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The Segmented Trend Line of Highest Life Expectancies

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IN THEIR WELL-KNOWN *Science* article, "Broken limits of life expectancy," Oeppen and Vaupel (2002) showed that the highest life expectancy observed in a given year increased linearly from 1840 up to 2000 at the annual pace of 0.25 years. They demonstrated that "best performance" life expectancy in the past repeatedly refuted experts who posited a looming upper limit to possible extension of improvements in mortality. Their analysis, using measures at the country level and limited to data for female populations, received wide attention but also fueled major controversy, especially when used to extrapolate future improvements in life expectancy at the same pace. Half a decade later, it is possible to expand the set of data used by Oeppen and Vaupel with a large quantity of additional data, including both data prior to 1840 that can inform us about the pace of life expectancy progress in earlier times, and data for the most recent period, a time that may herald a coming change in life expectancy trends.

Life expectancy increases as the result of the decline in mortality at different ages, and the relative weight of declines at specific ages has shifted dramatically over time. Age-specific mortality indicators can help to interpret trends in life expectancy at birth. In the first part of this article, we gather as much age-specific mortality data as possible and describe the gain in accuracy obtained when including different types of additional data in a larger dataset. In the second part, we examine whether Oeppen and Vaupel's straight line from 1840 to 2000 still fits when the database for the period studied by its authors is expanded and whether data for the years before and/or after that period confirm or invalidate a linear trend. At this stage, considering not only the trends in best life expectancy but also trends in the second-best

life expectancy is important in dealing with the problem of questionable data. In this respect, two countries, New Zealand and Japan, merit detailed discussion. In the third part, selecting significant large age groups, we disaggregate the difference between life expectancy at birth of the best-performing country and the mean life expectancy of the other countries according to the weight of each age, around 1850, 1900, 1950, and 2000. We analyze trends in highest survival rates within each of the selected age groups and in highest life expectancies from the starting points of these age groups. Finally, taking into account the importance of old-age mortality for future changes in life expectancy, we use the Kannisto–Thatcher Database to analyze life expectancy at age 80 and to confirm that the case of New Zealand is probably the Achilles' heel of the Oeppen–Vaupel straight line. Their line has to be broken into segments that correspond to the main historical phases of the health transition.

What do we gain from more data?

The precise universe upon which Oeppen and Vaupel's line is based is unknown, and it is not possible to reassess the line on the basis of the original data or to compare any new results obtained from that original universe using a different approach with either the original results or new results based on an enlarged universe.[1] However, it is possible to look at different results that we obtain today by using different universes that are largely homogeneous in quality of data, and then to compare the best result that we can get today with Oeppen and Vaupel's original results.

Data used

Although some advanced developing countries have already reached very high levels of life expectancy, we limit our study to countries in Europe and North America and to Japan, Australia, and New Zealand. A quick test showed that no developing country is yet approaching current Japanese levels, and older data are very rare outside the geographic areas just described.

We use five sources for our analyses (see Table 1 and Figure 1):

—The Human Mortality Database (HMD)[2] provides all standard life-table functions systematically computed annually on the basis of complete series of deaths and populations by single year of age and sex and single year of occurrence. This is the most reliable set of annual complete life-table functions in the world, and we use it as our primary source. A total of 2,884 annual female life tables were available from HMD.

—The Human Life Table Database (HLTD)[3] contains original life tables published (a) by statistical offices and similar institutions and (b) in the framework of ad hoc research projects. (This database makes available both

TABLE 1 Sources of data used (female populations only)

Initials	Name	Content	Number of life tables
HMD	Human Mortality Database	Complete annual life tables	2,884
HLTD	Human Life Table Database	Published life tables, heterogeneous according to age group and period length	309
MVDB	Meslé–Vallin Database	Any other life tables covering periods and countries not available in HMD or HLTD	750
e_0	Life expectation file	Life expectancy at birth published without life tables	679
KTDB	Kannisto–Thatcher Database	Age-specific mortality rates and life expectancies above age 80 computed with extinct-generation method	—[a]

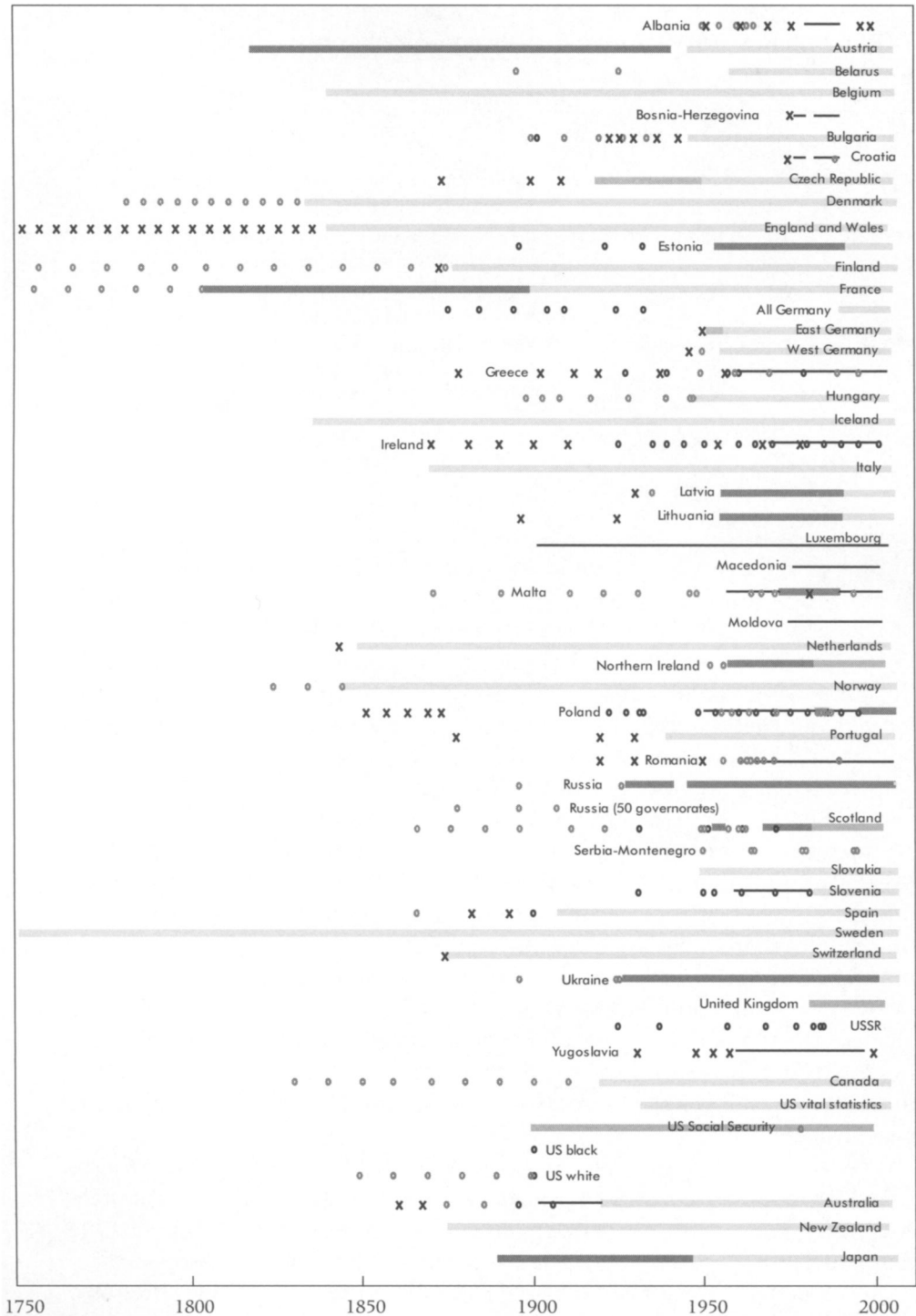[a]KTDB contains no life tables, only mortality rates above age 80.

facsimiles of original tables and reconstructed life-table functions from the most appropriate original data, using the same protocol.) We use the HLTD as our second priority source when it covers a country for a year that is not provided by HMD. Unlike HMD life tables, most HLTD life tables cover several years (only a few of them are limited to a single year); 309 additional female life tables were available from HLTD. HMD does not provide any data for the period/countries covered by these HLTD tables because HMD requires specific and basic distribution of deaths by year of occurrence and single year of age. But HLTD tables are not necessarily of lower quality.

—Because these two sources do not cover all existing reliable life tables, we included in an additional file, here called the Meslé–Vallin Database (MVDB), any other life tables available (or computable from age-specific mortality rates) for the relevant countries. The basic rule was to use only those tables that do not duplicate HMD or HLTD tables. Two exceptions were made, however, since we consider that the new estimates available for Russia (Meslé et al. 2003) and Ukraine (Meslé and Vallin 2003) are better than those given in HMD or HLTD. A total of 750 additional life tables are available from MVDB. The reason these 750 tables are not in HLTD is simply a question of time: HLTD is still being expanded and the MVDB tables will be added in the near future.

—As a fourth source, we used any available life expectancy figure published for relevant countries for years not covered by the previous sources (including those identified in Oeppen's personal file); thus 679 female life expectancies at birth do not overlap with the three previous sources.

—Finally, the Kannisto–Thatcher Database (KTDB) provides the most accurate source of age- and sex-specific mortality rates and life expectancies at age 80 and over, computed with the extinct-generation method. The KTDB cannot be used to assess the Oeppen–Vaupel straight line directly but is very

FIGURE 1   Synopsis of data used by source: 54 country-level sources, 1750–2006

LEGEND: Solid lines represent continuous series of yearly data: thick lines for life tables (light gray for HMD, medium gray for HLTD, dark gray for MVDB) and thin (black) lines when only e_0 is available. Circles (black for HLTD, gray for MVDB) represent discontinuous life tables; x represents irregularly available e_0.

useful when focusing on trends in old-age mortality as a means to better understand life expectancy trends.

Available life tables and life expectancies at birth and their reference years are listed in the Appendix.

While the collected data include information for both sexes separately, only female data are used here since the Oeppen–Vaupel line was based on female life expectancy. This choice is justified by the fact that females today have considerably longer length of life than males in all advanced countries.

Adding further data

Not only are HMD data of high quality in most cases, they also offer continuous yearly series. The database includes female life tables for more than 30 countries of our selected universe starting with 1750 up to the mid-2000s. Figure 2 shows maximum female life expectancy observed yearly from that source from 1750 to 2005, along with the number of countries involved each year. At the beginning, only one country (Sweden) is available, and maximum female life expectancy is identical with Swedish female life expectancy. From 1850 to 1870, however, seven countries are included, and the number gradually increases to around 11–13 for about four decades (1880–1918), 15–17 for two decades (1923–46), and 26–28 for three decades (1960–90),

FIGURE 2   Yearly maximum female life expectancy at birth according to life tables available from the Human Mortality Database, 1750–2005
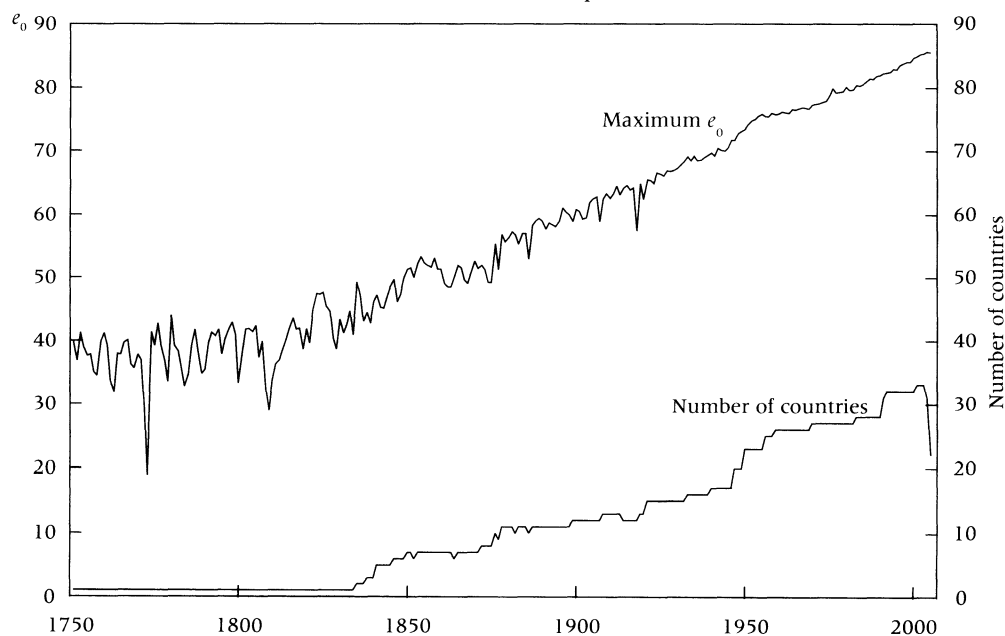
finally reaching 33 in 2003. Of course, in the most recent years the number of countries is smaller because of delays in updating.[4]

The upper line in Figure 2 shows that, at least since the late 1870s, maximum female life expectancy followed a fairly straight upward trend, although with large fluctuations observed until the 1920s. Oeppen and Vaupel did not show such fluctuations, relying more on life expectancies produced for periods of more than one year, while we systematically used yearly data. Before 1870, fluctuations are even larger and the general shape of the series is not in agreement with the straight line that could adjust the 1870–2005 series. Next we consider whether adding other data yields more refined results.

In a second step, we add HLTD and MVDB data to those of the HMD. As noted above, data from these two new files are both from published life tables for periods not covered by HMD.

The main difficulty when adding these data to HMD data is that most of them cover more than a single year, and when the reference period is an even number of years it cannot be allotted to a full central year, but must be assigned to a date shifted by half a year. It was also necessary to interpolate data to avoid producing artificial fluctuations.[5] The new series, depicted in Figure 3, shows a clear improvement when compared to the results obtained on the basis of the HMD alone. Fluctuations are smaller along the entire period, and the general shape of the series shows a better continuity. This is clearly

FIGURE 3 Yearly maximum female life expectancy at birth according to life tables in four combined databases, 1750–2005
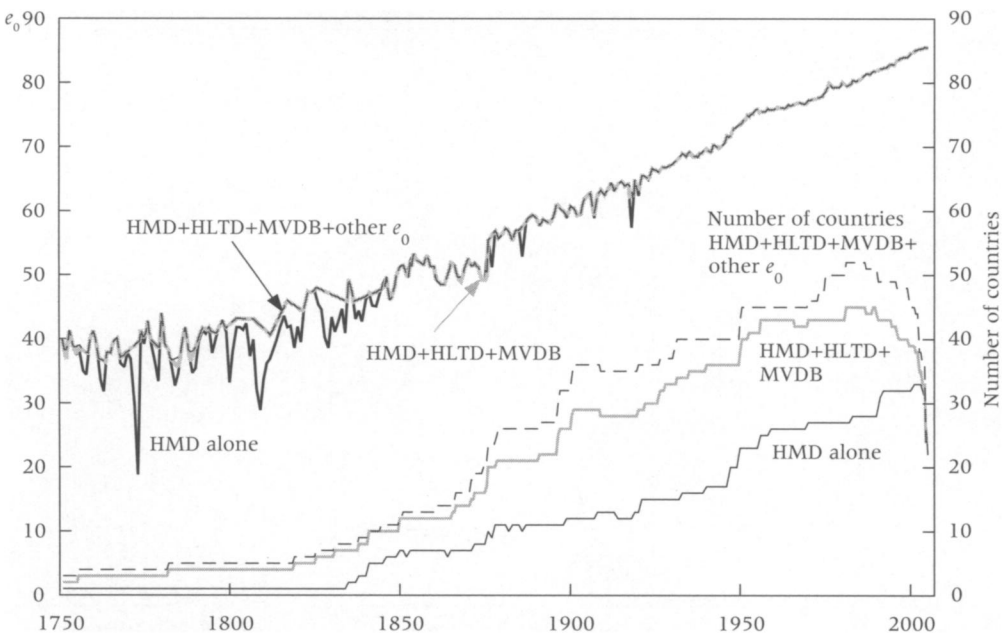
related to the larger number of countries included. Sweden is no longer alone, since France starts at the same time and Finland arrives soon after (1755), followed by Denmark (1783), and later Austria, Norway, and Canada in the early nineteenth century (1819, 1821, and 1831 respectively). Furthermore, the number of countries increases sharply in the first part of twentieth century, reaching 36 in 1941. The maximum number is reached in 1981 with 45 countries. However, the number starts to decrease sooner (1990) than when HMD alone is used, and at the very end of the series only two countries are taken into account in addition to those in the HMD.

Starting with 1846 these additional data do not change the general shape of the HMD series showing maximum female life expectancy. They only moderate or eliminate the extent of some falls in 1877, around 1888, and in 1918. For the preceding years, however, not only are the fluctuations greatly attenuated, but the general shape of the trends changes, especially from the late eighteenth century to the mid-nineteenth.

In a third step, we added country-years where only life expectancy at birth was available (Figure 3). The number of countries increases slightly, especially after 1880, but the results differ very little. The series of maximum life expectancy is changed only for a few specific years around 1752, 1757, 1785, 1788, 1868, and 1875. The new points in the eighteenth century are attributable to the earlier entry in the dataset of England and Wales. The nineteenth-century points are for Australia and then Ireland. Although this final addition of data is small, it significantly moderates a couple of fluctuations.

To better assess the reliability of these results, let us glance at the whole universe studied. The left-hand graph of Figure 4 compares maximum female life expectancy to both mean life expectancy and minimum life expectancy. At the beginning, the gap between maximum and minimum life expectancies is narrow. It becomes much wider from about 1850 to 1950, narrows in the 1950s and 1960s, and widens again from the 1970s on. The initial divergence probably took place earlier than it appears, however. For more than half a century, the number of countries involved is too small and too homogeneous to reveal the divergence that very likely started at the end of the eighteenth century, when life expectancy began to increase steadily in a few countries such as Sweden and England. The phase of divergence between highest and lowest life expectancy probably lasted until the end of the nineteenth century, when Russia among other countries started following the widespread European downturn in infectious disease mortality. Also, minimum life expectancy is subject to sharp fluctuations, because particular countries are affected at certain times by specific mortality crises, even in the twentieth century. The mortality caused by the Ukrainian famine of 1933 is an example.

As shown in the right-hand graph, the standard deviation varies considerably according to the number of countries in the dataset, but that variation is also related to the divergence and convergence observed within the group

FIGURE 4   Maximum female life expectancy as compared to average and minimum female life expectancy, and standard deviation of national life expectancies as compared to number of countries included, 1750–2005
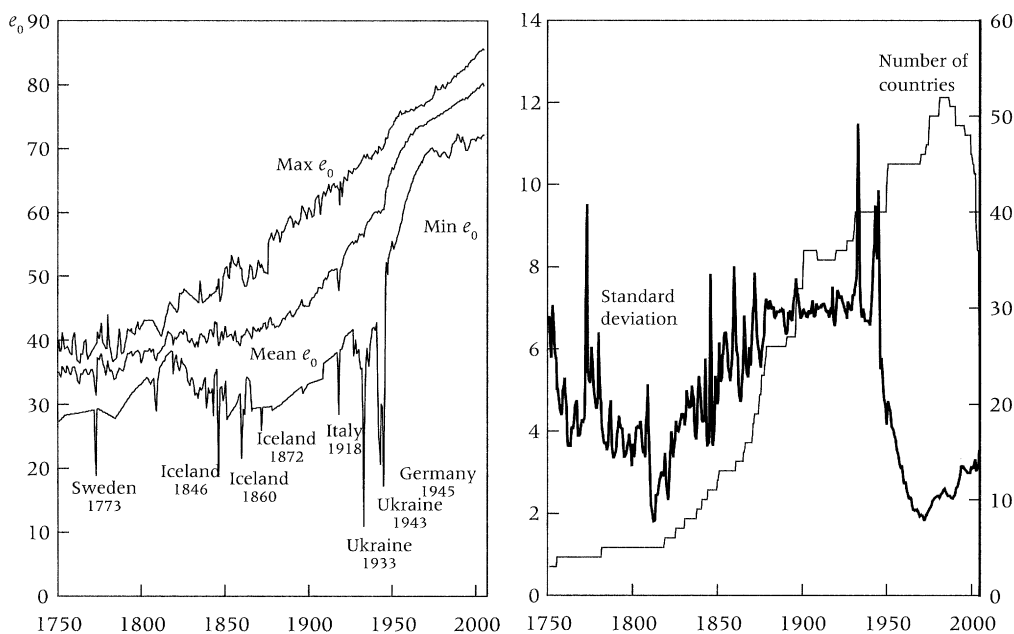

of countries involved. For example, at the beginning, the standard deviation declines because mortality in the few countries involved converges. The standard deviation then rises sharply when the number of countries increases in a phase of general divergence. After World War II, it falls sharply because of the convergence produced by the widespread fall of infectious disease mortality. And it starts rising again from the 1970s as a new process of divergence occurs with the cardiovascular revolution. For the most recent years, the rise in the standard deviation is accentuated by the decreasing number of countries involved.

Obviously, these observations indicate the need to be prudent when interpreting results, but it seems to us that maximum life expectancy is much less affected than the other indicators by the number of countries involved because high levels of life expectancy very likely are positively correlated with the early availability of data.

Countries contributing to maximum life expectancy

Countries contributing to maximum female life expectancy over time are mostly Sweden for the second part of eighteenth century, Denmark and then Norway for the first three quarters of the nineteenth century, New Zealand from 1875 to 1940, Iceland and Norway alternately from the early 1940s to

**FIGURE 5   Countries contributing to the time series of maximum
female life expectancy, 1750–2005**
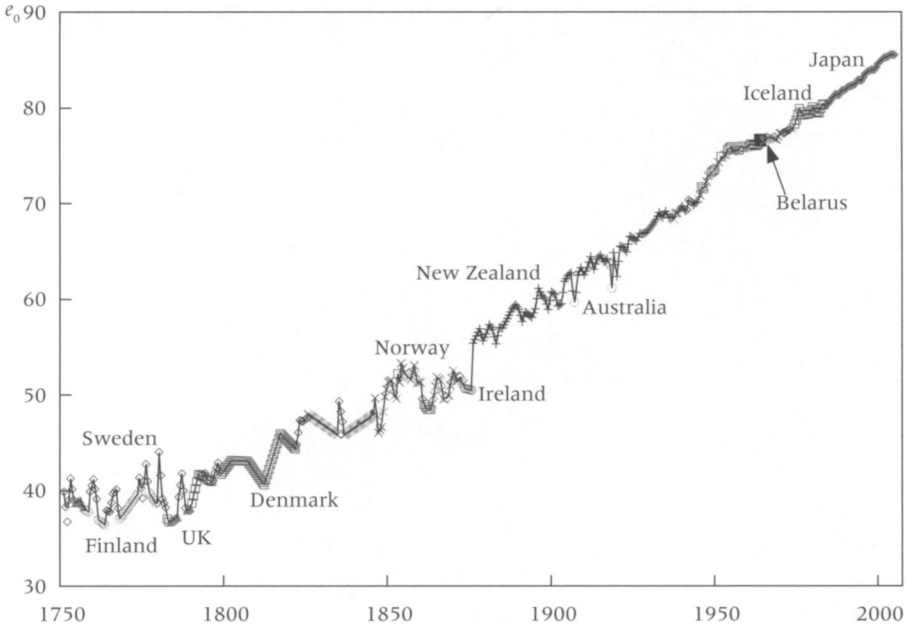
the late 1970s, and finally Japan from the 1980s to 2005 (Figure 5). A few
other countries contribute much less frequently: Finland and England and
Wales in some years in the eighteenth century, Ireland for a couple of years
around 1875, Australia in 1907 and 1918, and even Belarus, then a republic
of the USSR, in 1964. In the last case, however, this contribution entails a
very probable underestimation of mortality levels.[6] For the period covered
by Oeppen and Vaupel's analysis (1840–2000), the main contributors are es-
sentially the same, even if some minor differences appear, since our work is
systematically based on yearly estimates of life expectancy. However, a much
longer period of observation permits us to assess whether our results confirm
the Oeppen–Vaupel line or open new perspectives on the secular trend of
female life expectancy at birth.

Comparing our results with the
Oeppen–Vaupel straight line

Our results spanning the period 1750–2005 do not fit well with a monotonic
linear upward trend as proposed for 1840–2000 by Oeppen and Vaupel (Fig-
ure 6). The years before the late 1780s show no signs of an increase in maxi-
mum life expectancy: only fluctuations are observed. The Oeppen–Vaupel
principle comes up against an obvious limit were it to be extended to the more
remote past. This is not a surprise, since a backward extrapolation of the Oep-

FIGURE 6   Adjustment of the new results as compared to the Oeppen–Vaupel line, 1750–2005
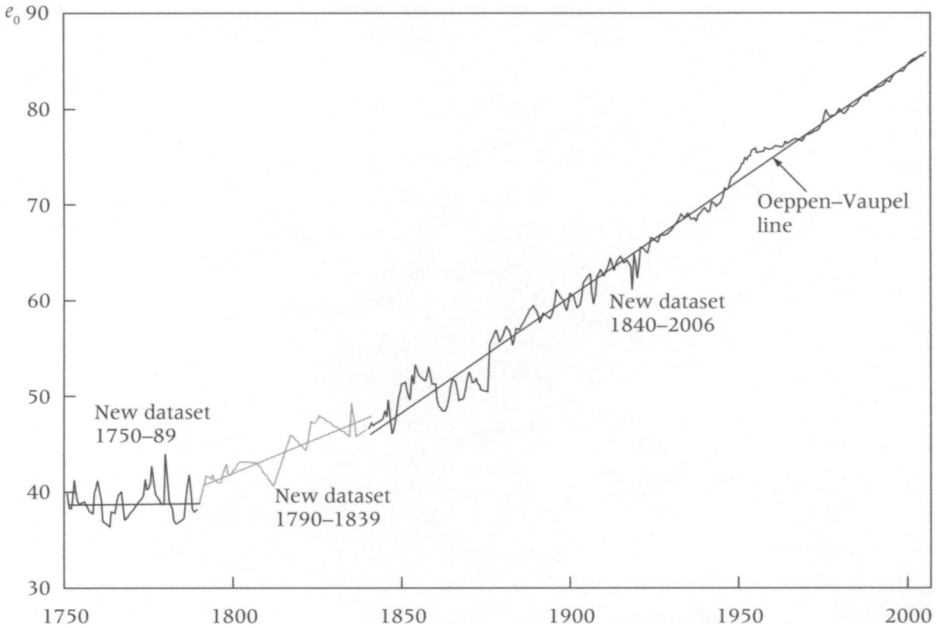
pen–Vaupel line would necessarily lead to absurdity (zero or even negative life expectancies). Still, we did not expect such a clear cutoff point coinciding with the period of the French Revolution. But it is clear that maximum life expectancy according to our new set of data coincides closely with the results of Oeppen and Vaupel for the common period 1840–2000.

From 1789 to 1840, however, maximum life expectancy was also not rising as rapidly as might have been suggested by a backward extrapolation of the Oeppen–Vaupel line. Taking into account such a result, one can obtain a good adjustment of our set of results by means of three successive straight lines. The first one summarizes the stagnation up to 1789, the second takes into account an initial period of progress in mortality decline at a moderate pace, from 1789 to 1840, and the third suggests that the 1840s mark the beginning of a new phase of accelerated improvement that has continued to the present.

Nevertheless, such a conclusion is questionable for two reasons. First, leaving the Oeppen–Vaupel adjustment aside, we should probably divide the full period starting with 1750 differently. After 1789, the second break should be placed around 1875 instead of 1840. Second, the mid-1950s are striking: while annual fluctuations have become negligible, a surprising deviation from the Oeppen–Vaupel line appears around 1955, with values higher than expected for a period of more than ten years.

It is not impossible that for some years maximum life expectancy is based on faulty data. One way to determine whether this is the case is to look at second-best life expectancy.

Does second-best life expectancy confirm the trends?

When comparing maximum life expectancy series to the series of second-best life expectancy (ignoring the maximum values in our dataset and considering the second-highest values), we obtain a different shape of the trajectory (Figure 7). Naturally the second-best values are always lower than the maximum, but for two periods the two series are consistently very close to each other. From 1750 to the mid-1790s the only marked differences appear for specific years in which maximum female life expectancy was substantially higher than the mean of national life expectancies; the differences mainly depend on annual fluctuations that vary from country to country. The second instance when the second-best values and the maximum values practically coincide is the period from World War II to the mid-1970s that includes the decade around 1955 when maximum life expectancy as we have calculated it significantly deviates from the Oeppen–Vaupel line.

Conversely, there are three periods when the second-best values are substantially lower than the maximum life expectancy:

FIGURE 7   Second-best female life expectancy as compared to maximum female life expectancy, 1750–2005
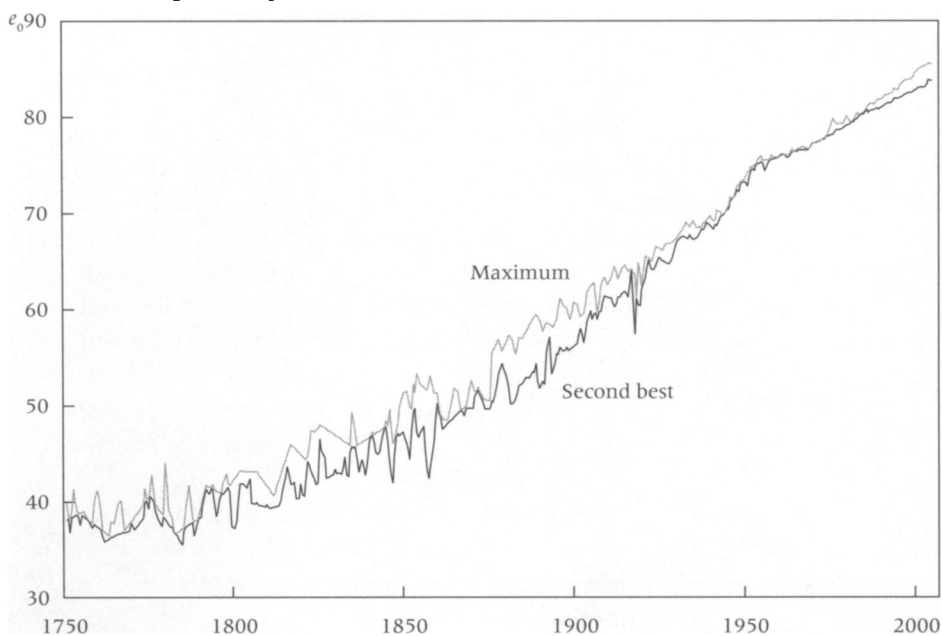
—from 1810 to 1860, when the gap between maximum and second best fluctuates strongly;

—from 1876 to 1930, when the gap between the maximum and second-best life expectancy suddenly increases (after 1930 this gap gradually diminishes until it vanishes between the two world wars);

—since 1988, when maximum life expectancy starts to diverge again from the second-best life expectancy so that the gap is quite wide by 2005.

1810–60: Questions about Denmark and Norway. As shown in Figure 7, during this period there is a curious gap between maximum life expectancy and second-best values. This gap is almost exclusively attributable to Denmark from 1810 to 1840 and to Norway from 1840 to 1860. Figure 8 focuses on these two deviations. The gap is much larger for the years 1840–60 than for 1810–40, but in both periods the series for Denmark and Norway are broken by sudden negative events that reduce life expectancy to markedly low levels. Life expectancy then resumes an upward trend but at a lower trajectory than previously.

For Denmark, it is well documented that life expectancy fell steeply in 1831 because of a severe epidemic of malaria that continued with less dramatic consequences until 1838 (Andersen 1984; Johansen 2002). But even

FIGURE 8   Trends in female life expectancy at birth in Denmark
(1782–1875) and Norway (1882–1900) compared to the second-best
female life expectancy (1780–1900)
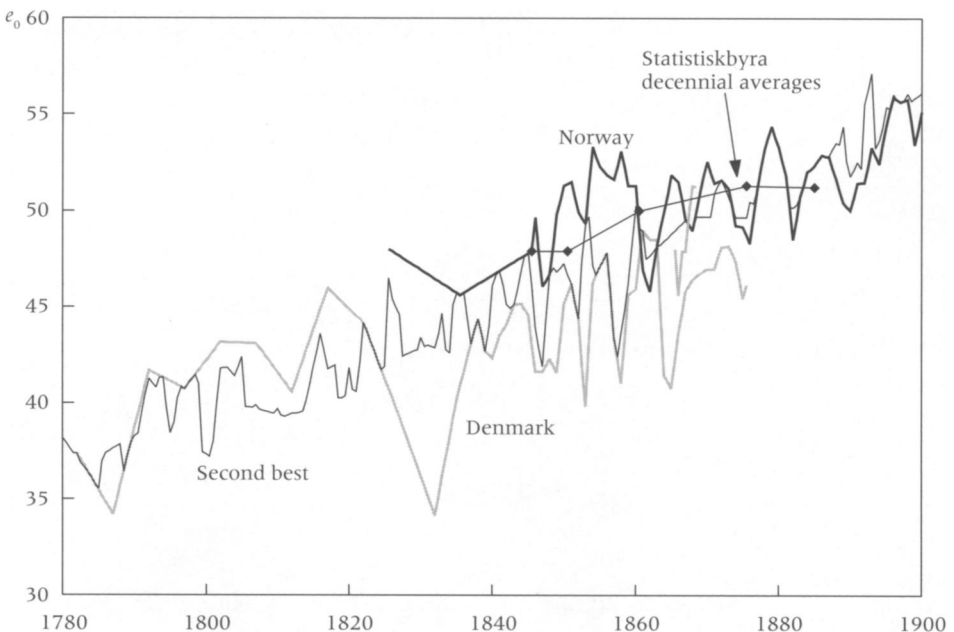
thereafter, the upward trend appears to be at a lower level than the past trends. Because we have no reason to suspect a change in data quality, we accept the Danish series as it is.

The situation is different for Norway. First, the literature does not provide an adequate explanation for the steep rise in mortality in 1862. Second, we know that important statistical changes took place in the 1860s: centralization of statistical publication occurred in 1861, and several reforms of the material transmitted by the parishes to the Ministry of the Interior occurred between then and 1866 (SSB 1969). It is plausible to assume an improvement in data collection during that period. Third, in a comparison between annual life expectancies given by HMD and the decennial averages published by Statistisk Sentralbyra (1969), a large difference appears for the decade 1846–55: 47.9 years in the Sentralbyra versus 50 years in HMD. It is quite possible that the Sentralbyra made an estimate of underregistration that was not taken into account by HMD. Consequently we prefer to eliminate Norwegian data for the years 1826–1866.

1876–1930: The singularity of New Zealand. The second notable gap between maximum life expectancy and second-best values is exclusively attributable to New Zealand. In 1876, the year when New Zealand enters our database,[7] the gap suddenly rises by more than 4 years (to 5.0 instead of 0.9 in the immediately preceding years) and even increases to 7 years in 1890 before gradually decreasing thereafter.

The explanation in this instance is straightforward. In 1840 New Zealand was populated by about 100,000 Maoris and barely 2,000 Europeans, but by 1896 the Maori population had plummeted to 42,000 while the number of Europeans had grown to 700,000.[8] The rapid growth of the non-Maori population was achieved mainly through large-scale immigration, which brought in new settlers who were strongly selected by the difficulties of acquiring the means to emigrate from Europe and surviving the long voyage. The health conditions of the initial European settlers were exceptionally favored by that selection. Then, as the population rose to several hundred thousand, conditions became more "normal" and life expectancy became more similar to other "best countries." We have eliminated New Zealand from our database because of its singular population history.

1988–2006: The case of Japan. The third gap, attributable to the remarkable recent progress in life expectancy achieved by Japan, is different from the previous ones. Some discussions in the literature raise questions about the credibility of age records at very old ages in Japan (Poulain, forthcoming), but they generally focus on marginal cases like Okinawa's longevity records, which could not affect the national data significantly (Saito, forthcoming). We see no compelling reason for excluding Japan, a country with a population of more than 100 million persons and with high-quality demographic data.

FIGURE 9   Maximum female life expectancy at birth after removal of Norway (until 1866) and New Zealand from our dataset and linear approximation of the trend in four time periods, 1750–2005
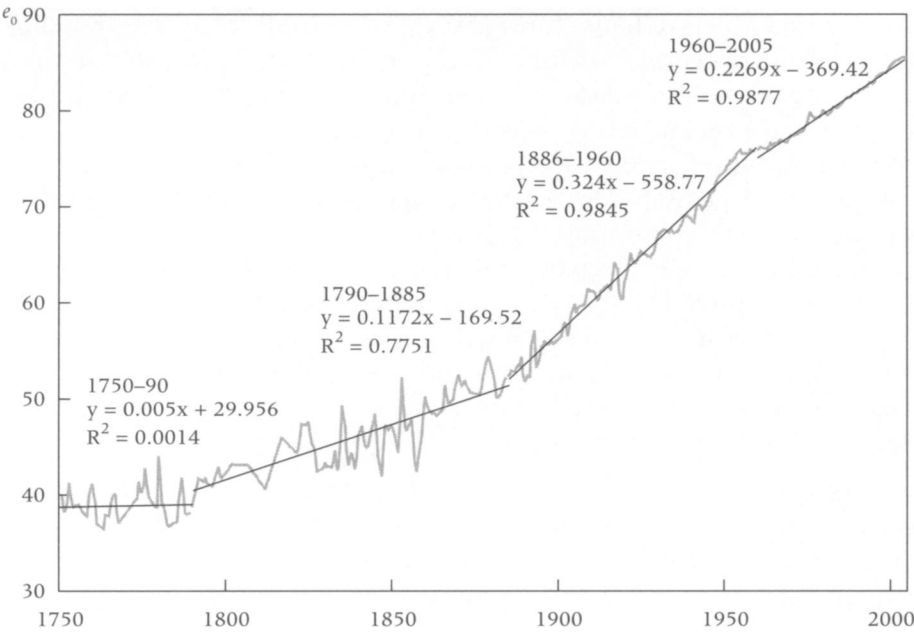
Remarkably, the effect of eliminating all data for New Zealand and some data for Norway is quite significant (Figure 9). The new series can no longer be described by a single linear fit, not even for the period after 1840 explored by Oeppen and Vaupel. Furthermore, instead of three successive linear approximations, the third of which starting in 1840 (as shown in Figure 6), four approximations are necessary, with the second break in 1885 and the fourth in 1960. Not only are these adjustments substantial (R^2 ranges between 0.78 and 0.99 for the three periods of life expectancy improvement), but the heretofore unexplained bump of the 1950s disappears. As a result, the mean pace of female life expectancy improvement is seen to have changed significantly from the start of health transition to modern times: slopes of 0.12 in 1790–1885, 0.32 in 1885–1960, and 0.23 since 1960.

The shifting weight of age-specific survival rates

The relative effect of the different age-specific mortality rates on progress in life expectancy varies substantially over time. This well-known phenomenon can be seen here by analyzing the difference between maximum and average life expectancies observed at various points of time where the number of countries

TABLE 2   Age components[a] of the difference between maximum female life expectancy and average female life expectancy for groups of countries with reliable statistics in 1850, 1900, 1950, and 2000 (number of countries shown in parentheses)

| | 1850 (11) | | 1900 (27) | | 1950 (40) | | 2000 (46) | |
Age	Years	Percent	Years	Percent	Years	Percent	Years	Percent
0–1	1.17	24.9	3.62	30.6	1.68	34.5	0.22	4.6
1–5	1.54	32.6	3.39	28.6	0.38	7.8	0.01	0.2
5–15	0.42	9.0	1.39	11.8	0.20	4.2	0.04	0.8
15–60	1.58	33.5	2.50	21.1	1.60	32.9	0.97	20.2
60+	0.00	0.0	0.93	7.9	1.00	20.6	3.57	74.2
Total difference	4.72	100.0	11.83	100.0	4.87	100.0	4.81	100.0

[a]Components of life expectancy differences have been computed with Andreev's method (Andreev 1982; Shkolnikov et al. 2001).

is sufficiently large to make such comparisons meaningful. For the sake of brevity, we limit the analysis to 1850, 1900, 1950, and 2000 (Table 2).

From 1850 to 2000, age-group weights changed radically (Figure 10 shows this in greater detail by age than is presented in Table 2). In 1850, the difference between the best e_0 and mean e_0 was 4.7 years, of which 2.7 years (57 percent of the total gap) were due solely to country differences in infant and early childhood mortality, while the whole range of mortality after age 5 contributed only 2.0 years (43 percent). In 2000, a reverse pattern is observed, with less than 5 percent of the difference explained by mortality below age 5, while more than 95 percent is explained by mortality above this age. What is

FIGURE 10   Age components of the difference between maximum female life expectancy and average female life expectancy in 1850 and 2000
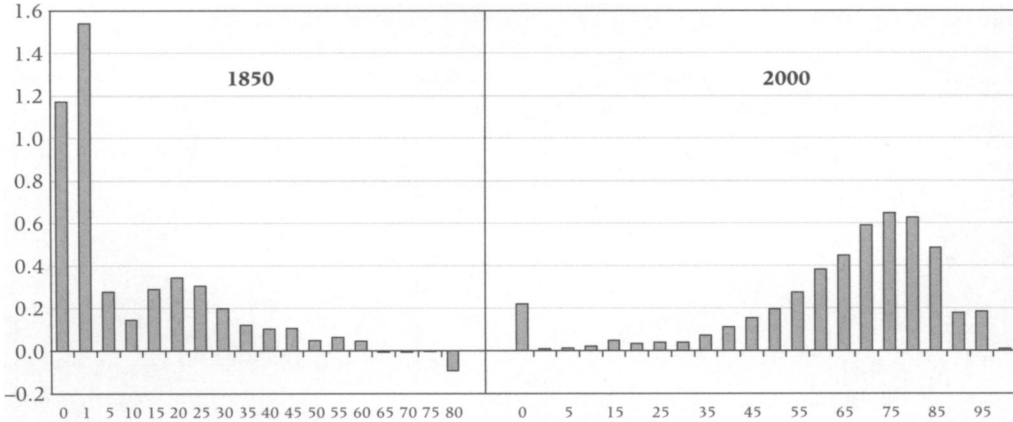
NOTE: The negative value of the difference of mortality over age 80 observed in 1850 is due to the superior quality of data of the country that show the highest life expectancy, not to a real difference in mortality at age 80 and over.

more, most of the total gap (74 percent) is attributable to mortality differences above age 60. Table 2 shows that such a change is rather new: the weight of infant mortality was still large in 1950.

## The changing pace of improvement with age

How can we demonstrate the extent to which age-specific survival rates contribute to the trends in female life expectancy at birth? As a first step, we examine survival probabilities within three age ranges (0–1, 1–15, and 15–60) as well as life expectancy at age 60 (Figure 11). Clearly, no curve among these four parameters follows a straight line over the last 150 years. Survival probabilities at 0–1 year and 1–15 years leveled off at close to 1.0 from the early 1950s, and the increase in survival rates at ages 15–60 years was suddenly broken in the late 1950s, while, on the contrary, female life expectancy at 60 years increased rapidly throughout the twentieth century. These trends are the result of the changing contribution of age-specific mortality reductions to gains in life expectancy at birth.

     Comparing survival probabilities within the youngest age groups with life expectancy at age 60 years is somewhat artificial, since indicators are not of the same nature. The survival gains of the youngest age group can be seen more clearly by using the logit transformation (Figure 12), which shows that the relative improvement lasts longer than it appears in Figure 11. Indeed, infant and 1–15 survival rates show steady gains throughout the twentieth century without interruption while, after the decade-long 1950s acceleration, the pace of gains in 15–60 survival rates is comparable to the

FIGURE 11   Trends in maximum female survival probabilities between ages 0 and 1, 1 and 15, and 15 and 60, and maximum female life expectancy at age 60, 1750–2005
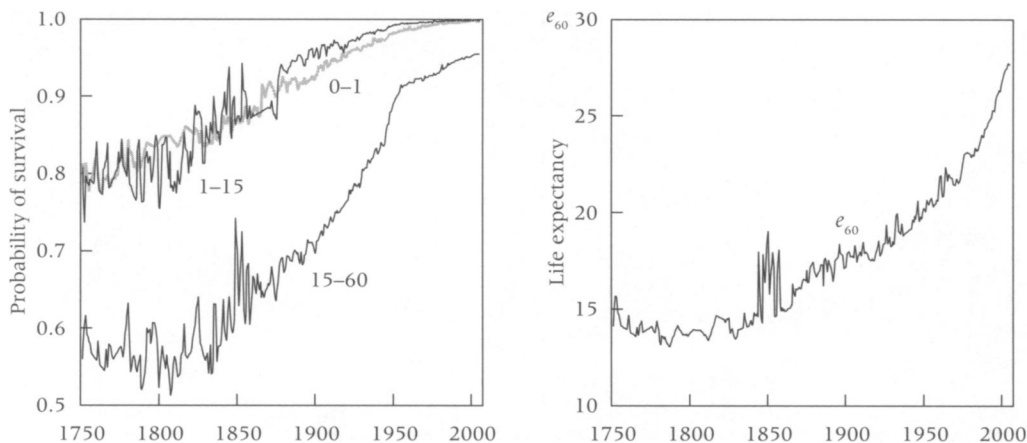
FIGURE 12   Trends in the logit of maximum female survival probabilities between ages 0 and 1, 1 and 15, and 15 and 60, 1750–2005
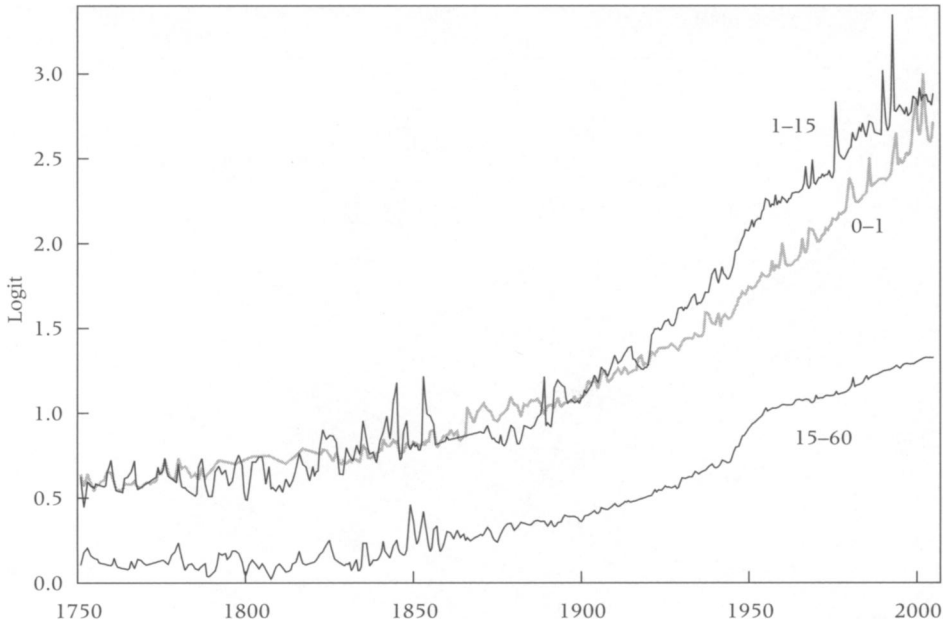

pace in the first half of the twentieth century. But such a presentation does not improve the comparability between the three closed age groups and the open 60+ age group.

The least unsatisfactory solution is probably to limit the comparison to open age groups by considering life expectancy at various ages. Figure 13 displays trends in the maximum life expectancies at ages 1, 15, 30, 40, 50, and 60 years and shows for each of them the linear adjustment within the four periods used in Figure 9 for life expectancy at birth. It is of interest that these four periods, which clearly delineate trends in life expectancy at birth and still apply quite well to life expectancy at age 1, no longer fit with life expectancy at older ages.

Even for age 1 year, as well as for ages above 1, an important difference appears: while the period breaks are still clear, the first linear adjustment (1750–90) shows a negative slope of the trend in maximum life expectancy instead of a horizontal line found at age 0. This means that the period was marked by a decline in the lowest infant mortality rates, while an increase in the lowest child, adult, and older mortality rates was offsetting these gains in mortality up to age 1 year.

For the other three periods, while linear adjustments of the maximum life expectancies at age 1 show trends very similar to those of life expectancy at birth (clear acceleration of the slope in period 3 and deceleration in period

FIGURE 13   Trends in maximum female life expectancies at various ages and linear approximations of the trends in four time periods, 1750–2005
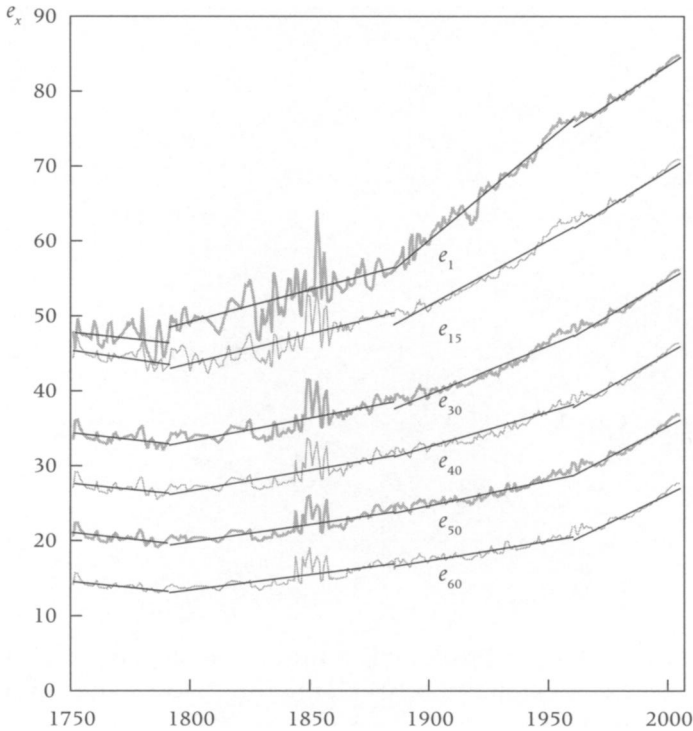
4), the trends become quite different at older ages. The slope becomes less and less steep with age for period 2 and 3, while it stays at almost the same gradient for period 4. Consequently, for life expectancy at age 15, adjustments for period 3 and 4 produce exactly the same slope and thus become perfectly aligned; then, at age 50, and even more clearly at age 60, adjustment for period 3 perfectly aligns with period 2 while a clear break is re-established with period 4.

Furthermore, if we had made specific adjustments for each age, we would certainly have chosen the periods differently. For example, for life expectancies at ages 15, 30, and 40, we would not have introduced any break in 1885 but would have done so in the early 1940s, when antibiotics brought radical progress against infectious diseases at young adult ages. It is also clear that for life expectancies at ages 50 and 60 the last linear adjustment should not have started before the early 1980s, when Japanese female life expectancy at these ages began to diverge upward from levels in the other most advanced countries (Meslé and Vallin 2006a). The case of life expec-

tancy at age 60 is particularly noteworthy. The slope of the trends observed since 1985 is obviously much steeper than the slope of the 1960–2005 linear adjustment, in contrast with the very flat slope observed for the entire previous period.

Given the growing role of older ages in the recent continuation of increases in maximum life expectancy, it is important to look at specific changes after age 60. To analyze life expectancy at older ages, however, we cannot use our full dataset, since the reliability of mortality rates for elderly populations is questionable in many countries. Fortunately, it is possible to compare our results with those from the Kannisto–Thatcher Database, which is much more accurate at oldest ages, even if it includes fewer countries for a shorter reference period.

The KTDB has been constructed with data from developed countries that produce detailed and accurate counts of deaths by single year of age after age 80 and until the age where no more deaths occur[9] (Kannisto 1994; Kannisto et al. 1994). Deaths by birth cohort are then used to estimate age-specific reference populations by single years of age according to the extinct-generation method (Vincent 1951). Age-specific mortality rates can thus be computed, by cohort and period, using reliable and appropriate denominators. Naturally, the number of countries in which statistics permit such calculations is smaller than in our full dataset (30 in 1995 instead of 49), and the period covered is shorter (starting in 1859 instead of 1750).

Figure 14 compares trends in maximum life expectancy at age 80 according to our dataset with various modifications and to the KTDB. At the level of old-age mortality, it is interesting to examine these trends again, starting with all countries involved, including New Zealand. Indeed, the first graph (upper left) of this figure shows a huge discrepancy for about 100 years (from 1873 to 1977). At that level, however, New Zealand may not be the only questionable country. More generally, the discrepancy may be attributable to very small countries for which old-age mortality rates are based on small numbers that are subject to large fluctuations due to random errors. Consequently, we eliminated Iceland, Luxembourg, and Malta in the upper right graph of Figure 14. The result, however, hardly changes. We then suspected another set of countries: those which, like Belarus, very likely underestimate mortality at oldest ages. Consequently, we dropped dubious Eastern European countries (countries of the former Soviet Union, Bulgaria, Romania, countries of the former Yugoslavia, and Albania) as well as the US black population, as shown in the lower left graph of Figure 14. This time, the results coincide almost perfectly with the KTDB since World War II and quite well from the beginning of the twentieth century. But a remarkable discordance persists from 1876 to the end of the nineteenth century, starting with a large gap in 1876, which then vanishes rapidly owing to a steady decrease in maximum life expectancy at age 80 up to the early

FIGURE 14   Trends in maximum female life expectancies at age 80 according to our complete new dataset and its various modifications and according to the Kannisto–Thatcher Database, 1750–2005
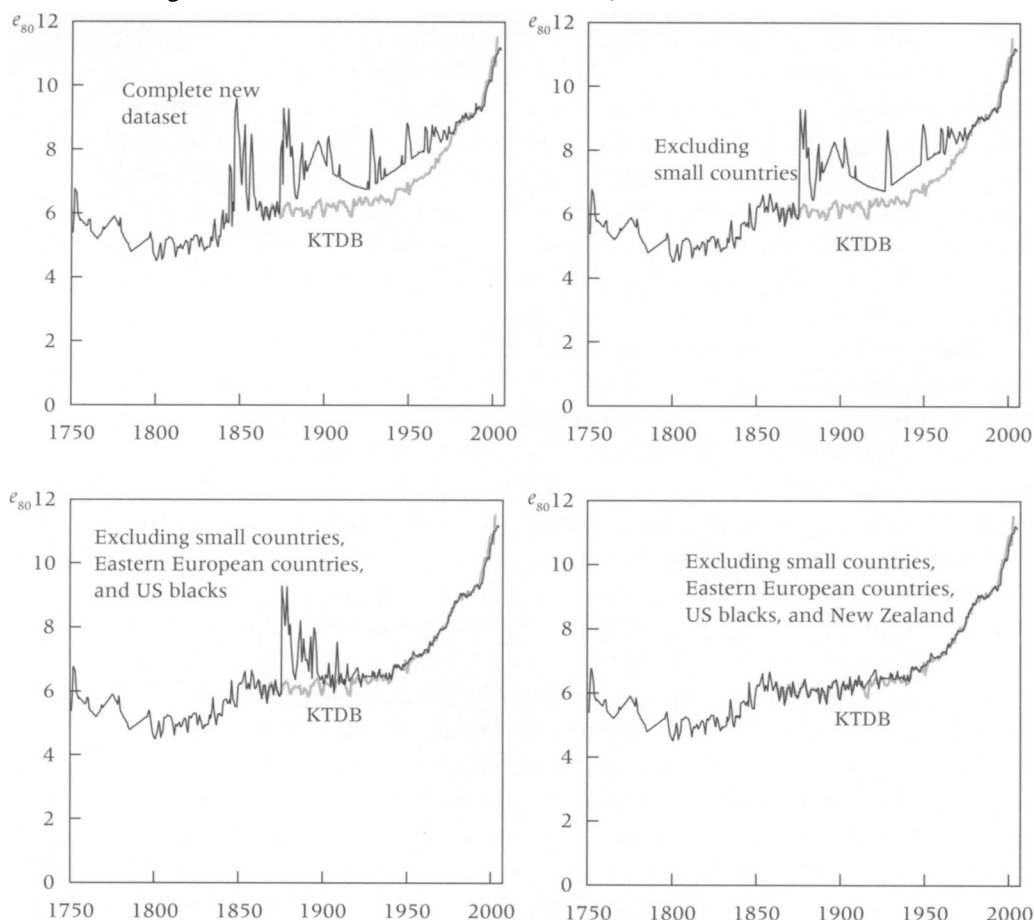
1900s. Finally, only by also dropping New Zealand in the lower right graph of Figure 14 do results from our dataset perfectly correspond to those of the KTDB when the latter become available in 1859. The consequence of dropping New Zealand is even more impressive here than when looking at life expectancy at birth. This is additional evidence of the need to exclude New Zealand from our dataset.

The accelerated rise of elderly survival

Results from our full dataset must be interpreted differently for the years before the mid-nineteenth century and the years after. The concave curve of the first 100 years of observation is probably artificial, mainly explained by the

small initial number of countries and the subsequent entry of a growing number of countries that very likely underestimated old-age mortality more than the pioneers. In contrast, especially when compared to the KTDB, the trend shown by our reduced dataset from the second half of the nineteenth century seems reliable. If this is the case, maximum female life expectancy at age 80 appears to have stagnated until the 1940s and then to have increased very rapidly, but in three different phases. First, from the early 1940s to the early 1980s the increase strongly accelerated. Then it slowed for around a decade. Finally, from the mid-1990s, the increase became faster than ever. Several observations may be made. First, it seems that, at these old ages, progress is much more recent than for younger ages. Second, this progress was probably largely initiated by the diffusion of antibiotics after World War II, in combination with significant improvements in living standards. It was also accelerated by both anti-influenza immunization and gains against cardiovascular diseases since the late 1960s until the impact of these two major effects became less pronounced at the end of the 1980s. Finally, a new acceleration occurred when individuals and public policies in some advanced countries adopted (from the mid-1990s) new approaches to increase the number of years spent in good health at advanced years (Meslé and Vallin 2006a).

Our age-specific analysis confirms results that we might have expected from the beginning. Trends in maximum life expectancy, as well as historical trends in individual country life expectancies, result from a combination of trends in mortality at various ages. Starting from a high mortality level, the increase in life expectancy relies mostly on infant and child mortality reduction, which itself depends on the major advances that have successively taken the lead in the reduction of infectious diseases: improved nutrition; better hygiene, social progress, and spread of education; and finally, vaccines, general pension and health insurance coverage, and antibiotics. The adult mortality decrease then took the lead role in rising life expectancy with successful policies to reduce mortality and morbidity associated with the use of alcohol and tobacco and accidents and the advances in new technologies and lifestyle changes to combat cardiovascular diseases. Finally, mortality at very old ages starts to decline faster when the elderly themselves benefit from the advances that have already improved adult health and from new approaches toward health problems associated with old age.

The segmented adjustment line

The benefits of these successive sources of progress affected trends in the highest life expectancy at birth differently according to the varying influence of mortality reduction at different ages. That explains why, since the mid-eighteenth century, the trajectory of the highest life expectancies can be adjusted by the four successive linear segments shown in Figure 9. From 1750 to 1790

no major mortality reduction occurred at any age, and, apart from annual fluctuations, the highest observed female life expectancy at birth stagnated at around 39 years. Then, from 1790 to 1885, maximum life expectancy rose steadily, from 39 years to 52 years, or by 12 years in 95 years at the annual pace of 0.12 years, owing to the first wave of infectious disease mortality reduction, with a major impact of infant and child mortality decline on life expectancy. From 1885 to 1960, new advances were made against infectious diseases, resulting in accelerated mortality reduction at a time when infant and child mortality decline still had a strong impact on life expectancy at birth. Maximum female life expectancy at birth jumped by 24 years (from 52 to 76) in 75 years, a pace of 0.33 years per year. By contrast, beginning in 1960 the continuous decline in infectious disease mortality no longer exerted a major impact on life expectancy, while the negative effects of modern lifestyles (such as smoking and traffic accidents) were growing (Omran 1971). These new negative factors were soon offset by the cardiovascular revolution that opened the way for a new wave of mortality reduction, while mortality associated with modern lifestyles was contained. However, this new source of progress is the result of mortality reduction at adult and old ages and produces less spectacular gains in terms of life expectancy at birth. Thus, from 1960 to 2005, female maximum life expectancy at birth rose by only 9 years (from 76 to 85) in 45 years, or 0.20 years per year. This is still a remarkable pace of progress, almost twice as rapid as the first wave of infectious disease mortality reduction, but much slower than the second wave.

This segmented adjustment of the trajectory of the world's maximum life expectancies seems to be much more realistic than Oeppen and Vaupel's straight line covering the period since 1840, as each segment corresponds closely to major changes that have raised life expectancy. After the 1750–90 period of stagnation, the second segment starts with a period of abundant agricultural and food production, improvements in transport, and the widespread introduction of Jenner's smallpox vaccine (McKeown 1976; Meslé and Vallin 2006b). The third segment was initiated with Pasteurization, the spread of education, and the implementation of social insurance systems that dramatically accelerated the early reductions in infectious disease mortality. Finally, the cardiovascular revolution of the early 1970s opened a new era of life expectancy increase after the break of the 1960s that ended the era of decline in infectious diseases.

The segmented line is also more realistic because it takes into account the differential impact of causes of mortality reduction according to the ages at which they produced their main effect. It is easy to understand that a given amount of mortality reduction gives a smaller return when applied to adult ages instead of infancy. We are led to conclude that Oeppen and Vaupel's suggestion of a possible extension of their straight line from 1840 to 2000 into the long-term future was too optimistic. The observed reduction in the pace of progress

when passing from Pasteur's revolution to the cardiovascular revolution is less promising but is closer to today's reality.

Furthermore, the cardiovascular revolution is itself becoming less and less productive in terms of gains in life expectancy at birth, as shown by less favorable trends observed in advanced countries like the United States and the Netherlands. But some other countries like Japan and France seem to be avoiding this slowdown, perhaps by entering a new era of progress resulting from a more successful fight against old-age mortality (Meslé and Vallin 2006a). This may explain the wide gap, seen in Figure 7, between Japan's best-performing life expectancy and the second-best life expectancy. Such an abnormally wide gap is perhaps the first sign of a new wave of progress.

In fact, the main key to the future does not lie in the extrapolation of the results of past waves of progress but in the nature of the ones that may lie ahead. Until now, whatever the mechanisms involved, mortality reductions have brought the mean age at death closer to the supposed maximum age at death—the curve of survival became progressively more "rectangular." After the cardiovascular revolution, there is clearly room to push life expectancy higher, but, unless some new breakthrough occurs to increase the human *life span*, progress will very likely decelerate as mortality reduction affects individuals at older and older ages. Indeed, to go faster, it would be necessary to significantly raise the maximum age at death to a level that is not easily imaginable today.

Appendix: Life tables and expectation of life at birth used in this article, by country, year, and database

Country	Life tables			Life expectancy at birth (various sources)
	HMD	HLTD	MVDB	
Europe				
Albania			1950–51, 1955–56, 1960–61, 1963–64, 1965–66	1951, 1961, 1969–70, 1976–77, 1980–81, 1982–83, 1983–84, 1984–85, 1985–86, 1986–87, 1987–88, 1988–89, 1989, 1990, 1996, 1999
Austria	1947–2005	1865–75, 1868–71, 1870–80, 1879–82, 1889–92, 1899–1902, 1901–05, 1906–10, 1909–12, 1930–33	1819 to 1940 yearly	1895–1900
Belarus	1959–2005		1896–97, 1926–27	
Belgium	1841–2005			
Bosnia-Herzegovina				1975; 1977 to 1980 yearly; 1983 to 1988 yearly; 1990
Bulgaria	1847–2005	1900–05	1899–1902, 1909–12, 1920–21, 1926–27, 1933–36	1921–25, 1925–28, 1927–34, 1935–39, 1946–47
Croatia			1988–90, 1989–90	1975; 1977 to 1980 yearly; 1983 to 1988 yearly; 1990
Czech Republic	1950–2005	1920 to 1949 yearly		1869–80, 1900–01, 1910–11
Denmark	1835–2006		1780–84, 1785–89, ..., 1830–34 (5 y)	
England and Wales	1841–2003	1838–54		1751, 1756, ...1841 (10 y)
Estonia	1992–2005	1897, 1922–23, 1932–34	1955 to 1991 yearly	
Finland	1878–2006		1751–60, 1761–70, ... 1871–80 (10 y)	1871–75
France	1899–2005		1740–49, 1750–59, ... 1800–09 (10 y); 1806 to 1898 yearly	
Germany, all	1991–2004	1871–81, 1881–90, 1891–1900, 1901–10, 1910–11, 1924–26, 1932–34		1900 to 1990 yearly

Country				
Germany, East	1956–2004	1952–53, 1953–54, 1954–55, 1955–56		1950
Germany, West	1956–2004	1949–51	1946–47	
Greece	1950–2005	1926–30, 1940, 1955–59, 1960–62, 1980	1950, 1960, 1970, 1990, 1996	1879, 1901–05, 1911–15, 1920, 1936–40, 1950, 1957; 1960 to 2004 yearly
Hungary	1950–2005		1900–01, 1901–10, 1910–11, 1920–21, 1930–31, 1941, 1948–49, 1949	1900–01, 1910–11, 1920–21, 1930–31, 1941
Iceland	1838–2006			
Ireland		1925–27, 1935–37, 1940–42, 1945–47, 1950–52, 1960–62, 1965–67, 1970–72, 1978–80, 1980–82, 1985–87, 1990–92, 1995–97, 2001–03		1870–72, 1881–83, 1890–92, 1900–02, 1910–12, 1955–57, 1960–62, 1965–67, 1968; 1970 to 2001 yearly
Italy	1871–2004			
Latvia	1991–2005		1934–36, 1956 to 1990 yearly	1929–32
Lithuania	1991–2005		1956 to 1990 yearly	1897, 1925
Luxembourg				1901 to 2004 yearly
Macedonia				1975; 1977 to 2002 yearly
Malta			1870–90, 1890–92, 1910–12, 1920–22, 1930–32, 1946, 1948, 1962–64, 1963–65, 1967, 1970–72; 1973 to 1980 yearly; 1982 to 1989 yearly; 1994	1956 to 1958 yearly; 1961 to 1964 yearly; 1967, 1971; 1973 to 2002 yearly
Moldova	1850–2004			1973, 1975; 1976 to 1986 yearly; 1988 to 2002 yearly
Netherlands	1850–2004			1840–49
Northern Ireland		1980–82, 1981–83, ... 2001–03 (each year)	1950–52, 1954–56, 1956–58, 1957–59, ... 1994–96 (each year)	
Norway	1846–2006		1821–30, 1831–40, 1841–50, 1881–90	

Appendix (continued)

Country	Life tables			Life expectancy at birth (various sources)
	HMD	HLTD	MVDB	
Poland		1922, 1927, 1931–32, 1948, 1952–53, 1960–61, 1965–66, 1970–71, 1975–76, 1980–81, 1985–86, 1990–91, 1995, 1995–96, 1996; 1997 to 2005 yearly	1955–56, 1958–59, 1963–65, 1970–72; 1983 to 1985 yearly; 1987	1850–52, 1856–58, 1862–64, 1868–71, 1872–75; 1950 to 2005 yearly
Portugal	1940–2005			1878, 1920, 1930
Romania			1956, 1961, 1963, 1964, 1964–67, 1968, 1970–72, 1989–91	1920, 1930, 1950, 1956; 1960 to 1978 yearly; 1980 to 2004 yearly
Russia	2006		1896–97, 1926–27; 1927 to 1940 yearly; 1946 to 2005 yearly	
Russia, 50 governorates			1874–83, 1896–97, 1907–10	
Scotland		1930–32, 1950–52, 1960–62, 1970–72; 1980–82, 1981–83, …. 2001–03 (each year)	1861–70, 1871–80, 1881–90, 1891–1900, 1910–12, 1920–22, 1930–32, 1948–50, 1949–51, 1952–54, 1953–55, 1954–56, 1956–58, 1959–61, 1961–63, 1967–69, 1968–70, 1969–71, 1971–73; 1972 to 1974 yearly; 1974–75, 1974–76, 1975, 1975–77, 1976, 1976–78, 1977, 1977–79, 1978, 1978–80, 1979, 1979–81, 1980	
Serbia-Montenegro			1950–51, 1964–65, 1964–66, 1965–66, 1979–80, 1979–81, 1980–81, 1994–95, 1994–96, 1995–96	
Slovakia	1950–2006			
Slovenia	1983–2006	1930–33, 1948–52, 1952–54, 1960–62, 1970–72, 1980–82; 1982 to 2004 yearly		1959 to 1982 yearly
Spain	1908–2006	1900	1863–70	1878–87, 1888–1900
Sweden	1751–2006			

Switzerland	1876–2006			
Ukraine	2001–06		1896–97, 1925–26, 1926–27; 1927 to 2000 yearly	1875
United Kingdom		1980–82, 1981–83, ... 2000–02 (each year)		
USSR		1926–27, 1938–39, 1958–59, 1969–70, 1978–79, 1983–84, 1985–86, 1986–87		
Yugoslavia				1931, 1948, 1952–54, 1958–59, 1960–61, ... 1968–69 (each year); 1970–71, 1971–72, ... 1987–88 (each year); 1988 to 1990 yearly; 1995 to 1997, 2000 yearly
North America				
Canada	1921–2004		1831, 1841, ... 1911 (10 y)	
US, vital statistics	1933–2004		1850, 1860, 1870, 1880, 1890, 1900	
US, Social Security[a]		1901 to 1999 yearly		
US, black		1901		
US, white		1901	1850, 1860, ... 1900 (10 y)	
Oceania				
Australia	1921–2004		1870–81, 1881–90, 1891–1900, 1901–10	1856–66, 1860–75; 1901 to 1920 yearly
New Zealand (non-Maori)	1876–2003			
Asia				
Japan	1947–2006		1891 to 1946 yearly	

NOTE: (5 y) or (10 y) indicates that each available life table covers a period of 5 or 10 years; "each year" indicates that life tables are available for successive overlapping triennial periods.
[a]US population covered by Social Security.

Notes

Figures in this article are available in color in the electronic edition of the journal.

1 James Oeppen, who collected the data, told us that he built his set of life expectancies at birth from data available from the Human Mortality Database at the time—supplemented by additional series of e_0 obtained from different sources—in a personal file that he has been updating since the *Science* article was published. He kindly provided us with the current version of that file. Obviously if we re-use the same data sources as Oeppen and Vaupel did for their article (HMD+Oeppen's personal file), we get a larger universe than the original one, since both sources have grown.

2 Jointly constructed and regularly updated by the Department of Demography at the University of California, Berkeley and the Max Planck Institute for Demographic Research (MPIDR) in Rostock, Germany, the HMD is accessible at «http://www.mortality.org» (Shkolnikov et al. 2005).

3 Jointly developed by the MPIDR, the Berkeley Department of Demography, and the Institut national d'études démographiques (INED, Paris), it is available at «http://www.lifetable.de».

4 For some specific years, the number of countries falls by one (e.g., in 1852, 1864, 1877, 1886). This is because HMD data were erroneous and the affected country had to be dropped from the dataset until appropriate corrections were made in HMD. Also, the number of countries falls during World War II, because HMD does not include incomplete data.

5 Whereas for single-year life tables (e.g., 1951) we allocated the result by convention to the point corresponding to the year (i.e., 1951), for multi-year life tables we attributed the result to the central year for an odd period (i.e., 1951 for the period 1950–52) and to the midpoint between the two central years for even periods (i.e., 1951.5 for 1950–53). Including one point for each year and mid-year position resulted in unexpectedly numerous and sharp fluctuations due to the fact that pluri-annual life tables are more often the only source in higher-mortality countries than in lower-mortality countries. Consequently, in most cases, the highest mid-year life expectancy is far less than the maximum life expectancy of the two surrounding exact years. To solve this problem, data were interpolated to derive exact-year and mid-year points for every country.

6 It has been shown that for other European countries that were part of the former USSR, especially Russia (Meslé et al. 2003) and Ukraine (Meslé and Vallin 2003), mortality (especially infant mortality) was still significantly underestimated in the 1960s.

7 Only life tables for the non-Maori population have been included in our dataset.

8 «http://www.stats.govt.nz/tables/ltds/ltds-population.htm», consulted in February 2009.

9 The KTDB includes 35 countries, from which we here excluded Chile (not in our database), Luxembourg (too small), and Lithuania, Poland, and Slovenia (which starts after 1970).

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