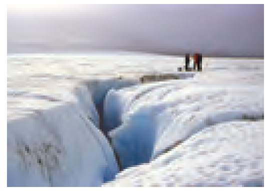
Essay



Climate variation: a simple geological perspective

There is much talk about current global warming, but that is not the main subject under discussion here. There is fairly general agreement on climate changes through geological time, and the cause or causes are becoming clearer. In this Feature, a simple backward look is given to climate events, particularly climatic cycles, in geological time, to help get in perspective some of the predictions for our near future.

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Ice ages

The climate has varied repetitiously throughout the history of the Earth, for example, as revealed by evidence of at least three ice ages in the Pre-Cambrian, the oldest of which occurred about 2.2 billion years ago, identifiable from layers of tillite (the sedimentary rock produced by the lithification of till or 'boulder clay'). For example, the Scottish Dalradian Argyll Group contains the famous Port Askaig Tillite (i.e. ancient till) some 600 Ma old, it is hundreds of metres thick and has been interpreted as containing over 400 separate ice advances. Evidence of subsequent glaciations is more widespread and better preserved, especially during the Permian (*c.* 245 to 286 Ma ago) in the lands that constituted the super continent of Gondwana, located around the South Pole.

The Earth's most recent 'ice' (or 'glacial') age is associated with the start of the Pleistocene, some 1.6 million years ago. However, recent evidence from forams and other marine species suggest that surface waters began to cool at least 50 million years ago, during the Eocene (Fig. 1). Knowledge of this cooling is becoming quite detailed, involving, as it does, land mass movements and the fundamental concepts of the carbon geochemical cycle. In essence: between 50 and 20 million years ago, world temperatures dropped approximately 5 °C and caps of ice may have begun to grow in the Antarctic. Gradual cooling continued and by 12 to 10 million years ago ice had formed on the mountains of Alaska; by 2.5 million years ago, an ice sheet had buried Greenland, and a half a million years ago ice was accumulating on the high mountains of Europe and North America. The Quaternary Ice Age, with its alternating mid-latitude continental ice sheet advances and retreats, had begun.

What causes all this? Geologists have generally concluded that ice ages share three requirements: sizeable land masses at or near the poles; nearby oceans to provide moisture that falls as snow; and mid-latitude land masses with relatively high average elevation. Such conditions put land masses at elevations and latitudes where the climate is naturally colder and so glaciers tended to grow. Over geological time, it is plate tectonics that manipulates the positions of the Earth's ocean basins and elevated land masses. No other forcing factor can match this for importance in cold climate growth. For example, the global cooling that started some 50 million years ago and led to our current ice age began after Antarctica had moved to the South Pole and other land masses had travelled to positions north of the Arctic Circle. As the plates converged, several of the Earth's higher mountain ranges rose steadily in

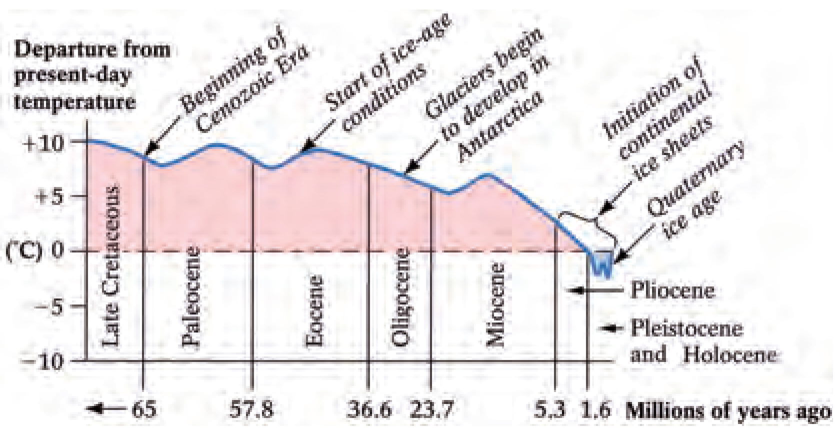

Fig. 1. Changes in global climate cooling during the Cenozoic era.

Table 1. Mega scale: the principal ice ages. Length uncertain but ice ages of the order of a few million years but generally colder for longer. Most likely cause(s): Continent Configuration (tectonic plate movement) and long term Eruptive Volcanicity Events (rock dust and gases including CO_2). Will have contained Macro, Meso and Micro time-scale events.

Period	Very approximate date (Ma (BP))	Time since previous ice age (Ma)
Late Cenozoic (Quaternary)	2.5–present	237.5
Gondwanan	240	170
Ordovician	430	250
Varangian	680	80
Sturtian	760	210
Gnejsö*	970	–

*Earlier ice ages known (e.g. 2.2 billion years ago), but less clear evidence

elevation at plate margins to exceed regional snow lines.

However, plate tectonic motion moves slowly, and from ice core and other studies we know that within an 'ice age' glacial periods have lasted for periods of approximately 50 000 to 100 000 years, separated by briefer interglacial periods of about 10 000 to 50 000 years. These fluctuations in climate (and concomitant glacial advances and retreats) are unrelated to plate tectonics and may have been driven by one cause or more, including volcanism, variations in the amount of solar energy reaching certain parts of the Earth's surface, meteorite impacts, and changes in the global circulation patterns of the Earth's oceans. However, none of these forcing factors gives a satisfactory single explanation for the advance or retreat of the Pleistocene continental ice sheets.

In addition to the climatic changes that occur over geological time (e.g. the repeated glacial and interglacial episodes of the Quaternary), there are important climatic variations that influence geomorphological processes over much shorter periods. Examples include the North Atlantic Oscillation (NAO), the El Niño Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO) and the effects of volcanic eruptions.

Magnitude and frequency of climate change

Climate change has occurred over a variety of time scales and over various extents of temperature fluctuation from geological epochs to decades. Figure 2 shows repetitive variation in world climate over the past billion years and illustrates crudely magnitude and frequency of ice events. Such events were probably triggered by tectonic combinations of the important forcing factors with time. In order to attempt to simplify the complexity of the ice age maze, and at the risk of oversimplification, four tables have been produced as an attempt to encapsulate various data on the different scales of event, from mega to micro. The tables are capable of various interpretations but we have tried to adhere to more generally accepted factual data.

Table 1, the Mega scale, shows the principal continental ice ages of the geological past and the present. Table 2, the Macro scale, records the principal major glacial advances and retreats (i.e. glaciations and interglacials) within an ice age, of which the table shows one set of dates and names—there being others, typically influenced by parts of the world where researchers have done most of their work, e.g., North America, UK or Europe, or wherever

Table 2. Macro (± *c.* 10 °C) scale. Simplified glacial, interglacial and postglacial stages of the later parts of the Quaternary. Tectonic configuration of land/sea masses and combinations of Earth movement cycles: axial tilt (*c.* 41 ka periodically); eccentricity (*c.* 100 ka); precession (*c.* 23 ka); orbital inclination (*c.* 100 ka) and meteoric dust (*c.* 100 ka) and their influence on 'where and when' of solar radiation.

Sequence of glacial and inter-glacial stages	Britain	NW Europe	Alps	North America	Marine oxygen isotope stages	Approximate date (Ka BP)§	Length (ka)
Holocene	Flandrian				1	12–present	12++
Last glacial*	Devensian	Weichselian	Würm	Wisconsin	2-4	71–12	59
Last Interglacial	Ipswichian	Eemian		Sangamon	5	128–71	57
Penultimate* glaciation	Wolstonian†	Saalian	Riss	Illinoian	6	186–128	58
Penultimate interglacial	Hoxnian	Holsteinian		Yarmouth	7	245–186	59
Older glacial ‡	Anglian	Elsterian	Mindel	Kansan	8	303–245	58

* Various sub-divisions (stadials and interstadials) identified
† The Wolstonian did not produce an ice cap in Britain
‡ Details of the even older glacial periods somewhat uncertain
§ Other interpretations exist (with large differences) e.g. the Devensian/Ipswichian stages are commonly given as *c.* 120 ka and the Ipswichian/Wolstonian as *c.* 200 ka.

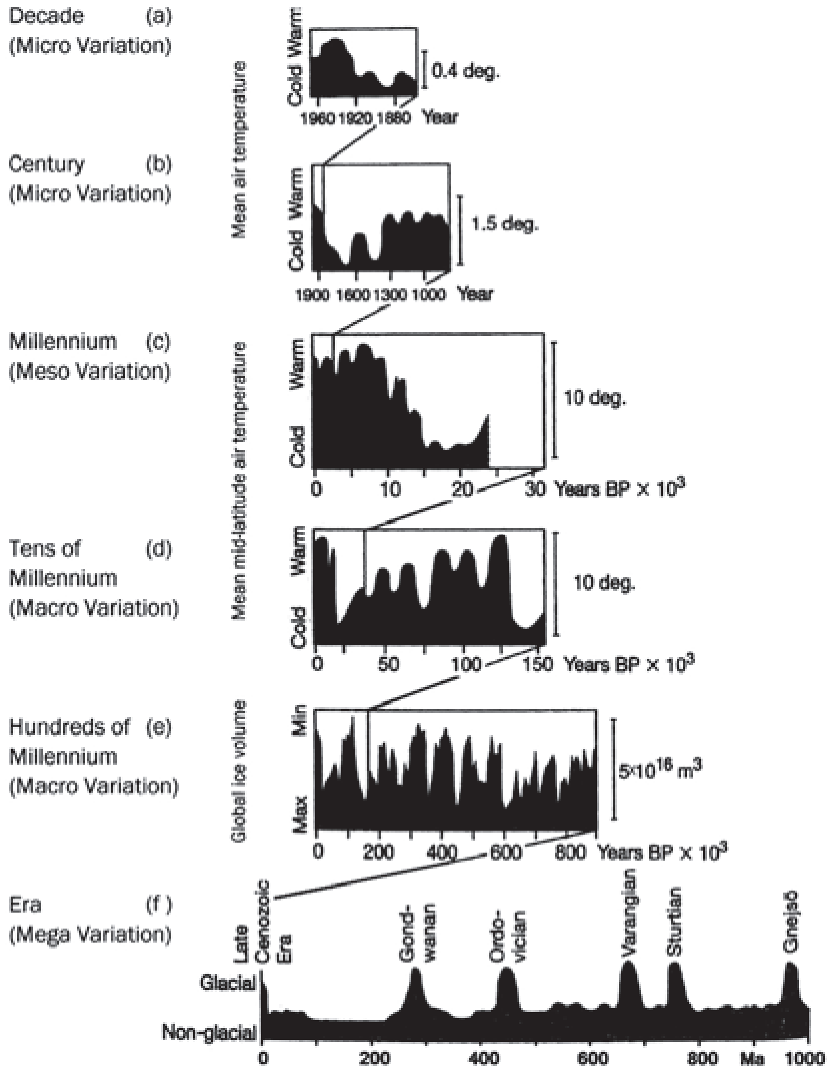

Fig. 2. The repetitive variation in world climate over the past billion years (after Goudie, 2005).

(Fig. 3). Table 3, the Meso scale, gives the recent post-glacial events, which are fairly well dated on pollen and other biological techniques as well as absolute dating. Table 4, the Micro scale, gives the smaller climate changes and recent short-time events about which perversely there is perhaps more debate about the causes and effects than preceding bigger events.

The Mega events help to interpret stages of global tectonics and the configuration of land/sea masses at the time. They also help in explanations of biological evolution and local stratigraphy. The three other scales, Macro to Micro, being much closer to us geologically, provide considerable visual evidence of the physical effect of climate changes and have developed into a whole branch of the science of geology about which much has been written. We have summarized some principal points following.

Forcing factors within the Pleistocene Ice Age

Variation in the Earth's Orbit Possibly the most talked about of the causes of the glacial/interglacial fluctuations within the Pleistocene and what many geologists have come to believe is the primary cause of the glacial fluctuations during an ice age, are variations of the Earth's position and orientation relative to the Sun. This was first proposed by a British physicist, John Croll, in the late 19th century, and further refined by the famous Yugoslavian astronomer, M. Milankovitch, about 1930. The concept suggests that whereas the total amount of solar radiation reaching the Earth may only vary relatively little, it is the periodic changes that relate to when and where the radiation strikes which profoundly affects the global climate.

The critical region for determining global glacial advances and retreats during ice ages is some 65° North, where the big ice sheets have developed repeatedly during the last several million years but which today remain largely ice free. This latitude has and has had for the more recent geological past the greatest concentration of land high above sea level and adjacent to ocean sources of moisture, to provide centres from which the ice can grow. At times when this area receives less solar radiation and becomes sufficiently cold for winter snow to accumulate and survive the summer melting, the snow pack thickens from year to year until glaciers form. Once global glacial expansion has begun, the world's climate further cools, and then 65° South, for example, where for some time now although there has been relatively little land mass, the high areas within it such as the current Andes, can also develop glaciers.

The magic of Milankovitch's work was the calculation of three periodic astronomical factors to show how they might combine to lower the radiation levels reaching the Earth at 65° North and why they happen at recurrence intervals of some 100 000 years in the last million years. The three factors include: variations in the shape of the Earth's orbit

Table 3. Meso (± *c.* 1.5 °C) scale. The climatic periods of the European Holocene (the Blytt–Sernander scheme). Devensian deglaciation started about 15 000 to 14 500 BP. Likely cause(s): consequent ice cover and vegetation changes post-glaciation, and related oceanic salinity current and climatic effects.

Period	Pollen dating zone	Climate	Approximate date (BP)*	Approximate length (years)
Sub-Atlantic	VIII	Cool/wet	2600–present	2600+
Sub-Boreal	VIIb	Warm/dry	5700–2600	3100
Atlantic	VIIa	Warm/wet	7800–5700	2100
Boreal	V/VI	Warm/dry	10 500–7800	2700
Pre-Boreal	IV	Cool/dry	11 500–10 500	1000

* Other interpretations exist (with small differences).

Fig. 3. Lithified Gondwanan tillite rests on ice-striated andesite in South Africa.

drop) but these additional factors must contribute to further macro ice age climate deterioration that leads to the world-wide expansion or retreat of glaciers within the ice age, i.e. this is where the tectonic plate movement, on occasions like now or in the past, conspires with the Milankovitch orbital factors to produce a solar radiation minimum around the current 65° North land masses. This situation needs other climatic factors to maximize change, including reflectivity of the Earth's surface (e.g., vegetation, water) and, importantly, changes to the oceans' salinity that alter large scale oceanic circulation. As ice and snow grow, covering darker coloured rock and soil (which absorb radiation rather than reflecting), the percentage of incoming radiation reflected from surfaces back into space increases sharply and, as more incoming radiation is reflected, less remains available to warm the Earth's surface, and the Earth's climate cools further.

Ocean Currents—the Atlantic example The thermohaline circulation (THC) is the ocean circulation in the Atlantic, driven by density (i.e., temperature and salinity) differences between

around the Sun, from circular to elliptical (i.e. oval shaped); variations in the tilt of the Earth's axis towards or away from the Sun; shift or procession of the spring and autumn equinoxes caused by the wobble of the Earth's axis as the Earth spins like a top (Fig. 4).

Each of these factors is insufficient to produce a full-blown continental glacial expansion but climate experts have estimated that, taken together, they can reduce solar radiation enough to lower global temperatures by about 4 °C. It is clear that this falls short of the mega ice age temperatures (say a 10 °C

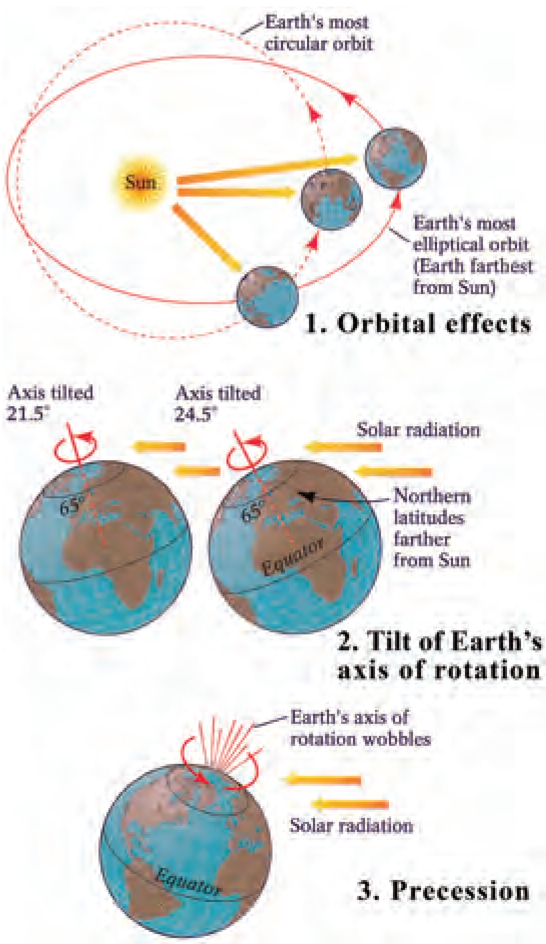

Fig. 4. The three astronomical factors proposed by Milutin Milankovitch that interact to affect the amount of solar radiation striking the Earth's high northern latitudes.

Table 4. Micro (± c. 0.5°C) scale. Some current and recent short time events

Range	Name*	Approx. date	Likely cause(s)
Millennial	Mediaeval	750 → 1300 AD	Sunspot activity (inc. combinations of various macro and meso time scale events)
	Warm Period ('Little Optimum')	(max. 1100 → 1300)	
	'Little Ice Age'	1300 → 1900 AD	Sunspot activity (inc. combinations of various macro and meso time scale events)
Decadal	Current NAO	Decadal cycles†	Subtropical high and Icelandic low air pressures in Atlantic
	Current El Niño	Decadal cycles†	Warm ocean surface temperature in Pacific
	Current La Niña	Decadal cycles†	Cold ocean surface temperature in Pacific

* Not including modern warm 'greenhouse effects' considered due to industrial CO_2 (highest for > 20 Ma), from approximately 1700 to present, max. 1950 to present.
† Current events, little knowledge of past extent but similar events likely.
NAO = North Atlantic Oscillation

different water bodies. The deep outflow of cold North Atlantic Deep Water is matched by a warm northward surface flow. This effectively transports heat into the North Atlantic; Europe is up to 8 °C warmer than other regions in the same latitude, with the largest effect in winter.

It is believed that the THC operates in two modes: a warm switched-on mode similar to the present-day Atlantic; and a cold switched-off mode with cold water forming south of Iceland. This appears to be associated with major inputs of freshwater, either from surging glacial ice sheets (Heinrich events) or meltwater floods (e.g. Younger Dryas event around 13 000 BP when temperatures in Europe were 9 °C colder than today, called the Loch Lomond Stadial in Great Britain).

The cold Younger Dryas event occurred due to changes in the flow of meltwater from the retreating Laurentide ice sheet on North America. During the initial stages of deglaciation the meltwater had flowed to the Gulf of Mexico via the Mississippi River; as the ice sheet retreated further it flowed out of the St Lawrence waterway to the North Atlantic, where it freshened it sufficiently to halt the THC circulation.

The Quaternary period

The Quaternary has been a time of marked climatic instability. Amongst the key features of this period have been the last c. 2.5 Ma, especially the last 1.6 Ma, i.e., the Pleistocene, are:

1 marked global temperature fluctuations, from values similar to present day during interglacials, to levels that were sufficiently cold to treble the volume of land ice during glacial periods (Fig. 5). There have been at least 17 major glacial/interglacial cycles in the last *c.* 1.6 Ma (Table 2);

2 the build up of ice sheets up to 4 km thick over mid to high latitudes, especially in the northern hemisphere. Beyond the ice limits, permafrost and periglacial conditions had a profound impact on slope stability (e.g. widespread landsliding and solifluction in the Northern Hemisphere). The last major glacial advance, the Devensian in UK, had its peak around 18 000 BP, with deglaciation starting around 15 000 BP and continuing to the present day (Tables 2 and 3);

3 marked fluctuations in global sea level, a drop of over 100 metres due to water being taken to create continental ice sheets in the glacials and released during the warmer interglacials to raise the sea level again. Previous higher global sea-levels during the Quaternary were similar to the present levels. Since the end of the last glaciation, global sea-level rose rapidly (*c.* 12.5 mm per year) from around 15 000 BP, reflecting the melting of ice sheets. After 8000 BP the rise was slower. Local sea-level curves for the Holocene vary because of the effects of isostatic recovery. This fall and rise resulted in buried valleys below modern rivers; complex river terrace sequences along valleys; onshore relict cliffs and raised beaches; dead coral reefs; submarine canyons extending from continental shelves to the deep sea;

4 extensive covering of much of the land and sea bed surface by complex till sequences (i.e. morainic material) from both valley and continental glacial rock debris;

5 vast volumes of granular glaciofluvial debris issuing from the margins and snouts of glaciers, often covering the tills laid down by the glaciers themselves;

6 formation of numerous lakes of all sizes near the glaciated regions, often containing laminated clay (winter) and silt (summer) deposition;

7 enormous volumes of silt (rock flour) carried away by the wind from valleys that drained the melting glaciers and deposited as loess (predominantly silt and fine sand) over vast areas of the Northern Hemisphere continents (Fig. 6);

8 abrupt changes between warm and cold periods. For example, at the end of the last glaciation, the transition from the Younger Dryas (near-glacial wetter conditions around 13 500 to 11 200 BP) to the Holocene period (warmer conditions) is believed to have occurred in less than a decade, as noted above (Table 3);

9 rapid retreat and decay of the ice sheets during the interglacial periods, with a replacement of tundra landscapes by forest in the mid-latitudes; and,

10 in low latitudes the growth and contraction of the mid-high latitude ice sheets generally corresponded with times of greater moisture (pluvials) and times of less moisture (interpluvials). In deserts, sand seas developed and advanced during dry periods.

Fig. 5. The 'Inland Ice' of Greenland is the northern hemisphere's one remaining really large and really thick ice sheet.

During the current interglacial period, the Holocene (Tables 3 and 4), there have been notable climatic changes superimposed on the overall glacial/interglacial cycle. For example around 7000 BP the present day Sahara experienced a prolonged humid period. Over the last millennium climate has continued to change on Mesa and Micro scales (Tables 3 and 4). In the UK a 'Mediaeval Warm Period' (around 1100–1300 AD) was followed by a deterioration to a period of colder and stormier conditions known as the 'Little Ice Age' (around 1300–1900 AD; Fig. 7). Evidence suggests that these changes were related to sunspot activity; the so-called 'Grand Maximum' and the 'Spörer' and 'Maunder' Minima respectively.

Where geology merges into history and climatology, as shown in Table 4, the Micro scale events and geological explanations merge with the work of other disciplines. Having said that, we offer the following that is, we hope, not only more or less correct, but also helps clarify this rapidly expanding and somewhat complex field.

Fig. 6. Terraces cut into the vast thickness of Pleistocene loess in the Gansu area of central China.

Current climate changes related to meteorological conditions

The North Atlantic Oscillation (NAO) This involves the north-south shift (or vice versa) in storm and depression tracks across the North Atlantic Ocean and into Europe. The NAO index varies from year to year, but tends to remain in one phase for several years for reasons not clearly understood (Table 4).

Positive NAO index (e.g., winter/springs of 1989, 1990 and 1995); a strong subtropical high pressure centre and a deep Icelandic low. The increased pressure difference results in stronger and more frequent winter storms crossing the Atlantic Ocean on a more northerly track, i.e., warm and wet winters in Europe, and cold and dry winters in northern Canada and Greenland. The eastern US experiences mild and wet winter conditions.

Negative NAO index (e.g., winter/springs of 1917, 1936, 1963 and 1969); a weak subtropical high and a weak Icelandic low. This results in fewer and weaker winter storms crossing the Atlantic on a more west-east pathway, bringing moist air into the Mediterranean and cold air to northern Europe. The US east coast experiences more cold air and snow conditions.

El Niño Southern Oscillation (ENSO) ENSO is associated with strong fluctuations in ocean currents and surface temperatures within the Pacific Basin, again for reasons not well understood. It causes abnormal atmospheric and environmental conditions, primarily in equatorial regions (Table 4). There are two components:

El Niño (the 'Little Boy'); associated with unusually warm ocean surface temperatures in the Equatorial region of the Pacific. During typical El Niño conditions, warmer sea surface temperatures spread further east. This coincides with a weakening of the atmospheric circulation (the Walker circulation; an east-west atmosphere circulation pattern characterized by rising air above Indonesia and the western Pacific, and sinking air above the eastern Pacific). It may cause lower rainfall over the western Pacific, and excessive rain on parts of Peru and Ecuador. The most intense El Niño of the twentieth century occurred in the period 1997–98; it followed the longest recorded event, from 1991 to 1995.

La Niña (the 'Little Girl') associated with abnormal cold ocean surface temperatures in the Equatorial Pacific. La Niña events are associated with cooler sea surface temperatures extending further west. Strengthening of the Walker circulation causes an increase in precipitation, particularly over Indonesia, and drier conditions over Peru and Ecuador.

The Southern Oscillation Index (SOI) is used to quantify the strength of an ENSO event. It is calculated from the difference between the sea level pressure at Tahiti and Darwin, Australia. The frequency of El Niño events has been increasing; since

Table 5. Pacific Decadal Oscillation (PDO)

PDO phase	North Pacific sea surface pressure	North Pacific sea surface temperature	Influence on El Niño conditions	Influence on La Niña conditions
Positive	Low	Cold	Enhance	Weaken
Negative	High	Warm	Weaken	Enhance

1970 there have been five events (1972–73, 1982–83, 1986–88, 1991–95 and 1997–98); the same number occurred in the preceding 70 years.

The Pacific Decadal Oscillation (PDO) PDO is an oscillation in northern Pacific sea surface temperatures, between normal and below-normal conditions (Table 5). The pattern operates on a 20–30 year time scale. Shifts in the PDO regime occurred in 1925, 1947, 1977 and, possibly, 1995. PDO phases can combine with El Niño/La Niña conditions to affect climate, particularly in winter.

Volcanic eruptions Explosive volcanic eruptions can have a significant influence on today's global and regional climate. Particles are ejected into the lower stratosphere and spread to form a veil over the whole planet, reducing the amount of the solar energy which reaches the Earth's surface. An individual eruption may generate mean global cooling of 0.2–0.3 °C for around 1–2 years. For example, the explosion of Santorini (Thera) in the Eastern Mediterranean around 3628 BP led to a period of cooler, wetter climate. After Tambora, Indonesia, exploded in 1815 the following year became known as 'the year without a summer' in many parts of the Northern Hemisphere.

Evidence for future human-induced climate change

It is widely believed that global climatic changes are occurring as the result of accumulation of 'industrial' greenhouse gases such as carbon dioxide (CO_2) in the atmosphere. Geochemical evidence from ice cores, supplemented by direct measurements since the mid-1950s, reveals a steady rise in greenhouse gas concentrations from the late 1700s, changing to a rapid rise post-1950. Atmospheric concentrations of CO_2, the main man-related greenhouse gas, have risen from about 270 ppm in pre-industrial times to over 360 ppm (the current concentrations have probably not been exceeded in the last 20 M years). The debate continues on the contributions that man is making to the current climate changes.

Global temperature has risen by about 0.6 ± 0.2 °C since the beginning of the 20th century, with about 0.4 °C of this warming occurring since the 1970s. In the 20th century, precipitation increased by 0.5 to 1 per cent per decade over the Northern Hemisphere continents; there was also a 2 to 4 per cent increase in the frequency of heavy precipitation events. Warm El Niño episodes have become more frequent, persistent and intense since the 1970s.

Fig. 7. Retreat of a Himalayan glacier leaves bare rock and debris inside its arcuate terminal moraine left during the Little Ice Age.

Climate change predictions

There is clearly more to the causes of glaciation and climate change than meets the eye and more discoveries are certain to come to light as the mysteries of the ice cores, and other approaches in the developing science around glaciation, are researched.

The Inter-governmental Panel on Climate Change (IPCC) was established by the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP) in 1988. Climate predictions have been made in a series of Assessment Reports; the most recent (the Third Assessment Report) was published in 2001. The IPPC moved from a position where the cause of global warming was uncertain (second report in 1997) to clearly related to anthropogenic emmissions (third report in 2001). The problem had been that CO_2 was rising through the twentieth century but there wasn't a consistent pattern of warming (1940–60s were quite cold). The breakthrough came when warming from greenhouse gases was modelled together with natural climate cycles, and the match was nearly perfect. Results show that mid-century cooling reflects part of the natural cycle, but that post-1970s warming differs from current expectation based on natural change, and is largely an effect of increasing CO_2. New CO_2 is isotopically light (as it comes from coal and oil), and warming can therefore be explained quite convincingly as largely anthropogenic. [The fourth report was published during the production of this essay.]

The Third Assessment Report results provide an indication of the scale of changes that could be expected by 2100:

1 a mean global surface temperature rise is projected

Fig. 8. Prime beach resorts may shift with displaced climate belts.

by 1.4–5.8 °C. Note that warming at the higher end of this range would shift climatic zones towards the poles by about 550 km (Fig. 8);

2 glaciers and ice caps will continue to retreat (they have retreated throughout the 20th century) and Northern Hemisphere snow covered land and sea ice will decrease. There remains the remote possibility of a collapse of the West Antarctic Ice Sheet; this and other ice melting could cause sea-level to rise rapidly by around 6 m;

3 at latitudes of 45° or greater (i.e. northern Europe, Russia, China, northern and central USA, Canada and the southern extremes of South America), annual precipitation will increase by 100–300 mm;

4 in lower latitudes 5–45° (i.e. Australia, southern Africa, southern USA, western South America, Central America, the Caribbean, north Africa, the Mediterranean region, the Middle East and India), annual precipitation will decrease by 100–700 mm. It is also likely that the strength and duration of the Asian summer monsoon will become more variable;

5 around the Equator annual precipitation changes are expected to be complex, with a decrease of 100–600 mm predicted for the Americas and South-east Asia, but an increase of 100–300 mm expected in central Africa; and

6 global mean sea-levels are expected to rise by between 0.1 and 0.8 m, in response to thermal expansion of sea water. The central value of 0.48 m (4 mm per year) would give an average rate of two to four times the rate experienced in the 20th century.

Changes in the weather

It is not just the climate that could change, but also the weather. It is expected that the frequency of climate extremes (droughts, hurricanes, intense rainstorms, periods of extreme heat and cold, etc.) will increase. The predicted changes in the weather are expected to lead to significant changes in the behaviour of many earth surface systems, i.e. changing patterns of landsliding, erosion, sediment transport and deposition. However, the response to climate change is likely to be complex.

In southern England, for example, over the next century there could be up to a 25 per cent increase in mean monthly effective rainfall (i.e. the precipitation minus evapotranspiration). This could result in an increase in landslide risk to coastal communities, such as Ventnor on the Isle of Wight. The town has grown up on an old landslide that is susceptible to slow movement during periods of heavy winter rainfall. A monthly effective rainfall of 150 mm is sufficient to trigger a phase of movement. As a result of climate change, the return period (i.e. annual probability) of a monthly effective rainfall total of 150 mm is predicted to change from the current 1 : 200 years to 1 : 50 years, under a 'high emissions' scenario and is expected to cause an increase in the frequency of landslide activity.

There remain major uncertainties associated with the forecasting of future climate change, some of which arise from the reliability of the available Global Circulation Models, the emission scenarios and the climate variables that are modelled. These uncertainties are compounded by speculations about the possible impact on numerous geomorphological processes such as the slope stability in southern England and elsewhere.

Suggestions for further reading

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