‘Coastal Processes and Climate Change Predictions in the Coastal Study Areas’

LIFE Environment Project 2003-2006 ‘RESPONSE’: LIFE 03 ENV/UK/000611

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1 Introduction

This report forms part of RESPONSE Task 3: Coastal Study Area Investigations, which aims to "develop and test an effective, transferable methodology for coastal evolution studies and risk mapping that can be applied across the EU to allow local authorities and Regions to assess and prepare for the impacts of climate change along their coastline". The report comprises two sections: an assessment of coastal processes and a review of predicted climate change in the RESPONSE Coastal Study Areas.

'Coastal Processes' is a collective term covering the action of natural forces on the shoreline, and the nearshore seabed. The coast is a complex and dynamic system and slight changes in coastal processes can lead to larger scale changes with wide ranging implications for the entire coastal environment. A review of coastal processes for each of the five RESPONSE coastal study areas is presented in Section 3.

An appraisal of the causes and likely implications of future climate change is presented, taking advantage of the most up-to-date reports and publications and using 'state of the art' information sources. This is followed by a review of climate change scenarios and the likely impacts of climate change in each of the RESPONSE Study Areas, in Section 5.

1.1 Objectives/context of this report

Climate change has the capacity to alter almost all coastal processes and landforms. There is a need to determine the extent to which climate change could effect the distribution, frequency and magnitude of flooding, deposition and erosion hazards. RESPONSE aims to develop a mapping methodology to identify and prioritise coastal hazards, in view of the likely impacts of climate change. The mapping methodology is based on a geomorphological characterisation and sensitivity analysis, integrating the best current climate change predictions. The process of assessing and prioritising coastal risk is outlined in Figure 1.1.

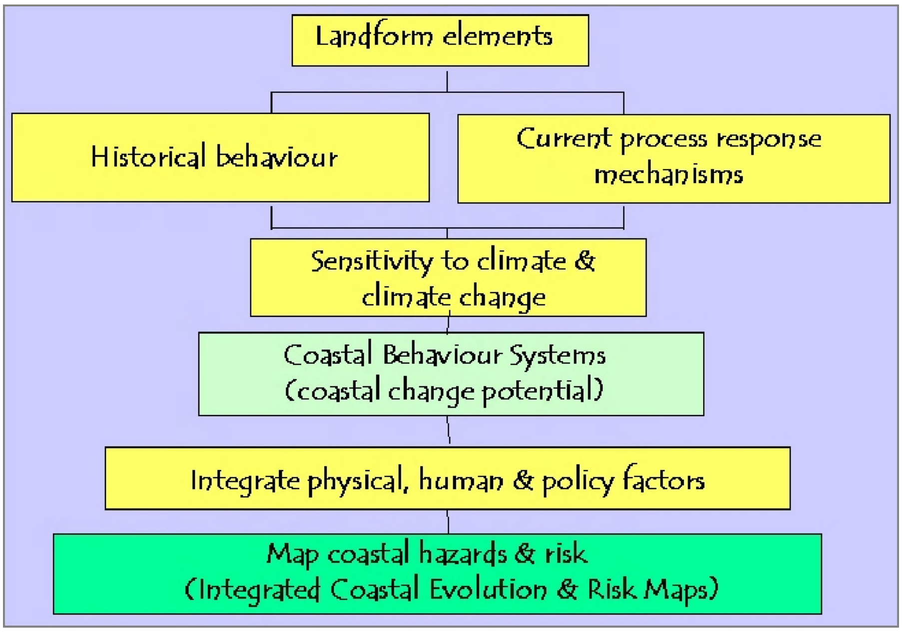

Figure 1.1 Flow chart illustrating the RESPONSE mapping methodology

Before an assessment of hazards, risk and vulnerability to climate change can be made, it is first essential to achieve a good understanding of coastal processes, and to recognise how these processes have resulted in coastal change in the past. Through an understanding of how the coastline has responded to historical coastal processes, it is possible to estimate how the coast will change in future years. An appreciation of coastal processes also allows an assessment to be made of the sensitivity of the coast to climate and climate change.

Obtaining detailed climate change information for each of the RESPONSE coastal study areas is problematic since climate change data is collated and interpreted differently in each country. Consequently it is not possible to employ directly comparable climate change data in each of the five coastal study areas. The methodology for assessing the likely impacts of climate change will therefore make use of the best currently available climate change data in each coastal study area.

2 Coastal Processes

Natural coastal processes are the result of the energetics of waves and tidal motion. The latter tend to be dominant in estuaries, the former along the open coast. However, they often combine to produce distinctive coastal landforms and are responsible for the movement of sediment along-shore and on- and off-shore.

A preliminary assessment of coastal processes is extremely important in the identification of areas at risk and in the prediction of the impacts of climate change. The evolution of the coastline involves a complex interaction of many factors, including:

- Coastal geology
- Foreshore and seabed settlements
- Foreshore slope and seabed bathymetry
- Current velocities and directions
- Wave heights and directions
- Coastline aspect

An understanding of both the geomorphology and geology of the coastline is fundamental to the understanding of its past evolution and is an indicator of its likely future response. The geological formations underlying the coast may fundamentally control both the present morphology and the nature/rate of future response to environmental forcing. The broad outline of the coastline owes much to the variety of rocks and large-scale geological structures, which have different levels of resistance to erosion (May and Hansom, 2003).

Coastal areas underlain by very resistant rock types have not changed measurably in the historic past and are not expected to significantly change within the next 100 years despite predicted changes in relative sea level or wave energy. However, even within very resistant rock types, rapid changes can occur due to cliff failure along joint or fault planes. Weaker rock types provide less resistance to erosion but may provide much of the sediment supply to beaches and barriers. The composition and nature of this sediment supply is determined by the lithology of the eroding geological formations. Thus a rapidly eroding formation of glaciogenic tills may provide large quantities of muds, which may be transported in suspension to ultimately be deposited on intertidal mudflats many kilometres away. Conversely the erosion of such deposits may provide very little coarse-grained material to feed the beaches immediately adjacent to the eroding cliffs.

Sediment transport plays a central role in coastal processes and a study of the sedimentary system is essential to gaining a clear picture of coastal processes and assessing past, present and future coastal change. "The results of the EUROSION case studies and other Europe wide evidence, suggests that too often in the past insufficient attention has been paid to the functioning of the whole sedimentary system" (EUROSION, 2004).

During the past few decades, sediment has been lost from beaches, resulting in decreased width and increased slope. Globally, this situation has been far more common than cases where sediment is accumulating and propagation occurring. The cause of this trend is unclear, though the key forcing factors include rising sea levels and reduction in offshore sediment supply (May and Hansom, 2003). Another factor is the influence of shoreline management practices, in many cases extending back at least to the mid-nineteenth century, which often proves to be a decisive control of contemporary sediment transport.

Eroded sediment is ultimately deposited either along the coast or on the continental shelf. Some have been accumulating over a period of thousands of years as the post-glacial rise in sea level increasingly drowned the continental shelf around the modern landmass. As sea level has risen, earlier coastal deposits may have been driven landwards. In some areas extensive intertidal flat deposits were formed which later became drowned or are presently being eroded. Most of the coastal lowlands around the modern coast are underlain by intertidal deposits, which formed in past millennia and have been drained and reclaimed by Man. Conversely; parts of the coastline have remained relatively unaltered for long periods of time. In some cases the modern shoreline is reoccupying embayments with a long geological history sometimes stretching back hundreds of thousands or even millions of years. Raised beach deposits from previous interglacial periods lying close to modern beaches are evidence of this long geological inheritance. Large-scale geological structure may also form an underlying control to coastal alignment and the size and nature of embayments.

Headland positions, for example, may be controlled by large-scale geological folds and the nature and frequency of coastal landslips may be influenced by the amount and direction of dip of formations at the coast.

In some areas, particularly those that historically have seen the greatest rates of change, the geomorphology may have been significantly altered by the activities of man. These effects are either direct, e.g. where coastal cliffs have been defended and landscaped, or indirect, e.g. where construction at one coastal location has significantly altered the coastal processes so that an adjacent or nearby coastal landform has been affected.

3 Coastal Processes in the RESPONSE Coastal Study Areas

3.1 Central-South Coast of England, UK

Important features in the South Central England Coastal Study Area include the Isle of Wight and the Solent. Geologically the coast encompasses the Hampshire Basin, a major syncline, which exposes relatively unlithified Tertiary formations in its centre with relatively more resistant and older formations to the east and west. The Tertiary formations at the coast stretch from Studland, Dorset in the west to Brighton, East Sussex in the east. The Isle of Wight sits astride a major east-west geological structure, the Isle of Wight monocline, which forms part of the southern flank of the Hampshire Basin. The Isle of Wight was formerly part of a ridge which lay to the south of a major river system, the Solent River, which ran eastwards through the modern Poole and Christchurch Bays and the Solent to enter the Channel east of the present island.

The coastline has a broadly east to west orientation, but there are numerous local variations. This results in contrasts in exposure to wave energy, which provides one basis for explaining differences in wave energy, which provides the basis for explaining differences in coastal landscape. However, the fundamental controls are those of rock character, geological structure, the history of relative sea level rise, erosion and deposition over the last 10,000 years.

3.1.1 Early History of the English Channel

During the last two million years glacio-eustatic sea level changes have repeatedly exposed the bed of the English Channel to sub aerial conditions. These sea level lowstands correspond to periods of glaciation in the northern hemisphere, the last such episode reaching a maximum around 18,000 years ago. Although still controversial, the modern consensus of opinion is that the southern limit of glacial ice did not reach the English Channel, reaching only as far south as the English Midlands and South Wales. Southern England at this time would have been exposed to periglacial conditions and weathering, leaving thick solifluction and head deposits that extended southwards to the modern south coast of England. The offshore area of the English Channel was the site of extensive fluvial deposits including river terrace deposits, which covered a large proportion of the area now occupied by the English Channel. Fluvial downcutting of the rivers in southern England may have occurred at this time in response to the lowered sea level. Incision may have been enhanced by episodic high-energy river discharges in a periglacial environment. Fluvial incision in a cold climate is suggested to be at least partly involved in the formation of the Northern palaeovalley and the former River Arun valley east of Owers Bank (Bellamy, 1995).

During the preceding interglacial period between 120,000 and 130,000 years ago, sea level was similar to that of the present day and the English Channel was a shelf sea separating Britain from the European landmass. At this time beaches and cliffs existed along the south coast, remnants of which are preserved at a variety of locations. Raised interglacial beaches are found at a number of sites, but most in this area are now believed to date from an even earlier interglacial period (Keen, 1995). The raised beach at Portland Bill, which lies between 6.95 and 10.75m OD, dates from the last interglacial. Offshore there is a palaeo cliff line that may date from this period and which could be used as a possible indicator of post-glacial coastal recession. The Chalk ridge between Purbeck and the Isle of Wight may have been initially breached during this interglacial period when the gap was only approximately 11km wide compared to 25km today (Nowell, 2000).

The flooding of the English Channel commenced from the west as sea levels began to rise. By about 10,000 years ago the eastern end of the marine embayment had reached as far east as Beachy Head and Britain was still connected by dry land to the continent across the eastern English Channel and Dover Straits region. By 8,000 years ago the entire English Channel and Dover Straits area was inundated but there was still a shallow land connection separating this water body from the North Sea. This connection was breached around 7,500 years ago, linking the English Channel to the North Sea. Tidal models have shown that the opening of the Dover Straits initiated the strong eastward transport in the eastern Channel (Austin, 1991).

The transgression of the English Channel region probably led to the destruction or reworking of many of the fluvial terrace deposits to form either beaches, which rolled onshore, and/or marine bedforms in the shallow sea. As the transgression continued these newly formed shelf sediments may have moved extensively before sea levels reached approximately their present level about 5,000 years ago. Since that time there may have been small oscillations in sea level. Additional sediment may then have been made available through coastal erosion, initially perhaps with the reoccupation of the former interglacial shoreline, which was probably mantled with periglacial solifluction deposits.

3.1.2 Bathymetry

From Newhaven to Selsey Bill, the seafloor forms a gently sloping plateau less than 20m deep which lies to the north of a deeper east-west trending valley feature. This valley, which in places contains water in excess of 70m deep, is the partially infilled remnant of a larger palaeovalley, the 'Northern Palaeovalley' a relict feature cut during the successive transgressive-regressive cycles, which occurred over the last two million years. Deeper water occurs closer to the coast off Beachy Head as the Northern Palaeovalley approaches the modern headland. On the nearshore plateau to the south east of Selsey Bill the Owers Bank has water depths of as little as one metre below Chart Datum. A scour hole, which lies just to the south of the Outer Owers, has very steep sides, particularly on the northern flank, and a maximum depth of 67m (or approximately 45m deeper than the general level of the surrounding sea floor) and separates Outer Owers from Hooe Bank.

Reefs, which run obliquely from the coast and include Barn Rocks and Bognor Rocks, occur in the nearshore zone off Bognor Regis and extend up to 2km offshore. They are the result of cemented horizons in the London Clay formation. Other shoal areas, e.g. Shelly Rocks to the east, may also be bedrock-controlled features.
To the south of the Isle of Wight, an elongate enclosed bathymetric depression, St Catherines Deep (Brampton, et al., 1998), is approximately 21km long and 1.2km wide, with a maximum depth of 68m below Chart Datum (or approximately 30 to 40m deeper than the surrounding sea floor). St Catherines Deep lies offshore from the major landslip complex of the southeastern Isle of Wight and runs parallel to the coastline. It appears to be parallel to the strike of the underlying geological formations and its erosion may therefore reflect the relatively less resistant sand and clay beds within the Lower Cretaceous formations that are exposed on the seabed. The erosion appears to be connected with the headland of St Catherines Point although the inception of erosion may be related either to tidal scour, during a previous interglacial period, or to scour during an earlier stage of the Holocene marine transgression. It is also possible that marine scour has accentuated a previously incised fluvial valley formed during a sea level lowstand. It is not known whether marine erosion continues to the present time and therefore whether it forms a potential offshore source of sediment, although tidal streams are presently very strong at this location. The

bathymetric deep means that deep water is present relatively close to the toe of the Isle of Wight Undercliff and this may have an effect on wave energy striking this section of coast. Off the south-western coast of the island, ledges oriented west-south-west to east-north-east are similarly parallel to the strike of the underlying Lower Cretaceous Formations and reflect harder bands within the sequence.

The Isle of Wight is separated from the mainland by the Solent, which generally has maximum water depths of 10 to 15m in the western Solent and 10 to 20m in the eastern Solent. There are however a number of deeper bathymetric depressions, most notably in the western Solent off Hurst Spit and adjacent to the Shingles Bank where water depths reach 60m below Chart Datum. The Solent follows the line of an old fluvial valley running eastward, which formerly entered the Channel to the east of the Isle of Wight (Brampton et al., 1998). This bathymetric depression is however incised into the floor of the former palaeovalley and appears to be related to modern seafloor scour. Its location coinciding with the strongest tidal current velocities in the area.

The Shingles Bank and Dolphin Bank, which lie just to the south of Hurst Spit, lie along the western margin of this scoured depression. Parts of the Shingles Bank may dry at low water. Christchurch and Poole Bays form a larger shallow embayment with water depths generally less than 20m. Christchurch Ledge, which extends over 5km southeastwards from Hengistbury Head, is a geological bedrock feature in part controlled by a NW-SE running fault. This fault downthrows to the south, separating sediments of the Barton Group, south of the fault, from deposits of the Bracklesham Group (younger) to the north of the fault.

St Albans Ledge runs southwestward from St Albans Head and partly encloses a generally shallow area between here and Portland Bill where water depths are less than 25m. This prominent ledge is formed of resistant Portland Limestone and follows the submarine outcrop of this formation. Immediately to the north of this positive ridge lies a long depression with water depths up to 55m below Chart Datum, or approximately 35m below the general level of the sea floor. It appears to be parallel to the bedding in the underlying Kimmeridge Clay and parallel to the more resistant ridge of St Albans ledge. It would appear to be the result of erosion in the less resistant Kimmeridge Clay, perhaps exacerbated by the positive form and shallower water depths over the adjacent ledge. It is not known whether erosion is occurring at the present time and therefore whether or not the depression might represent a contemporary offshore source of sediment, although Donovan and Stride (1961) suggested that this scoured depression was contemporary with modern tidal conditions.

The Shambles is a sandbank, which lies to the southeast of Portland Bill, which has formed in the centre of an anticlockwise gyre in the tidal currents, which pass the headland (Pingree, 1978). The bank is approximately 6km long, 1.5km wide and stands about 20m high.

3.1.3 Geology

Contrasts in rock composition and resistance to both marine and non-marine processes of weathering and erosion provide a basis for understanding the variety of coastal forms in the region. The well-defined headlands of chalk on the east Purbeck and Isle of Wight coasts owe their existence to their superior durability in comparison to adjacent clay, shale and sandstone rock outcrops. The strong limestones of south

Purbeck and the 'Isle' of Portland support high cliffs that descend into deep water. By contrast, weak rocks along the frontage of the West Sussex coastal plain has created rapid rates of retreat (prior to artificial protection) and a virtual absence of cliffs. The striking differences between the northern and southern coasts of the Isle of Wight are partially the product of basic differences in rock materials.

The south coast of England is primarily controlled by a series of east-west trending tectonic structures, which folded the rock strata during Tertiary times. The Wealden anticline dominates the eastern section of this coast. The northern and southern limbs are of Chalk, which creates the upland ridge of the North Downs and the headlands of Dover and South Foreland (northern limb) and the upland ridge of the South Downs and the headland at Beachy Head (southern limb). The core of the anticline, which is exposed along the coast between these two Chalk outcrops, exposes less resistant Lower Cretaceous formations, which form lower cliffs and areas of lowland, that provide sediment to the coastal zone through erosion.

Within the central south coast lies the Hampshire Basin, a broad syncline exposing easily erodible formations of Tertiary age. The coastline in this section is consequently relatively low and has been broadly incised by a number of river systems. An east-west trending monocline runs through the Isle of Wight with more resistant Cretaceous chalk forming headlands at either end of the island.

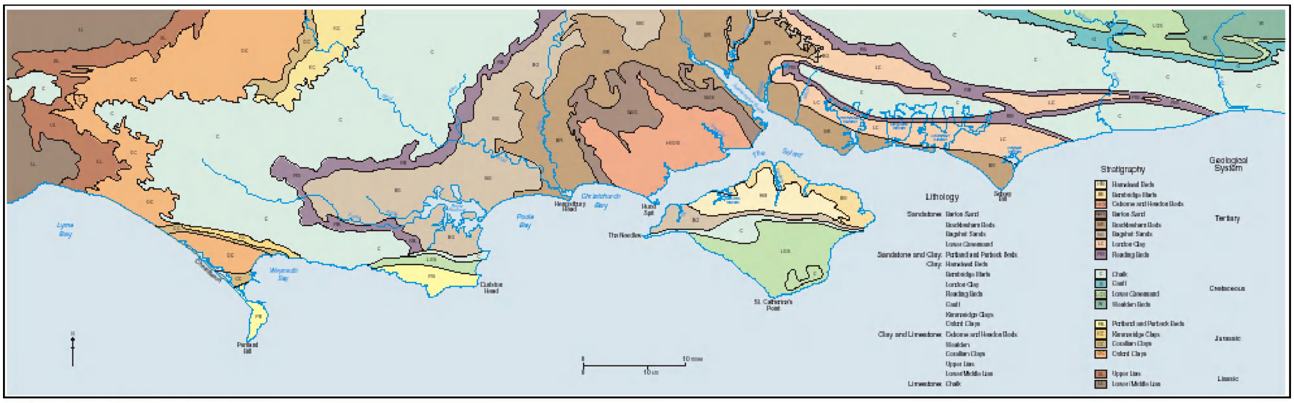

Figure 3.1 Geology

Coastal cliffs form the dominant erosional features along the coastline of south-central England. Their variety reflects the complex interactions between rock character, geological structure and inland relief on the one hand and applied forces of both marine and non-marine processes on the other. Soft cliffs comprised of clays and sandstones form a key geomorphological element along the coastline of south-central England. The whole of this coastline is composed of rocks within this category (with the exception of chalk and other limestones), and they are particularly susceptible to the impacts of coastal erosion and weathering. Located along a relatively exposed position facing the English Channel and towards the Atlantic prevailing storm waves have resulted in significant rates of cliff recession along these soft cliff frontages. Previous research (Defra 2002) has identified recession rates of 3 mpa at Black Ven, Dorset, 0.9 mpa at Barton-on-Sea, Hampshire, 5 mpa at Blackgang, IW and between 0.5-0.7 mpa along parts of the West Sussex coastline.

The rates of coastal retreat are some of the highest to be found in the United Kingdom. Cliff retreat is characterised by both gradual recession as a result of marine erosion, slow moving landslips which may be reactivated as a result of increased erosion and higher ground water levels, and more sudden dramatic failures such as those that have occurred at Blackgang Isle of Wight, along the West Dorset coast and elsewhere in recent years.

3.1.4 <u>Sediment Transport</u>

Sediment transport is an integral part of the coastal system and its trends reflect coastal change and climatic influences. A clear understanding of sediment transport is therefore important in any assessment of coastal processes.

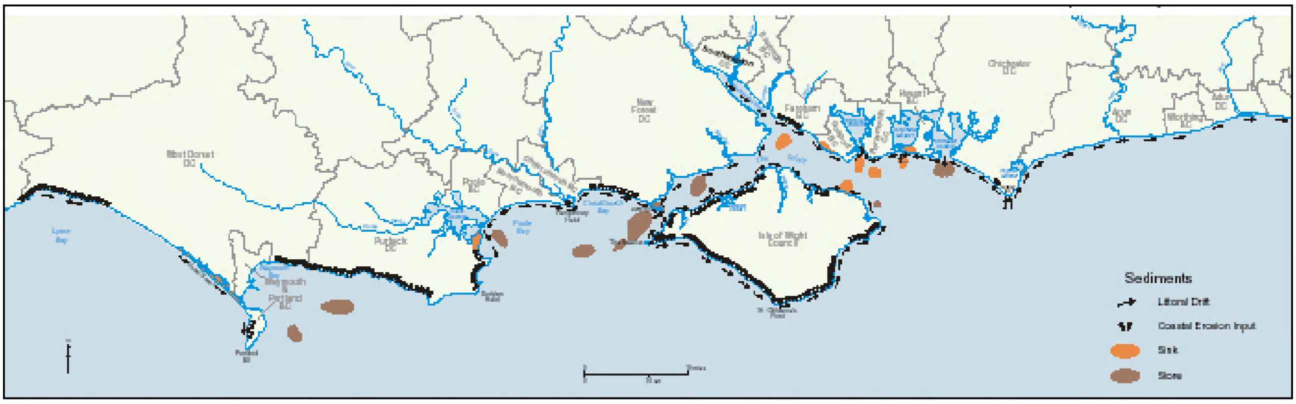

Figure 3.2 Sediment Transport: Inputs, Pathways, Stores and Sinks

<u>Sea Bed Sediments</u>

The seafloor sediments of the area are dominated by gravely deposits (Hamblin et al., 1992). This reflects the largely relict nature of the seafloor. The thickness of these gravely deposits is generally less than one metre (Hamblin et al., 1992). Sandy sediments are of a more restricted distribution and are generally found in the more sheltered areas such as Poole and Christchurch Bays and within the Solent. Even in these areas the sandy sediments rest on a scoured surface and are often accumulated in the form of discrete sandbanks. An area of more extensive sands with the formation of sandwaves occurs 10 to 15km offshore of the coast between Worthing and Beachy Head (Hamblin et al., 1992). The sandwaves here are up to 4m high and are oriented with their steeper faces eastwards, indicating sand transport in that direction. Between St Albans Head and Portland, sandy sediments are thin and patchy. Muddy sediments are almost entirely restricted to areas within the Solent, particularly the eastern Solent, although muddy sands also occur in Weymouth Bay where deposition may be the result of the sheltering effect of the headland of Portland.

The main potential sediment sources in the area are:

- Rivers
- Coastal erosion
- Seafloor erosion
- Advection of water masses from the North Atlantic or southern North Sea
- Windblown sediment

The relative importance of these potential sources is different for different size fractions.

<u>Gravels</u>

There is little doubt that extensive deposits of gravel-bearing sediments existed in the area that is now offshore, as a result of fluvial and periglacial processes at the end of

the last glaciation. As sea levels rose, the marine transgression flooded the former river valleys and eroded the pre-existing deposits as the littoral zone moved landwards. There is evidence in places of the existence of earlier coastal cliff lines, which would eventually have been reoccupied by the widening English Channel. It is likely that these former cliff lines were mantled with solifluction deposits preserved now only as remnants at the modern coastline. These cliffs may have been significant contributors of sediment. At the present time the main areas where coastal cliffs might contribute gravel to the beach sediments are the south Dorset Coast, the south coast of the Isle of Wight and the cliffs of east Sussex.
Gravel beaches, formed earlier in the transgression, may have migrated landwards either at the toe of these cliffs or, in areas of lower topography, as barriers in front of diminishing lowland areas. At the present time there is unlikely to be significant movement of gravel on the shelf in water depths greater than 20m (HR Wallingford, 1993). In areas of less than 10m depth, onshore gravel transport may be significant, particularly during storm conditions.

<u>Sands</u>
The main sources for sand in the area are from seabed and coastal erosion. In common with the comments above for gravels, sand-bearing sediments were probably extensively distributed on what is now the floor of the English Channel, before the Holocene marine transgression. These sands have been readily redistributed as the marine sand transport system evolved so that their distribution has probably been completely altered and therefore is to a large extent not relict. The main sources for sand from coastal erosion are the cliffs of soft sandy Tertiary formations of Poole and Christchurch Bays and within the Solent. The Lower Cretaceous formations of the southern coast of the Isle of Wight are a further significant source.

<u>Muds</u>
The rivers along this part of the south coast have relatively small discharges and are not believed to contribute greatly to the deposition of fine-grained sediment. Coastal erosion is expected to be a major source particularly from the unlithified mud-rich Tertiary formations of Christchurch Bay and within the Solent. Other mud-rich formations occur on the Isle of Wight and on the Dorset coast. Sea floor erosion may also contribute to the supply of mud as indicated by the scour hollows carved into the Kimmeridge Clay formation off the Dorset coast. A further source of fine-grained sediment comes from advected water from the western English Channel and Southern North Sea.

<u>Offshore Sediment Transport</u>
On a regional scale the Eastern English Channel exhibits a dominantly eastward transport as determined from bedform asymmetry and other indicators. A major bedload parting has been identified, which lies north south across the Channel from the Isle of Wight to the Cotentin peninsula. To the west of this line bedload transport is dominantly towards the west. Palaeotidal modelling suggests that the location of this bedload parting has moved variably eastward or westward over the last few thousand years but has retained its general location (Austin, 1991).

A number of detailed studies of sediment transport (mostly for sand) have been carried out in this area. To the east of the Isle of Wight, bedform asymmetry has been used to predict bedload sediment transport pathways (HR Wallingford, 1993; Figure 18). The dominant transport direction is eastwards (HR Wallingford, 1993; Figure 19) as this area lies to the east of the bedload parting already mentioned. A more minor bedload parting has been identified between Ryde on the Isle of Wight and Gosport on the mainland. Transport to the east of the parting is southeastwards into the English Channel, to the west, transport is northwestwards into the Solent. A possible anticlockwise circulation can be identified to the south east of Selsey Bill in the vicinity of the Owers. A bedload convergence is present to the east of the Isle of Wight.

To the west of the Isle of Wight an extensive survey of sediment transport pathways was carried out by Brampton *et al.* (1998). Bedforms indicate a dominant southwestward transport away from Hurst Spit and Shingles Bank towards Purbeck with a clockwise circulation around Dolphin Bank (Brampton et al., 1998; Figure 3.36). There are relatively few bedforms within Poole and Christchurch Bays (Brampton et al., 1998; Figure 3.35), so no other strong trends have been identified using this technique. Other information derived from numerical models and a study of longshore transport indicates a dominantly clockwise circulation within the bays (Brampton *et al.*, 1998). Analysis of historic bathymetric charts from 1937 and 1987 has shown that the Shingles Bank has reduced in volume by approximately 2.4 x 106m^3 over this 50-year period, representing a loss of approximately 48,000m^3/year.

The Offshore (> 10 m depth)

Generally, the morphology of the seabed is related to the nature of its bedrock, the supply of mobile sediment and the region's exposure to wave and tidal action. For the South Coast, offshore sediment transport, typically of medium- and coarse-grained material, is primarily controlled by peak offshore tidal currents rather than the wave climate (Brampton *et al.*,1998). This is supported by bedform analysis (HR Wallingford, 1993). Indeed, long-term (24 years) wave measurements have been analysed to show that, in water depths greater than 30 m, bottom sediments are affected by waves less than 1% of the time (Grochowski and Collins, 1994). However, over temporal periods > 100 years, the cumulative effect of regular storm waves upon sediment transport can be important, as shown in recent depth of closure studies (Hinton, 2001). Although higher magnitude, more infrequent, storm waves can affect the seabed, for example at depths of 60 m in the Channel mouth (Draper, 1967), their long-term effect is insignificant as regards net sediment movement due to their low frequency of occurrence (Soulsby, 1987). Therefore, it is tides that control the long-term sediment transport patterns of the offshore Eastern English Channel, since wave effects are too infrequent and so inconsequential over this period (> 100 years) (Grochowski *et al.*, 1993b).

The Nearshore (< 10 m depth)

A more complex pattern of sediment transport behaviour is observed in the nearshore due to estuarine (tidal currents) and wave-induced current interaction. Pronounced headlands and sheltered embayments result where alongshore variations in geological strength occur (Komar, 1998). Consequently, wave refraction occurs which results in wave energy being greatest upon the headlands and weakest within the embayments. Potential changes in the future wave climate, namely wave direction, could result in changes in this present pattern of wave energy within the nearshore region along the South Coast. Eroding cliffs and beaches represent the main source of sediment (cf. Bray, 1995). Typical examples of sinks are banks located at i) headlands (for example Shambles Bank); and ii) estuaries (for example the West and East Banks of Langstone Harbour).

3.1.5 Tidal Processes

Risks of coastal flooding depend on three factors, which contribute to the total observed sea level. These are the mean sea level, the tides and the meteorological effects. The first is the subject of intensive research in anticipation of global warming and sea level rise. Tides are very stable because of the constancy of the astronomy of the earth-moon-sun system, and of the deep ocean basins; however, small but significant local differences are sometimes observed. Weather effects can only be forecast in the long term as statistical probability estimates.

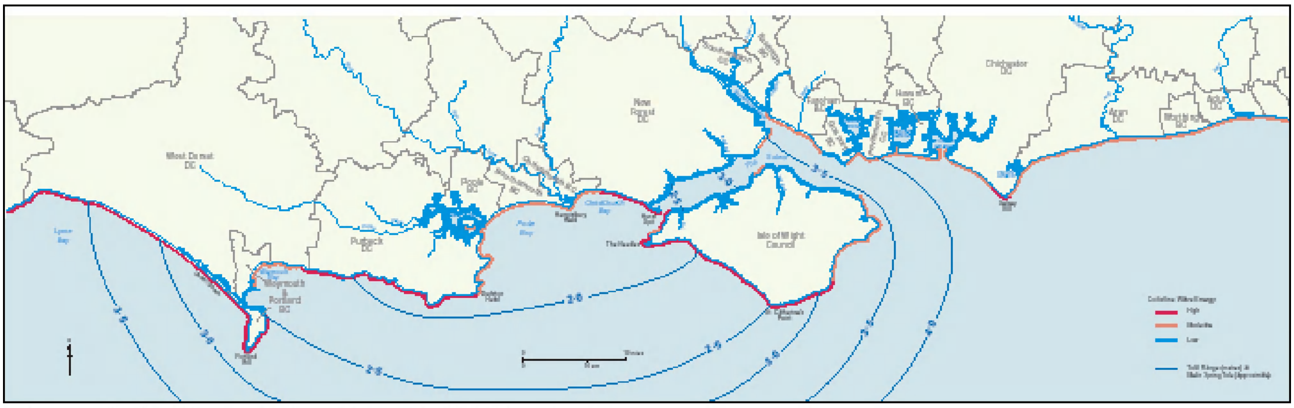

Figure 3.3 Wave Climates; Tidal Currents

Meteorological forces (atmospheric pressure, wind speed and direction) cause significant variability in sea level about the predicted tide. A 'surge' in sea level is the difference between the predicted tidal sea level and the real sea level. Surges are generally the result of the west to east passage of intense weather systems across the UK. Low-pressure weather systems, which allow a rise in sea level beneath them and are thus a common cause of flooding in coastal regions, damage to sea defences, and coastal erosion. Surges can have dramatic and expensive societal and economic impacts on the coastal zone.

The strength and effects of a sea level surge is dependant on:

- The change in atmospheric pressure associated with the passing weather system (a greater change in pressure will generate a larger surge).
- The speed of the weather system (sea level takes time to respond to changes in atmospheric pressure).
- The speed and direction of the wind (onshore transport of water will exacerbate a positive surge).
- The timing of the peak of the surge relative to the tidal high water (the most damaging surges occur at the same time as high water spring tides).
- The height of waves associated with the passing weather system (coastal defence damage and over-topping is considerably worsened when large storm waves are superimposed on a positive surge).

Given the strong links between weather patterns and storm surges there are clear implications associated with our current knowledge of changes in climate. There is increasing interest in developing a longer-term understanding of how the strength and frequency of surge events may respond to, for instance, increased storm occurrence or a rise in mean sea level. Thus forecasting of surge events is important on a short time scale in the context of providing sufficient warning for flood protection measures to be taken, and on a longer term to provide sound advice for the management and planning of coastal protection, and for the assessment of insurance risks.

To a large extent, the role of forecasting surge events and collating data has been satisfied by the implementation of the Southeast Regional Coastal Monitoring Programme (SRCMP), hosted by the Channel Coastal Observatory at the Southampton Oceanography Centre (www.channelcoast.org). The programme is managed on behalf of the Coastal Groups of the Southeast of England and is funded by DEFRA, in partnership with local Authorities of the southeast of England and the Environment Agency.

One component of the SRCMP is the maintenance of a sea level database using available sea level recorders along the coast, including the implementation of web-based real-time sea level data access.

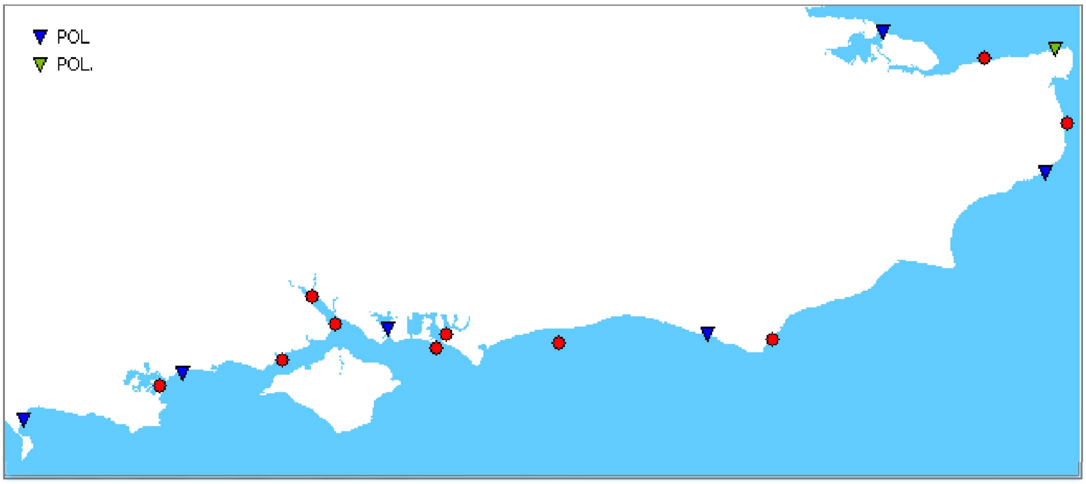

Figure 3.4: Locations of sea level gauges

The Channel Coast Observatory already has responsibility for maintaining a database of the sea level data collected by gauges marked in Figure 3.4 In addition to that data the Observatory also collates data on waves, coastal geomorphology, and sea defences. Thus, the Observatory serves as a centre for information and data on sea level variability linked to the risks of flooding and erosion.

The regular tidal and continual meteorological effects on changing sea levels are very occasionally overwhelmed by a quite different effect. This is the generation and propagation of a tsunami following an earthquake or seabed slump. Although exceedingly rare in the Atlantic Ocean, there are well-documented occurrences, and the south coast of England is exposed to tsunami generated in the open Atlantic Ocean. No systematic study has been made of the possible frequency, severity, and impact of such extreme events, in part because there is little observational data.

There is a clear need for post-surge analysis of events on the south coast of England towards a better understanding of surge generation and propagation, surge effects being amplified by local bathymetry or meteorological effects, and surge responses due to the relatively open access to the North Atlantic Ocean.

3.2 North-east Coast of England (North Yorkshire), UK

The geology of the area reflects its recent glaciation and the subsequent rise in sea level. For the majority of the coast quaternary drift deposits of Boulder Clay cover the older Jurassic Lias deposits of shales, sandstones and limestones. The Jurassic sequences rise and fall producing a coastline of headlands made of solid outcrops and embayment, such as Runswick Bay and Robin Hood's Bay, formed where glacial drift material occurs at sea level. The Jurassic strata, especially the lias shales are weak and can be subject to considerable rates of erosion dependent upon local characteristics, such as aspect and the presence of rock platforms.
The headlands rise to form cliffs of up to 200m, whilst the bays are characterised by sandy beaches backed by lowland cliffs. The wave cut platforms run into the cliffs with small deposits of cobbles or boulder materials derived from slope instability.
The glacial till, an unconsolidated mixture of clays, sands and gravels, are easily eroded by wave action, groundwater effects and mass movement such as rotational slips, often taking place synchronously. The boulder clay frequently caps the Jurassic cliffs and in places has slumped to cover the in situ solid strata. Where this has occurred the resulting cliff has a steep near vertical lower section and a lower angle upper profile.

Shore platforms act with varying degrees of effectiveness as dissipaters of wave incident energy. In some areas these platforms are the only protective barrier in front of the cliffs.

Offshore the area is characterised by a superficial deposit of sand and gravel. These deposits result from the Holocene reworking of glacial drift and the erosion of the prevalent solid geology by a combination of marine and sub-aerial processes.

The tidal regime along the North Yorkshire coast is macrotidal. It follows an anti-clockwise pattern and results in a south flowing residual tidal current. Spring tidal currents are twice as strong as neap tides, during which the maximum tidal current speeds (in knots) at mean spring tide of:

0.7 between Saltburn and Robin Hood's Bay
0.75 between Robin Hood's Bay and Filey Brigg
1.00 between Filey Bay and Speeton
1.25 along the northern coats of Flamborough Head

The wave climate of the coast is dominated by a combination of local wind direction and the influence of swell waves. The wind direction data indicate that south westerlies predominate, however these are relatively unimportant as generators of waves. Winds from the north and northeast, which have the longest fetch across the North Sea result in waves, which have the greatest effect on the coast, dependent on coastal aspect and dominant wave direction.

The offshore bathymetry of the North Sea ensures that the waters along the northern section of the study area are deeper than those of the south. Consequently the predicted 50 year maximum deep-water wave height of 20m with a period of 13 seconds reduces around Flamborough to 10m in the shallower southern waters.

The coastline of the study area is also subject to swell waves, particularly from the northwest to northeast with a high incidence of swell waves in spring and summer. In the open seas of the coastline swells of 5m height or more may come from any direction of the coastline means that it is generally protected from the influence of southerly swells. Consequently the main contribution of swell to the wave climate of the coastline is to add to the general trend or wind generated waves from the north and northeast.

The nearshore seabed sediments, mapped by the British Geological Society have generally been described as sand. At three localities the sediment type locally changes possibly due to unrecorded circulatory currents e.g. Filey Bay, has increased gravel component towards the 'centre' of the bay.
Beaches are subject to degradation and aggradation due to changes in the nature of the wave regime. Shifts in the supply of appropriately sized material and variations in the directions and strength of long shore and shore normal sediment transport. There is limited data on the precise rates at which cliff erosion are mostly concentrated around Filey Bay, the cliffs between Ravenscar and Huntcliffe. The erosion rate for Filey Bay during the period 1950 and 1978 is estimated at 0.15cm per year but the rate doubled between 1928 and 1964.

Recorded erosion data points to two important trends. Firstly, the bays are receding more quickly than the headlands, resulting in an increasingly incised coastline. Second, rates of cliff top erosion are generally lower than erosion rates at the toe of the cliff. This reflects the fact that most cliffs profiles are higher than the upper limit of wave erosion.

In the short term, steepening of the cliff profile is possible but the physical nature of the boulder clay and shale cliffs places restrictions on the extent to which steepening can go on before slope failure occurs.

The cyclic nature of cliff regression has been summarised with relation to the cliffs at Whitby (Clark) 1991). Four stages are recognised:

1. Removal of material from the base of the cliff by marine erosion, creating a wave cut notch.
2. Collapse of the cliff producing over steepened slopes.
3. Further cliff failure, involving initial re-mobilisation of displaced blocks.
4. Removal of failed material from the base of the cliff by marine erosion. As a consequence the cycle starts again.

Clark (1991) discusses the history of coastal instability around Whitby:

"The geology of the area in general terms can be divided into two distinctive types, a lower middle Jurassic bedrock and an overlying sequence of glacial hills and flavio glacial sands and gravels. The Yorkshire coast and Whitby in particular is a classic example where glacial hills and weak rocks are subject to wave attack. The problem is compounded at Whitby with a significant amount of erosion and instability being caused by groundwater flow from the fluvioglacial materials within the cliff".

Clark (1991) continues:

"In addition to landsliding caused by removal of material be marine erosion, the saturation and remobilisation of previously failed material by groundwater and undercutting of slopes by seepage erosion also contributes to the instability of the area".

The significance of groundwater in the mobilisation of cliffs was demonstrated in the collapse of the cliffs at Holbeck, Scarborough. Silke (1993) concluded that:

"The cliff collapse that left the four star Holbeck Hall Hotel tottering 60m above the bay was almost certainly triggered by the effects of two months of heavy rainfall, after a prolonged dry period, on an unstable cliff".

There exists a key link between climate and cliff stability. The water balance and nature of precipitation events are significant. The Holbeck event illustrates the point that there will be locations along the coast where it may be the climatic changes associated with future seabed change that prove to be most significant factors for coastal cliff instability rather than the actual change in local sea level itself.

3.3 Central-East Coast of Italy (Regione Marche)

3.3.1 The Adriatic Sea Geomorphology

The Pleistocene continental sedimentation

During the Pleistocene Würm glacial period approximately 20,000 years B.P., sea levels in the Adriatic Sea were 90 to 130 m lower than present and the coastline was approximately 300 km further south, leaving an emerged plain in the northern part of the Adriatic region. The late Pleistocene continental complex is formed largely of interbedded layers of clay, sand and peat; the continental origin of which is confirmed by the textural characteristics of the sediment layers and their palaeontological contents. Studies by Bortolami *et al.* (1977) on pollen, obtained from samples from different cores in the Lagoon of Venice and the Lower Po Valley, provide important information on the subsidence and climatic fluctuations in the northern Adriatic region. Their study briefly indicates:

- Following a continuous subsidence and sedimentation rate of about 1.3 mm/yr from before 40,000 to 22,000 years B.P, the least glacial peak, the sedimentation rate increased drastically to at last 5 mm/yr, most likely caused by an accelerated downward movement of the basin, i.e. an isostatic effect;
- A sedimentation gap ends the Pleistocene (18,000-7,000 years B.P.), and
- An episode of emergence that corresponds to the compaction and overconsolidation of a clay layer considered as an indicator of the Holocene/Pleistocene boundary.

Bortolami *et al.* (1977) also found that the Pleistocene peat samples consist of the same type of Cyperaceae peat throughout the stratigraphic column indicating that the growth conditions, i.e. the hydrologic situation, must have been approximately the same during each period of peat development. Furthermore the authors suggest that a good correlation betweeen age and depth of the sediments implies that the sedimentation was strictly related to the subsidence of the basin floor.

Palynologic analyses provides indications on the climatic variations and on the related vegetational phases for the time span between 40,000 and 18,000 years B.P. A study by Bortolami *et al.* (1977) on pollen from peat samples from the Northern Adriatic basin gives a C14 date of 39,000 B.P. and indicates the following five climatic phases:

- A Gramineae steppe period with *Juniperus*, *Artemisia*, *Ephedra* and some scattered pine trees indicateng a cold and dry climate;

- Sixty percent increase in tree pollen percentage such as oak forest elements, traces of beech (*Fagus*), fir (*Abies*), pines (*Pinus*), birch (*Betula*) and spruce (*Picea*); between 38,000 to 34,000 years B.P. could be attributed to warmer and more humid conditions with some climatic changes within the same period.
- With the occurrence of steppe vegetation such as Gramineae. Chenopodiaceae and few pines at 33,000 years B.P. a change to cold climate could be recorded;
- Between 32,000 and 23,000 years B.P., 50% increase in pine pollen with fairly high value for Gramineae, *Artermisia*, *Ephedra* and *Juniperus* indicates an open pine forest in the steppe with a dry climate. But between 31,000 and 29,000 years B.P. more humid condition were developed as indicated by the presence of oak (*Quercus*), elm (*Ulnus*) and poplar (*Populus*), and
- A steppe type vegetation with up to 70% Gramineae, *Artemisia*, *Juniperus* and *Chenopodiaceae* characterized the 22,000-18,000 yeas B.P. period with very dry and cold climate. The authors also report a striking resemblance, despite the great distance, when they correlate the vegetation phases of the Venetian region with those from other locations in the Mediterranean area.

Pleistocene emergence

The Pleistocene period ends with a phase of no sedimentation (18,000-7,000 B.P.) in the Venetian lagoon. During the final phase of the Pleistocene period the shallow argillaceous deposits are drained, compacted and oxidized to form the overconsolidated levels known in the Venetian lagoon as "caranto'' and representative of the Holocene/Pleistocene limit. The lack of sedimentation corresponds to the beginning of the deglaciation, the Flandrian transgression.

The Flandrian transgression

With the climate improvement that started about 17,000 B.P. and reached its maximum about 6,000 B.P., the sea level began to rise and the coastline moved progressively northwards over the Adriatic palaeoplain until it reached approximately the present position about 6,000 B.P. That period was characterised by an intense and prolonged alluvial phase. Wave motion and sea current reworked and dispersed the fluvial sediments carried to the sea.

The present day morphology of the Adriatic Sea

At the present time the Adriatic Sea may be divided into 3 parts from North to South: the Northern Adriatic Sea from the Trieste gulf to the Ancona promontory; the Central Adriatic Sea from the Ancona promontory up to the Gargano promontory; and the Southern Adriatic Sea from the Gargano promontory up to Otranto. The Northern Adriatic Sea is comprised in the continental shelf. The bottom slope is oriented to S-E with values of 0,25-0,60 m/km up to the isobath 100 m at the southern limit of this part of the Adriatic Sea. The rate of sedimentation is about 4 mm/year. The main part of sediment yield is due to the Po River. The central Adriatic Sea again lies on the continental shelf, but with a bottom slope from 0,75 to 12 m/km. It is characterised by raised areas, which sometimes emerge to produce isles, and by a large depression (the mesoadriatic depression) formed by three small basins oriented NNE-SSW with depth around 270 m. This depression is the emerged border of the Po paleoplain during the upper Pleictocene. The Southern Adriatic Sea is very different and can be divided in three physiographic units: the continental shelf, the continental slope and a bathial plain at the border with the Ionian Sea. The continental shelf extends up to the depth of 180 m.

3.3.2 Evolutionary trend of the Adriatic coastal zone

Since the beginning of the 20th century, coastal areas around the world have been affected by a widespread regression. During the previous century the general trend affecting the coastal zone was one of accretion.

The 8,000 km Italian coastline is shaped by a great variety of coastal processes. Today about forty-five percent of the Italian coast is threatened by a progressive and general degradation which mainly is manifested as beach erosion. This phenomenon seemed to worsen in the 1950s after a long period of general beach stability. Human intervention has contributed to the rapid change of the coastal zone. For example by demolishing the dunes to create beaches and summer residential and marine areas; the diminished fluvial sediment load to the sea by haphazard removal of riverbed material; the increased subsidence caused by groundwater and gas and oil extractions in areas too close to the sea.

Increased economic development, with no consideration of environmental sustainability, tends to worsen the already precarious situation. From the end of the1950s, up to the present day, the coastal area has been threatened by a lack of understanding about sustainable development and sustainable tourism.

Conclusions
Evidence from various studies demonstrates that coastal erosion and related issues are very difficult to solve. "Understanding the dynamic nature of the coastal margin is a key factor in managing coastal erosion" (Eurosion, 2004). A significant issue is the construction of coastal defence structures, built after the initiation of the erosive process, by which time it is often irreversible. Intervention at a later stage is, of course, more expensive and more difficult. Major human activity on the coastal zone at the present time is the undeniable cause of problems in the coastal environment. Another issue is the frequency of storm waves that cause destabilisation of the coastline, which is already compromised by human activity. These experiences are not specific to Italy and examples of the implications of human intervention on natural coastal processes can be found throughout Europe. In order to better understand the processes that control the coastal evolution it is necessary to assess the influence of the climatic variations and the possible interaction with human activity on the landscape.

3.3.3 Coastal Zone Evolution of the Marche Region

From Gabicce to the Ancona promontory and from here to the mouth of the Tronto river, the Marche region coastal zone is characterised by a narrow, sandy and gravely strip, which, in some places, lies at the toe of a cliff belonging to the Apennines Mountains, very often close to the Adriatic Sea. The shoreline of the first section, from Pesaro to Ancona, and that of the second one, from Ancona to the Tronto River, is interrupted by the mouths of many minor rivers flowing from the Apennines close to the hinterland. Defence works against erosion from winter storm waves protects 42% of this coast. The coastline from Pesaro to Ancona and from south Ancona to the Tronto River is mainly sandy and gravely.

From the Gabicce promontory to Pesaro and where the Ancona promontory is found, the narrow backshore, at the foot of the high cliff, is composed of boulders and gravel with sand. Samples, collected from the shoreline, indicate gravel with sand from the shoreline to 2-3m depth in correspondence of the Gabicce-Pesaro cliff and the Ancona promontory (Ciabatti et al. 1976). Sand (according to 1957 classification by Nota: quantity of sand 95%) and pelitic sand (quantity of sand between 70 – 95 %) are then found up to 10m depth (Brambati et al.1983).

In the stretches from Pesaro to Ancona and from the Potenza River to the Tronto River, sand and pelitic sand are present from the shoreline to 3-5m depth, very sandy pelite (quantity of sand between 30 – 70 %) and sandy pelite (quantity of sand between 5–30%) follow.

Historical records, which predate cartographic documents, suggest that the Marche coast was inhabited before the Roman Empire with the ancient towns located at the mouths of rivers into the sea. The first information about shoreline variation come from a description by Luigi Ferdinando Marsili (1708 – 1715) testing a general advancing of the shoreline that following studies show to continue up to the first half of the XIX century. From 1850 up to 1940 (Buli & Ortolani, 1947) there is the beginning of the regression of the shoreline and the end of the general advancing of the precedent century.

The dynamic evolution of this coastal zone is quite simple. The sources of sediments, reworked by the waves and distributed along the shore by the longshore current from south to north, are the material transported by the rivers to the sea and the material derived from the landslides of the cliff from Gabicce to the Ancona promontory. In the past the large sediment yield from the rivers to the sea indicates a general advancing of the shoreline in the northern sandy littoral up to Gabicce, with the maximum values corresponding to the rivers outlets. The cliffs, from Gabicce to the south, were characterised by many periodical landslides with regression of the cliffs and the supply of the failed material into the sea by the longshore current along the narrow backshore at the foot of the cliffs. The heavy precipitation (rain and snow) of the cold/wet periods is the main cause of landslides in the region.

The general advancing of the shoreline for the whole area, in spite of same local regressions of the cliff in the south, was continuous from the 1600 up to the beginning of the XXth century. Cartographic data confirm this statement. After the first decade of the 1900s, only some sectors continued to increase, but at a significantly slower rate than in the past.

Most of this stretch of coastline experienced a static period followed by a regression of the shoreline during the 1950s, with an increasing rate and intensity up until the end of the 1970s. This increased rate of erosion coincided with the increase of storm wave action connected with the cold/wet weather in the 1950-70 period and the diminished sediment yield to the sea due to the coastal engineering structures, which were constructed to prevent landsliding onto the Adriatic railway line, and to the rash removal of riverbed material. Consequently there was a general regression of the shoreline and an increased bottom slope up to the breaker zone. As a result of the above, storms today are much more effective and destructive.

The comparison of the shoreline variation from 1944 up to the present day shows a rapid increase in the rate of erosion with a regression of the shoreline between 1954 and 1980. Also of significance is that the major points of regression correspond to the river mouths. The comparison of the situation between 1980 and 1999 shows a slower rate of regression and a modest advancing of the shoreline. This situation is due to the intense construction of coastal defence structures along the entire Marche coast after 1980.

Conclusions

The shoreline variations are very similar in the North and South Ancona zones even though there are great differences in coastal processes and the construction of coastal defence works.

The natural nourishment of the beaches, in the past, has been due to fluvial yield and to the input of cliff material derived from landslides (Buli, 1947). In the XIX century the coastline was progressing, thanks to the southern longshore current still rich in sediment yield. However, since the beginning of the XX century widespread regression dominated, reaching a critical stage after the Second World War, sometimes with irreversible effects. A reversal in this trend was caused by several factors:

- The urbanisation of large coastal zones due to tourism without regarding the natural environment.
- The decrease in material from the cliffs caused by the construction of seawalls to protect the railway from storm waves (A. Cancelli et al., 1984).
- The continued excavation of sand and gravel along the minor rivers has drastically lowered the supply of sediments to the shore.
- The longshore currents deprived of sandy material decrease their importance in the coastal regime. While the onshore – offshore transport carrying the beach sands toward the open sea.
- The bottom slope is then increasing near the shoreline and, consequently, storm waves are much more effective and destructive in spite of defence works.

3.4 Languedoc-Roussillon Coast of France

The Languedoc-Roussillon, study area covers 200 km of coastline and incorporates a wide variety of coastal landforms, including cliffs, sandy beaches and coastal wetlands. The Gulf of Lion is a silico-clastic passive margin stretching between the Pyrenean and Alpine orogenic belts in the Northern part of the Western Mediterranean Basin. The development of this margin was initiated during the Oligocene rifting (Gueguen, 1995; Sioni, 1997) followed by oceanic opening during the Miocene (Speranza *et al.*, 2002). The accumulation of the sedimentary wedge occurred during the Plio-Quaternary period, principally controlled by glacio-eustasy (Bessis, 1986).

The Gulf of Lion is dominated by wave regimes. At the coast, the south-easterly dominant wave regime drives a south-westwarly longshore drift. The geostrophic Liguro-Provencal current drives the oceanographic circulation (Millot, 1994).

3.4.1 Geological setting

The Gulf of Lion continental margin forms the western part of the Provençal Basin, which was formed during a short Oligo-Aquitanian rifting event that separated the Corsica-Sardinia microplate from continental Europe. The rifting itself occurred between 30 and 24 Ma and produced a series of tectonic grabens in the Gulf of Lion. A distinct syn-rift sequence is locally visible on the seismic sections, overlain by a thick post-rift sequence dominated by clastic sedimentation. Recent studies in the western part of the margin have revealed that the Miocene sequence is offset by a number of normal Late Miocene faults associated with an extensional phase dated from the latest

Miocene – Early Pliocene. The cause of this extensional phase has yet to be clarified and may be linked to uplift in the eastern Pyrenees. The thickness of the post-rift sequence increases toward the centre of the basin, where it reaches more than 7 km.

The post rifting sedimentation in the Gulf of Lion area was strongly influenced by the Messinian Salinity Crisis (Hsü *et al*., 1973), which started 5.96 Ma ago (Rouchy, 1981;Gautier *et al*., 1994; Krijgsman *et al*., 1999). In the deep basin, the post-rift deposits include an evaporite sequence that correlates landward with the Messinian erosion surface (MES) (Montadert et al., 1970; Lofi *et al*. in press). Overlying the shelf, the post-Messinian sequence consists of a thick Plio-Quaternary succession whose deposition began in the Early Pliocene and led to a progradation of the Gulf of Lion margin by as much as 120 km (Lofi *et al*., 2003). Up to 2000 metres of Plio-Quaternary sediment covers the Messinian unconformity beneath the outer shelf. Following a rapid lower Pliocene marine transgression, attested by the extremely limited transgressive systems tract above the, MES, Pliocene and Quaternary sediments prograded over the margin, forming a new continental shelf and clino-forms over the eroded Miocene shelf.

Recent geology

The continental shelf of the Gulf of Lion is about 250 km long from the southwest to the northeast. It is a relatively flat platform, which slopes gently seaward (gradient of 1 to 3% in the inner zone and 0.1 to 0.5% in the mid-outer zone). The eastern part of the shelf is narrow (20 km) and the western part is broader (50 to 70 km wide). The shelf/slope break (120-130m) is incised by numerous canyon heads and shelf edge slumps. The continental rise develops at about 1500m depth and is characterised by transverse features such as giant sand ridges (Pyreneo-Catalonian Ridge) and a major deep sea fan (Rhône Deep Sea Fan) (see e.g. Droz 1983 ; Mear 1983 ; Coutellier 1985).

The Gulf Of Lion constitutes a wide indentation in the continental domain. It is bordered by paleozoic aged massifs, calcareous Mesozoic massifs, sandy Cenozoic coastal prisms and sedimentary fans, and by quaternary surficial deposits.

The upper sediment sequences observed on the shelf mostly correspond to deposits posterior to the Last Glacial Maximum (LGM). Holocene coastal barriers (from 8000 years BP to present day) are directly overlying Plio-Quaternary sequences (Martin, 1978). When the last transgression began about 18 000 years ago, the sea-level was 130 below present-day sea-level (Aloisi, 1986). The velocity of the transgression was strongly irregular, with periods of stability alternating with periods of rapid sea-level rise (reaching 1 cm/year). During phases of low transgression, littoral ridges were built, and are still present on the continental shelf (Ausseil, 1978, Aloisi, 1986).

Sea-level rise ended 4 500 years ago (BP) at more or less at the present day sea-level (Martin, 1978). Some authors are still discussing a possible rise at +2m above present sea-level (Ambert, 1991, Laborel, 1998). It is estimated that sea-levels have been more or less stable during the last 5500 years BP.

Surficial deposits currently observed on the shelf are:

- Sands at the shelf edge corresponding to the low stand level around 18 000 years BP,

- Large deltaic and pro-deltaic systems constructed from 5 500 BP when sea level reached its present elevation. They are described by Aloïsi (1986) as, a particular application of the epicontinental sedimentary prisms. Proximal parts are characterised by large silty-muddy depocenters. Distal parts are composed of mud between 30 and 85m water depth. Thickness of the depositions are closely linked to the Rhône sediment supply. Secondary sources also played an important role, as seen seaward of the Aude river inlet where 30m of sediment were deposited.

Surficial sediments

The coastal barrier and delta front deposits are well sorted, horizontally-bedded beach sands, grading seaward from interbedded shoreface silts and sands to fine laminated silts and clays of the lower shoreface (Gensous *et al*., 1993). Seaward, prodeltaic and organic rich deposits are found in front of the main distributaries.

The mid continental shelf is blanketed by an extensive mud belt (metric to decimetric in thickness) between 50 and 90 m water depth. In the western part of the shelf, it is interrupted by sandy shoals between 30 and 60 m water depth. The outer shelf is covered by relict sands, locally overlain by a thin covering of hemipelagic mud. The shelf edge occurs at 120 m depth. It delimits a steep continental slope affected by large-scale slumping and sediment failure (Canals and Got, 1986).

3.4.2 Coastal processes

Oceanographic regime

The Gulf of Lion is a wave-dominated microtidal environment experiencing relative low energy levels (mean wave height of 0.8m). Under fair-weather conditions, significant sediment transport is restricted to the upper shoreface (5 to 7m depth); in winter, waves generated by easterly storms can remove deposits as deep as 30 meters (Blanc, 1977; Bertrand et L'Homer, 1975).

Two dominant wind regimes prevail in this area: marine wind from SE-E, and Tramontane from NW-W. Tramontane is observed most of the time (more than 2/3 of wind occurrences), and is characterised by strong winds with velocities reaching 30m/s. Marine wind is not very frequent but can generate storms from the SE, with high wave energy that have a significant impact on the coastal dynamics. The maximum wave height recorded during a SE storm event was about 10.8m, in front of Sete (Dec 1997).

The general circulation is southwestward and seems to be forced during wintertime by thermohaline processes (involving the formation of dense water) as well as for smaller scale phenomena induced by gusts of wind (such as up- and downwellings, oscillatory currents and internal waves at the inertial period).

River sediment supply

The main rivers in the Gulf of Lion are (from the south): the Tech, the Têt and the Agly in the Roussillon ; the Aude, the Orb, and the Hérault in the Languedoc, and the Rhône in the eastern part. 80% of the sediment supply in the Gulf of Lion, about 7.4×10^6 tons.yr^{-1}, is provided by the Rhône River (Pont et al., 2002), even though the total load was significantly reduced by human intervention during the last century. Small rivers of the Languedoc-Roussillon have a reduced contribution to the coastal system. The mean river sediment supply can reach thousands of tons of coarse sediment per year. However, most of this sediment amount is carried to the coast during extreme flash flood events (as observed in 1940 when an important spit breaching occurred at the Tech river mouth generating a 2 km southward relocation of the river outlet).

3.4.3 Geomorphology

The coastline of the Gulf of Lion can be divided in 6 areas from South to North:

- The rocky coast from Cap Cerbere to the Racou: this stretch of rocky coast is about 30 km long. A few pocket beaches can be observed, composed by sands (Collioure) or shingle (Banyuls, Cerbere)
- The low coast from the Racou until Cap Leucate: this linear coastline is formed by a sand ridge interrupted by several torrents and rivers, and extends till the cliff at Cap Leucate.
- From Leucate to the Hérault river outlet: the shoreline orientation becomes SSW-NNE. The coastal barrier usually has a low elevation, and is composed by sands. In this area, coastal wetlands tend to accumulate sediment. At the northern extremity, the Orb and Hérault river mouths interrupt the coastline.
- From Agde to Sète: this part of the coast is strongly eroding both westward and eastward of the Cap d'Agde volcanic rocks.
- From Sète to La grande Motte: in this area, the coastal barrier is not only composed of sands. Several beaches are covered by shingle, and others are composed mainly by this coarser sediment
- The Rhone Delta and the petite Camargue: here, beaches are composed of sands. A particular point of this area is the Espiguette Spit, that is one of the only few accreting points of the coast.

Characteristics of the beaches widely vary from South to North. They can be highly reflective in the southern part, while they are dissipative near Narbonne. The entire Gulf of Lion nearshore zone is characterised by the presence of one or several bars that can be either crescentic in the southern part or linear in the northern part of the Gulf.

Actual sediment dynamics

The main wave climate from SE-E yields a convergent dynamics in the Gulf of Lion. In the southern part, the shore is N-S oriented, and the main longshore drift is south to north, whereas in the northeastern part, ESE waves generate a westward longshore transport. The refraction processes around rocky points locally perturb this general scheme. However, this sediment transport pattern generates an accumulation zone in the centre of the Gulf (near Narbonne), while southern and northeastern parts are eroding. Most of the sediment budget studies have evidenced a lack of sediment that probably results on the offshore transport (Durand, 1999). Moreover, recent seismic studies (Certain, 2002) have shown that in some places, the sedimentary stock is very poor and limited to the volume of the nearshore bars.

With the exception of the central part of the Gulf, which is more or less stable, the entire Languedoc Roussillon coastline is progressively eroding. This natural process has been considerably increased by human interventions, diminishing fluvial sediment load, trapping the littoral drift and altering the dune system. In many places, beach erosion is strictly related to works undertaken in the vicinity to protect a tourism area and beach recreation activities.

3.5 The Aquitaine Coast of France

The Aquitaine coast is located in the gulf of Gascogne margin, which is characterised by a wide continental shelf (180 km in front of South Brittany) progressively decreasing in width towards the south (55 km in front of the Landes, and 2 km at the Capbreton canyon). Surface sediments are composed of sands and mud overlying a coarser substrate.

The Aquitaine coast can be divided in two main areas: the sandy coast from the Gironde to the Adour river mouths, and the rocky coast from the Adour river to the Spanish border. Several lagoons once interrupted this otherwise uniform coastline, of which the Arcachon lagoon is the only one still connected to the ocean through a morphologically active tidal inlet (Cayocca, 2001).

The sandy coast is a 230 km long coastal system oriented N-S. A large coastal lagoon, the Arcachon Basin, and small rivers interrupt this long strait of sandy beaches. The rocky coast of the Basque Region is 35 km long.

3.5.1 Sedimentology of the internal continental shelf

The northern part of the Aquitaine shelf, between the Gurp and Montalivet, is characterised by a thick sandy layer, overlying an Oligo-Miocene and Eocene rocky substrate (Cirac et al., 2000). This cover tends to become more homogenous towards the south, in front of the Cap Ferret.

Further south, in front of the Landes, the thickness of the mobile sediment is strongly associated with the incised paleo-valleys. In this area, sands are interbedded with coarse sand or shingle.

The median shelf is storm-dominated as shown by Cirac et al., 2000. It exhibits a thin layer (about 1-2m) of sandy sediments overlying coarse-grained deposits. This surface sand sheet is shaped into various bedforms: sand patches separated by depressions, large transverse dunes, and large wave ripples. In front of the Adour river inlet, shallow sediments are composed of medium sands (Augris *et al.,* 1999). Symmetric large ripples (1-2 m wavelength) can be observed until 45 m in water depth.

3.5.2 Recent geology

The recent geological history of the Aquitaine coast was driven by the Last Glacial Maximum (LGM) transgression (from approximately 18 000 years BP) which was very rapid. At 10 000 years BP, the sea-level was approximately 50m below present day sea level.

During the Holocene, at 6 000 years BP, the sea-level stabilised at the present highstand level. During that period, the long shore sediment transport progressively closed the small estuaries that were previously active, and coastal wetlands developed behind the dune field.

The present day geomorphology of the Aquitaine coast results primarily from eolian processes (Allard et al. 1974, Penin 1980, Bressolier et al. 1990, Tastet et al. 1993). During the Holocene, the coastline evolution was characterised by important dune invasion. These dune fields, covering a 4 to 8 km wide area, form a continuous system from the Gironde river mouth to the Adour River, i.e. along a 250 km long shoreline.

Three generation of transgressive dune fields have been identified:

- The oldest dunes (6 000-5 000 years BP) are parabolic dunes. They were built with sands from the coastal spits and coastal barriers progressively closing the small estuary mouths. They form isolated dune fields, as in La Teste or southward of Moliet in the Landes. Part of these dunes is fixed by vegetation.
- The second system is a barkhanoid dune field build around 2000 years BP. These dunes are very mobile and migrated onshore, generating a complex dune system over the parabolic dune field. These barkhan constructions yielded the closure of several coastal estuaries (Hourtin and Lacanau). The dune heights reach 70 m in the Gironde (Pedreros, 1999). Recent studies suggest that the formation of these systems began 500 years ago (Tastet, personal communication, in Pedreros, 1999).
- During the XIV century, the dune coastal system was fixed by human interventions (plantation of the pine forest). The elevation of this mobile dune system can reach 28m (at the Gurp) (Thauront, 1994).
- The present littoral prism was formed between the end of the XIXth century and the beginning of the XXth century (Buffault, 1942).
- South of the Adour, present day erosion at river mouth may be related to subsidence processes in this area (Alexandre et al. 2003).

3.5.3 Sediment dynamics

Morphology of the Aquitaine open sea beaches is characterised by the presence of sedimentary features such as the ridge and runnel systems in the intertidal area, and the subtidal crescentic bar systems.

On this N-S stretch of coast, wave climate from WNW prevails. This results in a dominant southward longshore sediment transport. However, in some places the dominant transport can be inverted as on the Medoc coastline (between the Pointe de Grave and Pointe de la Négade) south of the Gironde river inlet (Aubié and Tastet, 2000).

The southward longshore transport that generated the Cap Ferret spit is interrupted at the Arcachon lagoon entrance. Here, the long-term cyclic behaviour of sediment by-pass (more or less 80 years, Michel (1997)) permits the release of sediment to the southern coast. The process involved in this sediment by-pass is typical of the classical model of outer channel shifting and the breaching of the spit platform (FitzGerald et al., 2001).

A strong seasonal pattern is superimposed to this global evolution. It is characterised by the typical summer/winter cross-shore profile variations.

3.5.4 The "Pays Basque" coastline

This stretch of coast is 35 km long, limited by the Adour river mouth to the north and by the Bidassoa river mouth at the Spanish border. The coastline orientation N-S tends to become NNE-SSW near Anglet, and NE-SW from Guethary to the south of the area.

Geological settings

The tectonic history of the Basque region is related to the opening of the Gulf of Gascogne (Razin and Mulder, 2003). Sedimentary processes in this region began during the Trias by the rifting event generating volcanic productions. This rifting movement ended during the Jurassic-cretaceous. This was the beginning of a calm period characterised by the formation of a carbonated shelf. During the Albien, tectonic activity was re-activated with the rotation of the Iberian plate (30-40° anticlockwise) with respect to the European plate. This resulted in the formation of pull-apart basins where flyschs were deposited. It is the first period of important sedimentation characterised by black flyschs. The second period took place during the Conacien-Campanien.

During the Quaternary, alluvial sedimentation called "the Barthes" was deposited on the main alluvial plains (Sénix, Erromardie, Nivelle, Untxin and Bidassoa rivers) and composed of silts, gravels and pebbles.

Geomorphology

To the north, the coast located between the Adour River and the Saint Martin spit constitutes the southern extremity of the Landes dune system. It is composed of sandy beaches over 4-5 km. Southward of this area; the rocky coast extends until the Spanish border. Throughout this area cliffs are frequent and, for most of them, active at the present time.

- From the Saint Martin spit to le rocher de la Vierge, cliffs are almost vertical and can reach 45 m height.
- Southward to Guethary, cliffs dominate open sea beaches. Their heights can reach10-50m and their slope ranges from 45° to 90°. They are locally interrupted by coastal plain, as at the Uhabia river mouth.
- Between Guethary and Saint Jean de Luz, four pocket beaches called interrupt cliffs: Senix, Mayarko, Lafitenia and Erromardie, with small rivers in Senix and Erromardie bays. Toward the pointe Sainte Barde, small bays interrupt the 40m high cliffs. Then, to the south, the Bay of Saint Jean de Luz contains the Nivelle and Utxin river mouths.
- From Socoa to the bay of Loya, the cliff is called La Corniche. It is a 20-40m high system where mean slope ranges from 25 to 45°.
- Rocky outcrops and small islands developing 800m seaward of the surrounding coastline form the Pointe Sainte-Anne. The cliffs are sub-vertical and can be 30-40m high.
- The bay of Fontarabie is enclosed between the Pointe Sainte-Anne and the Cap du Figuier in Spain. The beach of Hendaye is an old spit fixed by human interventions.

4 Climate Change

4.1 Introduction to climate change and the greenhouse effect

Climate change is not a new phenomenon. The World's climate has always been changing. What is different now is that it is the belief of many scientists that the impacts of human forcing on climate change have become discernible in addition to the natural changes. The RESPONSE project is concerned with the presently expected changes that should be prepared for over the next 100 years. These changes, by necessity, are the human induced changes as natural changes (e.g. by solar or orbital effects or volcanic eruptions) either can not be predicted or are insignificant on timescales as short as a century, and so are not incorporated into climate-change model runs. Whether these changes are in fact due to natural or human induced causes makes little difference to the impacts that they will have and the necessary planning response.

On a day-to-day basis we receive frequent reports of apparently exceptional weather conditions that have recently been recorded. This is not a new phenomena, it is fundamental to the recording of meteorological information that natural variability will lead to the recording of extremes from time to time, so such events alone cannot be considered as evidence of climate change. Indeed, it has not yet been proven that frequencies of extreme events are changing, although the IPCC 2001 report says that it is "likely" (66-90% chance) that some (e.g. heavy precipitation events) are increasing in frequency. The recording of such weather events does improve our understanding of the climate that we should expect.

"Recent extreme weather events in Europe have highlighted the vulnerability of our society. More than 20,000 people are thought to have died during Europe's 2003 heat wave *with temperatures topping 40 °c (Nature, January 2004). Events such as these have emphasised that unless we start preparing now, the potential impacts on our economy and the environment will be severe".*

However, it is an acknowledged scientific fact that the composition of the atmosphere is changing significantly and that human activities that result in the emission of so-called greenhouse gases are implicated strongly. The greenhouse effect itself is a natural occurrence, which has operated for billions of years. Without the natural greenhouse effect the earth's temperature would be some 33°C cooler. Human activities have contributed significantly to the rising concentrations of greenhouse gases recorded in the atmosphere. Evidence from ice cores supplemented by direct measurements since the mid-1950s shows a steady rise in concentrations from the late 1700s changing to a rapid rise post 1950. Atmospheric concentrations of carbon dioxide (CO_2), the primary anthropogenic greenhouse gas, have risen from about 270ppm in pre-industrial times to over 360ppm now (Met Office 1999a).

The majority of scientific opinion now agrees that human influences on the global climate are beginning to become detectable above and beyond natural changes. This is particularly the case for near surface global mean temperature. Since the industrial revolution man has been changing the composition of the atmosphere, primarily by the burning of fossil fuels. Through the study of historical weather records and future projections with numerical models there is good evidence to suggest that human influenced climate change is taking place, and is likely to accelerate in the future.

In a speech given by the UK Prime Minister on 27 April 2004, Tony Blair announced " I see climate change as the greatest challenge facing Britain and the World in the 21st century". Sir David King, the UK Government's chief scientific adviser highlighted the importance of preventative action against the impacts of climate change, stating, "If we do not begin now, more substantial, more disruptive, and more expensive change will be needed later on."

4.2 Study of climate change and climate modelling

The most authoritative reports on the science of climate change are those produced by the Inter-governmental Panel on Climate Change (IPCC), which brings together the leading scientists from around the world. The World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP) set up the IPCC in 1988, with the objective of assessing the scientific, technical and socio-economic information relevant for the understanding of the risk of human-induced climate change. The IPCC does not carry out new research or monitor climate, but it bases its assessments on published and peer reviewed scientific technical literature.

Given the potential importance of regional climate changes for the development of national policies, and the impacts of extreme, climate-related weather events such as droughts, floods, and hurricanes on agriculture and human safety, how reliable are the projections of future change?

Computer-run, mathematical simulations or models of the atmosphere and ocean are the principal tool for predicting the response of the climate to increases in greenhouse gases. The most sophisticated of these, called general circulation models, or GCMs, express in mathematical form what is known of the processes that dictate the behavior of the atmosphere and the ocean. There are limits, however, to how much complexity can be handled by the computers on which the models are run.

Owing to this inherent complexity, neither climatological observations nor present climate models are sufficient to project how climate will change with certainty. The most authoritive approach is that adopted by the Intergovernmental Panel on Climate Change (IPCC), which is based on projections of the expected growth of greenhouse gases and the combined results of many GCMs.

Climate scenarios present coherent, systematic and internally consistent descriptions of changing climates. Scenarios are typically used as inputs into climate change vulnerability, impact or adaptation assessments. The climate change scenarios developed for use in UKCIP (united Kingdom Climate Impacts Programme) studies rely largely on two sets of GCM experiments completed by the Hadley Centre during 1995 and 1996. These experiments were undertaken using a coupled ocean-atmosphere GCM called HadCM2. This model has been extensively analysed and validated and represents one of the leading global climate models in the world. It features prominently in the Third Assessment Report of the IPCC (2001). (UKCIP, 2001).

Since no single climate change scenario can adequately capture the range of possible climate futures, four alternative climate scenarios for the UK are presented – Low, Medium-Low, Medium-High and High. For these four scenarios, the world warms globally by the 2020s by between 0.6°C and 1.4°C, a decadal rate of warming of between 0.11°C and 0.28°C per decade. For comparison, the observed rate of global warming for the past two decades has been about 0.14°C per decade. By the 2080s, the UKCIP98 scenarios generate a warming range of 1.1°C to 3.5°C. The global-mean sea-level changes and carbon dioxide concentrations associated with the four UKCIP98 scenarios similarly reflect a range of values that may be used in climate change impact assessments.

Scientists from the Hadley Centre for Climate Prediction and Research, part of the UK Met Office, recognise the limitations of global climate models resulting from the coarse resolution employed. Local climate change is influenced greatly by local features such as mountains, which are not well represented in GCMs. Regional climate models (RCMs) using a typical resolution of 50km, have been constructed for limited areas by the Hadley Centre, UK.

4.3 The Global Response to Climate Change

Climate change is a global issue that will affect us all. The IPCC 1992 report was fundamental to development of the UN Framework Convention on Climate Change (UNFCCC), which was agreed at the Earth Summit in Rio de Janeiro in 1992 and has been ratified by over 170 countries. Under the Convention, developed countries agreed to return their greenhouse gas emissions to 1990 levels by 2000.

With more information and the results of Global Climate Models (GCMs), the UNFCCC recognised that further cuts in global emissions were needed to prevent serious climatic impacts in future. Each year, the countries that ratified the Rio Convention held a Conference of Parties (COP). In 1997 the 3rd COP meeting was held in Kyoto, Japan. After reviewing the original targets of the Rio Convention and finding them to be too weak, the countries came up with new targets. The text of the Kyoto Protocol was adopted in Kyoto on 11 December 1997. The protocol sets out to reduce climate emissions of developed countries by some 5.2% below 1990 levels over the period 2008-2012. Additionally, the Kyoto Protocol introduced mechanisms to allow developed countries to buy emission reductions that have taken place in other countries and count them as their own. These mechanisms are Joint Implementation, Clean Development and Emissions Trading. Carbon sinks for the sequestering of CO^2, for example the proposed 'Kyoto Forests' are also allowed under the protocol.

The protocol was first agreed in 1997, but required the agreement of countries responsible for at least 55% of global emissions measured in 1990. The US, the world's largest emitter of greenhouse gases, withdrew from the protocol in 2001, saying it would gravely damage the US economy. The Bush administration also criticised the protocol for not forcing developing nations including India and China to cut emissions immediately. Australia, which has a large coal industry, has also refused to ratify Kyoto.

After the United States refused to ratify it, only Russia, responsible for 17% of emissions, could enable this threshold to be passed. In November 2004 Russian President Vladimir Putin signed the Kyoto protocol, finally allowing the protocol to be formally sanctioned. The Kyoto Protocol is to become a legally binding treaty on 16 February 2005. Countries that fail to meet the targets will face penalties and the prospect of having to make deeper cuts in future. "The entry into force of Kyoto is the biggest step forward in environmental politics and law we have ever seen," said Jennifer Morgan, director of the World Wide Fund for Nature (WWF) conservation group's climate change programme.

4.4 Climate Change Evidence and Predictions

4.4.1 Introduction

It must of course be recognised that the earth's climate has always been changing, and this is evidenced particularly well through geological records. There is evidence that there have been ice ages at time intervals of some 150 million years or so and such ice ages last for several million years. The period from 1.6 million years ago to 10,000 years ago has been referred to as the age of Ice Ages. This was a largely ice age period however there were several interglacials lasting about 20,000 years during that time. It is believed that changes in planetary and solar orbits cause ice ages, and it is inevitable that the Earth will eventually enter another ice age, but this is over a much longer timescale, thousands of years, whilst that of human influence is hundreds of years. There are a number of other known 'natural' reasons why our climate varies in addition to the impacts of the so-called enhanced greenhouse effect. These include volcanic activity (which can release dust) and fluctuations in the solar output from the sun. However, these effects are believed to be minor when compared with the anticipated impacts of anthropogenic global warming.

Although there has been much study of climate change, it is still not yet possible to relate individual extreme events, such as the heavy rainfall and subsequent major flooding events of autumn 2000, directly to anthropogenic changes to the atmospheric composition. However, consensus of expert opinion suggests that extreme events such as these will become more frequent and intense in a more energetic future climate as global temperatures rise.

4.4.2 Temperature records

Over the last three centuries mean temperature over central England rose by about 0.7º C, with 0.5º C of this rise in the last century, (Hulme and Jenkins, 1998). When considering global mean surface temperatures, there has been a warming of about 0.7º C since the end of the 19th century, and some 0.5°C since about 1970 (Met Office, 2000). The temperature statistics also show that four of the five warmest years in the 340-year long central England temperature record were in the 1990s and that 1999 was the joint warmest year ever. Globally, 1999 was significantly cooler than the record year of 1998, primarily due to temperature changes over the Pacific due to the cyclic El Nino/La Nina circulation. Many scientists believe that human influences on the climate through the emission of greenhouse gasses are at least in part responsible for the changes that have been seen.

4.4.3 Past Changes in effective rainfall

The IPCC WGI (Working Group 1: The physical basis of climate change) Third Assessment Report (2001) does not comment specifically on past changes in effective rainfall (rainfall minus evapotranspiration), although the report does conclude "it is very likely that precipitation has increased by 0.5 to 1% per decade in the 20th century over the Northern Hemisphere continents". Further, the report states, "it is likely that there has been a 2 to 4% increase in the frequency of heavy precipitation events". No specific reference is made to past changes in evapotranspiration although by inference the evident rise in temperature will have directly contributed to an increase in evapotranspiration.

4.4.4 Sea-level changes

The sea level occurring at any time is made up of the following primary components:

- Mean sea-level
- A tidal component due to gravitation effects of the sun, moon and planets
- Frictional effects on the propagation of the tidal wave and, occasionally, amplification due to bathymetric effects.
- A storm surge component due to meteorological effects and interactions between the above components.

When considering temporal changes in mean or extreme sea levels, it is important to also include changes in local land level due to tectonic or post-glacial geological influences.

While changes in mean sea-level should be of concern to coastal planners, it is the occurrence of extreme high water events that causes most problems with coastal flooding and erosion. The tidal forcing component is relatively fixed, but changes in mean sea-level can cause changes in propagation of the tidal wave. Changes to the frequency and intensity of storm surges may also occur under a warmer climate.

4.4.5 Changes in global mean sea-level

Changes in mean sea-level relative to land levels are clearly important for the design and management of coastal defences. Such changes may also impact on sediment transport and morphological change.

It is generally recognised that global mean sea-level has been rising for many years. Indeed, sea levels on the south coast of England were some 25m lower than present some 10,000 years ago, and rapidly rose to almost present levels about 5,000 years ago, since when there has been a slowing rate of rise. Whilst global sea-levels have been rising, local changes can often be dominated by movements of the land-mass. This includes recovery after loading during the last Ice Age, consolidation of soft materials, as ground water is removed, and tectonic movements etc. The Permanent Service for Mean Sea-level (PSMSL), which is operated from the Proudman Oceanographic Laboratory (POL), catalogue mean sea-level data from sites all over the world. The mean sea-level data are measured against a local reference datum, and so provide measures of sea level relative to the land.

Although most estimates available for future sea-level rise are globally based it is not expected that mean sea-level rise will be constant everywhere. This is principally because the heating up of the oceans will not be uniform. Geographical patterns of sea-level change due to differing thermal expansion have been estimated using GCMs at the Hadley Centre. The present generation of GCMs do not represent the melting of ice sheets and glaciers internally, and such calculations are undertaken off-line and added to the results.

5 Climate Change in the RESPONSE Coastal Study Areas

5.1 Central-South Coast of England, UK

5.1.1 Past Changes in effective rainfall

Climate change records from the south central coast of England at Pinhay (3km west of Lyme Regis, Dorset), the Ventnor Undercliff (Isle of Wight), and Bognor Regis (West Sussex) lend support to the conclusions of the IPCC. Analysis of rainfall records at Pinhay, indicates annual rainfall has increased by 75mm or 10% over the period 1868-1998. A much greater increase of 150mm or 20% in annual rainfall was recorded between 1839-2000 at Ventnor. Over the period from 1898 to 2000 the total annual rainfall data for Bognor Regis shows an increase of 65mm or 9% over this period. The data for Bognor also indicates the year 2000 to have been the second wettest in the record, with a total rainfall of 1,050mm, compared to 1099mm in 1960.

Strong links between antecedent rainfall, coastal landsliding and ground movement have been reported by Lee and Moore (1991), Ibsen and Brunsden (1994) and Brunsden and Chandler (1996). These studies demonstrate the significance of wet year sequences, which are probably of greater importance than increases in average conditions and the occurrence of extreme precipitation events, although the latter are clearly important as a trigger of ground movement and landslides. In this respect, it should be noted there are many preparatory and triggering factors other than climate effects that can contribute to coastal slope instability (Jones and Lee 1994; Hutchinson 1988; McInnes 2000).

The Ventnor record provides the best dataset available within the region from which the relationship between antecedent effective rainfall and landsliding can be illustrated (Lee, Moore & McInnes 1998). The relationship shows that some areas are highly susceptible to ground movement or landsliding due to antecedent effective rainfall with an expected annual probability of 0.9 (or every 1:1.1 years). Other areas are less sensitive to effective rainfall, with annual probabilities of less than 0.02 (1:50 years). Some areas have no recorded incidents of ground movement or landslide events over the period of climate records, and consequently are unlikely to be affected by antecedent effective rainfall events with annual probabilities greater than 0.05 (1:200 years). During extreme wet periods many more landslide systems may become active, as was witnessed in the winter of 1960/61, the highest on record.

5.1.2 Predicted Changes in Effective Rainfall

The UKCIP98 climate change scenarios give estimates of future potential change to mean precipitation and mean evapotranspiration for the southern England region. The maximum four-month antecedent effective rainfall (4AER) between September and January is significantly correlated with past ground movement and landslide events in the Ventnor Undercliff. Therefore, in the context of assessing the impacts of climate change on coastal stability the September to November and December to February periods used by UKCIP are the most relevant. The UKCIP98 estimates have been applied to the mean monthly effective rainfall at Ventnor for these two periods. It should be noted, however, UKCIP's arbitrary division into two winter periods and the use of mean data is not directly comparable with the maximum 4AER parameter.

The application of the UKCIP change scenarios to the Ventnor data does nevertheless give an indication of the likely magnitude of change to mean effective rainfall. The estimates indicate a 5-6% increase in mean monthly effective rainfall under the Low scenario and a 12- 25% increase for the High scenario. The greatest estimated change occurs in the December to February period. It is noted that these estimates are comparable with the historic trend of increasing effective rainfall at Pinhay and Ventnor.

The estimated increase in mean monthly effective rainfall will also result in an increase in the frequency or probability of events, assuming the distribution of events will be similar to the historic record. Potential increases in event frequency equally apply to the established relationship between effective rainfall and ground movement susceptibility.

The consequence of higher antecedent effective rainfall will lead to increases in coastal erosion, landsliding and re-activation of pre-existing landslide complexes. The UKCIP98 scenarios estimate an increase in mean effective rainfall. Other potential climate change effects, such as increases in the number and duration of wet year sequences, the intensity of rainfall events and sea-level rise are all likely to have additional significant effects on coastal instability.

5.1.3 Changes in tides due to global warming

In shallow coastal areas, increasing water depths due to changes in mean sea-level can modify the tidal dynamics. In this respect the whole of the UK continental shelf can be considered shallow. Only a limited amount of study of these phenomena has been undertaken. Flather and Williams (2000) reported on mathematical modelling of changes in tides around the whole of the UK due to a 50cm rise in mean sea-level. They used a tide and surge model of the continental shelf, with a resolution of about 12km. In a few areas, e.g. Severn Estuary, Morecambe Bay, German Bight and Skagerrak they found substantial increases (order of 10cm) in both tidal range and mean high water level (MHW). They concluded that for a rise in mean sea-level of 50cm, MHW will increase by 40 to 60cm on the north west European coast.

For the South Central England coast the tidal changes found by Flather and Williams were fairly minor. Mean tidal range was found to increase to the east of the Isle of Wight and decreases to the west, with changes less than 5cm. Similarly mean high water increases were less than 2cm.

5.1.4 Changes in Storm Surges due to Global Warming

There has been far less research on the frequency and magnitude of storm surges than there has been on changes in mean sea-level. Since there is considerable uncertainty over the influence of global warming on the frequency, magnitude and track alignment of depressions, there is much greater uncertainty over future changes in surges than for mean sea-level changes or tides. The most appropriate way to study the impacts of climate change on storm surges is to use predicted future climate data from the GCM experiments to drive storm surge models covering the northwest European shelf. Flather and Williams (2000) reported on earlier studies that had found small changes between control and $2xCO^2$ simulations, which were barely significant when natural variability was taken into account. They also described more detailed work still in progress using GCM output to drive a 12km grid size nested storm surge model. Preliminary results presented indicate small (<5cm) increases in the 1 in 50yr surge in the eastern English Channel, and even smaller decreases west of the Isle of Wight. However, the results were found to be very sensitive to the method of analysis adopted for extrapolating the extremes.

5.1.5 Changes in wind climate

Wind data relating to the South Central England coastline was obtained from the Met Office, for two locations offshore at Lyme Regis and Shoreham, to give an indication of the variability along the frontage. Daily mean and max wind data was output from the Hadley Centre Regional Climate Model for two scenarios, a 10 year control period, representing current atmospheric conditions, and the 2080's medium-high scenario. Daily mean wind data for a location off the south coast of England was also obtained from the more recent HADCM3 model via the University of East Anglia's LINK project. These sources provided the following data:

- Daily max wind data from Hadley RCM;
- Daily mean wind data from HADCM3; and
- Daily mean wind data from Hadley RCM.

The HADCM3 model is more recent, and hence based on improved understanding/techniques, than the Regional Climate Model. The output from this newer model was obtained for comparison purposes, to check that the RCM output was compatible with the more recent modeling.

The daily maximum data was used to assess extreme wind speeds in the South Central England area, whilst the primary use of the mean wind speed data was for the derivation of the wave climate in the region. The HADCM3 data obtained was not directional and as such could not be used itself for generation of wave data. Initial review of the RCM and HADCM3 mean daily wind data showed the two to be similar in terms of the relative differences between the control and future wind speeds.

5.1.6 Wave Climate changes

An assessment of wave climate changes around the UK for MAFF (now Defra) was undertaken by HR Wallingford between 1989 and 1991 (HR Wallingford, 1991). It was found that there appeared to be reasonably well-established evidence of increasing wave heights in the northeast Atlantic over the last 40 years. This evidence came from the work of a number of previous researchers that had analysed both instrumental and observational records, for example Bacon and Carter (1991). These studies found an increase in mean wave heights of the order of 1.5 to 2% per year. However, evaluations of wind data from a similar period showed no equivalent trend. This would suggest that the wave climate change is due to increased swell wave propagation into the area.

The relatively short periods of available wave data (40yr) for such assessments mean that differentiation of reliable estimates of long term trends from the high natural variability are not possible. By comparison, temperature records for trend analysis are available for about 200years. It follows that it cannot be proven whether trends in mean offshore wave climate may or may not continue to increase.

One of the main data locations that has been used in assessing offshore wave climate change is Seven Stones lightship, off Lands End. This information should therefore be directly applicable to waves that propagate up the English Channel towards the South

Central England region. HR Wallingford (1991) have undertaken a study of long term wave climate change. However, the data available for analysis was primarily based on recorded wind data typically available for around 20years. Wind data were taken from a broad range of sites around England and Wales. The analysis by Bacon and Carter of 'long term' recorded offshore wave data is commented on, but the 'best data set' used is that from the Seven Stones lightship, which only covers the period from 1962 to 1986. The Seven Stones data shows a 1% or 2cm per year rise in mean wave height. It should be noted that more recent studies appear to suggest that these trends may be spurious. The report also presented a ten year recorded wave data set off Perranporth, which showed a conflicting trend to that at Seven Stones. The report goes on to use the wind data to derive hindcast waves, and then to look at trends in potential alongshore drift rates. These were quite significant due to small changes in the dominant wave direction. However, it is noted that recent work by the Kaas and Andersen (2000) suggests that the 1%/yr rise in mean annual wave height may be more to do with inhomogeneous data than a real trend.

5.2 North-east Coast of England (North Yorkshire), UK

At present in the North Yorkshire region sea levels and mean annual temperatures are rising. Mean sea levels along the coast have risen at rates of between 1.5mm and 3.6mm per year over the last 80 years. Long-term temperature records show the 1990s were the warmest decade since the 19th Century. Evidence also suggests that winters in the 1990s were wetter than ever before, for example there was a threefold increase in the number of "wet" winter days at Whitby during the 1990s.

By the 2050s the agricultural growing season in the Vale of York will have increased by one month, and by the 2080s snowfall in coastal towns will be a thing of the past. Unusual climatic events such as droughts and floods could become the norm within a human lifetime.

The new climatic scenarios produced by the UK Climate Impacts Programme (UKCIP) suggest that North Yorkshire will be between 1°C and 2.5°C warmer by the 2050s and 1.5°C to 4°C warmer by the 2080s. The warming will occur throughout the year with the greatest rises in summer months of up to 4.5°C by the 2080s. Wetter winters and drier summers will accompany this warming. The UKCIP scenarios suggest an overall reduction in rainfall of up to 10%, a two-fold increase in warm summer days and hot summers every year rather than 1/100 year. Winters are expected to have 60% more rain than average, accompanied by less frost. Climatic change will lead to more depressions giving stronger winds and increased extreme wind speeds.

The coastal zone of North Yorkshire is particularly vulnerable to rising sea levels, changing patterns of tidal flooding and coastal erosion and the warming of seawaters.

The average UK sea level is 10cm higher than in 1900. The scenario for sea level rise in North Yorkshire for 2080 gives a rise above the 1900 level of between 15-75cms.The Defra recommended planning guidance for sea level rise is 4mm/year, north of Flamborough. The rising sea levels will lead to: -

- Coastal Squeeze- as intertidal habitats are lost to the sea as they are trapped between rising seawaters and hard coastal defences.
- Increased risk of tidal flooding including the overtopping, bypassing and breaching of coastal defences due to sea level rise and increased storminess.

- Growing concern regarding tidal flood risks potentially leading to "insurance blight" for businesses and households.
- Changing sea temperatures that will affect the type and quality of fish stocks. The area has already seen a reduction in cod stocks and an increase in red mullet due to warming waters.
- Storm surges are expected to increase in height and frequency.

North Yorkshires diverse natural environment supports, through the North York's Moors national Park and Heritage coast, a strong tourist industry and provides protection for important habitats and landscapes. The main impacts of climate change on the natural environment will be: -

- Northward movement of species that can migrate e.g. Black Grouse some gains in species will occur i.e. Speckled Wood Butterfly.
- Increased bracken invasion due to warming and drying of heathlands and moorland.
- Increased risk of fire on the moorland.

The North Yorkshire coast currently erodes at 9cm per year where the geology is predominantly shale and 28cm per year where the dominant geology is glacial drift. As climate changes, these rates will increase. Soils will be become susceptible to drying and cracking, which will enhance the erosion process. The North Yorkshire coast is also particularly susceptible to landslips and it is believed that these climate change could potentially accelerate this process.

In conclusion the key impacts for the region are related to increased temperatures all year round, wetter winters and drier summers. On the coast the likely impacts will be the loss of land due to increased erosion rates, loss of internationally important habitats, and increased tidal flooding. However increasing temperatures may lead to increased tourism and the regeneration of the coastal zone, new habitats will be created and new fisheries as species migrate northwards.

5.3 Central-East Coast of Italy (Regione Marche)

5.3.1 Climatic change and coastal protection

The Po River delta, which developed out of the Adriatic Sea, is surrounded by the Venice lagoon in the North and the sandy coastal zone of the Romagna (Ravenna) with the Po plain to the rear, at the South up to the promontory of Gabicce, where the Apennines Mountains meet the Adriatic Sea.

The Po River delta covers an area of 73,000 hectares, of which 60,000 is reclaimed land and the remainder is brackish lagoons, with dams or open foreshores and emerging sandy banks. In ancient times, the natural river system was subject to periodical ruinous floods, causing serious problems to early settlements on the Po floodplain. Periodical breaches, caused by floods during periods of bad weather, modified the hydrology and morphology of the Po floodplain and the configuration of the Po delta.

The dynamic advancement of the Po river delta is quite simple. Sediments are transported by the river to the sea, where they are reworked by wave action to form sand bars both at the front and at the sides of the river mouths. If the supply of sediment is great and constant, the bars tend to grow and become fixed by marsh vegetation and then join the mainland. This forms an area of lagoons and small pockets of water behind the delta system. Such a process can be cyclical.

From 1600 until the present day the coastline of the Adriatic Sea, around the Po delta, has been advancing seaward. The rate of advancement slowed in the early 20th Century. Historical sources show that prior to 1600 A.D there were some changes – both natural and anthropogenic – in the river and delta system. An important event - the "breach of Ficarolo" - occurred in the twelfth century (1125) near Ferrara in the left bank of the Po, causing the main riverbed to move northward with its abundant sediment yield. By 1500, the southern Venetian Lagoon was on the verge of being filled in, jeopardising port activity. To avoid this, in 1600 the Venetian Republic diverted the Po to the south by constructing the 7 km long canal "Taglio di Porto Viro". After its construction, the Po Delta began to take on its present configuration with an accretion velocity much greater than the previous one toward the south.

To explain the different rate of advancement in different periods it is necessary consider the climatic changes. At the end of the last century, Brückner (1890) published a study identifying a sequence of climatic fluctuations, based on a review of meteorological data, which caused similar results in other parts of the Northern Hemisphere, during the same period. Using geological, geomorphological, glaciological, palaeobotanical, archaeological and historical investigations, it has been possible to reconstruct the sequence of climatic variations with a high level of accuracy for this period.

The identified climatic fluctuations of some hundred years are cold/wet periods alternated with warm/dry periods. These cold/wet periods alternating with warm/dry periods have been well identified by dendrochronological curves. Within these "large scale" periods, are small climatic fluctuations of 10-35 year periods of cold/wet and warm/dry cycles, which continue up to the present day. There is also a notable correspondence between the major development of the Po delta system and the cold/wet weather conditions. It is particularly evident for the Ficarolo breach (XII Century) due to a bad climatic period. Another example is the large advancement of the Po delta building from 1600 up to 1820 during the "Little Ice Age".

Between the end of the 1970s and the present day the warm/dry weather and lack of rain, floods and storms indicates a calm situation along the coast after the precedent cold/wet period. The difference between the present and the past situation is that the last critical period; around 20 years, produced a regression of the shoreline instead of advancement. This suggests that the violence of storm waves caused the natural nourishment of the sediment yield by the river. This change in the trend may be due to human activity on the coastal zone (artificial rash removals of river bed material, destruction of sand dunes, the subsidence by the artificial extractions of fluids, etc.), which diminished the sediment yield to the sea allowing storm attack during the cold/wet weather conditions.

It is interesting to note that the climatic changes noted by Brückner and other scientists in Europe are present, in the same periods, everywhere in the world. For example, the coincidence of events in the same periods in Europe and China is evident, using dendrocronology. However, according to the available data, the climatic zones can shift 8º-10º latitude to the north and south, due to an enlargement of the equatorial area, during the warmer periods and to an enlargement of the ice caps during the colder periods. This means that the environmental effect of the same climatic phases differs according to latitude.

The effect of climatic changes on the evolution of the natural environment is of as much importance today as in the past. However, one cannot simply state that cold/wet climate induces a greater precipitation with a greater sediment supply to the sea and therefore shoreline advancement. In fact, these weather conditions imply an even greater frequency of strong storms, which may cause a shoreline regression. In a period of cold/wet weather the coastal equilibrium is controlled by the relationship between the large sediment supply from rivers and the frequency of sever storms. If the sediment supply is greater than the removal of sediments caused by the wave action, the beach becomes wider and vice versa. In a period of warm and dry weather, the sediment supply to the sea is less and storms are infrequent. Therefore, the tendency is for the coastline to move around an equilibrium point or move slightly seawards. Thus, cold and wet weather conditions are central to coastal evolution. The reason for the advancement of the coastal zone between 1600 up until the last century is that the fluvial sediment input, connected with the "Little Ice Age", was much greater than the output caused by the attack of the waves in storm conditions.

The smaller climatic variations, with a 10-35 year periodicity, have led to a progressive reduction in the coastline advancement, since the beginning of the present century and reaching its full extent during the 1950s, when the sediment supply, typical of cold periods, became inadequate because of human activity in the coastal zone and on the areas behind. In such an environment, with a lack of sediment supply from the rivers, wave action becomes the controlling factor causing erosion.

If it is possible to predict bad weather conditions, it becomes possible to undertake preventive actions on the coastal zone, which have, as yet, never been made.

5.3.2 climatic changes at different time intervals

An accurate study of environmental impacts on sea levels and shoreline changes due to global warming requires a detailed investigation and interpretation of the events that have occurred during the past 20,000 years. This time interval corresponds to two significant climatic global changes: the last Wurmian glaciation during the Upper Pleistocene and the warming during the Holocene. The general increase of temperatures continues today and is global interest. The rate of temperature increase, due to CO_2 and green houses gases is expected to become very high in the next century. This increase of temperature will lead to a dangerous increase in sea levels.

In conclusion, it is known that the general trend for the Holocene is towards a general climatic improvement if we compare it with the last glacial stage (Wurm). Inside this general trend during the Holocene some secondary climatic changes (some hundred years length) can be identified which have strongly influenced the environmental conditions. Within these large-scale climatic cycles are shorter periods (10-30 years) cold/wet weather alternating with warm/dry periods, known as “Bruckner cycles”. The effect of climatic change on the natural environment is of primary importance. These phenomena are not regional, but of planetary interest and they continue to develop to produce a strong influence on the natural environment everywhere in the world.

The final result of this superimposition of different periodicities of climatic fluctuations is that, considering the general trend of the temperature increasing during the last 10,000 years, the most recent warm period of 100 years time scale is warmer than the precedent period. On the other hand the most recent cold period is less cold if compared with the precedent cold periods. This produces different effects even during the repetition of the same type of cold or warm periods. The same effect of gradual increasing of warm characters is evident even during the shorter times fluctuations (Bruckner cycles) 10-35 years frequency. The distribution of climatic fluctuations at different time scales is important not only to understand the modality of climatic change, but also to consider how the effect on coastal zone evolution may be different.

The mechanism of climatic changes in 3 different time periodicities (n x 1000 years, n x 100 years, n x 10 years) is clear, but the repetition of the sequences is irregular, both in intensity and in time. This variability is very evident in the shortest time intervals (n x 10 years). To understand this event it is necessary to consider the interference of the effects of the NAO (North Atlantic Oscillation) with the effects of the Southern Oscillation El Nino, (ENSO). The NAO index is defined as the normalised difference of surface air pressure from N to S at Lisbon (Portugal) and Stykkysholmur (Iceland). The SO (Southern Oscillation) from E to W is defined as a perennial but irregular air pressure oscillation in the tropical area of the Pacific Ocean. This oscillation is caused by a displacement of air mass between the Indonesian equatorial low-pressure cell and the South Pacific Tropical high pressure cell. The warm phase (El Nino) occurs at irregular intervals of several years developing in one-two years. Very long time El Nino phases were recorded in 1911-14, 1939-42 and 1989-94. During these warm phases there is an increase of temperature, a decrease in winds and a reduction in rainfall in the eastern pacific area. The consequence is a monsoon season marked by aridity in Australia, Indonesia, India and eastern Africa.

The interference and the superimposition of the climatic cycles at different times scale produces a general regression of the shoreline on long time scales (n x 1000 years) but with oscillations of advancing or retreating of the shoreline during the climatic cycles with (n x 100 years) more modest duration.

5.3.3 <u>Recent climatic variations</u>

In addition to long-term climatic variations on a geological timescale, there is evidence of recent short-term climatic fluctuations. At the end of the last century, Brukner (1890) published a study pointing out a sequence of climatic fluctuations based on the comparison of meteorological data, which coincided with similar results in other parts of the Northern Hemisphere. Using geological, geomorphological. glaciological, palaeobotanical, archaeological and historical investigations, it has been possible to reconstruct the sequence of climatic variations with accuracy for the historical times.

For the last 3,000 years, five cold and humid periods have been identified, which had a great impact on the Mediterranean basin. The periods were: 1400-1300 B.C.: 900-300 B.C.; 400-750 A.D.; 1150-1300 A.D.; 1550-1850 A.D. These cold/wet periods were alternated with warm/dry periods and have been identified by dendrochronological curves. Within these “large scale” periods, small climatic fluctuations of 10-35 years continued with cold/wet and warm/dry cycles up to the present day. The influence of these climatic changes on the environmental evolutionary trend is obvious considering the variations of the shoreline along the Adriatic coastal zone.

5.4 French Coastal Study Sites

5.4.1 Regional trends for temperatures and rainfall

Annual rainfall in France has been showing an increasing general trend since 1900. However, summer rainfall has been general decreasing over the same period.

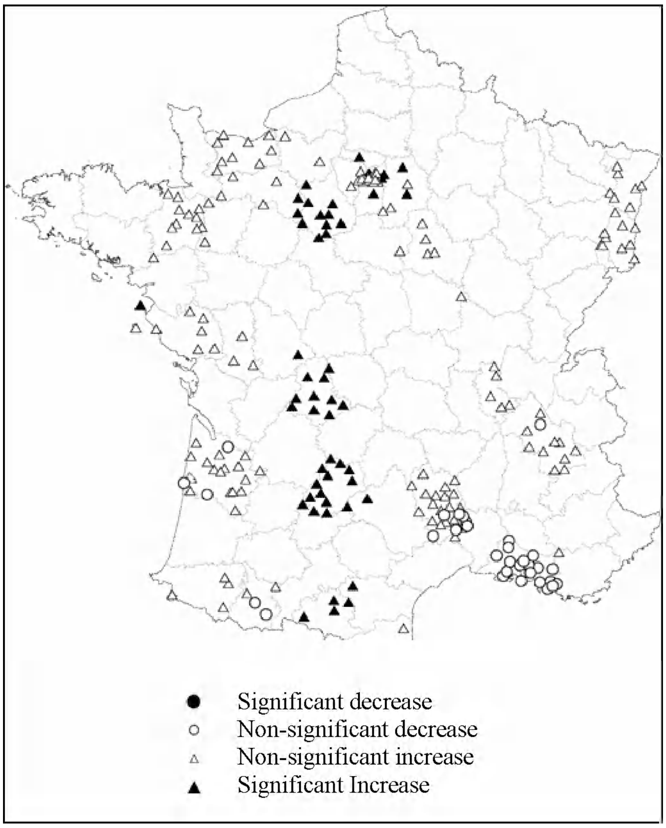

Figure 5.1 Annual rainfall trends in France since 1900

Numerical modelling undertaken by Météo France, based on the hypothesis of the doubling of carbon dioxide concentration in the atmosphere, evaluated probable changes at a regional scale for temperatures and rainfall on a seasonal time scale. Using the most probable scenario of carbon dioxide emissions, the point when carbon dioxide levels will be doubled is anticipated to be around 2060.

The results of this study are summarised, for the Response French Coastal Study Areas in the following tables:

Aquitainee

Temperatures Change (°C)				Rainfall Change (mm/d)			
Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
+ 1 to + 2	+ 1 to +3	+ 2 to +3	+ 2 to +3	+ 1 to + 2	-0,2 to +0,6	-0,2 to + 0,2	-2,0 to -0,6

Table 1 - Temperatures and rainfall changes considering carbon dioxide concentration doubling

Languedoc - Roussillon

Temperatures Change (°C)				Rainfall Changes(mm/d)			
Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
+ 2 to + 4	+ 2 to +3	+ 2 to +3	+ 2 to +4	+0,2 to +0,6	-0,6 to +0,0	-0,2 to + 0,2	-0,6 to +0,6

Table 2 - Temperatures and rainfall changes considering carbon dioxide concentration doubling

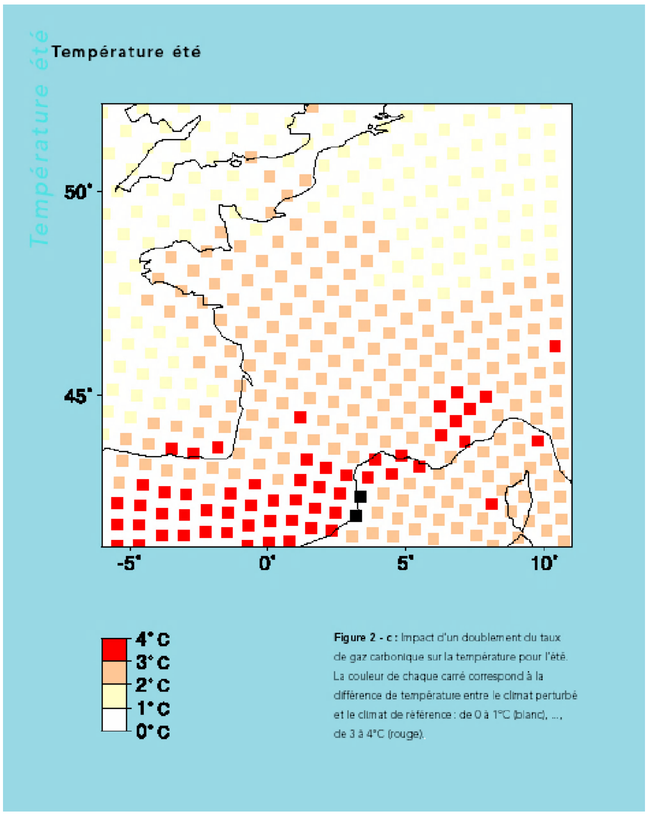

Figure 5.2 Example of temperature change over France during summer based on the hypothesis of carbon dioxide concentration doubling. (From: Impacts potentiels du changement climatique en France au XXIe siècle)

5.4.2 <u>Sea level rise</u>

Global warming due to increasing emissions of green-house gases will create a global sea level rise. Measurements recorded during the 20th century demonstrate an average uplift of approximately 0.7 mm/year, and therefore a total rise of around 0.07 m. Global models are predicting for the 21st century an increase from 0.1m to 0.9 m depending the chosen emission scenario. The most probable scenarios predict a rise of 0.25 to 0.35 cm by 2100. It should be noted that the worse case scenario predicts a rise of 0.25 m by 2050.

5.4.3 <u>Trends for storms, wave heights and storm surges in France</u>

Statistical studies considering storm events do not show any significant trends from 1950 to the present day in terms of the number of events. The same studies considering maximum wind speeds during storms also show no significant trends.

However, these measurements may have been distorted by technological changes in measuring devices during the 1970s.

Observations of storms did detect changes in levels of swell. Maximum wave height measurements during storms show an increase of around 1% per year (this is corresponding of a 2 to 3 cm increase of the annual average wave height).

Increasing wave heights and sea level rise should have some implication on storm surge heights and storm frequency. This change will be particularly apparent in estuaries. However, there is no validated quantitative evaluation of changes in wave heights that may have occurred during the 21st century.

6 Potential Impacts of Climate Change on Risk

6.1 Management

Understanding the risk management framework and the broader social and political context provides a basis for speculating about how climate change and sea-level rise will impact upon the European coastline over the next 100 years or so. It should be stressed that because of the nature of social systems, there is probably more uncertainty as to how society and politicians will respond to these changes than their impact on coastal processes.

6.2 Increased Demand for Coast Defence Funds

Over the next 100 years, climate change and sea-level rise will result in an increase in the probability of damaging events. However, it is uncertain as to how the operating authorities will be able to manage the increased risks. To maintain the current standards of coastal protection will require considerable investment in defence improvements and maintenance. The risk management framework will need to adjust to increased competition for financial resources.

One possible consequence is that defences that are currently protecting marginally economic and clearly uneconomic sites will either be abandoned or maintained at a lower standard of protection. It is possible that there will be modifications to what are considered to be acceptable risks and suitable standards of protection. It should be appreciated, however, that society has become less risk tolerant. It follows that there may be a need to improve the standards of protection in high-risk urban areas to reflect these trends. This would lead to increased polarisation in the exposure to risk experienced by individuals in built up and rural areas.

6.3 Habitat Losses

Climate change and sea-level rise is likely to generate additional pressures on a variety of coastal zone uses, from tourism and amenity uses, marine aggregate extraction (e.g. for beach feeding programmes), port and harbour operations to nature conservation and the protection of historical sites and monuments.

However, it should be noted that a changing climate presents opportunities as well as risks. Though some habitats will most likely be lost in a particular area due to climate change, other habitats may thrive under the new climatic conditions.

6.4 Increased Competition for Coastal Resources

These and other pressures will be manifest in heightened competition between different interest groups over how best to manage coastal resources. As society's values and political attitudes towards social welfare change, so the rationale behind the public subsidy of private property may be challenged. It seems likely that the debate over the true costs (financial and environmental) and benefits of coastal defence to society will develop and intensify. This could lead to modifications to the risk management framework, especially greater emphasis on environmental and social costs in the project appraisal procedures.

The need to reconcile competing demands on limited resources will probably lead to the risk management framework becoming more complex, with a greater need for formal consents and consultation, with more formal public participation in the decision making process. There may be greater opportunity of trade-offs and bargaining. Further delays and increased expenditure on plan development and implementation are, perhaps, inevitable. The ever-increasing complexity of the framework will reinforce the institutional barriers to innovative solutions to coastal defence issues, favouring the status quo.

It is clear that both the physical environment (increased hazard) and cultural environment (changing attitudes and priorities etc.) will be sensitive to the effects of climate change and sea-level rise. The legislative and administrative framework, however, is likely to be relatively insensitive, being the product of gradual evolution rather than radical change. Thus, there will be a tendency to attempt to address climate change and sea-level rise within the existing legislative and administrative framework.

6.5 Co-ordinated Decision Making

There is a need to consider the possible compoundment of risk due to continued management of the coastline, i.e. raising flood defences, toe protection measures. Clearly this is idealist, but the point should be made that defences do fail, and the stresses to be placed on defences in the future will clearly be greater given climate change and sea-level rise. This means that the chance of catastrophic failures will be increased, especially if funding and engineering designs are not factored up to accommodate these stresses. At the same time we have increasing pressure for development in hazardous places which often proceeds where defences are in place giving a false sense of security - the risk remains; consequently the potential losses are also increasing. Decisions by planners, developers and the engineering fraternity are often taken in isolation, when clearly there is a need to consider these 'holistic' consequences at an early stage of decision-making (pro-active) rather than dealing with the disasters and clear-up that may well have been avoided.

6.6 Summary

There can no longer be any doubt that our climate is changing. Whether this change is caused by anthropogenic or natural factors is not the issue – the impacts of a changing climate are already being felt globally. The IPCC (2001) states, "Globally it is very likely that the 1990s was the warmest decade, and 1998 the warmest year, in the instrumental record (1861-2000)". The IPCC (2001) also states, "There are preliminary indications that some human systems have been affected by recent increases in floods and droughts. The rising socio-economic costs related to weather damage and to regional variations in climate suggest increasing vulnerability to climate change".

Extreme weather events are a major source of climatic-related impacts and it is predicted that climate change will increase the frequency of severe weather events. Given that there exist strong links between weather patterns and coastal processes, there are clear implications associated with our current knowledge of climate change. Risks associated with climate change are increasing and will continue to increase according to most global climate change scenarios.

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