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Past and Future Changes in Extreme Sea Levels and Waves

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11.1 Introduction

Coastal impacts of sea-level change can result from individual extreme sea-level and wave events, or long-term fluctuations in mean sea level, or most likely from a combination of processes. An example of a combined impact is the damage caused by Hurricane Katrina at New Orleans, which resulted in unprecedented storm-surge levels and failure of coastal defenses. This was compounded by the rate of local mean sea-level rise relative to the land level of the Mississippi Delta of several times the global average, as occurs naturally in all major deltas, together with anthropogenic changes to the delta wetlands. On much longer timescales, extremes and mean-sea-level change are both major factors in determining coastal evolution including the development of coastal ecosystems.

It will be seen below that, although it is difficult to determine how mean sea level has changed in the past and will change in the future and to determine the reasons for change (the main topics of this volume), the very nature of extreme events makes estimation of future extreme levels a more difficult task. However, for many practical purposes, the study of extremes is far more important than that of mean sea level alone. Extremes often result in loss of life and great damage to infrastructure and the environment, and knowledge of their historical, and potential future, amplitudes and frequencies determines the scale of resources required for adaptation and coastal protection (see Figure 11.1).

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Figure 11.1 The flooding at Sea Palling, Norfolk, UK, due to the storm surge of January 31–February 1, 1953. This storm surge led to major investment in coastal protection along the east coast of the UK and in the Netherlands. (Picture courtesy of Eastern Daily Press.)

This chapter discusses changes in extreme sea levels and waves and is divided into four parts. First, we review changes in extreme sea levels and waves in the recent past. Then we discuss changes in the atmospheric storm events that drive extreme sea-level changes. There follows a review of recent advances in the modeling of future extreme events. (The reader is referred to the list of abbreviations and acronyms at the front of the book for models mentioned in the text.) The European shelf, Bay of Bengal and Australian regions have been investigated in greater detail than most other areas, and are selected for this section as special case studies of future change. Finally, we highlight issues that we believe need to be addressed in order to further understand the changes of the past and better predict those of the future.

11.2 Evidence for Changes in Extreme Sea Levels and Waves in the Recent Past

11.2.1 Past Changes in Extreme Sea Levels

As extreme events often result in flooding and loss of life, an important question is whether their amplitudes and frequencies are changing, and if the levels of extreme high waters are changing in a significantly different way to mean sea

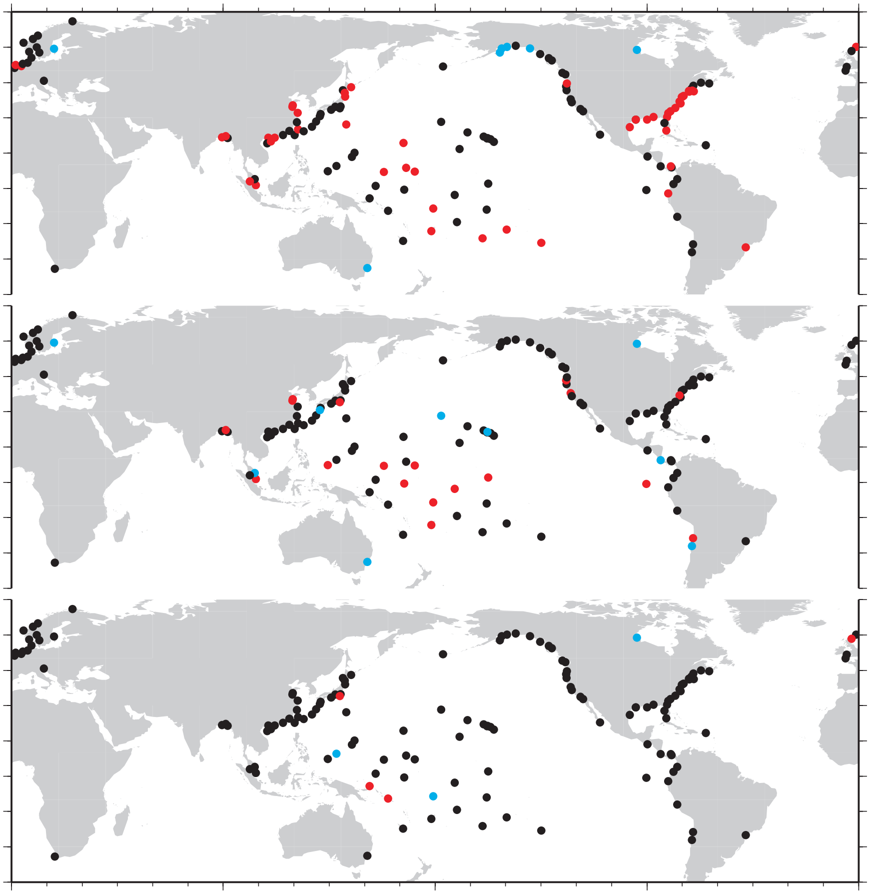

Figure 11.2 Distribution of tide-gauge stations selected for time-series analysis. Top: stations with observed trends in 99th percentile since 1975 significantly different from zero are shown in red (positive trend) or blue (negative trend) while others are shown in black. Middle: as before but with 99th percentile time series reduced to medians. Bottom: as before but with 99th percentile time series reduced to medians and with the tidal contributions to the percentiles removed. (From Woodworth and Blackman 2004. © American Meteorological Society.)

levels. The only study which has attempted a quasi-global investigation of this topic is that of Woodworth and Blackman (2004), who studied data from 141 stations, and concluded that there is indeed evidence for an increase in extreme high water levels worldwide since 1975, as reported frequently in the press. However, in most cases, the secular changes and the interannual variability in the extremes were found to be similar to those in mean sea level (i.e. compare top and middle maps of Figure 11.2). Zhang et al. (1997a, 2000) obtained a similar conclusion with regard to the rate of rise in the level of extremes and mean sea level along the US east coast, and considered that there had been no discernible long-term secular trend in storm-surge activity or severity during the past century.

A number of other studies of sea-level extremes at particular locations are available, although as they are for different epochs and use different methods, it is difficult to arrive at general conclusions. One of the longest data sets studied is that from Liverpool, UK (1768 onwards), from which Woodworth and Blackman (2002) observed annual maximum surge at high water to have been larger in the late-18th, late-19th, and late-20th centuries than for most of the 20th century, qualitatively consistent with knowledge of the regional variation in storminess.

(We use here the terms “surge” and “nontidal variation” almost interchangeably as the meteorologically-induced storm surge is responsible for much of the nontidal variability at mid and high latitudes). The Liverpool record is one of the few time series of extremes which is of comparable length to the corresponding mean-sea-level record (Woodworth 1999). Vassie, reported in Pugh and Maul (1999), concluded that there was no discernible trend over the last century in the statistics of nontidal sea-level variability around the UK above the considerable natural sea-level variability on decadal timescales. Other European studies include those of Bouligand and Pirazzoli (1999) and Pirazzoli (2000), who detected evidence for a slight decrease in the main factors contributing to surge development on the French Atlantic coast in the last half century. On the other hand, Pirazzoli et al. (2006) concluded that the medium-term (recent decades) coastal flood risk from high waters had increased on the English side of the Channel and less so on the French coast. Aráujo et al. (2002) computed trends in nontidal variability at six Channel sites. At Brest and Newlyn (120 and 84 years of data respectively) small but significant trends in extreme sea level were found. However, the authors cautioned that part of the observed trends may be due to changes in technology from float to bubbler pressure gauges.

In the Mediterranean, Raicich (2003) found no evidence for a trend in weak and moderate surges at Trieste over the period 1939–2001, while the frequency of both strong positive and negative surges decreased (see also Trigo and Davies 2002). Pirazzoli and Tomasin (2002) and Lionello (2005) determined that although Venice had experienced floods in the historic past, the frequency and intensity of floods had increased in the recent past, with positive trends in extreme surges due to changes in regional climate largely responsible for the observed changes. Ullmann et al. (2007) concluded that maximum annual sea levels had risen twice as fast as mean sea level during the 20th century (4 rather than 2 mm/year) in the Camargue (Rhone Delta) region of southern France, largely due to changes in the wind field in recent decades.

Bromirski et al. (2003) undertook a study of nontidal residuals at San Francisco since 1858, concluding that winter residuals had exhibited a significant increasing trend since about 1950. In one of the few studies from South America, D’Onofrio et al. (1999, 2008) observed a trend of extreme levels at Buenos Aires since 1905 similar to that in mean sea level. Church et al. (2006) provided examples of changes in extremes at a number of Australian locations over extended periods, and showed that high waters of the two longest records (Fort Denison in Sydney, New South Wales, and Fremantle, Western Australia) have risen during the 20th century faster than the median sea level.

Differences between observed sea levels and those expected from the tide can arise from a wide range of ocean processes in addition to storm surges (Pugh 1987). Firing and Merrifield (2004) studied extreme sea levels due to ocean eddy activity rather than storm surges. They found long-term increases in the number and height of extreme daily mean sea-level values at Honolulu, if levels were measured relative to a fixed datum (the highest ever value being due to an anti-cyclonic eddy system in 2003) but no evidence for an increase relative to the underlying upward trend in mean sea level.

Altogether, we conclude that there is little evidence for extreme sea levels changing over an extended period by amounts significantly different to mean sea level at most locations. This is an important finding with regard to coastal impact studies implying that the major uncertainties in the future projection of extremes are likely equivalent to those in mean sea level, at least over the next few decades. However, further into the future, changes in atmospheric storminess may also start to become important at some locations (see section 11.3 and Lowe and Gregory 2005).

Observational Considerations

Two technical aspects of the study of past extremes must be mentioned. The first is that research into extremes is far more difficult than into mean sea-level changes, owing to problems of access to raw sea-level data (e.g. hourly values). Most countries now make their data freely available for research, although the multiplicity of data formats and sampling frequencies means that a major effort in data processing is often required before scientific analysis can begin. Gradually, these difficulties are being addressed through international programs such as the Global Sea Level Observing System (GLOSS) and the Global Climate Observing System (GCOS). However, some countries continue to restrict access to raw data for reasons of cost recovery or national security. The result is a lack of century-timescale time series for analysis, especially in the Southern Hemisphere.

The second technical aspect is related to the clear identification of an extreme sea level. As high a recording frequency as possible is clearly required for the proper identification of an extreme (e.g. 6 or 15 min rather than the conventional hourly sampling) but in practice one often does not record the true extreme value due to the regular sampling. In addition, unusually high levels are sometimes outside the instrumental recording range (e.g. as for acoustic gauges during Hurricane Katrina, New Orleans, in 2005). There are also concerns about degradation of data quality at the limits of the range. In some circumstances, simple human errors can enter the historical data set and distort an extreme analysis (e.g. an error in handwritten tabulations of observed high waters). The study of the 99th or 99.9th percentile water-level values, instead of the high waters themselves (or 100th percentiles), can guard against errors in the recording of extremes to some extent (Woodworth and Blackman 2004; von Storch and Reichardt 1997).

A particular problem in defining an extreme arises when one wishes to investigate data from before the era of the automatic tide gauge. For study of the very longest records, extending back to the 18th or early 19th centuries, in which high waters were recorded rather than the full tidal curve, one is forced to use parameters such as annual maximum high water, annual maximum surge at high water, or surge at annual maximum high water, rather than annual maximum surge, which is clearly of greatest interest for climate research. Woodworth and Blackman (2002) discussed the relative merits of each parameter.

An important point with regard to extremes relates to the role of the tide and the fact that, in most regions with predominantly semi-diurnal tide, there will be perigean (quasi 4.5-year) variations in high- and low-water levels which have a similar period to El Niño variability. This may have contributed to confusion as to the reasons for flooding in some parts of the world. Locations where anecdotal evidence for sea-level rise, based on evidence of extreme sea levels and associated flooding, is particularly strong include low-lying Pacific islands such as Tuvalu (Hunter 2002, 2004; Woodworth and Blackman 2004). However, it is difficult to separate reasons for extremes and flooding (e.g. tide, surge, El Niño, global sea-level rise) simply from anecdotal evidence and short observational records. Of course, perigean spring tides in combination with storm surges are well known to often result in flooding and erosion in other parts of the world (e.g. northeast US coast; Wood 1978). At some locations (e.g. Hamburg), there is evidence that storm surges have been elevated by human-made water works, such as changes made to coastal defenses. This must be considered when interpreting historical records and simulations of past surge changes (von Storch and Woth 2008).

Modeling Considerations

The success of operational tide-surge modeling in many regions (Flather 2000), and the confidence acquired in the ability of models to describe observed surge events, has led to the use of barotropic models (two-dimensional depth-averaged models) for construction of long time series of historic water levels. The main requirements in such work are adequate spatial model resolution, accurate bathymetry, and reliable meteorological data sets of high spatial and temporal resolution. Examples of such work are by Flather et al. (1998), Langenberg et al. (1999), and Weisse and Plüß (2006), who undertook separate simulations of almost half a century of water levels for the North Sea area. Wakelin et al. (2003) and Tsimplis et al. (2005) used the Flather data set to investigate the correlation of the North Atlantic Oscillation (NAO) with mean-sea-level variability around the North Sea, while Woodworth et al. (2006) subsequently demonstrated a similar (if not identical) spatial dependence of correlations with the NAO of high and low waters and mean sea level. Langenberg et al. (1999) showed that positive trends in high percentiles (high waters) of winter sea levels during 1955–93 were largest in the German Bight, with only small trends along the Dutch and English coasts, while subtraction of winter mean values considerably reduced the larger trends (i.e. the range of short-term variations remained almost unchanged with time). Woodworth et al. (2006) confirmed the spatial pattern of trends in winter means and high and low waters around the North Sea, and the relationships between them, and pointed to the importance of the epoch studied (i.e. to periods of different NAO phase).

Bernier and Thompson (2006) modeled 40 years of tides and surges in the northwest Atlantic (using an approach similar to that of Flather et al. 1998) and observed a slight reduction in extreme sea levels between 1960 and 1999 due to a reduction in extreme storm surges, including a reduced contribution from the inverse barometer response of air-pressure minima. They combined their 40 years of modeled surges with data retrieved from short tide-gauge records to reconstruct total sea levels and map the spatial dependence of extreme-sea-level return periods (Bernier et al. 2007). They introduced seasonal dependence into their return-period reconstructions, and downscaled their results to the urban/ecosystem level using Digital Elevation Models to provide maps of return periods of coastal inundation under current conditions and under projected scenarios of sea-level rise and changing meteorology for the next century. These maps have the distinct advantage of displaying the current flooding risks and the plausible impacts of climate change in terms of inundated landmarks as opposed to elevation above arbitrary datums such as chart datum and mean sea level. Several groups are employing global barotropic models in order to investigate time series and return periods of storm surges worldwide; in such cases the requirements given above remain, notably the need for high-resolution meteorological data and bathymetry. The adequacy for using a barotropic model in such studies, compared with a full three-dimensional model, has been demonstrated by Kauker and Langenberg (2000).

Several further technical points can be mentioned here. One is that the Waves and Storms in the North Atlantic (WASA) Group (1998) contains an important digression on the problems of homogeneity in observational data sets and in the meteorological fields used to drive numerical surge and wave models. Using the particular examples of the Greenland and the North Sea regions, the authors found only the data sets from the latter to have acceptable homogeneity for their purposes. Such data sets must always be used with regard to the historical spatial variations in data coverage. A second point is that there are high-frequency, meteorologically driven, resonance-like processes (sometimes inappropriately called “meteorological tsunamis”) which are not well resolved by the spatial and temporal resolution of certain models or tide gauges. These have been observed in the Irish and North Seas, Adriatic, and northern Pacific (e.g. Lennon 1963; Vilibić et al. 2004), and inevitably result in an underrecording of the true extreme. A third technical point relates to the estimation of return periods from either modeling or observational information, or both in combination. Different methods of estimating return periods may give different results. Methods may depend on the quality of the data, the local tidal regime, and assumptions concerning the duration of an exceedance event. Therefore, results obtained using different methods are sometimes difficult to compare, especially if no proper error estimates are presented.

At any location, ongoing observations of extreme events can sometimes result in a major revision of existing estimates of 100- or 1000-year return-period levels. For example, Hurricane Katrina levels at New Orleans were by far the highest recorded, and the 100-year return levels shown in updated Flood Insurance Rate Maps exceed previous estimates by 1–3 m (FEMA 2006).

11.2.2 Effects of River Flow

Sea-level extremes and subsequent coastal flooding can also be exacerbated by intense rainfall in river catchments, the changes in the frequency of which may be related to climate change, enhanced by channeling of rivers and loss of floodplains to industry and housing. Extreme sea levels in many coastal areas may result from hydrometerological extremes of a different nature. For instance, van den Brink et al. (2005) showed that extreme sea levels in the coastal area of the Netherlands may result from the extreme sea storm-surge levels, waves, and river discharges and that it is difficult to quantify which one is a major contributor to a particular extreme event. Singh (2001) studied the effect of rainfall and subsequent runoff on the sea-level variability in the Bay of Bengal, finding that at least 50% of the trend in mean tidal level off the coast of Bangladesh could be related to Monsoon effects, including runoff of Monsoon rainfall from the land through the Meghna, Ganges, and Brahmaputra river systems.

The need for investment in the science, forecasting, and mitigation of combined river and coastal (tide + surge + wave) extremes is now widely recognized. Extremes can sometimes occur due to a combination of factors within their normal range of variability (e.g. large but not unusual tide, surge, or river flow combining to produce a notable overall event) as much as due to long-term change or fluctuation in one or more parameters individually. Svensson and Jones (2004) looked at these joint probability events at several sites around the UK coastline, noting that the relative importance of river flow and surge to flooding can be highly site-dependent. The estimation of change in risk from modifications in extremes will need statistically rigorous appreciation of the interdependence of all relevant meteorological and ocean parameters.

11.2.3 Past Changes in Wave Characteristics

Wave heights in the North Atlantic are known to have increased during the past half century, with some of the observed variability in wave height related to fluctuations in the NAO (e.g. Carter and Draper 1988; Bacon and Carter 1993; Kushnir et al. 1997; Günther et al. 1998; Gulev and Hasse 1999; Wang and Swail 2001, 2002, 2006a; Woolf et al. 2002; Tsimplis et al. 2005; Weisse and Günther 2007). Numerical wave-modeling exercises have confirmed this general picture, although at many locations studied trends are only weakly positive (Vikebø et al. 2003). The WASA Group (1998, and references therein) conducted one of the largest studies of northeast Atlantic climate and, while also concurring that the storm and wave climate in most of the region had become more severe in recent decades (see also Alexander et al. 2005), it pointed out that there had been significant variations on timescales of decades (some of it related to the NAO) and that the then present (in 1998) intensity of the storm and wave climate was comparable to that at the beginning of the 20th century. One notes that northeast Atlantic storminess quantified using simple counts, estimated winds, and depth of the storm centers during the 1990s was also only slightly in excess of that in the 1880s and 1890s. Furthermore, some of the most recent years had the lowest storm activity on record (e.g. Alexandersson et al. 2000 and update in figure 3.41 of Trenberth et al. 2007; Schmidt 2001; Weisse et al. 2005; Weisse and Günther

2007). Lozano and Swail (2002) discussed the relationship between North Atlantic wave heights and storm tracks during the last four decades. They found the largest waves to be associated with latitude shifts of storm tracks, in turn related to the expansion and contraction of the polar front and the NAO. On the other hand, Wolf and Woolf (2006) concluded that it is the strength of the prevailing westerly winds (again related to the NAO) which is the most effective parameter for increasing mean and maximum monthly wave heights, rather than the frequency, intensity, track, and speed of storms.

Similar evidence exists for increasing eastern North Pacific wave heights during the past 20–30 years obtained from buoy records and hindcast wave models (Allan and Komar 2000; Wang and Swail 2001, 2006a; Gower 2002). Sasaki et al. (2005, 2006) concluded that a recent increase in summertime extreme wave heights in the western North Pacific was due to an increase in total duration of intense tropical cyclones. Quasi-decadal variability of autumn extreme wave heights in the same area were considered attributable to changes in storm tracks of intense tropical cyclones around the south of Japan.

There are fewer studies of changes in wave characteristics in the Southern Hemisphere, and most of these are concerned with the relationships of mean significant wave height (SWH) to the El Niño Southern Oscillation (ENSO) and other climate variability, rather than with longterm trends in SWH or changes in extreme wave heights. For example, Laing (2000) constructed a wave climatology for New Zealand waters from 1985 based on satellite altimeter data and studied relationships of empirical orthogonal function (EOF) patterns of SWH spatial variability to ENSO. In the subtropical north of the region, spatial patterns for high wave heights were found to differ considerably from those of SWH. Goodwin (2005) constructed a wave climatology for southeastern Australia and studied the relationship between mean wave direction and climate indices, notably ENSO. Hemer et al. (2007) collected Australian wave data spanning several decades from wave models, satellite altimetry, and a network of 30 wave-rider buoys. They determined long-term means, annual cycles, and interannual variability of the regional wave climate, with Southern Ocean wind anomalies found to be a dominant mechanism for much of the variability. Correlations between monthly mean SWH and ENSO were found to be significant along Australia's eastern margin. Studies of extreme wave heights remain to be performed.

The only recent study of changes in wave height throughout the global ocean based on wave measurements has been that of Gulev and Grigorieva (2004). Although in principle it was worldwide in scope, most of the information in that study was also from the Northern Hemisphere. The authors processed data from voluntary observing ships, with such data being regarded as relatively little affected by changes in observational practice. Trends in wave height for 1958–2002 were statistically significant and positive over most of the mid-latitudinal North Atlantic and North Pacific, in addition to the western subtropical South Atlantic, eastern equatorial Indian Ocean, and the East and South China seas. The largest positive trends were found in the northeast Atlantic and northeast Pacific, with negative values in the western tropical Pacific, eastern Indian Ocean, Tasman Sea, and southern Indian Ocean. Gulev and Grigorieva (2006) attempted to separate the contributions to change in wave height due to wind waves and swell, concluding that changes in the northeast Atlantic over the second half of the 20th century were primarily due to swell rather than wind waves, and indirectly to the number of cyclones, whereas in the North Pacific spatial patterns of change due to wind wave and swell were similar (Figure 11.3).

Gulev and Grigorieva (2004) also provided estimates for linear trends in wave heights on century (1902–2002) timescales. Trends in SWH were found to be significantly positive throughout the North Pacific, with a maximum of 8–10 cm/decade (up to 0.5% per year). These inferences are supported by the buoy records mentioned above, for both annual and winter means, and by hindcast wave modeling (e.g. Graham and Diaz 2001; Wang and Swail 2001). Trends in SWH in the North Atlantic were slightly negative (with marginal significance), with a decrease of 5.2 cm/decade (0.25% per year) in the western Atlantic storm-formation region. In the shorter 1950–2002 period, changes in the North Atlantic region were also found to be positive.

A more suitable database for studies of changes in waves on a global basis has been acquired through the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-40 wave climatology hindcast reanalysis project, and in particular the Royal Netherlands Meteorological Institute (KNMI)/ERA-40 wave atlas and related work based on the 45-year period 1957–2002 (Sterl and Caires 2005). The model results have been extensively validated against buoy and altimeter data. The model limitations are that the spatial resolution is 1.5° × 1.5° and the temporal resolution 6 h, so that tropical cyclones are not resolved and the details of mid-latitude storms are not well-resolved. The model tends to overestimate low waves and underestimate high waves which may be due to limitations of resolution. Section 5.5 of the atlas (available at http://www.knmi.nl/waveatlas) deals with trends and utilized the methods of Wang and Swail (2001). Statistically significant differences between the return values of the 100-year return-period SWHs estimated from three different decades (1958–67, 1972–81, and 1986–95) occur only in a small number of regions including the North Atlantic (an increase in the region around 20°W, 51–56°N and a decrease around 28°W, 42°N when comparing estimates for the third decade relative to the second) and the North Pacific (an increase around 150–180°E, 40°N when comparing estimates for the second decade to the first). Spatial patterns of trends in the high percentiles of wave height were similar to those of the means but magnitudes of trends were larger. As regards the North Atlantic during periods when the NAO index is positive the storms tend to move from North America in the direction of the Norwegian Sea. When the NAO index is negative the storms move in the direction of the Mediterranean Sea (figure 3 of Rogers 1997), and the wave conditions are milder (see Wang and Swail 2002). The North Atlantic part of the KNMI/ERA-40 reanalysis database provides findings comparable in all but the most extreme events to those from the regional AES40 hindcast (a North Atlantic wind and wave climatology developed at Oceanweather with support from the Climate Research Branch of Environment Canada), with

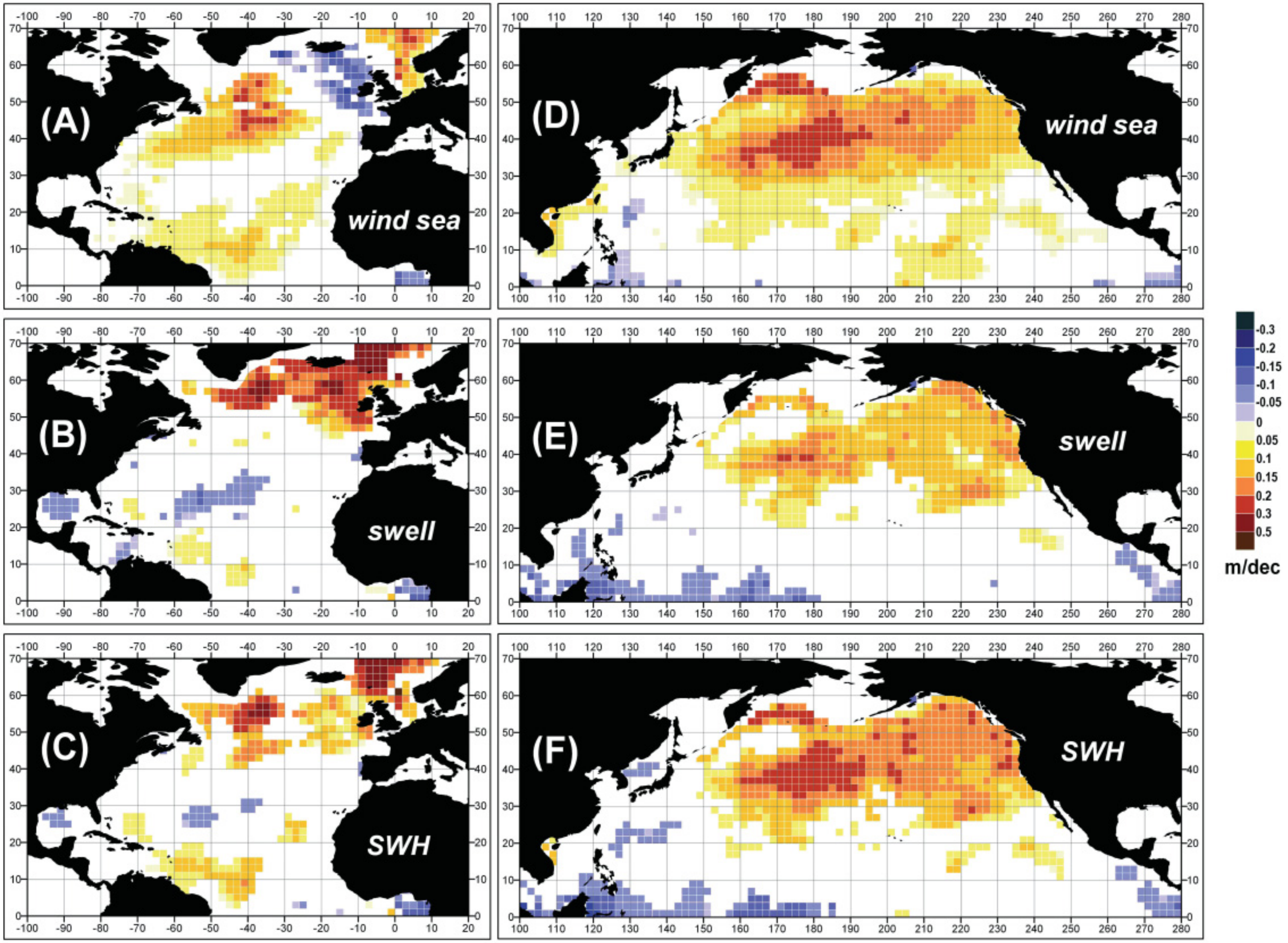

Figure 11.3 Linear trends (m/decade) in winter (January–March) wind sea height (A, D), swell height (B, E), and SWH (C, F) for the North Atlantic (A–C) and North Pacific (D–F) for 1958–2002. Only trends significant at 95% level and according to the Hayashi criterion are shown. (From Gulev and Grigorieva 2006. © American Meteorological Society.)

spatial patterns of trends in the region similar to those reported previously by the WASA Group (Günther et al. 1998).

There are two main limitations of the above body of research into past changes in wave characteristics. The first is that most studies are concerned with changes in annual or monthly mean SWH, rather than extreme (or high percentile) wave heights. The second is that relatively few studies are concerned with changes in wave direction, which are as important as changes in wave height when considering possible coastal impacts, through modification of longshore sediment transport and coastal evolution. (For example, Tsimplis et al. (2005) suggest a 20° change of direction per unit NAO index change in the one southern-England location at which they looked.)

The combined effects of extremes in tides, surges, and waves have maximum impact at the coast. For example, coral islands have elevations of typically 1–2 m above mean sea level and are often used in case studies of impacts of climate change (linked to coral mortality and increases in wave energy and erosion; see Sheppard et al. 2005) and sea-level rise. One of the first island floods of which the world took notice occurred in April 1987 in the Maldives when they were exposed to major ocean swell propagating from the Southern Ocean (Harangozo 1992). The floods were used by the Government of the Maldives and international environmental nongovernmental advocacy groups to alert the United Nations and other intergovernmental bodies to the dangers faced by reef islands from a major sea-level rise. The potential future modification of wind waves and swell as a consequence of climate change is clearly an issue which needs attention alongside sea-level rise. In many cases waves cause erosion as a consequence of which a sea-level extreme results in a coastal flood. However, waves are almost never recorded alongside sea levels at tide-gauge stations (see Vassie et al. 2004) and the literature contains only a limited number of examples of tides, surges, and waves in combination (e.g. Wolf and Flather 2005). More comprehensive studies of combined tide, surge, and wave extremes, and their interactions (see Mastenbroek et al. 1993), using observations and modeling of recent decades and simulations of future conditions, are clearly required around the global coastline.

11.3 Mid-Latitude and Tropical Storms: Changes in the Atmospheric Drivers of Extreme Sea Level

11.3.1 An Introduction to Storms

Both mid-latitude and tropical storms are associated with extremes of sea level. Storm surges are generated by low atmospheric pressure and intense winds over the ocean. The latter also cause high wave conditions.

Synoptic-scale extratropical cyclones, also known as depressions or storms, are baroclinic systems that form in mid-latitudes and are an important part of mid-latitude weather and climate. The main energy source for these cyclones is the temperature contrast between the cold polar and warm subtropical atmosphere. The storms tend to be organized in regions and these are known as storm tracks. The major Northern Hemisphere storm tracks extend across the North Atlantic and North Pacific. There is a smaller track in the Mediterranean region which is closely associated with North Atlantic mid-latitudinal track and influenced by the local diabatic heating over the Mediterranean Sea. These storms, being largely responsible for the extreme hydrometerological events in southern Europe, will contribute to extreme sea levels at the Mediterranean and Black Seas coasts.

Tropical cyclones are synoptic-scale low-pressure systems with a warm core (atmospheric temperature anomaly) relative to the surrounding environment in the middle to upper troposphere, and having a well-defined cyclonic circulation near the surface. The cyclones, which form in the tropics or subtropics, derive their energy from moisture evaporated from the ocean surface locally or converged in toward the storm from the surrounding environment. As moisture condenses in the cyclone to form precipitation and cloud, latent heat is released to help fuel the storm. Tropical cyclones can produce devastating storm surges and extreme-sea-level events. The question examined here is whether there have been any long-term trends in past tropical cyclone activity and what types of change might have been expected on the basis of current model simulations.

From the perspective of extreme sea levels, changes in many different aspects of cyclone characteristics are important. In addition to variations in cyclone number, track, intensity, size, and frequency, changes in the occurrence of extreme deepening (so-called meteorological bombs) and changes in cyclone propagation velocity are also important. Gulev et al. (2001) demonstrated on the basis of storm tracking of National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis data that some of these characteristics experienced significant changes in the last several decades, in particular a growing number of rapidly intensifying extratropical cyclones in parts of the Northern Hemisphere was noted.

11.3.2 Observed Changes in Atmospheric Storms and Their Drivers

The natural variability of the Northern Hemisphere storm tracks is related to the phase of many large-scale modes of variability, for example the NAO (Rogers 1990, 1997; Ueno 1993; Hurrell and van Loon 1997; Hurrell et al. 2003) and the ENSO (Zhang et al. 1997b; Sickmöller et al. 2000; Graham and Diaz 2001; Chang and Fu 2002; Bengtsson et al. 2006), and any future change in the frequency of one phase over the other may impact on the nature of future storms. Some studies have concentrated on the last half century, looking at changes in maps of atmospheric pressure at mean sea level (e.g. see section 3.5 of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4); Trenberth et al. 2007) or using methods such as the tracking of individual storms in meteorological reanalysis products (Bengtsson et al. 2006). Gillett et al. (2003, 2005) noted some increases in Northern Hemisphere mid-latitude pressure gradients since the 1970s that could not be explained by natural variability alone. These changes might be related to increases in storm-track intensity. Trenberth et al. (2007) also highlighted the results of Wang et al. (2006), who noted a northward shift of the storm track in the North Atlantic region by around 200 km. The overall IPCC conclusion was that, in the Northern Hemisphere, it is likely that there has been an increase and poleward shift in the wintertime storm track during the second half of the 20th century, but uncertainties in the magnitude of changes remain. It also reported some evidence of decreases in extratropical cyclone number (and increases in their depth) in the Southern Hemisphere over the last two decades but noted even greater uncertainty than for the Northern Hemisphere results. The Northern Hemisphere results are consistent with observed trends in SWH since 1950 observed by Gulev and Grigorieva (2004).

These studies have typically focused on relatively short time periods, typically a few decades, but some modes of climate system variability take place on longer timescales. Therefore, studies of much longer time series can usefully place the more recent changes into context. For example, Bärring and von Storch (2004) and Jónsson and Hanna (2007) found no evidence for long-term changes in storminess in two Scandinavian and one Icelandic time series respectively, each approximately 200 years long, although considerable multidecadal variability was evident.

Turning to tropical storms, evidence is now emerging of significant sea-surface warming trends in both the Atlantic and northwest Pacific tropical cyclogenesis regions, with anthropogenic forcing likely playing a detectable role in the warming (Santer et al. 2006). The Indian Ocean/western tropical Pacific warm pool region also shows a particularly pronounced long-term warming, with a larger trend during the past half century than occurred in the tropical north Atlantic (e.g. Knutson et al. 2006). The emergence of such increases in sea-surface temperatures (SSTs) in the regions where tropical cyclones form and intensify raises the question of whether tropical cyclone characteristics may have changed significantly during the 20th century.

Several recent studies have considered a number of hurricane intensity-related indices, but provide conflicting information on long-term trends. One such index is Emanuel's (2005, 2007) power dissipation index (PDI) which is the accumulated sum of the cube of maximum surface wind speeds (one value per storm every 6 h) observed in tropical cyclones. Emanuel found a clear increase in this index in the Atlantic since the mid-1970s and an increase since 1950 as well, although data reliability decreases as one goes back earlier in the record, such as into the pre-satellite era (pre-1966). While Emanuel's (2007) Atlantic PDI is well correlated with tropical Atlantic SST on multiyear timescales, Swanson (2008) reports that Atlantic PDI is also correlated at least as well, if not better, with tropical Atlantic SST minus tropical mean SST. Landsea's (2005) PDI for US landfalling Atlantic tropical cyclones (1900–2004) shows no evidence of an upward trend. Mann and Emanuel (2006) present a time series of numbers of tropical cyclones in the Atlantic basin since the late 1800s which roughly tracks the low-frequency variations of SSTs in the Atlantic tropical cyclogenesis region, including the century-scale increases. The question remains as to how reliable the tropical cyclone count data are, particularly for the full basin for years prior to aircraft reconnaissance which began in the mid-1940s. For example, Vecchi and Knutson (2008) find that Atlantic tropical storm counts, after an estimated correction for missing storms in the pre-satellite years based on ship-track densities, does not exhibit a statistically significant increase since 1878. Landsea et al. (2009) discuss the impact of duration thresholds on Atlantic tropical cyclone counts.

Emanuel (2007) reports that multibasin PDI series since about 1950 for the northwest Pacific and Atlantic, or for the northeast Pacific, northwest Pacific, and Atlantic basins combined (wind.mit.edu/~emanuel/antho2.htm) show substantially increasing trends. The increase amounts to roughly a doubling over the past 30 years, due to both increased intensity and increased storm duration. These PDI series correlate to some degree with low-frequency variations and trends in tropical SSTs.

Webster et al. (2005) report a large increase in the number of category 4 and 5 tropical cyclones (but not overall tropical cyclone numbers) over the past three decades, with increases occurring in all six basins during that time. A follow-on study by Hoyos et al. (2006) establishes a stronger statistical link between the increasing numbers of category 4 and 5 storms and the SSTs in the various basins. However, Bogen et al. (2007) test whether the positive trend in North Atlantic SSTs since 1970 explains increased hurricane intensities and find only a “weak association” with PDI. Chan (2006) extends the analysis of Webster et al. for the northwest Pacific basin back to earlier years and argues that the “trend” in that basin is part of a large interdecadal variation. Chan uses unadjusted data from the earlier part of the record, in contrast to the adjustments for this period proposed by Emanuel (2005) for this basin. The Emanuel and Webster et al. studies continue to be the subject of much debate in the hurricane research community (e.g. Knaff and Sampson 2006; Landsea et al. 2006; Klotzbach 2006), particularly with regard to homogeneity of the tropical cyclone data over time and the required adjustments. Kossin et al. (2007) have attempted to present a more homogeneous (in time) and globally consistent analysis of hurricane variability and trends. Their analysis extends only over the period July 1983 to December 2005, a shorter period than analyzed by Emanuel (2005) and Webster et al. (2005). They use satellite-derived measures of intensity to infer past hurricane activity in a more homogeneous manner. Their results support the existence of an increase in activity in the Atlantic basin (1983–2005), but in other basins their results find trends which are contrary to those obtained using the existing “Best Track” data sets for tropical cyclones over that period. The implications of the various findings for the results obtained in earlier studies using longer records (e.g. Emanuel 2005) have not yet been thoroughly investigated. Emanuel’s (2007) analysis indicates that the Kossin et al. (2007) results in the northwest Pacific basin, when combined with the longer record of Emanuel (2007), still yield an increase in PDI in that basin since the 1950s.

The literature on tropical cyclones continues to expand enormously. Recent studies include those of Wu et al. (2008) who examine how the annual frequency, lifetime, and intensity of tropical cyclones contribute to the changes in annual accumulated PDI. They find a significant upward trend between 1975 and 2004 in the North Atlantic only, together with some indication that the the trend was due to decreased wind shear and warming ocean. Briggs (2008) tests the number and rate of development of tropical cyclones in the North Atlantic and concludes that any increase in cumulative yearly storm intensity is due to the increasing number of storms rather than increase in intensity of individual storms.

11.3.3 Future Changes in Mid-Latitude Storms

The analyses of changes in mid-latitude cyclones in climate models have used a variety of analysis techniques for analyzing storms and their activity in the storm-track regions. These methods include band-pass filter statistics (Blackmon 1976) to look at variability on synoptic timescales (e.g. Hall et al. 1994; Christoph et al. 1997) and the number of gales (e.g. Carnell et al. 1996; Weisse et al. 2005; Fischer-Bruns et al. 2005). In addition, they have been applied to studies of eddy kinetic energy (e.g. Yin 2005), Eady parameter (Lindzen and Farrell 1980) to look at changes in the baroclinicity (e.g. Lunkeit et al. 1998), cyclone densities without tracking (e.g. Lambert 1995), and cyclone densities with tracking (e.g. König et al. 1993; Carnell et al. 1996). A variety of different methods have been used to identify the location and path of cyclones and these have been applied to 1000 hPa geopotential height, mean-sea-level pressure and 850 hPa relative vorticity at 24-, 12-, or 6-h intervals (e.g. König et al. 1993; Murray and Simmonds 1991; Carnell et al. 1996; Knippertz et al. 2000; Hoskins and Hodges 2002; Wang et al. 2006). The use of these different techniques makes it hard to compare the results of each study (Cubasch et al. 2001) or to assess if there is any underlying climate change signal. The majority of studies on future changes in storms (e.g. Carnell and Senior 1998; Knippertz et al. 2000; Fyfe 2003; Leckebusch and Ulbrich 2004) use data from models with low horizontal resolution and this can lead to errors with the simulation of mid-latitude cyclones. For example, the storms are too weak (Lambert et al. 2002) and the north Atlantic storm track is often located too far south (Lambert et al. 2002; Lambert and Fyfe 2006). These errors can often be greater than the climate change signal and so contribute to the uncertainty of the results. Improvements to the physics and dynamics of the models along with increased horizontal resolution have helped to improve the simulation of storms. Some groups have analyzed storms in higher-resolution models, but the simulation of storms does not necessarily improve as resolution is increased (Pope and Stratton 2002) and it is often possible to only run short experiments with these models and so the sample of data is small. The use of data at intervals of 6 h or less is becoming more common and this helps to improve the tracking of cyclones.

There is a common assumption that global warming may lead to increased storminess. However, the evidence is somewhat contradictory. The IPCC Third

Assessment Report (TAR) report found that climate change simulations of the impact of global warming on mid-latitude storm frequency and intensity were inconclusive (Cubasch et al. 2001). Sinclair and Watterson (1999) used the Commonwealth Scientific and Industrial Research Organisation (CSIRO) general circulation model (GCM) of the atmosphere to examine changes in the frequency and strength of mid-latitude storms under a doubled-carbon dioxide scenario. The polar regions were found to warm more than the tropics, reducing the equator-to-pole temperature difference. Reducing this gradient results in fewer and weaker storms, but there is some evidence of increased winter cyclone activity near the downstream end of the principal storm tracks. The results of modeling studies carried out since the TAR show that large uncertainties remain (Geng and Sugi 2003; Leckebusch et al. 2006; Lambert and Fyfe 2006; Bengtsson et al. 2006). Some modeling studies are tending to agree on there being fewer storms in winter in both hemispheres but there is no agreement on local changes in frequency.

Results are available from atmosphere-only models (HadAM3P and JMA; see list of abbreviations and acronyms at the front of the book for a list of full model names), and models which have both an atmosphere and an ocean (ECHAM5-OM, HadCM2, CSIRO2, ECHAM4/OPYC3, and ECHAM5/MPI-OM1). The ECHAM5-OM (Bengtsson et al. 2006), JMA (Geng and Sugi 2003), HadAM3P (Leckebusch et al. 2006), and CSIRO2 (McInnes et al., unpublished work) models show more storms around the UK in the future, but the ECHAM4/OPYC3 and ECHAM5/MPI-OM1 models show reduced storminess around the UK (Leckebusch et al. 2006) and HadCM2 shows no change (Carnell and Senior 1998). There was little change in the location of the cyclones in an average of GCM models prepared for the AR4 (Lambert and Fyfe 2006), although this may be because of the low horizontal resolution of the cyclone frequency data. The Northern Hemisphere storm tracks in McInnes et al. (unpublished work) became more zonal in structure producing an increase in storms over Europe and the eastern Pacific due to enhanced baroclinicity from warmer SSTs on the eastern edge of the ocean gyres. A similar relationship between changes in storm tracks and SSTs was also found in the CSIRO Mark 3 model. Storm-track predictability was investigated by Compo and Sardeshmukh (2004). They found that a predictable SST-forced storm-track signal exists in winter, but its strength and pattern can change substantially from winter to winter. The wide disparity in SST response in coupled ocean–atmosphere GCMs reported by Liu et al. (2005) suggests that the lack of agreement between GCM simulations on the specific geographic changes in storm tracks may continue to be a source of uncertainty in future projections of storm-track changes.

Yin (2005) found a consistent poleward shift and intensification of storm tracks in an ensemble of 21st-century climate simulations using 15 coupled climate models using eddy kinetic energy as an indicator of storminess. Lambert and Fyfe (2006), using the same ensemble of climate models, report a reduction of cyclone frequency and an increase in intensity using cyclone density. These seemingly conflicting results suggest that the increase in storm tracks reported in Yin (2005) occurs due to a change in the intensity of the systems which more than compensates the reduction in numbers. This finding is consistent with the Southern Hemisphere results of McInnes et al. (unpublished work), using both measures of storminess, and Lim and Simmonds (2007) who show that the tendency for fewer but more intense cyclones extends from the surface to 500 hPa in the CSIRO Mark 2 model. Yin (2005) refers to recent results observed in reanalysis-based studies showing that there has been a poleward shift in the mean latitude of extratropical storms and cyclones have been fewer but more intense in the latter half of the 20th century. However, it is difficult to attribute this to the effects of increasing atmospheric concentrations of greenhouse gases as yet.

Chang et al. (2002) provided a useful review of storm-track dynamics and found storm tracks exhibit notable variation in intensity on decadal timescales. Fischer-Bruns et al. (2005) studied storm variability on even longer timescales in a 500-year historical simulation and noted that anomalous temperature regimes, such as the late Maunder minimum, are not associated with systematic changes in storm conditions. It remains to establish a causal relationship between temporal variability of storm-track eddies (cyclones and anticyclones) and that of the background flow.

In summary, the AR4 (Meehl et al. 2007, section 10.3.6.4) concluded that the majority of future climate models show a northward shift in storm-track position in the Northern Hemisphere in a warming climate. Many of the models used in the IPCC Assessment also showed some indication of an intensification of their storm tracks over the northeast Atlantic near the UK (Lowe et al. 2009). Although the focus here has been on the Northern Hemisphere, many of the studies mentioned above also simulate Southern Hemisphere storms. The AR4 concluded that there is a tendency for models to show a poleward shift in their Southern Hemisphere storm tracks in a warming climate.

11.3.4 Future Changes in Tropical Storms

Two techniques for diagnosing tropical storms have been commonly used in global climate model experiments. The first technique locates and tracks individual cyclones, as centers of maximum relative vorticity which have a warm core (e.g. Haarsma et al. 1993; Bengtsson et al. 1995; Vitart et al. 1997). The second technique provides an estimate of tropical storm activity using a genesis parameter, which is calculated from seasonal means of the large-scale fields and so avoids the problems of simulating individual cyclones. The parameter needs to be chosen with care as it may not be appropriate to use a parameter that has been tuned for present-day conditions for global warming experiments (see Royer et al. 1998; McDonald et al. 2005 and Chauvin et al. 2006). Tropical storm-like features have been analyzed in studies with numerical models that range from low-resolution climate GCMs, to regional climate models, to very high-resolution hurricane prediction models.

The horizontal scale of tropical storms is much smaller than the horizontal grid-scale of most GCMs and, because of this, there has been some debate over the utility of GCMs in studying tropical storm behavior (e.g. Lighthill et al. 1994; Henderson-Sellers et al. 1998). However, some analysis has been carried out using models with higher horizontal resolution (e.g. Bengtsson et al. 1996; Sugi et al. 2002; McDonald et al. 2005) but the grid-scale is still larger than the scale of tropical cyclones and so these models are unable to simulate the intense core of tropical cyclones. Experiments have been run at 20-km model resolution (Oouchi et al. 2006), which improves the simulation of tropical storms, but models of this resolution are too expensive to be run at present by most climate modeling centers. Confidence in predictions would be increased by demonstrating the skill in the simulation of present-day mean winds and variability (Walsh 2004). In addition, objectively derived, resolution-dependent criteria for the detection of tropical cyclones in model simulations are required (Walsh et al. 2007).

Coupled atmosphere–ocean GCM experiments, run with increasing greenhouse gas concentrations, project enhanced SSTs and atmospheric moisture in the tropical region (Cubasch et al. 2001) that may change the intensity and location of tropical storms (Henderson-Sellers et al. 1998). However, factors other than SSTs are also likely to be important (see for instance, Bengtsson et al. 1995, 1996, 2006).

There is currently large uncertainty in the future changes in tropical cyclone frequency predicted by climate models forced with future greenhouse gases. The changes in frequency of storms simulated by models are often smaller than those due to natural variability. The IPCC TAR concluded that the results of GCM experiments are inconclusive (Giorgi et al. 2001). The JMA T106 (a JMA GCM with T106 spatial resolution (1.1° × 1.1°); Sugi et al. 2002), HadAM3 (McDonald et al. 2005), and ECHAM5-OM (Bengtsson et al. 2006) models all have fewer tropical storms in the future, whereas the NCAR Community Climate Model version 2 (CCM2) has slightly more storm days (Tsutsui 2002), although not all of these changes are greater than natural variability. There are regional variations in the sign of the changes and these vary between models. For example there are more storms in the North Atlantic region in the future in the JMA model (Sugi et al. 2002) but fewer in the HadAM3 model (McDonald et al. 2005) or the coupled model of Bengtsson et al. (2007). Yoshimura and Sugi (2005) found that the decrease in tropical storm frequency in their model was due to the direct effect of increased carbon dioxide on the atmosphere with the SST changes having a relatively small impact. The frequency of tropical storms also decreased in the higher-resolution 20-km JMA future simulations (Oouchi et al. 2006). While there were more storms in the North Atlantic with climate warming in this model, tropical cyclone frequency decreased overall. Nevertheless, the number of intense tropical cyclones increased markedly. However, one notes that a relatively short coupled model simulation period was used to investigate the climate-change signal.

Several high-resolution modeling studies of the relation between greenhouse warming and hurricane intensity have been conducted using the Geophysical Fluid Dynamics Laboratory (GFDL) hurricane model in idealized mode (e.g. Figure 11.4, taken from Knutson and Tuleya 2004). Under warmer, high-carbon dioxide conditions, simulated hurricanes are more intense (and have higher precipitation rates) than under present-day conditions. The simulated sensitivity is

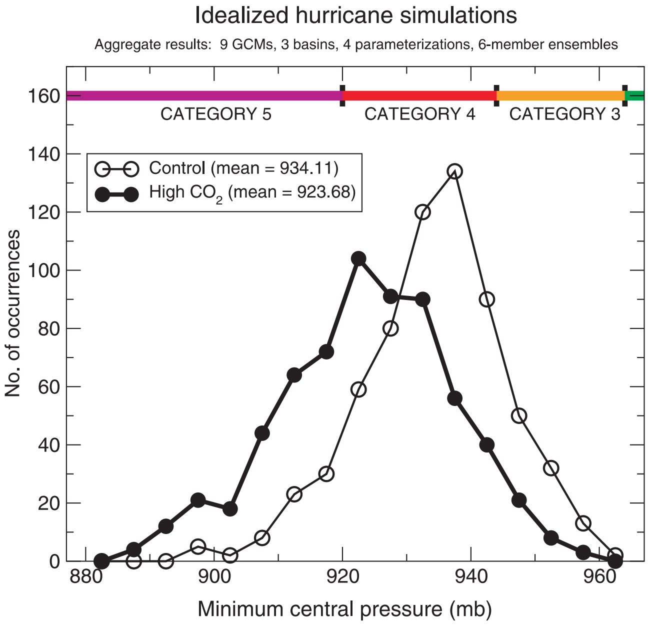

Figure 11.4 Histograms showing simulated hurricane intensity results (mb) from a series of idealized hurricane simulations. The histograms are formed from the minimum central pressures, averaged over the final 24 h from each 5-day model experiment. The thin line with open circles shows results for the control-CO$_2$ cases and the dark line with solid circles shows the high-CO$_2$ cases. High-CO$_2$ experiments represent conditions in which atmospheric CO$_2$ concentrations approximately double over a period of 80 years, relative to the control values. (From Knutson and Tuleya 2004. © American Meteorological Society.)

roughly a half category on the Saffir–Simpson scale (14% in terms of pressure fall, 6% in terms of maximum surface winds) for the warming associated with an 80-year buildup of carbon dioxide at 1%/year compounded. The GFDL results are broadly robust to the use of different climate models to define the high-carbon dioxide conditions, and to details of the treatment of moist convection in the hurricane model. Earlier studies with a similar model (Knutson et al. 2001) indicate the results are robust to inclusion of ocean coupling. The SST changes due to increased carbon dioxide in these experiments ranged from about +0.8 to +2.4°C (average 1.75°C), which is substantially greater than the approximately 0.5°C warming experienced in the tropical Atlantic and other tropical basins during the 20th century. The sensitivity of storm intensity to SST warming obtained in the Knutson and Tuleya study is similar, although slightly smaller, than that obtained using theories of hurricane potential intensity (about 5%/°C according to Emanuel 2005). Some additional modeling evidence for more intense hurricanes at the high end of the intensity distribution has been reported from other simulations using relatively high-resolution global or regional models (Oouchi et al. 2006; Bengtsson et al. 2007; Walsh et al. 2004; Stowasser et al. 2007).

In comparing the GFDL simulations with the historical intensity trends reported by Emanuel (2005) it is necessary to make assumptions about lapse-rate trends during the past three decades, for which the observed lapse-rate trends are uncertain. Assuming historical lapse-rate trends (per degree of SST warming) are close to those from +1%/year carbon dioxide experiments, the results imply that any trends in tropical cyclone intensity in the various basins should be too small to be detectable at this time, in contrast to the observational findings of Emanuel

(2005) and Webster et al. (2005). The Knutson and Tuleya (2004) simulations focused on intensity alone, and did not address the effects of changes in either storm frequency or duration, which were additional important factors in the historical tropical cyclone increases reported by Emanuel (2005). Efforts are continuing to reconcile the model-based and observation-based sensitivities.

11.4 Future Extreme Water Levels

Currently, predictions of extreme water level a few days ahead are produced for a number of regions using output from numerical weather-prediction models to drive storm-surge models (Flather 2000). Here we report on potential changes in extreme sea level over the coming decades. Changes in the number, path, and strength of atmospheric cyclonic storms, as discussed in section 11.3, may alter the formation and evolution of storm surges. Such changes could result in either increases or decreases in the surge climatology, with results being highly location-dependent. Individual surge events depend on the driving meteorology, so individual surges cannot be predicted more than a few days ahead at most. For times that are 50 or 100 years into the future, the best we can do is to predict, for a given set of assumptions on future greenhouse gas emissions, how many events of a given size or type will occur, on average, in a given length of time.

Extreme water levels will also increase as local mean sea levels rise in the future, so predictions of the regional change in mean sea level will also be necessary for predicting changes in extreme water levels a few decades ahead. The limitations of climate models in simulating future changes in mean sea level are discussed in Chapter 13.

11.4.1 Tools for the Simulation of Future Extreme Water Levels

Two main approaches to simulate future changes in extreme sea level have been employed: the statistical method and the dynamical method.

In the statistical approach, relationships between large-scale driving meteorology and local storm-surge heights are developed from observations or atmospheric and storm-surge model simulations of the recent past or present day. These relationships must be capable of explaining a significant fraction of the surge-height variability. Next, a projection is made of future large-scale meteorology using a global climate model and the future storm-surge characteristics are estimated from these using statistical relationships (von Storch and Reichardt 1997; Langenberg et al. 1999; Grossman et al. 2007). This category of future extreme-water-level estimation also includes combining relationships between extreme sea level and large-scale indices, such as the NAO (as described by Wakelin et al. 2003; Tsimplis et al. 2005; Woodworth et al. 2006), with climate model projections of these indices. However, in the case of the NAO the current generation of climate models appear unable to adequately replicate the observed variability of this index (Osborne 2004; Kuzmina et al. 2005). While removing the complexity of the need to run a storm-surge model, the statistical techniques assume that the relationship between the large-scale variables and the surges, which hold in the present-day climate, remain unchanged in a future perturbed climate. The validity of this assumption at particular locations is uncertain, although the general approach has been tested using climate models. For instance, Mearns et al. (1999) noted the inability of a statistical approach to reproduce some of the simulated changes in a regional model study of atmospheric parameters over eastern Nebraska. Busuioc et al. (2006) noted some skill in a statistical method when applied to simulate the future climate over Romania. However, even for the best predictor case there were notable differences in the magnitude of response compared to the dynamical method.

In the alternative, dynamical approach, physically based models of shallow-water dynamics are used to simulate storm-surge levels in past/present-day and future periods. The storm-surge models are usually barotropic in formulation (e.g. the Proudman Oceangraphic Laboratory (POL) CS3/CSX model, the Tidal Residual and Intertidal Mudflat Model (TRIMGEO; Casulli and Cattani 1994), or the barotropic versions of Princeton Ocean Model (POM) and Global Coastal Ocean Model, depth-average version (GCOM2D)) although some baroclinic models (e.g. POL Coastal-Ocean Modelling System (POLCOMS), a three-dimensional model for shelf regions)) are now being used in studies of storm surges. Kauker and Langenberg (2000) found that for investigating storm surges in the North Sea the barotropic models are adequate. The barotropic models solve the equation of continuity and a depth-averaged version of Newton's second law of motion in a rotating fluid, given the tidal and meteorological (wind stress and air pressure) forcings across the model domain. Parameterizations of the surface stress and bottom friction, and effects of horizontal viscosity, are required (e.g. Dyke 2001). Tidal and meteorological (often simple inverse barometer) boundary conditions are applied at the open boundary.

In many studies using the dynamic approach, the driving winds and pressure are taken directly from atmospheric climate models for both past/present and future periods. For example, Flather and Smith (1998) used the ECHAM3 climate model to drive a storm-surge model for two 5-year time slices, which represented present-day and future climate conditions. Global atmospheric climate models, or the atmospheric component of coupled ocean–atmosphere climate models, may not have adequate horizontal resolution to credibly simulate the local-scale meteorology; the horizontal resolution of the atmosphere in HadCM3, for example, is 2.5° × 3.75°. Some studies have used a one-way nested high-resolution regional atmospheric model to derive fine-scale winds and atmospheric surface pressure from the large-scale climate simulated by the coarser global climate models (e.g. Jones et al. 1995). These drivers are then used as the input to the dynamic storm-surge models, as in Lowe et al. (2001), Lowe and Gregory (2005), Woth (2005), Woth et al. (2006), and Unnikrishnan et al. (2006). The details of these studies are elaborated in the case studies section below. McInnes et al. (2003, 2005b) use an alternative approach to generate the meteorological drivers, typically using observed storm characteristics for the 20th century and perturbing these using the large-scale predictions from global climate models. In the tropics, synthetic 20th-century tropical cyclones are constructed based on sampling the range of storm characteristics from observations noting that cyclone intensity was represented using extreme-value statistical theory applied to observed cyclone intensities, whereas in mid-latitudes extreme-value statistical theory is used to extrapolate the modeled surges from actual storms in the observational record to longer return periods. These dynamic methods do not rely on a universal relationship between past storm behavior and extreme water levels.

Once a population of extreme future water-level events has been generated, there are numerous ways in which they can be presented and used. The simplest is to use percentiles (e.g. Woth et al. 2006 looked at changes in and exceedence of the 99.5th percentile of Northern Hemisphere winter extreme water levels; the water level will exceed this for approximately 12 h per winter season). This method has the significant advantage of not requiring a fit to a particular parametric distribution.

The alternative method to analyzing the extreme water levels is to fit them to an extreme-value parametric distribution (for example, Reiss and Thomas 1997; Coles 2001). This has the advantage that it enables results to be extrapolated beyond the relatively short periods of some climate model experiments. For instance it allows an estimate of the 50-year return-period event from 30-year time-slice experiments. The parametric method also enables the changes in the extreme water levels to be characterized and described by a small number of parameters (e.g. a location and shape parameter). Two commonly used parametric approaches are the generalized-extreme-value method and the peak-over-threshold method. The latter approach uses more of the original data. An obvious problem with these methods is that with relatively small samples the uncertainty in the fit might be large. With the generalized-extreme-value method it is quite easy to increase the sample size by including more than one maximum from each year (e.g. Smith 1986) but one has to ensure that the events can still be considered extreme. Furthermore, generalized-extreme-value or peak-over-threshold methods sometimes give a poor fit to the observed distribution of extremes, for example when surges induced by relatively rare but intense tropical cyclones are present. One should also be cautious when extrapolating results for long return periods, given that using a short sample to estimate the parameter values will not include all the effects of long period variability, which is known to affect the climate (Lowe et al. 2009). For example, there have been significant increases during the late 20th century in the number of severe storms over the UK since the 1950s (Alexander et al. 2005), which appear to be related to changes in the NAO to a more positive phase, although since the mid-1990s there is evidence of a reduction in storminess in this region as discussed in section 11.2.3. It remains uncertain whether the multidecadal NAO variability is related to climate change (Tsimplis et al. 2005).

The statistical analysis methods considered so far typically treat points in space independently so that information on the joint probability of the extreme events at different locations is discarded. Work by Dixon and Tawn (1992) and more recent work by the same group attempts to retain information on the spatial structure of the extreme events. In future, it might also be useful to combine aspects of the dynamic and statistical approaches. For instance, the dynamic method could be used to estimate changes in sea-level extremes on a scale of a few kilometers and the statistical method used to downscale these to individual point locations.

11.4.2 Case Studies

Extreme sea levels are affected by local meteorology and small-scale geographical features, such as the shape of the coastline, making results specific to particular sites. It is thus not possible to generalize the results from one region to another or the entire globe. Here we present case studies for three regions: the European coastline, the Bay of Bengal, and the Australian coast.

European Shelf Region

A number of studies have looked at storm surges in the shelf seas around Western Europe, especially in the southern North Sea, where surges are driven by mid-latitude storms and are strongly affected by the region's topography. It is also a region where significant damage and loss of life have resulted from coastal flooding (McRobie et al. 2005).

von Storch and Reichardt (1997) found that the change in storm-surge height (relative to mean sea level) resulting from changes in climate associated with a doubling of atmospheric carbon dioxide fell within the limits of natural variability. This was also found by Langenberg et al. (1999), who used different techniques for analyzing the surge heights along the coastline of the North Sea, including both the statistical and dynamic methods.

Flather and Smith (1998) used the ECHAM3 climate model to drive a storm-surge model for present-day and future climate time slices. They found that the surge extremes were different for future and present-day simulations but the differences were mostly within the range of natural variability, as estimated from a longer storm-surge simulation driven by surface forcing from a meteorological reanalysis of the period 1955–94 (Flather et al. 1998). This work was updated in the Regional Storm, Wave and Surge Scenarios for the 2100 century (STOWASUS) study (dmiweb.dmi.dk/pub/STOWASUS-2100), which used the ECHAM4 model to project changes in the driving meteorology and used longer time slices. The study did find significant changes in storm-surge height in the future climate for some locations. Lowe et al. (2001) looked at the projected 21st-century changes in extreme water levels using 20- and 30-year time slices from the Hadley Centre global ocean–atmosphere coupled climate model (HadCM2) and downscaled these to 50 km using the atmospheric regional model HadRM2. Again, significant changes were projected at some locations. Debernard et al. (2002) ran a storm-surge model for two 20-year time slices, representing the present day and a period centered on 2040, using the 50-km high-resolution limited-area regional climate model (HIRLAM) to provide driving meteorology. Significant changes in surge extremes were found in the southern and western North Sea in the autumn season but these did not greatly affect the annual results. Lowe and Gregory (2005) used 30-year time slices, the HadCM3/HadRM3 climate models and the Special Report on Emissions Scenarios (SRES) A2 and B2 emission scenarios to look at changes in extreme water levels during the 21st century. In this study, the changes in surge height were combined with both mean sea-level rise and vertical land movements, with a sizeable increase resulting at the southern end of the North Sea. The studies by Woth et al. (2006) and Woth (2005) took results from the Prediction of Regional Scenarios and Uncertainties for Defining European Climate Change Risks and Effects (PRUDENCE) project (prudence.dmi.dk) and used global and regional climate models (HIRLAM, Rossby Centre Regional Atmosphere-Ocean model (RCAO), Climate Version of the Local Model (CLM; a non hydrostatic regional climate model developed from the LM by the CLM Community; clm.gkss.de), and the Hamburg regional climate model (REMO)) to drive a storm-surge model for 30-year time slices of the present day and of future (approximately the end of 21st century) climates. Projected changes in extreme (high percentile in this case) storm-surge height along the UK coastline tended to be within the estimate of natural variability but significant changes were seen along part of the coast of continental Europe. However, there were no significant differences between the changes in extreme sea levels derived from different combinations of global and regional models and different emissions scenarios (see Figure 11.5).

Svensson and Jones (2006) have combined results from the Lowe and Gregory study with simulated river discharge to look at the future joint probability of combined surge and river flooding for selected UK sites. This type of work is currently being repeated for the River Thames as part of the Thames Estuary in 2100 (TE2100) project of the UK Environment Agency (Lowe et al. 2009), with river flow being calculated using the most sophisticated grid-to-grid river routing models available, and with a focus on quantifying uncertainty.

Bay of Bengal

If the severity of a storm surge is measured in terms of the number of lives lost during the 20th century, then the most severe events have occurred in the Bay of Bengal, where extreme water levels are driven by tropical cyclones (e.g. Cyclone Aila, Figure 11.6). Several hundred thousand people (perhaps 300 000, although estimates vary) are thought to have been killed by the 1970 cyclone alone (Murty et al. 1986; Murty and Flather 1994). Cyclones Sidr (2007) and Nargis (2008) have provided more recent examples of major loss of life due to both the storm itself and the accompanying surge.

In this section, we concentrate primarily on the northern part of the Bay; the storm-surge problem in the Bay of Bengal as a whole has been discussed in detail by Murty et al. (1986). This region contains one of many megadeltas in Southeast

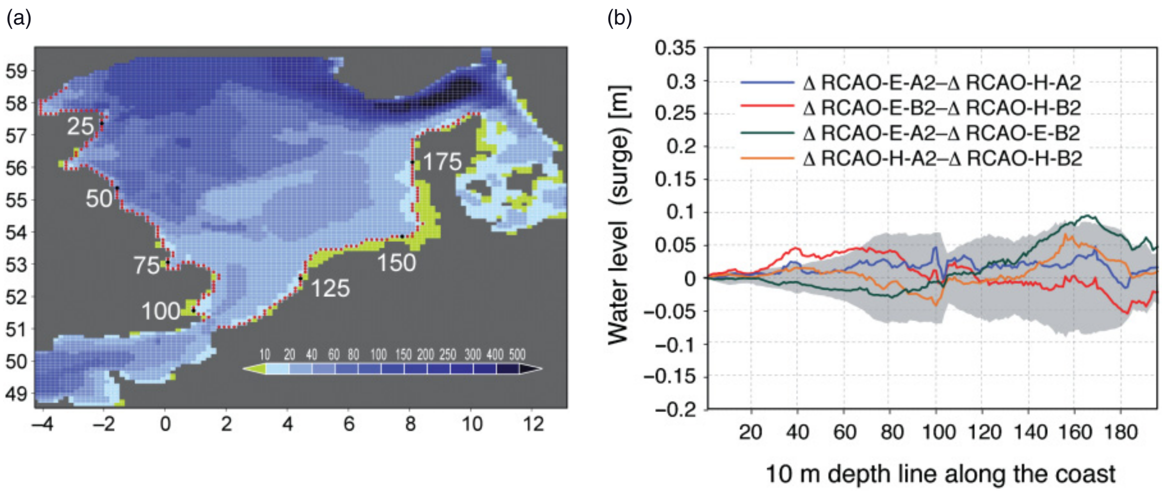

Figure 11.5 (a) Model domain of the tide-surge model TRIMGEO: the bathymetry (m) and the 196 near-coastal grid cells (red points) located along the 10-m depth line along the North Sea coast beginning with 1 in Scotland and ending with 196 in Denmark. (b) Differences (Δ) in the height of the simulated 99.5th percentile of future (2071–2100) winter water level/surge relative to today's climate (1961–90) calculated for a range of climate model and emission scenario combinations: H denotes the HadAM3H climate model, E denotes the ECHAM4/OPYC3 model, while A2 and B2 denote SRES emission scenarios. Each calculation is performed with the RCAO regional atmosphere–ocean model (Döscher et al. 2002). The plot shows the differences between combinations of Δ values as a function of grid cell number. For methods see Woth (2005).

Figure 11.6 Temporary shelters became home to thousands of people on the embankments surrounding the island of Padma Pakur, southern Bangladesh following Cyclone Aila and its storm surge in May 2009. Over 300 people were killed during this one storm. On the left side is the Bay of Bengal, on the right the flooded island, which used to contain villages, cultivated land and fishing farms. (Photo credit: Espen Rasmussen/Panos Pictures.)

and East Asia undergoing rapid change due to sea-level rise and human activities (Parry et al. 2007). Das (1972) and Das et al. (1974) used a linear shallow-water model for the northern Bay of Bengal to simulate the severe cyclone of 1970. A simple superposition of their model surge with the astronomical tide overestimated observed sea-level elevation at the time of landfall, suggesting that interactions between the surge and tide may be important. More recently, Dube et al. (1985) used a nonlinear surge model with improved representation of the coastal boundary to simulate storm surges using winds and pressure for three observed cyclonic storms. The simulated water levels compared well with tide-gauge observations at Chittagong port.

Flather and Khandker (1993) used a depth-averaged (two-dimensional) surge model to investigate the effect of a rise in mean sea level on the height of storm surges in the northern Bay of Bengal. Their model included a simple one-dimensional representation of the many channels of the delta which feed into the bay and which complicate the study of surges in this region. Using low-level winds and atmospheric surface pressure from an observed cyclone in May 1985, the authors predicted that a 2-m increase in mean sea level would cause lower surges in some parts of the bay (measured relative to the sum of mean sea level and tide level) but higher surges in other parts. Flather (1994) made use of an improved version of the Flather and Khandker scheme to produce surge hindcasts for two cyclones that occurred during 1970 and 1991.

As-Selek and Yasuada (1995) employed a model of the Northern Bay of Bengal with a resolution more than 10 times greater than that of Flather and Khandker to demonstrate the importance of the Swatch of No Ground (an underwater trench) to the bay's circulation and to investigate the effect of a range of mean sea level rise scenarios. The results supported those from the lower-resolution model of Flather and Khandker, again suggesting that mean sea-level rise could, in some parts of the bay, reduce the height of water levels below that expected by simply adding together the mean-sea-level rise and storm surges predicted for present sea level. The authors also examined the effect of changes in the bathymetry, which are brought about by the large sediment transports through the delta, predicting that small changes in bathymetry will not increase the height of storm-surge peaks but will alter the horizontal span of the surges.

Unnikrishnan et al. (2006) and Mitchell et al. (2006) have used output from the HadCM2 and HadRM2 climate models to drive barotropic surge models, although the methodologies used were somewhat different. Both noted changes in the height of storm surges in some parts of the bay. This work has been repeated and combined with fluvial flooding estimates using an improved experimental design as part of the international Climate and Sea Level in parts of the Indian Subcontinent (CLASIC) project. For example, Figure 11.7 shows the simulated change in the height of the 99.9th percentile of annual surge residuals in the northern Bay of Bengal (measured relative to the tide) between present day and the 2080s for a future in which human-made emissions into the atmosphere follow the mid-range SRES B2 scenario (Nakicenovic and Swart 2000), with

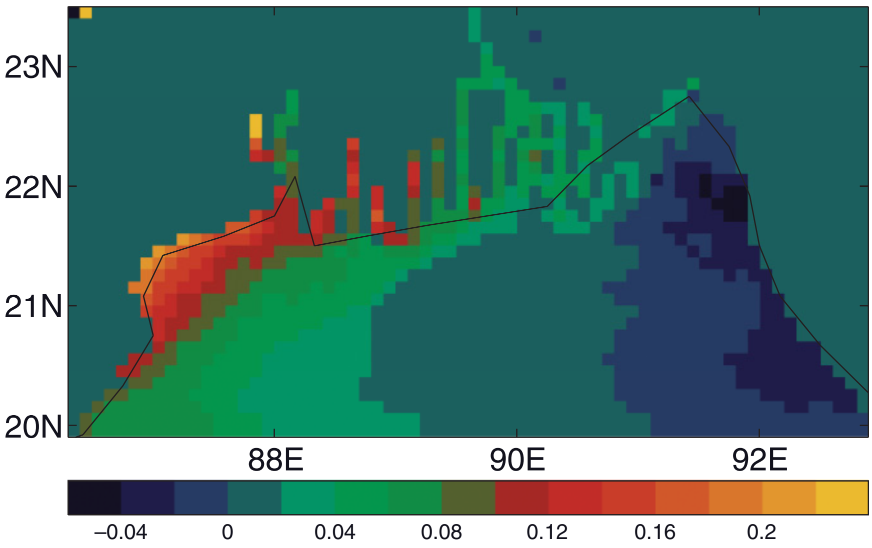

Figure 11.7 CLASIC project findings for simulated change in the height (m) of the 99.9th percentile of annual surge residuals in the northern Bay of Bengal (measured relative to the tide) between the present day and the 2080s assuming the SRES B2 emission scenario. The thin black line indicates the coastline.

simulations made using the HadRM3 regional climate model and the POL storm-surge model.

Recent studies on the occurrence of cyclones in the Bay of Bengal have not shown any trends during the last century. However, studies of intensification of cyclones have shown that the frequency of intense cyclones in the bay during November has been increasing (SMRC 2000). Unnikrishnan et al. (2006) made a similar conclusion for the future while analyzing the HadRM2 data for the northern Indian Ocean, in which the frequency of intense cyclones in the bay was found to be larger in an increased carbon dioxide model run (IS92a scenario) than in a control run. A corresponding increase in large surges was found in storm-surge simulations for the bay, when the surge model was forced with winds from the increased carbon dioxide run.

Australian Region

The effects of climate-driven changes in extreme sea levels around the coastline of Australia have been extensively studied. The northerly Cairns region is affected by surge events driven by tropical cyclones. McInnes et al. (2003) found that including an estimate of climate change to 2050 (with both changes in cyclone characteristics and a mean sea-level rise being considered) led to an increase in the area inundated by the most severe 5% of storms. McInnes et al. (2005b, 2006, 2009) examined change in extreme water levels to the south of Australia in the Bass Strait, where surges are driven by mid-latitude storms. McInnes et al. (2005b, 2006) included climate driven changes in wind speeds from 13 climate models, some of which predicted an increase and some a decrease. The lower projections

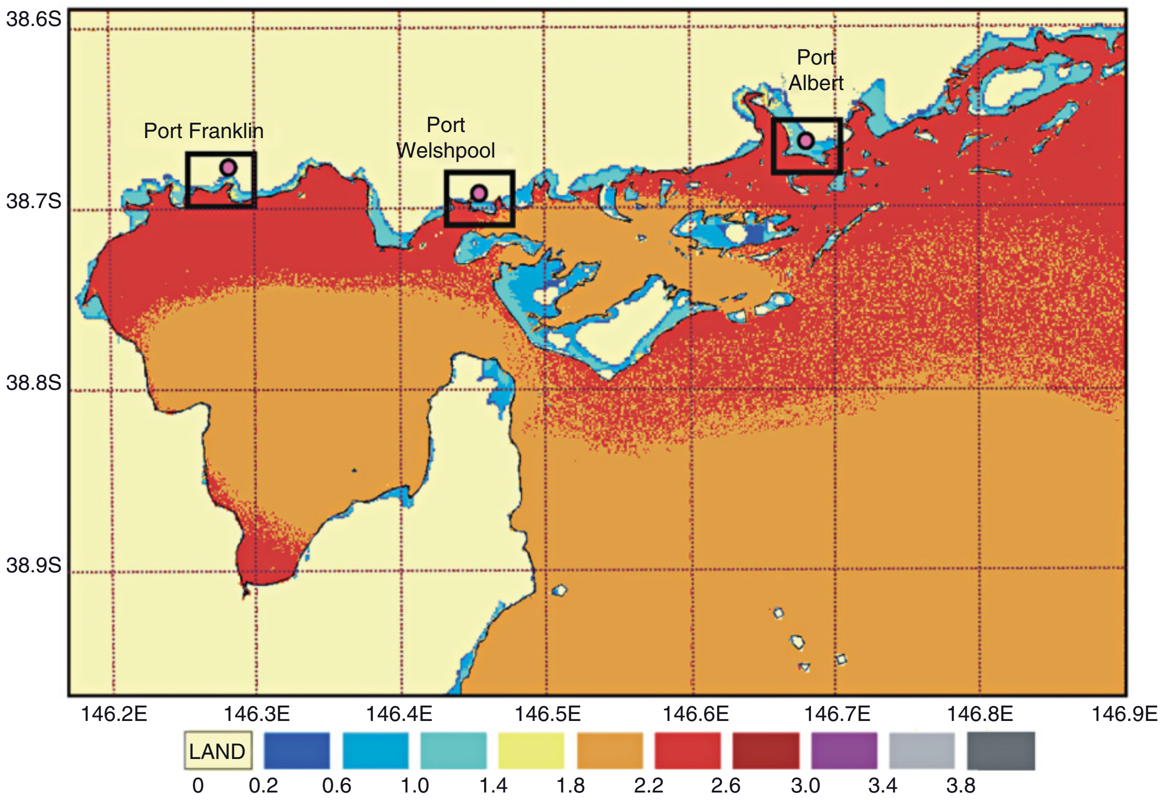

Figure 11.8 The coastal areas around Corner Inlet (south coast of Victoria, Australia) likely to experience inundation during a projected future one-in-100-year event (as presently estimated) for epoch 2070 following a high mean-sea-level rise scenario (McInnes et al. 2006). Levels are shown in meters relative to present-day mean sea level over the sea, and relative to the land surface over the land. The coastline is shown by a thin black line and flooded areas of land can be readily identified in blue.

of the climate models yielded little change in extreme water levels. However, the higher climate model projections gave rise to a significant increase in extreme-level events by 2070, driven mainly by the increase in mean sea level rather than by stronger winds.

Inundation levels due to the projected future one-in-100-year event around coastal townships within Corner Inlet along the southeastern coastline of Victoria were found to increase by between 15 and 30% (relative to land level) under a 2070 worst-case scenario (Figure 11.8). However, approximately 100 km along the coast to the northeast, around the Gippsland Lakes, inundation levels were found to increase by 166% under the same scenario (McInnes et al. 2006). The authors note that land subsidence could exacerbate the problem considerably.

11.4.3 Uncertainty in Storm-Surge Projections

Lowe and Gregory (2005) produced a simple comparison of some of the major sources of uncertainty in projected changes in the extreme water levels in the North Sea region using the IPCC TAR's estimate of global mean-sea-level rise (Church et al. 2001), the range of spatial sea level changes simulated in coupled climate models (Gregory et al. 2001), three storm-surge simulations from different driving models, and simulations using the same model set up but for different SRES emissions scenarios. They found that all of these contributions are important, but the relative importance can vary over quite small spatial scales. Natural variability is also important.

Woth et al. (2006) used a number of regional climate models to examine the uncertainty from the downscaling step from coarse global climate models to the regional-scale meteorological models. The spread in the results made with the alternative regional climate models suggests that this downscaling step does introduce some uncertainty but this is relatively small. Woth (2005) compared projected changes in extreme storm surges using results from two different global climate models, but found these were not statistically separable. The authors noted that these two models had similar physical formulations, and thus it is unlikely that they sampled a large fraction of the range of plausible global model response space.

McInnes et al. (2005b) studied the uncertainty in surge projections using a range of projections in future climate from several different climate models using the pattern scaling technique of Whetton et al. (2005) (see McInnes et al. 2005a). This approach incorporates an estimate of the range of uncertainty due to future emissions, climate sensitivity, and spatial variation, although the probability distribution of different climate model projections was not estimated. The changes in wind speed per degree of warming were estimated from 13 global and regional climate models then combined with estimates of temperature rise for nonintervention and stabilization emission scenarios to give a range of potential changes to meteorological conditions in the future. These, in turn, were combined with current meteorological conditions and then used to drive their storm-surge model, producing an estimate of the uncertainty range in extreme-water-level conditions.

11.4.4 Contribution of Waves to Future Coastal Extremes

Wave setup can contribute to changes in mean sea level at the coast (Longuet-Higgins and Stewart 1962). During a storm event, the wave setup may be of the order of a meter at certain locations, although at most locations it is usually much less. The actual value depends on the direction of wave approach and details of the nearshore bathymetry. Waves can cause overtopping of sea defenses with consequent failure or coastal erosion which may increase the future exposure of the coastline to further attack. Changes in the direction of storm waves or swell may change longshore drift and associated sediment transport. As with the prediction of future changes in storm surges, future changes in wave characteristics can be determined using both dynamic modeling and statistical techniques. The same advantages and disadvantages of each approach, as discussed in section 11.4.1, apply here.

Wang et al. (2004) employed an observed relationship between the observed wave conditions and the NAO (see section 11.2.3), and assumed the relationship will continue to hold in the future. Projected changes in waves were then linked to a projection that the occurrence of the positive phase of the NAO will be more frequent under global warming. A study by Terray et al. (2004) supports this view and suggests that the main change in wintertime weather patterns will result in more positive NAO patterns. On the other hand, Jones et al. (2003) showed that the influence of the NAO has varied significantly over the last 150–200 years and has been particularly strong recently. It is notable that the availability of satellite measurements of waves over the last quarter century coincides with a particular phase of the NAO. Thus, it is still not clear how important the NAO will be in the future and how much NAO changes will be linked with anthropogenic climate change (Tsimplis et al. 2005).

Caires et al. (2006) derived return value estimates of SWH up to the end of the 21st century using projections of the sea-level pressure under three different forcing scenarios from the Canadian coupled climate model. The methodology employed used regression methods to link the climate model pressure simulations to wave height. Under all forcing scenarios, significant changes are to be expected in different regions of the globe with the larger and more significant changes occurring under the more severe emission scenarios. Under all future scenarios considered, significant positive trends are to be expected in the North Pacific. Similar patterns were seen in a study using different climate models (Wang and Swail 2006b).

The WASA and STOWASUS projects both included an element to estimate future climate-driven changes in waves (see Kaas and Andersen 2000). The simulated time slices in the WASA experiment were rather short to isolate a clear signal but the experimental design was improved for STOWASUS. Using a dynamical wave model driven with atmospheric winds from a set of global high-resolution simulations a future increase in high waves was found in the northeastern part of the North Atlantic but decreases occurred further southwest. Andrade et al. (2007) studied possible changes in wave conditions around Portugal by the end of the 21st century with the use of the HadCM3 climate model coupled with a spectral wave model. Results suggest that mean wave heights will be essentially unchanged although intra-annual distributions may change, in addition to wave direction, with possible modifications in longshore transports.

Wolf and Woolf (2006) used a dynamic wave model approach to show how different climate change effects (e.g. increase in wind speed or change in wind direction) are likely to alter wave conditions in the waters around the UK. This type of sensitivity study is a valuable step towards being able to understand the predicted changes in waves resulting from a range of policy relevant future emissions scenarios. Changes in sea-ice extent have important implications for waves, in changing the fetch over which the wind is blowing. Recently Arctic sea ice has been reducing (e.g. Rigor and Wallace 2004).

11.4.5 Tsunamis

There are many processes other than storm surges which can result in a high coastal sea level. These include seiches (e.g. Pugh 1987, chapter 6), "meteorological tsunamis" (a combination of storm surge and resonance, e.g. Monserrat et al. 2006), and tsunamis themselves. The latter can be localized to a particular ocean area such as the Mediterranean (e.g. Tinti et al. 2006), or global in scale as demonstrated by the Sumatra 2004 event (Titov et al. 2005; Woodworth et al. 2005).

The very rare and unpredictable nature of earthquakes and their associated tsunamis makes it very difficult to include them in probability estimates of extreme events as they are less likely (than storm surges, for example) to have been included in the instrumental record. This introduces further grounds for caution in application of published extreme-level curves derived from periods without tsunamis.

Attempts at inclusion of tsunami risk in extreme-level estimates are best performed with the use of numerical modeling, combined with geological and other insight into the likely frequency and magnitude of tsunami events, and with due attention to their often very localized coastal impact (Horsburgh et al. 2008). There is no reason to expect more, or larger, tsunamis due to projected century-scale climate change. However, with the increase in coastal populations, the impacts of any such events are likely to be greater.

11.5 Future Research Needs

Extreme sea levels are closely linked to serious impacts in the coastal zone, and so their continued monitoring and improved prediction are important.

11.5.1 Extending the Evidence Base for Change

The limitations of historical data sets of extreme sea levels referred to in section 11.2.1 need to be addressed urgently. This applies to extremes for which the probability of occurrence is consistent with the present-day distribution of levels (e.g. Figure 11.9a). In other cases, extremes occur as a consequence of individual catastrophic events such as the Katrina storm surge (or a number of major surges in the Bay of Bengal discussed above, or even tsunamis), which lead to existing probability distribution curves needing to be revised (Figure 11.9b). In each case, an underlying mean sea level rise can add to the surge contribution.

Figure 11.9 (a) The Ponte della Paglia in Venice, an example of regular flooding which occurs from a spectrum of large surge events coupled with a mean-sea-level rise. (b) New Orleans after the Katrina hurricane and storm surge, an example of an individual catastrophic "outlier" event. (Photographs copyright Sarah Quill and UK Met Office.)

As regards sea-level data sets, historical information which exists still in paper form (e.g. tide-gauge charts) needs to be converted into computer-accessible formats, so that studies of extremes can take place alongside those of mean sea-level change (a process called "data archaeology"). Such information is known to exist in several European countries as a consequence of measurements in their former colonies. India, Brazil, and several other countries are also known to hold such information. In addition, some historic data from tide gauges lack vertical datum information which it would be good to determine if possible. For the present day, monitoring at sites in the GLOSS and GCOS networks needs to be undertaken to modern standards (i.e. at sufficiently high frequency) to establish where and at what rate extreme sea level is changing. In a complementary fashion, spatial information on sea-level extremes in the open ocean should also become possible if the present altimetric record can be extended into the future. However, if altimeters are to be used to study extremes, higher spatial and temporal sampling than provided by an individual present-day, nadir-pointing instrument is required. More routine observations are also necessary to adequately monitor changes in the wave climate, including wave direction. In addition to their direct use, wave observations provide a proxy for storminess. Further observational studies of changes in coastal morphodynamics (by direct surveying or by aerial or satellite remote sensing) would also be extremely useful.

Barotropic modeling provides understanding of historical storm surges over a region, complementing the time-series information from gauges, while the necessary construction of high-resolution meteorological data sets needed for such work can also be applied to investigate the temporal variability in wave heights. The development of such historical regional and global meteorological data sets (as free as possible from time-dependent biases) is a priority. A prerequisite for reconstructing past developments with models, possibly augmented by assimilating homogeneous time series into the models, requires the availability of homogeneous space-time detailed analyses of wind and air pressure for the past decades. Efforts such as regional reanalysis, making use of a large variety of local observations as well as dynamical downscaling efforts, constrained by large-scale analyses, are needed globally, not only for Europe (e.g. Feser et al. 2001) but also for tropical regions affected by storms. Long runs of regional and global barotropic models, forced by historical meteorological information, also need to be employed to derive extreme-level curves for the entire global coastline, enabling coastal planners to estimate changes in risk to potential mean-sea-level change at any location.

In order to build a case on which decisions regarding future emissions reductions can be made there is a need, at each location where large sea level (and wave) variations have been observed, to identify as far as possible that part of historical change in both mean levels and extremes that have resulted from human activity and that which is due to natural drivers of change (see Woodworth and Blackman 2004; Hunter 2002, 2004; Woodworth 2005; Sheppard et al. 2005). Such investigations are necessarily multidisciplinary and might usefully be similar to the formal detection and attribution methodology already applied to temperature, rainfall, and runoff.

11.5.2 Increasing the Mechanistic Understanding of the Drivers of Change

There are significant gaps in our understanding of global mean sea level rise, the spatial pattern of these time mean changes, and changes in atmospheric storminess as the climate warms. These drivers of extreme sea level change have been discussed in this and previous chapters.

Advances are likely to require more observations in order to construct and test detailed models of key elements of the climate system. Work is also needed to understand the importance of large-scale planetary changes on the local scale. For instance, there are still gaps in our knowledge of how individual local feedbacks combine to produce the large-scale pattern of temperature rise, which in turn affect the rate and pattern of sea-level rise and atmospheric storminess changes.

11.5.3 Improving Prediction

Improved understanding of changes in the meteorological drivers of extreme water level should be combined with improved models of regional sea level and waves (for instance at higher spatial resolution and with coupling to river-routing models) in order to produce better predictions of future extreme sea level at a fine spatial scale. The improvements in meteorological insight will benefit the projection of changes in waves also. There is also the need to improve experimental design with longer simulated time slices or larger sets of initial condition ensembles, and better awareness of available statistical methods. Because results cannot be generalized from region to region, these models need to be applied to a wider range of regions, perhaps with the technology to make these simulations being transferred to the nations likely to be affected. This is especially important for developing countries where the spending on climate change modeling and climate change adaptation is limited.

A rigorous comparison of the dynamical and statistical methods in a wide range of regions is desirable, in order to allow recommendations to be made on the appropriate techniques for future work in each area. The dynamical methods will require the best possible information on bathymetry and its temporal evolution near the coast.

In parallel with improved model predictions, we also need to better quantify the uncertainty in the extreme sea level predictions. Initial results have been described here but further developments are required. One such development is the use of perturbed parameter ensembles of global climate models (e.g. Murphy et al. 2004) to produce estimated changes in driving meteorology. Another development is the wider use of observational constraints to validate models and assess the likelihood of different model configurations.

Finally, a key reason for modeling extreme sea-level changes, waves, and river flows is to provide advice on the impacts in the coastal zone, such as inundation and coastal erosion. Often it is the joint probability of occurrence of extreme events in these quantities rather than the occurrence of an individual extreme that results in the most serious damage. Such studies require that investigators of extremes participate in a more widespread communication with scientists and engineers in possession of models of inundation, coastal erosion, and other impacts (different types of model employed for different applications). While this is starting to happen (e.g. in the UK Tyndall Coastal Simulator Project; http://

vrlab.env.uea.ac.uk/wiki/index.php), improvements are required. These impacts models will need detailed information on natural and human-made coastal defenses, which do not exist in many countries.

11.6 Conclusions

A general conclusion based on tide-gauge observations complemented by numerical modeling is that at most locations there is so far little evidence for extreme sea levels changing by amounts significantly different to changes in mean sea level. However, that conclusion is limited to those parts of the world where adequate historical data exist. In the last few years, there has been great progress in collecting and interpreting observations and in the making of predictions of extreme sea level. There is an urgent need for sustained observational data sets and for a range of improved numerical modeling and statistical techniques. Together these will lead to the improved understanding of past changes and projections of future ones.

One concludes that improvement of the quantification of uncertainty for regions of interest is a research priority. Since one is interested in the extreme water levels and waves, the uncertainties in meteorological drivers and mean-sea-level changes are both required. Local vertical land-movement information is also required. Ultimately, projections of the probability distributions of extreme water-level changes, not just their ranges, are needed in order to undertake quantitative risk assessments of the effects of inundation events on the coastal natural environment and on strategic coastal infrastructure.

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