and explain what is inexplicable' in human history: changes in population size.[2]

Voltaire's vision has attracted few imitators. Although legions of historians have studied individual governments and religions in the seventeenth century, until recently few have tracked population trends and even fewer have considered the impact of climate change. Nevertheless, Voltaire was right: around 1618, just as the human population reached unprecedented size, a phase of global cooling began that produced extreme climate events, disastrous harvest failures, and frequent disease epidemics. Human demographic systems cannot adapt swiftly to such adversity, yet instead of seeking ways to mitigate the natural disasters and save lives, most governments around the globe exacerbated the crisis by continuing their existing policies, above all their wars. These various natural and human factors constituted a 'placenta' (to use the metaphor of the Spanish writer Javier Cercas) capable of nourishing a global catastrophe for two generations, until the global population had diminished by one-third.[3]

CHAPTER ONE

The Little Ice Age[1]

'A Strange and Wondrous Succession of Changes in the Weather'

In 1614 Renward Cysat, botanist, archivist and town historian of Luzern in Switzerland, began a new section of his chronicle entitled 'The seasons of the year'. Because 'the past few years have seen such a strange and wondrous succession of changes in the weather', Cysat decided to

> record the same as a service and a favour to future generations because, unfortunately, on account of our sins, for some time now the years have shown themselves to be more rigorous and severe than in the past, and we have seen deterioration amongst living things, not only among mankind and the animal world but also in the Earth's crops and produce.[2]

Cysat was correct: the 'strange and wondrous succession of changes in the weather' that he reported continued for almost a century. In Africa, Angola and the semi-arid belt of savanna south of the Sahara that stretches from the Atlantic Ocean to the Red Sea, and which is known as the Sahel, faced drought from 1614 until 1619. All Europe experienced an unusually cold winter in 1620–21: the Zuiderzee and many rivers froze so hard that for three months they could bear the weight of loaded carts and, most spectacularly, the Bosporus froze over so that people could walk across the ice between Europe and Asia (apparently a unique climatic anomaly). The summer of 1627 was the wettest recorded in Europe during the past 500 years, and 1628 saw a 'year without a summer', with temperatures so low that many crops never ripened. Between 1629 and 1632, much of Europe suffered excessive rains followed by drought, while northern India suffered a 'perfect drought' followed by catastrophic floods. In China, heavy snow fell in 1618 in subtropical Fujian, and four provinces reported a severe winter in 1620. In the Americas, droughts from 1616 to 1621 afflicted the Valley of Mexico and reduced the crops in the Chesapeake basin so severely that the new Virginia colony almost failed.

After a few years of better weather, drought and frost significantly stunted the growth of trees throughout the western United States from 1640 to 1644, while the Canadian Rockies experienced severe drought from 1641 until 1653. The lack of rain in the Valley of Mexico in 1640, 1641 and 1642 led the clergy of Mexico City to organize processions with the Virgen de los Remedios, an image believed to possess special efficacy in bringing rain, to beg God's intervention before everyone starved to death (the first time the image had ever been used in consecutive years). In Massachusetts, Governor John Winthrop noted early in 1642 that

> The frost was so great and continual this winter that all the bay was frozen over, so much and so long, as the like, by the Indians' relation, had not been so these forty years ... To the southward also the frost was as great and the snow as deep, and at Virginia itself the great [Chesapeake] bay was much of it frozen over, and all of their great rivers.

To the north, English settlers on the coast of Maine complained of the 'most intolerable piercing winter' and found it 'incredible to relate the extremity of the weather'.[3]

Abnormal weather also prevailed on the other side of the Pacific. In Japan the first winter snow of 1641 fell on Edo (as Tokyo was then known) on 28 November, almost the earliest date on record (the average date is 5 January), and both that year and the next saw unusually late springs. According to a 1642 pamphlet published in the Philippines, because of the 'great drought' throughout the archipelago 'a great famine is feared'; and two years later, a resident of Manila recorded that once again 'this year there has been much famine among the Indians [Filipinos] because the rice harvest was a poor one on account of the drought'.[4] In northern China, numerous gazetteers reported drought in 1640 and the following year the Grand Canal, which brought food to Beijing, dried up for lack of rain (another unparalleled event). Between 1643 and 1671 Java fell prey to the longest drought recorded during the past four centuries.

The Mediterranean lands also experienced extreme weather. Catalonia suffered a drought in spring 1640 so intense that the authorities declared a special holiday to enable the entire population to make a pilgrimage to a local shrine to pray for water – one of only four such events in the past five centuries. In 1641 the Nile fell to the lowest level ever recorded and the narrow growth rings laid down by trees in Anatolia reveal a disastrous drought. By contrast, in Macedonia the autumn saw 'so much rain and snow that many workers died through the great cold'; in Spain, the Guadalquivir broke its banks and flooded Seville in 1642; and throughout Andalusia the years 1640–43 remain the wettest on record.[5]

Men and women in England noted 'the extraordinary distemperature of the season in August 1640, when the land seemed to be threatened with the extraordinary violence of the winds and unaccustomed abundance of wet', and in Ireland frost and snow in October 1641 began what contemporaries considered 'a more bitter winter than was of some years before or since seen in Ireland'.[6] Hungary experienced uncommonly wet and cold weather from 1638 to 1641; summer frosts repeatedly devastated crops in Bohemia; and 1641 remains the coldest year ever recorded in Scandinavia. In the Alps, unusually narrow tree rings reflect poor growing seasons throughout the 1640s, and farmsteads and even whole villages disappeared as glaciers reached their maximum extent in historical times, a mile beyond their current positions. In eastern France, each grape harvest from 1640 to 1643 began a full month later than usual and grain prices surged, indicating poor cereal harvests. In the Low Countries, all along the river Maas (or Meuse), floods caused by snowmelt early in 1643 created 'the greatest desolation that one could imagine: the houses all broken open and overturned, and people and animals dead in the hedgerows. Even the branches of the highest trees contained a number of cows, sheep and chicken'. Perhaps most striking of all, a soldier serving in central Germany recorded in his diary in August 1640 that 'at this time there was such a great cold that we almost froze to death in our quarters and, on the road, three people did freeze to death: a cavalryman, a woman and a boy'.[7]

Data from the southern hemisphere reveal similar climatic aberrations. In Potosí (modern Bolivia), the second largest city in the Americas, 'following a long drought came heavy rains' in 1626 that buckled the walls of the great Caricari reservoir, built to supply water to the *ingenios* (engines) used to refine silver. Eyewitnesses described how in a matter of minutes a 'mountain of water' washed away more than thirty engines, destroyed some 2,000 houses and drowned perhaps 4,000 people. In Chile, lack of precipitation from 1615 to 1637 led an inquisitor to apologize to his superiors that he could not send them any proceeds from fines and confiscations because 'we have not collected a penny on account of the drought'.[8] Tree-rings show significantly cooler weather throughout Patagonia in the 1640s, and the glaciers in Bolivia and Peru reached their maximum extent between 1630 and 1680. In Africa, Angolan records show a unique concentration of droughts, locust infestations and epidemics in the second quarter of the seventeenth century.

The 1640s ended with another bout of extreme weather throughout the northern hemisphere. On the Isle of Wight in southern England, a local landowner lamented that 'from Mayday till the 15th of September [1648] we had scarce three dry days together', and when King Charles I (imprisoned nearby) asked him 'whether that weather was usual in our island? I told him that in this forty years I never knew the like before'. In Scotland, 'The long great rains for many weeks did prognosticate famine', and Ireland experienced 'so great a dearth of corn ... not seen in our memory'.[9] The following winter, the barge carrying the corpse of King Charles up the river

Thames to its final resting place after his execution on 30 January 1649 had to contend with ice floes. Other parts of Europe also experienced unusual precipitation – 226 days of rain or snow according to a meticulous set of records from Fulda in Germany (compared with an annual upper limit of 180 days in the twentieth century) – followed by 'a winter that lasted six months'. In France, appalling weather in 1648, 1649 and 1650 delayed the grape harvest into October and drove bread prices to the highest levels in almost a century. In China, the winter of 1649–50 seems to have been the coldest on record. In North America, an epic drought in 1649 created a 'hungry winter' that, according to Kathryn Magee Labelle, 'changed everything' for the Wendat living around Lake Huron: although not destroyed, the Wendat were dispersed for ever.[10]

The 1650s brought no respite. In 1651 the combination of snowmelt and a storm tide caused the worst flooding for eighty years in coastal regions of the Dutch Republic, and snowmelt also caused the Vistula, the Seine and other major rivers to burst their banks. Conversely, the same year saw the longest recorded drought in Languedoc, in southern France: 360 days, or almost an entire year. In the Balkans, in spring 1654 eyewitenesses 'had never before seen such snowstorms and frost, moisture and cold', and even olive 'oil and wine got frozen in the jars', and England experienced an 'unusual drought, which has lain upon us for some years, and still continues and increases upon us'.[11]

The northern hemisphere experienced a landmark winter in 1657–58. Along America's Atlantic coast, deer ran across the frozen Delaware river. In Europe, people rode their horses on the ice across the Danube at Vienna, across the Main at Frankfurt and across the Rhine at Strasbourg; the canal between Haarlem and Leiden remained frozen for two months; and the Baltic froze so hard that the Swedish army with all its artillery marched 20 miles over ice from Jutland to launch a surprise attack on Copenhagen. A diplomat travelling through the Balkans noted in February 1658 that the weather was so cold that even migrating birds turned back, 'causing everyone to wonder'; while John Evelyn judged that he and his compatriots had just lived through 'the severest winter that man alive had known in England: the crow's feet were frozen to their prey; islands of ice enclosed both fish and fowl frozen, and some persons in their boats'. Inevitably, the following spring brought disastrous flooding as the snow and ice melted: the Seine inundated Paris and many other towns, and dikes broke all over the Netherlands. Lieuwe van Aitzema, the official historian of the Dutch Republic, devoted two pages of his chronicle to the extreme climatic events around Europe during 1658, 'a year in which the winter was as harsh and severe at the beginning as at the end'.[12]

Such extreme climatic events often came in unusual concentrations. Of sixty-two recorded floods of the river Seine in and around Paris, eighteen

occurred in the seventeenth century. In England (and probably elsewhere in northwest Europe), 'bad weather ruined the harvests of corn and hay for five years from the autumn of 1646 onwards', with five more bad harvests between 1657 and 1661: ten harvest failures in sixteen years. The Aegean and Black Sea regions experienced the worst drought of the last millennium in 1659; in 1675 much of the northern hemisphere experienced another 'year without a summer'; and for six weeks in 1683–84 the Thames at London froze over so hard that enterprising tradesmen built streets and booths on the ice, visited by 'many thousands of people walking sometimes together at once'.[13] In 1686 a military engineer on campaign in what is now Romania complained that 'for three years now, I haven't seen a single drop of rain'. Lakes and rivers dried up, and 'in the swampy soil, cracks were so deep that a standing man could not be seen . . . I doubt if there is another example of such a terrible and lasting drought.'[14] In Russia, tree-ring, pollen and peat-bed data show that the springs, autumns and winters between 1650 and 1680 were some of the coldest on record; and, in China, the winters between 1650 and 1680 formed the coldest spell recorded in the Yangzi and Yellow river valleys over the last two millennia. The Turkish traveller Evliya Çelebi encountered snow and hail when he visited Egypt in the 1670s, and complained that 'no one here used to know about wearing furs. There was no winter. But now we have severe winters and we have started wearing fur because of the cold.'[15]

The Search for Scapegoats

So much abnormal weather led some contemporaries to suspect that they lived in an era of climate change. In June and July 1675 (the century's second 'year without a summer'), the Paris socialite Madame de Sévigné complained to her daughter, in Provence, that 'It is horribly cold: we have the fires lit, just like you'; and confided that 'like you, we think the behaviour of the sun and of the seasons has changed'. A generation later the Kangxi emperor, who collected and studied weather reports from all over China, speculated that 'The seasons of Heaven and the physical character [qi] of Earth have undergone some changes' because, in the south,

> We remember that before 1671 there would be a new crop of winter wheat by the eighth day of the fourth lunar month [which in 1671 fell on 16 May]. On an earlier tour of Ours to Jiangnan, on the eighteenth day of the third month people were already eating flour from the wheat crop. Now in the middle of the fourth month, the wheat crop has not been harvested . . . I have also heard that in the region of Fujian hitherto there was never any snow. Since the time the great armies of this dynasty reached that region [1645], there has been snow.

The emperor also noted with puzzlement that in the north of his empire, 'It used to be that the ice froze to a thickness of eight feet. Now however the weather is milder, not like it was earlier.'[16]

Many contemporaries attributed the extreme weather to divine displeasure. In China, the heavy and prolonged snows in 1641–42 convinced the scholar Qi Biaojia that 'Heaven is extremely angry'; and somewhat later, the Kangxi emperor claimed that 'If our administration is at fault on Earth, Heaven will respond with calamities from above.' A Chinese folk song from the period was blunter:

> Old skymaster, you're getting on,
> Your ears are deaf, your eyes are gone.
> Can't see people, can't hear words.
> Glory for those who kill and burn;
> For those who fast and read the scriptures,
> Starvation.

In 1641, a Jesuit living in the Philippines speculated that the simultaneous eruption of three volcanoes meant that 'Divine Providence wishes to show us something, perhaps to warn us of some approaching catastrophe, which our sins so deserve, or the loss of some territory, because God is angry'. Eight years later a pamphlet published in London, entitled *The way to get rain, by way of question and answer*, included the exchange: '[Question:] Why hath the Earth sometimes too much raine? Answer: Because the Lord is pleased in judgement to send it.'[17]

Such statements reflected the prevailing peccatogenic outlook (from *peccatum*, the Latin word for sin): attributing misfortunes such as military defeats, bad weather and famine to human misconduct, thereby rendering 'intelligible and therefore more bearable a catastrophe in itself unpredictable, while making possible some degree of remedial action'.[18] Examples abound. According to a leading adviser to Philip IV of Spain in 1648: 'The principal cause of the calamities that afflict this kingdom are the public sins and injustices committed', so that punishing the former and 'administering justice with due rectitude and speed are the most important ways to oblige Our Lord to provide the successes that this Monarchy needs so much'.[19] In Germany, in the 1630s, Protestant magistrates in Nuremberg commanded citizens to show moderation in food, drink and fashion and to refrain from sensual pleasure (especially if it involved adultery, sodomy or dancing) in order to avert divine displeasure. Their Catholic neighbour, Maximilian of Bavaria, likewise forbade dancing, gambling, drinking and extramarital sex; limited the duration and cost of wedding festivities; forbade women to wear skirts that revealed their knees; proscribed the joint bathing of men and women; and periodically prohibited carnival and *Fastnacht*

celebrations. In the 1640s, the English Parliament 'authorized and required' the magistrates of London 'to pull down and demolish' all theatres, to have all actors publicly whipped and to fine all playgoers, because plays tended 'to the high provocation of God's wrath and displeasure, which lies heavy upon this kingdom'.[20]

The search for scapegoats also fed a witch craze in Europe and its overseas colonies that saw thousands of people tried and executed as sorcerers because their neighbours held them responsible for their misfortunes. As Wolfgang Behringer has noted, not only did the seventeenth century see a notable rise in accusations that blamed witches for unnatural weather, but the peaks of persecution occurred in the coldest decades. Most of the victims were women unable to support themselves unaided, and many lived in marginal areas for crop cultivation (in Lorraine and the Rhineland for vines; in Scotland and Scandinavia for cereals) where the impact of global cooling was felt first and worst. Thus in southern Germany, a hailstorm in May 1626 followed by Arctic temperatures led to the arrest, torture and execution of 900 men and women suspected of producing the calamity through witchcraft. Two decades later, the Scottish Parliament likewise blamed a winter of heavy snow and rain followed by a poor cereal harvest on 'the sin of witchcraft [which] daily increases in this land'; and, to avert more divine displeasure, it authorized more executions for sorcery than at any other time in the country's history. In North America, a witch panic gripped the Wendat during the dearth of 1635–45, and it is no surprise that the Salem witch trials of 1691–92 occurred during a time of unusual cold and scarcity. In China, too, 'To anyone oppressed by tyrannical kinsmen or grasping creditors', a witchcraft accusation 'offered relief. To anyone who feared prosecution, it offered a shield. To anyone who needed quick cash, it offered rewards. To the envious it offered redress; to the bully, power; and to the sadist, pleasure.'[21]

The invocation of sex, stage plays and sorcery to explain catastrophes in the seventeenth century paled when compared with five other suspects: stars, eclipses, earthquakes, comets and sunspots. In Germany, a Swedish diplomat wondered in 1648 whether the spate of contemporaneous rebellions might 'be explained by some general configuration of the stars in the sky'. According to a chronicler in Spain, only 'the malign influence of the stars' could explain the coincidence that 'in a single year [1647–48] in Naples, Sicily, the Papal States, England and France', such 'atrocities and extraordinary events' had occurred. A few years later, Majolino Bisaccione likewise argued that only 'the influence of the stars' could have created so much 'wrath among the people against the governments' of his day.[22]

Others blamed eclipses. In 1640, the author of a Spanish almanac confidently asserted that a recent eclipse of the sun had produced 'great upsets in war, political upheavals and damage to ordinary people'. An English contemporary predicted that the two lunar eclipses and unusual planetary conjunction forecast for 1642 would bring 'sharp tertian fevers, war, famine, pestilence, house-burnings, rapes, depopulations, manslaughters, secret seditions, banishments, imprisonments, violent and unexpected deaths, robberies, thefts and piratical invasions'. In India, even the Mughal emperor Aurangzeb, a devout Muslim, took special precautions during eclipses, staying indoors and eating and drinking little. In Iran, a solar eclipse in 1654 led some 'Persian wise men' to assert that it meant 'that the King had died; others said that there would be a war and blood would be shed.'[23]

Many seventeenth-century people also believed that earthquakes presaged catastrophe. In 1643, a Dutch pamphleteer assured his readers that:

> [The] earthquake not long since felt in the year 1640, was a token of great commotions, and mighty shakings of the kingdomes of the Earth, for a little before and shortly thereupon was concluded the revolt of Cathalonia, the falling-off of Portugal, the stirres in Scotland, the rebellion of the Irish, [and] those civill (uncivill) warres, great alterations, [and] unexpected tumults in England.[24]

Likewise, when severe tremors shook the buildings of Istanbul in 1648, the Ottoman minister and intellectual Kâtib Çelebi solemnly noted that 'when an earthquake happens during daytime in June, blood is shed in the heart of the empire': he was therefore not surprised by the murder of Sultan Ibrahim two months later.[25] Such equations multiplied in the mid-seventeenth century in part because earthquakes became more common. French sources recorded twice as many tremors in the 1650s and 1660s as in any other decade of the century, including one of the most intense ever recorded; and surveys of data from other areas likewise showed a peak of seismic activity around 1650.[26]

Comets also became more frequent. The English astronomer John Bainbridge was apparently the first to suggest that they had become more numerous 'than in many ages before' in one of a multitude of works published in Europe following the appearance of three comets in 1618, predicting dire consequences for humanity, since comets normally brought in their wake 'discord, irritations, deaths, upheavals, robberies, rape, tyranny and the change of kingdoms'.[27] Astronomers in Ming China also interpreted the comets of 1618 as a portent of disasters, and the chronicles of their northern neighbours in Manchuria contain 'an overwhelming number of reports of such heavenly signs'. In Russia, the same comets provoked discussion and doleful interpretations among 'wise men'; in India, a Mughal chronicler claimed that 'no household remained unaffected' by fear, and blamed the comets for both an epidemic of plague and the subsequent rebellion of the crown prince; in Istanbul, writers attributed to their baleful

influence not only the extreme weather but also the deposition of one sultan in 1618, the murder of another in 1622, and the provincial revolts that followed.[28] As late as 1683, in Boston, Massachusetts, the Reverend Increase Mather devoted three pages of his *Kometographia, or a discourse concerning comets* to the 'prodigy' of 1618 which, he claimed, had 'caused' not only a major drought throughout Europe, an earthquake in Italy, a plague in Egypt and 'the Bohemian and Germanic war, in which rivers of blood were poured forth', but also 'a plague amongst the Indians here in New England which swept them away in such numbers, as that the living were not enough to bury the dead'.[29]

Some contemporaries blamed the catastrophes that surrounded them on a combination of these natural phenomena. In 1638 Robert Burton assured readers of his *Anatomy of melancholy* that:

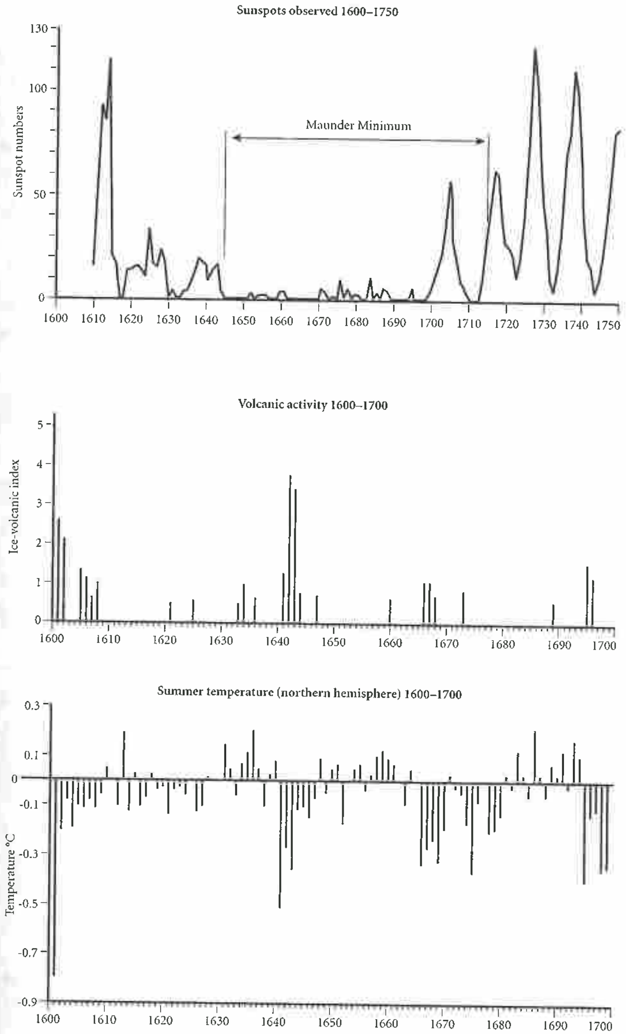
> The heavens threaten us with their comets, starres, planets, with their great conjunctions, eclipses, oppositions, quartiles, and such unfriendly aspects. The air with his meteors, thunder and lightning, intemperate heat and cold, mighty windes, tempests, unseasonable weather; from which proceed dearth, famine, plague, and all sorts of epidemicall diseases, consuming infinite myriads of men.[30]

Others, however, doubted such precise links. One Italian historian ridiculed the idea that 'certain celestial constellations have the power to move the spirits of the inhabitants of a country to sedition, tumults and revolutions' in many different places at once; while the comets of 1618 provoked animated debates between astronomers and astrologers over whether or not they were capable of causing 'catastrophes'. Such uncertainty prompted a handful of observers to suggest an alternative natural explanation for the extreme weather of the seventeenth century: fluctuations in the number of sunspots – those dark, cool regions of intense magnetic activity on the solar surface surrounded by flares that make the sun shine with greater intensity. Even though they incorrectly argued that *more* sunspots would produce cooler temperatures on Earth (whereas the reverse is true), unlike comet-watchers and stargazers, the early solar astronomers had identified an important cause of climate change in the seventeenth century.[31]

The development of powerful telescopes after 1609 enabled observers to track the number of sunspots with unprecedented accuracy. They noted a maximum of around 100 spots each year between 1612 and 1614, followed by a minimum with virtually none in 1617 and 1618, and markedly weaker maxima in 1625–26 and 1637–39. And then, although astronomers around the world made over 8,000 observations between 1645 and 1715, the grand total of sunspots observed in those seventy years scarcely reached 100, fewer than appear in even a single year of the twentieth-first century. This striking absence, which solar physicists call the Maunder Minimum, suggests a marked reduction in solar energy received on Earth.

Other data confirm this hypothesis. Trees (like other plants) absorb carbon-14 from the atmosphere, and the amount rises as solar energy received on Earth declines; so the increased carbon-14 deposits in many seventeenth-century tree-rings suggests reduced global temperatures. In addition, the *aurora borealis* (the Northern Lights, caused when highly charged electrons from the solar wind interact with elements in the Earth's atmosphere) became so rare that when the astronomer Edmond Halley saw an aurora in 1716 he wrote a learned paper describing the phenomenon – because it was the first he had seen in almost fifty years of observation.[32] Neither Halley nor any other astronomer between the 1640s and the 1700s mentioned the brilliant corona visible nowadays during a total solar eclipse: instead they reported a pale ring of dull light, reddish and narrow, around the moon. All three phenomena confirm that the energy of the sun diminished between the 1640s and the 1710s, a condition normally associated with both reduced surface temperatures and extreme climatic events on Earth.

A further astronomical aberration troubled seventeenth-century observers: the appearance of dust-veils in the sky that made the sun seem either paler or redder than usual. A Seville shopkeeper lamented that during the first six months of 1649, on the few occasions when the sun shone, 'it was pale and yellow, or else much too red, which caused great fear'. Thousands of miles to the east, Korea's royal astronomers reported on several days that 'the skies all around are darkened and grey as if some kind of dust had fallen'.[33] Both the dust-veils and the reddened skies stemmed from an unusual spate of major volcanic eruptions in the mid-seventeenth century, each one hurling sulphur dioxide into the stratosphere, where it deflected some of the sun's radiation back into space and thereby reduced temperatures in the Earth beneath. One day in 1641, a Spanish garrison in the Philippines saw at noon 'a great darkness approach from the south which gradually extended over that entire hemisphere and blocked out the whole horizon. By 1 p.m. they were already in total night and at 2 p.m. they were in such profound darkness that they could not see their own hands before their eyes.' Ash fell on them for twelve hours. They had just witnessed a Force Six eruption, which was heard at exactly the same time 'throughout the Philippines and the Moluccas, and as far as the Asian mainland, in the kingdoms of Cochin-China, Champa and Cambodia – a radius of 900 miles, a wondrous thing which seems to exceed the bounds of the natural world'.[34] The dust veils produced by this and at least eleven other volcanic eruptions around the Pacific from 1638 to 1644, combined with Maunder Minimum, both cooled the Earth's atmosphere and destabilized its climate (Fig. 2).



2. Sunspot cycles, volcanic anomalies and summer temperature variations in the seventeenth century.
The number of sunspots observed and recorded by European astronomers (*top*) shows the Maunder Minimum (1643–1715), in which fewer sunspots appeared in seventy years than appear in a single year now. Measurements of volcanic deposits in the polar ice cap (the 'ice-volcanic index') reveal a peak in the 1640s. Both phenomena show a striking correlation with lower summer temperatures in the northern hemisphere.

Blame it on El Niño?

The global cooling caused by reduced sunspot and increased volcanic activity seems to have triggered a change in the phenomenon known as El Niño, which affects much of the world's climate. As the air above the equatorial Pacific warms each spring it creates massive rain clouds: in a normal year, the rain falls on Asia as the monsoon that nurtures the harvest, but in an El Niño year the monsoon weakens and heavy rains fall instead on America, causing floods. Today this reversal – also known as ENSO (El Niño–Southern Oscillation) – happens about once every five years, but in the mid-seventeenth century it happened twice as often: in 1638, 1639, 1641, 1642, 1646, 1648, 1650, 1651, 1652, 1659, 1660 and 1661. The same period saw some of the weakest East Asian monsoons of the past two millennia.

El Niño cannot be blamed for every disaster, because the climates of some regions are El Niño-sensitive whereas others are not (in Africa, the Eastern Cape is susceptible to droughts in El Niño years whereas the Western Cape is not). The global footprint of El Niño normally includes three regions besides the lands adjoining the Pacific: the Caribbean suffers floods; Ethiopia and northwest India experience droughts; and Europe experiences hard winters. In most of the twenty El Niño episodes recorded between 1618 and 1669, and in all twelve from 1638 to 1661, adverse weather afflicted each of these three regions.

The changed climate in the Pacific Ocean during this period emerges starkly from two anomalies recorded in historical sources. The Chinese coastal province of Guangdong suffered more typhoon landfalls between 1660 and 1680 than at any other time in recorded history; and the voyages of galleons sailing from Acapulco to Manila took longer than in any other period. In the first and last decades of the seventeenth century crossing the Pacific took an average of eighty days, but between 1640 and 1670 the average duration rose to over 120 days (and three voyages took over 160 days). Some ships never arrived: of the eleven galleons known to have sunk or run aground before reaching Manila during the seventeenth century, nine did so between 1639 and 1671. The return voyage from Manila to Acapulco also took much longer: the average duration rose from 160 to well over 200 days, and the longest voyages ever recorded (240 days, or eight months) took place in the 1660s. Nothing except a major shift in wind pattern could explain such a dramatic change. Diego de Villatoro, a crown official who had made the round trip twice, saw the connection clearly. In a memorial written in 1676 he noted sadly that 'now we consider a voyage from the Philippines to Acapulco that takes less than seven months to be good', and he perceptively ascribed the longer duration 'to a change in the monsoons'.[35]

Villatoro, of course, lacked the expertise either to blame this change on increased El Niño activity or to associate El Niño with weaker Asian

monsoons and increased volcanic activity. But we now know that in normal years, when easterly winds prevail, the Pacific stands some 60 centimetres higher off the Asian than off the American coast, whereas in El Niño years, when westerly winds prevail, those levels reverse. The movement of such a huge volume of water places enormous pressure on the edges of the Earth's tectonic plates around the Pacific periphery, where the most violent and most active volcanoes in the world are located, and this may trigger a spate of eruptions. If this hypothesis is correct, it creates a deadly cycle:

- Reduced solar energy received on Earth lowers global temperatures, which increases the risk of more, and more severe, El Niño events.
- El Niño events may trigger volcanic eruptions around the Pacific that throw sulphur dioxide into the stratosphere, which further reduces the solar energy received on Earth.
- Major volcanic eruptions reduce solar energy received on Earth.

Whatever the exact connections between these natural phenomena (and not all scientists agree), the mid-seventeenth century experienced a marked increase in earthquakes, comets, volcanic eruptions and El Niño episodes, as well as a drastic reduction in sunspot activity, the weakest monsoons and some of the lowest global temperatures recorded in the past few centuries.

Climate and Crops

So what? To a sceptic, global cooling that amounts to a fall of only one or two degrees Celsius in mean summer temperatures may seem insignificant; but that is to think in linear terms. The mean global temperature has shown remarkable stability over the last six millennia: the difference between the Medieval Climate Optimum (the hottest temperatures recorded until the late twentieth century) and the Little Ice Age was probably less than 3°C at the equator. A change of even one degree is thus highly significant. Moreover, in the northern hemisphere, home to the majority of humankind and site of most of the wars and revolutions of the seventeenth century, solar cooling reduces temperatures far more than at the equator, in part because increased snow cover and sea ice reflect more of the sun's rays back into space. The extension of the polar ice caps and glaciers in the mid-seventeenth century would thus have significantly reduced mean temperatures in northerly latitudes.

A recent model of the probable global climate in the later seventeenth century shows significantly colder weather in Siberia, North Africa, North America and northwest India; colder and drier weather in central China and Mongolia; and cooler and less stable conditions in the Iberian Peninsula, France, the British Isles and Germany. As already noted, the states in these same areas – the Russian and Ottoman empires in Eurasia; the Ming and Qing empires in East Asia, and the dominions of Philip IV, Charles I, Louis XIV and Ferdinand III in Europe – reported not only cooler weather in the 1640s and 1650s but also a significant number of extreme weather events. This should cause no surprise: an overall decline in mean temperatures is normally associated with a greater frequency of flash floods, freak storms, prolonged droughts, and abnormal (as well as abnormally long) cold spells. Since each of these anomalies can critically affect the yield of crops that feed the people, each may cause economic, social and political upheavals.

In the temperate zone, which stretches roughly from thirty to fifty degrees of latitude, a cold spell during germination, a drought in the early growing season and a major storm just before harvest affect crop yields disproportionately. In areas of wet rice cultivation, a fall of 0.5°C in the average spring temperature prolongs the risk of the *last* frost by ten days, while a similar fall in the average autumn temperature advances the risk of the *first* frost by the same amount. Either event suffices to kill the entire crop. Even without frosts, a fall of 2°C during the growing season – precisely the scale of global cooling in the 1640s – reduces rice harvest yields by between 30 and 50 per cent, and also lowers the altitude suitable for wet rice cultivation by about 400 metres. Likewise, in cereal-growing regions, a fall of 2°C shortens the growing season by three weeks or more, diminishes crop yields by up to 15 per cent, and lowers the maximum altitude at which crops will ripen by about 150 metres. Drought, too, destroys harvests by depriving crops of the precipitation they required. As a Chinese manual of agriculture, published in 1637, warned: 'All rice plants die if water is lacking for ten [consecutive] days.'[36]

Extreme weather can also destroy crops indirectly. Drought favoured locusts. In 1647 a Moldavian nobleman reported that 'about the time of the year when people pick up their sickles to harvest the wheat', he and some companions were on the road and 'suddenly noticed a cloud towards the south':

> We thought it was a rainstorm until we were suddenly hit by the locust swarm, coming at us like a flying army. The sun disappeared immediately, veiled by the blackness of these insects. Some of them flew high, at three or four metres, while others flew at our level, or even right above the ground . . . They flew around us without fearing anything . . . It took an hour for a swarm to pass, and then after an hour and a half there came another, and then another, and so on. It lasted from noon till dusk. No leaf, no blade of grass, no hay, no crop, nothing remained.

Excessive rain, by contrast, might allow rodents to multiply. In Moldavia in 1670 'myriads of mice' not only ate 'all they found in the vegetable gardens' but also, 'climbing up the trees, ate all the fruit, finishing them up; and to end the job' they consumed all the wheat in the field.[37]

North of the temperate zone, the impact of global cooling increases because the growing season is shorter. In Manchuria, with a total of only 150 frost-free days even in good years, a fall of 2°C in mean summer temperature reduces harvest yields by a stunning 80 per cent. In Finland, where the growing season is the shortest compatible with an adequate harvest even in normal years, a single summer night's frost can kill an entire crop. Seventeenth-century Finland saw eleven crop failures (compared with only one in the eighteenth century).

Global cooling also increases not only the scale but also the frequency of harvest failures:

- In the temperate zone, if early winters or summer droughts occur with a frequency of P=0.1, the harvest will fail once every ten years, and two consecutive harvests will fail once every century. If, however, early winters or summer droughts occur with a frequency of P=0.2, the harvest will fail once every five years (double the risk) while two consecutive harvests will fail every twenty-five years (quadruple the risk).
- In latitudes north of the temperate zone, each fall of 0.5°C in mean summer temperatures decreases the number of days on which crops ripen by 10 per cent, doubles the risk of a single harvest failure and increases the risk of a double failure sixfold.
- For those farming 300 metres or more above sea level, a fall of 0.5°C in mean summer temperatures increases the chance of two consecutive failures a hundredfold.

Climate and Calories

In densely populated parts of the early modern world, most people relied on a single crop, high in bulk and in carbohydrates, known as a 'staple'. Cereals (wheat, rye, barley and oats) formed the principal staple in Europe, northern India and northern China. Rice played the same role in much of Asia, maize in much of the Americas, and millet in upland India and much of sub-Saharan Africa. The economic allure of staple crops is almost irresistible. An acre under cereals feeds between ten and twenty times as many people as an acre devoted to animal husbandry; furthermore, the same amount of money usually bought 10 pounds of bread but only 1 pound of meat. An acre planted with wet rice yields up to 6 tons of food: three times as much as an acre of wheat or maize and sixty times as much as an acre devoted to animal husbandry. Not surprisingly, therefore, according to a Chinese textbook printed in 1637, '70 per cent of the people's staple food is rice'. In Europe, cereals likewise provided up to three-quarters of the total calorie intake of every family (not only in the form of bread but also as a filler for soups and as the basic ingredient for beer and ale).[38]

Steven L. Kaplan has rightly insisted on the tyranny of popular dependence on staple crops in the pre-industrial world. In Europe:

> Cereal-dependence conditioned every phase of social life. Grain was the pilot sector of the economy; beyond its determinant role in agriculture, directly and indirectly grain shaped the development of commerce and industry, regulated employment, and provided a major source of revenue for the state, the church, the nobility, and large segments of the [ordinary population] . . . No issue was more urgent, more pervasively felt, and more difficult to resolve than the matter of grain provisioning. The dread of shortage and hunger haunted this society.[39]

Shortage and hunger could arise in three distinct ways. First, since food accounted for up to half the total expenditure of most families, an increase in staple prices soon caused hardship. Second, spending more on food left little or nothing with which to purchase other goods, leading to a fall in demand, which threw many non-agricultural workers out of work and reduced the wages received by the rest. Their income thus fell precisely when their expenditure rose. Third, any shortfall in the harvest reduced the food supply *geometrically* and not arithmetically because the impact of harvest failure on the price of cereals is non-linear. Suppose that:

- In a normal year a European farmer sowed 50 acres with grain and harvested 10 bushels an acre, a total of 500 bushels. Of this, he needed 175 bushels for animal fodder and seed corn and 75 bushels to feed himself and his family – a total of 250 bushels – leaving 250 for the market.
- If bad weather reduced his crop by 30 per cent, the harvest would produce only 350 bushels yet the farmer still needed 250 of them for his immediate use. The share available for the market therefore dropped to 100 bushels – a fall of 60 per cent.
- But if bad weather reduced crops by 50 per cent, the harvest would produce only 250 bushels, all of them needed by the farmer, leaving virtually nothing for the market.

This non-linear correlation explains why a 30 per cent reduction in the grain harvest often *doubled* the price of bread, whereas a 50 per cent reduction *quintupled* it. It also explains why starvation almost always followed when the harvest failed for two or more consecutive years.

Kaplan concluded his study of famines in early modern France by suggesting that this cruel calculus 'produced a chronic sense of insecurity that caused contemporaries to view their world in terms that may strike us as grotesquely or lugubriously overdrawn'. However, a study by Alex de Waal of the Darfur famine of 1984–85 in East Africa rejected the notion of 'overdrawn' because, where harvest shortfalls are concerned, even today failures can 'cross a threshold of awfulness and become an order of magnitude worse'. Not only do large numbers of people die, so does their entire way of life.[40] De Waal identified three characteristics of these landmark famines:

- They force those affected to use up their assets, including investments, stores and goods. Although a family might choose to go hungry for a season in order to preserve its ability to function as a productive unit (for example by keeping back grain to feed its livestock or to use as seed corn), it can rarely maintain that strategy for a second, let alone a third year. Two or three successive harvest failures will leave victims destitute.
- Prolonged starvation also forces those affected to use up their social claims. A hungry family may avoid begging for assistance from other individuals and institutions for a short period, but (once again) it can rarely maintain that strategy for long. If many families suddenly become destitute, the communities where they live may be crippled if not destroyed.
- As communities cease to be viable, some families migrate. Initially, migration may form a reasonable coping strategy in a famine because, although migrants necessarily abandon both their assets and their social claims by leaving their community, those who survive can return to their homes and their previous way of life when conditions improve; but prolonged dearth will sever the links with the world they have left. This will destroy their entire way of life.

Calories and Death

Each day, every human needs to consume around 2,000 calories to maintain her or his basic metabolic rate. Pregnant women and those who earn their living by physical labour require far more: 5,000 calories for those spending eight hours of the day marching or tending their crops; 5,500 calories for those spending eight hours building; 6,500 calories for those harvesting, cutting trees or carrying a heavy load.[41] Few people in the early modern period were so lucky: during the Italian plague of 1630–31, hospital records show that each patient received a daily ration of half a kilo of bread, a quarter of a kilo of meat (probably in a stew), and half a litre of wine – a daily intake of scarcely 1,500 calories (and one seriously deficient in vitamins). Even in normal years during the seventeenth century, the average Frenchman or woman consumed barely 500 calories more than their basic metabolic requirement, and the average Englishman or woman barely 700 calories more.

Nevertheless, as Mirkka Lappalainen pointed out in her study of the Great Finnish Famine of 1695–97, 'Human beings are resilient: it is not easy to starve to death.' We can adjust to a reduced food supply by cutting back on energy demands (working more slowly, resting longer); and, as body weight declines, we can also survive with fewer calories to sustain the basic metabolism (and the reduced physical activity). Lappalainen found that in the 1690s many Finns suffered 'semi-starvation, which people can withstand for months or longer, although they become increasingly weak and apathetic.'[42] Nevertheless, although a weight loss of 10 per cent reduces energy by about one-sixth, a weight loss of 20 per cent reduces energy by about one-half, and if a woman or man loses 30 per cent of their normal body weight, blood pressure falls and the ability to absorb nutrients fails. In this weakened condition, any additional stress on the body, such as disease, usually proves fatal – and, amid the social disruption normally associated with famine, infectious diseases often spread rapidly – while cold and damp further weaken those who cannot get enough food.

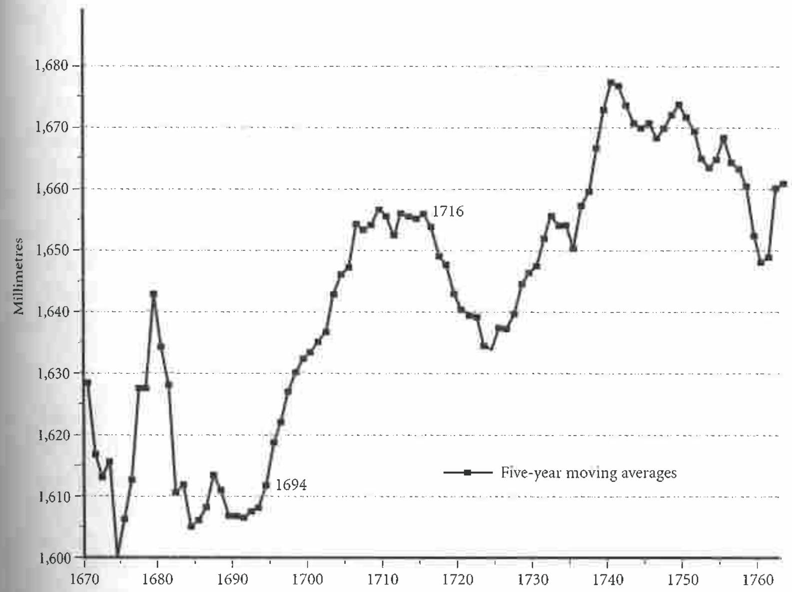
Finnish records studied by Lappalainen revealed that the most striking feature of those suffering from semi-starvation was oedema of face, limbs and abdomen because of protein deficiency: they mentioned people who were swollen and bloated far more often than those who were thin. The commonest cause of death was 'deadly bloody diarrhoea.' A seventeenth-century Chinese official and philanthropist reported much the same:

> All beings are physically the same, alike in their intolerance of cold. Those people with old, tattered clothes . . . go nearly naked in the dead of winter, their hair dishevelled and feet bare and their teeth chattering; crying out and terrified . . . Being solitary, they have no place to go . . . [and] falling snow covers their bodies. At this point, their organs freeze and their bodies stiffen like pieces of wood. At first they are still able to groan. Gradually they cough up phlegm. Then, their lives are extinguished.[43]

Famines afflicted the young with especial severity. Many infants died because their mothers had no milk to feed them, and even those who survived suffered stunting: the offspring of women who become pregnant during times of dearth are often shorter. Human remains from the Little Ice Age show unmistakable evidence of stunting. When archaeologists excavated the skeletons of fifty workers buried in the permafrost at Smeerenburg ('Blubber Town'), a whaling station maintained by the Dutch on the island

of Spitsbergen in the Arctic between 1615 and 1670 (when the cold forced them to withdraw), no fewer than forty-three showed evidence of stunting and a corresponding reduction in height. Even more striking, French soldiers born in the second half of the seventeenth century were on average about 3 centimetres shorter than those born after 1700; and those born in famine years were notably shorter than the rest. Stunting reduced the average height of those born between 1666 (when the data first became available) and 1694 to 161 centimetres or less: the lowest ever recorded (Fig. 3).

Malnutrition often impairs the development of major organs as well as long bones, making children more vulnerable to both contagious and chronic diseases, which can further diminish stature. John Komlos, the demographer whose research revealed the reduced height of Louis XIV's soldiers, was surely correct that the seventeenth-century crisis 'had an immense impact on the human organism itself'. His data provide perhaps



3. Estimated heights of French males born between 1666 and 1770.
John Komlos assembled 38,700 'observations' from the personal records of French males who enlisted in the army born between 1666 and 1770. Even though recruiting officers rejected the shortest volunteers, the 'stunting' effect of global cooling is evident. The average height of Louis XIV's soldiers was 1,617 millimetres, or 5 feet 3 inches.

the clearest – and saddest – evidence of the impact of the Little Ice Age on the human population. The repeated famines not only killed: many of those who survived literally embodied Hobbes's grim assertion that 'the life of man' had become 'solitary, poor, nasty, brutish and short'.[44]

An Overpopulated World?

Although Hobbes and his contemporaries apparently stood somewhat shorter than their grandparents, they were far more numerous. A benign climate for most of the sixteenth century had allowed the human population in most parts of Europe and Asia to increase and in some areas to double, until by 1618 China boasted perhaps 150 million inhabitants, India 116 million and Europe 100 million. In some areas, the number of inhabitants had increased so fast that local resources no longer sufficed to feed them because of another cruel calculus: *population increases geometrically while agricultural output grows only arithmetically*. Just like compound interest, a sustained demographic increase of 1 per cent per year over a century causes a population not merely to double, but to triple; while a 2 per cent increase over a century produces a sevenfold growth. Since crop yields rarely increase at this pace, food shortages can occur very rapidly.

Many people in the early seventeenth century could see that some parts of the world possessed more mouths than could be fed, and they feared the consequences. China's Lower Yangzi Valley, known as Jiangnan, boasted a population of about 20 million by 1618, equivalent to almost 1,200 persons per square mile (by way of comparison, the most densely settled areas of the world today boast 1,000 persons per square mile). According to Alvaro Semedo, a Jesuit long resident in the region, in the 1630s Jiangnan was 'so full of all sorts of people that not only the villages but even the cities can now be seen one from another' and, in some areas, 'settlement is almost continuous'. Indeed, he mused:

> This kingdom is so overpopulated [*eccessivamente popolato*] that after living there for twenty-two years, I remain almost as amazed at the end as I was at the beginning by the multitude of people. Certainly the truth is above any exaggeration: not only in the cities, towns and public places . . . but also on the roads there are normally as many people as would turn out in Europe [only] for some holiday or public festival.

Since 'the number of people is infinite', Semedo concluded, 'there can be no capital sufficient for so many, or money enough to fill so many purses'.[45]

Many of Semedo's contemporaries also considered Europe overpopulated. Sir Ferdinando Gorges claimed that England's 'peaceable time affords no means of employment to the multitude of people that daily do increase', and he sent colonists to settle in Maine primarily to reduce population pressure at home. His rivals in the Virginia Company, fearing 'the surcharge of necessitous people, the matter or fuel of dangerous insurrections', likewise sought to remove them from England to their new colony. These and other measures enjoyed such success that by the 1630s thousands crossed the Atlantic each year, which (according to some) promoted England's stability because the colonies 'serve for drains to unload their populous state which else would overflow its own banks by continuance of peace and turn head upon itself, or make a body fit for any rebellion'.[46]

Scarcely had the ink dried on these words than the global population contracted sharply. In China, the victorious Qing believed that in the mid-seventeenth-century crisis 'over half of the population perished. In Sichuan, people lamented that they did not have a single offspring.' In the 1650s, after a decade of sectarian violence and civil war in Ireland, an English eyewitness wrote that 'a man might travel twenty or thirty miles and not see a living creature' except for 'very aged men with women and children' whose skin was 'black like an oven because of the terrible famine'; and a generation later, another English eyewitness estimated that over 500,000 Irish men and women had died 'by the sword and famine and other hardships' in the 1640s. Contemporaries elsewhere made similarly bleak assessments. In southern Germany, one survivor of the Thirty Years' War believed that 'there have been so many deaths that the like of it has never been heard in human history'. A Lutheran minister wrote despondently in 1639 that of his 1,046 communicants a decade earlier, barely one-third remained: 'Just in the last five years, 518 of them have been killed by various misfortunes. I have to weep for them', he continued forlornly, 'because I remain here so impotent and alone.' In France, ravaged by war, famine and disease, Abbess Angélique Arnauld of Port-Royale (just outside Paris) estimated in 1654 that 'a third of the world has died'.[47]

Subsequent research has corroborated each of these striking claims. In China, 'the cultivated area of land decreased by about one-third' during the Ming–Qing transition, while 'the demographic losses were nearly the same'. Sichuan suffered particularly badly, with perhaps a million killed. Ireland's population fell by at least one-fifth during the mid-seventeenth century. In Germany, 'about 40 per cent of the rural population fell victim to the war and epidemics' between 1618 and 1648, and 'in the cities, the losses may be estimated at about 33 per cent'. Many villages in the Île-de-France suffered their worst demographic crisis of the entire Old Regime in 1648–53.[48] These staggering losses were not caused by the Little Ice Age alone, however: it required the misguided policies pursued by religious and political leaders to turn the crisis caused by sudden climate change into catastrophe.