international program of data collection at sea, which has been gaining impetus ever since. Ship's officers have always recognized the value of good marine weather data (which was even more important in the days of sailing ships than today), and so the quality of the merchant ship record (though by no means perfect, as we shall see) is remarkably good. The extremely laborious task of entering all these decades of data from around the world into computer-compatible form is also now largely complete (there were about 63 million SST observations alone, to 1979); various versions of the world record of marine observations, known as the Comprehensive Ocean-Atmosphere Data Set or COADS, are now readily available for interested users, in various stages of editing and compression. In addition to sea surface temperature, this data set contains surface winds, air pressure, temperature and humidity, cloud cover and rainfall, which also provide valuable information from which - given our present understanding of the ocean as a dynamical system - changes in ocean circulation can be inferred. However, most of their value is in meteorology, and detailed discussion is beyond the scope of this book.

The second data set consists of a few long-term tide-gauge records, mostly from Europe and North America. These have been much studied in connection with the possibility of long-term sea-level rise as a result of increasing CO_2 levels. We will address both their limitations and the things that have been learned from them.

Thirdly, accurate profiles of ocean temperature and salinity throughout depth have been undertaken since the introduction of the Nansen bottle and the reversing thermometer, the precursors of the modern CTD, some 110 years ago. However, reliable sections across ocean basins do not go back further than about 70 years, and examples of high-quality sections that have been repeated a few decades apart are quite rare; thus the interpretation problem in this case is usually one of the representativeness of the data rather than one of data quality.

Sea surface temperature

In the early days of the merchant ship measurement program, sea surface temperature (SST) was measured by picking up a water sample in a canvas bucket and measuring its temperature when it reached the ship's deck. Evaporation from the bucket's walls will generally result in cooling, depending on weather conditions and the time taken to make the measurement. By contrast, for the last forty years SST has mostly been measured by devices installed in the intake for the engine cooling system; in this case water is usually warmed during its transit from the ocean to the thermometer. The difference between uninsulated bucket temperatures and engine room intake temperatures is generally in the range 0.3-0.7°C. Since the data forms filled out by the officers usually did not include a space for recording the device used for measurement (uninsulated bucket, insulated bucket or engine room thermograph), there is an inherent uncertainty in the long-term SST records. Reasonable assumptions have been made about the change of instrumentation through time, but these cannot now be directly checked. Similarly, air temperatures are often measured in rather sheltered locations that may be subject to deck heating during daytime, and such details are not recorded. Nevertheless, it has been found that when reasonable correction procedures are applied to each data set, the magnitude of the corrections turns out to be extremely consistent between, for example, the northern and southern hemisphere, and

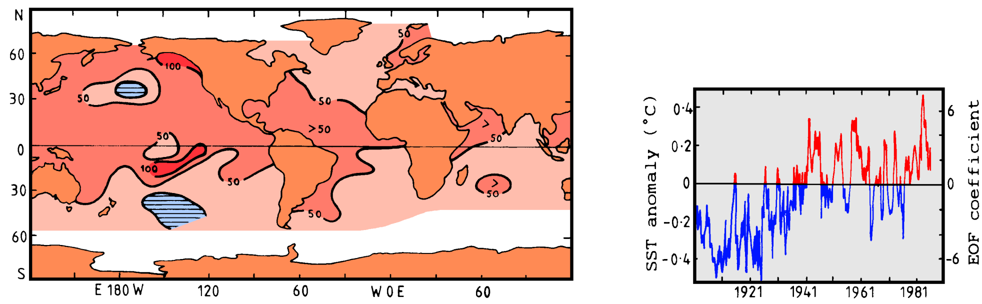

Fig. 20.1. Empirical Orthogonal Eigenfunction analysis of sea surface temperature. First eigenfunction: (a) spatial pattern (arbitrary units, negative values hatched), (b) temporal amplitude. From Folland *et al*. (1986a)

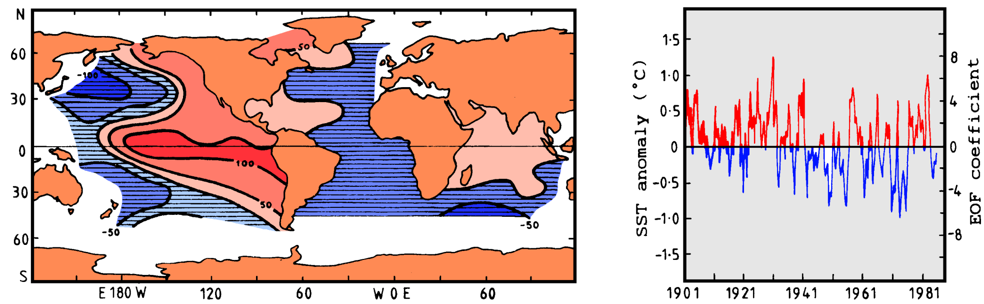

Fig. 20.2. As for Fig. 20.1 but for the second Empirical Orthogonal Eigenfunction.

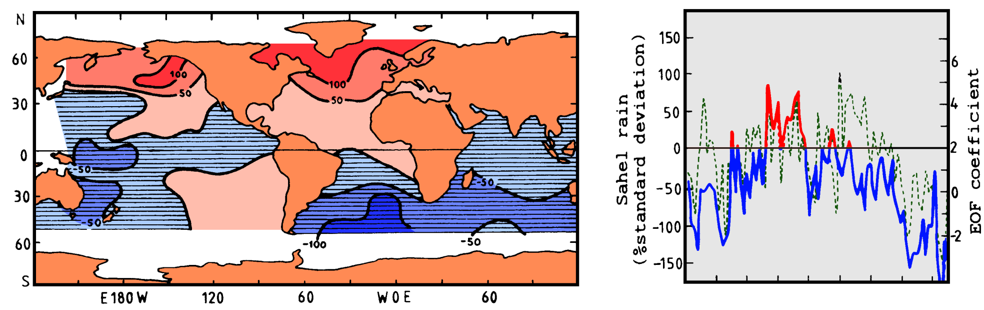

Fig. 20.3. As for Fig. 20.1 but for the third Empirical Orthogonal Eigenfunction. The dashed line in Fig. 20.3b shows an area average of rainfall in the Sahel region.

Subtracting the second EOF and applying the procedure once again produces the third EOF shown in Figure 20.3. $F3$(x,y) shows positive values in the north Atlantic and north Pacific Oceans and negative values through most of the Southern Hemisphere, while the time function shows slow variation over several decades. It might be thought that after such mathematical manipulations the result would be more noise than signal; however, there is

last century are 1.8±0.1 mm/year (Douglas, 1991) and 2.4±0.9 mm/year (Peltier and Tushingham, 1991). Both of the new estimates rely on a global model of postglacial rebound, which indicates that far away from the previously glaciated regions, coastal lands are rising relative to the sea. It is apparently the correction of this effect which leads to the discrepancy between Gornitz and Lebedeff's(1987) estimate and the two newer estimates. The sharpening of the estimate of sea level trends achieved by correcting for postglacial rebound is illustrated in Figure 20.5; note that the corrected trend is clearly greater than zero. However, Peltier and Tushingham(1991) report that their estimate of global mean sea level rise is "extremely sensitive to relatively modest alterations to the analysis procedure" which no doubt applies also to Douglas' estimate. All estimates are of necessity biased by the heavy concentration of available sea level records in Europe and North America.

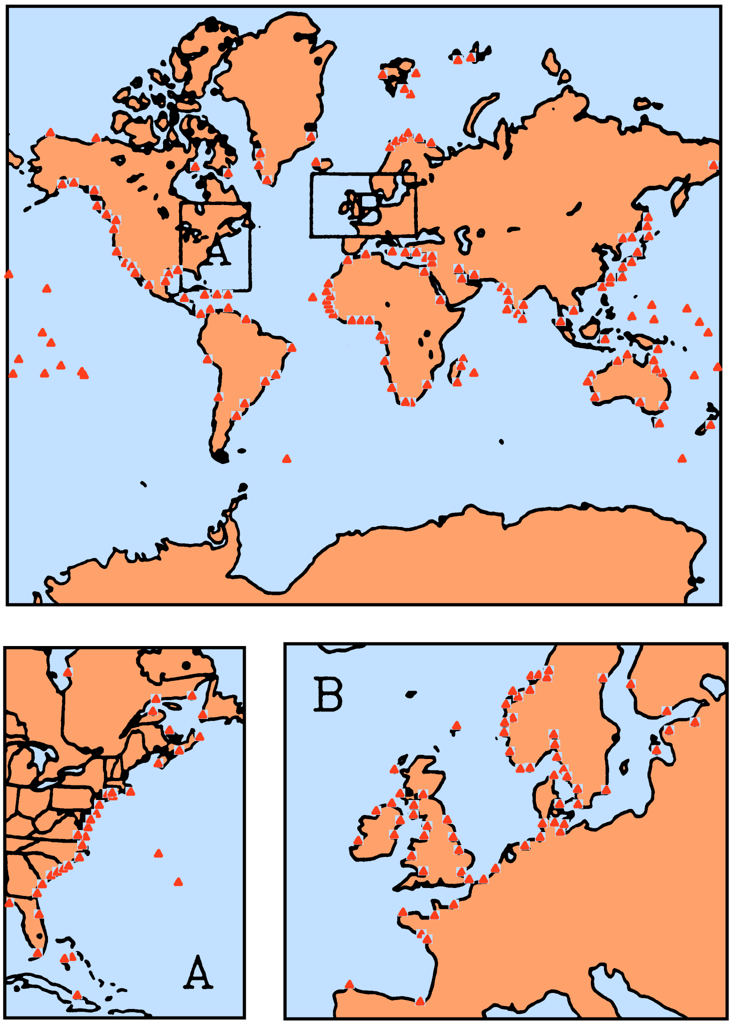

Fig. 20.4.

Locations of validated tide gauges from which records are available that are of length greater than 10 years. The data are archived with the Permanent Service for Mean Sea Level at Bidston, Merseyside, United Kingdom.

Adapted from Peltier and Tushingham (1991).

A complete assessment of sea level rise has to include a number of other factors. The volume of water generated by the observed melting of non-polar glaciers over the last century is equivalent to a sea level rise of 0.46±0.26 mm/year (Meier, 1984). It is seen that the two effects together, thermal expansion and non-polar glacier melt, yield between them sea level rise estimates of 1.3±0.5 mm/year, somewhat below the most recent estimates quoted above (1.8±.1 mm/year; 2.4±.9 mm/year). The uncertainties in the remaining contributions are certainly large enough to account for the discrepancy. The effects of a warming on Greenland and Antarctica are believed to be of opposite sign, and neither is well known — the large ice sheets on Greenland's flanks are thought to have retreated under warmer conditions, whereas Antarctica (and inner Greenland) are so cold that the warming should have produced little or no melting over the last century. Instead, increased sea temperatures should have generated increased snowfall over Antarctica and inner Greenland. The net contribution from both polar ice sheets is believed to be near zero. However, this can evidently only be a very approximate figure, and the uncertainty of our estimate of the total sea level rise in the last century is substantially greater than the figure of ±0.5 mm/year from thermal expansion and non-polar ice melt alone.

Contributions of both signs arise also in consideration of groundwater, the water trapped on or under land masses. Artesian bores have removed substantial quantities of groundwater over the last century, while large water storages for hydroelectric dams etc. have been created. Newman and Fairbridge (1986) estimate that the latter effect would have reduced sea level by up to 0.75mm/year from 1957-1980, mostly in small water storages. The USSR Committee for the International Hydrologic Decade (Korzun, 1978) estimated a sea level rise of 0.8 mm/year due to reduction of groundwater storage.

In summary, our best estimate at present is that the combined contribution from groundwater and ice storage to sea level rise has been positive over the last century, and perhaps of the same order of magnitude as the combined contribution from thermal expansion and non-polar ice melt. However, in the absence of better information, the most recent projections of future sea level rise assume that there will be no net contribution from polar ice and groundwater.

Regional variations of sea level on decadal time scales

Before leaving the topic of long-term sea level change it is worth noting that after correction for postglacial rebound, other observations of interest from the point of view of decadal sea level change can be extracted from the available sea level records on the eastern coast of the USA and Canada.

Significant differences in the rate of sea level rise do occur from place to place, that probably originate in oceanographic effects. When sea level, corrected for postglacial rebound, from tide gauges along the North American east coast is examined for a trend over the period 1930-1980, it is found that over the 50-year interval sea level rose about 0.05 m more at gauges south of 38°N than at gauges to the north of 38°N (Figure 20.7). No tectonic explanation for this feature is known. The most likely cause is that the Gulf Stream altered its strength over the period. A very strong mean drop in steric sea level of order 0.7 m, about the strongest in the world ocean, is associated with the separation of the Gulf Stream from the coast near 35-38°N. The break in sea level trends over the past 50

200 m. Lazier (1980) suggested that abnormal northerly winds during these years blew sea ice southward, leading to greater ice melt in summer.

Brewer *et al.* (1983) complemented Lazier's work by examining two salinity sections across the Atlantic near 57°N, one taken in 1962 and the other in 1981. They found a systematic salinity decrease of about 0.02 between the two cruises. A plot of mean and standard deviation of salinity as a function of σ_{1000} from each cruise is seen in Figure 20.9 (σ_{1000} is the density the water would have if it was brought to 1000 m without changing salinity or potential temperature). The freshening is particularly evident when σ_{1000} is greater than 37.1 and for the range $36.8 < \sigma_{1000} < 36.9$. The first of these water mass modifications is thought to originate north of Denmark Strait, the latter in the Labrador Sea. These studies show that widespread changes in deep water can occur quite rapidly in response to rather modest changes in atmospheric conditions.

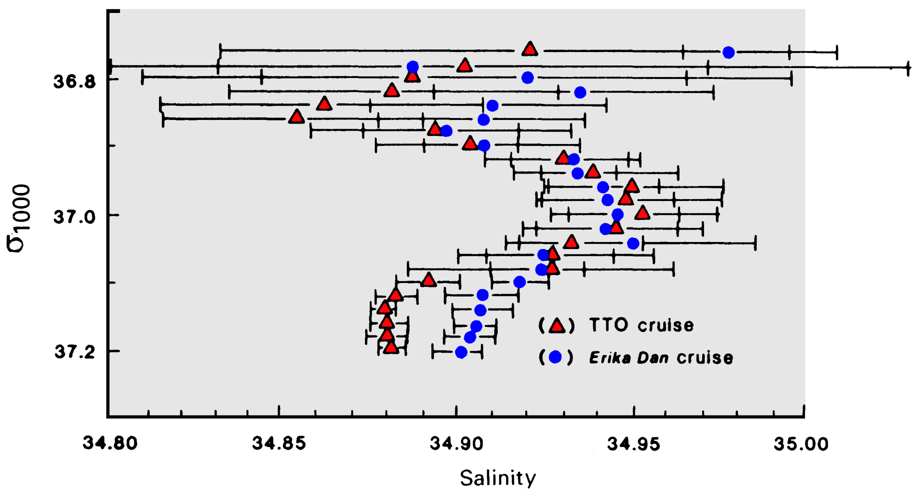

Fig. 20.9. Salinity means and standard deviations (horizontal bars) from two cruises across the North Atlantic near 57°N (dots for the 1962 cruise, triangles for the 1981 cruise) as functions of density σ_{1000} (for explanation see text). Note the clear freshening of the later curve, below $\sigma_{1000} = 37.1$ (corresponding to potential temperatures of about 2.5°C) and for σ_{1000} near 36.8 - 36.9. From Brewer *et al.* (1983) .

These deep water effects are not the only large-scale changes that have been observed in the north Atlantic Ocean over the last few decades. Levitus (1989) undertook a statistical study of the changes in the north Atlantic circulation from 1955-59 to 1970-74, using the data bank of all historical hydrographic observations. Unfortunately the north Atlantic Ocean is the only region where sufficient data exist to make such an analysis possible on a basin-wide scale. Figure 20.10b shows the difference in the depth of the 26.5 σ_θ surface for 1970-74 against 1955-59. Evidently, the thermocline shallowed significantly in most of the subtropical gyre, with some deepening on the inshore edge of the Gulf Stream. The net

little change in water mass properties on surfaces of constant density. A slight freshening for water of temperature 8°C or higher can account for a rise in sea level of about 2-3 cm, roughly equal to the observed rate of sea level rise over 20 years.

In conclusion, it will be evident from these examples that, while interdecadal variations definitely have occurred on basinwide scales in the ocean, our ability of keeping track of these interdecadal changes observationally is extremely sketchy. This needs to be borne in mind when considering results from numerical model studies.

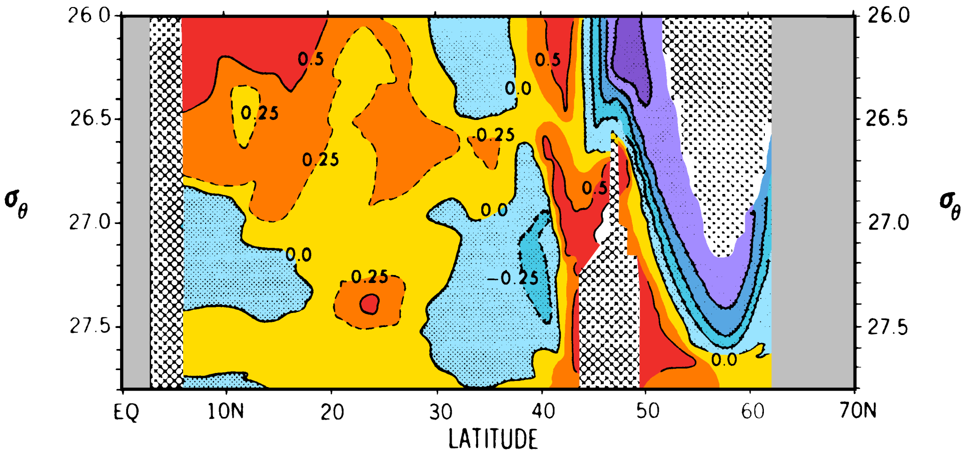

Fig. 20.11. Change of potential temperature 1970-1974 minus 1955-1959 (°C) on potential density surfaces along 49.5°W, as a function of potential density. Cross-hatching indicates regions where the corresponding potential density does not exist. From Levitus (1989).

Model results, salinity and climate

In an attempt to extend our understanding of long-term climate change beyond the limits posed by the available data, several research groups have begun the task of developing numerical models of the coupled ocean/atmosphere system. Such models require massive computing power, which is becoming available now. When applied to a simulation of our present climate, most models give satisfactory results when the ocean or the atmosphere are modelled in isolation but develop unreasonable climate trends (e.g. a rapid warming of the ocean surface) when the two components are treated as a coupled system. The salt budget proves to be particularly difficult, most probably because we do not yet understand how to incorporate the process of tropical rainfall correctly. A number of more or less empirical methods have been developed to prevent the models from diverging from the known climate trend of the last decades. Our hope is that by applying these methods to simulations into the future we can get reasonably accurate estimates of future climate trends.

One of the most intriguing results from these models is the role of sea surface salinity. Models which simulate the oceanic and atmospheric circulation for several thousand years

coupled model; however, as already mentioned, modelling tropical rainfall is one of the weak points of all models at present.

Whether the ocean circulation (within the confines of the present world topography) can, or did in the past, have more than one stable steady state as indicated by models, is a subject for paleoceanography. Whatever the answer will be, there is no doubt that the north Atlantic Ocean is the major determinant of the process. Consider the sketch shown in Figure 20.13. Deep convection in the Greenland Sea will be inhibited if the salinity in the northward flow of water from the subtropics is reduced; this is the mechanism behind Figure 20.12. The same effect would be observed if the amount of freshwater and ice exported from the Arctic Ocean is increased to cover the surface layer of the Greenland and Iceland Seas. This would force the warm, salty water from the south to submerge below the fresher surface water well before entering the Greenland Sea (in today's climate it does not submerge until it reaches the Greenland Sea; see Chapter 7). The fresh surface layer would insulate the underlying subtropical water and prevent it from cooling, stopping the deep convection in the Greenland Sea. Formation of North Atlantic Deep Water can thus be inhibited by various means, and it seems more and more likely that circulation patterns without NADW formation did exist in the past. To give just one example, sediment cores from the Antarctic Circumpolar Current region show large variations in carbon isotope composition between periods of glaciation and interglacial periods, which can be related to changes in the NADW contribution to Circumpolar Water (Charles and Fairbanks, 1992) and suggest that NADW formation was much reduced during the last ice age. This of course means that a circulation with very little or no NADW formation can develop again. Does the introduction of greenhouse gases into the atmosphere promote the change to such a pattern, or does it stabilize the existing circulation? The answer, although impossible to give today, is of tremendous interest to the people of Europe, which would see drastic changes if the north Atlantic sea surface temperature were to fall by several °C.

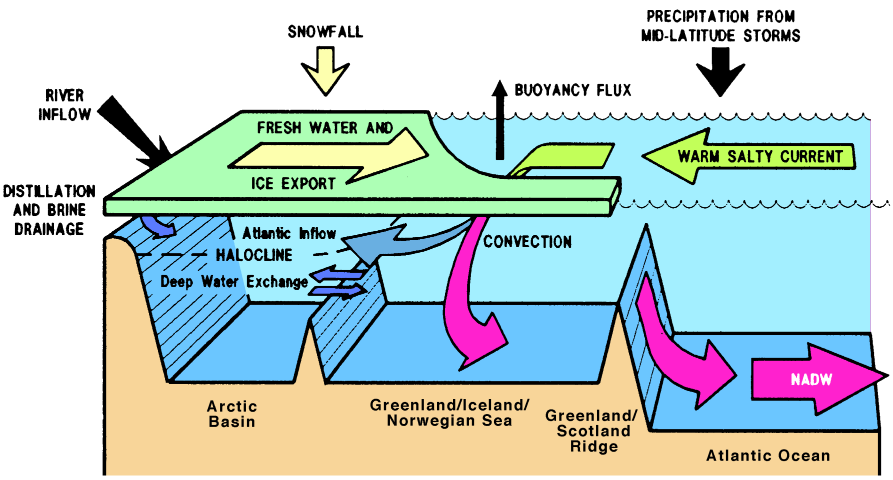

Fig. 20.13. Sketch of the circulation in the north Atlantic Ocean.