirical average of the variables Z_{i1}, \dots, Z_{iT} by $\bar{Z}_{i,T} = T^{-1} \sum_{t=1}^T Z_{it}$. To simplify the notation, we will omit the subscript T in $\bar{Z}_{i,T}$ in what follows. Similarly as with $\hat{\psi}_{ij,T}^0(u, h)$, for each i and j , we introduce the normalized and corrected Gaussian kernel averages

$$\phi_{ij,T}^0(u, h) = \left| \frac{\phi_{ij,T}(u, h)}{(\sigma_i^2 + \sigma_j^2)^{1/2}} \right| - \lambda(h), \quad (3.8)$$

where

$$\phi_{ij,T}(u, h) = \sum_{t=1}^T w_{t,T}(u, h) \{ \sigma_i(Z_{it} - \bar{Z}_i) - \sigma_j(Z_{jt} - \bar{Z}_j) \} \quad (3.9)$$

with $w_{t,T}(u, h)$ defined in (3.5).

Next, in the same way as in (3.7), we define the global Gaussian test statistic

$$\Phi_{n,T} = \max_{1 \leq i < j \leq n} \max_{(u,h) \in \mathcal{G}_T} \phi_{ij,T}^0(u, h) \quad (3.10)$$

and denote its $(1 - \alpha)$ -quantile by $q_{n,T}(\alpha)$.

Our multiscale test of the hypothesis $H_0 : m_1 = m_2 = \dots = m_n$ is defined as follows:

For a given significance level $\alpha \in (0, 1)$, we reject H_0 if $\hat{\Psi}_{n,T} > q_{n,T}(\alpha)$.

Remark 3.1. *To prove the theoretical results in Section 4, we will use the following fact. By our assumption that the long-run variance σ_i^2 does not depend on i (i.e. $\sigma_i^2 = \sigma_j^2 = \sigma^2$), we can rewrite the Gaussian normalized kernel averages (3.8) as*

$$\phi_{ij,T}^0(u, h) = \frac{1}{\sqrt{2}} \left| \sum_{t=1}^T w_{t,T}(u, h) \{ (Z_{it} - \bar{Z}_i) - (Z_{jt} - \bar{Z}_j) \} \right| - \lambda(h),$$

which means that the distribution of the Gaussian test statistics does not depend neither on the data $\mathcal{W}_i = \{(Y_{it}, \mathbf{X}_{it}) : 1 \leq t \leq T\}$, $\mathcal{W}_j = \{(Y_{jt}, \mathbf{X}_{jt}) : 1 \leq t \leq T\}$, nor on any unknown quantities such as σ_i^2 or σ_j^2 , and thus can be regarded as known. In addition to exploiting this fact while proving the theoretical results, we will also use it for calculating (approximately) the quantiles of $\Phi_{n,T}$ by the Monte Carlo simulations in Section 3.5. However, for the sake of similarity to $\hat{\psi}_{ij,T}^0(u, h)$, in what follows, we will stick to the definition (3.8), which involves the long-run variances σ_i and σ_j .

Remark 3.2. *By construction, the $(1 - \alpha)$ Gaussian quantile $q_{n,T}(\alpha)$ depends not only on the number of times series considered n and the sample size T , but on the choice of the set of location-bandwidth pairs \mathcal{G}_T as well. However, we do not explicitly include this dependence since we believe it will only lead to the unnecessary complication of the notation.*

3.4 Locating the differences

Suppose we reject the null hypothesis H_0 . This fact does not provide us with a lot of information about the behaviour of the trend functions $m_i(\cdot)$. After performing the test described in Section 3.3, we can only make confidence statements that some of the trend functions are not equal somewhere on $[0, 1]$ (with a given statistical confidence), but we can not tell which of the functions are different and where they differ. Hence, we need an additional step in the testing procedure in order to locate those differences. Formally, for a given pair of time series (i, j) and for any given interval $\mathcal{I}_{(u,h)} = [u - h, u + h]$ such that $(u, h) \in \mathcal{G}_T$ we consider the hypothesis

$$H_0^{[i,j]}(u, h) : m_i(w) = m_j(w) \text{ for all } w \in [u - h, u + h].$$

We view $H_0^{[i,j]}(u, h)$ as the 'local' null hypothesis because it is concerned with only two trend functions $m_i(\cdot)$ and $m_j(\cdot)$ and their equality on a small, 'local', interval $\mathcal{I}_{(u,h)} = [u - h, u + h]$. In contrast, we refer to H_0 introduced in (1.2) as the global null hypothesis.

We define the multiscale test of the hypothesis $H_0^{[i,j]}(u, h)$ as follows:

For a given significance level $\alpha \in (0, 1)$, we reject $H_0^{[i,j]}(u, h)$ if $\hat{\psi}_{ij,T}^0(u, h) > q_{n,T}(\alpha)$.

For each pair of time series (i, j) , denote the set of intervals $\mathcal{I}_{(u,h)}$ that consists of the intervals where we reject $H_0^{[i,j]}(u, h)$ at a significance level α by $\mathcal{S}^{[i,j]}(\alpha)$. We will prove later in Section 4, that we can make the following confidence statements:

We can state with (asymptotic) probability at least $1 - \alpha$ that for all i, j , $1 \leq i < j \leq n$, we have that $m_i(\cdot)$ and $m_j(\cdot)$ differ on all of the intervals $\mathcal{I}_{(u,h)} \in \mathcal{S}^{[i,j]}(\alpha)$.

3.5 Implementation of the test in practice

In practice, we implement the test procedure described in Sections 3.3 and 3.4 in the following way.

Step 1. Fix a significance level $\alpha \in (0, 1)$.

Step 2. Compute the (approximated) quantile $q_{n,T}(\alpha)$ by Monte Carlo simulations. Specifically, draw a large number N (say $N = 5000$) of samples of independent standard normal random variables $\{Z_{it}^{(\ell)} : 1 \leq t \leq T, 1 \leq i \leq n\}$ for $1 \leq \ell \leq N$. For each sample ℓ , compute the value $\Phi_{n,T}^{(\ell)}$ of the Gaussian test statistics $\Phi_{n,T}$ and store them. Calculate the empirical $(1 - \alpha)$ -quantile $\hat{q}_{n,T}(\alpha)$ from the stored values $\{\Phi_{n,T}^{(\ell)} : 1 \leq \ell \leq N\}$. Use $\hat{q}_{n,T}(\alpha)$ as an approximated value of the quantile $q_{n,T}(\alpha)$.

Step 3. Carry out the test for the global hypothesis H_0 by calculating $\widehat{\Psi}_{n,T}$ and checking if $\widehat{\Psi}_{n,T} > \widehat{q}_{n,T}(\alpha)$. Reject the null if it is true.

Step 4. For each i, j , $1 \leq i < j \leq n$, and each $(u, h) \in \mathcal{G}_T$, carry out the test for the local null hypothesis $H_0^{[i,j]}(u, h)$ by checking if $\widehat{\psi}_{ij,T}^0(u, h) > \widehat{q}_{n,T}(\alpha)$. For each pair of time series (i, j) , find the set of intervals $\mathcal{S}^{[i,j]}(\alpha)$ that consists of the intervals where we reject $H_0^{[i,j]}(u, h)$.

Step 5. Display the results. One of the possible ways to do that is to produce a separate plot for each of the pairwise comparisons and draw only the intervals where we reject the corresponding local null. Formally, on each of the plots that present the results of the comparison of time series i and j , we display the intervals $\mathcal{I}_{(u,h)} = [u - h, u + h] \in \mathcal{S}^{[i,j]}(\alpha)$, i.e. the (rescaled) time intervals where we reject $H_0^{[i,j]}(u, h)$.

4 Theoretical properties of the test

In order to investigate the theoretical properties of our multiscale test, we introduce two auxiliary test statistics. First auxiliary test statistics $\widehat{\Phi}_{n,T}$ can be regarded as a version of $\widehat{\Psi}_{n,t}$ which is exactly equal to it under the global null:

$$\widehat{\Phi}_{n,T} = \max_{1 \leq i < j \leq n} \max_{(u,h) \in \mathcal{G}_T} \widehat{\phi}_{ij,T}^0(u, h), \quad (4.1)$$

where

$$\widehat{\phi}_{ij,T}^0(u, h) = \left| \frac{\widehat{\phi}_{ij,T}(u, h)}{\{\widehat{\sigma}_i^2 + \widehat{\sigma}_j^2\}^{1/2}} \right| - \lambda(h) \quad (4.2)$$

$$\text{and } \widehat{\phi}_{ij,T}(u, h) = \sum_{t=1}^T w_{t,T}(u, h) \{(\varepsilon_{it} - \bar{\varepsilon}_i) + (\beta_i - \widehat{\beta}_i)^\top (\mathbf{X}_{it} - \bar{\mathbf{X}}_i) - (\varepsilon_{jt} - \bar{\varepsilon}_j) - (\beta_j - \widehat{\beta}_j)^\top (\mathbf{X}_{jt} - \bar{\mathbf{X}}_j)\}.$$

Here we denote $\bar{\varepsilon}_i = \bar{\varepsilon}_{i,T} := T^{-1} \sum_{t=1}^T \varepsilon_{it}$ and $\bar{\mathbf{X}}_i = \bar{\mathbf{X}}_{i,T} := T^{-1} \sum_{t=1}^T \mathbf{X}_{it}$. Note that under the global null, we have $\widehat{\phi}_{ij,T}(u, h) = \widehat{\psi}_{ij,T}(u, h)$, $\widehat{\phi}_{ij,T}^0(u, h) = \widehat{\psi}_{ij,T}^0(u, h)$ and $\widehat{\Phi}_{n,T} = \widehat{\Psi}_{n,T}$, where the first two equalities hold true even under the corresponding local null $H_0^{[i,j]}(u, h)$. Hence, in order to determine the distribution of our main test statistic $\widehat{\Psi}_{n,T}$ under the null, we can simply study the behaviour of $\widehat{\Phi}_{n,T}$.

However, $\widehat{\Phi}_{n,T}$ depends on the covariates \mathbf{X}_{it} whereas the Gaussian version $\Phi_{n,T}$ that is used to calculate critical values for our test (defined in (3.10)) is independent of them. This is the reason why we need to introduce additional intermediate test statistic that does not include the covariates, therefore, connecting $\widehat{\Phi}_{n,T}$ and $\Phi_{n,T}$. This intermediate test statistics will play an important role in the proof of our main theoretical result.

Formally, for each i, j we construct the kernel averages as

$$\widehat{\phi}_{ij,T}(u, h) = \sum_{t=1}^T w_{t,T}(u, h) \{(\varepsilon_{it} - \bar{\varepsilon}_i) - (\varepsilon_{jt} - \bar{\varepsilon}_j)\}.$$

We can view these kernel averages as constructed under the null from the unobserved variables \widehat{Y}_{it} and \widehat{Y}_{jt} given by the following formula:

$$\begin{aligned} \widehat{Y}_{it} &:= Y_{it} - \beta_i^\top \mathbf{X}_{it} - \frac{1}{T} \sum_{t=1}^T (Y_{it} - \beta_i^\top \mathbf{X}_{it}) = \\ &= m_i\left(\frac{t}{T}\right) - \frac{1}{T} \sum_{t=1}^T m_i\left(\frac{t}{T}\right) + \varepsilon_{it} - \frac{1}{T} \sum_{t=1}^T \varepsilon_{it}. \end{aligned}$$

The intermediate statistic $\widehat{\Phi}_{n,T}$ is then defined as

$$\widehat{\Phi}_{n,T} = \max_{1 \leq i < j \leq n} \max_{(u,h) \in \mathcal{G}_T} \left\{ \left| \frac{\widehat{\phi}_{ij,T}(u, h)}{(\widehat{\sigma}_i^2 + \widehat{\sigma}_j^2)^{1/2}} \right| - \lambda(h) \right\} \quad (4.3)$$

with $\widehat{\sigma}_i^2$ being an estimator of the long-run error variance $\sigma_i^2 = \sum_{\ell=-\infty}^{\infty} \text{Cov}(\varepsilon_{i0}, \varepsilon_{i\ell})$ which is computed from the unobserved sample $\{\widehat{Y}_{it} : 1 \leq t \leq T\}$. We thus regard $\widehat{\sigma}_i^2 = \widehat{\sigma}_i^2(\widehat{Y}_{i1}, \dots, \widehat{Y}_{iT})$ as a function of the variables \widehat{Y}_{it} for $1 \leq t \leq T$. As with the estimator $\widehat{\sigma}_i^2$, we assume that $\widehat{\sigma}_i^2 = \sigma_i^2 + o_p(\rho_T)$ with $\rho_T = o(\sqrt{h_{\min}}/\log T)$.

The statistics $\widehat{\Phi}_{n,T}$ can thus be viewed as a version of the statistic $\widehat{\Phi}_{n,T}$ without the covariates. We formally prove that these two statistics are close in Proposition A.8.

Now we can formally state our main theoretical result which characterizes the asymptotic behaviour of the statistic $\widehat{\Phi}_{n,T}$.

Theorem 4.1. *Suppose that the error processes $\mathcal{E}_i = \{\varepsilon_{it} : 1 \leq t \leq T\}$ are independent across i and satisfy (C1)–(C3) for each i . Moreover, let (C4)–(C13) be fulfilled and assume that for all i , $m_i(\cdot)$ is a continuously differentiable function on $[0, 1]$ satisfying the property $\int_0^1 m_i(u) du = 0$. Furthermore, for all i , $i \in \{1, \dots, n\}$ assume that we have $\sigma_i^2 = \sigma^2$, $\widehat{\sigma}_i^2 = \sigma_i^2 + o_p(\rho_T)$ and $\widehat{\sigma}_i^2 = \sigma_i^2 + o_p(\rho_T)$ with $\rho_T = o(\sqrt{h_{\min}}/\log T)$. Then*

$$\mathbb{P}(\widehat{\Phi}_{n,T} \leq q_{n,T}(\alpha)) = (1 - \alpha) + o(1).$$

Theorem 4.1 is the principal instrument for deriving theoretical properties of our multiscale test. The full proof of the theorem is provided in the Appendix. Here, we briefly present the main arguments.

First, we show that the distribution of the intermediate statistics $\widehat{\Phi}_{n,T}$ introduced in (4.3) is indeed close to the distribution of $\widehat{\Phi}_{n,T}$, and therefore, we can approximate the distribution of $\widehat{\Phi}_{n,T}$ with the help of $\widehat{\Phi}_{n,T}$.

Second, we show that we can replace $\widehat{\Phi}_{n,T}$ by an identically distributed version $\widetilde{\Phi}_{n,T}$ which is close to the Gaussian statistics $\Phi_{n,T}$ defined in (3.10). Formally, by the means of strong approximation theory derived in Berkes et al. (2014) we prove that there exist statistics $\widetilde{\Phi}_{n,T}$ which are distributed as $\widehat{\Phi}_{n,T}$ for any $T \geq 1$ and which have the property that

$$|\widetilde{\Phi}_{n,T} - \Phi_{n,T}| = o_p(\delta_T), \quad (4.4)$$

where $\delta_T = o(1)$.

Then, we employ the anti-concentration results derived in Chernozhukov et al. (2015) in order to show that $\Phi_{n,T}$ does not concentrate too strongly in small regions of the form $[x - \delta_T, x + \delta_T]$. Or, in other words, it holds that

$$\sup_{x \in \mathbb{R}} \mathbb{P}(|\Phi_{n,T} - x| \leq \delta_T) = o(1) \quad (4.5)$$

Taking (4.4) together with (4.5) and the fact that $\widetilde{\Phi}_{n,T}$ has the same distribution as $\widehat{\Phi}_{n,T}$ yields that

$$\sup_{x \in \mathbb{R}} |\mathbb{P}(\widehat{\Phi}_{n,T} \leq x) - \mathbb{P}(\Phi_{n,T} \leq x)| = o(1).$$

And finally, by the fact mentioned in the beginning of this proof that the distribution of the intermediate statistics $\widehat{\Phi}_{n,T}$ is close to the distribution of $\widehat{\Phi}_{n,T}$, we conclude that

$$\sup_{x \in \mathbb{R}} |\mathbb{P}(\widehat{\Phi}_{n,T} \leq x) - \mathbb{P}(\Phi_{n,T} \leq x)| = o(1),$$

which immediately implies the statement of Theorem 4.1.

Remark 4.1. *The proof of Theorem 4.1 builds on two important theoretical results: strong approximation theory developed in Berkes et al. (2014) and anti-concentration results proved in Chernozhukov et al. (2015). These results were already combined together for the purpose of developing the multiscale test for dependent data in Khismatullina and Vogt (2020). We can say that our proof can be regarded as a further development of the proof strategy in Khismatullina and Vogt (2020) where they proposed a similar testing procedure for investigating properties of the trend function in one time series. We extend their theoretical result not only by working with multiple time series, but also by including the covariate terms in the model (1.1). Hence, our proof strategy builds on the similar stones but is much more technically involved.*

Now we examine the theoretical properties of the testing procedure proposed in Sections 3.3 and 3.4 with the help of Theorem 4.1. The following proposition (which is a direct consequence of Theorem 4.1) states that our test has correct (asymptotical) size.

Proposition 4.2. *Suppose that the conditions of Theorem 4.1 are satisfied. Then under the null H_0 , we have*

$$\mathbb{P}(\widehat{\Psi}_{n,T} \leq q_{n,T}(\alpha)) = (1 - \alpha) + o(1).$$

The next proposition characterizes the behaviour of our multiscale test under a particular class of local alternatives. To formulate this result, we consider a sequence of pairs of functions $m_i := m_{i,T}$ and $m_j := m_{j,T}$ that depend on the sample size and that are locally sufficiently far from each other.

Proposition 4.3. *Let the conditions of Theorem 4.1 be satisfied. Moreover, assume that for some pair of indices i and j , the functions $m_i = m_{i,T}$ and $m_j = m_{j,T}$ have the following property: There exists $(u, h) \in \mathcal{G}_T$ with $[u - h, u + h] \subseteq [0, 1]$ such that $m_{i,T}(w) - m_{j,T}(w) \geq c_T \sqrt{\log T / (Th)}$ for all $w \in [u - h, u + h]$ or $m_{j,T}(w) - m_{i,T}(w) \geq c_T \sqrt{\log T / (Th)}$ for all $w \in [u - h, u + h]$, where $\{c_T\}$ is any sequence of positive numbers with $c_T \rightarrow \infty$. Then*

$$\mathbb{P}(\widehat{\Psi}_{n,T} \leq q_{n,T}(\alpha)) = o(1).$$

Proof of Proposition 4.3 is provided in the Appendix.

Finally, we turn our attention to the local null hypotheses $H_0^{[i,j]}(u, h)$. Since we are testing many hypotheses at the same time, we would like to bound the probability of making even one false discovery. For this purpose, we employ the notion of the family-wise error rate (FWER) which is equal to the probability of making one or more type I errors. Formally, FWER is defined as:

$$\text{FWER}(\alpha) = \mathbb{P}(\exists i, j \in \{1, \dots, n\}, (u, h) \in \mathcal{G}_T : \mathcal{I}_{(u,h)} \in \mathcal{S}^{[i,j]}(\alpha) \text{ and } H_0^{[i,j]}(u, h) \text{ is true}).$$

We say that the FWER is controlled at level α if $\text{FWER}(\alpha) \leq \alpha$. The following result assures that for our testing procedure, it is indeed the case:

Proposition 4.4. *Suppose that the conditions of Theorem 4.1 are satisfied. Then*

$$\text{FWER}(\alpha) \leq \alpha.$$

Proposition 4.4 is a direct consequence of Theorem 4.1. Nevertheless, the detailed proof of this proposition is provided in the Appendix.

The following corollary is an immediate consequence of Proposition 4.4 and gives the theoretical justification necessary for making simultaneous confidence statements about the locations of the differences between the trends.

Corollary 4.5. *Under the conditions of Theorem 4.1, for any given $\alpha \in (0, 1)$ we have*

$$\mathbb{P}\left(\forall i, j \in \{1, \dots, n\}, (u, h) \in \mathcal{G}_T \text{ such that } H_0^{[i,j]}(u, h) \text{ is true} : |\hat{\psi}_{ij,T}^0(u, h)| \leq q_{n,T}(\alpha)\right) \geq 1 - \alpha + o(1).$$

With the help of Corollary 4.5, we are able to make simultaneous confidence statements about which of the trends are different and where:

We can state with (asymptotic) probability at least $1 - \alpha$ that for all $i, j \in \{1, \dots, n\}$, we have that $m_i(\cdot)$ and $m_j(\cdot)$ differ on all of the intervals $\mathcal{I}_{(u,h)} \in \mathcal{S}^{[i,j]}(\alpha)$.

5 Estimation of the parameters

5.1 Estimation of β_i

As was already mentioned in Section 3.1, for each i , we construct a differencing estimator $\hat{\beta}_i$ of the vector of unknown parameters β_i using the first differences:

$$\hat{\beta}_i = \left(\sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta \mathbf{X}_{it}^\top \right)^{-1} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta Y_{it} \quad (5.1)$$

where $\Delta \mathbf{X}_{it} = \mathbf{X}_{it} - \mathbf{X}_{it-1}$ and $\Delta Y_{it} = Y_{it} - Y_{it-1}$. The asymptotic consistency for this differencing estimator is given by the following theorem:

Theorem 5.1. *Under the conditions of Theorem 4.1, we have*

$$\beta_i - \hat{\beta}_i = O_P\left(\frac{1}{\sqrt{T}}\right),$$

where $\hat{\beta}_i$ is the differencing estimator given by (5.1).

Detailed proof of the Theorem 5.1 is provided in the Appendix. Here we briefly outline the main steps of the proof.

After rearranging the terms, we can write

$$\begin{aligned} \sqrt{T}(\hat{\beta}_i - \beta_i) &= \left(\frac{1}{T} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta \mathbf{X}_{it}^\top \right)^{-1} \frac{1}{\sqrt{T}} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta m_{it} \\ &\quad + \left(\frac{1}{T} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta \mathbf{X}_{it}^\top \right)^{-1} \frac{1}{\sqrt{T}} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta \varepsilon_{it}, \end{aligned} \quad (5.2)$$

where $\Delta m_{it} = m_i\left(\frac{t}{T}\right) - m_i\left(\frac{t-1}{T}\right)$ and $\Delta \varepsilon_{it} = \varepsilon_{it} - \varepsilon_{it-1}$.

We look at each part of (5.2) separately. First, by Assumption (C6) and applying Chebyshev's and Cauchy-Schwarz inequalities we show that

$$\frac{1}{\sqrt{T}} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta m_{it} = O_P\left(\frac{1}{\sqrt{T}}\right).$$

Then, by similar arguments and applying Proposition A.10, we have that

$$\left| \left(\frac{1}{T} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta \mathbf{X}_{it}^\top \right)^{-1} \right| = O_P(1),$$

where $|A|$ with A being a matrix is any matrix norm.

These two facts together lead to the fact that the first summand in (5.2) is $O_P(1/\sqrt{T})$.

Finally, we turn our attention to the second summand in (5.2). We already know that $\left| \left(\frac{1}{T} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta \mathbf{X}_{it}^\top \right)^{-1} \right| = O_P(1)$. Moreover, by Proposition A.13,

$$\left| \frac{1}{\sqrt{T}} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta \varepsilon_{it} \right| = O_P(1).$$

Hence, we have that

$$\left(\frac{1}{T} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta \mathbf{X}_{it}^\top \right)^{-1} \frac{1}{\sqrt{T}} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta \varepsilon_{it} = O_P(1). \quad (5.3)$$

The statement of the theorem follows.

5.2 Estimation of σ_i^2

Following Kim (2016), we estimate the long-run variance σ_i for each of the time series i using the variant of the subseries variance estimator proposed first by Carlstein (1986) and then extended by Wu and Zhao (2007). Formally, we set

$$\hat{\sigma}_i^2 = \frac{1}{2(M-1)s_T} \sum_{m=1}^M \left[\sum_{t=1}^{s_T} \left(Y_{i(t+ms_T)} - Y_{i(t+(m-1)s_T)} - \hat{\beta}_i^\top (\mathbf{X}_{i(t+ms_T)} - \mathbf{X}_{i(t+(m-1)s_T)}) \right) \right]^2, \quad (5.4)$$

where s_T is the length of subseries and $M = \lfloor T/s_T \rfloor$ is the largest integer not exceeding T/s_T . As per the optimality result in Carlstein (1986), we set $s_T \asymp T^{1/3}$. For a finite sample, we choose $s_T = \lfloor T^{1/3} \rfloor$. According to Lemma A.14 in Appendix, $\hat{\sigma}_i^2$ is an asymptotically consistent estimator of σ_i^2 with the rate of convergence $O_P(T^{-1/3})$. Recall that the rate of convergence of $\hat{\sigma}_i^2$ necessary for proving our theoretical results is $o_P(\rho_T)$ with $\rho_T = o(\sqrt{h_{\min}}/\log T)$. Hence, for our theory to work with this estimator, we need to put some restrictions on ρ_T . Specifically, we need to have $T^{-1/3}/\rho_T = o(1)$ which can be translated to the following condition on the minimal bandwidth:

$$h_{\min} \gg T^{-2/3} \log^{2+2\iota} T \text{ for some } \iota > 0. \quad (5.5)$$

Remember that under Assumption (C13), we have that $h_{\min} \gg T^{-(1-\frac{2}{q})} \log T$. Taking into account (5.5), we can rewrite Assumption (C13) as follows:

(C13*) $h_{\min} \gg \max\{T^{-(1-\frac{2}{q})} \log T, T^{-2/3} \log^{2+2\iota} T\}$, that is, $h_{\min}/\{T^{-(1-\frac{2}{q})} \log T\} \rightarrow \infty$ with $q > 4$ defined in (C2) and $h_{\min}/\{T^{-2/3} \log^{2+2\iota} T\} \rightarrow \infty$ for some $\iota > 0$, and $h_{\max} < 1/2$.

This means that we can for example have $\rho_T = T^{-1/3} \log^l T$, which is still a slower rate of convergence than $T^{-1/3}$. To sum up, under the Assumptions (C1) - (C12), (C13*), the subseries variance estimator provided by (5.4) satisfies the necessary conditions for Theorem 4.1, and thus can be used for the construction of our multiscale statistics $\widehat{\Psi}_{n,T}$.

6 Applications

6.1 Analysis of the GDP growth

To illustrate our test method from Section 3, we repeat an application example from Zhang et al. (2012), where the authors test the hypothesis of a common trend in the GDP growth data for 16 OECD countries. Since we do not have access neither to the original dataset from Zhang et al. (2012), nor to the exact data specifications, we perform our analysis on the data available from the most commonly used sources: Barro-Lee Educational Attainment dataset (Barro and Lee, 2013), Refinitiv Datastream, OECD.Stat database, and Federal Reserve Economics Data (FRED). In our illustration example, we consider the specification of the data that is as close as possible to the one in Zhang et al. (2012) with one important distinction. In the original study, the authors examine 16 OECD countries (not specifying which ones), whereas we consider only 11 OECD countries: Australia, Austria, Canada, Finland, France, Germany, Japan, Norway, Switzerland, UK, and USA. The reason for focusing our attention on 11 countries lies in the fact that only for these countries there exist quarterly data of good quality covering the time period used in the original study: from the fourth quarter of 1975 up to and including the third quarter of 2010. In the appendix, we repeat the analysis for these 11 countries plus additional 5 countries for which some of the time series contain missing values. We use linear extrapolation to impute the missing values for these countries. Details how this extrapolation is done are deferred to Section ??.

For this example, we collect the data from multiple sources. In the following list, we provide the specifications for the variables that we use in our analysis.

1. **GDP:** We use data on the Gross Domestic Product - Expenditure Approach (*GDP*) downloaded from the OECD.Stat database (<https://stats.oecd.org/Index.aspx>). The data are freely available and were accessed on 7 December 2021. To be as close as possible to the specification of the data in Zhang et al. (2012), we use the seasonally adjusted quarterly data on the GDP expressed in millions of 2015 US dollars.¹ The data span from 1960 to 2021 which fully covers the time period necessary for our analysis (1975Q4 to 2010Q3).

¹Since the publication of the original paper in 2013, the OECD reference year has changed from 2005 to 2015. We have decided to analyse the latest version of the data in order to be able to make more accurate and up-to-date conclusions.

2. **Capital:** We use data on Capital Stock at Constant National Prices (K) from the Penn World Table (Feenstra et al., 2015) retrieved from FRED (<https://fred.stlouisfed.org/>, accessed on 7 December 2021). The data are given in the millions of the 2017 US dollars. Since the observations are at an annual frequency, we linearly interpolate the data to obtain the quarterly values. Our approach is different from the one in Zhang et al. (2012) where they use the quarterly data from the beginning. The reason for such discrepancy is the fact that we have not found the quarterly time series of sufficient quality on Capital Stock at Constant National Prices in the common sources. We repeat the analysis using the quarterly data on Gross Fixed Capital Formation instead of Capital Stock in the Appendix.
3. **Labour:** We collect the data on the Number of Employed People (L) from various sources. For most of the countries (Austria, Australia, Canada, Germany, Japan, UK and the USA) we download the OECD data on Employed Population: Aged 15 and Over retrieved from FRED (<https://fred.stlouisfed.org/>, accessed on 7 December 2021). The data for France and Switzerland were downloaded from Refinitiv Datastream on 7 December 2021. For all of the aforementioned countries the observations are at quarterly frequency and seasonally adjusted. The data for Finland and Norway were also obtained via Refinitiv Datastream on 7 December 2021, however, the only quarterly time series that are long enough to fully cover the time period under consideration are not seasonally adjusted. Hence, for these two countries we perform the seasonal adjustment ourselves. We do that using the default method of the function `seas` from an R package `seasonal` (Sax and Eddelbuettel, 2018) which is an interface to X-13-ARIMA-SEATS, the seasonal adjustment software used by the US Census Bureau. We repeat the analysis using not seasonally adjusted data for all of the 11 countries as a robustness check and we report the results in the Appendix.

For all of the countries, the observations are given in thousands of persons.

4. **Human capital:** We use Educational Attainment for Population Aged 25 and Over (H) collected from <http://www.barrolee.com> (accessed on 7 December 2021) as a measure of human capital. Since the only available data is five-year census data, we follow Zhang et al. (2012) and use linear interpolation between the observation and constant extrapolation on the boundaries (second and third quarters of 2010) to obtain the quarterly observations.

We thus observe a panel of $n = 11$ time series $\mathcal{W}_i = \{(Y_{it}, \mathbf{X}_{it}) : 1 \leq t \leq T\}$ of length $T = 140$ for each country $i \in \{1, \dots, 11\}$, where $Y_{it} = \Delta \ln GDP_{it} := \ln GDP_{it} - \ln GDP_{i(t-1)}$, $\mathbf{X}_{it} = (\Delta \ln L_{it}, \Delta \ln K_{it}, \Delta \ln H_{it})^\top$ with $\Delta \ln L_{it} := \ln L_{it} - \ln L_{i(t-1)}$,

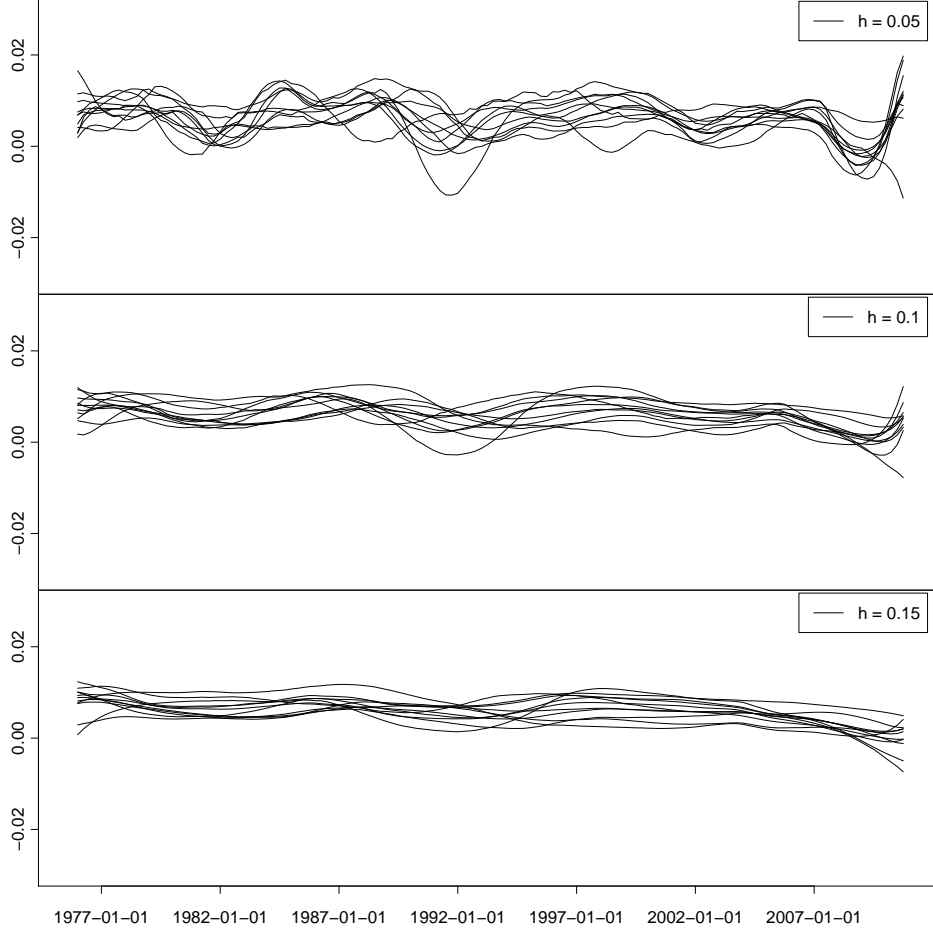


Figure 1: Local linear kernel estimates of the $n = 11$ original time trends from the application of Section 6.1. Each panel shows the estimates for a different bandwidth h .

$\Delta \ln K_{it} := \ln K_{it} - \ln K_{i(t-1)}$ and $\Delta \ln H_{it} := \ln H_{it} - \ln H_{i(t-1)}$. Without loss of generality, we let $\Delta \ln GDP_{i1} = \Delta \ln L_{i1} = \Delta \ln K_{i1} = \Delta \ln H_{i1} = 0$. The time series \mathcal{W}_i is assumed to follow the model

$$Y_{it} = \beta_i^\top \mathbf{X}_{it} + m_i\left(\frac{t}{T}\right) + \alpha_i + \varepsilon_{it} \quad (6.1)$$

for $1 \leq t \leq T$, where $\beta_i = (\beta_{i,1}, \beta_{i,2}, \beta_{i,3})^\top$ is a vector of unknown parameters, m_i is a country-specific unknown nonparametric time trend, and α_i is a fixed -effect term. Similarly to Zhang et al. (2012), we rewrite the model (6.1) as

$$\Delta \ln GDP_{it} = \beta_{i,1} \Delta \ln L_{it} + \beta_{i,2} \Delta \ln K_{it} + \beta_{i,3} \Delta \ln H_{it} + m_i\left(\frac{t}{T}\right) + \alpha_i + \varepsilon_{it}, \quad (6.2)$$

for $i \in \{1, \dots, 11\}$ and $t \in \{1, \dots, 140\}$.

Our testing procedure involves estimation of many unknown parameters. As noted in Khismatullina and Vogt (2020), estimating the long-run error variance in such models under general weak dependence conditions is a particularly difficult problem. Estimators often tend to be quite imprecise. Hence, in practice we opt for imposing

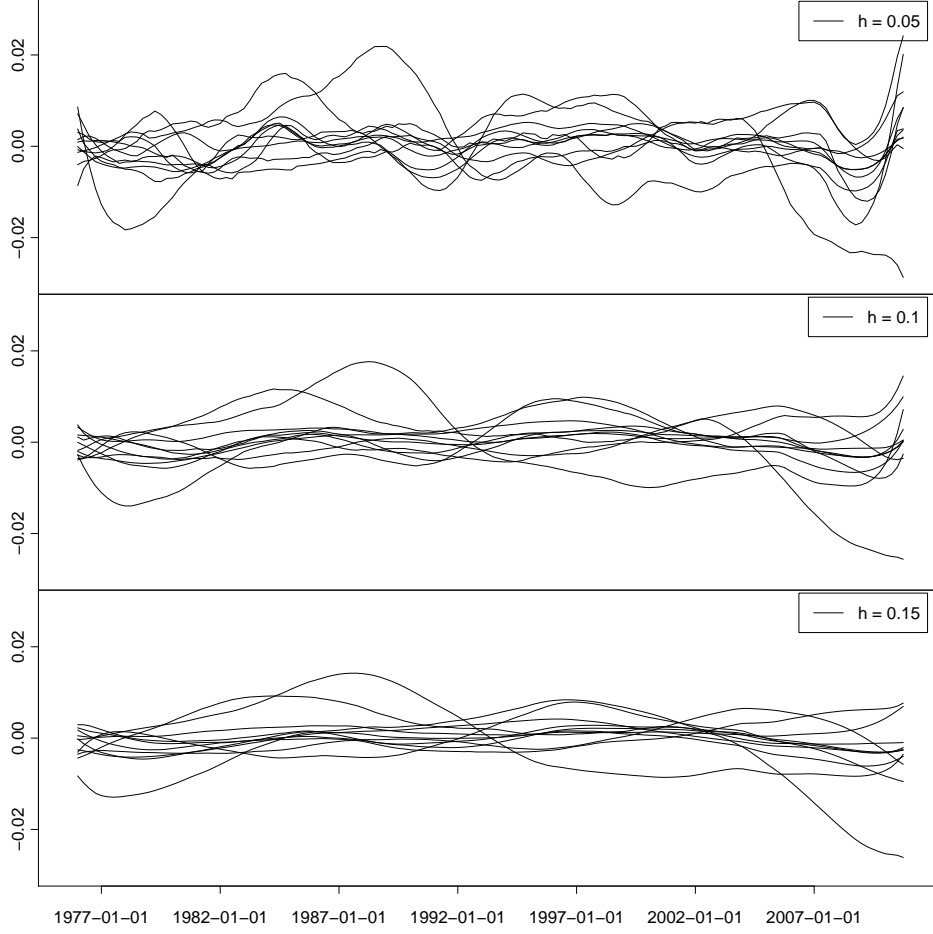


Figure 2: Local linear kernel estimates of the $n = 11$ augmented time trends from the application of Section 6.1. Each panel shows the estimates for a different bandwidth h .

certain conditions on the error processes $\mathcal{E}_i = \{\varepsilon_{it} : 1 \leq t \leq T\}$. Specifically, in our example for each i the error process \mathcal{E}_i is assumed to have the $\text{AR}(p_i)$ structure $\varepsilon_{it} = \sum_{j=1}^{p_i} a_{i,j} \varepsilon_{i(t-j)} + \eta_{it}$, where the order of the process p_i is country-specific and not known and η_{it} are i.i.d. innovations with mean zero. We choose p_i for each country separately based on the values of the information criterion (need to elaborate here). We aim to test whether the time trend m_i is the same at each of the 11 countries. In other words, we want to test the null hypothesis $H_0 : m_1 = \dots = m_n$ with $n = 11$ in model (6.2). To do so, we implement the multiscale test from Section 3 in the following way.

1. We choose K to be an Epanechnikov kernel.
2. We let $\mathcal{G}_T = U_T \times H_T$ with

$$U_T = \left\{ u \in [0, 1] : u = \frac{5t}{T} \text{ for some } t \in \mathbb{N} \right\}$$

$$H_T = \left\{ h \in \left[\frac{\log T}{T}, \frac{1}{4} \right] : h = \frac{5\ell}{T} \text{ for some } \ell \in \mathbb{N} \right\}.$$

We thus take into account all locations u on an equidistant grid U_T with step length $5/T$ and all bandwidths $h = 5/T, 10/T, 15/T, \dots$ with $\log T/T \leq h \leq 1/4$. Note that the lower bound $\log T/T$ is motivated by (C13) which requires that $\log T/T \ll h_{\min}$ (given that all moments of ε_{it} exist).

3. We estimate the unknown parameters $\beta_i = (\beta_{i,1}, \beta_{i,2}, \beta_{i,3})^\top$ for each country i separately using the first-differencing approach described in Section 5.
4. We compute the estimator of the fixed-effect term α_i using the formula (3.3). We then work with the augmented time series $\hat{Y}_{it} = Y_{it} - \hat{\beta}_i^\top \mathbf{X}_{it} - \hat{\alpha}_i$ instead of the original data on the GDP growth rate Y_{it} .
5. To obtain an estimator $\hat{\sigma}_i^2$ for the long-run error variance σ_i^2 , for each i we apply the procedure from Khismatullina and Vogt (2020) to the augmented values \hat{Y}_{it} with $\underline{r} = 1$, $\bar{r} = 10$ and $q = 15$. We use $\hat{\sigma}_i^2$ for calculating the value of our main test statistic $\hat{\Psi}_{n,T}$.
6. The significance levels are taken to be $\alpha = 0.05$ and $\alpha = 0.1$ (Zhang et al. (2012) report the results for testing at a significance level $\alpha = 0.1$).
7. To obtain the (approximate) critical values $q_{n,T}(\alpha)$ of the multiscale test, we simulate 5000 values of the statistic $\Phi_{n,T}$ defined in Section 3.3 and compute their empirical $(1 - \alpha)$ quantile $\hat{q}_{n,T}(\alpha)$.

We are now ready to apply the test procedure to the data. Figure 1 depicts a smoothed version of each of the original time series on the GDP growth rate $\{Y_{it} : 1 \leq t \leq T\}$ for each of the countries i of the $n = 11$ countries under consideration. Figure 2 presents local linear estimates of the trend functions m_i for these countries after factoring out the effects of the covariates and the fixed-effect terms (i.e. calculated from the augmented time series \hat{Y}_{it}). In both figures, each panel corresponds to a different value of the bandwidth h .

As can be seen in Figure 1, in the original data on the GDP growth there are some notable differences between the countries for bandwidths $h = 0.05$ and $h = 0.1$. For example, while most of the countries experience the increase in the growth rate in the last two years, the data for one of the countries suggests a decrease in the same period of time. Moreover, using the smallest bandwidth ($h = 0.05$) allows us to notice considerable differences in the behaviour of the time series in the middle of our time region. In contrast, the value of the bandwidth $h = 0.15$ is too big to detect any heterogeneity in the behaviour of the trend. As we see, the choice of the bandwidth is crucial in making conclusions in this example.

Now we look at the local linear estimates of the trend functions m_i after excluding the effects of the covariates (Figure 2). We can see that the differences between the trends

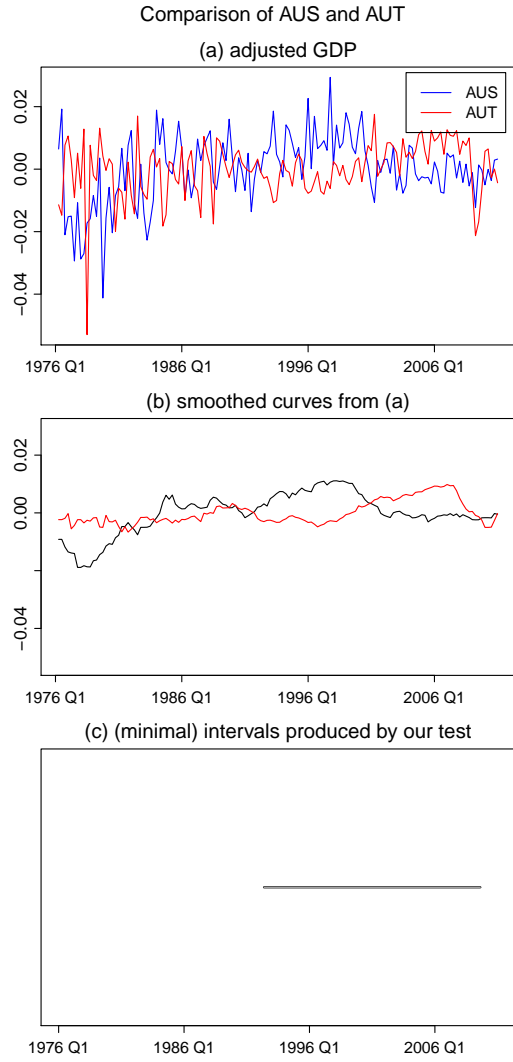


Figure 3: Test results for the comparison of Australia and Austria.

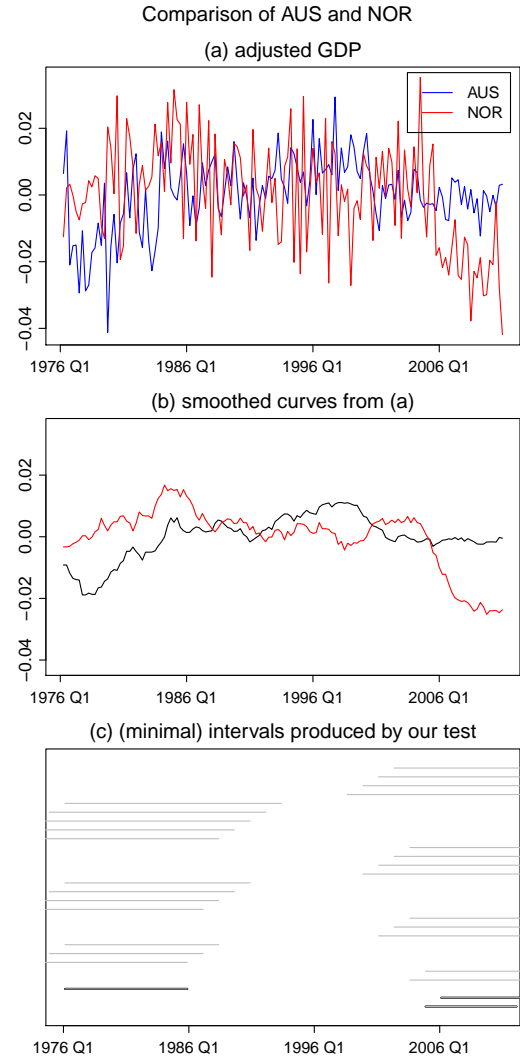


Figure 4: Test results for the comparison of Australia and Norway.

Note: In each figure, panel (a) shows the two augmented time series, panel (b) smoothed versions of the augmented time series, and panel (c) depicts the set of intervals $\mathcal{S}^{[i,j]}(\alpha)$ in grey and the subset of minimal intervals $\mathcal{S}_{min}^{[i,j]}(\alpha)$ in black.

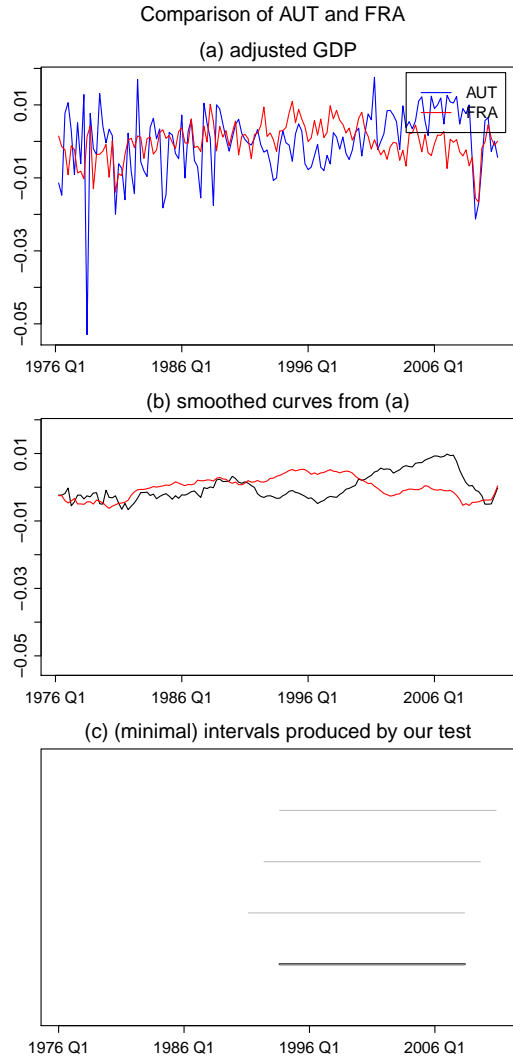


Figure 5: Test results for the comparison of Austria and France.

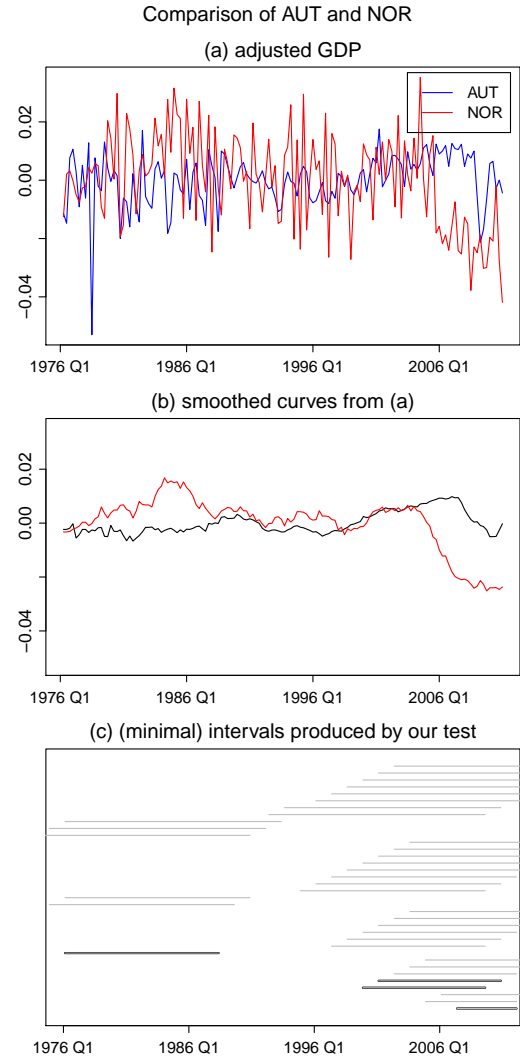


Figure 6: Test results for the comparison of Austria and Norway.

Note: In each figure, panel (a) shows the two augmented time series, panel (b) smoothed versions of the augmented time series, and panel (c) depicts the set of intervals $\mathcal{S}^{[i,j]}(\alpha)$ in grey and the subset of minimal intervals $\mathcal{S}_{min}^{[i,j]}(\alpha)$ in black.

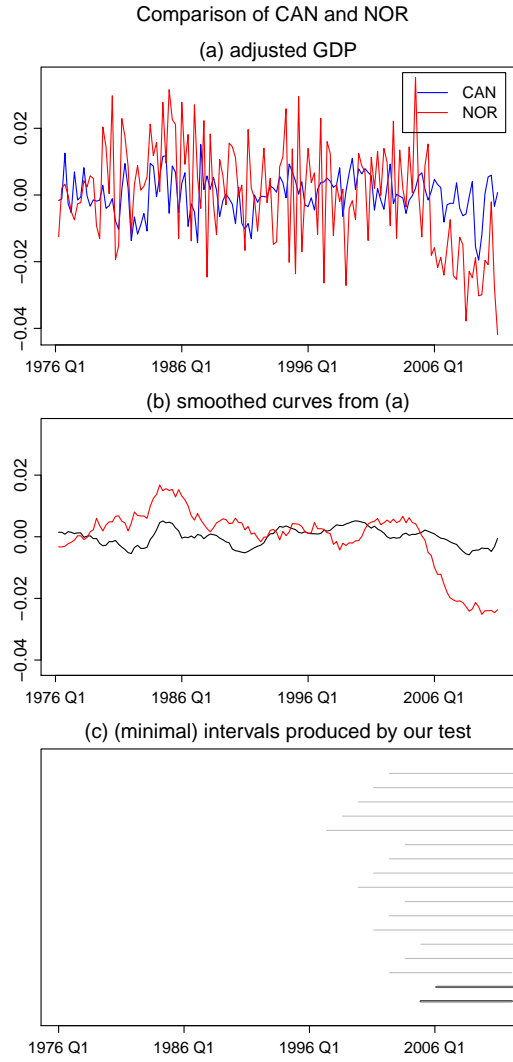


Figure 7: Test results for the comparison of Canada and Norway.

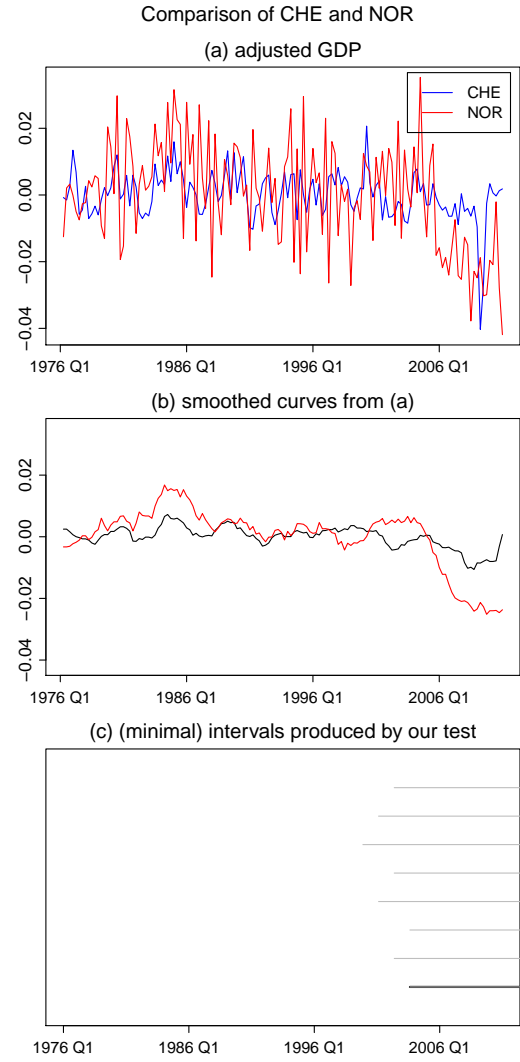


Figure 8: Test results for the comparison of Switzerland and Norway.

Note: In each figure, panel (a) shows the two augmented time series, panel (b) smoothed versions of the augmented time series, and panel (c) depicts the set of intervals $\mathcal{S}^{[i,j]}(\alpha)$ in grey and the subset of minimal intervals $\mathcal{S}_{min}^{[i,j]}(\alpha)$ in black.

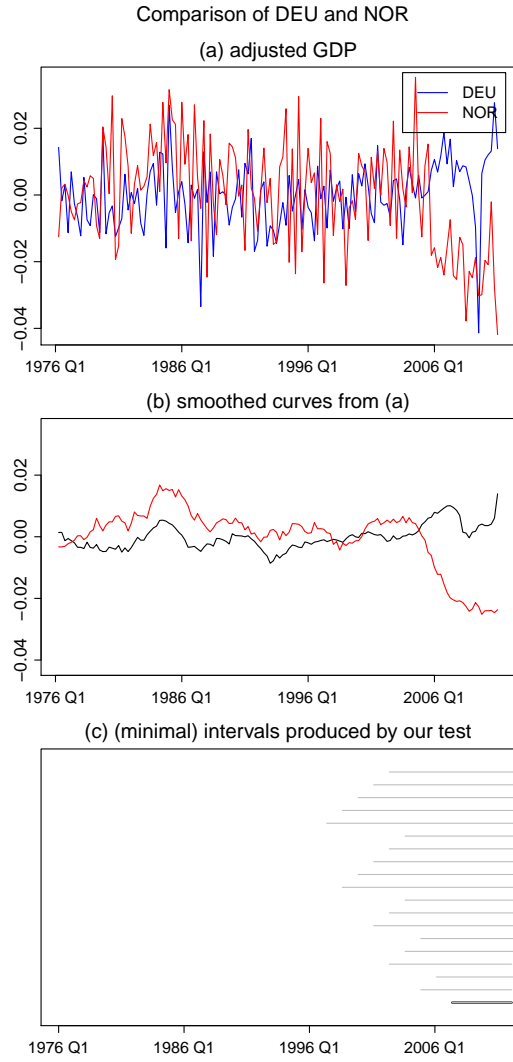


Figure 9: Test results for the comparison of Germany and Norway.

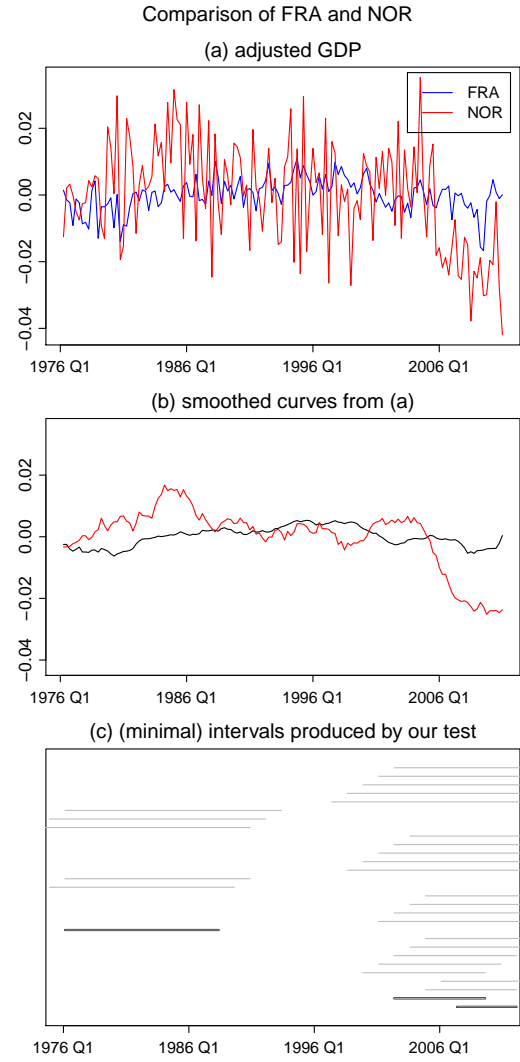


Figure 10: Test results for the comparison of France and Norway.

Note: In each figure, panel (a) shows the two augmented time series, panel (b) smoothed versions of the augmented time series, and panel (c) depicts the set of intervals $\mathcal{S}^{[i,j]}(\alpha)$ in grey and the subset of minimal intervals $\mathcal{S}_{min}^{[i,j]}(\alpha)$ in black.

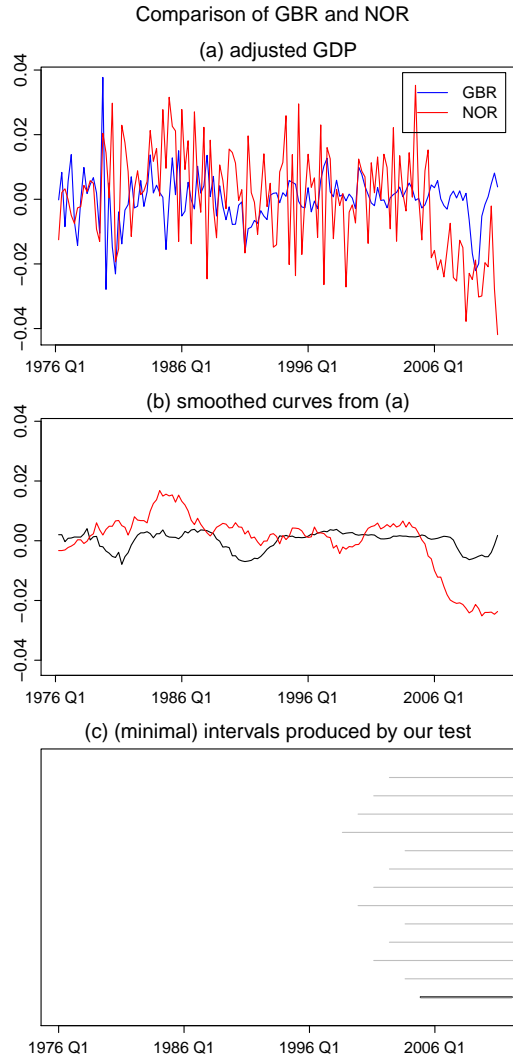


Figure 11: Test results for the comparison of the UK and Norway.

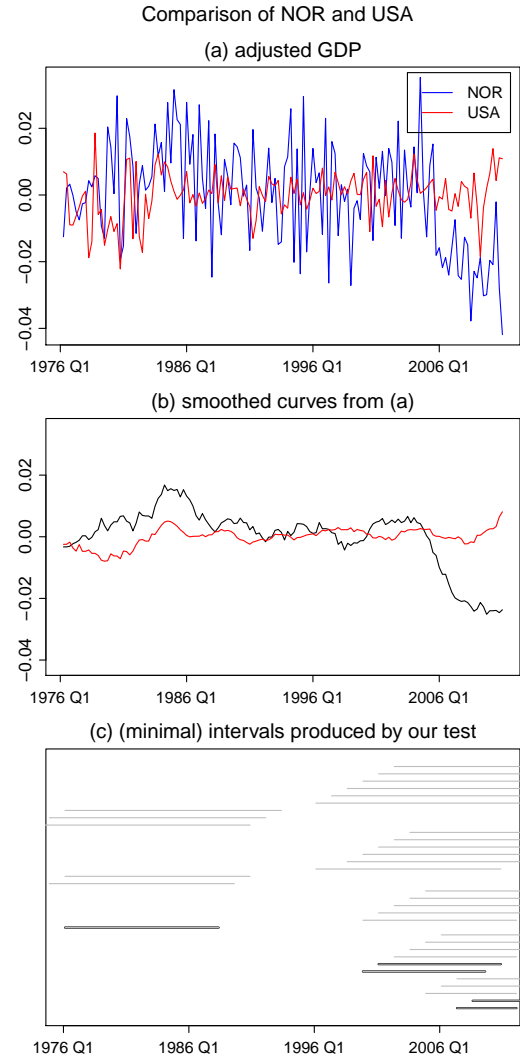


Figure 12: Test results for the comparison of Norway and the USA.

Note: In each figure, panel (a) shows the two augmented time series, panel (b) smoothed versions of the augmented time series, and panel (c) depicts the set of intervals $\mathcal{S}^{[i,j]}(\alpha)$ in grey and the subset of minimal intervals $\mathcal{S}_{min}^{[i,j]}(\alpha)$ in black.

are much more pronounced and some heterogeneity between the countries is notable even for large values of h .

The results of applying our test are completely in line with the conclusions from the visual inspection. The test rejects the null hypothesis H_0 at both levels $\alpha = 0.05$ and $\alpha = 0.1$ which is consistent with the findings of Zhang et al. (2012) where the authors report a rejection of the null hypothesis of a common trend at the level $\alpha = 0.1$. However, in contrast to Zhang et al. (2012), we can say much more about the comparison of the trends between these 11 countries. Specifically, we can make simultaneous confidence statements about which of the countries have different trends and where they differ. With the help of our multiscale method, we simultaneously test all of the local null hypotheses $H_0^{[i,j]}(u, h)$ that $m_i = m_j$ on the interval $\mathcal{I}_{(u,h)} = [u - h, u + h]$ for each $i, j, 1 \leq i < j \leq n$, and each $(u, h) \in \mathcal{G}_T$. The results are presented in Figures 3–12, with each figure corresponding to a specific pair of countries (i, j) from our sample. Each figure is divided into three panels (a)–(c). Panel (a) shows the augmented time series \widehat{Y}_{it} and \widehat{Y}_{jt} for the two countries i and j that are being compared. Panel (b) presents smoothed versions of the time series from (a), that is, it shows nonparametric kernel estimates (specifically, Nadaraya-Watson estimates) of the two trend functions m_i and m_j , where the bandwidth is set to 14 quarters (which corresponds to $h = 0.1$) and a rectangular kernel is used. Finally, panel (c) presents the results produced by our test for a significance level $\alpha = 0.05$: it depicts in grey the set $\mathcal{S}^{[i,j]}(\alpha)$ of all the intervals for which the test rejects the local null $H_0^{[i,j]}(u, h)$. The minimal intervals in the subset $\mathcal{S}^{[i,j]}(\alpha)$ are highlighted in black. Note that according to (4.5), we can make the following simultaneous confidence statement about the intervals plotted in panels (c) of Figures 3–12: we can claim, with confidence of about 95%, that there is a difference between the functions m_i and m_j on each of these intervals.

Now we briefly comment on the results. Out of 55 pairwise comparisons, our test detects the differences in the trends 10 times. In 8 and 3 of these instances, one of the countries involved comparison is Norway or Austria respectively. This fact suggests that among considered countries there may be groups that exhibit similar trends. Hence, it is very reasonable to investigate the data further using clustering methods. (Need to comment more).

7 Conclusion

In this paper, we develop a new multiscale testing procedure for multiple time series for testing hypotheses about nonparametric time trends in the presence of covariates. This procedure addresses two important statistical problems about comparison of the time trends. First and foremost, with the help of the proposed method, we are able to test if all the time trends in the observed time series are the same or not. We prove

the main theoretical results of the paper that the test has (asymptotically) the correct size and has an (asymptotic) power of one against a specific class of local alternatives. Second, our multiscale procedure allows us to tell which of the time trends are different and where the differences are located. For the purpose of pinpointing the differences, we consider many local null hypotheses at the same time, each corresponding to only a pair of time trends and a specific time interval. Our method allows us to test all of these hypotheses simultaneously controlling the family-wise error rate, i.e. the probability of wrongly rejecting at least one true null hypothesis (making at least one type I error), at a desired level α . This result allows us to make simultaneous confidence statements as follows:

We can state with (asymptotic) probability at least $1 - \alpha$ that for every pair of time series and every interval where our test rejects the local null, the trends of these time series differ at least somewhere on this particular interval.

For the proof of the theoretical results, the main tools that are used are strong approximation theory developed in Berkes et al. (2014) and the anti-concentration bounds for Gaussian random vectors verified in Chernozhukov et al. (2015). The proof strategy that we employ in our paper has already been used in Khismatullina and Vogt (2020), however, in that paper the authors proposed a multiscale method for testing qualitative hypotheses only about one time series. Our method can be regarded as a generalized version of the test developed in Khismatullina and Vogt (2020) where we not only consider comparison between various time series, but also add the covariates to the model and propose an estimation procedure for the unknown parameters.

Regarding future research, this project suggests some interesting issues and topics for consideration. First, consider the situation that the null hypothesis $H_0 : m_1 = \dots = m_n$ is violated in the general panel data model (1.1). Even though some of the trend functions m_i are different in this case, there may still be groups of time series with the same time trend. An interesting statistical problem to investigate in the future is how to estimate the unknown groups (and their unknown number) from the data. Second, as was already mentioned, it should be possible to extend our theoretical results to the case where the number of time series slowly grows with the sample size. Further insight can be gained by broadening the current work in these and possibly other directions.

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A Appendix

In the Appendix, we provide detailed proofs for the theoretical results from Sections 4 and 5. We use the following notation: The symbol C denotes a universal real constant which may take a different value on each occurrence. For $a, b \in \mathbb{R}$, we write $a \vee b = \max\{a, b\}$. For $x \in \mathbb{R}, x \geq 0$, we write $\lfloor x \rfloor$ to denote the integer value of x and $\lceil x \rceil$ to denote the smallest integer greater than or equal to x . For any set A , the symbol $|A|$ denotes the cardinality of A . Finally, the notation $X \stackrel{\mathcal{D}}{=} Y$ means that the two random variables X and Y have the same distribution.

A.1 Statistics used in the Appendix

In the proof of Theorem 4.1, we use a number of different test statistics, either already defined in Section 3 or introduced below. Each of these statistics plays an important role in one or more steps of the proof. In the following list, we present these statistics, describe how they are constructed and explain in which parts of the proof they are used.

- Our main multiscale test statistic (defined in (3.7)):

$$\widehat{\Psi}_{n,T} = \max_{1 \leq i < j \leq n} \max_{(u,h) \in \mathcal{G}_T} \left\{ \left| \frac{\widehat{\psi}_{ij,T}(u,h)}{(\widehat{\sigma}_i^2 + \widehat{\sigma}_j^2)^{1/2}} \right| - \lambda(h) \right\},$$

with $\widehat{\psi}_{ij,T}(u,h) = \sum_{t=1}^T w_{t,T}(u,h)(\widehat{Y}_{it} - \widehat{Y}_{jt}).$

This statistic is our main quantity of interest because the kernel average $\widehat{\psi}_{ij,T}(u,h)$ measures the approximate distance between the trends m_i and m_j on an interval $\mathcal{I}_{(u,h)} = [u-h, u+h]$.

- The Gaussian statistic that is used for calculating the critical values for our test procedure (defined in (3.10)):

$$\Phi_{n,T} = \max_{1 \leq i < j \leq n} \max_{(u,h) \in \mathcal{G}_T} \left\{ \left| \frac{\phi_{ij,T}(u,h)}{(\sigma_i^2 + \sigma_j^2)^{1/2}} \right| - \lambda(h) \right\},$$

with $\phi_{ij,T}(u,h) = \sum_{t=1}^T w_{t,T}(u,h) \{ \sigma_i(Z_{it} - \bar{Z}_i) - \sigma_j(Z_{jt} - \bar{Z}_j) \}.$

- Auxiliary test statistic (defined in (4.1)) that can be regarded as the version of our multiscale statistic under the null.

$$\widehat{\Phi}_{n,T} = \max_{1 \leq i < j \leq n} \max_{(u,h) \in \mathcal{G}_T} \left\{ \left| \frac{\widehat{\phi}_{ij,T}(u,h)}{\{\widehat{\sigma}_i^2 + \widehat{\sigma}_j^2\}^{1/2}} \right| - \lambda(h) \right\},$$

with $\widehat{\phi}_{ij,T}(u,h) = \sum_{t=1}^T w_{t,T}(u,h) \{ (\varepsilon_{it} - \bar{\varepsilon}_i) + (\beta_i - \widehat{\beta}_i)^\top (\mathbf{X}_{it} - \bar{\mathbf{X}}_i) - (\varepsilon_{jt} - \bar{\varepsilon}_j) - (\beta_j - \widehat{\beta}_j)^\top (\mathbf{X}_{jt} - \bar{\mathbf{X}}_j) \}.$

Our main theoretical result (Theorem 4.1) investigates the distribution of $\widehat{\Phi}_{n,T}$.

- Intermediate statistic that is close to $\widehat{\Phi}_{n,T}$ but is constructed from the kernel averages $\widehat{\phi}_{ij,T}(u, h)$ that are different from $\widehat{\phi}_{ij,T}(u, h)$ only by the fact that they do not include the covariates \mathbf{X}_{it} :

$$\widehat{\Phi}_{n,T} = \max_{1 \leq i < j \leq n} \max_{(u,h) \in \mathcal{G}_T} \left\{ \left| \frac{\widehat{\phi}_{ij,T}(u, h)}{\{\widehat{\sigma}_i^2 + \widehat{\sigma}_j^2\}^{1/2}} \right| - \lambda(h) \right\},$$

with $\widehat{\phi}_{ij,T}(u, h) = \sum_{t=1}^T w_{t,T}(u, h) \{(\varepsilon_{it} - \bar{\varepsilon}_i) - (\varepsilon_{jt} - \bar{\varepsilon}_j)\}.$

We can view these kernel averages as constructed (under the null) from the unobserved variables \widehat{Y}_{it} that are defined by

$$\begin{aligned} \widehat{Y}_{it} &:= Y_{it} - \beta_i^\top \mathbf{X}_{it} - \frac{1}{T} \sum_{t=1}^T (Y_{it} - \beta_i^\top \mathbf{X}_{it}) = \\ &= m_i\left(\frac{t}{T}\right) - \frac{1}{T} \sum_{t=1}^T m_i\left(\frac{t}{T}\right) + \varepsilon_{it} - \frac{1}{T} \sum_{t=1}^T \varepsilon_{it}. \end{aligned}$$

The definition of $\widehat{\Phi}_{n,T}$ also includes the auxiliary estimator $\widehat{\sigma}_i^2$ of the long-run error variance σ_i^2 which is computed from the augmented sample $\{\widehat{Y}_{it} : 1 \leq t \leq T\}$. We thus regard $\widehat{\sigma}_i^2 = \widehat{\sigma}_i^2(\widehat{Y}_{i1}, \dots, \widehat{Y}_{iT})$ as a function of the variables \widehat{Y}_{it} for $1 \leq t \leq T$. As with $\widehat{\sigma}_i^2$, we assume that $\widehat{\sigma}_i^2 = \sigma_i^2 + o_p(\rho_T)$ with $\rho_T = o(\sqrt{h_{\min}}/\log T)$.

- Auxiliary statistic that has the same distribution as $\widehat{\Phi}_{n,T}$ for each $T = 1, 2, \dots$:

$$\widetilde{\Phi}_{n,T} = \max_{1 \leq i < j \leq n} \max_{(u,h) \in \mathcal{G}_T} \left\{ \left| \frac{\widetilde{\phi}_{ij,T}(u, h)}{\{\widetilde{\sigma}_i^2 + \widetilde{\sigma}_j^2\}^{1/2}} \right| - \lambda(h) \right\},$$

with $\widetilde{\phi}_{ij,T}(u, h) = \sum_{t=1}^T w_{t,T}(u, h) \{(\widetilde{\varepsilon}_{it} - \widetilde{\varepsilon}_i) - (\widetilde{\varepsilon}_{jt} - \widetilde{\varepsilon}_j)\},$

where $[\widetilde{\varepsilon}_{i1}, \dots, \widetilde{\varepsilon}_{iT}] \stackrel{\mathcal{D}}{=} [\varepsilon_{i1}, \dots, \varepsilon_{iT}]$ for each i and T . In Proposition A.3, using the strong approximation theory by Berkes et al. (2014), we formally prove that such statistic exists and has the property of being close to the Gaussian statistic $\Phi_{n,T}$.

A.2 Auxiliary results

Here, we state some auxiliary results that will be used further in the proof of Theorem 4.1.

Definition A.1. For a given $q > 0$ and $\alpha > 0$, we define dependence adjusted norm as $\|X\|_{q,\alpha}^q = \sup_{m \geq 0} (m+1)^\alpha \sum_{t=m}^\infty \delta_q(X, t).$

Theorem A.1. *Wu and Wu (2016) Assume that $\|X.\|_{q,\alpha}^q < \infty$, where $q > 2$ and $\alpha > 0$, and $\sum_{t=1}^T a_t^2 = T$. Moreover, assume that $\alpha > 1/2 - 1/q$. Denote $S_T = a_1 X_1 + \dots + a_T X_T$. Then for all $x > 0$,*

$$\mathbb{P}(|S_T| \geq x) \leq C_1 \frac{|a|_q^q \|X.\|_{q,\alpha}^q}{x^q} + C_2 \exp\left(-\frac{C_3 x^2}{T \|X.\|_{2,\alpha}^2}\right),$$

where C_1, C_2, C_3 are constants that only depend on q and α .

Theorem A.2. *Wu (2007) Let $(\xi_i)_{i \in \mathbb{Z}}$ be a stationary and ergodic Markov chain and $g(\cdot)$ be a measurable function. Let $g(\xi_1) \in \mathcal{L}^q, q > 2, \mathbb{E}[g(\xi_0)] = 0$ and l be a positive, nondecreasing slowly varying function. Assume that*

$$\sum_{i=n}^{\infty} \left\| \mathbb{E}[g(\xi_i)|\xi_0] - \mathbb{E}[g(\xi_i)|\xi_{-1}] \right\|_q = O([\log n]^{-\beta}),$$

where $0 \leq \beta < 1/q$ and

$$\sum_{k=1}^{\infty} \frac{k^{-\beta q}}{[l(2^k)]^q} < \infty.$$

Then $S_n = g(\xi_1) + \dots + g(\xi_n) = o_{a.s.}[\sqrt{nl(n)}]$.

Proposition A.1. *Wu (2007) Let $(\epsilon_n)_{n \in \mathbb{Z}}$ be i.i.d. random variables, $\xi_n = (\dots, \epsilon_{n-1}, \epsilon_n)$ and $g(\cdot)$ be a measurable function such that $g(\xi_n)$ is a proper random variable for each $n \geq 0$. For $k \geq 0$ let $\tilde{\xi}_k = (\dots, \epsilon_{-1}, \epsilon'_0, \epsilon_1, \dots, \epsilon_{k-1}, \epsilon_k)$, where ϵ'_0 is an i.i.d. copy of ϵ_0 . Let $g(\xi_0) \in \mathcal{L}^q, q > 1$ and $\mathbb{E}[g(\xi_0)] = 0$. For $n \geq 1$ we have*

$$\left\| \mathbb{E}[g(\xi_n)|\xi_0] - \mathbb{E}[g(\xi_n)|\xi_{-1}] \right\|_q \leq 2 \left\| g(\xi_n) - g(\tilde{\xi}_n) \right\|_q.$$

Proposition A.2. *Under the conditions of Theorem 4.1, for all $i \in \{1, \dots, n\}$ it holds that*

$$\bar{\mathbf{X}}_i = \frac{1}{T} \sum_{t=1}^T \mathbf{H}_i(\mathcal{U}_{it}) = o_P(\log^{2/q'} T / \sqrt{T}). \quad (\text{A.1})$$

Proof of Proposition A.2. Take any $i \in \{1, \dots, n\}$. To prove (A.1), we will use two results from Wu (2007) stated above. First, fix $j \in \{1, \dots, d\}$. Denote $\xi_t = \mathcal{U}_{it}$, $\tilde{\xi}_t = \mathcal{U}'_{it}$ and $g(\cdot) = H_{i,j}(\cdot)$. Then by Assumption (C6), $g(\xi_0) = H_{i,j}(\mathcal{U}_{i0}) \in \mathcal{L}^{q'}$ for $q' > 4$ and $\mathbb{E}[g(\xi_0)] = \mathbb{E}[H_{i,j}(\mathcal{U}_{i0})] = 0$ and we can apply Proposition A.1 (Proposition 3(ii) in Wu (2007)) that says that for all $s \geq 1$ we have:

$$\left\| \mathbb{E}[g(\xi_s)|\xi_0] - \mathbb{E}[g(\xi_s)|\xi_{-1}] \right\|_{q'} \leq 2 \left\| g(\xi_s) - g(\tilde{\xi}_s) \right\|_{q'},$$

or, equivalently,

$$\left\| \mathbb{E}[H_{i,j}(\mathcal{U}_{is})|\mathcal{U}_{i0}] - \mathbb{E}[H_{i,j}(\mathcal{U}_{is})|\mathcal{U}_{i(-1)}] \right\|_{q'} \leq 2 \left\| H_{i,j}(\mathcal{U}_{is}) - H_{i,j}(\mathcal{U}'_{is}) \right\|_{q'}.$$

Since this holds simultaneously for all $j \in \{1, \dots, d\}$, we can use the obvious bound $\left\| H_{i,j}(\mathcal{U}_{is}) - H_{i,j}(\mathcal{U}'_{is}) \right\|_{q'} \leq \left\| \mathbf{H}_i(\mathcal{U}_{is}) - \mathbf{H}_i(\mathcal{U}'_{is}) \right\|_{q'} = \delta_{q'}(\mathbf{H}_i, s)$ and Assumption (C8) to write

$$0 \leq \sum_{s=t}^{\infty} \left\| \mathbb{E}[g(\xi_s)|\xi_0] - \mathbb{E}[g(\xi_s)|\xi_{-1}] \right\|_{q'} \leq \sum_{s=t}^{\infty} \delta_{q'}(\mathbf{H}_i, s) = O(t^{-\alpha}),$$

where $\alpha > 1/2 - 1/q'$.

Now we want to apply Theorem A.2 (Corollary 2(i) in Wu (2007)). As a parameter β in the theorem we can take any value satisfying assumption $0 \leq \beta < 1/q'$ because for every $\beta \geq 0$ we have

$$\sum_{s=t}^{\infty} \left\| \mathbb{E}[g(\xi_s)|\xi_0] - \mathbb{E}[g(\xi_s)|\xi_{-1}] \right\|_{q'} \leq \sum_{s=t}^{\infty} \delta_{q'}(\mathbf{H}_i, s) = O(t^{-\alpha}) = O([\log t]^{-\beta}).$$

Furthermore, as a positive, nondecreasing slowly varying function l we can take $l(x) = \log^{2/q' - \beta}(x)$. Then,

$$\begin{aligned} \sum_{k=1}^{\infty} \frac{k^{-\beta q'}}{[l(2^k)]^{q'}} &= \sum_{k=1}^{\infty} \frac{k^{-\beta q'}}{[\log^{2/q' - \beta}(2^k)]^{q'}} \\ &= \sum_{k=1}^{\infty} \frac{k^{-\beta q'}}{k^{2 - \beta q'} (\log 2)^{2 - \beta q'}} \\ &= \frac{1}{(\log 2)^{2 - \beta q'}} \sum_{k=1}^{\infty} \frac{1}{k^2} \\ &< \infty. \end{aligned}$$

Hence, $S_T = g(\xi_1) + \dots + g(\xi_T) = o_{a.s.}[\sqrt{T} \log^{2/q' - \beta}(T)]$, or, equivalently, $\bar{X}_{i,j} = S_T/T = o_{a.s.}[\log^{2/q' - \beta}(T)/\sqrt{T}]$. We can write the statement without the parameter β as well: $\bar{X}_{i,j} = S_T/T = o_{a.s.}(\log^{2/q'} T/\sqrt{T})$ for each $j \in \{1, \dots, d\}$. Trivially, this means that $\bar{\mathbf{X}}_i = o_P(\log^{2/q'} T/\sqrt{T})$. \square

A.3 Proofs of theoretical properties of the test

Proof of Theorem 4.1

The main steps of the proof of the Theorem 4.1 are described below. We will build the proof on the auxiliary results stated in A.2.

1. First, we introduce the intermediate statistic $\widehat{\widehat{\Phi}}_{n,T}$ that can be regarded as the version of $\widehat{\Phi}_{n,T}$ where we excluded the regressors \mathbf{X}_{it} from the construction of

the kernel averages. Next, we show that we can replace $\widehat{\widehat{\Phi}}_{n,T}$ by an identically distributed version $\widetilde{\Phi}_{n,T}$ which is close to the Gaussian statistics $\Phi_{n,T}$ defined in (3.10). Formally, in Proposition A.3 we prove that there exist statistics $\widetilde{\Phi}_{n,T}$ for $T = 1, 2, \dots$ which are distributed as $\widehat{\widehat{\Phi}}_{n,T}$ for any $T \geq 1$ and which have the property that

$$|\widetilde{\Phi}_{n,T} - \Phi_{n,T}| = o_p\left(\frac{T^{1/q}}{\sqrt{Th_{\min}}} + \rho_T \sqrt{\log T}\right),$$

where $\Phi_{n,T}$ is the Gaussian statistic.

2. Second, in Proposition A.5 we demonstrate that $\Phi_{n,T}$ does not concentrate too strongly in small regions of the form $[x - \delta_T, x + \delta_T]$ with δ_T converging to zero as $T \rightarrow \infty$. Or, in other words, it holds that

$$\sup_{x \in \mathbb{R}} \mathbb{P}(|\Phi_{n,T} - x| \leq \delta_T) = o(1)$$

with $\delta_T = T^{1/q}/\sqrt{Th_{\min}} + \rho_T \sqrt{\log T}$.

3. Then, we make use of Lemma A.6 to show that

$$\sup_{x \in \mathbb{R}} |\mathbb{P}(\widehat{\widehat{\Phi}}_{n,T} \leq x) - \mathbb{P}(\Phi_{n,T} \leq x)| = o(1).$$

This statement directly follows from the previous two steps and the fact that $\widetilde{\Phi}_{n,T}$ is distributed as $\widehat{\widehat{\Phi}}_{n,T}$ for any $n \geq 2, T \geq 1$.

4. In the fourth step, in Propositions A.7 and A.8 we formally show that the introduced intermediate statistic $\widehat{\widehat{\Phi}}_{n,T}$ is close to $\widehat{\Phi}_{n,T}$, i.e. there exists a sequence of positive numbers γ_T that converges to 0 as $T \rightarrow \infty$ **sufficiently fast enough** such that for all $x \in \mathbb{R}$

$$\begin{aligned} \mathbb{P}\left(\widehat{\widehat{\Phi}}_{n,T} \leq x - \gamma_T\right) - \mathbb{P}\left(|\widehat{\widehat{\Phi}}_{n,T} - \widehat{\Phi}_{n,T}| > \gamma_T\right) &\leq \mathbb{P}(\widehat{\Phi}_{n,T} \leq x) \\ &\leq \mathbb{P}\left(\widehat{\widehat{\Phi}}_{n,T} \leq x + \gamma_T\right) + \mathbb{P}\left(|\widehat{\widehat{\Phi}}_{n,T} - \widehat{\Phi}_{n,T}| > \gamma_T\right), \end{aligned}$$

and

$$\mathbb{P}\left(|\widehat{\widehat{\Phi}}_{n,T} - \widehat{\Phi}_{n,T}| > \gamma_T\right) = o(1). \tag{A.2}$$

We show that we can take $\gamma_T = O(T^{1/q}/\sqrt{Th_{\min}} + \rho_T \sqrt{\log T})$ for the results to hold. Note that (A.2) does not involve x . Hence, this result is uniform over all $x \in \mathbb{R}$.

5. And finally, by the means of Proposition A.9 we prove that

$$\sup_{x \in \mathbb{R}} |\mathbb{P}(\widehat{\Phi}_{n,T} \leq x) - \mathbb{P}(\Phi_{n,T} \leq x)| = o(1),$$

which immediately implies the statement of Theorem 4.1.

Step 1

The auxiliary statistics $\widehat{\Phi}_{n,T}$ defined in (4.1) is equal to our multiscale statistics $\widehat{\Psi}_{n,T}$ under the null hypothesis, but has the property that it depends on the known covariates \mathbf{X}_{it} , whereas the Gaussian version $\Phi_{n,T}$ defined in (3.10) is independent of them. This is the reason why we need to introduce additional intermediate test statistics that do not include the covariates and connect $\widehat{\Phi}_{n,T}$ and $\Phi_{n,T}$.

We do it in the following way. For each i and j , consider the kernel averages

$$\widehat{\phi}_{ij,T}(u, h) = \sum_{t=1}^T w_{t,T}(u, h) \{(\varepsilon_{it} - \bar{\varepsilon}_i) - (\varepsilon_{jt} - \bar{\varepsilon}_j)\}.$$

We can view these kernel averages as constructed (under the null) based on the unobserved variables \widehat{Y}_{it} and \widehat{Y}_{jt} defined by

$$\begin{aligned} \widehat{Y}_{it} &:= Y_{it} - \beta_i^\top \mathbf{X}_{it} - \frac{1}{T} \sum_{t=1}^T (Y_{it} - \beta_i^\top \mathbf{X}_{it}) = \\ &= m_i\left(\frac{t}{T}\right) - \frac{1}{T} \sum_{t=1}^T m_i\left(\frac{t}{T}\right) + \varepsilon_{it} - \frac{1}{T} \sum_{t=1}^T \varepsilon_{it}. \end{aligned}$$

The intermediate statistic is then defined as

$$\widehat{\Phi}_{n,T} = \max_{1 \leq i < j \leq n} \max_{(u,h) \in \mathcal{G}_T} \left\{ \left| \frac{\widehat{\phi}_{ij,T}(u, h)}{(\widehat{\sigma}_i^2 + \widehat{\sigma}_j^2)^{1/2}} \right| - \lambda(h) \right\} \quad (\text{A.3})$$

with $\widehat{\sigma}_i^2$ being an estimator of the long-run error variance $\sigma_i^2 = \sum_{\ell=-\infty}^{\infty} \text{Cov}(\varepsilon_{i0}, \varepsilon_{i\ell})$ which is computed from the unobserved sample $\{\widehat{Y}_{it} : 1 \leq t \leq T\}$. We thus regard $\widehat{\sigma}_i^2 = \widehat{\sigma}_i^2(\widehat{Y}_{i1}, \dots, \widehat{Y}_{iT})$ as a function of the variables \widehat{Y}_{it} for $1 \leq t \leq T$. As with the estimator $\widehat{\sigma}_i^2$, we assume that $\widehat{\sigma}_i^2 = \sigma_i^2 + o_p(\rho_T)$ with $\rho_T = o(\sqrt{h_{\min}}/\log T)$.

The statistics $\widehat{\Phi}_{n,T}$ can thus be viewed as a version of the statistic $\widehat{\Phi}_{n,T}$ without the covariates. We formally prove that these two statistics are close in Step 4.

Here, we are interested in another matter. Specifically, the main theoretical result of this step is the fact that there exists a version of the multiscale statistic $\widehat{\Phi}_{n,T}$ with the same distributional properties and that is close to the Gaussian statistics $\Phi_{n,T}$ **where** distribution is known. More specifically, we prove the following result.

Proposition A.3. *Under the conditions of Theorem 4.1, there exist statistics $\widetilde{\Phi}_{n,T}$ for $T = 1, 2, \dots$ with the following two properties: (i) $\widetilde{\Phi}_{n,T}$ has the same distribution as $\widehat{\Phi}_{n,T}$ as defined in (A.3) for any **n and** T , and (ii)*

$$|\widetilde{\Phi}_{n,T} - \Phi_{n,T}| = o_p\left(\frac{T^{1/q}}{\sqrt{T}h_{\min}} + \rho_T \sqrt{\log T}\right), \quad (\text{A.4})$$

where $\Phi_{n,T}$ is a Gaussian statistic as defined in (3.10).

Proof of Proposition A.3. For the proof, we draw on strong approximation theory for each stationary process $\mathcal{E}_i = \{\varepsilon_{it} : 1 \leq t \leq T\}$ that fulfills the conditions (C1)–(C3). By Theorem 2.1 and Corollary 2.1 in Berkes et al. (2014), the following strong approximation result holds true: On a richer probability space, there exists a standard Brownian motion \mathbb{B}_i and a sequence $\{\tilde{\varepsilon}_{it} : t \in \mathbb{N}\}$ such that $[\tilde{\varepsilon}_{i1}, \dots, \tilde{\varepsilon}_{iT}] \stackrel{\mathcal{D}}{=} [\varepsilon_{i1}, \dots, \varepsilon_{iT}]$ for each T and

$$\max_{1 \leq t \leq T} \left| \sum_{s=1}^t \tilde{\varepsilon}_{is} - \sigma_i \mathbb{B}_i(t) \right| = o(T^{1/q}) \quad \text{a.s.}, \quad (\text{A.5})$$

where $\sigma_i^2 = \sum_{k \in \mathbb{Z}} \text{Cov}(\varepsilon_{i0}, \varepsilon_{ik})$ denotes the long-run error variance.

We apply this result for each stationary process $\mathcal{E}_i = \{\varepsilon_{it} : 1 \leq t \leq T\}$ so that each process $\tilde{\mathcal{E}}_i = \{\tilde{\varepsilon}_{it} : t \in \mathbb{N}\}$ is independent of $\tilde{\mathcal{E}}_j = \{\tilde{\varepsilon}_{jt} : t \in \mathbb{N}\}$ for $i \neq j$.

Furthermore, we define

$$\begin{aligned} \tilde{\Phi}_{n,T} &= \max_{1 \leq i < j \leq n} \max_{(u,h) \in \mathcal{G}_T} \left\{ \left| \frac{\tilde{\phi}_{ij,T}(u,h)}{(\tilde{\sigma}_i^2 + \tilde{\sigma}_j^2)^{1/2}} \right| - \lambda(h) \right\} \\ \text{with } \tilde{\phi}_{ij,T}(u,h) &= \sum_{t=1}^T w_{t,T}(u,h) \{(\tilde{\varepsilon}_{it} - \tilde{\varepsilon}_i) - (\tilde{\varepsilon}_{jt} - \tilde{\varepsilon}_j)\}. \end{aligned}$$

where $\tilde{\sigma}_i^2$ are the same estimators as $\hat{\sigma}_i^2$ with $\hat{Y}_{it} = (\beta_i - \hat{\beta}_i)^\top \mathbf{X}_{it} + m_i(t/T) + (\alpha_i - \hat{\alpha}_i) + \varepsilon_{it}$ replaced by $\tilde{Y}_{it} = \tilde{\varepsilon}_{it} - \tilde{\varepsilon}_i$ for $1 \leq t \leq T$. Since $[\tilde{\varepsilon}_{i1}, \dots, \tilde{\varepsilon}_{iT}] \stackrel{\mathcal{D}}{=} [\varepsilon_{i1}, \dots, \varepsilon_{iT}]$, we have $\sum_{\ell=-\infty}^{\infty} \text{Cov}(\tilde{\varepsilon}_{i0}, \tilde{\varepsilon}_{i\ell}) = \sum_{\ell=-\infty}^{\infty} \text{Cov}(\varepsilon_{i0}, \varepsilon_{i\ell}) = \sigma_i^2$. Hence, by construction, $\tilde{\sigma}_i^2 = \sigma_i^2 + o_P(\rho_T)$.

In addition, we let

$$\Phi_{n,T}^\diamond = \max_{1 \leq i < j \leq n} \max_{(u,h) \in \mathcal{G}_T} \left\{ \left| \frac{\phi_{ij,T}(u,h)}{(\sigma_i^2 + \sigma_j^2)^{1/2}} \right| - \lambda(h) \right\}$$

with $\phi_{ij,T}(u,h) = \sum_{t=1}^T w_{t,T}(u,h) \{ \sigma_i(Z_{it} - \bar{Z}_i) - \sigma_j(Z_{jt} - \bar{Z}_j) \}$ as defined in (3.9) with $Z_{it} = \mathbb{B}_i(t) - \mathbb{B}_i(t-1)$. With this notation, we can write

$$|\tilde{\Phi}_{n,T} - \Phi_{n,T}| \leq |\tilde{\Phi}_{n,T} - \Phi_{n,T}^\diamond| + |\Phi_{n,T}^\diamond - \Phi_{n,T}|. \quad (\text{A.6})$$

First consider $|\tilde{\Phi}_{n,T} - \Phi_{n,T}^\diamond|$. Straightforward calculations yield that

$$|\tilde{\Phi}_{n,T} - \Phi_{n,T}^\diamond| \leq \max_{1 \leq i < j \leq n} \left((\tilde{\sigma}_i^2 + \tilde{\sigma}_j^2)^{-1/2} \max_{(u,h) \in \mathcal{G}_T} |\tilde{\phi}_{ij,T}(u,h) - \phi_{ij,T}(u,h)| \right). \quad (\text{A.7})$$

We have already noted that $\tilde{\sigma}_i^2 = \sigma_i^2 + o_P(\rho_T)$. Moreover, for all $i \in \{1, \dots, n\}$ we know that $\sigma_i^2 \neq 0$. Hence,

$$\max_{1 \leq i < j \leq n} (\tilde{\sigma}_i^2 + \tilde{\sigma}_j^2)^{-1/2} = O_P(1). \quad (\text{A.8})$$

Next, using summation by parts, $(\sum_{i=1}^n a_i b_i = \sum_{i=1}^{n-1} A_i(b_i - b_{i+1}) + A_n b_n$ with $A_i = \sum_{j=1}^i a_j$) we obtain that

$$\begin{aligned} & |\tilde{\phi}_{ij,T}(u, h) - \phi_{ij,T}(u, h)| \\ &= \left| \sum_{t=1}^T w_{t,T}(u, h) \{(\tilde{\varepsilon}_{it} - \bar{\varepsilon}_i) - (\tilde{\varepsilon}_{jt} - \bar{\varepsilon}_j) - \sigma_i(Z_{it} - \bar{Z}_i) + \sigma_j(Z_{jt} - \bar{Z}_j)\} \right| \\ &= \left| \sum_{t=1}^{T-1} A_{ij,t}(w_{t,T}(u, h) - w_{t+1,T}(u, h)) + A_{ij,T} w_{T,T}(u, h) \right|, \end{aligned}$$

where

$$A_{ij,t} = \sum_{s=1}^t \{(\tilde{\varepsilon}_{is} - \bar{\varepsilon}_i) - (\tilde{\varepsilon}_{js} - \bar{\varepsilon}_j) - \sigma_i(Z_{is} - \bar{Z}_i) + \sigma_j(Z_{js} - \bar{Z}_j)\}.$$

Note that by construction $A_{ij,T} = 0$ for all pairs (i, j) . Denoting

$$W_T(u, h) = \sum_{t=1}^{T-1} |w_{t+1,T}(u, h) - w_{t,T}(u, h)|,$$

we have

$$\begin{aligned} |\tilde{\phi}_{ij,T}(u, h) - \phi_{ij,T}(u, h)| &= \left| \sum_{t=1}^{T-1} A_{ij,t}(w_{t,T}(u, h) - w_{t+1,T}(u, h)) \right| \\ &\leq W_T(u, h) \max_{1 \leq t \leq T} |A_{ij,t}|. \end{aligned} \tag{A.9}$$

Now consider $\max_{1 \leq t \leq T} |A_{ij,t}|$. Straightforward application of the triangle inequality provides the following bound:

$$\begin{aligned} \max_{1 \leq t \leq T} |A_{ij,t}| &\leq \max_{1 \leq t \leq T} \left| \sum_{s=1}^t \tilde{\varepsilon}_{is} - \sigma_i \sum_{s=1}^t Z_{is} \right| + \max_{1 \leq t \leq T} \left| t(\bar{\varepsilon}_i - \sigma_i \bar{Z}_i) \right| \\ &\quad + \max_{1 \leq t \leq T} \left| \sum_{s=1}^t \tilde{\varepsilon}_{js} - \sigma_j \sum_{s=1}^t Z_{js} \right| + \max_{1 \leq t \leq T} \left| t(\bar{\varepsilon}_j - \sigma_j \bar{Z}_j) \right| \\ &\leq 2 \max_{1 \leq t \leq T} \left| \sum_{s=1}^t \tilde{\varepsilon}_{is} - \sigma_i \sum_{s=1}^t Z_{is} \right| + 2 \max_{1 \leq t \leq T} \left| \sum_{s=1}^t \tilde{\varepsilon}_{js} - \sigma_j \sum_{s=1}^t Z_{js} \right| \\ &= 2 \max_{1 \leq t \leq T} \left| \sum_{s=1}^t \tilde{\varepsilon}_{is} - \sigma_i \sum_{s=1}^t (\mathbb{B}_i(s) - \mathbb{B}_i(s-1)) \right| \\ &\quad + 2 \max_{1 \leq t \leq T} \left| \sum_{s=1}^t \tilde{\varepsilon}_{js} - \sigma_j \sum_{s=1}^t (\mathbb{B}_j(s) - \mathbb{B}_j(s-1)) \right| \\ &= 2 \max_{1 \leq t \leq T} \left| \sum_{s=1}^t \tilde{\varepsilon}_{is} - \sigma_i \mathbb{B}_i(t) \right| + 2 \max_{1 \leq t \leq T} \left| \sum_{s=1}^t \tilde{\varepsilon}_{js} - \sigma_j \mathbb{B}_j(t) \right|. \end{aligned}$$

Applying the strong approximation result (A.5), we can infer that

$$\max_{1 \leq t \leq T} |A_{ij,t}| = o_P(T^{1/q}). \quad (\text{A.10})$$

Standard arguments show that $\max_{(u,h) \in \mathcal{G}_T} W_T(u,h) = O(1/\sqrt{Th_{\min}})$. Plugging (A.10) in (A.9), and taking the result together with (A.8) and plugging them in (A.7), we can thus infer that

$$\begin{aligned} |\tilde{\Phi}_{n,T} - \Phi_{n,T}^\diamond| &\leq (\tilde{\sigma}_i^2 + \tilde{\sigma}_j^2)^{-1/2} \max_{(u,h) \in \mathcal{G}_T} W_T(u,h) \max_{1 \leq i < j \leq n} \max_{1 \leq t \leq T} |A_{ij,t}| \\ &= O_P(1) \cdot O\left(\frac{1}{\sqrt{Th_{\min}}}\right) \cdot o_P(T^{1/q}) \\ &= o_P\left(\frac{T^{1/q}}{\sqrt{Th_{\min}}}\right). \end{aligned} \quad (\text{A.11})$$

Now consider $|\Phi_{n,T}^\diamond - \Phi_{n,T}|$. Trivially,

$$\begin{aligned} |\Phi_{n,T}^\diamond - \Phi_{n,T}| &\leq \max_{1 \leq i < j \leq n} \max_{(u,h) \in \mathcal{G}_T} \left| \frac{\phi_{ij,T}(u,h)}{\{\tilde{\sigma}_i^2 + \tilde{\sigma}_j^2\}^{1/2}} - \frac{\phi_{ij,T}(u,h)}{\{\sigma_i^2 + \sigma_j^2\}^{1/2}} \right| \\ &\leq \max_{1 \leq i < j \leq n} \left(\left| (\tilde{\sigma}_i^2 + \tilde{\sigma}_j^2)^{-1/2} - (\sigma_i^2 + \sigma_j^2)^{-1/2} \right| \max_{(u,h) \in \mathcal{G}_T} |\phi_{ij,T}(u,h)| \right) \end{aligned} \quad (\text{A.12})$$

Since $\tilde{\sigma}_i^2 = \sigma_i^2 + o_P(\rho_T)$ by the note above and $\hat{\sigma}_i^2 = \sigma_i^2 + o_P(\rho_T)$ by our assumptions, we have that

$$\max_{1 \leq i < j \leq n} \left| (\tilde{\sigma}_i^2 + \tilde{\sigma}_j^2)^{-1/2} - (\sigma_i^2 + \sigma_j^2)^{-1/2} \right| = o_P(\rho_T). \quad (\text{A.13})$$

Then, $\phi_{ij,T}(u,h) = \sum_{t=1}^T w_{t,T}(u,h) (\sigma_i Z_{it} - \sigma_j Z_{jt}) - \sum_{t=1}^T w_{t,T}(u,h) (\sigma_i \bar{Z}_i - \sigma_j \bar{Z}_j)$, where the first part is distributed as $N(0, \sigma_i^2 + \sigma_j^2)$ and the second part is distributed as $N\left(0, (\sigma_i^2 + \sigma_j^2)(\sum_{t=1}^T w_{t,T}(u,h))^2/T\right)$ for all $(u,h) \in \mathcal{G}_T$ and all $1 \leq i < j \leq n$. Note that $(\sum_{t=1}^T w_{t,T}(u,h))^2 \leq C \cdot T$ by (A.34), $|\mathcal{G}_T| = O(T^\theta)$ for some large but fixed constant θ by Assumption (C12), n is fixed. Hence, **by well-known results in probability theory on the bounds of a maximum of Gaussian random variables, we have**

$$\max_{1 \leq i < j \leq n} \max_{(u,h) \in \mathcal{G}_T} |\phi_{ij,T}(u,h)| = O_P(\sqrt{\log T}), \quad (\text{A.14})$$

which together with (A.12) and (A.13) leads to

$$|\Phi_{n,T}^\diamond - \Phi_{n,T}| = o_P(\rho_T) \cdot O_P(\sqrt{\log T}) = o_P(\rho_T \sqrt{\log T}). \quad (\text{A.15})$$

Plugging (A.11) and (A.15) in (A.6) completes the proof. \square

Step 2

In this step, we establish some properties of the Gaussian statistic $\Phi_{n,T}$ defined in (3.10). We in particular show that $\Phi_{n,T}$ does not concentrate too strongly in small regions of the form $[x - \delta_T, x + \delta_T]$ with δ_T converging to zero.

The main technical tool for proving these results (specifically, Proposition A.5) are anti-concentration bounds for Gaussian random vectors. The following proposition slightly generalizes anti-concentration results derived in Chernozhukov et al. (2015), in particular Theorem 3 therein.

Proposition A.4. *Khismatullina and Vogt (2020) Let $(X_1, \dots, X_p)^\top$ be a Gaussian random vector in \mathbb{R}^p with $\mathbb{E}[X_j] = \mu_j$ and $\text{Var}(X_j) = \sigma_j^2 > 0$ for $1 \leq j \leq p$. Define $\bar{\mu} = \max_{1 \leq j \leq p} |\mu_j|$ together with $\underline{\sigma} = \min_{1 \leq j \leq p} \sigma_j$ and $\bar{\sigma} = \max_{1 \leq j \leq p} \sigma_j$. Moreover, set $a_p = \mathbb{E}[\max_{1 \leq j \leq p} (X_j - \mu_j)/\sigma_j]$ and $b_p = \mathbb{E}[\max_{1 \leq j \leq p} (X_j - \mu_j)]$. For every $\delta > 0$, it holds that*

$$\sup_{x \in \mathbb{R}} \mathbb{P}\left(\left|\max_{1 \leq j \leq p} X_j - x\right| \leq \delta\right) \leq C\delta\{\bar{\mu} + a_p + b_p + \sqrt{1 \vee \log(\bar{\sigma}/\delta)}\},$$

where $C > 0$ depends only on $\underline{\sigma}$ and $\bar{\sigma}$.

Proposition A.5. *Under the conditions of Theorem 4.1, it holds that*

$$\sup_{x \in \mathbb{R}} \mathbb{P}(|\Phi_{n,T} - x| \leq \delta_T) = o(1), \quad (\text{A.16})$$

where $\delta_T = T^{1/q}/\sqrt{Th_{\min}} + \rho_T \sqrt{\log T}$.

Proof of Proposition A.5. We write $x = (u, h)$ along with $\mathcal{G}_T = \{x : x \in \mathcal{G}_T\} = \{x_1, \dots, x_p\}$, where $p := |\mathcal{G}_T| \leq O(T^\theta)$ for some large but fixed $\theta > 0$ by our assumptions. Moreover, for $k = 1, \dots, p$, we set

$$U_{ij,2k-1} = \frac{\phi_{ij,T}(x_{k1}, x_{k2})}{\{\sigma_i^2 + \sigma_j^2\}^{1/2}} - \lambda(x_{k2})$$

$$U_{ij,2k} = -\frac{\phi_{ij,T}(x_{k1}, x_{k2})}{\{\sigma_i^2 + \sigma_j^2\}^{1/2}} - \lambda(x_{k2})$$

with $x_k = (x_{k1}, x_{k2})$. This notation allows us to write

$$\Phi_{n,T} = \max_{1 \leq i < j \leq n} \max_{1 \leq k \leq 2p} U_{ij,k} = \max_{1 \leq l \leq (n-1)np} U'_l$$

where $(U'_1, \dots, U'_{(n-1)np})^\top \in \mathbb{R}^{(n-1)np}$ is a Gaussian random vector with the following properties: (i) $\mu_l := \mathbb{E}[U'_l] = \{\mathbb{E}[U_{ij,2k}] \text{ or } \mathbb{E}[U_{ij,2k-1}]\} = -\lambda(x_{k2})$ and thus

$$\bar{\mu} = \max_{1 \leq l \leq (n-1)np} |\mu_l| \leq C\sqrt{\log T},$$

and (ii) $\sigma_l^2 := \text{Var}(U'_l) = 1$ for all $1 \leq l \leq (n-1)np$. We would like to apply Proposition A.4 (Proposition S.3 in Khismatullina and Vogt (2020)) to $(U'_1, \dots, U'_{(n-1)np})^\top$, and for this, we need to check the assumptions therein. First,

$$a_{(n-1)np} := \mathbb{E}\left[\max_{1 \leq l \leq (n-1)np} (U'_l - \mu_l)/\sigma_l\right] = \mathbb{E}\left[\max_{1 \leq l \leq (n-1)np} (U'_l - \mu_l)\right] =: b_{(n-1)np}.$$

Moreover, as the variables $(U'_l - \mu_l)/\sigma_l$ are standard normal, we have that $a_{(n-1)np} = b_{(n-1)np} \leq C\sqrt{\log((n-1)np)} \leq C\sqrt{\log T}$. With this notation at hand, we can apply Proposition A.4 to obtain that

$$\sup_{x \in \mathbb{R}} \mathbb{P}\left(|\Phi_{n,T} - x| \leq \delta_T\right) \leq C\delta_T \left[\sqrt{\log T} + \sqrt{\log(1/\delta_T)}\right] = o(1)$$

with $\delta_T = T^{1/q}/\sqrt{Th_{\min}} + \rho_T\sqrt{\log T}$, which is the statement of Proposition A.5. \square

Step 3

Lemma A.6. *Khismatullina and Vogt (2020)* Let V_T and W_T be real-valued random variables for $T = 1, 2, \dots$ such that $V_T - W_T = o_p(\delta_T)$ with some $\delta_T = o(1)$. If

$$\sup_{x \in \mathbb{R}} \mathbb{P}(|V_T - x| \leq \delta_T) = o(1),$$

then

$$\sup_{x \in \mathbb{R}} |\mathbb{P}(V_T \leq x) - \mathbb{P}(W_T \leq x)| = o(1).$$

Applying Lemma A.6 to $\tilde{\Phi}_{n,T}$ and $\Phi_{n,T}$ (taking $V_T = \Phi_{n,T}$ and $W_T = \tilde{\Phi}_{n,T}$) together with the results (A.4) and (A.16) and noting the fact that $\tilde{\Phi}_{n,T}$ is distributed as $\hat{\hat{\Phi}}_{n,T}$ for any $n \geq 2, T \geq 1$ immediately leads to

$$\sup_{x \in \mathbb{R}} |\mathbb{P}(\hat{\hat{\Phi}}_{n,T} \leq x) - \mathbb{P}(\Phi_{n,T} \leq x)| = o(1). \quad (\text{A.17})$$

Step 4

As was already mentioned in Step 1, the statistics $\hat{\hat{\Phi}}_{n,T}$ can be viewed as an approximation of the statistics $\hat{\Phi}_{n,T}$. Heuristically, the kernel averages $\hat{\phi}_{ij,T}(u, h)$ are close to the kernel averages $\hat{\phi}_{ij,T}(u, h)$ because of the properties of our estimators $\hat{\beta}_i, \hat{\sigma}_i^2$ and assumptions on \mathbf{X}_{it} . In the following two propositions we prove it formally.

Proposition A.7. *For any $x \in \mathbb{R}$ and any $\gamma > 0$, we have*

$$\begin{aligned} \mathbb{P}\left(\hat{\hat{\Phi}}_{n,T} \leq x - \gamma\right) - \mathbb{P}\left(|\hat{\hat{\Phi}}_{n,T} - \hat{\Phi}_{n,T}| > \gamma\right) &\leq \mathbb{P}(\hat{\Phi}_{n,T} \leq x) \\ &\leq \mathbb{P}\left(\hat{\hat{\Phi}}_{n,T} \leq x + \gamma\right) + \mathbb{P}\left(|\hat{\hat{\Phi}}_{n,T} - \hat{\Phi}_{n,T}| > \gamma\right). \end{aligned} \quad (\text{A.18})$$

Proof of Proposition A.7. From the law of total probability and the monotonic property of the probability function, we have

$$\begin{aligned} \mathbb{P}(\hat{\Phi}_{n,T} \leq x) &= \mathbb{P}\left(\hat{\Phi}_{n,T} \leq x, |\hat{\hat{\Phi}}_{n,T} - \hat{\Phi}_{n,T}| \leq \gamma\right) + \mathbb{P}\left(\hat{\Phi}_{n,T} \leq x, |\hat{\hat{\Phi}}_{n,T} - \hat{\Phi}_{n,T}| > \gamma\right) \\ &\leq \mathbb{P}\left(\hat{\Phi}_{n,T} \leq x, \hat{\hat{\Phi}}_{n,T} - \gamma \leq \hat{\Phi}_{n,T} \leq \hat{\hat{\Phi}}_{n,T} + \gamma\right) + \mathbb{P}\left(|\hat{\hat{\Phi}}_{n,T} - \hat{\Phi}_{n,T}| > \gamma\right) \\ &\leq \mathbb{P}\left(\hat{\hat{\Phi}}_{n,T} \leq x + \gamma\right) + \mathbb{P}\left(|\hat{\hat{\Phi}}_{n,T} - \hat{\Phi}_{n,T}| > \gamma\right). \end{aligned}$$

Analogously,

$$\mathbb{P}(\widehat{\Phi}_{n,T} \leq x - \gamma) \leq \mathbb{P}(\widehat{\Phi}_{n,T} \leq x) + \mathbb{P}(|\widehat{\Phi}_{n,T} - \widehat{\Phi}_{n,T}| > \gamma).$$

Combining these two inequalities together, we arrive at the desired result. \square

The aim of the next proposition is to determine the sequence of values of γ_T that may depend on T such that the difference between the distributions of $\widehat{\Phi}_{n,T}$ and $\widehat{\Phi}_{n,T}$ is not too big. In other words,

Proposition A.8. *Suppose we have a sequence of positive real numbers γ_T such that $\gamma_T = O(\rho_T \sqrt{\log T} + T^{1/q} / \sqrt{Th_{\min}})$. Then we have*

$$\mathbb{P}(|\widehat{\Phi}_{n,T} - \widehat{\Phi}_{n,T}| > \gamma_T) = o(1). \quad (A.19)$$

Proof of Proposition A.8. Straightforward calculations yield that

$$\begin{aligned} |\widehat{\Phi}_{n,T} - \widehat{\Phi}_{n,T}| &\leq \max_{1 \leq i < j \leq n} \max_{(u,h) \in \mathcal{G}_T} \left| \frac{\widehat{\phi}_{ij,T}(u,h)}{(\widehat{\sigma}_i^2 + \widehat{\sigma}_j^2)^{1/2}} - \frac{\widehat{\phi}_{ij,T}(u,h)}{(\widehat{\sigma}_i^2 + \widehat{\sigma}_j^2)^{1/2}} \right| \\ &\quad + \max_{1 \leq i < j \leq n} \max_{(u,h) \in \mathcal{G}_T} \left| \frac{\widehat{\phi}_{ij,T}(u,h)}{(\widehat{\sigma}_i^2 + \widehat{\sigma}_j^2)^{1/2}} - \frac{\widehat{\phi}_{ij,T}(u,h)}{(\widehat{\sigma}_i^2 + \widehat{\sigma}_j^2)^{1/2}} \right|. \end{aligned}$$

Obviously,

$$\begin{aligned} &\max_{1 \leq i < j \leq n} \max_{(u,h) \in \mathcal{G}_T} \left| \frac{\widehat{\phi}_{ij,T}(u,h)}{(\widehat{\sigma}_i^2 + \widehat{\sigma}_j^2)^{1/2}} - \frac{\widehat{\phi}_{ij,T}(u,h)}{(\widehat{\sigma}_i^2 + \widehat{\sigma}_j^2)^{1/2}} \right| \\ &\leq \max_{1 \leq i < j \leq n} \left(\left| (\widehat{\sigma}_i^2 + \widehat{\sigma}_j^2)^{-1/2} - (\widehat{\sigma}_i^2 + \widehat{\sigma}_j^2)^{-1/2} \right| \max_{(u,h) \in \mathcal{G}_T} \left| \widehat{\phi}_{ij,T}(u,h) \right| \right) \end{aligned}$$

and

$$\begin{aligned} &\max_{1 \leq i < j \leq n} \max_{(u,h) \in \mathcal{G}_T} \left| \frac{\widehat{\phi}_{ij,T}(u,h)}{(\widehat{\sigma}_i^2 + \widehat{\sigma}_j^2)^{1/2}} - \frac{\widehat{\phi}_{ij,T}(u,h)}{(\widehat{\sigma}_i^2 + \widehat{\sigma}_j^2)^{1/2}} \right| \\ &\leq \max_{1 \leq i < j \leq n} \left((\widehat{\sigma}_i^2 + \widehat{\sigma}_j^2)^{-1/2} \max_{(u,h) \in \mathcal{G}_T} \left| \widehat{\phi}_{ij,T}(u,h) - \widehat{\phi}_{ij,T}(u,h) \right| \right). \end{aligned}$$

Furthermore, the difference of the kernel averages $\widehat{\phi}_{ij,T}(u,h) - \widehat{\phi}_{ij,T}(u,h)$ does not include the error terms (they cancel out) and can be written as

$$\begin{aligned} |\widehat{\phi}_{ij,T}(u,h) - \widehat{\phi}_{ij,T}(u,h)| &= \left| \sum_{t=1}^T w_{t,T}(u,h) \{ (\beta_i - \widehat{\beta}_i)^\top (\mathbf{X}_{it} - \bar{\mathbf{X}}_i) - (\beta_j - \widehat{\beta}_j)^\top (\mathbf{X}_{jt} - \bar{\mathbf{X}}_j) \} \right| \\ &\leq \left| (\beta_i - \widehat{\beta}_i)^\top \sum_{t=1}^T w_{t,T}(u,h) \mathbf{X}_{it} \right| + \left| (\beta_i - \widehat{\beta}_i)^\top \bar{\mathbf{X}}_i \right| \left| \sum_{t=1}^T w_{t,T}(u,h) \right| \\ &\quad + \left| (\beta_j - \widehat{\beta}_j)^\top \sum_{t=1}^T w_{t,T}(u,h) \mathbf{X}_{jt} \right| + \left| (\beta_j - \widehat{\beta}_j)^\top \bar{\mathbf{X}}_j \right| \left| \sum_{t=1}^T w_{t,T}(u,h) \right| \end{aligned}$$

Hence,

$$\begin{aligned}
|\widehat{\Phi}_{n,T} - \widehat{\Phi}_{n,T}| &\leq \max_{1 \leq i < j \leq n} \left| (\widehat{\sigma}_i^2 + \widehat{\sigma}_j^2)^{-1/2} - (\widehat{\sigma}_i^2 + \widehat{\sigma}_j^2)^{-1/2} \right| \max_{1 \leq i < j \leq n} \max_{(u,h) \in \mathcal{G}_T} \left| \widehat{\phi}_{ij,T}(u,h) \right| \\
&\quad + 2 \max_{1 \leq i < j \leq n} (\widehat{\sigma}_i^2 + \widehat{\sigma}_j^2)^{-1/2} \max_{1 \leq i \leq n} \max_{(u,h) \in \mathcal{G}_T} \left| (\beta_i - \widehat{\beta}_i)^\top \sum_{t=1}^T w_{t,T}(u,h) \mathbf{X}_{it} \right| \\
&\quad + 2 \max_{1 \leq i < j \leq n} (\widehat{\sigma}_i^2 + \widehat{\sigma}_j^2)^{-1/2} \max_{1 \leq i \leq n} |(\beta_i - \widehat{\beta}_i)^\top \bar{\mathbf{X}}_i| \max_{(u,h) \in \mathcal{G}_T} \left| \sum_{t=1}^T w_{t,T}(u,h) \right|.
\end{aligned} \tag{A.20}$$

We consider each of the three summands separately.

We start by looking at the first summand in (A.20). Since $\widehat{\sigma}_i^2 = \sigma_i^2 + o_P(\rho_T)$ and $\widehat{\sigma}_i^2 = \sigma_i^2 + o_P(\rho_T)$ by our assumptions, we have that

$$\max_{1 \leq i < j \leq n} \left| (\widehat{\sigma}_i^2 + \widehat{\sigma}_j^2)^{-1/2} - (\sigma_i^2 + \sigma_j^2)^{-1/2} \right| = o_P(\rho_T). \tag{A.21}$$

Then, we investigate $\max_{(u,h) \in \mathcal{G}_T} |\widehat{\phi}_{ij,T}(u,h)|$. Specifically, we are interested in its distribution. We know by Proposition A.3 that there exists $\widetilde{\phi}_{ij,T}(u,h)$ that has the same distribution as $\widehat{\phi}_{ij,T}(u,h)$ for all $1 \leq i < j \leq n$ and all $(u,h) \in \mathcal{G}_T$:

$$\mathbb{P}(\widehat{\phi}_{ij,T}(u,h) \leq x) = \mathbb{P}(\widetilde{\phi}_{ij,T}(u,h) \leq x) \text{ for all } x \in \mathbb{R}.$$

So instead of looking at the distribution of $\max_{(u,h) \in \mathcal{G}_T} |\widehat{\phi}_{ij,T}(u,h)|$, we now turn our attention at the distribution of $\max_{(u,h) \in \mathcal{G}_T} |\widetilde{\phi}_{ij,T}(u,h)|$ instead.

In bounding $\mathbb{P}(\max_{(u,h) \in \mathcal{G}_T} |\widetilde{\phi}_{ij,T}(u,h)| \leq x)$, we can use the strategy from the second part of the proof of Proposition A.7. For any $c_T \in \mathbb{R}$ we have

$$\begin{aligned}
&\mathbb{P} \left(\max_{(u,h) \in \mathcal{G}_T} |\phi_{ij,T}(u,h)| \leq c_T/2 \right) \\
&\leq \mathbb{P} \left(\max_{(u,h) \in \mathcal{G}_T} |\widetilde{\phi}_{ij,T}(u,h)| \leq c_T \right) + \mathbb{P} \left(\left| \max_{(u,h) \in \mathcal{G}_T} |\widetilde{\phi}_{ij,T}(u,h)| - \max_{(u,h) \in \mathcal{G}_T} |\phi_{ij,T}(u,h)| \right| > \frac{c_T}{2} \right) \\
&\leq \mathbb{P} \left(\max_{(u,h) \in \mathcal{G}_T} |\widetilde{\phi}_{ij,T}(u,h)| \leq c_T \right) + \mathbb{P} \left(\max_{(u,h) \in \mathcal{G}_T} |\widetilde{\phi}_{ij,T}(u,h) - \phi_{ij,T}(u,h)| > \frac{c_T}{2} \right).
\end{aligned}$$

Hence,

$$\begin{aligned}
&\mathbb{P} \left(\max_{(u,h) \in \mathcal{G}_T} |\widehat{\phi}_{ij,T}(u,h)| \leq c_T \right) = \mathbb{P} \left(\max_{(u,h) \in \mathcal{G}_T} |\widetilde{\phi}_{ij,T}(u,h)| \leq c_T \right) \\
&\geq \mathbb{P} \left(\max_{(u,h) \in \mathcal{G}_T} |\phi_{ij,T}(u,h)| \leq c_T/2 \right) - \mathbb{P} \left(\max_{(u,h) \in \mathcal{G}_T} |\widetilde{\phi}_{ij,T}(u,h) - \phi_{ij,T}(u,h)| > \frac{c_T}{2} \right).
\end{aligned} \tag{A.22}$$

By (A.15) we have

$$\max_{(u,h) \in \mathcal{G}_T} \left| \tilde{\phi}_{ij,T}(u,h) - \phi_{ij,T}(u,h) \right| = o_P \left(\frac{T^{1/q}}{\sqrt{T}h_{\min}} \right).$$

Furthermore, $\phi_{ij,T}(u,h)$ is distributed as $N(0, \sigma_i^2 + \sigma_j^2)$ for all $(u,h) \in \mathcal{G}_T$ and all $1 \leq i < j \leq n$, and $|\mathcal{G}_T| = O(T^\theta)$ for some large but fixed constant θ by Assumption (C12). By standard results from the probability theory, we know that

$$\max_{(u,h) \in \mathcal{G}_T} |\phi_{ij,T}(u,h)| = O_P(\sqrt{\log T}).$$

Since $T^{1/q}/\sqrt{T}h_{\min} \ll \sqrt{\log T}$, we can take $c_T \gg \sqrt{\log T}$ in (A.22) to get the following:

$$\begin{aligned} & \mathbb{P} \left(\max_{(u,h) \in \mathcal{G}_T} \left| \hat{\phi}_{ij,T}(u,h) \right| \leq c_T \right) \\ & \geq \mathbb{P} \left(\max_{(u,h) \in \mathcal{G}_T} |\phi_{ij,T}(u,h)| \leq \frac{c_T}{2} \right) - \mathbb{P} \left(\max_{(u,h) \in \mathcal{G}_T} \left| \tilde{\phi}_{ij,T}(u,h) - \phi_{ij,T}(u,h) \right| > \frac{c_T}{2} \right) \\ & = 1 - o(1) - o(1) \\ & = 1 - o(1), \end{aligned}$$

which means that

$$\max_{(u,h) \in \mathcal{G}_T} \left| \hat{\phi}_{ij,T}(u,h) \right| = o_P(\sqrt{\log T}). \quad (\text{A.23})$$

Combining (A.21) and (A.23) and taking into consideration that n is fixed, we get the following:

$$\begin{aligned} & \max_{1 \leq i < j \leq n} \left| (\hat{\sigma}_i^2 + \hat{\sigma}_j^2)^{-1/2} - (\sigma_i^2 + \sigma_j^2)^{-1/2} \right| \max_{1 \leq i < j \leq n} \max_{(u,h) \in \mathcal{G}_T} \left| \hat{\phi}_{ij,T}(u,h) \right| \\ & = o_P(\rho_T) \cdot o_P(\sqrt{\log T}) \\ & = o_P(\rho_T \sqrt{\log T}). \end{aligned} \quad (\text{A.24})$$

Now we evaluate the second summand in (A.20).

First, by our assumptions $\hat{\sigma}_i^2 = \sigma_i^2 + o_P(\rho_T)$. Moreover, for all $i \in \{1, \dots, n\}$ we know that $\sigma_i^2 \neq 0$. Hence,

$$\max_{1 \leq i < j \leq n} (\hat{\sigma}_i^2 + \hat{\sigma}_j^2)^{-1/2} = O_P(1). \quad (\text{A.25})$$

Then, by Theorem 5.1, we know that

$$\beta_i - \hat{\beta}_i = O_P\left(\frac{1}{\sqrt{T}}\right). \quad (\text{A.26})$$

Now consider $\sum_{t=1}^T w_{t,T}(u,h) \mathbf{X}_{it}$. Without loss of generality, we can regard the covariates \mathbf{X}_{it} to be scalars X_{it} , not vectors. The proof in case of vectors proceeds analogously.

By construction the weights $w_{t,T}(u, h)$ are not equal to 0 if and only if $T(u - h) \leq t \leq T(u + h)$. We can use this fact to rewrite

$$\left| \sum_{t=1}^T w_{t,T}(u, h) X_{it} \right| = \left| \sum_{t=\lfloor T(u-h) \rfloor}^{\lceil T(u+h) \rceil} w_{t,T}(u, h) X_{it} \right|.$$

Note that

$$\sum_{t=\lfloor T(u-h) \rfloor}^{\lceil T(u+h) \rceil} w_{t,T}^2(u, h) = \sum_{t=1}^T w_{t,T}^2(u, h) = \sum_{t=1}^T \frac{\Lambda_{t,T}^2(u, h)}{\sum_{s=1}^T \Lambda_{s,T}^2(u, h)} = 1. \quad (\text{A.27})$$

Denoting by $D_{T,u,h}$ the number of integers between $\lfloor T(u - h) \rfloor$ and $\lceil T(u + h) \rceil$ incl. (with obvious bounds $2Th \leq D_{T,u,h} \leq 2Th + 2$) and using (A.27), we can normalize the weights as follows:

$$\sum_{t=\lfloor T(u-h) \rfloor}^{\lceil T(u+h) \rceil} \left(\sqrt{D_{T,u,h}} \cdot w_{t,T}(u, h) \right)^2 = D_{T,u,h}.$$

According to Theorem A.1 (Theorem 2(ii) in Wu and Wu (2016)), if we define the weights from the theorem as $a_t = \sqrt{D_{T,u,h}} \cdot w_{t,T}(u, h)$, we can bound the probability as follows:

$$\begin{aligned} & \mathbb{P} \left(\left| \sum_{t=\lfloor T(u-h) \rfloor}^{\lceil T(u+h) \rceil} \sqrt{D_{T,u,h}} \cdot w_{t,T}(u, h) X_{it} \right| \geq x \right) \\ & \leq C_1 \frac{(\sum_{t=\lfloor T(u-h) \rfloor}^{\lceil T(u+h) \rceil} |\sqrt{D_{T,u,h}} \cdot w_{t,T}(u, h)|^{q'}) \|X_{i\cdot}\|_{q',\alpha}^{q'}}{x^{q'}} + C_2 \exp \left(-\frac{C_3 x^2}{D_{T,u,h} \|X_{i\cdot}\|_{2,\alpha}^2} \right), \end{aligned} \quad (\text{A.28})$$

where $\|X_{i\cdot}\|_{q,\alpha}^q$ is the dependence adjusted norm as defined by Definition A.1. Taking any $\delta > 0$ and applying Boole's inequality and (A.28) subsequently, we get

$$\begin{aligned} & \mathbb{P} \left(\max_{(u,h) \in \mathcal{G}_T} \left| \sum_{t=\lfloor T(u-h) \rfloor}^{\lceil T(u+h) \rceil} w_{t,T}(u, h) X_{it} \right| \geq \delta T^{1/q} \right) \\ & \leq \sum_{(u,h) \in \mathcal{G}_T} \mathbb{P} \left(\left| \sum_{t=\lfloor T(u-h) \rfloor}^{\lceil T(u+h) \rceil} w_{t,T}(u, h) X_{it} \right| \geq \delta T^{1/q} \right) \\ & = \sum_{(u,h) \in \mathcal{G}_T} \mathbb{P} \left(\left| \sum_{t=\lfloor T(u-h) \rfloor}^{\lceil T(u+h) \rceil} \sqrt{D_{T,u,h}} \cdot w_{t,T}(u, h) X_{it} \right| \geq \delta \sqrt{D_{T,u,h}} T^{1/q} \right) \\ & \leq \sum_{(u,h) \in \mathcal{G}_T} \left[C_1 \frac{(\sqrt{D_{T,u,h}})^{q'} (\sum |w_{t,T}(u, h)|^{q'}) \|X_{i\cdot}\|_{q',\alpha}^{q'}}{(\delta \sqrt{D_{T,u,h}} T^{1/q})^{q'}} + C_2 \exp \left(-\frac{C_3 (\delta \sqrt{D_{T,u,h}} T^{1/q})^2}{D_{T,u,h} \|X_{i\cdot}\|_{2,\alpha}^2} \right) \right] \\ & = \sum_{(u,h) \in \mathcal{G}_T} \left[C_1 \frac{(\sum |w_{t,T}(u, h)|^{q'}) \|X_{i\cdot}\|_{q',\alpha}^{q'}}{\delta^{q'} T^{q'/q}} + C_2 \exp \left(-\frac{C_3 \delta^2 T^{2/q}}{\|X_{i\cdot}\|_{2,\alpha}^2} \right) \right] \end{aligned}$$

$$\begin{aligned}
&\leq C_1 \frac{T^\theta \|X_i\|_{q',\alpha}^{q'}}{T^{q'/q} \cdot \delta^{q'}} \max_{(u,h) \in \mathcal{G}_T} \left(\sum_{t=\lfloor T(u-h) \rfloor}^{\lceil T(u+h) \rceil} |w_{t,T}(u,h)|^{q'} \right) + C_2 T^\theta \exp \left(-\frac{C_3 \delta^2 T^{2/q}}{\|X_i\|_{2,\alpha}^2} \right) \\
&= C \frac{T^{\theta-q'/q}}{\delta^{q'}} + CT^\theta \exp(-CT^{2/q} \delta^2).
\end{aligned}$$

where the symbol C denotes a universal real constant that does not depend neither on T , nor on δ , and takes a different value on each occurrence. Here in the last equality we used the following facts:

1. $\|X_i\|_{q',\alpha}^{q'} = \sup_{t \geq 0} (t+1)^\alpha \sum_{s=t}^\infty \delta_{q'}(H_i, s) < \infty$ holds true since $\sum_{s=t}^\infty \delta_{q'}(H_i, s) = O(t^{-\alpha})$ by Assumption (C8);
2. $\max_{(u,h) \in \mathcal{G}_T} \left(\sum_{t=\lfloor T(u-h) \rfloor}^{\lceil T(u+h) \rceil} |w_{t,T}(u,h)|^{q'} \right) \leq 1$ because for every $x \in [0, 1]$ we have $0 \leq x^{q'/2} \leq x \leq 1$. Thus, since $\sum_{t=1}^T w_{t,T}^2(u,h) = 1$ by (A.27) we have $0 \leq w_{t,T}^2(u,h) \leq 1$ for all $t \in \{1, \dots, T\}$ and all $(u,h) \in \mathcal{G}_T$, we get

$$0 \leq |w_{t,T}(u,h)|^{q'} = (w_{t,T}^2(u,h))^{q'/2} \leq w_{t,T}^2(u,h) \leq 1.$$

This leads to a bound

$$\max_{(u,h) \in \mathcal{G}_T} \left(\sum_{t=\lfloor T(u-h) \rfloor}^{\lceil T(u+h) \rceil} |w_{t,T}(u,h)|^{q'} \right) \leq \max_{(u,h) \in \mathcal{G}_T} \left(\sum_{t=\lfloor T(u-h) \rfloor}^{\lceil T(u+h) \rceil} w_{t,T}^2(u,h) \right) = 1.$$

3. $\|X_i\|_{2,\alpha}^2 < \infty$ (follows from 1).

By Assumption (C6), $\theta - q'/q < 0$ [currently the assumption is formulated differently] and the term on the RHS of the above inequality is converging to 0 as $T \rightarrow \infty$ for any fixed $\delta > 0$. Hence,

$$\max_{(u,h) \in \mathcal{G}_T} \left| \sum_{t=\lfloor T(u-h) \rfloor}^{\lceil T(u+h) \rceil} w_{t,T}(u,h) X_{it} \right| = o_P(T^{1/q}),$$

and similarly,

$$\max_{(u,h) \in \mathcal{G}_T} \left| \sum_{t=\lfloor T(u-h) \rfloor}^{\lceil T(u+h) \rceil} w_{t,T}(u,h) \mathbf{X}_{it} \right| = o_P(T^{1/q}). \quad (\text{A.29})$$

Combining (A.25), (A.26) and (A.29), we get the following:

$$\begin{aligned}
&\max_{1 \leq i < j \leq n} (\hat{\sigma}_i^2 + \hat{\sigma}_j^2)^{-1/2} \max_{1 \leq i \leq n} \max_{(u,h) \in \mathcal{G}_T} \left| (\beta_i - \hat{\beta}_i)^\top \sum_{t=1}^T w_{t,T}(u,h) \mathbf{X}_{it} \right| \\
&= O_P(1) \cdot O_P(1/\sqrt{T}) \cdot o_P(T^{1/q}) \\
&= o_P(T^{1/q}/\sqrt{T}).
\end{aligned} \quad (\text{A.30})$$

Now consider the third summand in (A.20). Similarly as before,

$$\max_{1 \leq i < j \leq n} (\hat{\sigma}_i^2 + \hat{\sigma}_j^2)^{-1/2} = O_P(1) \quad (\text{A.31})$$

and

$$\beta_i - \hat{\beta}_i = O_P\left(\frac{1}{\sqrt{T}}\right). \quad (\text{A.32})$$

Furthermore, by Proposition A.2,

$$\bar{\mathbf{X}}_i = o_P(\log^{2/q'} T / \sqrt{T}). \quad (\text{A.33})$$

Finally, consider the local linear kernel weights $w_{t,T}(u, h)$ defined in (3.5). Again, by construction the weights $w_{t,T}(u, h)$ are not equal to 0 if and only if $T(u - h) \leq t \leq T(u + h)$. We can use this fact to bound $\left| \sum_{t=1}^T w_{t,T}(u, h) \right|$ for all $(u, h) \in \mathcal{G}_T$ using the Cauchy-Schwarz inequality:

$$\begin{aligned} \left| \sum_{t=1}^T w_{t,T}(u, h) \right| &= \left| \sum_{t=\lfloor T(u-h) \rfloor}^{\lceil T(u+h) \rceil} w_{t,T}(u, h) \cdot 1 \right| \\ &\leq \sqrt{\sum_{t=\lfloor T(u-h) \rfloor}^{\lceil T(u+h) \rceil} w_{t,T}^2(u, h)} \sqrt{\sum_{t=\lfloor T(u-h) \rfloor}^{\lceil T(u+h) \rceil} 1^2} \\ &= \sqrt{1} \cdot \sqrt{D_{T,u,h}} \\ &\leq \sqrt{2Th + 2} \\ &\leq \sqrt{2Th_{\max} + 2} \\ &\leq \sqrt{T + 2}. \end{aligned}$$

Hence,

$$\max_{(u,h) \in \mathcal{G}_T} \left| \sum_{t=1}^T w_{t,T}(u, h) \right| = O(\sqrt{T}). \quad (\text{A.34})$$

Combining (A.31), (A.32), (A.33) and (A.34), we get the following:

$$\begin{aligned} \max_{1 \leq i < j \leq n} (\hat{\sigma}_i^2 + \hat{\sigma}_j^2)^{-1/2} \max_{1 \leq i \leq n} |(\beta_i - \hat{\beta}_i)^\top \bar{\mathbf{X}}_i| \max_{(u,h) \in \mathcal{G}_T} \left| \sum_{t=1}^T w_{t,T}(u, h) \right| \\ = O_P(1) \cdot O_P(1/\sqrt{T}) \cdot o_P(\log^{2/q'}(T)/\sqrt{T}) \cdot O(\sqrt{T}) \\ = o_P(\log^{2/q'}(T)/\sqrt{T}). \end{aligned} \quad (\text{A.35})$$

Plugging (A.24), (A.30) and (A.35) in (A.20), we get that

$$\begin{aligned} |\hat{\Phi}_{n,T} - \hat{\Phi}_{n,T}| &= o_P(\rho_T \log T) + o_P(T^{1/q}/\sqrt{T}) + o_P(\log^{2/q'} T / \sqrt{T}) \\ &= o_P\left(\rho_T \log T + T^{1/q}/\sqrt{T}\right) \\ &= o_P\left(\rho_T \log T + \frac{T^{1/q}}{\sqrt{Th_{\min}}}\right) \end{aligned}$$

and the statement of the proposition follows. \square

Step 5

Proposition A.9. *Under the conditions of Theorem 4.1, it holds that*

$$\sup_{x \in \mathbb{R}} |\mathbb{P}(\widehat{\Phi}_{n,T} \leq x) - \mathbb{P}(\Phi_{n,T} \leq x)| = o(1). \quad (\text{A.36})$$

Proof of Proposition A.9. First, we consider those $x \in \mathbb{R}$ such that $\mathbb{P}(\widehat{\Phi}_{n,T} \leq x) \geq \mathbb{P}(\Phi_{n,T} \leq x)$. Then by Proposition A.7 for a sequence $\gamma_T > 0$ that satisfies the conditions of the Proposition A.8 we have

$$\begin{aligned} |\mathbb{P}(\widehat{\Phi}_{n,T} \leq x) - \mathbb{P}(\Phi_{n,T} \leq x)| &= \mathbb{P}(\widehat{\Phi}_{n,T} \leq x) - \mathbb{P}(\Phi_{n,T} \leq x) \\ &\leq \mathbb{P}(\widehat{\widehat{\Phi}}_{n,T} \leq x + \gamma_T) + \mathbb{P}(|\widehat{\Phi}_{n,T} - \widehat{\widehat{\Phi}}_{n,T}| > \gamma_T) - \mathbb{P}(\Phi_{n,T} \leq x) \\ &= \mathbb{P}(\widehat{\widehat{\Phi}}_{n,T} \leq x + \gamma_T) - \mathbb{P}(\Phi_{n,T} \leq x + \gamma_T) \\ &\quad + \mathbb{P}(\Phi_{n,T} \leq x + \gamma_T) - \mathbb{P}(\Phi_{n,T} \leq x) + \mathbb{P}(|\widehat{\Phi}_{n,T} - \widehat{\widehat{\Phi}}_{n,T}| > \gamma_T) \\ &\leq \mathbb{P}(\widehat{\widehat{\Phi}}_{n,T} \leq x + \gamma_T) - \mathbb{P}(\Phi_{n,T} \leq x + \gamma_T) \\ &\quad + \mathbb{P}(|\Phi_{n,T} - x| \leq \gamma_T) + \mathbb{P}(|\widehat{\Phi}_{n,T} - \widehat{\widehat{\Phi}}_{n,T}| > \gamma_T). \end{aligned}$$

Now consider such $x \in \mathbb{R}$ that $\mathbb{P}(\widehat{\Phi}_{n,T} \leq x) < \mathbb{P}(\Phi_{n,T} \leq x)$. Analogously,

$$\begin{aligned} |\mathbb{P}(\widehat{\Phi}_{n,T} \leq x) - \mathbb{P}(\Phi_{n,T} \leq x)| &\leq \mathbb{P}(|\Phi_{n,T} - x| \leq \gamma_T) + \mathbb{P}(\Phi_{n,T} \leq x - \gamma_T) \\ &\quad - \mathbb{P}(\widehat{\Phi}_{n,T} \leq x - \gamma_T) + \mathbb{P}(|\widehat{\Phi}_{n,T} - \widehat{\widehat{\Phi}}_{n,T}| > \gamma_T). \end{aligned}$$

Note that since $\gamma_T = O(\rho_T \sqrt{\log T} + T^{1/q} / \sqrt{T h_{\min}})$, we can use the anti-concentration results (A.16) for the Gaussian statistic $\Phi_{n,T}$: $\sup_{x \in \mathbb{R}} \mathbb{P}(|\Phi_{n,T} - x| \leq \gamma_T) = o(1)$. Moreover,

$$\mathbb{P}(|\widehat{\Phi}_{n,T} - \widehat{\widehat{\Phi}}_{n,T}| > \gamma_T) = o(1)$$

by Proposition A.8 and this probability does not depend on x .

Thus,

$$\begin{aligned} \sup_{x \in \mathbb{R}} |\mathbb{P}(\widehat{\Phi}_{n,T} \leq x) - \mathbb{P}(\Phi_{n,T} \leq x)| &\leq \\ &\leq \max \left\{ \sup_{x \in \mathbb{R}} \left| \mathbb{P}(\Phi_{n,T} \leq x - \gamma_T) - \mathbb{P}(\widehat{\widehat{\Phi}}_{n,T} \leq x - \gamma_T) \right|, \right. \\ &\quad \left. \sup_{x \in \mathbb{R}} \left| \mathbb{P}(\Phi_{n,T} \leq x + \gamma_T) - \mathbb{P}(\widehat{\widehat{\Phi}}_{n,T} \leq x + \gamma_T) \right| \right\} + \\ &\quad + \sup_{x \in \mathbb{R}} \mathbb{P}(|\Phi_{n,T} - x| \leq \gamma_T) + \sup_{x \in \mathbb{R}} \mathbb{P}(|\widehat{\Phi}_{n,T} - \widehat{\widehat{\Phi}}_{n,T}| > \gamma_T) = \\ &= \sup_{y \in \mathbb{R}} \left| \mathbb{P}(\Phi_{n,T} \leq y) - \mathbb{P}(\widehat{\widehat{\Phi}}_{n,T} \leq y) \right| + o(1) + o(1) = o(1). \end{aligned}$$

□

Proof of Proposition 4.3

Proof. To start with, note that for some constant C we have

$$\lambda(h) = \sqrt{2 \log\{1/(2h)\}} \leq \sqrt{2 \log\{1/(2h_{\min})\}} \leq C\sqrt{\log T}. \quad (\text{A.37})$$

Write $\widehat{\psi}_{ij,T}(u, h) = \widehat{\psi}_{ij,T}^A(u, h) + \widehat{\psi}_{ij,T}^B(u, h)$ with

$$\begin{aligned} \widehat{\psi}_{ij,T}^A(u, h) &= \sum_{t=1}^T w_{t,T}(u, h) \{ (\varepsilon_{it} - \bar{\varepsilon}_i) + (\beta_i - \widehat{\beta}_i)^\top (\mathbf{X}_{it} - \bar{\mathbf{X}}_i) - \bar{m}_{i,T} \\ &\quad - (\varepsilon_{jt} - \bar{\varepsilon}_j) - (\beta_j - \widehat{\beta}_j)^\top (\mathbf{X}_{jt} - \bar{\mathbf{X}}_j) + \bar{m}_{j,T} \}, \\ \widehat{\psi}_{ij,T}^B(u, h) &= \sum_{t=1}^T w_{t,T}(u, h) \left(m_{i,T}\left(\frac{t}{T}\right) - m_{j,T}\left(\frac{t}{T}\right) \right), \end{aligned}$$

where $\bar{m}_{i,T} = T^{-1} \sum_{t=1}^T m_{i,T}(t/T)$.

Without loss of generality, consider the first scenario: by assumption, there exists $(u_0, h_0) \in \mathcal{G}_T$ with $[u_0 - h_0, u_0 + h_0] \subseteq [0, 1]$ such that

$$m_{i,T}(w) - m_{j,T}(w) \geq c_T \sqrt{\log T / (Th_0)} \quad (\text{A.38})$$

for all $w \in [u_0 - h_0, u_0 + h_0]$. Since the kernel K is symmetric and $u_0 = t/T$ for some t , it holds that $S_{T,1}(u_0, h_0) = 0$ and thus,

$$w_{t,T}(u_0, h_0) = \frac{K\left(\frac{\frac{t}{T} - u_0}{h_0}\right) S_{T,2}(u_0, h_0)}{\left\{ \sum_{t=1}^T K^2\left(\frac{\frac{t}{T} - u_0}{h_0}\right) S_{T,2}^2(u_0, h_0) \right\}^{1/2}} \quad (\text{A.39})$$

$$= \frac{K\left(\frac{\frac{t}{T} - u_0}{h_0}\right)}{\left\{ \sum_{t=1}^T K^2\left(\frac{\frac{t}{T} - u_0}{h_0}\right) \right\}^{1/2}} \geq 0. \quad (\text{A.40})$$

Together with (A.38), this implies that

$$\widehat{\psi}_{ij,T}^B(u_0, h_0) \geq c_T \sqrt{\frac{\log T}{Th_0}} \sum_{t=1}^T w_{t,T}(u_0, h_0). \quad (\text{A.41})$$

Using the Lipschitz continuity of the kernel K , we can show by some straightforward arithmetic calculations that for any $(u, h) \in \mathcal{G}_T$ and any natural number ℓ ,

$$\left| \frac{1}{Th} \sum_{t=1}^T K\left(\frac{\frac{t}{T} - u}{h}\right) \left(\frac{\frac{t}{T} - u}{h}\right)^\ell - \int_0^1 \frac{1}{h} K\left(\frac{w - u}{h}\right) \left(\frac{w - u}{h}\right)^\ell dw \right| \leq \frac{C}{Th}, \quad (\text{A.42})$$

where the constant C does not depend on u , h and T . With the help of (A.42), we obtain that for any $(u, h) \in \mathcal{G}_T$ with $[u - h, u + h] \subseteq [0, 1]$,

$$\left| \sum_{t=1}^T w_{t,T}(u, h) - \frac{\sqrt{Th}}{\kappa} \right| \leq \frac{C}{\sqrt{Th}}, \quad (\text{A.43})$$

where $\kappa = (\int K^2(\varphi)d\varphi)^{1/2}$ and the constant C does once again not depend on u , h and T . From (A.43), it follows that $\sum_{t=1}^T w_{t,T}(u, h) \geq \sqrt{Th}/(2\kappa)$ for sufficiently large T and any $(u, h) \in \mathcal{G}_T$ with $[u - h, u + h] \subseteq [0, 1]$. This together with (A.41) allows us to infer that

$$\widehat{\psi}_{ij,T}^B(u_0, h_0) \geq \frac{c_T \sqrt{\log T}}{2\kappa} \quad (\text{A.44})$$

for sufficiently large T .

Furthermore, since $\widehat{\psi}_{ij,T}^A(u, h) = \widehat{\phi}_{ij,T}(u, h) + (\bar{m}_{j,T} - \bar{m}_{i,T}) \sum_{t=1}^T w_{t,T}(u, h)$, by arguments completely analogous to those for the proof of Proposition A.8, we have

$$\max_{(u,h) \in \mathcal{G}_T} |\widehat{\psi}_{ij,T}^A(u, h)| = O_p(\sqrt{\log T}). \quad (\text{A.45})$$

With the help of (A.44), (A.45) and (A.37) and the assumption that $\widehat{\sigma}_i^2 = \sigma_i^2 + o_p(\rho_T)$, we finally arrive at

$$\begin{aligned} \widehat{\Psi}_{n,T} &\geq \max_{1 \leq i < j \leq n} \max_{(u,h) \in \mathcal{G}_T} \frac{|\widehat{\psi}_{ij,T}^B(u, h)|}{\{\widehat{\sigma}_i^2 + \widehat{\sigma}_j^2\}^{1/2}} - \max_{1 \leq i < j \leq n} \max_{(u,h) \in \mathcal{G}_T} \left\{ \frac{|\widehat{\psi}_{ij,T}^A(u, h)|}{\{\widehat{\sigma}_i^2 + \widehat{\sigma}_j^2\}^{1/2}} + \lambda(h) \right\} \\ &= \max_{1 \leq i < j \leq n} \max_{(u,h) \in \mathcal{G}_T} \frac{|\widehat{\psi}_{ij,T}^B(u, h)|}{\{\widehat{\sigma}_i^2 + \widehat{\sigma}_j^2\}^{1/2}} + O_p(\sqrt{\log T}) \\ &\geq \frac{c_T \sqrt{\log T}}{2\kappa} \min_{1 \leq i < j \leq n} \{\widehat{\sigma}_i^2 + \widehat{\sigma}_j^2\}^{-1/2} + O_p(\sqrt{\log T}) \\ &\geq C \frac{c_T \sqrt{\log T}}{2\kappa} + O_p(\sqrt{\log T}). \end{aligned} \quad (\text{A.46})$$

Since $q_{n,T}(\alpha) = O(\sqrt{\log T})$ for any fixed $\alpha \in (0, 1)$ and $c_T \rightarrow \infty$, (A.46) immediately implies that $\mathbb{P}(\widehat{\Psi}_{n,T} \leq q_{n,T}(\alpha)) = o(1)$. \square

Proof of Proposition 4.4

Proof. By Proposition A.9, we have

$$\sup_{x \in \mathbb{R}} |\mathbb{P}(\widehat{\Phi}_{n,T} \leq x) - \mathbb{P}(\Phi_{n,T} \leq x)| = o(1). \quad (\text{A.47})$$

By definition of the quantile $q_{n,T}(\alpha)$, it holds that $\mathbb{P}(\Phi_{n,T} \leq q_{n,T}(\alpha)) \geq 1 - \alpha$, which together with (A.47) immediately yields

$$\mathbb{P}(\widehat{\Phi}_{n,T} \leq q_{n,T}(\alpha)) \geq 1 - \alpha + o(1). \quad (\text{A.48})$$

Now for the sake of simplifying notation, denote by \mathcal{M}_0 the set of quadruples $(i, j, u, h) \in \{1 \dots, n\}^2 \times \mathcal{G}_T$ that has the property that $H_0^{[i,j]}(u, h)$ is true. Analogously, denote by \mathcal{M} the full set of quadruples: $\mathcal{M} := \{1 \dots, n\}^2 \times \mathcal{G}_T$. Then we can

write FWER as

$$\begin{aligned}
\text{FWER}(\alpha) &= \mathbb{P}\left(\exists(i, j, u, h) \in \mathcal{M}_0 : |\hat{\psi}_{ij,T}^0(u, h)| > q_{n,T}(\alpha)\right) \\
&= \mathbb{P}\left(\max_{(i,j,u,h) \in \mathcal{M}_0} |\hat{\psi}_{ij,T}^0(u, h)| > q_{n,T}(\alpha)\right) \\
&= \mathbb{P}\left(\max_{(i,j,u,h) \in \mathcal{M}_0} |\hat{\phi}_{ij,T}^0(u, h)| > q_{n,T}(\alpha)\right) \\
&\leq \mathbb{P}\left(\max_{1 \leq i < j \leq n} \max_{(u,h) \in \mathcal{G}_T} |\hat{\phi}_{ij,T}^0(u, h)| > q_{n,T}(\alpha)\right) \\
&= \mathbb{P}(\hat{\Phi}_{n,T} > q_{n,T}(\alpha)) \leq \alpha + o(1),
\end{aligned}$$

where the third equality holds true because under $H_0^{[i,j]}(u, h)$, $\hat{\psi}_{ij,T}^0 = \hat{\phi}_{ij,T}^0$ by the observation in the beginning of Section 4. \square

Proof of Corollary 4.5

Proof. By Proposition 4.4,

$$\begin{aligned}
1 - \alpha + o(1) &\leq 1 - \text{FWER}(\alpha) \\
&= \mathbb{P}\left(\nexists(i, j, u, h) \in \mathcal{M}_0 : |\hat{\psi}_{ij,T}^0(u, h)| > q_{n,T}(\alpha)\right) \\
&= \mathbb{P}\left(\forall(i, j, u, h) \in \mathcal{M}_0 : |\hat{\psi}_{ij,T}^0(u, h)| \leq q_{n,T}(\alpha)\right) \\
&= \mathbb{P}\left(\forall i, j \in \{1, \dots, n\}, (u, h) \in \mathcal{G}_T \text{ such that } H_0^{[i,j]}(u, h) \text{ is true : } |\hat{\psi}_{ij,T}^0(u, h)| \leq q_{n,T}(\alpha)\right),
\end{aligned}$$

which gives the statement of Corollary 4.5. \square

A.4 Asymptotic consistency of the estimators

A.4.1 Asymptotic consistency of $\hat{\beta}_i$

Before proceeding to the proof of Theorem 5.1, we first prove several auxiliary results. In order to do that, we define the first-differenced regressors as follows.

$$\Delta \mathbf{X}_{it} = \mathbf{H}_i(\mathcal{U}_{it}) - \mathbf{H}_i(\mathcal{U}_{it-1}) := \Delta \mathbf{H}_i(\mathcal{U}_{it}).$$

Similarly,

$$\Delta \varepsilon_{it} = \varepsilon_{it} - \varepsilon_{it-1} = G_i(\mathcal{J}_{it}) - G_i(\mathcal{J}_{it-1}) = \Delta G_i(\mathcal{J}_{it}).$$

We now can prove the following propositions.

Proposition A.10. *Under Assumptions (C4) and (C6), $\|\Delta \mathbf{H}_i(\mathcal{U}_{it})\|_4 < \infty$.*

Proof of Proposition A.10. By Assumption (C6) and the triangle inequality,

$$\|\Delta \mathbf{H}_i(\mathcal{U}_{it})\|_4 \leq \|\mathbf{H}_i(\mathcal{U}_{it})\|_4 + \|\mathbf{H}_i(\mathcal{U}_{it-1})\|_4 < \infty.$$

\square

Proposition A.11. Under Assumption (C9), $\Delta \mathbf{X}_{it}$ (elementwise) and $\Delta \varepsilon_{it}$ are uncorrelated for each $t \in \{1, \dots, T\}$.

Proof of Proposition A.11. By Assumption (C9),

$$\begin{aligned}
\mathbb{E}[\Delta \mathbf{X}_{it} \Delta \varepsilon_{it}] &= \mathbb{E}[(\mathbf{X}_{it} - \mathbf{X}_{it-1})(\varepsilon_{it} - \varepsilon_{it-1})] \\
&= \mathbb{E}[\mathbf{X}_{it} \varepsilon_{it}] - \mathbb{E}[\mathbf{X}_{it-1} \varepsilon_{it}] - \mathbb{E}[\mathbf{X}_{it} \varepsilon_{it-1}] + \mathbb{E}[\mathbf{X}_{it-1} \varepsilon_{it-1}] \\
&= \mathbb{E}[\mathbf{X}_{it}] \mathbb{E}[\varepsilon_{it}] - \mathbb{E}[\mathbf{X}_{it-1}] \mathbb{E}[\varepsilon_{it}] - \mathbb{E}[\mathbf{X}_{it}] \mathbb{E}[\varepsilon_{it-1}] + \mathbb{E}[\mathbf{X}_{it-1}] \mathbb{E}[\varepsilon_{it-1}] \\
&= (\mathbb{E}[\mathbf{X}_{it}] - \mathbb{E}[\mathbf{X}_{it-1}]) (\mathbb{E}[\varepsilon_{it}] - \mathbb{E}[\varepsilon_{it-1}]) \\
&= \mathbb{E}[\Delta \mathbf{X}_{it}] \mathbb{E}[\Delta \varepsilon_{it}]
\end{aligned}$$

□

Proposition A.12. Define

$$\Delta \mathbf{U}_i(\mathcal{I}_{it}) := \Delta \mathbf{H}_i(\mathcal{U}_{it}) \Delta G_i(\mathcal{J}_{it}).$$

Under Assumptions (C2), (C3), (C6), (C7) and (C10), we have that $\sum_{s=1}^{\infty} \delta_2(\Delta \mathbf{U}_i, s) < \infty$.

Proof of Proposition A.12. By the triangle inequality and the definition of the physical dependence measure δ_2 , we have that

$$\begin{aligned}
\delta_2(\Delta \mathbf{U}_i, t) &= \|\Delta \mathbf{U}_i(\mathcal{I}_{it}) - \Delta \mathbf{U}_i(\mathcal{I}'_{it})\| \\
&= \|\Delta \mathbf{H}_i(\mathcal{U}_{it}) \Delta G_i(\mathcal{J}_{it}) - \Delta \mathbf{H}_i(\mathcal{U}'_{it}) \Delta G_i(\mathcal{J}'_{it})\| \\
&= \|\mathbf{H}_i(\mathcal{U}_{it}) G_i(\mathcal{J}_{it}) - \mathbf{H}_i(\mathcal{U}_{it-1}) G_i(\mathcal{J}_{it}) - \mathbf{H}_i(\mathcal{U}_{it}) G_i(\mathcal{J}_{it-1}) + \mathbf{H}_i(\mathcal{U}_{it-1}) G_i(\mathcal{J}_{it-1}) \\
&\quad - \mathbf{H}_i(\mathcal{U}'_{it}) G_i(\mathcal{J}'_{it}) + \mathbf{H}_i(\mathcal{U}'_{it-1}) G_i(\mathcal{J}'_{it}) + \mathbf{H}_i(\mathcal{U}'_{it}) G_i(\mathcal{J}'_{it-1}) - \mathbf{H}_i(\mathcal{U}'_{it-1}) G_i(\mathcal{J}'_{it-1})\| \\
&\leq \|\mathbf{H}_i(\mathcal{U}_{it}) G_i(\mathcal{J}_{it}) - \mathbf{H}_i(\mathcal{U}'_{it}) G_i(\mathcal{J}'_{it})\| + \|\mathbf{H}_i(\mathcal{U}_{it-1}) G_i(\mathcal{J}_{it-1}) - \mathbf{H}_i(\mathcal{U}'_{it-1}) G_i(\mathcal{J}'_{it-1})\| \\
&\quad + \|\mathbf{H}_i(\mathcal{U}_{it-1}) G_i(\mathcal{J}_{it}) - \mathbf{H}_i(\mathcal{U}'_{it-1}) G_i(\mathcal{J}'_{it})\| \\
&\quad + \|\mathbf{H}_i(\mathcal{U}_{it}) G_i(\mathcal{J}_{it-1}) - \mathbf{H}_i(\mathcal{U}'_{it}) G_i(\mathcal{J}'_{it-1})\| \\
&= \delta_2(\mathbf{U}_i, t) + \delta_2(\mathbf{U}_i, t-1) \\
&\quad + \|\mathbf{H}_i(\mathcal{U}_{it-1}) G_i(\mathcal{J}_{it}) - \mathbf{H}_i(\mathcal{U}'_{it-1}) G_i(\mathcal{J}_{it}) + \mathbf{H}_i(\mathcal{U}'_{it-1}) G_i(\mathcal{J}_{it}) - \mathbf{H}_i(\mathcal{U}'_{it-1}) G_i(\mathcal{J}'_{it})\| \\
&\quad + \|\mathbf{H}_i(\mathcal{U}_{it}) G_i(\mathcal{J}_{it-1}) - \mathbf{H}_i(\mathcal{U}'_{it}) G_i(\mathcal{J}_{it-1}) + \mathbf{H}_i(\mathcal{U}'_{it}) G_i(\mathcal{J}_{it-1}) - \mathbf{H}_i(\mathcal{U}'_{it}) G_i(\mathcal{J}'_{it-1})\| \\
&\leq \delta_2(\mathbf{U}_i, t) + \delta_2(\mathbf{U}_i, t-1) \\
&\quad + \|(\mathbf{H}_i(\mathcal{U}_{it-1}) - \mathbf{H}_i(\mathcal{U}'_{it-1})) G_i(\mathcal{J}_{it})\| + \|\mathbf{H}_i(\mathcal{U}'_{it-1}) (G_i(\mathcal{J}_{it}) - G_i(\mathcal{J}'_{it}))\| \\
&\quad + \|(\mathbf{H}_i(\mathcal{U}_{it}) - \mathbf{H}_i(\mathcal{U}'_{it})) G_i(\mathcal{J}_{it-1})\| + \|\mathbf{H}_i(\mathcal{U}'_{it}) (G_i(\mathcal{J}_{it-1}) - G_i(\mathcal{J}'_{it-1}))\| \\
&\leq \delta_2(\mathbf{U}_i, t) + \delta_2(\mathbf{U}_i, t-1) \\
&\quad + (\delta_2(\mathbf{H}_i, t-1) + \delta_2(\mathbf{H}_i, t)) \|G_i\| + (\delta_2(G_i, t-1) + \delta_2(G_i, t)) \|\mathbf{H}_i\|.
\end{aligned}$$

Here $\mathcal{U}'_{it} = (\dots, u_{i(-1)}, u'_{i0}, u_{i1}, \dots, u_{it-1}, u_{it})$, $\mathcal{U}'_{i(t-1)} = (\dots, u_{i(-1)}, u'_{i0}, u_{i1}, \dots, u_{it-1})$, $\mathcal{J}'_{it} = (\dots, \eta_{i(-1)}, \eta'_{i0}, \eta_{i1}, \dots, \eta_{it-1}, \eta_{it})$, $\mathcal{J}'_{i(t-1)} = (\dots, \eta_{i(-1)}, \eta'_{i0}, \eta_{i1}, \dots, \eta_{it-1})$ are coupled processes with u'_{i0} being an i.i.d. copy of u_{i0} and η'_{i0} being an i.i.d. copy of η_{i0} .

Therefore,

$$\begin{aligned} \sum_{s=1}^{\infty} \delta_2(\Delta \mathbf{U}_i, s) &\leq \sum_{s=0}^{\infty} \delta_2(\mathbf{U}_i, s) + \sum_{s=1}^{\infty} \delta_2(\mathbf{U}_i, s-1) \\ &+ \sum_{s=1}^{\infty} (\delta_2(\mathbf{H}_i, s-1) + \delta_2(\mathbf{H}_i, s)) \|\mathbf{G}_i\| + \sum_{s=1}^{\infty} (\delta_2(G_i, s-1) + \delta_2(G_i, s)) \|\mathbf{H}_i\|. \end{aligned}$$

By Assumptions (C2), (C3), (C6), (C7) and (C10), the RHS is finite. Statement of the proposition follows. \square

Proposition A.13. *Under Assumptions (C1) - (C10),*

$$\left| \frac{1}{\sqrt{T}} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta \varepsilon_{it} \right| = O_P(1).$$

Proof of Proposition A.13. For this proof, we will need the following notation:

$$\begin{aligned} \mathcal{P}_{i,t}(\cdot) &:= \mathbb{E}[\cdot | \mathcal{I}_{it}] - \mathbb{E}[\cdot | \mathcal{I}_{i(t-1)}], \\ \kappa_i &:= \frac{1}{T-1} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta \varepsilon_{it}, \\ \kappa_{i,s}^{\mathcal{P}} &:= \frac{1}{T-1} \sum_{t=2}^T \mathcal{P}_{i,t-s}(\Delta \mathbf{X}_{it} \Delta \varepsilon_{it}). \end{aligned}$$

Since $\mathcal{P}_{i,t}(\cdot)$ is a projection operator, we have that

$$\begin{aligned} \|\kappa_{i,s}^{\mathcal{P}}\|^2 &\leq \frac{1}{(T-1)^2} \sum_{t=2}^T \left\| \mathcal{P}_{i,t-s}(\Delta \mathbf{X}_{it} \Delta \varepsilon_{it}) \right\|^2 \\ &= \frac{1}{(T-1)^2} \sum_{t=2}^T \left\| \mathbb{E}(\Delta \mathbf{X}_{it} \Delta \varepsilon_{it} | \mathcal{I}_{i(t-s)}) - \mathbb{E}(\Delta \mathbf{X}_{it} \Delta \varepsilon_{it} | \mathcal{I}_{i(t-s-1)}) \right\|^2 \\ &= \frac{1}{(T-1)^2} \sum_{t=2}^T \left\| \mathbb{E}(\Delta \mathbf{X}_{it} \Delta \varepsilon_{it} | \mathcal{I}_{i(t-s)}) - \mathbb{E}(\Delta \mathbf{X}'_{it,s} \Delta \varepsilon'_{it,s} | \mathcal{I}_{i(t-s)}) \right\|^2, \end{aligned}$$

where $\Delta \mathbf{X}'_{it,s} \Delta \varepsilon'_{it,s}$ denotes $\Delta \mathbf{X}_{it} \Delta \varepsilon_{it}$ with $\{\zeta_{i,t-s}\}$ replaced by its i.i.d. copy $\{\zeta'_{i,t-s}\}$. In this case $\mathbb{E}(\Delta \mathbf{X}'_{it,s} \Delta \varepsilon'_{it,s} | \mathcal{I}_{i(t-s-1)}) = \mathbb{E}(\Delta \mathbf{X}'_{it,s} \Delta \varepsilon'_{it,s} | \mathcal{I}_{i(t-s)})$. Furthermore, by linearity of the expectation, Jensen's inequality, **and by the definition of the norm**

$\|\cdot\| = (\mathbb{E}|\cdot|^2)^{1/2}$, we have

$$\begin{aligned}
\|\kappa_{i,s}^{\mathcal{P}}\|^2 &\leq \frac{1}{(T-1)^2} \sum_{t=2}^T \left\| \mathbb{E}(\Delta \mathbf{X}_{it} \Delta \varepsilon_{it} | \mathcal{I}_{i(t-s)}) - \mathbb{E}(\Delta \mathbf{X}'_{it,s} \Delta \varepsilon'_{it,s} | \mathcal{I}_{i(t-s)}) \right\|^2 \\
&\leq \frac{1}{(T-1)^2} \sum_{t=2}^T \mathbb{E} \left[\left\| \Delta \mathbf{X}_{it} \Delta \varepsilon_{it} - \Delta \mathbf{X}'_{it,s} \Delta \varepsilon'_{it,s} \right\|^2 \middle| \mathcal{I}_{i(t-s)} \right] \\
&= \frac{1}{(T-1)^2} \sum_{t=2}^T \left\| \Delta \mathbf{X}_{it} \Delta \varepsilon_{it} - \Delta \mathbf{X}'_{it,s} \Delta \varepsilon'_{it,s} \right\|^2 \\
&= \frac{1}{(T-1)^2} \sum_{t=2}^T \left\| \Delta \mathbf{H}_i(\mathcal{U}_{it}) \Delta G_i(\mathcal{J}_{it}) - \Delta \mathbf{H}_i(\mathcal{U}'_{it,s}) \Delta G_i(\mathcal{J}'_{it,s}) \right\|^2 \\
&= \frac{1}{(T-1)^2} \sum_{t=2}^T \left\| \Delta \mathbf{U}_i(\mathcal{I}_{it}) - \Delta \mathbf{U}_i(\mathcal{I}'_{it,s}) \right\|^2 \\
&\leq \frac{1}{(T-1)^2} \sum_{t=2}^T \delta_2^2(\Delta \mathbf{U}_i, s) \\
&= \frac{1}{T-1} \delta_2^2(\Delta \mathbf{U}_i, s)
\end{aligned}$$

with $\mathcal{U}'_{it,s} = (\dots, u_{i(t-s-1)}, u'_{i(t-s)}, u_{i(t-s+1)}, \dots, u_{it})$, $u'_{i(t-s)}$ being an i.i.d. copy of $u_{i(t-s)}$, $\mathcal{J}'_{it,s} = (\dots, \eta_{i(t-s-1)}, \eta'_{i(t-s)}, \eta_{i(t-s+1)}, \dots, \eta_{it})$, $\eta'_{i(t-s)}$ being an i.i.d. copy of $\eta_{i(t-s)}$, and $\zeta'_{it} = (u'_{it}, \eta'_{it})^\top$ and $\mathcal{I}'_{it,s} = (\dots, \zeta_{i(t-s-1)}, \zeta'_{i(t-s)}, \zeta_{i(t-s+1)}, \dots, \zeta_{it})$. Moreover,

$$\begin{aligned}
\kappa_i - \mathbb{E}\kappa_i &= \frac{1}{T-1} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta \varepsilon_{it} - \mathbb{E}\kappa_i \\
&= \frac{1}{T-1} \sum_{t=2}^T \mathbb{E}(\Delta \mathbf{X}_{it} \Delta \varepsilon_{it} | \mathcal{I}_{it}) - \mathbb{E}\kappa_i \\
&= \frac{1}{T-1} \sum_{t=2}^T [\mathbb{E}(\Delta \mathbf{X}_{it} \Delta \varepsilon_{it} | \mathcal{I}_{it}) - \mathbb{E}(\Delta \mathbf{X}_{it} \Delta \varepsilon_{it})] \\
&= \frac{1}{T-1} \sum_{t=2}^T \sum_{s=0}^{\infty} [\mathbb{E}(\Delta \mathbf{X}_{it} \Delta \varepsilon_{it} | \mathcal{I}_{i(t-s)}) - \mathbb{E}(\Delta \mathbf{X}_{it} \Delta \varepsilon_{it} | \mathcal{I}_{i(t-s-1)})] \\
&= \frac{1}{T-1} \sum_{t=2}^T \sum_{s=0}^{\infty} \mathcal{P}_{i,t-s}(\Delta \mathbf{X}_{it} \Delta \varepsilon_{it}) = \sum_{s=0}^{\infty} \kappa_{i,s}^{\mathcal{P}}.
\end{aligned}$$

Thus, by Proposition A.12,

$$\|\kappa_i - \mathbb{E}\kappa_i\| \leq \sum_{s=0}^{\infty} \|\kappa_{i,s}^{\mathcal{P}}\| \leq \frac{1}{\sqrt{T-1}} \sum_{s=0}^{\infty} \delta_2(\Delta \mathbf{U}_i, s) = O\left(\frac{1}{\sqrt{T}}\right)$$

Since $\mathbb{E}\kappa_i = 0$ by Proposition A.11, we conclude that

$$\left\| \frac{1}{T} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta \varepsilon_{it} \right\| = O\left(\frac{1}{\sqrt{T}}\right).$$

Therefore, the proposition follows. \square

Proof of Theorem 5.1. Before we begin, we need to introduce some additional notation that we will use throughout the proof. First, define $\Delta m_{it} = m_i\left(\frac{t}{T}\right) - m_i\left(\frac{t-1}{T}\right)$. Then, by Assumption (C4), we can rewrite the first-differenced regressors $\Delta \mathbf{X}_{it}$ as

$$\Delta \mathbf{X}_{it} = \mathbf{H}_i(\mathcal{U}_{it}) - \mathbf{H}_i(\mathcal{U}_{it-1}) := \Delta \mathbf{H}_i(\mathcal{U}_{it})$$

with $\Delta \mathbf{H}_i(\mathcal{U}_{it}) := (\Delta H_{i1}, \Delta H_{i2}, \dots, \Delta H_{id})^\top$.

Similarly, by Assumption (C1), we have

$$\Delta \varepsilon_{it} = \varepsilon_{it} - \varepsilon_{it-1} = G_i(\mathcal{J}_{it}) - G_i(\mathcal{J}_{it-1}) = \Delta G_i(\mathcal{J}_{it}).$$

Then, the differencing estimator $\hat{\beta}_i$ can be written as

$$\begin{aligned} \hat{\beta}_i &= \left(\sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta \mathbf{X}_{it}^\top \right)^{-1} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta Y_{it} \\ &= \left(\sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta \mathbf{X}_{it}^\top \right)^{-1} \sum_{t=2}^T \Delta \mathbf{X}_{it} \left(\Delta \mathbf{X}_{it}^\top \beta_i + \Delta m_{it} + \Delta \varepsilon_{it} \right) \\ &= \beta_i + \left(\sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta \mathbf{X}_{it}^\top \right)^{-1} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta m_{it} + \left(\sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta \mathbf{X}_{it}^\top \right)^{-1} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta \varepsilon_{it}. \end{aligned}$$

Hence,

$$\begin{aligned} \sqrt{T}(\hat{\beta}_i - \beta_i) &= \left(\frac{1}{T} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta \mathbf{X}_{it}^\top \right)^{-1} \frac{1}{\sqrt{T}} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta m_{it} \\ &\quad + \left(\frac{1}{T} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta \mathbf{X}_{it}^\top \right)^{-1} \frac{1}{\sqrt{T}} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta \varepsilon_{it}. \end{aligned} \tag{A.49}$$

We look at the parts that constitute (A.49) independently and for clarification purposes, we break the proof into three steps.

For the sake of simplicity, we focus our attention on the individual vector components and we prove the necessary bounds and inequalities for each of the components separately, combining them together in the end.

Step 1.

First, we take a closer look at the part of the first summand in (A.49), specifically,

$$\frac{1}{\sqrt{T}} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta m_{it}.$$

Fix $j \in 1, \dots, d$. By Chebyshev's inequality, for any $a > 0$ we have

$$\mathbb{P} \left(\frac{1}{T} \sum_{t=2}^T |\Delta H_{ij}(\mathcal{U}_{it})| > a \right) \leq \frac{\mathbb{E} \left[\left(\sum_{t=2}^T |\Delta H_{ij}(\mathcal{U}_{it})| \right)^2 \right]}{(T-1)^2 a^2} \tag{A.50}$$

and

$$\mathbb{E} \left[\left(\sum_{t=2}^T |\Delta H_{ij}(\mathcal{U}_{it})| \right)^2 \right] = \sum_{t=2}^T \mathbb{E} [\Delta H_{ij}^2(\mathcal{U}_{it})] + \sum_{\substack{t=2, s=2, \\ t \neq s}}^T \mathbb{E} [|\Delta H_{ij}(\mathcal{U}_{it}) \Delta H_{ij}(\mathcal{U}_{is})|]. \tag{A.51}$$

Note that by the Cauchy-Schwarz inequality for all t and s we have

$$\mathbb{E}[|H_{ij}(\mathcal{U}_{it})H_{ij}(\mathcal{U}_{is})|] \leq \sqrt{\mathbb{E}[H_{ij}^2(\mathcal{U}_{it})]}\sqrt{\mathbb{E}[H_{ij}^2(\mathcal{U}_{is})]} = \mathbb{E}[H_{ij}^2(\mathcal{U}_{i0})] \quad (\text{A.52})$$

and

$$|\mathbb{E}[H_{ij}(\mathcal{U}_{it})H_{ij}(\mathcal{U}_{is})]| \leq \mathbb{E}[|H_{ij}(\mathcal{U}_{it})H_{ij}(\mathcal{U}_{is})|] \leq \mathbb{E}[H_{ij}^2(\mathcal{U}_{i0})].$$

Hence,

$$\begin{aligned} \mathbb{E}[\Delta H_{ij}^2(\mathcal{U}_{it})] &= \mathbb{E}[H_{ij}^2(\mathcal{U}_{it})] - 2\mathbb{E}[H_{ij}(\mathcal{U}_{it})H_{ij}(\mathcal{U}_{it-1})] + \mathbb{E}[H_{ij}^2(\mathcal{U}_{it-1})] \\ &\leq \mathbb{E}[H_{ij}^2(\mathcal{U}_{i0})] + 2\mathbb{E}[H_{ij}^2(\mathcal{U}_{i0})] + \mathbb{E}[H_{ij}^2(\mathcal{U}_{i0})] \\ &= 4\mathbb{E}[H_{ij}^2(\mathcal{U}_{i0})] \end{aligned}$$

and the first summand in (A.51) can be bounded by $4(T-1)\mathbb{E}[H_{ij}^2(\mathcal{U}_{i0})]$, where the expectation is finite due to Assumption (C6).

Now to the second summand in (A.51):

$$\begin{aligned} \mathbb{E}[|\Delta H_{ij}(\mathcal{U}_{it})\Delta H_{ij}(\mathcal{U}_{is})|] &\leq \mathbb{E}[|H_{ij}(\mathcal{U}_{it})H_{ij}(\mathcal{U}_{is})|] + \mathbb{E}[|H_{ij}(\mathcal{U}_{it-1})H_{ij}(\mathcal{U}_{is})|] \\ &\quad + \mathbb{E}[|H_{ij}(\mathcal{U}_{it})H_{ij}(\mathcal{U}_{is-1})|] + \mathbb{E}[|H_{ij}(\mathcal{U}_{it-1})H_{ij}(\mathcal{U}_{is-1})|] \\ &\leq 4\mathbb{E}[H_{ij}^2(\mathcal{U}_{i0})], \end{aligned}$$

where in the last inequality we used (A.52). This means that the second summand in (A.51) can be bounded by $4(T-1)(T-2)\mathbb{E}[H_{ij}^2(\mathcal{U}_{i0})]$.

Plugging these bounds in (A.51), we get

$$\begin{aligned} \mathbb{E}\left[\left(\sum_{t=2}^T |\Delta H_{ij}(\mathcal{U}_{it})|\right)^2\right] &\leq 4(T-1)\mathbb{E}[H_{ij}^2(\mathcal{U}_{i0})] + 4(T-1)(T-2)\mathbb{E}[H_{ij}^2(\mathcal{U}_{i0})] \\ &= 4(T-1)^2\mathbb{E}[H_{ij}^2(\mathcal{U}_{i0})], \end{aligned}$$

which together with (A.50) leads to $\frac{1}{T}\sum_{t=2}^T |\Delta H_{ij}(\mathcal{U}_{it})| = O_P(1)$.

Next, by the assumption in Theorem 5.1, $m_i(\cdot)$ is Lipschitz continuous, that is, $|\Delta m_{it}| = |m_i(\frac{t}{T}) - m_i(\frac{t-1}{T})| \leq C\frac{1}{T}$ for all $t \in \{1, \dots, T\}$ and some constant $C > 0$. Hence,

$$\begin{aligned} \left|\frac{1}{\sqrt{T}}\sum_{t=2}^T \Delta H_{ij}(\mathcal{U}_{it})\Delta m_{it}\right| &\leq \frac{1}{\sqrt{T}}\sum_{t=2}^T |\Delta H_{ij}(\mathcal{U}_{it})| \cdot |\Delta m_{it}| \\ &\leq \frac{C}{\sqrt{T}} \cdot \frac{1}{T}\sum_{t=2}^T |\Delta H_{ij}(\mathcal{U}_{it})| \\ &= O_P\left(\frac{1}{\sqrt{T}}\right). \end{aligned}$$

Since it holds for each $j \in \{1, \dots, d\}$ (and d is fixed), it is obvious that

$$\frac{1}{\sqrt{T}} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta m_{it} = \frac{1}{\sqrt{T}} \sum_{t=2}^T \Delta \mathbf{H}_i(\mathcal{U}_{it}) \Delta m_{it} = O_P\left(\frac{1}{\sqrt{T}}\right). \quad (\text{A.53})$$

Step 2.

Now we look at the other part of the first summand in (A.49), specifically, $\left(\frac{1}{T} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta \mathbf{X}_{it}^\top\right)^{-1}$. Using similar arguments as in Step 1 and applying Proposition A.10, we can show that

$$\left| \frac{1}{T} \sum_{t=2}^T \Delta H_{ij}(\mathcal{U}_{it}) \Delta H_{ik}(\mathcal{U}_{it}) \right| = O_P(1),$$

for each $j, k \in \{1, \dots, d\}$, which trivially leads to

$$\left| \frac{1}{T} \sum_{t=2}^T \Delta \mathbf{H}_i(\mathcal{U}_{it}) \Delta \mathbf{H}_i(\mathcal{U}_{it})^\top \right| = \left| \frac{1}{T} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta \mathbf{X}_{it}^\top \right| = O_P(1),$$

where $|A|$ with A being a matrix is any matrix norm.

Furthermore, by Assumption (C5), we know that $\mathbb{E}[\Delta \mathbf{X}_{it} \Delta \mathbf{X}_{it}^\top] = \mathbb{E}[\Delta \mathbf{X}_{i0} \Delta \mathbf{X}_{i0}^\top]$ is invertible, thus,

$$\left| \left(\frac{1}{T} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta \mathbf{X}_{it}^\top \right)^{-1} \right| = O_P(1). \quad (\text{A.54})$$

Step 3

Here we turn our attention to the second summand in (A.49). We already know that $\left| \left(\frac{1}{T} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta \mathbf{X}_{it}^\top \right)^{-1} \right| = O_P(1)$. Moreover, by Proposition A.13,

$$\left| \frac{1}{\sqrt{T}} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta \varepsilon_{it} \right| = O_P(1).$$

Taking these two facts together, we have that

$$\left(\frac{1}{T} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta \mathbf{X}_{it}^\top \right)^{-1} \frac{1}{\sqrt{T}} \sum_{t=2}^T \Delta \mathbf{X}_{it} \Delta \varepsilon_{it} = O_P(1). \quad (\text{A.55})$$

Finally, from (A.53) and (A.54) we get that the first summand in (A.49) is $O_P(1/\sqrt{T})$, and by (A.55) the second summand is $O_P(1)$. The statement of the theorem follows. \square

A.5 Asymptotic consistency of $\hat{\sigma}_i^2$

Lemma A.14. *Let $s_T \asymp T^{1/3}$. Then, under Assumptions (C1) - (C10), for each $i \in \{1, \dots, n\}$ we have*

$$\hat{\sigma}_i^2 = \sigma_i^2 + O_P(T^{-1/3}).$$

where $\hat{\sigma}_i^2$ is the subseries variance estimate of σ_i^2 introduced by (5.4).

Proof of Lemma A.14. For notational convenience, we let $Y_{it}^* = Y_{it} - \beta_i^\top \mathbf{X}_{it}$. Note that

$$\begin{aligned} Y_{i(t+ms_T)}^* - Y_{i(t+(m-1)s_T)}^* &= \alpha_i + m_i \left(\frac{t + ms_T}{T} \right) + \varepsilon_{i(t+ms_T)} \\ &\quad - \alpha_i - m_i \left(\frac{t + (m-1)s_T}{T} \right) + \varepsilon_{i(t+(m-1)s_T)} \\ &= m_i \left(\frac{t + ms_T}{T} \right) + \varepsilon_{i(t+ms_T)} - m_i \left(\frac{t + (m-1)s_T}{T} \right) + \varepsilon_{i(t+(m-1)s_T)} \\ &= Y_{i(t+ms_T)}^\circ - Y_{i(t+(m-1)s_T)}^\circ, \end{aligned}$$

where Y_{it}° is the dependent variable in a well-studied standard nonparametric regression discussed in Section 3.1.

Now, using simple arithmetic calculations, we can rewrite $\hat{\sigma}_i^2$ as

$$\begin{aligned} \hat{\sigma}_i^2 &= \frac{1}{2(M-1)s_T} \sum_{m=1}^M \left[\sum_{t=1}^{s_T} \left(Y_{i(t+ms_T)}^\circ - Y_{i(t+(m-1)s_T)}^\circ \right) \right]^2 \\ &\quad + \frac{1}{2(M-1)s_T} \sum_{m=1}^M \left[\sum_{t=1}^{s_T} (\hat{\beta}_i - \beta_i)^\top (\mathbf{X}_{i(t+ms_T)} - \mathbf{X}_{i(t+(m-1)s_T)}) \right]^2 \\ &\quad - \frac{1}{(M-1)s_T} \sum_{m=1}^M \left[\sum_{t=1}^{s_T} \left(Y_{i(t+ms_T)}^\circ - Y_{i(t+(m-1)s_T)}^\circ \right) \sum_{t=1}^{s_T} (\hat{\beta}_i - \beta_i)^\top (\mathbf{X}_{i(t+ms_T)} - \mathbf{X}_{i(t+(m-1)s_T)}) \right], \end{aligned} \quad (\text{A.56})$$

By Carlstein (1986) and Wu and Zhao (2007), we have

$$\frac{1}{2(M-1)s_T} \sum_{m=1}^M \left[\sum_{t=1}^{s_T} \left(Y_{i(t+ms_T)}^\circ - Y_{i(t+(m-1)s_T)}^\circ \right) \right]^2 = \sigma_i^2 + O_P(T^{-1/3}). \quad (\text{A.57})$$

Furthermore, by our assumption that $s_T \asymp T^{1/3}$, Assumption (C5) and Theorem 5.1, we have

$$\frac{1}{2(M-1)s_T} \sum_{m=1}^M \left[\sum_{t=1}^{s_T} (\hat{\beta}_i - \beta_i)^\top (\mathbf{X}_{i(t+ms_T)} - \mathbf{X}_{i(t+(m-1)s_T)}) \right]^2 = O_P(T^{-2/3}). \quad (\text{A.58})$$

Finally, applying (A.57) and (A.58) together with the Cauchy-Schwarz inequality, we obtain

$$\frac{1}{(M-1)s_T} \sum_{m=1}^M \left[\sum_{t=1}^{s_T} \left(Y_{i(t+ms_T)}^\circ - Y_{i(t+(m-1)s_T)}^\circ \right) \sum_{t=1}^{s_T} (\hat{\beta}_i - \beta_i)^\top (\mathbf{X}_{i(t+ms_T)} - \mathbf{X}_{i(t+(m-1)s_T)}) \right] = O_P(T^{-1/3}). \quad (\text{A.59})$$

Applying (A.57) - (A.59) to (A.56), the lemma trivially follows. \square