FLUSHING TIMES OF THE NORTH SEA
# CONTENTS

## Part I

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>General summary</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>Flushing times and related subjects, by L Otto</td>
<td>14</td>
</tr>
</tbody>
</table>

## Part II

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>North Sea, general review</td>
<td>28</td>
</tr>
<tr>
<td>5</td>
<td>Biological subdivisions of the North Sea, by J A Adams</td>
<td>34</td>
</tr>
<tr>
<td>6</td>
<td>The use of plankton distributions for the study of residual circulation, by J A Adams and D Harding</td>
<td>59</td>
</tr>
<tr>
<td>7</td>
<td>Orkney-Shetland inflow, by H D Dooley</td>
<td>70</td>
</tr>
<tr>
<td>8</td>
<td>Norwegian trench inflow-outflow, by G Furness and M Mork</td>
<td>72</td>
</tr>
<tr>
<td>9</td>
<td>Straits of Dover, by L Otto</td>
<td>76</td>
</tr>
<tr>
<td>10</td>
<td>The Skagerrak, by A Svansson</td>
<td>82</td>
</tr>
<tr>
<td>11</td>
<td>Run-off, by L Otto</td>
<td>83</td>
</tr>
<tr>
<td>12</td>
<td>Precipitation and evaporation, by G A Becker</td>
<td>86</td>
</tr>
<tr>
<td>13</td>
<td>Box 1, by K P Koltermann</td>
<td>95</td>
</tr>
<tr>
<td>14</td>
<td>Box 3', by H D Dooley</td>
<td>98</td>
</tr>
<tr>
<td>15</td>
<td>Box 3'', by J A Durance</td>
<td>100</td>
</tr>
<tr>
<td>16</td>
<td>Box 4, by L Otto</td>
<td>103</td>
</tr>
<tr>
<td>17</td>
<td>Box 5, by G A Becker</td>
<td>106</td>
</tr>
<tr>
<td>18</td>
<td>Box 7, by G A Becker</td>
<td>109</td>
</tr>
<tr>
<td>19</td>
<td>Outcome of mathematical models, by A M Davies</td>
<td>112</td>
</tr>
</tbody>
</table>

References | 142 |
Appendix Table 1 | 159 |
1. Introduction

The present report is produced by a study group of the International Council for the Exploration of the Sea. This group was established by the Council according to Resolution 1976/5:1 "to consider the work on the flushing times of the North Sea".

The group met in Lowestoft on 2-3 February 1977, and reported to the next statutory meeting (CM 1977/C:2). In this report it proposed a subdivision of the North Sea, for which "turn-over times" should be estimated on the basis of available information.

In the years 1977-1981 this work was further developed, in the course of which the group met two times, once in Liège (27 April 1980) and once again in Lowestoft (27 and 28 February 1981), after which a final draft was presented to ICES. The Council decided to publish this report after final editing as a "Cooperative Research Report".

This introductory chapter and the general summary (chapter 2) are under common authorship. The following chapters are by different authors, but they have been discussed in the group and as good as possible harmonized to the common framework.

The following members took, in various stages, part in the work of the group:

2. General summary

The present report deals with an attempt to establish the possibility of using the concept of "flushing time" in a practical situation of the North Sea. The exercise should be looked upon as a basis for further studies. Especially in connection with research of marine pollution this may be relevant.

In that connection data given here might also be used in practical pollution problems. At the present stage, however, this might easily lead to mis-use of data that are presented for another purpose. And although in the following some of the considerations given are of a practical nature in order to illustrate the significance of the concepts, the aims of the report are primarily to contribute to scientific work, and results presented here will only become more and more firm as they are supported by further scientific evidence.

Transport processes in the sea, involving both advection and turbulent diffusion largely determine the distribution of the concentration of dissolved substances. Studies of marine pollution require a description of these transport processes and an understanding of the mechanisms involved. Also for various other studies the transport processes in the sea are of importance.

The study of dynamical oceanography has resulted in the mathematical modelling of transport processes. Although each model is only an imperfect replica of the reality, the mathematical models have evolved into a strong tool for the above-mentioned studies. In this report A.M. Davies deals with such models in section 19.

Yet for various studies the use of numerical models might be unnecessary. When one has to decide whether or not certain pollutants are potential hazards, in how far certain chemical or biological processes are predominant over others, or what the best sampling strategy would be for a certain study, it can be useful to have other tools to analyse the situation or to decide whether further, more detailed studies (e.g. with mathematical numerical models) are required.

In this context time scales play a role (e.g. Goldberg, 1976). Especially the time scale found by dividing the volume of a sea area by the flux of water entering should be mentioned.

This time scale is often called residence time, transit time or flushing time. As these terms, when properly defined, are in many cases
different from the simple quotient of volume over flux, the more neutral
term "turn-over time" ($T_o$) is recommended. So,

$$T_o = \frac{\text{volume}}{\text{mean flux entering}}$$

This turn-over time under stationary conditions is equal to the
mean transit time, that is the time water elements entering the area
remain there. It is also equal to the mean age, that is the mean time
the water elements present in the area have been there since they entered
for the last time, if the sea area is "well mixed", that is if the
properties of the water are the same everywhere in the area.

Under the same conditions the turn-over time is equal to the mean
flushing time, that is the mean time the elements in the area will stay
there before they leave.

Because of these equalities the turn-over time is often used in
estimating possible concentrations that may arise from a source of
dissolved substance in the area. The idea is that the total quantity of
a substance that is introduced over a period equal to the turn-over time
gives, when divided by the total mass of water in the area, the mean
concentration. If this refers to a discharge of pollutants, discharge safety
margins might be established on the basis of a permissible concentration.

With respect to this reasoning it is important to note that, apart
from the condition that the water entering from other sea areas (besides
that entering with the source) should be clean, the condition of stationarity
and well-mixed conditions should apply. When, as is usual in reality,
this is not the case, the estimates obtained in this way are only to be
considered as a first guess for the average concentration. Locally
higher concentrations may be expected and for very variable fluxes the
most pessimistic (lowest) values might better be considered if one wants
to be safe.

Also if one wants to use other, less general methods for assessing
concentrations, e.g. numerical models, the time scale given by the turn-
over time is important in deciding whether such a method should be
based upon annual mean conditions, seasonal conditions or whether shorter
time variability should explicitly be taken into account.

The turn-over time is also an important parameter when one considers
the vulnerability of an area for uncontrolled discharges of substances that
may turn up to be harmful. It is clear that areas with a long mean flushing
time may remain longer affected than areas with a short mean flushing time,
all other conditions being equal. As an estimate of the mean flushing time
the turn-over time is a measure for such a vulnerability.

Finally, the turn-over time may play a role in deciding the most efficient monitoring frequency of a sea area.

Trying to use the turn-over time in this way one encounters a number of problems. The problem that the assumption of well-mixed conditions usually is more or less remote from reality has already been mentioned. Non-stationarity is the second problem. One may eliminate the variations over periods short compared with the turn-over time by taking an average over $T < \tau_0$ and introducing an exchange parameter accounting for the turbulent exchange over the smaller time scales. But in practice there are often significant variations over periods longer than $\tau_0$ which one might best account for by taking the most pessimistic conditions.

In section 3 the problem of non-stationarity is addressed in a general way, in section 19 the variability resulting from seasonal variations is shown in the outcome of model calculations.

Finally, there is a problem in obtaining reliable flux estimates, even in a comparatively well-known area as the North Sea. The present report gives estimates which for certain sub-regions still have a considerable margin of uncertainty.

In this connection the turbulent exchange mentioned above is to be considered. Advective fluxes from one sea area to the other may, with smaller or larger margins of uncertainty, be determined from classical hydrographic data and from numerical models.

However, the turbulent exchange is even more difficult to establish. Given advective fluxes, and the distribution of a conservative tracer and its sources, one may come to an estimate. This may be done for the North Sea on the basis of the salinity distribution and the fresh water input. However, in this report such an estimation has not been carried out because the prerequisite, a sufficiently reliable picture of the advective fluxes, is not established, at least for some of the areas.

If we for the moment neglect the turbulent exchange in estimating the turn-over time, this means that the values that are based upon the advective flux estimates only are estimates of an upper value of $\tau_0$. As such they are considered still useful, because using such upper values gives some additional safety in assessing permissible discharges in the way outlined at the beginning.
However, turbulent exchange in the long run brings back substances from the sea area "downstream" when there has been a gradual build-up of the concentration in that area, and it transports substances "upstream", so annihilating the condition that the water entering should be clean. It is clear that for a better understanding of the concentration resulting from a source in one sea area the whole system of interconnecting sea areas has to be considered.

An example of this is given in a publication by the National Radiological Protection Board and Commissariat à l'Énergie Atomique (1979). It should be mentioned that the data used in that publication for the North Sea are not easy to evaluate in the context of this work, especially also because exchange may depend on the choice of the sea areas.

Yet such a box-model might be further developed on the basis of the present work. Also for this reason sections 11 and 12 give data on run-off and evaporation/precipitation estimates.

The report gives a subdivision in a number of areas on the basis of hydrographic considerations (section 4), supported by biological considerations (section 5).

The subdivision is based upon a rectangular grid of $1^\circ \times 1^\circ$ latitude-longitude rectangles. This has been done to facilitate comparison with statistical data, and also because boundaries following other contours were thought to suggest a better definition of the various areas than in reality. Figure 2.1 shows this subdivision.

This choice manifests a problem which, however, for another choice equally may exist, that is that the flux in and out of a region may change considerably with slight changes in the boundaries. In how far should water just passing through a corner of a region be taken into account? This problem and the closely related problem of short-time variations in the flux is in fact a problem of the length-scale and time-scale of advective versus "diffusive" transport.

In section 19 Davies gives estimates, based upon numerical model calculations, of turn-over times obtained from integrated transports through boundaries and from in- and outflow for the individual grid-points of the model used. The results differ considerably. For the Norwegian Channel, where the inflow and outflow from the Norwegian Sea are close together and pass for a large part through the length of the Norwegian Channel down to the Skagerrak, these inflows and outflows should be considered separately. For the other sea areas there appears to be no firm reason not to take fluxes integrated over the boundaries.
The turn-over times may be estimated from current observations, from model computations and from the analysis of the spreading of tracers (Cs 137). With respect to the latter method the following can be stated.

Artificial and natural tracers, i.e. drift bottles and cards, fish-eggs and larvae (see for the latter categories also section 6 by Adams and Harding) have been used to estimate the Lagrangian flow in the North Sea and assess its circulation. Recently, artificial tracers with distinct properties have been used, as i.e. Rhodamine B dye, radionuclides etc. Where the dye experiments were mainly set for investigations of diffusion on a rather small scale, the radio-active isotopes, i.e. Cs 137, discharged from plants near Cherbourg (Channel) and Windscale (Irish Sea) were monitored, and these data have been used to gain insight into the large-scale circulation of the North Sea (Kautsky 1973, 1976).

Comparing estimates from different Lagrangian investigations one notes sometimes a wide span of residence-times calculated for given areas. So natural tracers as fish-eggs yield travel-times for certain distances differing an order of magnitude with estimates from Cs 137 data.

Such discrepancies could be explained by sampling and interpretation problems. These surveys may take place in a time and space domain that might not be well suited to estimate drift of "water bodies". Further there are problems with the interaction of the radionuclides with the sea water and particularly the sediment, where re-suspension processes could deteriorate simple decay and diffusion argumentation.

Further developments, especially the use of an "internal clock" based on the different decay of different isotopes are likely to add substantially to our understanding of travel times. (Jefferies, Preston and Steele, 1973; McKinley et al., 1981; Livingston, Bowen and Kupferman, 1982; Jefferies, Steele and Preston, 1982).

Dye tracers, on the other hand, have recently led to large-scale interpretation problems, because it could not be well established if one monitors, after some time, the same "cloud". It also seems possible, that under certain hydrographic conditions dye is locked to small-scale hydrographic features with higher concentrations, which in turn either escape future surveys and damage the concentration balance or, if found, lead to unrealistically high concentrations and derived assumptions on the transport processes involved.
It therefore seems necessary as these tools present a strong case for assessing the circulation magnitude and pattern of an area, to compare in depth the suggested and applied techniques for sampling and interpretation. This is especially important as this may further indicate the importance of variability versus average pictures.

Concluding, one may say that there is still uncertainty in the values for the advective flux into the various sea areas ("boxes"). The estimates for the advective turn-over times of these boxes and the results from mathematical models show a wide range of values. For a number of boxes the agreement between estimates and computations is reasonable, for others there is still a great discrepancy, and this indicates where further assessment is necessary (especially boxes 3, 6 and 7).

A complete box model is therefore not to apply before further testing with appropriate data. Apart from that, such a model should include adjoining areas of the North Sea. Especially the Baltic should be included, as water leaving the North Sea for the Baltic returns ultimately.

The accompanying summary diagram with table show the general pattern as it was thought to be. But the appeal of such a scheme should not distract from the necessity to consider carefully the background of the estimates given and the particularities of the various boxes. For this reason for each box a review is given in the sections 13-18. The discussion of the conditions in the boxes 2 and 6 is included in the sections dealing with the inflow and outflow between North Sea and Atlantic Ocean/Norwegian Sea (sections 7 and 8).
fig. 2.1. Subdivision of the North Sea used in this report.
fig. 2.2 Summary diagram of exchange pattern between North Sea areas. Estimated advective fluxes between boxes in $10^6$ m$^3$/s (turbulent exchange indicated by dashed arrows between boxes). (See also page 12.)
Summary table to Figure 2.2.

<table>
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<tr>
<th>Box</th>
<th>volume ( (10^{12} \text{ m}^3) )</th>
<th>est. ( \tau_0 ) (adv.), years</th>
<th>Net flux (from obs.) in ( 10^6 \text{ m}^3/\text{s} ) from box:</th>
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<td>0.4</td>
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<td></td>
<td></td>
<td></td>
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<td>1 0.3</td>
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<td>3'       ?</td>
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<td>7'       ?</td>
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<td>0.3 / 0.3</td>
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<td></td>
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<td></td>
<td></td>
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<td>7'         ？</td>
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Symbols used in Contrib. 3 "Flushing times and related subjects".

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<th>Symbol</th>
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<tr>
<td>$c$</td>
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</tr>
<tr>
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<td>phase-velocity wave</td>
<td>m/s</td>
</tr>
<tr>
<td>$D$</td>
<td>depth reservoir</td>
<td>m</td>
</tr>
<tr>
<td>$E$</td>
<td>exchange factor</td>
<td>m$^3$/s</td>
</tr>
<tr>
<td>$f(t)$</td>
<td>flushing-time distribution</td>
<td>m$^3$/s</td>
</tr>
<tr>
<td>$F$</td>
<td>volume flux</td>
<td>m$^3$/s</td>
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<td>m$^2$/a</td>
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<td>m</td>
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<td>$m(t)$</td>
<td>mass in reservoir with age $t$</td>
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<td>$M$</td>
<td>total mass of reservoir</td>
<td>kg</td>
</tr>
<tr>
<td>$P$</td>
<td>tracer quantity released per unit depth or unit cross-section</td>
<td>kg/m, kg/m$^2$</td>
</tr>
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<td>$q(t)$</td>
<td>mass flux with transit time</td>
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<td>naperian-time of reservoir</td>
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<tr>
<td>$\tau_f$</td>
<td>flushing-time of an element in a reservoir</td>
<td>s</td>
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<tr>
<td>$\tau_t$</td>
<td>transit time of an element passing a reservoir</td>
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</tr>
<tr>
<td>$\tau_0$</td>
<td>turn-over time</td>
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<tr>
<td>$\tau_k$</td>
<td>quasi-stationary turn-over time</td>
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</tr>
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<td>transit-time distribution function of a mass flux $Q$</td>
<td>1/s</td>
</tr>
<tr>
<td>$\psi$</td>
<td>age distribution function of a mass $M$</td>
<td>1/s</td>
</tr>
<tr>
<td>$\omega$</td>
<td>circle frequency of oscillation</td>
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</tr>
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Chapter: | Equation: | |
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<td>(4)</td>
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</table>
3. Flushing times and related subjects (L. Otto)

3.1. Introduction

The concept of "residence time" and related concepts are dealt with for stationary conditions by Eriksson (1971), Bolin and Rodhe (1973) and Nir and Lewis (1975). For non-stationary conditions the theory has been developed further by Lewis and Nir (1978). Although the conditions in the sea are rarely (if at all) stationary, the simplicity of the stationary-state approach makes the description of the exchange processes in a sea area along these lines still a useful attempt, be it only as a first approach (which in some cases may even suffice). However, the complications induced by non-stationary conditions should not be neglected and here attention will to some extent be given to this aspect.

The theory is especially of interest because it serves as the basis of so-called "box-models" in which a sea area is divided into a number of mutually ex-changing reservoirs ("boxes"). As a rule these boxes are each considered as "well-mixed" (Groen and Schönhed, 1961; National Radiological Protection Board and Commissariat à l'Energie Atomique, 1979). We will here give some consideration to the use of such models.

3.2. Transit time

Consider the mass of a sea area $M$, a mass flux entering this area $Q_1$ and a mass flux leaving, $Q_0$. Although $Q_1$ and $Q_0$ are functions of time, we consider them to be constant (and thus $Q_1 = Q_0$) unless explicitly stated otherwise. If we neglect variations of water density we may instead of mass and mass flux also use volume and volume flux, $V$ and $F$ respectively.

We may now define the transit time $\tau_t$, that is the time a certain element entering the area will remain within that area before leaving again.

The total entering mass of the elements with a transit time $\tau_t \leq \tau$ is given by $q_1(V)$. It follows that

$$\lim_{\tau \to \infty} q_1(V) = Q$$

The transit time distribution of the elements entering the area is given by the normalized function $\phi_1$.

$$\phi_1(V) = \frac{1}{Q} \frac{dq_1}{d\tau}$$
In a similar way we may consider the elements leaving after a certain transit time $\tau_t \leq \tau$, that is a total mass $q_0(\tau)$, and the transit time distribution of the elements leaving the area $\phi_0$. In the stationary case $q_0(\tau) = q_1(\tau)$ and $\phi_0(\tau) = \phi_1(\tau)$.

### 3.3. Age

We may also define the age $\tau_a$ of an element in an area as the time the element has been in the area since it entered for the last time.

The total mass of elements in the area with an age $\tau_a \leq \tau$ is given by $m(\tau)$. It follows that

$$\lim_{\tau \to \infty} m(\tau) = M$$

The age distribution function of the elements in the area is given by

$$\psi(\tau) = \frac{1}{M} \frac{\partial m}{\partial \tau}$$

### 3.4. Local age distribution

The elements at a certain location within the sea area also have a certain local age distribution. This local age distribution is represented by:

$$\psi_1(\hat{\mathbf{r}}, \tau)$$

Consider a small segment of $M$ around $\hat{\mathbf{r}}$, $\delta M$, then the total mass of the elements with an age $\tau_a \leq \tau$ is given by

$$m_1(\hat{\mathbf{r}}, \tau) = \delta M \int_0^\tau \psi_1(\mathbf{r}, \tau_a) d\tau_a$$

This local age distribution gives the concentration at $\hat{\mathbf{r}}$ of a property that enters with a variable concentration $c_1(\tau)$. The concentration at $\hat{\mathbf{r}}$ is

$$c(\hat{\mathbf{r}}, t) = \int_0^\infty c_1(t - \tau) \psi_1(\hat{\mathbf{r}}, \tau) d\tau$$

This local age distribution function would therefore be an ideal tool for determining the concentrations in the sea. However, they will be difficult to obtain.
The mean local age is given by

$$\bar{\tau}_a(r) = \int_0^\infty \tau \psi(r, \tau) d\tau$$

(7)

3.5. Flushing time

Complementary to the age of an element within the reservoir is the time an element will yet remain within the reservoir. This time has been called "residence time" (Zimmerman, 1976; Maier Reimer, 1977). However, the term "residence time" is also used as equivalent to the mean transit time (Bolin and Rodhe, 1973) and to the mean age (Eriksson, 1971) of the elements in a reservoir.

Maier Reimer elsewhere (personal communication) uses for this value the term "flushing time". This latter expression is also used for "the time required to remove or reduce to a permissible concentration any dissolved or suspended contaminant in an estuary or harbor" (Baker, Deebel and Geisenderfer, 1966). This general formulation encompasses the use of "flushing time" by Maier Reimer, and we propose here to use this expression to indicate the time required to leave for the elements within a reservoir at a certain instant.

It follows that an element that at a certain instant has an age \( \tau_a \) and for which the transit time is \( \tau_t \) has a flushing time \( \tau_f \) that is given by

$$\tau_f = \tau_t - \bar{\tau}_a$$

(8)

In the same way as the local age distribution function we may define a local flushing time distribution

$$f_f(r, \tau)$$

This local flushing time distribution gives for a tracer that is introduced at \( r \) in variable quantities \( M_{ir}(t) \) the quantity leaving the reservoir, \( M_o(t) \).

$$M_o(t) = \int_0^\infty M_{ir}(t-\tau)f_f(r, \tau) d\tau$$

(9)

The mean local flushing time is given by

$$\bar{\tau}_f(r) = \int_0^\infty \tau f_f(r, \tau) d\tau$$

(10)
The integral flushing time distribution function, at time $t$, follows from the consideration that the mass with flushing time $T_f$ is the mass that entered at the times $t - \tau_a$ ($\tau_a$ variable) with a transit time $T_t = \tau_a + T_f$. For stationary conditions

$$f(\tau) = \frac{Q}{M} \int_0^\infty \psi(\tau + \tau_a) d\tau_a = \frac{Q}{M} \int_0^\infty \psi(x) dx$$

(11)

3.6. Response function

If we observe at the exit the concentration of a tracer that enters the reservoir as a momentaneous input we find the so-called response function $h(\tau)$. From the foregoing we find that if $L$ is the position of the exit,

$$h(\tau) = \psi(L, \tau)$$

(12)

At first sight one might assume that $\phi(\tau)$ and $h(\tau)$ are identical. This is indeed the case where unidirectional flow is (implicitly) assumed (Nir and Lewis, l.c.). However, generally this is not the case as will be discussed later. The inequality occurs when there is not only advective transport at the exit, but also diffusive transport.

3.7. Turn-over time

Still under stationary conditions it can be shown that

$$\phi(\tau) = -\frac{M}{Q} \frac{d\psi(\tau)}{d\tau}$$

(13)

This relation can be derived by considering the amount of water leaving per unit time with the age between $\tau$ and $\tau + \Delta\tau$. This amount is given by $Q\phi(\tau)\Delta\tau$, but in order to keep constant the age distribution $\psi(\tau)$ of the water in the area, it must be equal to

$$-M \frac{d\psi(\tau)}{d\tau} \Delta\tau$$

Bolin and Rodhe introduce the term "turn-over time"

$$\tau_0 = \frac{M}{Q}$$

(14)

which gives in (13)

$$\phi(\tau) = -\tau_0 \frac{d\psi(\tau)}{d\tau}$$

(15)
Furthermore the average transit time $\bar{t}_t$ is, under stationary conditions:

$$\bar{t}_t = \int_0^\infty \phi(t)dt = \frac{M}{Q} \tau_0$$

(16)

3.8. Relations between mean age and mean transit time.

With respect to the mean age $\bar{t}_a$ and the mean transit time $\bar{t}_t$ under stationary conditions Bolin and Rodhe give the following situations:

1. $\bar{t}_a < \bar{t}_t$.

In this case the elements introduced in the reservoir have a high chance to remain there for some time. In the sea, this can be the case if the water enters and leaves the area at points that are so situated that it is very unlikely that elements entering will rapidly arrive at the exit. One may envisage this by an elongated sea area where the entrance is at one side and the exit at the other.

If, in the extreme case, no mixing takes place within the area it can be shown that

$$\frac{1}{2} \bar{t}_t = \bar{t}_a$$

(Björkström, 1976, 1978).

So for situation (1) we find

$$\frac{1}{2} \tau_0 < \bar{t}_a < \tau_0$$

(17)

2. $\bar{t}_a = \bar{t}_t$.

Although various other conditions can be imagined giving this result, a special case can be defined by

$$\psi(\tau_a) = \phi(\tau_t) = \frac{1}{\tau_0} e^{-\tau/\tau_0}$$

(18)

This solution is found when all the elements in the area have an equal probability to be removed. This condition may be approached for an area where the internal mixing is very intense. Otherwise formulated: where the "mixing time" (see [24]) is short compared with the turn-over time.
In the well-mixed case the local age distribution function and the local flushing time distribution do not vary throughout the reservoir.

The flushing time distribution function follows from (11)

$$f(\tau_f) = \frac{1}{\tau_o} \int_0^{\infty} \frac{1}{\tau_o} e^{-\tau_f/\tau_o} \tau_o^\tau e^{-\tau_f/\tau_o} d\tau_a = \frac{1}{\tau_o} e^{-\tau_f/\tau_o}$$ (19)

The mean flushing time is in that case

$$\bar{\tau}_f = \bar{\tau}_a = \bar{\tau}_t = \tau_o$$ (20)

There is an apparent paradox in the fact that for individual elements we have relation (8)

$$\tau_f = \tau_t - \tau_a$$

whereas for the average we have relation (20).

The explanation is in the fact that \(\tau_f\) and \(\tau_a\) are averages over the mass (or volume) of the reservoir, whereas \(\tau_t\) is an average over the flux in or out of the reservoir.

3. \(\tau_a > \tau_t\).

This situation is found if the majority of elements entering are quickly removed again. One may envisage this by a sea area where there is a short-circuit between inflow and outflow.

A general relation between \(\tau_a\) and \(\tau_t = \tau_o\) is given by Björkström (1978)

$$\tau_a = \tau_o/2 + \sigma_t^2/2\tau_o$$ (21)

where \(\sigma_t^2\) is the variance of the transit time distribution

$$\sigma_t^2 = \int_0^{\infty} (\tau_t - \tau_0)^2 \psi(\tau_t) d\tau_t$$ (22)

3.9. Short-period variability

The foregoing discussion was based upon the condition of stationarity, whereas simultaneously the effect of internal mixing is considered. This means that the current in the area may be described in the well-known Reynolds approach as

$$u(t) = \bar{u} + u'(t)$$

where \(\bar{u}\) is a time-independent mean current for an averaging period \(\tau_A\) and

$$\int_0^{\tau_A} u'dt = 0$$
Our assumption of stationarity implies that \( \bar{u} \) will be time-independent.

The effect of the short-period variability on the distribution of properties in the area can be parameterized by a diffusion coefficient \( K \). This diffusion coefficient is generally scale-dependent. However, assuming that there is a well-defined class of eddies of size \( l \) that is most effective (e.g. tidal eddies) we may parameterize the diffusion by a Fickian type diffusion (\( K \) independent of scale). In that case the concentration of a tracer injected at \( r = 0, t = 0 \) for certain values of \( r \) and \( t \) is, for \( \bar{u} = 0 \) (or \( r = 0 \) moving with the mean current) in the two-dimensional case

\[
\Phi_c(r,t) = (4\pi K t)^{-1} e^{-\frac{r^2}{4Kt}}
\]

and in the one-dimensional case

\[
\Phi_c(r,t) = (4\pi K t)^{-\frac{1}{2}} e^{-\frac{r^2}{4Kt}}
\]

where \( P \) is the quantity released per unit depth or per unit cross-section respectively (e.g. Groen and Schönfeld, 1961).

Many problems in a reservoir theory are very much simplified if it may be assumed that the reservoir is well-mixed and equation (18) is applicable. Such a condition may be assumed, as a first approximation, if the mixing time, that is the time in which a roughly homogeneous concentration is reached over the reservoir, is small compared with the turn-over time. As a measure for this time we use the mixing time, defined by

\[
T_m = \frac{L^2}{2K}
\]

where \( L \) is the typical dimension of the reservoir.

It is seen that for \( t = T_m \) the concentration \( c \) at \( r = L \) is 60% of the top value at \( r = 0 \).

So we assume well-mixed conditions for

\[
\tau_0 >> T_m
\]

This means for a rectangular basin with a length \( L \) between entrance and exit and a mean current \( \bar{u} \) that the following inequality should be valid

\[
\frac{\bar{u}}{L} << \frac{2K}{L}
\]
3.10. Effect of diffusive transport across the boundaries.

Still the variability of u' is the cause of a problem in the application of reservoir models in the sea: the same variability that occurs in u may also be expected to occur in Q, which means that we should account for an additional (quasi-) turbulent exchange of water across the boundaries of the area. Only there, where a natural boundary can be defined over which the water exchange occurs in a different way (one-directional) compared with the internal exchange, this problem may not occur. Examples of the latter are the exchange through the sea surface by evaporation and precipitation, exchange through a thermocline by entrainment and river inflow at the head of an estuary. However, in general the exchange processes across a boundary of a sea area are not much different from those at either side, and (quasi-) turbulent exchange across the boundary should be taken into account.

This same difficulty as it occurs in the application of this theory in chemical reactors has been dealt with by Gibilaro (1978), and his arguments are largely followed here.

The problem is that elements entering at the entrance may, because of turbulent exchange, leave again by this way after a short while, whereas elements leaving at the exit may rapidly enter again by this route. This affects the whole concept seriously.

In order to deal still with this problem within the transit-time concept it should be realized that this concept is not developed for tracing the histories of individual elements of whatever small a size. It is developed as a tool for estimating the bulk behaviour of a reservoir. We therefore may still regard the theory applicable as long as we consider elements not smaller than the size l of the most energetic eddies in the turbulent field and as long as we neglect sojourns of elements on the other side of an area boundary that last briefer than the typical period of these eddies, T. Note that our approach means that \( T < T_A \), and of course \( l < L \), the size of the area considered.

If we limit ourselves to elements above this size and to time spans of longer duration the problem outlined above does not essentially influence the application of the theory.

We now consider the advection - diffusion equation of material that enters at a certain instant and that might be considered as to be marked by a tracer. We consider the one-dimensional case, taking the coordinate x along the streamlines of \( \bar{u} \). Assuming parallel streamlines and a Fickian-type diffusion, the effect of diffusive transport on the applicability of the theory is investigated.
For a tracer with a concentration $c$ the flux through the cross-sectional area $S$ is given by

$$F_c = \left(uc - K \frac{\partial c}{\partial x}\right) S \quad (27)$$

From (238) with $r = x - \bar{u}t$ we find for the concentration of a mass $P$ of a tracer injected at $x = 0$, $t = 0$,

$$\rho c(x,t) = \frac{(x-\bar{u}t)^2}{4Kt} e^{-\frac{(x-\bar{u}t)^2}{4Kt}} P \quad (28)$$

It can be shown from (27) that the net flow of elements of a certain age is always unidirectional, both at the entrance and at the exit (see Gibilaro, l.c.). However, the response function is now different from the transit time distribution.

It follows, from (28) that for $x = L$

$$h(\tau) = \frac{g^2(\tau - \bar{t}_p)^2}{4K} e^{-\frac{g^2(\tau - \bar{t}_p)^2}{4K}} \quad (29)$$

However, as not all the elements introduced at the beginning enter at the same instant, and as the elements arriving at $x = L$ are not all leaving simultaneously, $\phi(\tau)$ is now different from $h(\tau)$. Gibilaro has shown that the following relation can be used

$$\phi(\tau) = \frac{\tau}{\bar{t}_p} h(\tau) \quad (30)$$

Considering (30) we see that well-mixed reservoirs can only exist, if the mixing within the reservoir does not occur across the boundaries, because under well-mixed conditions per definition $h(\tau) = \psi(\tau) = \phi(\tau)$. 


3.11. Long-periodic variations

If the flux shows a long-periodic variability that is if

\[ \bar{u} = \frac{1}{T_A} \int_0^T \dot{u} \, dt \]

varies with time, the foregoing theory is not generally applicable. Only under certain conditions can we apply it for order of magnitude approximations of the flushing times and related concepts. The same can be stated, of course, if the mass \( M \) is variable in time.

Time variations in \( M \) and \( Q \) are related by

\[ \frac{dM}{dt} = Q_i(t) - Q_o(t) \]  \hspace{1cm} (31)

A change in \( M \) will generally cause a change in sea level, which may result in changes in hydrostatic pressure gradients over the reservoir boundaries, and thereby changing again \( Q_i \) or \( Q_o \).

If no other forces are acting on the reservoir, changes in \( Q_i \) or \( Q_o \) will be transmitted through the reservoir, as free progressive waves. The phase velocity of these waves is given by

\[ c = \sqrt{gD} \]  \hspace{1cm} (32)

where \( D \) is the effective depth of the reservoir.

For a reservoir with a length \( L \) the transmission time of a disturbance in \( Q \) will be

\[ T_t = \frac{L}{c} = L \cdot \frac{1}{\sqrt{gD}} \]

In sea areas like the North Sea the transmission time is of the order of hours to days.

However, if other external forces, in particular from the wind or atmospheric pressure fields over the reservoir are acting, the changes in \( Q_i \) or \( Q_o \) are transmitted as forced waves. Large variations in \( Q \) or \( M \) in practice are the result of storm surges. Their duration is of the order of days. Longer periodic variations in \( M \) are usually small.

Therefore, in practice, one may consider \( M \) constant for the longer-periodic time variations. So then

\[ Q_i(t) = Q_o(t). \]
Generally the effect of variations in $Q$ is not open to an analytical approach. However, if one may assume that the reservoir is well-mixed, it is possible to find expressions for the age-distribution function for given periodicities and intensities of the variations in $Q$.

If

$$Q = Q_0 + Q_1 \cos \omega t$$

($Q \geq Q_1$)

The age-distribution function is found to be (see Otto: in preparation).

$$\psi(t,\tau) = \frac{1}{\tau_0} \cdot \frac{Q(t-\tau)}{Q_0} \cdot e^{-\frac{\tau}{\tau_0}}$$

with

$$\tau_0^x = \tau + \frac{Q_1}{Q_0} \cdot \frac{1}{\omega} \{ \sin \omega t - \sin \omega(t-\tau) \}$$

If we define $\tau_n$, the age for which the total mass above that age comprises a fraction $e^{-1}$ (the napierian time), then $\tau_n = \tau_0$, the turn-over time, for the stationary case, and $\tau_n = \tau_0^x$ for the quasi-stationary case, where $\tau_0^x$ is given by $\tau_0^x = N/Q(t)$.

It can be shown how closely $\tau_n$ approaches either $\tau_0$ or $\tau_0^x$, depending on the period of oscillations $T$ and on the relative amplitude, given by $Q_1/Q_0$.

In the following table the values of $T/\tau_0$ are given at different values of $Q_1/Q_0$ for which $\tau_n$ approaches within 10% the stationary flushing time $\tau_0$ or the quasi-stationary flushing time $\tau_0^x$.

<table>
<thead>
<tr>
<th>$Q_1/Q_0$</th>
<th>$\tau_n$ within 10% of $\tau_0$</th>
<th>$\tau_n$ within 10% of $\tau_0^x$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>$T/\tau_0 = 1.2$</td>
<td>$T/\tau_0 = 4.5$</td>
</tr>
<tr>
<td>0.5</td>
<td>0.6</td>
<td>7.2</td>
</tr>
<tr>
<td>0.7</td>
<td>0.5</td>
<td>11.0</td>
</tr>
</tbody>
</table>

Between the indicated values of $T/\tau_0$ one should expect a definite more complex behaviour of the reservoir than is given by the stationary or quasi-stationary approach.
3.12. The use of box models in estimating concentrations.

The above concepts are used for making simple so-called "box-models" for estimating concentrations of substances released in the sea (Groen and Schönfeld, 1961; National Radiological Protection Board and Commissariat à l'Energie Atomique, 1979).

Such models usually calculate fluxes of the tracer as given by (27), using concentration gradients at the boundary at r that are approximated by

$$\frac{3c}{3l} = \frac{c(r+l) - c(r-l)}{2l}$$

(35)

again with l the typical eddy size.

This gives in (27)

$$F_c = \frac{S}{2} \left( \frac{\bar{u}c(r) - \bar{K}c(r+l) - c(r-l)}{l} \right)$$

or

$$F_c = \frac{Q}{2\rho} c(r) - \frac{SK}{l} c(r+l) + \frac{SK}{l} c(r-l)$$

(36)

Usually one assumes the concentration in the reservoirs at either side of the boundary to be spatially uniform (well-mixed reservoir), and the concentration at the boundary to be the average between the two. So with two reservoirs 1 and 2

$$F_c = \frac{1}{2} \left( \frac{Q}{\rho} [c_1 + c_2] + \frac{SK}{l} [c_1 - c_2] \right)$$

(37)

(e.g. Groen and Schönfeld, 1961).

Here $c_1$ and $c_2$ are the concentrations in the boxes 1 and 2 respectively.

Alternatively, for boxes that are not well-mixed, we may introduce the mean concentrations $\bar{c}_1$ and $\bar{c}_2$ in both boxes. In the case that $c$ varies linearly along the axis of the series of boxes we may use, analogous to (37)

$$F_c = \frac{1}{2} \left( \frac{Q}{\rho} [\bar{c}_1 + \bar{c}_2] + \frac{SK}{l} [\bar{c}_1 - \bar{c}_2] \right)$$

(37A)
The exchange may be simulated by considering adjoining boxes with fluxes passing through the same boundary in opposite directions: $Q_{12}$ and $-Q_{21}$, whereas (for the well-mixed case)

$$\rho_F = Q_{12} c_1 - Q_{21} c_2$$

(38)

It follows that

$$Q_{12} = \frac{1}{2} (\rho E + Q) \quad \text{(39)}$$

$$Q_{21} = \frac{1}{2} (\rho E - Q)$$

Here $E = \frac{SK}{L}$

(40)

is called the "exchange factor". In the case that we consider mean concentrations for a linearly varying concentration distribution we have instead

$$E = \frac{SK}{L}$$

(40A)

$E$ is determined, $Q$ given, from the distribution of a conservative property (salt) and the condition that under stationary circumstances the net flux of the property in a reservoir should be zero (if there are no sources or sinks).

As comes already from the discussion in Ch. 10 the assumption of well-mixed reservoirs is strictly theoretically untenable. We may, however, consider the alternative approach, using mean concentrations and the relevant equations (37A) and (40A) as far as the relation between $T_o$ and $T_m$ is concerned.

One should note that the turn-over time is now not only determined by the net-flux $Q$ but also by the exchange. So,

$$T_o = \frac{M}{Q \cdot \rho E}$$

In the ideal situation of a rectangular reservoir with length $L$ and cross-sectional area $S$ we find

$$T_o = \frac{L}{U + K/L}$$
And with (24) we find

$$\tau_0 = T_m \left( \frac{1}{\bar{u}/L_{m}} \frac{1}{T_m} + \frac{1}{2} \right)$$

(41)

From this we find that, if $$\bar{L}/\bar{u}$$ (the turn-over time disregarding exchange) is much larger than $$T_m$$, $$\tau_0$$ is roughly twice $$T_m$$. In that case it may be allowed to use the well-mixed approach as a first approximation.

However, it has been pointed out by Svansson (1980) that the value of $$E$$ found in this way depends on reservoir size. Relation (24) now should determine the box size, together with the condition that $$L/\bar{u} >> T_m$$.

This brings us again to eq (26), be it that this condition now does not mean that the well-mixed situation occurs, but only that it is as closely as possible approximated.

Taking as a typical order of magnitude value of $$K$$ at the reservoir sizes $$10^5 - 10^6$$ m the range $$10^3 - 10^4$$ m$^2$/s (see e.g. Okubo, 1971) we find from this condition that

$$\bar{u} < 10^{-2}$$ m/s.

Usually residual current speeds are one order of magnitude higher, and well-mixed conditions are approximated only for much smaller values of $$L$$ at unchanged values of $$K$$. However, because of the scale-dependency of $$K$$ we may expect at smaller values of $$L$$ also smaller values of $$K$$.

Our conclusion therefore is that box models assuming well-mixed conditions within the boxes will often fail and are only applicable under special conditions. Figures resulting from such models at best give order of magnitude estimates of concentrations.
4. North Sea, General review

4.1. Introduction

In this section information is given on the hydrography of the North Sea as a whole, as a background to the various regional contributions and as a basis for the proposed subdivision. Various authors have published more or less extensive reviews on the North Sea hydrography: Lee and Ramster (1968), Lee (1970), Hill (1973) and Lee (1980). This chapter only gives the most essential information.

4.2. Dimensions

The boundaries of the North Sea as accepted for the purpose of this report are those defined by the International Hydrographic Bureau (1937). Roughly they are:

- **Channel boundary**: Narrowest part of the Straits of Dover.
- **Skagerrak boundary**: Line Hanstholm - Lindesnaes.
- **Atlantic Ocean boundary**: Line Scotland - Orkneys - Shetlands.
- **Norwegian Sea boundary**: Meridian of 0°53'W between Shetlands and 61°N, further along the 61° parallel to the Norwegian coast.

These boundaries are at some points different from those used by others and therefore the dimensions may differ from those published elsewhere. The most important point is that the often cited study by Kossinna (1921) includes the Skagerrak in the North Sea, while this is here considered as a separate sea area.

The dimensions of the North Sea within these boundaries were calculated by G. Becker on the basis of a 20 km grid, taking into account a reduction of the chart depths to mean sea level. They are:

- Surface area: 575,300 km²
- Volume: 40,3 km³
- Mean depth: 70 m

4.3. Sea level and total mass

The actual sea level varies around the mean value and accordingly the mass and volume of the sea are not constant. Rossiter (1967) has analysed the long-term sea level variations. They are far within the limits of accuracy we are aiming...
at. Meteorological effects cause annual and short-time variations. Wyrtki (1952) discussed these variations. Part of the sea level variation arises from temperature (density) variation and involves no change of mass. This density effect gives an annual sea level variation with an amplitude of about 2.5 cm (volume variation with amplitude of about 15 km$^3$). Annual variations in atmospheric pressure and wind are responsible for a sea level variation with an amplitude of about 10 cm (volume equivalent 50 km$^3$). The irregular month-to-month variations caused by meteorological (wind and pressure) effects are of the order of 100 km$^3$. Such variations in volume and/or mass are small compared with the accuracy at which we can establish fluxes into and out of the area. Also the density variations (for a typical salinity range 35$^0/00$ - 34$^0/00$ and temperature range 15 - 6°C approximately $+ 4^0/00$) are negligible.

4.4. Tides

The tides in the North Sea are fairly well known. For the purpose of this discussion we may refer to the atlas on the predominant semi-diurnal tides by Sager (1963).

The residence-time scales discussed here are orders of magnitude greater than the semi-diurnal and diurnal period, and long-periodic tides have small amplitudes.

Therefore the effect of the tides on our problem is primarily by mixing. However, the flux caused by the tidal Stokes drift may be important in connection with other fluxes. Various investigations have been made in connection with the theoretical and observational assessment of the Stokes drift (e.g. Dooley, 1974; Ramster and Durance, 1975). As other than tidal effects also contribute to the Stokes drift (Zimmerman, 1979) there are problems in the theoretical interpretation of such experiments. However, on the scales that are relevant here the tidal Stokes drift is believed to be dominant over the effect from temporary or local variability. This tidal Stokes drift can be assessed from the data on the vertical and horizontal tide.

4.5. Winter and Summer conditions

During winter the major part of the North Sea is vertically well-mixed or only slightly stratified. During summer the warming-up of the surface waters gives vertical stratification in large parts of the central and northern North Sea, except for areas where the small depths and strong tidal currents bring about sufficient turbulence to give a good vertical mixing, notwithstanding the advection of bouyancy at the surface. For this reason one has to discriminate between winter and summer conditions, even if the more elementary theory of residence times presupposes stationary conditions.
The stratification for various months is given in charts published by Tomczak and Goedecke (1964) and by Dietrich (1950). Seasonal variations in the circulation pattern and in the in- and outflow are furthermore to be noted. They are addressed in the various separate regional chapters.

4.6. Residual circulation

Because of the difficulty of obtaining residual current data before the introduction of feasible self-recording current meters, the early knowledge of the residual circulation of the North Sea had to be based upon observations from light vessels (not always in the best positions for this purpose and mainly concentrated along the coasts), upon short-period observations from anchored ships (giving less representative data because of the short duration of the observations) and on circumstantial evidence (drifter recoveries, water mass distribution).

The still often-mentioned residual current map of Böhnecke (1922) is based upon this type of data. It can be considered as the product of an intelligent combination of the various pieces of evidence, but certainly has its shortcomings. New representations have been made with the aid of mathematical models (see part 19), on newly available data sets from self-recording current meters (observational programmes of long duration, see Hill, 1971 and Ramster and Koltermann, 1976, or of a wide geographical coverage such as JONSOAP 73 and 76, see Ramster, Medler and Jones, 1976, and Riepma, 1980) or on a combination of the two methods.

4.7. Water types and water masses

Water types are bodies of water with fixed properties (in the deep ocean usually salinity and potential temperature), whereas water masses are bodies of water consisting of a mixture of two or more water types in varying proportions.

In shallow seas as the North Sea such concepts are difficult to apply. The temperature usually cannot be considered as a conservative property, and the other properties that are sometimes used to define water types or water masses are not always useful or appropriate for general application, either because they are not conservative (e.g. turbidity) or because data on such properties (e.g. "Yellow substance" or "natural fluorescence") are less commonly available.

Only the salinity remains as a (quasi-) conservative property on which sufficient data exist. The salinity distribution as given in the ICES atlas (Conseil perm. int. pour l'Explor. de la Mer, 1962) can be explained mainly on the basis of advection and mixing, although to a minor degree precipitation
and evaporation play a role (Schott, 1966).

However, one property is not sufficient for the discrimination between more than two water types. Nevertheless, subdivisions of the North Sea into different water masses or water types have been proposed. Well-known is that given by Laevastu (1963). This classification is rather general and only for the surface waters. The use of this classification as the basis for the description of plankton communities appears to be only partly successful (Fraser 1965, 1973).

Lee (1980), recognizing the above-mentioned arbitrariness, prefers a subdivision into six basic water masses (North Atlantic, Channel, Skagerrak, English, Coastal, Scottish Coastal and Continental Coastal) corresponding with Laevastu's water types of the same name, but considers the other water masses (Northern North Sea Water and Central North Sea Water) not as special categories but as mixtures of the others. He furthermore gives some figures on the typical temperature, nutrient and trace metal concentrations within these six basic water masses.

It should be mentioned that the extent of the various water masses varies considerably as is shown from figures produced by Rogalla et al. (1966) on the conditions in Spring and Autumn of 1960 and 1961.
4.8. Distinct boundaries

At some places boundaries between different bodies of water may be fairly well-defined. Depending on the regional variation of the factors depth and tidal stream velocity there may be marked frontal zones between stratified and unstratified waters with especially temperature differences between the surface waters on either side. Such thermal fronts have been identified on the basis of both infrared satellite data and direct in-situ observation by Pingree and Griffiths (1978) and Pingree, Halligan and Mardell (1978) for the North Sea.

They indicate the following fronts:
- South of the Shetland Isles and east of Orkney Isles, southwards to about 59°N.
- Flamborough Head Front, from Flamborough Head roughly eastwards to about 2°W, and perhaps continued eastwards to the German Bight.

Furthermore various authors identified in the German Bight the
- German Bight convergency zone, stretching from the Elbe estuary in a northwesterly direction to about 55°N (e.g. Goedecke, 1968, Becker and Prahm-Rodewald, 1980).

4.9. Movement of radioactive tracers

The movement of water marked by the radioactive isotope Cs137, discharged from plants near Cherbourg (Channel) and Windscale (Irish Sea) has been observed in the years 1971-1975 (Kautsky, 1973, 1976). These tracers enter the North Sea by the Straits of Dover and the Pentland Firth between Scotland and Orkney respectively. Their movement is in agreement with the generally accepted circulation pattern along the coasts in an anti-clockwise direction. Only after some delay does the tracer penetrate into the central parts (Kautsky, 1978).

4.10. Subdivision of the North Sea

The differences in the hydrographic conditions in the North Sea make a subdivision desirable. This is certainly also the case for the estimate of flushing times and other time scales. Such a subdivision therefore has been proposed by the Study Group, taking into account not only hydrographic conditions but also biological (section 5) information.

The subdivision should preferably not be too fine, because this would complicate the problem.

Because of the natural variability of the various hydrographical regions well-defined boundaries are seldom possible. Therefore a subdivision in $\frac{1}{4} \times 1$ degree (latitude x longitude) rectangles, as used in ICES for statistical studies, is thought the best suitable.
The proposed subdivision is given in Figure 2.1. (page 10)
The following properties characterise each area in qualitative terms:

Area 1  Slow-moving water mass of recent oceanic origin.
        Summer stratification.

2  Fairly rapid water movement of mixed oceanic-coastal waters.
    In summer only partly stratified.

3  Slow-moving southerly drift.
    Transient stratification.
    Fresh water content increasing southwards.

3'  Relative deep water (> 50 m).
3'' Relative shallow water (< 50 m).

4  Inflow of Channel water, mixed with coastal water.
    Strong horizontal gradients of salinity.
    Vertical stratifications only close to the coast.

5  Northward drift.
    Coastal water mass with some stratification.

6A  Surface layers:
    Northward movement of Norwegian coastal water and Baltic outflow.

6B  Deeper layers:
    Laterally inhomogeneous, with southerly flow in the west (water of recent oceanic origin) and northerly flow in the east (mixed water masses).

7  Water moving in variable directions, with slow net movements.
    Strongly developed summer thermocline.
    Central North Sea water mass.
    In summer two separate areas underneath the thermocline, north and south of the Dogger Bank. (The two areas indicated by 7' and 7'')
5. Biological Subdivisions of the North Sea (J.A. Adams)

5.1. Introduction

It is a generally held premise that the distribution of marine organisms is a function of the distribution of physical factors (Haedrich and Judkins, 1979) and many studies refer to similarities in the geographical variation of biological and hydrographic features. For example, Jones (1972) showed that subdivisions of the North Sea based on the results of fish tagging experiments were not inconsistent with subdivisions based on hydrographic and plankton data.

This section considers the biological subdivision of the North Sea with reference to the subdivisions (Figure 2.1) proposed by the Flushing Times Group, although, in addition to bearing in mind Fraser's (1965) cautionary notes about the compromises involved in drawing limits, it should be remembered that the biological characteristics used to differentiate one area from another are not necessarily of equal ecological importance.

5.2. The plankton communities

Although there are difficulties in attempting to classify the geographical distributions of plankton organisms (Smayda, 1958; Hart and Currie, 1960; Colebrook, Glover and Robinson, 1961; Glover, Cooper and Forsyth, 1961; Wimpenny, 1966) one may write in terms of species being (i) Arctic, boreal, warm temperate etc. (Figure 5.1), and (ii) neritic, intermediate or oceanic (Figure 5.2). Regarding Figure 5.1, many species are found in more than one zone. Briggs (1970) states that, over much of the North Atlantic, there are three basic distribution patterns: Arctic-boreal, eurythermic temperate and broad eurythermic tropical. Arctic-boreal species are those extending from the Arctic Basin to the southern limit of the boreal zone, eurythermic temperate species occur in both boreal and warm temperate zones, while eurythermic tropical species are tropical and sub-tropical species which range well into the warm temperate zone. However, it is likely that at least some wide-ranging distributions result from the composite distribution of a number of independent populations, a fact which is also relevant to some of the species with an intermediate type distribution in the series neritic to oceanic (Edinburgh, Oceanographic Laboratory, 1973 and the references therein).
For convenience the boreal or Arctic-boreal species may be referred to as "northern species", the eurythermic temperate and eurythermic tropical species as "southern species".

Dividing the North Sea into three main areas on the basis of depth (Figure 5.3), the plankton communities may be described as follows.

5.2.1. The offshore area of the northern North Sea

Neritic species are relatively scarce while intermediate species are abundant. Particularly notable are northern intermediate species, e.g. the chaetognath Sagitta elegans, the euphausiid Thysanoessa inermis and the copepod Calanus finmarchicus. In addition some southern intermediate species, e.g. the copepod Centropages typicus, Candacia armata and Metridia lucens are also found, particularly in the autumn. At about the same time a considerable variety of oceanic species arrive in the area, having been carried beyond their main area of distribution.

The offshore area of the northern North Sea may be considered as corresponding with that part of the North Sea which would be described as the "mixed water" (i.e. an admixture of oceanic and shelf water) region by some authors (e.g. Fraser, 1961) and of which Sagitta elegans is the classical indicator. On the other hand, Southward (1962) has claimed that it, and many "mixed water" forms, are cold water stenotherms whose distributions have little connection with the presence of "mixed water". However, whatever the factors controlling their distribution, Sagitta elegans and associated species form a rather distinctive community (albeit with some changes in the relative abundance of its species) extending from the northern North Sea via the west of the British Isles to the Celtic Sea. In the northern North Sea the western and southern extent of the main region of this community can often be traced by a marked decrease in the numerical dominance of Calanus (Figure 5.4). Nevertheless, various species of this community are often abundant in the Moray Firth and in the more northwesterly parts of the central North Sea.

This community can also be distinguished by its having a coastal Atlantic type of seasonal variation of its phytoplankton standing stock (Colebrook and Robinson, 1965) i.e. it shows a spring peak in May and a second, much smaller, peak in September although, since the initial increase starts about a month
later in the northern North Sea than off the west coast (between March and April rather than between February and March), the northern North Sea has a more oceanic type of cycle.

The offshore area of the northern North Sea can be readily identified with the combined Areas 1 and 2 of Figure 2.1. Some differentiation between Areas 1 and 2 becomes apparent when one considers the standing stock of phytoplankton in late spring. At that time a characteristic feature is the Fair Isle current where it appears that a greater degree of water column stability (see Dooley, 1976) and possibly lower zooplankton grazing, allows a higher phytoplankton standing stock to develop.

In addition, the fact that the Fair Isle current transports to Area 2 (and Area 3) species associated with the "mixed water" area to the west of Britain results in Area 2 having rather higher numbers of such species than does Area 1 while the latter area has the greater abundance of oceanic species (Fraser, 1965) which arrive in peak numbers via the Faroe-Shetland Channel and the north of Shetland in September (Fraser, 1968). It is interesting to note also that Colebrook (1963), in his study of the spatial variation in the annual fluctuations in the abundance of *Calanus finmarchicus*, found that the area between Shetland and the Moray Firth could be grouped with an area in the Atlantic to the west of Ireland and the United Kingdom whilst the rest of the northern and central North Sea could be grouped with the Norwegian Sea and the Faroes area.

5.2.2. The Moray Firth, central and southern North Sea

In this area of the North Sea, which is that of less than 100 m depth, numerous neritic species are abundant. Some, e.g. the cladoceran *Podon leuckarti* and the copepods *Centropages hamatus* and *Temora longicornis* are generally distributed. Others are more restricted in their distribution: for example, the copepods *Isias claviges* and *Labidocera wollastoni* to the area from the Dogger Bank southwards; the chetognath *Sagitta setosa* to the area south of a line from the Firth of Forth to Stavanger.

Intermediate species are also important with certain species more characteristic of the northern North Sea e.g. *Calanus finmarchicus* and *Sagitta elegans*, being found in reasonable numbers southwards to about the Dogger Bank and warmer water species, e.g. the cladoceran *Podon intermedius* and
Corycaeus anglicus extending to varying degrees over the area.

A few oceanic species arrive via the northern North Sea, their southward extent varying from year to year (Fraser, 1965) while some, e.g., the scyphozoan Pelagia noctiluca, are brought into the southern North Sea through the English Channel (Baan, 1967).

The hydrography of the central and southern North Sea appears to be of considerable importance in maintaining this areal overlap of neritic, northern intermediate, southern intermediate (and oceanic) species, although there is a certain degree of separation in terms of the times of peak abundance. Neritic species flourish in the fluctuating environment generally found in the more coastal areas; the southern intermediate species benefit during the summer from the warm waters of the whole water column of the southern North Sea (14-16°C) and the surface waters of the central North Sea (14-16°C); the northern species find suitable conditions in the colder, tidally mixed western area and in the sub-thermocline central North Sea. Indeed, depth by depth, the central North Sea is, below depths of 20 to 30 m, slightly colder during the summer than the northern North Sea (see Tomczak and Goedecke, 1962), and there is some evidence that the more southerly species in the central North Sea are mainly above the thermocline, the more northerly species below e.g. Fraser (1939). Furthermore, recruitment to the area, to whatever extent it may be necessary, can take place via the southerly water movements in the west and in the east and via the water movements through the English Channel.

The area considered in the previous four paragraphs covers Areas 3', 3'', 4, 5 and 7 of Figure 2.1 and various authors (for reviews see Russell, 1939 and Fraser, 1965) have described the different plankton communities which can be associated with the different water bodies. Their sub-divisions agree to a greater or lesser extent with those proposed for the study of flushing rates; for example the divisions used by Fraser (1965) correspond with the present divisions as follows;

Scottish coastal water — 3'
English coastal water — 3''
Channel water — 4 (offshore region)
Continental coastal water — 4 (inshore region) and 5
Central North Sea Water — 7
Fraser (1965) should be consulted for lists of the species which can be considered as typical of each, and the extent to which some boundaries can be very marked is illustrated by Evans (1973). Characterising the zooplankton of Northumberland coastal waters he states: "While there are numerous individual records from Northumberland of species normally limited to north-east Scotland, perhaps a hundred miles away, there are few or none of, for instance, Sagitta setosa, Isias clavipes and Labidocera wollastoni, all known from the Yorkshire coast less than fifty miles to the south".

The North Sea can also be subdivided on the basis of the extent to which wind-and-tide induced vertical mixing determines the availability of light energy and inorganic nutrients for phytoplankton production. For example one may distinguish, as did Steele (1958), between (a) the inshore waters where mixing is dominated by tide, and where there is a high total phytoplankton production spread evenly over the spring to autumn period but finishing fairly early; and (b) the offshore waters having a lower production with greater seasonal variation and, since mixing is mainly controlled by the occurrence of gales, the year to year production is much more variable.

More recently Pingree (eg Pingree et al., 1978) has, on theoretical consideration, charted for the northwest European shelf the predicted position of the frontal boundaries between well mixed and stratified (in summer) waters. Additionally he has shown a transitional zone about the frontal boundaries; in this zone periods of stability are interrupted by wind-induced mixing and increased tidal mixing at spring tides. Understandable, bearing in mind the criteria used to subdivide the North Sea for the present study, Areas 3′, 3′′, 4 and 5 are characterised by waters of the well mixed or transitional zone while Area 7 is largely stratified in the summer (Figure 5.5a). Also stratified in the summer are Areas 1 and 2 (dealt with in 5.2.1) and Area 6 (dealt with in 5.2.3).

Some examples of the differing seasonal cycles of the phytoplankton standing stock (as measured by the greenness of Continuous Plankton Recorder silks) at 10 m in 1° x 2° squares in the southern and central North Sea are shown in Figure 5.6. Squares LV and LW can be considered as characteristic of the stratified waters of Area 7; spring and autumn peaks contrast with a shorter or longer period in the middle of the year, when the supply of inorganic nutrients to the surface waters is largely prevented by the establishment of the thermocline.
At this time any concentrations of plant cells which do occur are likely to be at the thermocline and therefore not sampled by the Continuous Plankton Recorder. Squares NV, NW, OV and OW are representative of Areas 3‴ and 4 where well mixed or transitional zones are predicted by Pingree. Interestingly in the more southerly squares OV and OW, where the waters are largely well mixed throughout the year, the standing stocks show a general decrease from June onwards while in NV and NW the standing stocks remain relatively high until October or November. These differences support the suggestion by Pingree et al. (1978) that the transitional zones are the most productive regions during the summer months.

Further details regarding phytoplankton production and standing stocks in Area 4 are given by Gieskes and Kraay (1975, 1977a, 1977b) while Reynolds (1978) deals with the west central North Sea and Dooley (1976) with the fronts off Orkney and North East Scotland (Area 3‴).

5.2.3. The Norwegian Deeps

The Norwegian Deeps (or Trench) can be considered as a separate area in particular because of its greater depth where, below 100 m, a considerable body of water remains at less than 7°C throughout the year. Note should also be taken of (i) the presence of an inflow of oceanic water along its western boundary; and (ii) the low salinity, northward flowing, surface waters derived from the Baltic, the Southern Bight and the Norwegian fjords; a very early spring increase of phytoplankton is associated with these waters.

In addition to the more common North Sea species, one may encounter some Arctic species (e.g. the copepods Metridia longa and Calanus hyperboreus and the chaetognath Eukrohnia hamata) and those boreal species which appear to find most of the North Sea continental shelf too shallow (e.g. the copepod Heterorhabdus norvegicus and the adults of the euphausiid Meganyctiphanes norvegica).

5.3. Fish population

Above, in describing the plankton communities of the North Sea, frequent reference was made to the biogeographical zones (Figure 5.1) with which the various species could be associated and to whether or not they were neritic, oceanic or intermediate (Figure 5.2). The fish species may be described in a
similar way although in place of the terms neritic etc., one is more likely to refer to them as being shelf or oceanic species or to the depth zones in which a particular species is most abundant. In addition it is possible to distinguish, for a number of species (i) different areas in which particular stages of the life cycle eg spawning fish, juvenile fish, feeding adults, are most abundant; and (ii) different sub-stocks between which there is little exchange of individuals.

5.3.1. The offshore area of the northern North Sea. (Figure 5.3)

This area is particularly associated with high numbers of haddock, Norway pout and herring, the latter notably during its summer feeding migrations. All are boreal or Arctic-boreal species. Other northerly species e.g. witch, cod and saithe are found in reasonable numbers although the latter two have (at least in terms of the North Sea south of 61°N) their main centres of abundance outside this area.

Warm temperate species are also present, in particular (i) a sub-stock of whiting which extends from Shetland eastwards (Hislop and MacKenzie, 1976); (ii) the western stock of mackerel which moves into the area during the summer months and mixes with, (iii) the more northerly members of the North Sea mackerel stock.

It is difficult to decide on the extent to which Areas 1 and 2 may be differentiated on the basis of the fish populations, although Area 1 does tend to have larger populations of immediately post-larval 0-group gadoids than does Area 2. This is in spite of the fact that there is little difference in the abundance of eggs and larvae in the two areas (Figure 5.7). It is suggested that larvae hatched out in, or entrained into, the Fair Isle current which passes through Area 2 will be carried eastwards out of Area 2.

Of the offshore species, witch appears to have a centre of abundance in the southwest of Area 2 (Rae, 1970) while, of the more inshore species, sprat extends into Area 2.

5.3.2. The Moray Firth, central and southern North Sea

A large number of fish species are associated with this region, either permanently or at certain stages of their life.
Of the flatfishes the following examples may be associated with particular areas: sole and scaldfish (*Arnoglossus laterna*) with the Southern and German Bights; plaice with the waters from the Dogger Bank southwards and with certain inshore sandy grounds from Shetland southwards; lemon sole with the northwest from Shetland to Flamborough; dab and long rough dab (*Hippoglossoides platessoides*) with the central and southern North Sea. With the exception of the warm temperate sole and scaldfish, all are boreal or Arctic-boreal species.

Of the gadoids, cod and whiting are both generally distributed while saithe, which spawns along the edge of the continental shelf north of about 61°N, is very abundant as juveniles of up to two-three years of age in the very near shore areas from Shetland to northern England; haddock is present in reasonable numbers as far south as the Dogger, although this present southerly limit appears to be the result of a contraction and shift to the northwest of the haddock population during this century (Lundbeck, 1963; Sahrhage and Wagner, 1978). Further details regarding cod and whiting are of interest.

Cod spawns in the Southern and German Bights, at a number of places around (but not on) the Dogger Bank, off the northeast coast of England, at Ling Bank, Long Forties and the Moray Firth. Its nursery areas reflect, to a certain extent, the distribution of the spawning grounds but young fish are also very abundant in inshore regions from which, at least in the southern North Sea, spawning fish are completely absent.

Whiting is most abundant in the south-eastern North Sea, in the Moray Firth and its seaward area, and off the Northeast of England. Tagging, and the use of parasites as biological tags, shows that there is very little mixing between the whiting of the northern and southern parts of the North Sea (Hislop and MacKenzie, 1976).

Another abundant species is the boreal or arctic-boreal lesser sandeel (*Ammodytes marinus*), which is closely associated with the presence of suitable substrates of clean coarse sands, or fine gravel into which it burrows. It is found southwards and eastwards of the Dogger Bank, in the Ling Bank area, west and east of Shetland and in the Moray Firth (Smith Bank).

Of the commercially important pelagic fish, herring, sprat and mackerel are the most abundant. Herring have a number of spawning grounds along the
western margin of the area (at present the Orkney and Clyth Ness spawning grounds of the Buchan stock being by far the most important), nursery grounds in most of its coastal waters and the adjacent deeper water (in particular in the southeastern North Sea) and feeding grounds to the north and west of the Dogger. Sprat show less obvious difference in the distribution of the different stages of their life cycle and are found fairly generally in the area, while the North Sea stock of mackerel is generally most abundant in the central North Sea where it spawns in June-July. The 0-group occurs in the same but the I- and II-groups have a wider and more scattered distribution.

More southerly species - the pilchard and the horse mackerel - increase in abundance in the area during the spring and summer period. Pilchards move eastwards from the English Channel into the Southern Bight, where a spawning takes place in late spring and early summer, while horse mackerel also migrate eastwards from overwintering areas in the Channel. They spawn over the greater part of the southern North Sea from May to August but the peak density of eggs is encountered in the Southern Bight; a summer increase in the number of horse mackerel off the northeast of Scotland may be fish which have arrived from the west of Britain via the north. An influx via the north of Scotland and down the western side of the North Sea is definitely shown by the rather more exotic visitor, Ray's bream (*Brama brama*) (Wheeler and Blacker, 1972).

Bearing in mind the extensive distributions which have been described above for many species, it will be realised that some difficulties arise in attempting to characterise each of the five Areas into which the Moray Firth, central and southern North Sea region have been divided by the Flushing Times Group. Furthermore, the results of fish tagging experiments (Figure 5.8), although to a certain extent suggesting similar subdivisions to those used in this Report, emphasise that fish stocks of Areas 4 and 5 clearly extend into that part of Area 7' - 7" which lies south of the Dogger.

Nevertheless, bearing these limitations in mind, a listing of the more important fish populations in each of the five Areas is attempted in Appendix Table 1 (p.159). Unless otherwise stated, it can be assumed that all stages of the life cycles are well represented although seasonal migrations may take place.
Particular note will be taken of three species: blue whiting, mackerel and herring. However, numerous other species which are common in the shallower areas of the North Sea are also present, some of their Norwegian coastal populations probably being independent of the other North Sea populations (e.g. cod and haddock). In addition at least one Arctic species is very occasionally found (i.e. capelin, Mallotus villosus) while a southern species, the sea bream (Pagellus centrodontus), is abundant enough to appear in the fishery statistics. (Postuma, 1978). These extremes are a reflection of the varied environmental conditions that are found in Area 6 and already referred to on page 39.

Blue Whiting (Micromesistius poutassou) is a boreal oceanic species whose adult distribution can basically be described as a summer feeding area in the Norwegian Sea and a spring spawning area north and west of Britain. D-group fish are rather more widely distributed and are present in the northern North Sea, while a small concentration of adults is also found along the western edge of the Norwegian Deeps.

North Sea mackerel are particularly associated with the Norwegian Deeps as over-wintering adults in its deep waters. In early summer they appear in the upper waters for feeding and although some spawning takes place over the southern half of the Norwegian Deeps, many migrate to spawn in the central North Sea.

At least prior to 1970 large numbers of North Sea herring also moved to the Norwegian Deeps (and Skagerrak) for over-wintering and where, it was believed, they benefitted from the early spring plankton production (Steele, 1961). With the decline in the North Sea herring stock, few over-wintering herring are at present found in the area.

In preparing the section on the fish populations, frequent use has been made of the ICES Cooperative Research Reports No. 74 (1978) and No. 86 (1979). The reader is referred to these for further details and references. Furthermore it will be noted that, in general, only the English names have been used for the various fish species; the scientific names are as given by Holden (1978).
5.4. The benthic communities

Since the post-larvae and adult stages of benthic organisms are neither transported by water movements nor (with certain exceptions) involved in extensive wanderings, the distribution of some groups provides a better indication of the hydrographic conditions in a particular area than does the plankton (Holme, 1961; Golikov, 1968; Könnecker, 1977). However, in addition to factors associated with the overlying water, others such as depth, the nature of the substrate and biological interactions are also important, and one is able to recognise various groups of organisms that characteristically occur in particular habitats e.g. in offshore sand, in offshore mud, in deep mud etc. (Jones, 1950).

These groups are generally referred to as "communities" (for a review of the controversy that has surrounded the community concept see Mills, 1969) and for the North Sea and Danish inner waters twelve such communities were listed by Thorson in 1957 each being named after one or more of the characterising species. However, the distribution of the various benthic communities of the North Sea is not yet known in detail and for our present purposes it is perhaps more useful, in the first instance, to simply refer to the three "étages" which Glémarec (1973) has suggested can be used for grouping the communities (Figure 5.9). These are the "étage du large" or open sea étage, the "étage côtier" or coastal étage and the "étage infralittoral", and they basically reflect the varying ranges of temperature to which the various groups of communities are exposed.

In the following discussion the three main depth zones of the North Sea (Figure 5.3) are again dealt with in turn.

5.4.1. The offshore area of the northern North Sea

This area of the northern North Sea closely corresponds with that part of the open sea étage lying to the west of the Norwegian Deeps. Over much of the area a so-called "Foraminifera community", of which Saccammina spherica is the most characteristic species numerically, appears to be present. Among the associated metazoa, the polychaetes, mostly small thread-like species e.g. Paraonis gracilis oculata and Myriochele heeri, form the dominant group making up about 58% of the total weight, while the lamellibranchs, in
particular *Thyasira equalis*, are the only other group to make a significant contribution to the biomass (McIntyre, 1961).

It is not possible on the basis of our present knowledge to distinguish between Areas 1 and 2 (Figure 2.1).

5.4.2. The Moray Firth, central and southern North Sea

This area is occupied by the coastal and the infralittoral étages, the boundary between the two running along the northern slope of the Dogger Bank, a line of demarcation which is emphasised by Stephen (1933) on whose "natural faunistic divisions" Clémarec's chart of the étages of the North Sea is based, at least in terms of their geographical extent.

Although a number of detailed investigations of the benthic communities of these two étages have been carried out (see Clémarec, 1973 and McIntyre, 1978 for references), they tend to have been limited geographically. Thus, in attempting to consider the similarities between the subdivisions shown in Figure 2.1 for the areas of less than 100 m depth, and geographical variations in the benthos, it is more convenient to use the studies of the central North Sea echinoderms and lamellibranchs by Ursin and Petersen respectively.

Ursin (1960) provides eight charts (reproduced here as Figure 5.10) showing sketchy outlines of the distribution patterns of 46 species of echinoderms, patterns which he believes can be more closely related to distinct water masses than to temperature and which will be referred to below as "distribution types" 1 to 8. In terms of the present subdivisions, Area 3' can be associated in particular with those species having a distribution of type 1 and with the western North Sea part of distribution type 3. Taking both distribution types together, southern species account for 11 of the 20 species represented (see legend to Figure 5.10); this probably shows the influence in Area 3' of waters originating to the west and south of Britain. Area 3'' can be characterised by the general absence of species other than those of distribution types 7 and 8 (virtually all southern species) while Areas 4 and 5 have the same group of species with the number of species being lower in the more coastal waters.

The distinction between Areas 7' and 7'' is reflected in the occurrence of species of distribution types 4 and 5 north of the Dogger and in species
of distribution type 8 having more representatives south of the Dogger. However, it must be noted that species of distribution type 5 do extend into Area 7B east and west of the Dogger.

Petersen (1977), in describing the distribution of the lamellibranchs in the central North Sea, showed that they could be arranged in major groups associated with water masses, temperature and depth and emphasised a zonation parallel to the Dogger Bank (Figure 5.11). Again a number of similarities with the Areas proposed by the Flushing Times Group can be detected.

5.4.3. The Norwegian Deeps.

The Norwegian Deeps belong to the open sea étage. Characteristic communities are the *Maldane sarsi - Ophiura sarsi* community and the *Amphilepis norvegica - Pecten vitreus* community (Glémarec, 1973).

The North Sea distribution of two of the characterising species - the echinoderms *Amphilepis norvegica* and *Ophiura sarsi* - are shown by Ursin in his type 2 distribution (Figure 5.10). Their close association with the Norwegian Deeps area is clearly seen.

5.5. Conclusions

Hopefully the material discussed in this Section has shown that subdivisions of the North Sea based on hydrographical considerations are similar to those based on biological features. It is certain that the underlying uniting factor is the North Sea's pattern of depth distribution. Not only does this determine to a large extent the environmental conditions, which will be encountered by the plants and animals in the various areas, but it also influences the pattern of water movements be they wind-driven, tidal or otherwise.
Figure 5.1 Biogeographical zones of the North Atlantic and adjacent seas based on various sources but in particular Brown et al. (1975) for Canadian and Greenland waters, Wiborg (1955) for the Norwegian Sea, and Colebrook (1972) and Edinburgh, Oceanographic Laboratory (1973) for the area as a whole. The terminology used is that preferred by the present author.

The broken oblique hatching indicates the area where warm temperate plankters overlap extensively with boreal plankters.
Three basic types of distribution found for planktonic species in the North Atlantic and adjacent areas; neritic, intermediate, and oceanic. The intermediate and oceanic distributions can be further sub-divided e.g. northeast intermediate, southeast intermediate, northeast oceanic etc (see Colebrook, 1972, from whose charts this figure is derived, for further details). The rectilinear boundaries indicate the limits of the Continuous Plankton Recorder survey data used by Colebrook; the two sizes of circle can be considered as representing, within each type of distribution, lower and higher levels of abundance of the species while the absence of a circle indicates that the species are either normally absent or present only in low numbers.

The term "intermediate" would appear to be synonymous with the terms "open neritic" (Tokioka, 1979) and "distant neritic" (Beklemishev, 1971).
Figure 5.3 Three depth zones of the North Sea. The Norwegian Deeps is delineated by the 200 m depth contour, the offshore area of the northern North Sea by the 100 m depth contour.
Figure 5.4 (a) Calanus, as a percentage (by number) of the macrozooplankters in the northern North Sea in June 1965.

(b) The average abundance of Calanus copepodites I-IV in June during the period 1957 to 1967 as reported by Bainbridge and Forsyth (1972).
Figure 5.5 (a) Predicted distribution of waters which are stratified in summer

; well-mixed throughout the year ;

transitional (From Pingree et al., 1978).

(b) Location of the 1° x 2° areas referred to in Figure 5.6.
Figure 5.6 The seasonal variation of phytoplankton standing stock at 10 m (averaged for the period 1949-1960) in the six areas of the North Sea shown in Figure 5.5(b). The units are an arbitrary scale of greenness of Continuous Plankton Recorder silks. From Cushing (1967).
Figure 5.7 (a) Average distribution and abundance of haddock larvae (numbers per m$^2$) in April-May 1962-70. (b) Distribution and abundance of 0-group haddock (numbers per 1 hour trawl) in June-July 1974.
Figure 5.8 Diagrammatic chart of cod tagging results (R Jones, personal communication). Arrows indicate movements from areas of release. Similar results would be shown for haddock, whiting, plaice and lemon sole.
Figure 5.9 Limits of the various benthic étages as proposed by Glémarec (1973). Reproduced with permission of George Allen and Unwin.
Figure 5.10 Sketchy outline of distributional patterns of 46 species of echinoderms in the North Sea (Ursin, 1960). Areas with fewer species are shaded. For list of the species in each group the reader must refer to Ursin's original paper. The general geographical distributions of the species in each group can be summarised as follows:

<table>
<thead>
<tr>
<th>Type of distribution</th>
<th>Northern species</th>
<th>Southern species</th>
<th>Boreal species</th>
<th>Widely distributed species</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>8</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>4</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>-</td>
<td>3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>-</td>
<td>4</td>
<td>-</td>
<td>1</td>
</tr>
</tbody>
</table>

Ursin defines the terms used above thus: "The term 'boreal species' covers species not recorded more northerly than Iceland and not more southerly than the French Atlantic coast. 'Northern species' are also known from arctic waters. 'Southern species' are known south of the French Atlantic coast but not more northerly than Iceland. 'Widely distributed' are species occurring both north and south of the boreal region (Iceland-French Atlantic coast)."
Figure 5.11 The main types of lamellibranch distribution in the central North Sea as depicted by Petersen (1977).

A Species found in deep northern areas

B Species found north of the Dogger Bank

C Species occurring from the northern slope of the Dogger Bank to Hirtshals

D Species in the deeper water south of the Dogger Bank

E Species found on the top of the Dogger Bank and on the shallow southern areas

F Species found inshore
6. The use of Plankton Distributions for the Study of Residual Circulation
(J.A. Adams and D. Harding)

6.1. Introduction

Since plankton, by definition, is carried along by water movements, there was an early realization that the distribution of certain species might be used to help trace the movement of water masses (e.g. Russell, 1935), those species which were considered as being of particular value for this purpose being known as "indicator species". Examples are (i) certain oceanic species which arrive in the North Sea in the late summer and autumn of each year; (ii) shore animals' eggs and/or larvae, which, if found some distance offshore, are taken as indicating that inshore waters have contributed in some way to the waters offshore; (iii) the eggs and larvae of certain fish which have restricted and well-known spawning sites from which the subsequent drift of the eggs and larvae can be tracked.

In addition some species, rather than indicating water movements, indicate the presence of a particular water mass. For example, Fraser (1961) gives the chaetognath *Sagitta elegans* as a good indicator of the "mixed" water mass formed by the mixing of oceanic and coastal waters on the north west European shelf - but see page 62.

In this section the following topics are briefly considered:
(i) the arrival and distribution of oceanic species in the northern North Sea,
(ii) the measurement of the drift of plaice eggs and larvae in the Southern Bight by "patch tracking", and (iii) some reasons why plankton cannot always be used to indicate rates of water movements.

6.2. The arrival and distribution of oceanic species in the North Sea

The following account is based on Fraser (1968). In the late summer and autumn of each year, plankton species which have been carried northwards from the warmer oceanic areas to the west and south west of the British Isles appear in the northern North Sea. Peak numbers (in terms of average number of species) are usually observed about September-October, when various species which have been carried through the Faroe-Shetland Channel arrive via the north of Shetland, but an earlier small increase is seen in July as some arrive via the shelf area west of Orkney and the Orkney-Shetland Channel.
However, the timing of the arrival of peak numbers of oceanic species cannot be taken as indicating a peak inflow of oceanic water; it merely reflects the time taken for the organisms to be transported from the area south of approximately 54° N where they successfully overwinter. Fraser (1968) claimed that the oceanic species had moved northwards at a speed which agreed very well with Craig’s (1959) hydrographic assessment of 6-9 km per day although it should be noted that Craig’s figures refer to the movement of mixed oceanic and coastal water over the continental shelf rather than to the oceanic water beyond the shelf.

Nor must it be assumed that the numbers of oceanic species, or the abundance of the individual species, are necessarily a measure of the strength of the inflow of oceanic water since their abundance at their source and the extent to which they have been able to survive and reproduce in transit will also determine their abundance in the expatriate area. For example, the salp, Salpa fusiformis, which is one of the more tolerant species, may, if conditions are warm enough, increase 100-fold in 12 days while being carried towards the North Sea (Fraser, 1969). Nevertheless, that part of the North Sea that has 75 or more arbitrary units of oceanic zooplankton abundance (Figure 5.1) does correspond approximately with Area 1 (Figure 2.1) which is characterized as having water of recent oceanic origin, but it is surprising that the oceanic water flowing south along the western edge of the Norwegian Deeps is not more clearly indicated on the chart by high numbers of oceanic zooplankters. This may, however, be because the sampling intensity was inadequate in relation to the relatively narrow and deep oceanic current in this area.

6.3. Measuring the drift of plaice eggs and larvae in the Southern Bight by 'patch tracking'

Fish eggs and early larvae can be of particular value as indicators of water movements on a shorter time scale. Firstly, they are non-motile (or at least relatively so in the case of the early larvae) and cannot regulate their position by migrating vertically up and down in the water column (see page 63). Secondly, they pass through a number of developmental stages which can be readily differentiated morphologically. Thirdly (at least for the more common species), their rates of development in relation to temperature are known.
Simpson [1953] was the first person to, in effect, track, in a preliminary way, patches of plaice eggs in the Southern Bight of the North Sea. He described the drift of plaice eggs over two successive periods, i.e. between 12-16 February and 1-5 March and between 1-5 March and 20-22 March 1952. For the first time interval (Figure 6.2(a) and (b)) he distinguished between the area east of Lowestoft where a patch at 53°30'N 2°45'E indicated insignificant residual drift and the area to the north where an easterly water movement of about 60 miles in 17 days (equivalent to 7.6 cm sec⁻¹) was suggested. Further to the east the interpretation of the changes was less certain. During the second time interval (Figure 6.2(c) and (d)) a generally widespread north-northeasterly drift of at least 60 miles in 17 days was indicated. Simpson made no attempt to correlate these movements with hydrographic observations made at the same time since his aim was to show that, although the method had limitations, it could be used to estimate the drift of planktonic organisms.

Laevastu [1952], using some of Simpson's data for 1950, demonstrated that plaice eggs in the Southern Bight do not follow the turbulent diffusion formulae of Joseph and Sendner (1958) and Hela and Voiža (1960) in a quantitative way. He also pointed out that eddies of current close to the northwest boundary of the inflowing channel water (which occupies a central position in the Southern Bight) might be responsible for the aggregation of plaice eggs in patches and that the buoyant eggs were distributed through the water column, held in suspension by slowly sinking water in the centres of the clockwise eddies.

Beverton and Lee [1965] and Harding and Talbot [1973] demonstrated that the drift of plaice eggs and larvae in the Southern Bight could change dramatically from year to year as exemplified by distributions of eggs and larvae in 1962 and 1963. Eggs spawned in an average year such as 1962 usually reach the Dutch coast near Texel as metamorphosing larvae towards the end of their pelagic life. But in a cold winter such as occurred in 1963, when water temperatures were much lower than average, development of the eggs was delayed allowing them to drift further to the north east into the Heligoland Bight towards the nursery grounds in the German Wadden-Sea (Figure 6.3).

Ramster et al. [1973] considered the drift of plaice egg and larva patches in the eastern English Channel and showed that their model-predicted patch positions compared best with the actual positions when they used the mass transport of water through the Strait of Dover (Figure 6.4), as calculated from the daily mean flow implied by the changes in electrical potential induced by
the flow of tidal streams over the GPO telephone cable linking Dover with Calais. Their simple model has been extended to patches of eggs and larvae moving through the Southern Bight (Harding, unpublished), and was also linked to local winds.

Talbot (1977) has also shown that the GPO telephone cable records can be usefully applied to the determination of the water drift in the Southern Bight, and he showed good agreement between the residual flows calculated from the cable data and both the current meter records and displacement of a dye patch, provided that an allowance is made for the residual flows being a factor of 4.5 times greater at Dover than in the central Southern Bight. He also suggested that notable differences in the development of the plaice egg and larva distributions which have been observed between the two years 1962 and 1969 were mainly related to difference in residual flow through the Dover Strait. Later (1978) he considered this relationship for 1962, 1963, 1969 and 1971 and found that in the case of northeasterly flow the movement through the Dover Strait is approximately five times that of the eggs and larvae (Figure 6.5), a finding that is in substantial agreement with his earlier conclusions.

More recently Hill and Harding (1978) and Harding (unpublished) carried out patch tracking exercises in the Southern Bight in the early spring of 1978 and 1980 with the objective of linking the small-scale movements of patches of plaice eggs and larvae with residual drift deduced from moored current meters, a Rhodamine-B dye patch, local winds and a wind-driven model. The movements of a plaice egg patch in 1978 are illustrated (Figure 6.6), and the table below compares the distances and directions of movement of the egg patch and the associated water mass, derived respectively from successive plankton surveys and moored current meters. The rate of drift was 31.5 miles in 13.3 days

<table>
<thead>
<tr>
<th>Grid</th>
<th>Mid-date</th>
<th>Inter-grid period days</th>
<th>Drift of egg patch n miles/ direction</th>
<th>Current meter residuals n-miles/ direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2 Feb</td>
<td>4.3</td>
<td>3.37 28°</td>
<td>2.70 34°</td>
</tr>
<tr>
<td>2</td>
<td>6 Feb</td>
<td>3.5</td>
<td>0.97 38°</td>
<td>1.12 41°</td>
</tr>
<tr>
<td>3</td>
<td>10 Feb</td>
<td>5.5</td>
<td>2.47 41°</td>
<td>1.31 25°</td>
</tr>
<tr>
<td>4</td>
<td>15 Feb</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>13.3</td>
<td>2.37 35°</td>
<td>1.82 31°</td>
</tr>
</tbody>
</table>
(equivalent to 5 cm sec\(^{-1}\)) towards 35°, while the current meters deployed in the same area of sea gave an average rate of drift of 3.9 cm sec\(^{-1}\) towards 31°.

6.4. A cautionary note on the use of plankton drift as an indicator of water movements.

The relatively satisfactory agreement between the drift of patches of plaice eggs and young larvae and water movements described above largely stems from (i) the non-motile nature of the eggs and the relatively non-motile young larvae and (ii) the shallowness of the area. However, zooplankters (and some phytoplankters) are not as much at the mercy of the water movements as their name (taken from a Greek word meaning "that which is made to wander or drift" (Hardy, 1956)) might imply. It is well known that estuarine zooplankton maintain themselves in an estuary by migrating vertically between the landward flowing bottom waters and the seaward flowing surface waters. Furthermore, Hardy (1953) has discussed how vertical migration in effect gives "each tiny creature... ten-league boots to set it striding through the sea", and Dooley (1977) has developed these ideas of Hardy and those of Riley (1976) to demonstrate that the diel vertical migration of zooplankters in the western North Sea could interact with the phase of the tide and its vertical shear in such a way that horizontal movements of the plankton in excess of 100 km per month could take place independently of any residual water movements. Similar calculations have been made by Dippner (1980).

Additionally, Hamner and Hauri (1981) claim that it is "certainly tenable to suppose" that, for certain long-lived planktonic species, marked seasonal horizontal differences in their distribution patterns "are generated behaviourally via directed horizontal migration rather than simply via transport by regularly recurring oceanic or coastal water movement".
Figure 6.1 The levels of abundance of oceanic zooplankton in the North Sea. The chart is based on Scottish data obtained during 1920 to 1963 and the scale is an arbitrary one. For further details see Fraser (1965).
The drift of plaice egg patches in the Southern Bight of the North Sea in 1952: (a) stage 1 eggs, 12-16 February; (b) stage 5 eggs, 1-5 March, derived from stage 1 eggs on 12-16 February; (c) stage 1 eggs, 1-5 March; (d) stage 5 eggs, 20-22 March, derived from stage 1 eggs on 1-5 March. Arrows indicate direction of drift, + indicates the centres of high concentrations of stage 1 eggs. Diagrams based on those given by Simpson (1953).
Figure 6.3 Larval drift in the Southern Bight of the North Sea in 1962 and 1963. The arrows indicate the direction of drift in a normal year, 1962, and in the cold winter of 1963, when drift took the larvae further to the north-east and into the German Bight.
<table>
<thead>
<tr>
<th>Key</th>
<th>A: 1st sighting of patch</th>
<th>B: Re-sighting.</th>
<th>C: Days elapsed between sightings</th>
<th>D: Position after maximum model displacement</th>
</tr>
</thead>
</table>

Patch 1: A = 1st sighting of patch; B = Re-sighting.

A comparison of the movements of plaice eggs and larvae on successive cruises in the eastern English Channel and Southern Bight of the North Sea observed during surveys in 1971. The minimum model displacement was given by the assumption that water moved en masse through the area, the volume of water passing any cross-section line being the same as the volume passing the Strait, and the velocity at any point on a given cross-section was the same as at any other. The maximum model displacement was given by the assumption that the central part of the Channel and southern North Sea behaved as a discrete 'pipe' of the same cross-sectional area as the Strait. From Ramster et al., (1973).
Figure 6.5 Movements of patches of plaice eggs and larvae in the centre of the Southern Bight compared with the flow of water through the Strait of Dover. From Talbot (1978).
Figure 6.6 A patch of developing eggs of the plaice on successive cruises in the Southern Bight of the North Sea, 2 - 15 February 1978. From Hill and Harding (1978).
7. Orkney - Shetland Inflow. (H.D. Dooley)

7.1. Introduction

Area 2 of the Flushing Time chart is the region of inflow of mixed Coastal/Atlantic waters. The existence of this flow was first noted by Smed (1947) and this was supported later by Fraser (1949) and Craig (1952), who provided plankton and hydrographic evidence for its existence.

The first direct positive evidence for the existence of this flow came from current measurements made east of Orkney in September 1969 (Dooley, 1974). At this time south-going residual current speeds of up to 30 cm/sec were measured over a fairly small area associated with the salinity gradient between coastal and offshore water. Because of the relative scarcity of data it is, however, not possible to make further general statements regarding the current's characteristics.

7.2. Time variations of flow

Residual currents within the Orkney - Shetland inflow have been measured on ten occasions for periods up to 1 month since 1969. Thus very little is known about seasonal and shorter period fluctuations in its speed. Wind clearly plays some part in causing short-period fluctuations, most notably westerly winds which have been observed to significantly increase its strength. JONSDAP 76 measurements in March-April of 1976 provide some information to suggest that at this time of year the inflow is weak (or diffuse) but other measurements in May, July, August, September and November suggest that a well developed flow is present at these times. Long period mean currents do, however, appear to be very constant with near surface currents of 10-15 cm/sec being measured east of Orkney in most years. An exception was 1977 when near surface currents of only 5 cm/sec were measured with negligible near bottom (residual) currents.

7.3. Spatial variations in flow

In summer the track of the current is known to approximately follow the southern and western boundaries of Area 2 which is also the 100 m contour. Its extent offshore is determined by the location of the cold deep bottom waters of the central northern North Sea in Area 1 and consequently the position of the current does not alter much. JONSDAP 76 suggests, however, that the current path is less clearly defined in late winter/early spring, especially in the western part of the area. There is no information which can elucidate its progress into the North Sea at this time.
The known composition of the current shows considerable lateral variation in its structure. Measurements during July 1979 east of Orkney demonstrated little change in the surface flow across the width of the current, but near the bottom strong flows were present only near the core of the current. Thus the current is typified by a high transport barotropic core but becomes baroclinic towards its eastern and western extremities. In the central North Sea where the current dissects the central North Sea water masses, current during May 1973 decreased with depth on the northern edge of the flow and increased with depth near its southern edge.

7.4. Estimates of net flow.

Typical salinities in the area of inflow vary from 34.7°/oo west of Orkney to 35.1°/oo east of Orkney and 34.9°/oo in the central North Sea. Thus it is likely that the current is undergoing considerable mixing and entrainment during its passage through the North Sea. Rough estimates based on observations in 1973 and 1974 suggest that the volume transport is doubling between west and east Orkney and doubling again between east Orkney and the central North Sea. These estimates were obtained by means of combining geostrophic calculations with observed current measurements.

East of Orkney in August 1974 volume transports ranging from 0.1 to 0.8 \times 10^6 \text{ m}^3/\text{sec} were measured in a 3 week period with an overall mean of 0.3 \times 10^6 \text{ m}^3/\text{sec}. This figure agrees with Dooley (1974) and also Craig (1952) who computed transport values from freshwater fraction arguments. Because of entrainment and mixing it is possible that the transport of this current from Area 2 to Area 6 will be at least 0.6 \times 10^6 \text{ m}^3/\text{sec} and it is this figure that must be considered when computing the water mass balance of the Norwegian Channel.

An additional flux, passing along the Scottish - English coast should be assumed to cope with the water transport through that region. This additional flux is assumed to be only a minor fraction of the flux passing through box 2. A value of 0.03 \times 10^6 \text{ m}^3/\text{s} is estimated.

7.5. Tides

Spring Tidal - Currents in Area 2 range from a very fast 200 cm/sec near Fair Isle to a mere 30 cm/sec in the central North Sea. This distribution of currents is reflected in the vertical water mass structure, the water remaining vertically well mixed throughout the year near Fair Isle but in the centre of the area a well marked (> 7°C) thermocline develops in the summer.
8. Norwegian Trench Inflow - Outflow (G. Furness and M. Mork)

8.1. Some characteristics of the area

Box 6 covers the Norwegian trench inclusive the slope areas on its western side from 61°00' N and southwards to the entrance of Skagerrak. A typical section across the trench as obtained at 59°20'N is shown below. The cross-sectional area here is 26 km² of which 18 km² is occupied by the Norwegian trench current and 8 km² by the opposite-directed slope current.

Figure 7.1
The surface area is 61,600 km² and the volume 13,800 km³. The mean depth is, hence, 192 m. In the vicinity of 59°N there is a saddle point with increasing depths towards the south into Skagerrak and towards the north into the Norwegian Sea. From bathymetric charts published by the Norwegian Hydrographic Office the following depth distribution is found:

<table>
<thead>
<tr>
<th>depths over</th>
<th>percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 m</td>
<td>100</td>
</tr>
<tr>
<td>100 m</td>
<td>75</td>
</tr>
<tr>
<td>160 m</td>
<td>57</td>
</tr>
<tr>
<td>200 m</td>
<td>52</td>
</tr>
<tr>
<td>250 m</td>
<td>42</td>
</tr>
<tr>
<td>300 m</td>
<td>15</td>
</tr>
<tr>
<td>350 m</td>
<td>2</td>
</tr>
<tr>
<td>400 m</td>
<td>1/4</td>
</tr>
<tr>
<td>450 m</td>
<td>0</td>
</tr>
</tbody>
</table>

8.2. Hydrography.

The water masses in box 6 are characterized by the fresh water content and the baroclinic structure throughout the year. The main fresh water sources stem from terrestrial run-off to the Baltic Sea, to the southern part of the North Sea and from the Norwegian coast. The surplus of fresh water from the Baltic Sea is approximately 450 km³/year which accounts for about half the estimated fresh water transport of the Norwegian Coastal Current. The salinity range in coastal waters is 32 o/oo - 35.3 o/oo. Isohalines and isopycnals slope down towards the coast and intersect the sea surface at a distance from the coast. The boundary between coastal water and Atlantic water may at times be characterized as a salinity or density front. In certain seasons, mainly early spring or late summer, when there are substantial temperature differences between the two water masses, the isotherms also depict the same frontal structure. The width and depth of the coastal wedge vary through the year. The wedge is narrow and deep in February, when the static stability is least, and wide and thin in July/August, when the light coastal top layer spreads out laterally and overlayers the denser Atlantic water. The transition region is subjected to wave motion on several scales, to interleaving, and to mixing.
8.3. Tides

The dominant tidal constituent in the area is the semidiurnal $M_2$ at 12.42 hours, but other semidiurnal constituents, for example $S_2$ and $K_2$, also have significant amplitudes. The tidal elevation is very small in the southern part, where an amphidromic point is assumed to be found, but increases northwards along the coast. The tidal ellipses at the sea surface rotate in a clockwise direction. The major axis of the ellipse in this area is oriented in a north-south direction. The tidal velocities are of order 10 cm/s. Both the major and minor axis of the $M_2$ tidal current ellipse usually decrease with depth. However, close to the coast the minor axis has been found to increase with depth close to the sea bed. Near the coast the ellipses also change sense of rotation between sea surface and sea bed. The tide-induced residuals in the Norwegian trench are expected to be small, of order 2-3 cm/s. A further discussion of the tidal currents in the North Sea, based upon observed and computed $M_2$ tidal currents, is given by Davies and Furness (1970).

8.4. Estimates of flow

The flow budget of box 6 is based, to a great extent, on information obtained from current measurements and numerical modelling in connection with the JONSDAP 76 experiment. Information from long series of hydrographical observations as well as other current measurements have also been taken into account.

The flow in and close to the Norwegian trench is found to be highly variable, both in time and space. The most pronounced time-variations can, to a high degree, be related to the windfield over the North Sea. Another important feature is that the trench flow is coupled to the south-flowing slope/edge current inasmuch as time-variations in the one are associated with corresponding but opposing variations in the other. This indicates that the water which leaves the trench is to some extent replaced by the slope/edge water.

In spite of the fact that the variability can often be much greater than the mean value and that the mean value possibly can be of rare occurrence, we will in the following try to give some estimates of the flow in and out of box 6.
The main inflow comes from the northern North Sea through two sources, which are easily distinguished by their different salinity. The slope current, which transports the most saline water, is a branch of the North Atlantic Current system which turns south into the Norwegian trench at the Tampen plateau. When it enters box 6 the flow is estimated to be $0.7 \times 10^6 \text{ m}^3/\text{s}$. The shelf water also originates from the North Atlantic Current but has passed across the north-west shelf area with considerable mixing with less saline water. The main branch of this current system presumably crosses the North Sea via box 2. The input from this northern North Sea water to box 6 is estimated to be $0.7 \times 10^6 \text{ m}^3/\text{s}$ from box 2 and $0.3 \times 10^6 \text{ m}^3/\text{s}$ from box 1. The exchange between box 6 and Skagerrak gives as a result a net inflow to box 6 of $0.2 \times 10^6 \text{ m}^3/\text{s}$ which is the contribution from the southern part of the North Sea, via the Jutland Current and the surplus of fresh water from the Baltic. The exchange between box 6 and Skagerrak is, however, dominated by the trench flows, of opposite directions and the Norwegian Coastal Current is at the entrance of box 6 estimated to be $10^6 \text{ m}^3/\text{s}$. The coastal current increases in magnitude along its path and the flux at the exit of box 6 is $1.8 \times 10^6 \text{ m}^3/\text{s}$.

As a summary we have the following water budget for box 6.

**Inflow:**
- Trench flow along the western slope: $0.7 \times 10^6 \text{ m}^3/\text{s}$
- Shelf contribution from box 1 and box 2: $0.9 \times 10^6 \text{ m}^3/\text{s}$
- Coastal current - Skagerrak: $1 \times 10^6 \text{ m}^3/\text{s}$

**Outflow:**
- Coastal current at Northern boundary: $1.8 \times 10^6 \text{ m}^3/\text{s}$
- Trenchflow into Skagerrak: $0.8 \times 10^6 \text{ m}^3/\text{s}$

**Turn-over time**

\[
\frac{11843 \times 10^9 \text{ m}^3}{2.6 \times 10^6 \text{ m}^3/\text{s}} = 53 \text{ days.}
\]

9.1. Characteristic dimensions

The characteristic dimensions of the Straits of Dover are (Sager and Adam, 1969) for the section South Foreland-Cap Gris Nez.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width</td>
<td>33 km</td>
</tr>
<tr>
<td>Cross-sectional area (with respect to local datum plane)</td>
<td>$1.26 \text{ km}^2$</td>
</tr>
<tr>
<td>Cross-sectional area (with respect to mean sea level)</td>
<td>$1.37 \text{ km}^2$</td>
</tr>
<tr>
<td>Maximum depth (with respect to local datum plane)</td>
<td>61 m</td>
</tr>
<tr>
<td>Mean depth (with respect to local datum plane)</td>
<td>38 m</td>
</tr>
<tr>
<td>Mean depth (with respect to mean sea level)</td>
<td>42 m</td>
</tr>
</tbody>
</table>

A detailed profile of this section is given by Van Veen (1938).

According to Van Veen (1936).

9.2. Tides.

The tides in the area are strong. Not only the M2 tidal constituent but also other semi-diurnal constituents ($S_2$, $M_2$, $K_2$) have significant amplitudes.

In Table 9.1 some figures for the vertical tide are given, as well as for the total flow through the Straits as given by Prandle and Harrison, 1975 (Table 4 of that publication).

Tidal charts of the area are given by Van Veen (1936), Sager (1968).

A rough estimate can be made of the Stokes drift, $S$, through the Straits using the relation

$$ S = h x u x \cos (\phi_h - \phi_u) x L $$

where $h$ and $u$ are the amplitudes of the vertical and horizontal tide respectively, $\phi_h$ and $\phi_u$ are the corresponding phases and $L$ is the width of the Straits.

Using (in accordance with the figures of Table 9.1 for $M_2$)

- $h = 2.23 \text{ m}$
- $u = 1.00 \text{ m/s}$
- $\phi_h = 330^0$
- $\phi_u = 0^0$
- $L = 33 \times 10^3 \text{ m}$

we find

$$ S = 33 \times 10^3 \text{ m}^3/\text{s} $$
### Table 9.1
Comparison of the tidal constituents of cable voltage with the constituents for computed and recorded flows

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Cable Voltage</th>
<th>Q</th>
<th>Velocity</th>
<th>Tide at Dover</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10^{-4} V</td>
<td>10^{-3} V</td>
<td>10^{-4} V</td>
<td>10^{-3} V cm</td>
</tr>
<tr>
<td>Mean</td>
<td>-22</td>
<td>200</td>
<td>4</td>
<td>-1</td>
</tr>
<tr>
<td>Q</td>
<td>81</td>
<td>30</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>L</td>
<td>15</td>
<td>66</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>N2</td>
<td>123</td>
<td>27</td>
<td>20</td>
<td>11</td>
</tr>
<tr>
<td>V</td>
<td>39</td>
<td>3</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>M2</td>
<td>720</td>
<td>29</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>M2</td>
<td>262</td>
<td>15</td>
<td>14</td>
<td>7</td>
</tr>
<tr>
<td>M4</td>
<td>34</td>
<td>8</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>M6</td>
<td>12</td>
<td>4</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

Results 1, 4 and 6 — present study; 2 — Cartwright [1961]; 3 — Bowden [1956]; 6 — Veen [1938]; 7 — Doodson [1930]

### 8.3. Estimates of the net flow

The net flow has been estimated by various authors. A summary is given in table 9.2

<table>
<thead>
<tr>
<th>nr.</th>
<th>author</th>
<th>mean flow</th>
<th>method</th>
<th>remarks</th>
<th>period</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Gehrke, 1907</td>
<td>2.0x10^3</td>
<td>64x10^3</td>
<td>from published current charts</td>
<td>excluding Stokes drift</td>
</tr>
<tr>
<td>2.</td>
<td>Carruthers, 1935</td>
<td>2.7x10^3</td>
<td>85x10^3</td>
<td>from average residual current at Varne L.V.</td>
<td>excluding Stokes drift</td>
</tr>
<tr>
<td>2A.</td>
<td>Carruthers (corrected)</td>
<td>3.5x10^3</td>
<td>118x10^3</td>
<td>estimated Stokes drift added to (2)</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>Van Veen, 1936, 1938</td>
<td>1.8x10^3</td>
<td>56x10^3</td>
<td>tidal average of flow, various stations, corrected for annual variation</td>
<td>including Stokes drift, short period calm weather</td>
</tr>
<tr>
<td>4.</td>
<td>Cartwright, 1961</td>
<td>7.4x10^3</td>
<td>238x10^3</td>
<td>telephone cable data, tidal calibr. factor used</td>
<td>less representative years?</td>
</tr>
<tr>
<td>6.</td>
<td>Alcock and Cartwright, 1977</td>
<td>5.3x10^3</td>
<td>168x10^3</td>
<td>telephone cable data, tidal calibr. factor used</td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>Prandle, 1978B</td>
<td>4.9x10^3</td>
<td>155x10^3</td>
<td>numerical model S. North Sea (Prandle, 1975)</td>
<td>model boundary across Straits</td>
</tr>
<tr>
<td>8.</td>
<td>Meier-Reiffer, 1979</td>
<td>4.0x10^3</td>
<td>130x10^3</td>
<td>numerical model S. North Sea</td>
<td></td>
</tr>
</tbody>
</table>
9.4. Discussion of the flow estimates

The estimates given in Table 9.2 fall into three groups:

1) Based upon current measurements (1, 2, 3).
2) Based upon telephone cable measurements (4, 5, 6).
3) Based upon numerical models (7, 8).

The estimates are not completely independent: cable measurements rely on calibrations from direct current measurements, and numerical models may have been trimmed in such a way that their results are in good agreement with observations.

The first group is less reliable because the estimates are based upon only one regular series of observations (2) or upon a short period only (3). Apart from that, (2) does not include Stokes drift, but for that one may apply a correction (2A).

The cable measurements are dependent on the choice of the calibration factor. There is still uncertainty with respect to this factor. Most estimates (4, 6) use a calibration factor of about 0.7 V/ms\(^{-1}\) (Bowden, 1956; Cartwright, 1961). Prandle and Harrison (1975) obtained a different factor, resulting in reduced estimates (5), but arguments have been given (Ramster, Griffiths and Prandle, 1978) that this calibration factor should be used with caution. In addition, Robinson (1977) in a theoretical investigation concludes that for tidally induced residuals (according to Prandle, 1978 A, responsible for about half the total flow) the application of the principal (semi-diurnal) calibration factor might lead to significant underestimation. So for the time being the estimates from cable measurements remain questionable.

The third group depends on the choice of the modelling parameters and the boundary conditions. For the present discussion there is an advantage in the approach of Prandle (1978 A) who considers the flow as the superposition of the tidal residual (including Stokes transport), the residual due to wind forcing and residuals due to sea-surface gradients or density gradients (the latter relatively negligible). In the following these different contributions are considered in turn.

Leaving out the wind forcing, we find a value of 123 x 10\(^3\) m\(^3\)/s. Subtracting the Stokes transport (estimated value 33 x 10\(^3\) m\(^3\)/s) and dividing by the cross-sectional area (1.37 km\(^2\)) we may find a cross-sectional mean value of the so-called "basic current" or "residual current at calms". The value thus obtained (6\(\frac{1}{2}\) cm/s) is somewhat higher than estimates from current measurements at the Varne L.V. by Lawford and Veley (1955): 2.4 - 4.1 cm/s or by Veley (1960): 3.2 cm/s. As there are other indications (see later)
that the residual flow mainly follows the deeper channels, this difference can readily be explained. However, assuming for a while that there is really an overestimate of this value by Prandle, we have to reduce his estimate by about \( \frac{3.3}{0.5} \) (123 - 33) \( 10^3 \) m\(^3\)/s or 45.\( 10^3 \) m\(^3\)/s.

The wind effect as found by Prandle closely corresponds with the results obtained from an analysis for the observed flow by Bowden (1956). In a similar numerical study of the wind effect on the flow through the Straits by Oerlemans (1978) the wind direction for maximum transport is found to differ 16° with the results of Prandle and the transport for the same wind speed is 1.0 - 1.3 times higher in the results of Oerlemans. The difference may be mainly caused by different boundary conditions.

Supposing for a while that the results of Oerlemans are more applicable, this would result in a wind-effect that certainly is less than 1.3 times the value of Prandle, in view of the compensating effect of opposing winds, or less than + 11 \( 10^3 \) m\(^3\)/s.

A similar analysis of the estimate of Maier-Reimer (1978) is not possible because his model is not linearized. However, in an earlier study (Maier-Reimer, 1977) the effect of a mean stress field and the tide on the estimate is unlikely low (20.\( 10^3 \) m\(^3\)/s). Although in the later study considered, here the introduction of a surface slope of 10 cm over the North Sea gives the better matching estimate nr. (8). It remains remarkable that this change makes so much difference, since Prandle's linear model indicates a contribution of only a quarter of the total flow. As a reason for this discrepancy one might think of the wind-stress field applied (obtained from the annual mean wind field squared) and the rather unfavourable position of the model boundary: across the Dover Straits.

In a study of Fedorov (1967) this author relates the changes in the flow to salinity changes, using a salinity balance equation. An attempt to apply this method as a means to discriminate between the different estimates does not lead to conclusive results. Apparently the underlying assumptions do not allow a detailed analysis.

Concluding, one may state that presently the estimate given by Prandle (1978 B) finds support in the comparison with other studies and may be close enough to be used as the best estimate available. However, as margins of uncertainty one might use the possible corrections discussed above and resulting in \( 10^3 \) m\(^3\)/s.

Tidal residuals and sea-surface slope - (0 - 45)?
Wind forcing - (0 - 11)?

So the range around Prandle's result might be
\[ 110 \times 10^3 \text{ m}^3/\text{s} - 166 \times 10^3 \text{ m}^3/\text{s}. \]
9.5. Cross-sectional differences in the flow

The flow is not equally distributed over the cross-section. Residual current calculations by Cartwright (1961) show some differences, but one might especially consider the work of Cartwright and Crease (1963) who concluded from their analysis of cable voltages as related to sea-surface slopes that the residual current is mainly concentrated in the deeper channels.

Also, the presence of ebb- and flood-channels in the Goodwin Sands (Cloet, 1954) and the Flemish Banks (Van Veen, 1936) indicates relatively small-scale differences in the residual flow across the Straits.

9.6. Water properties and water masses

The inflowing water is usually indicated as "Channel water" and has a relatively high salinity. It is mainly of Atlantic origin, but somewhat diluted by fresh water from S. England and the Continent. Cross-sectional differences in salinity are indicated in the charts, but documentation on the detailed distribution is scarce. From data presented by Lumby (1935) one can conclude that the most diluted water is found along the eastern border, with salinities some 0.3 - 0.5 °/oo below the maximum.

9.7. Time variations of the residual flow

The residual flow may be subject to a fortnightly modulation (spring-neap tide cycle). The fortnightly period in the cable measurements is attributed to a non-linear response and not to current variations by Alcock and Cartwright (1977), but nevertheless the fortnightly periodicity clearly shows in the currents as recorded by Carruthers, Lawford and Veley (1950).

Wind effects may give significant irregular variations. According to Prandle (1978 A) 15 knots winds from NE cause a reverse of the direction of the flow.

Winds speeds higher than 15 knots (5 Beaufort and more) from the NE do occur at the L.V. Noordhinder (Verploegh, 1958) with a frequency of about 2%, winds with equivalent speeds from N and E have together a frequency of about 3½%, thus together 5½% of the cases. Although this cannot directly be related to the frequency of reversals (this also depends on the persistency), it roughly indicates an order of magnitude.

The monthly means still show a considerable variation (Prandle, 1978 B), with a standard deviation between 1/2 to 1/3 of the mean value. Statistics of the monthly mean current at Varne over about 6 years (75 individual months) (Carruthers, 1935) show directions between N and E with a few
exceptions, and speeds in the range 4 to 10 cm/s in two thirds (50) of the months.

The annual mean values given by Prandle are fairly constant (standard deviation about 15%). The annual mean values of current at Verne confirm this point (Carruthers, 1935). However, Dickson (1970) describes anomalies in salinities which might be (partly) the result of variations in the flow. As these variations have very long periods (3 - 5 years) and appear to be related to variations in the meteorological conditions over the North Atlantic, they might be the result of long-periodic variations in the sea-surface gradient (which is taken constant in Prandle's estimates).
10. The Skagerrak (A. Svansson)

The Skagerrak is sometimes included in the North Sea (North Sea = North Sea Proper + Skagerrak), as it constitutes a natural part of the Norwegian Trench. But the Skagerrak may alternatively be looked upon as a part of the Baltic "channel" system because of the drastic width change at the borderline between the Skagerrak and the North Sea (proper).

As realized for instance during JONSDAP '76 there is a permanent water flow along Norway towards north in box no. 6 (Furness and Saelen, 1977). According to arguments presented in Svansson (1975), most of this water flow has passed cyclonically through the Skagerrak. At subsurface depths it originates from the Norwegian Sea, circulating in the Norwegian Trench along isobaths, which is nicely shown in the Skagerrak 1966 expedition atlas (Anon., 1970). In the near surface layers North Sea water from "all" directions is converging and flowing into the Skagerrak southern parts.

This permanent picture is strongly disturbed by wind influence. As shown by Davies (1979) west winds over the North Sea cause an amplified cyclonic circulation in the Skagerrak, whereas east winds weaken it.

The surplus of fresh water from Skagerrak rivers and from the Baltic Sea Area, about \(0.017 \times 10^6\) m\(^3\)/s (Svansson loc. cit.), is insignificant in comparison with the circulation water. The circulation transport was estimated from a few days measurement by Lybeck and Svansson (1962) to be \(0.5 \times 10^5\) m\(^3\)/s. The JONSDAP '76 experiments resulted in a 50 days mean of approximately \(1.0 \times 10^6\) m\(^3\)/s. As there is a flushing contribution from the large circulation variations, lacking better knowledge, we choose the higher of the two alternatives, one \(10^6\) m\(^3\)/s. A Knudsen relation between a Skagerrak box No. 6 for a one \(10^6\) m\(^3\)/s transport would lead to a salinity difference of \(0.6\) \%/oo, supposed to be more realistic than \(1.2\) \%/oo for a \(0.5 \times 10^6\) m\(^3\)/s alternative.

Even if the Baltic net outflow of fresh water is small the Baltic exchange conditions may be of some interest. The present author has constructed an 8 box model of the water system Skagerrak-Kattegat-Baltic. If in this model an annual discharge of 10 000 tonnes/year of a conservative substance into the innermost part of the Baltic is assumed, there will be a small influence also in the Skagerrak. If we assume that the influence is nil (zero-concentration) in a North Sea large enough to have a mean salinity which is \(1\) \%/oo higher than the Skagerrak mean, then the Skagerrak concentration would be \(0.5\) tonne/km\(^3\)(= mg/m\(^3\)). Due to the long flushing time of the Baltic it would take some 35 years after the discharge start before half of this steady state concentration was reached.
The run-off into the North Sea is a very small fraction of the water-budget. However, its influence on the salinity distribution and on the distribution of river-advected substances merits a separate discussion. Run-off may strongly vary from month to month and from year to year. Average values found in various publications and reports and presented here may therefore vary according to the period of years for which the calculations were made.

Most observations are made by regular gauging stations. These data are often supplemented by estimates on basis of catchment area times specific discharge for the region under consideration.

The data are summarised in the table below.

<table>
<thead>
<tr>
<th>Area</th>
<th>Coastline</th>
<th>River</th>
<th>Catchment (km²)</th>
<th>Period</th>
<th>Mean discharge km³/y</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 a</td>
<td>Moray Firth</td>
<td></td>
<td></td>
<td></td>
<td>18</td>
<td>Craig, '59.</td>
</tr>
<tr>
<td>3 b</td>
<td>Fraserburgh, Arbrough</td>
<td>Tay</td>
<td></td>
<td></td>
<td>12</td>
<td>Craig, '59.</td>
</tr>
<tr>
<td>3 c</td>
<td>Firth of Forth</td>
<td>Tyne</td>
<td></td>
<td></td>
<td>1.6</td>
<td>James + Head, 1970.</td>
</tr>
<tr>
<td>3 d</td>
<td>Thames est.</td>
<td>Humber + Trent</td>
<td></td>
<td></td>
<td>7.7</td>
<td>Denman, '79.</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>E. Britain</td>
<td>115,472</td>
<td>52</td>
<td></td>
</tr>
<tr>
<td>4 a</td>
<td>Flanders</td>
<td>Scheldt</td>
<td>3,231</td>
<td>1941-'60</td>
<td>1</td>
<td>Grindley, '72.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mense</td>
<td>21,000</td>
<td>1941-'60</td>
<td>10</td>
<td>Grindley, '72.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rhine</td>
<td>32,870</td>
<td>1941-'60</td>
<td>10</td>
<td>Grindley, '72.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ysselake</td>
<td>159,683</td>
<td>1941-'60</td>
<td>65</td>
<td>Grindley, '72.</td>
</tr>
<tr>
<td>4 b</td>
<td>Neth. Wadden Sea</td>
<td></td>
<td>4,647</td>
<td>1941-'60</td>
<td>9</td>
<td>Anon, 1974.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.6</td>
<td>Anon, 1974.</td>
</tr>
</tbody>
</table>


Seasonal variability depends on the type of river. For the purpose of this report, where we make a subdivision in summer (5 months, May - September, incl.) and winter (7 months, October - April, incl.), the following typical figures may be cited.

<table>
<thead>
<tr>
<th>Area</th>
<th>Coastline</th>
<th>River</th>
<th>Catchment (km²)</th>
<th>Period</th>
<th>Mean discharge km³/y</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>W. Denmark</td>
<td>Ems</td>
<td>13,401</td>
<td>1941-'60</td>
<td>4.4</td>
<td>Grindley, '72.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Weser</td>
<td>45,253</td>
<td>1941-'60</td>
<td>12</td>
<td>Grindley, '72.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Elbe</td>
<td>144,055</td>
<td>1941-'60</td>
<td>24</td>
<td>Grindley, '72.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10,850</td>
<td>1941-'60</td>
<td>4</td>
<td>Grindley, '72.</td>
</tr>
<tr>
<td></td>
<td>Skagerrak Denmark</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sweden</td>
<td></td>
<td>2,670</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Norway</td>
<td></td>
<td>99,300</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Norway (Lindesnes-62°)</td>
<td></td>
<td>45,474</td>
<td>1941-'60</td>
<td>110</td>
<td>Grindley, '72.</td>
</tr>
</tbody>
</table>

Summer run-off km³/month (5 months)  Winter run-off km³/month (7 months)  Author

Thames (Teddington, 1960-1976)  0.12  0.27  Marsh + Littlewood, 1978.
Rhine (Lobith)  4.9  5.6
Weser (Intschede, 1926-1935)  0.7  1.2  Landolt-Börnstein, 1952.
Elbe (Darchau)  1.7  2.3  Landolt-Börnstein, 1952.
Although there is a marked difference between e.g. the regime of the run-off from e.g. England and that of Norway, the overall run-off has no marked seasonal variation.

Year-to-year variations as given by Grindley (l.c.) for the period 1941-1960 vary between 327 km$^3$/y (1958) and 228 km$^3$/y (1959), but in the separate catchment areas the run-off may exhibit individual variability. So the year 1941 shows high values for Central European rivers and low values for Norway, whereas in 1943 and 1949 the reverse is the case.

For the southern North Sea, south of 55$^\circ$ monthly mean values of the run-off are given by Marsh (personal communication) for the years 1964-1973 (incl.).

The following table gives monthly means, maxima and minima for the summer and winter periods (in km$^3$/month).

<table>
<thead>
<tr>
<th></th>
<th>mean</th>
<th>max</th>
<th>min</th>
</tr>
</thead>
<tbody>
<tr>
<td>summer</td>
<td>11.2</td>
<td>23.5</td>
<td>4.5</td>
</tr>
<tr>
<td>winter</td>
<td>14.5</td>
<td>37.5</td>
<td>5.0</td>
</tr>
</tbody>
</table>
12. Precipitation and Evaporation  (G. Becker)

12.1. Introduction

The hydrographic conditions of the North Sea are influenced, in a twofold manner, by the freshwater supply from the atmosphere. The water budget influences the stability of the vertical stratification and promotes the setting-up and breakdown of the seasonal pycnocline (Dietrich, 1957). The freshwater supply influences the general circulation and could strengthen the residual current system. On the other hand, considerable quantities of pollutants and toxic materials are introduced into the North Sea via the precipitation. Hence, not only the whole amount of the precipitation is of importance, but also the excess of the precipitation over that of the evaporation.

12.2. Precipitation

To date, sufficiently precise precipitation measurements at sea are not available in large enough quantities: when taken from travelling ships, these cannot provide quantitative evidence. Estimates of the precipitation for the North Sea are available (Grindley, 1972), which are based upon the extrapolation of the precipitation measured at coastal stations. On the basis of twenty years' of monthly series (1941 to 1960) this reveals a clear annual cycle with considerable variations from year to year (Fig. 12.1). Averaged over twenty years, one can calculate - according to Grindley - 458 km\(^3\) y\(^{-1}\) precipitation for the whole of the North Sea. A regional subdivision has not been undertaken. Owing to the fact that Grindley did not reduce the coastal station precipitation values, these values would seem to be an over-estimation. According to earlier investigations (G. Wüst, 1938; F. Möller, 1951; W. Wundt, 1938) the mean reduction factors of land stations lie between 0.72 to 0.84. A detailed investigation by F. Schott (1966) showed that the reduction factors also show a clear annual cycle, which lies between 0.82 (June) and 1.03 (October). However, these values are only applicable to the flat luff-side coasts of the North Sea. For the lee-side coasts, the reduction factors have not been determined with the same accuracy and are burdened with considerable uncertainties.

In the determination of the amount of precipitation over the sea, R. Schmidt (1979) used a completely different method. The frequency of the occurrence of precipitation observed from on board merchant ships was subjected to a relative calibration in an area in which observations from not only lightships but also merchant ships are available (German Bight).
Each month, the quotient from the mean monthly total of precipitation on the lightships and the mean relative frequency of the occurrence of precipitation were calculated. On the assumption that the raindrop size spectrum over the North Sea - at first sight - is constant, the mean precipitation frequencies observed for each month were multiplied by that quotient, which is a measure for the quantity of rain. For better confidence coefficient, Schmidt has also given quarterly means for different regions of the North Sea. On the basis of these data, contrary to the values given by Grindley, there results an amount of precipitation - reduced by about 15% - of 394 km$^3$ y$^{-1}$ referred to an area of 575,300 km$^2$. As the area of the North Sea given by Grindley is about 15% too large, the amount of precipitation is reduced to 390 km$^3$ (Grindley) and 334 km$^3$ (Schmidt).

12.3. Evaporation

In situ, the evaporation is scarcely measurable. For that reason, the evaporation is determined, in general, by theoretical consideration or even more simply by means of bulk formulas. On the basis of estimates which Schott (1966) has given, the annual amounts of evaporation for the North Sea has been determined by Otto (1976) as being 330 km$^3$.

Climatological values of the mean net surface heat exchange (Becker, 1979) are available for the North Sea. From the mean latent heat flux one can determine the monthly degree of evaporation, with

$$ E = \frac{Q_E}{L} \cdot \Delta t $$

$Q_E$ = latent heat flux W m$^{-2}$

$L$ = latent heat of evaporation J kg$^{-1}$

$\Delta t$ = time interval

From these values, there results an annual amount of evaporation of about 250 km$^3$.

12.4. Excess of precipitation over evaporation

The precipitation values given by Schmidt (1979) were used in the following, to show the regional and temporal differences in the distribution of the excess between precipitation (S) and evaporation (E).

$$ S - E = F $$

$F$ = net input.

Figures 12.2-12.6 show the remarkable local and temporal differences. Therefore the evaporation - as a result of the lee effect of the British coasts - dominates in the winter season (4th and 1st quarters) in the western resp. southwestern North Sea. The water budget is negative, that means that the convective mixing is strengthened owing to this effect. Simultaneously,
the surface salinity distribution gives the false impression of an increased
advection of the Atlantic Water for this time of the year, which is caused
by the salinity increase owing to the evaporation. During the summer season,
the whole of the North Sea's water budget is positive; that means, the
set-up of the vertical density gradients are stimulated.

On a yearly average, about 86 km$^3$ freshwater from the excess between
precipitation and evaporation is supplied to the North Sea.
Figure 12.1 Monthly precipitation over the North Sea.

\[ \bar{p} = 458 \pm 48 \text{ km}^3\text{y}^{-1} \]
Figure 12.2 Precipitation excess North Sea (1st quarter)
Figure 12.3  Precipitation excess North Sea (2nd quarter)
Figure 12.4  Precipitation excess North Sea (3rd quarter)
Figure 12.5 Precipitation excess North Sea (4th quarter)
Figure 12.6 Precipitation excess North Sea (whole year)
13. Box 1 (A+B)  (K.P. Koltermann)

13.1. Topography and Dimensions

Box 1 covers the northermost area of the North Sea, it is towards west bordered by the Shetlands - their islands Unst and Fetlar represent the only surface features in the box - and towards east it connects to Box 5, which covers the Norwegian Coastal Current regime in the Norwegian trench.

The bathymetry shows a rather gentle depth distribution, sloping from about 120 m depth in the west to 145 m in the east towards the Norwegian trench, with only isolated banks and grounds, i.e. Bressay Bank and Utsira Ground showing shallower depths. Few features are deeper with depths of ca. 160 m, like Bressay Ground of The Holes. Thus it is the deepest part of the northern North Sea except for the Norwegian trench and the Continental margin to the north.

Its area is $8.84 \times 10^4 \text{ km}^2$ with an average depth of ca. 130 m, and an average volume of ca. $9.92 \times 10^3 \text{ km}^3$.

13.2. Hydrography

Box 1 shows the largest oceanic influence of all North Sea subareas, its hydrography is dominated by the Atlantic inflow through the Fair Isle Passage between the Orkneys and Shetlands and along its entire northern boundary. Only in the east, the Atlantic character experiences, due to the Norwegian Coastal Current major modifications of the oceanic properties.

The main water masses of the area are the North Atlantic water NA with summer temperatures of 12 - 14 °C and winter temperatures of 6 to 8 °C, with salinities higher than 35.1, and the Skagerrak water Sk with temperatures of 14 to 16 °C in summer and 2 to 5 ºC in winter. Here salinities are less than 34.0.

Summer temperatures show at the surface a maximum of 12.5 °C in September, a minimum of ca. 7° in March, with bottom temperature varying between 7 to 9 °C in October and 7 to 8 °C in March. The salinity range observed is ca. 35.2 in December and 35.3 in spring and early summer. At the bottom, again, the minimum occurs in March/April with 35.2 and the maximum in October with ca. 35.5.
The Atlantic inflow is mainly concentrated in two areas, namely in a western branch that comes through the Fair Isle Passage (Box 2) and an eastern branch between 2 and 3°E longitude. The western branch shows minimum temperatures of ca. 7°C in March, a maximum of ca. 12.5°C in September, whereas in the east the variations are larger, with temperatures between 7.0 and 7.5°C in February/March and a maximum of 10 - 14°C in August/September. The annual temperature amplitudes in the west are 5.5°C throughout the water column, increasing to 6.5°C in the eastern part at the surface, but with only 2.5°C in the bottom water.

These vertical and horizontal variations indicate external influences which Dooley (1974) quantified with 9.5 x 10^3 km^3/y for the Orkney/Shetland and 34.7 x 10^3 km^3/y for the Shetland/Norway inflow into the North Sea. Of these transports ca. 1.7 x 10^4 km^3/y enter Box 1 and continue towards Boxes 2 and 6 with 8.5 x 10^3 km^3/y each. In general, this leads to a marked distinction of the water masses of the area, which show a north-south separation. In the western part we have a moderate thermal stratification in summer and vertical salinity gradients most of the year, in the eastern part of Box 1 stronger horizontal and vertical salinity gradients persist throughout the year due to the lateral influences of the Skagerrak outflow, sometimes showing up as weak to moderate hydrographic fronts.

13.3. Tidal currents

The tidal currents are mainly of a semidiurnal character and a range from 30-60 cm/s, the main axes of the tidal current ellipses being, in general, north-south orientated. Diurnal tidal currents account only for 10 - 15% of the semidiurnal in amplitudes. The tidal range in the box is of the order of 0.9 m. Higher harmonics play no significant role here.

13.4. Residual currents

Residual currents, as a composite of non-linear effects of the tidal currents, density driven currents and, mostly, wind driven currents, range from 5 - 30 decreasing with depth. Only in areas of larger bottom slopes, namely north of Viking Bank and south of Bergen Bank they show a strong increase towards the bottom with the flow being parallel to the isobaths.
Dooley (1974) characterizes the residual flow in the northern North Sea as "variable and wind driven". Recent investigations of data collected during JONSDAP '76 (Koltermann, 1980) show strong quasi-periodic variations of the residual current field with periods of 2 - 5 and 10 d. Their horizontal coherence pattern implies wave-lengths of 30 - 55 km, indicating eddy-like structures that no longer are directly related to the prevailing wind regime. This low frequency variation shows a clear dependence on the density stratification, as it either disappears in summer or changes towards higher frequencies. Furthermore, the low density stratification in winter, locally very often broken up by strong convective processes, enhances the vertical and horizontal energy transfer from the wind field to the current field throughout the water column.

The overall long-term mean circulation, in view of these low frequency fluctuations, is to be considered as a time integral only; it shows preferred directions of transport to the south and southeast along the meridional sides of Box 1, with almost no distinct directional preference within. Magnitudes, expect for the before-mentioned inflow, are variable and depend very much on the wind field.

13.5 Turn-over time

Estimates for residence- and turn-over times are given by Davies (pers. comm) for Box 1, calculated with a three-dimensional model, as 129 d. This agrees fairly well with estimates using Kautsky's data (1973, 1976) from surveys of radionuclides, having in mind certain reservations about sampling and interpretation approaches in general.
14. Box 3’ (H.D. Dooley)

14.1. Scottish coastal waters

This area is occupied by well or partly mixed coastal waters with salinities less than 35°/oo and considerably less than this near major rivers such as the Tay and Forth. Water movements are dominated by tidal and wind driven processes.

14.2. Tidal currents

The pattern of tidal currents is very complex and reflects the changes in coastal topography. The strongest tidal currents (~ 100 cm/sec) occur near Orkney and around the Kinnaird’s Head promontory between the southeast Moray Firth and Aberdeen. Weaker currents (~ 30 cm/sec) occur in the middle of the Moray Firth and off the Firth of Forth and in these areas vertical stratification develops in the summer. Tidal currents contribute to the circulation of the area by way of non-linear effects. For example the Stokes’ drift transport through the area is about 1 nautical mile per day which means that a water particle can pass from Orkney to 56° N in about 6 months. Along the southern shore of the Moray Firth tidal streams are responsible for a strong localised residual current of about 30 cm/sec. This arises from the tight curvature of the topography which produces asymmetry in the tidal streams.

14.3. Wind driven currents

In an area as complex as this it is very difficult to generalise about its response to wind. Most of the available information is described in Dooley (1971) who shows that considerable variations can occur over relatively small distances off the Aberdeenshire coast. For example wind driven currents reverse in direction beyond the 20 m contour. Inshore of this contour currents are predominately parallel to the coast with a direction consistent with the wind direction component parallel to the coast. Thus northwesterly through southerly to southeasterly winds generate a north flowing current (sometimes exceeding 25 cm/sec), but northerly winds drive a significantly smaller southerly flow. Thus on average one might expect a north flowing coastal stream and south flowing currents offshore. The horizontal scale of such flows, however, is poorly understood but horizontal mixing in this area of relatively weak density gradients may result in a weak net mean flow.
The results of Kautsky (1976) also suggest that on the basis of Caesium 137 distributions, the overall mean flow is weak and of similar magnitude to the Stokes drift component of tidal flow.
English coastal waters

15.1. Introduction

This area extends from Whitby in the north to North Foreland in the south. It covers an area of $2.7 \times 10^4 \text{km}^2$ and has a volume of $850 \text{km}^3$ (Kautsky, 1976). The mean depth is therefore 31 m but most of the area south of the Humber estuary is shallower than this with numerous sandbanks.

The salinity is generally less than 34.5 and considerably less than this in the estuaries of the Humber and Thames. Over most of the area the waters are well mixed throughout the year but the deeper water in the extreme north of the area is thermally stratified in the summer months. The stratified region is separated from the well mixed water to the south and west by a well defined front.

Water movements are characterised by strong tidal streams and variable winddriven currents.

15.2. Tidal currents

The tidal streams in this area are some of the strongest in the North Sea. Over most of the area the maximum tidal current velocity exceeds 100 cm/sec during spring tides, and off the Norfolk coast the maximum exceeds 150 cm/sec (Lee & Ramster, 1979). These strong tidal streams drive a component of the Eulerian residual current through non-linear interactions and are also responsible for a Stokes' drift component. With the exception of small areas near headlands where gyres may be formed the former is probably not important. Over most of the area the Stokes' drift is about 2 cm/sec at spring tides in a southerly direction, but off the Norfolk coast where the strongest tidal streams coincide with a low tidal wave propagation speed it could be as high as 20 cm/sec (Durance, 1977). At neap tides the Stokes' drift is smaller by a factor of four and along the Yorkshire and Lincolnshire coasts the average speed over a fourteen-day period is likely to be 1.0 - 1.5 cm/sec.
15.3. Residual Currents

It is generally accepted that there is a southerly residual current from the northern boundary of this area to the East Anglian coast where the current turns eastwards (Böhnecke, 1922) (Hill, 1973). An inshore current continues further south along the coast of East Anglia before turning northeasterwards, but the greater part of the water entering the area at the northern boundary leaves the area north of latitude 53°N. This general circulation pattern has been confirmed by Kautsky (1973) from the spread of Caesium 137 into the North Sea. He estimates a southerly flow of about 1 cm/sec off the Yorkshire coast.

Current meter records have shown that throughout the area the currents are variable in magnitude and direction and are mainly wind-driven. Moderate wind speeds of 10 knots produce currents with typical speeds up to 10 cm/sec.

In the northern part of the region long-term current meter measurements at JONSIS station I (54°13'N 0°01'E) show that the currents are variable and wind-driven throughout the winter, but during the summer months April to October a persistent circulation develops with offshore flow in the surface layer and onshore flow near the bottom. This circulation is probably associated with the nearby frontal system and is not typical of the area to the south. Observations off the Humber in 1977 and 1978 which show an easterly flow near the bottom support this view. The top meter at JONSIS I also shows a southerly longshore component in the summer, which can be as large as 10 cm/sec but is usually 5 cm/sec or less. Although the top meter is about one-third of the way down the water column and therefore might be expected to be representative of the greater part of the water movement, it must not be overlooked that this southerly flow probably follows the frontal system and turns eastwards out of Box 3'' without contributing to the flushing of the major part of this box.

During the period September 1971 to March 1972 when Kautsky's estimate of a 1 cm/sec southerly flow was made, the JONSIS current meters showed no net southerly flow and in fact in the latter part of this period a significant northerly flow was measured. These observations suggest that the southerly flow measured by Kautsky is accounted for by the Stokes' transport and that an additional wind-driven component of the current may be present in some seasons.
South of latitude 52°30'N Ramster, Medler and Jones (1976) have shown the residual currents to be northeasterly in southwesterly winds and southwesterly in northerly winds. North of this latitude the wind and observed current are not simply correlated and the circulation is determined by the history of the wind action on the whole North Sea (Riepma, 1980).

15.4. The estimation of turnover time

Kautsky's estimate of a 1 cm/sec flow through the northern boundary of Box 3'' is probably an underestimate of the mean annual flow. The Eulerian component which is probably wind-driven may be 2 to 3 cm/sec, a mean transport from Box 3' to Box 3'' of 0.02 x 10^6 cu m/sec, and a turnover time of 1.3 years. Strong variable wind-driven currents could significantly reduce the turnover time by contributing to the turbulent exchange between the adjacent boxes.
16. Box 4

(L. Otto)

16.1. Introduction, topography.

Box 4 includes the southern and eastern parts of the Southern Bight and the waters in front of the Frisian Islands.

The surface area is 335.10^3 km^2, the volume 1,225 km^3 and the mean depth 36.5 m. The greatest depths are along the southwestern boundary, in the "Deep Water Channel". There depths as deep as over 60 m are found (approx. 52°10' N, 2°15' E).

Detailed topographic charts of the area are given by Stocks (1956) and Houbolt (1968).

The depth distribution is as shown in the following table:

<table>
<thead>
<tr>
<th>depths over</th>
<th>percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 m</td>
<td>100</td>
</tr>
<tr>
<td>10 m</td>
<td>95</td>
</tr>
<tr>
<td>20 m</td>
<td>86</td>
</tr>
<tr>
<td>30 m</td>
<td>43</td>
</tr>
<tr>
<td>40 m</td>
<td>13</td>
</tr>
<tr>
<td>50 m</td>
<td>1</td>
</tr>
</tbody>
</table>

16.2. Hydrography

Due to the rather strong tidal currents and the small depth, vertical mixing is intense and vertical stratification cannot develop but in areas close to the coast where advection of brackish water maintains vertical salinity differences.

The long-term residual current pattern as deduced from observations is to the northeast (Otto, 1970). Various numerical models show the same general pattern (Prandle, 1978). Also the drift, especially of sea-bed drifters that are less influenced by the wind, shows a similar pattern (Carruthers, 1926; Ramster, 1955).

The water from the Rhine and Meuse estuary usually turns to the northeast, with the mean residual flow, and follows closely the Dutch coast. According to Van Bennekom, Gieskes and Tijssen (1975) off Ijmuiden 50% of the river discharge is transported in a 15 km wide strip along the coast. Only the water from the Scheldt estuary, apparently under influence of the southwest directed tidal residual along the Belgian coast (Nihoul and Ronday, 1975), turns mainly to the southwest and presumably only leaves the area of the Flemish Banks in a northeasterly direction after further mixing with Channel water entering from the Straits of Dover. This mixture can be identified as
a separate water mass just north of 52°N, to the west of the Rhine-Meuse plume (Otto, 1967).

Part of the Rhine-Meuse plume penetrates the western Wadden Sea and mixes there with water sluiced from the IJssel Lake (Zimmerman, 1976; Postma, 1954). The water, finally returning to the North Sea, has obtained different characteristics and may be found as a separate water mass along the Frisian Islands (Otto, 1967).

An important point in the hydrography of the area is the mixing process taking place near the westernmost Frisian Islands, described by Dietrich (1953) and named by him "Texel Mühle" (Texel mill). Here, because of the rather wide shape of the tidal ellipse in that area, strong offshore-onshore water movements take place in the course of a tidal period, combined with stratification of water masses. Subsequent vertical mixing of these layered structure was thought by Dietrich to be a very effective lateral mixing mechanism.

The bulk mixing coefficient was estimated by Schott (1966). Using a simple model for the mixing of water with different salinity, he considers the balance between longitudinal salt advection with the main residual current and transversal mixing (thus neglecting longitudinal mixing). Assuming fixed salinities along both coastlines and a mean transport through the Straits of Dover of 132 km³/month he finds a lateral mixing coefficient of 100 m²/s across the Southern Bight, a rather low value considering the length scale. Using an estimate of the Channel inflow that is 2 or 3 times greater, in accordance with more recent estimates, the mixing coefficient becomes also 2 or 3 times greater.

These values of the mixing coefficient give, for the typical width of the box (L = 100 km) mixing times (defined by $T_m = \frac{L^2}{2K}$) of the order of a year, thus larger values than the typical turn-over time. We may therefore conclude that the waters within this box will not really become well-mixed during their residence within the box, and that a subdivision of this box for various applications can be necessary.

The following subdivision is suggested:
1. Area of the Flemish Banks. This area is characterized by
   a. Influence of the Scheldt river outflow.
   b. Special water mass characteristics ("Biologisches Altwasser", biologically old water, identified by Kalle (1937) in this area in January 1937).
   c. Separate current system of the tidal residuals (Nihoul and Ronday, 1975).
   d. Small depth with many ebb-and-flood-channels between the sand banks (Van Veen, 1936).
2. and
3. The Rhine-Meuse plume and the more saline waters to the west of it.
   Any separation between these two areas is more or less arbitrary. However,
   the eastern part is strongly characterized by the Rhine-Meuse run-off,
   the western part only slightly or not at all. For the Rhine-Meuse plume
   the transit-time distribution was estimated by Otto (1978) on the basis of
   the salinity variations at the northern boundary near Texel.
4. The area in front of the Frisian Islands.
   Here the influence of the Wadden Sea may be observed, and the Rhine-Meuse
   plume is less distinct because of the more intense lateral mixing as
   described by Dietrich.

Smaller scale variability of the water properties of the current pattern
may be observed locally (Riepma, 1977), presumably under influence of
interaction between the tide and the bottom topography (Zimmerman, 1978),
or temporarily because of variations in the run-off from the rivers or
variations of the residual current under influence of changing wind fields.
These variations mainly act as a large-scale turbulent exchange mechanism
on the mean properties of the water at the time scales of interest here.
Only variations in the residual current at time scales comparable to the
mean transit-time (order: some months) or larger affect the present box
model approach.

The variability of the residual current is shown in a number of long-
term current observations from lightships or by automatic current meter
rigs (e.g. Ramster and Koltermann, 1976).

In an analysis of JONSDAP 73 data, Ramster, Medler and Jones (1976)
find a more or less uniform response of the Southern Bight residual current
to variations of the wind. Variations of the in- and outflow of the Southern
Bight according to these authors appear to occur largely via the area to the
northwest of Texel ("Texel Gate"). This would mean that variations at
longer time scales affect the whole of Box 4 more or less in a similar way.
17. Box 5  
(G. Becker)

17.1. Introduction, Topography

Box 5 comprises the area of the German Bight with the Ems-, Jade, Weser- and Elbe Estuaries and the area off the west coast of Denmark. It covers an area of about 44,103 km², and its volume is 969 km³. Thus the mean depth is about 22 m. The extended East Frisian and North Frisian Wadden Seas covering about 7% of the total area are unique for the whole North Sea as to their ecological importance.

The topography of Box 5 is formed by the old, post-glacial valley of the River Elbe running through the German Bight in northwesterly direction.

Blaavandshuk north of Esbjerg and Horns Rev with the Vestslugen - a deep-lying between them terminate the German Bight towards the north and are a transition to the relatively (undisturbed) uniform topography off the coast of Jutland.

The depth distribution in per cent is given in the table below:

<table>
<thead>
<tr>
<th>depth over</th>
<th>0 m</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 m</td>
<td>78%</td>
<td></td>
</tr>
<tr>
<td>20 m</td>
<td>57%</td>
<td></td>
</tr>
<tr>
<td>30 m</td>
<td>30%</td>
<td></td>
</tr>
<tr>
<td>40 m</td>
<td>5%</td>
<td></td>
</tr>
</tbody>
</table>

(7% Wadden Seas; depth 0 - 2 m).

Topographical maps of the area have been submitted by Stocks (1961).

17.2. Hydrography

The horizontal distribution of the hydrographic parameters in this area is determined by the mixing of the western North Sea water with the coastal water (Goedecke, 1951; Kalle, 1956). The amplitudes of the annual wave of temperature and salinity reach the highest values of the North Sea in the inner German Bight. The amplitudes of the annual harmonic sea surface temperature and salinity waves are about 8 K (Dietrich, 1951; Becker, 1979) respectively 2°/oo (Schott, 1966). Influenced by the highly depth-dependent tide current turbulence, the transition zone from vertically mixed to seasonally stratified water runs through Box 5 (Simpson and Pingree, 1978).

So, extremely vertically temperature gradients of more than 10 K, m⁻¹ may occur in Box 5 (Becker, 1973.). By the influx of fresh water from the Rivers Elbe and Weser, salinity fronts reaching far out to the northwest are observed (Becker and Prahm-Rodewald, 1980). The mean circulation of the
residual currents in general shows a current system parallel to the coast setting northeast or north, respectively (Mandelbaum, 1934; Mittelstaedt, pers. comm.). The mean residual current is between 2 and 5 cm. s\(^{-1}\).

Eddies have been observed temporarily in this area (Kalle, Goedecke) which, however, are not stationary and on whose duration of life no investigations are available so far.

The density-induced current must not be neglected (Backhaus, 1979); it intensifies the general circulation.

The local wind seems to influence the circulation of the residual current only to a small extent (Koltermann and Lange, 1975); this circulation seems to be generally coupled with the large-scale circulation system.

Observations (Wendicke, 1913) and numerical models (Backhaus, 1979) have confirmed that strong vertical current shear may occur in the area of Box 5.

This is not only true of the tidal current, but also of the non-tidal residual current. Especially in the Elbe valley, transports in opposite directions were observed in the surface layer and in the bottom layer (Becker et al., 1979).

Schott (1966) showed that there is a high correlation between the salinities in the vicinity of the lightvessels "Elbe 1" and "Halskov Rev" which confirms the transport parallel to the coast. Hickel (1980) could prove that the Wadden Sea north of Sylt contains portions of Elbe water which travels from the Elbe River to the Wadden Sea north of Sylt with a velocity of 4 - 5 cm. s\(^{-1}\).

All these examples show that Box 5 is not well mixed, neither horizontally nor vertically. Only with time intervals of more than 1 year may Box 5 be considered as a homogeneous area, as investigations of the long time-series of light vessels and fixed stations have shown (Becker and Kohnke, 1978). Like in Box 4, a sub-division of Box 5 into smaller unities seems to be necessary for special requirements.

A reasonable sub-division could be as follows:

17.3. Wadden Seas.

In the Wadden Seas whose bottom generally gets dry during low water, only the tidal phase around the tidal high water is of essential importance (Göhren, 1974). The tidal ellipses are strongly deformed there, so that a pronounced residual current occurs in the direction of the current that is present at the time of the tidal high water. Thus, Wadden Sea areas are areas where enrichment of solved and of particulate substances (due to physico-chemical processes) may occur (Hickel, 1979). With extreme weather
situations these substances may be dissolved or suspended again and may also be transported back into the open North Sea.

1 (a) East Frisian Wadden Sea.
   This area behaves in a similar way as the West Frisian Wadden Sea area described in connection with Box 4, with intense lateral mixing processes of the Rivers Ems, Jade and Weser.

1 (b) North Frisian Wadden Sea.
   This area comprises the North Frisian Wadden Sea and the northern and southern Wadden Sea off Sylt. This Wadden Sea area is strongly influenced by the Elbe water. The horizontal gradients are generally low. Biologically, this area is characterized by high numbers of larvae of Spionidae and *Noctiluca miliaris* (Martens, 1978).

17.4. Coastal waters

The coastal water comprises the homothermal areas north of the East Frisian Wadden Sea and the area west of the North Frisian Wadden Sea which are bounded by the more or less strongly pronounced thermal front. The transition from the mixed to the stratified water may be determined by the stratification parameter

\[ S = \log_{10} \left( \frac{h}{|u|^{1/3}} \right) \]

where:

- \( h \) = water depth
- \( u \) = surface tidal stream amplitude.

The coastal water also comprises the Elbe and Weser River plume which is also present beyond the thermal front. Both front systems (plume fronts and thermal fronts) are interacting. The coastal water is characterized by high nutrient and seston contents.

17.5. North Sea water

Optically, the North Sea water can very well be distinguished from the more turbid coastal water. It shows, on the one hand, a clearly lower annual variation of the salinity fluctuation but, on the other hand, a seasonal vertical temperature gradient.

This water mass is in interchange with Box 7, with the weather situation playing an important role.

3 (a) western North Sea water of the covering layer;
3 (b) western North Sea water of the bottom layer.
18. Box 7 (G.A. Becker)

18.1. Topography

The topography of Box 7 is very strongly characterized by the Dogger Bank and the post-glacial river valleys of the Rhine and the Elbe/Weser surrounding it. The Dogger Bank has a considerable influence on both the current system of the North Sea and the distribution of the water masses.

To the southeast of the Dogger Bank 7' is a relatively shallow sea area with depths between 40 and 50 m, being a continuation of the continental lowlands.

To the north of the Dogger Bank 7' the sea bottom falls relatively sharply from 40 m to 80 m in depth and then merges into the largely undisturbed topography of the central North Sea. The Devil's Hole embedded therein, the depths of which are as much as 240 m, spreads out too little to have a significant influence on hydrography. The Little Fisherbank forms the northeastern boundary between Box 7 and Boxes 5 and 6.

18.2. Hydrography

The water of Box 7 cannot be associated with a uniform, unchanging water mass. The greater part of the area is covered by the water of the central North Sea, a water mixture which shows strong seasonal variations. As such, the central North Sea water is subject to mixing processes, in particular with Boxes 3, 4 and 5.

This can be derived from satellite IR images of the North Sea. The IR radiation pattern is significantly different between Box 7 and the surrounding waters. Very often eddy-like structures are found in the surrounding Boxes 3, 4, 5, 6 and at the edges of Box 7 (Typical length scale 10 to 50 km). Such "dynamic" structures are not seen within Box 7. Hence it follows that turbulent mixing processes can differ by some orders of magnitude within Box 7 from the surrounding Boxes.
Strong horizontal salinity gradients are observed at the edges of Box 7.

Characteristic of Box 7 is the formation of a strong seasonal thermocline, which persists to the north of the Dogger Bank from around May to October. The thermocline in this part of Box 7 is destroyed neither by tidal current turbulence nor by meteorological events such as severe summer storms. This is confirmed by numerous individual investigations (Ann. Biol.) as well as by atlases of mean distributions.

The structure of the thermocline is controlled in the central North Sea mainly by the local net heat flux at the air-sea interface (Becker, 1981). Advective heat transports presumably play no part in this area. In the summer months, the water of the surface layer clearly differs from that of the bottom layer in temperature and salinity characteristics, whereby precipitation causes a reduction of salinity in the surface layer.

In the autumn and winter months, cooling at the surface is responsible for convective processes, which mix the water column down to the sea bottom, even in the Devil's Hole.

Usually no or only slight vertical gradients appear above the Dogger Bank. Stratification parameters (Pingree and Griffiths, 1978) derived from numerical tidal models show the Dogger Bank to be a stratified area leading to the assumption that the vertical mixing above the Dogger Bank is mainly controlled by wind-induced turbulence.

To the south of the Dogger Bank, a summer thermocline is generally observed in Box 7. Investigations carried out by G. Prahm (1962) show that the thermocline can be temporarily destroyed by meteorological influences also during the summer. The breakdown of the thermal stratification usually occurs in August. This part of Box 7 is influenced by seaward heat transports from the shallower coastal regions. There is not yet sufficient information available concerning the residual current system of Box 7. Investigations carried out by Ramster (1965), Ramster and Koltermann (1976) and Dooley (1974) show that considerable seasonal variations in the current system are to be reckoned with.
In general the residual currents within Box 7 are mainly induced by wind. The currents are therefore weak and variable in direction. As a result of the ICES Exercise on Permanent Moored Oceanographic Stations in 1970/71 it became obvious that remarkable vertical shear of the residual currents in that area occurs. This happens during all seasons. An influence of the stratification of the water column cannot yet be estimated.

To the southeast of the Dogger Bank relatively stable residual currents extend in a northeasterly direction towards the Skagerrak. North Sea numerical models (Maier-Reimer, 1977) show speeds of some 10 to 20 cm s\(^{-1}\) in this area. Current observations at the Netherlands lightvessels result in residual currents of about one order of magnitude less (Otto, 1964). To the west of the Dogger Bank the residual currents reverse direction with the main seasons. Typical speeds here are around 5 cm s\(^{-1}\).

To the north of the Dogger Bank the current system is to a large extent dependent on the wind field, whereby the correlation between the local wind and the residual current appears to be low. In general the residual currents in this area lie on average below 5 cm s\(^{-1}\), with varying directions.

It must be stated that the mean advective flux as well as the mean turbulent "exchange" are comparatively small within Box 7 especially during the summer season.
1. Introduction

Two-dimensional numerical models have been used extensively over the last 10 years to calculate changes in sea surface elevation produced by tidal forces (e.g. Davies (1976)) and changes produced by meteorological effects (storm surge models) (e.g. Davies and Flather, 1978). The emphasis in these models has been the calculation of sea surface elevations, although depth mean currents and hence transports can be computed using such two-dimensional models.

Pollution problems on the other hand require a detailed knowledge of the depth and horizontal variation of current, and changes in sea surface elevation are of secondary importance. Using the Galerkin method, Davies (1980a) has developed a numerical modelling method in which a continuous depth variation of current can be computed, information which is particularly important in any pollution model.

In this paper such a model is applied to the computation of meteorologically induced residual currents over the Northwest European Shelf. These residual currents are subsequently used to compute turn-over times of specific areas of the North Sea.

The concept of a turn-over time T for a sea area is particularly important in pollution problems; Bolin and Rodhe (1973) have defined it as

\[ T = \frac{M}{F} \]

where M is the total mass of water in the sea area, and F is the total flux of mass leaving per unit time.

In the steady state, when the total mass, fluxes and internal processes within a sea area are independent of time, the turn-over time is equivalent to the residence time or average transit time, and is the mean time water particles have been in the sea area at the moment they are leaving it (Bolin and Rodhe, 1973). In the sea a true steady state is never achieved, however, in a numerical model such a state can be readily obtained.

The finite difference grid of the three-dimensional numerical model in these calculations is shown in Figure 19.1. The model has a grid resolution of 1/3° latitude by 1/2° longitude, and a staggered finite difference scheme is used in the horizontal. With this grid, surface elevation (\( \zeta \)), computed at the centre
of the grid square, the north-south component of current (V), at the northern and southern sides of the square, and the west-east component of current (U), at the western and eastern sides. Using such a grid, the flux through a particular area can be readily computed, provided the boundaries of the area coincide with the grid lines used in the model.

For the purpose of computing the turn-over time of the various regions of the North Sea, a division into seven areas has been made (see Figure 19.1). This division is of course arbitrary, but is chosen to agree as closely as possible with the ICES division [Otto 1977] of the North Sea (Figure 2.1). (Slight differences in the boundaries of the various areas arose, because the ICES regions did not coincide with the finite difference grid of the model). Region seven in the central North Sea is further divided into northern (Region 7') and southern (Region 7") areas.

2. Other numerical models

To the author's knowledge, no other numerical modelling work aimed specifically at computing the turn-over time of areas of the North Sea, or of the North Sea as a whole have been performed.

Previous numerical calculations which are particularly relevant to the problem of turn-over times were performed by Maier-Reimer (1977, 1979). He used a two-dimensional North Sea model to compute the residual circulation induced by the $M_2$-tide and an annual mean wind stress. From this circulation the time taken for a particle of pollutant to leave the North Sea, starting from a particular location was determined. This calculation showed that a particle released in the sea area adjacent to the west coast of Norway took the shortest time (less than 12 months) to leave the North Sea. On the other hand, particles released in the German Bight took in excess of 60 months.

The effect of a mean surface slope between the English Channel and the northern North Sea of 10 cm/1000 km (produced by raising water levels in the English Channel by 10 cm) was also investigated by Maier-Reimer (1979). He found that including this surface slope reduced the time taken for particles to leave the North Sea by approximately 12 months. Subsequently river discharge and diffusion were also included within the model, and produced a further reduction of 6 months.
3. Calculation of Meteorologically-Induced Residual Currents and Turn-over Times

(a) Meteorologically-induced residual currents

The seasonal wind stress distributions over the shelf for the four seasons, December/January/February, March/April/May, June/July/August, and September/October/November, at every grid point of the model were interpolated from the wind stress distributions published by Hellerman (1967/68). The annual mean wind stress was derived in a similar manner from Hellerman's data. Annual and seasonal atmospheric pressure gradients over the shelf, and distributions of atmospheric pressure along the open boundaries of the model, were interpolated from pressures given in the Technical Report of the Japanese Meteorological Agency (1968).

Details of how these data were used, with the three-dimensional numerical model, to compute the wind-induced circulation on the shelf, are given in Davies (1982) and will not be repeated here. (Also for a detailed description of the mathematical methods used in the model, the reader is referred to Davies (1981)).

Figures 19.2 to 19.5 show the meteorologically-induced currents (surface, bottom and depth mean) on the shelf for the periods December/January/February, March/April/May, June/July/August and September/October/November. The annual mean circulation is shown in Figure 19.6.

The convention used to depict currents in these figures, is that the model grid point is indicated by a circle, and the direction of flow is away from this point along the current vector. The length of this vector and the number of vector lines indicate the magnitude of the current. It is apparent from Figures 19.2 to 19.5 that the surface current for each season exhibits a characteristic southeast going flow of water into the North Sea, induced by the predominant westerly winds. The maximum surface current occurs during the winter period (December/January/February), when the wind stress is at maximum, with the minimum in the summer (June/July/August), the period of minimum wind stress.

Depth mean currents for all seasons show an influx of water into the North Sea, between the north of Scotland and the Shetland Islands. Part of this water mass moves due eastward towards the Norwegian coast, and then flows to the southeast along the western edge of the Norwegian trench into the Skagerrak.
The remainder of the water flows southward along the east coast of England. At approximately the latitude of Aberdeen this water mass bifurcates, with some water flowing due eastward into the Skagerrak, and the remainder continuing to the southeast. This southeasterly flow produces a rise in water levels in the German Bight, which, in the steady state, balances the imposed wind stress and pressure gradients. A northerly flow of water out of the German Bight, along the west coast of Denmark, driven by the north-south gradient of sea surface elevation, produced by the rise in water levels in the German Bight is evident in each seasonal circulation. This northerly flow subsequently enters into the Skagerrak along the north coast of Denmark.

At the eastern end of the Skagerrak, water flows into the deep Norwegian trench, and subsequently leaves the North Sea along the west coast of Norway. Despite the changes in magnitude of currents from season to season, these major features of the North Sea circulation persist throughout.

A circulation pattern for the northern North Sea, corresponding to that described above, was postulated by Dooley (1974), based upon observations taken in the North Sea. The fact that Dooley's circulation pattern from various sets of observations corresponds to that computed with the numerical model, confirms the persistence of the major features of the northern North Sea's circulation determined here.

The spatial distributions of bottom currents in the North Sea from season to season also exhibit identical dominant features. In particular, the easterly flow across the northern North Sea, the flow of water northward out of the German Bight, and the northerly transport within the Norwegian trench.

For completeness, surface, bottom and depth mean currents induced by the annual mean wind stress and pressure gradients are shown in Figure 19.6.

(b) Calculation of turn-over time $T$

Although the spatial distributions of the wind-induced seasonal circulations show similar patterns, the magnitude of the currents from season to season is different and hence values of $T$ for the various North Sea areas will have a seasonal variation. The magnitude of current also changes through depth, and this variation must be taken into account when computing $T$ for pollutants which are not uniformly dispersed throughout the water column (e.g. oil, which is mainly confined to the surface layer).
For each area, for the respective seasonal and annual circulations, turn-over times were calculated (a) for the 10 meter surface layer together with the corresponding bottom layer, and (b) for the entire water column from sea surface to sea bed.

The turn-over time for each North Sea area can be readily computed once the volume of the area, and the flux through it, are known. In the numerical model the surface area and average depth of each grid box are known exactly. Hence the total volume and surface area for a specific sea region can be determined. These volumes together with surface areas, are given in Table 19.1. Since the numerical model calculates currents across each side of a grid box, and a continuous current profile through depth, the flux into and out of a particular sea area can be readily computed for any layer of the sea, and for the total depth. In order to calculate the total flux through a layer of fluid, the vertical flux must also be included. Although the vertical velocity is approximately less than one hundredth of the horizontal velocity, the horizontal area of the grid box involved in the flux calculation is large and hence the vertical flux is appreciable. Vertical transport of pollutants is particularly important in coastal regions where downwelling and upwelling occur.

Having determined the flux into and the flux out of a particular North Sea area, at each grid point on the boundary of the region, the total flux into and total flux out of the area can be computed by separately summing the individual fluxes. In the steady state the respective fluxes in and out are equal.

Using this method the flux in or out of each North Sea area was computed. From this the turn-over time was determined from equation (1), by dividing the appropriate volumes given in Table 19.1, by the corresponding fluxes. Since density is constant in the model, mass is replaced by volume, and mass flux in equation (1).

The turn-over time for the surface and bottom layers can be computed in a similar manner, by computing the layer's volume from its thickness and surface area (given in Table 19.1) and dividing by the total flux through the layer. In the case of a layer, the total flux is the sum of the horizontal and vertical fluxes, care being taken to sum separately the flux into and out of a layer.

In practice this method of computing the turn-over time may give an artificially low value for the case in which the flow meanders across the boundary used to define the area for which the turn-over time is being computed (see Figure 19.7)
Figure 19.7 shows an extreme case in which the flow meanders across the line AB which, together with the line AD and the land boundaries, define a region for which the turn-over time is to be computed. In this case the numerical model would yield fluxes $q_0, q_1, \ldots, q_5$ at current points situated at the centre of each model grid line, computed as described above. If the flux into and out of the area is now computed by summing these individual fluxes (method A) we obtain

\[
\text{FLUX IN} = q_0 + q_2 + q_4
\]
\[
\text{FLUX OUT} = q_1 + q_3 + q_5
\]

If, however, we sum the fluxes along each side of the region before computing the flux into and out of the region (method B), this gives

\[
\text{FLUX IN} = q_0
\]
\[
\text{FLUX OUT} = (q_1 + q_3 + q_5 - q_2 - q_4).
\]

Since in the steady state FLUX IN = FLUX OUT, it does not matter which flux we use to compute the turn-over time.

Method (A) gives a turn-over time,

\[
T_1 = \frac{V}{(q_0 + q_2 + q_4)},
\]

where $V$ is the volume of the area, and method (B) gives a turn-over time,

\[
T_2 = \frac{V}{q_0}.
\]

Obviously method (A) will give a lower turn-over time than method (B).

For the case in which the current does meander along the boundary of the region, method (A) is probably not physically realistic. This method implies that the pollutant which is in the region ABCD (Figure 19.7) is removed by the fluxes $q_1, q_3$ and $q_5$ and that unpolluted water enters the region through the fluxes $q_0, q_2$ and $q_4$. In practice, however, it appears reasonable to assume that a large proportion of the pollutant that leaves in flux $q_1$, probably returns in flux $q_2$, and similarly with $q_3$ and $q_4$. Consequently the major influx of unpolluted water into the region is produced by the flux $q_0$ and it is this flux which has the greatest influence upon the turn-over time. By using method (B), the effect upon the computed turn-over time of a current meandering along a straight boundary is removed, and only a truly external flux of water into the region is used to compute the turn-over time.
Turn-over times in years determined by using an annual mean wind stress, computed with methods A and B, are given in Table 19.2.

Comparing turn-over times computed using methods A and B, it is apparent that times computed, using method (A) (Table 19.2), are significantly lower than those computed using method (B). The reason for this can be understood from Figures 19.1 and 19.6. Referring to these figures it is evident from Figure 19.8 that there is a high degree of spatial variability in the currents and that many of these currents do to some extent meander across the boundary lines which determine the various North Sea areas (Figure 19.1).

As shown previously, turn-over times computed using method (A) may be unrealistically low since they include this effect. However, by summing grid point fluxes over the straight line sections, which determine the boundaries of each area (method B), these effects are removed, and turn-over times computed with method (B) may be more physically realistic.

Using method (B) and taking into account changes in current direction through the water column, seasonal turn-over times have been computed for the upper 10 m layer of the sea (Figure 19.8), the 10 m layer near the sea bed (Figure 19.9), and the total water column (Figure 19.10). (Note differences in scale used in these Figures).

It is evident from Table 19.3 and Figures 19.8, 19.9 and 19.10 that the turn-over time for the surface 10 m layer is significantly less than for the bottom 10 m layer, due to the reduction in current magnitude with depth.

It is clear from Table 19.2 and Figures 19.8, 19.9 and 19.10 that T exhibits a strong seasonal dependency, reflecting the seasonal variations in the magnitude of the wind stress. Values of T also vary from one area of the North Sea to another. Considering the turn-over time of the total volume, it is evident from Figure 19.10 that for all seasons, Area 1 has the largest value of T. It is apparent from Figure 19.1 that Area 1 is situated in the central northern North Sea, a region where current magnitudes are significantly smaller than in other Areas (see Figures 19.2 to 19.6). Also the volume of Area 1 is larger than many other Areas of the North Sea (see Table 19.1). This combination of large volume, with small currents, explains the large T value for Area 1. Area 5, however, has the shortest T, due to its small volume (Table 19.1), and higher currents (Figures 19.2 to 19.6).
4. Concluding Remarks

The persistence of the major spatial features of the North Sea circulation from season to season is particularly interesting and reflects the dominance of the westerly wind component in each seasonal wind field, and also the influence of bottom topography.

The change in direction and magnitude of the meteorologically-induced currents through depth, illustrate the importance of using a three-dimensional model to study wind-induced circulation on the shelf.

The short turn-over time (of the order of days, in some areas during winter (see Figure 19.8)) for the surface layer, clearly shows that it is the magnitude of the wind stress on a daily, and not a seasonal basis, which will determine how long it takes a pollutant in the surface layer to leave a particular sea area. Also from Figures 19.8, 19.9 and 19.10, it is evident that particularly in the winter, the turn-over time for some areas, even for the bottom layer, can be shorter than the 3 months' period over which the wind stresses have been averaged. This demonstrates that changes in wind stress on a shorter time scale than 3 months can determine how long a pollutant remains in a given area.

The values of turn-over time given clearly show its dependence upon the magnitude of the meteorological forcing. For this reason it is doubtful whether turn-over times of North Sea areas are applicable in pollution problems, since the wind field over the North Sea, particularly in winter time, changes on a time scale of three to five days, associated with depressions moving from Iceland to Scandinavia.
Table 19.1  Volume and surface areas of North Sea regions used in the calculation of turn-over times.

<table>
<thead>
<tr>
<th>Area</th>
<th>Total Volume $\times 10^{-12}$ m$^3$</th>
<th>Surface layer $\times 10^{-11}$ m$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.86</td>
<td>0.62</td>
</tr>
<tr>
<td>2</td>
<td>5.33</td>
<td>0.54</td>
</tr>
<tr>
<td>3</td>
<td>3.68</td>
<td>0.80</td>
</tr>
<tr>
<td>4</td>
<td>1.18</td>
<td>0.44</td>
</tr>
<tr>
<td>5</td>
<td>0.89</td>
<td>0.40</td>
</tr>
<tr>
<td>6</td>
<td>12.60</td>
<td>0.68</td>
</tr>
<tr>
<td>7'</td>
<td>6.57</td>
<td>0.98</td>
</tr>
<tr>
<td>7''</td>
<td>2.86</td>
<td>0.74</td>
</tr>
</tbody>
</table>
Table 19.2  
Turn-over time (years) computed with annual meteorological forcing.

<table>
<thead>
<tr>
<th>Area</th>
<th>Surface Layer</th>
<th>Sea Bed Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5m</td>
<td>10m</td>
</tr>
<tr>
<td>1</td>
<td>31</td>
<td>43</td>
</tr>
<tr>
<td>2</td>
<td>27</td>
<td>32</td>
</tr>
<tr>
<td>3</td>
<td>90</td>
<td>97</td>
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<tr>
<td>4</td>
<td>28</td>
<td>37</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>6</td>
<td>27</td>
<td>38</td>
</tr>
<tr>
<td>7'</td>
<td>45</td>
<td>51</td>
</tr>
<tr>
<td>7''</td>
<td>32</td>
<td>49</td>
</tr>
</tbody>
</table>

Table 19.3  
Turn-over time (days) computed using method (B) with meteorological forcing averaged over a year.
Figure 19.1 Finite difference grid of the model, and sea areas used to compute turn-over times.
Figure 19.2 S Meteorologically-induced currents at surface for period December - February
Figure 19.2 B Meteorologically-induced currents at sea bed for period December - February
Figure 19.2 M  Meteorologically-induced depth mean currents
for period December - February
Figure 19.3 S Meteorologically-induced currents at surface for period March - May
For period March - May

Figure 193 B Meteorology-induced currents at sea bed
Figure 19.3 M Meteorologically-induced depth mean currents for period March - May
Figure 19.4 S  Meteorologically-induced currents at surface for period June - August
Figure 19.4 M Meteorologically-induced depth mean currents for period June - August
Figure 19.5 S  Meteorologically-induced currents at surface for period September - November
Figure 19.5 B Meteorologically-induced currents at sea bed for period September - November
Figure 19.5 M Meteorologically-induced depth mean currents for period September - November
Figure 19.6 S Meteorologically-induced currents at surface for an annual period
Figure 19.6 B Meteorologically-induced currents at sea bed for an annual period
Figure 19.6 M Meteorologically-induced depth mean currents for an annual period
fig. 19.7

Schematic representation of flow through a rectangular sea region ABCD.

\[ \text{Flow streamline.} \]
Fig. 19.8: Turn-over time of the surface 10 m layer, computed with seasonal meteorological forcing for period December to February --- March to May --- June to August --- September to November
Fig. 19.9: As figure 19.8, but for the 10 m layer near the sea bed.
Fig. 19.10: As figure 19.9, but for the total water depth.
References


Becker, G.A. 1975. Mean net surface heat exchange of the North Sea. ICES C.M. 1979/C:36


Bowden, K.F., 1956 The flow of water through the Straits of Dover related to wind and differences in sea level. Philos Trans. r. Soc. (A) 248: 517.


Carruthers, J.N., 1926 The water movements in the southern North Sea. Pt. II. The bottom currents. Fish. Inv. II 9 (3).


Conseil perm. int. pour l'Explor. de la Mer, 1962. Mean monthly temperature and salinity of the surface layer of the North Sea and adjacent waters. ICES, Charlottenlund.


<table>
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<th>Author(s)</th>
<th>Year</th>
<th>Title</th>
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</tr>
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<tr>
<td>Dickson, R.R.</td>
<td>1970</td>
<td>Long-term changes in the hydrography of the European shelf seas since 1905, and the effect of these upon the distribution and abundance of various marine organisms.</td>
<td>Thesis Univ. E. Anglia.</td>
</tr>
<tr>
<td>Dietrich, G.</td>
<td>1950</td>
<td>Die natürlichen Regionen der Nord- und Ostsee auf hydrographischer Grundlage.</td>
<td>Kieler Meeresforschung. 7 (2)</td>
</tr>
</tbody>
</table>

Dooley, H.D., 1974b  Hypotheses concerning the circulation of the Northern North Sea.

Dooley, H.D., 1976  Phytoplankton standing crop adjacent to ocean boundaries in the northern North Sea. ICES CM 1976/L: 28


Eriksson, E., 1971  Compartment models and reservoir theory.


Fedorov, K.N., 1967  The variability of flow through the Straits of Dover from observations of salinity.
Oceanology, 7: 467-471 (Eng. transl.).


Fraser, J.H., 1949  The distribution of Thaliacea (Salps and Doliolids) in Scottish waters 1920-1939.

Fraser, J.H., 1961  The oceanic and bathypelagic plankton of the north-east Atlantic and its possible significance to fisheries.

Fraser, J.H., 1965  Zooplankton indicator species in the North Sea.

Fraser, J.H., 1968  The overflow of oceanic plankton to the shelf waters of the north-east Atlantic. Sarsia, no. 34, 313-330.
Fraser, J.H., 1969. Variability in the oceanic content of plankton in the Scottish area. Prog. in Oceanogr., 5, 149-160.


Hickel, W., 1979  
Das Wattenmeer als Sinkstoff-Falle.  
Umschau in Wiss. u. Tech.

Hickel, W., 1980  
The influence of Elbe river water in the Wadden Sea  
of Sylt (German Bight, North Sea).  
DHZ, 1980 (in press).

Hill, H.W., 1971  
A report on the UK-German-Dutch-Belgian Pilot Ocean  
Data Station Networks for the North Sea.  

Hill, H.W., 1973  
Currents and Water Masses.  
North Sea Science, NATO North Sea Science Conf.  

Bight of the North Sea in 1978. ICES C.M. 1978/C:2

Merlangius merlangus (L.) of the northern North Sea.  

Holden, M.J., 1978  
Long-term changes in landings from the North  
11-28.

Holme, N.A., 1961  
The bottom fauna of the English Channel. J. mar. biol.  
Ass. U.K., 41: 397-461.

Houbolt, J.J.H.C., 1968  
Recent sediments in the Southern Bight of the North  
Sea.  
Geologie en Mijnbouw, 47 (4) : 245-273.

International Hydrographic Bureau, 1937. Limites des Océans et des Mers,  
Special Publication 23.

pressure for the North and South hemispheres, Forecasting  
Research Laboratory, Meteorological Research Institute.

James, A. and P.C. Head, 1970. The discharge from estuaries and their effect  
on primary productivity.  


Jefferies, D.F, A.K. Steele and A. Preston 1982: Further studies on the distribu- 
tion of 137 Cs in British Coastal Waters - I. Irish  

Jones, N.S., 1950  

Jones, R., 1972,  
The subdivision of demersal stocks within the North  
Dt. Hydrogr. Z., 11 (2), 49-77.


Kalle, K., 1956 Chemisch-hydrographische Untersuchungen in der inneren Deutschen Bucht.


Lee, A.J., 1970
The currents and water masses of the North Sea.

Lee, A. 1980
North Sea: Physical Oceanography.
From: The North-West European Shelf Seas: The sea
bed and the Sea in Motion.
Vol. II, Elsevier Oceanography Series, 248
Elsevier, Amsterdam

The Hydrography of the North Sea. A review
of our knowledge in relation to pollution problems.

MAFF Lowestoft, Fisheries Research Technical Report
no. 20.

Lewis, S. and A. Nir. 1978. On tracer theory in geophysical systems in the
steady and non-steady state. Part II.
Non-steady state - theoretical introduction.

Livingston, H.D., V.T. Bowen and S.L. Kupferman, 1982. Radionuclides from
Windscale discharges I: non-equilibrium tracer
experiments in high latitude

Ljoen, R. (1980)
Atlas over middeltemperatur, saltholdighet og tetthet om
sommeren fra nordlige Nordsjøen.
Fisker og Havet, nr. 2, 1980, Bergen

Lumby, J.R., 1935
Salinity and temperature of the English Channel.
Estimation of mean values for the upper water layer
over the 25 years period 1903-1927.
Fish. Inv. Ser. II. 14 (3).

Lundbeck, J., 1963
Biologisch-statistische Untersuchungen Über die deutsche
Hochseefischerei - IV, 7, Ertrags- und Bestandsver-
Meeresforsch., 17: 45-118.

Lybeck, L. and A. Svansson, 1962. Currents in the Skagerrak II.
ICES 1962 Hydr. Cttex. 130

Maier-Reimer, E. 1977
Residual circulation in the North Sea due to the
M2-tide and mean annual wind stress. Dt. hydrogr.


Postuma, K.H., 1978 Immigration of southern fish into the North Sea. 

Prahm, G., 1962 Ein Beispiel für den Einfluss des Wetters auf die 
Temperaturstratifikation im Meere. Ber. d. Deutschen 
Wettdienstes Nr. 91.

Prandle, D., 1978 A. Residual flows and elevations in the southern North 

Prandle, D., 1978 B. Monthly-mean residual flows through the Dover Straits 
1949-1972. 

Prandle, D. and A.J. Harrison, 1975. Relating the potential difference 
measured on a submarine cable to the flow of water 
through the Straits of Dover. 
 Dt. hydr. Z., 28 : 207-226.

sand area of the German Bight, 1967 to 1975. 

Rae, B.B., 1970 The distribution of flatfishes in Scottish and adjacent 

Ramster, J.W., 1965a Studies with the Woodhead sea-bed drifter in the southern 
North Sea. 
Fish. Lab. Lowestoft, Laboratory Leaflet (Nw. Ser. B.)

Ramster, J.W. 1965b in A. Lee: The Currents and Water Masses of the North 
Sea. 

of the drift of a parachute drogue with estimates of 
Lagrangian drift calculated from data collected at a 
triangle of moored current meter stations. 
ICES C.M. 1973/C:4

Ramster, J., C.G. Griffiths and D. Prandle, 1978. The measurement of tidal 
currents from anchored ships in the Straits of Dover 
during the Joint North Sea Data Acquisition Project 
of 1973 (JONSDAP 73). 
ICES C.M. 1978/C:15.


Riepma, H.W., 1977 Spatial variability of residual currents in an area of the southern North Sea.
ICES C.M. 1977/C:43.

Riepma, H.W., 1978: Residual current in the North Sea during the IN/OUT phase of JONSDAP'76. ICES C.M. 1978/C:42.


Stocks, T., 1956

Stocks, Th., 1961

Svansson, A., 1975
Physical and chemical oceanography of the Skagerrak and the Kattegat. Fish. Board of Sweden, Inst. of Mar. Res. Rept. No. 1

Svansson, A., 1980

Talbot, J.W., 1977

Talbot, J.W., 1978

Thorson, G., 1957

Tokioke, T., 1979

Tollan, A., 1973

Tomczak, G. and E. Goedecke (1962).

Tomczak, G. and E. Goedecke, 1964.

Ursin, E., 1960

Veen, J. van, 1936


Wimpenny, R.S., 1966 The plankton of the sea. Faber and Faber Ltd., London.


Appendix Table 1.
The distribution, by Areas in which they are most abundant, of the more important fish species in the Moray Firth, central and southern North Sea.

<table>
<thead>
<tr>
<th>Species</th>
<th>Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3'</td>
</tr>
<tr>
<td>Herring</td>
<td>As spawners and juveniles</td>
</tr>
<tr>
<td>Horse mackerel</td>
<td>+</td>
</tr>
<tr>
<td>Mackerel</td>
<td>+</td>
</tr>
<tr>
<td>Pilchard</td>
<td>+</td>
</tr>
<tr>
<td>Sprat</td>
<td>+</td>
</tr>
<tr>
<td>Sprat</td>
<td>+</td>
</tr>
<tr>
<td>Cod</td>
<td>+</td>
</tr>
<tr>
<td>Haddock</td>
<td>+</td>
</tr>
<tr>
<td>Saithe</td>
<td>As juveniles</td>
</tr>
<tr>
<td>Whiting</td>
<td>+</td>
</tr>
<tr>
<td>Brill</td>
<td>+</td>
</tr>
<tr>
<td>Dab</td>
<td>+</td>
</tr>
<tr>
<td>Long Rough Dab</td>
<td>+</td>
</tr>
<tr>
<td>Lemon sole</td>
<td>+</td>
</tr>
<tr>
<td>Plaice</td>
<td>+</td>
</tr>
<tr>
<td>Scalfish</td>
<td>+</td>
</tr>
<tr>
<td>Sole</td>
<td>+</td>
</tr>
</tbody>
</table>