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Interannual, decadal and multidecadal scale climatic variability and geomorphology

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Abstract

Climatologists have identified and started to explain a range of different modes of climatic variability which seem to be essential components of behaviour of the global climatic system. Of potentially high geomorphological importance are oscillations in climate over interannual to century scales. A range of geomorphological impacts of such climatic oscillations has been recognised, such as alterations in streamflow and sediment yield, mass movement frequencies and coastal erosion, some recent findings on which are reviewed here. Geomorphological impacts of interannual, decadal and multidecadal scale climatic variability vary from place to place and time to time, and are often complexly related to impacts of tectonic and human factors. The importance of improved understanding of decadal scale climatic variability for the progress of geomorphology in general is discussed in terms of the development of geomorphic ideas.

Keywords: ENSO; NAO; geomorphic response; climate oscillations

1. Introduction

In recent decades, climatologists have become increasingly aware of a series of modes of variability within the global climate system which operate over a range of temporal and spatial scales. Our understanding of the nature of these modes of variability, their inter-relationships and links to global climate change has progressed hugely within recent years, and new interpretations continue to emerge. As well as identifying various modes of variability within the present-day climate, studies have also focused on elucidating their longer term histories, often using evidence from a range of environmental archives, such as tree rings, ice cores and geomorphic phenomena. Climate oscillations have been recognised at a whole series of time scales (Table 1). For example, in the tropics, a sub-annual, intra-seasonal 40- to 60-day period Madden–Julian oscillation has been identified (Madden and Julian, 1971). At a slightly longer time scale, there is a 2- to 2.5-year oscillation in the equatorial jet in the lower stratosphere, called the Quasi-Biennial Oscillation (QBO) (Baldwin et al., 2001). The El Niño Southern Oscillation (ENSO) has a periodicity of around 4 years (Philander, 1999). Decadal and inter-decadal variability is evident in the North Atlantic Oscillation (NAO) and the Pacific Decadal Oscillation

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Table 1
Examples of climate oscillations at less than century to millennial scales

Antarctic Circumpolar Wave
Antarctic Oscillation
Arctic Oscillation
Atlantic Multidecadal Oscillation
El Niño
Interdecadal Pacific Oscillation
La Niña
Madden–Julian Oscillation
North Atlantic Oscillation
Pacific Decadal Oscillation
Pacific-North American Teleconnection/Pattern
Quasi-Biennial Oscillation
Southern Oscillation
Southern Annular Mode
Northern Hemisphere Annual Mode

(PDO). At even longer time scales (not shown in Table 1), there are such important phenomena as the Dansgaard–Oeschger Cycles, Bond Cycles and Heinrich events, which occur at century to millennial scales. The three main aims of this paper are briefly to review current understanding of modes of climatic variability operating at interannual, decadal and multidecadal time scales (i.e. between annual and century scale), to illustrate their impacts on geomorphic processes, and to consider their importance to the development of geomorphological ideas.

2. ENSO

ENSO is the primary global mode of climatic variability in the 2- to 7-year time band. The Southern Oscillation is a widespread interannual oscillation in sea-level pressure between Northern Australia and the central Pacific. Its warm phase is related to the occurrence of El Niño, an intensive warming of the upper ocean in the tropical eastern Pacific lasting more than 5 months, and its cold phase is related to La Niña (Philander, 1999; Wang et al., 1999). The system oscillates between warm and cold conditions on c. 4-year time scales (Fig. 1a and c). The climatic impacts of ENSO are spatially and temporally complex and may involve considerable time lags (see Jacobs et al., 1994).

Although each El Niño event is distinctive, precipitation and temperature anomaly patterns appear to characterise all El Niño warm episodes. These can be summarised as follows:

- The eastward shift of thunderstorm activity from Indonesia to the central Pacific usually results in abnormally dry conditions over northern Australia, Indonesia and the Philippines.
- Drier-than-normal conditions are also usually observed over southeastern Africa and northern Brazil.
- During the northern summer season, the Indian monsoon rainfall tends to be less than normal, especially in the northwest.
- Wetter-than-normal conditions are usually found along the West Coast of tropical South America, and at subtropical latitudes of North America (the Gulf Coast) and South America (southern Brazil to central Argentina).
- Over the USA, winter temperatures are warmer than normal in N Central areas and cooler in the southeast and southwest.
- El Niño conditions are thought to suppress the development of tropical storms and hurricanes in the Atlantic but to increase the numbers of tropical storms over the eastern and central Pacific Ocean.

La Niña conditions tend to produce the opposite tendencies to El Niño conditions with, for example, drier-than-normal conditions over islands in the equatorial Pacific ocean, wetter-than-normal conditions in Southern Africa and the monsoon regions of India, Indonesia and Northern Australia, drier-than-normal conditions in East Africa, western equatorial Indian Ocean, southern South America and southeastern USA. The most pronounced extratropical temperature signals produced by La Niña conditions are in the USA, where winter temperatures are warmer than usual in the southeast and cooler in the northwest.

The dates of major El Niño and La Niña events in the twentieth century are shown in Table 2. In all there were around 25 warm events of differing strengths, with that of 1997–1998 being seen as especially strong (Changnon, 2000). ENSO was relatively quiescent from the 1920s to the 1940s (Kleeman and Power, 2000). The frequency and intensity of ENSO has been unusual since the mid-1970s until 1998, in comparison with earlier in the century, with relatively more frequent, persistent and intense warm phases and

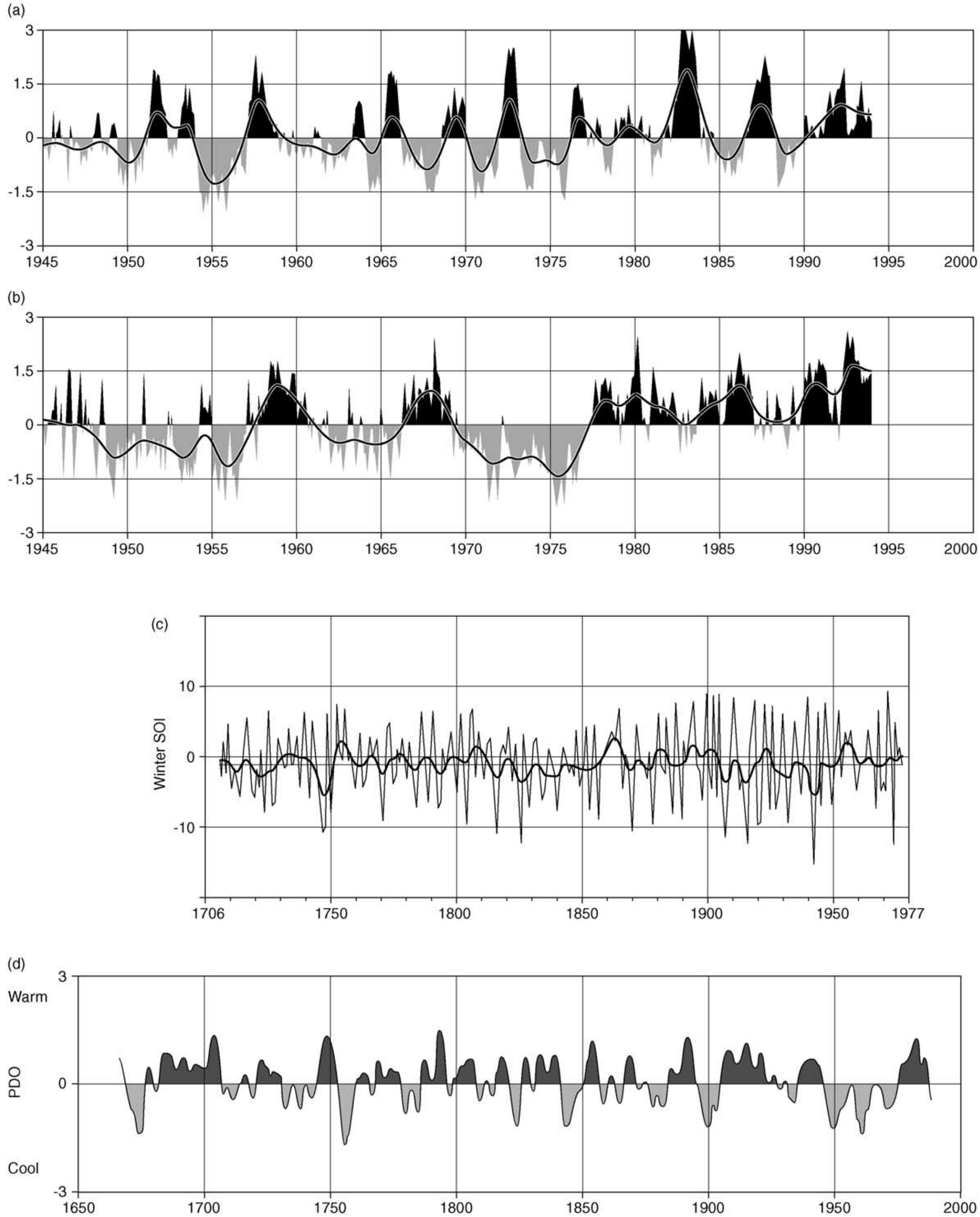


Fig. 1. Time series for ENSO and the PDO. (a) ENSO and (b) PDO. The superimposed lines represent heavily smoothed versions of the time series (modified from Barlow et al., 2001, Fig. 3a and b). (c) Reconstructed winter SOI values from 1706 to 1977 using tree rings from subtropical North America and Indonesia (modified from Stahle et al., 1998, Fig. 5). (d) Reconstructed PDO from 1660 to 1990 using tree rings from southern and Baja California (modified from Biondi et al., 2001, Fig. 3).

Table 2
Twentieth century Pacific warm (El Niño) and cold (La Niña) episodes

Year	Episode	Intensity
1902–1903	Warm	Weak
1903–1904	Cold	Strong
1905–1906	Warm	Strong
1906–1908	Cold	Strong
1909–1910	Cold	Strong
1911–1912	Warm	Strong
1913–1914	Warm	Moderate
1916–1918	Cold	Strong
1918–1919	Warm	Strong
1923	Warm	Moderate
1924–1925	Cold	Moderate
1925–1926	Warm	Strong
1928–1929	Cold	Weak
1932	Warm	Moderate
1938–1939	Cold	Strong
1939–1941	Warm	Strong
1946–1947	Warm	Moderate
1949–1951	Cold	Strong
1951	Warm	Weak
1953	Warm	Weak
1954–1956	Cold	Strong
1957–1959	Warm	Strong
1963	Warm	Weak
1964–1965	Cold	Moderate
1965–1966	Warm	Moderate
1968–1970	Warm	Moderate
1970–1971	Cold	Moderate
1972–1973	Warm	Strong
1973–1976	Cold	Strong
1976–1977	Warm	Weak
1977–1978	Warm	Weak
1979–1980	Warm	Weak
1982–1983	Warm	Strong
1983–1984	Cold	Weak
1984–1985	Cold	Weak
1986–1988	Warm	Moderate
1988–1989	Cold	Strong
1990–1993	Warm	Strong
1994–1995	Warm	Moderate
1995–1996	Cold	Weak
1997–1998	Warm	Strong
1998–1999	Cold	Strong

From data in Table 2.1, Kousky and Bell (2000).

less frequent La Niña conditions (Houghton et al., 2001). A persistent La Niña from late 1998 to early 2001 might signal the end of this warm phase.

ENSO has a long history and various methods have been used to reconstruct the history of the phenomenon back into the Holocene and beyond. Archival materials, tree-ring chronologies and coral isotope records all give a picture of ENSO history over the past few centuries (see e.g. Felis et al., 2000; Ortlieb, 2000; Stahle et al., 1998). The Holocene history of El Niño has been a matter of some controversy (Wells and Noller, 1999) but it appears that the modern periodicity of El Niño may have been established about 5 Ka BP, possibly in response to orbitally driven changes in solar radiation (Clement et al., 2000; Liu et al., 2000). Further back in the Holocene, Grosjean et al. (1997) have discovered more than 30 debris flow events caused by heavy rainfall events between 6.2 and 3.10 Ka BP in the northern Atacama. The stratigraphy of debris flows has also been examined by Rodbell et al. (1999), who have been able to reconstruct their activity over the last 15 Ka. Between 15 and 7 Ka BP, the periodicity of deposition was equal to or greater than 15 years and then progressively increased to a periodicity of 2–8.5 years.

Studies of the geochemistry of dated *Porites* corals from the last interglacial of Indonesia have shown that at that time there was an ENSO signal with frequencies nearly identical to the instrumental record from 1856 to 1976 (Hughen et al., 1999). More recent coral records from c. 5370 years BP on the Great Barrier Reef in Australia (Gagan et al., 1998) imply a very different pattern of ENSO, or its teleconnections to Australia, in the mid-Holocene. Certainly, despite much uncertainty and apparent regional differences in records, there is increasing evidence for variations in the intensity and frequency of ENSO over the Holocene.

Severe El Niños, like that of 1997/1998, can have a remarkable effect on rainfall amounts. This was shown with particular clarity in the context of Peru (Bendix et al., 2000), where normally dry locations suffered huge storms. At Paita (mean annual rainfall 15 mm), there was 1845 mm of rainfall while at Chulucanas (mean annual rainfall 310 mm), there was 3803 mm. Major floods resulted (Magilligan and Goldstein, 2001). ENSO also affects tropical cyclone activity. As Landsea (2000, p. 149) remarked, "Perhaps the most dramatic effect that El Niño has upon the climate system is changing tropical cyclone characteristics around the world." In some regions, an El Niño phase brings increases in tropical cyclone formation (e.g. the South Pacific and the North Pacific between 140°W and 160°E), while others tend to see decreases (e.g. the North Atlantic, the Northwest Pacific and the Australian region). La Niña phases typically bring opposite conditions. Landsea sees a variety of reasons why ENSO should relate to cyclone activity: modulation of the intensity of the local monsoon trough, repositioning of the location of the monsoon trough, and alteration of the tropospheric vertical shear.

The differences in cyclone frequency between El Niño and La Niña years are considerable (Bove et al., 1998). For example, the probability of at least two hurricanes striking the US is 28% during El Niño years, 48% during neutral years and 66% during La Niña years. There can be very large differences in hurricane landfalls from decade to decade. In Florida, for instance, over the period 1851–1996, the number of hurricane landfalls ranged from three per decade (1860s and 1980s) to 17 per decade (1940s) (Elsner and Kara, 1999). Given the importance of hurricanes for slope, channel and coastal processes, changes of this type of magnitude have considerable geomorphological significance. Mangroves, for example, are highly susceptible to hurricanes, being damaged by high winds and surges (Doyle and Girod, 1997).

There has been much recent debate over whether ENSO is influenced by global warming, with the severe El Niño of 1997/1998 being seen as perhaps enhanced by global warming (Trenberth and Hoar, 1997). Houghton et al. (2001, p. 151) draw no clear conclusions over this, saying that it remains a key question, especially as El Niño affects global climate itself.

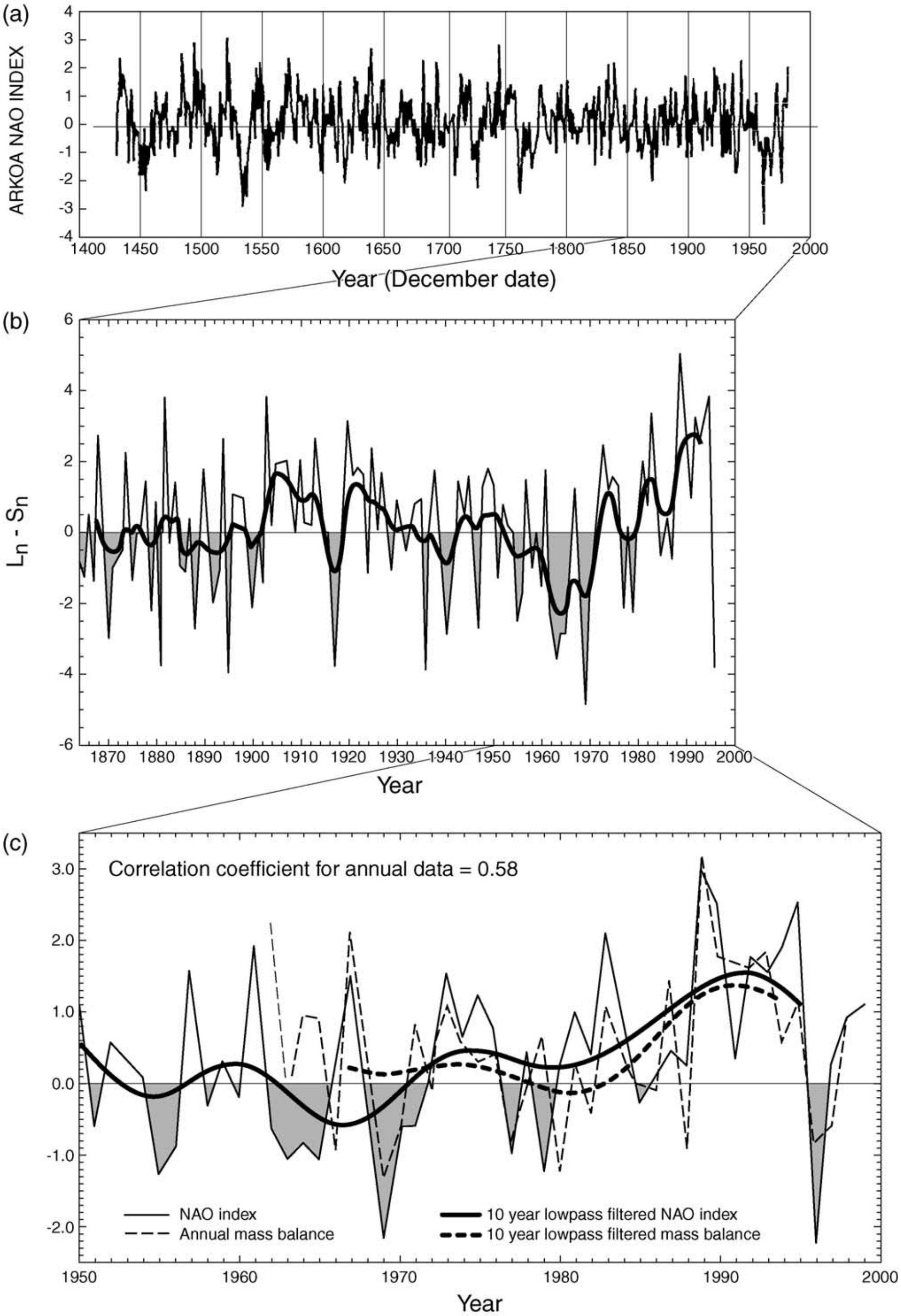
3. The Pacific Decadal Oscillation and IPO

As well as ENSO, other modes of climatic variability operating at decadal to multidecadal time scales have been recognised in the Pacific. These longer term oscillations are relatively more prominent over the extra-tropical parts of the Pacific basin, especially the northwest area. The Pacific Decadal Oscillation is a long-lived El Niño-like pattern of Pacific climate (Fig. 1b). According to Houghton et al. (2001, p. 151), the Interdecadal Pacific Oscillation is likely to be a Pacific-wide manifestation of the PDO and shows three major phases in the twentieth century. From 1922 to 1946, and again from 1978 to 1998, it was positive, whilst between 1947 and 1976, it was in a negative phase. During positive phases, SSTs over much of the SW Pacific and extra-tropical NW Pacific are cold, whilst SSTs in the central tropical Pacific are warm (but not as warm over the equatorial far eastern Pacific as in ENSO). The IPO and PDO appear to be important in modulating ENSO variability over a range of areas (e.g. the South Pacific and teleconnections across North America) (Salinger et al., 2001). The PDO and IPO appear to be part of a continuous spectrum of ENSO variability. Since 1900, El Niño (La Niña) events have been more prevalent during positive (negative) phases of the IPO. There is evidence from tree-ring studies that decadal-scale reversals of Pacific climate have occurred throughout the last four centuries (Biondi et al., 2001) (Fig. 1d). Such variability in the PDO is important for understanding changes in precipitation in the western United States (McCabe and Dettinger, 1999).

4. North Atlantic Oscillation

The North Atlantic Oscillation is one of the dominant modes of Northern Hemisphere climate variability (Perry, 2000; Wanner et al., 2001). Its positive phase sees below-normal pressure in the region of the Icelandic Low and above-normal pressure in the Azores. This leads to strong south westerlies over northern Europe and northwestern Asia, with above-average temperatures in these regions. In its negative phase, the Icelandic Low and Azores High pressure weaken and migrate southward, shutting off this southwesterly surface flow (Ottersen et al., 2001). This results in more severe winters in northern and western Europe.

As with ENSO, the NAO has shown variability in its frequency and intensity over time (Fig. 2). A quasi-decadal, 6- to 10-year, pattern of variability of the NAO has been more pronounced over the latter half of the twentieth century, while a quasi-biennial pattern dominated the early instrumental record (Houghton et al., 2001). Changes in the strength of the North Atlantic Oscillation have been traced back for over a thousand years by means of the analysis of a stalagmite from NW Scotland (Proctor et al., 2000). It may also be possible to reconstruct past NAO behaviour through tree-ring analysis (Fig. 2a) (Briffa,


(a)
ARKOA NAO INDEX
Year (December date)
(b)
$L_n - S_n$
Year
(c)
Correlation coefficient for annual data = 0.58
NAO index
Annual mass balance
10 year lowpass filtered NAO index
10 year lowpass filtered mass balance
Year

2000) and the Greenland ice core record (Glueck and Stockton, 2001). The NAO index exhibits considerable long-term variability. The 1960s displayed an extreme negative phase, whereas a prolonged positive phase occurred in the late 1980s and early 1990s (Hurrell, 1995). Major negative phases similar to those of the 1960s occurred in 1759–1777, 1549–1562, 1528–1539 and 1445–1460 (Glueck and Stockton, 2001).

Among the responses to changes in the NAO are the distribution, intensity and prevalence of storms, wave climate (Wang and Swail, 2001), sea ice volume and iceberg flux (Dickson et al., 2000). However, although in recent decades increased storminess in the North Atlantic has been linked to the strongly positive state of the NAO index, this was not the case during the period of exceptional storminess at the close of the nineteenth century. At that time, many episodes of exceptional storminess were associated with index values that were sometimes negative (Dawson et al., 2002).

5. The Arctic and Antarctic Oscillations

The Arctic Oscillation (AO) is one in which there is an oscillation in atmospheric pressure at polar and mid-latitudes in the Northern Hemisphere. In its negative phase, higher-than-normal pressure occurs over the polar region and lower-than-normal pressure at about 45°N. The positive phase brings opposite conditions that steer ocean storms further north, bringing wetter conditions to Alaska, Scotland and Scandinavia, but drier conditions to more southerly locations, such as California, Spain and the Middle East.

The NAO may be a manifestation of the AO in the Atlantic sector. Since the 1960s, the AO has tended toward a positive index. Recent modelling suggests that the recent trend in the AO, and the strengthening of the atmospheric vortex over the Arctic, are quite possibly a result of greenhouse gas forcing (Shindell et al., 2001). Its counterpart in the middle and high latitude of the Southern hemisphere is the Antarctic Oscillation (AAO). This is a large-scale alternation of atmospheric mass between mid-latitude and high-latitude surface pressure (Gong and Wang, 1999). It is also known as the Southern Annular Mode (Kushner et al., 2001). The Arctic Oscillation is also sometimes referred to as the Northern Hemisphere Annular Mode.

6. The Atlantic Multidecadal Oscillation

The Atlantic Multidecadal Oscillation (AMO) is a recently discovered 65- to 80-year cycle with a 0.4 °C temperature range. During AMO warming, most of the USA experiences less-than-normal rainfall, and between AMO warm and cool phases Mississippi River outflow varies by 10% (Enfield et al., 2000).

7. The Pacific-North American (PNA) pattern

The Pacific-North American pattern develops in the northern Pacific. The teleconnection between the PNA and tropical Pacific climate is characterised by above-normal temperatures in Alaska and western North America and below-normal temperatures in the southeastern United States. A negative phase of the pattern dominated the periods from 1964 to 1967 and 1989 to 1990 while a positive pattern dominated from 1976 to 1988 and again from 1991 to 1993.

8. Climatic variability: past, present and future

It is clear from the above examples that many modes of climatic variability have been identified, and that there are clear interactions between them. In many places, regional climates are seriously impacted by combinations of these modes of variability. Barlow et al. (2001), for example, report on the combined

Fig. 2. The North Atlantic Oscillation (NAO). (a) A 555-year reconstruction of the NAO for 1429–1983 based on tree-ring analyses (modified from Glueck and Stockton, 2001, Fig. 4). (b) The NAO index for December–March from 1864 to 1996. This is based on the difference in normalized mean sea-level pressure between Lisbon and Iceland. The anomalies at each station were normalized by division of each seasonal pressure by the long-term (1864–1983) standard deviation (modified after Hurrell, 1995). (c) NAO index (1950–1999) and mass balance of Nigardsbreen Glacier (Norway) (1962–1998) (modified after Reichert et al., 2001, Fig. 13).

influence of ENSO, PDO and NPM on summertime rainfall, drought and streamflow in the USA, whilst Felis et al. (2000) find correlations between Red Sea coral isotope records and NAO, ENSO and North Pacific climate variability since 1750. The long-term drought in the USA from 1962 to 1966 related strongly to the combined impacts of these three modes of variability. Much recent work has been aimed at trying to relate decadal scale variability to longer term changes (such as future climatic change resulting from anthropogenic activity). Increasingly, evidence shows that such climatic variability has great antiquity and has, for example, affected oceanic systems during the Late Pleistocene (Beaufort et al., 2001). Over the past 1000 years, there is now good evidence for variations in both ENSO and NAO, with, for example, switches to more positive NAO values occurring several times since 1500 (Jones et al., 2001). Thus, although the climatic oscillations we discuss operate on geomorphologically short time spans, their long-term presence within the climate system and medium-term changes in their nature may have important geomorphic consequences.

9. Selected geomorphological impacts

The potential geomorphological importance of the modes of climatic variability we have introduced in the previous sections is a result of the disruption they cause to biospheric, oceanographic and earth surface processes. Most of these climatic oscillations cause all or some of the following:

These changes occur unevenly over space and force knock-on alterations in ecological and geomorphological systems (often complex and sometimes with a time lag). So, for example, increasing precipitation levels will produce increased river flows and may also encourage vegetation growth. As Plisnier et al. (2000, p. 481) comment in relation to the influence of ENSO on East African ecosystems "Not all climate and land surface variables are teleconnected to ENSO in the same way, which leads to a complex impact of ENSO on the ecosystem. Moreover, the ENSO impact is highly differentiated in space..." Some of the changes induced will also feed back into further climatic changes. Thus, reduction in precipitation levels may cause increasing production of dust in susceptible environments, which may in turn affect the climate. Different environments will be affected by different combinations of atmospheric and oceanographic fluctuations, and sometimes the impacts may be very complex indeed. Geomorphic systems are also affected by other external factors, such as tectonic events and human impacts, and they also have important internal thresholds which, when overtopped, can lead to dramatic geomorphic change without any external forcing (Brunsden, 2001). Thus, identifying the contribution of climatic vs. nonclimatic forcing to geomorphic change can be difficult, and the importance of climatic factors will vary from place to place.

In Table 3, we list some of the major geomorphological impacts that have been recognised as resulting from decadal to century scale climatic oscillations.

Atmospheric changes:

- Elevation and depression of sea surface temperatures
- Rise and fall of air temperatures
- Increase and decrease in precipitation
- Intensification and reduction of storm activity

Oceanographic changes:

- Expansion and contraction of sea ice volume
- Growth and decline in wave heights

Table 3
Examples of geomorphological effects of decadal to century-scale oscillations

Environment affected	Impacts upon
Terrestrial hydrology	Glacier mass balance
	Lake levels
	River flows
	Snow cover
	Permafrost
Terrestrial geomorphology	Soil erosion
	Floodplain sedimentation and erosion
	Slope instability/ mass movements
	Dune movements
	Geochemical sediment growth
	Effects on fire frequency with knock-on effects on weathering, runoff and slope instability
Coastal/marine ecology and geomorphology	Coastal erosion
	Mangrove defoliation/land loss
	Coral bleaching
	Coastal dune activation

Many of these are interlinked, with for example changes in fluvial systems having knock-on effects on coastal systems in many places. As can be seen in Table 3, it is difficult to separate purely geomorphological impacts from ecological and hydrological impacts.

10. Terrestrial hydrological impacts

10.1. Lake level fluctuations

The levels of lakes can show great variability in response to changes in rainfall inputs to their catchment areas and outputs from changing amounts of evapotranspiration. There is an increasing body of evidence that climate oscillations can cause substantial changes (Nicholson, 1998). For example, El Niño warming in 1997 led to an increase in rainfall over East Africa that caused Lake Victoria to rise by c. 1.7 m and Lake Turkana by c. 2 m (Birkett et al., 1999). The abrupt change in the level of the Caspian (2.5 m between 1978 and 1995) has also been attributed to ENSO phenomena (Arpe et al., 2000). Similarly, the 3.7-m rise in the level of the Great Salt Lake (Utah, USA) between 1982 and 1986 was at least partly related to the record rainfall and snowfall in its catchment during the 1982–1983 El Niño (Arnow and Stephens, 1990). The enormous changes that occur in the volume of Lake Eyre result from ENSO-related changes in inflow, with the greatest flooding occurring during La Niña phases (Kotwicki and Allan, 1998) (Fig. 3) such as those of 1949–1952 and 1974.

10.2. Glacier mass balance

The mass balance of glaciers is controlled by rates of ablation (where temperatures are the major factor) and accumulation (where precipitation inputs are the major factor). Other things being equal, hot spells cause glaciers to retreat, whereas snowy spells cause them to advance. Thus variation in atmospheric circulation, precipitation and temperature associated with climate oscillations are of considerable importance (McCabe et al., 2000).

The positive mass balance (and advance) of some Scandinavian glaciers in recent decades, notwithstanding rising temperatures, has been attributed to increased storm activity and precipitation inputs coincident with a high index of the NAO in winter months since 1980 (Zeeberg and Forman, 2001; Nesje et al., 2000). In the case of Nigardsbreen (Norway), there is a strong correlation between mass balance and the NAO index (Reichert et al., 2001) (Fig. 2c). A positive mass balance phase in the Austrian Alps between 1965 and 1981 has been correlated with a negative NAO index (Schoner et al., 2000). Indeed, the mass balances of glaciers in the north and south of Europe are inversely correlated (Six et al., 2001) (Fig. 4a and b). Conversely, glacier retreat in the tropical Andes can be attributed to increased ablation during the warm phases of ENSO (Francou et al., 2000). However, further south, in the southern Andean Patagonia of Argentina, El Niño events have been found by Depetris and Pasquini (2000) to lead to increased snow accumulation, causing glaciers to advance so that they create barriers across drainage, forming glacier-dammed lakes. It may even be possible to relate the mass balance of glaciers in Svalbard to heat flux exchanges in the tropical Pacific Ocean (Washington et al., 2000), while those of northwestern North America can be related to the PDO (Bitz and Battisti, 1999; Moore and Demuth, 2001, and Fig. 4c and d). Glacier mass

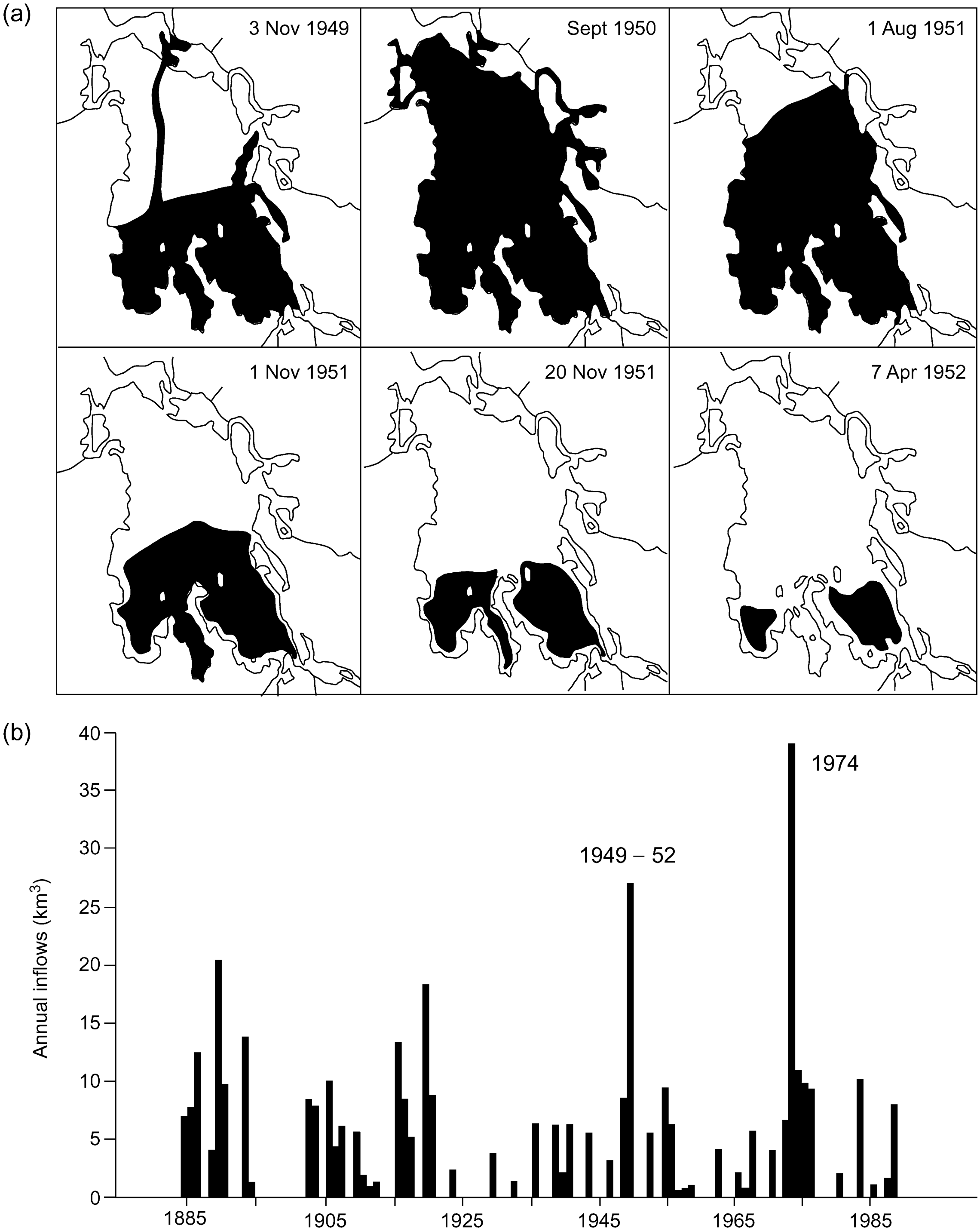


Fig. 3. The flooding of Lake Eyre. (a) Extent of flooding in 1949–1952 (after Bonython and Mason in Mabbutt, 1977, Fig. 54). (b) Estimated annual inflows to Lake Eyre North for the period 1885–1989 (based on Kotwicki and Isdale, 1991, Fig. 2). Both 1949–1952 and 1974 were strong La Niña events.

balances on Novaya Zemlaya, by contrast, have been found to relate to the NAO.

10.3. Streamflows and sediment yields

ENSO events produce streamflow anomalies, the global distribution of which has been established by Arnell (2002) (Fig. 5a) and is largely related to ENSO-influenced precipitation trends (Peel et al., 2002, and Fig. 5b). One area where there have been many investigations of the links between ENSO and streamflow is in the western United States. There is a tendency for the southwest to be wet and the northeast to be dry during the El Niño warm phases (Negative Southern Oscillation Index), and vice versa for La Niña (Cayan et al., 1999). There is some evidence that the effect on streamflow is amplified over that on precipitation. As Fig. 6a shows, the recurrence interval of discharge events in Arizona differs greatly between El Niño and La Niño years.

A study of sediment yields in southern California showed that during strong El Niño years, severe storms and extensive runoff occurred, producing sediment fluxes that exceeded those of dry years by a factor of about 5. The abrupt transition from a dry climate to a wet climate in 1969 brought a suspended sediment flux in the rivers of the Transverse Range of 100 million tons, an amount greater than their total flux during the preceding 25-year period (Inman and Jenkins, 1999). The wet period from 1978 to 1983 caused a significant response on alluvial fans and in channels in desert piedment areas (Kochel et al., 1997).

The link between ENSO and stream discharges in the southwest may have a long history. By reconstructing a palaeoflood history for catchments in Arizona and Southern Utah, and comparing this to an extended chronology of strong El Niño events since AD622, reconstructed from accounts of Nile River discharges and El Niño conditions in coastal Peru, Ely (1997) was able to show that (p. 194) "The highs and lows in the average frequency of El Niño events over this time period parallel precisely the sharp decreases and subsequent increase in the southwestern paleofloods over the same interval".

There has been a long debate in the southwest USA about the causes of channel entrenchment (arroyo formation) and aggradation. It is likely, however, that alternations of drought, which reduce vegetation cover, and subsequent floods, which cause erosion, have contributed to these changes in valley bottom morphology (Bull, 1997). Crucial here, may be fluctuations either side of the peak in the sediment yield curve of Langbein and Schumm (1958). For that reason, desert regions may be especially sensitive to change as effective precipitation varies across the 30-cm threshold (Kochel et al., 1997). Furthermore, the nature of vegetation cover can be transformed radically and studies in Southeast Arizona and Southwest New Mexico (Brown et al., 1997) have shown that high winter precipitation since the late 1970s has caused the density of woody shrubs to increase three-fold and the grass cover to be reduced. This has implications for erosive processes. Similarly, D'Odorico et al. (2001) find that winter rainfall erosivity patterns in the southwest United States are related (nonlinearly) to ENSO, with El Niño years having an erosivity much larger than the average. Likewise, working on the Rio Puerco catchment of New Mexico, Molnar and Ramirez (2001) have suggested that increasing vegetation cover during recent wet decades has altered the rainfall–runoff relationship, so that there has been a decreasing trend in maximum runoff events.

Investigations have also been undertaken in South America to assess the links between ENSO, streamflow and sediment yields. In Chile (Fig. 6b), the recurrence interval of peak flows is far higher in El Niño years compared to normal ones. North eastern South America (including north equatorial Brazil, Guyana, Venezuela and Northeast Colombia) has one of the most consistent ENSO–precipitation relationships found anywhere, with El Niño events resulting in relatively dry periods, and La Niña associated with high rainfall. Regression of the discharge of the Magdalena River of Columbia on the Southern Oscillation Index (SOI) shows that 68% of the variability of the Magdalena streamflow is explained by the SOI. Sediment load is also correlated with SOI with a coefficient of variation of $R^2 = 0.54$ (Restrepo and Kjerfve, 2000). The mean daily sediment yields during El Niño and La Niña years are 256 and 511 tons day^{-1}, respectively.

Overall, many tropical rivers show reduced discharges during the ENSO warm phase (e.g. The Nile, Congo, Amazon, Lake Eyre basin). This may be attributable to global-scale subsidence associated with the major upwelling in the eastern Pacific Ocean (Amarasekera et al., 1997). In central Australia, the flow regime of Cooper Creek has been found to be associated with ENSO, with a 48-year hydrograph

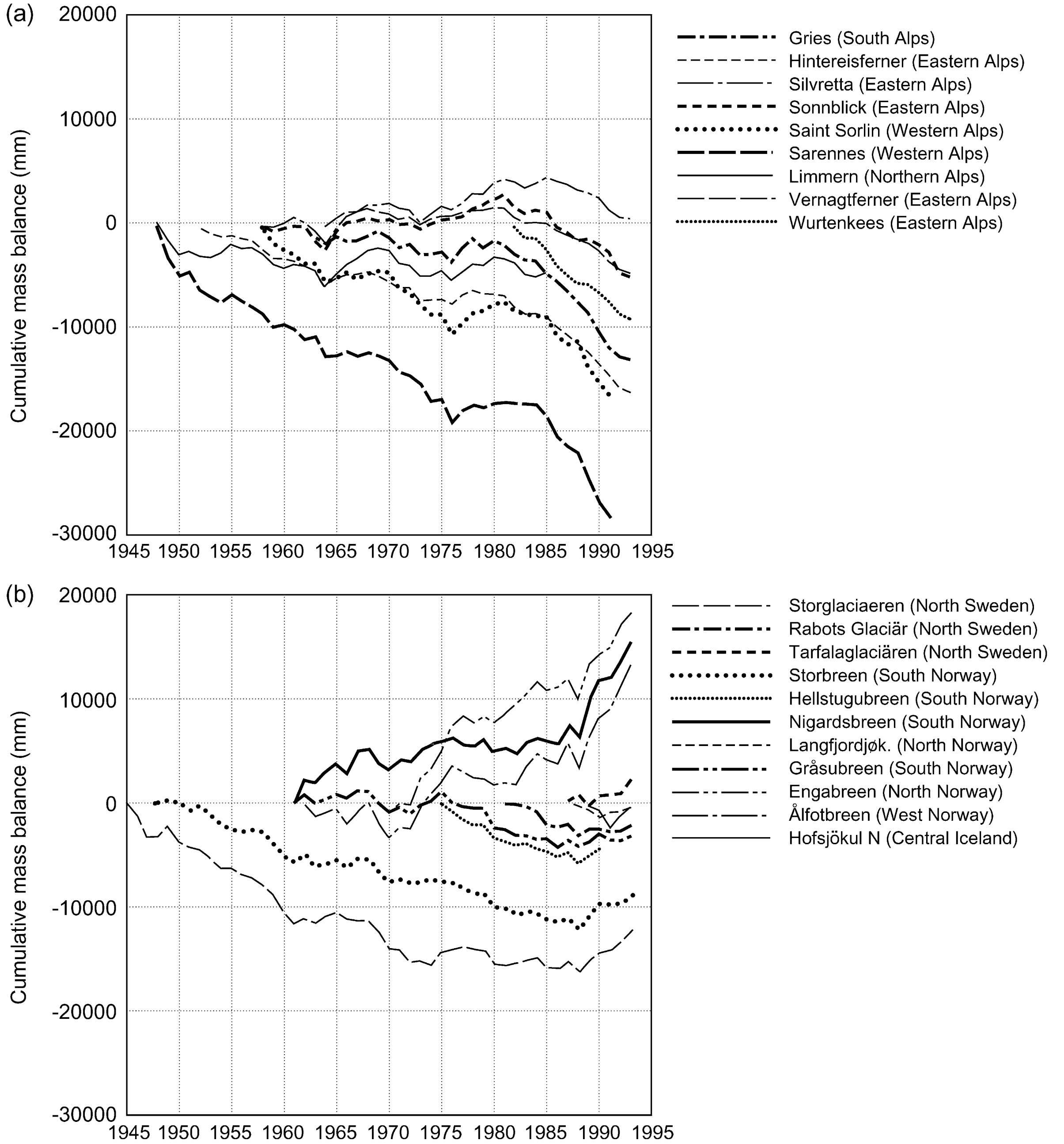


Fig. 4. The changing mass balance of glaciers in (a) the European Alps and (b) Scandinavia. Note the inverse pattern (from Goudie, 2001, window 2.6). (c) Time series of measured and reconstructed mass balances for Pace Glacier, British Columbia, Canada, 1892–2000 (after Moore and Demuth, 2001, Fig. 7). (d) Time series of Winter PDO and SOI from 1900 to 2000 (Moore and Demuth, 2001, Fig. 3).

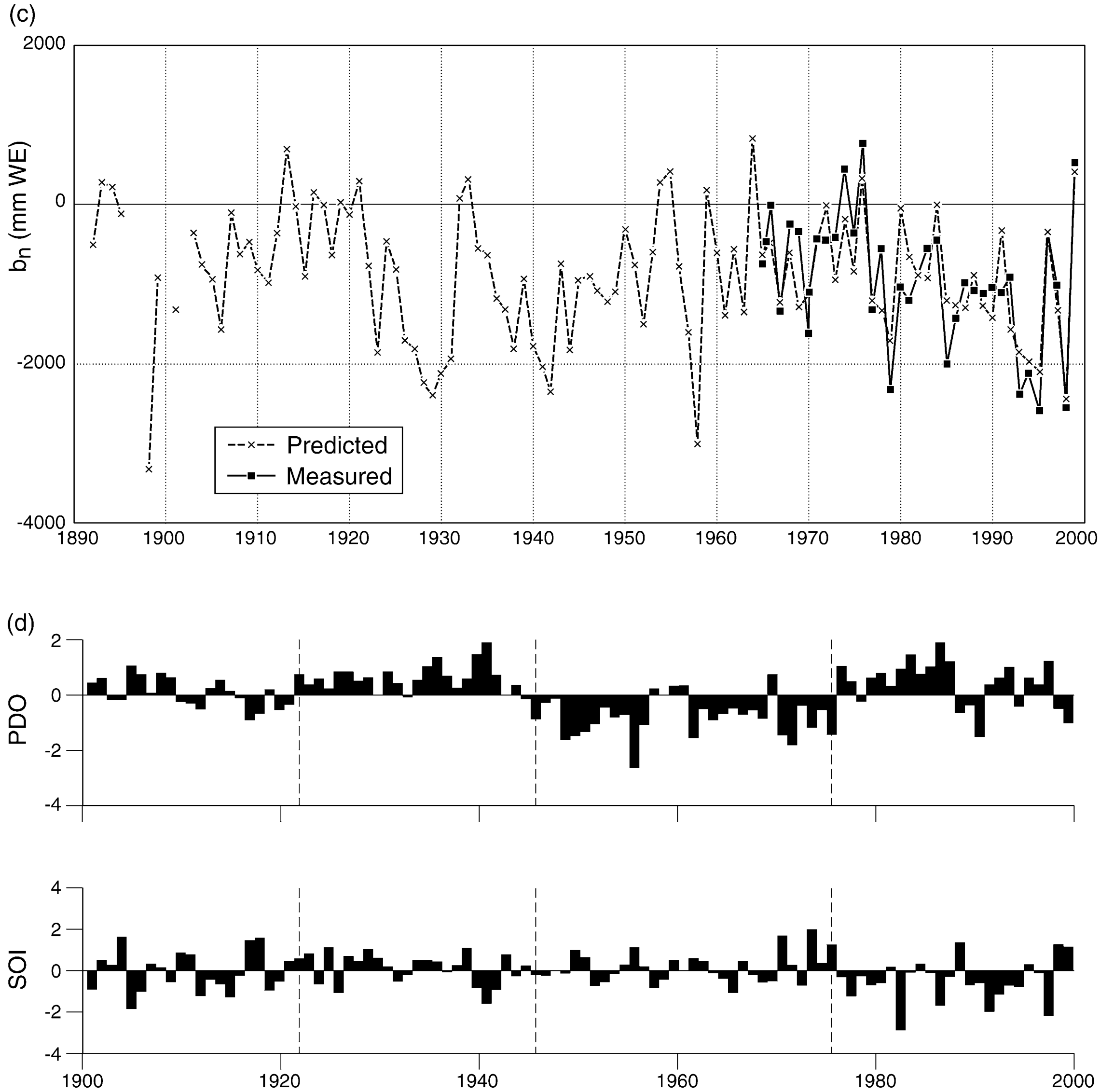


Fig. 4 (*continued*).

record showing floods clustered in La Niña episodes (Puckridge et al., 2000).

Links have also been established between the PDO, NAO and streamflow. In southeast Alaska, for example, Neal et al. (2002) find that monthly stream discharge changes with PDO modes. Because the NAO governs the path of Atlantic-derived mid-latitude storm tracks and precipitation across the eastern Mediterranean into the Middle East, this has a marked impact on the flow of the Tigris and Euphrates rivers (Cullen and DeMenocal, 2000). Streamflow links with the Atlantic Multidecadal Oscillation have been established by Enfield et al. (2000).

Phases of high sediment yield may themselves have geomorphological consequences. It has been

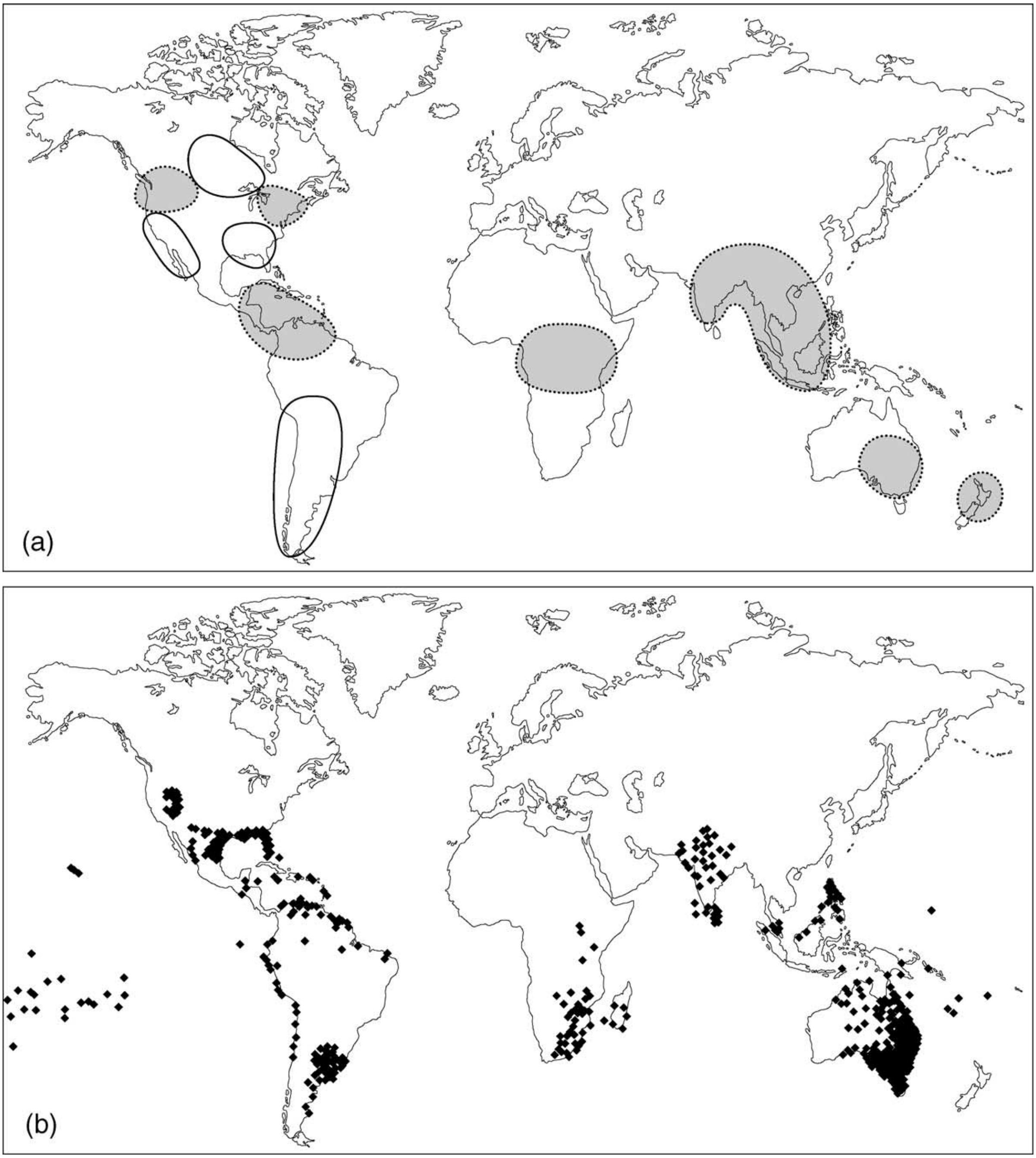


Fig. 5. The effect of ENSO on: (a) Global streamflow anomalies (modified from Arnell, 2002, Fig. 4.25). Areas receiving lower streamflows during El Niño years are shaded. Areas receiving higher streamflow during El Niño years are outlined with a solid line. (b) Precipitation trends. Map showing locations of stations in El Niño-influenced zones, having at least 10 years of complete precipitation records and 120 months of mean temperature (modified from Peel et al., 2002, Fig. 2).

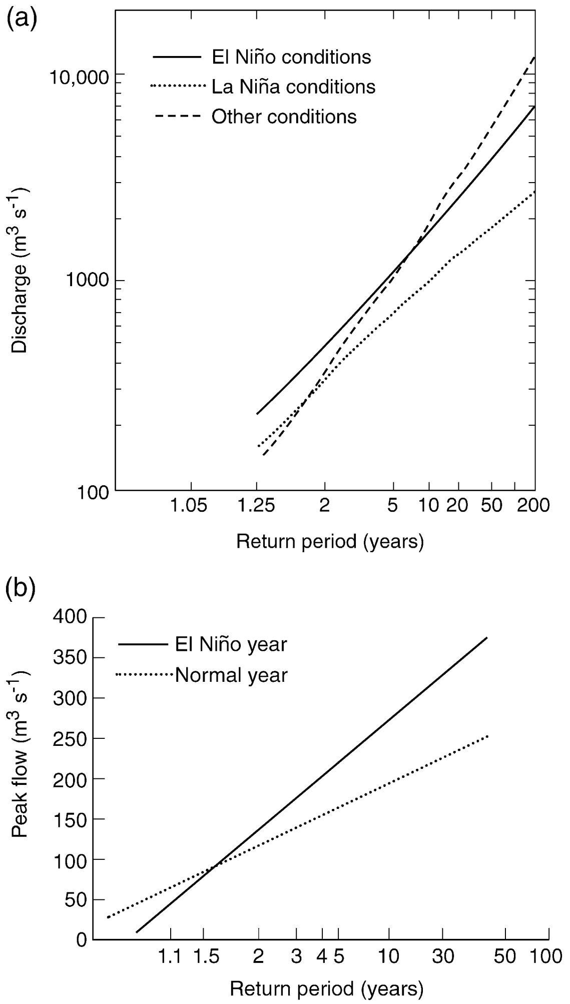


Fig. 6. Examples of changing return periods of river flows in response to ENSO. (a) Flood frequencies of the Salt River, AZ, USA, 1925–1988 (modified from Caya and Webb, 1992, Fig. 3.11). (b) Flood frequencies for the Aconcagua River, central Chile (modified from Waylen and Caviedes, 1990).

argued, for example, that Holocene beach ridge sequences along the north coast of Peru may record El Niño events that have occurred over the last few thousands of years. The argument (Ortlieb and Machare, 1993) is that heavy rainfall causes exceptional runoff and sediment supply to coastal rivers. This, combined with rough sea conditions and elevated sea levels, is potentially favourable for the formation of beach ridge sequences. The high sea levels caused by El Niño, often amounting to 20–30 cm, can contribute to washover of coastal barriers (Morton et al., 2000).

11. Terrestrial geomorphological impacts

11.1. Slope instability

Heavy rainfall events associated with ENSO phenomena can cause slope instability, as happened during the 1997–1998 El Niño event in Kenya (Ngecu and Mathu, 1999) and indeed widely across South America, East Asia and East Africa (Westerberg and Christiansson, 1999). Some of the most distinctive landslides in the southwest of the USA have occurred during El Niño events, and they can be especially serious if the heavy rainfall events occur on slopes that have been subjected to fires associated with previous drought episodes (Swetnam and Betancourt, 1990). Fig. 7 shows the distribution of damaging landslides resulting from the 1997–1998 El Niño in the San Francisco Bay area of California. In the same region, monitoring of the Penitencia Creek landslide in Santa Clara County revealed that during four ENSO events (1986–1987, 1993, 1994 and 1997–1998), landslide creep rates accelerated from a long-term mean of 3–17 to 10–39 mm per year for periods of 5–11 months (Nelson and Tepel, 1999).

On the other hand, exceedingly wet years can in due course cause a great increase in vegetation cover on slopes that may persist for some years and so create more stable conditions. On the arid islands of the Gulf of California, for example, plant cover ranges from 0% to 5% during ‘normal’ years, but during rainy El Niño periods, it rises to 54–89% of the surface available for growth (Holmgren et al., 2001). Wet ENSO events can provide rare windows of opportunity for the recruitment of trees and shrubs. Such woodland can be resilient and, once established, can persist.

In the Atacama of South America, Grosjean et al. (1997) found evidence for more than 30 debris flow events triggered by heavy rains and suggested a link with ENSO. Likewise, Vargas et al. (2000) related twentieth century debris and mudflows (*aluviones*) near Antofagasta to El Niño events. Similarly, Trauth et al. (2000) have suggested that there is an ENSO

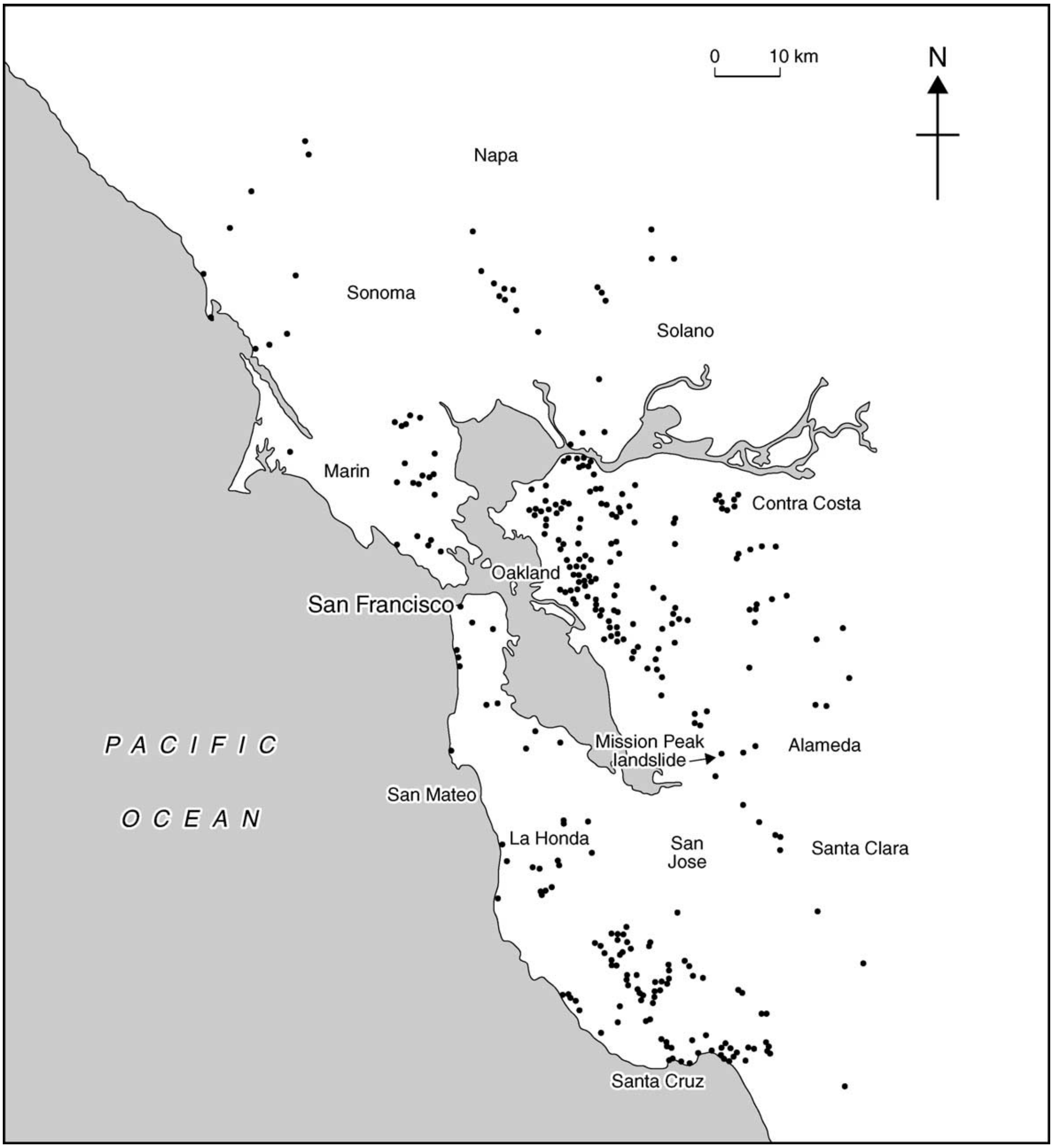


Fig. 7. The locations of damaging landslides (black dots) in the San Francisco Bay area of California resulting from the 1997–1998 El Niño rainstorms (modified from Godt and Savage, 1999, Fig. 1).

control of landslides in the eastern Argentine cordillera. High rainfall events have caused accelerated undercutting of valley side slopes along deeply incised, narrow valleys together with increased porewater pressures.

Over time, the relations between climatic variability and mass movements may change. Trustrum et al., (1999) have examined over 2000 years of change within the Tutira catchment, North Island, New Zealand and found that before European settlement, La Niña phases were associated with high rainfall storms and major landsliding. After European forest clearance, landsliding increased by an order of magnitude.

11.2. Droughts, dust and dunes

ENSO can be associated with intensified drought conditions and so can influence the activity of dust storms and of dunes, particularly in areas which are at a threshold for dust entrainment or dune activation. Such areas will be those where in wet years there is just enough vegetation to stabilise ground surfaces. Moulin et al. (1997) have shown that the NAO is an important control of the export of dust from the Sahara to the North Atlantic and the Mediterranean Sea. This control is affected both through changes in precipitation and in atmospheric circulation. In the USA, dust emissions in the period 1983–1984 were greatly reduced following the heavy rainfall of the 1982 El Niño (Lancaster, 1997). Likewise, Forman et al. (2001) have reconstructed the history of dune movements in the Holocene in the USA Great Plains. They have found that phases of dune activity have been associated with a La Niña-dominated climate state and weakened cyclogenesis over central North America.

The extent of the Sahara has shown considerable interannual variability as determined by remote sensing observations since 1980. The greatest annual north–south latitudinal movement of the southern Sahara boundary was 110 km between 1984 and 1985 and resulted in a decrease in desert area of 724,000 km^2 (Tucker et al., 1991). About 75% of the interannual variation in the Sahara's area can be accounted for by the combined effects of the NAO and ENSO (Oba et al., 2001).

11.3. Weathering and chemical sedimentation

Recent work using Rb/Sr ratios in lake sediment from a watershed in northern China has shown decadal and century scale variability in chemical weathering rates since the early sixteenth century which can be related to changes in air temperature and precipitation (Jin et al., 2001). Low rates of chemical weathering are associated with cold but wet phases. Similar fluctuations in chemical sediments in the form of speleothem have also been found to relate to changes in climate at the decadal scale. Growth of a stalagmite from Anjohibe Cave, Madagascar, for example, indicates a good correlation with SOI (Brook et al., 1999). Fluctuations in tufa deposition rates in streams and around springs, may also be related to such climatic variability, although no detailed studies have yet been made of this. Alterations in both weathering and chemical sedimentation rates can have huge importance for geomorphology, in either providing or storing erodible material.

12. Coastal and marine impacts

12.1. Coral reefs

Coral bleaching, which can produce mass mortality of corals in extreme cases, has been found to be strongly correlated with elevated water temperatures and high UV solar irradiance (e.g. Brown, 1997; Spencer et al., 2000). Although bleaching itself is a complex phenomenon to which corals can respond in a variety of ways (Brown et al., 2000; Fitt et al., 2001; Loya et al., 2001), ENSO-related heating, cooling and migrations of ocean water masses have been found to be important controls of mass bleaching episodes (Spencer et al., 2000). For example, in 1998, sea surface temperatures in the tropical Indian Ocean were as much as 3–5 °C above normal, and this led to up to 90% coral mortality in shallow areas (Wilkinson et al., 1999; Reaser et al., 2000; Edwards et al., 2001). McClanahan (2000) notes that warm conditions of between 25 and 29 °C favour coral growth, survival and species richness, and that somewhere above 30 °C, there are species-, environment-, or regionally specific thresholds above which many of the dominant coral species are lost. As Fig. 8 shows, many previous bleaching events in the Indian Ocean can be correlated with El Niño events. As Hoegh-Guldberg (1999), Souter and Linden (2000) and others have suggested, continued warming trends superimposed on interannual and decadal patterns of variability are likely to increase the incidence of bleaching and coral mortality unless significant adaptation to increased temperatures occurs.

Individual ENSO-related bleaching events may have quite different manifestations. For example, Glynn et al. (2001) report on the different patterns

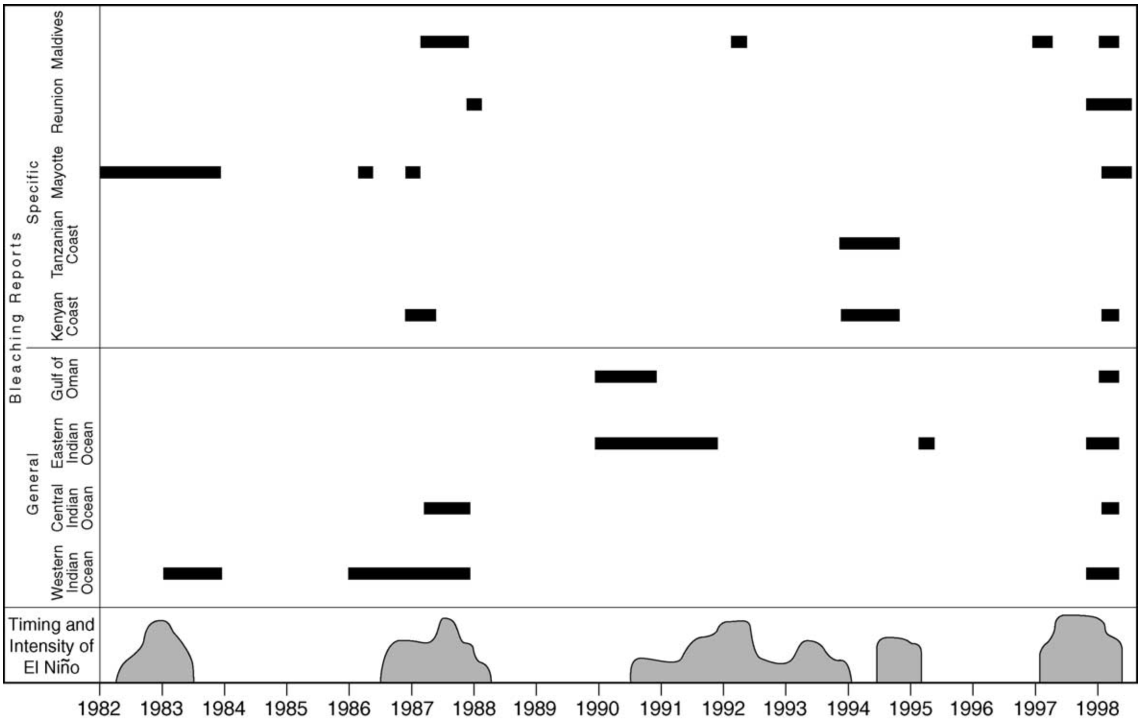


Fig. 8. Coral bleaching events from the Indian Ocean and their relation to ENSO intensity by season (modified from NOAA, 1998 and Spencer et al., 2000, Fig. 13).

of sea surface temperatures and bleaching response in Panama and Ecuador during the 1982–1983 and 1997–1998 El Niño events, and similar complex responses were noted from reefs on the Pacific coast of Colombia by Vargas-Angel et al. (2001). Coral reefs may take a long time to recover from such serious episodes of mortality, with Wilkinson et al. (1999) indicating that fast-growing, shallow-water corals may take 5–10 years to recover, whereas slower growing, deeper water corals may take 25–50 years to recolonise. Several studies indicate that climatic variability may have long-term impacts on coral growth rates. Dunbar et al. (1994), for example, illustrate from the Galapagos how, over decadal and centennial scales, coral growth rates may show considerable variation (from 5 to 22 mm per year). Such trends can be related to climatic variability, as Bessat and Buigues (2001) find in records of calcification of massive corals from Moorea (French Polynesia) over two centuries, which appear to reflect ENSO dynamics and may also reflect PDO patterns (see Fig. 9).

12.2. Coastal erosion

ENSO and other manifestations of climatic variability can produce clusters of storm events which in turn may lead to periods of intense coastal erosion (Dingler and Reiss, 2001). California, for example, experienced severe winter storms during the El Niño of 1982–1983 which produced high rates of coastal erosion. Comparisons between the effects of the 1982–1983 and 1997–1998 events show that the earlier event was more destructive, because of a combination of oceanographic and human factors. In 1982–1983, large wave events coincided with more southerly and higher velocity winds, as well as high tides. In 1997–1998, the largest waves occurred at lower tides, with lower wind speeds (Storlazzi et al., 2000). Similar erosive effects were observed in the 1997–1998 El Niño event along many parts of the US West Coast. Allan and Komar (2002) discuss the nature and erosive impacts of storms in both the 1997–1998 El Niño and 1998–1998 La Niña episodes along the Pacific northwest coast of the USA.

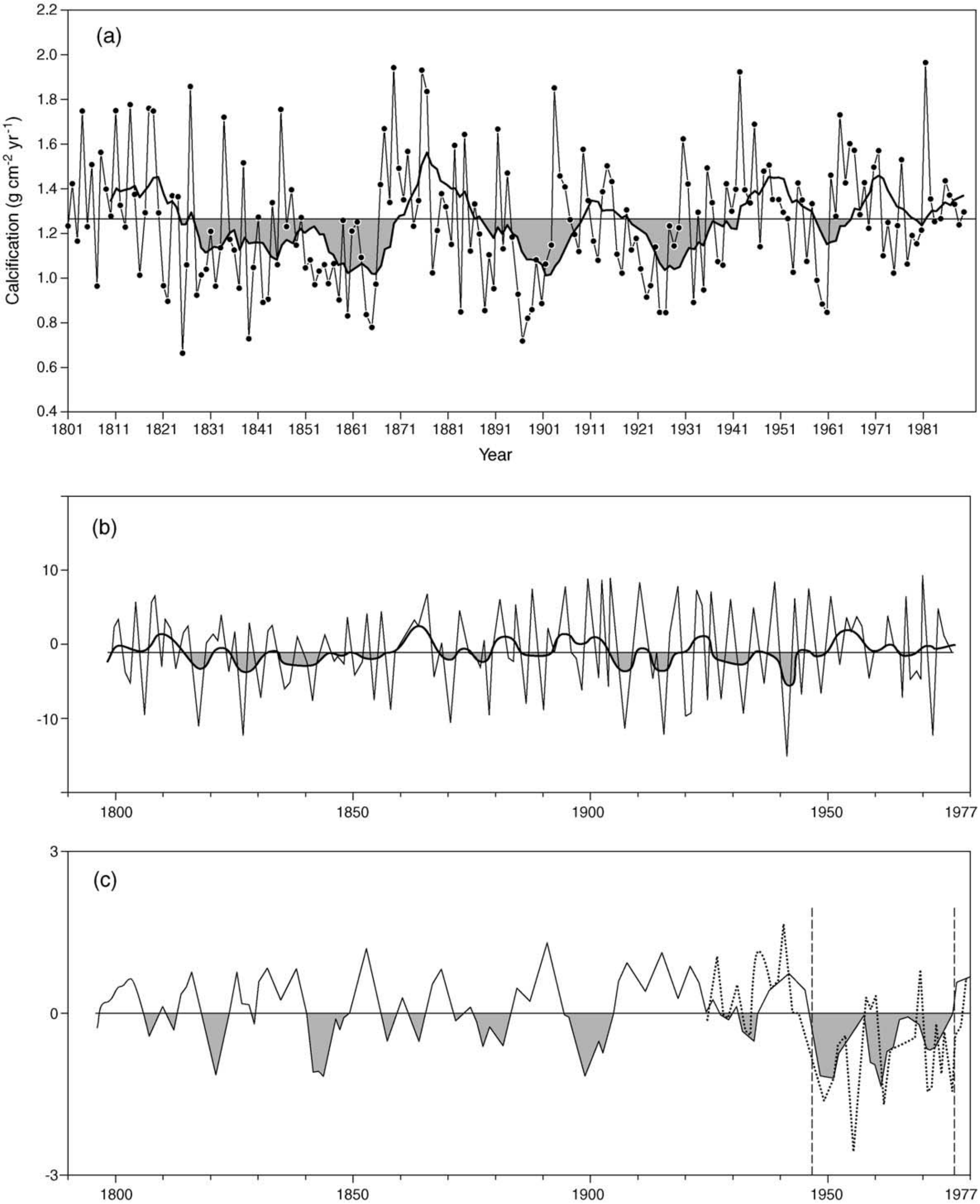


Fig. 9. (a) Time series of calcification (density × extension) in a massive coral head from Moorea Island, French Polynesia (after Bessat and Buigues, 2001, Fig. 3). Thick line represents data smoothed with a 10-year filter. (b) ENSO (from Fig. 1c) and (c) PDO (from Fig. 1d).

Extreme high water levels in these ENSO-related storm episodes led to rapid erosion on the coasts of Oregon and Washington.

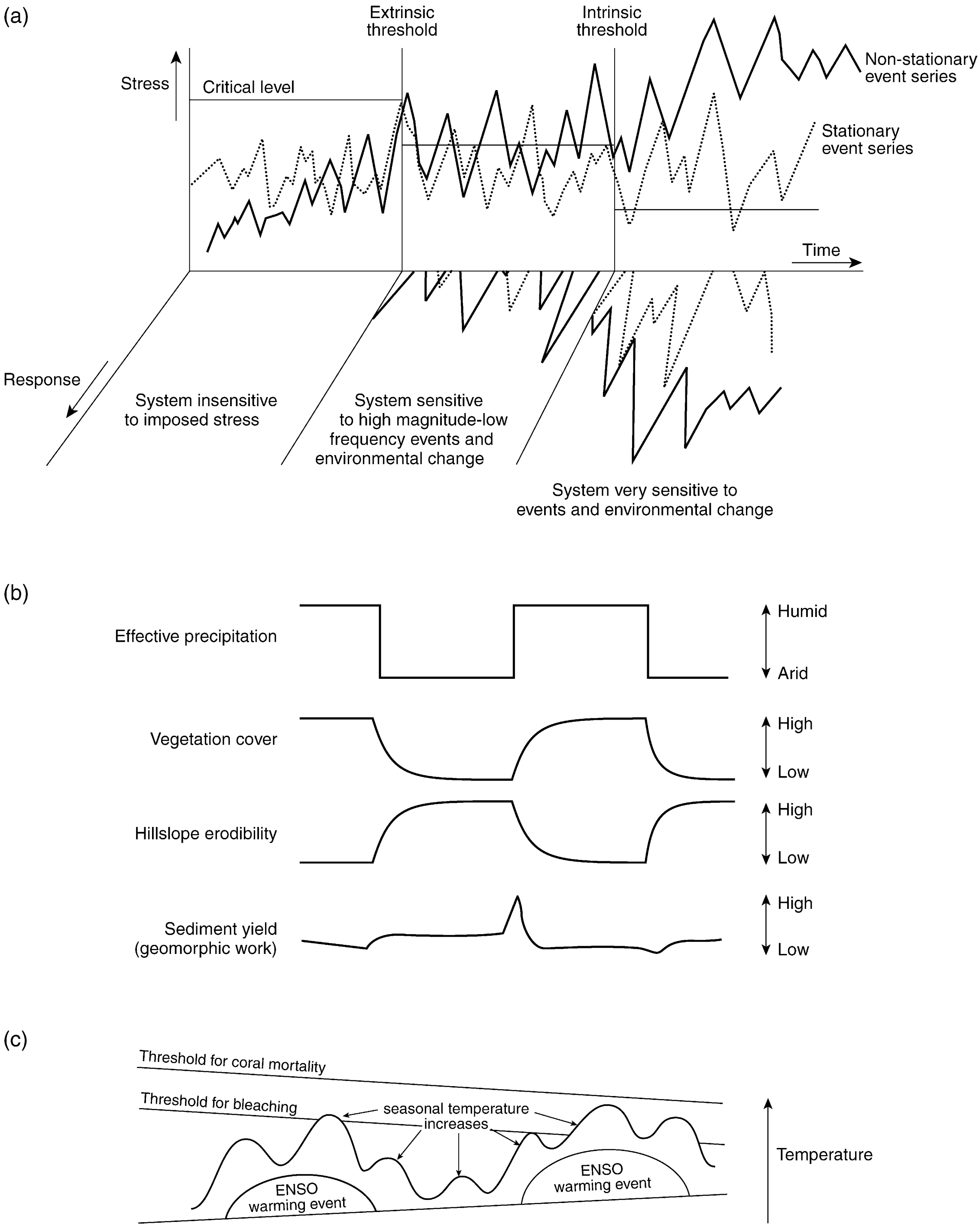
Such episodic change can occur in tandem with longer term erosive trends as seen, for example, along the Pacific barrier island coast of Colombia. Here, beach erosion has been noted since 1970 and was accelerated by subsidence following an earthquake in 1991. The 1997–1998 El Niño event produced accelerated erosion and migration of inlets (Correa and Gonzalez, 2000). In a very different setting, analysis of storm surge events in New Zealand over the latter part of the twentieth century found relations with the IPO and ENSO. Larger and more frequent storm surges occurred during the period from 1960 to 1976, with reduced frequency and magnitude after 1976 (De Lange and Gibb, 2000). Although many studies have shown that periods of increased storminess cause a large amount of coastal erosion and change, it is not always possible to relate increases in coastal storminess to specific modes of climatic variability. Camuffo et al. (2000), for example, failed to find any link between storminess in the Adriatic and Western Mediterranean over the last millennium and either ENSO or NAO.

13. Climatic variability and geomorphic ideas

As well as impacts on individual geomorphic processes and landforms, recent developments in our understanding of modes of interannual, decadal and multidecadal scale climatic variability and their geomorphic impacts have considerable importance for how we understand geomorphic change in general. However, at the outset, we have to remember that climate is not the only control of geomorphology, and not leap to construct a new geomorphic paradigm based on climatic variability at all scales (a sort of climatogenetic geomorphology for the 2000s). Many geomorphic systems, such as gullies, change not only as a result of external (climatic or tectonic) forcing, but also because of internal adjustments (Brunsden, 2001). Despite these caveats, the known impacts of climatic variability have many implications for geomorphology.

If climatic events (such as droughts and storms) are sometimes clustered into longer term groups as a response to ENSO and other modes of variability, then their impacts may vary not simply in relation to their size, thus complicating any simple magnitude and frequency relationship. Instead, storms of similar magnitude coming immediately after other storms may have much less geomorphic effect than those which occur in isolation (as all the geomorphic work will have been done by the preceding storms). Alternatively, long clusters of storms may have a compound, more serious geomorphic effect than would the same number of events operating in isolation. Such ideas of the importance of timing as well as magnitude and frequency have been employed by Richards (1999) and others for some time as a critique of the magnitude and frequency ideas of Wolman and Miller (1960). Indeed, ideas of persistent periods of wet and dry climatic conditions date back to the Hurst effect identified in 1950 (as discussed by Kirkby, 1987). However, our improved knowledge of the range of modes of climatic variability and their geomorphic roles improves our ability to understand the importance of sequence and position. Starkel (1999) presents a hierarchy of time units of relevance to geomorphology with events (days to months), clusterings (years to decades), phases (centuries to millennia) and stages (tens to hundreds of millennia). Climatic variability is one key cause of clusterings in this system. Identification of modes of climatic variability occurring at the decadal scale way back into the Holocene and earlier may help to test the effectiveness of different events within real event histories, and also to test the role of clusterings within the broader sweep of geomorphological explanation. However, there is some danger of circularity here, as geomorphic indicators are often used as tools to reconstruct the palaeoclimatology of ENSO and other modes of variability and so care needs to be taken in interpretations.

Fig. 10. Representations of the impacts of climatic variability on geomorphic systems. (a) Stress-response sequences including thresholds under stable and changing climate conditions (adapted from Brunsden, 2001, Fig. 1). (b) A simplified view of the biogeomorphic response model (adapted from Knox, 1972 and Roberts and Barker, 1993, Fig. 6.1). (c) A model of the possible interactions of different time scales of warming and their impact on coral bleaching (adapted from Williams and Bunkley-Williams, 1990 and Viles and Spencer, 1995, Fig. 6.11).


(a)
Extrinsic threshold
Intrinsic threshold
Stress
Critical level
Non-stationary event series
Stationary event series
Time
Response
System insensitive to imposed stress
System sensitive to high magnitude-low frequency events and environmental change
System very sensitive to events and environmental change
(b)
Effective precipitation
Humid
Arid
Vegetation cover
High
Low
Hillslope erodibility
High
Low
Sediment yield (geomorphic work)
High
Low
(c)
Threshold for coral mortality
Threshold for bleaching
seasonal temperature increases
ENSO warming event
ENSO warming event
Temperature

ENSO and other modes of climatic variability, as has been pointed out by Douglas et al. (1999) in terms of their effects on geomorphology and ecology in the Danum Valley, Sabah, can produce a form of punctuated equilibrium in the landscape. Alternating periods of high geomorphic change (*rhexistasie*) followed by periods of stability in ecosystem and geomorphology (*biostasie*) seem to have occurred in the recent past at Danum Valley as a response to the changing rhythm of ENSO. Although the concepts of *biostasie* and *rhexistasie* are not new to geomorphology [having been introduced by Erhart (1956) and utilised by Knox (1993, 2001) amongst others], the recent discoveries of yet more modes of climatic variability, often with complex temporal rhythms, affecting large areas over long time spans make them ever more relevant. These ideas can also be linked to notions of complex response in the landscape (Brunsden, 2001), if we visualise change as a wave pulsing through a patchy landscape with different areas possessing varied resistances to change. Thus, decadal climatic variability may set off a pulse of activity resulting in a complex landscape response. The impacts of climatic variability on ecological and geomorphic systems may be nonlinear, as recently found for rainfall erosivity and ENSO in the SW USA (D'Odorico et al., 2001) and the NAO and wild and domestic herbivores (Mysterud et al., 2001).

Several of these ideas on the clustering of events and complex responses to them can be presented as conceptual diagrams. Fig. 10a indicates in a general way how clusters of climatic events can produce variable overtopping of geomorphic thresholds, although it represents a simple linear view of geomorphic response which may be an oversimplification for many geomorphic systems. Fig. 10b illustrates how complex chains of linkages between climatic, vegetation and geomorphic processes produce a complex geomorphic response, and Fig. 10c provides a simple conceptual model of the synergistic associations between different scales of warming producing coral bleaching. Such conceptual diagrams provide a useful starting point for analysing the relationships between climatic variability and geomorphology as a prelude to more detailed empirical and computational studies.

A number of recent studies have used a combination of empirical data and computer modelling to investigate system dynamics, and to try and separate the role of climatic and other forcing factors. The study by Dearing and Zolitschka (1999) of the behaviour of a catchment–lake system from Germany over a 10,000-year period is a good example. At different times, the system has behaved differently, because of changes in system dynamics as well as in forcing factors (climate change and human impacts). However, human impacts, such as deforestation, seem to have been responsible for major shifts in sediment delivery during the Holocene. Coulthard et al. (2000) have developed a cellular automaton model to investigate the relative impacts of climatic change and human activity on sedimentation in a limestone upland catchment. Although climatic instability was found to have a slightly greater impact when the factors were treated individually, the two factors combined to produce a much greater overall effect. The conclusion is that the river system here is "...climatically driven, but culturally primed" (Coulthard et al., 2000, p. 2044). Such methods may prove useful to geomorphologists in trying to untangle the effects of decadal climatic variability on the landscape.

However, geomorphologists have long debated whether it is possible meaningfully to untangle the different roles of the various external forcing factors (climate, tectonics and human activity) and internal factors (thresholds) in causing geomorphic response. Increasingly, many geomorphologists have come to suspect that this is a very difficult task because of the nonlinear, chaotic and complex behaviour of geomorphic systems. Recent work on the far-from equilibrium nature of the global system and its propensity for abrupt change (see the review by Lockwood, 2001) comes to similar conclusions about the climatic system, echoing ideas about ecological systems (e.g. Pahl-Worstl, 1995). Following these lines of argument, climatic variability acting on different temporal scales (e.g. glacial–interglacial cycles, the Little Ice Age and ENSO) cannot simply be disaggregated to different layers in a hierarchy. So, identification of links between non-linear climatic, ecological and geomorphological systems should lead us to search for increased understanding of their mutual interactions and behaviour, not to use parts of them in simple cause–effect relationships.

Finally, improved conceptualisation of the impacts of decadal scale climatic variability on geomorphology can only help aid the quality of our predictions of the impacts of future climate change on geomorphological processes. It is no longer good enough to conceive of future change as being smooth and progressive; from all the evidence presented in this paper, it is clear that variability and clustering of events in time and space will be an important part of the geomorphic future. Furthermore, our increased understanding of the nature of decadal climatic variability means that we should be in a better position to understand the possibilities and limitations of extrapolating short-term process observations. If, for example, data on coastal erosion rates is collected during particular phases of the NAO in northern Europe, it should be extrapolated with care to longer periods containing other NAO behaviour.

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