CHAPTER 10

On the Track of the World's Economic Center of Gravity

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Abstract

This chapter proposes a refined and updated measurement of the World's Economic Center of Gravity over the 1950–2008 period, based on historical data provided by Maddison (2010) and on the detailed grid data of the G-Econ (Nordhaus, 2006) database. The economic center of gravity is located in the vicinity of Iceland during the first three decades, and then heads strongly toward the East since 1980. Regarding geographic concentration, world production is less concentrated than population across the Earth's surface, and becomes even less so over time. A new decomposition technique is proposed, which suggests a structural break at the end of the 1970s. Measures of R&D activity, education expenditures and literacy as growth related indicators depict a spatial pattern that is consistent with the Eastern shift of the world economic center of gravity.

Keywords: Spatial distribution, economic growth

JEL classifications: R12, 040

1. Introduction

Many would agree with the assertion of French (2005) that the recent growth performance of China and India has been pulling "the globe's economic center of gravity decidedly towards Asia." But by how much? How fast? And since when? A first objective of this chapter is to answer those questions relying on the concept of the world's economic center of gravity (WECG) introduced by Grether and Mathys (2010) and further

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applied by Quah (2011). While the previous attempts were limited to the past 30 years, here the observation period is expanded back to 1950 (and forward to 2008), which provides evidence that the strong Asian shift initiated at the end of the 1970s. A second objective is to increase the precision of estimates: while previous attempts were based on less than 1,000 location points, calculations are based here on the spatial grid established by Nordhaus et al. (2006), which provides information on the distribution of economic activity across the globe for more than 27'000 different grid cells. A third objective of this chapter is to better document this trend by analyzing a characteristic of the WECG that has been neglected so far, namely the length of the vector of the corresponding center of gravity, which is a measure of how economic production is concentrated upon the Earth's surface. As it turns out, this length has been decreasing across the sample period, which means that production has become geographically more evenly spread.[1] This is confirmed by a new decomposition technique that identifies the sources of change along the three dimensional space. Finally, a fourth objective is to apply the same methodology to other growth-related indicators such as R&D expenditures, education expenditures, and the number of literate people. The same trends are identified in terms of mean direction and concentration, although innovation and education efforts appear to be geographically more concentrated at the beginning of the sample period than economic activity.

Section 2 defines the theoretical concepts of mean direction and mean concentration on a sphere, Section 3 presents results and discusses the evolution of the different centers of gravity, and Section 4 concludes.

2. *Measuring the world's economic center of gravity*

This section provides a brief recap of how the WECG is calculated, then proposes and discusses a new decomposition of the concentration index represented by the length of the WECG vector. For a detailed description of the concepts, see Appendix B.

2.1. Mean direction and mean concentration on a sphere

As exposed by Grether and Mathys (2010), socioeconomic centers of gravity, or centers of mass, can be defined by assuming that the Earth is a perfect sphere and that "mass" is represented by a socioeconomic variable, V, which is GDP in the case of the world *economic* center of gravity (WECG, $V = E$), human population in the case of the world *demographic* center of gravity (WDCG, $V = D$), and land in the case of the world

[1] In this chapter the units of observation are always grid cells on the Earth surface, not people. Therefore the reported evidence is not appropriate to discuss per capita income inequalities.

geographic center of gravity (WGCG, $V = G$). We assume that the Earth's surface is covered by a regular lattice defining n location points $i = 1,\ldots,n$ and that all Cartesian coordinates are expressed as a fraction of the Earth's radius (so that all reported distances should be multiplied by 6371 to get the corresponding value in kilometer). The weight of each location point is given by the share of that location in the world total of the corresponding socioeconomic variable, so that the position vector of the world center of gravity is given by:

$$\overrightarrow{OG^V} = \left(\sum_{i=1}^{n} \theta_i^V x_i, \sum_{i=1}^{n} \theta_i^V y_i, \sum_{i=1}^{n} \theta_i^V z_i\right)^{\mathrm{T}} \tag{1}$$

where θ_i^V represents the share of location i in total land in the case of the WGCG, in total population in the case of the WDCG, and in total production in the case of the WECG.

The center of gravity encapsulates the two major descriptive dimensions commonly used in spherical statistics (see, e.g., Mardia & Jupp, 2000). On the one hand, it indicates a direction in space, which is usually extended to its projection onto the Earth's surface[2] and referred to as the *mean direction*. The mean direction vector is simply the normalized gravity vector, that is:

$$\overrightarrow{OG_0^V} = \frac{\overrightarrow{OG^V}}{||\overrightarrow{OG^V}||} \tag{2}$$

This will be the direction indicator reported and discussed below.[3]

On the other hand, the length of the vector of the center of gravity, usually referred to as the *mean resultant length*, is an indicator of the concentration of the weighting variable upon the Earth's surface (at the limit, if all the weight is concentrated on a single point, the length is 1). We will denote this length by c_V, so that its square is given by:

$$c_V^2 = ||\overrightarrow{OG^V}||^2 = \left(\sum_{i=1}^{n} \theta_i^V x_i\right)^2 + \left(\sum_{i=1}^{n} \theta_i^V y_i\right)^2 + \left(\sum_{i=1}^{n} \theta_i^V z_i\right)^2 \tag{3}$$

This will be our concentration measure.[4]

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[2] Note that the convention followed by Quah (2011) is different as he orthogonally projects the center of gravity onto the cylinder wrapping up the Earth around the equator. We discarded that alternative projection technique in our context, because it mixes the influence of the two dimensions of the center of gravity vector that we want to disentangle (i.e., direction and length).

[3] If the Cartesian coordinates of the mean direction vector are denoted by (x_0, y_0, z_0) then the corresponding polar coordinates are given by: $(\pi/2)-\cos^{-1}(z_0)$ for the latitude, and $\tan^{-1}(y_0/x_0)$ for the longitude.

[4] As concentration and dispersion are mirror images of the same reality, some authors propose $2(1-c_V)$ or $1 - c_V^2$ as a measure of spherical variance (e.g., Mardia & Jupp, 2000, p. 164).

2.2. From land to population and from population to production

If production activity is clustered in particular spots on the Earth's surface, it is in good part because human population is also concentrated in particular areas. And if human population is concentrated in specific places, it is also partly because a substantial share of the Earth's surface is inhospitable to human settlements. To clarify this chain of links between the three indicators of economic (c_E), demographic (c_D), and geographic (c_G) concentration, let us first note that, as all location points are regularly spread across the Earth's surface, the sum of the Cartesian coordinates is zero (e.g., $\sum_{i=1}^{n} x_i = 0$). This implies that each one of the squared elements that appears in equation (3) can be written as a simple covariance [e.g., $\sum_{i=1}^{n} \theta_i^V x_i = n\mathrm{cov}(\theta_i^V, x_i)$], so that the concentration index can be rewritten:

$$c_V^2 = n^2\Big\{\big[\mathrm{cov}(\theta_i^V, x_i)\big]^2 + \big[\mathrm{cov}(\theta_i^V, y_i)\big]^2 + \big[\mathrm{cov}(\theta_i^V, z_i)\big]^2\Big\} \quad (4)$$

Second, define μ_X^G, μ_Y^G, μ_Z^G as the share of each directional element in the geographic concentration index (e.g., $\mu_X^G \equiv [n\mathrm{cov}(\theta_i^G, x_i)]^2 / c_G^2$ and similarly for μ_Y^G and μ_Z^G), g_D as the *densification rate* of c_D^2 with respect to c_G^2, that is, $c_D^2 = c_G^2(1 + g_D)$, and $g_{D,X}$ as the directional densification rate of the x-dimensional element of the concentration index when switching from the geographic to the demographic case, that is, $g_{D,X} = [\mathrm{cov}(\theta_i^D, x_i)/\mathrm{cov}(\theta_i^G, x_i)]^2 - 1$ and similarly for $g_{D,Y}$ and $g_{D,Z}$. If we adopt similar notational conventions to define the densification rate when switching from demographic to economic concentration [i.e., $c_E^2 = c_D^2(1 + g_E)$], then simple algebra combining equations (3) and (4) shows that:

$$g_D = g_{D,X}\mu_X^G + g_{D,Y}\mu_Y^G + g_{D,Z}\mu_Z^G \quad (5a)$$

$$g_E = g_{E,X}\mu_X^D + g_{E,Y}\mu_Y^D + g_{E,Z}\mu_Z^D \quad (5b)$$

Equations (5a) and (5b) state that the densification rate of the concentration index is a weighted average of the three directional densification rates. Each directional densification rate reflects the effect of increased concentration along a particular dimension. For example, a positive $g_{D,X}$ means that population tends to be more polarized along the x dimension than land is, so that it reinforces the concentration pattern along that dimension. Similarly, directional densification rates in (5b) reflect the impact of production distribution across persons, that is, if $g_{E,X}$ is positive, it means that along the x-axis, production tends to concentrate where people are already concentrated.

Let us illustrate these relationships on the basis of a very stylized example in which a single direction is relevant. Assume that land, people, and production are homogenously allocated across the surface of four concentric slices of a given hemisphere obtained by cutting the Earth along planes parallel to the equator, as if we were preparing a sauce and slicing half an onion in four slices of equal thickness. As all dots are uniformly spread around the common axis, only the vertical dimension is relevant (i.e., in terms of equations (5a) and (5b), we have $\mu_Z^G = 1$ and $\mu_X^G = \mu_Y^G = 0$). Another convenient property of that example is that the surface of a slice is proportional to its thickness, so that each slice has the same weight of 1/4, which makes concentration indices straightforward to calculate (see Section 4.1 in Appendix B for more details). Let us assume first a pattern of increasing concentration in the sense that, starting from the equator, there is nothing on the first slice, only land in the second one, land and people on the third one and land, people and production on the fourth one reaching the pole. As each variable is homogenously spread across the surface of each slide, we obtain easily[5] that $c_G = 0.625$, $c_D = 0.75$, and $c_E = 0.875$, from which we get $g_D = 44\%$ and $g_E \cong 7\%$. As an alternative pattern, consider that land and population distributions are kept unchanged with respect to the first case but that production locates in the third slice, that is, spreading away from the core. The new values are $c'_E = 0.625$ and $g'_E \cong -31\%$, that is, illustrating first a magnification effect from geographic to demographic concentration and then a dilution effect from demographic to economic concentration. Of course what makes things more interesting in the real world is that we have three dimensions and nonhomogenous distributions, which is what we want to analyze now, but keeping in mind this simple example, which will turn out to be quite close to what happened in reality.

3. *Tracking the centers of gravity*

To estimate the centers of gravity defined in the previous section, detailed data on production, population, and land area are needed over a long time horizon and on a geographically detailed grid basis. These data are not readily available. Hence we propose to combine two international databases to construct the information needed (for another approach based on city data see Grether & Mathys, 2010). The first dataset, the G-Econ database (for a description see Chen, 2008 and Nordhaus et al., 2006, for an application to macroeconomics see Nordhaus, 2006) reports the gross cell product and population for the years 1990, 1995, 2000, and 2005 at a 1° longitude by 1° latitude resolution at a global scale (roughly 27,000 cells). To extend the time-dimension of our computations, we combine this geographically detailed data with the dataset prepared by Maddison (2010) reporting GDP and population data for 159 countries

[5] The average location along the vertical axis is 0.125 for the first slice (average between 0 and 0.25) and 0.375, 0.625, and 0.875 for the three following ones. The positions of the centers of gravity are obtained by taking the average of the last three numbers for c_G, of the last two for c_D, and by considering only the last number for c_E.

from 1950 to 2008. National population and GDP figures are allocated across grid cells according to their shares in 1990. The selected sample of 159 countries represents 99.8% of world population, 99.6% of world GDP, and 89.7% of emerged land in 1990, the smaller representativeness for land being due to the voluntary exclusion of Antarctica, a continent with neither production nor human population.

3.1. Moving eastward: mean direction trends 1950–2008

Figure 1 shows the projection on the Earth surface of all three centers of gravity and over time for the population and economic center (the geographic one remains fixed by definition). Almost all identified centers (except in the 1950s for the economic center) lie on the same quarter of the northern hemisphere, where coordinates for all three dimensions (x, y, z) are positive. The geographic center, a fixed point located in the Black sea, has no interest by itself but is rather used as a point of comparison, showing the hypothetical economic or demographic center if all people and all economic activity were allocated homogeneously on all land slots. The demographic center of gravity is located roughly at the same latitude as the geographic center but almost 5,000 km more to the East. If economic activity would have been distributed on a per capita basis (i.e., equal per capita incomes, denoted as the "flat-world" in Quah, 2011), the economic center would coincide with the

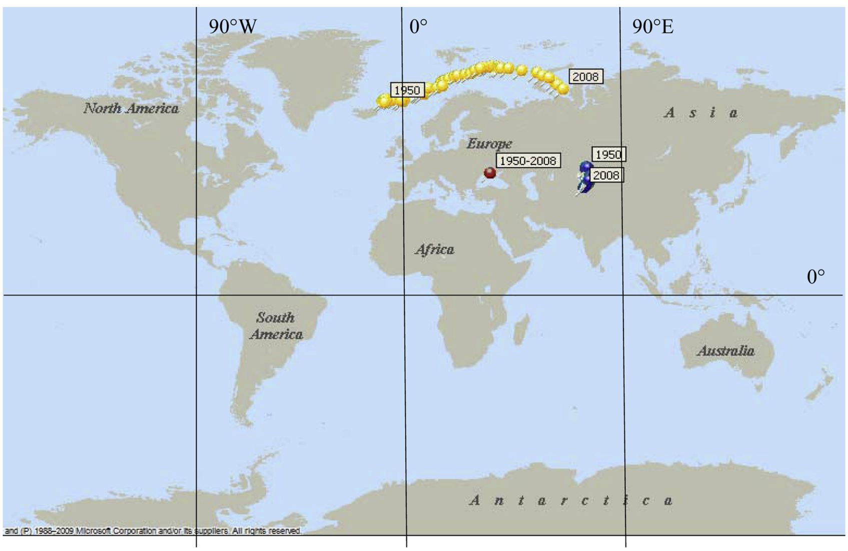

***Fig. 1. Mean direction of geographic (isolated balloon), demographic (dark) and economic (pale) center of gravity, 1950–2008*. Copyright © and (p) 1988–2009 Microsoft Corporation and/or its suppliers. All rights reserved.**

demographic center. Given the observed income distribution over the period 1950–2008, the WECG has been located more to the North and more to the West than the demographic center, although its eastward shift is remarkable.

Figure 2 depicts more clearly the trajectory of the demographic center, lying in Kazakhstan in 1950, moving clearly to the South over the whole period, and since the 1970s also west-wards, mainly due to the increased share in population of South America, Sub-Saharan Africa and South Asia (see Table A1 for average regional shares for land, population, and production). In 2008 the demographic center has crossed Kyrgyzstan and Tajikistan and is heading toward Afghanistan.

This shift to the South at the global level is also supported by a simple analysis of the share of the main regions/countries in the demographic center as drawn in Figure 3. It can be seen that while India and the Rest of the World are increasing their shares, the share of the EU is significantly decreasing. China has had an increase in its share up to 1980 but saw its share decrease thereafter.

Figure 4 gives the details on the trajectory of the WECG. In the 1950s the center sets off from the coast of Iceland and is up to 1980 moving slowly and afterwards quickly toward Russia where it reaches the mainland in 2008. This shift to the East is faster than what had been predicted in Grether and Mathys (2010). Note also that the trend toward

Fig. 2. Mean direction of the demographic center of gravity, 1950–2008.
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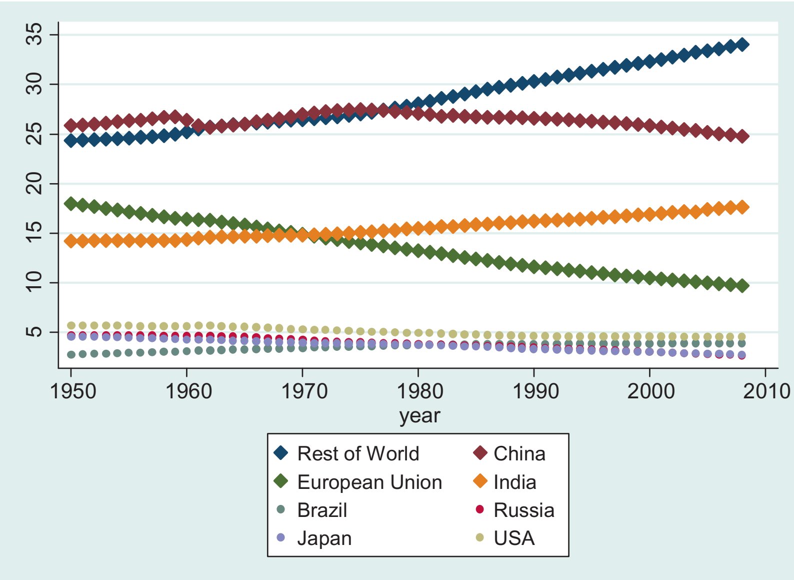

Fig. 3. Average share in demographic center of gravity by large regions and countries.

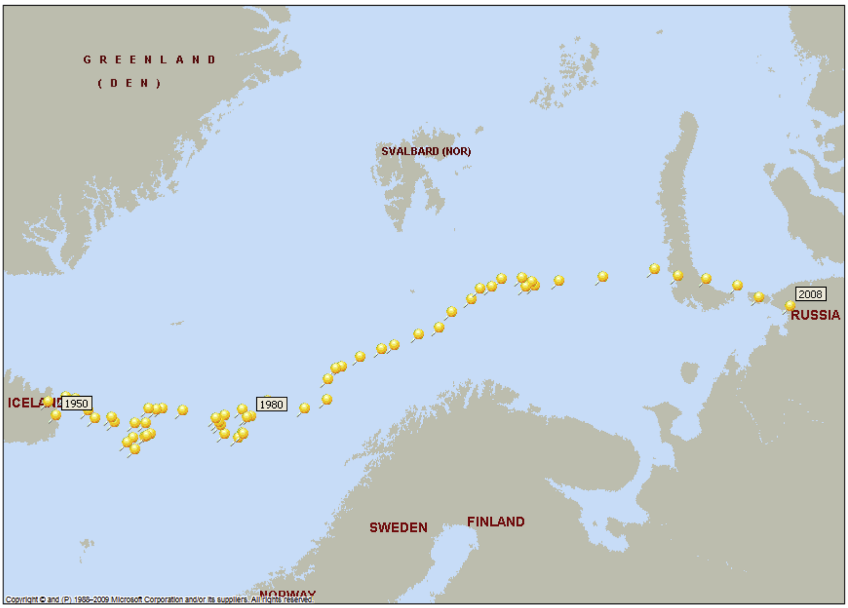

Fig. 4. Mean direction of the economic center of gravity, 1950–2008. **Copyright © and (p) 1988–2009 Microsoft Corporation and/or its suppliers. All rights reserved.**

the North that can be observed from 1950 to 2000 is not pursued; instead the "new" trend is rather to the South. The demographic and economic centers end up roughly on the same longitude but with the demographic center being much more to the South than the economic one.

Figure 5 shows the evolution of the average shares of main regions/countries in the WECG. As one would expect, the EU and the USA display strongly decreasing shares while China and India report increasing shares mainly since the 1980s. Japan has seen its share increase from 1960 to 1990 but reports a decreasing share afterwards. The average share of the rest of the world is weakly increasing.

To sum up, we can put forward three findings. First, all socio-economic centers of gravity locate in the Northern Hemisphere, and while the geographic and demographic centers locate both to the East of the Greenwich Meridian (and more so for the latter), the economic center has been to the West for the period 1950–1975 but to the East afterwards. Second, the demographic center displays a clear shift to the South with a less pronounced shift to the West since the 1980s. Third, the WECG is shifting since 1980 quickly to the East and since 2000 also to the South. Does the movement of the economic center of gravity towards the demographic center of gravity mean that GDP distribution is becoming more equal? This question is addressed in the next section.

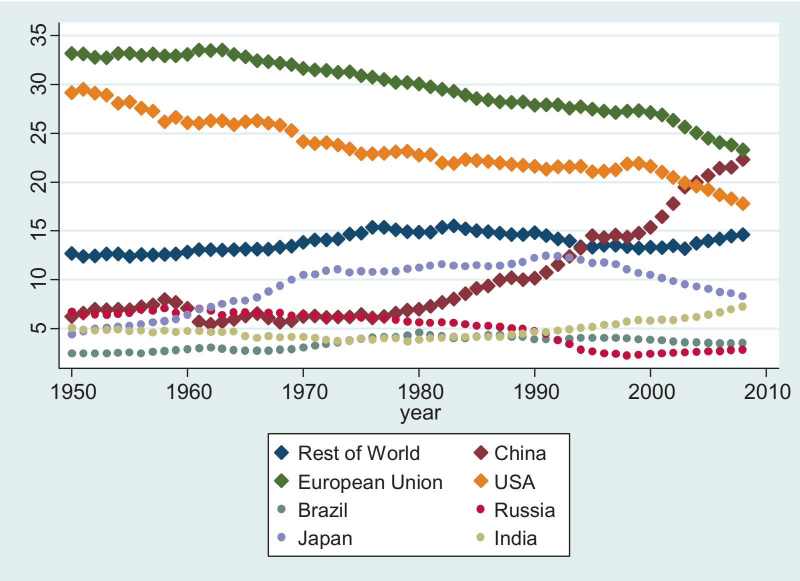

Fig. 5. Average share in economic center of gravity by large regions and countries.

3.2. Mean concentration decomposition 1950–2008

Complementary to the analysis on the mean direction trends, this section reports the evolution of the concentration indices defined in Section 2. Figure 6 depicts the evolution of the concentration indices over time for the three variables: land, population, and production (see Table A2 for regional shares in concentration). Concentration is highest for population over the whole sample period although there is a weak downward trend. The concentration index for production is just below the demographic one at the beginning of the period but is significantly decreasing over time since 1968 with a weak rebound since 1997. This means that production tends to be less concentrated than population across the Earth's surface and that it becomes even less so over time. The concentration index for land, as a benchmark, is several orders of magnitude smaller, suggesting that land is a lot more homogenously spread than production or people.

Figure 7 reports the evolution of the densification rates g_D and g_E. The hollow dots indicate that people are much more concentrated than land areas on the globe. The solid dots indicate that production is less concentrated than people (i.e., the distribution of production is biased toward less densely populated areas) and that this tendency is reinforced over time.

To better understand the evolution of the concentration index, we decompose it along the three different axes, starting with the shift from geographic to demographic concentration (i.e., equation (5a)). To clarify

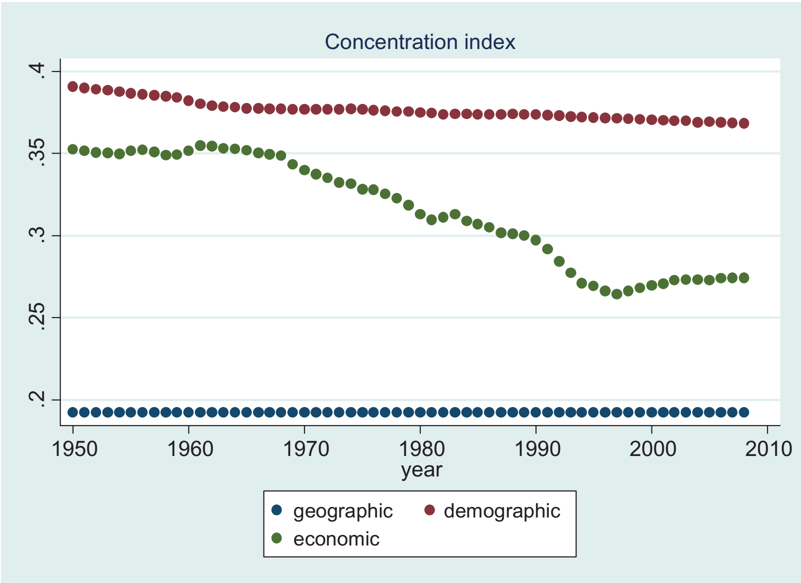

Fig. 6. Average concentration indices.

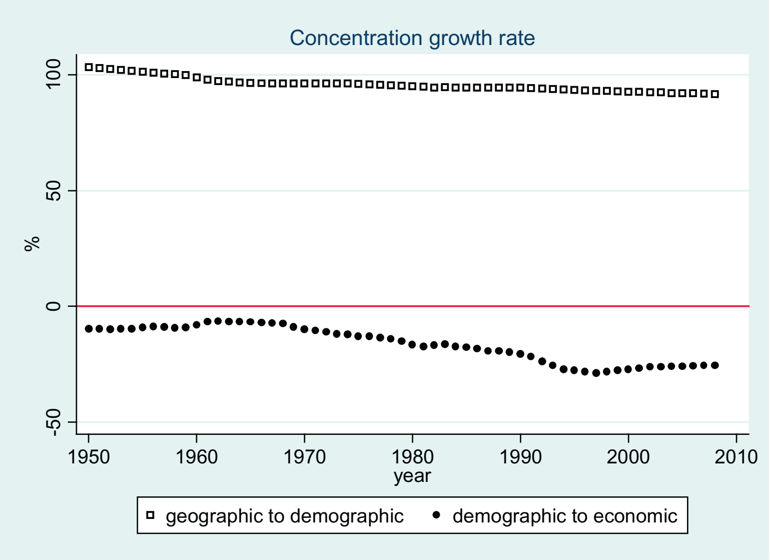

Fig. 7. Average densification rates.

the spatial interpretation, we take the view of an Euro-centric observer who is facing the prime meridian at the level of the equator, with two obvious directions: North/South (z-axis) and East/West (y axis), and a third one that is hidden behind the prime meridian denoted by close/away (x axis, with decreasing values indicating a location getting further away from the observer, deep into the Earth). The contributions of each axis to the geographic center of gravity (i.e., μ_X^G, μ_Y^G, μ_Z^G) do not change over time and should be taken as a benchmark (that is why no figure is worth reporting in this case). The North/South dimension turns out to be the most important (61%), the East/West dimension intermediate (30%) and the close/away dimension the least important (9%), meaning that the corresponding vector is pretty close to the plane that cuts the Earth along the 90° Meridian. In short, what matters most in terms of land distribution is its concentration into the Northern hemisphere.

Figure 8 plots the densification rates ($g_{D,X}, g_{D,Y}, g_{D,Z}$) when moving from the geographic to the demographic center of gravity. By far the largest effect is the one reported along the East/West axis, with an order of magnitude close to 1000% (while the other two effects are a lot smaller and tend to cancel each other out). This may come as a surprise because at first sight, on Figure 1, the demographic center does not seem so much further to the East than the geographic center. However one should keep in mind that Figure 1 only reports the mean *orientation*, that is, the projection onto the Earth's surface. The densification rate along the y-axis (i.e., East/West) also takes into account the fact that geographic *concentration* is a lot

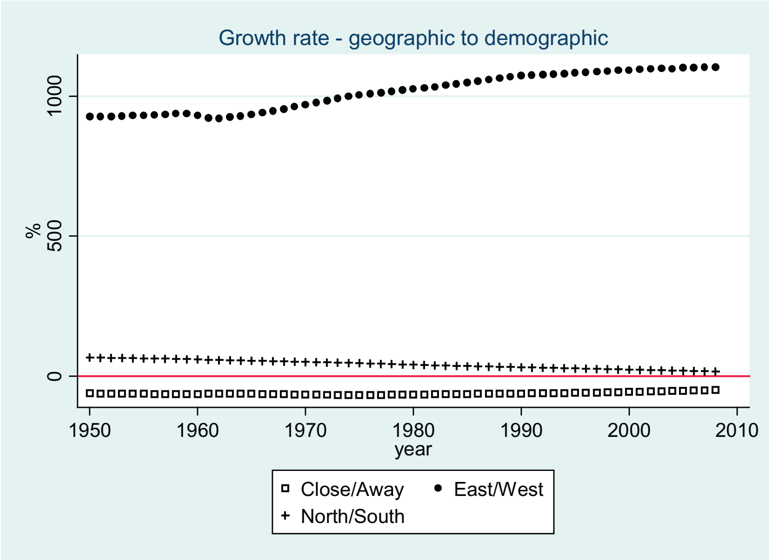

Fig. 8. Densification rate of concentration: from geographic to demographic.

smaller, that is, the effective geographic center is a lot closer to the Earth's center than the demographic center, which explains why the densification rate is so large. Thus, the outstanding result in this figure is that population is a lot more concentrated than land, and this is particularly telling along the East/West axis, meaning that population density is relatively more important in the East compared to land density.

Next let us turn to the move from the demographic concentration measure to the economic concentration measure (Equation (5b)). Figure 9 reports the importance of the three dimensions in the location of the demographic center (i.e., μ_X^D, μ_Y^D, μ_Z^D). Given the shift to the South of the center, shares are modified over time. However the basic picture remains one in which two dimensions of roughly equal magnitude, North/South and East/West drive the result, while the close/away dimension has no significant contribution. In short, and keeping in mind that concentration is larger in this case than for the geographic center (Figure 6), these shares basically illustrate that human population is concentrated in the Eastern side of the Northern hemisphere.

Figure 10 draws the densification rates when going from demographic to economic concentration (i.e., $g_{E,X}$, $g_{E,Y}$, $g_{E,Z}$). This time the pattern is more varied and changing than in the geographic–demographic comparison where Eastern densification is the major driver. Along the East–West axis, production appears to be a lot less concentrated than people, with a drop of close to 100%. However, production is more concentrated up North (z-axis) and, at least at the beginning of the period, closer to our

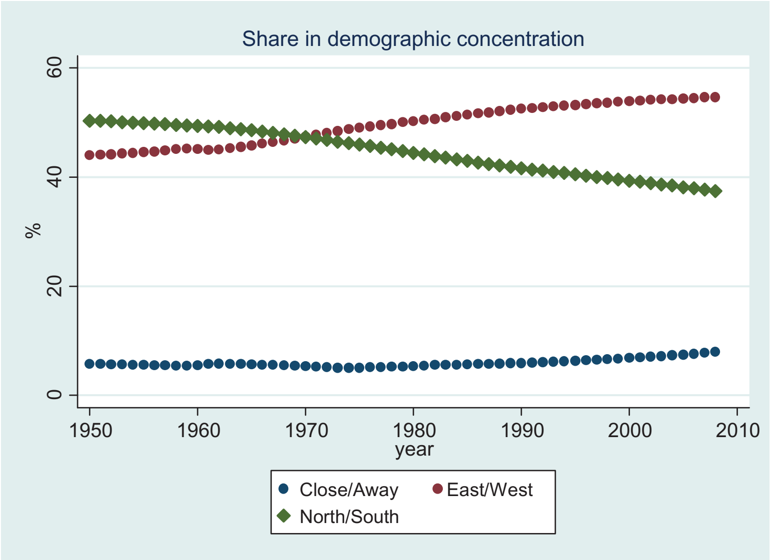

***Fig. 9.* Dimensional shares of the demographic center of gravity.**

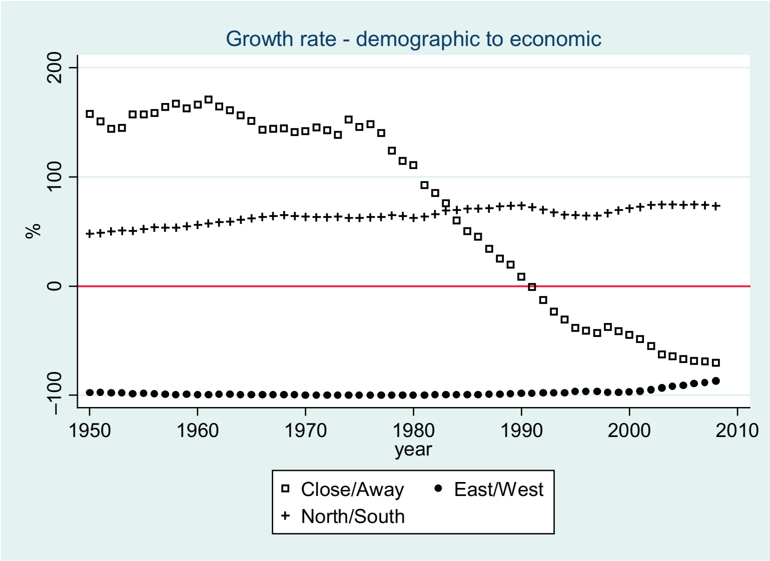

***Fig. 10.* Densification of the concentration rate from demographic to economic.**

Euro-centric observer (x-axis). This pattern changes remarkably over time. Starting in 1976, there is a progressive drop of the close/away densification rate, which is associated with both the acceleration of the North-Eastern shift of the economic center identified in Figure 3, and with the converse South-Western shift of the demographic center identified in Figure 2. A few years after 1990, the relative magnitude of the covariances is reversed and the close/away densification rate becomes negative (the economic center is now deeper into the Earth than the demographic center). As a result, at the end of the sample period, there are now two dimensions along which production appears to be less concentrated than people: toward the West and further away from the observer. Note also that if current trends are pursued in the following decades (extrapolating the upward trend of the Eastern densification rate at the end of the period in Figure 10), one should expect that a similar reversal would affect the East–West densification rate (when the economic center will eventually locate to the East of the demographic center).

To sum up, over the past six decades, while most of humanity has remained fairly concentrated in the same areas of the Northern hemisphere, economic activity has become geographically more evenly widespread across the Earth's surface, with a strong reversal of the concentration pattern along one particular dimension (close/away) of the three-dimensional space.

3.3. Education and R&D

In the growth literature a large number of variables have been identified to be closely related to GDP growth. The location and shifts in the center of gravity for some important variables with this respect are analyzed. The variables used are: public expenditure in education, R&D expenditures, and the number of literate adults. The data are taken from the World Development Indicators (2010), are available at the country level and have been averaged over five 10-year periods from 1960 to 2009. Production shares have been used to allocate national R&D expenditure at the intra-national sublevel, while population shares have been used for public expenditures on education and literate adults. Note that results for these variables should be taken with a grain of salt because of two shortcomings in the data. First, some countries do not have any data on these variables and could therefore not be included in the computation of the center of gravity, which might bias results. Second, some countries report suspicious data. Although there is not much we can do about that, it has to be recognized that this may have biased the location of the centers of gravity. However, as most large (and hence influential in terms of the center of gravity) countries do provide reliable data, we believe that the main results reported here are reasonably robust.

Figure 11 shows the location of the center of gravity of R&D and education expenditures and literate adults. The number of literate adults

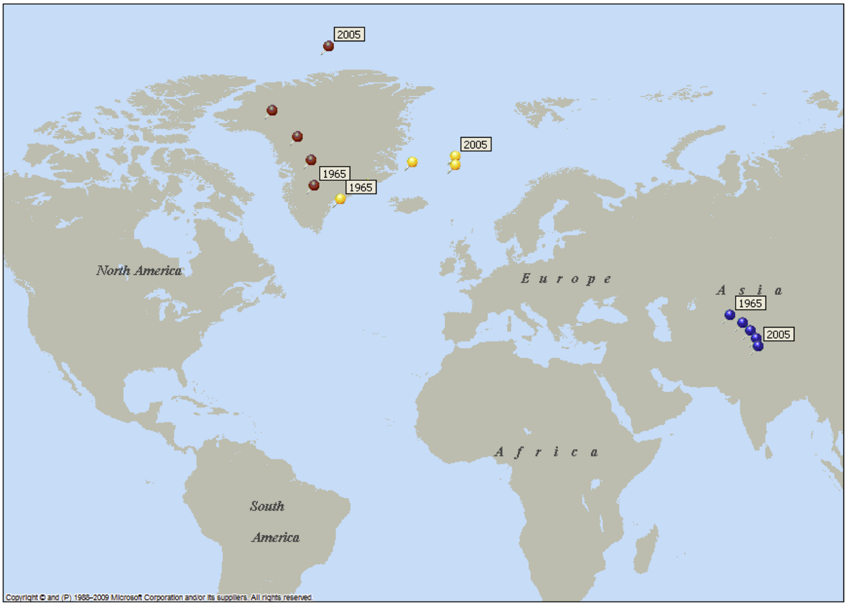

Fig. 11. Center of gravity 1965–2005 for literate adults (dark right balloons), R&D expenditures (dark left) and public education expenditures (pale). **Copyright © and (p) 1988–2009 Microsoft Corporation and/or its suppliers. All rights reserved.**

follows closely the location of the demographic center of gravity reported in Figure 1. The center of gravity for R&D expenditures locates more to the North and to the West than the economic center and is taking the shortest way to Tokyo. The center of gravity of public expenditures on education is not far from the economic center and is also moving eastwards.

The corresponding concentration indices are reported in Figure 12. As for the location analysis, we find that the time pattern for R&D and education expenditures is similar to the time pattern for economic activity, i.e. a decreasing geographic concentration (or increasing geographic dispersion) over time, while literacy concentration is quite stable, as in the case for the population at large. However, note that the initial level of concentration is larger for R&D and education expenditures, which suggests that at the beginning of the sample period innovation and human capital investment activities were quite concentrated amongst industrial countries.

To sum up, we computed the center of gravity for several growth related variables and found that R&D expenditures and public expenditures on education follow relatively closely the mean direction of the WECG (the center for R&D expenditures is however more to the West) and display also decreasing geographic concentration but at a higher level than the one

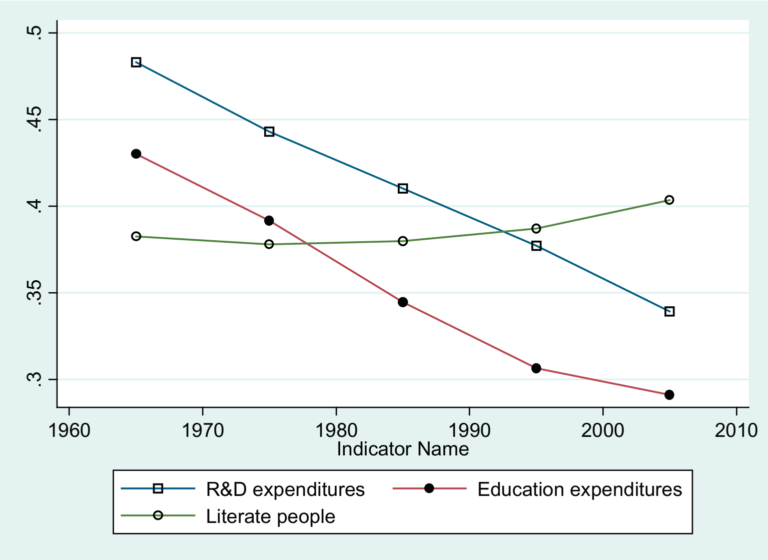

Fig. 12. ***Average concentration indices – growth-related variables.***

measured for economic activity. The mean direction for literate people follows the mean direction of the population, and concentration levels are also of comparable magnitude, although the one for literate people exhibits a slightly increasing trend.

4. Conclusion

This chapter presented estimates of the location of the world center of gravity of land, population, production, R&D, education expenditure and literate people and the associated concentration of these variables. The identified trends are broadly consistent with the common perception of centers of gravity shifting to the East. The demographic center of gravity is moving South and West-wards from Kazakhstan toward Afghanistan. The economic center of gravity starts off on the coast of Iceland and is heading East first very slowly and then very quickly towards the coast of Russia. During the last few years a small tendency toward the South can also be observed. During the 1950s, economic activity was already more geographically widespread than human population. It has become even more so over time, along two out of three spatial dimensions, and with a structural break that seems to coincide with the second oil shock at the end of the 1970s. The growth-related variables present a spatial pattern that is consistent with these stylized facts, with education and R&D expenditures exhibiting a strong correlation with overall output, while literate people and total population are closely linked.

This chapter includes information on the entire spatial distribution of population and economic activity and condensates it to a simple, tractable measure. This allows tracking the demographic and economic power balance at the world-wide level and taking geography into account, which in turn allows for a better understanding of past, present, and future distribution of political and economic power. Any field depending on global policies, such as trade, the financial and monetary system, environmental protection, global security and justice and also economic growth, have been and will be affected by the global distribution of economic power (see Quah, 2010).

It would be of interest in future research to test in which way the shift of the center of gravity influences international negotiations or regional development. The measure of the distance to the center of gravity could also be used in gravity equations of international trade (see Antweiler, 2008 for an application with time-varying distances) or in growth equations. Finally, two caveats should be kept in mind and could nurture further refinements. First, as was made clear upfront, this chapter focuses on economic concentration in a geographic sense, that is, in terms of dollars of production per square kilometer, which is related but different from economic concentration across people, that is, in terms of dollars of production per capita. Second, the fact that production turns out to be substantially less concentrated than human population is interesting per se but also calls for an explanation that would ideally encompass both policies (i.e., obstacles to the international mobility of factors of production) and economic incentives (in particular the agglomeration effects evidenced by the economic geography literature).

Acknowledgments

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Appendix A

Table A1. Average regional shares (%)

	1950s	1960s	1970s	1980s	1990s	2000s
Area						
Oceania & Pacific Islands	6.05	6.05	6.05	6.05	6.05	6.05
North & Central America	16.73	16.73	16.73	16.73	16.73	16.73
South America	13.17	13.17	13.17	13.17	13.17	13.17
Europe (excl. FSU)	3.63	3.63	3.63	3.63	3.63	3.63
Former Soviet Union	17.01	17.01	17.01	17.01	17.01	17.01
Middle East & North Africa	8.49	8.49	8.49	8.49	8.49	8.49
Sub-Saharan Africa	17.61	17.61	17.61	17.61	17.61	17.61
South Asia	5.57	5.57	5.57	5.57	5.57	5.57
South East Asia	2.88	2.88	2.88	2.88	2.88	2.88
East Asia	8.86	8.86	8.86	8.86	8.86	8.86
Population						
Oceania & Pacific Islands	0.41	0.42	0.41	0.4	0.38	0.38
North & Central America	8.77	8.85	8.5	8.19	8.01	7.92
South America	4.58	5	5.28	5.54	5.67	5.78
Europe (excl. FSU)	14.8	13.37	11.73	10.23	8.99	8.1
Former Soviet Union	7.08	6.91	6.3	5.77	5.16	4.49
Middle East & North Africa	3.62	3.88	4.12	4.62	5.06	5.5
Sub-Saharan Africa	7.33	7.72	8.25	9.18	10.25	11.46
South Asia	20.08	20.6	21.26	22.45	23.54	24.6
South East Asia	6.53	6.87	7.17	7.51	7.73	7.84
East Asia	26.81	26.37	26.98	26.12	25.2	23.94
Production						
Oceania & Pacific Islands	1.37	1.34	1.3	1.26	1.28	1.26
North & Central America	30.31	28.46	26.37	26.11	26.04	24.55
South America	5.65	5.67	6.26	6.14	5.9	5.36
Europe (excl. FSU)	29.69	30.19	28.62	26.04	23.29	20.56
Former Soviet Union	9.59	9.9	9.34	8.21	4.56	3.98
Middle East & North Africa	2.57	2.82	3.57	4.01	3.98	3.99
Sub-Saharan Africa	2.76	2.58	2.52	2.24	2.03	2.04
South Asia	5.75	5.46	5.37	5.62	6.88	8.36
South East Asia	2.61	2.47	2.8	3.39	4.64	4.81
East Asia	9.71	11.1	13.84	16.99	21.4	25.1

Table A2. Average regional shares in concentration (%)

	1950s	1960s	1970s	1980s	1990s	2000s
Area						
Oceania & Pacific Islands	7.25	7.25	7.25	7.25	7.25	7.25
North & Central America	16.3	16.3	16.3	16.3	16.3	16.3
South America	13.64	13.64	13.64	13.64	13.64	13.64
Europe (excl. FSU)	4.06	4.06	4.06	4.06	4.06	4.06
Former Soviet Union	15.3	15.3	15.3	15.3	15.3	15.3
Middle East & North Africa	9.62	9.62	9.62	9.62	9.62	9.62
Sub-Saharan Africa	16.3	16.3	16.3	16.3	16.3	16.3
South Asia	5.71	5.71	5.71	5.71	5.71	5.71
South East Asia	2.59	2.59	2.59	2.59	2.59	2.59
East Asia	9.22	9.22	9.22	9.22	9.22	9.22
Population						
Oceania & Pacific Islands	0.49	0.51	0.5	0.48	0.47	0.47
North & Central America	7.2	7.27	6.99	6.78	6.67	6.67
South America	4.63	5.03	5.3	5.54	5.66	5.75
Europe (excl. FSU)	16.74	15.3	13.6	12.02	10.69	9.71
Former Soviet Union	7.81	7.69	7.08	6.57	5.94	5.22
Middle East & North Africa	4.25	4.59	4.91	5.54	6.12	6.67
Sub-Saharan Africa	6.71	7.08	7.56	8.38	9.31	10.4
South Asia	17.84	18.31	18.9	20.06	21.2	22.3
South East Asia	5.24	5.52	5.73	5.97	6.14	6.23
East Asia	29.1	28.7	29.43	28.66	27.81	26.58
Production						
Oceania & Pacific Islands	1.64	1.57	1.51	1.46	1.51	1.51
North & Central America	26.08	24.56	22.72	22.14	21.68	20.22
South America	6.07	6.06	6.59	6.48	6.12	5.56
Europe (excl. FSU)	31.17	31.19	29.21	26.95	24.7	22.37
Former Soviet Union	9.87	10.15	9.55	8.4	4.79	4.07
Middle East & North Africa	3.05	3.3	4.1	4.66	4.66	4.74
Sub-Saharan Africa	2.87	2.63	2.49	2.23	2.02	2.05
South Asia	5.64	5.42	5.36	5.44	6.48	7.69
South East Asia	2.44	2.33	2.54	3	3.92	4.01
East Asia	11.17	12.79	15.92	19.25	24.11	27.79

Appendix B. : The world economic center of gravity explained

Delphine A. Troyon-Guédat

B.1. How is a center of gravity measured?

In physics, the *center of mass* of a body formed by *n* individual point masses is the point where all the mass of the object can be considered to be concentrated. When the body is subject to a uniform gravitational field, as we assume here, its center of mass coincides with its *center of gravity*.

Consider first the case of a *discrete* distribution of *n* point masses located at coordinates (x_i, y_i), $i = 1, \ldots n$. The coordinates (x_{cg}, y_{cg}) of the center of gravity of this collection of points are given by the following formulas:

$$x_{cg} = \sum_{i=1}^{n} \frac{m_i}{m} x_i, \text{ and } y_{cg} = \sum_{i=1}^{n} \frac{m_i}{m} y_i \tag{B.1}$$

where m_i is the mass of point i and $m = \sum_{i=1}^{n} m_i$ is the total mass (in kilogram, or dollars for the WECG). In other words, the coordinates of the center of gravity are equal to the mass-weighted average of the coordinates of the individual points. Figure A1 represents the case of two point masses.

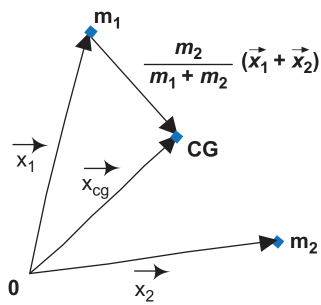

Fig. A1. Center of gravity of a system with two point masses.

For a *continuous* mass distribution, the weighted average formulas are replaced by the following integral forms:

$$x_{cg} = \frac{\int x\rho(x)dx}{m} \text{ and } y_{cg} = \frac{\int y\rho(y)dy}{m} \tag{B.2}$$

Where $\rho(x)$ [or $\rho(y)$] is the mass per unit length (or density) of the body along the x (or y) dimension.

B.2. Location on a sphere: polar and Cartesian coordinates

B.2.1. Conversion between polar coordinates and Cartesian coordinates

Consider a system of polar (or spherical) coordinates where r represents the radius, θ the inclination angle (i.e., the angle between the zenith direction and the considered line segment) and φ the azimuth angle (i.e., the angle between the azimuth direction and the projection of the line segment on the reference plane). Then for any point, the polar coordinates (r, θ, φ) can be obtained from the Cartesian coordinates (x, y, z) by the following formulas:

$$r = \sqrt{x^2 + y^2 + z^2} \quad \text{(B.3)}$$

$$\theta = \cos^{-1}\left(\frac{z}{r}\right) \quad \text{(B.3')}$$

$$\varphi = \tan^{-1}\left(\frac{y}{x}\right) \quad \text{(B.3'')}$$

Conversely, Cartesian coordinates may be retrieved from polar coordinates (r, θ, φ) where $r \in [0, \infty]$, $\theta \in [0,\pi]$ $\varphi \in [0,2\pi]$, by:

$$x = \mathrm{r}\ \sin(\theta)\cos(\varphi) \quad \text{(B.4)}$$

$$y = \mathrm{r}\sin(\theta)\sin(\varphi) \quad \text{(B.4')}$$

$$z = \mathrm{r}\cos(\theta) \quad \text{(B.4'')}$$

These formulas assume that the two systems have the same origin, that the spherical reference plane is the Cartesian x-y plane, that θ is the inclination from the z direction, and that the azimuth angles are measured from the Cartesian x axis (so that the y axis has $\varphi = +90°$). If θ measures elevation from the reference plane instead of inclination from the zenith, $\cos^{-1}$ becomes $\sin^{-1}$, and the cos(θ) and sin(θ) above are switched.

B.2.2. Geographic coordinates

Geographic coordinates are a particular type of polar coordinates when all points locate on the surface of a planet (normally the Earth). They are measured in degrees and represent angular distances calculated from the center of the Earth.

It is important to note that the value of the angle depends on the choice of the origin (North or East, for example) and the sense of rotation (counter-clockwise or clockwise). Therefore, the conventions adopted for calculations should be clearly mentioned.

Latitude (θ) is used in degrees North (90°) or South (−90°) of the equator plane (0°) in the range $-90° \leq \theta \leq 90°$. It is an elevation instead of an inclination angle (see B.2.1).

Longitude (φ) is measured in degree East (180°) or West (−180°) from the conventional Greenwich reference meridian and its range is $-180° \leq \varphi \leq 180°$.

For positions on the Earth, the reference plane is usually taken to be the plane perpendicular to the axis of rotation. The zenith angle or inclination, which is (90°–θ) and ranges from 0 to 180°, is called colatitude in geography. The radial distance is the distance between the planet's center and some surface reference like for example sea level, which is approximately 6,371 km for the Earth.

B.3. Descriptive statistics on a sphere

Applying classical arithmetic averages to angles does not make sense. For example, the mean between 1° and 359° cannot be 180°. This is due to the property that the beginning and the end of the scale coincide (0° = 360°). To control for that property, which also affects the center of gravity calculations, we have to introduce two notions. The first one is the *mean direction*, which indicates the average direction in space of any distribution of point masses. The second one is the *mean resultant length*, which indicates the concentration of those points.

B.3.1. Circle

Let us start with the circle (or circular data), by considering the distribution of n points of equal mass along a trigonometric circle of unit radius. Those points are given by unit vectors $\vec{x}_i$, to $\vec{x}_n$, with Cartesian coordinates (x_1, y_1) to (x_n, y_n) and corresponding angles θ_1 to θ_n $[x_i = \cos(\theta_i),\ y_i = \sin(\theta_i)]$. They are represented by the solid squares in Figure A2.

As all points have equal weights, applying formula (B.1), we get the following Cartesian coordinates for the center of gravity:

$$x_{\text{cg}} = \frac{1}{n}\sum_{i=1}^{n}\cos(\theta_i),\ \text{ and }\ y_{\text{cg}} = \frac{1}{n}\sum_{i=1}^{n}\sin(\theta_i) \tag{B.5}$$

The *mean direction* (or circular mean) is the angle between the center of gravity vector, $\vec{x}_{\text{cg}}$, and the horizontal axis. It is given by:

$$\overline{\theta} = \begin{cases} \tan^{-1}\left(\frac{y_{\text{cg}}}{x_{\text{cg}}}\right) & \text{if } x_{\text{cg}} \geq 0 \\ \tan^{-1}\left(\frac{y_{\text{cg}}}{x_{\text{cg}}}\right) + \pi & \text{if } x_{\text{cg}} < 0 \end{cases} \tag{B.6}$$

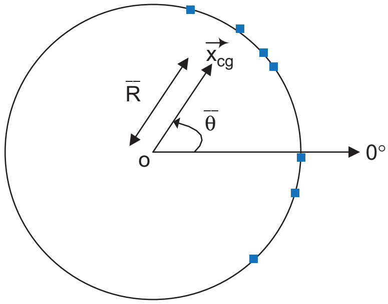

Fig. A2. Mean direction and mean resultant length on a circle.

The *mean resultant length* is the length of the center of gravity vector, given by:

$$\overline{R} = ||\vec{x}_{cg}|| = \sqrt{(x_{cg})^2 + (y_{cg})^2} \tag{B.7}$$

The unit vector of angle $\overline{\theta}$ can be referred to as the *mean direction vector* ($\vec{x}_0$). It corresponds to the normalized center of gravity vector ($\vec{x}_0 = \vec{x}_{cg}/||\vec{x}_{cg}||$).

If points are tightly clustered then $\overline{R}$ will be almost 1. In contrast, if points are widely and uniformly dispersed then $\overline{R}$ will be almost 0. The mean resultant length $\overline{R}$ is the most common (inverse) indicator of circular dispersion. However, as it is a concentration index, not a direct measure of dispersion, some authors prefer to refer to the circular variance, often defined as $1-\overline{R}^2$.

B.3.2. Sphere

When we work in a three-dimensional framework the same principles apply, except that the mean direction will be defined by two angles rather than one. Let us analyze then a distribution of n equally weighted points on the surface of a sphere with a unit radius. Each point i can be associated with a unit vector $\vec{x}_i$ with polar coordinates $(1,\theta_I, \varphi_i)$ and Cartesian coordinates (x_i, y_i, z_i) (Figure A3).

Following expression (B.1), the Cartesian coordinates of the center of gravity are given by:

$$x_{cg} = \frac{1}{n}\sum_{i=1}^{n} \sin(\theta_i)\cos(\varphi_i), \quad y_{cg} = \frac{1}{n}\sum_{i=1}^{n} \sin(\theta_i)\sin(\theta_i)\sin(\varphi_i),$$

$$z_{cg} = \frac{1}{n}\sum_{i=1}^{n} \cos(\theta_i) \tag{B.8}$$

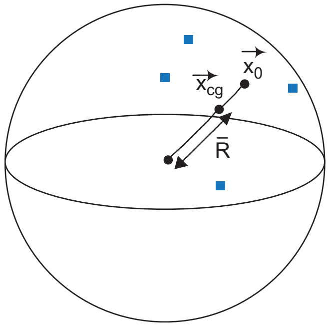

Fig. A3. Mean direction and mean resultant length on a sphere.

where θ represents the colatitude so that $90^\circ\text{–}\theta$ denotes latitude and φ denotes longitude.

We can retrieve the polar coordinates of the center of gravity, which reflect the *mean direction*, applying the following expressions (i.e., equations (B.6) adapted to the three dimensional case):

$$\theta_{cg} = \cos^{-1}(z_{cg}). \tag{B.9}$$

$$\varphi_{cg} = \begin{cases} \tan^{-1}\left(\frac{y_{cg}}{x_{cg}}\right) & \text{if } x_{cg} \geq 0 \\ \tan^{-1}\left(\frac{y_{cg}}{x_{cg}}\right) + \pi & \text{if } x_{cg} < 0 \end{cases} \tag{B.9$'$}$$

And the *mean resultant length* is given by:

$$\overline{R} = ||\vec{x}_{cg}|| = \sqrt{(x_{cg})^2 + (y_{cg})^2 + (z_{cg})^2} \tag{B.10}$$

As before regarding the circle, equation (B.10) is a measure of the concentration of the distribution on the surface of the sphere. Note also that the *mean direction vector*, $\vec{x}_0$, obtained as the normalized center of gravity vector, that is,

$$\overline{x}_0 = \frac{1}{||\overline{x}_{cg}||}\overline{x}_{cg} \tag{B.11}$$

corresponds to the projection of the center of gravity vector upon the surface of the sphere, as illustrated by Figure A3.

B.4. Specific cases

In this section we consider particular cases of centers of gravity calculations on spheres, which are useful to analyze the results reported in the chapter.

B.4.1. Spherical caps

Let us remind first that the surface of a spherical cap, as the one represented by Figure A4, is given by:

$$S = 2\pi r\, h = \pi(a^2 + h^2) \tag{B.12}$$

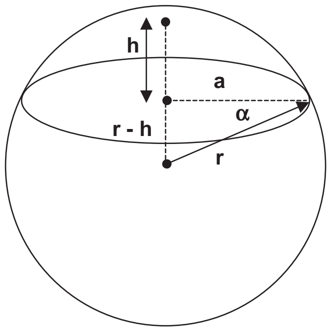

Fig. A4. A spherical cap.

Where h is the height of the spherical cap, r the radius of the sphere, and a the radius of the spherical cap. This simple formula has important consequences for center of gravity calculations.

To see why, assume now that we slice this spherical cap into m spherical rings, parallel to the equator plane, and of equal "thickness" along the height dimension. A corollary of formula (B.12) is that the surface of each one of these rings is strictly identical. This may appear slightly surprising at first sight, as the radius of the ring becomes smaller and smaller when one gets closer to the pole. However, working oppositely is the fact that the difference between the inner and outer circle of each ring becomes bigger and bigger, which exactly compensates the first effect.

Let us finally cover this spherical cap by points of equal weight uniformly, in the sense that the number of points per unit of surface remains constant. Consider calculating the Cartesian coordinates of the center of gravity of this spherical cap. As the cap is perfectly symmetric along the polar axis, all points perfectly compensate each other along the x and y dimensions when applying formula (B.1), that is, $x_{cg} = 0$ and $y_{cg} = 0$. What remains is the height, or the z dimension, but for which we know that we can decompose the cap into m slices of equal weight, and whose distance to the origin vary between $(r-h)$ and r. At the end of the day the mean direction is only determined by the average distance of the cap with respect to the origin, namely:

$$x_{cg} = 0, \quad y_{cg} = 0, \quad z_{cg} = r - \frac{h}{2} \tag{B.13}$$

For example, if we consider the spherical cap which slices the northern hemisphere into two equal parts, with a height equal to just half of the radius, then the corresponding center of gravity vector will have coordinates (0,0,0.75r).

B.4.2. A case of three spherical caps

To conclude, consider the three caps case represented in Figure A5. Those caps are not perfectly symmetrical nor aligned along the polar axis, but we assume that we can apply the above principles to estimate their centers of gravity. Those caps are named after the three main economic zones (USA, EU, Asia) that matter most in terms of world GDP or population. Thus, although very sketchy, Figure A5 may serve as a reference diagram to analyze the actual shifts of the WECG and WDCG.

Each pale point represents the projection of the WECG upon the Earth's surface (or the extremity of the mean direction vector) for a given year. The corresponding world center of gravity vector is a weighted average of the center of gravity vectors of each cap. The pale points are shifting to the East, because the economic weight of Asia is continuously increasing along time. A similar construction lies behind the dark points, which represent the projections of the WDCG on the Earth's surface. Here again, there is a temporal shift, first towards the South-East, then toward

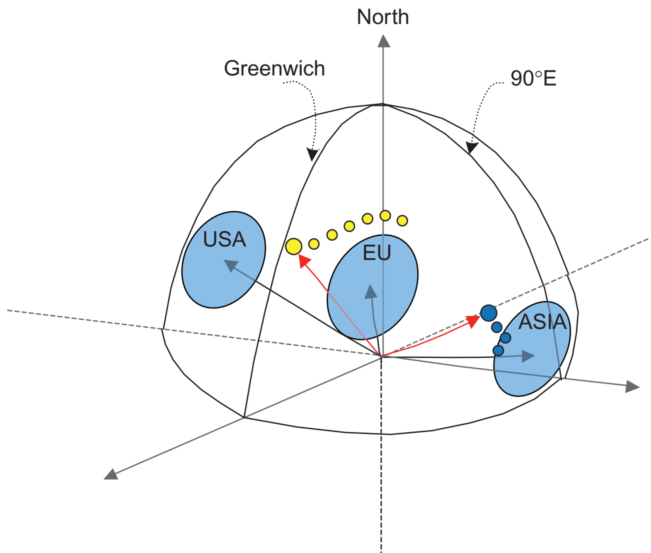

Fig. A5. A stylized vision of the world.

the South-West, a reversal that would be best explained by enriching the diagram with other continents (see the main text for more details).

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