Chapter 2

Temperature, salinity, density, and the oceanic pressure field

The ratios of the many components which make up the salt in the ocean are remarkably constant, and salinity, the total salt content of seawater, is a well-defined quantity. For a water sample of known temperature and pressure it can be determined by only one measurement, that of conductivity.

Today, the single most useful instrument for oceanographic measurements is the CTD, which stands for "Conductivity-Temperature-Depth". It is sometimes also known as the STD, which stands for "Salinity-Temperature-Depth"; but CTD is the more accurate description, because in both systems salinity is not directly measured but determined through a conductivity measurement. Even the term CTD is inaccurate, since depth is a distance, and a CTD does not measure its distance from the sea surface but employs a pressure measurement to indicate depth. But the three most important oceanographic parameters which form the basis of a regional description of the ocean are temperature, salinity, and pressure, which the CTD delivers.

In this text we follow oceanographic convention and express temperature T and potential temperature Θ in degrees Celsius (°C) and pressure p in kiloPascal (kPa, 10 kPa = 1 dbar, 0.1 kPa = 1 mbar; for most applications, pressure is proportional to depth, with 10 kPa equivalent to 1 m). Salinity S is taken to be evaluated on the Practical Salinity Scale (even when data are taken from the older literature) and therefore carries no units. Density ρ is expressed in kg m^{-3} or represented by $\sigma_t = \rho - 1000$. As is common oceanographic practice, σ_t does not carry units (although strictly speaking it should be expressed in kg m^{-3} as well). Readers not familiar with these concepts should consult textbooks such as Pickard and Emery (1990), Pond and Pickard (1983), or Gill (1982); the last two include information on the Practical Salinity Scale and the Equation of State of Seawater which gives density as a function of temperature, salinity, and pressure. We use z for depth (z being the vertical coordinate in a Cartesian xyz coordinate system with x pointing east and y pointing north) and count z positive downward from the undisturbed sea surface $z = 0$.

A CTD typically returns temperature to 0.003°C, salinity to 0.003 parts per thousand, and depth to an accuracy of 1 - 2 m. Depth resolution can be much better, and advanced CTD systems, which produce data triplets at rates of 20 Hz or more and apply data averaging, give very accurate pictures of the structure of the ocean along a vertical line. The basic CTD data set, called a CTD station or cast, consists of continuous profiles of temperature and salinity against depth (Figure 2.1 shows an example). The task of an oceanographic cruise for the purpose of regional oceanography is to obtain sufficient CTD stations over the region of interest to enable the researcher to develop a three-dimensional picture of these parameters and their variations in time. As we shall see later, such a data set generally gives a useful picture of the velocity field as well.

For a description of the world ocean it is necessary to combine observations from many such cruises, which is only possible if all oceanographic institutions calibrate their instrumentation against the same standard. The electrical sensors employed in CTD systems do not have the long-term stability required for this task and have to be routinely calibrated against measurements obtained with precision reversing thermometers and with

inside a frame, with 12 or more bottles around it (Figure 2.2). The water samples collected in the bottles are used for calibration of the CTD sensors. In addition, oxygen and nutrient content of the water can be determined from the samples in the vessel's laboratory.

The CTD developed from a prototype built in Australia in the 1950s and has been a major tool of oceanography at the large research institutions since the 1970s. Two decades are not enough to explore the world ocean fully, and regional oceanography still has to rely on much information gathered through bottle casts, which produce 12 - 24 samples over the entire observation depth and therefore are of much lower vertical resolution. Although bottle data have been collected for nearly 100 years now, significant data gaps still exist, as is evident from the distribution of oceanographic stations shown in Figure 2.3. In the deep basins of the oceans, where variations of temperature and salinity are small, very high data accuracy is required to allow integration of data from different cruises into a single data set. Many cruise data which are quite adequate for an oceanographic study of regional importance turn out to be inadequate for inclusion in a world data set.

To close existing gaps and monitor long-term changes in regions of adequate data coverage, a major experiment, planned for the decade 1990 - 2000, is under way. This World Ocean Circulation Experiment (WOCE) will cover the world ocean with a network of CTD stations, extending from the surface to the ocean floor and including chemical measurements. Figure 2.4 shows the planned global network of cruise tracks along which CTD stations will be made at intervals of 30 nautical miles (half a degree of latitude, or about 55 km). As a result, we can expect to have a very accurate global picture of the distribution of the major oceanographic parameters by the turn of the century.

Because of the need for a global description of the oceanic parameter fields, researchers have attempted to extract whatever information they can from the existing data base.

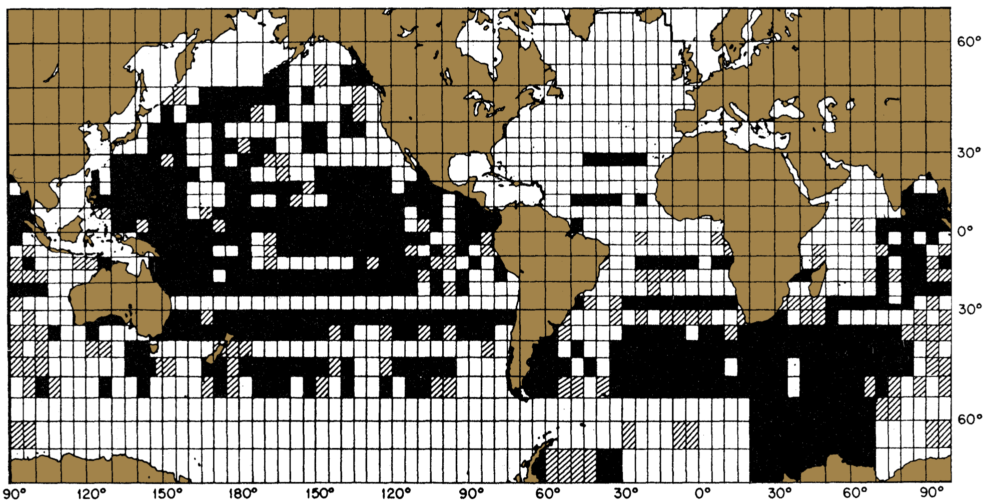
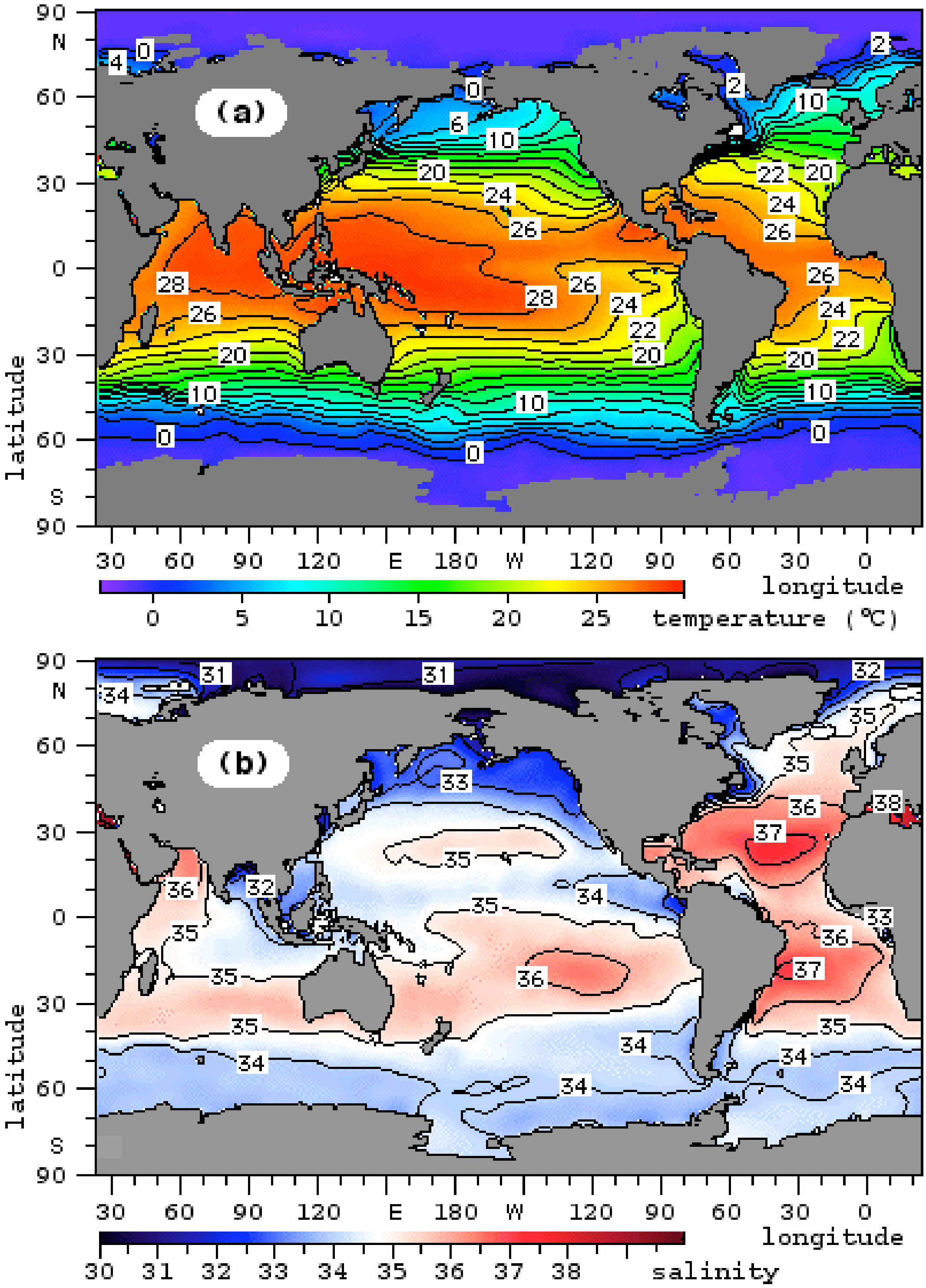
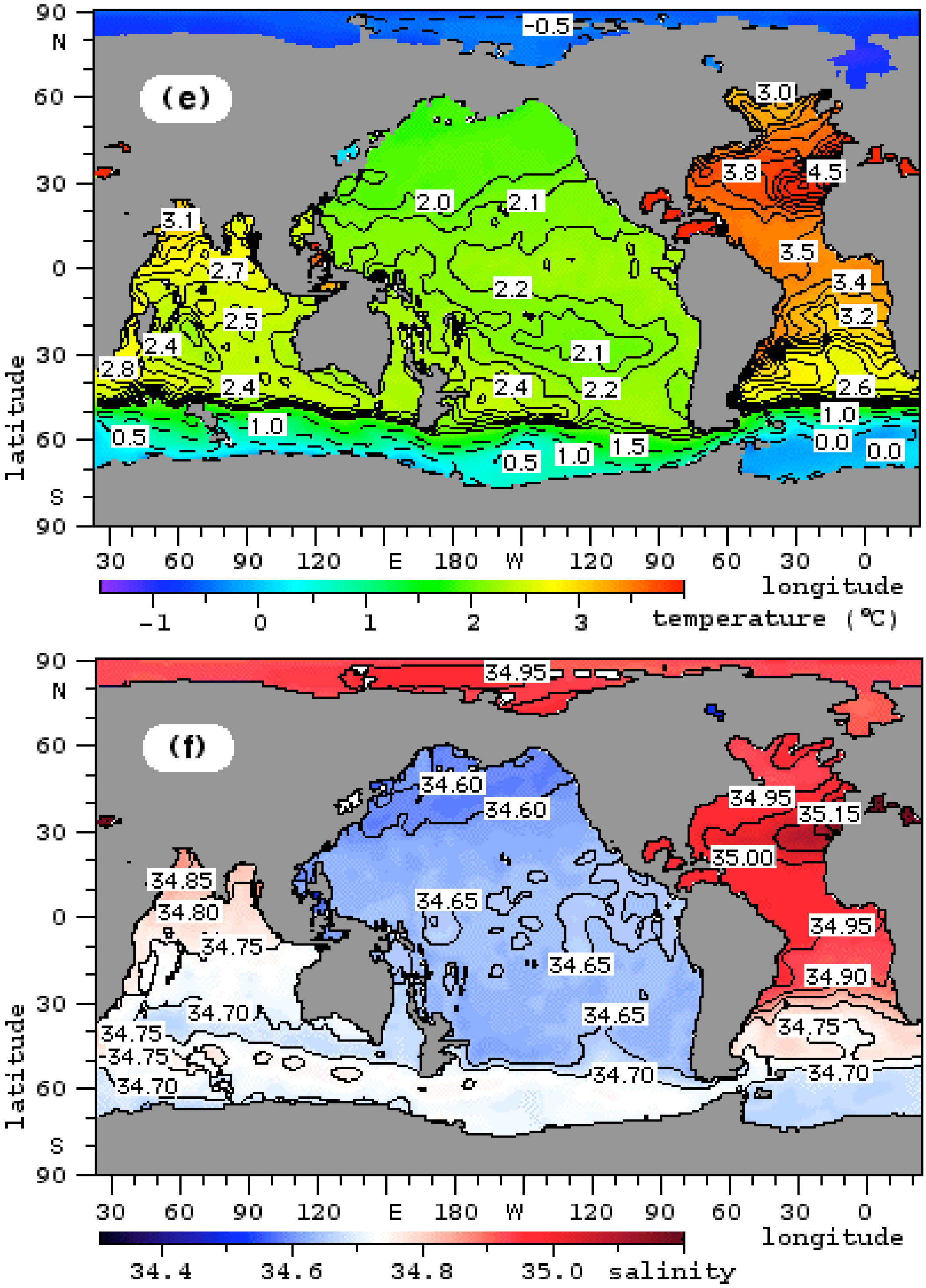


Fig. 2.3. World wide distribution of oceanographic stations of high data quality shortly before 1980. Unshaded 5° squares contain at least one high-quality deep station. Shaded 5° squares contain at least one high-quality station in a shallow area. Black 5° squares contain no high-quality station. Adapted from Worthington (1981)


(a)
90 N 60 30 0 30 60 S 90
latitude
30 60 90 120 E 180 W 120 90 60 30 0
longitude
0 5 10 15 20 25
temperature (°C)
(b)
90 N 60 30 0 30 60 S 90
latitude
30 60 90 120 E 180 W 120 90 60 30 0
longitude
30 31 32 33 34 35 36 37 38
salinity


(e)
-0.5
3.0
3.8
4.5
3.1
2.0
2.1
2.7
3.5
3.4
2.2
2.5
3.2
2.4
2.1
2.8
2.4
2.4
2.2
2.6
1.0
1.0
0.5
0.0
0.0
1.5
1.0
0.5
90 N
60
30
0
30
60
S 90
latitude
30 60 90 120 E 180 W 120 90 60 30 0
longitude
-1 0 1 2 3
temperature (°C)
(f)
34.95
34.60
34.60
34.95
35.15
35.00
34.85
34.80
34.65
34.75
34.95
34.65
34.90
34.70
34.65
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34.75
34.75
34.70
34.70
34.70
latitude
longitude
34.4 34.6 34.8 35.0 salinity

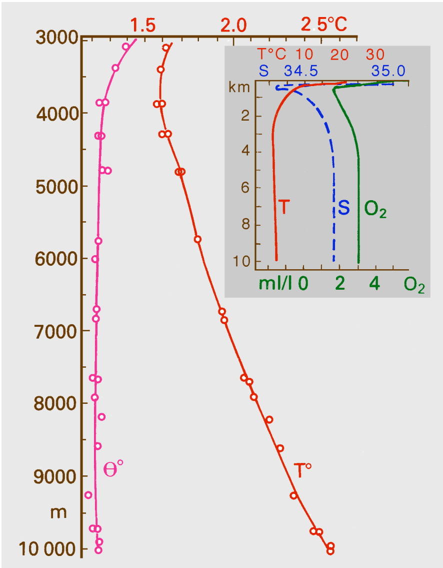

Fig. 2.6. Temperature T and potential temperature Θ in the Philippines Trench.

The inset also shows salinity S and oxygen O_2. From Bruun *et al.* (1956)

Precise knowledge of the density field is the basis for the second step, accurate calculation of the pressure field $p(z)$ from the hydrostatic relation

$$\partial p / \partial z = g \rho \quad , \qquad (2.2)$$

where g is gravity, $g = 9.8$ m s^{-2}, and depth z increases downwards. This equation is not uniformly valid (it does not hold for wind waves, for example); but it can be shown that it holds very accurately, to the accuracy of eqn (2.1), if it is applied to situations of sufficiently large space and time scales. It forms the basis of regional oceanography.

Evaluation of the pressure field from the hydrostatic equation involves a vertical integration of density. The advantage of an integration is that it eliminates the uncertainty in the measurement of depth as a source for inaccuracy. Its disadvantage is that it requires a reference pressure as a starting point. Without that information, eqn (2.2) can be used to get *differences* between pressures at different depths. An alternative way, which is common practice in oceanography, is to determine the distance, or depth difference, between two surfaces of constant pressure. For this purpose, a quantity called steric height h is introduced and defined as

$$h\ (z_1, z_2) = \int_{z_1}^{z_2} \delta\ (T,\ S,\ p)\ \rho_o dz \quad , \qquad (2.3)$$

where ρ_o is a reference density, and

surface p_1 and draw contours of constant steric height. The first method is well known from meteorology; daily weather forecasts are based on maps of isobars at sea level (considered flat for the purpose of meteorology). In oceanography the position of the sea surface is unknown and has to be determined by analysis. Oceanographers therefore map the shape of the sea surface by showing contours of equal steric height relative to a depth of no motion, where pressure is assumed to be constant.

It is easy to show - subject to our assumption of a depth of no motion - that at any depth level, contours of steric height coincide with contours of constant pressure. The hydrostatic relation (eqn 2.2) tells us that if pressure is constant at $z = z_o$, the quantity $\rho_o\, g\, h\,(z, z_o)$ measures the pressure variations along a surface of constant height z. Thus, a contour map of h is an isobar map scaled by the factor $\rho_o\, g$ (see Figure 2.7).

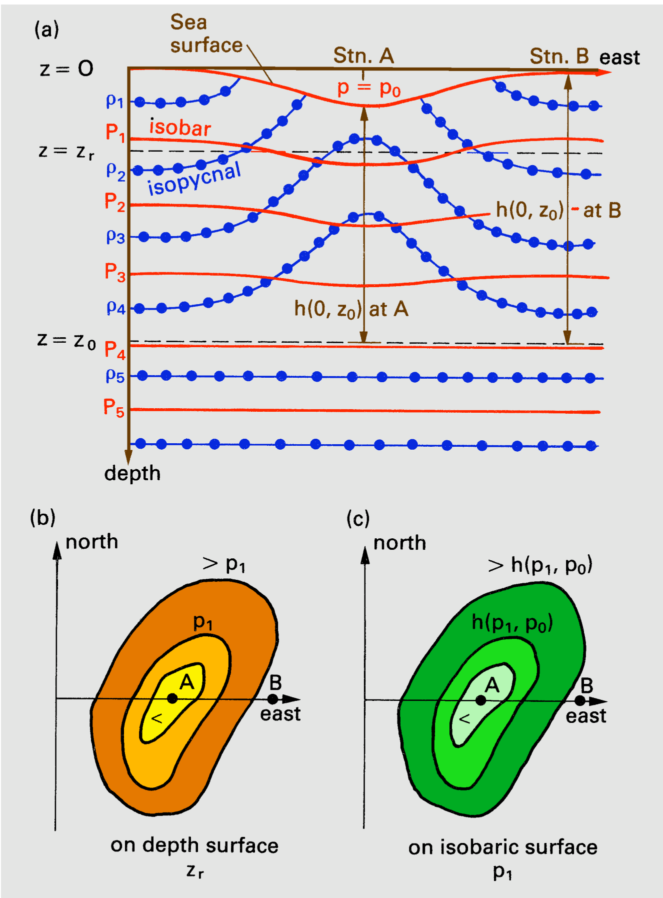

Fig. 2.7. Schematic illustration of steric height as a measure of distance between isobaric surfaces, and of the relationship between maps of isobars at constant height and maps of steric height at constant pressure.
(a) Distribution of isobars and isopycnals: at any depth level above $z = z_o$, water at station A is denser than water at station B. As the weight of the water above $z = z_o$ is the same, the water column must be longer at B than at A. The steric height of the sea surface relative to $z = z_o$ is given by $h(p_o, p_4)$, which in oceanographic applications is often given as $h(0, z_o)$, i.e. with reference to depth rather than pressure. The difference is negligible.
(b) The corresponding pressure map at constant depth $z = z_r$. (c) The corresponding map of steric height at constant pressure $p = p_1$.
The diagram requires some study, but it is well worth it; understanding these principles is the basis for the interpretation of many features found in the oceanic circulation.

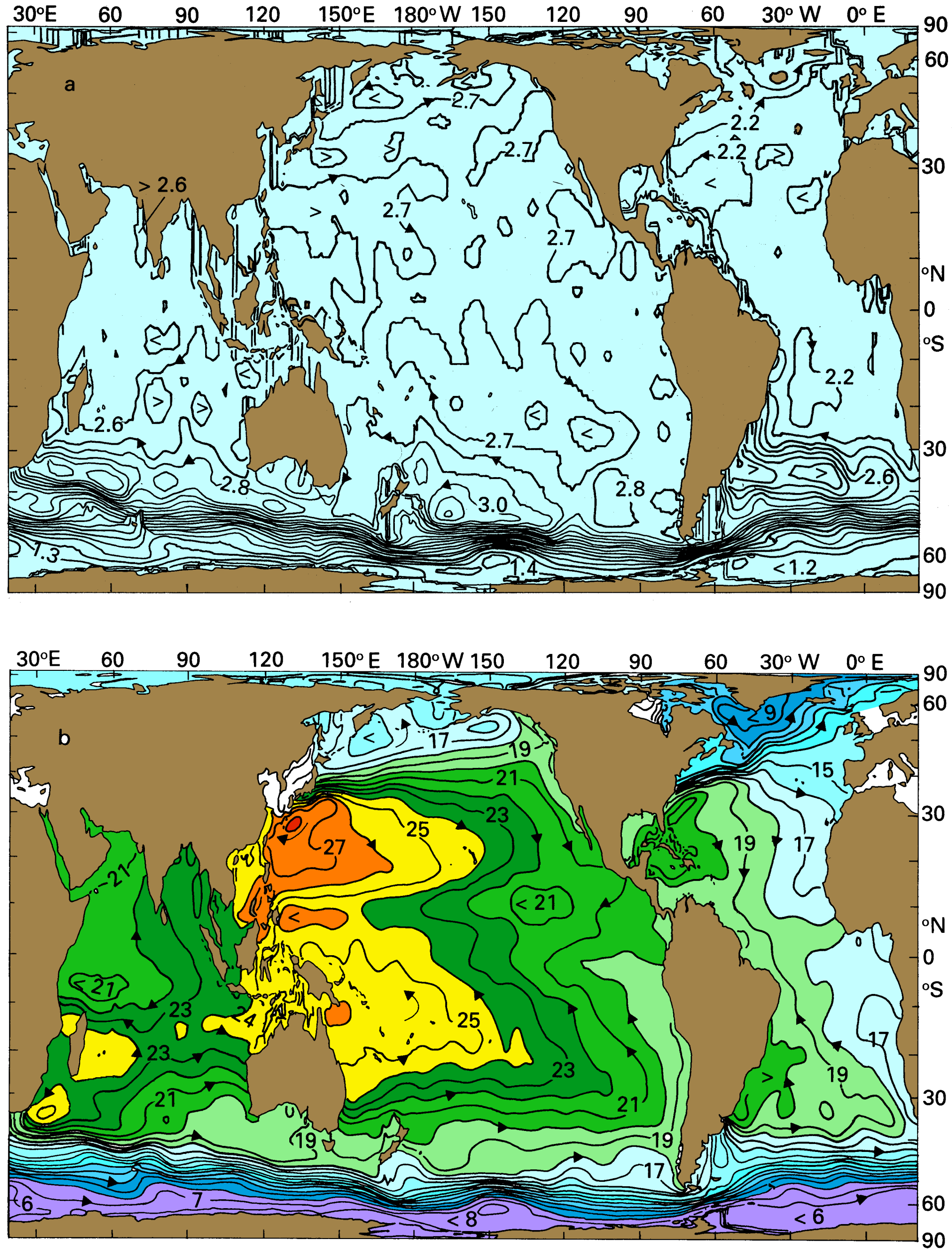

Fig. 2.8. Dynamic height ($m^2\ s^{-2}$), or steric height multiplied by gravity, for the world ocean. (a) at 1500 m relative to 2000 m, (b) at 0 m relative to 2000 m. Arrows indicate the direction of the implied movement of water, as explained in Chapter 3. (Divide contour values by 10 to obtain approximate steric height in m.) From Levitus (1982).