combine water mass analysis with our knowledge of the constraints on possible flows posed by geostrophy and Ekman dynamics. This approach, which infers water movement from the effect it has on the distribution of oceanic parameters, is known as "inverse modelling". This is a field of active research, mathematically quite complex and beyond the scope of this book. An understanding of the processes involved in water mass formation and of the life history of water masses is, however, required in regional oceanography.

Water masses, water types, and T-S diagrams

We begin with a brief review of concepts and definitions. In the past, oceanographers have used terms such as water mass and water type rather loosely to describe waters with common or outstanding properties. For the purpose of a quantitative description of the transport of water properties in the ocean it is necessary to introduce unambiguous definitions, even though they may not always correspond with earlier uses of the terms. We define a *water mass* as a body of water with a common formation history. An example of water mass formation is the cooling of surface water near the Antarctic continent, particularly in the Weddell Sea, which increases the density and causes the water to sink to great depth. All water which originates from this process shares the same formation history and is called Antarctic Bottom Water. It is found in all oceans well beyond its formation region, extending even into the northern hemisphere.

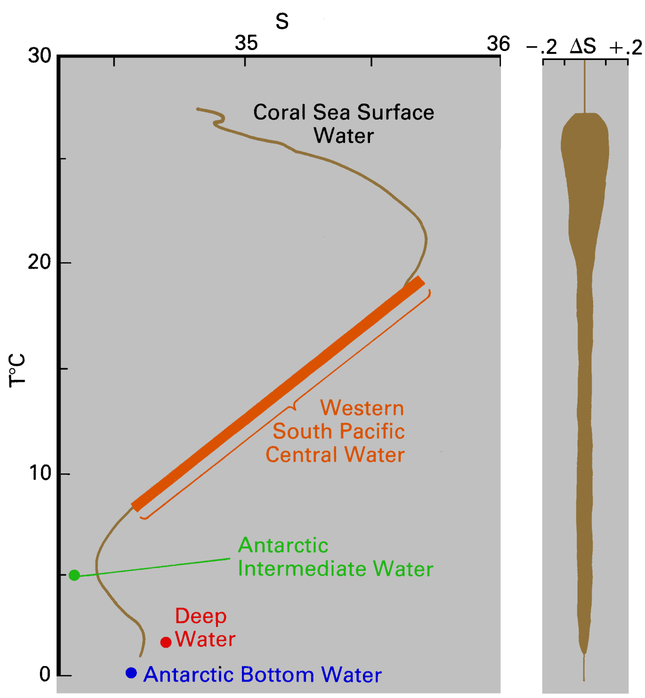

Fig. 5.1. Mean T-S diagram and standard deviation ΔS of salinity (for given temperatures) in the eastern Coral Sea, in comparison to water mass definitions in the south Pacific Ocean. Large dots and the heavy line indicate water mass properties in the formation regions, which for all but Surface Water are located far outside the Coral Sea. The standard deviation was determined by comparing stations in the region with a space average and does not include variability in time. Similar standard deviations can be derived for temperature and other properties. Based on Tomczak and Hao (1989).

The seasonal, tropical, and permanent thermoclines

Most water masses are formed at the ocean surface. This is a region of strong mixing, which produces uniformity of properties above a layer of rapid property change. The term thermocline was occasionally used for this layer in the last two chapters. In the context of water mass formation it is necessary to sharpen our definition of a thermocline.

Oceanographers refer to the surface layer with uniform hydrographic properties as the *surface mixed layer*. This layer is an essential element of heat and freshwater transfer between the atmosphere and the ocean. It usually occupies the uppermost 50 - 150 m or so but can reach much deeper in winter when cooling at the sea surface produces convective overturning of water, releasing heat stored in the ocean to the atmosphere. During spring and summer the mixed layer absorbs heat (moderating the earth's seasonal temperature extremes by storing heat until the following autumn and winter; this aspect is discussed in detail in Chapter 18), and the deep mixed layer from the previous winter is covered by a shallow layer of warm, light water. During this time mixing does not reach very deep, being achieved only by the action of wind waves. Below the layer of active mixing is a zone of rapid transition, where (in most situations) temperature decreases rapidly with depth. This transition layer is called the *seasonal thermocline*. Being the bottom of the surface mixed layer, it is shallow in spring and summer, deep in autumn, and disappears in winter (An example can be seen in Figure 16.27). In the tropics, winter cooling is not strong enough to destroy the seasonal thermocline, and a shallow feature sometimes called the *tropical thermocline* is maintained throughout the year. Figure 5.2 shows the thickness of the surface isothermal layer. It was obtained using the data from Levitus (1982) by extracting the depth where the temperature differed from the temperature at the surface by more than 0.5°C and is representative of the depth of the seasonal thermocline.

Mixed layer dynamics are quite complex, and we refer the reader to other text books (for example Pickard and Emery, 1990) for details. The point of interest here is that turbulent energy levels in the winter mixed layer drop drastically, by a factor of 1000 or more, after it is covered by lighter water during spring - mixing then becomes so slight that the water characteristics established before the turbulence falls off become "frozen". These layers of "fossilized mixing", which retain their signatures for long time spans, are the source layers of most water masses, and their generation is the essence of water mass formation.

The depth range from below the seasonal thermocline to about 1000 m is known as the *permanent* or *oceanic thermocline*. It is the transition zone from the warm waters of the surface layer to the cold waters of great oceanic depth and provided the model for the interface of our $1^1/_2$ layer representation of the ocean. The temperature at the upper limit of the permanent thermocline depends on latitude, reaching from well above 20°C in the tropics to just above 15°C in temperate regions; at the lower limit temperatures are rather uniform around 4 - 6°C depending on the particular ocean. Wherever the word thermocline is used without further specification in this book, the term refers to the permanent thermocline. Again, a detailed description of the various thermoclines and their seasonal life cycle can be found in other textbooks (Dietrich *et al.*,1980; Pickard and Emery, 1990).

tion and Ekman pumping. Figure 4.3 tells us that the subtropics are a region of negative curl(τ/*f*), which means that water is pumped downwards. As this water is not denser than the underlying water, it gets injected into intermediate depths, following the isopycnal surface of its own density. This process, which is known as *subduction* and illustrated in Figure 5.3, is responsible for the formation of the water masses in the permanent thermocline. Its intensity varies with the seasons, partly in response to variations in the strength of the Ekman pumping but mainly because of the seasonal development of the seasonal thermocline: The summer mixed layer depth is shallower than the depth of the winter mixed layer; the water trapped between (the fossilized mixing region) is available for subduction. If, for example, in late autumn and winter the bottom of the mixed layer (z_1 in Figure 5.3) progresses downward faster than the surface water moves downward as a result of Ekman pumping, water pumped from the surface during summer is caught by the expanding surface mixed layer before it can escape into the permanent thermocline, and the properties of the water subducted into the permanent thermocline are determined by the surface water properties during late winter only. In other words, although subduction is a permanent process, water mass formation occurs only in late autumn and winter. This can be verified by comparing the properties of the surface mixed layer in the Subtropical Convergence with those of the permanent thermocline in the tropics, i.e. by comparing T-S diagrams along the lines *ABCD* and *A'B'C'D'* in Figure 5.3. An example of such a comparison from the Indian Ocean is shown in Figure 5.4; it demonstrates that over the T-S range of the thermocline the two T-S diagrams are nearly identical in late winter (August - October) but differ during all other seasons.

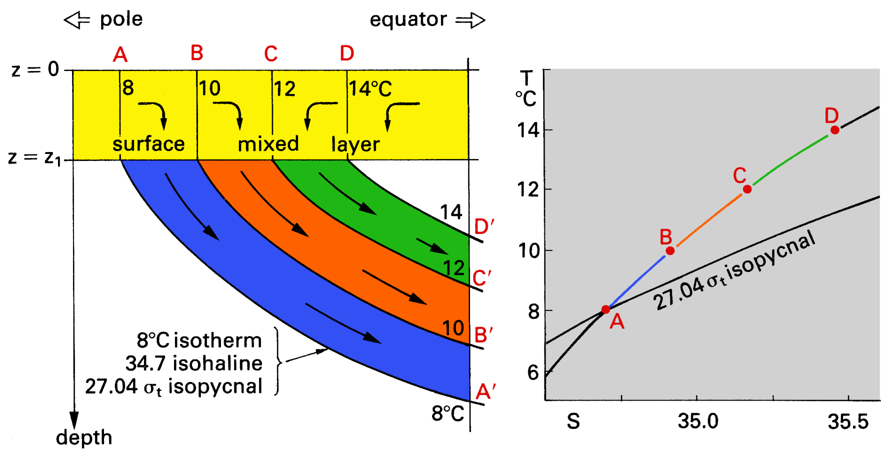

Fig. 5.3. Sketch of water mass formation by subduction in the Subtropical Convergence. The T-S diagram shows both the meridional variation of temperature and salinity between stations *A* and *D*, and the vertical variation equatorward of station *D* from the surface down along the line *A'B'C'D'*. For more detail, see text.

Water masses subducted into the thermocline are commonly known as Central Water. The term was introduced sixty years ago to differentiate between thermocline water of the

shows the thickness of the surface isopycnal layer, i.e. the layer over which density does not change. This map was obtained by determining the depth where density is larger than the density at the surface by an amount which corresponds to the temperature change of 0.5°C used in the construction of Figure 5.2. This amount depends strongly on temperature and also on salinity. To make sure that the distributions of Figures 5.2 and 5.6 are comparable, the density increment is not constant across the map but was evaluated locally from the surface temperature and salinity. Figure 5.7 shows a map of the differences between the calculated isothermal and isopycnal layer thicknesses.

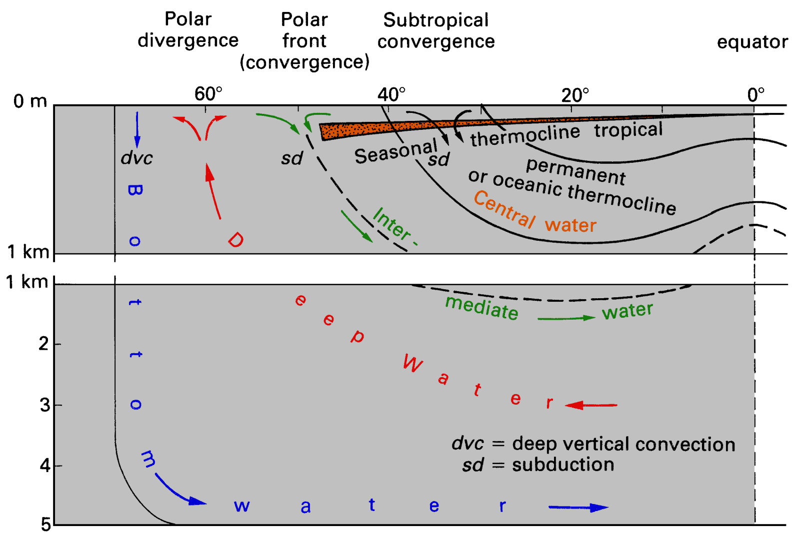

Fig. 5.5. Meridional section through a hypothetical ocean, showing the permanent thermocline, the seasonal and tropical thermoclines, the various surface convergences and divergences, and the major water masses. Note the scale change at 1000 m depth, which underestimates the volume of Deep and Bottom Water. On the other hand, the importance of the tropics does not come out in this graph since it does not show the convergence of meridians towards the poles.

If the classical assumption were correct, the differences shown in Figure 5.7 should be close to zero everywhere. There are indeed large ocean areas which display very small differences. But we also notice regions where the difference is clearly not zero. In the tropics, the difference between isothermal and isopycnal layer depth is often positive, indicating a density change within the isothermal layer. The density change is caused by salinity stratification. In these regions, the halocline is the true indicator of mixed layer depth. The tropical surface water has low salinities and high temperatures and therefore very low densities; it spreads in a thin layer over the top of the water column. Subtropical surface water, on the other hand, has high salinities; when this water is subducted in regions of Ekman pumping it cannot be pushed very deep before it spreads sideways, forming a salinity maximum below the surface layer. If the temperature gradient is insignificant, the result of both processes is a halocline within the isothermal layer.

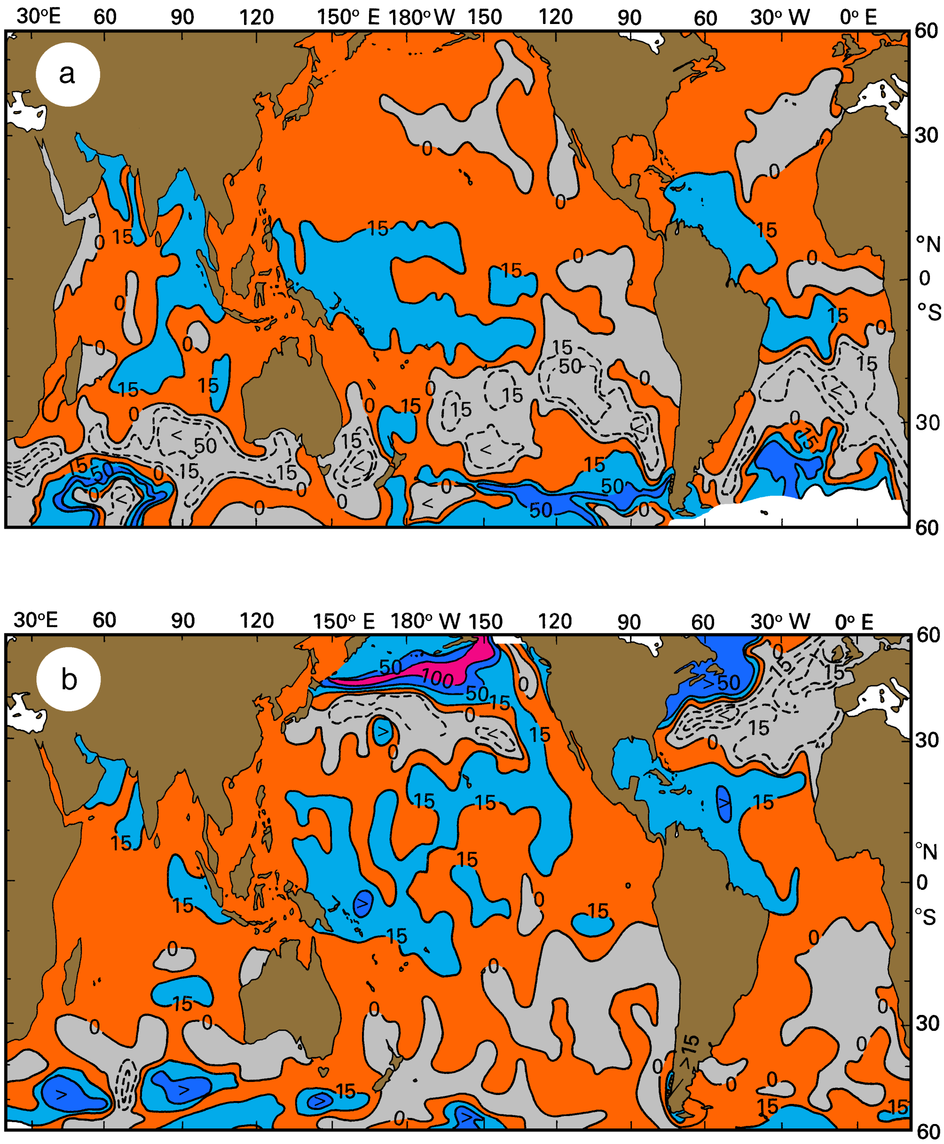

Fig. 5.7. Mean depth difference (m) between isothermal and isopycnal layer (barrier layer thickness). (a) August - October, (b) February - April. Broken contours indicate negative differences. Adapted from Sprintall and Tomczak (1990).

reaches down into the thermocline, an important sink is located at the bottom of the mixed layer where cold water is entrained from below. The presence of a barrier layer means that the water entrained into the mixed layer has the same temperature as the water above.