The transfer of pollutants in two southern hemispheric oceanic systems

Proceedings of a workshop held at Plettenberg Bay, South Africa, 23-26 April 1979

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PREFACE

The National Committee for Environmental Sciences is the South African committee for SCOPE (Scientific Committee on Problems of the Environment), the body set up in 1970 by ICSU to act as a focus for non-governmental international scientific effort in the environmental field. A proposal to hold a workshop on marine pollution in the southern hemisphere was first made during the Third General Assembly of SCOPE (Paris, 1976) in relation to the SCOPE project on monitoring and assessment. This became the workshop on the transfer of marine pollutants in two southern hemispheric oceanic systems, held on 23-26 April, 1979, at Plettenberg Bay, South Africa, as a national contribution to the SCOPE programme. The oceanic systems considered were the Agulhas longshore current system and the Benguela upwelling system. These two systems, as examples of contrasting regimes of upwelling and longshore currents, provided a case study from which extrapolations to similar conditions elsewhere could be drawn, and also provided information on two of the more important oceanic systems in the southern hemisphere.

The workshop had the following aims:

- To assess the importance of different phenomena and processes affecting the transfer and fate of pollutants into and between contrasting regimes of upwelling and longshore currents.

- To assess the available information, especially baseline information, on these phenomena and processes.

- To assess the progress made with the relevant research (and thereby identify key questions for future research and monitoring) and to discuss conceptual models of certain key processes and phenomena.

A set of questions was prepared in order to facilitate preparation for the workshop and to focus attention on certain aspects which were regarded as relevant. The pre-workshop responses to the questions received from participants were incorporated into a draft document which was sent to all participants before the workshop.

The draft document formed the basis for discussion and was extensively revised during the workshop. The present document is an edited version of the proceedings. The names and addresses of participants at the workshop are included in Appendix 1. A number of poster papers were also presented at the workshop (Appendix 2).

ABSTRACT

Available information on the sources and principal routes by which pollutants enter the sea around southern Africa is summarized. The importance of different physical, chemical and biological processes is discussed in relation to the transfer of pollutants into and between the Agulhas and the Benguela oceanic systems around southern Africa. The two systems serve as examples of an oceanic current and an upwelling system. Extrapolations are drawn, as far as possible, to the rest of the southern hemisphere and similar conditions elsewhere. The major pollutant types discussed include petroleum hydrocarbons, toxic elements, organic wastes, halogenated hydrocarbons, radioactive materials and heat. Processes involved in the transfer of pollutants to the sea, transfer across watermass boundaries and interface transport processes are discussed. The relative importance of different processes is assessed, gaps in knowledge are identified and recommendations are made for future research.

SAMEVATTING

Beskikbare inligting oor die bronne en die hoofroetes waarlangs besoedelstowwe die see rondom suidelike Afrika bereik word saamgevat. Die belangrikheid van verskillende fisiese, chemiese en biologiese prosesse word bespreek met verwysing na van die oordrag van besoedelstowwe na en tussen die Agulhas en Benguela oseaanstelsels om suidelike Afrika. Die twee stelsels dien as voorbeelde van 'n seestroom en 'n opwellingsisteem. Bevindinge word, sover moontlik, geëkstrapoleer na die res van die suidelike halfrond en soortgelyke toestande elders. Die groepe besoedelstowwe bespreek sluit in petroleumkoolwaterstowwe, toksiese elemente, organiese afval, gehalogeneerde koolwaterstowwe, radio-aktiewe stowwe en hitte. Prosesse betrokke by die oordrag van besoedelstowwe na die see, oordrag tussen watermassas en interfase oordragprosesse word bespreek. Die relatiewe belangrikheid van verskillende prosesse word geëvalueer, gapings in kennis word geïdentifiseer en aanbevelings vir toekomstige navorsing word gemaak.

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1. INTRODUCTION

Marine pollution may be defined as the introduction by man, directly or indirectly, of substances or energy into the marine environment (including estuaries), resulting in such deleterious effects as harm to living resources, hazard to human health, hindrance to marine activities, including fishing, impairing the quality for use of sea-water and reduction of amenities (GESAMP 1976).

This definition implies that the term "pollutant" refers to differences between the total amount of a substance (or energy) in the marine environment and the level ascribable to natural or ambient origins. In some cases the natural levels may be negligible, e g chlorinated hydrocarbons, most of which are anthropogenic in origin. In other cases, however, significant natural levels exist in the marine environment (e g petroleum hydrocarbons and heavy metals). In these cases reliable estimates of pollutant fluxes require that only the increase in total fluxes due to man must be taken into account. The definition therefore excludes phenomena such as red tides which can introduce substances into the marine environment which may result in deleterious effects to man or marine biota. Appendix 3 lists the major categories of marine pollutants recognized by GESAMP.

For purposes of discussion at the workshop, the GESAMP list was simplified, and discussion was limited to the major categories of marine pollutants listed in Table 1. Sediments were not discussed as a pollutant as such (although an increase in sediments due to man's activities may under certain circumstances have a deleterious effect on the marine environment), but as a transport medium as well as a source and/or sink of pollutants.

There are several significant differences betweeen the oceans in the northern and southern hemispheres. These differences include the existence of the Antarctic circumpolar current, the large surface area of ocean in the southern hemisphere relative to the northern hemisphere and the high productivity and rich fisheries associated with important upwelling systems in the southern hemisphere. Such factors emphasize both the need for concern about possible marine pollution and the need for coordinated studies of marine pollution in the southern hemisphere.

Table 1. List of pollutants discussed by the workshop.

1.	Petroleum hydrocarbons
2.	Organic wastes (and nutrients)
	- domestic sewage
	- fish factory effluents
	- other high BOD wastes such as pulp and paper mill wastes or wastes from fruit canning factories
3.	Chlorinated hydrocarbons
	- DDT and its degradation products, aldrin, dieldrin and lindane
	- PCB's
4.	Toxic elements
	- lead, mercury, cadmium, etc
5.	Radioactive materials
6.	Heat

Southern hemispheric marine pollution could be expected to be less than that in the northern hemisphere because of the higher degree of industrialization in the latter. Use of the measure (albeit crude) of potential pollution given by the ratio of gross national product to area of countries in the two hemispheres (Goldberg 1976), indicates that pollution could be expected to be seven to eight times more severe in the northern than in the southern hemisphere. Pollution originating in the northern hemisphere is not necessarily confined to that area, however, as long-range transfer systems may exist on an oceanic, hemispheric or global scale. Pollutant transfer can take place at the surface or along deep bottom currents such as the deep undercurrents crossing the equatorial zone in western boundary regions. Atmospheric transfer may also occur. While the intertropical convergence zone is a very effective barrier against tropospheric air exchange

across the equator, pollutants with long residence times will undergo significant exchange between the two hemispheres. In addition to oceanic and atmospheric transfer between the hemispheres, man's activities may contribute to the inter-hemispheric transfer of pollutants. The transport of an appreciable amount of the world's oil around the Cape of Good Hope is a conspicuous example.

The Southern Ocean is of special global relevance, not only because its circumpolar flow links the major oceans, but also because of the effect of the Antarctic bottom water formation on the maintenance of the main thermocline throughout the world oceans. For a number of reasons, including considerable logistical difficulties involved, neither the general dynamics of water movement nor the extent and distribution of marine pollution in the Southern Ocean have yet been investigated to the warranted degree.

The winds over the Southern Ocean are essentially westerly, giving net surface water transport away from the Antarctic continent. The west wind drift, the South Atlantic gyre and the Agulhas current interact some 200 to 250 km south-west of the Cape of Good Hope with the generation of large scale vorticity. The vorticity is advected towards the west coast of southern Africa and may moderate or enhance upwelling. This feature, along with the effect of two prominent capes (the Cape Peninsula and Cape Columbine), the bottom topography and, perhaps most importantly, the meteorology, complicates description of the Benguela system south of about 33° S. North of 33°, winds are persistent throughout the year with slight seasonal variation and a diurnal land/sea breeze at certain times of the year. The shelf is of fairly constant depth and width, and the coast is free of peninsulae and large embayments. Steady state upwelling occurs in this region with seasonal modulation.

The Agulhas current is one of the major western boundary currents, gaining its identity off the northern Natal coast from the confluence of the Mozambique current and westward moving waters of the southwest Indian Ocean. It is fairly well defined along the southeast coast of southern Africa, the flow being roughly parallel to the coast although it does not have an unvarying structure and path. Separation from the coast generally occurs in the Port Elizabeth region. To the south the complicated Agulhas retroflexion area exists, and tremendous variations can occur in the main flow. Transfer of Agulhas current water into the Benguela

regime may possibly exist directly across the Agulhas Bank and by the northwards movement of anti-cyclonic rings which have separated from the main flow of the

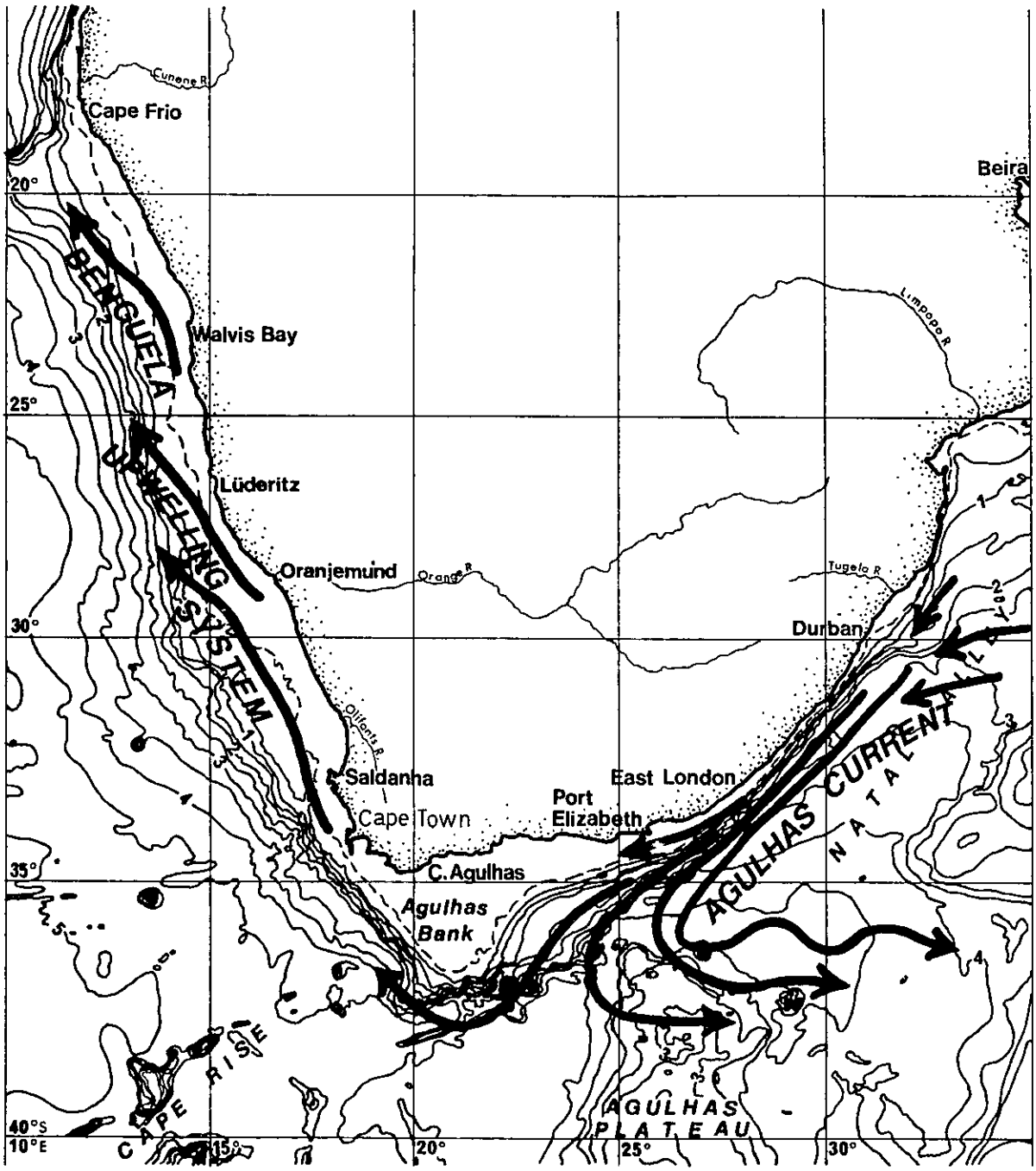


Figure 1. The relation of the Agulhas current and the Benguela upwelling system to the bathymetry off the coast of southern Africa (bathymetry reproduced by kind permission of E S W Simpson. Isobaths at 500 m intervals plus 200 m isobath).

Agulhas at its maximum western penetration (a position only a few degrees east longitude). Figure 1 illustrates the main flows of the Agulhas current and the Benguela upwelling system in relation to the bathymetry off the coast of southern Africa.

In order to estimate the distribution of pollutants in the marine environment and to assess future ocean pollution, knowledge is required of the mechanisms which control the rate of pollutant transfer, both to the ocean and within the ocean, and the major environmental factors affecting transfer processes should be identified.

Identification of the major pollutant sources and determination of the inputs via various pathways into the ocean (quantities, qualities and rates of release) are required to construct an environmental transport estimate or mass balance. In principle, such a model could be used to predict pollutant levels in the environment, given adequate information on the input, storage and output rates for a reservoir such as the ocean, although actual measurements of pollutant levels will, in practice, be required to validate the model. Comparison of expected levels in the ocean with dose-response data may indicate the hazard posed by materials in the system under consideration. However, extreme care must be used in this approach due to effects of synergism and bioaccumulation.

The various transfer processes may be schematized as in Figure 2. Possible pathways from other reservoirs to the ocean include influxes from rivers, coastal outfalls (including pipeline discharge, seepage and run-off), the atmosphere, intentional discharge and the sea bottom. An attempt is made in Chapter 2 to identify major pollutant sources and the various pathways into the oceanic areas under consideration.

The transfer of pollutants in the ocean is influenced by many different physical, chemical and biological processes, the relative importance of each often being dependent upon the specific pollutant under consideration. Of basic importance however are the complicated physical processes which influence the transfer of pollutants across water mass boundaries. These processes and their relevance are considered in Chapter 3.

Interface transport processes are important in all parts of the marine environment. Basic atmospheric/ocean exchange processes and the chemistry and sampling of the air/sea interface are considered in Chapter 4. Another interface of fundamental importance is the sediment/water interface (Chapter 5). Sediments may act as sources, as sinks and as transport media for many substances.

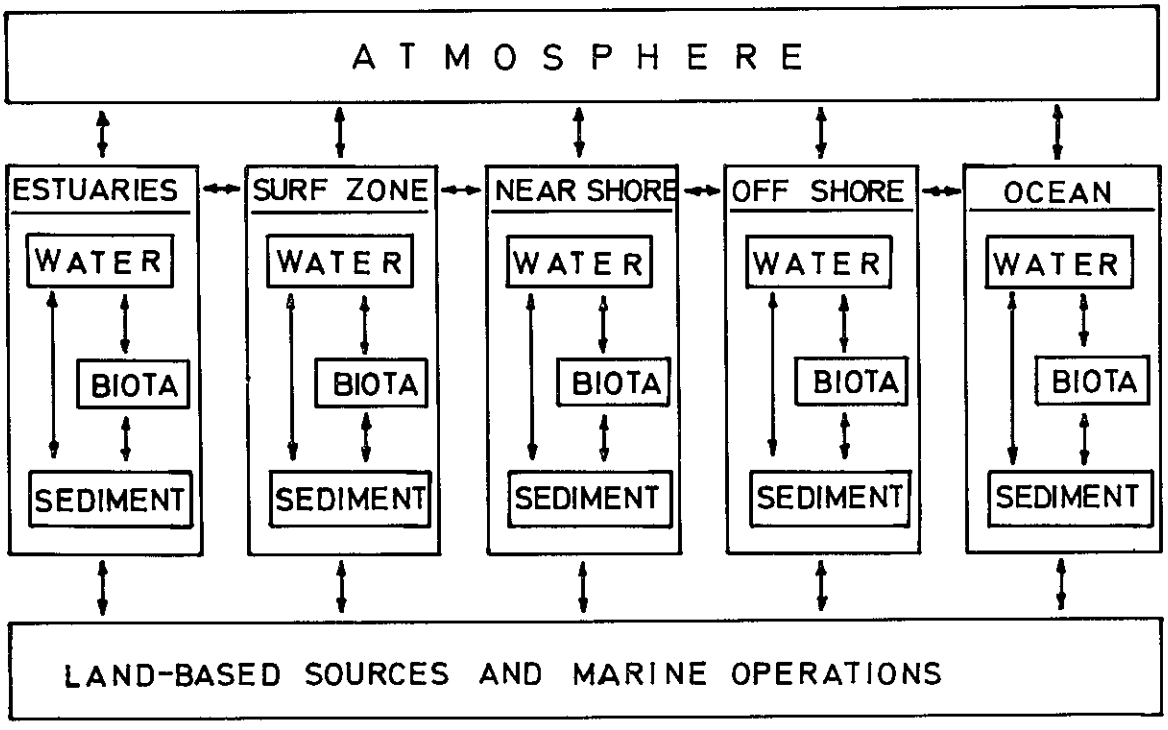


Figure 2. Schematic representation of marine pollutant transfer processes.

Transport processes involving biota include the uptake, metabolism and release of pollutants by organisms and also the rôle organisms play in transporting pollutants within and between segments of the marine environment. These topics are addressed in Chapter 6, while a general summary and conclusions are presented in Chapter 7.

2. TRANSFER OF POLLUTANTS TO THE OCEAN

2.1 ROUTES BY WHICH POLLUTANTS ENTER THE MARINE ENVIRONMENT

A simple classification is shown in Table 2 of some major direct inputs of marine pollutants into the marine environment. For the purpose of discussion, the workshop accepted a classification (GESAMP 1976) of the relative importances of the routes by which pollutants enter the marine environment (Appendix 4). Land-based sources and inputs from marine operations are covered in the present chapter, whereas atmospheric inputs into the marine environments are dealt with in Chapter 4.

Table 2. Direct inputs of marine pollutants into the marine environment

Land-based sources	Direct outfalls (domestic sewage and industrial outfalls)
	Rivers
	Run-off (agriculture, forestry, urban)
Marine operations	Deliberate dumping
	Operational discharges from ships
	Accidental releases from ships and sub-marine pipelines
	Exploitation of the seabed mineral resources
Atmospheric transport	Gas exchange
	Dry particulate deposition
	Precipitation

2.2 PETROLEUM HYDROCARBONS

Direct data for the input of petroleum hydrocarbons into South African waters are generally not available. First estimates have therefore been derived from various selected published global studies with appropriate scaling. These are discussed in the following section and are summarized in Table 3. Considerable caution should, however, be exercised when considering these figures, because of the uncertainties involved in their derivation.

Table 3. Estimates of the orders of magnitudes of petroleum hydrocarbon inputs in tonnes per annum ($t\ a^{-1}$).

Source	Estuaries	Surf zone	Near-shore	Offshore	Ocean
Oil refineries	←	$0{,}02 \times 10^3$	→		
Other industrial and domestic discharges	←	$0{,}5 \times 10^3$	→		
Urban and land run-off	$0{,}3 \times 10^3$ →				
Oil discharges from tankers and other vessels[1]			←	$40\text{-}600 \times 10^3$ →	
Accidental losses from vessels				20×10^3 →	
Atmosphere[2]	←		4×10^3	→	
Offshore exploration	—	—	—	—	—

1 Not restricted to South African territorial waters

2 No data available for non-petroleum sources but considered to be significant source of wide range of hydrocarbons

2.2.1 Oil refineries and single buoy mooring (SBM)

Oil in the effluent from coastal refineries in South Africa discharging directly to the sea is estimated at 20 tonnes for 1978 (D S F Mulligan personal communication). Whilst this may be regarded as an average annual value for the purposes of this exercise some slight variations may occur depending upon operating procedures and control. Effluent from other refineries is treated by the local authority before being routed to the sea. No information is available on the quantity or nature of the petroleum hydrocarbon components that remain after passage through sewage treatment and therefore enter the sea, although it is assumed that the amount is included in the estimates for other industrial and domestic discharges.

In 1971 the single-buoy mooring (SBM) off Durban had a reported spill for every five ship calls and a reported spillage rate of 0,000 59 per cent (Devanney and Stewart 1974). Subsequent re-design of this buoy in 1975 has improved the situation considerably and during the period 1976-1978 the spillage rate dropped to 0,000 2 per cent of the throughput. It is impossible to present a figure for the quantity involved because of lack of knowledge of throughput but the amount is not considered to be significant in relation to other inputs, except perhaps locally.

2.2.2 Other industrial and domestic discharges of petroleum hydrocarbons

The average value of petroleum hydrocarbons in domestic sewage in South Africa is estimated as $3\ mg\ l^{-1}$ (R T Rudd personal communication). No comparable data are available for industrial effluents in South Africa and a similar level of petroleum hydrocarbon loading was assumed (NAS 1975). On the basis of a total annual discharge of about $180 \times 10^6\ m^3$ of industrial and domestic waste into South African waters (see Tables 6 and 7), it can be calculated that $0{,}5 \times 10^3\ t\ a^{-1}$ of oil enter the estuarine, surf and nearshore waters via this route. This figure will clearly vary to some extent depending upon volume of inputs and operational control. Using the information on geographical distribution of discharges

contained in Tables 6 and 7 it can be calculated that input of petroleum hydrocarbons into the regions Mozambique to Cape Recife, Cape Recife to Cape Point and Cape Point to the Orange River are about 400, 90 and 40 t a^{-1}, in that order.

2.2.3 Urban and land run-off of petroleum hydrocarbons

If it is assumed that the quantity of petroleum hydrocarbons from this source would be about half that discharged from municipal and industrial wastes (NAS 1975) then a total input of $0,3 \times 10^{3}$ t a^{-1} is obtained. Since the vast majority of this is likely to enter via estuaries and to vary depending upon rainfall and population distribution, the relative proportions for various areas of the country cannot be determined.

2.2.4 Tanker and other vessel operations

Oil is released into the marine environment as a result of certain cleaning practices of tankers during return to their loading port in ballast. The magnitude of these releases depends upon a number of factors, not least the operating practices of the vessels concerned (e g use of load-on-top, crude oil washing, segregated ballast tanks). For this reason, no direct data are available for the sea areas around South Africa. An indication of the possible quantities involved can, however, be obtained by reference to various worldwide studies in relation to the total quantity of oil transported along the Cape sea route.

In 1977 about 650×10^{6} t of petroleum were transported around the Cape of Good Hope, which was about 38 per cent of the world movement of oil by sea (Figure 3). In the same period 3 279 tankers and 3 632 other vessels passed the Cape, while a total of 5 249 ships passed the Cape in the period January to November 1978.

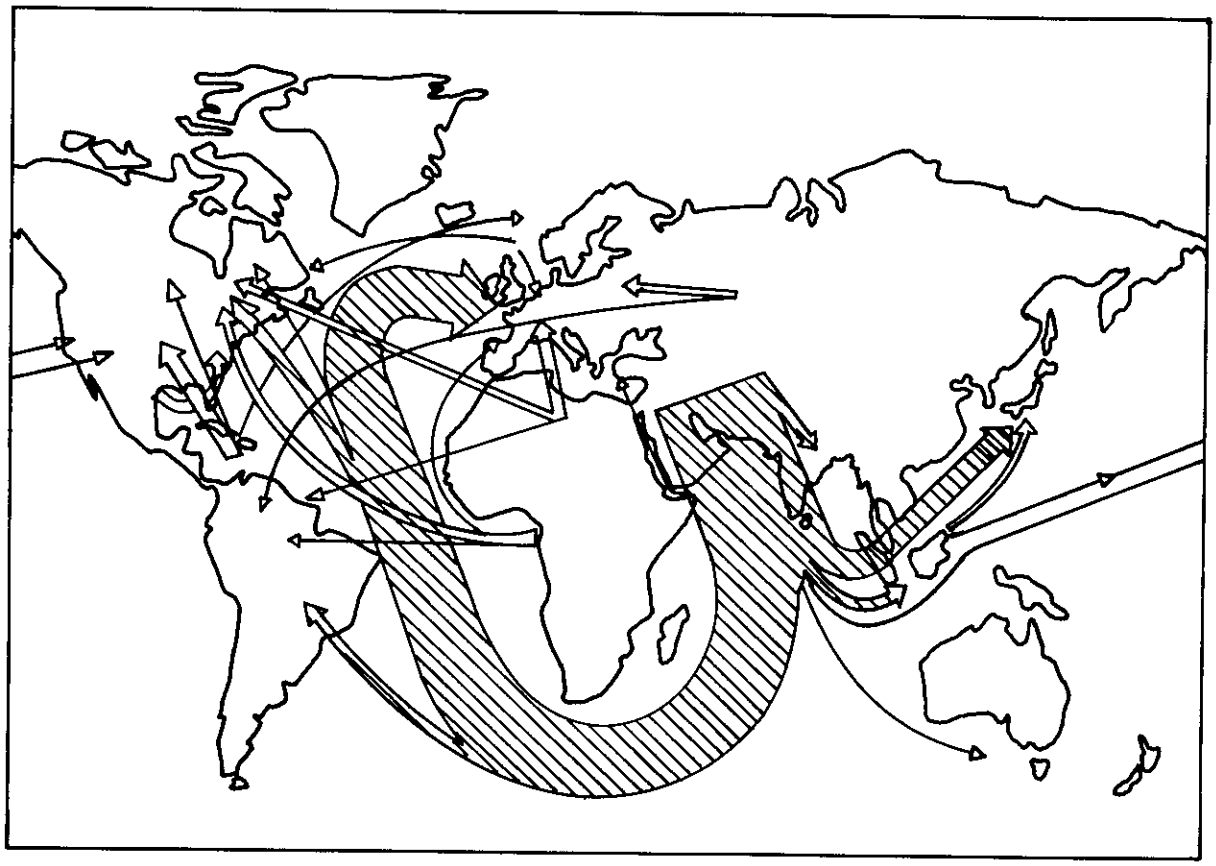


Figure 3. Main oil movements by sea in 1977 (British Petroleum 1977).

If about 80 per cent of tankers used the load-on-top procedure (LOT) with an efficiency of about 90 per cent (Victory 1973) and assuming that the average amount discharged in a ballast voyage by a non-LOT tanker would be about 0,35 per cent of the carrying capacity of the ship (NAS 1975), a total loss of $0{,}63 \times 10^{6}$ t a^{-1} from operational discharges of tankers is obtained for the Middle East to North America/Europe route. If on the other hand it is assumed that all tankers use the LOT procedures and that the ratio of operational discharge to total cargo space is 1:15 000 (IMCO 1969), a total loss of $0{,}04 \times 10^{6}$ t a^{-1} is obtained for the Middle East to North America/Europe route. An intermediate value of $0{,}16 \times 10^{6}$ t a^{-1} is obtained on the basis of the calculation of Grossling (1977) that 0,025 per cent of the oil cargo is discharged by tankers operating LOT.

The precise location of these discharges and therefore the amount of oil entering the southern oceanic systems cannot be determined, but it certainly should not be assumed that it is constant throughout the voyage as the successful operation of the technique requires a minimum time period. It is also worth noting that any oil discharge within 50 nautical miles of land is prohibited according to the 1969 Amendments to the 1954 Oil Pollution Convention. The visual observations of oil slicks around the Cape and of oil on beaches may suggest that this and other requirements of the convention are not being adhered to by all tankers or other vessels.

The rate of loss due to bilge cleaning and bunkering is estimated as $0{,}5 \times 10^{6}\ t\ a^{-1}$ globally, with an average loss per vessel of about $10\ t\ a^{-1}$ (NAS 1975). On the assumption that there could be 1 500 different vessels passing the Cape of Good Hope annually, a total discharge of $15 \times 10^{3}\ t\ a^{-1}$ is assumed. However this will be distributed throughout the sea areas visited by these vessels and will therefore not even be confined to the southern hemisphere.

2.2.5 Accidental losses from vessels

A major potential source of oil pollution is accidental loss from tankers and other vessels. The incidence of oil pollution caused by ship accidents in South African waters during the period 1968 to 1978 is summarized in Appendix 5. The total quantity of oil lost during this period is estimated as $0{,}2 \times 10^{6}$ t.

It is extremely difficult to predict the losses from ship accidents with any degree of accuracy as many factors are involved. These include the pattern of transport, the size and age of vessels, the competence of ships-officers and changes in international regulations and vessel design. Analysis of oil spill statistics (Devanney and Stewart 1974, Holdsworth 1971, Porricelli et al 1971, Porricelli and Keith 1973, Gilmore et al 1970) does, however, indicate that:

- the size range of an individual spill is extremely large,

- the great majority of all oil spills are at the lower end of this range, and

- a few very large spills account for most of the oil spilt accidentally.

In addition, the relatively small number of very large spills prevents the deduction of any statistical regularity. On the basis of past spill history around South Africa an average loss of 20×10^3 t a^{-1} has been assumed.

2.2.6 Atmospheric transport of petroleum hydrocarbons

The total world influx of petroleum derived hydrocarbons to the oceans from the atmosphere is estimated at $0{,}6 \times 10^6$ t a^{-1} (NAS 1975). On the basis of relative petroleum consumption a figure of 4×10^3 t a^{-1} is suggested for South Africa. This figure excludes the hydrocarbons derived from other combustion sources.

2.2.7 Offshore oil exploration

To date, oil has not been found in exploitable quantities within South African territorial waters. There are extensive areas of offshore exploration and production in other areas of the southern hemisphere, but no input data are available.

2.2.8 States in which petroleum hydrocarbons reach the sea

In view of the nature of operational and accidental inputs from vessels and the specific gravity of most oils it is possible to make the generalized statement that

the majority of petroleum hydrocarbons entering the sea via these routes will initially float at the air/sea interface or be dispersed as fine droplets in the surface waters. In addition, soluble components may also be present in operational discharges from ships. Similar observations may be made about effluent discharges from oil refineries that enter the sea directly. The situation will, however, undoubtedly be more complicated in the case of petroleum hydrocarbons that enter the sea together with other industrial or domestic discharges, as adsorption onto organic and inorganic particulate matter will occur. The same will be true for direct land and urban run-off.

For several reasons, it is impossible to be more precise about the state of the petroleum hydrocarbons that enter via the various routes. These reasons include lack of data on the various physical and chemical forms of the petroleum hydrocarbons, the ease with which biological and chemical modifications can occur, the stability of the various byproducts in the marine environment and the lack of any detailed chemical analytical data for the various inputs. A diagrammatic summary of the fate of oil after leaking or spilling into the sea is given in Figure 4. Some recent reviews on the impact of petroleum on the marine environment and its fate include GESAMP (1977), NAS (1975), Wolfe (1977), Malins (1977), Korte (1977) and Stegeman (1976). The status of research on the fate and effects of oil in the marine environment is summarized by Gould and Koons (1978).

2.3 ORGANIC WASTES

2.3.1 Sewage and urban run-off

Sewage is discharged into the seas around South Africa in both treated and untreated forms. In the case of some discharges the effluent quality complies with the standards applicable to discharge into rivers. In other cases lesser to no treatment is applied, the effluent being discharged via channels and pipelines

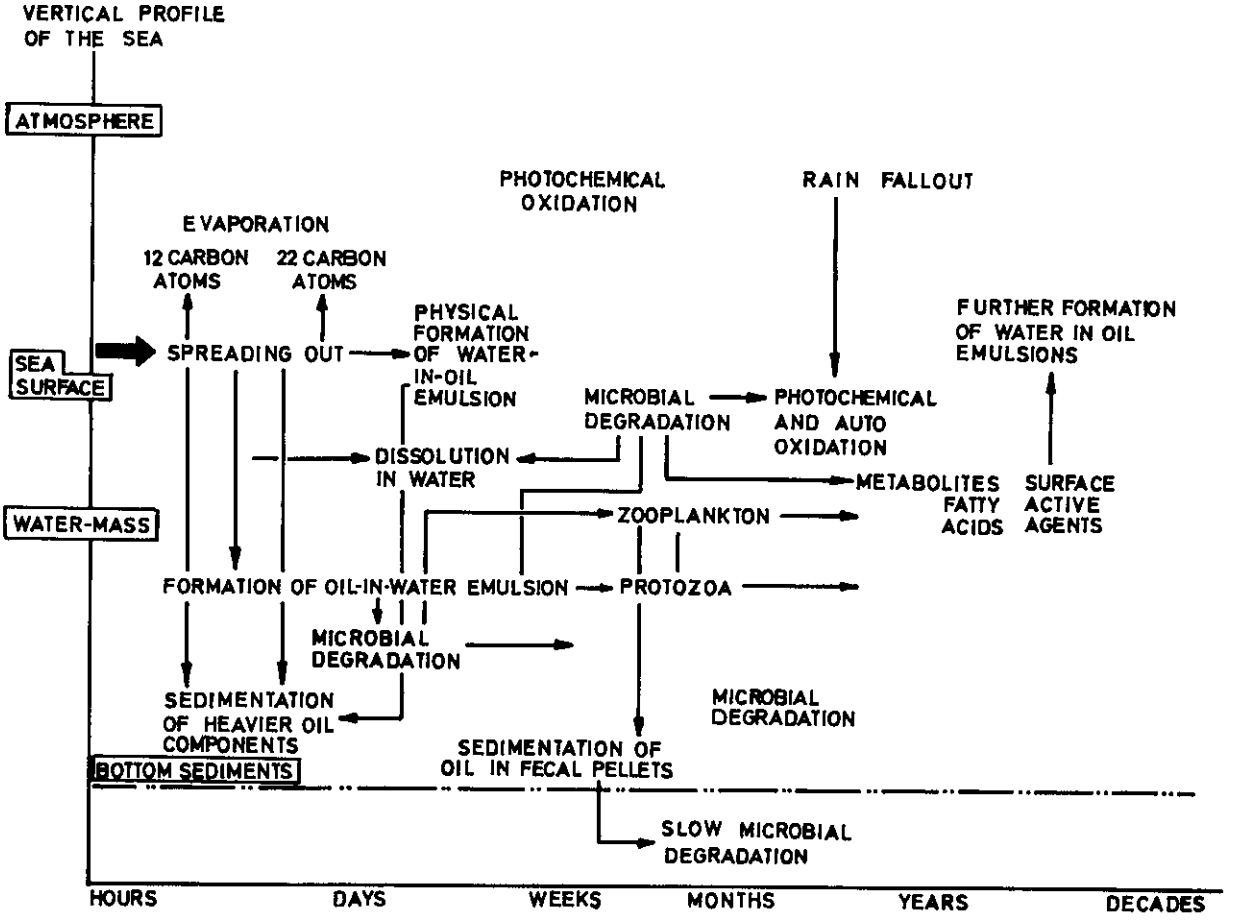


Figure 4. Diagrammatic summary of the fate of oil after leaking or spilling into the sea (GESAMP 1977).

directly into the sea. Some data on the amount of domestic sewage entering the sea around the South African coast are given in Appendix 6. Figure 5 shows the location of the sewage outfalls and indicates the approximate quantities and quality of the effluent.

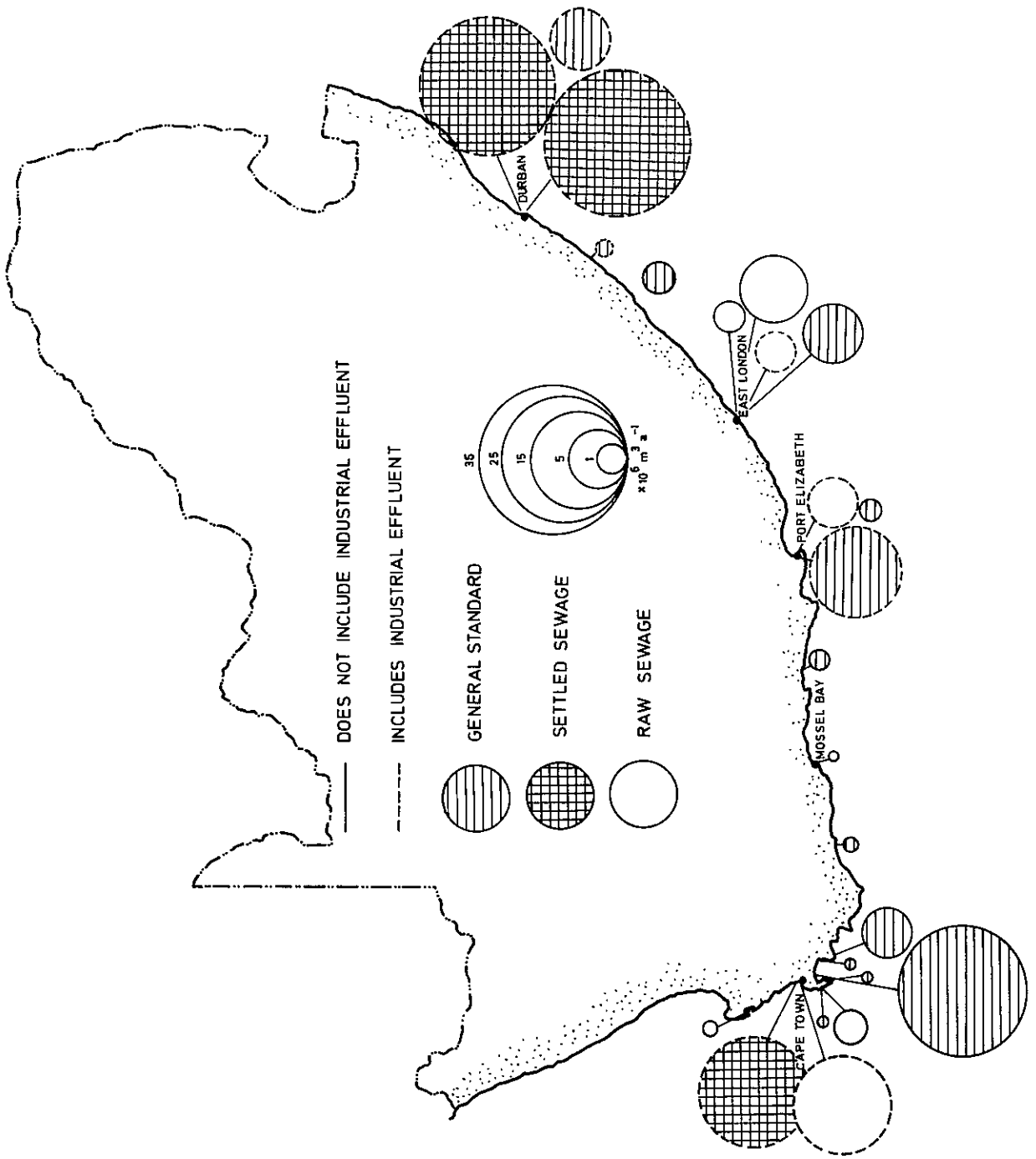


Figure 5. Sewage effluent pipelines along the coast of South Africa.

2.3.2 Industrial effluents

Industrial effluents are released into the marine environment around South Africa on a fairly small scale. Most of the discharges are situated on the east coast which is relatively poor in commercial fisheries but very important in terms of recreational activities (landings of commercially important species on the east coast account for 10 per cent of the total fish catch in South Africa). On the west coast, however, where the main commercial fisheries are situated there are at present few industries producing toxic wastes. The situation could change over the next decade however with the development of the area. Appendix 7 lists present industrial effluent pipelines along the coast.

In addition to the above inputs it may be worth mentioning the occurrence of duff coal entering the system in areas along the coastline of Natal. Duff coal is deposited in dumps in the catchment area of the Pongolo, Mkuzi, Mfolosi and Tugela River systems. Leaching of this coal into the rivers results in elevated levels of lignin being transported to the sea. A brown foam which could be related to this phenomenon has been known to occur along these stretches of coastline.

2.3.3 Fish factory effluents

Effluents from factories off-loading and processing pelagic fish have for the last three decades presented an environmental and socio-economic problem. Prior to 1974, pelagic fish were discharged from boats by means of a wet process, the fish being pumped out in a sea-water medium with the waste water being returned directly to sea. With firm fish such as adult pilchards the pollution problem was moderate, but with stale fish and anchovy, which decompose rapidly, serious organic pollution with consequent reduction of the dissolved oxygen concentration of the receiving water resulted. The problem was reduced in 1974 with the introduction of dry offloading (vacuum lift), although the system is not always properly applied. During summer and autumn, pollution of the sea by fish factories still represents the major source of pollution along the Cape west coast, although

major ecological damage tends to be limited to an area within a radius of about one kilometre of the discharge point.

Pelagic fish factories along the west coast are of necessity situated in bays and sheltered waters where boats can offload conveniently. In certain circumstances, considerable amounts of organic matter are released by these factories. This may cause severe contamination of the immediate marine environment and subsequent changes in the structure and dynamics of the ecosystem although the normal structural complexity found in ecosystems around the South African coast does have a buffering influence.

Some data on fish factory effluents are given in Appendix 8. The locations and approximate quantities involved are illustrated in Figure 6.

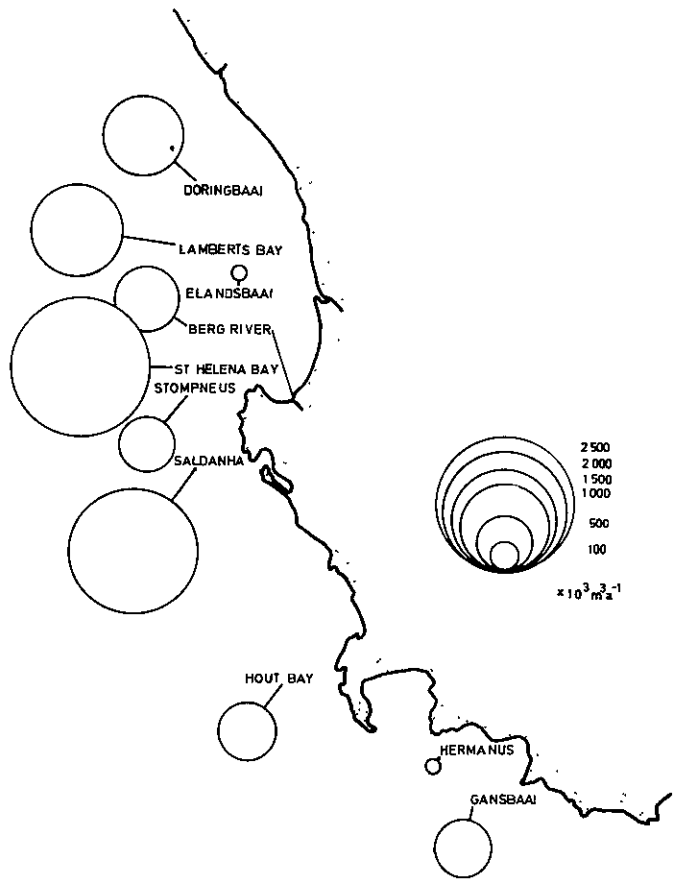


Figure 6. Fish factory effluents along the south-western Cape coast. Quantities are subject to a wide margin of error, as fishing is seasonal, and erratic within a given season.

The standard of effluent varies considerably at different harbours and at different times of the year. A study group appointed by the Water Research Commission is at present investigating the possibility of effluent treatment with a view to improved quality control in the future. The findings of this group should identify the magnitude of the threat of fish factory effluents as a possible source of marine pollution.

The average discharge of a fish processing factory may be as much as 10 to 20 per cent of the fish intake and typical analyses of these effluents are available for most harbours. Of this discharge about 75 per cent are suspended and about 25 per cent dissolved solids.

2.3.4 Dumping at sea

The Convention on the Prevention of Marine Pollution by Dumping of Wastes and other Matter was adopted on 29 December 1972, the date of entry into force being 30 August 1975. South Africa acceded to this so-called London Dumping Convention in 1978, which precludes the dumping of certain materials into the deep ocean and limits such disposal of other wastes.

Appendix 9 summarizes information on dumping which is known to have occurred off the South African coast prior to the ratification of the London Dumping Convention.

2.4 CHLORINATED HYDROCARBONS

2.4.1 Organochlorine pesticides

The most commonly used organochlorine pesticides in South Africa have probably been DDT, BHC, dieldrin, endrin, aldrin and endosulfan. These are all used as insecticides either for agricultural pest or public health control. Of these the sale

of DDT was prohibited in April, 1976, although limited malaria spraying (5 to 7 $t\,a^{-1}$) is still undertaken by the Department of Health in the northern and eastern Transvaal and the Kosi Bay area, Natal.

Spraying from the air is a common means of application in some areas. Some of the material sprayed will inevitably be lost to the atmosphere. A proportion of this will reach the sea by exchange with the atmosphere, via rain or absorbed on air-borne particulate matter. Figure 7 summarizes a general scheme for the cycling of pesticides in the environment. The atmosphere may be a major route for transfer of DDT residues into the oceans, and probably for analogous compounds as well (Wheatley 1973). It is estimated that aerial transport accounts for at least

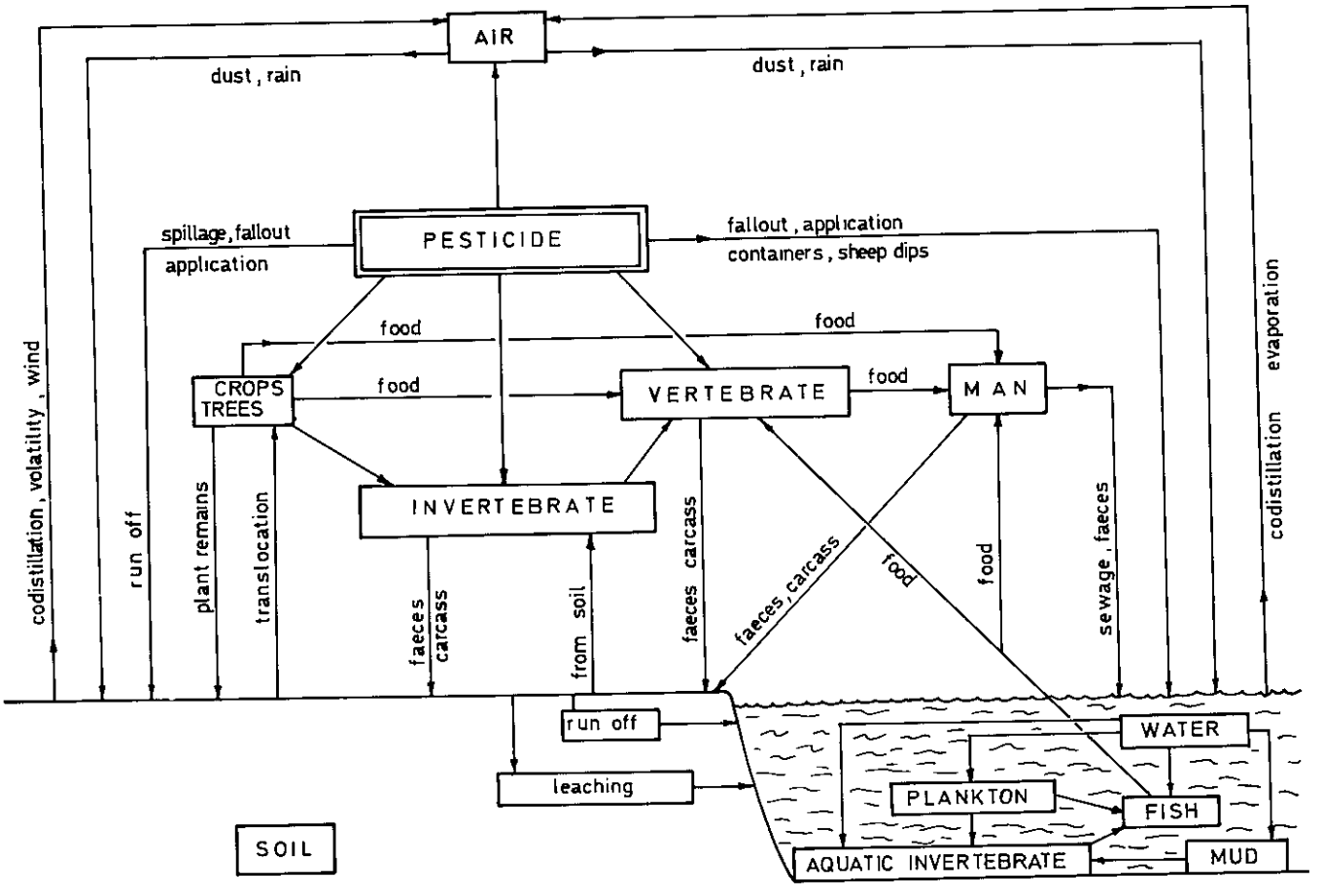


Figure 7. Pesticide cycling in the environment (Fishbein 1973).

50 per cent of the material reaching the sea and that the proportion of the annual production of organochlorine pesticides reaching the sea may be 40 to 60 per cent (GESAMP 1976). The sales of chlorinated hydrocarbon compounds in the Republic of South Africa during the period 1 July 1974 to 30 June 1977 were about 4 000 $t\,a^{-1}$ (Appendix 10) of which it is estimated that of the order of about 500 to 600 $t\,a^{-1}$ may enter the sea. These pesticides can be accumulated by such organisms as lamellibranchs which live in or near the surf zone and concentrated in their body tissues. Some concentrations of chlorinated pesticides found in surf zone mussels along the east and south coast of South Africa are summarized in Appendix 11.

2.4.2 PCB's

There are various possible routes by which PCB's enter the environment. A generalized model for the distribution and transport of PCB's is shown in Figure 8 and estuary and ocean submodels are shown in Figures 9 and 10.

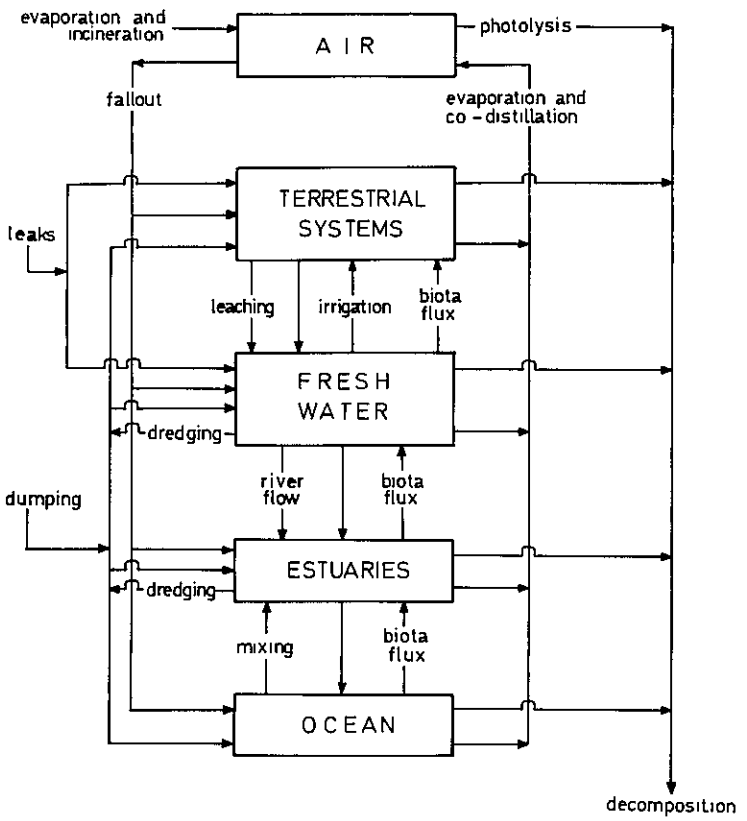


Figure 8. Generalized model for the transport of PCB's in the environment (Fishbein 1973).

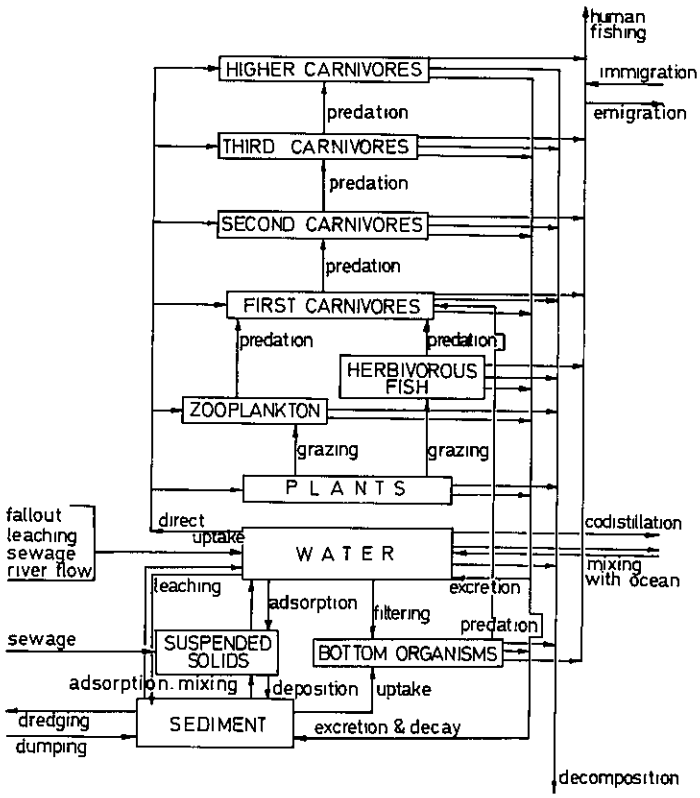


Figure 9. Submodel of PCB transport through and within estuaries (Fishbein 1973).

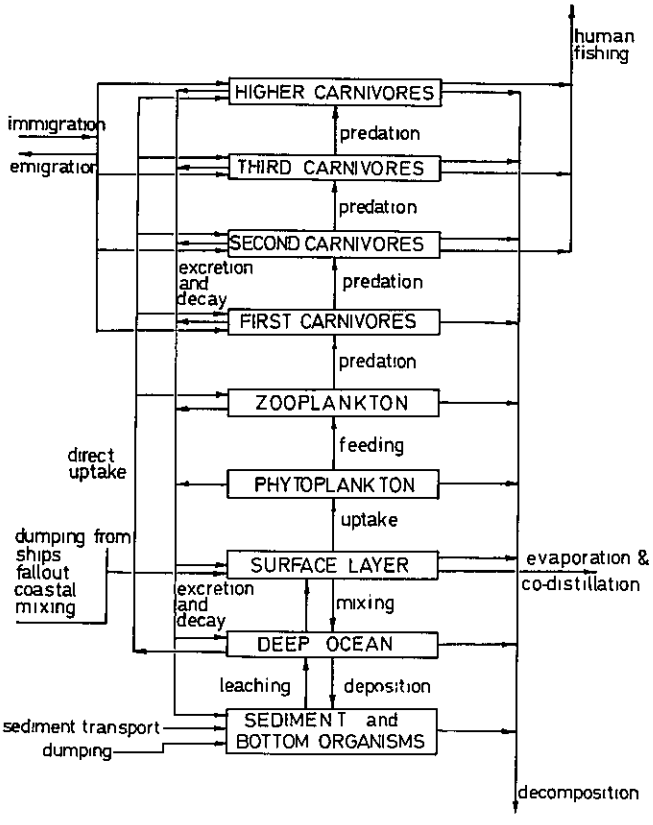


Figure 10. Submodel of PCB transport to and within the ocean (Fishbein 1973).

PCB's have been determined in various samples from the South African east and west coasts and appreciable levels have been found in cats from Marion Island (Gardner 1979).

2.5 TOXIC ELEMENTS

In the South African context, the contribution of toxic elements to the sea via rivers and estuaries is, at this stage, very small. However, there is a distinct possibility that with the development of smelter facilities for zinc and copper ores, this contribution will soon increase. A comparison of trace element concentrations around the South African and Australian coastlines is given in Appendix 12.

2.6 RADIOACTIVITY

Although there is at present no radioactive waste disposal off the South African coast, South Africa's first nuclear power station, Koeberg, is under construction by the Electricity Supply Commission (ESCOM) at Duynefontein, on the coast 28 km north of Cape Town. The proposed commissioning date for the first 922 MW reactor is early 1983 and the second will follow within a year or two.

The operation of a nuclear reactor leads to a large amount of radioactive fission products in the reactor core - about a megacurie per thermal megawatt. More than 200 different radionuclides are formed in the fission process, but are normally well contained by the fuel cladding. Furthermore, activation products are produced by neutron interaction with the structural materials which may be released by corrosion and other processes. However, under normal operating conditions only an extremely small fraction of the total radioactive inventory is released to the environment and it is consequently very difficult to predict either the amount or the radionuclides involved.

Because of their high yields, long half-lives and high radiotoxicity, the fission products ^{90}Sr, ^{137}Cs, ^{106}Ru and ^{144}Ce are potentially the most hazardous. The radionuclides ^{89}Sr, ^{90}Sr, and ^{137}Cs have gaseous precursors and can therefore escape through pinholes in the cladding. Also of importance because of their long half-lives, lack of containment and, especially, their concentration by marine organisms are ^{51}Cr, ^{65}Zn, ^{59}Fe, ^{60}Co and ^{124}Sb, which are formed by (n,γ) reactions, as well as ^{54}Mn formed by (n,p) reaction on the structural materials. The hazards from the release of natural or even enriched uranium fuel are comparatively small due to its low specific activity and low radiotoxicity. Consequently it is the resultant plutonium, which presents the main alpha radiation hazard, and the large amounts of tritium which may be present (especially in heavy water reactors), which deserve attention.

At the request of ESCOM, a pre-operational investigation on stable element concentrations in seawater and in marine plants and animals was carried out by the Atomic Energy Board to determine the safe rates of radioactive releases into the cooling water to the sea (no allowance was made for subsequent dispersion and dilution in the ocean). By agreement with ESCOM, attention was given to the corrosion elements Fe, Zn, Co, Cr, Sb and Mn, which could have radioisotopes present in the effluent and which are known to be of biological importance, to the specified fission products ^{90}Sr, ^{137}Cs, ^{106}Ru, ^{91}Y, ^{95}Zr, ^{141}Ce, ^{144}Ce, ^{95}Nb, ^{143}Pr, ^{147}Nd and ^{147}Pm, as well as to ^{239}Pu and tritium.

Estimates of the safe release rates for each element were supplied to ESCOM who consequently specified $10\,Ci\,a^{-1}$ for unspecified beta-gamma emitters, plus $10\,000\,Ci\,a^{-1}$ for tritium. With a cooling water flowrate of $82\,m^3\,s^{-1}$ for both reactors, this results in a maximum concentration of $3{,}9\,pCi\,l^{-1}$ for the former, which should be compared with the natural radioactivity (mainly ^{40}K) of $350\,pCi\,l^{-1}$ in seawater.

The present state of knowledge of the activity input of radioactive materials is good in both the southern and northern hemispheres. Direct input of land generated artificial radioactivity is at present negligible in South Africa and probably in the southern hemisphere as a whole, and the expected radioactive

releases from future nuclear power stations will be subject to very strict regulatory control which has already been decided upon. The levels of artificially produced radionuclides in the southern oceans are therefore not such as to give any cause for concern. This situation is likely to be maintained unless and until nuclear fuel reprocessing plants and/or oceanic dumpsites are established in the southern hemisphere. The potential use of such nuclides as sensitive tracers of marine processes should, however, not be overlooked.

Recycling of atmospheric nuclear weapon test fallout from land to sea via river catchment areas could lead to minor increases of fallout nuclide levels in estuaries although settling of sediments in impoundments could reduce this.

2.7 HEAT

The present five power stations on the coast range in capacity from 100 to 300 MW, with up to 16 $m^3 s^{-1}$ coolant flows, raising outlet temperature to 5 to 8^{o} C above ambient (Appendix 13).

The Koeberg Nuclear Power Station will operate at 2 x 920 MW and will discharge a coolant flow at 82 $m^3 s^{-1}$ with 12^{o} C rise at output. A nearshore dynamics project presently being conducted in the vicinity of Koeberg can lead to the prediction of the extent of any thermal plumes. It may be of interest to monitor the ecology of the Koeberg area before and after the nuclear reactor comes on stream (Cook 1978).

2.8 SEDIMENTS

2.8.1 Estuarine/river input

Rainfall amount and intensity are important to rates of transfer of sediments and pollutants. Anomalous rainfall events appear to create the largest pollutant and sediment transport problems in regard to the marine environment.

Standing waves in the circumpolar jet stream often occur due to persistent energy inputs at particular meridians. This "blocking pattern" tends to deflect major westerly atmospheric waves with dry weather to the rear and wet weather to the front of long wavelength troughs. Figure 11 depicts this situation whereby anomalous seasons may be created in South Africa.

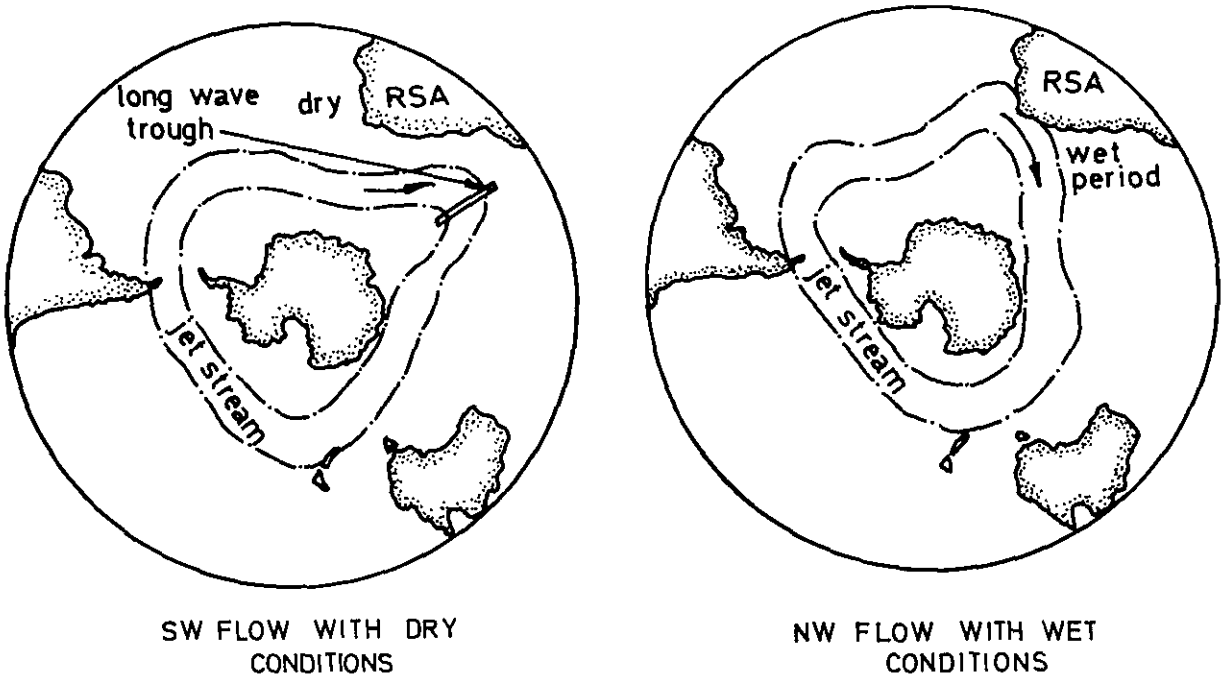


Figure 11. Effect of standing waves in the circumpolar jet stream on rainfall patterns in South Africa.

Seasonal rainfall patterns in southern Africa are shown in Figure 12. The eastern third of the country receives rainfall primarily via thunderstorms which dump large amounts and high intensities of large droplet rain over small areas on a diurnal-quasi-synoptic cycle. The sporadic nature of thunderstorm rainfall should be emphasized. In the winter rainfall area, events are more synoptically controlled with smaller amounts falling over larger areas of the south-western coastal strip.

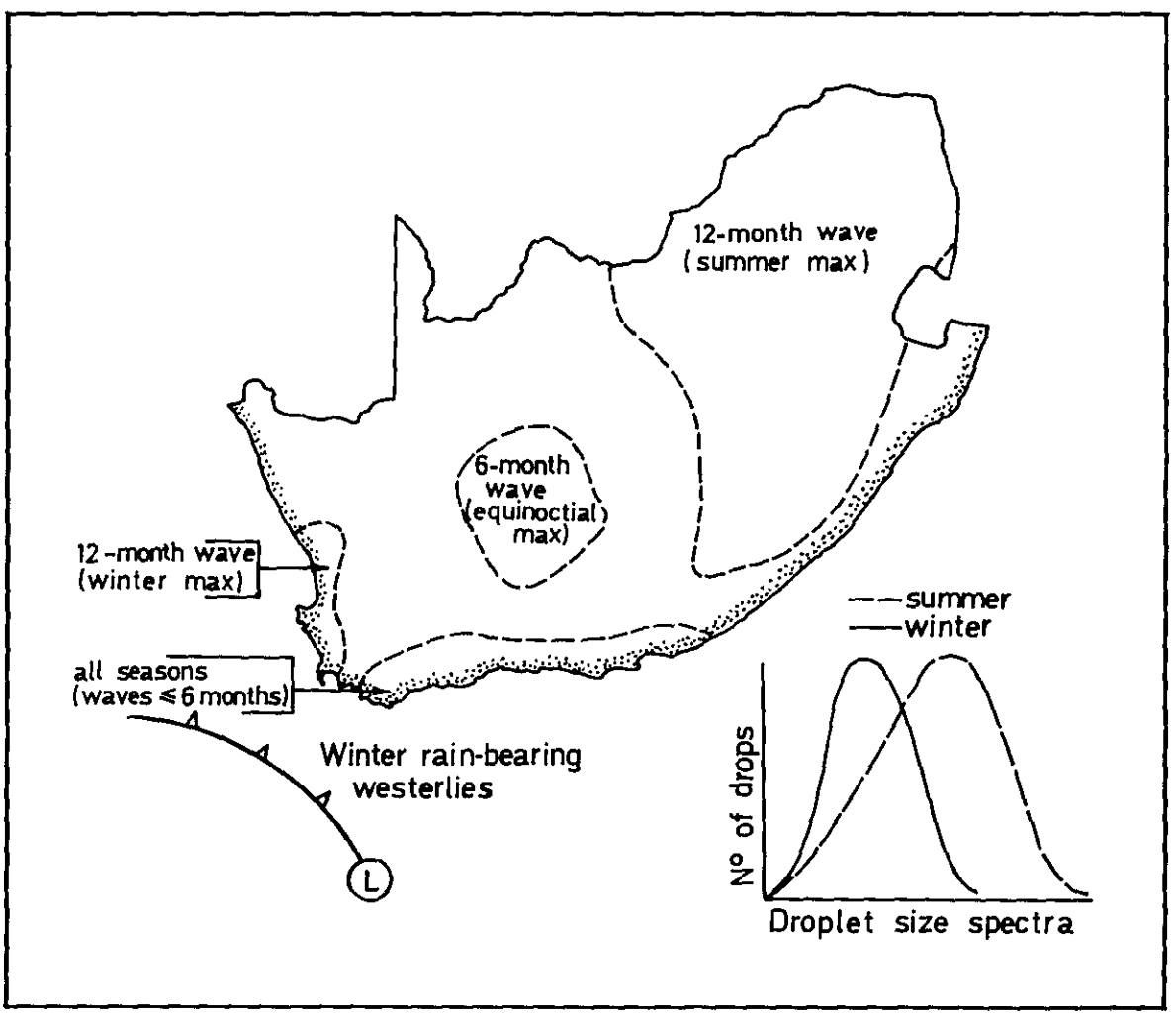


Figure 12. Spatial coincidence of seasonal rainfall regimes (Keen and Tyson 1973).

Surface rainfall observing stations leave appreciable gaps in determining catchment rainfall "loading". These could be filled by using such techniques as satellite imagery and weather radar (see Figure 13). Radar reflectivity (a function of the cube of droplet size) is related to rainfall rates when droplet size spectra is assumed. Reflectivity levels and durations may be recorded by computer to yield rainfall isolines thus answering the question of catchment loading.

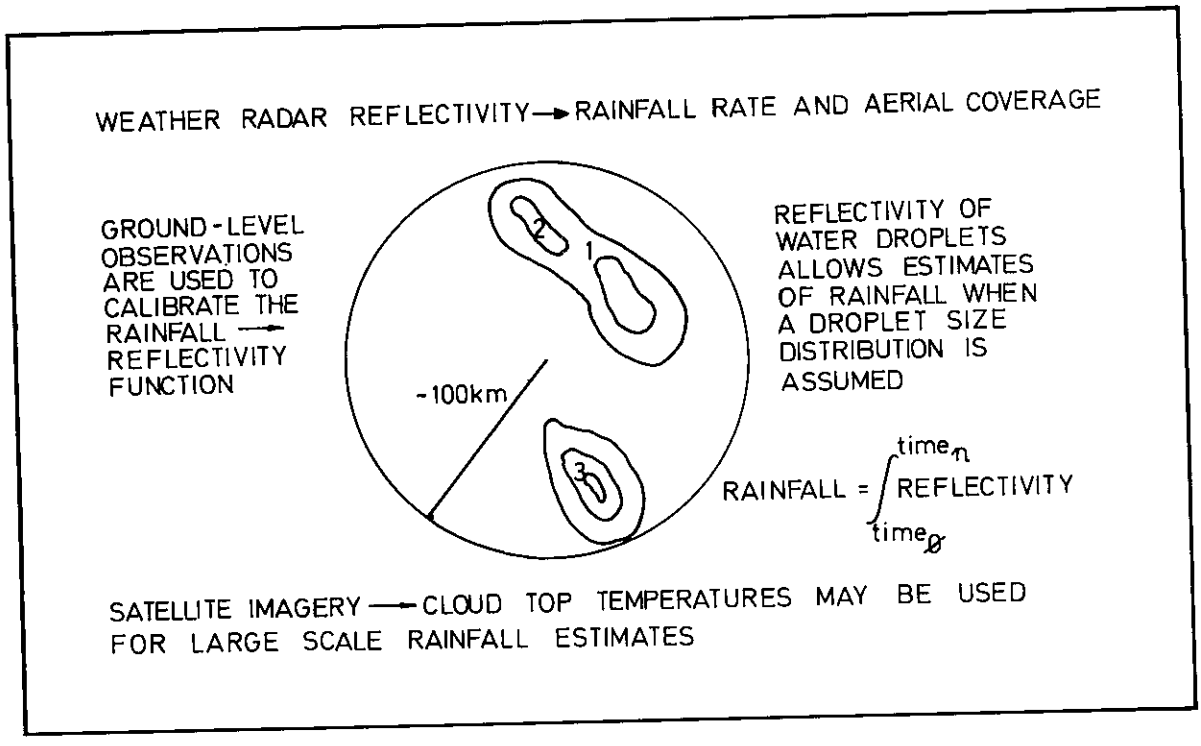


Figure 13. Schematic illustration of radar and satellite imaging techniques for measuring rainfall.

Rainfall is thus the origin of mechanisms which physically transport pollutants and sediments directly from land to sea. Pulsing and the opening and closing of rivermouths dominated by rainfall run-offs all introduce time delayed episodic events affecting the marine environment.

Approximately eight per cent of South Africa's total rainfall returns to the sea as river discharge. Perennial rivers occur over a quarter of the land surface, most being strongly seasonal. The variations in total annual flow can be large, making estimates of annual run-off into the sea uncertain. The Orange River system is

the largest single river system in South Africa, draining about 47 per cent of the land area and contributing about 22 per cent of the total run-off. Estimates of the mean annual run-off of South African rivers into the ocean are given in Table 4:

Table 4. Estimates of mean annual run-off from South African rivers into the ocean.

Region	Volume (10^6 m^3 a^{-1})	Percentage of total
East coast (Mocambique border to Cape Recife):		
Tugela	3 500	
Umzimvubu	2 600	
Others	6 900	
Total for east coast	13 000	55
South coast (Cape Recife to Cape Point):		
Breede	1 200	
Others	600	
Total for south coast	1 800	8
West coast (Cape Point to Orange River):		
Berg	750	
Olifants	450	
Orange	7 350	
Others	50	
Total for west coast	8 600	37
Total for country	23 400	100

In contrast, the total run-off based on rainfall figures is approximately 52 000 x 10^6 m^3 a^{-1}. Therefore about 45 per cent of the total run-off reaches the sea.

Estimates of sediment influx into the ocean are subject to a very wide margin of error. Rooseboom (1975) estimates a total sediment yield of 100-150 x 10^6 t a^{-1} for the whole country. Assuming that the same proportion (45 per cent) as the

run-off reaches the sea, an estimate of the input of sediment from river flow into the sea is $45\text{-}68 \times 10^6 \text{ t a}^{-1}$. This can be assumed, as a first estimate, to be distributed amongst the three coastal areas with the above-mentioned percentages of run-off. Some characteristics of the sediment inputs into the sea via South African rivers and estuaries are given in Table 5.

2.8.2 Coastal and nearshore erosion

In the coastal and nearshore zones, sediment is also eroded, for instance by wave erosion of coastal dunes. This process, as all wave-induced processes, is very wave-height dependent with more than 80 per cent of the movement taking place over approximately five per cent of the time during which storm waves occur. The seaward transport of material eroded from the coastal dunes is therefore an intermittent phenomenon, which can reach a maximal rate of approximately $100 \text{ m}^3 \text{ m}^{-1} \text{ h}^{-1}$, or about $4\text{-}8 \times 10^6 \text{ t km}^{-1}$ of shoreline d^{-1}. Keeping the duration of storms (fractions to multiples of days) in mind, the relative importance of this input can be assessed. Some information on the input of sediments to the coastal and nearshore zones around the South African coasts is given in Table 5.

2.8.3 Engineering activities

Dredging and reclamation activities associated with harbour development and maintenance and other coastal engineering works can be considered as a mechanism of direct sediment transfer into the coastal environment. The larger more recent engineering projects along the South African coastline involving dredging and reclamation works are summarized in Table 5.

Table 5. Direct sediment inputs to the sea around the South African coast.

Sources of input	Characteristics	Mode of input	Time variability	Quantity	Controlling factors
ESTUARINE Estuary/ river	Terrigenous (predominantly) clay, silt, sand, gravel Biogenous sand, gravel	90% suspended 10% bedload bedload	Seasonal (east coast) to episodic (west coast	100–150x10^6 t a^{-1} into estuary 45–68x10^6 t a^{-1} into nearshore 60% east coast 30% west coast 10% south coast	1. River and tidal flow 2. Mouth characteristics 3. Land-use patterns 4. Sediment characteristics
COASTAL/ NEARSHORE EROSION Surf/near= shore zone	Terrigenous (75%) 100 μ + Biogenous (25%) sand, gravel	Suspended (predominantly) + bedload initially Bedload	Short term (dependent on storms) with seasonal overtones	Maximum: 0 to 4–8x10^6 td^{-1} km^{-1} Storm duration fraction of day to multiples of days	1. Wave regime 2. Coastal plan form 3. Sediment characteristics 4. Beach profile 5. Availability of sediments (geology)
ENGINEERING ACTIVITIES Surf zone/ nearshore/ offshore	Terrigenous clay, silt, sand, gravel Biogenous	Suspended initially	Once off or continuous/ periodic	Saldanha: 40x10^6 m^3 once off Cape Town: 15x10^6 m^3 once off East London: ? continuous Durban: 0,6x10^6 m^3 a^{-1} for 75 years Richards Bay: 68x10^6 m^3 a^{-1} for three years	1. Economics 2. Engineering technique 3. Sediment characteristics

2.9 GAPS IN KNOWLEDGE (in order of priority)

2.9.1 It is clear that precise data on the input of petroleum hydrocarbons into South African waters are lacking. However, such generalized information, although of possible academic interest, would have little relevance to the overall consideration of the fate and transfer of petroleum hydrocarbons in the southern oceanic system in view of the enormous variation in the composition of the inputs, the physical, chemical and biological complexity of these substances and their modification once in the environment. It is also relevant to note that regulation of the quantities entering the southern oceanic systems via the various routes can in most cases only be achieved by national or international control.

Knowledge of the levels of petroleum hydrocarbon components actually occurring in various parts of the southern oceanic system is important, as well as knowledge of their fate and transfer. Attention should be given to the distribution of oil slicks at sea and on beaches as determined by visual means, location of known inputs and, perhaps most importantly, to similar programmes (including those on effects) being carried out in South Africa and elsewhere.

Particular attention within this broad framework should be given to the processes controlling the movement of oil slicks at sea and near the coast (e g inshore current systems) as this will be of direct practical relevance to the programmes currently being undertaken in South Africa on oil spill response contingency planning. The prediction of the possible impact of oil and various clean-up processes on coastal resources together with the fate of physically and chemically dispersed oil requires attention. In addition priority areas for protection must be identified.

2.9.2 Except for some measurements of chlorinated pesticides in marine fish (Henry 1974) and in the blubber of the Cape fur seal (Henry 1976), virtually no data exist on the levels of these compounds along the south and west coasts of southern Africa.

2.9.3 Analytical methodology to determine the forms in which metals enter the marine environment is insufficiently developed.

2.9.4 Basic data on the quantities of sediment transported into the sea by rivers as well as on suspended/bedload ratios are lacking.

2.9.5 The environmental impact of major marine engineering projects is often insufficiently known.

2.9.6 The Department of Water Affairs flow gauging network does not provide adequate estimates of river discharges into South African estuaries.

2.9.7 There is a lack of knowledge in both the southern and northern hemispheres on the chemical form in which radionuclides enter the marine environment.

2.9.8 In order to obviate a similar situation to that experienced by northern hemispheric industrialized countries, information is needed on the present baseline levels of metals in the coastal environment and their longterm variations. Such surveys have been undertaken along certain parts of the coastline only.

2.10 RECOMMENDATIONS (in order of priority)

2.10.1 Basic data on the concentration of major petroleum hydrocarbons component groups in water, sediment and biota at selected sites around the South African coast should be obtained.

2.10.2 Available information on the fate and transfer of various oils and petroleum hydrocarbons should be examined in the context of the southern oceanic system to identify gaps in knowledge, i e whether or not the information can be translated to the southern oceanic systems and whether or not further study is required on the processes controlling such transfers. Particular attention should be devoted to the processes controlling the movement of surface oil slicks around South Africa.

2.10.3 Data on the concentrations of chlorinated pesticides and PCB's in estuaries and the surf zone of the south and west coasts should be obtained.

2.10.4 An investigation into the chemical forms and residence times of toxic elements in the South African environment must be undertaken.

2.10.5 There is a need to collect basic data on quantities of sediment transported into the sea by rivers together with suspended load/bedload ratios.

2.10.6 More specific and extensive information on the volumes of fresh water entering the marine environment is required.

2.10.7 Environmental impact assessments must be undertaken prior to the start of all major marine and coastal engineering projects.

2.10.8 The distribution and relative abundance of toxic elements along certain parts of the South African coastal environment have been established. Such surveys should be extended to the whole coast.

2.10.9 The chemical form in which radionuclides enter the marine environment should be determined.

3. TRANSFER OF POLLUTANTS ACROSS WATER-MASS BOUNDARIES

3.1 INTRODUCTION TO THE PROBLEM OF PHYSICAL TRANSPORT

The problem dealt with in this chapter is the transfer of pollutants, and other relevant material, across different boundaries in the sea, taking into account the various sources (or source functions) giving inputs of pollutants. These sources include inputs from land via rivers, pipelines, run-off, atmosphere and inputs at sea by dumping and accidents.

The transfer of pollutants in the ocean is influenced by many different physical, chemical and biological processes. In order to understand the distribution of pollutants in the marine environment all these processes must be considered together. The relative importance of the processes will often depend upon the type of pollutant. However, the complicated movement of water masses in the ocean is basic to the study of transfer of pollutants in the oceanic environment, and it is vitally important to determine which physical processes dominate in any particular area.

An attempt is made to identify significant processes for transfer and mixing, to formulate what needs to be known in order to assess the importance of these processes for various sources and pollutants, and to summarize available information and identify the gaps in knowledge.

A framework for discussion can be provided by different conceptual models of the dynamical structure in the sea.

An outstanding feature of the ocean is the stable density stratification which occurs in most regions. Because of this, the turbulence in the ocean is much weaker than in the atmosphere and wave motion plays an important rôle. This has a major influence on mixing and, as is shown in Figure 14, the water column some distance from the coast can usually be divided into four different regimes:

- The surface boundary layer where the effects of the air/sea interaction dominate.

- The pycnocline (thermocline and halocline) layer where buoyancy effects dominate and turbulent motion is intermittent.

- The deep water layer where internal waves are important and turbulent motion may occur intermittently.

- The bottom (side wall) boundary layer where friction effects dominate.

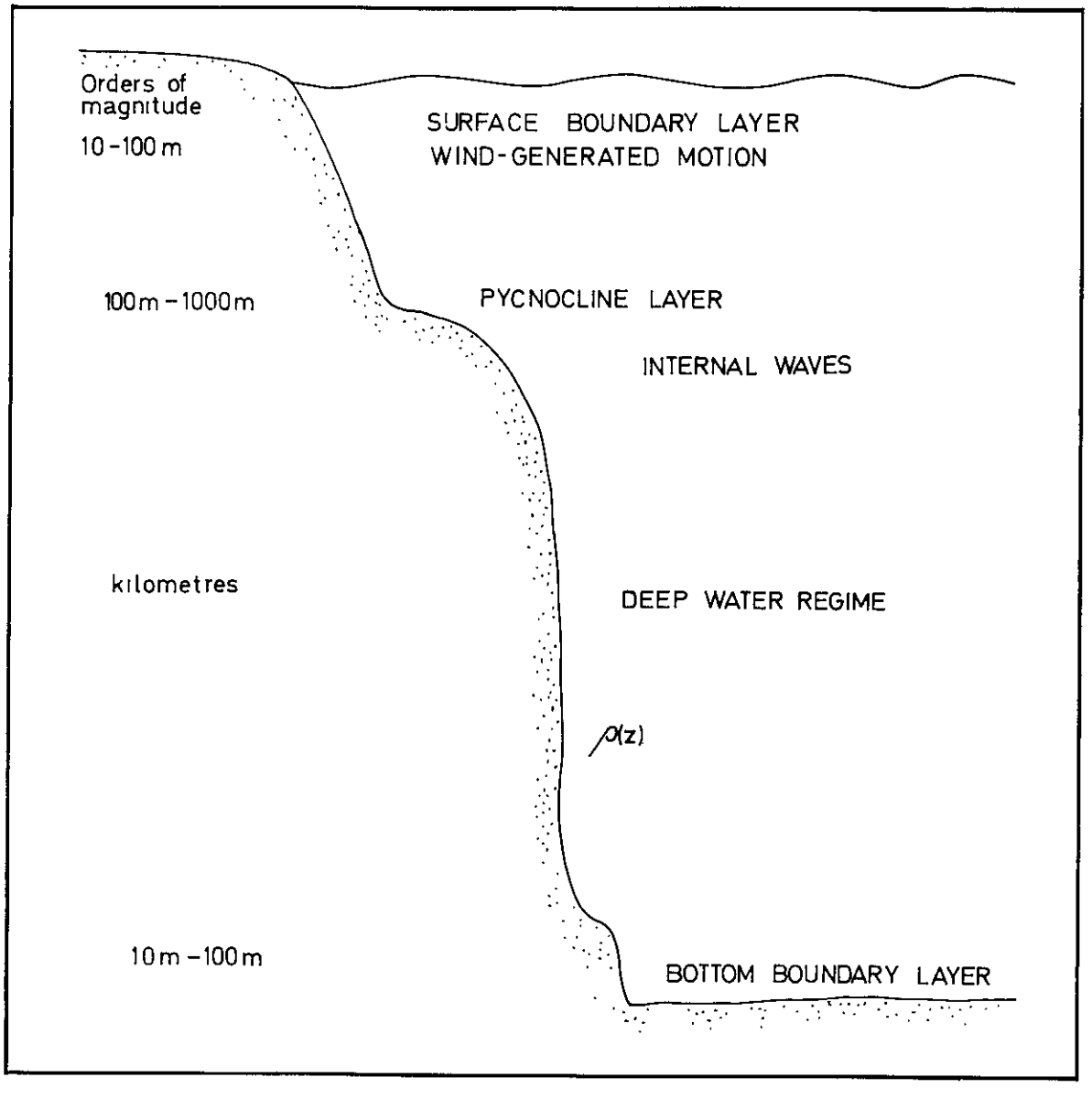


Figure 14. Vertical structure related to the density distribution.

Leaving aside the surface micro-layer for the moment and considering the surface wind-mixed layer, the mean depth of this layer usually will be predicted (using one dimensional models) as a function of net radiation, wind stratification and time. Various assumptions regarding the vertical current structure are used to close the models (Kraus 1977).

In the thermocline layer, vertical mixing is suppressed by the stable density stratification. Most authors agree that vertical mixing across the thermocline is weak and that only a small fraction of the energy transferred from the wind to the water is consumed in changing the potential energy distribution in the water column. Mixing in the thermocline layer is much influenced by the breaking of internal waves. The breaking can be due to different types of instabilities, such as the Kelvin-Helmholtz (Woods 1968), the Orlanski-Bryan where particle velocities exceed the phase velocity (Orlanski and Bryan 1969), wave-wave interactions or current-wave interactions (Thorpe 1978). The breaking generates local and intermittent mixing on vertical scales in the range 0,1 to 1 m.

An important mixing mechanism on small to intermediate scales in regions with shear is the combined action of shear and mixing perpendicular to the shear. This will generate an apparent spreading in that direction. Various models of shear diffusion have been formulated and reasonable agreement with field observations obtained (Kullenberg 1974).

Garrett (1977) has recently reviewed our present knowledge of the mixing in the interior of the ocean, its importance for climate and general conditions in the marine environment.

The physics of the bottom boundary layer is analogous to that of the surface boundary layer. The bottom Ekman layer is of the order of 10 m thick, (in some active areas it may become of the order of 100 m) and the logarithmic layer is of the order of 1 m thick. The conditions for transportation of sediments along the bottom and in the boundary layer have been much studied in recent years (McCave 1973).

The generation of turbulence in the bottom layer can be due to friction or breaking internal waves influenced by the stratification as well as the bottom slope, and a

well-mixed bottom layer with a considerable amount of suspended matter is found in many areas both in the open ocean and in enclosed seas. It is clear that the vertical density structure of the ocean considerably influences the mixing and transfer of pollutants caused by the type of internal waves and interactions that may be present, with consequent currents, turbulence and upwelling/downwelling.

An alternative conceptual approach to distinguishing vertical zones is to consider the various horizontally defined dynamical zones, starting from the beach and going out into the ocean.

Most pollutants enter the sea in the coastal region. Here the various scales of motion must be investigated beginning with the effect of the sometimes violent turbulence of the surf zone where many pollutants are introduced. To understand this, information on the dominant wave field is required as well as on the long shore drift and sediment transport.

Meteorological conditions, in particular the wind field and freshwater run-off, have an important influence on conditions in the nearshore zone. Information on the local topographic features such as small headlands, bays and bottom structure is also vital. Here past experience can be useful to predict current behaviour, but supplementary measurements are often necessary (Harris 1978).

On a yet larger scale, coastal boundary layers can then be delineated depending on the larger shelf dimensions. The vertical oceanic structure will probably become important, with various modes being excited by meteorological forcing. Finally the major oceanic circulation systems are involved. These are important for the renewal of coastal water.

It is useful conceptually to define the following zones (Figure 15):

- The nearshore zone, where the waves are the essential forcing factor

- The coastal boundary layer which may be defined by the internal Rossby radius of deformation R_i, R_i being given by

$$R_i = \sqrt{\frac{g \Delta \rho H}{\rho f^2}} \qquad (1)$$

where g is the acceleration of gravity, $\Delta\rho$ is the density difference between surface and deep water, H is the depth on a characteristic vertical scale and f is the Coriolis parameter.

- The oceanic regime, where the oceanic currents play a major rôle.

- The bottom boundary layer which essentially extends across the three other zones.

- The surface boundary layer.

These zones obviously overlap and should only be regarded as forming a conceptual model. The extent as well as the relative importance of the zones will vary,

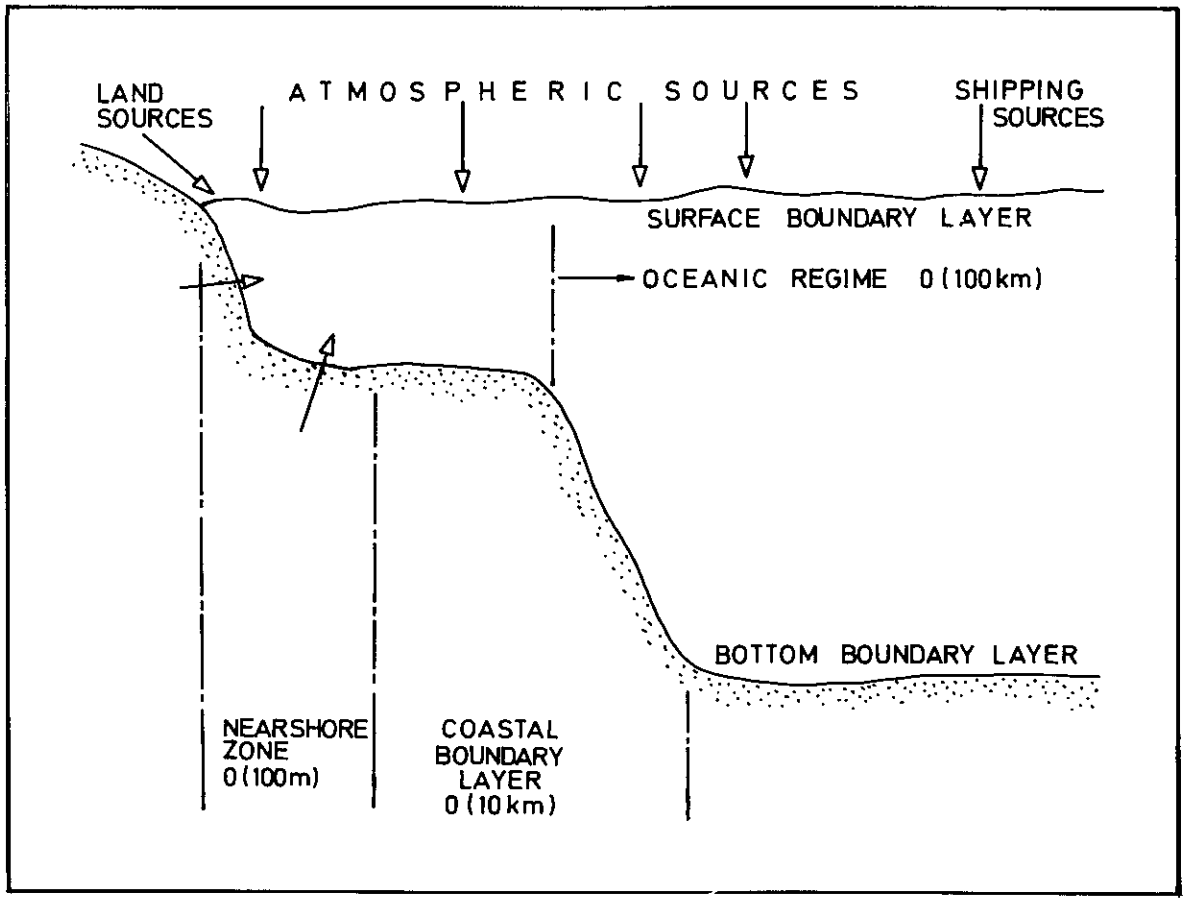


Figure 15. Horizontal dynamic structure with overlapping zones. Sources of pollutants are found in each zone. 0(100 m) means of the order of 100 m, etc.

and various sub-zones may also be defined. However, the dynamics in these zones merit a separate discussion. Subsequently our major problem is the transfer between the zones.

3.2 PHYSICAL PROCESSES IN UPWELLING AND WESTERN BOUNDARY CURRENT ENVIRONMENTS

3.2.1 Wave-generated processes in nearshore regimes

3.2.1.1 Mechanisms of littoral sediment transport

The South African coastline consists mainly of sandy beaches, with sand grain sizes varying between 0,1 and 1,0 mm. A dynamic interaction takes place between these sandy beaches and the action of waves, currents and tides. As a result, beach sediment is continually being moved by wave and current action. It is reasonable to expect that pollutants not dissolved in the water will, within limits, be transported in a similar manner as *in situ* beach sediment. A short general summary is therefore given of littoral sediment transport phenomena as a possible aid to the understanding of pollutant transport.

Littoral transport is the movement of sedimentary material in the littoral zone by waves and currents. The littoral zone extends from the shoreline to just beyond the most seaward breakers. Littoral transport is classified as onshore-offshore transport or as longshore transport. Onshore-offshore transport has an average net direction perpendicular to the shoreline, while longshore transport has an average net direction parallel to the shoreline. The instantaneous motion of sedimentary particles has both an onshore-offshore and a longshore component. Onshore-offshore transport is usually the most significant type of transport in the offshore zone, except in regions of strong tidal currents. Both longshore and onshore-offshore transport are significant in the surf zone.

Littoral transport occurs in two modes. Bedload transport is the motion of grains rolled over the bottom by the shear of water moving above the sediment bed while suspended-load transport is the transport of grains by currents after the grains have been lifted from the bed by turbulence. Both modes of transport are usually present at the same time, but it is hard to distinguish where bedload transport ends and suspended-load transport begins. It is more useful to identify two zones of transport based on the type of fluid motion initiating sediment motion, as shown in Figure 16. In the offshore zone, transport is initiated by wave-induced motion over ripples, while in the surf zone transport is initiated by the passing breaker. In either zone, net sediment transport is the product of two processes: the periodic wave-induced fluid motion that initiates sediment motion, and the superimposed currents (usually weak) which transport the sediment set in motion.

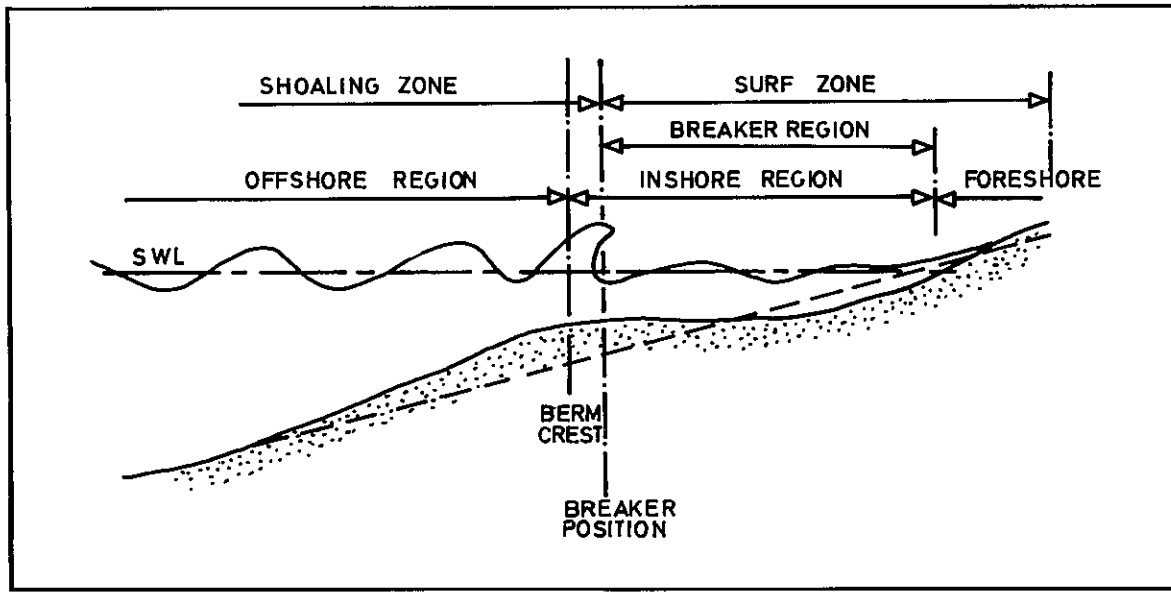


Figure 16. Schematic view of zones on a beach.

3.2.1.2 The offshore zone

In the offshore zone, as shown in Figure 17, waves travelling towards shallow water eventually reach a depth where the water motion near the bottom begins to affect the sediment on the bottom. At first, only low-density material is moved, such as seaweed and other organic matter. This material oscillates back and forth with the waves, often in ripple-like ridges parallel to the wave crests. For a given wave condition, as the depth decreases, water motion immediately above the sediment bed increases until it exerts enough shear to move sand particles. The sand then forms ripples with crests parallel to the wave crests. These ripples are typically uniform and periodic, and sand moves from one side of the crest to the other with the passage of each wave.

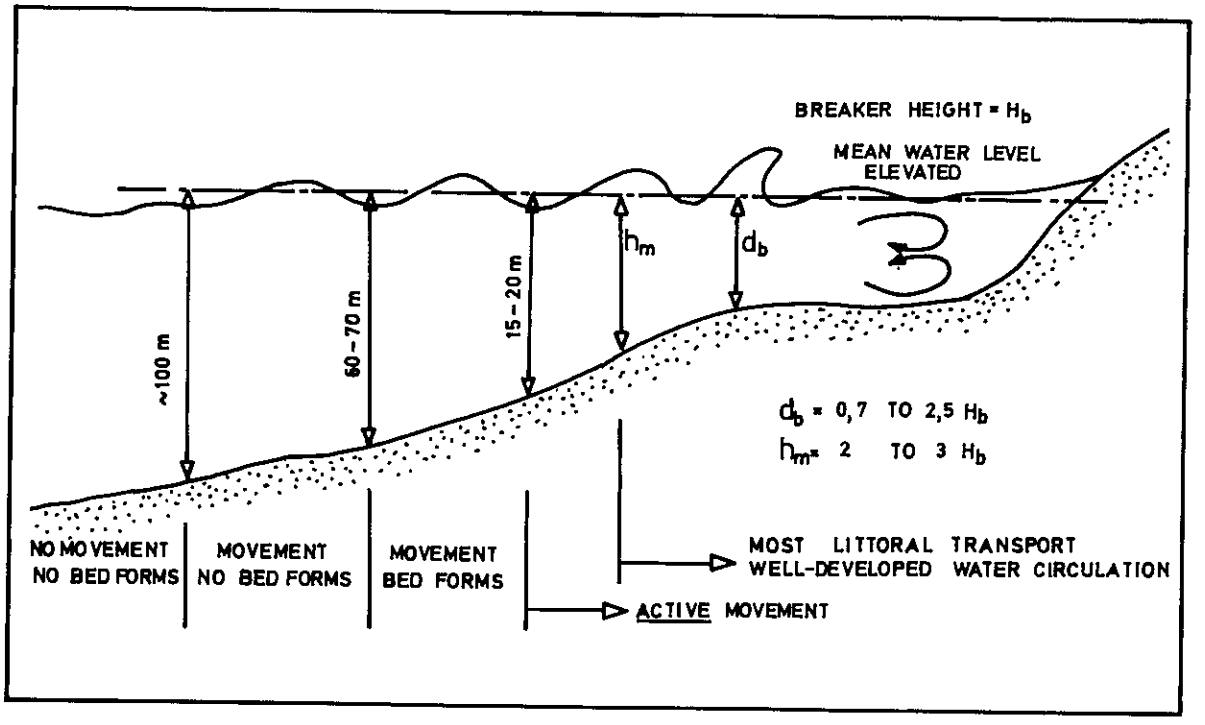


Figure 17. Schematic view of an unlimited sandy seabed, showing the effects of waves. All limits indicated are wave dependent.

As depth decreases to a value several times the wave height, the velocity distribution with time changes from approximately sinusoidal to a distribution that has a high shoreward component associated with the brief passage of the wave crest, and lower seaward velocities associated with the longer time interval occupied by the passage of the trough. As the shoreward water velocity associated with the passing crest decreases and begins to reverse direction over a ripple, a cloud of sand erupts upward from the lee (landward) side of the ripple crest. This cloud of sand drifts seaward with the flow under the trough. At these shallow depths, the distance travelled by the cloud of suspended sediment is two or more ripple wave-lengths, so that the sand concentration at a point above the ripples usually exhibits at least two maxima during the passage of the wave trough. These maxima are the suspension clouds shed by the two nearest upstream ripples. The approach of the next wave crest reverses the direction of the sand remaining suspended in the cloud. The cumulative effect of this cyclic process seems to be a gradual propagation of the ripple form in the shoreward direction. There is a degree of sorting going on, however, since the lighter particles stay in suspension more easily and are continually moved seaward.

As the fluid velocity is increased beyond the value needed to initiate sand ripples, the ripples grow in height and in propagation velocity. A critical fluid velocity is reached, however, beyond which their height decreases and the ripple wave-length decreases. With high enough fluid velocities the ripples will vanish completely. The direction of the above oscillatory sand movements (as both bed and suspended load) is along perpendiculars to the wave crest. The net sand motion, if any, may then have a longshore component, called longshore transport, if the waves do not approach the coast normally.

For the nearshore profile to be in equilibrium with no net erosion or accretion, the average rate at which sand is carried away from a point on the bottom must be balanced by the average rate at which sand is added. Any net change will be determined by the net residual currents near the bottom which transport sediment set in motion by the waves. These currents include longshore currents and mass-transport currents in the onshore-offshore direction.

3.2.1.3 The inshore, surf and foreshore zones

As shown in Figures 16 and 17, the outer limit of the surf zone is given by the breaker line. Waves can break either as a result of dynamic instability (vertical upward particle accelerations exceed downward gravitational acceleration) or due to kinematic instability (internal horizontal particle velocities exceed wave propagation speed). Typical values for wave height to water depth ratios at wave breaking for spilling breakers (caused by dynamic instabilities) and plunging breakers (caused by kinematic instabilities) range between 0,4 and 1,3. These represent breaker depths of 2,5 to 0,7 times the breaking wave height.

Perhaps the most striking characteristics of natural beaches are found in the inshore zone (Figure 16). Primary among these is the system of large-scale bars and troughs formed by action of the breaking waves. It is the location of the seaward-most bar which is used to define the outer limit of this inshore zone. The inner limit is defined by the intersection of the beach surface and mean low

water. Since this is a zone of breaker action, the turbulence level is high and suspended sediment motion is predominant. The deep troughs between the bars form natural channels for longshore currents, which are produced primarily by the breaking of obliquely incident waves. Because of the high turbulence, there is constant removal of fines from this area. Air bubbles are pulled down into the water mass by the wave-breaking process. Air bubble intrusion is more severe for plunging than for spilling breakers. The troughs serve as feeding grounds for fish.

The foreshore (Figure 16) is generally defined as the fairly steep beach face lying between mean low water and the limit of uprush from the breaking wave. Sediment transport in this zone may be bedload or suspended load. Where breakers are spilling or surging, the level of suspended sediment will be low and bedload movement will predominate (these breaker types are most common on very flat and very steep slopes, respectively). For plunging breakers the uprush may be loaded with suspended material. Offshore-directed sediment movement is especially dramatic when the foreshore is backed by coastal dunes in the backshore (landward of the foreshore) area. Losses from this backshore are of a soil-mechanical nature (slumping).

When waves approach the coast obliquely, the bedload of the uprush and downwash follows a zigzag pattern producing a net longshore sediment movement known as beach-drift. This same fluid phenomenon produces longshore currents onshore of the breaker. These are often called "feeder" currents, as they feed a "rip", or concentration of seaward flow (Figure 18) which is required for satisfaction of continuity when some irregularity of the land form has blocked the flow of water. The driving force for longshore currents is the longshore component of the influx of momentum due to obliquely-incident waves into the surf zone. The dissipative forces are bed friction and lateral (onshore-offshore) mixing. The longshore current typically has a distribution which reaches a maximum somewhere inside the surf zone (approximately two-thirds of the breaker-zone width from the shore) and tails off to zero at approximately three breaker zone widths. Typical maximum velocities are 0,5 to 1,5 m s^{-1}. Median annual up or down coast maxima

range from 0,1 to 0,3 m s^{-1}. The overall median velocities of both up and down coast components are less than this and depend on the wave climate, with particular reference to the angle of incidence between waves and the coastline.

Rip currents on the open coast occur mostly at locations where the mean water level inside the surf zone is lower than that in the adjacent surf zone areas. Rip currents therefore either move alongshore because the lower surf zone water level is caused by longshore irregularities in the incoming waves (which can move alongshore) or are fixed because the lower water level in the surf zone is caused by some permanent topographical feature, like an offshore island or shallow rocky area.

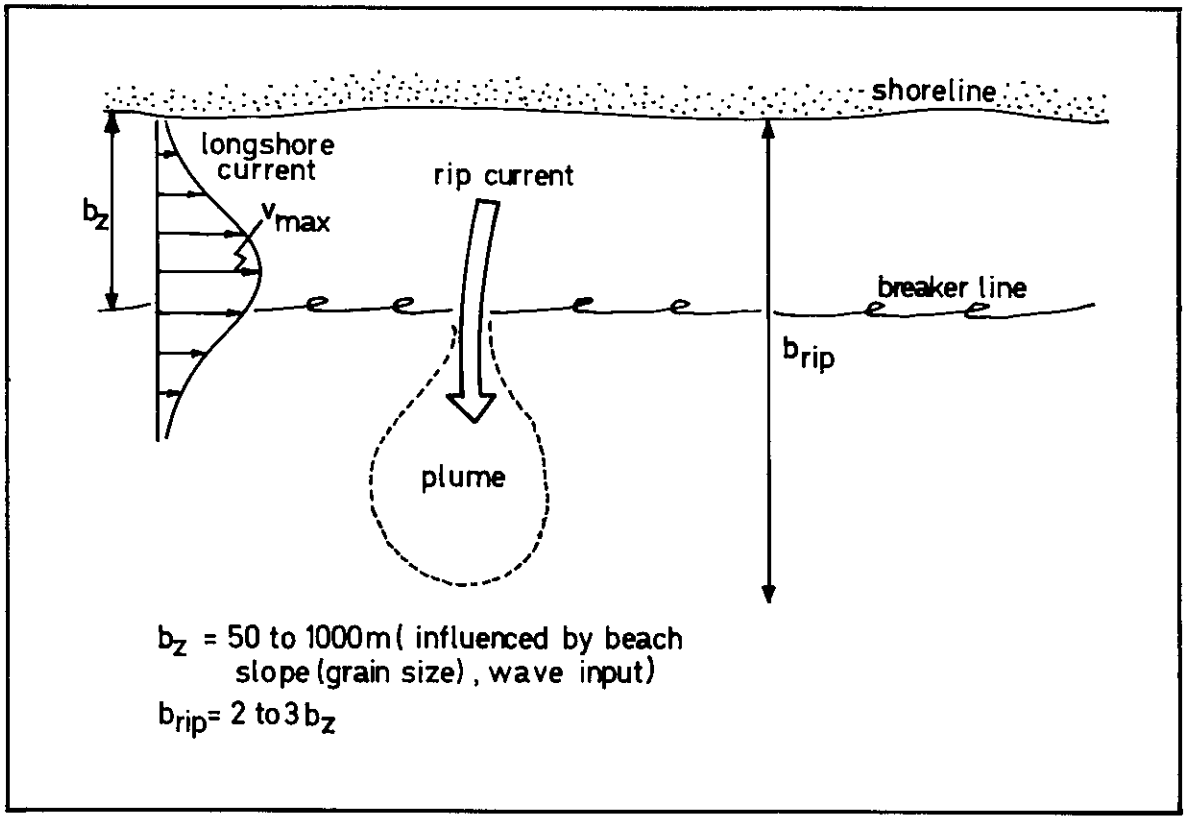


Figure 18. Schematic view of a beach showing longshore and rip currents.

Rip currents are narrow and well defined, having longshore dimensions at their throat of approximately 10 to 20 m. Maximum velocities at the throat approach

2 to 3 m s^{-1}. Rip currents often occur in groups spaced along the length of the beach and thus form cellular circulation patterns that can act as traps to re-circulate soluble or suspended materials.

Under South African conditions tidal-induced currents are generally speaking not of importance for sediment movement, except for tidal circulations in restricted water bodies like estuaries.

An interesting paradox arises when one considers the longshore transport of very fine sediment (< 0,1 mm). Because the fine material is associated with a very flat beach slope (1 in 100 inside the surf zone) one would intuitively expect low longshore currents and associated longshore transport. However, the bed forms in fine material are very small with, as a consequence, less resistance to flow and therefore larger longshore current velocities and longshore transport.

To summarize, the primary features of sediment transport on beaches are the following:

- Bedload motion due to the intense near-bottom fluid velocities.

- Entrainment of large quantities of sediment by the turbulent action of the breaking wave.

- Transport of fine material as suspended load in a manner similar to the local fluid mass transport.

The suspended transport may be in the offshore direction owing to rip currents (3D cellular circulation) and other, less severe, return flows (2D circulation), or in the onshore direction due to fluid mass transport (2D or 3D circulation), or it may be parallel to the shore due to the longshore currents. The oscillatory bedload movement may be onshore or offshore, and may have a longshore component. The direction of onshore-offshore sediment movement is determined primarily by the beach slope and the wave steepness. Offshore-directed sediment movement occurs mostly on steep beaches as a result of waves with a large incident wave steepness, whereas onshore-directed sediment movement occurs more frequently on flat beaches as a result of waves with a low incident wave steepness.

The factors influencing littoral sediment transport are therefore:

particle characteristics	-	grain size - shape factor } or fall velocity - specific gravity
wave characteristics	-	wave height, period and direction
	-	frequency of occurrence of each wave condition
	-	breaker type
beach characteristics	-	beach slope
	-	beach profile to about two breaker depths.

It therefore appears that the zone of most active nearshore sediment transport is situated between the tops of the coastal dunes and approximately the 20 m depth contour. Within this area sediment becomes mixed to a maximum depth of 2 to 3 m below the bed level and a typical maximum for the beach profile envelope (maximum difference in recorded bed level at a given location) is 4 to 5 m.

3.2.1.4 Net wave-driven sediment transport along the South African coast

The main generating area for waves reaching the South African coast is provided by the "roaring forties". As a result the angle of wave approach is such that the net wave-driven longshore sediment transport is generally directed upcoast, from south to north. Along the west coast, for example, the wave height decreases steadily upcoast but the angle of incidence increases (see Figure 19). The net longshore transport rate does, therefore, not vary drastically along the west coast. Typical values of the significant wave height H_{sig} (height of highest one third of the waves in a wave spectrum) which is exceeded once per year are:

Location	H_{sig}
A	10 m
B	4 m
C	4 to 5 m

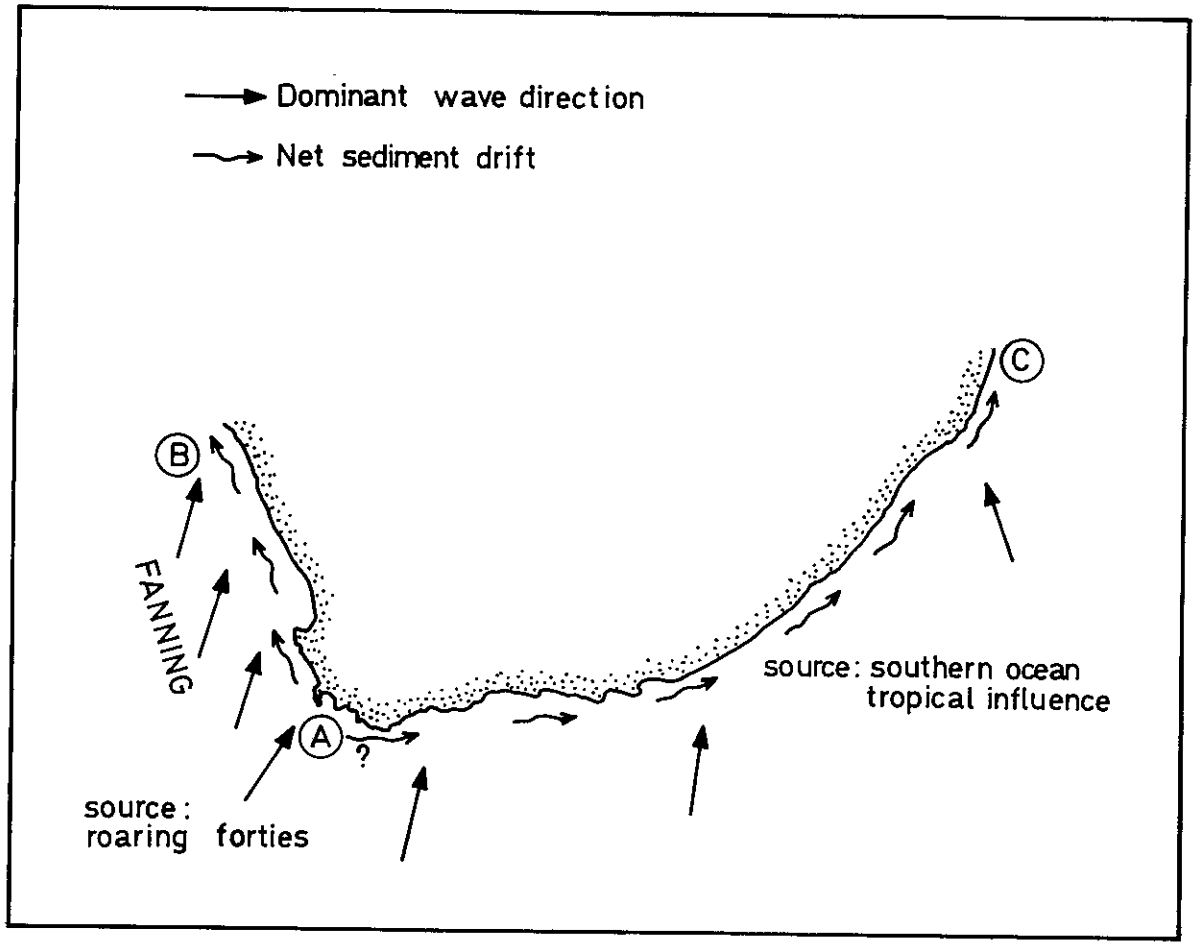


Figure 19. Dominant wave directions and net sediment drift along the coast of southern Africa. Locations A, B and C are referred to in the text.

Sediment transport normally takes place in coastal cells, determined by coastal features such as headlands. Some of these coastal cells are closed, in that no sediment is lost from them, while in other cells an active interchange takes place with adjoining cells. Gross annual longshore transport rates vary between less than 100 000 $m^3 a^{-1}$ to a few million $m^3 a^{-1}$, depending upon the local conditions. A large percentage of this total annual transport takes place during storms which only constitute a small percentage of the total transport time.

As an order of magnitude figure it may be assumed that approximately 80 to 90 per cent of the littoral sediment transport takes place during approximately five per cent of the time.

The onshore-offshore transport is also strongly storm-dependent. Large quantities of sediment are moved offshore during short-duration storms, only to be brought back inshore over a much longer period of time.

A crude estimate of the maximum possible coastal erosion during a storm on an open coastline is 4 to $8 \times 10^{6}\ td^{-1}\ km^{-1}$ of shoreline. Interesting diversions from this normal cyclic behaviour occur in areas of artificial beach nourishment where the offshore losses always exceed the onshore recuperation as a result of the steep, artificially created beach slope.

3.2.2 Other physical processes in nearshore regimes

The water column can be divided into four strata in which, from top to bottom, the following different processes dominate:

- air/sea interaction
- buoyancy forces
- internal wave breaking
- friction effects

Under certain conditions, all four strata could be present in shallow nearshore waters. More often there would only be three strata or even a two layer system with a well mixed surface layer reaching to near the bottom where the bottom boundary layer is encountered.

3.2.2.1 Wind effects

Some wind effects are peculiar to the nearshore region, while others may be found in any sea area. The obvious and direct effect of wind is a surface drift current. In the southern region of the west coast of South Africa the currents are in fact very wind dependent - a reversal of wind can cause a reversal of current. The speed of reversal and depth of penetration of current in these instances is a complex function of previous time history of wind stress and direction and current vectors. Orographic effects on the wind stress greatly affect resulting sea currents. Bottom topography and associated friction effects in shallow water will affect the wind generated currents. Entrainment eddies and stagnant areas are formed as the currents sweep past headlands and other coastal land forms. Larger changes in coastline orientation can deflect these currents away from the coast.

In addition, changes in coastline orientation relative to the wind direction, say at a headland, can produce very marked well localized centres of upwelling on the scale of one to two kilometres perpendicular to the coast and five kilometres alongshore on a time scale of half a day to several days. Any layered temperature structure in the water column is radically altered by this upwelling in the nearshore region. The effect is additional to the overall upwelling Benguela system, which is driven by southerly wind stress.

This localized upwelling, notably at Melkbosch (25 km north of Cape Town), is very sensitive to the angle of wind. Southwesterly winds cause downwelling and surface onshore movement, whereas south-southwesterly to southeasterly winds cause upwelling with attendant onshore bottom currents and offshore surface currents.

Langmuir circulations (or windrows) are generated when wind speeds of a few metres per second or greater occur over a body of water and may be an important mechanism for vertical mixing at the air/sea interface (Langmuir 1938, Garrett 1976). Langmuir cells can be visualized as pairs of counter-rotating helical vortices pointing in the direction of the current shear. Foam and floatables collect along the parallel lines of convergence which have a horizontal separation

scale of tens of metres. The vertical circulation scale is considered to be approximately half that of the horizontal scale.

Limited experimental work has been done on Langmuir circulations and it may be of interest to pursue this important process for vertical mixing.

With regard to transfer processes between the nearshore regime and the shelf current regime, winds causing upwelling will generate an offshore movement of surface waters and onshore movement of deeper waters, and vice versa for winds causing downwelling. The vertical exchange generated by these processes is usually very significant. The wind regime and meteorological factors thus play an important part in processes in the nearshore region.

3.2.2.2 Fronts

Fronts act as horizontal restraints on the transfer of material across watermass boundaries. Important fronts are generated by the overall wind generated upwelling sytem. Processes generating crossfrontal transfer include shear diffusion mechanisms, intrusions and interleafing. Fronts on smaller scales can appear for shorter or longer periods in connection with river mouths and in other areas of marked density variations.

3.2.2.3 Inertial currents

In a zone where the currents are virtually dominated by wind forcing, currents in calm conditions are very sluggish (about 1 $km\,d^{-1}$) and may follow a counter clockwise trajectory of radius and period that indicates they are inertial in nature.

A process particularly significant in shallow nearshore waters is diurnal solar heating. In protected kelp beds temperatures a few hours after sunrise can be up to $4^{o}C$ above those in adjacent open wave-mixed water. Pollutants could be trapped in such local systems.

3.2.2.4 Groundwater seepage into saltwater interfaces

The rate of seepage of fresh groundwater from the land to the sea is a function of the hydraulic gradient and the ground/sediment type through which the water moves. In riverine sands of dry rivers on desert coasts, seepage can be relatively rapid (values not available), but in other areas such as consolidated sands and gravels bounded with bed rock 25 m below ground surface, rates of one metre per week have been measured.

3.2.3 Atmospheric forcing mechanisms in the coastal boundary layer

Surface winds play a critical rôle in determining the movement of pollutants. By means of frictional drag a direct transport along the interface is induced. Indirectly, surface winds play an important rôle in the forcing of currents and nearshore current fluctuations which induce surface and subsurface transports.

In the southern hemisphere the distribution of land and sea is such that no continental barriers perturb circurpolar westerly flow between 40 and 60^{o}S latitude. The result is to stabilize and intensify west wind drift. Sea surface temperature (SST) patterns as a result of oceanic boundary currents provide variable latent heat energy to westerly wave cyclones causing enhancement over warmer currents and damping (subsidence) over cooler currents. Semipermanent anticyclones reside over subtropical ocean areas and are inhibited from propagating eastwards by the orographic barriers of the Andes mountains and the South African plateau, giving rise to these west coastal upwelling systems.

South Africa, lying in the temperate zone, is subject to seasonal variations which correspond to shifting of the subtropical ridge and westerly jet stream waves as they follow the solar incident.

The interactions of these wind belts in combination with the smaller scale fluctuations of differential land-sea heating and orography produce the highly variable wind stress patterns found in the nearshore regions of southern Africa. Figure 20 represents the probability of winds blowing from a particular sector during the year.

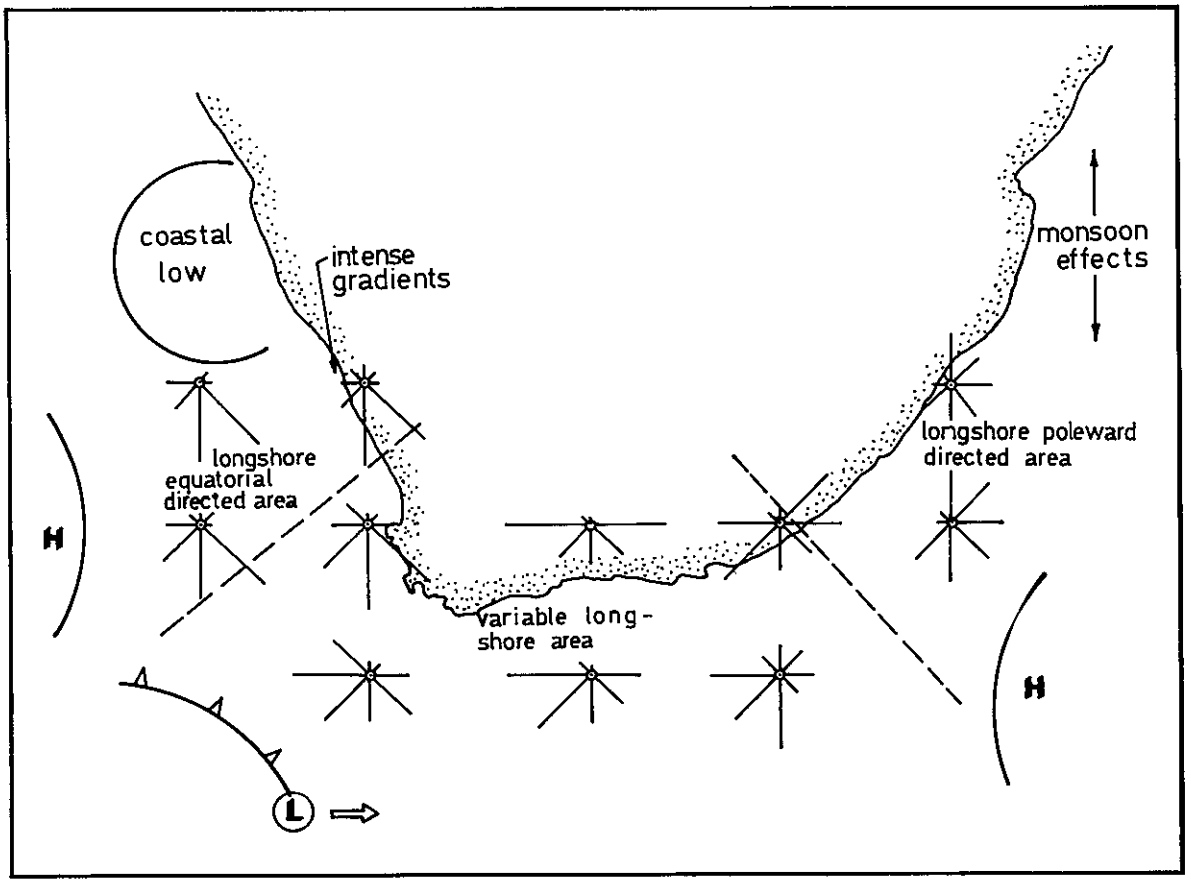


Figure 20. Probability of winds blowing from a particular sector during the year (from US Naval Hydrographic Office).

Interpretation of this figure reveals that longshore winds predominate along the entire coastline of southern Africa. Along the west coast equatorially directed winds blow with constancy. Synoptic weather events create regular longshore wind reversals along the south coast. Along the eastern seaboard predominantly poleward directed winds are found during summers with seasonal reversal of the trade current caused by effects of the Asian monsoon. Offshore wind components are very small along the entire South African coast.

In considering mesoscale effects on the nearshore winds, topographic and thermal - diurnal mechanisms may be distinguished. A good example of the former is the "Cape effect" found near Cape Town. Varying wind trajectories resulting from synoptic weather events have forcing locations which enhance surface wind stress (τ) at sea. Figure 21 displays the effects of this Bernoulli-type forcing under two wind regimes. Coastal mountains become the "nozzle" with an atmospheric thermal inversion providing a "lid" thus inhibiting flow over the mountains. A longshore low level jet results from this dynamical compression, as anticyclones propagate eastwards during summers.

Oceanic response to this longshore jet is observed in the Ekman layer as strong upwelling plumes develop under the τ maxima. This is the area in which the Benguela current originates and where the oceanic thermal front aligns with the zero wind stress curl line (longshore jet). Along the coastline bordering the Agulhas current system, increased moisture content creates buffering effects in the atmosphere. The result is to dampen mesoscale effects which magnify alongshore variabilities. Seasonally dependent features are of greater importance in this region and wind effects on pollutant dispersal are lessened by the higher oceanic current velocities in and below the mixed layer.

The difference between anticyclone and cyclone prevalence on the nearshore winds may be schematized as in Figure 22. During summers high pressure systems pass south of the country yielding a longshore low-level wind jet at some distance offshore ($\sim$ 100 km). During winters, on the other hand, low pressure systems skirting the southern tip of the continent create increasing winds offshore and tend to bring west wind drift shorewards. Wind reversals complicate this seasonal pattern and create wide fluctuations in oceanic response.

Trajectory variations in the wind field as a result of synoptic scale cyclic events create pulsations in both wind stress and nearshore oceanic response. Of particular importance is the movement and intensity of coastal lows which pass counterclockwise around southern Africa about once every five days. These unique shallow disturbances (trapped shelf waves) have diameters $\leq$ 200 km and propagate at about 10 m s^{-1}. They have strong influences on the coastal boundary layer and may cause current fluctuations or eddies at sea.

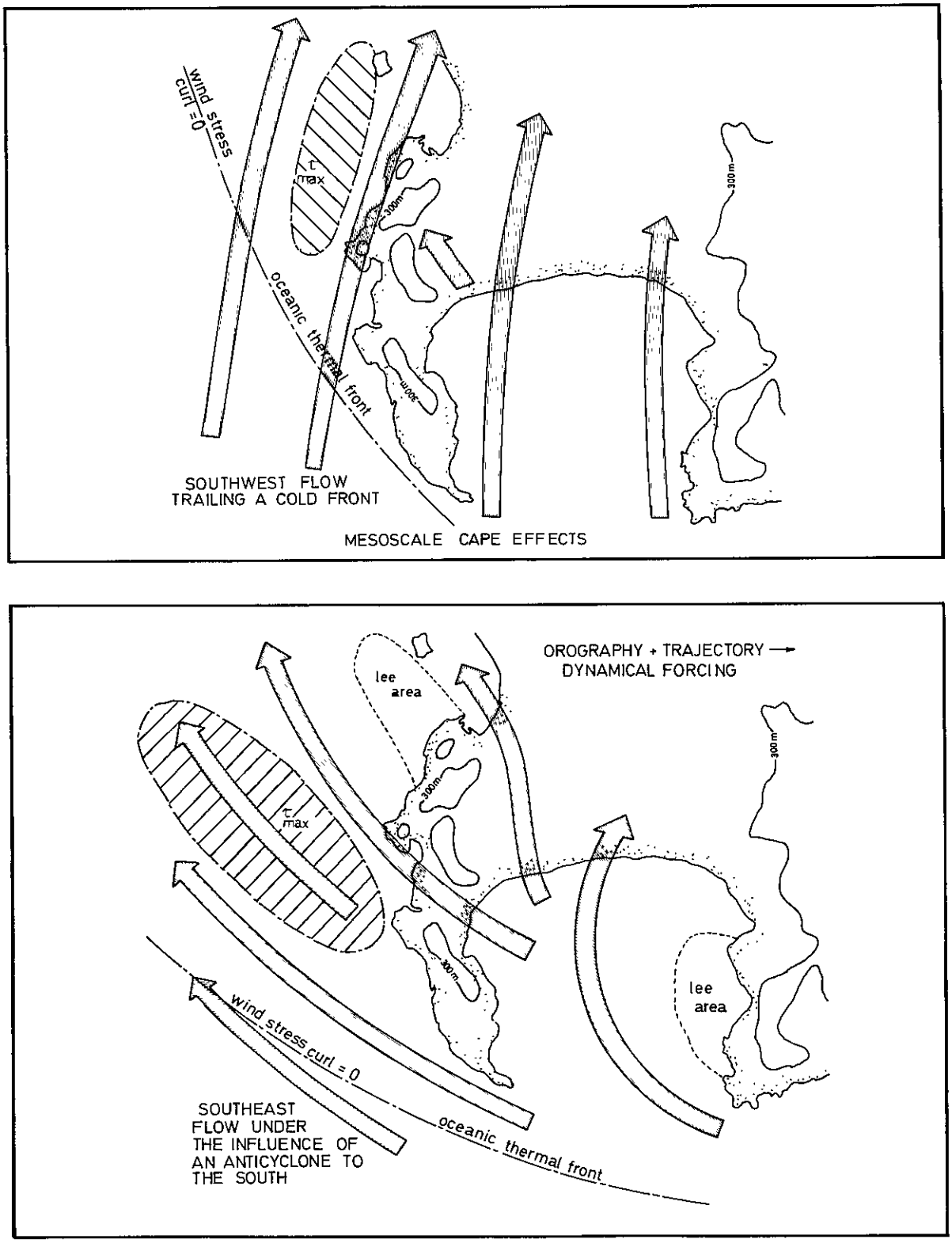


Figure 21. Oceanographic effects of south-west (above) and south-east (below) winds around the Cape Peninsula (~34° S,~18° E).

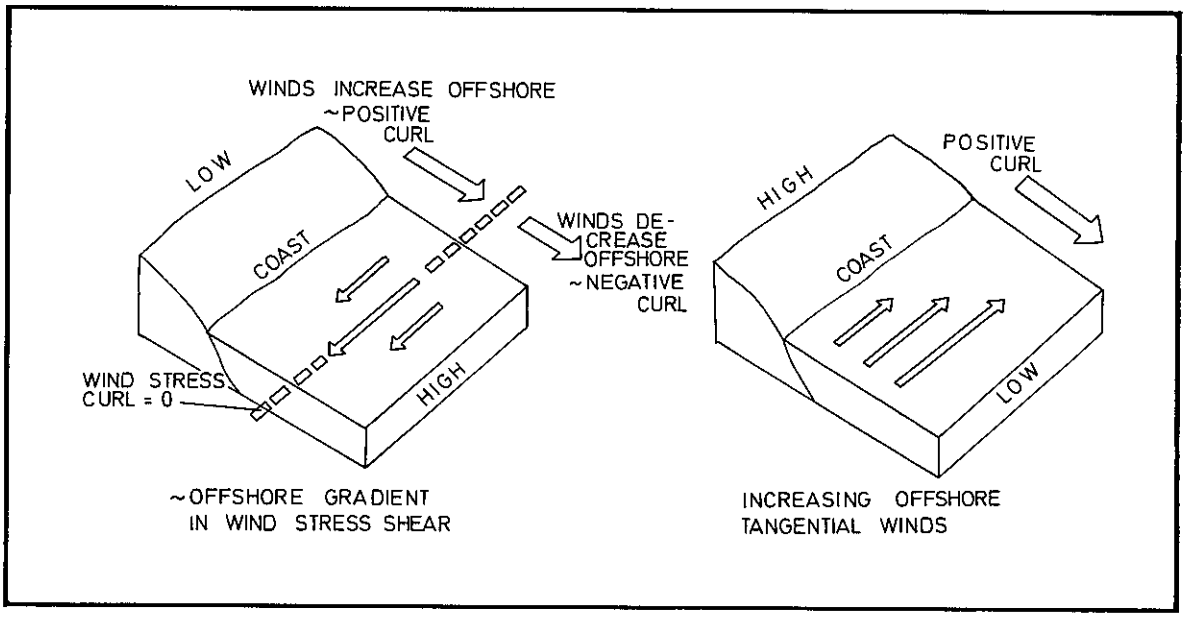


Figure 22. Variable wind shear under differing synoptic weather conditions.

Figure 23 depicts a relationship between wind change and mass transport in the nearshore surface Ekman layer. The idealized sinusoidal patterns show variable repeat cycles of 2 to 14 days.

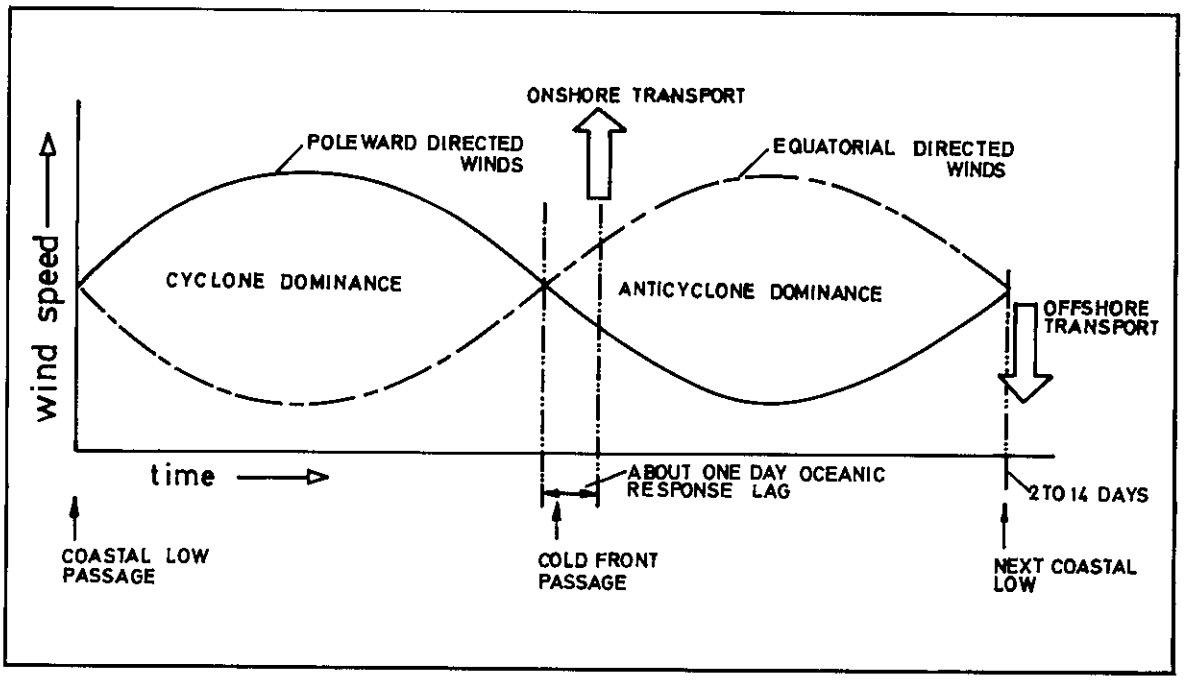


Figure 23. Relation between wind change and mass transport in the Ekman layer at a fixed position.

Thermal forcing refers to diurnal heating (cooling) which is differentially absorbed (emitted) by land and sea. General examples may be used to describe the land/sea breeze phenomena and its superimposition over a synoptically induced longshore flow.

During the early morning when the land breeze predominates, subtropical longshore flow is weakest. As offshore temperature gradients increase, onshore flow is rotated to additive longshore flow yielding high tangential wind speeds in late afternoons of summer-like weather.

Nocturnal relaxation of this phenomenon occurs thereafter (see Figure 24).

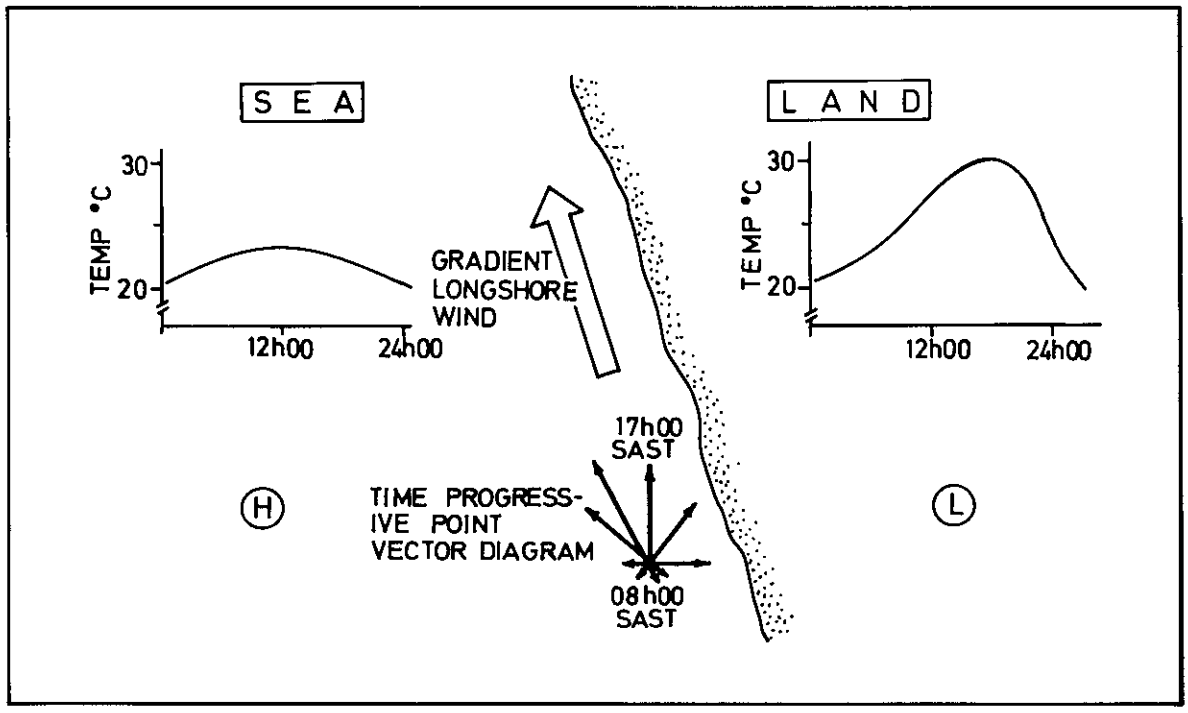


Figure 24. Typical patterns of thermally forced land/sea and longshore breezes along the Cape west coast.

Thermal forcing is observed in river valleys as winds move onshore, up the valleys in afternoons and offshore in the early mornings. This disturbs longshore gradient flow around rivermouths creating areas where shoreward oceanic transport may occur. Thermal forcing is greatest along the Namib desert coastline.

Thermal forcing by means of land-sea breezes is thus a mechanism by which pollutants may be driven normal to the coastline on 24 hour cycles during summers. Thermal forcing becomes negligible during subpolar winter-like weather.

Coupling of atmospheric forcing and oceanic response is of primary importance regarding transfer processes.

Monitoring of this coastal boundary layer by means of surface land-based stations has proved to be of some value, although extrapolation seawards is not often reliable. Ship and sea-based stations are also of questionable benefit, yet appear to fill considerable gaps in determining atmospheric coupling in the outer-shelf regions.

It appears that aerial survey and satellite imagery may be some of the best ways to monitor surface physical transport mechanisms in the marine environment.

3.2.4 Processes on the shelf and in the open ocean

3.2.4.1 Coastal upwelling with particular reference to the Benguela current system

The phenomenon of coastal upwelling is well known and occurs amongst other areas off Peru, Oregon and California, the north-west coast of Africa and off the west coast of southern Africa. In all but the last area, the process has been extensively studied. In fine detail there are differences among all of these areas determined by differences in coastal and bottom topography and meteorological factors, but in basic features, these areas exhibit common dynamics.

The driving force behind coastal upwelling is wind-driven motion of water over the shelf region and to some distance seaward of the shelf-edge caused by longshore winds. Under these conditions there is a net transport of water offshore under the action of the Coriolis force, and cold sub-surface water moves in across the shelf bottom, rising at the coastal boundary to maintain the continuity of the fluid (Figure 25).

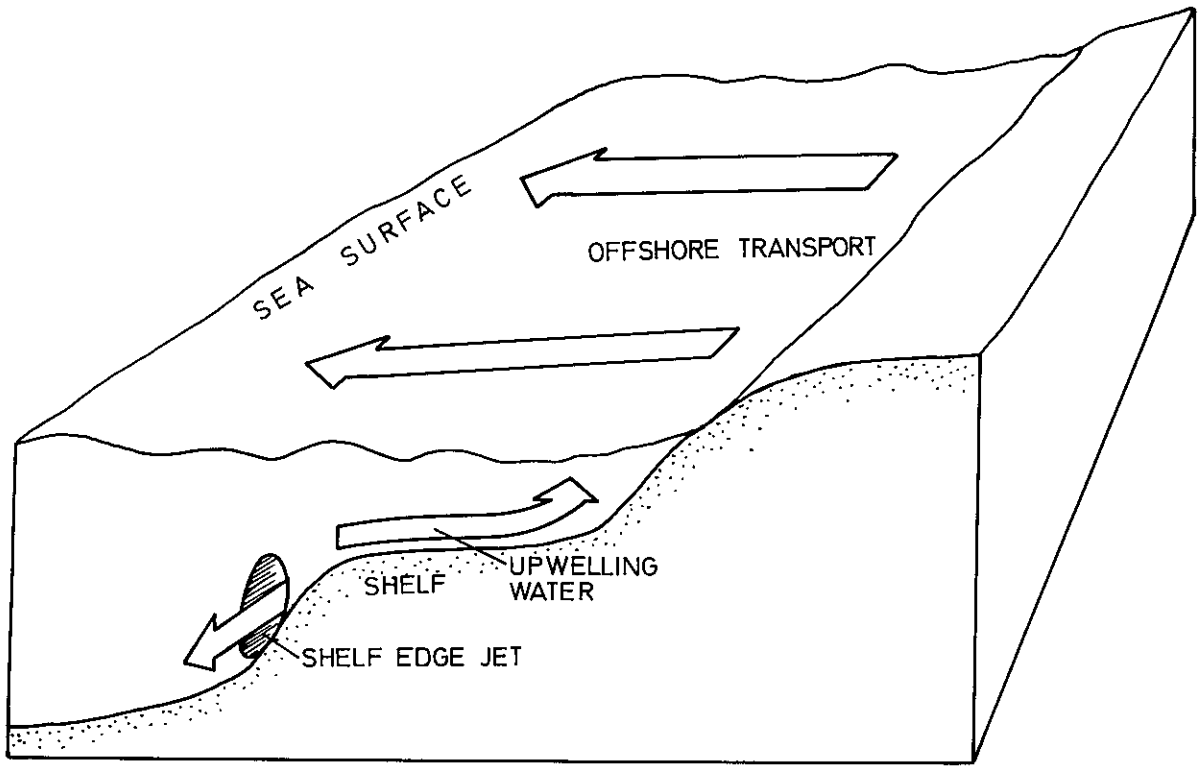


Figure 25. Schematic view of a typical upwelling system.

The surface water moves offshore from the west coast of continents by what may loosely be termed an Ekman transport process, in a northwesterly direction in the southern hemisphere and a southeasterly direction in the northern hemisphere. At some distance offshore, seaward of the shelf edge, an oceanic front is formed. Beyond this front, the water is in a state of semipermanent geostrophic flow associated with the global oceanic gyral systems and at times of diminished wind stress, the geostrophic flow regime may extend coastwards onto the shelf region. Associated with these upwelling regions is a broad and weak equatorward flow maintained by the gyral geostrophic movement.

During active upwelling, the inflowing surface water may sink at the oceanic front and move in the longshore direction of the wind, possibly as a sub-surface jet. In order to preserve continuity of the fluid, there must be a compensation return

current (Figure 25). Such a current has been detected in the Benguela system by Hart and Currie (1960). This is the classic view of upwelling. There are several complications, particularly in the southern Benguela system.

The equations of motion for a fluid on a rotating plane are

$$\frac{\partial u}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} + f^{(i)} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu \nabla^2 u_i + F^{(i)} \qquad (2)$$

where u is current velocity, f the Coriolis force, ρ density, p pressure, ν dynamic viscosity, t time and i,j = 1,2,3 correspond to axes x,y,z with z vertical and y in a north-south direction.

The fluid is incompressible so that $\frac{\partial u_i}{\partial x_i} = 0$

The vertical force $F^{(3)}$ is gravitational and the Coriolis component $f^{(3)}$ is taken to be negligible. Vertical velocities are usually of several orders of magnitude smaller than the horizontal and this leads to the hydrostatic approximation

$$p(z) = \rho g z \qquad (3)$$

where g is the acceleration of gravity.

Various situations arise depending on prevailing conditions. When the wind stress derived from $F^{(1)}$ and $F^{(2)}$ balance the longshore pressure gradient $\partial p/\partial y$, no acceleration occurs and the Coriolis forces $f^{(1)}$, $f^{(2)}$ balance viscous drag $\nu\nabla^2 u_i$. Under these conditions it can be shown by the classic analysis of Ekman that mass transports in the x and y directions are

$$M_x = \rho \int_0^\infty u(z)dz \text{ and } M_y = \rho \int_0^\infty v(z)dz = 0 \qquad (4)$$

Most of this transport occurs in the surface layers which, in practice, is complicated by local factors. For one thing, if the wind field is spatially variable the local acceleration terms $\partial u/\partial t$ are non-zero. Secondly, non-linear wave interactions and coupling between the wind and wave fields through the terms $u_i(\partial u_i/\partial x_j)$ will lead to surface currents.

Another complication occurs if vorticity or momentum is advected into the area in which case the processes represented by $u_i(\partial u_i/\partial x_j)$ are no longer negligible.

When the ocean is stratified, waves may develop in the pycnocline layer and if the amplitude of these waves is large, roll vortices characterized by surface slicks separated by distances of the order of 100 m will develop. The associated vertical velocities will be comparable to the vertical velocities which may be derived from the surface coastal divergence and volume continuity as in the Ekman mechanism.

A final criticism of this simple approach to upwelling dynamics is that the surface fluid is turbulent and molecular viscosity is replaced by vertical turbulent momentum transfer which is assumed to be uniform. This will normally not be the case.

The upwelling system west of southern Africa extends from the end of the continent at 35° S to approximately 18° S, but over this length of several thousand kilometres, there is much variability in the features of the system. North of 33° S, winds are persistent throughout the year with slight seasonal variation and a diurnal land/sea breeze at certain times of the year. The shelf is of fairly constant depth and width, and the coast is free of peninsulae and large embayments. Steady state upwelling occurs in this region with seasonal modulation.

South of 33° S the situation is very different. The wind blows cyclically with a period varying between six and 14 days in the summer months. The winds here are governed by the migration of the South Atlantic high pressure cell around the continent blowing periodically with great force as the pressure cell ridges round the continent and slackening off to zero as it splits up. Additionally, complicating the wind stress field, the orography of the Cape Peninsula mountains causes 'shadow' areas out to sea during gales in the area (see Figure 21).

A second complicating factor is the bottom topography. At the southern boundary, the shelf drops off steeply and ends at one point in a canyon. Cold central Atlantic water moves up the southern boundary during periods of high wind stress and slips off the shelf again when the wind relaxes. It is not known how this

relaxation affects currents in the upper layers near the coast, but the effect will doubtless be found to be exceptionally complicated.

Two capes in the southern region of the Benguela system, the Cape Peninsula and Cape Columbine have the effect of producing plumes (Figure 26). No detailed current study of these plumes is available, but some recent experiments using drogues have suggested that there may be a very strong southward moving current on the coastward side of the plume in the surface layer.

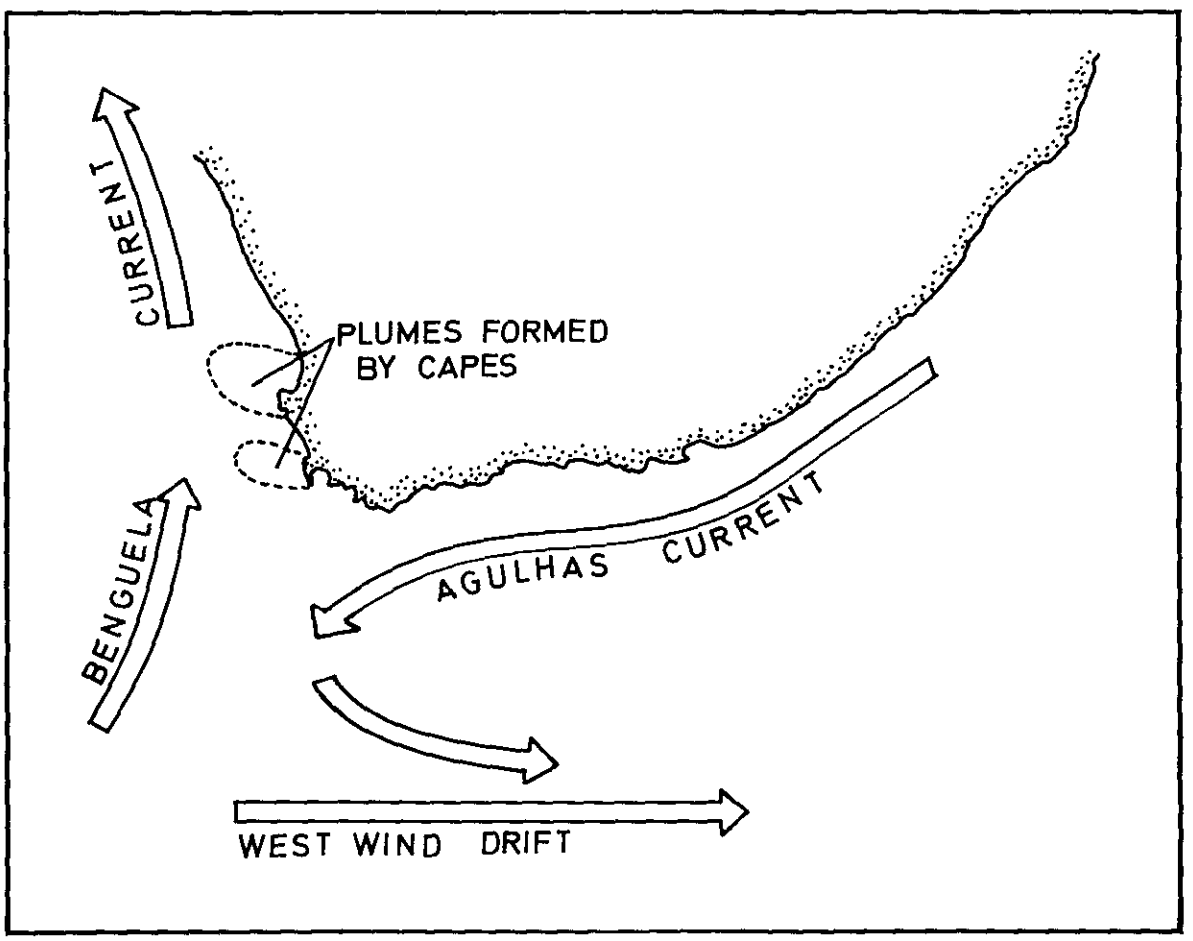


Figure 26. Positions of plumes formed off the Cape Peninsula and Cape Columbine.

Finally, the tip of the continent is so placed that three current systems, the Agulhas, the west wind drift and the South Atlantic gyre interact some

200 to 250 km to the south-west with the generation of large scale vorticity. This vorticity is advected towards the west coast and may moderate or enhance upwelling when moving up onto the shelf region.

It is seen that all the factors discussed above on a theoretical basis are to be taken into consideration in the Cape Peninsula area. In particular, currents in the top few metres can be expected to be of a very variable nature.

Experimental work undertaken in the Benguela upwelling system to date is not extensive. Much of this work is directed at a study of the thermo-haline structure with currents being derived indirectly by techniques which are questionable. Evidence of a frontal jet in the Cape Peninsula plume and of a deep compensation return current has been found.

3.2.4.2 The Agulhas current regime - an example of a western boundary current

The Agulhas current is one of the major western boundary currents, gaining its identity off the northern Natal coast from the confluence of the Mozambique current and westward moving waters of the south-west Indian Ocean (Duncan 1970). The first source operates sporadically at times, Menaché (1963) finding no contribution during October/November in 1957. The latter source consists of at least two components, with an input of high salinity subtropical water rounding the southern coast of Madagascar and then moving westward to the African coast, while a recirculation of Agulhas current water from the south also adds to the flow. The overall circulation pattern in the south-west Indian Ocean is illustrated in Figure 27.

Harris and Van Foreest (1977) speculated that a western boundary type current may also flow along the Mozambique Ridge, with contributions pulsing through to join the Agulhas current. In the deeper water east of the ridge, rings have been found with similar characteristics to those found in other oceans (M L Gründlingh personal communication), and it is probable that these also play an important part in the circulation dynamics of the south-west Indian Ocean.

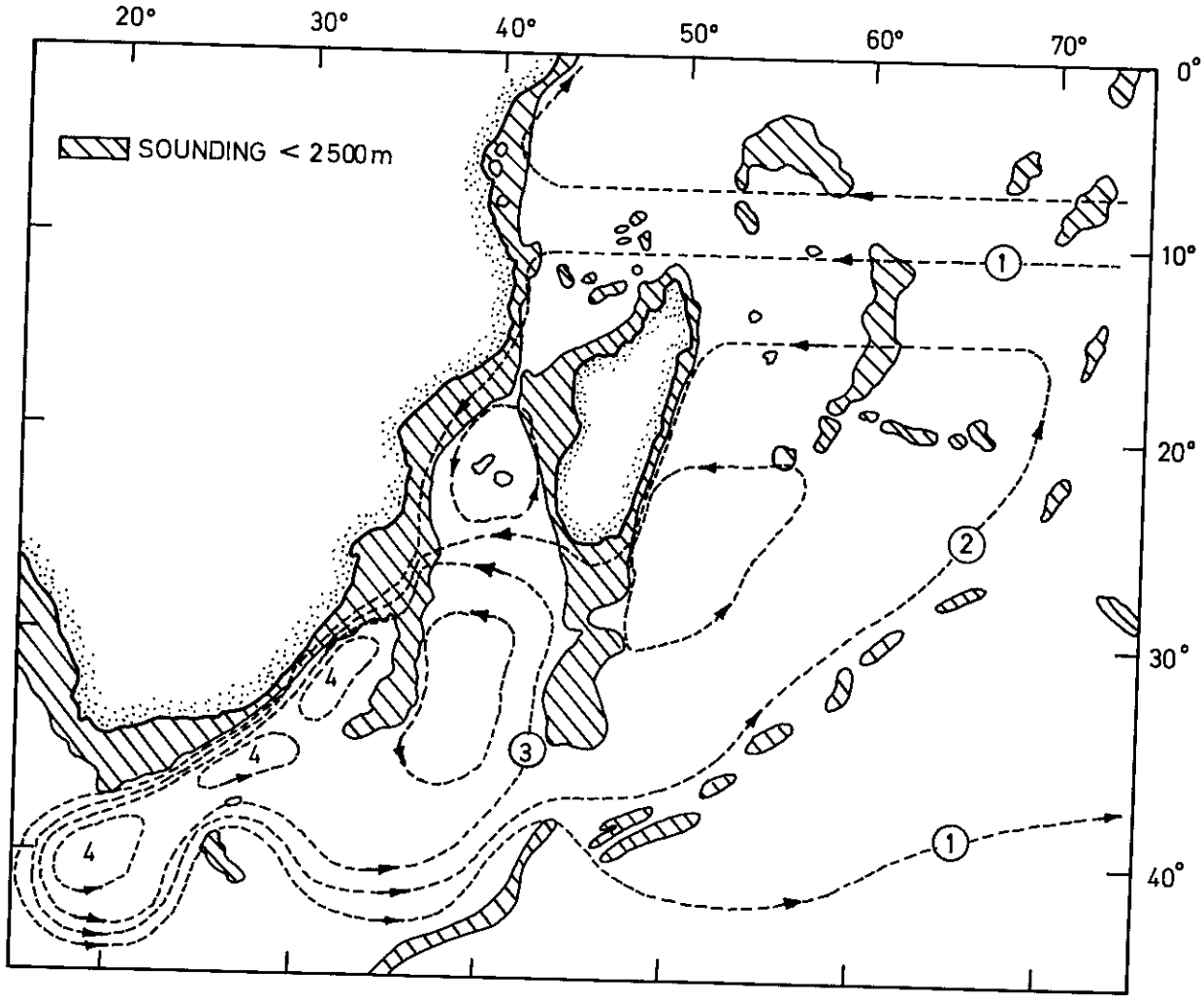


Figure 27. Main surface circulation features and bottom topography in the south-west Indian Ocean.

At its head in the north, the Agulhas current is fairly shallow (less than 2 000 m). As the depth increases southward, water from the abovementioned sources filters in from the east. Thus satellite tracked drifters reported by Stavropoulos and Duncan (1974) and Gründlingh (1977) joined the main current just south of Durban, while interior flow models (e g Greenspan 1969) also predict an increase in western boundary strength with movement poleward.

There is still uncertainty about possible seasonal variations in the flow of the Agulhas current, from the results of Darbyshire (1964) that it was strongest in April and weakest in October, to the conclusion of Duncan (1970) that the transport is

greatest in winter and least in summer. However, Pearce (1975) found no evidence of any pronounced seasonal changes in core velocity, mainly due to the intensity of the shorter term irregularities. In a recent analysis of nine sections measured by the R V Meiring Naudé off the Natal coast to a depth of 1 000 m, Gründlingh (1979a) was also unable to determine any definite seasonal variation, although the tendency was to confirm Duncan's conclusions. Comparisons with other studies also gave an increase of about $6 \times 10^6 \, m^3 \, s^{-1}$ per 100 km in the total flow.

At this stage, then, it is not possible to append an accurate figure to the Agulhas current transport: with the variability of the region it is probable that such a figure would in any case be meaningless. Nevertheless, as an indication of the type of value that may be encountered in any one set of measurements, an approximate value of $70 \times 10^6 \, m^3 \, s^{-1}$ seems appropriate. This value is also supported by a theoretical estimate by Veronis (1973).

The current generally acquires its maximum speed in the region south of Port Edward and north of East London. Here it is close inshore, hugging the narrow shelf, with core speeds commonly in excess of $2 \, m \, s^{-1}$. However, it is also true that southward propagating meanders appear to originate here, a feature described by Harris and Bang (1974) in terms of topographic Rossby waves. A similar deflection was observed in satellite infra-red images by Harris et al (1978), who found a propagation speed of approximately $13 \, km \, d^{-1}$. In a recent analysis of four sequential cruises in 1973, Gründlingh (1979b) was also able to trace a southward movement of a broad meander originating on the Transkei coast.

In the region off Natal, topographic variations play an important part in delineating different flow regimes (Figure 1). Thus in the north off Cape St Lucia, the shelf is narrow (with the 200 m isobath being some 10 km offshore) and the current in close inshore. To the south the shelf widens, mainly due to a gentle bight in the coastline, and reaches its maximum width of close on 50 km. The current is then also forced further offshore, consequently limiting its effect on the dynamics of this area.

Further south off Durban a terrace-like structure occurs, with the shelf to 200 m depth being only about 10 km wide, but then the 1 000 m isobath is some 55 km offshore. Thereafter, the shelf slopes steeply to the Natal Valley, here over 3 000 m deep. In this area the current core is situated on the average some 40 or 50 km offshore.

Continuing south, off Port Edward the 200 m isobath is still about 10 km offshore, but from there the shelf slopes to such an extent that at 30 km the depth reaches 2 500 m. Further offshore the Natal Valley is deeper than 3 500 m. Here the current has generally moved onshore with the topography, gaining in speed and volume. This narrow shelf configuration extends for a considerable distance along the Transkei coast, until in the vicinity of East London in the eastern Cape it again broadens to eventually join up with the Agulhas Bank.

Detailed work on the Agulhas current and coastal environment off Natal has been undertaken by the CSIR since about 1960. In particular a series of 45 sections off Durban, and 19 off Port Edward, occupied between 1972 and 1975, have provided valuable data on current characteristics. Pearce (1977a, 1977b) has made a comprehensive analysis of these cruise results to determine features of the upper 500 m (this being the maximum depth measured). In particular he attempted to define characteristics of the core, width and other parameters (Figure 28). Of particular interest was the close correlation found between the sea-surface temperature and current gradients on either side of the high velocity current core region.

As is the case with other western boundary currents, it is erroneous to consider the Agulhas current as having constant characteristics. Variations have already been mentioned, and Pearce (1977b) has described five days in July, 1973, when the inner boundary varied from day to day between about 15 and 70 km offshore. The origins of this variability are not yet understood, but two mechanisms may operate. In the first place, the inherent characteristics of the waters forming the current must play a vital part in the reaction to topographic changes. These characteristics will have been engendered in the earlier history of the system, reaching back possibly several years. Secondly, local input in the form of meteorological forcing and the associated generation of shelf waves may also have its part to play.

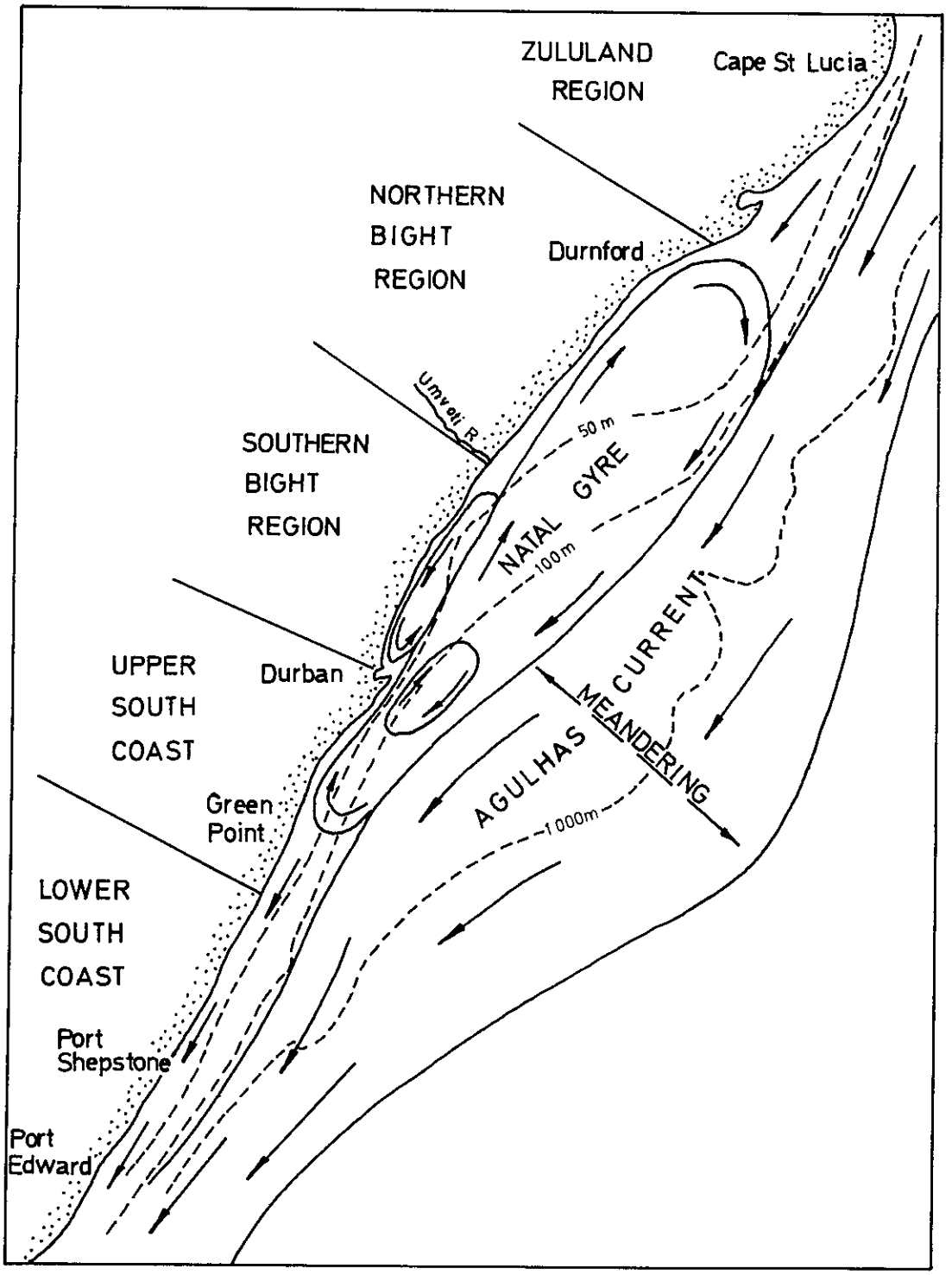


Figure 28. Hypothesized Natal shelf circulation (Pearce 1977a).

Gill and Schumann (1979) have modelled the Agulhas current between the changing topographic regimes off Durbán and Port Edward, using a three layer model and

potential vorticity functions varying with stream function. The essential variations in the current structure were reproduced, and in particular the predominantly northward flow on the shelf off Durban emerged as a consequence of the analysis. This flow has been reported by several observers, with a general review given by Pearce et al (1978).

Thus off Durban the elements of a cyclonic (clockwise) gyre exist, with northward flow generally offshore to 10 or 20 km and southward flow of the Agulhas current further offshore. The longshore scales are not fully known. Anderson et al (1970), however, have reported the gyre closing to the north, and a LANDSAT image shown by Malan and Schumann (1979) clearly shows a closed gyre in this region.

Further north on the wider shelf area, not as many measurements have been made. It seems likely that with the Agulhas current further offshore the conditions may be much more responsive to meteorological forcing. Variable flow could therefore be expected with inshore waters being retained for prolonged periods, which would have important consequences for the short-lived larvae of estuarine fishes (Heydorn et al 1978).

Shelf waves have been found to exist on many coastlines in the world, and also recently on the south-east coast (Schumann 1979). These waves are generated primarily by the wind, and can play an important part in the dynamics of coastal regions.

Baroclinic (depth varying) shelf waves have offshore scales of the order of the internal Rossby radius of deformation, while barotropic (depth independent) waves extend over the shelf region. Currents associated with waves are of the order of tens of $cm\,s^{-1}$, while surface variations in sea level are generally less than 10 cm. However, with vertical structure present in the ocean, thermoclinic deviations on the passage of a wave can be of the order of tens of metres and can thus be highly relevant to the occurrence of upwelling. The wave modes excited depend on the bathymetry, current and vertical structure and on the frequency of the forcing meteorological factors. In order to understand the larger scale patterns, however, a long section of coastline has to be studied.

An interesting possibility raised by the work of Gill and Schumann (1979) is that of supercritical flow with respect to some of the long wave modes occurring in the region where the Agulhas current achieves its maximum flow. A consequence of this could be the formation of a front downstream of this region, and indeed upwelling zones are commonly found south of the area around Port St John to East London.

Finally, in the offshore region tidal currents are generally much less than the other background currents, being less than $10\,cm\,s^{-1}$. It is probable that these currents are polarized parallel to the coastline, originating in the Kelvin waves which have been commonly found to propagate the tidal patterns.

3.2.4.3 The intermediate zone separating two major current systems - Agulhas current retroflexion and mixing with the Benguela regime

By the time the Agulhas current in its passage southwards has reached the area of Port Elizabeth, it is generally some distance offshore, with colder inshore water being a common feature. On several occasions satellite images have also shown substantial meanders in the current structure, while further southwest vortices have separated on the inshore side from the main stream. This is then an area similar in nature to that where the Gulf stream separates from Cape Hatteras, although a major difference here is the final turnabout of the general Agulhas current to finally flow eastwards in the Southern Ocean.

Before reaching that final stage, however, possibilities exist for the transference of Agulhas current water into the Benguela regime on the west coast of southern Africa. At present, two paths appear to exist for the transfer, namely:

- A direct path across the Agulhas Bank. This is of necessity a shallow surface phenomenon, and measurements on the Bank itself have indicated a sharply layered region (thermoclines involving a temperature change of around $10^{o}\,C$ in under 10 m not being uncommon). A satellite tracked buoy originally in the mainstream of the Agulhas current was tracked some

distance across the Bank before being washed ashore in the vicinity of Mossel Bay. It is also possible that this path is dependent on meteorological forcing for its successful conclusion, as illustrated in Figure 29 which is based on ship's drift observations made during coastwise passages between Durban and Cape Town (Harris 1978).

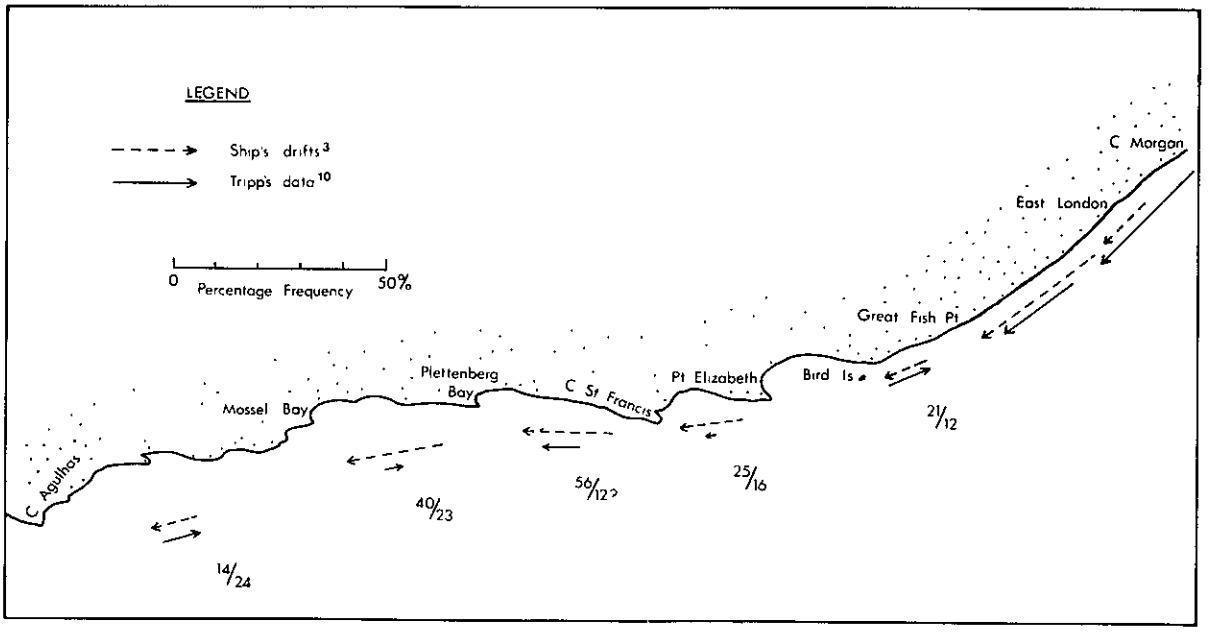


Figure 29. Net percentage frequency of current direction of inshore currents (annual) for ships' drift (data from Bray 1959-1964 and Tripp 1967). Lengths of arrows are proportional to the net percentage frequencies. Numbers are percentage frequencies of current against wind (top west-going currents, lower east-going).

- A flow of the Agulhas current in a southwesterly direction to a position only a few degrees east longitude. This is probably its maximum extent westwards, before turning to flow east. However, in this process it has been observed on several occasions that anti-cyclonic (anti-clockwise) rings of Agulhas current water separate from the main flow (cf Figure 30), and it is then possible that these move northwards to join the Benguela regime.

The current circulation between Mossel Bay and Cape Agulhas as deduced from bathythermograph data is presented in Figure 30.

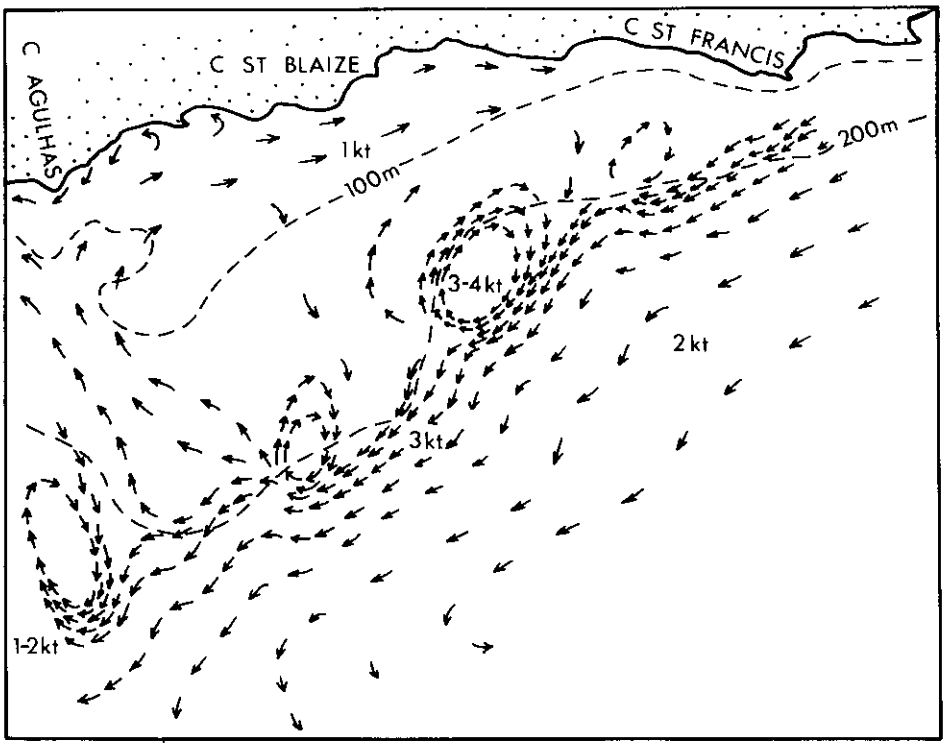


Figure 30. Current circulation inferred from bathythermograph data (Bang 1973).

A great deal of information on the flow of the return Agulhas current in its journey eastwards has been forthcoming from satellite-tracked drifters and satellite images, examples of which are given in Figures 31 and 32. Thus it appears that topographic features south of the African continent can initiate large amplitude topographic Rossby waves, with rings in some cases also separating at the peaks.

This eastward flow is part of the general easterly flow of the southern Indian Ocean merging with the West Wind Drift, and drifters released in South African waters have been found to penetrate right across the Indian Ocean.

It should be noted that there is a scarcity of data on coastal currents over the Agulhas Bank region (Harris 1978).

It is also worthwhile noting here that the beaches along the eastern and southern coasts of South Africa are subject to light but nevertheless chronic pollution by petroleum hydrocarbons, tarballs in particular. In view of the importance of the area for recreation this chronic pollution as well as the catastrophic type of oil pollution resulting from tanker accidents at sea, further knowledge about the currents in the area is a high priority. South Africa provides data for the IGOSS project on visual sighting of floating pollutants using both ship and aircraft platforms. Regular, quarterly cruises are made across the shipping route at three places - the Agulhas current off Durban, the Agulhas Bank and the Benguela current off Saldanha Bay. In addition, a closely spaced grid of 120 stations extending up to 65 nautical miles offshore in the Cape Point region was sampled monthly for tarballs from mid-1977 to mid-1978. Data (Eagle et al 1979) showed tarballs to be concentrated in a band about 50 km offshore and generally moving from east to west. Drift cards were released at each station and when processed, data from these will give a better idea of the relation between surface drift and the movement of tarballs. Results so far indicate that the area, despite heavy tanker traffic, is little polluted by floating oil, probably because any oil spilt would be dispersed in this oceanographically energetic regime.

3.2.5 Physical background information to material transfer processes in the bottom boundary layer

Particulate matter introduced into a still water body will settle to the bottom at a velocity that is determined by physical parameters of both the particle and the fluid (McCave and Swift 1976). The most important of these are the average particle diameter, the particle shape, the particle density, the fluid density, and the fluid viscosity.

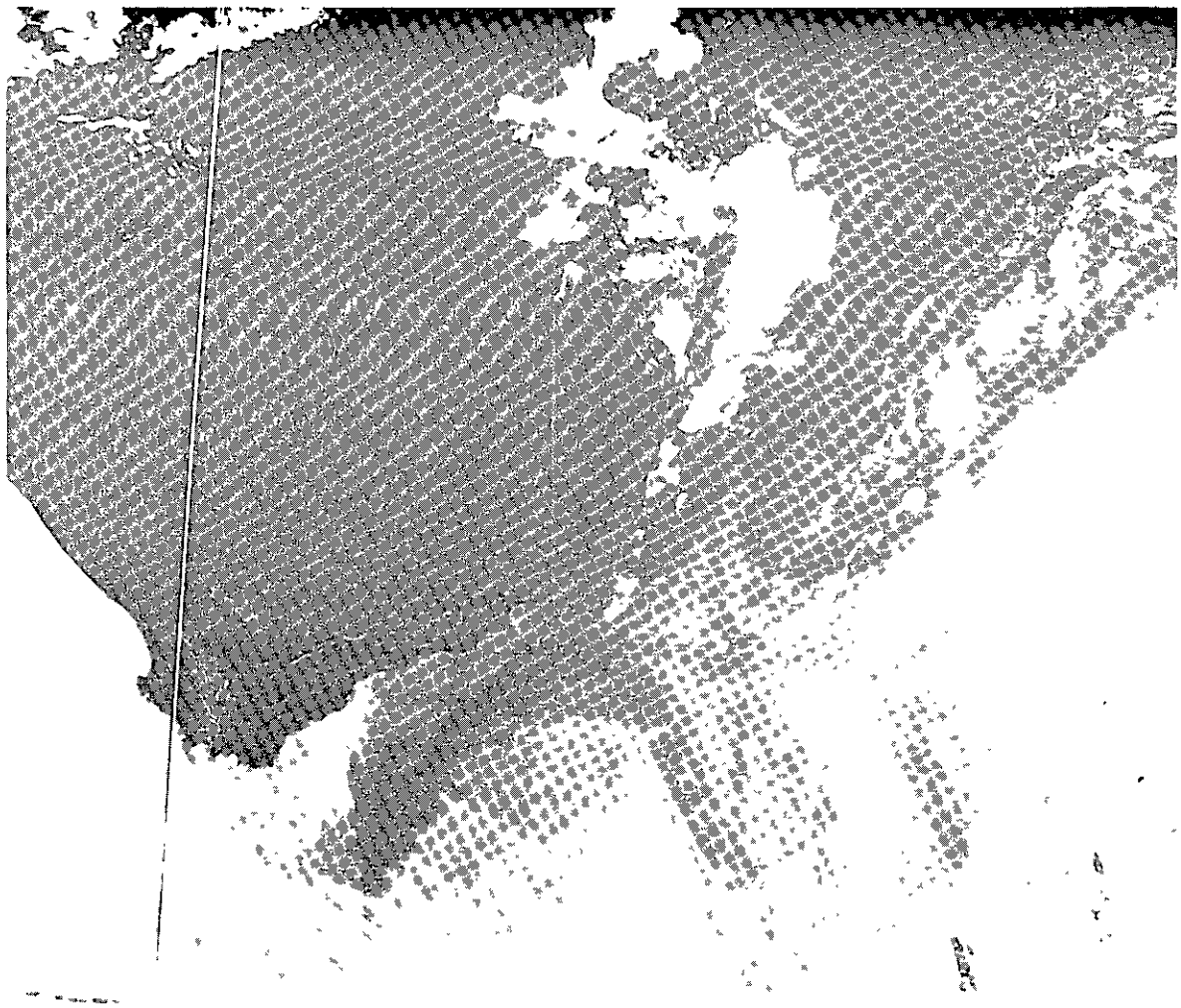


Figure 31. NOAA infra-red satellite image showing Agulhas current separating from the coast at Port Elizabeth. Elements of warmer water (darker grey) have invaded the Agulhas Bank, nearly as far west as Mossel Bay. Image should be tilted clockwise for true north - south orientation (after Harris 1978).

Open ocean water masses are rarely, if ever, at rest and a settling particle will therefore experience modifications to its course which depend on the magnitude of the force exerted on the particle by fluid motions. Near a solid boundary, e g the

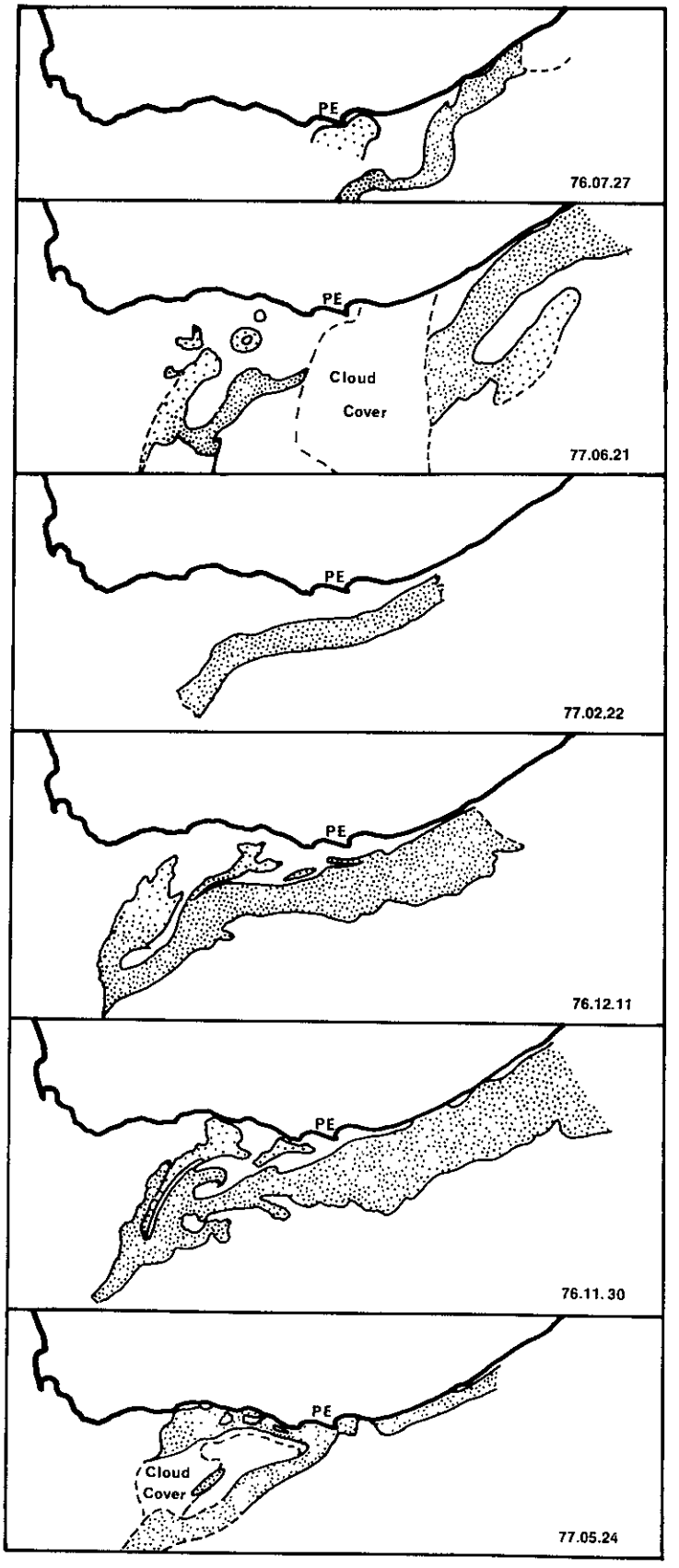


Figure 32. Sketches from NOAA infra-red images of Agulhas current trajectories. Warmer water dotted (Harris 1978).

seabed, fluid flow rates are reduced in the bottom boundary layer (BBL) as a result of friction along the boundary (Schlichting 1962). It will develop in any flow and its thickness is a function of flow velocity, depth of the water body, bed form characteristics, and to some extent also the fluid density and viscosity. In fact, the thickness (r) of the bed roughness layer depends on the flow pattern over the bedforms on the seabed. A low ratio of bed roughness r to bed form height Δr (e g crest to trough of a sandwave) will result, if little flow separation takes place and a high ratio results when flow separation does take place. It has been found empirically that the bed roughness to bedform height ratio is a function of the bedform steepness $\Delta r/\lambda r$. Thus -

$$r/\Delta r = 25(\Delta r/\lambda r) \qquad (5)$$

This functional relationship holds true for both wave and current induced bed forms. The ratio $r/\Delta r$ varies from about two to five for wave-generated bed forms and 0,5 to 1 for current-generated bed forms. Boundary layer thicknesses of up to several tens of metres have been observed, e g in the Agulhas current. In the context of the workshop, boundary layers will be expected to exist from the shoreline down to the deep ocean (McCave 1978). This does not mean, however, that it will be a single continuous layer. There will obviously be differences in structure from place to place depending mainly on wave and current activity, bed morphology, bed roughness and physical fluid properties.

It is clear that the motion of a particle entering into the BBL must be affected by these modifications in the flow, and it is equally clear that most particulate matter must ultimately pass through this boundary region. Understanding the physical processes active within the BBL are therefore of the utmost importance if material transfer processes are to be properly understood.

In general the flow within the BBL can be either laminar or turbulent, although most boundary-layer flows in the ocean appear to be turbulent. This means that besides the direction of mean flow (x) there exist secondary flow motions that can be expressed in terms of a lateral component (y) and a vertical component (z).

Fluid friction at the boundary exerts a tangential force known as the shear stress. This force is proportional to the square of the flow velocity. It forms an important parameter in the control of particle motion or non-motion and it is therefore essential that some measure of this force should be obtained. This can be done in a number of ways. For example, very close to the bed (i e a few tens of centimetres) the shear stress exerted on any plane parallel to the bed is directly related to the drag experienced at the bed and can thus be expressed by the equation

$$\tau_b = \rho \overline{u'w'} \qquad \text{kg m}^{-1}\text{s}^{-2} \qquad (6)$$

where τ_b is the shear stress, ρ is the density of the fluid, u' is the velocity in the flow direction (x), and w' is the velocity component in the vertical direction (z).

On the other hand, the shear stress is also directly dependent on the viscosity of the fluid and the velocity gradient near the bed. This relationship can be expressed by the equation

$$\tau_b = (\eta + \mu)d\bar{u}/dz \qquad (7)$$

where τ_b is again the shear stress, η is the eddy viscosity, μ is the molecular viscosity, and the $d\bar{u}/dz$ is the average velocity gradient. Shear stresses can thus be calculated either by making direct, instantaneous measurements of the horizontal and the vertical velocity components at a specific level within the BBL or, alternatively, by measuring the average velocity gradient near the boundary. The former can be measured directly, whereas the latter can be calculated by measuring the horizontal mean velocity at two different levels in the BBL. It has been established that the relationship between flow velocity and distance above the boundary approaches a logarithmic profile. The two measurements will therefore allow a reconstruction of the slope of a particular nearbottom velocity profile and hence also the determination of the velocity gradient (Figure 33).

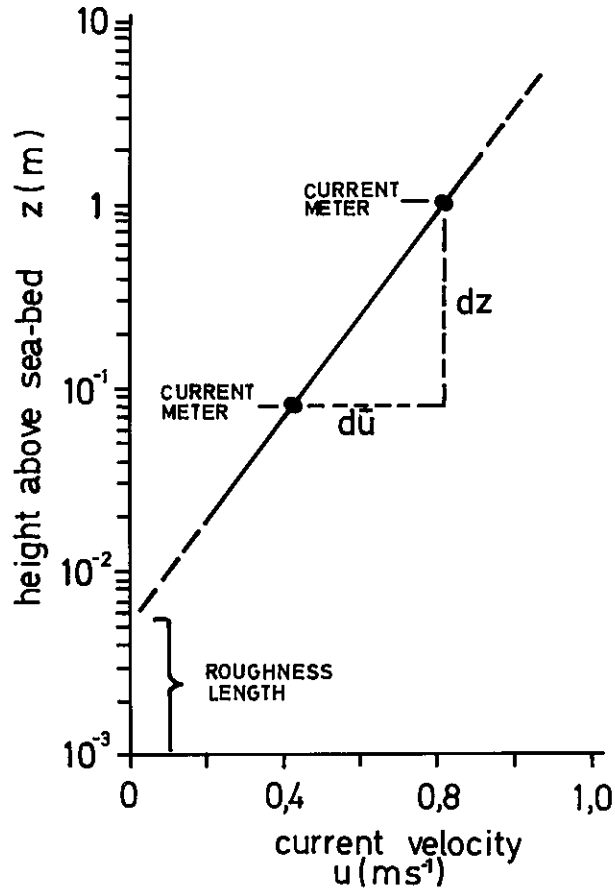


Figure 33. Current velocity as a function of height above seabed within a turbulent boundary layer.

From Figure 33 it can be seen that zero velocity is reached a small distance above the boundary which is known as the roughness length. The roughness length is strongly dependent on the nature of the bed material, e g whether it consists of gravel, sand or mud.

In addition to the logarithmic layer in which flow is always turbulent, the BBL may under certain conditions develop a viscous sublayer that is only a few millimetres thick and in which flow is more or less laminar. For this layer to be formed a bed of low roughness and a flow of relatively low velocity is required. It has been found that the viscous sublayer decreases rapidly in thickness with increasing current velocity (Figure 34). This aspect is rather important because for a given

flow velocity the bed material can be either smooth or rough depending on its size, or a given bed material can be either smooth or rough depending on the flow velocity. This can have far-reaching consequences for the behaviour of material transported within the BBL.

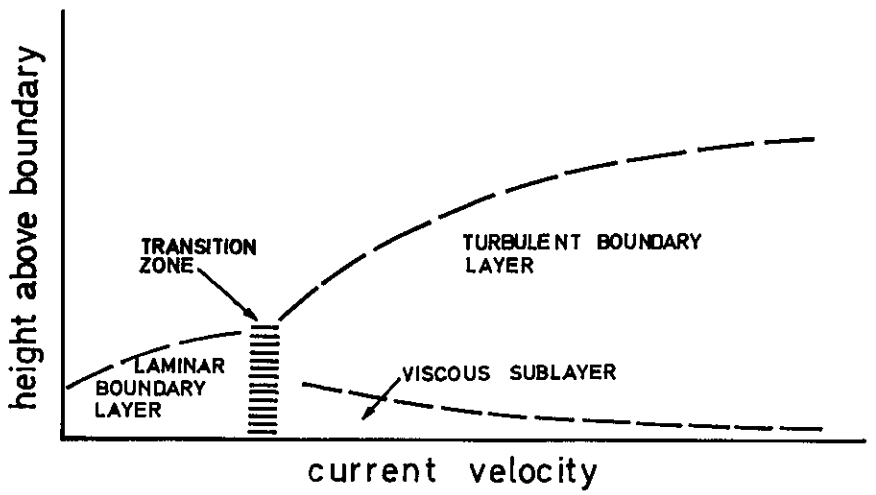


Figure 34. Boundary-layer structure in relation to current velocity.

Laminar flow in the viscous sublayer begins to be disrupted when the grain diameter of the bottom sediment, i e the height of the roughness element, exceeds about one third of the thickness of the sublayer, and flow becomes fully turbulent when grain diameters reach about seven times the thickness of the viscous sublayer.

It might be useful at this point to recall that on the average the current velocities observed in the deep oceans are significantly lower than those observed in shelf areas and one might therefore expect the viscous sublayer in deep ocean boundary layers to be considerably thicker than on continental shelves.

The relationship between flow velocity, bed roughness, and thickness of viscous sublayer is extremely important for sedimentation processes. Thus, at a specific flow velocity over a smooth bed, suspended sediment can be trapped within the viscous sublayer. If the settling velocity of the particles is greater than the

laminar flow velocity, they will be deposited. On the other hand, the same material under similar flow velocities may remain in suspension over a rough bed, because the sublayer has been disrupted and the boundary region has become fully turbulent with sufficient lift forces to prevent deposition (McCave 1973). Velocity measurements alone are therefore not sufficient to predict the behaviour of material transfer near a boundary, although they will provide a first approximation. However, in the long run it would be essential to obtain direct information about the nature of the seabed at any locality at which boundary-layer measurements are being undertaken.

A further complication is presented by the fact that material of different size is transported by different modes. It may be transported either in bedload with particles rolling or jumping along the bed or in suspension where particles are entrained in the flow, being supported by turbulent lift forces (Middleton and Southard 1978). To remain in suspension, the settling velocity of the particles must be less than about 1,6 times the shear velocity (u_*). The shear velocity is a velocity acting in the immediate vicinity of the seabed and it is mathematically expressed as -

$$u_* = \sqrt{\tau_b/\rho} \qquad (8)$$

The empirically derived relationship between shear velocity and particle diameter indicates that up to particle diameters of about 150 to 200 μm only suspension will occur, whereas larger particles will initially be transported in a bedload phase before going into suspension (Figure 35).

Information on the bed material can thus provide some idea about the boundary conditons prevalent during the deposition of that material (Sundborg 1967). Bedload fluxes have been found to be proportional to some power of the shear velocity

$$q_b \propto u_*^a \qquad (9)$$

Where q_b is the bedload flux, u_* is the shear velocity, and the power a is particle dependent varying between three for coarse grains (~600 μm) and six for fine grains (~100 μm).

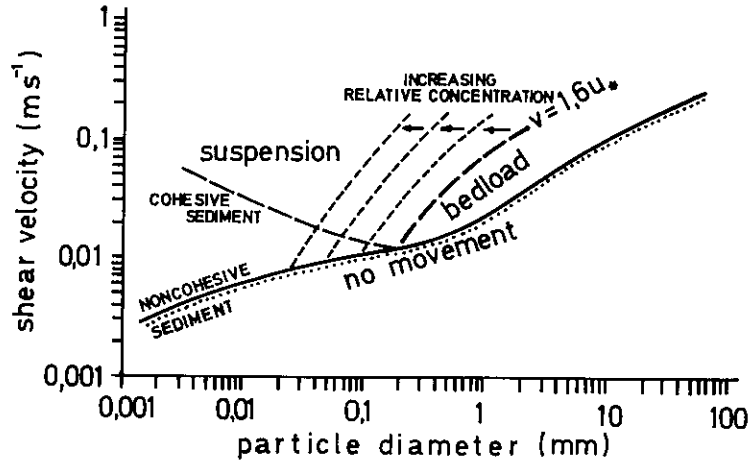


Figure 35. Initiation of bed movement and resulting mode of sediment transport as a function of particle size and shear velocity (modified after Open University 1978).

Suspended load fluxes at any specific level of the near-bottom flow, on the other hand, are simply derived by the product of the current velocity and the sediment concentration at that level

$$q_s = u' C_L \tag{10}$$

where q_s is the suspended load flux, u' is the velocity at a specific level, and C_L is the sediment concentration at the same level, which in turn is a function of u_*.

Rates of deposition are expressed by

$$R_d = C_b V (1 - \tau_b / \tau_L) \rho' \tag{11}$$

where R_d is the rate of deposition, C_b is the concentration very close to the bed, V is the settling velocity of the particles, τ_b is the shear-stress at the bed, τ_L is the critical shear stress at the bed below which the particles considered will deposit, and ρ' is a modifying factor that takes into consideration variations in bed roughness, resuspension processes, and any other local modifying factors.

3.2.6 Processes coupling the nearshore, shelf and ocean regimes

A major problem that emerged in the discussion on material transfer processes between water masses around southern Africa was the general lack of adequate data on the identification of significant boundaries, particularly on a smaller scale. Some good information is available locally from selective oceanographic investigations and on a regional scale from broad oceanographic surveys, supplemented more recently by satellite tracked buoys and infra-red satellite imagery. An indirect indication of circulation patterns and resulting dispersal of particulate matter can be obtained from continental shelf sediment distribution patterns which appear to follow and therefore reflect major boundaries between water masses dominated by different hydrodynamic regimes, e g wave-dominated and/or current-dominated areas. On account of the strong spatial as well as temporal variability of the sea state around southern Africa it was decided that the establishment of a definitive shore-parallel zonation scheme should be avoided in this context, as it would be too arbitrary and thus conjectural when applied locally.

This section therefore concentrates on a more general discussion of major boundary processes that should be anticipated around southern Africa in order to emphasize the need for special attention to them. In this respect the considerable difference between east coast and west coast conditions should be noted. The south coast, on the other hand, combines certain features of both the east coast and the west coast. It is the least important area with respect to pollution problems, with the important exception of oil spills.

A significant feature of the east coast area is the extremely narrow continental shelf. It is often no more than 5 km wide and never exceeds 40 km. This might be particularly relevant for the transfer of material to the open ocean and the deep ocean. The east coast is characterized by a net northward longshore drift component, and it must be anticipated that a certain proportion of material entering the sea, especially suspended materials, will be transferred in this direction. Since this transfer mechanism is not continuous, or at least does not operate at a constant rate, attention should be given to the effects on material transfer of this fluctuating process. It must further be anticipated that material is

intermittently exported from the longshore drift zone in the offshore direction by localized rip current systems and storm-generated return flow cells along the seabed.

The area adjacent to the surf and longshore drift compartment is characterized by a dynamically stable sand sheet which reaches down to about 50 m and which appears to be predominantly controlled by the local wave climate. There is ample evidence that excess bedload material must be able to reach this outer boundary where it is fed into the Agulhas current transport system (Flemming 1978). The fate of suspended material, on the other hand, is not clear. However, since there are no significant mud depocentres on the shelf itself, it must be assumed that this component also diffuses into the Agulhas current, from where it is carried into the Southern Ocean, perhaps even reaching the Benguela system. An important mechanism for material flux into the Agulhas current is probably supplied by the lateral migration and meandering of the current (Darbyshire 1972). This mechanism could be visualized as a pumping action, which would particularly affect the suspended load. The position of the Agulhas current relative to the coastal boundary has been found to vary by 50 km and more over a period of days, thus emphasizing the importance of this feature.

Two other features of the Agulhas current region that require attention are the return-flow eddy system off Durban (Pearce 1977a) and spin-off vortices along the offshore boundary of the current. The former is active between Green Point and Richards Bay and probably acts as a trap for sediment and thus potentially also for pollutants. The latter feature can be viewed as a mechanism for exporting suspended matter from the Agulhas current system into the surface layer of the south-western Indian Ocean.

The west coast is, by contrast, characterized by a considerably wider shelf which in many places displays a double shelf break, one at about 300 m and a second at about 500 m. Again, this morphological structure in coupling with the hydrodynamic regime appears to be important for the dispersal of material in this area. Here, too, the net littoral drift is northward with similar implications as have already been discussed for the east coast. Although the net gain is small in the south it increases dramatically north of the Orange River. Seaward of the influence sphere

of surf and longshore drift there is a dynamically stable sand sheet, although it is often poorly developed. However, in contrast to the east coast, there is neither an obvious mechanism nor evidence that significant quantities of bedload material escapes in a seaward direction beyond the outer limit of the sand sheet, because it is terminated by an extensive mud belt which indicates that suspended fines entering the system, mainly through the Orange River, the Olifants River and the Berg River, are trapped by a mechanism that has not yet been identified (Rogers 1977, Birch 1977). This raises the question of what happens to excess bedload material supplied to the sand sheet. The most likely mechanism would appear to be loss on the beaches by wind deflation. Evidence for this mechanism is supplied by abundant aeolian sand plumes, which occur particularly adjacent to beach areas attached to the north of river mouths.

Returning to the coast-parallel mud belt, it may be added that it stretches over several hundred kilometres from just north of the Orange River down to St Helena Bay opposite the mouth of the Berg River. This mud belt must be viewed as the most important potential sink of pollutants along the west coast south of the Orange River. There are indications of some loss of fines in the seaward direction. However, the quantities involved appear to be negligible when compared to the vast volumes of fines trapped in the mud belt. At this stage it is not clear whether the mud belt has already achieved a dynamic equilibrium, in which case all further fine sediment supplied would have to escape with an unknown destiny similar to that of the east coast.

To the north of the Orange River, there is no significant land-derived fine material as far north as Angola (Bremner 1977). However, strong upwelling supplies nutrient-rich waters from as deep as 500 m and gives rise to a prolific growth of phytoplankton in this area. As a result, the shelf area occupied by terrigenous muds in the south is here occupied by extensive deposits of diatomaceous muds, which thus act as an important sink for any pollutant that might be accumulated by the phytoplankton. In addition the upwelling regime in itself, with its far-reaching implications on the food-web, forms an important transfer mechanism that will require close attention, particularly as the water originates in the southern regions of the South Atlantic Ocean.

A final transfer mechanism of particulate matter that might require attention concerns the occasional injection of Agulhas current water into the Benguela system west of the Agulhas Bank. This mechanism may transfer suspended particulate matter from the east coast to the west coast.

The last region to be considered is the south coast regime stretching between Cape Point and Cape Recife. This area has received the least attention. As mentioned above, it has the lowest input of land derived matter. This feature may in fact become important from a pollution point of view, since there will obviously be a lower dilution of a given concentration of pollutants in the sediment by non-toxic or chemically inactive materials, which might lead to a quicker build up of pollutants in possible sediment traps in the area once a major source develops.

The south coast is similar to the west coast in that it has a wide shelf with indications of an ill-defined central shelf mud belt. It is similar to the east coast in that the outer shelf appears to be current controlled, at least intermittently. It furthermore receives injections of Agulhas current water, whereby particulate matter may reach the south coast region.

Longshore drift along the south coast is in an easterly direction, whereby headland protected bays act as major sinks for bedload material, and to a lesser extent also suspended matter. The remainder of the shelf area is sediment-starved, indicating a low potential as a pollutant receptor.

3.2.7 Long-range processes and their possible importance in the distribution of pollutants

Long-range transfer or trapping systems may exist on an oceanic, hemispheric or even global scale. Pollutant transfer can take place at the surface or along deep bottom currents. The strong equatorial and subpolar fronts, because of vertical motions associated with upwelling and sinking, act as barriers to transport in the upper layers. Surface transport is confined largely to the oceanic gyral motions. However, at depth, currents cross the equator.

At the fronts, strong mixing occurs. On the Antarctic polar front, planetary waves develop and large eddies can break away. Along fronts running in a north-south direction where planetary waves do not develop, turbulence is produced by shearing forces. Because of mixing in frontal zones and upwelling or sinking, these areas act as sources or sinks for the transfer of atmospheric pollutants from the northern to the southern hemisphere.

Material entering the oceans in the northern hemisphere may be transported to the southern hemisphere via deep undercurrents crossing the equatorial zone in western boundary regions.

A suggestion that such a pathway exists is given by relatively high levels of polychlorinated hydrocarbons found in the Southern Ocean. These compounds are produced predominantly in the northern hemisphere and enter the atmosphere there through industrial processes or enter the sea directly through dumping. A similar pathway for radioactive substances has not been established, possibly because of a limited data base.

A temperature-salinity analysis of water in the Agulhas system has shown the presence of high salinity Red Sea water. This would probably have had to move south under the Somali current, although the latter is dependent in a large measure on the Monsoons.

Another example of a deep undercurrent with velocities as high as $40\,cm\,s^{-1}$ is found in the Agulhas Gap region (south of Port Elizabeth) where water originating in the Weddell Sea enters the Transkei basin. The existence and significance of an Agulhas undercurrent has not been established.

The behaviour of the surface oceanic circulation can be studied using surface drifters. Two programmes have been undertaken in oceanic waters around South Africa, one a drift card investigation (Figure 36), the other a series of satellite tracked buoy experiments.

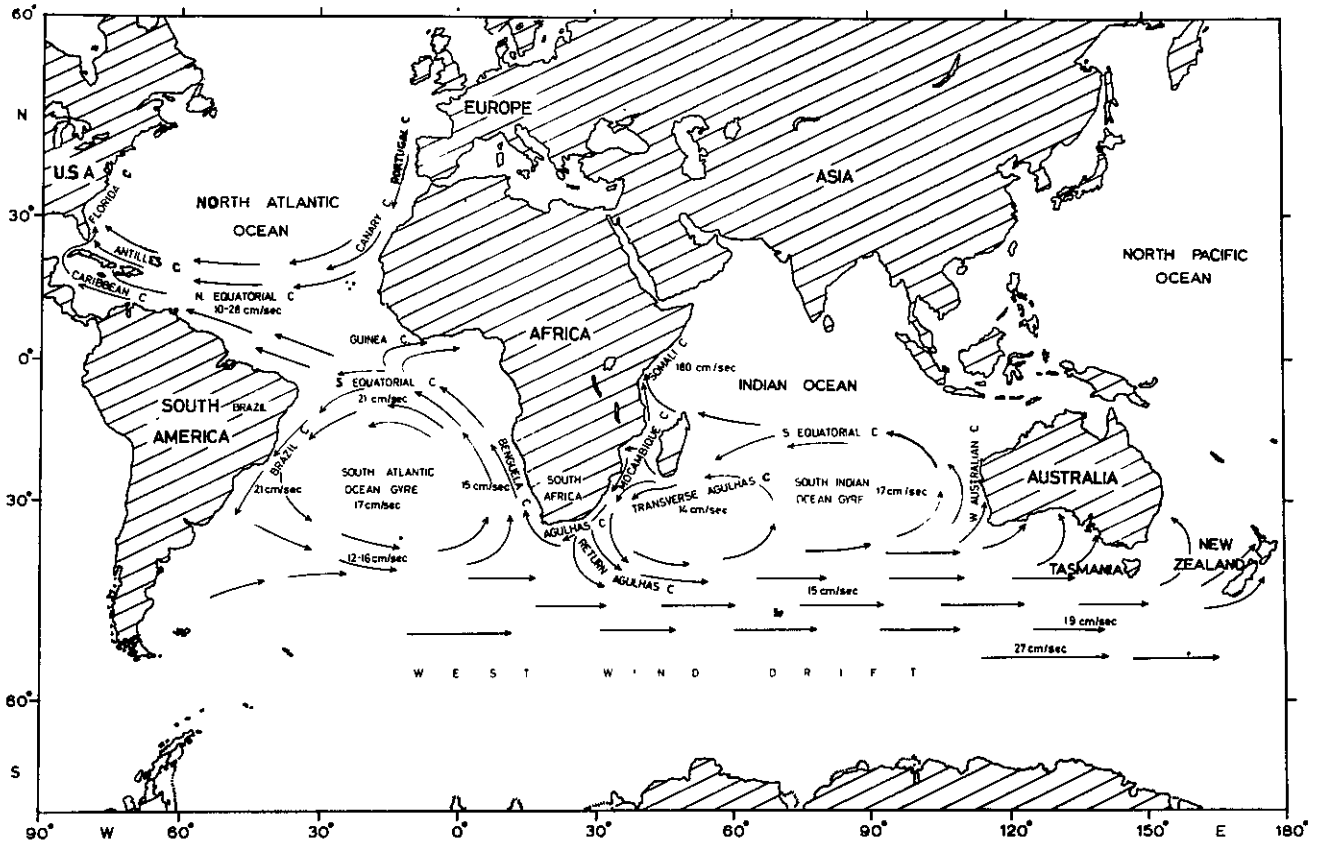


Figure 36. Current patterns and velocities as deduced from the recovery of plastic drift cards (Shannon et al 1973).

Plastic drift cards about 8 x 6 cm in area weighing a few grams are released in batches of 50 at a point of interest. These cards which bear a return address have been washed up on beaches of South and North America, North Africa and Australia. An interesting feature is that cards released at a point near the Agulhas retroflection area have found their way to entirely different continents. This may be explained in terms of a "random walk" process induced by critical momentum transfer to the card in the wave field in the initial stages, following which it enters one of three possible routes, the South Atlantic gyre, West Wind drift of return Agulhas current. Tar balls which are of comparable dimensions may be prone to such random transport processes from this area. The findings of these experiments have been reported by Shannon et al (1973). Some details of drift card releases are shown in Figures 37 to 39.

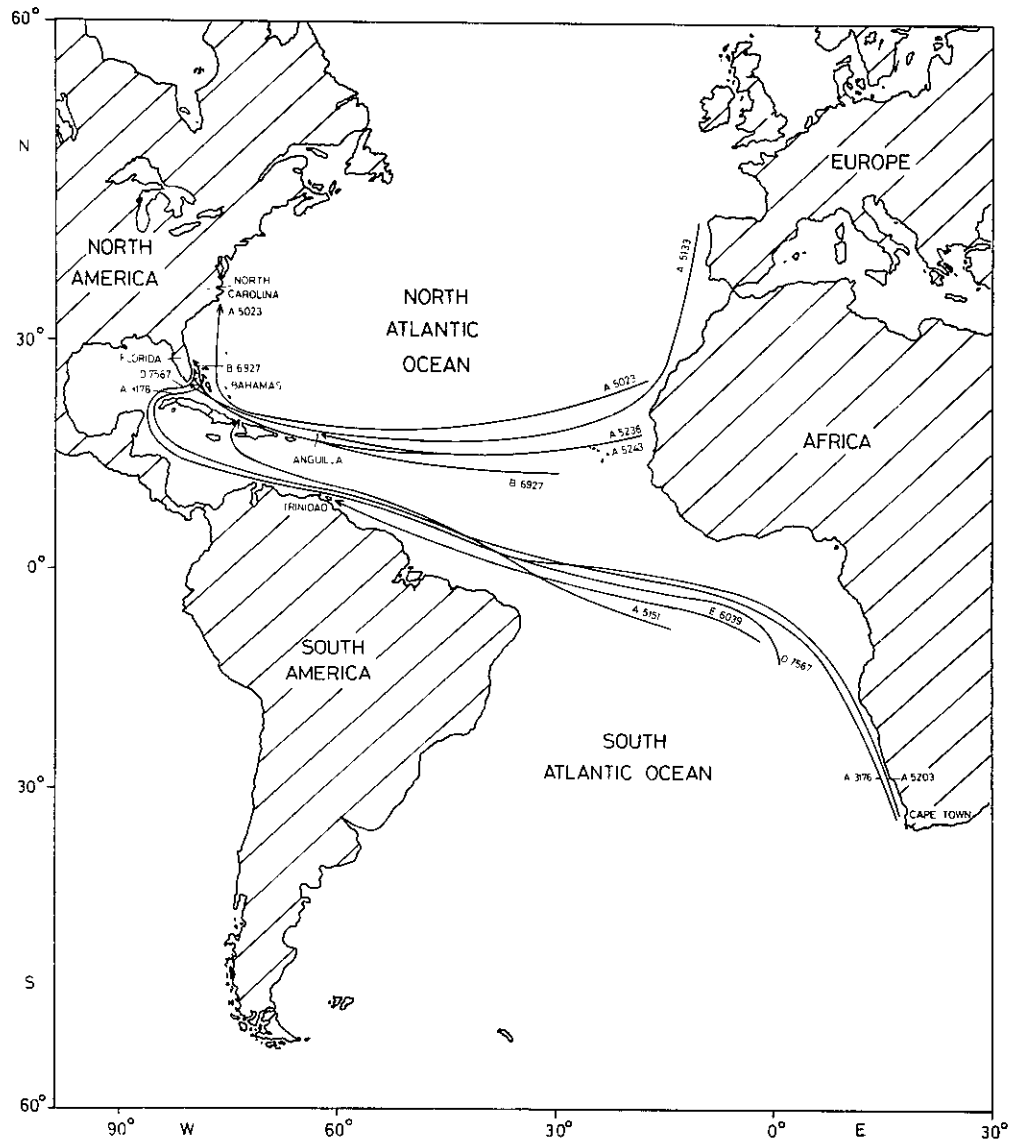


Figure 37. Drift card recoveries from countries bordering on the Atlantic Ocean north of latitude 10° N (Shannon et al 1973).

Satellite tracked buoys have been released in the Agulhas current and have been found to move in topographically induced meanders and eddies as anticipated. A buoy released in the Benguela current moved northwards to the vicinity of the equator and then westwards following the South Atlantic ocean gyre.

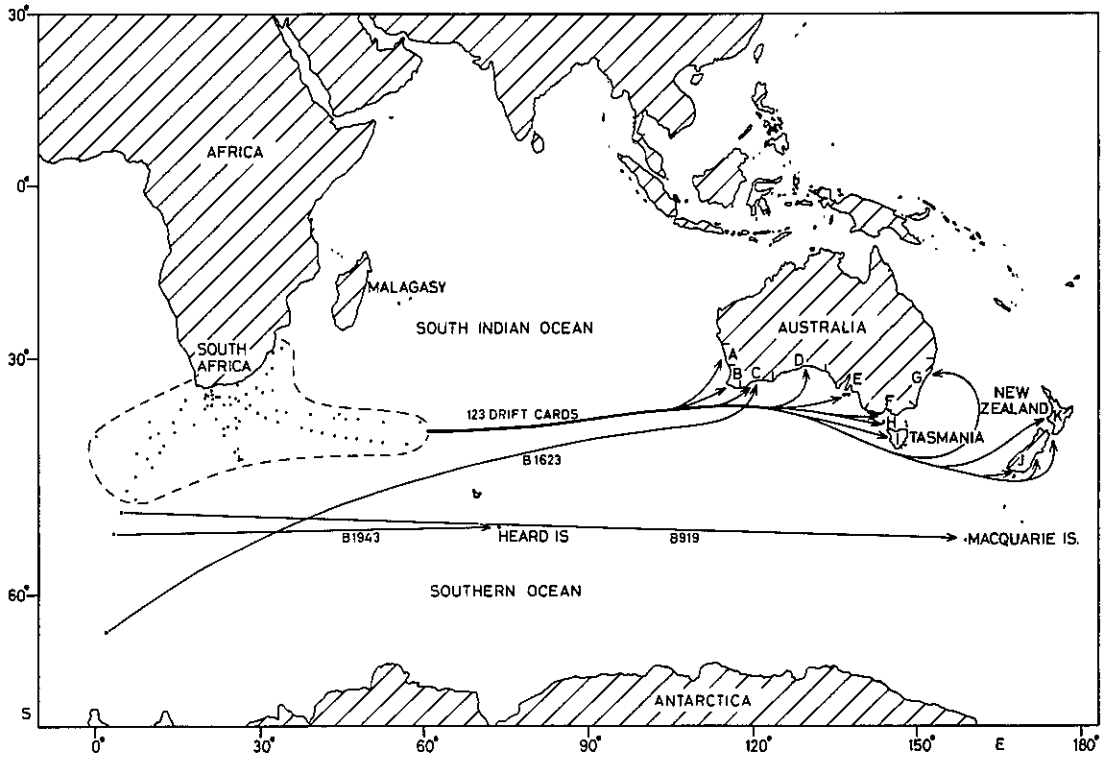


Figure 38. Recoveries from Australasia (Shannon et al 1973).

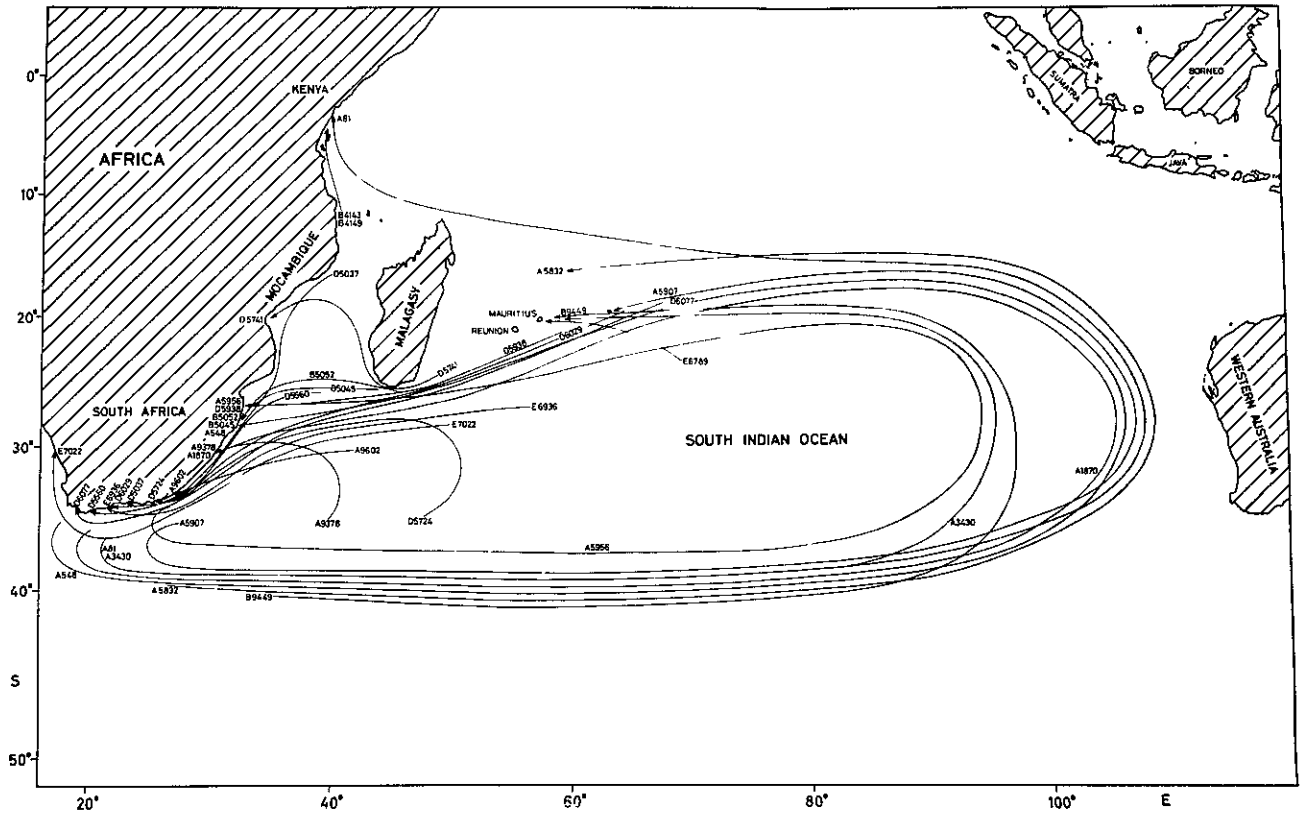


Figure 39. Recoveries from the south Indian Ocean (Shannon et al 1973).

The Agulhas retroflection area is of special significance to pollution studies because of its complex circulation hydrography, especially as regards oil spills, potentially the most serious source of contamination of the southern part of Africa and the Southern Ocean. In this area at about 42° S, the Subtropical Convergence is situated. Surface pollutants carried south in the Agulhas current would be trapped in the convergence zone. During intermittent sinking of nearly neutrally buoyant material or chemical byproducts from floating detritus, pollutants would enter Central Water and from there be transported onto the shelf region during coastal upwelling. Chemical results show raised levels of trace elements near the convergence, supporting the suggestion of a build-up. Pollutants could then be transported from this zone to the coastal upwelling zones.

Strong mixing at the Subtropical Convergence is indicated by an analysis of scales of motion in the Southern Ocean (Lutjeharms and Baker 1979). It has been found that the scales of motion are smaller, and energy levels higher, in the region south of Africa where the Agulhas current retroflection penetrates southward, compared with the situation in other areas of the Southern Ocean.

3.3 GAPS IN KNOWLEDGE

There are a number of gaps existing in our available knowledge of the physical transfer processes taking place in the oceans around South Africa. These are listed below, in order of importance.

3.3.1 Processes taking place in the zone between the Agulhas and Benguela current systems (i e off the southern coast of Africa). Surface currents are of particular importance. Wind forcing and resultant vertical mixing over the Agulhas Bank region, intrusions, exchanges of water and residence times are also important.

3.3.2 Circulation in the Benguela regime, in particular the postulated oxygen depleted undercurrent and the rôle of the mud zones along the west and south coasts as pollutant traps. The possible existence of a frontal jet in the upwelling system, and vertical processes at the oceanic front may also be important in the consideration of the physical transfer problem of pollutants, and the recycling of pollutants within the system.

3.3.3 Detailed knowledge about the wave climate around South Africa in combination with forecasting models, the trapping effect and recycling in the surf and nearshore zones also requires attention, particularly along the east and south coasts where a number of industrial effluent and sewage discharges are situated and more are planned.

3.3.4 Quantification of the circulation model off Natal, and recirculation in the Agulhas current system in relation to sources of possible pollution inside and outside the system. A better understanding of the time dependence of the Agulhas current-oscillations, and the associated pumping action is required for the understanding of the exchange between the current and the coastal waters.

3.3.5 Physical fate of suspended matter in various zones (deposition, resuspension) with particular reference to processes in the bottom boundary layer. Vertical deposition via zooplanktonic faecal matter (see Chapter 6) and boundary layer turbulence at the sediment layer require particular attention.

3.3.6 The marine boundary layer and the coupling of atmospheric forcing and oceanic response is not well understood. Aerial surveys together with a determination of the offshore wind fields are needed along the entire coastline.

3.3.7 For the purpose of better understanding of air/sea exchange processes and the temperature distribution in the sea, especially some coastal areas, better information about the heat budget is required.

3.4 RECOMMENDATIONS (in order of priority)

3.4.1 In view of the situation regarding oil and tarballs in the eastern and southern regimes, and as very little is known concerning the motion pattern along the southern coastline, it is recommended that efforts be made to study the field of motion in the southern regime with the aim of establishing the route of oil pollution, including spills and tarballs.

3.4.2 The natural oxygen demand associated with high productivity in upwelling areas is large and along the west coast it has been demonstrated that low oxygen content in bottom waters is common. Additional organic or inorganic loads with a high oxygen demand could have serious effects. Hence it is recommended that studies to establish the subsurface water circulation in the upwelling system are intensified.

3.4.3 It has been demonstrated that in the major western boundary current system along the eastern coast oscillations occur in current speed and direction which could be of great importance for the transfer of pollutants. Superimposed on these is the oceanic response to the predominantly onshore and longshore winds. Hence it is recommended that theoretical studies of the Agulhas current in relation to the Southern Ocean and Indian Ocean circulation systems be given priority.

4. AIR/SEA EXCHANGE PROCESSES

4.1 ATMOSPHERIC TRANSPORT TO THE OCEAN

4.1.1 Basic exchange processes

There has been increasing interest in the possibility that significant quantities of both natural and anthropogenic substances may be transported to the ocean via the atmosphere. An understanding of the importance of the atmosphere as a transport path is critical in determining the basic geochemical cycles and budgets of a variety of naturally occurring substances and in predicting the impact of anthropogenic material in nearshore and open ocean regions. However, less quantitative information is available in South African coastal areas, and in other coastal areas around the world, about atmospheric input than any of the other marine pollutant transport paths.

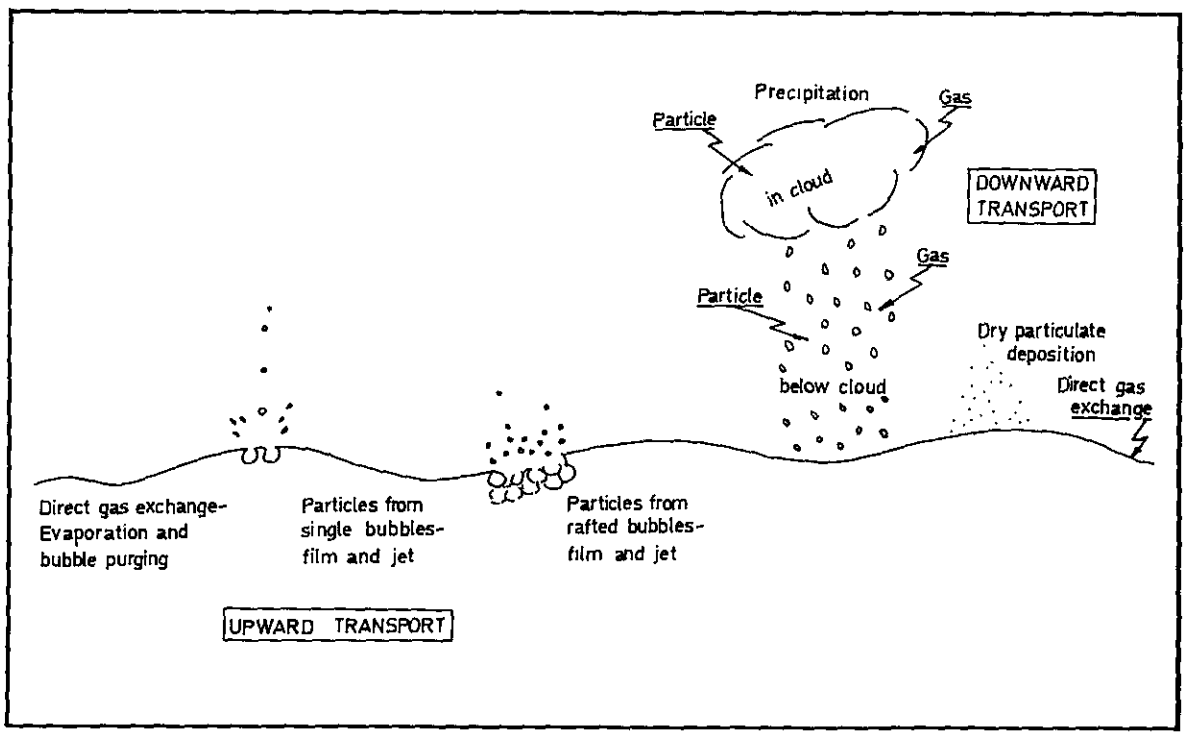


Figure 40. Mechanisms for the exchange of material across the air/sea interface.

Exchange of material between the atmosphere and the ocean can occur in a number of ways, as shown schematically in Figure 40. Downward transport includes direct exchange of material in the gas phase, dry deposition of atmospheric particulate matter, and atmospheric removal of both gaseous and particulate substances by precipitation. Recent reviews of the exchange of chemical substances across the air/sea interface have been given by MacIntyre (1974) and Liss (1975).

4.1.1.1 Direct gas exchange

A number of models for direct gas exchange across the air/sea interface have been developed (e g Liss and Slater 1974, Broecker and Peng 1975). These assume that the interface may be considered as a two layer film system with laminar conditions very close (~10 to 100 m) to the interface and turbulent conditions above and below. They also assume that the gases obey Henry's law. The basic gas flux (F) is:

$$F = K\Delta c \qquad (12)$$

where c is the concentration difference across the interface and K is the exchange coefficient of dimensions $[L][T]^{-1}$.

The reciprocal of K is a measure of the resistance to gas exchange, such that:

$$1/K = 1/\alpha k_l + 1/Hk_g \qquad (13)$$

where $1/K$, $1/\alpha k_l$ and $1/Hk_g$ are the total, liquid-phase and gas-phase resistances, H is the Henry's law constant for the gas concerned and α a factor depending on the reactivity of the gas in the liquid phase. For gases which are unreactive in the liquid phase, α is unity. It is greater than unity for reactive gases.

For highly soluble gases, where $\alpha >> 1$, e g NH_3 or SO_2, the gas-phase resistance is the limiting factor for gaseous flux across the air/sea interface. Similarly, for unreactive gases, where H is large ($>> 1$), e g 0_2 or CH_4, the liquid-phase resistance is the limiting factor.

To calculate fluxes, Henry's law constants for the gases of interest must be known. While these are well known for common gases they have not been measured for many pollutant organic gases particularly at low (natural) partial pressures. It is also often difficult to obtain ambient concentrations of these gases which tend to show large temporal and spatial variations in the atmosphere and ocean. Surface films do not appreciably affect gas exchange, although this might occur locally near oil slicks.

Model calculations lead to the conclusion that the sea is a sink for the more soluble gases such as H_2, CO_2, SO_2, NH_3 and also CCl_4 and freons, while the sea is a source for atmospheric N_2O, CO, CH_4, CH_3I and $(CH_3)_2S$. Hunter and Liss (1977) have also calculated that about 10 per cent and 0,5 per cent of the atmospheric PCB's and DDT found over the ocean may enter the sea in this way.

4.1.1.2 Dry particulate deposition

Many organic and heavy metal pollutants in the atmosphere are present on or as particles. A useful concept in evaluating dry deposition of atmospheric particles, or material present on the particles, to land or water surfaces is the deposition velocity, v_d:

$$v_d = F/C \qquad (14)$$

where F = the dry depositional flux of material on the particles to the surface (e g μg $cm^{-2}s$), and

C = the atmospheric concentration of material on the particles (e g μg cm^{-3}air)

v_d then has units of $cm\,s^{-1}$, and is an empirically derived value obtained from simultaneous measurements of atmospheric concentration and dry deposition to an appropriate collection surface.

Field measurements of deposition velocities for materials present on particles in the stable aerosol size range (i e diameter less than $\sim$ 10μm) close to the ground

are usually between 0,1 and 1 cm s^{-1}, although this varies considerably with particle size, wind speed, and surface roughness. Sehmel and Sutter (1974) investigated the particle deposition velocity over a water surface in a laboratory wind tunnel as a function of particle size and wind speed. They found a general decrease in deposition velocity with decreasing particle size at a given wind speed. For a given particle size greater than 1 μm diameter, the deposition velocity increases with increasing wind speed. Below approximately 1 μm diameter there appears to be no clear relation between deposition velocity and wind speed.

4.1.1.3 Wet deposition processes

Junge (1972) pointed out that dry deposition becomes less important as a removal mechanism as particle size decreases below $\sim 5\mu$m diameter, with precipitation often being the primary removal mechanism for the smaller sizes. For material present in the atmosphere as particles or as reactive gases (e g SO_2, HCl, NH_3, etc) a useful empirical relationship between the concentration of a particular substance in rain and the concentration of that same substance in the near surface atmosphere can be used. If the concentration in rain of any substance is expressed in g Kg^{-1} rain, and the concentration of that substance in the air is expressed as g Kg^{-1} air, the ratio of these concentrations is called the washout factor, W:

$$W = C_{rain}/C_{air} \sim 1\,000 \qquad (15)$$

W may range from 300 to 3 000 but is generally near 1 000 for reactive gases and particles. For relatively non-reactive gases, such as some of the heavier chlorinated hydrocarbons, W may be considerably less than 1 000 and the relationship above cannot be used.

From the simple considerations of the deposition velocity, v_d, and the washout factor, W, it is apparent that if atmospheric concentrations of pollutants in particulate form are available near the coastal zone, order of magnitude estimates of the flux of these pollutants to the surface via dry deposition and precipitation

can be made. It must be emphasized, however, that these will only be order of magnitude estimates at best. The absolute fluxes and the relative importance of dry deposition versus precipitation removal of atmospheric particles (and gases) are complex functions of the wind speed, the material's chemical reactivity and particle size, and the precipitation type, intensity, duration, and frequency.

4.1.2 Air/sea exchange climatology in southern Africa

In speaking of interface exchange processes around South Africa one must consider the stratification of the atmosphere with respect to the uptake and release of aerosols into the marine boundary layer.

South Africa is subject to seasonally shifting global patterns which determine basic aerosol flow trajectories as well as air mass characteristics. Figure 41 depicts this shifting pattern. The winter pattern at top reveals a marine invasion of cool air from the south west with onshore flow on the south and west coasts. Beneath is the summer pattern with basically opposite characteristics.

Apart from seasonal changes, the marine atmosphere experiences a permanent influence by the two contrasting currents in the area. Upward fluxes of heat energy are found over the Agulhas influenced area while downward fluxes are found over the Benguela upwelling area. A modification of the low-level atmospheric structure results from these heat sources (western boundary currents) and sinks (eastern boundary currents), as shown in Figure 42.

An indication of these heat energy fluxes is given by subtracting the sea surface temperature from the air temperature at 150 m. Over the upwelling area values exceeding $10^{\circ}C$ are common (from past experimental results) yielding a strongly stable stratification in the bottom few kilometres of atmosphere. Conversely, over the Agulhas the same subtraction leads often to negative values.

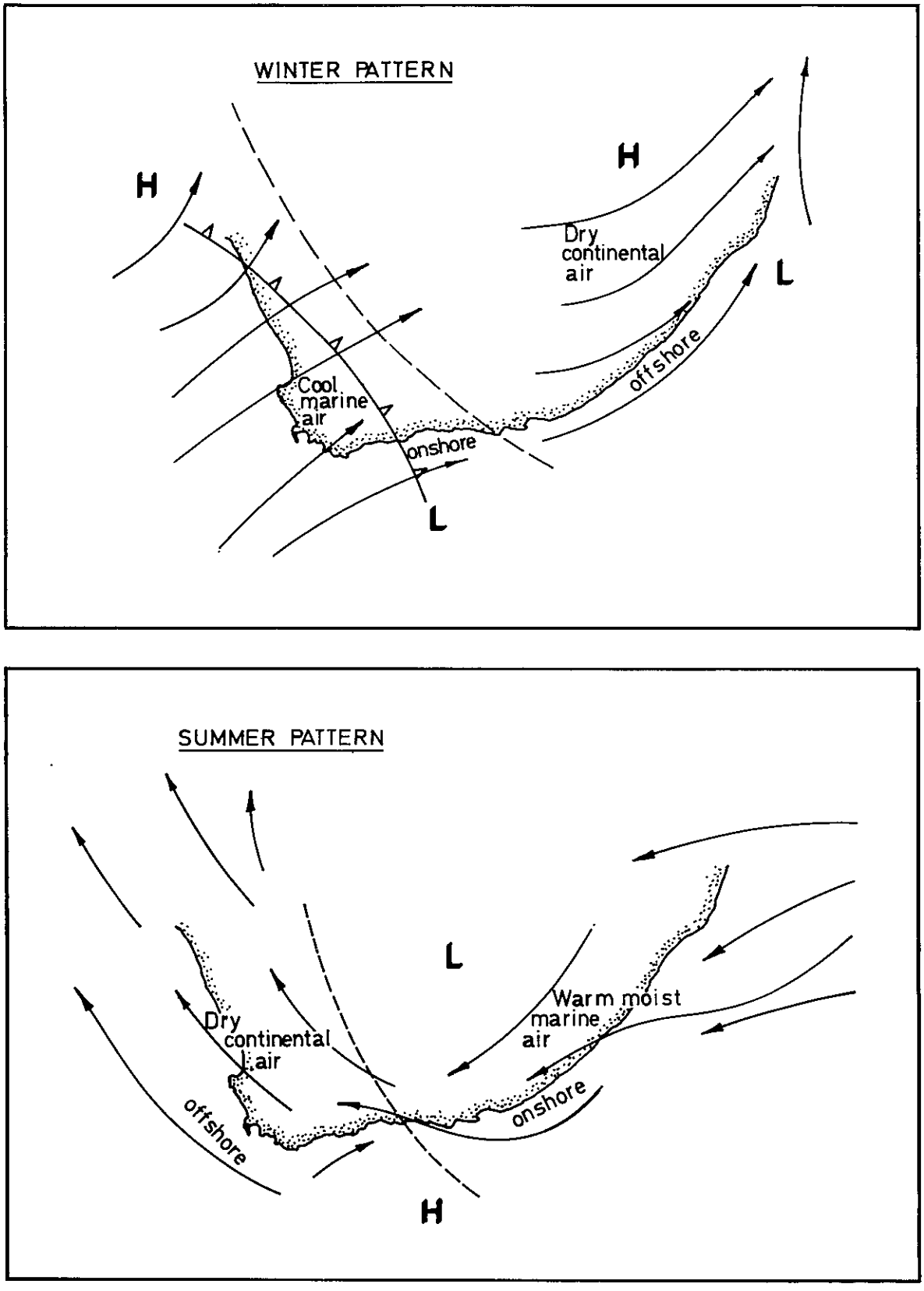


Figure 41. Aerosol transport patterns around the South African coast in winter and summer.

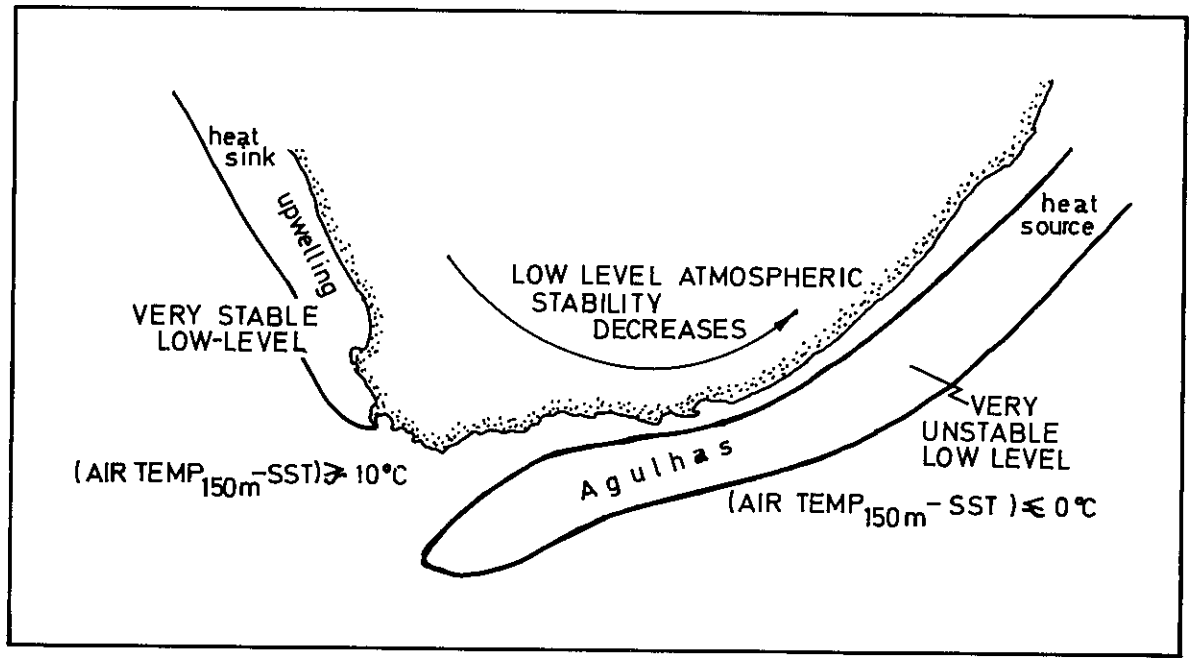


Figure 42. Effects of the Agulhas and Benguela current systems on atmospheric conditions.

The contrasting influences of sea on air may be exemplified by studying radiosonde profiles at Durban and Alexander Bay (Orange River mouth). Under similar synoptic meteorological conditions the vertical temperature and wind profiles are shown in Figure 43.

The vertical profile at Alexander Bay reveals a strong thermal inversion at $\sim$ 1 km with subsiding air compensating the low level heat sink (Benguela). The effect is to suppress vertical mixing and enhance laminar flow with strong vertical wind shears. The vertical atmospheric profile at Durban is more unstable with a thicker mixed moist layer under a weak inversion at $\sim$ 2 km. Vertical wind shears are small and convective mixing is enhanced by the Agulhas heat source. Consequently marine based aerosols are mixed to a greater vertical extent.

In looking at cyclic events at a fixed position we see the effect of the passage of a trough-ridge/coastal low pattern on vertical stratification (Figure 44).

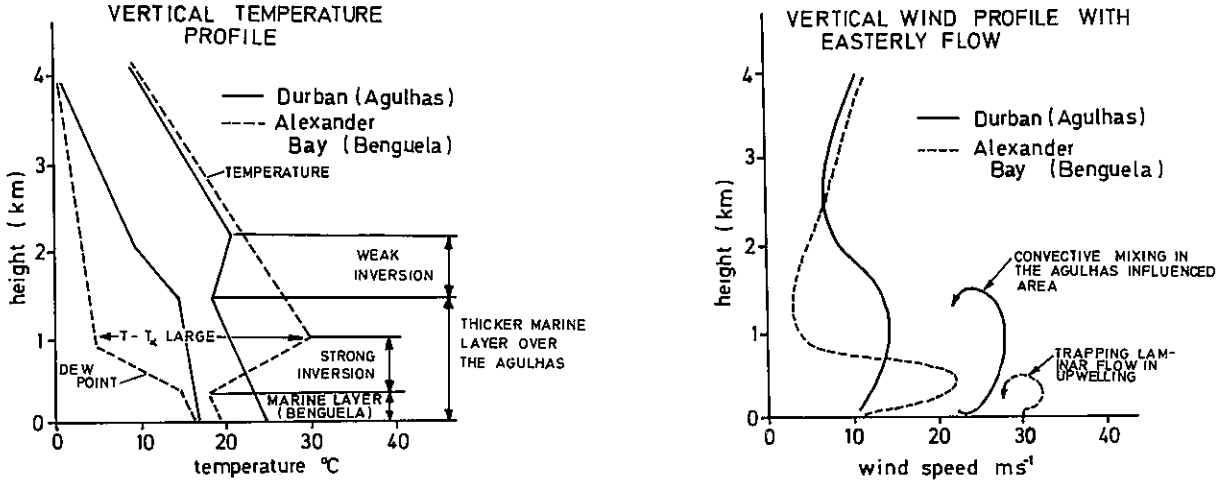


Figure 43. Meteorological relations between temperature and wind profile.

The level of vertical turbulent mixing increases as cold air is advected aloft, reducing stability. Under these conditions onshore flow of marine aerosols takes place. As the anticyclone moves eastward around the tip of the sub-continent easterly flow is capped by a strengthening inversion which reduces the level of turbulent mixing. The marine boundary layer reaches a minimum thickness with the approach of a coastal low as land-based aerosols flow seawards.

During lulls in synoptic scale forcing (stagnations) smaller scale influences (in particular thermal forcing or land-sea breeze cycles) have greater effects on aerosol transport. These cycles predominantly occur during summers along the west and south coasts.

Land-sea breezes are initiated by diurnal heating and differential heat absorption. The sea breeze begins at the coastline and spreads $\sim$ 20 km in both directions during midday. The vertical depth appears to be about 1 to 2 km with inflow at the surface from the marine boundary layer and outflow or return flow aloft in the weak inversion layer. Land breezes occurring in the early morning are of a reduced order of magnitude.

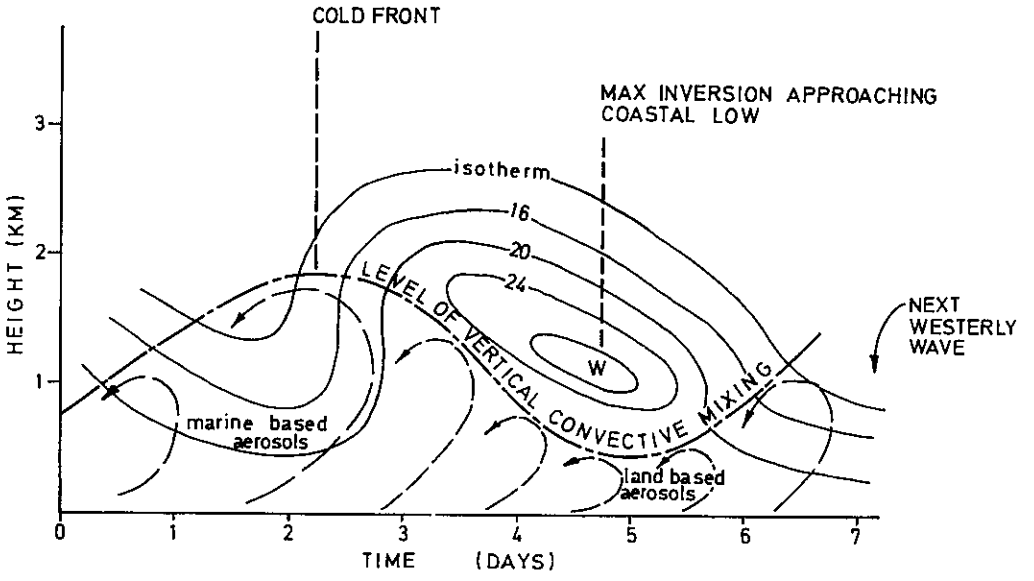


Figure 44. Changes in vertical nocturnal atmospheric mixing at a fixed location during passage of a cold front.

The importance of land-sea breeze cycles in the transport of aerosols (pollutants) between the land-air-sea interface has been observed. Helical recirculation, whereby convective rolling motions are superpositioned in gradient longshore flow, is a means of suspending and transporting urban - industrial aerosols for mixing in the air-sea interface (see Figure 45).

In this helical recirculation a "size sorting" deposition is found (Keen and Lyons 1978), whereby larger particles fall out earlier than smaller ones with each convective rolling movement.

Variations in heat input from the contrasting current systems produce stratified flow along the west coast and convective mixing along the east coast. Seasonal patterns superpositioned on these permanent differential heating effects create a wide variety of environments within which pollutants may be transported by the atmosphere between land and sea.

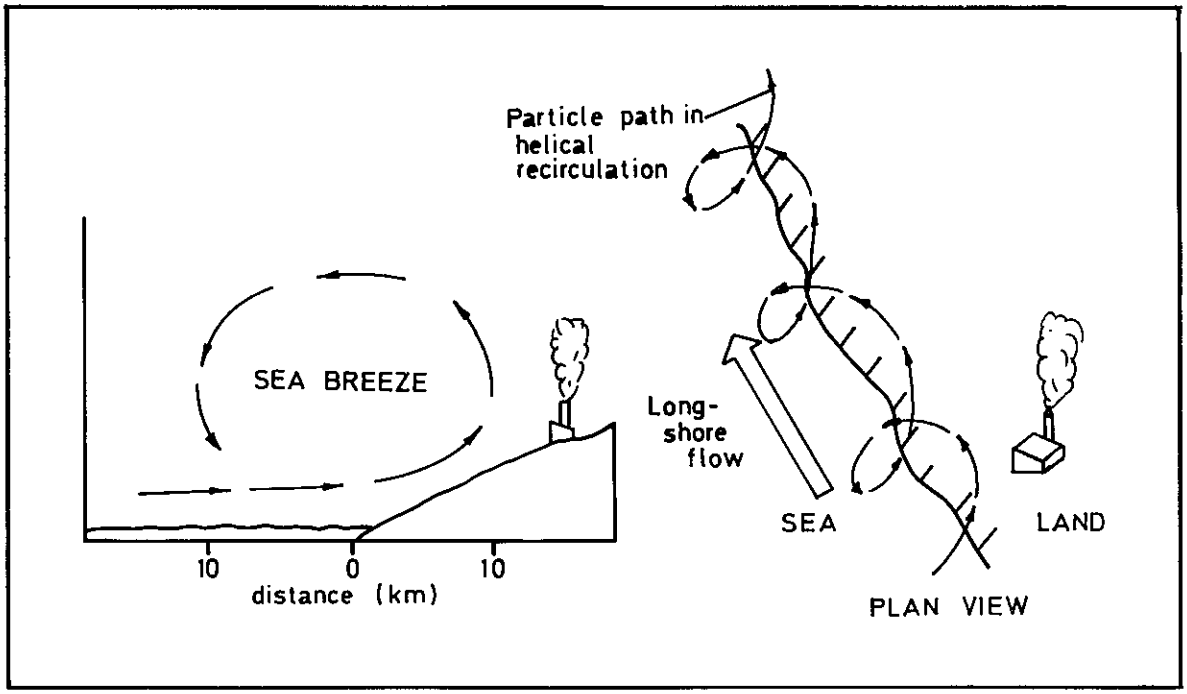


Figure 45. Effects of land/sea breezes on aerosol deposition.

4.1.3 Fluxes to the ocean

4.1.3.1 Estuarine and nearshore environments

There have been no investigations of the atmospheric input of pollutants to the coastal marine environment in South Africa or other southern hemisphere countries. Indeed, there have been very few such investigations anywhere in the world. Patterson et al (1976) found that a significant fraction of the lead found in the Southern California Bight came from direct atmospheric input. Similar conclusions were drawn for the New York Bight for lead and other heavy metals (Duce et al 1976). Cambray et al (1975) have shown that the input of various heavy metals (Cr, Mn, Fe, Ni, Cu, Zn, Cd, Pb and As) into the North Sea from rain is at least as important as that from the River Rhine.

Other investigators concluded that much of the PCB input into the Southern California Bight is via atmospheric transport. Beyond this little is known. All of

the studies above were undertaken in highly populated, heavily industrialized areas. It seems unlikely, therefore, that atmospheric transport of pollutants to the nearshore environment is a serious problem in South Africa at present. However, much more information is required before definite conclusions can be drawn.

In addition to air pollution measurements by local and state authorities in terms of the Air Pollution Prevention Act (including smoke, sulphur dioxide, motor vehicle exchaust pollutants, volatile organic compounds and high molecular weight organics), an atmospheric monitoring programme is currently being undertaken in South Africa as part of the National Programme for Environmental Sciences. The programme on trace elements consists of monthly filter collection with pumps installed at 22 locations. These include baseline stations at Cape Point, Sutherland (inland) and Marion Island, with the remainder selected to represent cities (e g Cape Town and Table Mountain), industrial areas (e g Witwatersrand) and developing regions (e g Saldanha Bay).

The filters are analyzed for 25 different elements by means of atomic absorption, neutron activation analysis and particle-induced X-ray emission. The background station at Cape Point also measures carbon monoxide (Junge method), fluorinated hydrocarbons (Lovelock method) and, more recently, ozone.

Radioactive fallout from atmospheric nuclear weapon tests has been measured in southern Africa since 1956, and has indicated a negligible pollution hazard. The scientific value of these studies has been limited by the fact that such testing took place predominantly in the northern hemisphere. The inter-hemispheric mixing time of about 12 months results effectively in the complete decay of the shorter-lived radionuclides. However, the French tests during 1966-1973 in the southern Pacific on the same latitude as Pretoria allowed the acquisition of valuable scientific information regarding atmospheric transport and biological uptake of various radionuclides.

4.1.3.2 Southern Ocean

It is now generally recognized that about 90 per cent of the world's air pollution arises north of the equator. Since there is evidence that such pollutants

as lead, mercury, vanadium, PCB's and DDT are carried to mid-ocean regions in the atmosphere, there has been some concern that these pollutants present could be transported from the northern hemisphere to the relatively clean southern hemisphere. The atmospheric residence times for the pollutants above range from a few days to perhaps a few weeks at most. The intertropical convergence zone is a very effective barrier against tropospheric air exchange across the equator. Exceptions may be large scale weak transequatorial flow over the Indian Ocean as a result of the monsoon. Current best estimates suggest that northern-southern hemisphere tropospheric exchange times are in the order of 6 to 12 months, but may be longer. If these exchange times are correct, it is apparent that relatively little of the northern hemisphere air pollutants with atmospheric residence times of days to a few weeks will reach the southern hemisphere. Pollutants with considerably longer residence times which are injected in large quantities into the northern hemisphere troposphere, such as carbon monoxide and carbon dioxide, do undergo significant exchange into the southern hemisphere.

There is no information on the flux of pollutants from the atmosphere to the ocean in open ocean areas in the southern hemisphere. However, there is evidence that measurable quantities of lead, vanadium, cadmium, arsenic and other metals, DDT, PCB's, low and high molecular weight hydrocarbons are transported to open ocean regions in the northern hemisphere in the atmosphere, either as particles or in the gas phase. These heavy metals have also been observed at clean air sites in American Samoa and the South Pole in the southern hemisphere. While no direct measurements of the fluxes of any of these substances to the open ocean in either hemisphere are available to date, an international research programme to make such measurements in the North Pacific trades has just begun at Enewetak Atoll (12° N, 163° S). This research programme is expected to move into the South Pacific trades at American Samoa (14° S, 171° W) in 1981. A background atmospheric monitoring station at Marion Island or Cape Point measuring heavy metals and various organic substances would be extremely valuable in attempts to understand hemispheric transport of these substances.

4.2 ATMOSPHERIC TRANSPORT FROM THE OCEAN

4.2.1 Bursting bubbles and spray

The primary mechanism for the production of atmospheric particles by the ocean is the bursting of bubbles produced by breaking waves. Such bubbles bursting at the sea-water surface form jets which eject two to five droplets into the air. Blanchard (1963) showed that these jet droplet diameters are approximately ten per cent of the diameters of the bubbles from which they are formed. A significant number of smaller droplets are also produced by the shattering bubble film cap. Blanchard (1963) estimates that on a global basis, three to four per cent of the ocean surface is covered by whitecaps at any time, resulting in an overall oceanic production rate of approximately 0,1 jet droplets $cm^{-2} s^{-1}$ and 0,07 film droplets $cm^{-2} s^{-1}$. These figures are based on individual bubbles bursting at the sea surface. Little information is available on the production of atmospheric particles by the bursting of bubble clusters or foams, although this is also believed to be an important source for these particles.

When bubbles break, they skim off a thin layer of the sea surface to form the film and jet droplets. MacIntyre (1968) has investigated this "microtome" effect and has shown that the material present in the top jet drop produced by a breaking bubble was originally spread over the interior of the bubble surface (both bubble cap and the portion submerged) at a thickness equal to approximately 0,05 per cent of the bubble diameter. Thus, the smaller bubbles produce jet droplets from a thinner layer of the water surface than the larger bubbles. The jet droplets are apparently composed of material skimmed off the top 0,05 μm to 0,5 μm of the water surface for bubbles with diameters of 100 μm to 1 000 μm. These bubble sizes are common in the ocean. Many natural and pollutant substances are concentrated at the air-sea interface. These substances are thus transferred preferentially into the atmosphere on the jet and film droplets and can subsequently be transported over long distances. The major components are surface-active organics, including PCB's and DDT, although metals and phosphate are also highly enriched relative to bulk seawater.

While large quantities of spray are produced in the nearshore zone, this generally consists of much larger particles with relatively little surface film. Since these particles have short atmospheric residence times, spray production will result in comparatively little return transport of marine material very far inland, except possibly during heavy storms.

4.2.2 Sea foams

Bubbles may also scavenge various foaming agents while they rise through the water column. These tend to lead to a reduction in the surface tension of the bubble interface. Foam stabilizing agents may also be scavenged, causing the production of stable sea foams. Three kinds of stable foams occur off the South African coastline:

- Storm produced foam (the most important), formation of which requires wind, waves and rocky coastlines.

- Frontal foam which forms at the convergence zones of, for instance, Langmuir circulation cells in the nearshore and offshore zone.

- Non-natural foam which occurs especially along the Natal coastline where lignin wastes enter the surf and nearshore zones. These wastes originate from cellulose factory outfalls and outputs resulting from coastal-mining activities.

Storm produced foams occur primarily off the west coast where there are a large number of kelp beds and frequent planktonic blooms. Experimental foam formation in the laboratory indicates phytoplankton and kelp exudates as main sources for surface active, foaming and stabilizing agents. Recent measurements (Velimirov in preparation) show these foams to contain high bacterial densities and consist of up to 22 per cent protein, five per cent lipid and two per cent carbohydrates. Nutrient values were very high and peaks of phytoplankton correlated with intense foam formation during strong onshore winds (northwesterly storms).

Owing to the enrichment of bacteria, trace metals and pollutants, all foams act as an important transfer medium for all these substances. Pollutants (as with other substances) can be taken up with the foam (and microlayer) by:

- being surfactants themselves
- associating with surfactants already present in the water
- forming surfactant compounds or ionic groups with other chemical forms present in the water.

A calculation of the mass of dissolved metals deposited on Third Beach, Clifton, Cape Town, (50 x 100 m) on one day during a storm was carried out by Espey and Orren (in preparation). For example 22,9 g of Zn, 12,1 g of Cu and 8,4 g of Pb were deposited by foam, this being in an unpolluted area. This high enrichment of metals in foams is also of importance when considering productivity at the air/sea interface.

Foam is also transferred from the surf zone to the atmosphere via wind-induced foam spray. Some of this is then deposited in other zones. The transfer of chemicals including pollutants by foam here and along the west coast of Australia (in the southern hemisphere) and along the west coast of Japan and the coast of California is of importance owing to the large volumes of foam which occur. A quantitative study of mass transfer of chemicals including pollutants could be carried out using a knowledge of the frequency and length of storms, the length of foam duration and aerial photography to obtain an overall picture of the occurrence of foam, followed by model studies using selected sea-water samples and controlled conditions of waves, wind and coastline approximating those occurring in the natural environment.

Another probable important transfer process is from the surface foam to the biota. Owing to the favourable environment of the foam, a large (as yet unknown) bacterial phytoplankton and zooplankton production takes place in the foam and fish have been known to feed on foam (McNaught and Hasler 1961). This transfer process may have an important influence on the production cycle in the west coast upwelling regime if large concentrations of pollutants are introduced into it.

4.2.3 Direct gas exchange

Gas exchange across the sea/air interface has already been discussed in Section 4.1.1.1. It should also be pointed out that 30 per cent to 50 per cent of the mass of a typical crude oil spill can evaporate within a few days of the spill (NAS 1975).

4.3 SAMPLING AND CHEMISTRY OF THE AIR-SEA INTERFACE

In recent years there has developed considerable interest in the distribution of chemicals, both organic and inorganic, at the air-sea interface. For the purpose of this discussion we will consider the interface layer to be the surface microlayer with a thickness of only a few μm. Heavy metals and many kinds of organics are supplied to rivers, lakes and estuaries by industrial wastes, domestic sewage, atmospheric fallout and industrial run-off. Evidence collected to date suggests that many of these metals and organics are accumulated at the air-sea interface. As an illustration of the scope of the problem, the following discussion will be restricted to organic material, but considerable research has been undertaken on the significant concentration and effects of heavy metal and other inorganic substances in the surface microlayer.

4.3.1 Sampling

The lack of information concerning organics and inorganics at the air-sea interface is due, in part, to the chemical complexities of the layer and the technical difficulties of collecting a representative sample. A number of sampling techniques have been developed which include the use of a wire screen (Garrett 1967) and the sorbent-in-a-can samplers (Estes et al 1973). More recently the use of a teflon disc has been reported (Miget et al 1974). Laboratory studies have indicated that the teflon sampler is capable of recovering a wide variety of organics with little selective discrimination. In all instances, the quantitative and

qualitative recovery of the various classes of organics tested, including crude oil and weathered crude oil, ranged from 87 to 96 per cent. However, n-alkanes below 16 carbon atoms were not as efficiently recovered by either the Teflon disc or the wire screen (Ledet and Laseter 1974a). Overall efficiency was higher for the teflon disc than the screen for aromatics, alkanes and fatty acids tested.

4.3.2 Chemistry

Surface waters generally have a mean dissolved organic carbon content greater than that of the underlying water. It has been reported that the quantity and distribution of fatty acids and alcohols at the sea surface differed from those found at 20 cm below. The highest concentrations of chlorinated hydrocarbons, pesticides, and polychlorinated biphenyls (PCB's) appear to be associated with the surface microlayer (150μm) of the Sargasso Sea and North Atlantic (Bidleman and Olney 1974). Duce et al (1972) analyzed samples from Narragansett Bay along the east coast of the United States and reported similar results for these organics as well as copper, lead, iron and nickel. Piotrowicz et al (1972) also found some enrichment of these and other heavy metals in the surface microlayer of the open North Atlantic ocean. More recently, Ledet and Laseter (1974b) analyzed the alkanes at the air-sea interface at 118 locations over a twelve month period in the Gulf of Mexico. Methyl branched alkanes, ranging from C_{15} to C_{35} and cyclo-alkanes were frequently the predominant components. These data suggest that the alkanes are produced by natural biological sources as well as human activities.

More recently the organics present at the air-sea interface of an estuary along the Gulf of Mexico have been characterized by high resolution gas chromatography and mass spectrometry (McFall et al 1979). Organics observed included chlorinated hydrocarbons, aromatic hydrocarbons, fatty acids, alcohols, phenolic compounds, and phthalic acid esters. Although some organics are clearly of biological origin, a large number are of industrial origin that entered the environment from industrial effluents, domestic sewage, atmospheric fallout and agricultural runoff. Analyses of several species of clams (Rangia) collected from the same area revealed the

presence of the same organics found at the air-sea interface in the tissues of these organisms (DeLeon et al 1979). These data suggest that the organics at the interface of shallow waters may be representative of those bioaccumulated by filter feeding organisms in the area. A general summary of the organics observed thus far at the air-sea interface is shown in Table 6.

The finding that the ratio of aromatic hydrocarbons to cycloalkanes decreases in non-volatile dispersed oil at the sea surface suggests that aromatic hydrocarbons may be destroyed by air and/or sunlight. Polycyclic aromatic hydrocarbons (PAH's), which are present in crude oils at the one to 3,5 per cent concentration range, can be oxidized in nature by ground state molecular oxygen in air and sunlight, by singlet oxygen already present in natural water or possibly generated by naturally occurring PAH's acting as photosensitizers.

The photo-oxidation of phenanthrene under air-sea simulated environment conditions resulted in the formation of at least thirteen oxygen containing products (Patel et al 1978). A list of major products is shown in Table 7. Phenanthrene may be considered a model for the conversion of PAH's in general at the air-sea interface to oxygenated products. The formation of proximate carcinogens in the aquatic environment through photochemical action is an important possibility with a prospective release of PAH's into the air-sea interface of the oceans in the southern hemisphere. Sources include combustion of coal and petroleum products and the direct release of petroleum into the marine environment through spills and runoff.

Due to the analytical complexity of air-sea samples it is necessary to use "state-of-the-art" methods in order to obtain reasonable results. This involves (following extraction and isolation of organic classes by liquid chromatography) the use of high resolution glass capillary GDS chromatographic columns followed by mass spectrometric characterization. Because of the extremely high volume of data that is generated by the use of such techniques, computerized data handling facilities are most desirable.

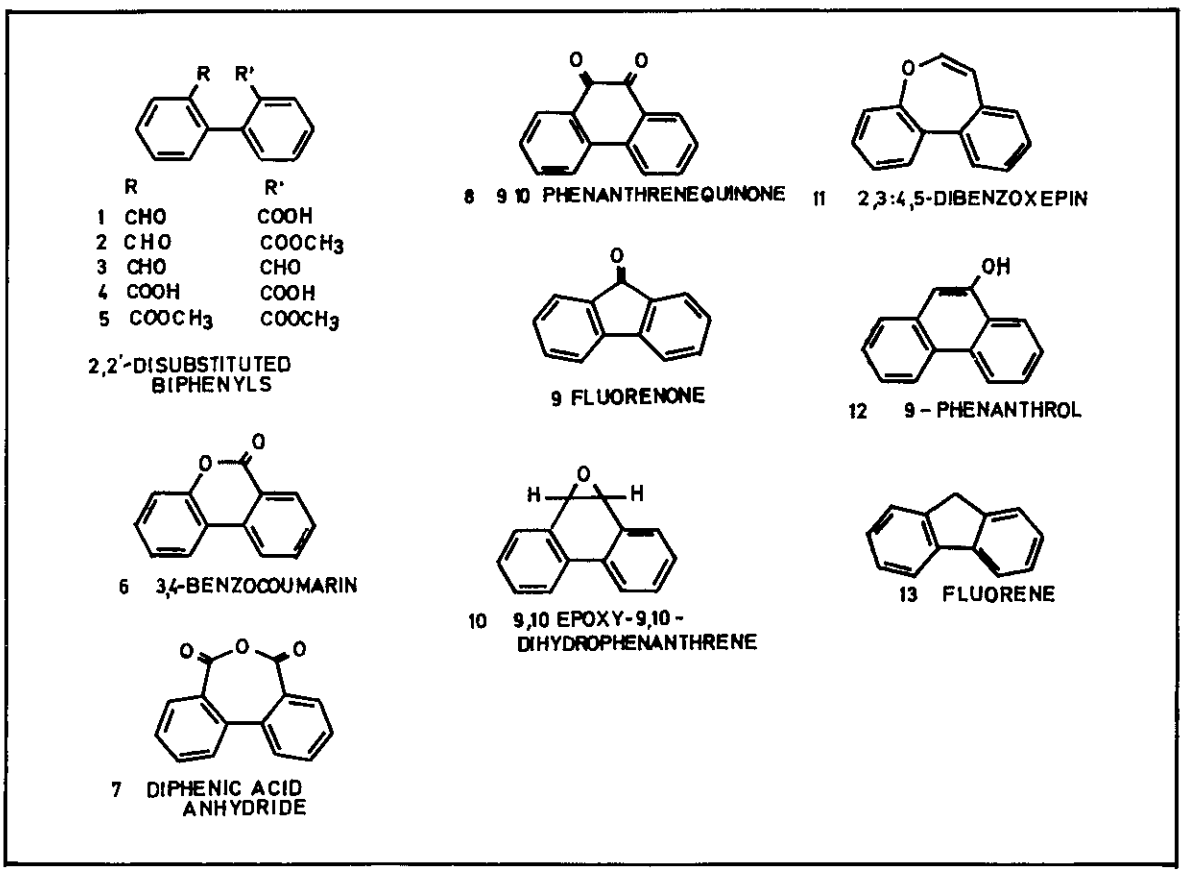
Table 6. Outline of organics reported at the air-sea interface during non-oil spill conditions.

1.	n-Alkanes	$C_{15} - C_{36}$	12.	Phenanthrene	
2.	Monomethyl substituted alkanes	C_{15} C_{28}	13.	Alkyl substituted phenanthrenes	
3.	Dimethyl substituted alkanes	$C_{15} - C_{28}$	14.	Diphenyl benzene	
4.	Isoprenoid alkanes	$C_{15} - C_{21}$	15.	Alkyl nitriles	
5.	Alkyl substituted cyclohexanes	$C_9 - C_{15}^{+}$	16.	Fatty acid methyl and ethyl esters	
6.	Alkyl benzenes	$C_{10} - C_{15}$	17.	Pyrene	
7.	PCB's (3 to 5 chlorine atoms substituted)		18.	Chlordane	
8.	Phenols		19.	Long chain alcohols	
9.	Indanes		20.	Nonachlor	
10.	Indenes		21.	Phthalates	
11.	Fluorene		22.	BHT isomers	

(continued in next column)

+ Length of alkyl side chain

Table 7. Photo-oxidation products from phenanthrene under simulated air-sea interface conditions.



4.4 GAPS IN KNOWLEDGE

4.4.1 There is no information on the flux of pollutants from the atmosphere to the ocean in open ocean areas in the southern hemisphere. Atmospheric monitoring at Marion Island or Cape Point to determine background levels of heavy metals and various organic substances would be extremely valuable in attempts to understand the hemispheric transport of these substances.

4.4.2 The importance of atmospheric pollutant transport to the coastal zone of southern Africa should be evaluated. Obviously the marine areas most susceptible to contamination via the atmosphere are those directly downwind (at least a reasonable fraction of the time) from large urban areas, industrial developments, or mining complexes.

Considering the South African meteorology and climatology discussed above, marine areas in South Africa likely to be most affected by atmospheric pollutant transport include the water near the urban area around Cape Town and the developing area of Saldanha Bay. Due to predominantly onshore or longshore air flow, the urban areas of Durban and Port Elizabeth would be expected to have a less important impact on the pollutant content of adjacent coastal water.

All four of these coastal locations have sampling stations monitoring the heavy metal content of the atmosphere, and estimates of the atmospheric flux of these metals to the near coastal environment can be made. The use of atmospheric trace metal data for appropriate wind climatic conditions combined with the deposition velocities and washout ratios discussed in the first section in this chapter, will enable one to obtain order of magnitude estimates of the trace metal input to the near coastal area per unit area and unit time for the specific meteorological stations utilized. These values can then be compared with measured inputs to the same coastal zone via other pathways, e g rivers, industrial and domestic sewage outfalls, etc to determine

whether more detailed studies of atmospheric input are warranted. If further studies are indicated, the most simple and inexpensive next step would be to collect and analyze rain samples in the coastal area of interest.

An obvious gap in even these very simple preliminary estimates is the paucity of atmospheric data for organic substances, particularly the chlorinated hydrocarbons, in the coastal environment. It is strongly recommended that atmospheric measurements of these substances be initiated at at least one or two coastal locations.

4.4.3 Coupling mechanisms in the marine boundary layer (<100 m) need to be determined. This problem, along with a pollutant dispersal monitoring programme, could be approached by the use of a few well equipped buoys moored < 50 km from shore (mid-shelf) spaced at regular intervals of ~ 400 km and by equipping existing marine aerial survey aircraft with sampling instrumentation.

4.4.4 To date there appears to be little or no data on the organics or inorganics in the air-sea layer associated with the South African coastline. Information of this type would be valuable in assessing the nature and sources of PAH's and other substances.

4.4.5 Very little is known about gas exchange processes. Some experiments are proposed in COMS (1977). Measurement of Radon 222 profiles in the water and air columns to determine the wind velocity dependence of gas exchange can be undertaken. South Africa is in a position to contemplate radon experiments for southern hemisphere weather systems due to the recent acquisition of suitable specialized detector equipment by the Atomic Energy Board (Pretoria).

4.4.6 There is no quantitative imformation on the mass transfer of pollutants by stable sea foam to the land, atmosphere or biota in the southern hemisphere.

4.5 RECOMMENDATIONS (in order of priority)

4.5.1 Where meteorological data and atmospheric trace metal or other pollutant concentration data are already available along coastal areas, order of magnitude estimates should be made of atmospheric input to the nearshore environment.

4.5.2 A small scale rain collection and analysis programme for inorganic and organic constituents should be initiated at a few highly developed coastal areas (e g Cape Town, Saldanha Bay, Durban). This should be supplemented, if possible, by very careful rain collection from research vessels working well offshore.

4.5.3 An atmospheric background monitoring station at Marion Island, or possibly Cape Point, for trace metals and various organic substances should be integrated with other southern hemisphere background programmes operating under the aegis of the World Meteorological Organization.

4.5.4 The measurement of concentrations and enrichments of important pollutants in stable sea foams around the southern African coastline should be undertaken. The fluxes of these pollutants from the sea via foam should be determined and the importance of these foams to marine biota should be investigated.

4.5.4 Although radioactive fallout presents, in general, a negligible health hazard, radioactivity can easily be measured quantitatively and qualitatively, and with a very high sensitivity. Furthermore, a minute mass is involved and, hence, such observations can serve as an excellent guide to the behaviour of non-radioactive pollutants, e g the rôle of faecal pellets in the oceanic transport of materials (cf Chapter 6) and run-off from river catchment areas (cf Chapter 2).

5. SEDIMENT/WATER EXCHANGE PROCESSES

5.1 SEDIMENT/WATER INTERACTION

Most pollutants ultimately find their way into the sediments on the sea floor, after being adsorbed onto particulate material and settling out. An understanding of the processes occurring at river mouths and estuaries is essential to any quantitative assessment of man's influence on the ocean. Rivers typically encounter the ocean in estuaries, which are semi-enclosed basins where freshwater and seawater mix. From a geochemical point of view an estuary is much more than a simple mixing basin: it is in fact a reaction vessel where continentally derived and ocean derived materials are altered physically, chemically and biochemically.

Once outside the estuary, pollutants are very rapidly diluted to the extent that they are seldom present above background levels. Consequently, most studies of pollutant sediment/water exchange processes have been confined to estuaries.

Pollutants which enter estuaries are predominantly associated with or occur in a particulate form. It is therefore essential to identify the nature of stream-carried particulate matter. The products of continental weathering processes are obviously of prime importance, but how do pollutants become associated with these naturally occurring particles and how do they behave in rivers and upon entering the ocean? Attempts to answer these questions have been made for heavy metals (e g Gibbs 1973, Brannon et al 1976, Trefry 1977), but almost no work has been carried out on organics. Several modes of association of metals with particles can be suggested for heavy metals, in addition to the lattice-held metals which are an inherent part of the particle. However, present analytical techniques do not permit an unequivocal assignment of metals to specific classes, although schemes such as that of Brannon et al (1976) permit at least a qualitative fractionation.

Adsorption-desorption reactions in the freshwater/seawater mixing zone are minor in many systems, but extensive chemical and biochemical reactions occur in the bottom sediments of all estuaries. These reactions mobilise certain heavy metals

and nutrients and make them more available to organisms while other potentially toxic compounds may be immobilised and fixed in the sediments. In most cases little sediment and therefore few pollutants are able to escape from the estuary, thus pollution problems may be intensified in localized areas yet have no widespread effect.

The suite of chemical reactions which occur in sediments after their deposition is referred to as diagenesis. In sediments biogenic processes are largely dependent on the amount of organic matter in the sediment. Bacterial breakdown of organic matter not destroyed during passage through the water column utilizes oxygen and produces bicarbonate, ammonium and phosphate ions and trace metals which together with other decomposition products are released into the interstitial water.

Where oxygen is present, the process of bacterial decomposition may be generalized by the reaction

$$(CH_2O)_{106}\ (NH_3)_{16}\ H_3PO_4 + 106\ O_2 \longrightarrow 106\ HCO_3^- + 16\ NH_4^+ + HPO_4^{2-} + 92\ H^+$$

As the oxygen fugacity (concentration and likely activity) decreases, electron acceptors such as nitrate, nitrite and sulphate mediate anaerobic bacterial degradation of organic matter. A highly schematic representation of these processes appears in Figure 46.

Surface sediments in most continental shelf and slope areas are oxic. However, interstitial waters at a few to several centimetres below the sediment-water interface are often devoid of free oxygen (Kanwisher 1962) and an anoxic environment develops at depth. The vertical extent of the oxic zone is a function of sediment accumulation rate and/or the concentration of metabolizable organic matter (Berner 1971).

In the anoxic zone, the sulphate reduction reaction (usually mediated by Desulphovibrio spp) may be expressed as follows

$$(CH_2O)_{106}\ (NH_3)_{16}\ H_3PO_4 + 53\ SO_4^{2-} \longrightarrow$$

$$106\ HCO_3^- + 53\ HS^- + 16\ NH_4^+ + HPO_4^{2-} + 39\ H^+$$

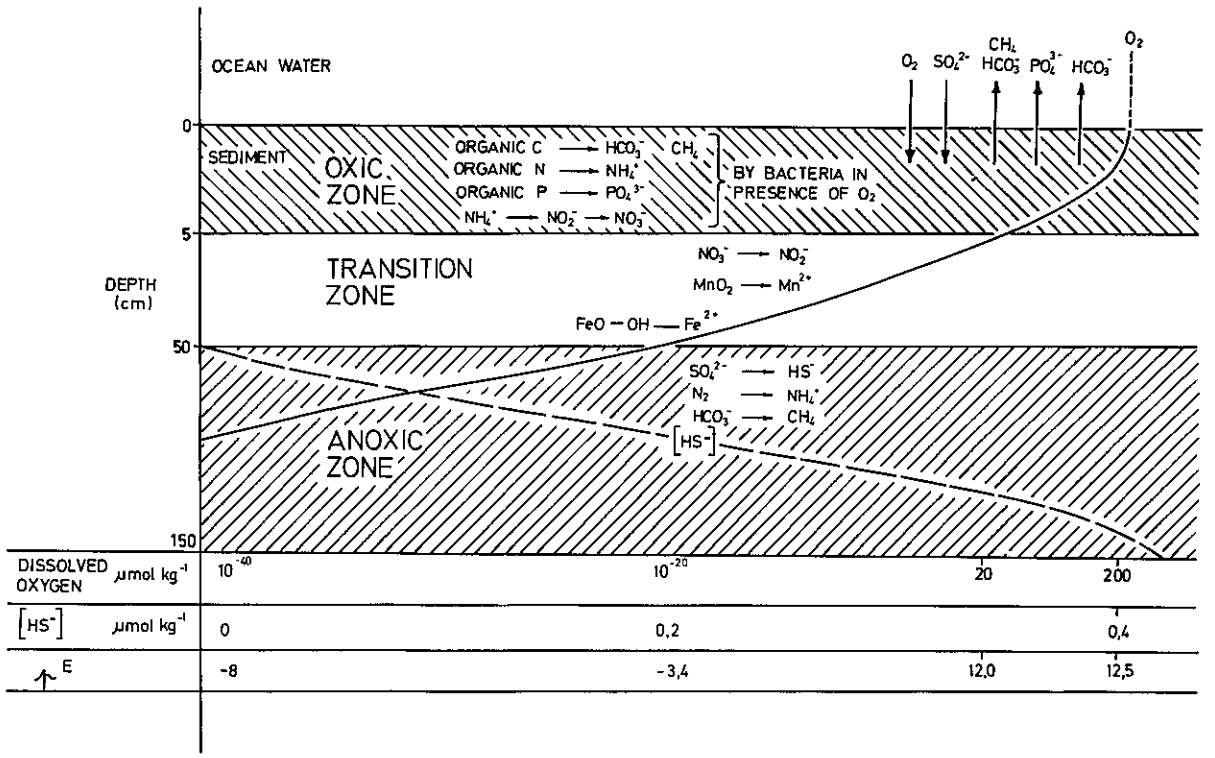


Figure 46. Schematic representation of diagenesis.

Hydrogen sulphide, a toxin to all aerobic organisms and perhaps to many anaerobic bacteria as well (Goldhaber and Kaplan 1974), is generated by this reaction. However, as iron is usually abundant in sediments, the sulphide ion is usually precipitated out as iron sulphide and consequently very low levels of hydrogen sulphide are generally found in the interstitial water (Nissenbaum et al 1972).

When anoxic sediment is covered by oxic sediment, certain species may be remobilized at depth. These may diffuse upward, re-oxidize in the surface sediment, and thus greatly concentrate a given species over natural levels in a surface layer. In addition, species rendered more soluble by oxidizing conditions may be released from sediments where there is a thin oxic zone. The nutrient

elements (nitrogen, phosphorous, silicon) and sulphur are subject to the greatest concentration changes of all primary dissolved species in surface sediment interstitial water. Except for silicon, these changes are controlled by the decomposition of organic matter and thus are greatest in sediments that have abundant organic matter (and are consequently anoxic).

Organic molecules themselves are also altered by the diagenetic process with formation of by-products by condensation, deamination, decarboxylation, and other reactions.

Production of ammonia and phosphate in anoxic sediments is often considerable and large concentration gradients are set up between the interstitial water and the overlying seawater. This leads to a diffusive flux of species across the sediment/seawater interface. Even relatively small fluxes from the sediment may, however, affect the quality of the overlying water in the case of nutrients or highly toxic substances.

Near the sediment/water interface, burrowing animals produce holes and often actively pump water through these holes for respiration and feeding. This activity facilitates the access of oxygen and the release of decay products and considerably complicates diagenetic processes.

Exchange across the sediment-water interface is thus of major importance in controlling the water column concentration and speciation of several elements, particularly N, P and Si. Assuming steady state, the flux of dissolved species through the interface is a measure of the depth-integrated reactions occurring below the interface and can be used to identify and constrain diagenetic reactions.

The specific products of sediment diagenesis and the mechanisms leading to their production are only partly understood. However, these processes will be maximized in areas where large amounts of organic-rich (>three per cent organic carbon) sediment are deposited, such as off the west coast of southern Africa.

5.2 GAPS IN KNOWLEDGE

5.2.1 Methodology

Sampling procedures which preserve the sediment/water interface or directly measure flux in situ are difficult to use and need improvement. There are no accepted standard methods for analysing sediments for pollutants, with respect to either chemical or physical forms.

Since at present little information is available about the chemical forms of elements that are toxicologically important, it will be necessary to continue the present approach of determining total trace metals released from a sample by specific chemical leaches. Speciation work on a routine basis is probably impossible at this stage of analytical development.

5.2.2 Sediment/water exchange processes

Very little work has or is being done on the sediment/water interface even on an international basis, and none in South Africa. Before this work can be attempted it is necessary to be able to analyse sediments themselves in a meaningful way.

More work is needed on methods to collect suspended particulate matter and to characterize it both chemically and physically.

Among the important parameters determining the ability of a sediment to retain and/or absorb pollutants are: pH, Eh (despite problems in interpretation), total organic carbon, bioturbation, sedimentation rate, mineralogy, sediment characteristics (e g porosity, particle size and permeability), interstitial water and infauna. Without knowledge of these parameters, many of which are seldom determined, we cannot hope to understand sedimentary processes.

Episodic events such as severe floods or sea storms can transfer immense quantities of sediment over long distances in a short time. Such transport can completely overwhelm the normal steady or periodic sediment transfer regime and efforts should be made to study such occasional catastrophic events.

5.2.3 Biological availability

An important aspect of pollutants associated with sediments is their biological availability to both the infauna and epifauna. Analysis of dredged samples of bottom organisms, particularly the burrowing types, will provide an indication of the uptake of pollutants by these organisms from the sediments and overlying water. To determine the biological availability of pollutants associated with the sedimentary materials, laboratory experiments should be conducted with detritus feeders in sediments simulating as closely as possible the natural benthic environment. Macoma balthica, a detritus-feeding mud clam, has been found particularly useful in such experiments conducted elsewhere (Luoma and Jenne 1977). Polychaetes Nereis succinea and N diversicolor, and a deposit-feeding shrimp, Palaemon debilis, have also proven useful test animals in this regard. Similar benthic animals common to South African coastal sedimentary regimes could be utilized for such experiments. Analysis of rooted aquatic marine plants e g Zostera capensis. could provide useful information on the availability and uptake of pollutants by such aquatic plants.

5.3 RECOMMENDATIONS (in order of priority)

5.3.1 The problem of alkylation of metals to produce toxic, mobile compounds in sediments should be investigated in collaboration with scientists from the northern hemisphere.

5.3.2 There is considerable controversy as to which chemical leaching procedure is appropriate and this problem requires investigation. It is

suggested that sieved bulk samples (2 mm mesh sieve) be used and that Fe and/or Al be measured and trace metal concentrations normalized relative to these elements.

5.3.3 Laboratory experiments with detritus feeders in sediments should be conducted to determine the biological availability of pollutants associated with sedimentary materials (cf Section 5.2.3).

5.3.4 The emanation from the sediments of Radon-222 (a noble gas free from biological complications) can be used to study the movement of dissolved substances across the sediment/water interface. Measurements in the quiet waters of small South African estuaries are recommended initially (Hammond et al 1977).

5.3.5 The South African National Committee for Certified Reference Materials should be approached to provide one or more certified sediments for use in pollution studies. The sediment should be certified with respect to as many pollutants as possible. Where differences pertaining to methods of dissolution, extraction and determination exist, some recommendations should be made. These reference materials should be available for purchase internationally.

5.3.6. Radioactive sediment dispersal experiments have been carried out routinely at various South African coastal sites for harbour development projects (Bain et al 1970, 1972). Analogous procedures could be used to trace physical transfer processes in estuaries. Two different radioisotopes labelling two different size fractions could be used simultaneously.

6. WATER/ORGANISM EXCHANGE PROCESSES

Biota can serve as sinks, transformers, carriers, and indicators of marine pollution. Transport processes involving biota include the uptake, metabolism and release of pollutants by organisms, and the rôle organisms play in transporting pollutants within and between segments of the marine environment. The effects of pollutants per se are not addressed here, but this is considered in one of the recommendations of this section.

The uptake of foreign compounds, i e chemical pollutants, is a general feature of living organisms. The mechanisms involve either active or passive transport across biological membranes, at respiratory or integumentary surfaces or in the gut. The rate and extent of these processes can vary with differences in chemical and biological factors such as the form of a heavy metal, or the sex and developmental stage of the animal.

Once accumulated by a plant or animal a pollutant will often undergo a transformation mediated by biochemical processes. These will also vary with the differences in chemical or biological factors. Aromatic hydrocarbons are, for example, metabolized by virtually all animal phyla, but the rates apparently differ substantially from one group to another (Pohl et al 1974). The metabolic fate of many compounds effectively removes them from the environment. Some pollutant materials such as organic wastes and many hydrocarbons are, for example, metabolized as a carbon source by bacteria, and are thus consumed.

Metabolism of compounds often results in detoxification. Some heavy metals may be detoxified by binding onto a protein (metallothionein), and hydrocarbons can be metabolized to soluble products which can be readily excreted. However, both types of compounds can be metabolized to derivatives that are more toxic than the parent compound, e g the methylation of mercury (Jensen and Jernelov 1969) or the formation of mutagenic derivatives of polynuclear aromatic hydrocarbons (Stegeman et al In press).

Either the parent compound or a metabolite of a pollutant can be released to the environment again by partitioning, by excretion, or in the degradation of dead animals. The residence time of a pollutant in an animal is determined by an interplay of the above processes, as influenced by biological and environmental factors. What follows is a brief discussion of several pollutant types in somewhat greater detail, as well as an indication of transport pathways.

6.1 PETROLEUM HYDROCARBONS

The passage of much of the worlds tanker traffic around the Cape of Good Hope suggests that pollution of beaches (and rocky outcrops by petroleum hydrocarbons) is likely. Such pollution does indeed occur frequently. Oil landing on shores can be in the form of sheets in various stages of weathering or in the form of tarballs. Such repeated inputs, although superficially inconspicuous, can be shown to lead to a chronic impoverishment in abundance (by an order of magnitude) and diversity of interstitial organisms which dominate south and west coast beaches in forms of biomass and production (McLachlan 1975).

Petroleum is comprised of many hundreds to thousands of compounds. Aliphatic hydrocarbons are in general substantially less toxic than aromatic hydrocarbons. Low molecular weight aromatic compounds (e g benzene and naphthalene) are quite toxic and alkylated derivatives even more so. These compounds may be responsible for much of the immediate toxicity associated with oil spills and are probably also of concern in effects of chronic exposures (Teal et al 1978). The higher molecular weight aromatics are of low immediate toxicity but may contribute via food organisms to the already substantial burden of chemical carcinogens to which man is exposed.

The uptake and subsequent distribution and accumulation in an organism is known to vary between compounds and this discrimination is thought to be related to differences in solubility and partition coefficient, mechanism and route of uptake, and mechanism and rate of elimination. The rate of uptake of dissolved or accommodated hydrocarbons has been shown to be directly related to concentration

in the water, at least when levels in water are relatively low (Stegeman and Teal 1973). The amount and type of particulate organic matter can influence this process (Boehm and Quinn 1976). It has been found experimentally that some marine animals, when continuously exposed to levels of hydrocarbons that occur in the environment, will begin to approach an equilibration by about eight weeks, possibly longer at lower levels (Shannon 1977). Under typical conditions with chronic contamination, animal concentrations (on a wet weight basis) of several 100's mg kg^{-1} can be achieved for petroleum hydrocarbons. Tarballs may be ingested but are not likely to have biologically available hydrocarbons, and will usually pass through as faecal material.

The rates at which fish metabolise hydrocarbons by mixed function oxygenases (in vitro) vary with the environment. In estuarine and coastal waters the rates may be quite high, even greater than in some mammalian species (Stegeman In preparation). In the open ocean, benthic fishes also have moderate potential for metabolism of hydrocarbons while mid-water species have relatively low potential (Stegeman personal communication). This may be a result of pollution. Hydrocarbon metabolism rates both in vitro and in vivo are known to change in response to hydrocarbon exposure (Payne and Penrose 1975, Statham et al 1978). A possible result is that capacity for metabolism and disposition will exceed the rate of uptake. Crustaceans seem to have a moderate to low capacity for hydrocarbon metabolism, and bivalves apparently metabolize aromatic compounds very slowly. Elimination of hydrocarbons by bivalves is rapid, however, and release without metabolism probably predominates.

6.2 SYNTHETIC ORGANICS

There are many compounds that could be included in this category, including those associated with the manufacture of plastics, such as phthalate esters, and pharmaceutical wastes. However, the most important groups are PCB's and DDT. The latter is important in Africa as it is used for malaria control.

The two groups of compounds usually considered under the heading PCB's and DDT and its metabolites are sometimes difficult to identify. Both of these, in fact, are suites of compounds. The identity of the original formulation of PCB's discharged to the sea may be quite difficult to determine from that identified in marine mammals and birds.

Nevertheless, these compounds are ubiquitous in the marine environment. Risebrough et al (1976) and Fishbein (1973) have discussed their transfer in the environment in some detail (cf Section 2.4). Both groups are readily taken up by phytoplankton and readily accumulate in animals. Gardner (1979) has reported on some aspects of their distribution in South Africa and Bacher (1971) has indicated some results for Australia.

An interesting question concerns the rather high levels of PCB's in the cats on Marion Island. The PCB formulation appears to match Arochlor 1260, although the identity needs to be confirmed and the sources and pathways to Marion Island are unknown at this stage.

6.3 TOXIC ELEMENTS

Ionic species adsorbed to particulate materials are readily available to filter feeders. In these species they are primarily absorbed through the gut wall. The valency of ionic metal determines its rate of absorption and desorption or depuration. The biological half-life of these elements may be on the order of a week or two (cf Bryan 1976).

Particulate materials with metal species fixed within the matrix will exhibit variable degrees of "leaching". Ores are the most obvious example of this type of material. Sulphide ores, for example, have a low solubility in general, but different ore bodies and different levels of various environmental parameters could give rise to increased solubilities. Little information appears to be available, but it could be assumed that the mineralogical form, the size of the particles and the presence of a highly oxidizing environment may affect the degree of leaching. As these metal species are basically of low solubility it will be through ingestion that any possible absorption must take place. The change in pH between outside

environment of the animal and the environment of the gut may give rise to a higher availability once the material is ingested than might be expected.

Toxicants in solution are, in general, in much lower concentrations than those reported from filterable material. However, the ionic forms in this aqueous phase may be much more readily available to biota and therefore are capable of being taken up by a variety of routes. It is to be expected that fairly rapid rates of uptake and depuration could be observed.

The whole question of the transfer of toxicants from seawater to marine biota is obscured by the lack of knowledge on the speciation of the metals present in the environment (Feely and Curl 1978). It is further complicated by the question of biological availability. Both topics are dealt with in Chapter 5.

Some toxic elements may be present in ferric, manganese and cyanide complexes. Some evidence suggests that they may be less rare than previously expected (M Waldichuk personal communication). It is thought that metals from such complexes may not be readily available to biota.

Methylated forms of heavy metals generated in the marine environment by biological activity have been shown to be taken up by the food chain (Hannerz 1968). Methylated compounds originating in the non-marine environment are most likely to be associated with particles, and therefore can be ingested by filter feeders. All the methylated forms appear to be rapidly mobilized and most are slow to depurate and thus the biological half-life is long.

Risebrough et al (1976) comment that studies of the relevance of input fluxes have yet to give "evidence for harmful effects of heavy metals and trace elements to marine birds and mammals" (p 308). Clark (1978), reporting on littoral surveys of the Severn Estuary-Bristol Channel, remarks that "despite heavy metal pollution in the Severn Estuary in recent years, there have been no changes in intertidal invertebrates attributable to pollution". Both these statements should however be put into a proper context. It may be that survey techniques are not yet sufficiently refined to illuminate sub-lethal effects, the signal, from the general

background noise of large-scale perturbations in littoral biota. Also, sedimentation and other physico-chemical parameters may restrict the effects of heavy metals to estuarine and nearshore zones. In such areas the higher concentrations of nutrients may enhance uptake of these materials by phytoplankton presumably by increasing growth rates.

On the west coast of South Africa the upwelling phenomenon and resultant high nutrient levels are important in this regard. The considerable areas of anoxic biogenic sediments presumably accentuate the significance of these phenomena.

6.4 RADIONUCLIDES

Data for artificially produced radionuclides in southern hemisphere marine organisms are not abundant, but such as are available show that the levels are unexceptional - lower than in the northern hemisphere as would be expected on account of the lower levels of nuclear fallout. In both the northern and southern hemisphere, the natural radiation dose rate to marine organisms is, in general, substantially in excess of that due to artificial sources of radioactivity.

Faecal matter often contains trace elements, radionuclides and chemical compounds at levels much higher than normally found in biological material (Fowler 1977). Vertical transport in the ocean can be investigated fruitfully using material collected in sediment traps, while analysis of individual faecal pellets can yield information about fluxes through a particular animal and across compartment boundaries.

6.5 TRANSPORT BY BIOTA

Many biological mechansims contribute to the transfer of pollutants from one phase to another. Excretory products return materials to the sediments and migrations may bring about horizontal transfers. The interaction of biological products with other materials may modify modes of interaction or bring about changes in state.

Examples of such effects are:

Plankton	-	entrained in currents
	-	transfer of pollutants to higher trophic levels
Benthos	-	sediment reworking, with pollutant release
Fish	-	migrations onshore/offshore along coastlines
	-	vertical migrations in midwater
	-	transfer to birds and man
Birds	-	faeces deposition in rookeries
	-	transfer to terrestrial carnivores

Some examples of such transfer mechanisms in the South African context are given below.

Particulate material in the ocean plays an important rôle in transferring chemical elements and compounds from surface waters to depth. Thus far, the discussion has centred on inorganic or mineral particles, but biologically derived particles play a very important role in transfer of pollutants through oceanic systems. These particulates then generally fall down from the surface toward deeper water at a rate depending on the size. Fine mineral particles of a few micrometres diameter fall at rates of the order of 100 m per year, whereas larger particles, such as zooplankton faecal pellets can fall at rates of up to almost 1 000 m d^{-1}.

Most of the mass concentration of particles in the open ocean appears to be provided by the finer particles, whereas it is the larger and rarer particles which account for most of the mass flux towards the ocean floor (Bishop et al 1977, 1978, Spencer et al 1978).

Recent data (Bishop et al 1977, 1978) indicate that most of the mass contribution to the coarse particulate fraction is provided by faecal pellets and faecal matter and that this faecal material provides a substantial percentage of the vertical mass flux through 400 m. Furthermore, trace element concentrations in faecal pellets

are generally at levels which are high compared to those found normally in marine organisms (Fowler 1977, Spencer et al 1978). Since these faecal pellets sink fairly rapidly and decompose relatively slowly it seems clear that they have the potential to reach the sea bottom in most areas. Material in the surface layer of the ocean which is eaten by zooplankton and then egested in particulate form can reach the sea floor in a short time scale.

The return of pollutants can be brought about by the process of ecdysis (moulting). Small and Fowler (1973) describe such a mechanism with regard to the vertical transport of zinc-65 in the open sea. Pollutants may also be transferred across water masses during migration processes. For example, along the east coast of South Africa there exists a substantial population of penaeid prawns. These enter estuaries as juveniles and on the approach of sexual maturity they migrate offshore to breed and do not return. In this migration we have a possible vehicle for the transfer of pollutants from estuaries to the open sea. Laboratory experiments have shown that prawns may accumulate a considerable sub-lethal body burden of fluoride, cadmium and mercury. These pollutants may remain with the prawns during migration and be released during the decay process. Estimates of the number of prawns involved suggest that this process may provide an important potential biological transfer pathway.

If the rich kelp bed areas of the west coast and the productive east coast estuarine regimes cause an increased dissolved organic matter concentration, it is possible that certain hydrocarbons (alkanes and isoprenoids) may be solubilized and transported elsewhere. Boehm and Quinn (1973) found that uncharacterized dissolved organic matter caused a significant increase in the amount of alkanes and isoprenoid hydrocarbons dissolved. Another effect of the organic-rich kelp bed areas is the generation of Vitamin B-12 in decay processes which again can lead to phenomena such as the development of "red water". This in turn has secondary toxic effects on marine fauna and man.

6.6 GAPS IN KNOWLEDGE

6.6.1 Reliable estimates of the rates of movement of pollutants, and of the quantities involved, between different components of the various marine systems surrounding southern Africa are not available. It is clear that in most places elsewhere in the world the same situation pertains.

6.6.2 Evaluating the state of a marine ecosystem under pollution stress has been a matter of concern to biologists for some time. The complexities of biological systems, coupled with uncertainties in regard to the biological availability of pollutants, has caused such confusion as to almost preclude the development of general concepts. This confusion, and its attendant lack of unifying concepts, has resulted in little progress having been made in defining the transfer of materials into and between biota.

6.6.3 If we use the conceptual model introduced in Chapter 1 there are two problem areas related to the estimation of the amount of material transferred and the rate of its movement:

- between the water, solids and biotic phases within each compartment, and

- between any two of the five compartments.

While transport of pollutants by biota can occur, the actual mass transport may not be great. However, it would be very useful to have estimates of the amounts of a variety of pollutants contained in biota being transported by the major current systems in southern oceans. This should include assessment of major gyres and inshore current features. Estimates of transport out of estuaries by biota are also needed, while estimates of biomass of sediment benthos involved in reworking and remobilizing pollutants and of deposit feeders, would be useful.

6.6.4 It is important, in the context of pollution transfer, that for such material to be of significance it should be biologically available. With this in mind, and recognizing the central role of the biotic component within a compartment, it appears logical that a biological tool to assay such materials should be developed.

The use of such a biological tool could have three uses:

- indications of the biological "health" of individuals or of assemblages (cf the US PRIMA program),

- monitoring, either of existing loads of pollutants as in the US Mussel Watch, or to detect infringements of environment protection measures, and

- measuring fluxes of materials in biotic systems.

An example of the third category might be the need to estimate the amount and rate of loss of a heavy metal, for example zinc, from an estuary to the sea. An appropriate array of biological assay units through the estuary entrance, running from within the estuary to the open sea would be established. Samples of the biota utilized in these units would then be analyzed for zinc at periodic intervals and this together with information on cross sectional area, net water flow and dose response rate, will enable calculations of mass transfers to be made.

It is essential that the biota selected for this exercise be capable of a rapid equilibrium with ambient concentrations of the pollutant of interest. Gilmour and Kay (1979) have proposed an outline of an approach to evaluating an animal for use as an indicator of biological "health". Many of these criteria apply to this proposal to develop a biological assay tool to measure fluxes of pollutants in marine systems.

Mussels may be an appropriate biological assay tool. Knowledge of their physiology is well developed. Mussels are being used in the Mussel Watch programme. This offers "fringe benefits" such as

international calibration exercises. Also, they are filter feeders and thus exposed to two of the modes of transfer of pollutants identified in the model. The Mussel Watch programme has also proposed the use of oysters and this is particularly important as mussels are not present in tropical regions. It has therefore been proposed that the Pacific or Japanese oyster (Crassostrea gigas) should be used. South African studies have indicated that:

- the rate of uptake of heavy metal is dependent upon the ambient concentration of the element (the same may be applicable to organic pollutants),
- accumulation is time dependent, and
- temperature and salinity have identifiable effects on uptake rates.

Both mussels and oysters could be utilized, as the latter are readily available and grow throughout South Africa. There are advantages to utilizing samples of cultured animals of a single cohort and possibly of a single clone. The development of a set of standardized techniques (including chemical) is essential, as are routine intercalibration exercises for participating laboratories.

6.7 RECOMMENDATIONS (in order of priority)

6.7.1 The relatively unpolluted status of southern waters should be exploited in obtaining baseline information on biological and biochemical indicators. Work in the southern hemisphere on certain biochemical parameters that have promise as early warning indicators should be considered. The ratios of free heavy metal to heavy metal binding protein as well as the capacity for hydrocarbon metabolism and the characteristics of the cytochrome P-450 systems in fishes and other groups might be considered in selected areas. Both of these could

provide valuable baseline data, and possibly reveal whether biochemical effects have occurred at present. Furthermore, characterizing hydrocarbon metabolizing systems in these clean waters may help determine whether certain properties seen in some fishes in the northern hemisphere (Stegeman and Binder 1979) are characteristic of natural or induced systems. Studies of other biochemical and biological indices, such as those considered at a recent ICES workshop (ICES 1979), should also be considered. These include, for example, physiological scope for growth, lysosomal function, and community structure. Such indices, and their significance, are also discussed elsewhere (Cole 1979). Developing the capacity for work in South Africa on these indices should be initiated, and where already in progress, continued.

6.7.2 A South African programme to evaluate information on pollutant transfer at appropriate sites around South Africa should be established. Cooperation with countries in South America and Australasia should be considered, as well as liaison with North American and European programmes.

6.7.3 In general there appears to be substantially less pollution in the southern hemisphere and South African waters than in the northern hemisphere. Parts of the southern hemisphere thus present an opportunity to obtain baseline data concerning effects of pollutants. It is possible that organisms in the less polluted southern waters may be more sensitive to pollutants. Some effects studies on economically important species should be carried out, especially the effects of oil pollution.

6.7.4 It appears that pollution by organic chemicals including petroleum is generally low round southern Africa. This must be confirmed. The chlorinated hydrocarbons, particularly DDT, dieldrin and PCB's, in marine animals of southern Africa should be identified. The source and transport pathways of the high levels of PCB's (Arochlor 1260) in the Marion Island fauna should be investigated. This may have implications for transfer to the Southern Ocean.

7. SUMMARY AND CONCLUSIONS

7.1 The aims of the workshop on the transfer of pollutants in two southern hemispheric oceanic systems were -

- To assess the importance of different phenomena and processes affecting the transfer and fate of pollutants into and between contrasting regimes of upwelling and longshore currents.

- To assess the available information, expecially baseline information, on these phenomena and processes.

- To assess the progress made with the relevant research (and thereby identify key questions for future research and monitoring) and to discuss conceptual models of certain key processes and phenomena.

7.2 For purposes of discussion the GESAMP definition of marine pollution was used, viz

The introduction by man, directly or indirectly, of substances or energy into the marine environment (including estuaries), resulting in such deleterious effects as harm to living resources, hazard to human health, hindrance to marine activities, including fishing, impairing the quality for use of seawater and reduction of amenities.

7.3 The major pollutant types were established as -

- Toxic elements

- Petroleum hydrocarbons

- Organic wastes

- Halogenated hydrocarbons
- Radioactive materials
- Heat

7.4 Three main topics were considered: the transfer of pollutants from land to sea, the transfer of pollutants across watermass boundaries and interface transport processes (air/sea, water/sediment, sediment-water/biota). Although the emphasis was on the oceanic areas surrounding southern Africa, attention was directed to the whole of the southern hemisphere as far as was possible.

7.5 The east coast of southern Africa, with a narrow continental shelf, is dominated by the strong southward flow of the warm Agulhas current, whereas the western coast is dominated by the weaker northward flowing cold Benguela current which is an upwelling regime of considerable biological and economic importance. The southern coast is an area of complex mixing between the two major current systems.

7.6 Periodic atmospheric driving mechanisms induce surface and subsurface transport in the nearshore region of southern Africa. Surface winds in the coastal boundary layer blow in predominantly longshore directions, with larger onshore components over the Agulhas, offshore/longshore over the Benguela, and variable westerly components in the retroflection area between the two currents.

7.7 Although the objective of the workshop was to consider the transfer of pollutants into and between oceanic systems in the southern hemisphere, the importance of the estuarine environment as a source of material for nearshore water masses was recognized and estuarine processes were included in the discussion.

7.8 As far as was possible, information on the routes by which pollutants are transferred into the ocean and the quantities involved was considered and evaluated.

7.9 The transfer of pollutants in the ocean is influenced by many different physical, chemical and biological processes, the relative importance of each being dependent on the type of pollutant. The movement of water masses in the sea is of basic importance in the study of pollutant transfer and attention was directed toward ascertaining which physical processes were dominant in any particular area.

Consideration was given to physical processes in upwelling and western boundary current environments, wave generated and other processes in nearshore regimes, atmospheric forcing mechanisms in the coastal boundary layer, processes on the shelf and in the open ocean, and processes coupling the nearshore, shelf and open ocean regimes. Some potential physical pollutant traps around the coast of southern Africa were identified.

7.10 Interface transport processes are important in all parts of the marine environment. Basic air/sea exchange processes were considered in relation to transport and fluxes to and from the ocean. Approximately 90 per cent of the world's air pollution is injected north of the equator. Current best estimates suggest that the northern-southern hemisphere tropospheric atmospheric residence times of the pollutants of concern here apparently range from days to a few weeks while exchange times are six to twelve months. Under these conditions, relatively small quantities of air pollutants will be transported from the northern to the southern hemisphere. No direct measurements of the flux of pollutants from the atmosphere to the open ocean are available for either South African waters or the southern oceans.

7.11 Many pollutants ultimately reach the sediments at the bottom of the ocean. At present sediment/water exchange processes of pollutants can not be meaningfully studied in the ocean, since all except possibly anthropogenic organic pollutants are rapidly diluted to background levels. The methodology for studying pollutants in sediments has not yet been satisfactorily established however, and this is a major stumbling block to investigations of sediment/water transfer.

7.12 The uptake of foreign compounds such as pollutants is a general feature of living organisms. Accumulated pollutants often undergo transformation by biological processes which can result in detoxification of metal and organic compounds, although metabolism can also produce derivatives that are more toxic than the parent compound.

7.13 Other topics considered were the transport of pollutants by biota, and the measurement of the biotic transfer flux.

7.14 Available information on each of the main topics was considered in an attempt to assess the extent and quality of baseline information in the southern hemisphere and particularly southern Africa. Important gaps in available knowledge were identified and recommendations were made as to their relative importance and the best means of filling such gaps. Detailed recommendations from individual sessions are contained in the relevant chapters.

7.15 Based on current knowledge, the South African marine environment is still relatively unpolluted apart from a few specific areas and provides an excellent opportunity for baseline investigations of pollutant transfer.

7.16 The most obvious pollution problem on the southern African coast is oil. Immediate and acute effects from oil spills and long-term chronic effects caused by shipping activities will have an impact on both the marine environment and on man. Efforts should therefore be directed towards obtaining baseline data on the concentrations of the major petroleum hydrocarbon component groups in water, sediments and biota at selected sites around southern Africa. Particular attention should also be given to the processes controlling the movement of oil at sea and near the coast as this will be of direct practical relevance to spill response contingency planning.

7.17 Future industrial development may result in increased quantities of other pollutants being introduced to the marine environment and necessitate a change in research priorities.

7.18 Maximum utilization should be made of the relatively pristine environment around the coast of southern Africa to obtain baseline information on the chemical composition of the marine atmosphere, water, biota and sediments. While obtaining a better appreciation of the chemistry and physics of the environment, efforts should be directed towards establishing the effects of organic pollutants (e g petroleum hydrocarbons, PCB's) on the marine biota in southern Africa. Of particular importance is the development of analytical capability and expertise.

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APPENDIX 1.

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Session 2: TRANSFER OF POLLUTANTS ACROSS WATER-MASS BOUNDARIES

Chairman:	G E B Kullenberg
Rapporteurs:	L V Shannon and G Nelson

Session 3: INTERFACE TRANSPORT PROCESSES

Chairman:	J J Stegeman
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APPENDIX 2.

POSTER PAPERS PRESENTED AT THE WORKSHOP

C A R Bain	Coastal dynamics in the Melkbosch vicinity
J K Basson	Determination of safe radioactive releases from the Koeberg nuclear power station
P Chapman, A Moldan and H O Fourie	Some effects of the Venpet/Venoil collision on the fauna of the Little Brak estuary
P Chapman, A Moldan and H O Fourie	Effect of ore jetty on Saldanha Bay ecosystem
G A Eagle	Baseline information from South Africa's south and west coasts
Q I Espey and M J Orren	A first approximation of the inorganic chemical composition of storm-produced stable sea foam
B W Flemming	Sediment transport patterns in the Agulhas current
A H Fricke	Meiofaunal aspects of the Venpet/Venoil spill
B D Gardner and A D Connell	Chlorinated hydrocarbon distribution in selected estuarine and marine faunas of the east coast of South Africa and including the cats of Marion Island
M R Jury	Meteorology and air/sea interactions of the south-western Cape upwelling region
M J Orren	Preliminary survey of the Orange River estuary

E H Schumann	Shelf currents off Natal and the influence of weather systems
R C Stanton and T P McClurg	The NIWR computerized data storage and data retrieval system as an aid to pollution monitoring on the east coast of South Africa
R J Watling and H R Watling	Trace metal studies on the South African south coast
J P Willis	Geochemistry of sediments in Saldanha Bay and Langebaan Lagoon, with emphasis on possible pollution by iron ore

APPENDIX 3. MAJOR CATEGORIES OF MARINE POLLUTANTS RECOGNIZED BY GESAMP (1976)

Category of pollutant

1. Domestic sewage

2. Pesticides

   Organochlorine compounds
   Organophosphorus compounds
   Carbamate compounds
   Herbicides
   Mercurial compounds
   Miscellaneous metal-containing compounds
   PCB's

3. Inorganic wastes

   Acids and alkalis
   Nutrients and ammonia
   Cyanide
   Antimony
   Arsenic
   Beryllium
   Cadmium
   Chromium
   Cobalt
   Copper
   Lead
   Manganese
   Mercury
   Nickel
   Phosphorus (elemental)
   Selenium
   Silver
   Sulphur (as sulphite)
   Titanium dioxide wastes
   Vanadium

4. Radio-active materials

5. Oil

6. Organic chemicals

   Acetone
   Acrolein
   Acrylonitrile
   Allyl alcohol
   Allyl chloride

(contd in next column)

Category of pollutant

6. Organic chemicals

(continued)

   Benzene
   Carbon disulphide
   Carbon tetrachloride
   Chlorobenzene
   Chloroform
   Cresol
   Crotonaldehyde
   Cumene
   O-dichlorobenzene
   P-dichlorobenzene
   Epichlorohydrin
   Ethyl alcohol
   Ethylbenzene
   Ethylene dibromide
   Ethylene dichloride
   Ethylene glycol
   Methyl alcohol
   Methylene chloride
   Naphthenic acid
   Phenol
   Phthalate esters
   Styrene monomer
   Tetramethyl lead
   Tetraethyl lead
   Toluene diisocyanate
   Trichlorobenzene
   Vinyl acetate
   Vinyl chloride
   Xylene

7. Organic industrial wastes

   (a) Pulp and paper mill wastes
   (b) Other high BOD wastes

8. Military wastes

9. Heat

10. Detergents

11. Solid objects

12. Dredging spoil and inert wastes

APPENDIX 4. RELATIVE IMPORTANCE OF THE DIFFERENT ROUTES BY WHICH POLLUTANTS ENTER THE SEA (GESAMP 1976)

Note: The ratings in this table refer to knowledge of the state of marine pollution at the present. As such they can be considered to provide guidance on future levels of pollution, provided existing controls are maintained or strengthened.

Key to symbols

3 Important
2 Significant
1 Slight
? Uncertain
0 Negligible
P Potentially important
+ Dependent on extent of weapons testing

Category of pollutant	(a) Manufacture and use of industrial products - disposal via direct outfalls and rivers	(b) Domestic wastes - disposal via direct outfalls and rivers	(c) Agriculture, forestry, public health - via run-off from land	(d) Deliberate dumpings from ships	(e) Operational discharge from ships in course of duties	(f) Accidental release from ships and sub-marine pipelines	(g) Exploitation of sea-bed mineral resources	(h) Transfer from the atmosphere
(1) Domestic sewage	0	3	0	2	1	0	0	0
(2) Pesticides								
Organochlorine compounds	2	2	2	0	0	P	0	3
Organophosporus compounds	2	1	2	0	0	P	0	3
Carbamate compounds	2	1	2	0	0	P	0	?
Herbicides	2	1	2	0	0	P	0	?
Mercurial compounds	2	0	3	0	0	P	0	?
Miscellaneous metal-containing compounds	2	1	1	0	0	P	0	?
PCB's	3	0	0	0	0	P	?	3
(3) Inorganic wastes								
Acids and alkalis	3	0	0	2	1	P	0	0
Nutrients and ammonia	2	2	3	1	0	0	0	0
Cyanide	3	0	0	1	0	0	0	0
Antimony	2	0	0	0	0	0	0	0
Arsenic	3	1	0	1	0	P	P	2
Beryllium	1	0	0	0	0	0	0	0
Cadmium	3	0	0	0	0	0	0	1
Chromium	3	0	0	1	0	0	0	0
Cobalt	2	0	0	0	0	0	0	0
Copper	3	2	1	1	0	0	0	0
Lead	2	1	0	?	0	0	0	3
Manganese	3	1	0	?	0	0	0	1
Mercury	3	2	0	0	0	P	0	3
Nickel	3	0	0	0	0	0	0	1
Phosphorus (elemental)	2	0	0	0	1	P	0	0
Selenium	2	0	0	0	0	0	0	1
Silver	2	0	0	0	0	0	0	0
Sulphur (as sulphite)	2	0	0	0	0	0	0	2
Titanium dioxide wastes	3	0	0	3	0	0	0	0
Vanadium	2	0	0	0	0	0	0	1
(4) Radioactive materials	3	0	0	1	0	P	0	P+
(5) Oil	3	1	0	1	3	2	1	?
(6) Organic chemicals								
Acetone	3	0	0	1	0	0	0	0
Acrolein	1	0	0	0	0	0	0	0

APPENDIX 4. (Continued).

Category of pollutant	(a) Manufacture and use of industrial products - disposal via direct outfalls and rivers	(b) Domestic wastes - disposal via direct outfalls and rivers	(c) Agriculture, forestry, public health - via run-off from land	(d) Deliberate dumpings from ships	(e) Operational discharge from ships in course of duties	(f) Accidental release from ships and sub-marine pipelines	(g) Exploitation of sea-bed mineral resources	(h) Transfer from the atmosphere
(6) Organic chemicals (continued)								
Acrylonitrile	3	0	0	P	P	P	0	?
Allyl alcohol	1	0	0	0	0	0	0	0
Allyl chloride	1	0	0	0	0	0	0	0
Benzene	3	0	0	P	P	P	0	?
Carbon disulphide	3	0	0	P	0	P	0	0
Carbon tetrachloride	3	0	0	P	0	P	0	?
Chlorobenzene	3	0	0	0	0	P	0	?
Chloroform	3	0	0	0	0	0	0	?
Cresol	3	2	2	1	1	P	0	0
Crotonaldehyde	3	0	0	0	0	P	0	0
Cumene	3	0	0	0	1	P	0	?
O-dichlorobenzene	3	0	0	0	0	P	0	?
P-dichlorobenzene	3	2	0	0	0	P	0	?
Epichlorohydrin	3	0	0	0	0	P	0	0
Ethyl alcohol	3	0	0	0	0	0	0	0
Ethylbenzene	3	0	0	0	0	P	0	?
Ethylene dibromide	2	0	1	0	0	0	0	1
Ethylene dichloride	3	1	0	1	2	P	0	?
Ethylene glycol	2	2	0	0	1	0	0	0
Methyl alcohol	3	0	0	1	0	0	0	0
Methylene chloride	3	0	0	1	0	0	0	?
Naphthenic acid	3	0	0	0	0	0	0	0
Phenol	3	1	1	1	1	P	0	0
Phthalate esters	3	2	0	0	1	P	0	?
Styrene monomer	3	0	0	0	1	P	0	0
Tetramethyl lead	2	0	0	0	0	P	0	?
Tetraethyl lead	2	0	0	0	0	P	0	?
Toluene	3	0	0	P	P	P	0	?
Toluene diisocyanate	3	0	0	0	0	P	0	0
Trichlorobenzene	3	0	0	0	0	P	0	?
Vinyl acetate	3	0	0	0	0	0	0	0
Vinyl chloride	3	0	0	0	0	0	0	?
Xylene	3	0	0	P	P	P	0	?
(7) Organic industrial wates								
(a) Pulp and paper mill wastes	3	0	0	0	0	0	0	0
(b) Other high BOD wastes	3	2	2	0	P	P	0	0
(8) Military wastes	?	0	0	?	?	?	0	0
(9) Heat	3	0	0	0	0	0	0	0
(10) Detergents	2	3	1	0	1	0	1	0
(11) Solid objects	2	1	0	3	3	1	1	0
(12) Dredging spoil and inert wastes	2	0	1	3	0	0	3	0

APPENDIX 5. OIL RELEASED TO THE SEA BY ACCIDENTS INVOLVING SHIPS OFF SOUTH AFRICA (1968-1978)

Year	Name of ship	Location of Accident	Estimate of amount released
1968	Sivella	Mouille Point	5 000 t
1968	Esso Essen	Cape Point	15 000 t
1968	Andron	Luderitz	Tanker sank with oil cargo probably 15 000 t
1968	World Glory	104 km ENE Durban	Tanker sank with oil cargo 45 000 t probably released
1970	Kazimah	Robben Island	1 000 t bunker oil
1971	Wafra	Cape Agulhas	6 000 - 10 000 t released at Agulhas, remainder of cargo of 63 000 t sunk with tanker 213 km off coast
1971	Alkis	Between Tristan da Cunha and Cape Town	Tanker sank with oil cargo probably 17 000 t
1971	Seatrader	Stompneus Bay	Contents of bunker tanks probably 1 000 t
1972	Silver Castle	Off Kenton-on-Sea	1 600 t released upon collision
1972	Oswega Guardian/ Texanita	Off Ystervark Point	Department of Industries estimates 10 000 t of cargo and fuel
1974	Wilstar	Between East London and Port Elizabeth	600 t upon fracture of bow and some in Algoa Bay
1974	Oriental Pioneer	Cape Agulhas	200 t bunker oil (1 800 t transferred or burnt off)
1974	Tekton	Between Durban and Algoa Bay	Sank with 400 t bunker fuel, 20 t diesel and 7 t lubes whilst being towed
1974	Sea Sovereign	Durban	Less than 1 t
1974	Produce	Aliwal Shoal	800 t bunker fuel, 90 t gas oil (19 000 t molasses)
1974	S A Oranjeland	East London	Probably 500 t
1976	Goel I	Robben Island	250 t diesel oil
1975	Rose II	Bushmans River mouth	Some bunker oil, probably 100 t
1976	Garcia Monte	Durban	Pumped oil into sea, quantity unknown
1976	Adabella Lykes	Durban	Small spill of bunker oil on grounding
1977	Venoil/Venpet	Off Cape St Francis	31 000 t of crude and bunker oil
1978	Pantelis A Lemos	8 km south of Saldanha	300 t bunker oil
1978	Kaiyo Maru No 1	510 km north of Walvis Bay	200 t diesel
			TOTAL $0,2 \times 10^6$ t

APPENDIX 6. SEWAGE OUTFALLS ALONG THE SOUTH AFRICAN COAST

Location	Discharge type	Quality[++]	Volume (10^6 m^3a^{-1})
From Mozambique/RSA border to Cape Recife			
Durban			
Central	Deep-sea pipe (3 km)	Settled sewage[+]	29,5[+]
Southern	Deep-sea pipe and disperser (1,5 km)	Settled sewage[+]	34[+]
Northern	Estuary	General standard[+]	6[+]
Port Shepstone	Surf zone	General standard[+]	0,44[+]
Other Natal outfalls	Surf zone	General standard	1,58
East London			
Nahoon	Surf zone	Raw	1,35
Bats Cave	Surf zone	Raw	6,57
Hood Point	Surf zone	Raw[+]	2,08[+]
Buffalo	Estuary	General standard	5,55
Port Elizabeth			
Fish Water Flats	Surf zone	General standard[+]	12,78[+]
Papenkuils River	Surf zone	Raw[+]	3,65[+]
Cape Recife	Surf zone	General standard	0,6
From Cape Recife to Cape Point			
Knysna	Estuary	General standard	0,58
Mossel Bay	Surf zone	Raw	2,0
Hermanus	Surf zone	General standard	0,5
Macassar	Estuary/surf zone	General standard	5,1
Cape Flats	Surf zone	General standard	25,55
Simonstown	Surf zone	General standard	0,4
Wildevoëlvlei	Lake (estuary)	General standard	0,73
From Cape Point to the Orange River			
Hout Bay	Surf zone	Raw[+]	?[+]
Llandudno	Surf zone	General standard	0,03
Camps Bay	Deep sea pipe and disperser (1 km)	Raw	1,83

APPENDIX 6. (Continued).

Location	Discharge type	Quality++	Volume (10^6 m^3a^{-1})
Mouille Point	Deep sea pipe and disperser (Old pipeline: 1,2 km. New pipeline to be built 1,7 km)	Raw+	14,60+
Athlone	Black River estuary	Settled sewage+	18,2+
Saldanha	Bay	Raw	0,07

\+ Includes industrial effluent

++ The qualities of raw, settled and general standard sewage are approximately as follows:

Raw:	COD		700 - 1 000	mg l^{-1}	
	SOG (soap oil and grease)	ca	70 - 100	mg l^{-1}	
	SS	ca	250	mg l^{-1}	
	PO_4 as P		7 - 20	mg l^{-1}	
	E coli I			$>10^6$ (100 ml)$^{-1}$	
Settled:	COD	ca	300	mg l^{-1}	
	SOG	ca	70 - 100	mg l^{-1}	
	SS	ca	100	mg l^{-1}	
	PO_4 as P		5 - 15	mg l^{-1}	
	E coli I			$>10^6$ (100 ml)$^{-1}$	
General Standard:	COD		75	mg l^{-1}	
	OA		10	mg l^{-1}	
	pH		5 - 9	mg l^{-1}	
	Free and saline Ammonia		10	mg l^{-1}	
	SS		25	mg l^{-1}	
	TDS		500	mg l^{-1}	above intake
	E coli I			$<10^3$ (100 ml)$^{-1}$	
	SOG		2	mg l^{-1}	

APPENDIX 7. INDUSTRIAL EFFLUENT PIPELINES ALONG THE SOUTH AFRICAN COAST

Location	Discharge	Type	Approximate composition	Volume (10^6 m^3a^{-1})
From Mozambique/RSA border to Cape Recife				
Ngoya Paper Mill	Surf	Industrial effluent	Chemical oxygen demand (COD) 20 000 mg l^{-1} lignin, stearates caustic	1,83
Richards Bay				
Alusaf	Harbour	Industrial effluent	40 mg l^{-1} F	?
Triomf	Harbour	Industrial effluent	40 mg l^{-1} F gypsum	?
Port Shepstone		Textiles and bakeries, industrial area and domestic sewage		0,44
Durban				
Central		Domestic sewage and industrial effluent		29,5+
Southern		Domestic sewage and industrial effluent		34 +
Northern		Domestic sewage and industrial effluent		6 +
Tongaat				
David Whitehead	Surf	Textile effluent	Dye house caustic + organic COD ca 1 000 mg l^{-1}	0,18
AECI Umbogintwini	Behind surf	Industrial effluent	NO_3, organics, neutral phosphoric acid, Hg	Classified
SA Titan Products	Behind surf	Industrial effluent	15% H_2SO_4, $FeSO_4$, TiO_2, cellulose effluent	0,66
SAICCOR	Deep sea pipe and disperser	Industrial effluent	Caustic (sulphite) lignin, stearate, COD 10 000 mg l^{-1}	29,2
East London				
Cyril Lord	Surf zone	Textile and herbicide wastes (mixed)	Caustic, dyes, organics, pH5-9, COD 450 mg l^{-1}	1,46
Hood Point		Canneries, domestic sewage. Other minor contributors include battery factories, fibre board manufacture, carpet manufacture, car assembly, beer bottling, grain milling		2,08+
Port Elizabeth				
Fish Water Flats		Purified domestic and industrial waste		12,78+

APPENDIX 7. (Continued).

Location	Discharge	Type	Approximate composition	Volume (10^6 m^3a^{-1})
From Cape Recife to Cape Point				
Mossel Bay	Beach surf zone	Food product effluents, cannery	Milk and cannery wastes, COD 2 000 mg l^{-1} suspended solids (SS) ca 50 mg l^{-1}	0,22
Hermanus	Surf zone	Municipal and fish factory		0,08
Somerset West	Surf zone	Food product effluents	Cannery, COD 10 000 mg l^{-1}	1,66
	Surf zone	Fertilizer		?
	Surf zone	Explosives and plastic		Classified
Wildevoëlvlei		Service industries		0,02
Simonstown	Surf zone (pipe)	Oil refinery effluents	COD 2 000 mg l^{-1} N 0,6 mg l^{-1}, SS 50 mg l^{-1}	0,05
Cape Flats		Domestic sewage and industrial effluents		25,55
From Cape Point to Orange River				
Hout Bay		Domestic sewage and industrial effluents		?
Mouille Point		Domestic sewage and industrial effluents		14,6
Milnerton	Deep sea pipe	Fertilizer effluents and oil refinery effluents	NO_3-N 1 700 mg l^{-1}, oil refinery, oil, caustic	0,37
	Deep sea pipe and disperser			1,06

\+ Also includes domestic sewage (see Appendix 4)

Information from the Pollution Control Section, Department of Water Affairs

APPENDIX 8. FISH FACTORY EFFLUENTS ALONG THE SOUTH AFRICAN COAST

Site	Activity	Type of effluent*	Volume of sea and fresh water effluent (1 000 $m^3 a^{-1}$)**
Doornbaai	Rock lobster	Washing water COD ca 500 kg d^{-1}	800
Lamberts Bay	Rock lobster Fish meal Cannery	Factory effluent N = 22,6 kg d^{-1} COD = 1 040 kg d^{-1} TSS = 96 532 kg d^{-1} Fats = 788 kg d^{-1} COD 20 000 mg l	1 000
Elands Bay	Rock lobster	Wash and tank water	15
Berg River	Fish meal Cannery	Factory effluent and wash water N = 44 kg d^{-1} COD = 272 kg d^{-1} TSS = 1 169 kg d^{-1} Fats = 32 kg d^{-1}	540
St Helena Bay	Fish meal Cannery	Factory effluent and wash water N = 2 442 kg d^{-1} COD = 39 569 kg d^{-1}	2 477
Stompneusbaai	Fish meal Cannery	Factory effluent and wash water N = 112,9 kg d^{-1} COD = 3 581 kg d^{-1} TSS = 4 320 kg d^{-1} Fats = 2 146 kg d^{-1}	406
Saldanha	Fish meal Rock lobster Cannery White fish	Factory effluent and wash water N = 4 265 kg d^{-1} COD = 55 353 kg d^{-1} TSS = 95 523 kg d^{-1} Fats = 11 042 kg d^{-1}	2 225
Pepper Bay	White fish Lobster	Factory effluent and wash water	2
Hout Bay	White fish Fish meal Cannery	Factory effluent and wash water	458
Hermanus	Abalone White fish Cannery	Floor washing and cleaning water	20
Gansbaai	Fish meal White fish Cannery	Factory effluent and wash water N = 1 283 kg d^{-1} COD = 18 957 kg d^{-1} TSS = 83 945 kg d^{-1} Fats = 17 603 kg d^{-1}	424

* As fishing is seasonal (and erratic within a given season) and the waste water from a rock lobster processing plant differs radically from that of a fish meal plant or a cannery, composition of the fish processing waste water can vary within extremely wide limits.

** Information from Fisheries Development Corporation of South Africa Limited. Circulation is estimated from rated capacities of pumps and hours worked and is therefore subject to considerable margin of error, as the pollution load is more nearly proportional to tonnage of fish processed than to quantity of water circulated.

Annual totals can be converted to approximate daily figures by dividing by the number of working days in a season, which is four months for most of the fish meal plants and about seven months for rock lobsters.

APPENDIX 9. DUMPING OFF THE SOUTH AFRICAN COAST*

Date	Location	Type
1946 May-July	Port Elizabeth from M/V Homeford	Mustard Gas
September 1966	Durban	26 x 1 lb sealed glass containers of ozonized ethers
February 1968	Between Mossel Bay and Port Elizabeth	1 200 x 46 gallon drums of Brine effluent weed killer by Shell Oil Company
February 1970	65 nautical miles west of Cape Town	Torch batteries - 200 cartons of 10 lbs each by Eveready (SA) Pty Ltd
January 1970	Outside 1 000 Fm line between Mossel Bay and Port Elizabeth	Drums of toxic effluents by Shell Chemicals (SA) Pty Ltd
December 1972	Outside 1 000 Fm line between Mossel Bay and Port Elizabeth	Drums of toxic effluents by Shell Chemicals (SA) Pty Ltd
December 1972	Beyond 500 Fm line west of Cape Town	5 434 cases (44 350 litres) of Fresca cool drink by South African Beverage Canners (Pty) Ltd
May 1976	± 100 miles off Durban	700 tons refinery wastes (caustic and 2 to 4% phenols)
July 1976	± 100 miles off Durban	1 000 tons refinery wastes (caustic and 2 to 4% phenols) NB 2 refineries each produced 150 tons/refinery month, i e 300 tons/ month for dumping. The dumping discontinued from January 1977.

NB disused munitions dumps occur off Cape Town, Cape Point and Port Elizabeth.

* Information from Sea Fisheries Branch.

APPENDIX 10.

SALES OF AGRICULTURAL CHEMICALS IN THE REPUBLIC OF SOUTH AFRICA FOR THE PERIOD 1 JULY 1974 TO 30 JUNE 1977

	1974/75	1975/76	1976/77
Wood preservatives	17 000	16 800	19 300
creosote	16 000	16 000	18 559
sodium bichromate	230	300	
PCP	160	46	
zinc naphthenate	130		
Herbicides	6 500	5 200	4 200
2,4 - D	2 800	1 300	530
atrazine	1 000	1 500	1 200
diuron	500	520	489
propop	370		
MCPA	325	284	181
EPTC	224	206	395
Fungicides	6 100	6 100	6 800
sulphur	3 900	3 500	4 227
dithiocarbamates	1 300	1 300	1 015
copperoxychloride	500	800	968
dicarboximides	59	66	84
systemic fungicides	42	56	65
formulated as dusting powder	3 900		
formulated as wettable powder	2 000		
formulated as emulsifiable concentrate	4		
Insecticides	6 000	6 000	5 700
mineral oil	2 000	1 600	2 583
carbaryl	950	910	484
endosulfan	500	215	342
DDT	400	1 500(3)	
parathion	170	220	173
mercaptothion (malathion)	160	260	
polysulphide sulphur			255
formulated as emulsifiable concentrate	3 800		
formulated as wettable powder	1 600		
formulated as dusting powder	100		
organophosphate compounds	1 235	1 019	1 015
chlorinated hydrocarbon compounds	1 270	2 000	863
carbamate compounds	1 000	956	570

APPENDIX 10. (Continued).

	1974/75	1975/76	1976/77
Swimming pool chemicals	2 700	2 900	3 600
sodium hypochlorite	2 100	2 700	
potassium hypochlorite	500	100	
calcium hypochloride			2 689
Fumigants	1 650	2 000	2 000
EDB	800	1 000	1 178
methylbromide	450	425	508
Planthormona	80	42	111
fatty acid alcohols	74	23	78
Insect repellants	11	13	10
diethyltolnamide	7	10	7
Slug and snail killers	9	10	13
metaldehyde	7	9	7
Verium killers	1	1,7	8
warfarin and conmatetralyl most commonly used			
TOTAL	40 000	39 500	41 742

Notes: (1) All quantities in metric tons

(2) Active ingredients totals are underlined

(3) For the period July 1975 to April 1976; sale prohibited 1 April 1976. Limited malaria spraying (5-7 ton p a) is undertaken by the Department of Health in Northern and Eastern Transvaal and Natal.

(4) Periods cover the 1st of July each year to 30th of June the following year.

(5) BHC and endrin were withdrawn in 1970 and mercury in 1974.

Data from the Registering Officer, Department of Agricultural Technical Services.

APPENDIX 11.

CHLORINATED PESTICIDES IN THE MUSSEL (PERNA PERNA) IN THE NATAL AND SOUTH COAST AREAS OF SOUTH AFRICA*

Place	Pesticide	Concentration $\mu g\ kg^{-1}$
Kosi area	DDT	6
	DDE	0,3
	TDE	3
	Dieldrin	ND
Sheffield Beach and Chaka's Rock	DDT	0,14 (7) ND-1
	DDE	2 (7) ND-14
	Dieldrin	8 (7) ND-53
Tongaat and Umhlanga Rocks	DDT	ND (5)
	DDE	8 (5) ND-22
	Dieldrin	2 (5) ND-6
	Lindane	ND
Bluff Beaches	DDT	11 (4) 1-17
	DDE	5 (4) ND-8
	Dieldrin	2 (4) ND-9
	Lindane	ND
Umbogintwini	DDT	1 (6) ND-7
	DDE	6 (6) ND-30
	Dieldrin	0,2 (6) ND-1
	Lindane	0,5 (6) ND-5
Park Rynie and Sezela	DDT	5,5 (8) ND-16
	DDE	0,3 (8) ND-2
	Dieldrin	4 (8) ND-31
	Lindane	ND
Hibberdene	Endrin	2 (6) ND-13
	DDT	4 (6) ND-20
	DDE	ND
	Dieldrin	1,5 (6) ND-9
	Lindane	5 (6) ND-25
Port Shepstone to Port Edward	DDT	10 (7) ND-37
	DDE	ND
	Dieldrin	6 (7) ND-23
	Lindane	ND

APPENDIX 11. (Continued).

Place	Pesticide	Concentration $\mu g\ kg^{-1}$
Presley Bay and Bashee	DDT	ND (1)
	DDE	ND
	Dieldrin	ND
Port Elizabeth	DDT	ND (5)
	DDE	ND
	Dieldrin	2 (5) ND-9
	Lindane	ND

* Data from B D Gardner (1978). The halogenated pesticides in the Marine Environment of Natal, Transkei and the South Eastern Cape (Preprint), National Institute for Water Research, Durban.

Notes :

(1) Mean (n) Range, ND = not detectable.

(2) Perna perna from the Port Elizabeth area contained 35 to 130 $\mu g\ kg^{-1}$ PCB (similar to Arachlor 1260).

APPENDIX 12.

COMPARISON OF TRACE ELEMENT CONCENTRATIONS AROUND SOUTH AFRICA AND AUSTRALIA

Interlaboratory variations make the comparison of published data on trace element concentrations in sediments and mussels difficult to interpret but an attempt is made here to compare Australian (Gilmour and Kay 1979) and South African results.

Unpolluted Australian and South African estuarine sediments have characteristic acid-extractable Cd concentrations of less than 0,5μg g^{-1}. Areas where pollution is known or suspected have much higher maximum values, e g Richards Bay (South Africa) about 1,6μg Cd g^{-1}, Berg River (South Africa) near fish factory outfall, about 1,8μg Cd g^{-1}, Port Philip Bay (Australia) expecially Corio Bay, which has a known input of Cd, up to 10 to 12μg Cd g^{-1}, and the Derwent River (Tasmania), polluted by a smelter and a pulp mill, up to 1 400μg Cd g^{-1}.

Sediments in unpolluted areas contain acid-extractable Cu values of 20μg g^{-1} or less. Again Richards Bay (40); Berg River (40); Port Philip Bay (up to about 100); and the Derwent River (exceeds 10 000) evidence pollution. The Olifants River (South Africa) although not polluted has relatively high levels of Cu (30 to 40 g g^{-1}) perhaps due to the presence of Cu deposits in its catchment area.

Concentrations of less than 10μg Pb g^{-1} or 50 μg Zn g^{-1} seem to indicate little pollution. Polluted areas (as above) have elevated levels (30 to 200μg Pb g^{-1}, 200 to 400μg Zn g^{-1}) excluding the Derwent River (Pb 41 200μg g^{-1}, Zn 104 000μg g^{-1}).

Gilmour and Kay (1979) have compared their results with published data and Cd and Pb levels in the Corio Bay area are about the same as in the polluted Severn and Firth of Clyde estuaries, while Zn and Cu levels are somewhat lower. The Derwent River is extensively polluted with all four elements and level are the highest yet published (the quoted concentrations suggest it might be economic to mine the river sediments!).

Comparison of mussel data is difficult due to biological variability but some trends appear. Mussels from unpolluted areas have Cd, Cu, Pb and Zn levels less than 10, 10, 10, and 200$\mu g\, g^{-1}$ respectively. Mussels from the polluted areas (above) show elevated levels of metals of about an order of magnitude.

It is interesting to note that severe metal pollution, comparable to or worse than that recorded for the heavily industrialized northern hemisphere, occurs in the supposedly little polluted southern hemisphere.

Table A. Trace elements in South African estuaries.

NOTES

1. Water units $\mu g\ l^{-1}$
   Sediment - $\mu g\ g^{-1}$ (dry)
   } Ranges : maximum and minimum given - data rounded somewhat
2. ND - Not detected - no data on lower limit
3. Stations chosen to be at head of estuary, i e those as near the river input as possible

	Ba	Br	Cd	Co	Cr	Cu	Fe	Hg	Mn	Mo	Nb	Ni	Pb	Rb	Sr	Th	V	Y	Zn	Zr
KOSI BAY(1)																				
Water - 1976			ND- 0,4	ND- 0,8		ND- 1,1		0,05- 0,08				0,7- 1,9	0,4- 1,0						ND- 5,7	
ST LUCIA ESTUARY(1)																				
Water - 1978			0,03- 0,25	0,08- 2,4		1,2- 17	460- 2 000	0,03- 0,13				1,2- 6,1							1,4- 11,7	
Sediment - 1978			0,08- 0,4	1- 27	7- 150	2- 61	3 000- 60 000	0,007- 0,04				2,9- 84	0,8- 19						3,4- 72	
RICHARDS BAY(1)																				
Water - 1974 (during dredging)			0,001- 0,025	-		0,25- 3,1		0,01- 0,38		-	0,53		3,9			-				
- 1976			0,04- 0,17	0,4- 4,0		0,1- 4,0		0,45- 1,92				ND - 13,0	ND - 4,2						ND - 3,8	
Sediment - 1974 (during dredging)			0,46- 0,76	-	-	8,3- 12,0	19000- 29000	0,017- 0,029				-	20-32						66- 175	
- 1976			0,6- 1,6	1,5- 23,5	-	1,1- 40,0	800- 11000	0,007- 0,039				2,2- 73	5,5- 33,0						14- 179	

Table A. (Continued).

	Ba	Br	Cd	Co	Cr	Cu	Fe	Hg	Mn	Mo	Nb	Ni	Pb	Rb	Sr	Th	V	Y	Zn	Zr
RICHARDS BAY : MZINGAZI LAKE[1]																				
Water - May 1974			0,04	-	-	1,55-4,79	-	0,006-0,011				-	0,04-10,5						0,4-12,5	
DURBAN BAY[1]																				
Water - 1978			ND-0,82	ND-3,2		0,57-27	15-800	0,17-0,37					ND-9,1						0,1-59	
Sediment - 1978			0,7-1,9	4,2-13	10-388	5,5-57	3 000-40 000	0,07-0,87	23-303			7-26	18-117						26-287	
UMZIMKULU RIVER[1]																				
Water - Station 1 - Aug 1974			0,004-0,015	-		0,90-2,21		0,05-0,13					0,38-3,5						7,5-8,9	
Sediment - Stations 1 and 2 - Sept 1974			0,4-0,6	-	-	4-10	9000-11000	0,001-0,005				-	5-9						33-649	
UMZIMVUBU RIVER[1] : August 1977																				
Water - Upper 2 Stns			0,13-0,24	1,5-1,6	-	1,1-1,9	390-460	0,33-0,40	-			-	2,2-2,9						11,5-20,1	
Sediment - do.			0,008-0,07	0,83-0,95	26-27	2,6-4,8	1420-1540	0,03-0,05	-			13-17	0,16-0,35						12,1-16,4	

Table A. (Continued).

	Ba	Br	Cd	Co	Cr	Cu	Fe	Hg	Mn	Mo	Nb	Ni	Pb	Rb	Sr	Th	V	Y	Zn	Zr
UMGABABA RIVER(1)																				
Water - 1st station			0,06	7,9	-	2,8	684	1,0				-	-						4,25	
Sediment - June 1976			0,52	12	21	9,6	12330	0,02				-	9						21	
- Feb 1977			0,35	-	7,6	2,2	5192	0,04				5,1	4,0						10,2	
MNGAZANA RIVER(1) : August 1977																				
Water - Upper stn			ND	ND	-	2,4	211	0,3	-			-	2,7						5,7	
Sediment - do			0,09	3,9	126	15	4990	0,09	-			35	1,4						71	
BASHEE RIVER(1)																				
Water - 1st Station - June 1975			0,22	-	-	0,9	120	-	-			-	0,12						35	
- Dec 1975			0,18			15,7		0,14					11,3						22,2	
Suspended matter in water (mg m^{-3}) - - June 1975			3,3			3,1	2330	0 10					64						540	
Sediment - June 1975			0,23		5,0	2,7	4780	0,001					5,3						8,4	
BUFFALO RIVER (East London) : April 1977(1)																				
Water - Upper 3 Stns - Unfiltered			ND - 0,035	0,7- 1,5	-	1,5- 1,7	72- 122	0,16- 0,23	-			-	ND - 0,02						0,094	
- Filtered			ND - 0,035	ND - 0,74	-	1,2- 3,2	22- 50	-	-			-	ND - 0,18						ND - 0,75	
Sediment - Top			0,04- 0,06	9-11	35-40	16,2- 18,6	25000- 36000	0,05- 0,16	150- 470			17-21	8,8- 9,5						52-69	

Table A. (Continued).

	Ba	Br	Cd	Co	Cr	Cu	Fe	Hg	Mn	Mo	Nb	Ni	Pb	Rb	Sr	Th	V	Y	Zn	Zr
SWARTKOPS RIVER(1)																				
Water - Stns 6 & 7 - Feb 1975			0,01-0,03	-	-	2,63-2,75	-	-				-	2,5-2,8						2,0-3,8	
- Station 5 - Dec 1975			2,8-3,5	-	-	0,21-0,22	-	0,06				-	7-8,7						-	
Sediment - Station 7 - Feb 1975			0,45	-	40	8,9	7320	0,035				-	13,1						21	
OLIFANTS RIVER(2)																				
Sediment (upper 10cm) Upper 2 Stns - - Feb 1976	553-585	8-10		29-31	105-116	65-74					11-13	46-51		138-149	154-161		127-143	32	110-122	152-192
- July 1977 (flood conditions)				ND - 23	15-82	3-61				ND	ND - 13	5-46	ND - 28	14-141	26-137	ND - 17	14-114	5-32	8-107	49-143

Table A. (Continued).

	Cd	Cu	Pb	Zn
Olifants River[1] (Summer) Sediment	ND to 0,41 $\bar{x}$ = 0,21 ± 0,12	0,95 to 30,8 $\bar{x}$ = 13,2 ± 10,1	2,20 to 21,5 $\bar{x}$ = 7,9 ± 6,1	2,50 to 78,5 $\bar{x}$ + 32,7 ± 25,5
Olifants River[1] (Winter) Sediment	ND to 0,20 $\bar{x}$ = 0,14 ± 0,04	ND to 42,9 $\bar{x}$ = 23,7 ± 12,7	0,82 to 16,3 $\bar{x}$ = 7,95 ± 4,96	1,04 to 85,5 $\bar{x}$ = 44,1 ± 28,7
Berg River[1] (Summer) Sediment	ND to 1,89 $\bar{x}$ = 0,67 ± 0,65	0,56 to 30,3 $\bar{x}$ = 5,23 ± 7,36	2,38 to 16,9 $\bar{x}$ = 5,99 ± 4,16	3,59 to 101 $\bar{x}$ = 29,6 ± 28,0
Berg River[1] (Winter) Sediment	ND to 1,69 $\bar{x}$ = 0,42 ± 0,39	0,1 to 45,9 $\bar{x}$ = 5,34 ± 8,60	1,80 to 120 $\bar{x}$ = 10,9 ± 8,60	2,6 to 207 $\bar{x}$ = 22,2 ± 41,8

(1) Analyses by AAS, acid-extractable fraction

(2) Analyses by XRF, total sediment

Table B. Concentrations (in μg/g) of four heavy metals in marine sediments (Gilmour and Kay 1979).

AUSTRALIA					
Location	Reference	Cadmium	Lead	Zinc	Copper
1. Western Port Bay (Vic)	Fabris and Harris 1974	0,1 - 1,0 0,3 (26)	0,7 - 46,6 7,8 (26)	2,1 - 52,8 21,8 (26)	1,0 - 35,4 10,9 (26)
2. Western Port Bay (Vic)	Stathan 1976	0,14 - 0,15 - -	1,3 - 11,1 5,25 (21) 4,24	1,0 - 16,1 5,42 (32) 4,37	- 1,8 -
3. Port Phillip Corio Bay (Vic)	Smith 1977	0,1 - 12,6 3,25 (31) 2,03	2,0 - 210,0 91,87 (31) 63,93	4,0 - 398,0 80,10 (31) 54,46	2,0 - 50,0 14,77 11,88
4. Port Phillip Corio Bay (Vic)	French and Thistlethwaite 1976	1,8 - 7,4 4,41 (8) 3,57	10,0 - 122,0 84,38 (8) 60,72	18,0 - 129,0 82,88 (8) 66,32	18,55 - 122,0 18,55 (8) 13,97
5. Port Phillip Bay	Talbot et al 1976	0,15 - 9,9 2,23	4,6 - 183,0 45,8 (20)	3,3 - 278,0 70,07 (20)	2,2 - 87,0 27,89 (20)
6. Port Phillip Corio Bay	Talbot et al 1976	0,8 - 9,9 5,68 (5) 4,40	19,2 - 183,0 103,38 (5) 82,37	44,4 - 278,0 156,02 (5) 131,41	13,5 - 62,3 30,36 26,68
7. Port Phillip Hobsons Bay	Talbot et al 1976	0,6 - 3,5 2,08 1,58	15,2 - 85,1 50,03 (4) 33,06	12,7 - 163,0 69,43 (4) 43,69	29,0 - 87,0 59,00 (4) 52,34
8. Port Phillip Werribee	Talbot et al 1976	0,98 - 1,53 1,25 (4) 1,24	16,7 - 38,7 29,35 (4) 27,96	27,0 - 94,0 62,45 (4) 55,12	3,3 - 59,0 21,73 (4) 12,96

Table B. (Continued).

Location	Reference	Cadmium	Lead	Zinc	Copper
9. Port Phillip	Talbot et al 1976	0,15 - 0,67	4,6 - 29,0	3,3 - 23,9	2,2 - 19,9
other		0,40 (7)	11,61 (7)	13,40 (7)	11,86 (7)
		0,36	9,17	11,36	9,14
10. Tamar River	Ayling 1974	3,4 - 4,0	86,0 - 93,0	351,0 - 380,0	53,0 - 380,0
		3,60 (5)	90,2 (5)	368,0 (5)	66,2 (5)
11. Derwent River	Bloom 1975	0,3 - 1400,0	97,0 - 41700,0	26,0 - 104000,0	0,8 - 10050,0
Estuary		87,05 (85)	2045,0 (87)	8594,0 (81)	537,0 (92)
		13,45	472,0	1658,0	102,0
12. South Towns-	Burden-Jones et al	0,1 - 0,3	0,5 - 4,1	4,2 - 17,8	0,6 - 3,5
ville (N Qld)	1977	-	-	-	-
13. Halifax Bay	Burden-Jones et al	0,1 - 0,4	0,5 - 5,3	5,8 - 17,8	0,9 - 2,5
	1977	-	-	-	-
14. Bowling Green	Burden-Jones et al	0,1 - 0,3	0,4 - 3,7	10,2 - 26,1	1,2 - 3,6
Bay	1977	-	-	-	-
WORLD					
Location	Reference	Cadmium	Lead	Zinc	Copper
15. Severn Estuary	Butterworth et al	1,6 - 4,7	130,0 - 200,0	420,0 - 590,0	-
	1972	3,70 (7)	162,86 (7)	471,43 (7)	-
		3,51	161,25	467,78	-
16. Tor Bay	Taylor 1974	0,2 - 0,7	21,3 - 65,7	17,2 - 42,0	2,6 - 7,6
(S England)		0,37 ( )	31,2 ( )	24,8 ( )	4,2 ( )

Table B. (Continued).

Location	Reference	Cadmium	Lead	Zinc	Copper
17. Firth of Clyde	Halcrow et al 1973	1,0 - 3,0 1,6 ( )	24,0 - 67,0 42,0 ( )	60,0 - 130,0 85,0 ( )	9,0 - 20,0 16,0 ( )
18. Solway Firth	Perkin et al 1973	ND - 2,4 1,0 ( )	ND - 72,0 37,0 ( )	24,0 - 105,0 63,0 ( )	5,0 - 19,0 10,0 ( )
19. Firth of Clyde	Mackay et al 1972	- 3,4 ( )	48,0 - 134,0 86,0 ( )	70,0 - 244,0 165,0 ( )	22,0 - 77,0 37,0 ( )
20. Firth of Clyde Sewage area	Mackay et al 1972	3,0 - 7,0 6,4 ( )	77,0 - 320,0 182,0 ( )	136,0 - 826,0 354,0 ( )	38,0 - 208,0 99,0 ( )
21. Norwegian fjords	Stenner and Nickless 1974	0,3 - 1,5 0,94 (7) 0,84	5,0 - 66,0 16,74 (7) 10,81	24,0 - 64,0 43,86 (7) 40,86	2,1 - 18,0 9,13 (7) 7,28
22. South Iberian (Pen)	Stenner and Nickless 1975	0,94 - 4,1 1,63 (6) 1,39	6,0 - 1600,0 276,83 (6) 24,14	6,0 - 3100,0 565,67 (6) 71,71	2,0 - 1400,0 240,92 (6) 13,27
23. Athens Sewerage area	Papakostidis 1975	- -	- -	45,0 - 1800,0 -	- -

Table C. Summary of results obtained for trace metals in mussels (South Africa).

Location	Reference	Cadmium	Copper	Iron	Manganese	Nickel	Lead	Zinc
Bloubergstrand (June)	Orren et al 1978	0,22-0,43	1,49-8,14	4,10-35,2	1,89-14,8	0,39-1,09	0,07-1,43	16,0-91,7
(November)		0,37-3,65	5,15-10,4	20,7-134	5,51-33,9	0,66-1,86	1,88-4,16	67,1-118
Saldanha Bay	Fourie 1976	1,53-2,27	4,53-8,00	46,0-133	11,3-16,0	0,67-2,00	0,27-0,67	30,7-100
	Watling and Watling 1974	0,73-21,9	4,21-16,7	44,0-222	3,25-27,8	1,04-5,39	0,65-11,1	40,8-122
Melkbosstrand	Van As et al 1975			Mean 133	Mean 18,0		Mean 0,67	Mean 106
Knysna	Watling and Watling 1975	Mean 6,10	Mean 5,80	Mean 264				Mean 86
South African East Coast	Stanton 1978	0,20-9,77	1,80-93,9	58,0-2160	3,50-17,1	ND-22,0	ND-157	30-1585
Narragansett Bay	Goldberg et al 1978	1,10-2,00	6,70-13,2	81,0-370	8,90-18,0	1,90-6,00	2,50-8,00	80-199
Bodega Head	Goldberg et al 1978	4,50-12,4	4,90-8,00	150-450	2,80-6,40	1,50-4,00	0,40-3,30	100-140

Notes : Data from Fourie (1976) and Van As et al (1975) were quoted on a wet mass basis and the figures given in this table have been calculated assuming the water content of the animals is 85%.

Data from Watling and Watling (1975) and Stanton (1978) refer to Perna perna, the Narragansett Bay (USA) data were from Mytilus edulis and the Bodega Head (USA) mussels were Mytilus californianus. The remaining South African analyses refer to Choromytilus meridionalis.

Table D. Concentrations (in μg/g) of four heavy metals in Mytilus species.

AUSTRALIA (Mytilus edulis)					
Location	Reference	Cadmium	Lead	Zinc	Copper
1. Western Port (Vic)	Phillips 1976b+	1,50 - 24,83 6,93 (9) 4,28		166,5 - 309,75 219,94 218,63	
2. Western Port (Vic)	Fabris et al 1976	0,11 - 4,41 1,05 (35) 0,86	0,3 - 11,6 1,72 (29) 1,17	141,0 - 331,0 203,17 (35) 198,70	1,7 - 10,3 4,71 (35) 4,41
3. Port Phillip Corio Bay (Vic)	Phillips 1976b+	20,40 - 136,20 70,59 (5) 57,72	7,20 - 14,93 10,70 (3) 10,23	194,25 - 523,50 333,30 316,59	3,00 - 6,38 4,41 (5) 4,27
4. Port Phillip Corio Bay (Vic)	Fabris et al 1976	12,7 - 127,0 40,63 (16) 32,65	4,4 - 101,0 20,92 (16) 12,85	111,0 - 48,7 272,56 (16) 245,09	3,0 - 10,0 6,10 (16) 5,79
5. Port Phillip Corio Bay (Vic)	Talbot and Magee 1977	2,8 - 88,0 33,73 (9) 19,81	3,4 - 19,8 10,02 (9) 8,16		
6. Port Phillip Corio Bay (Vic)	Smith 1977	9,8 - 53,0 22,6 (23) 21,27	1,2 - 9,7 3,5 (21) 2,83	110,0 - 410,0 164,48 (23) 155,20	4,8 - 21,0 7,33 (22) 6,77
7. Port Phillip Hobsons Bay (Vic)	Phillips 1976b+	5,03 - 13,58 8,73 (8) 8,26	5,33 - 75,15 24,63 (8) 19,00	250,50 - 728,25 484,03 (8) 453,66	3,53 - 7,35 5,97 (8) 5,85

Table D. (Continued).

Location	Reference	Cadmium	Lead	Zinc	Copper
8. Port Phillip Hobsons Bay (Vic)	Fabris et al 1976	1,07 - 7,76 3,70 (12) 2,99	2,8 - 38,9 12,83 (12) 9,01	77,0 - 362,0 192,92 (12) 170,23	4,2 - 12,3 5,79 (12) 5,49
9. Port Phillip Hobsons Bay (Vic)	Talbot and Magee 1977	6,8 - 24,8 15,72 (5) 14,02	9,7 - 22,4 16,10 (5) 15,55		
10. Port Phillip Werribee (Vic)	Talbot and Magee 1977	8,3 - 18,3 12,94 (3) 12,32	10,3 - 17,9 13,17 (3) 12,77		
11. Rest of Port Phillip Bay (Vic)	Phillips 1976b+	3,68 - 18,90 7,40 (10) 6,53	5,85 - 33,15 15,18 (9) 12,72	123,00 - 392,25 257,92 (9) 247,57	3,53 - 10,88 5,66 (10) 5,31
12. Rest of Port Phillip Bay (Vic)	Fabris et al 1976	1,24 - 5,21 3,15 (14) 2,85	0,6 - 16,6 4,93 (14) 3,14	100,0 - 247,0 160,93 (14) 153,88	3,9 - 8,9 5,38 (14) 5,25
13. Rest of Port Phillip Bay (Vic)	Talbot and Magee 1977	5,3 - 17,0 10,85 (8) 9,95	8,3 - 18,9 14,64 (8) 13,99		
14. Derwent River (Tasmania)	Bloom 1975	1,2 - 38,0 13,90 (35) 10,32	0,4 - 832,0 136,64 (35) 53,49	139,0 - 3160,0 525,0 (35) 386,0	6,5 - 102,0 34,27 (35) 26,94

Table D. (Continued).

Location	Reference	Cadmium	Lead	Zinc	Copper
NEW ZEALAND (Mytilus edulis)					
15. Around NZ	Nielson and Nathan 1975+	1,95 - 12,0 4,73 (-)	0,75 - 15,0 5,03 (-)	28,50 - 195,0 105,00 (-)	12,75 - 135,00 62,25 (-)
16. Tasman Bay NZ	Brooks and Rumsby 1965	10,0 - - - -	3,0 - 25,0 12,00 (6) 9,59	50,0 - 180,0 91,33 (6) 75,75	55,0 - 11,0 8,83 (6) 8,47
WORLD (Mytilus edulis)					
17. Bristol Channel	Nickless et al 1972	4,0 - 60,0 17,92 (12) 14,70	1,0 - 30,0 10,67 (6) 5,94	62,0 - 250,0 146,75 130,96	- - -
18. Poole Harbour	Boyden 1975	3,7 - 65,4 -	1,3 - 19,0 -	94,0 - 162,0 -	1,8 - 11,0 -
19. Scottish Waters	Topping 1973	0,08 - 2,0 -	0,2 - 3,9 -	12,5 - 82,5 -	0,5 - 5,0 -
20. Hardanger Fjord (Norway)	Stenner and Nickless 1974	4,8 - 140,0 25,50 (11) 14,56	15,0 - 3100,0 388,45 (11) 77,64	170,0 - 2370,0 725,00 (11) 522,65	3,0 - 22,0 14,82 (11) 13,40
21. Skjerstad Fjord (Norway)	Stenner and Nickless 1974	1,9 - 4,7 3,27 (3) 3,06	2,0 - 6,0 3,67 (3) 3,30	105,0 - 280,0 176,67 (3) 162,15	15,0 - 130,0 53,33 (3) 30,87

Table D. (Continued).

Location	Reference	Cadmium	Lead	Zinc	Copper
22. Baltic	Phillips 1977/1978	1,3 - 13,0 5,21 (21) 4,38	20,0 - 264,0 99,19 (21) 83,37	98,0 - 460,0 172,90 (21) 160,65	- - -
23. Sound and Great Belt	Phillips 1977/1978	0,6 - 4,2 1,53 (10) 1,27	4,5 - 99,0 29,50 (10) 16,93	30,0 - 177,0 86,70 (10) 72,19	- -
24. Kattegat and Skagerrak	Phillips 1977/1978	0,4 - 1,5 0,85 (23) 0,80	3,0 - 58,0 23,43 (23) 17,66	14,0 - 123,0 48,70 (23) 41,05	- -
25. South Iberian Peninsula	Stenner and Nickless 1975	1,7 - 3,6 2,66 (5) 2,58	2,0 - 15,0 6,75 (4) 5,23	190,0 - 370,0 265,00 (6) 259,60	6,5 - 14,0 10,92 (6) 10,51
(Mytilus galloprovincialis)					
26. NW (Med)	Fowler and Oregioni 1976	0,4 - 5,9 1,9	2,7 - 117,0 21,5	97,0 - 644,0 209,0	2,4 - 154,0 18,0

+ Wet weights converted by factor 7,5 to dry weight.

APPENDIX 13. MAJOR CONTRIBUTORS TO THERMAL POLLUTION IN THE MARINE ENVIRONMENT OF SOUTH AFRICA*

Power Station	Koeberg (comes into service in 1983)	Congella	East London	Zwartkops	Table Bay	Salt River
Capacity	ca 2000 MW	ca 107 MW	ca 107,5 MW	ca 240 MW	ca 200 MW	ca 300 MW
Anticipated load factor	ca 73%	ca 50% Will operate a diminishing load factor until decommissioning in the next few years.	ca 25% Load factor falling.	ca 40% Load factor falling. ESCOM provides an increasing proportion of the Port Elizabeth load.	ca 1% Operates on standby basis. Very low load factor. Will be decommissioned before 1980.	ca 50% Will decrease to ca 30% in next few years.
Average heat input to the sea	ca 200 TJ per day	ca 15 TJ per day	ca 8 TJ per day	ca 20 TJ per day Diminishing	A few TJ per day, mainly during the winter months.	ca 29 TJ per day
Marine growth control	Continuous low level chlorination. Residual concentration at the outfall will be less than 0,2 ppm.	Periodic dosing with chloride of lime. Residual concentration approximately zero.	Reducing cooling water flow rate and then increasing its temperature to ca 38°C for a few hours once or twice per year. Will have negligible effect beyond the station outlet.	Chlorination	Two canals - used alternately each month. (One dry and one in use).	Closing the cooling water for a maximum of 30 minutes three times a day according to the station loading. Thus a residual chlorine concentration of 0,5-0,25 ppm is produced at the condenser outlet. Chlorine content at the discharge funnel outlet is estimated to be effectively zero.
Cooling water obtained from	sea	Durban harbour	Near harbour mouth	Zwartkops river estuary	Cape Town harbour	Table Bay
Rate	ca 80 m^3s^{-1}		ca 2,3 m^3s^{-1}	ca 16,1 m^3s^{-1}	ca 15,2 m^3s^{-1}	ca 13 m^3s^{-1}
Returned	ca 10°C warmer		ca 8,4°C warmer	ca 6°C warmer	ca 7°C warmer	ca 5°C warmer

MW - megawatts
TJ - terajoule

* From Taljaard 1976.

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* Out of print.