Earthscan Studies in Natural Resource Management

TROPICAL BIOPRODUCTIVITY

ORIGINS AND DISTRIBUTION IN A GLOBALIZED WORLD

David S. Hammond

ROUTLEDGE

Tropical Bioproductivity

This book investigates the fundamental role that tropical bioproductivity – or more specifically net primary productivity – has played in shaping the global geographies of food, finance, governance and people.

The book examines the basic astronomical and thermal properties of our planet to illustrate the dynamic nature of the tropics and how the region resides at the very heart of global energetics, driving the environmental flows that shape planetary climate and bioproductivity. The author explores how the region's relatively small, but hyper-productive, land area provided the groundswell for the economic, social, political and demographic changes that fuelled empires, European colonialism and nation-building. Also covered are discussions on how the critical intake of capital needed to fuel the industrial and technological revolutions driving modern globalization was first expropriated from the tropics by harnessing the region's natural productivity and biological crop diversity and then transforming it into tradeable commodities using the inhabitants' labour and knowledge. With modern tropical nations accounting for the bulk of people living in poverty and registering some of the highest income disparities, the author presents cross-cutting evidence showing that their histories and the persistence of expropriating institutions have fostered anocratic tendencies, poor governance, unorthodox financial flows and mass migration.

Tropical Bioproductivity cuts across vast geographies, topics and histories to deliver a readable narrative that links people, places and events with the environmental mechanics of our planet. It will be of interest to students and researchers in the areas of environmental studies, economics, history, agriculture, anthropology and geography.

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Preface

This book attempts to understand the role of the tropics and their bioproductivity in shaping human society and in particular their role in globalization. It asks three questions: why are the tropics bioproductive, how is this bioproductivity distributed across the tropics and in relation to the extra-tropics and how has tropical bioproductivity been important to the history of globalization? This is not a book about environmental determinism – a much derided term suggesting that people fail to develop due to unfavourable environments. On the contrary, it attempts to show how the superior bioproductivity of the tropics did not engender a need by tropical societies to go global, but drove Europe to catapult global society into a fast-lane of globalization because the tropics offered biological prizes that it did not have, but needed in order to achieve greater demographic, economic and cultural growth. Whether we like it or not, the fate of many regions of the tropics by the sixteenth century was to be rapidly subsumed into European history. This collision drastically altered cultures and landscapes in the tropics, but also reflexively, fundamentally altered European cultures and landscapes as well. The relationship was reciprocal but inequitable. In the final chapters, the book examines how, if at all, this historic linkage has played out in modern tropical nations, whether bioproductivity has proven a benefit or burden in a globalized economy and what root principles need to be pursued to allow tropical nations to escape both the poverty and the middle-income traps that they currently face.

One might suggest that the brush is too broad in painting this picture. Environmental science, history, economics, botany, geography, political science, philosophy and anthropology are rare compatriots in part because some rely mainly on numbers and others rely mostly on words. Handling such diverse topics might have been better achieved by assembling a group of world experts in their fields, but then the project would be just that – an assembly of disjointed perspectives missing the key connections. Without doubt, I have missed some of these too but travelling across boundaries has also revealed, I hope, some interesting relationships. If globalization teaches us anything, then it is that our world is made up of reservoirs, concentrations and storehouses and that change occurs through fluxes, flows or exchanges between these pools – I have chosen to focus mainly on the latter in this book.

Facts are better than opinions, but neither is necessarily true. I have relied extensively on both numbers and words, many being documented centuries ago and cross-checked from alternate sources and metrics wherever possible. But antiquity has a way of funnelling information towards singular sources and I cannot attest to the veracity of each source: some may be treated as fact, but are actually opinion. This uncertainty – the fact–opinion duality in historical narrative – must be both the bread and bane of all historians, though I do not claim to be one. In every instance, I have relied on original sources whenever available and then considered more recent analyses and treatments in their absence or where further clarification or cross-checking was needed.

Numbers can reflect motive as much as words. Data can be used to impress, to report success, to advance careers, to cover failure, to seek changes in policy or allocation of resources, or to forebode spectacular profit or imminent danger. I cannot attest to the full accuracy of the many environmental, economic, agricultural and demographic datasets employed in this book. I have provided caveats to these data where they have been highlighted by others, but have purposefully avoided the sort of in-depth coverage of data and methods that is more typical of purely scientific research publications. Generally speaking, historical data are less accurate than modern data due to advances in measurement technologies and fewer sources available for verification. This could play on certain patterns or trends presented in some of the chapters. Comparisons between datasets collected contemporaneously may contain bias, but differences are less likely to be affected by changes in accuracy. For example, a concern over the difference between net primary productivity data calculated from ground-based methods compared to remotely sensed (satellite) approaches is more relevant to absolute amounts than to comparisons between the bioproductivity of different regions and ecosystems. Data, wherever constructed from proxy measurements, represent the pool of estimates made by multiple authors when these are available. A fine example is the very wide range of estimates constructed by various authors in determining the role of sugar in the daily caloric intake of British citizens. I have taken the average of this pool in estimating its changing role.

Nothing is built in a vacuum. I wish to express my professional gratitude to the many scientists and historians that have responded to information and publication requests. I would like to extend my thanks to various persons that sparked my interests in complex tropical landscapes and histories, including Hardy Eshbaugh for introducing me to the chilli pepper and tropical ethnobotany; Tim Whitmore (1935–2002) for his guidance in forest land use and ecology; Vincent Florens, Claudia Baider, Sharveen Persand and Sujit for introducing me to Mauritius' environment and the

world of endangered island ecosystems; Ramon Perez-Gil and Dennis Breedlove for their guidance in understanding milpa agriculture and the biodiversity of Chiapas and José, Ignacio, Pedro, Broads, Lagadou, Daniel, George, Roxroy and others for their great assistance with work in the fields, forests and rivers of Mexico, Colombia and Guyana. I wish also to thank the Maritime Navel Museum at Greenwich, London, the British Library and the Archivo de las Indias in Seville for access to their facilities, as well as the Bank of England, National Oceanic and Atmospheric Agency (NOAA), European Space Agency (ESA), World Wide Fund for Nature (WWF), the World Bank, the Food and Agriculture Organization of the United Nations (FAO) and Oregon State University (OSU) for making available important datasets used in producing results presented in this book.

Part I

Structure, origins and distribution

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1 Two tropics

Cartography has always had a distorting effect on the way we perceive our planet. It is precisely the distortions introduced by cartographers in their fifteenth-century maps of the world that led Christopher Columbus in his belief that sailing west would lead directly to the spice riches of the Orient, setting the stage for several hundred years of ensuing war as the competing powers fought over the trade in tropical commodities – a path that has proven to profoundly shape our modern, global society, as we shall explore more clearly later in this book. These cartographic misconceptions continue to this day. Many school children still see the island of Greenland as exceptionally large. It appears larger than the continent of Australia, when it is actually less than a third of its size. This has to do with the universal adoption of the Mercator map and the way in which an imperfect sphere is converted into a rectangular map using a special type of cylindrical projection that was suitable for use in navigating the majority of low-latitude shipping routes of the day, but hopelessly distorts proportions across the sub-polar regions of our planet. Using the Tropics of Cancer and Capricorn to delimit the tropics is equally distorting, but for different reasons. Their position, and the extent of the tropics, has nothing to do with maps.

In Greek, a turn or turning point is *tropos* and in the world of European languages, the tropics derive their modern name from this root. It is an interesting descendancy. If asked how best to describe the tropics, most of us would probably point out the constant, high temperatures or the plants, like palms, that rely entirely on this thermal constancy to prosper. For much of the planet's population, the word denoting the "tropics" builds on this perception. In Chinese Mandarin and Japanese the characters combined to symbolize the "tropics" translate literally as "hot belt". A similar outcome is reached in Hindi, where "tropic" is derived from the combination of symbols for "tepid" and "zone" or "girdle". The linguistic approach taken in the East and West to describe the tropics is obviously very different. In the West, it was guided by the early observations that at a certain latitude, the Sun would slowly rise in the sky across one half of the year until it reached a point overhead on the summer solstice, only to turn about on that day and roughly re-trace its earlier ascent over the latter half of the year. The name reflects the fascination attached to celestial cycles by early Middle Eastern and European astronomers. In the Far East, the etymological origin is, by contrast, distinctly terrestrial.

Neither approach is inherently more comprehensive, more accurate, than the other in describing the waist of our planet. These different approaches, celestial and terrestrial, are two sides of the same coin. They reflect on cause and effect, and the inextricable link between the astronomical interactions that govern the size and position of our planet's tropical zone and the relatively high temperature of its climate. But there are important, sometimes surprising, variations in the thermal behaviour across the tropics and these do not always fit with the cartographic depiction. It is this dynamism, both celestial and thermal, that places the entire island of Madagascar, not just that part north of the Tropic of Capricorn, firmly in the tropics. More importantly, it was also this connection that drove the early European explorers to the New World, creating a crucible of global economic competition, and sparked the race to control the abundant resources of tropical nations that continues to this day. The consequences have been profound, not only to the planetary environment, but to the social and economic prospects of a club of nations beset with the jewels in the crown of global environmental value – an immense propensity for bioproductivity and the very high levels of biodiversity that appear to march in step with this profligate primary production of biomolecules.

The Tropic of Gemini

If the American author Henry Miller had also been an amateur astronomer he might have chosen to title his famously controversial book *The Tropic of Gemini*. Although the title appears to have little bearing on its content[1] the namesake for the title he chose, *The Tropic of Cancer*, is more commonly recognized as the boreal, or northern, boundary of the tropics. This imaginary circle describes the northernmost latitude where the Sun, at its zenith, can be observed directly overhead at the summer equinox. Further north of this line, the Sun's highest point in the mid-day sky drops lower towards the horizon and never quite reaches a point directly overhead. The same can be said of its antipodes, the Tropic of Capricorn. Together, these parallel circles form the edges of a broad tropical belt that stretches around the mid-riff of our planet. The problem with Mr. Miller's title, and the continued use of Cancer and Capricorn, can be traced to their origins. Archaeological evidence suggests that the 12 common zodiacal constellations were organized into an astrological system of timekeeping by the ancient Babylonians around the fifth century BC. This system attached the position of the Sun at the four cardinal points in a year, the solstices and equinoxes, to the constellations that it appeared to intersect on those days. At the time, the Babylonians would have correctly observed that the Sun's track in the sky (the solar ecliptic) came in contact with the constellation of Cancer on the (northern) summer solstice sometime in the latter half of June. Equally, the solar ecliptic would have placed the Sun in front of Capricorn during the December winter solstice more than 1,500 years ago. The Babylonian scholars cleverly organized the celestial hemisphere into a timekeeping device that provided an accurate means of tracking time throughout the year. What they failed to understand was that this annual periodicity is subject to change at greater timescales and that the solar ecliptic would not remain permanently pinned to the constellations.

Four hundred years later it was the Greek astronomers, most notably Hipparchus and Ptolemy, who first documented that our planet does not simply spin on a fixed axis, but that the axis itself must be moving. They understood this by noting how the position of the stars had changed from the time of measurements recorded by their predecessors. It transpires that there are a number of cycles at work, but the Greeks recognized early one of the greatest of these manoeuvres: axial precession. Precession is best described as a wobble – the type we observe as a spinning top loses speed. The vertical axis of the fast-spinning top migrates from a perpendicular position relative to the surface towards a position parallel to the surface. As this happens, two imaginary cones are formed along the axis of spin. The base circles of these cones define the wobble and the time it takes for the axis to travel 360 degrees along the circle is the precessional cycle. We are currently moving 1 degree along this circle in an average person's lifetime, about 71 years. Considering this rate, the time it takes to complete a full wobble amounts to 25,560 years. Some 400 years after the Babylonian zodiac was established, it became clear that its position relative to the Sun was not fixed, but cycled through the 12 constellations in tandem with the Earth's wobble. At that rate, this places the current solar ecliptic in contact with Taurus (Gemini prior to 1990) and Sagittarius at the summer and winter solstices. In deference to long-established convention (but really to avoid all sorts of confusion), I reluctantly maintain this reference throughout the chapter. It may seem a point of historical trivia, but the underlying dynamical behaviour driving the need for a name change to two of the most widely known global geographic features highlights the difference in the way we can see the tropics as a fixed, geographic zone or as a dynamic consequence of celestial interactions and varying surface features that lead to changes in the distribution of global bioproductivity.

The celestial tropics are shrinking

The dynamic nature of planetary motion is continuously altering the geographic extent of the tropics. The Tropics of Cancer and Capricorn are currently positioned at 23.44 degrees north and south of the equator.

But their true position is changing based on a slow oscillation in the tilt of our planet relative to the Sun, referred to as obliquity. Obliquity is calculated by the difference between the angle of the line passing through the north and south poles – the same axis on which our planet spins – and another line running through our planet that is perpendicular to the ecliptic plane. The ecliptic plane describes the path of the Earth as it orbits the Sun, or, conversely, the position of the Sun in the sky as seen from the Earth. The wobble that causes precession of the equinoxes, as described earlier, is a consequence of this axial tilt. Without a tilt, the planet would spin but without its characteristic wobble, and there would be no long-term change in the direction the planet faces on the equinoxes or solstices. The same push-and-pull battle between gravitational forces that causes our planet to wobble over a 27,000+ year cycle simultaneously causes it to behave in a way that slowly changes its tilt relative to the Sun. This occurs more slowly than precession, taking approximately 41,000 years to complete a full cycle from the upper to lower limits of 24.5 and 22.1 degrees and back again.[2] Over hundreds of millennia, this pattern takes a signal form, as a repeating series of waves with ascending and descending phases. We are currently in the descent, which means that the axial tilt is lessening and our planet is moving towards the ecliptic plane. Figure 1.1 illustrates the oscillatory nature of obliquity and precession, the differences in their periodicities, and how these behave more like a trend than an oscillation at smaller timescales. Transcribed onto the surface of the planet, this pattern reveals the general effect of obliquity on the position of the Tropics of Cancer and Capricorn in relation to the surface of our planet. This movement equates to a little more than one-fifth of an arc-second, or about 6 metres, per year on average. But extended over the full breadth of the planet this amounts to around 5,500 square kilometres of surface area moving outside the tropics each year – an area twice the size of Luxembourg, slightly larger than the state of Delaware or the country of Trinidad and Tobago. As the current phase of the cycle continues to compress that part of our planet exposed to an overhead Sun, the surface area leaving the tropics each year will accelerate. This is due to our planet not being a proper sphere, but more ellipsoidal in shape. This has the effect of growing the circumference of the Tropics of Cancer and Capricorn at a faster rate as these boundaries slide towards the equator in tandem with a decrease in tilt. The anticipated motion over this cycle indicates that the next minimum obliquity should occur around 12,030 AD and then the tropics will abruptly turn course and begin marching back towards the poles. By then, the tropics will have contracted by slightly more than 5 per cent of their current area. This is a small fraction perhaps, but equivalent to a massive 10.2 million square kilometres, or an area larger than Canada.

Obliquity interacting with the ellipsoidal form of our planet determines the extent of the tropics by regulating how much of our planet's surface is

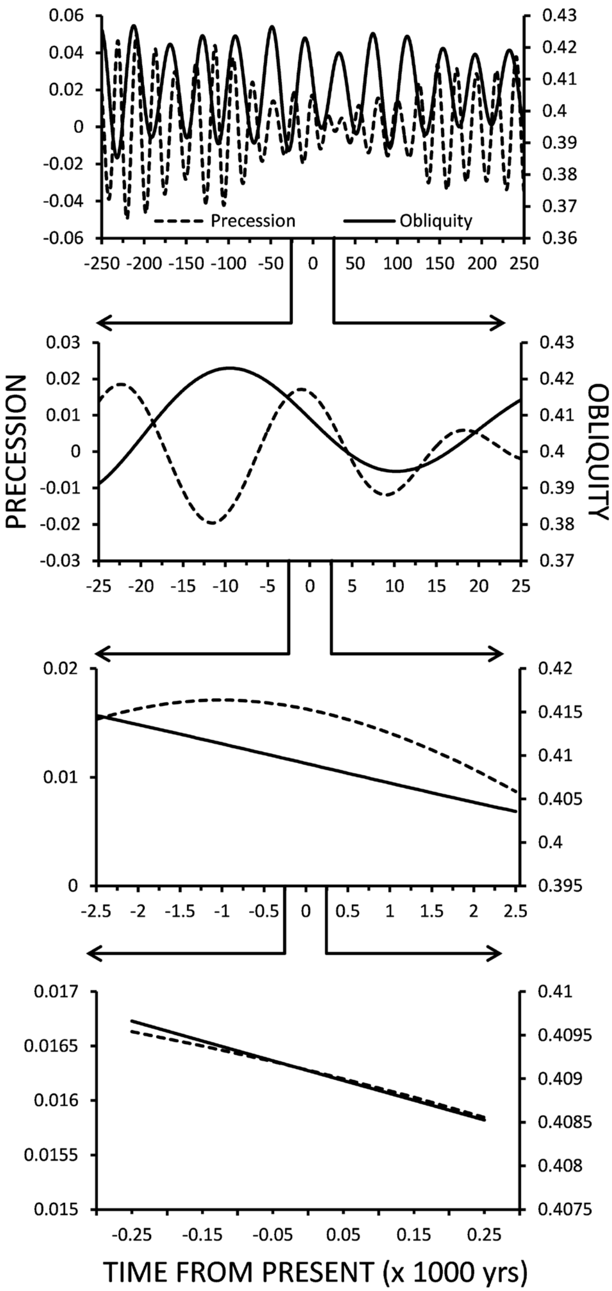

Figure 1.1 The behaviour of precession and obliquity decomposed into four logarithmic timeframes between 250,000 and 250 years before (–) and ahead (+) of present time.

exposed to more intense overhead sunlight. If we could position ourselves outside the solar system and accelerate the pace of time we would see a spectacle composed of many different dances, performed in harmony, each deriving its motion from differences in planetary mass and the forces altering these over different time periods. Some consist of slow, languid movements that only complete a cycle once every tens of thousands of years. Precession and obliquity, as we have described, are the most relevant motions, but others, such as the shape, or eccentricity, of the Earth's orbit around the Sun can play critical roles over longer timelines. Still others move more quickly, such as lunar nutation,[3] creating more frequent, less predictable, but substantively smaller inflections. The shape of the planet also changes over time and this contributes to changes in the extent of the tropics. Simply put, it is thought that this occurs as the distributions of water and ice are altered over the long term by the variation in the Earth's orientation and distance from the Sun and over the near term through oscillatory behaviour of very large environmental circulation systems, such as the El Niño Southern Oscillation (ENSO) or Pacific Decadal Oscillation,[4] or through changes in ice mass at the polar limits. All of these can "squeeze" or "release" the Earth to alter the amount of surface area falling within the tropics – they alter the geodetic state of our planet. Together, the continuous push-and-pull of gravitational forces exerted by the celestial bodies in our solar system combines with changes in the planet's shape through time to alter both the amount and distribution of solar radiation intercepted by our planet. This can clearly be seen by calculating the insolation at the current position of the Tropic of Cancer and then projecting the amount both in the past and future at different timescales, as seen in Figure 1.2. In the most immediate timeframe at the bottom of this graph, the amount of radiation received at this latitude is declining in line with the descending phase of obliquity. At larger timescales, changes to insolation become less periodic, reflecting the composite signal of overlapping cycles.

The tropics then, again, are not simply a cartographic construct. Nor is this area static. Unlike many other global map objects born from the great age of European exploration, the Tropics of Capricorn and Cancer were not imaginary lines put in place to better assist us in expanding transport and communications, to tell us where we are when faced with an infinite horizon, or, as was the case with the establishment of the Prime Meridian and fixed degrees of longitude, to parcel continuous time on a spinning globe to aid and abet growing European maritime power. In its most basic, physical form, the tropical zone is a composite signal formed from interacting celestial motion and mass. The result is a geographic area stalwart in its contribution to the global energy budget, but continuously changing in size; a puppet in fact – riding on a planet with mass and motion of its own, but suspended by gravitational strings, with our larger celestial neighbours in the collective role of puppet-master.

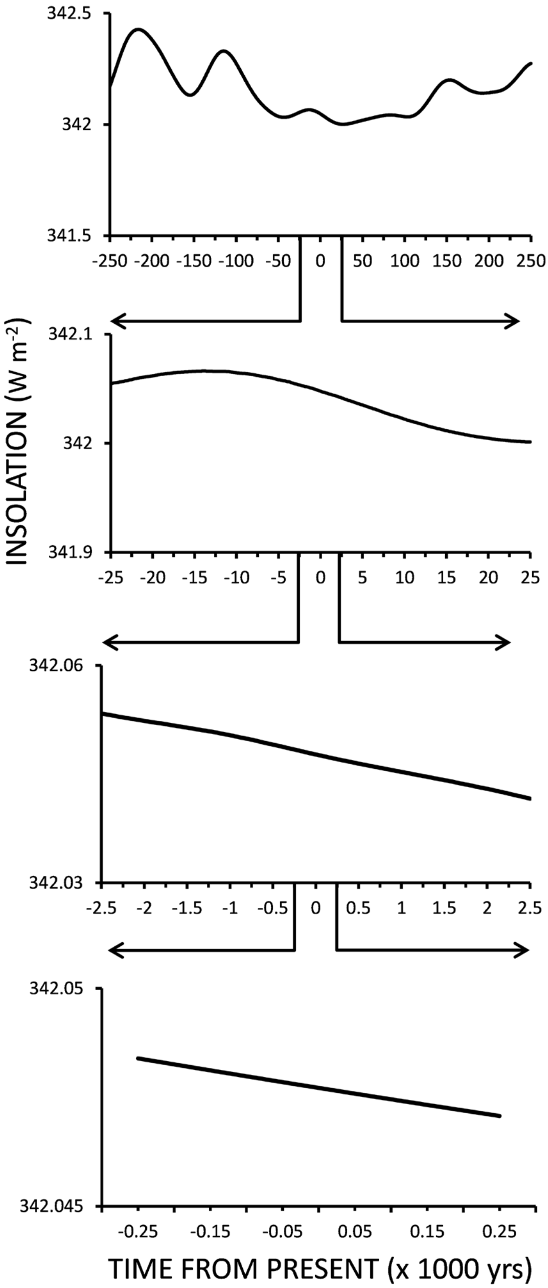

Figure 1.2 The change in total insolation intercepted by Earth as a function of Milankovitch cycling decomposed into four logarithmic timeframes between 250,000 and 250 years.

The thermal tropics are widening

The Greek astronomers and their predecessors had good reason to turn to the sky in describing the tropics. The motion of our planet manifestly shapes variation in the timing and duration of solar irradiance. It also drives the re-distribution of the energy imported through this irradiance and thus the potential bioproductivity of the Earth's surface. In turn, the amount of solar radiation received and re-distributed each day and throughout the year dictates temperatures, how much they vary and, in part through this, global patterns of bioproductivity. However, while the mechanics of gravitational interactions between our planet and its celestial neighbours are the primary cause of variation in the amount of energy received across the Earth's surface, other factors work vigorously to alter this blueprint. These factors then also create aberrations, distortions, often referred to as anomalies, in the global energy distribution. To understand the thermal effect of this variation, we can return to the Far East and their planet-bound, terrestrial definition of the tropics.

Faced with describing the tropics, virtually everyone I have ever asked employs "hot" or "warm" in their response, apart from a few unruly colleagues that invariably throw in a more expansive, but fine-tuned biological, chemical or geological description. On one hand, temperature is what we sense, what we feel. It is how our neural network communicates to our brain the differences between the ambient conditions and the exchange of energy that takes place between our surroundings and that of our own internal, self-regulated, thermal state. But temperature measured relative to how we sense differences, our skin temperature, is not the same as that measured using other approaches, commonly referred to as the surface temperature. Air temperature is strongly affected by the height above the planet's surface as clear air density declines at a constant rate up through the first ten kilometres of the atmosphere – the troposphere. This rate of decline, the adiabatic lapse rate, tells us what temperature we can expect at any given height, or altitude, above the surface at any given latitude. This of course is a critical factor in explaining the cooler temperatures we experience in ascending mountains on a clear day anywhere on the planet. Measuring surface temperature typically involves a single station positioned at a fixed point above the ground or, in the case of measurements taken remotely aboard aircraft or satellites, integrates the measurement over a pre-defined slice of air resting at the base of the troposphere closest to the ground. However, a critical issue in making comparisons between surface temperature datasets arises when values are derived from different altitudes, thereby altering, among other influences, the effect of lapse rate on the integrated temperature reading. Consequently, surface temperatures observed through different techniques may not yield the same results.

Calculating the lapse rate impact of elevation on temperature will typically get you very close to a measured reading when the atmosphere is clear and still. Yet we know that ideal conditions, when they occur, rarely remain across most regions of the planet. Wind and rain invariably take up a far larger slice of the year than many of us living in the rain belts would like, while bringing much anticipated, but all too brief, relief to those living in more arid environments. But these disturbances, long and short, create extraordinary deviations from surface temperatures as measured under ideal conditions. The difference between temperature measured on a clear, still day and that taken during a wet and windy day is apparent to anyone who has experienced the listless effect of tropical humidity or the bitter bite of high-latitude windstorms. Both conditions – high humidity and high wind – alter the surface temperature profile by changing the way in which energy near the Earth's surface is moved about. As a result, they alter our perception of temperature too. Those of us having experienced high tropical humidity know the stupefying effect it has in transforming the paradisiacal into purgatorial. Conversely, the freeze of a cold mid-winter's night can become practically cryogenic as the "wind-chill factor" drives the temperature we feel far below the actual air temperature near ground level. The difference between how we feel the heat or cold under these conditions and the actual temperature illustrates the difference between skin and surface temperatures. Most modern efforts to characterize temperature regimes have evolved sophisticated procedures to remove the varying effects of wind and humidity to reveal more comparable surface temperatures. Here, surface temperature, and how it is shaped by conditions within the lower troposphere, is always used in describing the thermal characteristics of the tropics. The interplay between surface temperature and humidity plays a particularly important role in defining terrestrial bioproductivity potential and efforts to classify the tropics into distinct vegetation growth zones and climate regimes have proven just how difficult it can be to separate temperature from humidity in particular while revealing that when it comes to the factors engendering elevated bioproductivity, more is not necessarily better.

The tropics are classified

An orderly approach to understanding how the distribution of temperature defines the tropics – as it deviates from that delimited by the Tropics of Cancer and Capricorn – can be found through climate classification, and its important relationship with plant growth. Perhaps the best known, and most well-received, classification system was developed by the Russian-German climatologist Wladimir Köppen over a 50-year period from 1884 to 1936. Köppen was one of the earliest climatologists during a time when very little of the mechanics governing planetary climate was understood. His system classified global climate into five broad types, according to temperature and precipitation (Köppen 1884, 1918). This was a sensible approach since both variables are intimately related to the amount of incoming solar radiation and biological productivity, as we will see later. Forever improving on his initial system, Köppen continued to refine the classifications and their geographic distributions until his death, at which time his friend and colleague, Rudolf Geiger, continued the work. His system, along with those later developed by others, remains a lynchpin in the general understanding and communication of global climate distribution and continues to be updated today (Rubel and Kottek 2010).

Köppen defined tropical climates as those experiencing average temperatures exceeding 18°C (64°F) in every month of the year. Virtually everyone on the planet, except the relatively few living above the polar circles and at the higher elevations of the greatest mountain chains, experiences mean monthly temperatures exceeding this limit. But these are seasonally driven by our planet's wobble and not sustained throughout the year. Applying Köppen's tropical limit to global temperature measurements derived from modern, satellite-borne instrumentation, averaged over the period 2000 to 2010, indicates that residents of Los Angeles, Miami, Cairo and Karachi were living in the tropics, at least for this decade. While all of these cities are known for their high temperatures, the surprise in this fact is that these cities are located up to 10 degrees of latitude north of the celestially defined limit – the Tropic of Cancer. In Asia, Köppen's classification extends only marginally beyond the Tropic of Cancer and noticeably less than across the Middle East, North Africa and North America. This limit also extends beyond the Tropic of Capricorn in the southern hemisphere, but only in South Africa, Madagascar, Western Australia and southern Chile is it seen to penetrate poleward to a similar extent, reaching cities such as Durban, Carnarvon and Antofagasta. The poleward extension of the secular tropics beyond their celestial boundary seems more the rule than the exception for both north and south limits, but only at regional scales.

Others followed Köppen's footsteps in developing classificatory schemes for global climate. Perhaps best known among these were the water-balance approach developed in the late 1940s by Charles Thornthwaite, a Professor of Climatology at John Hopkins University, and the life zone characterization scheme assembled by Leslie Holdridge, a tropical botanist and climate scientist based in Costa Rica. Thornthwaite was convinced that a basic water-balance approach – considering the variation in water arriving in an area as rainfall and leaving through evapotranspiration, absent surface run-off and storage – was the most accurate means of classifying climatological gradients since these were intimately linked to plant growth and through this, vegetation types. Temperature was rightly considered an indirect driver of the water balance, but unlike Köppen's approach, it was not employed directly in delimiting tropical climate. In his seminal 1948 article describing this two-pronged approach to climate classification (Thornthwaite 1948),[5] Thornthwaite indicated that he considered an average temperature of 23°C (73.4°F) to best delimit a tropical, megathermal condition from the more subtropical and temperate, mesothermal environments experiencing lower potentials for evapotranspiration due to increasing seasonality of day length and solar radiation.

A year prior to Thornthwaite's publication, Leslie Holdridge presented his life zone classification system (Holdridge 1947). This depicts the global climate as a series of graduated units ranging along a triangulated continuum of rainfall and evapotranspiration, but with the addition of temperature as a direct factor sorting life zone types along latitude and elevation. His triangular diagram depicting life zone compartments along rainfall, temperature and evapotranspiration gradients became an indispensable tool in standardizing the description of local climate. Holdridge, like his contemporary Thornthwaite, chose a much higher minimum average temperature, 24°C (75.2°F), in defining the tropical limit than their predecessor Köppen. In many ways, it is unclear why Holdridge and Thornthwaite chose this higher thermal limit in characterizing the secular tropics. Holdridge clearly recognized Köppen's tropical boundary by inserting a unique "critical temperature line" at the 18°C limit running across the belt of subtropical life zones to separate these from warm temperate regions. This would have been sensible in distinguishing subtropical zones that rarely experience lowland frosts, such as southern Florida or southern Yunnan Province in China, from the true lowland tropics that never experience such events. Holdridge also characterized thermal limits using an unusual temperature profile. He adopted a "biotemperature" that he believed would better shadow the limits to plant growth by averaging only those temperatures between 0°C and 30°C. At higher latitudes, this was meant to filter out the impact of long periods of sub-zero temperatures when there was no effective plant growth, but dealing with the tropics proved more complicated.

If we apply Thornthwaite's and Holdridge's tropical limits to the distribution of global land temperature as measured from satellites, we see a fundamental problem arising in their classification of the thermal tropics – most of the equatorial regions fall below their thermal minimum (Figure 1.3). This effectively excludes these core areas from the tropical zone designated to differentiate these very same areas from those experiencing wider ranging, lower temperatures. Using these average annual temperatures in Holdridge's system, most equatorial forests are classified as subtropical. Köppen, despite having developed his system more than a half-century prior, adopted a lower thermal limit that is more consistent with the full range of average temperatures across the tropics. It could be that Thornthwaite's and Holdridge's limits reflect a difference in the way that temperature is measured by satellite sensors compared to the more traditional, station-based thermometers that prevailed at the time – this is clearly a potential source of variation. But reading Holdridge's *Life Zone Ecology*, it is clear he knew that temperatures were lower at the equator than at the Tropics of Cancer and Capricorn, but in the absence of good

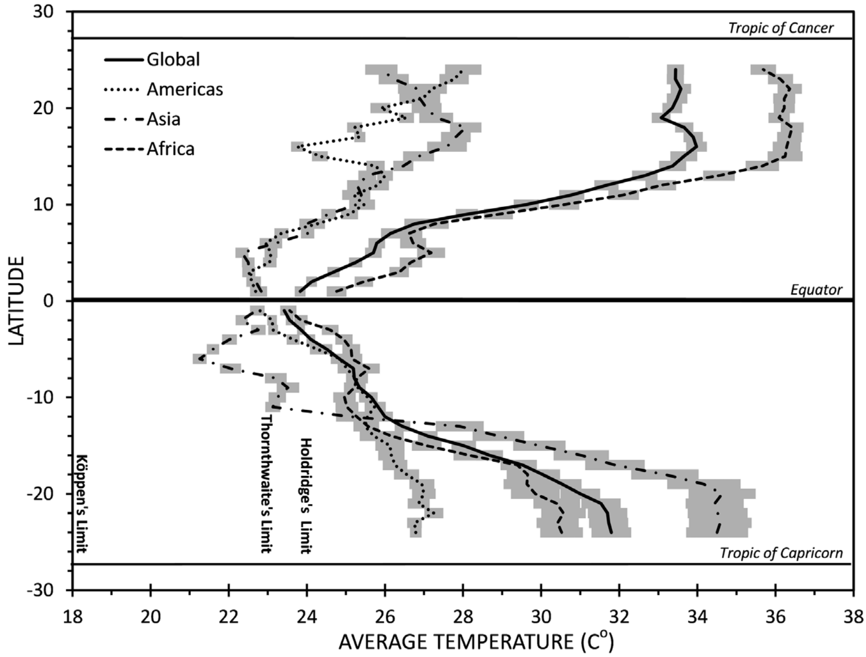

Figure 1.3 The pattern of average temperatures by latitude as recorded in 2000s across the global tropics and in each continent and referenced by the minimum "tropical" threshold temperature adopted in the three main climate zone classification schemes.

Note
Grey bars represent +/– 1 standard error of mean.

ground station coverage, it may be that he and Thornthwaite, without the advantage of remote-sensing, did not anticipate the degree of difference between these. Of course, what is said for them can also be said for Köppen. Could it be that they simply hinged their classification on average annual temperatures across the tropics, rather than discriminating, as Köppen did, regional differences by placing a minimum threshold on average monthly temperature? Examining the distribution of average annual temperatures over the same period, using the same data, unfortunately doesn't resolve this issue. Adopting an annual average temperature as the thermal limit simply extends the thermal distribution of the tropics poleward by 10 to 15 degrees latitude as high summer temperatures combine with more modest winter temperatures at the mid-latitudes to raise the average. The equatorial tropics, however, remain outside the thermal limit of Holdridge and Thornthwaite whether we adopt a monthly average or an annual average as the basis for discriminating the thermal minimum.

Distinguishing between areas consistently above this temperature and those that vary above and below tells us a great deal about thermal seasonality within the tropics and how this varies across the tropics, a fact that is often overlooked in describing the "hot belt". In retrospect, the minimum temperature limit placed on the thermal tropics by Köppen appears an amazingly good choice when we consider the relative dearth of solid climatological information available when he constructed his classification. His acumen led him to a system that accurately reflected transitional temperature gradients at a time when segmenting, separating and compartmentalizing the natural world into categories and classes really did drive the bulk of scientific thought. It turns out that for his successors, delimiting the outer bounds of the thermal tropics was not the main sticking point to tropical climate and life zone classification, but rather addressing an unanticipated dip in temperature from its centre to edge. As time has passed, Thornthwaite and Holdridge have kept much company in viewing the tropics as a thermally constant zone reaching from the equator to the Tropics of Cancer and Capricorn or declining along a gradient from equator to pole. Neither appears to be the case if we adopt a land temperature approach. We can see the magnitude of average temperature increase more clearly using the data collected on board NASA's CERES Terra satellite over the decadal period from 2000 to 2010 (Figure 1.3). These data allow us to see land surface temperature for the tropics as a whole and by regions. They are derived through a relationship between the amounts of radiation detected twice-daily at various band widths by the on-board MODIS spectrometer.[6] While very different from the traditional thermometric approach to measurements, they combine a much-needed departure from the disparate error margins of spatially unbalanced station-based monitoring with unparalleled pantropical coverage. To their detraction, the data have only been collected since the turn of the millennium, constraining their use in assessing longer-term patterns in temperature variation across the tropics.

The curves in Figure 1.3 illustrate the spatial decline in average global land temperature from the edge to centre of the tropics. We see in the composite curve (solid black line) a minimum pantropical temperature at the equator at 24°C. If we recall the dilemma presented by these modern satellite-borne data to Thornthwaite's and Holdridge's efforts to classify tropical climate, we can see that their chosen cut-off point fits relatively well with the global average equatorial temperature. It may be that they utilized this global average to render their classificatory limit for the region. But considering how land temperature changes within each region separately also reveals that there are considerable differences in the shape and depth of this decline across the tropics. The African tropics are considerably warmer than those in Asia or the Americas. This is particularly pronounced in the northern, or boreal, tropics where the equatorial region is squeezed between the vast Saharan and Kalahari deserts. Only in the outermost band of the southern, or austral, tropics is there a similarly rapid rise in temperature away from the equator as the deserts that make up the massive Australian Outback begin to take up an overwhelming share of the land area.

This then is the source of Thornthwaite's and Holdridge's dilemma. Their limits work nicely when considering temperature on a pantropical average basis (Figure 1.3). But this single average belies a large portion of the land area straddling the equator in Asia and the Americas that drops below their assigned limits and, consequently, falls into a subtropical classification. These anomalous regions are clearly visible in Figure 1.3. Köppen's limit varies from year to year in its poleward extension from the equatorial regions. In "warm" years it extends well beyond the Tropics of Cancer and Capricorn, absorbing many southern parts of the United States and China into the thermal tropics. During "cool" years, it contracts towards – and sometimes equatorward of – these celestially defined limits. But taking the average of all months over this same period, from 2000 to 2010, we can smooth out these important, but short-lived, variations. It yields a thermal tropical zone that is amazingly consistent with the invisible limits put in place by the gravitational interactions between our planet and its celestial neighbours, but it is important to remember that these too fluctuate.

The thermal tropics – the "hot belt" ascribed through East Asian languages – it seems is not necessarily more thermally constant than some extra-tropical regions. It expands and contracts from year to year, hovering around – not on – the celestial boundaries. Nor is it, as one might expect, the warmest at its centre – the equator. Land temperatures in areas as much as 10 degrees poleward of the tropical limits can average at or above those near the equator. Satellite-derived data also suggest a surprising amount of variation between tropical regions, most particularly between Africa and the other two main tropical regions in the Americas and Asia. The tropics then perhaps are most simply described as a frost-free zone that, on average, is warmer throughout the year than other similarly sized areas outside the tropics.

The wet and dry tropics

The tropics are differentiated by a minimum temperature threshold from the extra-tropics, but between the two outer boundaries the variation in temperature can be significant. This variation is relatively small compared to the extra-tropics for the reasons related to precession and eccentricity of our planet, but spatial and seasonal variation in precipitation is a much larger source of environmental change in the tropic zone. It is not my intent here to review the processes that govern precipitation patterns and there are many excellent volumes, such as Robinson and Henderson-Sellers (1999) and Hartmann (2015), focusing with great clarity on these as a fundamental component of our planetary climate. But understanding the distribution of bioproductivity, its origins and how it has surreptitiously stewarded globalization through to modern times relies in no small amount upon the factors impacting where and when rain falls across the tropics.

There are three major processes that dictate global patterns of tropical rainfall. Two operate at a global scale and one regionally. The most prominent feature at the regional scale is the action of a rapid rise in elevation. Mountain chains on all three continents act to "trap" moisture by forcing warm, moist air masses to rise, cool and precipitate as they move upslope, a process referred to as orogenic lifting. Cloud and elfin forests often form in the elevational band where this moisture condenses while the downslope run-off sustains high water tables in the adjoining lowland regions below. This rapid rise depletes the colliding air mass of its energy, leaving it relatively cool and dry as it descends the opposite side of the mountain range, often creating a "rain shadow" effect. The second process is the dynamic fluctuation in coupled atmospheric and oceanic conditions in the tropical Pacific related to ENSO. Changes in the state condition of ENSO create global changes in seasonal rainfall, particularly in northern South America, Central America and across the Pacific to South-East Asia (Ropelewski and Halpert 1987). The process is oscillatory in nature, characterized by recurrent migration of high sea surface temperatures and rainfall across the tropical Pacific in an accordion-like manner. Like the opposite slopes of a mountain chain, when one side of the Pacific under ENSO receives greater than average rainfall, the other is receiving less than normal. Other factors can shape rainfall variation in these regions of course, but ENSO, when in a non-neutral state can grow an imbalance between the east and west that dominates rainfall not only in the Pacific, but across other oceanic sectors as well. It also fundamentally shapes how energy is transferred poleward, but more about this important dynamic in the next chapter.

Orogenic lifting and ENSO create spatially anomalous changes in rainfall levels, but the largest segregating impact on rainfall within the tropics is governed broadly in the same way that our planet's angle, wobble and orbit interact with the Sun to determine the amount of solar insolation at a given latitude. The consequence is a tropical zone that is extremely hot and dry at its margins and warm and wet near the equator. Figure 1.3 illustrates the rise of temperatures towards the tropical margins and we can see the general inverse effect on rainfall in Figure 1.4. This graph represents the average annual rainfall as it varied with latitude between the years 2000 and 2010. The data are derived from NASA-JAEAs' Tropical Rainfall Measuring Mission (Kummerow *et al.* 1998). The minimum level of rainfall across the tropics occurs close to the margins at 20–25 degrees for both marine and terrestrial sectors, but you will notice that terrestrial rainfall near the Tropic of Capricorn is around 50 per cent greater than the

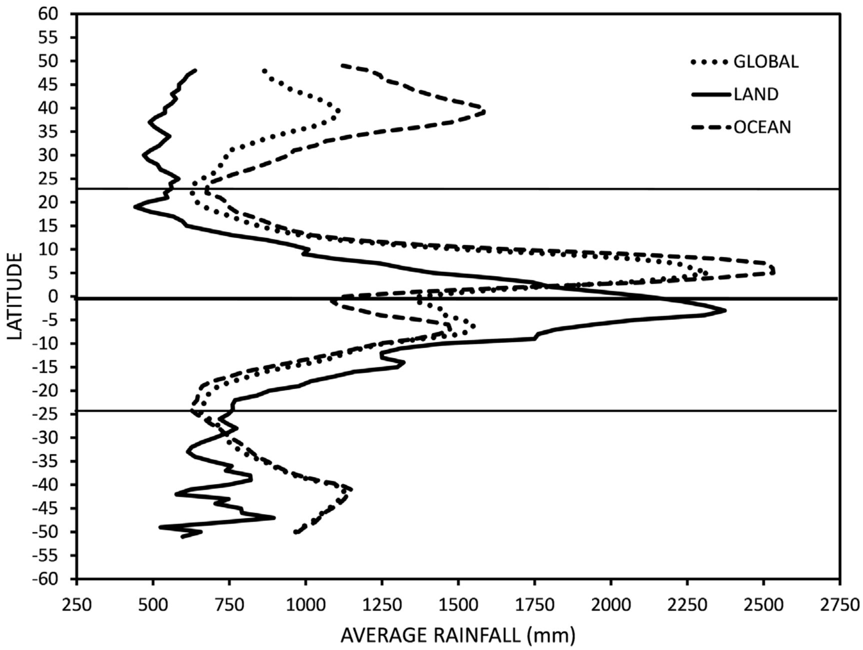

Figure 1.4 The average annual rainfall across tropical oceans and land by latitude derived from satellite observations between 2000 and 2010.

amount registering near the Tropic of Cancer. With much larger land area along the latter, a continentality effect reduces the mitigating effect of onshore flow of moisture along coastlines. This is most pronounced over North Africa where evaporation is extreme and strong westerlies carry off any available moisture to create the world's largest desert. This belt of aridity extends across Western Asia.

Over the oceans, the reduction in rainfall at the outer edges of the tropics is more symmetric because evaporation is not subject to this geographic change in moisture availability. Peak average rainfall over land and sea are also not spatially coincident. The oceanic peak is coincident with the average position of the Inter-Tropical Convergence Zone (ITCZ). Over the oceans, this position remains fairly stationary relative to its movement over the continents. Again, energy fluxes over land are more dramatic over time compared to those over oceans and this broader range drives the ITCZ to migrate over a broader range of latitude compared to oceans. You can also see a dip in rainfall over the equatorial oceans caused by the equatorial counter-currents. These currents emerge through surface wind displacement, allowing water to rise from depth, lowering sea surface temperatures and evaporation. The global pattern of rainfall described in Figure 1.4 is a precursor to understanding the distribution of tropical bioproductivity. Importantly, it also describes a broad, arid belt that separates the equatorial wet tropics from the moist, temperate latitudes. As I discuss in later chapters, the dry tropics are symptomatic of the global processes that geographically stratify the distribution of bioproductivity and it is this stratification that played a critical role in the emergence of globalization. Both terrestrial and marine environments are subject to this stratification, but making comparisons between similarly sized areas of ocean and land in the tropics is more difficult than one would think.

The blue tropics

This is due to the fact that tropical land is relatively scarce. The distorting effects of gravitational pull and spin on the shape of the Earth have left the tropical zone with more surface area than would be expected if our planet was a perfect sphere. Compression at the poles along the axis of spin, much like squeezing an orange between your hands, has left our planet with a middle-aged spread. This spread protrudes further outward at the waist of our planet, increasing the surface area that is in line with the plane of the Sun's irradiance (the solar ecliptic). As a consequence, the planimetric area[7] of the tropics, at around 203.6 million square kilometres, accounts for nearly 40 per cent of our planet's surface, but is bound within only 25 per cent of its latitudinal range. Yet despite this large surface area, the tropics contain only 34 per cent of the world's land area. The relative scarcity of tropical land is further appreciated when we consider that this accounts for a mere 10 per cent of the planet's surface. We can see this more clearly by calculating the amount of surface area allocated to land and ocean within each degree of latitude using a Mollweide, or other similar equal-area, cylindrical map projection. This does a very good job of translating the ellipsoid shape of our planet into a two-dimensional, map-like sheet without distorting the relative proportions of land and ocean, unlike the Mercator projection. If we examine the resulting distribution as a profile, seen in Figure 1.5, it is clear that tropical land area falls very short of the zone's relative contribution to total surface area.[8] This shortfall is not restricted to the tropics, but part of a general decline in land area southwards from the northern mid-latitudes, disappearing entirely between –55 and –65 degrees to form the great Southern Ocean. As in the tropics, land is remarkably scarce in the southern extra-tropics. Accounting for a mere 15 per cent of global land area, Antarctica alone accounts for more than half of the area south of the Tropic of Capricorn. Not surprising then that nearly 70 per cent of global land is situated at latitudes north of the Tropic of Cancer. While this has not always been the case through the long geological history of our planet, the effect of this current geodesic imbalance on the relationship between the tropics and the extra-tropics is omnipresent.

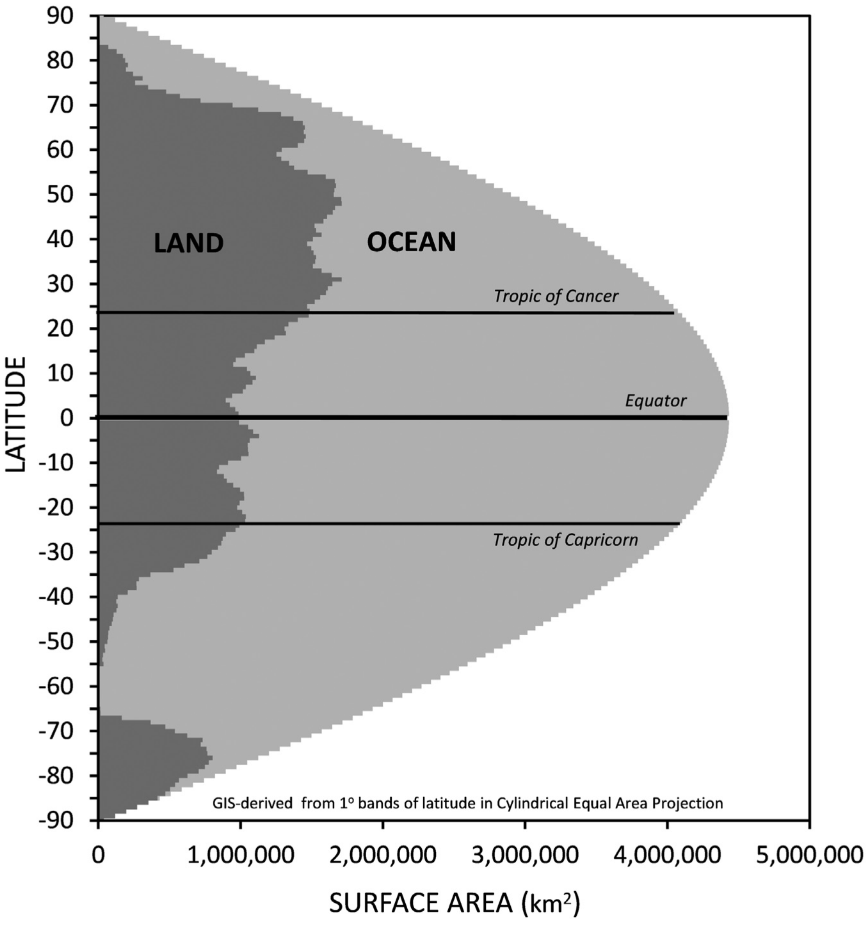

Figure 1.5 A depiction of Earth's land and ocean area as distributed by latitude.

Central to this effect are the tropical oceans. Estimated at around 153 million square kilometres, they currently account for about 42 per cent of global marine area. This equates to nearly one in every three square kilometres of our planet's surface. Combined with the relative dearth of land, the land-to-ocean ratio of the tropics at 1:3 is considerably higher than the extra-tropics at 1:2. This imbalance is caused by a striking difference in land distribution between north and south. In the north half of our planet, land and ocean are nearly equal in area across the extra-tropical regions. The southern extra-tropical oceans, by contrast, occupy 85 per cent of the surface area of this region. Again, this fairly obvious observation, gleaned from any map or model of Earth, is quantified in the profile diagram of Figure 1.5. The primary consequence of this asymmetry rests with the enormous exposure of the tropics to the Sun, the capacity of the region to absorb and convey energy and the impact of the relative occurrence of these two tropics – terrestrial and marine – on the distribution of bioproductivity across our planet.

Notes

1 Many of Miller's items of personal correspondence with friends suggest the title of his most famous work has more to do with the image of Cancer, and its zodiacal connection with the crab, than a celestial connection with the solar ecliptic.

2 These limits depend on the gravitational forces attributable to the Sun and planets within our solar system and their interaction. Over billions of years, the obliquity of Earth may exceed these limits as gravitational forces change with alterations in the state condition of the Sun, planets and their orbital geometries.

3 *Nutation* in this context describes a smaller variation in the precession-driven wobble of the Earth's polar axis. Current understanding attributes the main component of this motion to the interaction of the Sun and Moon on the distribution of surface water, called *tidal forces*, accounting for our planet's imperfect shape (and thus distribution of mass). A motion of this type has been calculated to cycle every 18.6 years, but imperfectly.

4 Longer-term changes in the distribution of moisture occur mainly as an indirect consequence of variation in our planet's obliquity, precession and eccentricity that alter the distribution of insolation. This has the effect of altering the extent and thickness of polar ice over glacial (Ice Age) and inter-glacial (present) stadia. Changes in the amount of polar ice then alter the distribution of planetary mass, impacting the extent of the equatorial "bulge". Near-term shifts in water due to oscillatory behaviour in the major oceanic and atmospheric circulations are also suggested to impact mass distribution, but at smaller timeframes and magnitudes of change (Chang and Tapley 2004).

5 This work was seminal in many ways, most notably in its introduction and use of potential evapotranspiration (PET). He would later further develop the rainfall-PET approach into a more detailed water balance, a widely used hydrological concept (Thornthwaite and Mather 1955).

6 The algorithm employed to translate the spectrometric readings into land surface temperatures is described in Wan (1999). The accuracy of the translation is placed at ± 0.5°C. Here, data presented as averages for each month between January 2000 and 2010 were averaged and partitioned by each degree of latitude. The values for each raster cell within each degree were then averaged to produce the temperature curves with measures of dispersion denoting spatial variation.

7 *Planimetric* refers to the smooth surface area without consideration of elevational effects. This is a conservative measure of area.

8 The measure of global surface area varies depending on assumptions made regarding the "true" shape of our planet, how this is transformed in the process of converting from a three to a two-dimensional depiction, and the size of the unit used to estimate area. Estimates here are derived from 1-degree bands of latitude in Cylindrical Equal Area Projection and calculated in a geographic information system (ArcGIS Pro). Land area distribution is based on data from the Shuttle Radar Topography Mission (SRTM) processed into a digital elevation model (DEM) by the Jet Propulsion Laboratory. SRTM only provides

coverage between 60 degrees north and 60 degrees south. The data used have a precision of 3 arc-seconds (SRTM3 "finished"). ASTER GDEM data, provided through NASA's LP DAAC were utilized for regions poleward of SRTM limits. ASTER GDEM data are newer, with a higher precision of 1 arc-second, but with less effort to reconcile anomalous elevational patches. Thus a higher error rate is expected compared to SRTM3.

2 Planet's powerhouse

The Forum, cradle of Greek philosophical and scientific debate, was filled for the final showdown between two legends. Aristotle, the renowned Greek polymath, was squaring off against a contemporary known for his originating work on atomic theory. Leukippos of Miletus insisted that a vacuum, what we would call space, existed as an entity separate from that of material bodies and Aristotle begged to differ. "Horror vacui" Aristotle is supposed to have rejoined (in ancient Greek of course), delivering the founding broadside in a debate surrounding space and matter that continues to this day. We know from the root laws of thermodynamics that change takes place only where state conditions are transformed, releasing energy in the process. We also know that energy flows from high to low states: hot to cold temperatures, high to low pressures. It follows that where the flow, or flux, of energy is small or absent, there is little if any change in the state condition. But the second law of thermodynamics tells us that this state cannot remain indefinitely and all stable conditions (at a low-energy state) invariably descend into chaos (through an influx of energy). The famous late-nineteenth-century French chemist, Henri Le Châtelier formally summed up this view with his equilibrium law: a change in one of the variables that describe a system at equilibrium produces a shift in the position of the equilibrium that counteracts the effect of this change. This is the crux of Aristotle's response.

But where nature simply abhors a vacuum, evolution despises. Planetary change – physical, biological and social – evolves around the availability of energy. Many of the evolutionary currencies – the dynamism of the physical landscape, the abundance and diversity of life and the complexity of society – lose their value when deprived of the energy necessary to impart change. Life prospers most where these forces deliver the natural means for production – water, light and nutrients wrapped up in a warm envelope. When they are absent – or only available outside the envelope such as in deep caves or at the polar ice caps – the abundance and diversity of life diminishes. We can also think about our modern cities in this context – their frantic pace of activity and continuous consumption. One quickly recognizes that cities are simply energy consumption hotspots evolving as food, water and materials flood in, only to re-radiate outward this energy transformed through work as structures, devices, ideas, trends and data. What would the modern city be if the flux of energy, in all of its forms, slowed or stopped? As the respected historian Ferdinand Braudel noted: "A world economy always has an urban centre of gravity" (Braudel 1984). The global flow of energy manifests itself through environmental, economic and demographic fluxes and the tropical region holds a pivotal position in driving these through its shaping influence on global bioproductivity. But to understand this substantive role we need to consider where energy originates and the three exogenous sources of energy driving the evolution of our planet: geothermal, mechanical and, above all, solar. This chapter is about these sources and the role of the tropics as the planet's powerhouse.

Geothermal energy – our planetary dynamo

Geothermal power is born from the physical evolution of our planet. It is most visually apparent in the steaming hot springs, erupting geysers, streaming lava flows and eruptions that characterize the most active volcanic regions of our planet. But these are merely the end-products of a process that builds, and then releases, energy flowing from the mantle to the planet's surface through convection of viscous rock towards relative weak points in the overlying crust. These weak points, commonly referred to as fault lines, run across the surface of the planet to form boundaries between two adjacent pieces, or plates, of crust. At some plate boundaries, new crust is being created, while at others it is being destroyed. Combined, this conveyor-like process of creative destruction, known as plate tectonics, very slowly overturns large parts of the planet's surface. The release of the bulk of geothermal energy occurs as the state condition of the material changes at these boundaries: either as rock moves from liquid to solid (cooling) or as it moves from solid to liquid (melting). Driving the entire process is the massive decay of the radioisotopic materials – uranium (mainly U-238), thorium-232, and potassium-40 – that heat the mantle material (Rama Murthy *et al.* 2003).[1] Radioisotopic decay under the extreme pressure conditions of the planet's interior is the root source of geothermal energy. Since the 1950s, geophysicists have been wrestling with exactly how much thermal energy is shunted from the inner planet to the surface through tectonic activity. Henry Pollack and colleagues of the University of Michigan arrived at an estimate of 87+/−2 milliwatts per square metre for mean global heat flow based on an extensive analysis of data from more than 20,000 measurement sites (Pollack *et al.* 1993). This amount, the equivalent needed to power two to three LEDs, is comparatively small. But expressed on a global basis, by considering the instantaneous flux of geothermal heat from the entire surface area of the planet, it amounts to about 44 terawatts – enough power to run global civilization for 2.5 years at current annual consumption rates.