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Sea-level change: causes and coastal landforms

Introduction

A rise in sea-level, or a fall in the land surface, encourages sea-water to transgress inland, thereby flooding river outlets. A fall in sea-level, or a rise in the land, exposes the ocean floor and leaves old beach deposits abandoned above high tide. The term 'relative sea-level' refers to the combined effects of changes in both land and sea surface.

There are many causes of sea-level change, and several ways in which these changes can be classified. A distinction is often made between changes which affect sea-levels worldwide, and those which are felt more regionally or locally. Relative sea-levels have fluctuated over geological time, but some of the most dramatic changes occurred during the last Ice Age, or Pleistocene and early post-glacial or Holocene periods. Human activities increasingly are influencing sea-levels and altering coastal configurations (Figure 1). A wide variety of coastal landforms have been created by relative changes in sea-level.

Global changes

Any alteration of the volume of water held within the oceans produces what is known as a eustatic change in sea-level. As most ocean basins are interconnected, such absolute changes in sea-level tend to be felt worldwide, although some evidence now suggests that these changes can also be regional. The most common cause of eustatic sea-level change has been the growth and melting of continental glaciers, which occurred during, and immediately after, the Pleistocene. Today, global warming is melting continental ice caps, which in turn is contributing to a rise in sea-level.

Fluctuations in the volume of water held in the ocean can also be brought about by changes in sea temperatures, salinities and atmospheric pressures. Rising sea temperatures for example, brought about by global warming, cause oceans to expand and sea-levels to rise. An increase in the volume of freshwater flowing into oceans lowers their salinity and causes sea-level to rise. A fall in atmospheric pressure, brought about, for example, by a deep atmospheric depression passing over a sea surface, also produces a rise in sea-level.

Major changes in the configuration of land and sea areas, as a result of plate movements, increase or decrease ocean basin capacity. An increase in ocean basin capacity could lower sea-levels worldwide.

The gradual deposition of sediment in the world's oceans, from weathering and erosion of the land, reduces their capacity and will lead to an increase in world sea-levels, albeit over a very long time scale.

Regional and local changes

The earth's crust and uppermost part of the mantle form tectonic or lithospheric plates, which float on an underlying, denser asthenosphere. When in equilibrium the weight of the plates is counterbalanced by their buoyancy, but the addition of a load in the form of ice, water or sediment can upset this isostatic balance. That part of the lithospheric plate under the weight of the load becomes compressed, but this is compensated by a rise elsewhere. After the weight is removed, the land directly below the load begins to rise, while towards the margins, where the weight was absent, the crust sinks. Glacio-isostatic subsidence occurred during the Pleistocene when the crust was depressed by ice sheets. Sediment-isostatic subsidence occurs when sediments accumulating in large deltas, such as the Mississippi, depress the underlying crust. Hydro-isostatic subsidence occurs when the weight of water depresses the ocean floor. This occurred for example when Pleistocene ice sheets melted and water flowed into the oceans. Although the mechanisms are complex, the net effect of hydro-isostatic subsidence, some geomorphologists suggest, is a seaward tilting of the continental margin which produces a fall in relative sea-level on the coast, as for example seen around the coast of Australia.

Mountain-building activity, tectonic movements and earthquakes all lead to relative changes in sea-level by uplifting or down-faulting land or sea areas. The elevated shore platforms near Wellington in New Zealand, for example, are believed to have been created by tectonic activity. Volcanic eruptions can also alter relative sea-

Figure 1: The North Norfolk coast is threatened by rising sea-levels

levels, as for example occurred at Pozzuoli near Naples in Italy.

The compaction of deltaic sediments which contain lots of water by the weight of overlying accumulating material causes the land surface to become lower. This in turn leads to a relative rise in sea-level. Many of the world's major deltas such as the Mississippi are threatened by sea-level rise as the result of such compaction and also sediment isostasy.

Glacial and post-glacial sea-level change

During cold phases in the Pleistocene, sea-water was progressively lost via precipitation as snow to create glaciers and ice fields. Abstraction of water from the hydrological cycle in this way caused an absolute fall in sea-level (glacio-eustasy). There were several cold periods during the Pleistocene, each lasting 100,000 years, and each time the sea-level fell. At the same time, the reduced temperature of the sea water caused it to contract, which further lowered sea-levels. During warmer phases, or inter-glacials, each of which lasted about 10,000 years, glacial melting caused the sea-level to rise to approximately current levels. Rising sea temperatures also caused the sea to expand, further increasing sea-levels. The last cold glacial period peaked at 18,000 BP, and at this time sea-level was about 140 m below its present position. After this the glaciers began to melt, causing sea-level to rise. Melting continued into the post-glacial or Holocene period. The rise in sea-level is known as the Flandrian transgression, and ended about 6,000 BP.

During the Pleistocene, continents were depressed under the weight of the ice. The greatest depression occurred where the ice was thickest. When the glaciers melted, the land rebounded and shorelines located near formerly ice-covered areas in Canada, Scandinavia and Scotland rose (glacio-isostasy). Readjustment to the removal of the ice has, however, been slow and over an extended period because the lithospheric plate is rigid, and consequently parts of north-west Scotland are still experiencing uplift of about 2 mm per year.

Figure 2: Slope-over-wall cliff

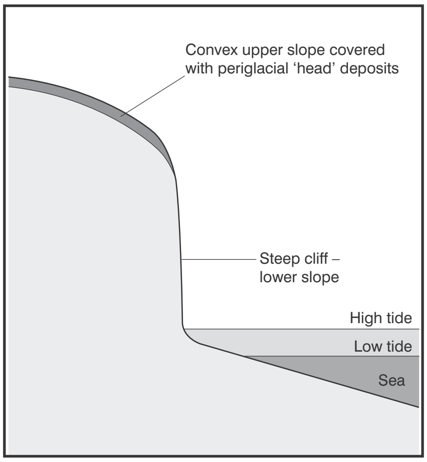
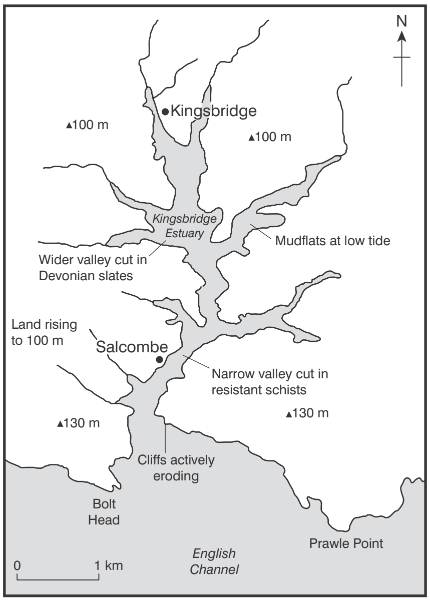


Figure 3: Kingsbridge Ria



While the lithospheric plate was depressed under the weight of thick ice sheets, at the margins of the depressed land area a forebulge developed, causing the land to rise slightly. When the land rebounded, the forebulge flattened, resulting in a rise in sea-level. This effect is still being felt in south-east Britain today, producing a 2 mm rise in sea-level annually (Figure 1).

Coastal landforms and sea-level change

Changes in relative sea-level have produced a variety of coastal landforms. Broadly these are grouped into submerged and emerged coastlines, although in reality many coastal areas have experienced both rises and falls in relative sea-level at different periods in their history. One example of a coastal landform formed in this way is a slope-over-wall cliff.

The cliff has a steep lower face and a gentler, convex upper profile (Figure 2). During interglacial periods in the Pleistocene, high sea-levels undercut the base of cliffs, creating a vertical face. In a succeeding cold phase the sea-level fell, so the cliff-line was not eroded by the sea. The cliff-line was, however, degraded by intense frost-shattering under periglacial conditions, and solifluction deposits or head moved downslope. Then a post-glacial rise in sea-level attacked the cliff again, producing the vertical lower face.

Submerged coastlines
(i) Rias
A ria is a sea inlet in an area of rugged relief where the lower reaches of a river valley and its tributaries have been drowned by a rise in sea-level (Figure 3). Many were created as the result of the Flandrian transgression, although, as a pre-cursor to this event, lower sea-levels during the Pleistocene would have encouraged rivers to cut deeply into their valley floors. Rias are common in Pembrokeshire, Devon and Cornwall in Britain, Brittany in France and in north-west Spain.

The shape of a ria is controlled by the form of its pre-existing river valley, which in turn is controlled by factors such as rock type and structure. In south-west Ireland, long, narrow inlets such as Bantry Bay have been created by the flooding of former river valleys. The river valleys were cut into shales which had been downfolded into synclines, while the surrounding hills were made of more resistant sandstone rocks upfolded into anticlines. In contrast, rias in South Devon, such as that at Kingsbridge, tend to be more branching than those in Ireland (Figure 3). Evidence from a 1:50,000 map that submergence has occurred include a number of finger-like inlets which become shallow inland, submarine contours marking the position of the former river channel, and cliffs at the outlet suggesting present day undercutting.

Rias vary in the amount of subsequent infilling after flooding. Some are fringed with salt-marsh and mudflats, while others end in rocky embayments. In some cases, estuaries may quickly fill with sediment, or keep pace with the rising sea-level so that no ria forms, e.g. Cuckmere Haven, East Sussex.

(ii) Drowned lowland estuaries
The Flandrian transgression also drowned lowland coastal valleys, creating broad, open estuaries and extensive mudflats, such as the Blackwater Estuary in Essex, and Pagham Harbour in West Sussex.

(iii) Dalmatian coastlines
In areas where mountain ranges lie parallel to the coast, a rise of sea-level produces a range of long, narrow islands separated by sounds. A good example where this has occurred is the Croatian coastline, where the outer ranges of the Dinaric Mountains are now islands, and coastal valleys between the ranges are occupied by the Adriatic Sea.

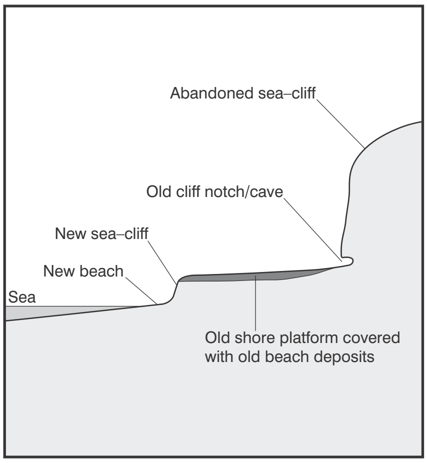
(iv) Submerged forests
Tree trunks and peat layers exposed at or below present day sea-level, such as that on the coast at Formby in Lancashire and Borth in Wales, represent forests which were submerged by the Flandrian transgression.

(v) Buried river channels
Buried channels can be found in the mouths of many river valleys. During cold phases in the Pleistocene, when sea-levels were low, rivers cut down into their channels to maintain their base levels. A subsequent rise of sea-level infilled the buried channels.

(vi) Offshore submerged benches and notches
Wave-cut platforms now just offshore mark the position of former coastlines which developed when sea-levels were much lower than they are today during cold phases in the Pleistocene. A subsequent post-glacial rise in sea-level has meant that these platforms now lie offshore, some hidden beneath marine sediments.

(vii) Other changes
The post-glacial rise in sea-level was responsible for severing the land link between Britain and continental Europe by 8,600 BP. Flooding also created the Isle of Wight and the Solent in southern Britain, and the Frisian Islands off the coast of the Netherlands. The Flandrian transgression also reworked sediment on the continental shelf, pushing it towards the coast, which ultimately led to the formation of large shingle complexes, such as the cuspate foreland at Dungeness, the spit at Orford Ness, and the tombolo at Chesil Beach.

Figure 4: An emerged/raised beach



Fjords, or glacial troughs, which are partly inundated by the sea, largely owe their origin to powerful glaciers which over-deepened their valley floors well below current day sea-level. A post-glacial rise in sea-level of perhaps 100 m added to the depth of water in the fjord, but in comparison with the glacial erosion, the sea-level rise was of minor importance in creating this landform. Sognefjord, for example, is over 4,000 m deep. Moreover, after glaciation the land would have risen isostatically, offsetting the effects of sea-level rise. Fjords occur on the western sides of continents at about 60 degrees north and south of the equator, for example in Norway, British Columbia in Canada, southern Chile, and South Island in New Zealand.

Emerged coastlines

Most emerged coastlines are Quaternary in age, although some formed earlier during the Tertiary period. Evidence of emerged coastlines include:

(i) Widening areas of salt-marsh and mangrove
As sea-levels fall, the area under salt-marsh and mangrove swamp increases. Rejuvenated streams incise into the marsh or swamp to reach new base levels.

(ii) Emerged or raised beaches
These are beaches of sand, shingle and shell deposits which stand well above the present sea-level (see Figure 4). The sediments often rest on old wave-cut platforms which are sometimes backed by abandoned caves, arches and stumps. On the Isle of Arran, for example, fossil cliffs and caves occur at the back of an old wave-cut platform.

Raised beaches are created by an uplift of the land, or a fall in sea-level. Repeated uplifts of the land or drops in sea-level produce a series of raised beaches, which can be radiometrically dated from the shell material they contain. Raised beaches which fringe the shores of Hudson Bay in Canada rise to 315 m above sea-level, and those around the Gulf of Bothnia in northern Europe were created as the result of isostatic readjustment following the removal of ice at the end of the Pleistocene. Some Scottish raised beaches were also created in this way when ice was removed from the Scottish Highlands. So called ‘raised beaches’ are also found in Southern Britain in Cornwall, Devon and Pembrokeshire, many being between 5 and 8 m above present mean sea-level. These platforms, which are known as ‘emerged beaches’, because they were not created by an uplift of land, were cut by high sea-levels during interglacial periods in the Pleistocene. Examples can be found at Portland Bill in Dorset where sand, pebbles and shelly material overlay periglacial head deposits.

Human causes of sea-level change

Human actions can also bring about alterations in relative sea-levels. The abstraction of groundwater from coastal aquifers, such as has occurred in Venice and Bangkok, causes the land surface to subside, which in turn leads to a relative rise in sea-level. The extraction of oil and gas reserves from rocks south of Los Angeles in California has similarly caused overlying sediments to subside and the sea to transgress inland. Drainage of salt-marsh causes the land surface to shrink, and the weight of industrial and port developments compacts sediments which lowers land levels and leads to a relative rise in sea-level.

Global warming is currently causing sea-levels to rise. This is partly because continental ice sheets and glaciers, such as those which overlay Greenland, are melting, and partly because the oceans are warming and therefore expanding. If all the remaining land-borne ice sheets, glaciers and snowfields were to melt on the continents, sea-level would rise by on average 60 m. It should, however, be noted that melting of sea ice in the Arctic Ocean and the ice shelves bordering Antarctica would not cause an increase in the volume of water in the oceans. This is because floating ice is already displacing water of a weight equal to its own.

Future changes

The Intergovernmental Panel on Climate Change (IPCC) in 2001 predicted that by the year 2100, sea-level will be rising on average at least 5 mm per year. This will lead to major changes in the configuration of coastlines such as the North Norfolk coast (Figure 1).

Specific changes to coastlines as the result of sea-level rise are:

(i) Cliffs, especially those composed of weak unconsolidated materials, will experience accelerated rates of erosion. Deeper water will encourage more powerful waves to attack the cliffs, leading to slope failures, while existing shore platforms will disappear below the sea. On drift-aligned coasts, however, the increased supply of sediment created by erosion is likely to be transported by longshore drift, to augment beaches elsewhere.

(ii) Sandy beaches will be eroded and sea-walls will be increasingly overtopped by waves. Beaches in front of sea-walls will become lower and narrower. Faced with increasing coastal erosion, the management options include holding the line by strengthening hard and soft defences; managed retreat, or abandonment to the sea.

(iii) Sand dunes will be eroded on their seaward faces and mobile dunes will migrate inland. In areas where dunes have been reclaimed, however, migration will not be possible. Slacks between dune ridges will become increasingly brackish, leading to changes in plant communities. In low-lying countries such as the Netherlands, where much of the coast is protected by sand dunes, defences will have to be strengthened.

(iv) Estuaries and inlets will become larger and deeper and salt-water will penetrate further inland, altering wetland habitats. The seaward edges of salt-marshes and mangroves will be eroded. Salt-marshes will be more frequently inundated by high tides. Plant communities will be displaced landwards, unless checked by a sea-wall, in which case coastal squeeze will lead to a narrowing of the wetland. The extent to which salt-marsh and mangroves can vertically accrete to keep pace with rising sea- levels will depend on factors such as availability of sediment, crustal stability, tides and currents, vegetation cover and the rate of sea-level rise. The Essex marshes are currently retreating and faced with this problem one solution has been to abandon old sea-walls and allow the sea to spread in. This in turn has encouraged new salt-marsh to form and created a natural form of sea defence.

(v) Deltas are likely to become increasingly eroded at their seaward edges unless maintained by coastal sedimentation. In Bangladesh, a low-lying, densely populated country, a 1 m rise in sea-level could result in the loss of 20% of the land area, which would affect 17 million people, many of whom are very poor. Salt-water intrusion already damages irrigation and drinking water supplies and flooding destroys rice crops. Erosion of coastal mangrove will lead to flooding of the Sundarbans, an ecologically important area, and home to the Bengal tiger. Tropical cyclones funnel up the Bay of Bengal creating storm surges and these, together with rising sea-levels, threaten coastal fishing and farming communities. Planting mangroves and strengthening coastal embankments can reduce the effects of flooding, and fishing communities may be able to relocate. Relocation is, however, not an option for poor agricultural communities, in a country where land is in short supply.

(vi) Low-lying islands which are less than 3 m above sea-level, such as the Maldives in the Indian Ocean, and Kiribati in the Pacific Ocean, face an increasing risk from rising sea-levels and more frequent, powerful tropical storms. Two uninhabited islands in Kiribati have already succumbed to the waves and on other islands farmland and homes are regularly flooded. Salt-water also intrudes into groundwater supplies, making water undrinkable. Corals can grow by up to 10 mm per year, although rates vary with water depth, sea-temperature and coral type. The extent to which coral atoll growth will be able to keep pace with future sea-level rise will depend not only on the rate of rise, but also whether corals are stressed by factors such as the increase in sea temperatures and pollution.

With 70% of the world's population now living in coastal areas and many large cities located by the sea, protecting the coast from sea-level rise will be expensive. The height of the Thames Barrier will have to be raised to protect London, while in Venice work has recently begun on the Moses Project. This involves constructing 78 gates across three inlets that link the lagoon to the Adriatic. Work started in 2008 and it is hoped it will be completed by 2014.

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Focus Questions

1. Define **relative** and **absolute** changes in sea-level. Describe and explain the main causes of these changes.

2. Describe and explain the coastal landforms associated with sea-level change. Refer clearly to particular stretches of coastline which you have studied.

3. Outline the human causes of sea-level change and likely impacts on coastlines. Use examples from a variety of countries or regions.