Chapter 1

Introduction: What drives the ocean currents?

Sixty years ago, this textbook would have been titled "Introductory Geography of the Oceans". Physical oceanography then was a close relative of physical geography and shared its descriptive character. This period culminated in textbooks such as *Geographie des Atlantischen Ozeans* (1912) and *Geographie des Indischen und Stillen Ozeans* (1935) by G. Schott, books which conveyed to the reader through a passioned yet accurate description of its features the fascination which the oceanic environment exerts on the oceanographer. Oceanography has come a long way since then, having concentrated on understanding the physical principles that drive the oceans and using the tools of mathematics and theoretical fluid dynamics to forecast their behaviour. Students of oceanography now spend more time trying to come to grips with vorticity, inverse methods and normal mode analysis than learning about the features of the deep sea basins and marginal seas or about the climatic regions of the oceans. And this is rightly so, for little is learned in science through mere description; analysis and conclusion are required before anyone can claim to understand.

As it turns out, understanding the ocean circulation is impossible without knowledge of geographical details - the depth of certain ocean sills, for example, or the peculiarities of the wind field and its seasonal variation. To separate the facts about the geography of the ocean from acquired knowledge about its dynamics would be like separating the memorizing of the vocabulary of a new language from the learning of its grammar. What we propose to do is describe the features of the world ocean both as a systematic exercise in geography and as examples of physical principles at work.

These physical principles are sufficiently powerful and all-pervasive that it is worth introducing them first. This and the following four chapters are a summary of some of the principles and their consequences, and will serve as a reference for all chapters to come. Students of oceanography who are using this book as their introduction to the discipline will find them essential reading. Advanced students who use the book because of a need to brush up their knowledge on the geography of the oceans can skip the first five chapters and go straight to the chapter of interest to them. Both should take particular notice of the figures which accompany the text. With a bit of guidance, much can be learnt by looking closely at observational data. Our text will provide the guidance, but it will not go into detailed descriptions of what can be seen more easily in figures. The figures are therefore not illustrations of the text; they are an integral part of this book.

Some knowledge of the geography of the oceans is essential in regional oceanography. While we attempted to include as much relevant geographical information as possible, clarity of figures must rank higher than detail in an introductory text. Sometimes the location of a feature can be determined by consulting the index. In other cases the use of an elementary geographical atlas may be required.

One final note on the use of geographic and oceanographic nomenclature, before some readers turn the page and proceed to other chapters. Although the use of geographical names and the rules on naming newly discovered geographic features are regulated by an international advisory body, use of geographical names in oceanography is not uniform. This is particularly true for features such as currents, fronts, or water masses, which are not covered by the international regulations on the use of geographical names. Oceanographers have an unfortunate habit of trying to make their mark by putting names to their liking on

warm air at the equator; and since the air pressure at the sea surface or on land is determined by the weight of the air above the observation point, air pressure at sea level is higher at the poles than at the equator - in other words, a pressure gradient is set up which is directed from the poles toward the equator. The pressure gradient in the upper part of the atmosphere has the opposite sign.

In fluids and gases, pressure gradients produce flow from regions of high pressure to regions of low pressure. If the earth were not rotating, the response to these pressure gradients would be direct and simple. Two circulation cells would be set up, one in either hemisphere, by the differential solar heating. At sea level, winds would blow from the poles to the equator; the air would then rise and recirculate back to the poles at great height. On a rotating earth this pattern is modified quite strongly, in two ways. Firstly, as air moves towards the equator, the rotation of the earth shifts ocean and land eastward under it. An observer moving with the land experiences the air movement as an "easterly" wind, i.e. a wind blowing from the east, with an equatorward component. In the tropics and subtropics this wind is known as the Trade Wind, in polar latitudes it occurs as the Polar Easterlies. The outcome is that the wind no longer blows from regions of high pressure to regions of low pressure along the most direct route but tends to follow contours of constant pressure (isobars) - hence the usefulness of isobars on the daily weather map in the television news.

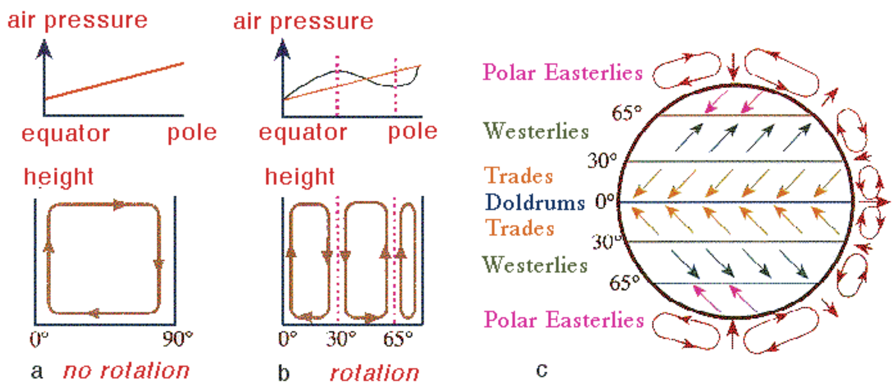


Fig. 1.1. Schematic diagram of the meridional air pressure distribution and associated air movement (a) on a non-rotating earth, (b) on a rotating earth without continents, (c) viewed from above.

Because on a rotating earth the flow of air is more zonal (directed east-west) than meridional (directed north-south), the importance of the vertical component of air movement is reduced: the flow can circle the earth with great speed without need for uplift or sinking. This produces the second, more drastic modification of the simple hemispheric cell arrangement. It turns out that zonal flow of high speed becomes unstable, creating eddies which in turn reshape the air pressure distribution. As a result, an intermediate air pressure maximum is established at mid-latitudes. The reversal of the meridional pressure gradient establishes a band of "westerly" wind, i.e. wind blowing from the west (Fig 1.1).

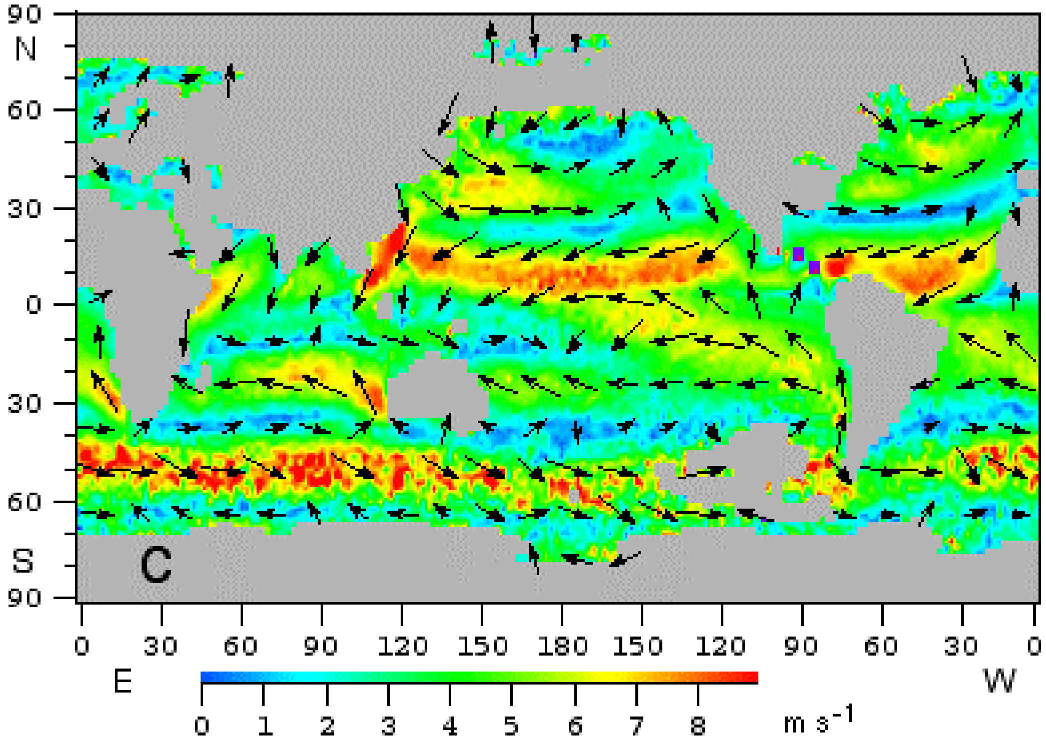


Fig. 1.2. Surface winds over the World Ocean. (a, page 4) Annual mean, (b, page 4) July mean, (c) January mean. Data from http://ferret.wrc.noaa.gov/las/, the NOAA Live Climate Data Server using the Comprehensive Atmosphere/Ocean Data Set (COADS) climatology. COADS is based on ship observations; regions without data are gray. Colour indicates wind speed.

Seafarers know them well and refer to them as the Roaring Forties, thus expressing their experience that between 40° and 50° latitude the winds are usually strong, highly variable and very gusty.

Figure 1.2 gives the winds at sea level in the real world. The features seen in Figure 1.1 come out clearly, but the presence of continental land masses modifies the atmospheric circulation further. Because air heats up faster over the continents than over the oceans during summer, and cools faster during winter, large land masses are characterized by low air pressure in summer - relative to air pressure over the ocean at the same latitude - and high air pressure in winter. This results in a deviation of average wind direction from mainly easterly or mainly westerly over some parts of the oceans. Some ocean regions experience strong seasonal variations in wind direction, including complete reversal. Such wind systems are known as monsoons.

In passing, it should be noted that the convention for indicating the direction of ocean currents differs from the convention used for wind directions. A "westerly" wind is a wind which blows from the west and goes to the east; a "westward" current is a current which

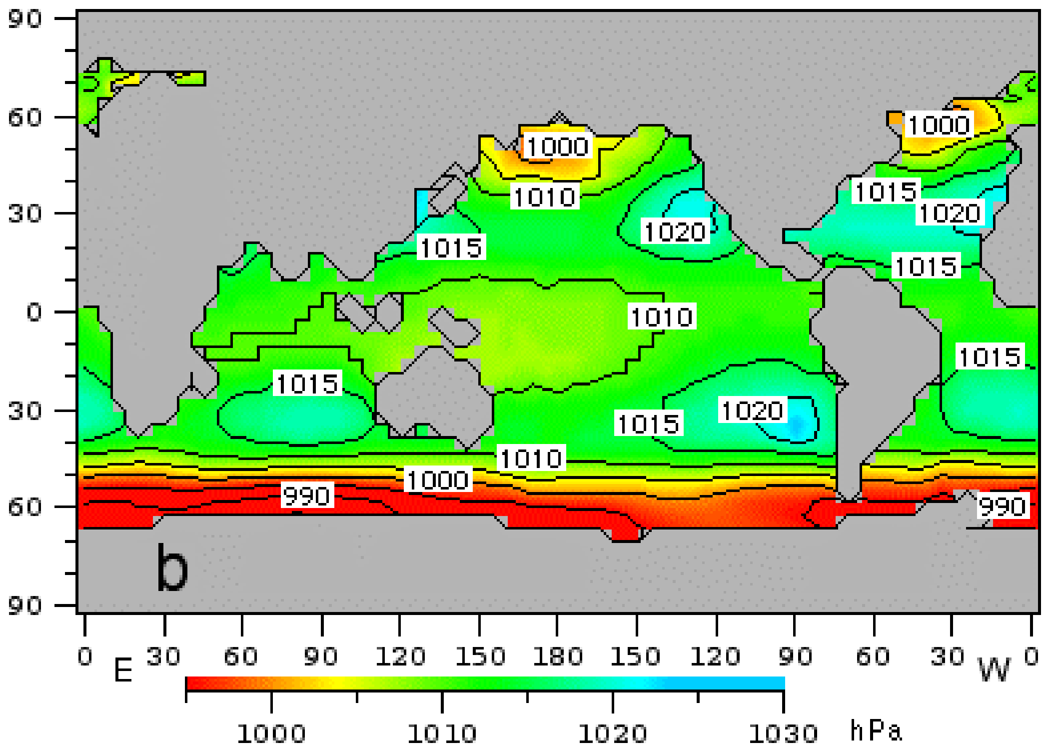
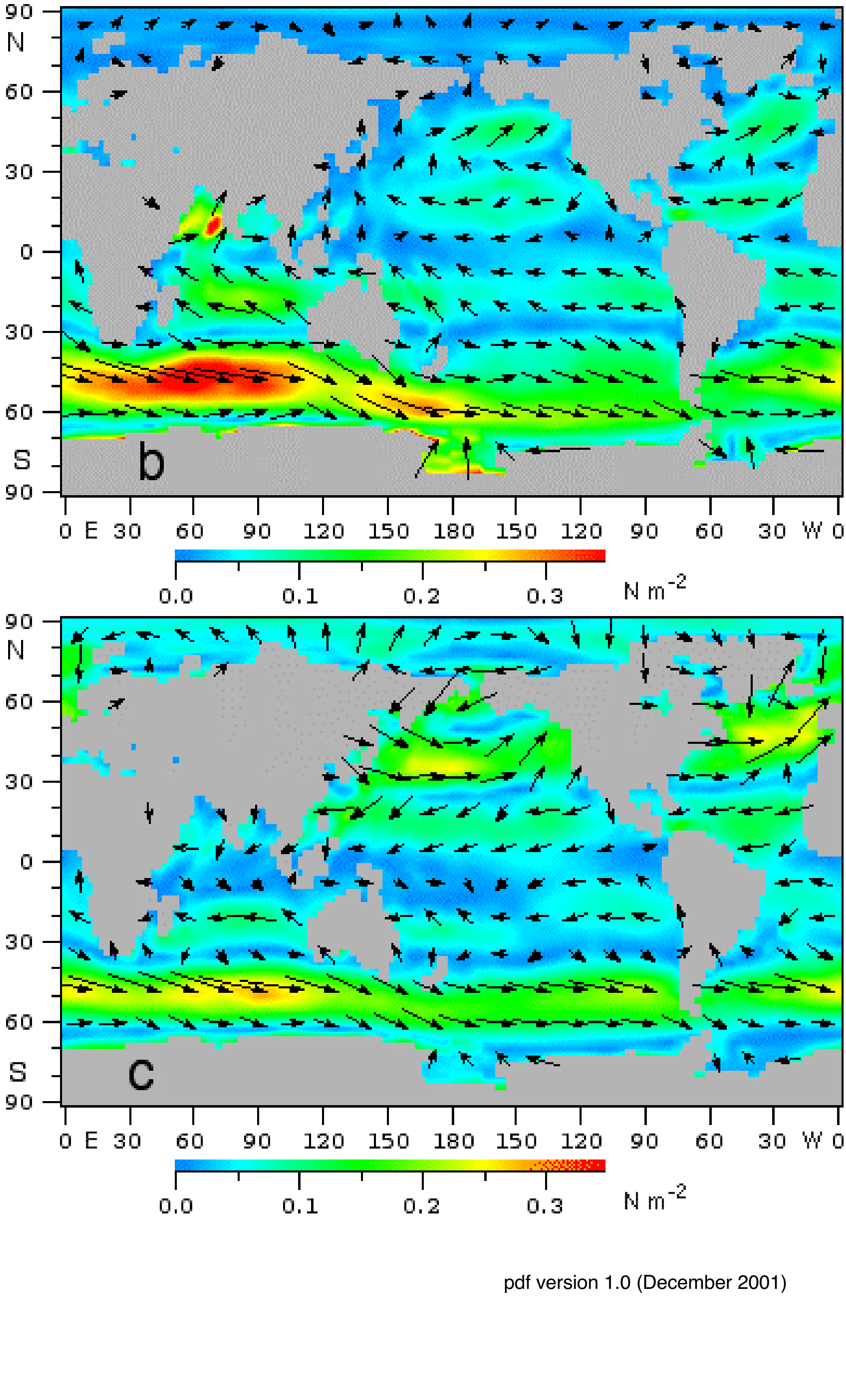


Fig. 1.3. Air pressure (hPa) at sea level. (a, page 6) July mean, (b) January mean. Broken lines show isobars at 5 hPa separation. Data from http://ferret.wrc.noaa.gov/las/, the NOAA Live Climate Data Server using the Comprehensive Atmosphere/Ocean Data Set (COADS) climatology. COADS is based on ship observations.

the northern Indian Ocean) a discussion of the oceanic circulation starts from a well-defined annual mean, meteorology rarely looks at the annual mean atmospheric circulation. This has to do with the low thermal capacity of air, which results in much larger seasonal changes in the atmosphere than in the ocean (see Chapter 18) and makes the annual mean a rather irrelevant quantity. Figure 1.3 therefore shows only the January and July situation. Nevertheless, it gives some useful and instructive information; a comparison with the corresponding wind fields of Figure 1.2 in later chapters will document that the same rules which will be derived for the ocean in chapters 3 - 5 operate in the atmosphere.

The modifications of the basic air pressure pattern of Figure 1.1 by the distribution of land and water are the outstanding features in the seasonal pressure maps. The zonal arrangement of high and low air pressure is seen most clearly in the southern hemisphere. Alternation between low pressure over continents and high pressure over the oceans during summer is particularly evident in the subtropics, but it is easy to see that the basic pattern is preserved in the zonal average. In the northern hemisphere the zonal distribution is disturbed by the Asian land mass which produces a summer low in northern Pakistan and an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above sea level, and C_d is the dimensionless "drag coefficient". (Here and in the following, we use bold characters to denote vectors and normal italics for scalars and constants.) Appropriate values for C_d are still the subject of active research, and the uncertainty about its value adds to the lack of precise knowledge about the wind stress distribution over the ocean. C_d varies from about 0.001 to 0.0025 depending on the air-sea temperature difference, the water roughness, and on the wind speed itself. A median value is about 0.0013. Figure 1.4 shows a recent representation of the oceanic wind stress field calculated from eqn (1.1) on the basis of merchant ship data and often used in numerical ocean models. Note that the mean wind stress is not necessarily parallel to the mean wind but is determined by the direction of the strongest winds. Around Antarctica, for example, mean winds are westerlies (Figure 1.2) but the mean wind stresses follow the northwesterly direction of the strong winds in the storm systems. In the northern hemisphere the gusty Westerlies produce larger stresses than the strong but less gusty Trades.

We conclude this chapter by briefly reviewing the atmospheric conditions imposed on the fluxes of heat and mass. Figure 1.5 gives annual mean solar radiation as received at the sea surface; 93% of it is absorbed by the ocean. Solar radiation is naturally largest in the tropics and in cloud-free regions. Again, the observed field shows significant departures from a simple zonal pattern as a result of the distribution of land and water, mainly through

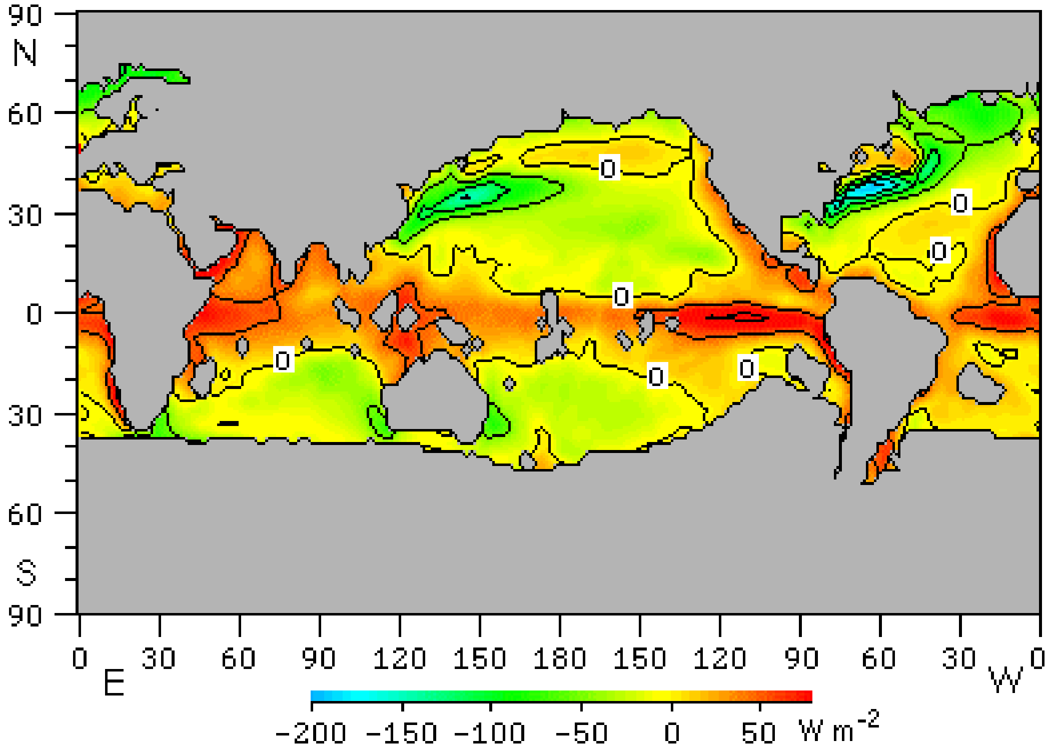

Fig. 1.6. Annual mean heat flux into the ocean (W m^{-2}). Minimum values in the Kuroshio exceed –150 W m^{-2}, in the Gulf Stream –200 W m^{-2}.Data from Oberhuber (1988). Regions with insufficient data to construct an annual mean are gray. The contouring interval is 50 W m^{-2}.

Generally speaking, the ocean gains heat in the tropics (between 20°S and 20°N) and loses heat in the temperate and polar regions. Departures from this simple zonal distribution are, however, so large that this generalization becomes rather meaningless. Cool water must flow into the regions of net ocean heat gain, and the warmed water must flow away from these regions; this advection does not occur uniformly at all longitudes but in currents of limited longitudinal extent, e.g. along the coasts of Peru and Somalia. Similarly the large heat losses in the Kuroshio and Gulf Stream regions along the coasts of Japan and the eastern USA are caused by rapid poleward advection of warm water. These processes will be addressed in detail in the discussion of individual oceans.

The mass or freshwater flux, i.e. the transport of water between the ocean and the atmosphere, is controlled by the difference between rainfall and runoff from land on one hand and evaporation from the ocean surface on the other hand. (Evaporation from land need not be considered here, since it does not represent a gain or loss to the ocean.) Figure 1.7 shows a recent estimate of the annual mean distribution of precipitation minus evaporation (*P-E*). Maximum *P-E* values are found in the ITCZ (known to mariners as the Doldrums) where moist air rises to great height, releasing its water vapour; values of 500 cm/year and more are observed east of Indonesia. Mean sea surface salinity, shown in Figure 2.5b, clearly reflects the mass flux field, most notably in the generally zonal arrangement of the isohalines: lowest salinities tend to occur in regions of maximum *P-E*, although the relationship is not that simple in detail. Again, modifications are generated by the distribution of land and water and by air and ocean currents. An obvious example is the effect of the limited communication between Indian Ocean and Red Sea waters which produces extreme surface salinities in the latter. Further discussion of these and other aspects is postponed to the appropriate chapters.