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Long-run productivity trends: A global update with a global index

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Abstract

This paper documents the results from a macroeconomic total factor productivity analysis with a special focus on disentangling efficiency change and technological change under variable returns to scale. A sample of 93 countries is investigated by nonparametric methods. For the measurement three variants of the Malmquist index (basic, biennial, and global) are used. Specific country groups and selected individual countries are examined. The results show that productivity development is mainly driven by the interplay of technological change and efficiency change with a reversal from a backward shifting frontier function until the mid-1990s to an advancing frontier thereafter.

KEYWORDS

macroeconomic productivity, Malmquist index, nonparametric measurement

JEL CLASSIFICATION

C14; E23; O11; O47

1 | INTRODUCTION

Productivity change is the key factor of long-run economic growth and development. This is well recognized since the first growth accountants (Abramovitz, 1956; Solow, 1957) and by economic historians (e.g., Mokyr, 2005). While economic growth driven by factor accumulation inevitably comes to an end because of the force of decreasing marginal returns, growth driven by productivity improvements can be sustained more easily. Two principal components of productivity change are distinct in nature. The first component is technological change, shifting the frontier function and changing the set of production possibilities. The second component is efficiency change, which is associated with either catching up to the frontier function or falling behind from the frontier function. Both aspects contribute to productivity change, but are of differential importance for countries at different stages of development.

The traditional method to measure macroeconomic total factor productivity change is growth accounting (Abramovitz, 1956; Solow, 1957). However, growth accounting can identify technological change only when there is no efficiency change. In general, some mix of efficiency change and technological change is estimated. A further crucial deficiency is that growth accounting requires price information to compute the weights for aggregating the inputs (assuming a single output variable as is usual in macroeconomic applications). Furthermore, these prices are supposed to represent marginal products which relies on perfect factor markets and factor remuneration according to marginal products in all countries.

Fortunately, there is a viable alternative method that requires much weaker assumptions and is able is to disentangle technological change and efficiency change. This alternative is based on nonparametric methods of productivity measurement instead of growth accounting (so-called data envelopment analysis, DEA). To apply these methods no factor price information for computing the weights to aggregate the inputs is required. Instead, the weights are computed as the solutions of a sequence of linear programming problems that rely only on data for input and output quantities. These solutions are assembled to compute the so-called Malmquist index of total factor productivity.

There exists a quite voluminous literature using various nonparametric methods for productivity measurement and analysis; see, among many others, Growiec (2012), Henderson and Russell (2005), Badunenko, Henderson, and Russell (2013), Krüger (2003, 2016, 2017), Ray and Desli (1997), and Kumar and Russell (2002). Here we perform a nonparametric investigation of productivity change for a sample of 93 countries at different stages of development over the period 1970–2014 for which a complete panel with annual data is available. This long period comprises several phases which are of particular interest from a productivity analysis perspective for both developed and developing countries. Four important phases are

1. the productivity slowdown following the oil price shocks (since 1974/75, see Griliches, 1988; Jorgenson, 1988),
2. the breakdown of communism (around 1990),
3. the productive decade (1995–2005) in the US and other developed countries (see Oliner, Sichel, & Stiroh, 2007) and
4. the impact of the financial crisis leading to the Great Recession (2007–2009, see Ng & Wright, 2013).

While the previous literature mainly focuses on productivity decompositions under constant returns to scale (CRS), we perform the analysis for the productivity and frontier dynamics under variable returns to scale (VRS). Clearly, the assumption of VRS comprises CRS as a special case and is generally the more realistic mode of analysis. We compare three variants of the Malmquist index that are throughout computed under VRS: basic (Färe, Grosskopf, Norris, & Zhang, 1994), biennial (Pastor, Asmild, & Lovell, 2011), and global (Pastor & Lovell, 2005) index variants.[1] Given the importance of productivity change and its components there is a need for correct measurement and for more frequent updating for a comprehensive country sample over a sustained time period. The main emphasis of the discussion of the results is on medium-run and long-run trends, which are succinctly visualized by plots of cumulative changes over the period 1970–2014.

The results reveal that the development of total factor productivity is mainly shaped by the interaction of technological change and efficiency change (i.e., catching up or falling behind). We identify a reversal from a backward shifting frontier function during the productivity slowdown to an advancing frontier around the mid-1990s, where the benefits of the widespread use of computers showed up first during the productive decade. There is a tendency of larger efficiency improvements when parts of the frontier function shift backward and smaller efficiency improvements or deteriorations when the relevant frontier function parts advance. The impact of the Great Recession is not very pronounced and is visible as a small dip in the results for the more advanced economies.

Taken together, the contribution of this paper is threefold: First, we establish results based on a comprehensive nonparametric productivity measurement for a broad country sample over a substantial time period of several decades, comprising several phases of particular interest for productivity development. Second, we compare the results of three variations of the Malmquist index that can be computed without imposing functional forms, without needing price information and without the restriction to CRS in two cases. Third, we exploit the opportunity of disentangling technological change and efficiency change which interact in a specific way in shaping the total factor productivity development.

The paper is organized by first explaining the three variants (basic, biennial, and global) of the Malmquist index of total factor productivity and the decomposition in Section 2. This is followed by the graphical presentation and the discussion of the results in Section 3. This discussion starts with the results of the total sample, proceeds to specific country groups, and finally discusses selected individual countries. Section 4 discusses the findings using a specific theoretical model. Section 5 concludes. Three appendices provide details on methods, data, and further results.

2 | PRODUCTIVITY MEASUREMENT

The initial application of nonparametric growth accounting was developed by Färe et al. (1994). Färe et al. (1994) adopted the Malmquist index, an index based on ratios of distance measures originally developed by Malmquist (1953) and Caves, Christensen, and Diewert (1982), and proposed a way to compute the distance functions by nonparametric methods of efficiency analysis (so-called DEA of Charnes, Cooper, and Rhodes [1978] and Banker, Charnes, and Cooper [1984]) adapted to a dynamic setting. These distance functions are based on the concept of the technology set and quantify the distance toward the boundary of this set, the so-called frontier function. This procedure allows to aggregate the inputs without requiring information about factor prices. In this paper we compare three variations of the Malmquist index. These are briefly described in this section, whereas the formal details and further discussion are relegated to Appendix A.

The first variation used is the basic Malmquist index originally introduced by Färe et al. (1994) for macroeconomic productivity measurement. This variant has the disadvantage of being only feasible for all countries in a sample under the assumption of CRS. CRS is a rather restrictive assumption when dealing with a broad country sample of very different sizes. Allowing for VRS causes an infeasibility problem that leads to a dropout of some countries and may bias the results. The second variation is the so-called global Malmquist index proposed by Pastor and Lovell (2005), and the third variation is the related biennial Malmquist index of Pastor et al. (2011). The biennial and global variants are always feasible also under VRS, and the global index furthermore has the beneficial property of circularity.

All three variations of the Malmquist index (*MI*) measure the change of total factor productivity and can be decomposed into two meaningful components, that is, $MI=EC\times TC$. Herein, *EC* represents efficiency change and shows the extent of catching up to the frontier function or falling behind from the frontier function. *TC* represents technology change associated with forward and backward movements of the frontier function itself. The Malmquist index and its components represent growth factors that are larger than one in the case of an improvement (of productivity, efficiency, or technology), smaller than one in the case of a deterioration, and equal to one in the case of no change. See Appendix A for the details of the decomposition.

As we will discuss further later, both components comprise essential aspects of productivity change that are of great importance for growth and development. There, we will relate the results to the growth model of Aghion (2004), which is particularly well adapted to this kind of empirics since it centers around the concept of a leading-edge productivity level pertaining to the productivity on the frontier. A technology gap measure and its dynamics are derived representing the distance to the frontier and its change over time. This is closely related to the efficiency change measure which is computed as the change of the distance of a country to the frontier functions at two points in time and represents the change in the exploitation of given technological opportunities.

As concerns data we only need quantities of the output and the inputs. These data are taken from the Penn World Table 9, described in Feenstra, Inklaar, and Timmer (2015). Our input–output specification uses output-side real gross domestic product (GDP) as the single output variable and physical capital as well as human capital as two input variables. The details of this input–output specification can be found in Krüger (2016). We obtain a balanced panel of n=93 countries over the period 1970–2014 (see Appendix B for a complete country listing).[2] With this database we are able to track productivity change and its components for a large country sample over a sustained period of several decades.

3 | RESULTS AND DISCUSSION

In this section we discuss the results obtained by applying the basic, biennial, and global variants of the Malmquist index to the sample of 93 countries observed over the period 1970–2014. We only consider the results for a VRS technology because of its greater flexibility compared to CRS. The results are presented in a top-down way starting with the total sample, proceeding to specific country subgroups, and finally looking at selected individual countries. It should be emphasized that these selections of groups and individual countries are just different views at the same results obtained for the total sample of 93 countries.

The results are presented graphically as a 3×3 arrangement of figures with the three variants of the productivity index in the columns and the decomposition in the rows. Each curve is constructed from the (multiplicatively) cumulated values of the index and its components (recall that they all represent year-to-year growth factors) starting from the value in 1970 normalized to one which is marked by a bullet point. This succinctly shows both the direction and the speed of the changes by the slopes of the curves on the one hand as well as the total accumulated change over the entire period on the other hand.[3]

3.1 | Total sample

Proceeding as outlined earlier we start with the total country sample. Figure 1 shows the corresponding results. The three lines represent the means over all sample countries (solid line) as well as the means of the 10% best-performing countries (dashed line) and 10% worst-performing countries (dotted line).

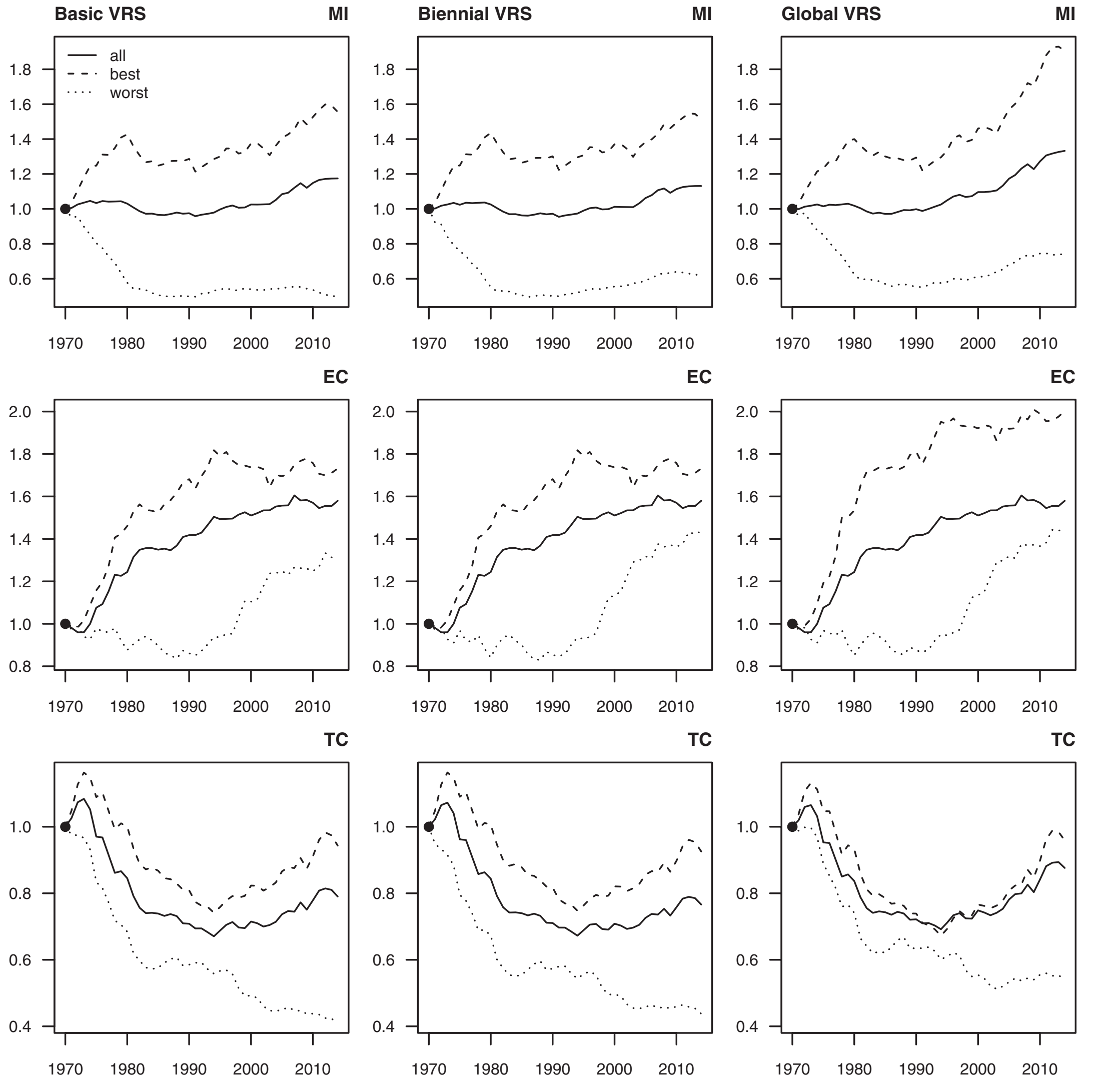

FIGURE 1 Total country sample. Each panel depicts the curves generated by multiplicatively cumulating the changes represented by the Malmquist productivity index and its components. The starting point is normalized to 1970 = 1 and is indicated by a bullet point. The columns refer to the three index variants, and the rows show the entire index (upper) and its components (middle and lower)

The best and worst performers are determined by the average total factor productivity growth over the first decade of the sample period.[4]

Considering first the basic index in the left column, we find the mean total factor productivity (*MI*) to be weakly decreasing until the beginning of the 1990s and slowly increasing afterward. It is steadily increasing for the best performers (about 1.6-fold over the entire sample period). For the worst performers productivity is rapidly declining until the beginning of the 1980s and stagnating thereafter. This, and in particular the development in the initial period, reflects the direct effect of the sorting of the worst- and best-performing countries. The pictures for the biennial and global index variants look rather similar with the notable exception of a slight increase of the productivity of the worst-performing countries in the final years of the sample period.

Regarding the components, we observe that mean efficiency (*EC*) is first increasing and stagnates since the financial crisis. Simultaneously, the curve for technological change (*TC*) shows a pronounced secular decline from the mid-1970s to the mid-1990s and is then increasing. Taking both components together, this implies that countries in the mean are first catching up with respect to a backward shifting frontier and largely maintain distance toward a weakly advancing frontier subsequently. Both developments jointly shape the development of total factor productivity.

This pattern is more pronounced in the case of the best-performing countries for which efficiency is steadily increasing until the turn of the millennium and then starts to decline. Technology declines similarly to the world mean until about 1995 and increases thereafter. It becomes evident that the technological development during the productive decade 1995–2005 was mainly driven by the advancing frontier function parts in the range of the best-performing countries. Note that while the solid line for the mean efficiency change is the same regardless of the index variant, the curves for the best and worst performers differ since the groups are determined by the productivity growth of the respective index variant considered.

For the worst-performing countries efficiency stagnates during the first half of the sample period and then picks up pace in the 1990s, leading to a strong overall catching-up movement. The technology component steadily declines during most of the period. Therefore, the productivity decline for this group is caused by a prolonged backward shift of the relevant parts of the frontier function jointly with stagnating efficiency. In the more recent period the productivity growth is mainly driven by catching up to the frontier by efficiency improvements which are then large enough to compensate the effect of the backward shifting frontier function. The main feature of this development, the interplay of frontier shifts and catching up or falling behind, shows up consistently across the three index variants considered.

The impact of the development during the four phases mentioned in the introduction (the productivity slowdown, the breakdown of communism, the productive decade, and the impact of the financial crisis) is most clearly visible in the technological change components. For all three variants this component reveals a prolonged backward movement of the frontier function from the mid-1970s through the mid-1990s. This applies to all three lines depicted in the last row of the figure and can therefore be taken as an indication that the entire world production frontier and not only certain parts moved backwards. Thus, the productivity slowdown was in fact a worldwide phenomenon. We will encounter this pattern repeatedly when we consider country groups and selected individual countries. As concerns total factor productivity, this regress is overcompensated by the contribution of efficiency change for the best-performing countries, while the compensation by efficiency change is largely offsetting for the mean and is insufficient for the worst-performing countries. The breakdown of communism also occurs in this period but cannot be identified as a separate incident since it is confined to a limited group of countries.

During the productive decade 1995–2005 we observe the reversal to an advancement of the frontier function parts pertaining to the best-performing countries. Looking at the technological change component, we find that this advancement continues during the years of the financial crisis. The same can be observed for the world mean to a smaller extent. The differential development of the mean of the worst-performing countries reveals that these countries are positioned behind other parts of the frontier that continue to move backwards also during the productive decade. A related finding is reported in Badunenko, Henderson, and Zelenyuk (2008) also reporting evidence that technological progress plays a key role for the divergence between rich and poor countries during the 1990s.

The impact of the Great Recession (2007–2009) is not clearly visible in the results of the productivity decomposition. There is just a small decrease in the technology change components with the right timing. This appears somewhat surprising. Even more puzzling is the increase in the technological change components after the main event that triggered the Great Recession, that is, the collapse of Lehman Brothers in September 2008, and its deterioration after 2010. It appears that the impact of this crisis is more of a transitory than a permanent nature, at least when viewed through the lens of technological progress and productivity change.

3.2 | Country groups

In this section we turn to the results for different country groups.[5] One classification is based on the region code classification of Barro and Lee, accompanying their human capital data set (see Barro & Lee, 2013). The other classification is according to terciles of real per capita income (low-middle-high). The figures reporting the results are constructed as in the previous section, now with colored lines representing the means of the respective country groups.

Figure 2 shows the results for the country groups according to the region code classification. Not surprisingly, the overall pattern of results for the advanced economies (consisting mostly of OECD countries) is rather similar to the mean of the best-performing countries discussed previously. A notable exception is the development of the efficiency change component that here rises until the 1990s and subsequently starts declining. Clearly visible is the impact of the financial crisis and the Great Recession in the curves for productivity and technological change around 2007–2009.

The Asian countries (comprising East and South Asia) experience increasing total factor productivity as measured by the basic and biennial index variants, which appears much stronger when using the global index and is close to the curve for the advanced economies in this case. The impact of the Asian financial, currency, and economic crisis starting in 1997 is clearly visible in the total factor productivity development irrespective of the index variant. The sources of the overall productivity increase are different, however. Whereas total factor productivity is mainly driven by the efficiency component (catching up) in Asia, the contribution of technological progress is much larger in the advanced economies. In contrast to the other country groups, the Asian countries are catching up to the frontier function more rapidly as indicated by the strong improvement of the efficiency change component. With regard to technological change, the Asian countries behave much like the Latin American, African, and Middle East countries that are mostly faced with backward shifting parts of the frontier function (especially during the 1970s and 1980s) which are weakly increasing only in the later years.

The group means of the Latin American, African, and Middle East countries are rather similar. They have the lowest total factor productivity growth among the groups, which is much a consequence of the low values of the technology change component. The catching-up movement of these countries is also not very strong and stagnates since the 1980s as can be observed from the efficiency change component. This is a crucial difference to the development in the Asian countries. Again, we observe a much greater similarity of the basic and the biennial index variants compared to the global index.

The findings for the African countries stand in contrast to the study of Badunenko, Henderson, and Houssa (2014) for roughly the same period finding widespread efficiency losses of the African countries combined with a negligible contribution of technological change. These differences can be explained by the fact that Badunenko et al. (2014) focus on a frontier function which is spanned exclusively by the African countries while we are here concerned with the world production frontier. Thus, when we look at the African countries in isolation, it appears that the frontier function stays largely constant, and many countries fall back from this frontier. This is perfectly compatible with our finding of backward shifting frontier function parts in the range of the African countries (which is driven by other countries) to which the African countries are catching up.

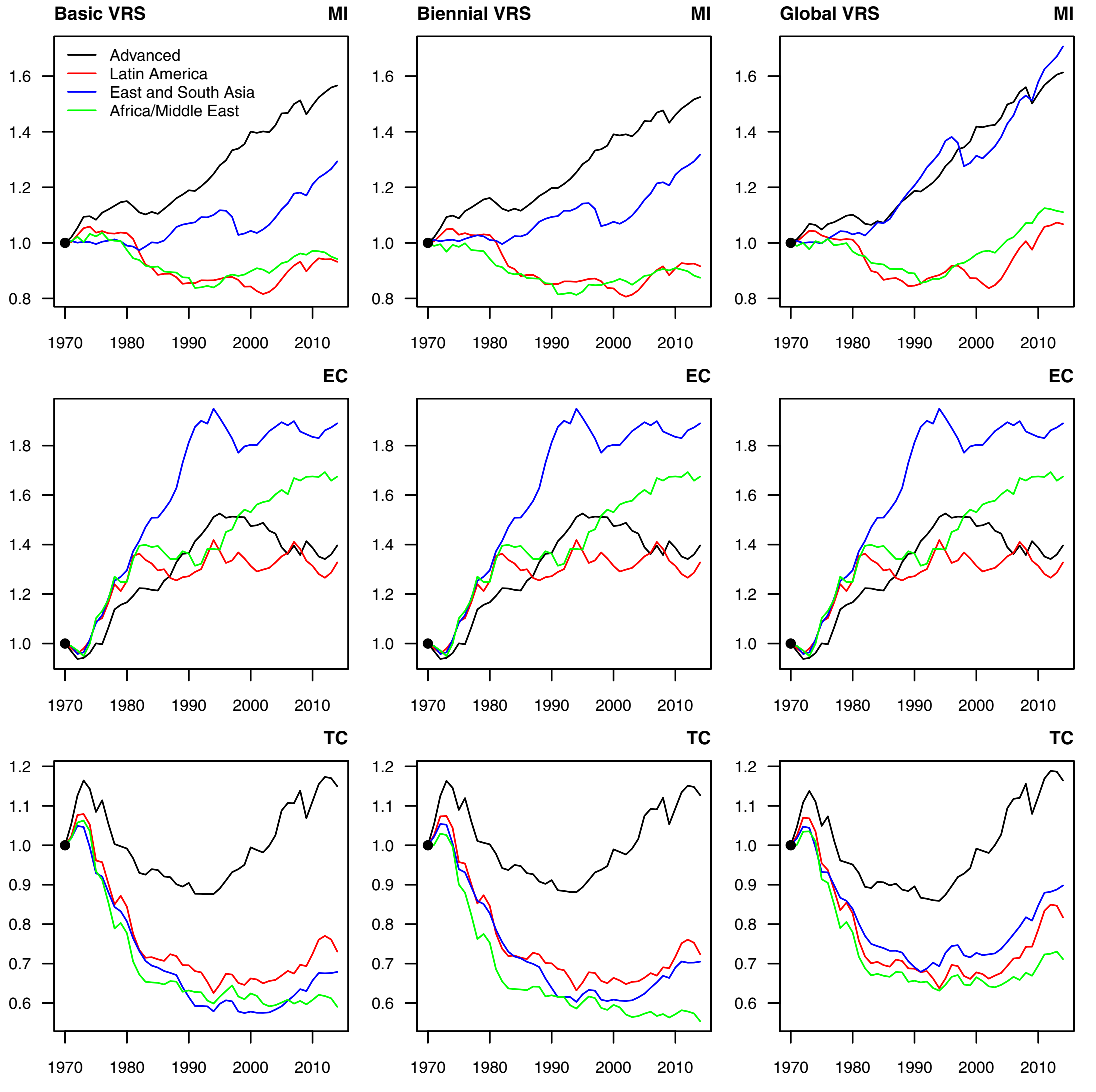

FIGURE 2 Country groups. Each panel depicts the curves generated by multiplicatively cumulating the changes represented by the Malmquist productivity index and its components. The starting point is normalized to 1970 = 1 and is indicated by a bullet point. The columns refer to the three index variants, and the rows show the entire index (upper) and its components (middle and lower) [Colour figure can be viewed at wileyonlinelibrary.com]

The income terciles are based on income per capita, according to the average per capita income during 1970–2014. The results are depicted in Figure 3. The countries in the highest tercile with the highest per capita incomes experience the largest cumulative increase in total factor productivity, which is mostly driven by the technological change component, while efficiency improvements play a smaller role for this group. As previously in the cases of the best-performing countries and the advanced countries the technology change component follows a ∪-shaped development.

The countries in the lowest income tercile experience the smallest cumulative increase in total factor productivity, which is close to that of the middle-income group during most of the period considered. Both curves pick up pace in the later years. The catching-up movement toward the frontier function is strongest for the countries in the low-income group, but this is accompanied by steadily

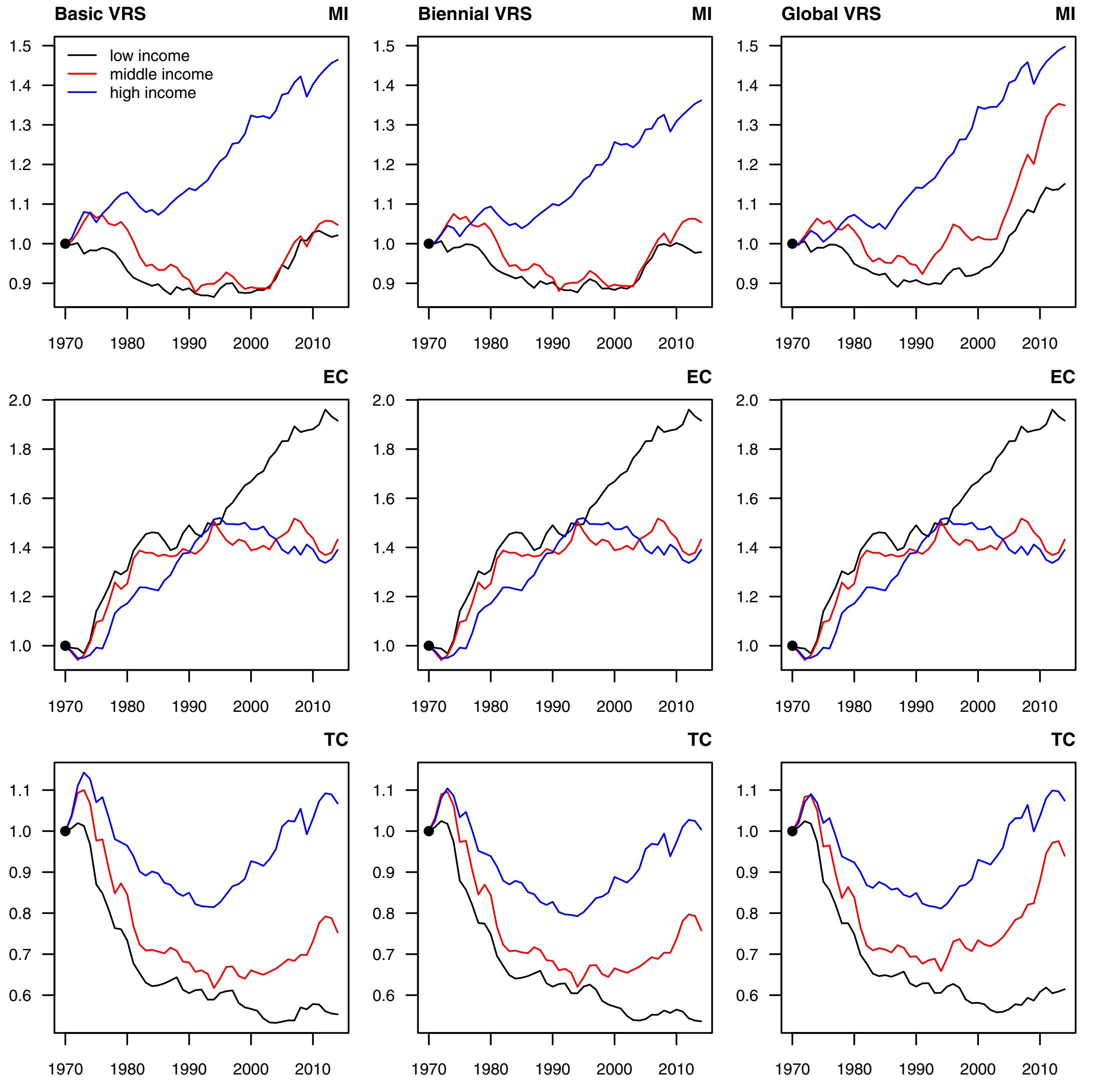

FIGURE 3 Income terciles. Each panel depicts the curves generated by multiplicatively cumulating the changes represented by the Malmquist productivity index and its components. The starting point is normalized to 1970 = 1 and is indicated by a bullet point. The columns refer to the three index variants, and the rows show the entire index (upper) and its components (middle and lower) [Colour figure can be viewed at wileyonlinelibrary.com]

backward shifting parts of the frontier function as revealed by the declining curve of the technology change component.

In the case of the global index, productivity growth of the middle- income countries is considerably larger. While the efficiency change is similar to that of the high-income countries, the differences in both groups are driven by the technology change component, which is largest for the high-income countries, followed by the middle-income countries and finally the low-income countries. Since the mid-1990s the middle-income countries manage to move into the range of the advancing frontier function parts, and their curve rises while the low-income countries remain in the range of the backward moving parts.

3.3 | Selected individual countries

After the discussion of the country groups we take a closer look at the results for selected individual countries. Selected are major advanced economies, southern and eastern European countries as well as major Asian economies, furthermore some nearly industrializing countries and some African growth tragedies. The results are reported in figures analogously to the previous sections with the countries indicated by their three-digit country codes.

We start with some examples of major advanced economies, that is, Canada (CAN), France (FRA), Germany (DEU), the United Kingdom (GBR), and the United States (USA). For these countries we observe quite diverging trends of total factor productivity growth in Figure 4. We also find a greater dependence of the results on the index variant since there is now no averaging of differences as before. The US experiences the largest overall productivity growth when considering the basic index, while it is in the center in the case of the other index variants. The efficiency change components are the same for all three index variants with a constant value for the US over the entire time span, indicating that the US observations are consistently on the frontier function. Interpreted jointly with the technological progress component, this indicates that the US observations are causal for the forward shift of the corresponding parts of the frontier. The lowest productivity growth is observed for Canada shaped jointly by the low values of both components and especially the falling behind from the frontier function in later years. The other countries of this group, that is, France, Germany, and the United Kingdom, benefit from both catching-up and technological progress to a different extent with no stable pattern across the index variants.

The development of the southern European economies Italy (ITA), Spain (ESP), Portugal (PRT), and Greece (GRC) is characterized by a steady improvement in productivity (see Figure 5). Efficiency change is substantially contributing to productivity growth in all four economies, so that they are all catching up to the frontier with similar total efficiency improvements at the end of the sample period (albeit reached along quite different paths). Compared to the advanced economies the efficiency component is much stronger in the southern European countries, so that total factor productivity growth in these countries is more a result of catching-up to the frontier. The contribution of the technological change component is lower than in the advanced economies or even points to a substantial deterioration in the cases of Portugal and Greece during the first half of the sample period.

Compared to the southern European economies the productivity development of the eastern European economies Hungary (HUN), Poland (POL), Bulgaria (BRG), and Romania (ROU) is quite different (Figure 6). Total factor productivity growth is much more erratic with downturns around 1990 and later which is presumably caused by the transformation of these economies after the breakdown of communism. Already some time before 1990 a weakening of catching-up to the frontier, which was strong during the 1970s, is recognizable from the efficiency change components. Romania is characterized by the overall largest catching-up, followed by Poland, Hungary, and Bulgaria. Some years after 1990 technological change started to contribute positively to productivity growth, while it was contributing negatively during the 1970s and the beginning of the 1980s. The productivity development was even more heterogeneous with Poland and Romania leading and Bulgaria loosing contact, mostly due to the better exploitation of catching-up opportunities. This has been supported by the successive integration in the common European market and actually started long before the formal membership and full integration in the European Union.

Rather different to that is the development of four major South and East Asian economies, that is, China (CHN), India (IND), Japan (JPN), and South Korea (KOR) as shown in Figure 7. In the case of Japan we observe a secular decline of total factor productivity during the whole period under investigation. This is driven by the development of the efficiency and technology components which

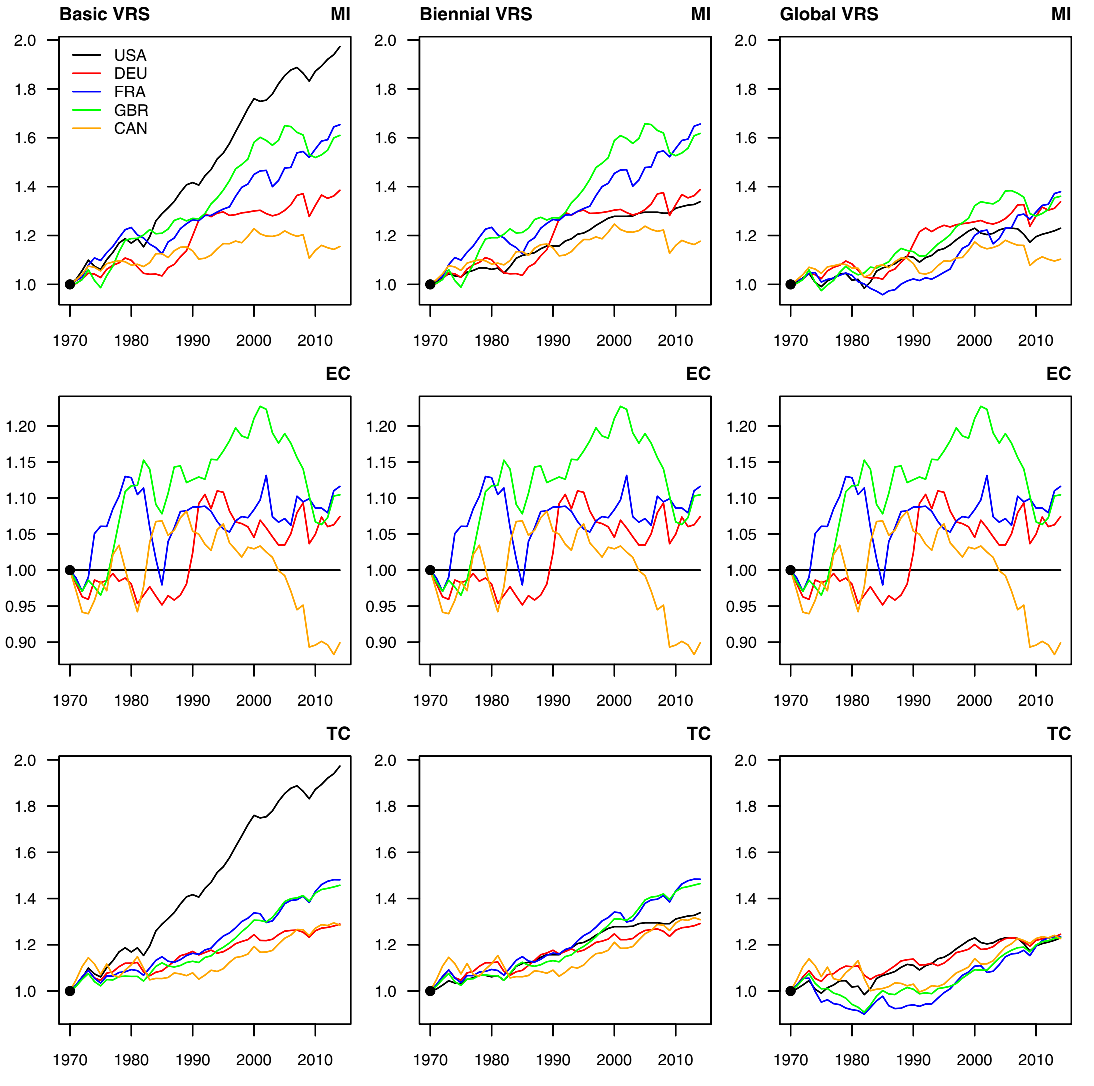

FIGURE 4 Advanced economies. Each panel depicts the curves generated by multiplicatively cumulating the changes represented by the Malmquist productivity index and its components. The starting point is normalized to 1970 = 1 and is indicated by a bullet point. The columns refer to the three index variants, and the rows show the entire index (upper) and its components (middle and lower) [Colour figure can be viewed at wileyonlinelibrary.com]

are stagnating or declining over the entire time span. Efficiency change is constant for a long part of the sample period, indicating that Japan determines a steadily backward shifting part of the frontier function during the 1970s, 1980s, and part of the 1990s. With the start of the Asian crisis Japan falls behind the frontier function. The productivity development in India and South Korea is mostly fueled by strongly catching up to the frontier. China experienced productivity growth until about 1990, driven by both efficiency change and technological progress. Since about 1990 China seems to have been located on a separate part of the frontier function (as can be seen from the absence of efficiency change) which is backward shifting, however. For these countries, the results from the basic and the biennial indices are rather different from that of the global index.

In Figure 8 the results for four countries that are commonly viewed as newly industrializing countries outside of South and East Asia are depicted, that is, Brazil (BRA), Mexico (MEX), Turkey

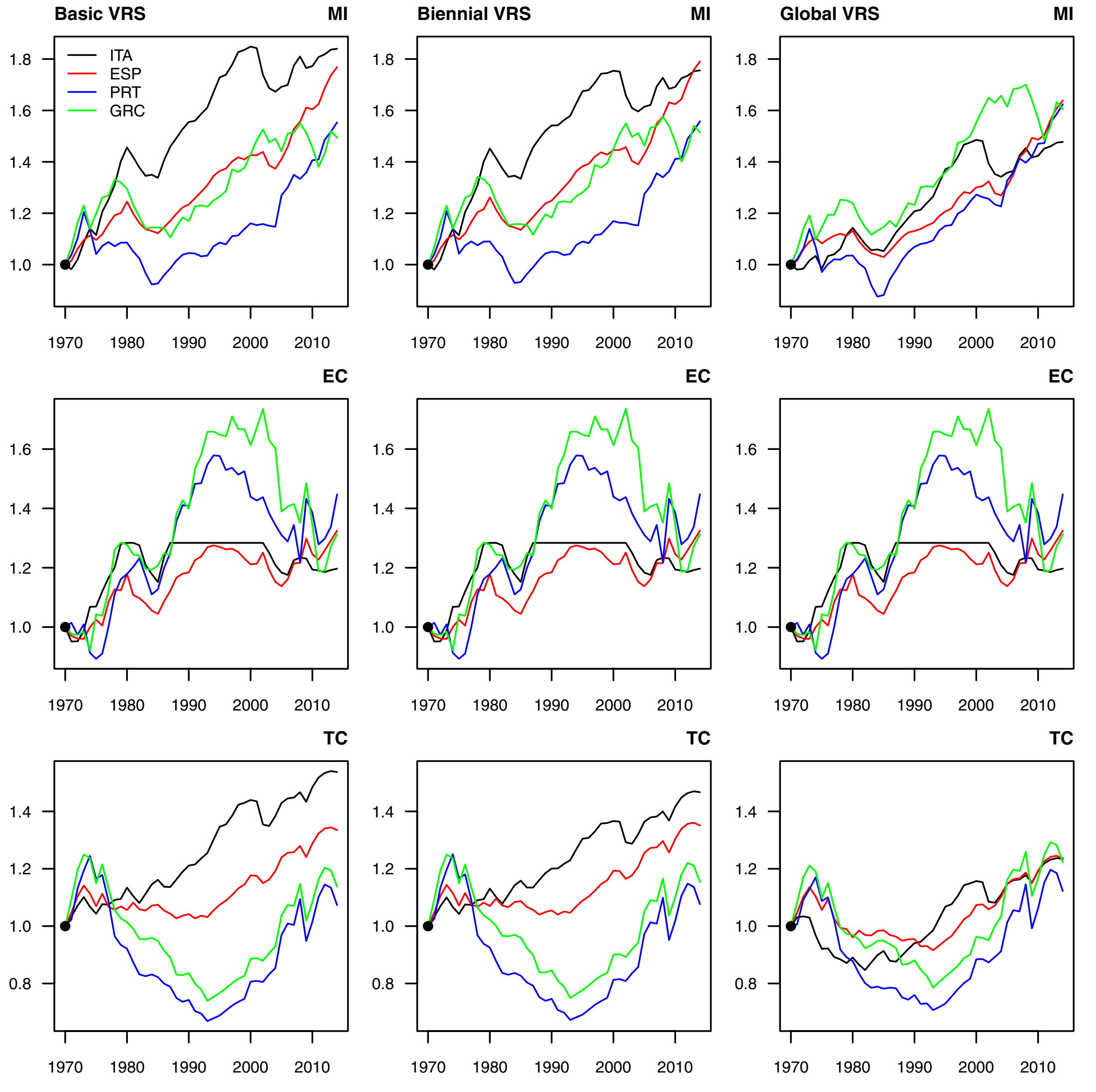

FIGURE 5 Southern European economies. Each panel depicts the curves generated by multiplicatively cumulating the changes represented by the Malmquist productivity index and its components. The starting point is normalized to 1970 = 1 and is indicated by a bullet point. The columns refer to the three index variants, and the rows show the entire index (upper) and its components (middle and lower) [Colour figure can be viewed at wileyonlinelibrary.com]

(TUR), and South Africa (ZAF). We see that the long-run productivity performance is rather diverse. In Mexico total factor productivity is declining over the whole time period but shows some stabilization since the 1990s on a low level. The decline is caused mainly by a falling-behind movement from the frontier function, and the stabilization is due to picking-up of technological progress. In the other three countries efficiency improvements are visible but are deteriorating at the end of the sample period when technological progress begins to pick up pace and the frontier function starts shifting forward. Mexico appears to be related to more rapidly shifting parts of the frontier function but is not able to maintain its distance to the frontier, which leads to a downward sloping efficiency curve. In the case of Turkey we observe an almost constant efficiency component since the 1980s so that the productivity change is here due to technological change.

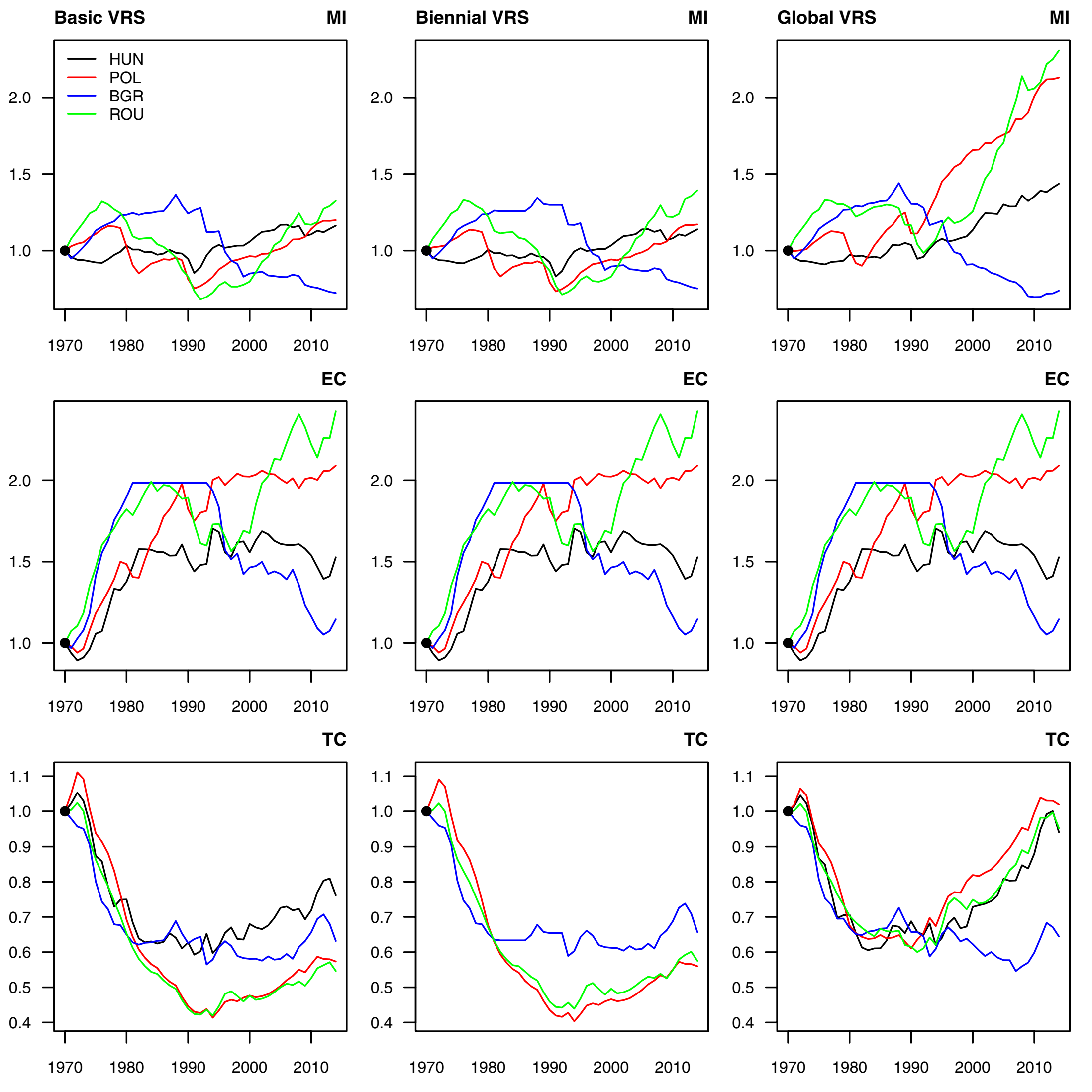

FIGURE 6 Eastern European economies. Each panel depicts the curves generated by multiplicatively cumulating the changes represented by the Malmquist productivity index and its components. The starting point is normalized to 1970 = 1 and is indicated by a bullet point. The columns refer to the three index variants, and the rows show the entire index (upper) and its components (middle and lower) [Colour figure can be viewed at wileyonlinelibrary.com]

Finally, we look at the results of four sub-Saharan African growth tragedies in Figure 9 (see Easterly & Levine, 1997). There are four countries with negative per capita income growth over the sample period, that is, the Democratic Republic of Congo (COD), Madagascar (MDG), Malawi (MWI), and Niger (NER). We find total factor productivity to be stagnating or declining, especially in the Democratic Republic of Congo.[6] Concerning the sources of total factor productivity growth we find efficiency improvements for Madagascar, Malawi, and Niger, but not in the case of the Democratic Republic of Congo. All four countries are, however, faced with dramatically backward shifting parts of the frontier function leading to almost linearly declining curves of the technological progress components.

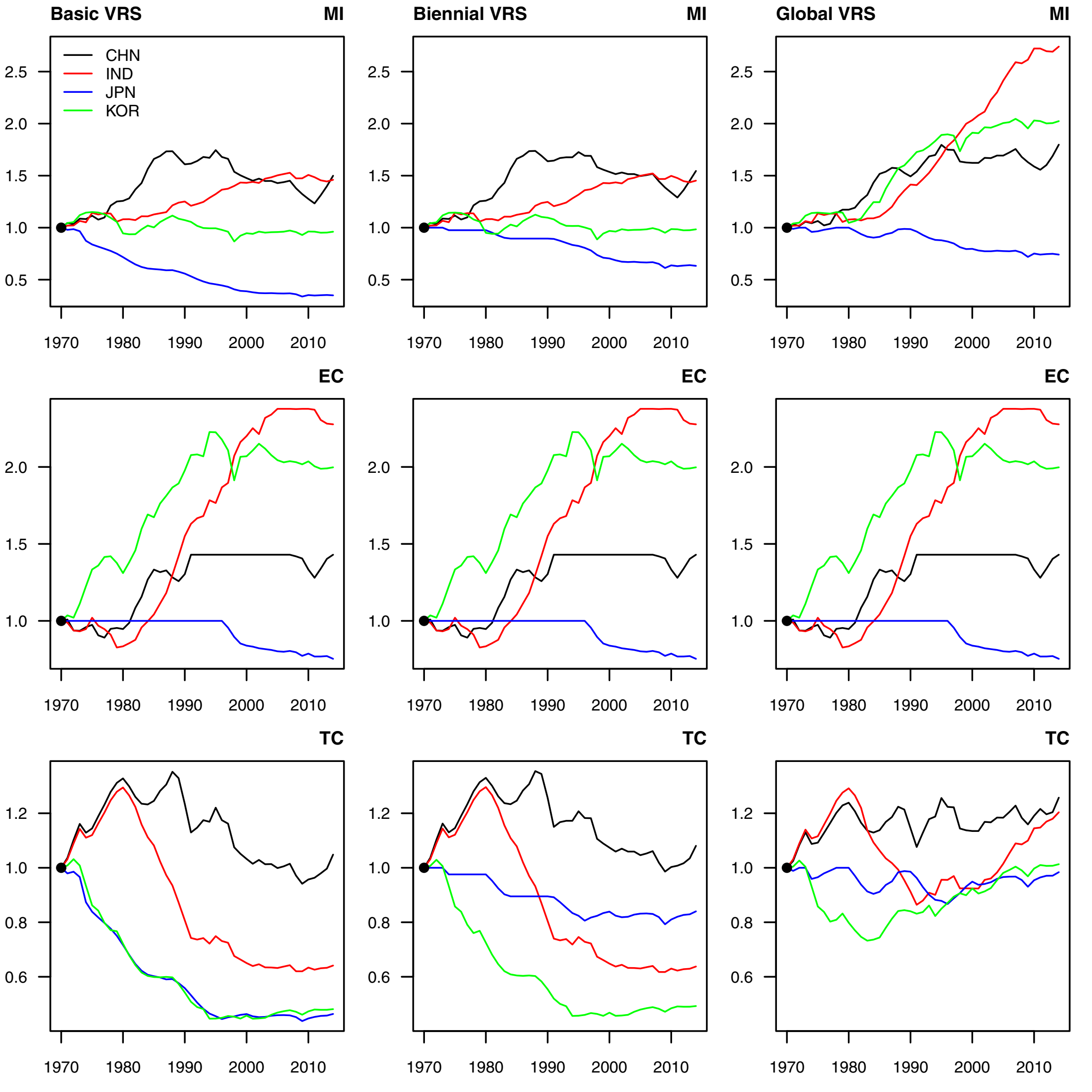

FIGURE 7 South and East Asian economies. Each panel depicts the curves generated by multiplicatively cumulating the changes represented by the Malmquist productivity index and its components. The starting point is normalized to 1970 = 1 and is indicated by a bullet point. The columns refer to the three index variants, and the rows show the entire index (upper) and its components (middle and lower) [Colour figure can be viewed at wileyonlinelibrary.com]

4 | INTERPRETATION AND DISCUSSION

As we repeatedly encountered in the discussion of the empirical results for several groups of countries and examples of individual countries, productivity change is driven both by the movement of the frontier function and by the movements of the countries behind this frontier function. For a deeper interpretation of the empirical findings we resort to the Schumpeterian branch of growth theory. Its implications for developing economies are explained by Acemoglu, Aghion, and Zilibotti (2006), Aghion (2004), and Banerjee and Duflo (2005), among others. Aghion (2004) provides a particularly useful theoretical framework for the interpretation of the empirical results.

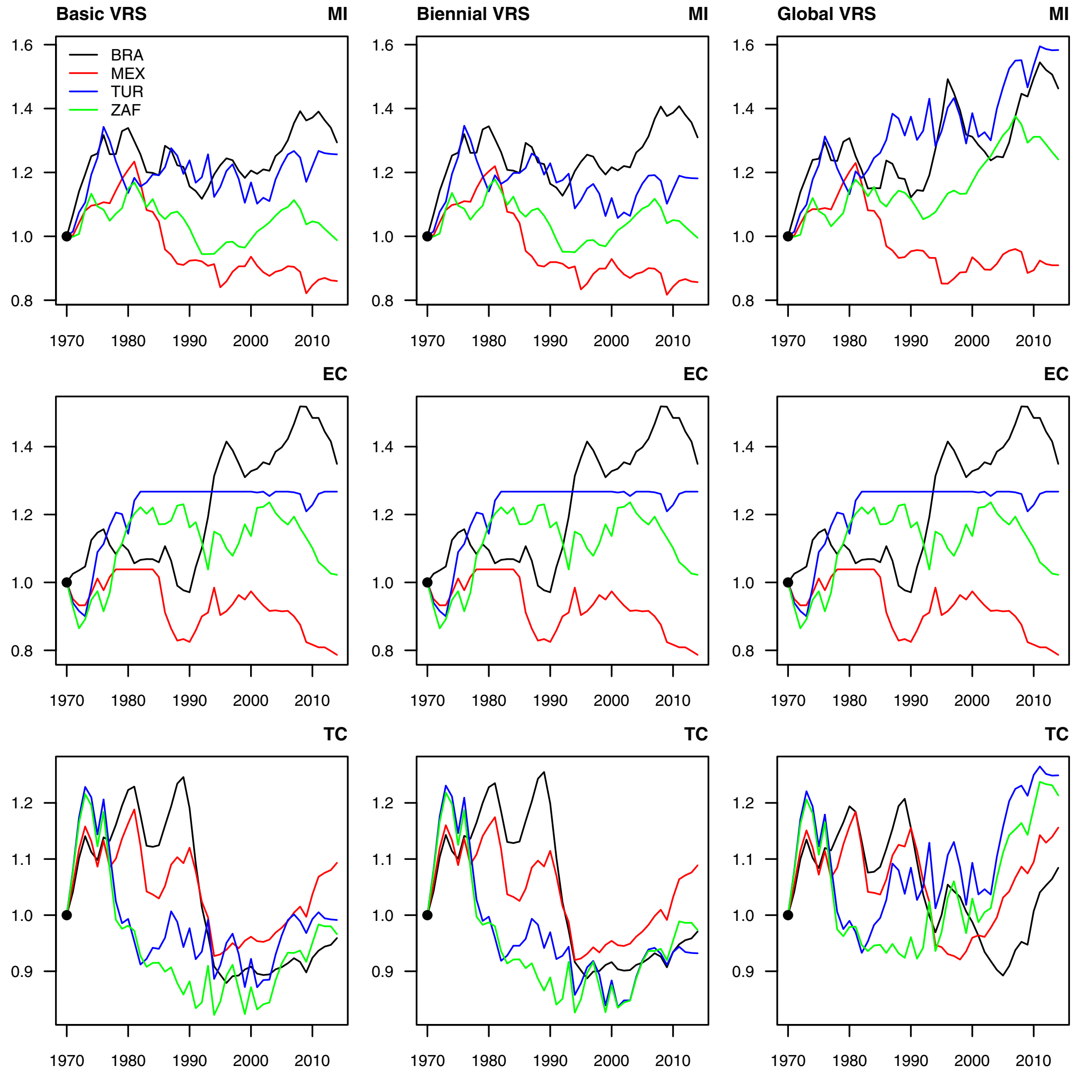

FIGURE 8 Newly industrializing economies. Each panel depicts the curves generated by multiplicatively cumulating the changes represented by the Malmquist productivity index and its components. The starting point is normalized to 1970 = 1 and is indicated by a bullet point. The columns refer to the three index variants, and the rows show the entire index (upper) and its components (middle and lower) [Colour figure can be viewed at wileyonlinelibrary.com]

In the theory put forward by Aghion (2004), the macroeconomic productivity level A in a country develops according to the law of motion

$$\dot{A} = \lambda\varphi(A^{\max} - A), \quad (1)$$

where the dot denotes the derivative with respect to time and $A^{\max}$ denotes the productivity level on the frontier function. The parameters λ and φ denote the productivity of R&D effort and the R&D intensity, respectively. Normalizing productivity leads to a measure $a = A/A^{\max}$ within [0, 1] which is interpreted as an inverse measure of the technology gap and corresponds to the same-period distance function used in the empirical analysis (case $s = t$ in Equation A2 of Appendix A). We have $a = 1$ for a country on

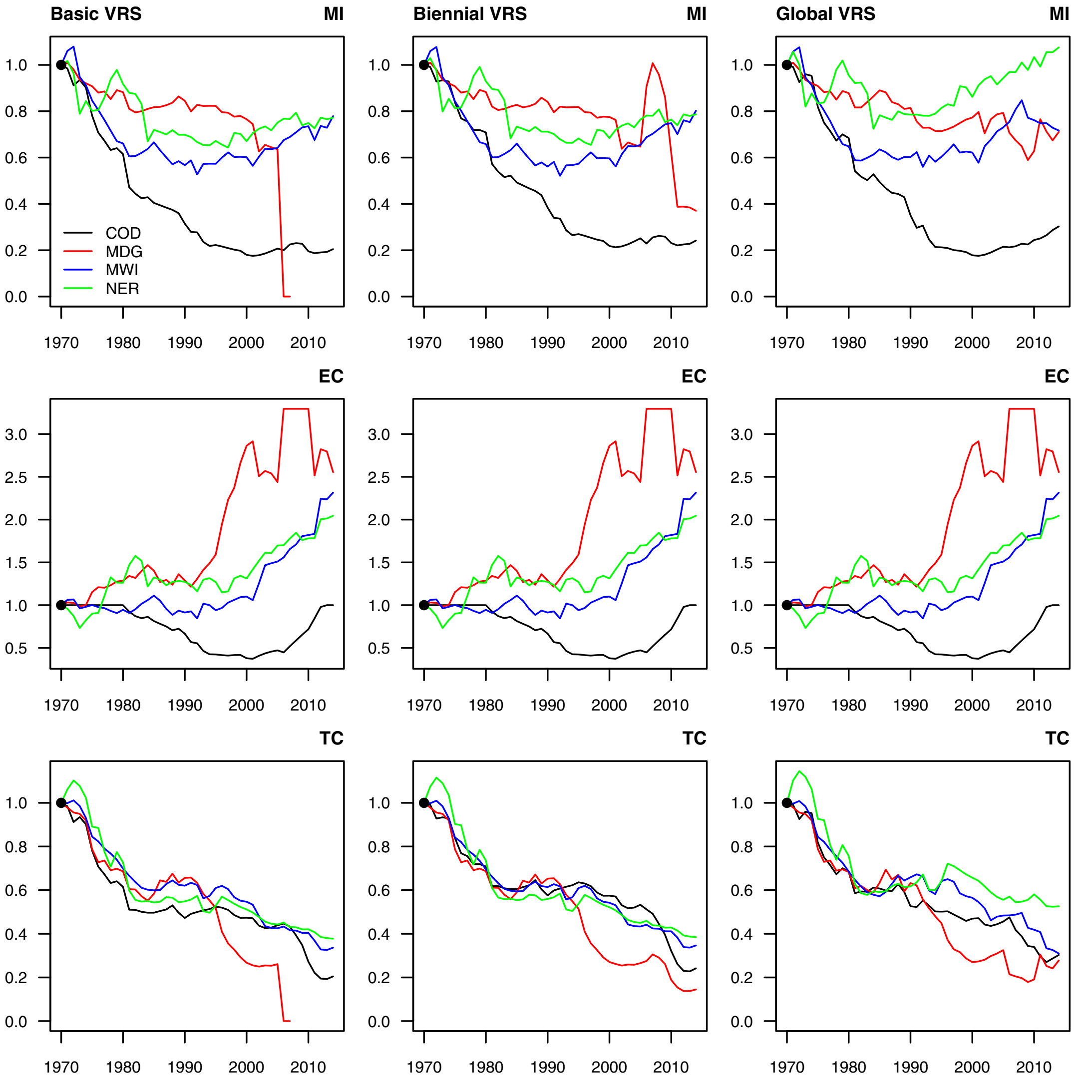

FIGURE 9 African tragedies. Each panel depicts the curves generated by multiplicatively cumulating the changes represented by the Malmquist productivity index and its components. The starting point is normalized to 1970 = 1 and is indicated by a bullet point. The columns refer to the three index variants, and the rows show the entire index (upper) and its components (middle and lower) [Colour figure can be viewed at wileyonlinelibrary.com]

the frontier function with $A = A^{\max}$ and $a < 1$ for a country below the frontier function with $A < A^{\max}$. Similarly, $1 - a = (A^{\max} - A)/A^{\max}$ can be viewed as a direct measure of the technology gap.

For convenience let the growth rate of $A^{\max}$ be fixed at a constant g. This represents the shift of the frontier function corresponding to the technological change component of the productivity change decompositions in Equations A5 and A11. The law of motion of a is

$$\dot{a} = \lambda\varphi(1 - a) - ag. \tag{2}$$

Equation (2) gives the change of efficiency relative to the frontier and corresponds to the efficiency change components in Equations A5 and A11. Herein, the first term of the equation shows that the technology gap tends to decrease (recalling that a is an inverse measure of the technology gap) with its size, depending on the values of the parameters λ and φ. The second term shows that the technology gap tends to increase as the frontier function advances (i.e., $g > 0$) which may be caused by innovations outside of the country under consideration.

The parameters λ and φ are crucial for the extent and the speed of catching-up. Their values are likely to be lower in developing countries as a result of a less favorable entrepreneurial environments, a lower level of education, less efficient credit markets and property rights enforcement. All these are aspects of the "social capability" of a country according to Abramovitz (1986). The extreme case when one of the parameters is equal to zero can be interpreted as extremely high barriers to innovation adoption in a country. Then, the first term in Equation (2) is zero, and the second term causes a continuous falling back from the frontier. When both parameters are larger than zero, we observe catching-up to the frontier if the first term is larger than the second. This can also be related to the concept of the "absorptive capacity," established by Cohen and Levinthal (1990) at the firm level. Firms in the countries need to engage in innovative activities not only to generate new products or improved processes but also to understand the innovations generated elsewhere and adapt them to their specific purposes.

This kind of dynamics provides a theoretical explanation of the interplay of technological progress and efficiency observed in the empirical results. When the frontier function advances ($g > 0$), caused by innovations in some countries, it becomes more difficult for many developing countries to sustain their technology gap to the frontier function, and they tend to fall behind. This is visible in decreasing technical efficiency and a downward sloping curve in the figures discussed earlier. The falling-behind movement is less pronounced for countries with a larger technology gap provided that λ and φ are large enough, implying that the "social capability" is sufficiently large. In the case of technological regress in the leading countries ($g < 0$), leading to a backward shifting frontier function, catching-up is much easier to realize since both terms in Equation (2) are positive. Then we observe increasing technical efficiency and an upward sloping curve. This pattern is exactly what we find for the country groups and for many individual countries. For specific countries and time periods, idiosyncratic events, such as natural disasters, political turmoil, and wars, may play a decisive role for deviations from this kind of dynamics, however.7

5 | CONCLUSION

The main lessons from the nonparametric investigation of the world production frontier for a sample of 93 countries on different stages of development over the period 1970–2014 can be summarized in several main conclusions. Before we turn to these conclusions we want to emphasize the need for more frequent updates of productivity measures as presented in this work, not as an end in itself but also as inputs for other empirical work and calibration exercises.

First of all, we find rather small overall increases of total factor productivity for the average of all sample countries over the entire period under investigation. This average development is driven by very heterogeneous productivity experiences across country groups and individual countries within the groups. Clearly, efficiency change (catching-up or falling behind) is the main source of this heterogeneity. Technological change is more similar across countries although there is systematic variation over time. Of course, this is a direct consequence of the limited number of frontier function segments moving over time against which the countries are evaluated.

The central finding is that the total factor productivity development is shaped by a specific interplay of efficiency change and technological change. Along the timeline we are first faced with a predominantly backward shifting world production frontier until the mid-1990s. This comprises the phases of the productivity slowdown and the breakdown of communism. Simultaneously, we observe considerable efficiency gains during this period, which implies that many countries manage to catch up to the frontier. We observe that since the mid-1990s, parts of the frontier function have been forward shifting, especially those pertaining to the more developed countries. This period comprises the productive decade 1995–2005 as well as the financial crisis and the Great Recession (the effect of the latter does not exert a great impact on the productivity figures, however). Simultaneously with the technological progress we now find less prevalent efficiency gains or even losses in many occasions, implying that countries are falling back from the advancing frontier function. Countries with high rates of productivity growth are able to sustain efficiency gains and to catch up further to the frontier function. Those countries benefit from both technological progress and efficiency gains.

The empirical method corresponds very well to main elements of the Schumpeterian growth model of Aghion (2004), which can be used to interpret the results theoretically. In this model the changes in the leading-edge productivity level correspond to the shifts of the frontier function that are driven by innovative activities. The change in the (inverse) measure of the technology gap closely corresponds to the efficiency change component. In this respect, the extent of a "social capability" (Abramovitz, 1986) in the political and economic system of a country appears to be crucial for the ability to catch up to the frontier function. Thus, the existence of "social capability" and "absorptive capacity" are essential for catching up to the leading countries on the frontier function, which exactly is what efficiency change measures.

Regarding the comparison of the variants of the Malmquist index, we can conclude that there are only small differences in the basic and the biennial variants under the VRS analysis in this paper. This does not imply that both index variants are always similar beyond the present application. Recall that the basic index may be subject to sample selectivity because of countries systematically dropping out (as a consequence of the infeasibility problem arising under VRS), whereas the biennial index can always be computed. The global index, which is also always feasible under VRS, leads to quantitatively different results. It can be observed that the differences are smaller for groups than for single countries. The reason for the differences is that the global frontier is determined by the most efficient country-year observations irrespective of their period of origin which may be quite distant from the actual year under evaluation. In contrast, in the case of the basic and the biennial variants of the index the frontier function is determined by only two adjacent years for which the Malmquist index and its decomposition are evaluated.

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CONFLICT OF INTEREST STATEMENT

There is no conflict of interest.

DATA AVAILABILITY STATEMENT

The data are taken from the Penn World Table 9, which is publicly available at https://www.rug.nl/ggdc/productivity/pwt.

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ENDNOTES

[1] See Kerstens, Shen, and Van de Woestyne (2018) for a related study comparing productivity indicators that is more methodologically oriented, whereas we here give more emphasis to the empirical results.

[2] As usual in macroeconomic productivity assessments we exclude countries which heavily rely on oil production as well as countries that are merely larger cities. Stated in World Bank country codes ARE, BHR, BRN, KWT, QAT, and SAU as well as HKG, LUX, MAC, and SGP are excluded.

[3] Relating this to the formal presentation in Appendix A, we report the results for the productivity change (abbreviated by *MI*, also when referring to *GMI* in Equation A11), efficiency change (abbreviated by *EC*), and technical change (abbreviated by *TC*, also when referring to *BPC* in Equation A11).

[4] Reported are unweighted means. Introducing weighting following Zelenyuk (2006) changes the quantitative results but not the general conclusions. See Appendix C on the author's website for the results.

[5] Strictly speaking the best-performing and worst-performing countries considered in the previous section are also groups.

[6] Notice that the curves for *MI* and *TC* break after 2005 in the case of Madagascar due to the infeasibility of the mixed-period linear programming problems of the basic index under VRS.

[7] The episodic nature of growth is also emphasized in the recent survey of the convergence literature by Johnson and Papageorgiou (2020).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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