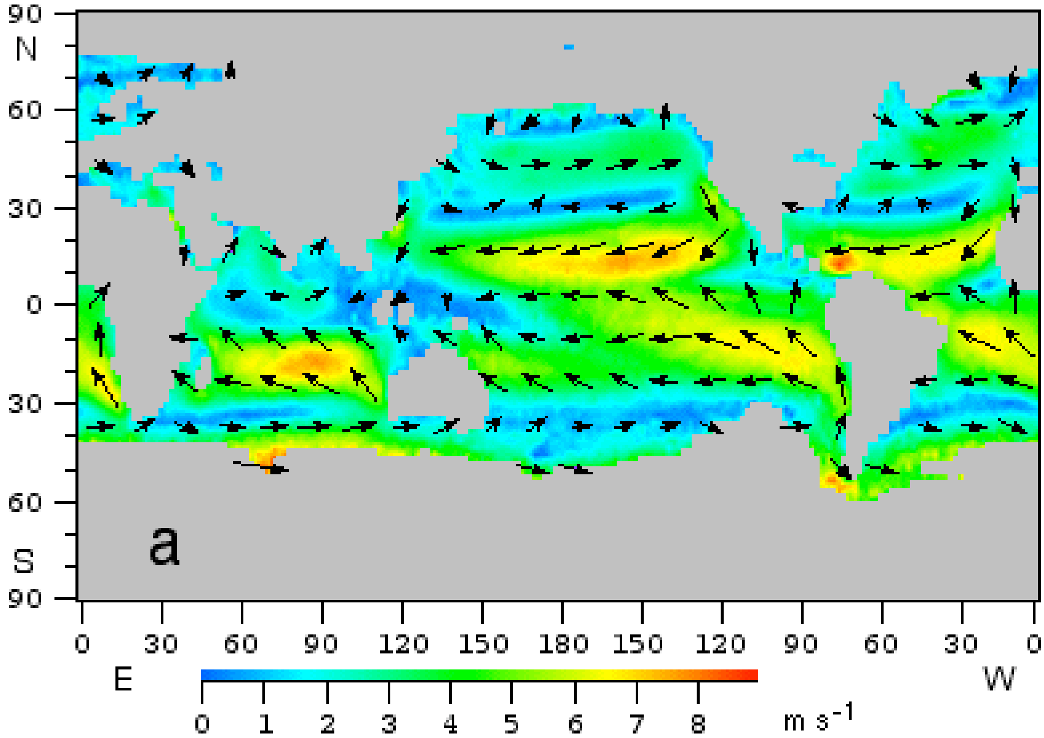
features which may or may not have been named before (probably to someone else's liking). In this text we adopt the principle that geographic features are referred to under the names used on the GEBCO charts (IHO/IOC/CHS, 1984). In references to currents and fronts we use generally accepted names where they exist, preferring names which include a reference to geographic features (e.g. Peru/Chile Current, not Humboldt Current). Universally accepted names for water masses exist only for the major oceanic water masses; other water masses can be found under a variety of names in the literature. Our usage of water mass names is based partly on historical use, partly on the systematic approach to water mass analysis described in Chapter 5. Wherever possible we use names already introduced by others and do not invent our own.

We return to our discussion of the most important physical principles. A discussion of what in essence are elements of geophysical fluid dynamics is not to everyone's liking; nevertheless, some of the principles determining ocean flows turn out to be quite simple, and by understanding them it is possible to go a long way towards understanding the role of the ocean in climate variations, both natural or man-made. The ocean is unique in this respect; it can absorb heat in one region, and restore it to the atmosphere (perhaps decades or centuries later) at a quite different place. This has become a topic of widespread interest and intensive research in recent years, and by spending some effort on understanding the underlying principles readers will find that they can gain an understanding of much of the modern literature on this topic.

If we exclude tidal forces, which have little effect on the long-term mean properties of the ocean, the oceanic circulation is driven by three external influences: wind stress, heating and cooling, and evaporation and precipitation - all of which, in turn, are ultimately driven by radiation from the sun. To understand why temperature, salinity and all other properties of the oceans' waters are distributed the way they are, a basic knowledge about these external forces is necessary. We therefore begin our description of the geography of the oceans with a brief look at the atmosphere, which holds the key to the question how the energy received from the sun keeps the ocean circulation going.

We note at the outset that this approach ignores the fact that the circulation of the atmosphere is in turn influenced by the distribution of oceanic properties, such as sea surface temperature (in oceanography often abbreviated as SST) and the distribution of sea ice. In particular, the amount of evaporation from the ocean depends strongly on the sea surface temperature; and when the evaporated water is returned as rain it releases its latent heat into the surrounding air. This heating is probably the strongest driving force for the atmospheric winds. To understand the oceanic and atmospheric circulation fully we should treat them as a single system of two interacting components, coupled at the air-sea interface through the fluxes of momentum, heat, and mass. This of course complicates the task and could not be achieved with traditional oceanographic or meteorological tools. Although the stage has now been reached where treatment of the ocean and the atmosphere as a coupled system is becoming more and more feasible, it seems good advice for an introductory text to follow the traditional approach and consider the state of the atmosphere as determined independently of the state of the ocean. We shall return to the question of interaction between ocean and atmosphere in the last three chapters when we discuss interannual climate fluctuations and long-term climate change.

The amount of heat radiation received by the outer atmosphere varies from the equator to the poles. The difference varies with the seasons, but on average the equatorial regions receive much more heat than the polar regions. The cold air at the poles is denser than the



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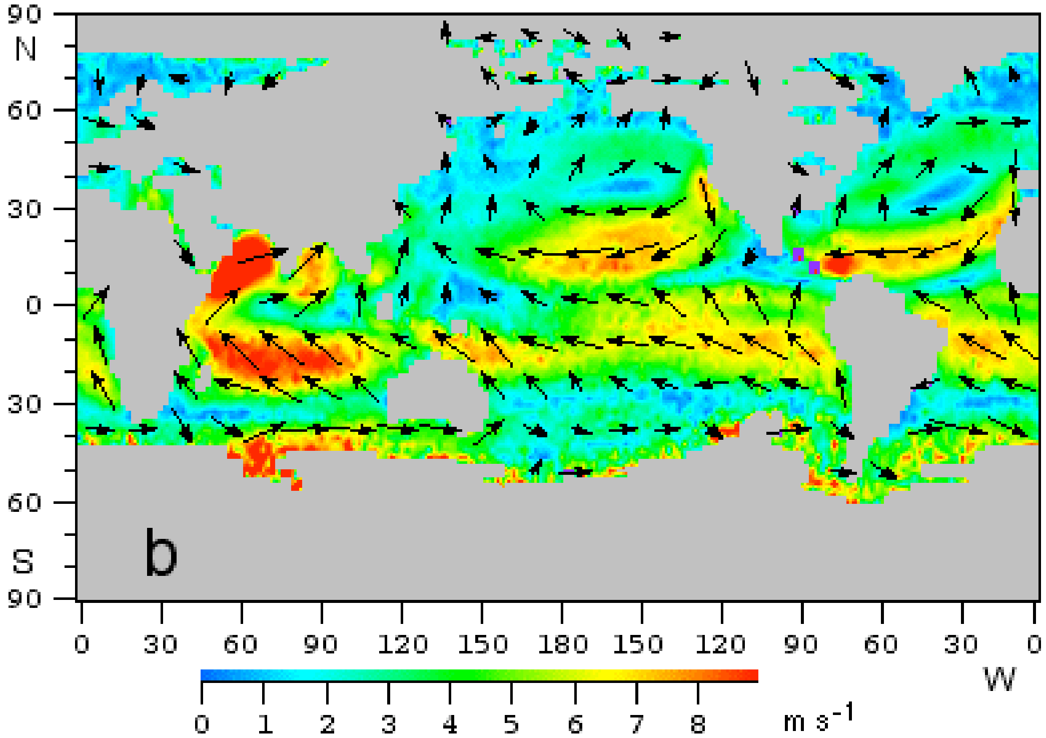

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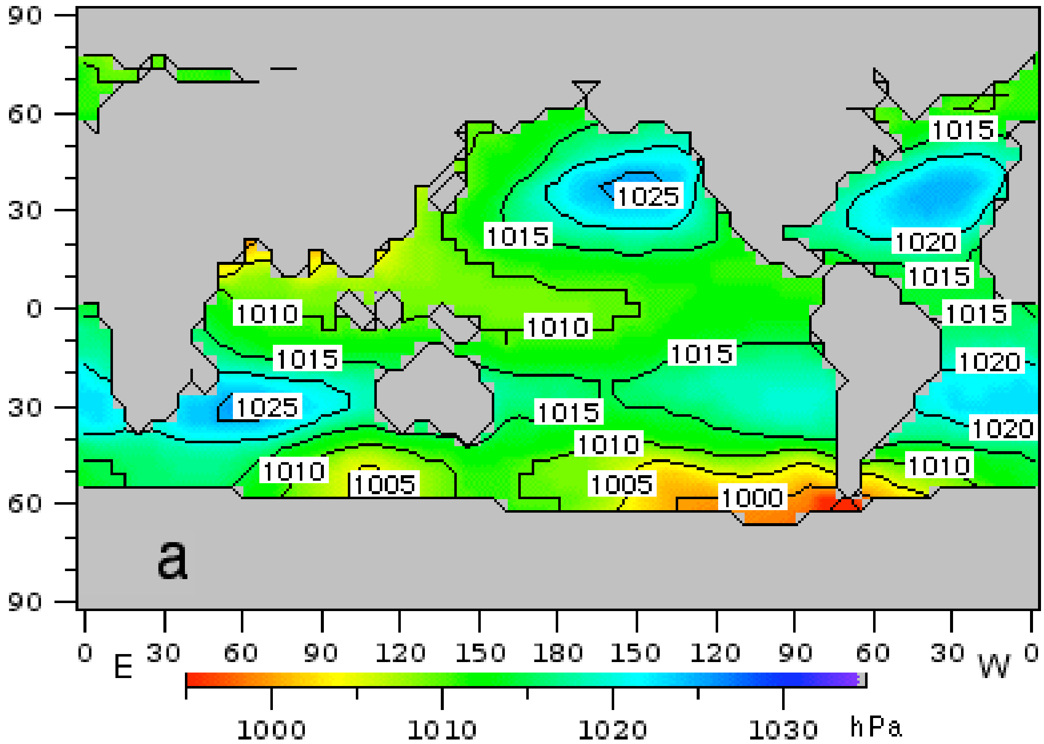


comes from the east and flows towards west. This can cause confusion to people who rarely, if ever, go to sea; but it is easily understood and remembered when related to practical experience with winds and ocean currents. On land, it is important to know from where the wind blows: any windbreak must be erected in this direction. Where the wind goes is of no consequence. At sea, the important information is where the current goes: a ship exposed to current drift has to stay well clear from obstacles downstream. Where the water comes from is irrelevant.

From the point of view of oceanography, knowledge of the planetary wind field above the sea surface has always been unsatisfactory. It is difficult to obtain quantitatively accurate wind data from the oceans, particularly from regions remote from major shipping routes. Advances in numerical modelling of the atmosphere and the use of drifting buoys equipped with pressure sensors greatly improved our knowledge of winds over the Antarctic ocean, but the data are still not adequate for many oceanographic purposes. What is needed in oceanography is accurate measurement of wind gradients rather than pure wind strength, which places much more stringent quality requirements on the individual data. However, significant progress has been made, and will be made over the next decade.

We include for completeness information on the distribution of air pressure at sea level. Air pressure variations affect the ocean only indirectly, through the associated wind systems, and oceanographers are not usually concerned with air pressure maps. Meteorologists need air pressure maps as a basic tool of their trade; but they prepare them for their own purposes. In contrast to physical oceanography, where (with the exception of

intense winter high over Mongolia and is responsible for the monsoon winds which dominate the Indian Ocean.

When the wind field is compared with the pressure field it is seen that the nearly zonal pressure distribution in the southern hemisphere produces strong and persistent Westerlies between 40° and 60°S. The remainder of the ocean is dominated by wind systems characterized by wind movement around centres of high and low pressure. During northern summer, for example, the Trade Wind and the Westerlies over the North Pacific Ocean are elements of a wind system in which air circulates around an atmospheric high in a clockwise manner. It is a general rule that air moves around atmospheric highs in a clockwise direction in the northern hemisphere and in an anti-clockwise direction in the southern hemisphere. Likewise, movement around atmospheric lows is anti-clockwise in the northern hemisphere, clockwise in the southern hemisphere. In meteorology and oceanography, circulation around a centre of low pressure is called cyclonic, circulation around centres of high pressure is called anti-cyclonic.

Winds drive ocean currents by releasing some of their momentum to the oceanic surface layer. The important quantity in this process is the wind stress, which is roughly a quadra-

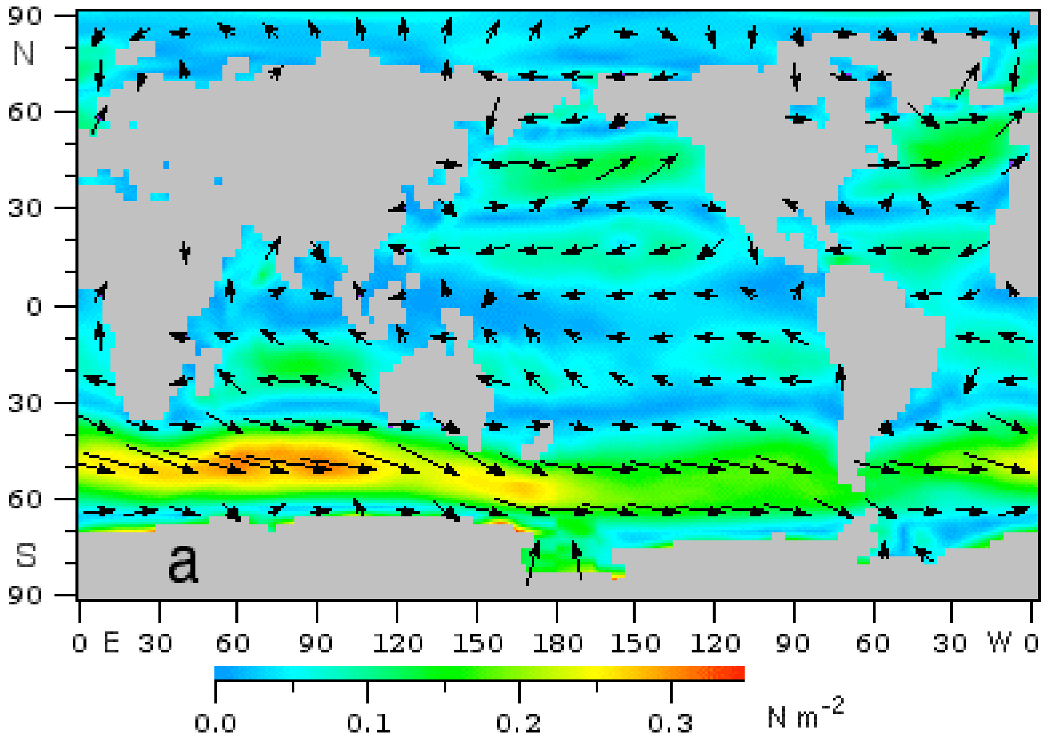


Fig. 1.4. Wind stress over the World Ocean. (a) Annual mean, (b, page 9) June - August, (c, page 9) December - February. Data from http://ferret.wrc.noaa.gov/las/, the NOAA Live Climate Data Server using the Trenberth *et al.* (1989) climatology. Colour indicates wind stress magnitude.

tic function of wind speed. Our knowledge of the wind stress distribution over the ocean is even less well established than our knowledge of the wind field. Most winds contain a considerable amount of turbulence, experienced as short gusts interspersed with periods of relative calm. Because of the quadratic relationship between wind speed and wind stress, gusty winds create larger stresses than would a steady wind of the same average speed. It is possible that our standard measuring equipment does not resolve all wind gusts adequately and that as a consequence our estimates of oceanic wind stress are too low. Direct measurement of the wind stress is difficult; it requires special equipment and has only been done in a small number of locations. The few direct observations were used to develop a formula useful for routine estimation of wind stress. The formula links the stress $\boldsymbol{\tau}$ to routine merchant ship observations of wind speed, air and sea temperatures, wave state and other relevant quantities. $\boldsymbol{\tau}$ is a vector with units of force per unit area (kg m$^{-1}$ s$^{-2}$, or Newton per square metre) that points directly downwind; its magnitude is calculated from

$$| \boldsymbol{\tau} | = C_d \, \rho_a \boldsymbol{U}^2 \, , \qquad (1.1)$$

where $\rho_a$ is air density (about 1.2 kg m$^{-3}$ at mid-latitudes), $\boldsymbol{U}$ is wind speed at 10 m

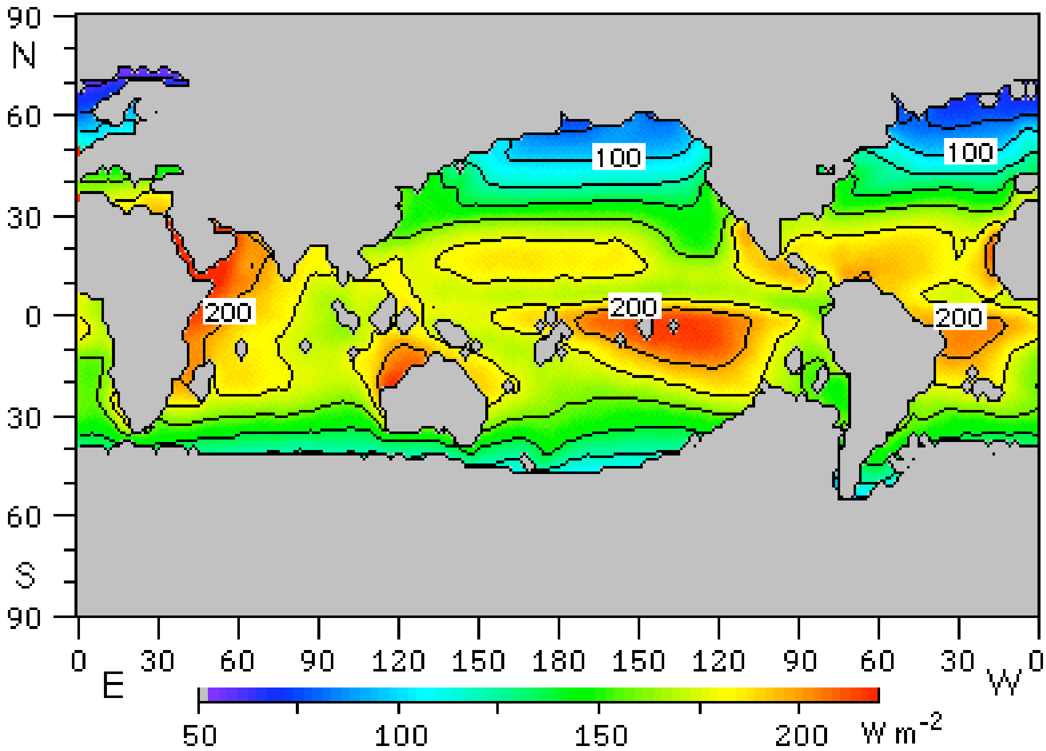


Fig. 1.5. Annual mean solar radiation (W m$^{-2}$) received at sea level. Data from Oberhuber (1988). 200 W m$^{-2}$ will warm a layer of water 50 m deep by about 2.5°C per month if unopposed by heat losses from other effects. Regions with insufficient data to construct an annual mean are gray. The contouring interval is 20 W m$^{-2}$.

the effect this distribution has on the distribution of atmospheric water vapour and clouds. As an example, the wind convergence between the northern and southern hemispheres' Trades, known as the Intertropical Convergence Zone or ITCZ, consistently shows strong cloud cover and high rainfall (this will be discussed in more detail in Chapter 18) and is thus characterized by a regional minimum of solar radiation. The heat flux through the ocean surface is determined by the balance between four components - incoming solar radiation, outgoing back radiation, heat loss from evaporation, and mechanical heat transfer between the ocean and the atmosphere (for details see Dietrich *et al.*, 1980, or Pond and Pickard, 1983), and their sum can be positive or negative. Each of the four contributions are hard to estimate accurately, so their balance is not very accurately established. Nevertheless, the need for heat flux values as input for ocean models caused several researchers to draw world maps of the balance (Figure 1.6).

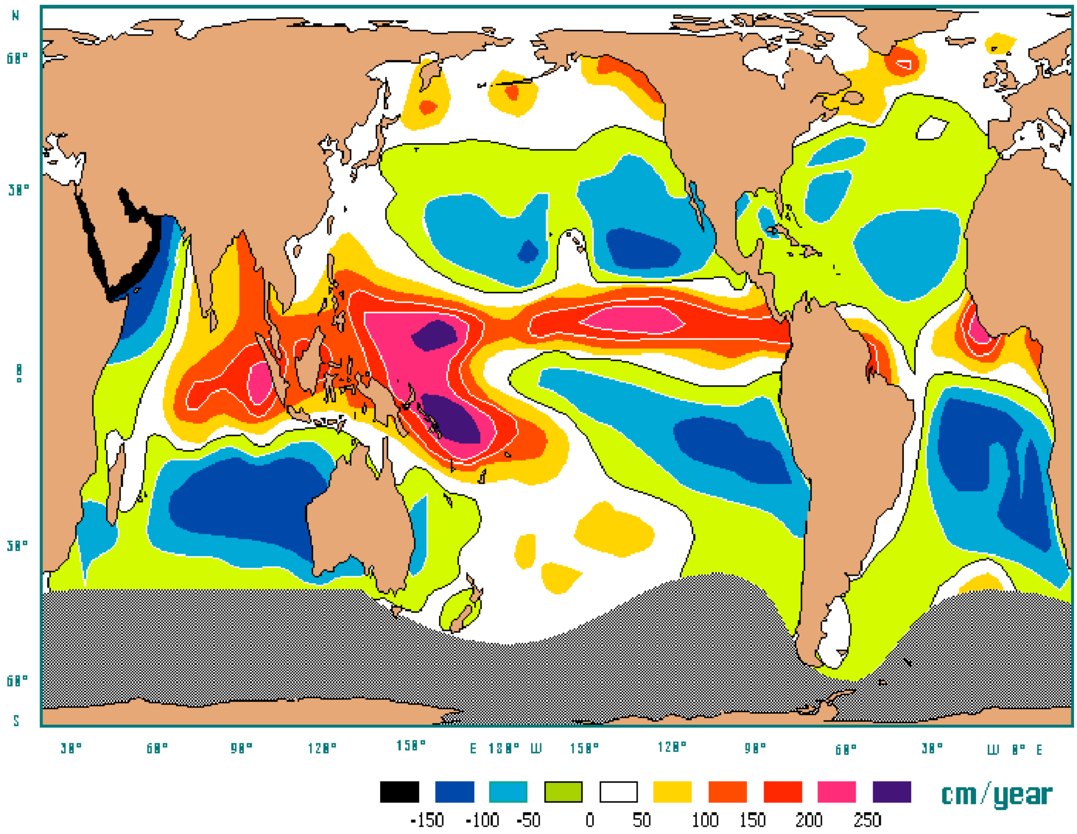


Fig. 1.7. Annual mean difference precipitation - evaporation (*P* - *E*, cm per year). Data from Oberhuber (1988). Positive values indicate freshwater gain. The quantity *E*-*P*, often seen in oceanography, is the negative of the quantity displayed here.