Prometheus, 2015
Vol. 33, No. 2, 165–186, http://dx.doi.org/10.1080/08109028.2015.1095979

RESEARCH PAPER

Patterns of innovative outputs across climate zones: the geography of innovation

Mario Coccia*

School of Public Affairs, Arizona State University, Phoenix, AZ, USA and National Research Council of Italy, Moncalieri, Torino, Italy

Technological innovation is a vital human activity that interacts with geographic factors and the natural environment. The purpose of the present study is to explain the relationship between climate zones and innovative outputs in order to detect factors that can spur technological change and, as a consequence, human development. The findings show that innovative outputs are high in geographical areas with temperate climate. In effect, warm temperate climates are an appropriate natural environment for humans that, by an evolutionary process of adaptation and learning, create complex societies, efficient institutions and communications systems. This socio-economic platform supports the efficient use of human capital and assets that induce inventions, innovations and their diffusion.

Overview of the problem

Are there different patterns of technological innovation across the climate zones of the globe? The economic literature shows that technological innovation is driven by several concomitant forces in specific geo-economic places (Coccia, 2005a, 2007, 2009a, 2010a, 2010b, 2010c, 2010d, 2012b, 2012c, 2012d, 2012e, 2014a, 2014b, 2014c, 2014e; Feldman and Kogler, 2010; Hall and Rosenberg, 2010; Coccia *et al.*, 2012; Coccia and Wang, 2015). Geographical characteristics of certain areas support concentration and location of innovative activities and are vital determinants of new technology (Krugman, 1991). The new geography of innovation analyses several factors relating to the origin and diffusion of technological innovation, such as spatial proximity and agglomeration (Rosenberg, 1992; Smithers and Blay-Palmer, 2001; Howells and Bessant, 2012). However, little is known about the relationship between climate and technological performance. In general, climate is the main geographical factor that affects human activity and economic development (Chhetri *et al.*, 2010, 2012). Climate and the environment also play a vital role in spurring and diffusing technological innovation, though this is a difficult assumption to test (Ruttan, 1997; Abler *et al.*, 2000; Moseley *et al.*, 2014; Robbins *et al.*, 2014; see also Feldman and Florida, 1994). This study endeavours to explain how climate causes and sustains innovative outputs in specific areas. It also explores the association between technological performance and latitude.

*Email: mario.coccia@ircres.cnr.it
Accepting editor: Dimitris Assimakopoulos

The backdrop of prior research

The new economic geography argues that '*all* production depends on and is grounded in the natural environment' (Hudson, 2001, p.300). A vital element of the natural environment is the climate system, based on the atmosphere, hydrosphere, cryosphere, lithosphere and biosphere. In general, the climate of a place is affected by its latitude, altitude, land, water system, etc. The climate affects natural resources, the natural environment and human activities. Long ago, Montesquieu (1947 [1748]) argued that the climate shapes human attitude, culture and knowledge in society.

Feldman and Kogler (2010) argue that the natural advantages of resource endowments and climate in certain places induce innovation and economic growth (Hayami and Ruttan, 1985; Ayres, 1998; Coccia, 2009b, 2009c; Coe *et al.*, 2012; Moseley *et al.*, 2014; Robbins *et al.*, 2014). Others focus on the relationship between natural resources and the development of new technology (Ruttan, 1997; Gitay *et al.,* 2001; Rodima-Taylor *et al.,* 2012). In particular, they argue that the complex societies of temperate latitudes require inputs for their production processes, which are derived from the natural environment and climate as resources (Turner *et al.*, 1994). This effective demand for natural resources spurs technological innovation, by a process of learning and adaptation, which improves the use of resources to support the socio-economic development of specific areas (Dicken, 2003). Ruttan (1997) argues that the development and adoption of new technology are attributable to changes in the geographic, economic and social environment (see Goldberg, 1996). Hayami and Ruttan (1985) explain the sources of technological change with the hypothesis of induced innovation: the process by which societies develop technologies that facilitate the substitution of relatively abundant (hence, cheap) factors of production for relatively scarce (hence, expensive) factors/resources. Lichtenberg (1960) shows that geographical factors, rather than proximity to raw materials or markets, influence the production of knowledge and the cumulative nature of several innovations (see also Macdonald, 1989; Krugman, 1991; Agee and Crocher, 1998; Lamberton, 1998; Coccia, 1999, 2004; Feldman and Audretsch, 1999; Cariola and Coccia, 2002; Audretsch and Feldman, 2003; Crevoisier, 2004; Coe *et al.*, 2012; Howells and Bessant, 2012). At a later stage, knowledge spillover and skilled labour support further technological change (Feldman, 2003). In effect, a favourable climate also induces a better 'institutional thickness' (Amin and Thrift, 1993), which provides a platform for organizing people and resources in order to support knowledge creation and innovative outputs (Allen, 1997; Marceau, 2000; Rosenthal and Strange, 2003).

The main examples of these fruitful relations are to be found in specific places in temperate latitudes, such as Italy during the *Rinascimento*, England during the Industrial Revolution and the United States in the nineteenth century. Innovation is associated with a range of forces and circumstances, such as the resurgence of societies after conflict (Coccia, 2015), demographic change (Coccia, 2014a), high democratization (Coccia, 2010b), appropriate economic governance, secure property rights, predominant religions and efficient institutions (Coccia, 2009a, 2014b). Audretsch and Feldman (1996) confirm that the agglomeration of innovative activities and firms is related to advantages in the natural environment, available resources and other factors of physical geography. In general, this concentration of human and geo-economic resources is located in specific geographical places, such as major cities, long known to be society's predominant engines of innovation and growth (Bettencourt *et al.*, 2007). However, the literature of the geography of innovation is yet to explain the relationship between the human activity of technological innovation and climate zones. The next section presents a methodology to analyse this association.

Methods

The study design is based on the following hypothesis:

*HP*ϕ: technological outputs are positively influenced by temperate latitudes.

The present study ascertains whether empirical evidence substantiates this hypothesis. The causal model of the study is schematically summarized in Figure 1.

The sample is derived from 109 countries (see Appendix A). The indicators of the statistical analysis and sources of data are shown in Table 1. In particular, innovative outputs are measured by the patents of residents, which indicate the current innovation of countries and commercially-promising inventions (Coccia, 2010a, 2012b).[1] Hunt and Gauthier-Loiselle (2010, p.32) claim that 'the purpose of studying patents is to gain insight into technological progress, a driver of productivity growth, and ultimately economic growth'. Patents have a positive influence on patterns of technological innovation and are the most common metrics of innovative output used to analyse technological performance in modern countries (see Jaffe and Trajtenberg, 2002; Coccia, 2010a, 2012b). The paper also considers other metrics of innovative outputs in order to increase the robustness of the empirical analysis:

- Research and Development (R&D) expenditures (as % of GDP)
- number of researchers in R&D
- number of scientific and technical journal papers.

These indicators reveal, approximately, the national level of technological innovation, which is the most important component of technological change (Coccia, 2010a, 2012a).

In addition, geographic and demographic variables are used to detect the barycentre of innovation across countries (Coccia, 2014a). The statistical analysis considers climate zones based on the world map of the Köppen–Geiger climate classification (see Kottek *et al.*, 2006). This classification is critical to understanding different patterns of technological innovation (Zscheischler *et al.*, 2012). The study divides the world into temperate and non-temperate climate zones (equatorial, arid and polar climates). Countries are located in these specific climate zones by latitude.

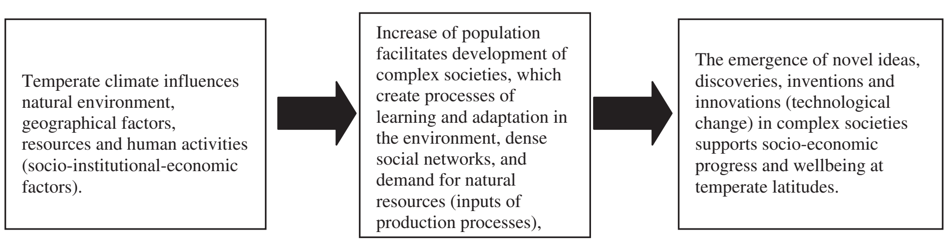

Figure 1. Causal model of the nexus between temperate climate and technological and economic progress in society

Table 1. Data and sources

Variables
• *Longitude* (GeoNames, 2014) – ***LONG****; Latitude* (GeoNames, 2014) - ***LAT***
• *Population growth (1990–96)ϕ* – ***POPGRW****:* Annual population growth rate for year *t* is the exponential rate of growth of mid-year population from year *t*–1 to *t*, expressed as a percentage.
• *Population total (1990–96) ϕ* – ***POPTOT****:* Population is based on the *de facto* definition of population, which counts all residents, regardless of legal status or citizenship (except for refugees not permanently settled in the country of asylum, who are generally considered part of the population of their country of origin).
• *Human development index* – ***HDI*** *2002*: This is a composite index, compiled by the United Nations Development Programme, that considers the education, life expectancy, and national income across countries.
• *GDP per capita PPP current Int. $ (1994–2000) ϕ* – ***GDPPC****:* Gross domestic product per capita (GDPPC) by purchasing power parity current international. The gross domestic product (GDP) – the value of all goods and services produced minus the value of any goods or services used in their creation – is the most common metrics applied in socio-economic studies to measure the economic activity and wealth of nations.
• *Patent applications of residents (1995–2001) ϕ* – ***PAR***: Applications filed through the patent cooperation treaty procedure or with a national patent office for exclusive rights to an invention (a product or process that provides a new way of doing something or offers a new technical solution to a problem).
• *R&D expenditure as % of GDP (1994–2000)ϕ* – ***R&D****:* Expenditure on R&D is current and capital expenditure on creative and systematic activity that increases the stock of knowledge. This includes fundamental, applied research and experimental development work leading to new devices, products or processes.
• *Researchers in R&D per million people (1995–2001) ϕ* – ***RSRCH****:* Researchers and technicians in R&D are people engaged in professional R&D activities who have received vocational and technical training in any branch of knowledge or technology.
• *Scientific and technical journal papers (1995–2001) ϕ* – ***STJOUR****:* These are the number of scientific and engineering papers published in the following fields: physics, biology, chemistry, mathematics, clinical medicine, biomedical research, engineering and technology, and earth and space sciences.
• *Population in urban agglomerations >1 million (% of total population) 1990–96 ϕ* – ***PUA***: Percentage of a country's population living in metropolitan areas that in 2000 had a population of more than one million.
• *Population in the largest city (% of urban population) (1990–96) ϕ* – **POPLAC**: Percentage of a country's urban population living in that country's largest metropolitan area.

Data were subjected to horizontal and vertical cleaning, excluding some years with missing values and/or outliers. The normal distribution of variables is checked by Kurtosis and Skewness coefficients, as well as by the normal Q–Q plot. As some variables do not have normal distributions, a logarithmic transformation has adjusted these distributions in order to apply correctly descriptive statistics, correlation analyses, ANOVA (Analysis of Variance) and parametric estimates. Time lags between variables are considered in order to analyse logical linkages better. Data are from the database of the World Bank (2008).

A preliminary statistical analysis is performed by descriptive statistics and bivariate correlation for temperate and non-temperate climates. The *main* statistical analysis is based on ANOVA, which considers two climate zones: temperate and non-temperate. In some statistical analyses, this study uses three climate zones: non-temperate climate, North temperate climate and South temperate climate. The statistical hypotheses of the ANOVA are:

H_0: average level of technological outputs in temperate latitudes = average level of technological outputs in non-temperate latitudes

H_1: average level of technological outputs in temperate latitudes ≠ average level of technological outputs in non-temperate latitudes

The expectation was that the ANOVA would reject H_0 in favour of H_1 (i.e. the average level of innovative outputs – measured by patents – in temperate latitudes is higher than in countries located in non-temperate latitudes). The robustness of results is checked by the Levene test of variance homogeneity, Test *T* of equality of mean, and the Welch–Brown–Forsythe test of robustness for equality of mean.

In order to determine the geo-economic area that is favourable/adverse to technological outputs (by using geographical coordinates), this study applies the following working equations:

LN patent applications per million people = f (longitude)

LN patent applications per million people = f (latitude)

The specification is based on cubic models since they fit very well with data scatter (Appendix B). The models (B1) and (B2) in Appendix B are estimated by the ordinary least squares method. The estimated relationships are polynomial functions, continuous and infinitely differentiable. The classic mathematical optimization method applied to these estimated relationships provides the local optimum/minimum that indicates the favourable/adverse geographical zone for supporting/impeding technological innovation.[2]

This study has also selected the largest 10 cities in each of 109 countries from a geographical database (GeoNames, 2014). These cities are associated with geographical coordinates (longitude and latitude) in order to compute the innovative centre of gravity of the country: in particular, the arithmetic mean of its geographical coordinates (longitude x_i and latitude y_i) weighted by its population n_i (see Appendix B, Eq. B3). The centre of gravity of innovative outputs also takes into account the roundness of the earth for extensive countries (Appendix B, Eqs. B4-B5). In fact, the geographical barycentre of the country, based on larger cities, is the predominant engine of innovation and wealth creation (Dicken, 2003, pp.69–76), confirming the benefits of urbanization economies that support innovation by means of the accumulation of human and physical capital (c.f. also Coccia, 2001; Coccia and Rolfo, 2007, 2009; Coccia and Cadario, 2014). Larger cities encourage the emergence and growth of a variety of infrastructural, economic, social and cultural facilities, and as a consequence, technological innovation (Bettencourt *et al.,* 2007). This study also analyses the spatial variability of innovative outputs by applying the decomposition of territorial dispersion and the decomposition of normal deviation in temperate and non-temperate climates (Statistical equations in Appendix B, Eqs. 6B-7B).

Empirical support for hypothesis ϕ

Figure 2 shows that indicators of technological innovation, demography and economic performance have an arithmetic mean in temperate climate zones that is higher than that in non-temperate climate zones (for details, see Table C1 in Appendix C). Bivariate correlation (Pearson's r) displays strong positive association between patent applications of residents (innovative outputs) and GDP per capita; human development index; and population in urban agglomerations >1 million (% of total population) in both temperate and non-temperate climates (except the correlation between PAR and PUA in temperate climates, where Pearson's r is lower: 0.207; see Table C2 in Appendix C). ANOVA and test of comparison of the arithmetic mean of innovative outputs between temperate and non-temperate climates confirm the results (Appendix C, Table C3): the average LN patent 1995–2001 per million people of countries in temperate climates is much greater than in countries in non-temperate climates, thereby supporting the alternative hypothesis H_1 (i.e. temperate climate is positively associated with technological output).

Figure 3 confirms that the arithmetic mean in North and South temperate climate zones is higher than in non-temperate climate zones. The Levene test and test of robustness for equality of mean (Welch–Brown–Forsythe) further confirm the

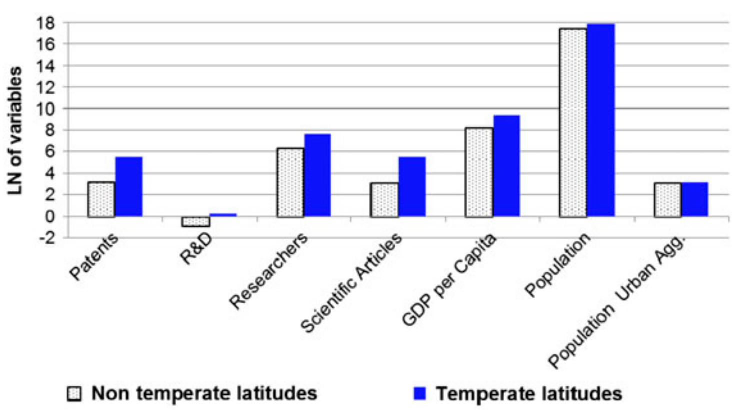

Figure 2. Arithmetic mean of innovative, economic and demographic indicators between non-temperate and temperate climates

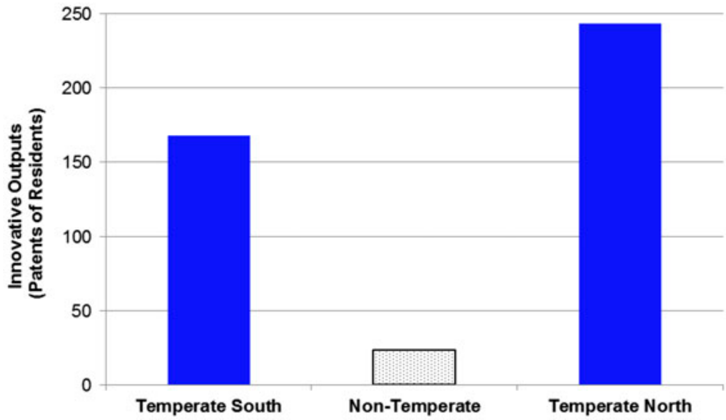

Figure 3. Arithmetic mean of patent applications per million people in three climate zones

positive effects of temperate latitudes on innovative outputs: the average LN patent 1995–2001 per million people of countries in North and South temperate climates is much greater than in countries located in non-temperate climates (see Tables C3–C5 in Appendix C). The application of other indicators of innovative outputs confirms these results. In order to determine the geographical centre of gravity that optimally supports technological outputs (PAR = patent applications of residents 1995–2001), the maximum/minimum of the estimated relationships of geographic coordinates is calculated (see Table C6 in Appendix C and Appendix D). The latitude and longitude favourable (or adverse) to innovative outputs are in Table 2.

The geographical barycentre of the globe that maximizes innovative outputs is at longitude 90° 52′ and latitude 60° 59′. These geographical coordinates are in the northern hemisphere in temperate latitudes (in the Russian Federation to the north-east of Novosibirsk). This result shows that innovative outputs are greater in temperate climate zones of the hemisphere. The geographical barycentre that minimizes innovative outputs is at longitude –24° 12′ and latitude –4° 19′ (below the equator, on the east coast of Brazil). This result confirms that high innovative outputs are lower in the non-temperate parts of the globe. Table 3 also shows that innovative outputs (first column) are in temperate climate zones with low territorial dispersion (last column).

Decomposition of the territorial dispersion of patent applications of residents (PAR) shows that the territorial dispersion of innovative outputs is mainly within groups (Table 4, a). However, the divergence of the barycentre between non-temperate and temperate climate zones plays a vital role in explaining the average difference between innovative outputs. In particular, the normal decomposition of total deviation

Table 2. Geographic coordinates favourable (*adverse*) to innovative outputs

Geographical coordinates	Max patent applications of residents (1995–2001)*Area favourable to innovative output	Min patent applications of residents (1995–2001) Area adverse to innovative output
Longitude	90° 52’	-24° 12’
Latitude	60° 59’	-4° 19’

Note: *Indicates maximum value. According to the sexagesimal system of angular measurement, °=grade=1/360 circle; ′ = primes = 1/60 grade.

Table 3. Spatial analysis of climate zones by patent applications (innovative outputs)

Climate zones	Average LN patent applications of residents (standard deviation)	Variable: LN patent applications of residents(1995–2001) Geographical barycentre Average longitude	Average latitude	Territorial dispersion $\sigma_{(x,y)}$
Temperate latitudes	4.06 (1.99)	28° 28′	41° 25′	56° 22′
Non-temperate latitudes	0.22 (1.81)	-53° 2′	14° 25′	127° 53′
Total	3.18 (2.53)	27° 10′	40° 59′	59° 12′

Note: According to the sexagesimal system of angular measurement, °=grade=1/360 circle; ′ = primes=1/60 grade.

Table 4. Decomposition of territorial deviation and total deviation

(a) Decomposition of territorial deviation		*Temperate*	*Non-temperate*	*Temperate vs. Non-temperate*
Value	5,737,078= 100%= DEV(X, Y)=	(5,117,452.52+ (89.20%+	429,209.03)+ 7.48%)+ WITHIN +	190,416.34 3.32% BETWEEN
(b) Decomposition of total deviation		*Temperate*	*Non-temperate*	*Temperate vs. Non-temperate*
Value*	3,292.69= 100%= DEV(X, Y)=	(1,571.13+ (47.72%+	383.97)+ 11.66%)+ WITHIN +	1,337.59 40.62% BETWEEN
Arithmetic* mean	3.18 Total	4.06 Temperate climate	0.22 Temperate climate	–
Standard deviation*	2.53 Total	1.99 Non-temperate climate	1.81 Non-temperate climate	–

Note: *Logarithmic value.

(Table 4, b) shows that an important source of variability of innovative outputs is also *between* groups of temperate and non-temperate climate zones (40.62%). Hence, technological outputs are affected by climate and positively influenced by temperate latitudes. This result further substantiates the HPϕ and nexus in model of Figure 1.

The statistical analysis shows, *ceteris paribus*, that, on average, innovative outputs are associated with temperate latitudes and with favourable factors of physical and human geography. In short, technological innovation, as a crucial human activity, thrives in temperate latitudes. This result also explains, on average, the localization of the majority of high-income countries in a temperate climate. In contrast, low- and middle-income countries are, on average, in non-temperate latitudes (Coccia, 2008, 2010e, 2014d). Adverse natural environment for human activities in non-temperate climate zones has negatively affected the creation of institutions, economic governance and democratization over time. These disadvantages induce low investment in physical and human capital, as well as low economic efficiency in the use of these factors to support technological innovation and achieve higher income (North, 1981). However, Acemoglu *et al.* (2001) argue that 'Once the effect of institutions is controlled for, countries in Africa or those closer to the equator do not have lower incomes'.

In addition, within temperate and non-temperate climate zones there is high variability in innovative performances because the relationship between climate and technological outputs is also affected by other socio-institutional and cultural factors (Coccia, 2005b, 2005c, 2011, 2012a, 2014a). For instance, Spain and the UK are in the same climate zone, but Spain has an annual average of about 57 patents per million people, whereas the UK has an annual average of roughly 334 patents (Coccia, 2014a). Institutions, democratization, cultural factors and other socio-economic factors differ across countries and tend to generate, *ceteris paribus*, a great variety of economic and technological performance, although the countries are in similar climate zones. In brief, climate is an important determinant in explaining differences in income per capita and innovative outputs across countries. However, there are also other complex factors that affect patterns of technological innovation in similar latitudes, such as national systems of innovation, demographic change, predominant religion, democratization, institutions, secure property rights and efficient economic governance (Coccia, 2014a, 2014b, 2015).

Explanation of the *nexus* between temperate climate and innovative outputs

In general, the statistical evidence seems to support hypothesis ϕ: on average, high innovation outputs are explained by the localization of countries in temperate climate zones. This result is attributable to some fruitful linkages: climate influences the natural environment, resources and human activities. In particular, temperate latitudes, with appropriate geographical factors, have attracted humans who created complex societies. These societies, by a process of learning and adaptation, use the natural resources of the environment as inputs to the production processes. The effective demand for natural resources generated stone (lithic) technology for better use of natural resources. Subsequently, concentration of human resources and capital created dense social networks and trusting environments to support further socio-economic development, patterns of technological innovation and their path-dependency (Coccia, 2009b, 2013; Lee and Rodríguez-Pose, 2013). Ethnologists, such as Tylor and Morgan, view: 'the production of novelties – new ideas, new ways of doing things, and the like – as the underlying force that propels cultures up the ladder of cultural complexity' (quoted by O'Brien and Shennan, 2010, p.4). In effect, concentration of people and social interactions in temperate latitudes support an effective circulation and diffusion of information, facilitating discoveries, inventions and innovations by new combinations of ideas and technical knowledge: 'Population growth produces an absolutely larger number of geniuses, talented men, and generally gifted contributors to new knowledge whose native ability would be permitted to mature to effective levels when they join the labour force' (Kuznets, 1960, p.328).

In addition, concentration of people in temperate latitudes leads to greater demand for new goods and services and, as a consequence, to demand-driven innovation. These crucial linkages generate an impetus for technological progress and economic growth in specific places in these tepid latitudes (Coe *et al.*, 2012). Hence, innovative activity in the specific socio-economic context of temperate climate is a combination of tangible and intangible elements that supports patterns of technological innovation (innovative milieu). Temperate latitudes have fruitful geographical factors that support some natural advantages for human activities and are a major source of attraction for populations. This natural and socio-economic environment induces the transmission of knowledge by intensive contacts among people (e.g. face-to-face interactions), and the sharing of common attitudes/interests (Von Hippel, 1994; Allen, 1997; Marceau, 2000; Feldman and Romanelli, 2006; Cavallo *et al*., 2014a, 2014b). Kremer (1993, pp.684–85) notices that: 'among technologically separate societies, those with high population had faster growth rates of technology and population'. Moreover,

> When people with common technical interests concentrate geographically, dense local social and professional networks emerge as their close proximity leads them to encounter one another more frequently, both by chance and through local institutions, and to develop ties that are more likely to endure than more costly-to-maintain distant ties. By facilitating repeated interactions and development of overlapping social and professional connections, local concentrations of people engaged in similar technical activities create an environment facilitating trust building and rapid and effective diffusion of ideas … Through these networks flows information about promising new technical developments and important unsolved puzzles that can stimulate innovation by facilitating novel combinations of ideas and technologies and identifying emerging market opportunities. … Technological proximity also matters. The cumulativeness of technological advances and specificity of knowledge bases to particular technical areas and market applications makes the value of potential spillovers greater within rather than across specialized technological applications. (Aharonson *et al.,* 2007, p.92)

The physical and human geography of certain temperate latitudes creates conditions for platforms and infrastructures for supporting technological innovation along fruitful historical developmental paths (Coe *et al*., 2012). Technological innovation is a human response to resource endowments, and environmental, climate and socio-economic changes (Chhetri *et al*., 2012; see also Singer *et al*., 1961). In particular, technological change is a human process of learning and adaptation to take advantage of important territorial opportunities and to cope with consequential environmental threats. Singer *et al.* (1961, vol. 1, Map 1 and p.37) show interesting maps that confirm the origin of the lithic technology in temperate latitudes in the northern hemisphere; in fact, several anthropological studies place Mousterian and other Palaeolithic industries of Neanderthal man in the geographical zone north of the Tropic of Cancer (see O'Brien and Shennan, 2010). Figure 4 shows these invariant linkages between climate and patterns of technological innovation over time.

Temperate climate has been vital for human activity to create adaptation and learning processes for the emergence of opportunities, discoveries and inventions, and for the diffusion of innovations (O'Brien and Shennan, 2010). Even in a

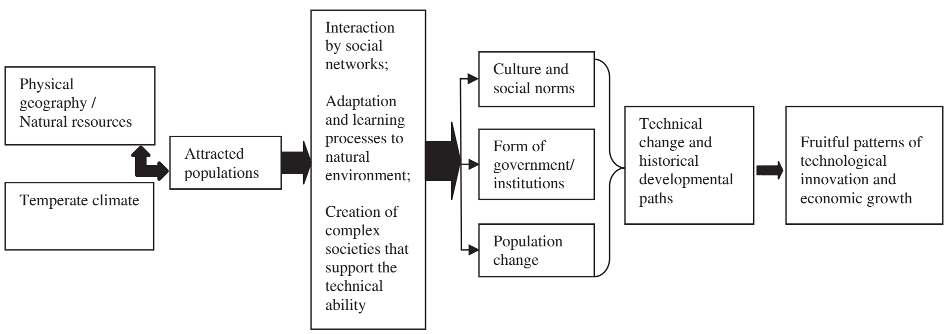

Figure 4. Invariant linkages from temperate climate and suitable physical geographic factors to technological and economic progress

globalizing world, economic and innovative activities are geographically localized in urban areas of temperate latitudes (Dicken, 2003, pp.69–76). Worldwide urbanization is important for sharing the costs of a whole range of services and creating a variety of infrastructural, economic and cultural facilities (Bettencourt *et al.*, 2007; c.f. also Coccia and Rolfo, 2007, 2013; Coccia, 2009d). This study shows that broad geo-economic areas in temperate latitudes support innovative outputs through a process of cumulative and self-reinforcing development. Temperate climate is basic to the population agglomeration required for the activities that lead to profitable paths of technological innovation: a central activity of learning and adaptation by complex societies to take advantage of important opportunities and/or to cope with consequential environmental threats (Rodima-Taylor *et al.*, 2012; Olwig, 2012).

In addition, some economies in temperate climates have generated innovations that have locked them into a technological pattern. This path-dependency persists until a new techno-economic paradigm induces disequilibrium in geo-economic systems and changes the distribution of economic and innovative activities. Temperate climate is a necessary, but not sufficient, condition for supporting technological innovations. Temperate climate has to be associated with other driving forces in order to support long-run patterns of technological innovation (Coccia, 2010b, 2014a, 2014b).

Concluding observations

Climate is a geographical factor of the natural environment and a condition inducing technological innovation. In particular, human and physical capital is affected by climate (Abler *et al.*, 2000) and temperate latitudes provide stimuli for social, technological and economic change (Hayami and Ruttan, 1985; Rosenberg, 1992; Smithers and Blay-Palmer, 2001). The progress of complex societies in temperate areas has generated innovation to reduce the influence of the natural environment and dependence on scarce resources (Hayami and Ruttan, 1985).

The present study shows high technological outputs in the temperate zones of the globe. This may be a result of the fortunate congruence of geographical and socio-cultural factors since the Palaeolithic period (Martin and Sunley, 1998; O'Brien and Shennan, 2010; Di Giano and Racelis, 2012). In particular, the temperate latitudes have created better conditions for supporting the ability of populations to adapt by means of technological innovations. Rodima-Taylor *et al.* (2012, p.107) claim that: 'Innovations are human adaptations to changing needs and socio-economic conditions, and are therefore embedded in social processes'. Moreover, climate also affects cultural traits of societies that, through a process of learning, react and self-adapt to natural environmental conditions and resource endowments (Chhetri *et al.*, 2012). Cultural traits are transmitted across generations within social systems, in the very long run as a result of institutions which preserve social memory (Walker *et al.*, 2006; Spolaore and Wacziarg, 2013). The social memory of institutions plays a vital role in transforming experience, knowledge and cultural traits of people into adaptive strategies and learning processes. By means of high technical capability and innovation, these permit response to adverse environmental consequences (O'Brien and Shennan, 2010; Di Giano and Racelis, 2012). Hence, the climate and other physical geographic factors spur technological pathways and support the fortune of certain places. The emergence of technological innovation is a consequence of current and/or expected environmental stimuli and/or problems in order to reduce geo-economic risks and/or exploit beneficial opportunities (Smithers and Blay-Palmer, 2001).

Overall, then, the theoretical framework, underpinned with the evidence presented here, explains the main characteristics of the relationship between technological innovation and climate.

(1) The present conceptual framework assigns a central role to climate, which is neglected by the dominant approaches to the origins of technological innovation.
(2) The framework explains the role of localized economies in temperate latitudes in supporting patterns of technological innovation.
(3) The cumulative nature of processes of localized technological development shows that patterns of innovation are influenced by temperate climate and the historical developmental path created by complex societies in specific places.
(4) These results may help policymakers find geographical locations suited to technological change.

Of course, this study is explorative and far from conclusive. The role of climate on technological innovation deserves further scientific analysis. Future research should focus on the complex interaction among climate, the emergence of complex societies, patterns of technological innovation and human development by adopting psychological, historical, sociological and anthropological approaches. The partial analysis of the present study, focusing on a basic and partial linkage, provides interesting findings, but as Wright (1997, p.1562) admits, 'In the world of technological change, bounded rationality is the rule'.

Acknowledgements

I gratefully acknowledge financial support from the National Research Council of Italy (STM Program 2011 and 2013) for my visits to Yale University, Georgia Institute of Technology, BETA (Strasbourg) and the University of Toronto, where this study started in 2011. I am also grateful for the financial support of UNU-MERIT (contract 606-UU-476), where this research was developed while I was a visiting scholar in 2014. This study was improved at Arizona State University during my research work in 2015 (funded by the Italian National Research Council). I am grateful to Enrico Filippi (University of Torino) and Richard Silberglitt (RAND Washington) for useful comments and helpful discussion as well as to two anonymous referees and the editors of *Prometheus* (Stuart Macdonald and Dimitris Assimakopoulos). Diego Margon provided excellent research assistance.

Disclosure statement

No potential conflict of interest was reported by the author.

Notes

1. Technology is based on inventions and innovations. Invention is a commercially promising product or service, based on new science and/or technology, that meets the requirements for a patent application. Innovation has already been granted a patent and is the successful entry of a new science or technology-based product into a market (Coccia, 2010a).
2. The necessary condition for the functions of one variable to have the solution $x = x^*$ as a maximum or a minimum is: $\frac{df(x)}{dx} = 0 \quad for\ x = x^*$ (1*); x is a stationary point.

ORCID

Mario Coccia http://orcid.org/0000-0003-1957-6731

References

Abler, D., Shortle, J., Rose, A. and Oladosu, G. (2000) 'Characterizing regional economic impacts and responses to climate change', *Global and Planetary Change*, 25, pp.67–81.

Acemoglu, D., Johnson, S. and Robinson, J.A. (2001) 'The colonial origins of comparative development: an empirical investigation', *The American Economic Review*, 91, 5, pp.1369–401.

Agee, M.D. and Crocker, T.D. (1998) 'Economies, human capital, and natural assets – forming empirical linkages', *Environmental and Resource Economics*, 11, 3–4, pp.261–71.

Aharonson, B.S., Baum, J.A.C. and Feldman, M.P. (2007) 'Desperately seeking spillovers? Increasing returns, social cohesion and the location of new entrants in geographic and technological space', *Industrial and Corporate Change*, 16, 1, pp.89–130.

Allen, P.M. (1997) 'Modelling the coevolution of communications and socio-economic structure', *Prometheus*, 15, 1, pp.83–100.

Amin, A. and Thrift, N.J. (1993) 'Globalisation, institutional thickness and local prospects', *Revue d'Economie Regionale et Urbaine*, 3, pp.405–27.

Audretsch, D. and Feldman, M.P. (1996) 'R&D spillovers and the geography of innovation and production', *The American Economic Review*, 86, 3, pp.630–40.

Audretsch, D. and Feldman, M.P. (2003) 'Knowledge spillovers and the geography of innovation' in Henderson, J.V. and Thisse, J. (eds) *Handbook of Urban and Regional Economics: Cities and Geography*, 4, North Holland Publishing, Amsterdam, pp.2713–39.

Ayres, R.U. (1998) 'Towards a disequilibrium theory of endogenous economic growth', *Environmental and Resource Economics*, 11, 3–4, pp.289–300.

Bettencourt, L.M.A., Lobo, J., Helbing, D., Kühnert, C. and West, G.B. (2007) 'Growth, innovation, scaling, and the pace of life in cities', *Proceedings of the National Academy of Sciences of the United States of America*, 104, 17, pp.7301–6.

Cariola, M. and Coccia, M. (2002) 'Analisi di un sistema innovativo regionale e implicazioni di policy nel processo di trasferimento tecnologico', Working Paper Ceris del Consiglio Nazionale delle Ricerche, Anno IV, n. 6, Torino (Italy).

Cavallo, E., Ferrari, E., Bollani, L. and Coccia, M. (2014a) 'Attitudes and behaviour of adopters of technological innovations in agricultural tractors: A case study in Italian agricultural system', *Agricultural Systems*, 130, pp.44–54.

Cavallo, E., Ferrari, E., Bollani, L. and Coccia, M. (2014b) 'Strategic management implications for the adoption of technological innovations in agricultural tractor: the role of scale factors and environmental attitude', *Technology Analysis & Strategic Management*, 26, 7, pp.765–79.

Chhetri, N., Chaudhary, P., Tiwari, P.R. and Yadawd, R.B. (2012) 'Institutional and technological innovation: understanding agricultural adaptation to climate change in Nepal', *Applied Geography*, 33, pp.142–50.

Chhetri, N., Easterling, W.E., Terando, A. and Mearns, L. (2010) 'Modeling path dependence in agricultural adaptation to climate variability and change', *Annals of the Association of American Geographers*, 100, 4, pp.1–14.

Coccia, M. (1999) 'Trasferimento tecnologico ed autofinanziamento', Working Paper Ceris del Consiglio Nazionale delle Ricerche, Anno I, n. 2, Torino (Italy).

Coccia, M. (2001) 'Satisfaction, work involvement and R&D performance', *International Journal of Human Resources Development and Management,* 1, 2/3/4, 268–82.

Coccia, M. (2004) 'Spatial metrics of the technological transfer: analysis and strategic management', *Technology Analysis & Strategic Management*, 16, 1, pp.31–51.

Coccia, M. (2005a) 'Countrymetrics: valutazione della performance economica e tecnologica dei paesi e posizionamento dell'Italia', *Rivista Internazionale di Scienze Sociali,* CXIII, 3, pp.377–412.

Coccia, M. (2005b) 'A taxonomy of public research bodies: a systemic approach', *Prometheus*, 23, 1, pp.63–82.

Coccia, M. (2005c) 'Metrics to measure the technology transfer absorption: analysis of the relationship between institutes and adopters in northern Italy', *International Journal of Technology Transfer and Commercialization*, 4, 4, pp.462–86.

Coccia, M. (2007) 'A new taxonomy of country performance and risk based on economic and technological indicators', *Journal of Applied Economics*, 10, 1, pp.29–42.

Coccia, M. (2008) 'Science, funding and economic growth: analysis and science policy implications', *World Review of Science, Technology and Sustainable Development*, 5, 1, pp.1–27.

Coccia, M. (2009a) 'Measuring the impact of sustainable technological innovation', *International Journal of Technology Intelligence and Planning*, 5, 3, pp.276–88.

Coccia, M. (2009b) 'What is the optimal rate of R&D investment to maximize productivity growth?', *Technological Forecasting & Social Change*, 76, 3, pp.433–46.

Coccia, M. (2009c) 'A new approach for measuring and analyzing patterns of regional economic growth: empirical analysis in Italy', *Italian Journal of Regional Science*, 8, 2, pp.71–95.

Coccia, M. (2009d) 'Bureaucratization in public research institutions', *Minerva, A Review of Science, Learning and Policy*, 47, 1, pp.31–50.

Coccia, M. (2010a) 'The asymmetric path of economic long waves', *Technological Forecasting & Social Change*, 77, 5, pp.730–38.

Coccia, M. (2010b) 'Democratization is the driving force for technological and economic change', *Technological Forecasting & Social Change*, 77, 2, pp.248–64.

Coccia, M. (2010c) 'Foresight of technological determinants and primary energy resources of future economic long waves', *International Journal of Foresight and Innovation Policy*, 6, 4, pp.225–32.

Coccia, M. (2010d) 'Energy metrics for driving competitiveness of countries: energy weakness magnitude, GDP per barrel and barrels per capita', *Energy Policy*, 38, 3, pp.1330–39.

Coccia, M. (2010e) 'Public and private R&D investments as complementary inputs for productivity growth', *International Journal of Technology, Policy and Management*, 10, 1/2, pp.73–91.

Coccia, M. (2011) 'The interaction between public and private R&D expenditure and national productivity', *Prometheus – Critical Studies in Innovation*, 29, 2, pp.121–30.

Coccia, M. (2012a) 'Political economy of R&D to support the modern competitiveness of nations and determinants of economic optimization and inertia', *Technovation*, 32, 6, pp.370–79.

Coccia, M. (2012b) 'Converging genetics, genomics and nanotechnologies for groundbreaking pathways in biomedicine and nanomedicine', *International Journal of Healthcare Technology and Management*, 13, 4, pp.184–97.

Coccia, M. (2012c) 'Driving forces of technological change in medicine: radical innovations induced by side effects and their impact on society and healthcare', *Technology in Society*, 34, 4, pp.271–83.

Coccia, M. (2012d) 'Evolutionary trajectories of the nanotechnology research across worldwide economic players', *Technology Analysis & Strategic Management*, 24, 10, pp.1029–50.

Coccia, M. (2012e) 'Cartilage tissue engineering with chondrogenic cells versus artificial joint replacement: the insurgence of new technological paradigms', *Health and Technology*, 2, 4, pp.235–47.

Coccia, M. (2013) 'What are the likely interactions among innovation, government debt, and employment?', *Innovation: The European Journal of Social Science Research*, 26, 4, pp. 456–71.

Coccia, M. (2014a) 'Driving forces of technological change: the relation between population growth and technological innovation – analysis of the optimal interaction across countries', *Technological Forecasting & Social Change*, 82, 2, pp.52–65.

Coccia, M. (2014b) 'Socio-cultural origins of the patterns of technological innovation: what is the likely interaction among religious culture, religious plurality and innovation?, Towards a theory of socio-cultural drivers of the patterns of technological innovation', *Technology in Society*, 36, 1, pp.13–25.

Coccia, M. (2014c) 'Converging scientific fields and new technological paradigms as main drivers of the division of scientific labour in drug discovery process: the effects on strategic management of the R&D corporate change', *Technology Analysis & Strategic Management*, 26, 7, pp.733–49.

Coccia, M. (2014d) 'Religious culture, democratisation and patterns of technological innovation', *International Journal of Sustainable Society*, 6, 4, pp.397–418.

Coccia, M. (2014e) 'Emerging technological trajectories of tissue engineering and the critical directions in cartilage regenerative medicine', *International Journal of Healthcare Technology and Management*, 14, 3, pp.194–208.
Coccia, M. (2015) 'General sources of general purpose technologies in complex society: theory of global leadership-driven innovation, warfare and human development', *Technology in Societies*, 42, pp.199–226.
Coccia, M. and Cadario, E. (2014) 'Organisational (un)learning of public research labs in turbulent context', *International Journal of Innovation and Learning*, 15, 2, pp.115–29.
Coccia, M., Finardi, U. and Margon, D. (2012) 'Current trends in nanotechnology research across worldwide geo-economic players', *The Journal of Technology Transfer*, 37, 5, pp.777–87.
Coccia, M. and Rolfo, S. (2007) 'How research policy changes can affect the organization and productivity of public research institutes', *Journal of Comparative Policy Analysis, Research and Practice*, 9, 3, pp.215–33.
Coccia, M. and Rolfo, S. (2009) 'Project management in public research organization: strategic change in complex scenarios', *International Journal of Project Organisation and Management*, 1, 3, pp. 235–52.
Coccia, M. and Rolfo, S. (2013) 'Human Resource Management and Organizational Behavior of Public Research Institutions', *International Journal of Public Administration*, 36, 4, pp.256–68.
Coccia, M. and Wang, L. (2015) 'Path-breaking directions of nanotechnology-based chemotherapy and molecular cancer therapy', *Technological Forecasting and Social Change*, 94, May, pp.155–69.
Coe, N., Kelly, P. and Yeung, H.W.C. (2012) *Economic Geography - A Contemporary Approach*, Wiley, New York, NY.
Crevoisier, O. (2004) 'The innovative milieus approach: toward a territorialized understanding of the economy?', *Economic Geography*, 80, 4, pp.367–79.
Di Giano, M.L. and Racelis, A.E. (2012) 'Robustness, adaptation and innovation: forest communities in the wake of Hurricane Dean', *Applied Geography*, 33, pp.151–58.
Dicken, P. (2003) *Global Shift, Reshaping the Global Economic Map in the 21st Century*, 4th edn, Sage Publications, Thousand Oaks CA.
Feldman, M.P. (2003) 'The locational dynamics of the US biotech industry: knowledge externalities and the anchor hypothesis', *Industry and Innovation*, 10, 3, pp.311–28.
Feldman, M.P. and Audretsch, D.B. (1999) 'Innovation in cities: science-based diversity, specialization, and localized competition', *European Economic Review*, 43, 2, pp.409–29.
Feldman, M.P. and Florida, R. (1994) 'The geographic sources of innovation: technological infrastructure and product innovation in the United States', *Annals of the Association of American Geographers*, 84, 2, pp.210–29.
Feldman, M.P. and Kogler, D.F. (2010) 'Stylized facts in the geography of innovation' in Hall, B. and Rosenberg, N. (eds) *Handbook of Economics of Technical Change*, 1, Elsevier, Amsterdam, pp.381–410.
Feldman, M.P. and Romanelli, E. (2006) 'Organizational legacy and internal dynamics of cluster: the US human biotherapeutics industry, 1976–2002', *Cinquièmes Journées de la proximité: la proximité, entre interactions et institutions*, Bordeaux, 28–38 June, p.31.
GeoNames (2014) Available from http://www.geonames.org/ [accessed April 2014].
Girone, G. and Salvemini, T. (1999) *Lezioni di statistica*, II, Cacucci, Bari.
Gitay, H., Brown, S., Easterling, E.W. and Jallow, B. (2001) 'Ecosystems and their goods and services' in McCarthy, J. (ed.) *Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, pp.235–342.
Goldberg, J. (1996) 'Review article environmental impact assessment: why reform is needed', *Prometheus*, 14, 1, pp.90–9.
Hall, B.H. and Rosenberg, N. (eds) (2010) *Handbook of the Economics of Innovation, 1–2*, Elsevier, Amsterdam.

Hayami, Y. and Ruttan, V.W. (1985) *Agricultural Development: An International Perspective*, Johns Hopkins University Press, Baltimore MD.
Howells, J. and Bessant, J. (2012) 'Innovation and economic geography: a review and analysis', *Journal of Economic Geography*, 12, 5, pp.929–42.
Hudson, R. (2001) *Producing Places*, Guilford, New York.
Hunt, J. and Gauthier-Loiselle, M. (2010) 'How much does immigration boost innovation?', *American Economic Journal: Macroeconomics*, 2, 2, pp.31–56.
Jaffe, A.B. and Trajtenberg, M. (2002) *Patents, Citations, and Innovations: A Window on the Knowledge Economy*, MIT Press, Cambridge MA.
Kottek, M., Grieser, J., Beck, C., Rudolf, B. and Rubel, F. (2006) 'World map of the Köppen-Geiger climate classification updated', *Meteorologische Zeitschrift*, 15, 3, pp. 259–63.
Kremer, M. (1993) 'Population growth and technological change: one million BC to 1990', *The Quarterly Journal of Economics*, 108, 3, pp.681–716.
Krugman, P. (1991) *Geography and Trade*, MIT Press, Cambridge MA.
Kuznets, S. (1960) 'Population change and aggregate output' in *Demographic and Economic Change in Developed Countries*, Special conference series n. 11 Universities National Bureau for Economic Research, Princeton University Press, Princeton NJ, pp.324–40. Reprinted in *Economic Growth and Structure: Selected Essays*, W.W. Norton & Co., New York, NY, 1965, pp.123–41.
Lamberton, D.McL (1998) 'Exogenous factors in economic theory', *Prometheus*, 2, 1, pp.128–33.
Lee, N. and Rodríguez-Pose, A. (2013) 'Innovation and spatial inequality in Europe and USA', *Journal of Economic Geography*, 13, 1, pp.1–22.
Lichtenberg, R.M. (1960) *One-tenth of a Nation: National Fortes in the Economic Growth of the New York Region*, Harvard University Press, Cambridge MA.
Macdonald, S. (1989) 'Human qualities necessary for invention: independent inventors and the stimulus of adversity', *Prometheus*, 7, 2, pp.333–48.
Marceau, J. (2000) 'Innovation and industry development: a policy-relevant analytical framework', *Prometheus*, 18, 3, pp.283–301.
Martin, R. and Sunley, P. (1998) 'Slow convergence? The new endogenous growth theory and regional development', *Economic Geography*, 74, 3, pp.201–27.
Montesquieu, C. (1947 [1748]) *The Spirit of Laws*, Harper and Row, New York.
Moseley, W.G., Perramond, E., Hapke, H.M. and Loris, P. (2014) *An Introduction to Human-Environment Geography*, Wiley, New York.
North, Douglass C. (1981) *Structure and Change in Economic History*, W.W. Norton & Co., New York.
O'Brien, M.J. and Shennan, S.J. (2010) *Innovation in Cultural Systems Contributions from Evolutionary Anthropology*, MIT Press, Cambridge MA.
Olwig, M.F. (2012) 'Multi-sited resilience: the mutual construction of "local" and "global" understandings and practices of adaptation and innovation', *Applied Geography*, 33, pp.112–18.
Robbins, P., Hintz, J. and Moor, S.A. (2014) *Environment & Society*, Wiley, New York.
Rodima-Taylor, D., Olwig, M.F. and Chhetri, N. (2012) 'Adaptation as innovation, innovation as adaptation: an institutional approach to climate change', *Applied Geography*, 33, pp.107–11.
Rosenberg, N.J. (1992) 'Adaptation of agriculture to climate change', *Climatic Change*, 21, pp.385–405.
Rosenthal, S.S. and Strange, W.C. (2003) 'Geography, industrial organization, and agglomeration', *The Review of Economics and Statistics*, 85, 2, pp.377–93.
Ruttan, V.W. (1997) 'Induced innovation, evolutionary theory and path dependence: sources of technical change', *Economic Journal*, 107, pp.1520–29.
Singer, C., Holmyard, E.J. and Hall, A.R. (eds) (1961) *A History of Technology*, Clarendon Press, Oxford.
Smithers, J. and Blay-Palmer, A. (2001) 'Technology innovation as a strategy for climate adaptation in agriculture', *Applied Geography*, 21, pp.175–97.
Spolaore, E. and Wacziarg, R. (2013) 'How deep are the roots of economic development?', *Journal of Economic Literature*, 51, 2, pp.1–45.

Turner, R.K., Pearce, D.W. and Bateman, I. (1994) *Environmental Economics: An Elementary Introduction*, Hemel Hempstead, Harvester Wheatsheaf.
Von Hippel, E. (1994) *The Sources of Innovation*, Oxford University Press, New York.
Walker, B., Gunderson, L., Kinzig, A., Folke, C., Carpenter, S. and Schultz, L. (2006) 'A handful of heuristics and some propositions for understanding resilience in social-ecological systems', *Ecology and Society*, 11, 1, art. 13.
World Bank (2008) *World Development Indicators on CD-ROM*, The World Bank, Washington DC.
Wright, G. (1997) 'Towards a more historical approach to technological change', *The Economic Journal*, 107, September, pp.1560–66.
Zscheischler, J., Mahecha, M.D. and Harmeling, S. (2012) 'Climate classifications: the value of unsupervised clustering', *Procedia Computer Science*, 9, pp. 897–906.

Appendix A. Countries of the sample

Algeria, Argentina, Armenia, Australia, Austria, Azerbaijan, Bangladesh, Belarus, Belgium, Bosnia and Herzegovina, Botswana, Brazil, Bulgaria, Canada, Chile, China, Colombia, Croatia, Cuba, Cyprus, Czech Republic, Denmark, Ecuador, Egypt, Estonia, Ethiopia, Finland, France, Gambia, Georgia, Germany, Ghana, Greece, Guatemala, Haiti, Honduras, Hong Kong, Hungary, Iceland, India, Indonesia, Iran, Iraq, Ireland, Israel, Italy, Japan, Kazakhstan, Kenya, Korea, Kyrgyzstan, Latvia, Lesotho, Libya, Lithuania, Luxembourg, Macedonia, Madagascar, Malawi, Malaysia, Malta, Mauritius, Mexico, Moldova, Monaco, Mongolia, Morocco, Netherlands, New Zealand, Nicaragua, Norway, Pakistan, Panama, Peru, Philippines, Poland, Portugal, Romania, Russian Federation, Saudi Arabia, Serbia and Montenegro, Singapore, Slovak Republic, Slovenia, South Africa, Spain, Sri Lanka, Sudan, Swaziland, Sweden, Switzerland, Syrian Arab Republic, Tajikistan, Tanzania, Thailand, Trinidad and Tobago, Tunisia, Turkey, Turkmenistan, Uganda, Ukraine, United Kingdom, United States, Uruguay, Uzbekistan, Venezuela, Vietnam, Zambia, Zimbabwe.

Appendix B. Equations applied in the empirical analyses

The specification of the cubic models is:

$$LN\,PAR_{i,1995-2001} = \theta + \varphi_1 LONG + \varphi_2 LONG^2 + \varphi_3 LONG^3 + u_{i,t} \tag{B1}$$

$$LN\,PAR_{i,1995-2001} = \alpha + \delta_1 LAT + \delta_2 LAT^2 + \delta_3 LAT^3 + \varepsilon_{i,t} \tag{B2}$$

where PAR=patent applications of residents (1995–2001). The models in Equations (B1) and (B2) are estimated by the ordinary least squares method (Girone and Salvemini, 1999). Centre of gravity of the country is the arithmetic mean of the geographical coordinates (longitude x_i and latitude y_i)[3] of cities weighted by their populations n_i (Girone and Salvemini, 1999). The formula is:

$$\bar{x} = \frac{\sum_{i=1}^{s} x_i n_i}{\sum_{i=1}^{s} n_i} \quad \bar{y} = \frac{\sum_{i=1}^{s} y_i n_i}{\sum_{i=1}^{s} n_i} \tag{B3}$$

$(\bar{x}, \bar{y})$ is the geographical barycentre of the country and is a strong indicator of the predominant engine of innovation and wealth creation (Bettencourt *et al.*, 2007).

The centre of gravity of innovative outputs, taking into account the roundness of the Earth in the case of large countries, is given by:[4]

$$\bar{x}_{rad} = arc\,\mathrm{tg}\left(\frac{\sum \sin x_i \cos y_i n_i}{\sum \cos x_i \cos y_i n_i}\right) \tag{B4}$$

$$\bar{y}_{rad} = arc\,\mathrm{tg}\left(\frac{\cos\bar{x}\sin x_i n_i}{\sum \cos x_i \cos y_i n_i}\right) \tag{B5}$$

The variability of the territorial distribution, measured by the territorial dispersion that considers the roundness of the Earth, is (Girone and Salvemini, 1999):

$$\sigma_{(X,Y)_{rad}} = ar\cos\left(\frac{\sum \mathrm{cosx_i\, cosy_i n_i}}{N\cos\bar{x}\cos\bar{y}}\right) \tag{B6}$$

Equation (B6) provides similar results to Equation (B7), which is based on the formulas in (B3):

$$\sigma_{(x,Y)} = \sqrt{\frac{\sum_{i=1}^{s}(x_i-\bar{x})^2 n_i + \sum_{i=1}^{s}(y_i-\bar{y})^2 n_i}{N}} \tag{B7}$$

The decomposition of territorial dispersion considers temperate and non-temperate climate. The statistical units of the territorial distribution are clustered in r sub-sets of N_k (k=*1, 2, …, r*) with a specific statistical feature: in this study k=2 (countries within temperate and non-temperate climate). n_{ki} is the frequency of the statistical unit i of the sub-set k (patents per million people), and n_i is the frequency of the statistical units of the whole set.

If the geographical coordinates of the centre of gravity of the phenomenon of each sub-set are:

$$\bar{x}_k = \frac{\sum_{i=1}^{s} x_i n_{ki}}{\sum_{i=1}^{s} N_k} \tag{B8}$$

$$\bar{y}_k = \frac{\sum_{i=1}^{s} y_i n_{ki}}{\sum_{i=1}^{s} N_k} \quad k = 1, 2, \ldots, r \tag{B9}$$

and if the centre of gravity of the phenomenon of the whole set is:

$$\bar{x} = \frac{\sum_{i=1}^{s} x_i n_i}{\sum_{i=1}^{s} N} \tag{B10}$$

$$\bar{y} = \frac{\sum_{i=1}^{s} y_i n_i}{\sum_{i=1}^{s} N} \tag{B11}$$

Then, the territorial deviation is:

$$Dev(X,Y) = N\sigma_{X^2} + N\sigma_{Y^2} = \sum_{i=1}^{s}\left[(x_i+\bar{x})^2+(y_i+\bar{y})^2\right]n_i \tag{B12}$$

Thereby, the decomposition of the territorial dispersion is (X=longitude; Y=latitude):

$$Dev(X,Y) = \sum_{k=1}^{r}\sum_{i=1}^{s}\left[(x_i+\bar{x}_k)^2+(y_i+\bar{y}_k)^2\right]n_{ki} + \sum_{k=1}^{r}\left[(\bar{x}_k+\bar{x})^2+(\bar{y}_k+\bar{y})^2\right]N_k \tag{B13}$$

The first is the sum of the territorial dispersion within each sub-set; the second is the territorial dispersion of the centres of gravity of each sub-set from the centre of gravity of the whole set. Equation (B13) assesses whether the territorial distributions of each sub-set are more or less homogenous considering their centre of gravity and territorial dispersion. The specified formula for this study is (14B):

$$\begin{aligned} Dev(X) + Dev(Y) = {} & Dev\left(X_{non\,Temp}\right) + Dev\left(Y_{non\,Temp}\right) + Dev\left(X_{Temp}\right) + Dev\left(Y_{Temp}\right) \\ & + \left(\bar{x}_{non\,Temp} - \bar{x}\right)^2 N_{non\,Temp} + \left(\bar{y}_{non\,Temp} - \bar{y}\right)^2 N_{non\,Temp} \\ & + \left(\bar{x}_{Temp} - \bar{x}\right)^2 N_{Temp} + \left(\bar{y}_{Temp} - \bar{y}\right)^2 N_{Temp} \end{aligned} \tag{B14}$$

Appendix C. Tables of the empirical analysis

Table C1. Descriptive statistics for non-temperate and temperate climate

	Non-Temperate Climate		Temperate Climate	
Variables	Arithmetic mean	Standard deviation	Arithmetic mean	Standard deviation
Patent applications of residents 1995–2001	23.21	198.65	235.81	437.76
R&D expenditure as % of GDP 1994–2000	0.40	0.44	1.35	0.91
Researchers in R&D per million people 1995–2001	527.89	936.36	2,146.92	1,356.13
Scientific and technical journal papers 1995–2001	22.89	71.40	240.68	277.38
GDP per capita PPP $US 1994–2000	3,843.83	3,722.53	12,485.98	9,982.74
Human Development Index – HDI 2002	0.65	0.16	0.83	0.11
Population growth 1990–96	2.11	0.72	0.64	1.25
Population total 1990–96	36,104,405.93	42,879,244.66	58,789,104.61	189,374,848.44
Population in the largest city (% of urban population) 1990–96	30.85	16.62	24.78	14.28
Population in urban agglomerations >1 million (% of total population) 1990–96	21.71	19.70	23.31	13.07

Table C2. Bivariate correlations (Pearson's *r*)

		NON-TEMPERATE CLIMATE			
		PAR	*GDPPC*	*HDI*	PUA
PAR		1	0.75(**)	0.675(**)	0.727(**)
	N	118	113	118	91
GDPPC			1	0.904(**)	0.859(**)
	N		113	113	86
HDI				1	0.794(**)
	N			118	91
PUA					1
	N				91
		TEMPERATE CLIMATE			
		PAR	*GDPPC*	*HDI*	PUA
PAR		1	0.611(**)	0.674(**)	0.207(**)
	N	397	380	376	280
GDPPC			1	0.781(**)	0.338(**)
	N		380	366	272
HDI				1	0.291(**)
	N			376	271
PUA					1
	N				280

Note: **Correlation is significant at 0.01; PAR= Patent Applications of Residents (1995–2001); GDPPC=GDP per capita PPP current Int. $ (1994–2000); HDI= Human Development Index – HDI (2002); PUA= Population in urban agglomerations >1 million (% of total population) 1990–96.

Table C3. ANOVA and test of comparison of arithmetic mean between temperate and non-temperate climates (Variable: Arithmetic mean of LN patent 1995–2001 per million people)

			Test for independent samples - Test *T* of equality of mean		Test of robustness for equality of mean Brown-Forsythe*
ANOVA		Levene test variance homogeneity	Equal variances	Not equal variances	
F	350.972	1.032	*T*=18.73	*T*=19.72	388.958
Sign.	(0.00)	(0.31) ψ	(0.00)	(0.00)	(0.00)
d*f*	514	513	513	208.25	df_1=1; df_2=208.25

Note: * *F* has an asymptotic distribution; ψ=not significant.

Table C4. Arithmetic mean of patent applications per million people of three climate zones

		PAR=Patent applications of residents (1995–2001)	
Climate zones	*N*	Arithmetic mean	Standard deviation
Temperate South	37	167.60	226.15
Non-temperate	118	23.21	198.65
Temperate North	360	242.82	453.57

Table C5. Comparison of arithmetic mean of three climate zones (temperate North, South *vs.* non-temperate climate; variable: arithmetic mean of LN patent 1995–2001 per million people)

Levene test variance homogeneity		Test of robustness for equality of mean: Welch*	Brown–Forsythe*
Test	4.832	201.11	151.24
Sign.	(0.008)	(0.00)	(0.00)
d*f*1	2	2	2
d*f*2	512	88.05	93.88

Note: * F has an asymptotic distribution.

Table C6. Geographic coordinate regressions (cubic model) [Dependent variable: LN patent 1995–2001 per million people (arithmetic mean)]

Latitude		Longitude	
Constant	−0.6394***	Constant	3.902***
Latitude	0.0317***	*Longitude*	−0.0198***
$Latitude^2$	0.0034***	$Longitude^2$	−0.0003***
$Latitude^3$	−0.00004***	$Longitude^3$	0.000003***
F(Sign)	233.05 (0.00)	F (Sign)	28.237(0.00)
R^2*Adj.(St. Err.)*	0.575(1.65)	R^2*Adj. (St. Err.)*	0.137(2.35)
N	515	*N.*	515

Note: ***=Sign. p<0.001.

Appendix D. Optimization of the estimated relationships

The maximum/minimum of the geographic coordinates relationships (D15) and (D18), estimated in Table C6 of Appendix C, is performed by the following steps. For latitude (LAT) function ($\varepsilon_{i,t}$ is the error term), let:

$$LN\ PAR_{i,1995-2001} = -0.64 + 0.032LAT + 0.003LAT^2 - 0.00004LAT^3 + \varepsilon_{i,t} \quad \text{(D15)}$$

If y=LNPAR and h=LAT=latitude, the necessary condition to maximize Equation (D15) is:

$$\frac{\mathrm{d}y}{\mathrm{d}h} = 0.032 + 0.006LAT^1 - 0.00012LAT^2 = 0 \quad \text{(D16)}$$

The first derivative equal to 0 gives:

$$y'(h) = 0 \quad h_1 = \ 90.88\ \text{(MAX)}; h_2 = -24.21\ \text{(MIN)} \quad \text{(D17)}$$

These values are the decimal latitudes of the globe that maximize (*minimize*) the throughput of technological outputs. *Mutatis mutandis,* f or longitude (LONG) function, let:

$$LN\ PAR_{i,1995-2001} = 3.902 - 0.019LONG - 0.0003LONG^2 + 0.000003LONG^3 + u_{i,t} \quad \text{(D18)}$$

If y=LNPAR and k=$LONG$=longitude, the necessary condition to maximize Equation (D18) is:

$$\frac{\mathrm{d}y}{\mathrm{d}k} = -0.019 - 0.0006LONG^1 + 0.000009LONG^2 = 0 \tag{D19}$$

The first derivative equal to 0 gives:

$$y'(k) = 0 \quad k_1 = \ 60.99\ (\mathrm{MAX}); k_2 = -4.33\ (\mathrm{MIN}) \tag{D20}$$

These values are the decimal longitudes of the globe that maximize (*minimize*) the throughput of innovative outputs.