ON THE PRESENTATION OF OCEAN SURFACE CURRENTS

by Klaus WYRTKI
CSIRO (*), Division of Fisheries & Oceanography, Cronulla, Sydney

---

Navigators as well as scientists are interested in information about the water movements at the surface of the oceans. The navigator needs this information to allow for the set of his ship by currents and to select his course properly. The scientist is not only interested in knowledge of the ocean currents and in their dynamics from an academic point of view, but requires such knowledge also as a basis for conclusions on the distribution of other factors in the oceans, such as temperature, salinity, ice, plankton and fishes. The kind of information demanded depends upon whether it is sought by the navigator or the scientist. Therefore it seems advisable to discuss the various ways of representing and mapping ocean currents, and their advantages and disadvantages for one purpose or the other.

Our information on ocean surface currents comes almost exclusively from observations made from merchant ships, and scientists appreciate this contribution by navigators to our knowledge of the oceans. The currents observed are in practice the difference between the dead reckoning and two astronomical fixes 24 hours apart, and are therefore partly influenced by winds. Consequently, this type of current observation is especially valuable for the use of navigators. Near the coast, tidal currents can also affect the observations, but this will not be discussed here. In contrast to the great number of observations from merchant ships, the number of direct current measurements from anchored ships is almost negligible, and their value lies in an increase of our knowledge regarding the structure of ocean currents. In recent years, direct current measurements from ships under way became possible by an electromagnetic method, developed by von ARX (1950), but the number in use is still too small to yield significant conclusions on the general worldwide distribution of ocean currents. In addition to these observations, scientific investigations of currents, of their dynamics and structure, are numerous and have certainly a value equal to that of direct observations in interpreting and explaining general circulation in the oceans.

(*) Commonwealth Scientific and Industrial Research Organization.

I. — THE STRUCTURE OF OCEAN CURRENTS

The statistical evaluation of current observations will often lead to contradictions, which cannot be solved from a consideration of the observations alone. Here the scientific analysis of water masses, of their upwelling and sinking, of the formation of current boundaries and current bands, enable interpretation of the observations, and result in a clear picture of the surface current pattern.

Before discussing the different ways of presenting ocean surface currents in the form of charts, we must consider the kind of information given on such charts, as required from both the nautical and scientific point of view. The navigator wants the most precise information possible on the expected set of his ship by currents both with regard to the location and the season, and also with regard to the weather. Moreover, he will not only want to know the expected average set of his ship, but also the maximal possible one that might cause danger. Hence the various wishes of navigators cannot be fulfilled by a simple presentation. The scientist, on the other hand, wants a logical picture of the surface circulation, indicating the positions of current axes, current boundaries, divergences, and convergences, which he may relate to other scientific observations and results. Here often the precise numerical value of the current velocity is of minor importance compared with that of the general current pattern. Certainly a proper way of presenting the surface currents from both points of view can be found, but it is of interest to investigate how far the requirements of the one meet those of the other.

Our knowledge of the circulation in the oceans has increased considerably in the last decades. Multiple ship operations, using modern instruments and navigation methods and advanced theories, have led to a deeper understanding of the structure and the dynamics of the ocean currents. We know now that broad permanent ocean currents with a very smooth velocity distribution are rare phenomena, which may not even be developed in the ranges of the equatorial currents. The ocean currents are normally concentrated in relatively small bands with a distinct current axis of maximal velocities. This current axis, however, varies considerably in time and space. Normally the major ocean current systems are composed of several such bands, having a limited extension also in the direction of the current, where they vanish and are replaced again by new current bands. In the Gulf Stream such current bands are 20 to 100 nautical miles wide and often only 200 to 500 miles long, and the velocities increase to five knots in their centre. These bands are not always straight, but curved, and are subject to wide lateral movements. Occasionally, a sideward displacement of the current axis of the Gulf Stream by 60 miles within one week has been observed. Between these current bands large eddies are formed, often with diameters of more than 100 miles. Usually the main ocean currents are accompanied by large well-developed countercurrents, which often extend over several hundred miles.

These features, especially characteristic of the major ocean currents, such as the Gulf Stream, the Kuroshio, the Agulhas, and the Somali currents, as well as the equatorial countercurrents, were investigated in the ranges of some of these current systems, but do not seem to be confined only to these strongest ocean currents. Similar features, like current bands, large eddies and countercurrents are present also in the primarily wind-induced ocean currents, such as the equatorial currents under the trade winds, and the antarctic circumpolar current under the west wind drift. Between these major ocean currents, wide regions are found where the water movements are generally weak and depend more or less on the actual wind and weather conditions, and on special effects of the general oceanic circulation, like upwelling and sinking of water masses.

This picture of the structure of the ocean currents demonstrates clearly that the high variability of velocity and direction in ocean currents is their most pronounced characteristic. The results of scientific investigations might make one despair and consider that the construction of a reliable current chart of the oceans is an impossible task. This feeling is not justified, however, because such a detailed picture of the velocity distribution in the ocean currents is only required for special scientific investigations. Normally the navigator as well as the scientist is interested in average current conditions over a considerable distance and time. The navigator wants to know the average current during 24 hours, in which time his ship travels several hundred miles. Here we must exclude navigation in regions of pronounced tidal currents, for which special charts are available. The scientist, on the other hand, is often interested in the average water movements over long distances and periods, and in their seasonal fluctuations. Therefore the current charts can, without being incorrect, show a smoothed picture of the circulation without the minor irregularities appearing within the actual currents. The average boundaries and the average positions of the current axes must be clearly indicated in current charts in order to allow an easy decision on the current system whose conditions are applicable.

In contrast to this confusing pattern of the detailed structure of the ocean currents, we know that the general oceanic circulation is a permanent, quasi-stationary process, with relatively small variations, like the climate of the earth. And this fact enables us to chart the general properties of the ocean currents. But when using these charts, one must always bear in mind that the general circulation is an average picture of a very complicated and, in time and space, highly variable motion. Only a consideration of this will avoid misinterpretations in the use of current charts.

II. — GENERAL PRINCIPLES OF CURRENT CHARTS

The seasonal variations of the oceanic circulation are of an order which requires their presentation at different times of the year. Especially in monsoon regions the circulation is often completely reversed during the two monsoons, and also the other more permanent current systems show considerable fluctuations in the course of the year. Charting currents twice in the year, at the full development of summer and of winter circulation, will give an indication of these changes, but leaves too much freedom in interpretation of the conditions during the transition stages. Therefore it has become usual to publish current charts for every month, giving a sufficient guide to the seasonal fluctuations.

The structure of the average circulation is such that it often shows marked local differences in the strength and direction of currents over distances of approximately 100 nautical miles. Consequently, currents must be averaged for 1°-squares, in order to give a reliable picture of average conditions. In some regions even 2°-squares are too large. It must, however, be mentioned that current observations themselves are averages over distances of about 200 to 400 miles — the distance which a ship travels within 24 hours at speeds of 8 to 16 knots. Thus the ship's observations are already considerably smoothed and cannot be applied to a discrete locality. This fact makes the use of 1°-squares for the calculation of average currents partly worthless.

The presentation of a current must not be confined to its average direction and strength, but should also give an impression of its variability. The use of a numerical value for the probability or the constancy of the current is often unsatisfactory, because it does not give a visual impression of the chart to the reader. This is especially true in cases in which two or more prevailing directions appear. Such cases are normally found in regions where currents are strongly related to weather conditions, and where two or more prevailing wind directions appear, according to the influence of cyclonic or anticyclonic atmospheric circulation. If such information is given, it becomes possible for the navigator to estimate the wind's influence and to select the expected currents according to the weather conditions present.

III. — RESULTANT CURRENT VECTORS

One would expect that a representation of the average distribution of ocean currents could be obtained by averaging all available current observations for every 1°-square and month. This method, applied in nearly all current atlases, does not, however, lead to a satisfactory picture of the general circulation. In these atlases current arrows are always found, which lie across or even opposite the general flow. This does not mean that such current observations are wrong, but they are not numerous enough to smooth out all the irregularities of the actual currents. This is apparent from inspection of the number of observations which are normally entered. The irregularities appear only in regions with small numbers of observations per 1°-square, say, in 1°-squares with less than 25 observations. Along the main shipping routes, where the number of observations is normally above 100 per 1°-square per month, irregularities are not observed, and the current arrows form a reliable picture of the circulation. An example of such a presentation of current vectors is given in figure 1.

It is interesting to investigate the effect of the number of observations on presentation of the average current. From the current charts of the Mediterranean, published by the Netherlands Meteorological Institute (1957), the frequencies of the average velocities in relation to the number of observations per 1°-square have been calculated and are given in table 1. It can be easily seen that average velocities above 22 M/day appear only in 1°-squares with less than 10 observations, while the frequency of lower average velocities increases with a greater number of observations. Also of

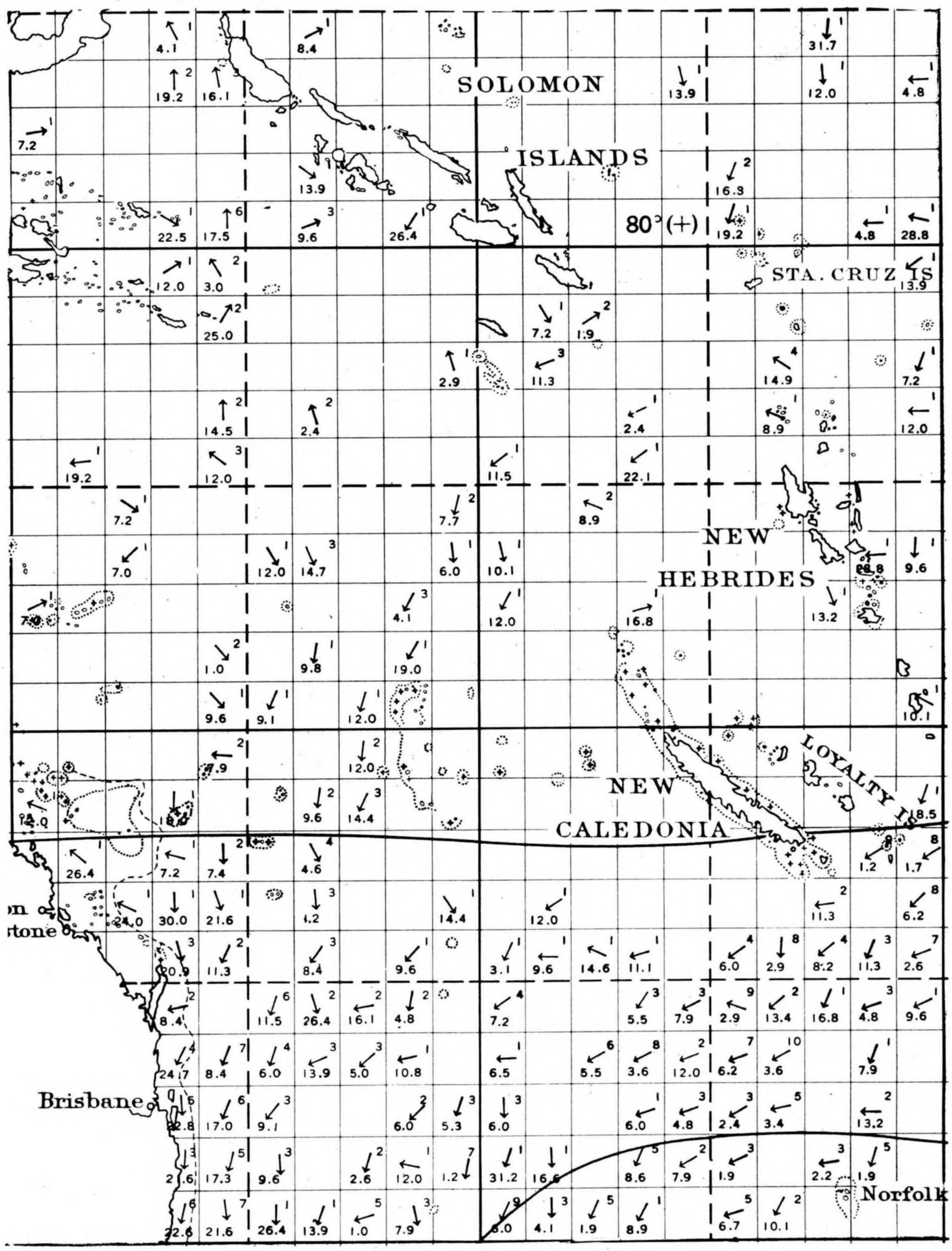

FIG. 1. — Chart of average monthly current vectors for 1°-squares. Section of the January chart of the Atlas of Surface Currents of the Southwestern Pacific Ocean, U.S. Navy Hydrographic Office, No. 568, 1954.

interest is the decrease of the average velocity with an increasing number of observations. In 1°-squares with less than 10 observations the average velocity is 8.7 M/day, in squares with 11 to 20 observations it is only 4.6 M/day, and decreases further to values below 4 M/day. These figures show

TABLE I

Frequencies of average current vector velocities as dependent on the number of observations per 1°-square, according to the Netherlands Meteorological Institute current atlas of the Mediterranean

Number of observations per 1°-square	Current velocity in nautical miles per day							Percentage of observations	Average velocity miles/day
	0-2	3-7	8-12	13-17	18-22	23-27	> 28		
1-10	4.8	17.1	11.5	6.2	1.2	1.1	0.9	42.8	8.7
11-20	2.7	5.7	1.5	0.2	—	—	—	10.1	4.6
21-50	3.9	6.4	1.6	0.1	—	—	—	12.0	4.2
51-100	3.8	4.7	0.2	0.2	—	—	—	8.9	3.3
101-200	6.8	6.3	1.0	0.1	0.1	—	—	14.3	3.2
> 200	4.6	6.2	1.0	0.1	—	—	—	11.9	3.6
Total	26.6	46.4	16.8	6.9	1.3	1.1	0.9	100.0	

clearly that to obtain a reliable average current velocity, it is necessary to have a certain number of observations. When discussing this question, Meyer (1923) distinguishes regions of uniform currents from those of variable currents. He points out that in the first case 18 observations should be available, and in the second case at least 35 observations, to permit the calculation of a reliable average current vector. In the present stage of collecting observations, however, we are still far from reaching this standard over large parts of the oceans. In the Netherlands Meteorological Institute current atlas of the Mediterranean, for example, 216 000 observations were used to cover an area of about 300 1°-squares. This would give an average of 60 observations per 1°-square per month, but due to the accumulation of observations along the main shipping routes, the actual distribution of observations differs considerably from this value. In fact, about 30 1°-squares remain empty and 140 have only 1 to 20 observations per month, while only 130, less than half the total number, have sufficient observations. Moreover, the Mediterranean is a region of relatively high density of observations compared to vast regions of the open oceans, especially in the Southern Hemisphere. An example of such a region where the number of observations is too small to give a proper picture of the circulation is shown in figure 1.

In this connection, it is interesting to compare the average current and the average wind vectors for the same region. Certainly the winds over the Mediterranean are as variable as the currents, but the average wind vectors give a sufficiently smooth pattern of the general air circulation in contrast to that of the water circulation. In the atlas mentioned above the number of wind observations is six times that of the current observations, so that most irregularities originating from an insufficient number of observations are smoothed out.

Consequently, at this stage in the collection of observations, charts presenting average current vectors do not give a fully reliable picture of the general circulation. There are too many and too large areas in which the number of observations is insufficient to smooth out the irregularities of the currents. In these regions the charts present a more or less random distribution of currents and may cause misleading conclusions about the general water movements, when they are used without reference to the number of observations; but fortunately these are normally indicated in the atlases. However, the charts of the average current vectors are an excellent and precise statistical presentation of our knowledge about the currents, and are probably of more interest to the scientist than to the navigator. On the other hand, the method of averaging current vectors often obscures the real picture of the circulation in cases when the average is drawn only from few observations. When drawing current charts of the western North Pacific Ocean, SCHOTT (1939) points out that the plotting of individual current observations usually gives a much more homogeneous picture of the circulation than the use of average current vectors. This is due to the fact that the eye easily eliminates those observations which do not fit into the general tendency of the currents of that area.

Moreover, attention should be given to the fact that every vector-averaging process tends to reduce the velocity. First, the observation itself gives too small a value, if the direction of the current changes during the period of observation; for example, a current flowing 12 hours northeast and 12 hours southeast at 1 knot gives only a displacement of 17 miles to the east, and the observed current velocity would be 0.7 knots. In the second step, when calculating the resultant current vector from the single observation, the same effect would again reduce the average velocity. Consequently, resultant current vectors always give minimal velocities of currents, and they should not be confused with the average current velocity, calculated without consideration of direction. All these facts make the use of average current vectors less advisable for navigators, although such vectors are a valuable source of basic information for the scientist.

IV. — CURRENT ROSES

In order to give a more detailed presentation of the actual current observations, current roses have been constructed, showing the frequency distribution of current velocities in different directions of the compass. Normally 8 or 16 main directions are selected, in which the frequencies of the current, subdivided into steps of current velocity, are given. An example of such current roses is given in figure 2. The construction of these current

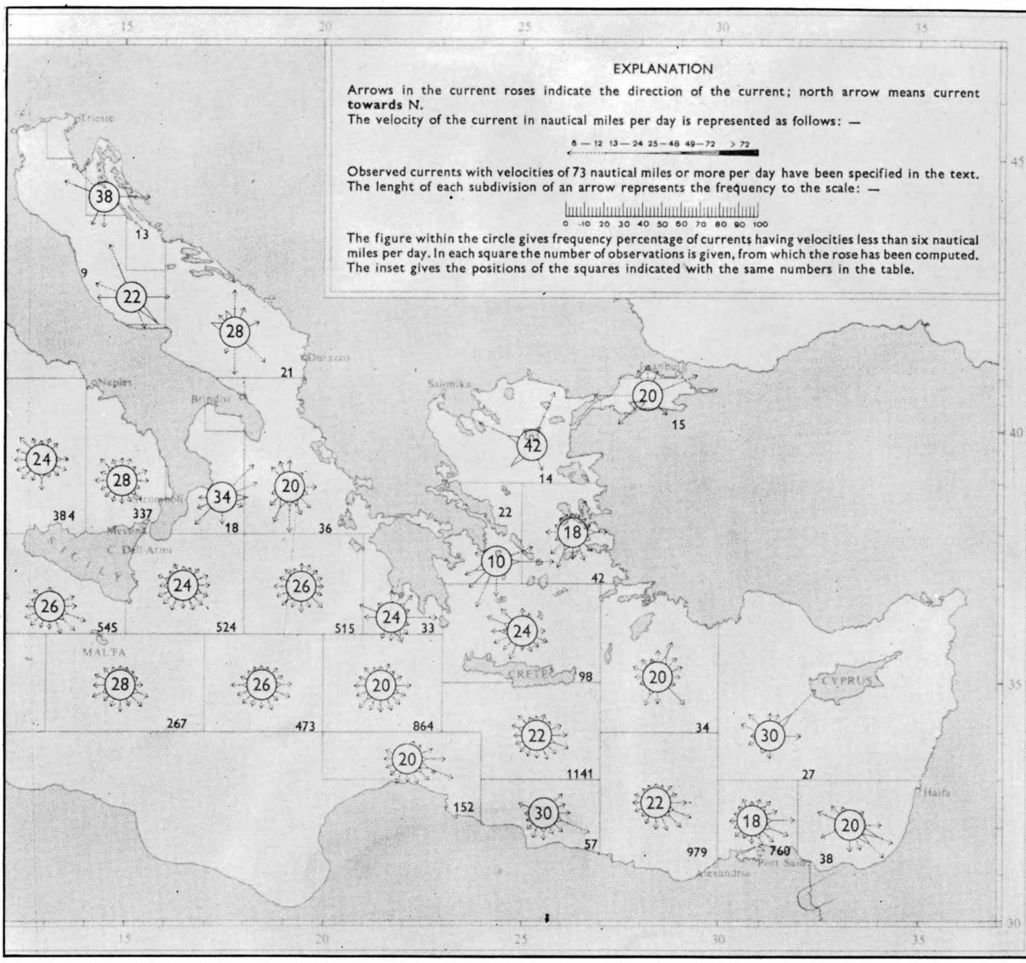

Fig. 2. — Chart of current roses. Section of the February chart of publication No. 138 of the Netherlands Meteorological Institute : Mediterranean Sea.

roses, however, requires many more observations than the calculation of a reliable resultant current vector. It can be said that at least 80 observations should be available. Therefore the current observations of a larger area, normally between 6 and 25 1°-squares, are combined for the construction of a current rose.

This combination of observations over a comparatively large area requires careful consideration of regions of a similar current character. The boundaries of areas for which current roses are constructed should never cross current boundaries, but coincide with them, in order to avoid the intermixing of observations of two different current systems. This implies that the areas for the construction of current roses can only be selected on the basis of an existing current chart, in which the boundaries of the different current systems are entered.

In contrast to the current vectors of 1°-squares, these current roses give a considerable variety of information. Normally one main current direction will be found, and the roses indicate the scattering of the current to both sides of this main direction. The scattering of the current velocity, the presence of strong currents in two different directions, and generally weak currents can also be seen from the current roses. These current roses are of special value if they are used against the background of weather conditions and are compared with the wind roses of the same area, which are usually added to current atlases. If the distribution of winds is similar to that of the currents it is likely that the currents of this area are strongly related to the actual wind, and observation of winds will help the navigator to determine the expected current, according to wind direction and force. If two or more pronounced current directions are indicated in the roses, the navigator can decide which current direction is applicable to the existing weather conditions. When the current of the region in question is not greatly dependent on the actual winds, as in most of the strongest ocean currents, this fact will easily be recognized from a comparison of the current and wind roses. In this case a current rose with a very pronounced direction and high velocities will correspond to a wind rose on which all directions, or only weak winds, appear. However, even in such cases, the actual winds can be used to decide whether the current will be deflected to the right or the left of its main direction, or will be strengthened or weakened by the wind. On the other hand, the existence of two pronounced current directions can indicate that a current boundary fluctuates, and that at times, currents of the other current regime are met in the area of the current rose under consideration. In such cases it is difficult for the navigator to decide which current vector should be used.

If the boundaries of the areas for which current roses are constructed are properly selected, and include areas of equal current characteristics, they then form the best information which can be given to the navigator. They give a considerable amount of information on the distribution of direction and velocity of the currents, and enable the navigator to select the expected current properly in relation to the wind roses and observations of the actual weather conditions. For scientific purposes, on the other hand, they give an obvious impression of the constancy or variability of the currents.

V. — NAUTICAL CURRENT CHARTS

Hydrographic offices of different countries publish current charts and atlases for the use of navigators. These normally contain one set of monthly current vector charts and one set of monthly current rose charts, but their appearance is somewhat different, even if certain standards of presentation have been proved to be most suitable, and these differences are worth some consideration.

Ocean current charts, showing only average current vectors for every month and every 1°-square, are published by the United States Navy Hydrographic Office. Examination of these atlases fully confirms the conclusions arrived at in the above section on resultant current vectors. Many of the 1°-squares are empty, and many others contain too few observations to present a conclusive picture of the oceanic circulation or to give even a reliable average current. Over vast areas these current atlases demonstrate nothing more than the variability of ocean currents (compare fig. 1). Only in regions with many observations along the main shipping routes do these atlases give conclusive information. Thus their value for navigation in regions outside the main shipping routes is very limited, but for the scientist they are a valuable source of observations for the study of currents, if the necessary precautions in evaluation are taken and the data critically considered.

The same applies to the average current vectors presented for every month and 1°-square in the atlases of the Royal Netherlands Meteorological Institute published for the China Sea, the Red Sea, the Mediterranean and the waters around Australia. The average vectors give a fairly good picture of the circulation only along the main shipping routes, but these atlases are accompanied by current roses, which supply much more information to the navigator. In the Netherlands current sheets for the Indian Ocean the vector averages are given for 2°-squares, resulting in a much better picture of the circulation of the ocean, and the current roses are superimposed on these vectors. This combination seems to be most suitable for use by navigators. The current roses are divided into 16 directions, giving in every case a sufficient presentation of the scattering of the currents.

Additional information given in the Netherlands atlases and in the British current charts is the listing of maximal observed ship sets. From these the navigator can calculate the maximal current velocities to be expected in the major ocean currents and allow for these.

The current atlases published by the British Admiralty normally use squares of 2° latitude and 4° longitude, for which the average current vectors are calculated. The observations are arranged quarterly by seasons, so that four charts are available. This method leads to a considerable increase of the number of observations available for the calculation of the average vectors, on the average, 24 times that of charts using 1°-squares and monthly intervals. On the other hand, this method very often suppresses local effects of the circulation, which are of special interest in waters relatively close to the coast. Thus, the speed of distinct coastal currents is normally slightly reduced by using 4° of longitude, and in some cases may even disappear. In the open ocean, on the other hand, where the number of observations is small and the annual variation of the circulation less important, this method has certain advantages. A serious disadvantage, however, is the use of seasonal charts in the monsoon regions, where the circulation is completely reversed twice a year, and the current pattern changes rapidly. In these regions a current system often collapses completely within the course of one month and is replaced by another one. For the current roses of the British atlases even larger squares are used, often comprising more than 50 1°-squares. Consequently, the number of observations in these areas will be sufficient to compile a very detailed rose for nearly all parts of the oceans, but too often currents of different current systems are combined in the roses.

All the atlases mentioned above are merely an objective presentation of statistical material about currents without any interpretation of the results. The only subjective factor in these charts is the selection of the boundaries of the regions for which current roses are constructed. But there are objections to the view of BARLOW (1939), who holds the opinion that this presentation of statistical material is the only way to chart ocean currents. First, every observation requires interpretation before reliable results can be derived. Second, our knowledge of the ocean currents goes far beyond what we have gained from observations alone, owing to other scientific investigations. Third, every observation is subject to errors and random fluctuations, which must be carefully considered before results can be derived. Consequently it is advisable and necessary not to restrict the charting of ocean currents to a pure presentation of observations, but to evaluate also other scientific results. These results of scientific investigations can considerably increase the information on ocean currents that may be given in charts. In particular, in regions with only a small number of observations, the scientific interpretation of them and the use of other types of information will result in a representative picture of the currents. Further, the derivation of the boundaries of the different branches of the circulation and their charting will give the navigator additional help in understanding the characteristics of surface currents, and will also lead to a more suitable selection of areas for which fully representative current roses can be constructed.

A number of current charts and atlases have been compiled to take account of these factors; these have a completely different appearance from those mentioned above. They consist of many current arrows, equally distributed over the charted region and giving a complete picture of the surface circulation. Indications are not always given as to whether the currents are derived from a large number of observations or are drawn from only a few observations and based on other results. The average current velocity is shown and sometimes also the constancy of the currents. In contrast to the presentation of current vectors and current roses, which give numerical values of the current derived from direct observations, these current charts permit more of a visual picture of the general circulation.

Such current charts are published by the United States Navy Hydrographic Office for Antarctica, the China Sea, and the Indonesian waters, for which monthly charts are drawn to meet the requirements of the highly variable monsoon circulation. An example, showing a section of the chart for the Antarctic, is given in figure 3. The general pattern of the circulation and the boundaries of the main currents are easily seen. The arrangement of the current arrows is to indicate stream lines, which permit us to follow the spreading of the different water masses. On the other hand, current velocity is indicated only by figures giving its rough average value. The same type of presentation is used for currents on pilot charts of the United States Navy Hydrographic Office. It can be said, however, that these values should normally be sufficient for the navigator, when considering the variability of currents and the relatively small number of observations available in large parts of the oceans. The precise numerical values of velocity, given in the atlases of the current vectors, on the other hand, give the illusion of high accuracy and often also of high constancy of current, which is normally not justified. Similar current charts are often added to sailing directions, to indicate currents of the region under consideration.

A similar type of current chart, but with more detailed information, is the Chart of Ocean Currents published by the German Hydrographic Institute, from which a section is reproduced as figure 4. In these current

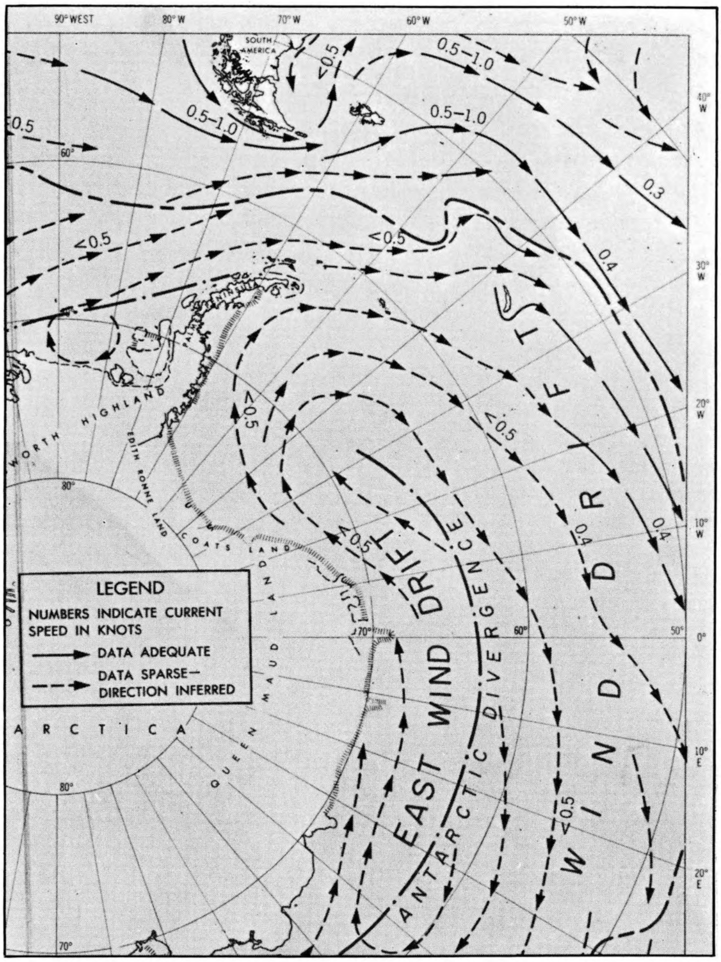

Fig. 3. — Chart of generalized surface circulation. Section of fig. 5 of the Oceanographic Atlas of the Polar Seas, Antarctic. U.S. Navy Hydrographic Office Publication No. 705.

charts, which are compiled from current observations as well as other scientific information, and which are described in detail by Schott (1942), the current arrows are not arranged to follow stream lines, but to cover the chart as adequately as possible. The velocity of the currents is indicated by the thickness of the current arrows, their constancy by the length of the arrows. In addition the current arrows are drawn more densely in the range of the stronger ocean currents, thus emphazing them and demonstrating the greater variability in the other regions. The current boundaries, their divergences and the convergences are entered in the charts, but these charts give only the average annual circulation of the oceans, except in the equatorial regions where the two monsoon seasons are charted. This presentation might be sufficient in large regions of very uniform current character, but at least in the monsoon regions it is insufficient for the navigator, because the circulation changes there very rapidly and the current pattern

FIG. 4. — Chart of ocean surface currents, demonstrating velocity and constancy of currents. Section of German Hydrographic Institute Chart No. 2802.

during the transition stages often differs considerably from that during the full development of the monsoons.

These current charts may unjustly seem to the navigator less accurate than a presentation of current vectors and roses giving numerical values. This may be because navigators prefer the use of numerical values, which they can use directly in their calculations, rather than graphical presentation, where they are forced to select or interpolate first the suitable value. For a general idea of the circulation, however, graphical charts are to be preferred, because they show a well-interpreted pattern of the circulation without gaps, rather than statistical raw material, in which random observations as well as adequately confirmed data are entered and their critical consideration is left to the reader.

VI. — SCIENTIFIC CURRENT PRESENTATIONS

Even if current atlases for use by navigators are drawn up by scientists, giving full consideration to nautical requirements, charts constructed for scientific purposes sometimes differ very much from these presentations. Purely scientific presentations should always show an interpretation of the observations, rather than the observations themselves. Besides direct current observations, results derived from the spreading of certain water masses, from the distribution of properties, from dynamical calculations, and from theoretical considerations are used for the construction of the charts. In regions with too few observations the currents are inferred from other kinds of information. Thus scientific current charts are often more a result of the analysis of various phenomena and aspects of ocean currents than a pure representation of observations.

The purposes of scientific current presentations differ greatly from those of current charts for the navigator. The scientist is, in general, less interested in the numerical values of the current velocity in a certain place than as in the general distribution of ocean currents. He wants a clear picture of the circulation pattern, indicating the positions of current axes, current boundaries, divergences and convergences, and large eddies and countercurrents, in order to obtain an insight into the structure of the current systems. To arrive at such a presentation various obsolete ideas must be discarded. These are firstly the conception of closed surface stream lines, indicating a circular flow of the water masses in the oceans. This conception is erroneous, because of the considerable importance of vertical movements in the oceans, causing large stationary divergences and convergences of the surface flow. On both sides of these lines, the current arrows show diverging or converging directions, and even opposite directions of flow may occur. The second misconception, which has now been overcome, is that of large streamless regions in the centres of the large eddies of the oceanic circulation, as in the Sargasso Sea. These assumptions could not be confirmed by scientific investigations.

Another questionable factor concerns the use of average current vectors for the compiling of current charts. It is now assumed that the average velocity in the most frequent direction results in a more plausible picture of the circulation than the average current vectors. SCHUMACHER (1940) points out in this connection that : " charts based on vector averages give, in my opinion, an idealized situation, which is certainly never simultaneously present over large areas, and for the precise calculation of which over large areas of the oceans the critical number of observations will never be available. Often these observations are distributed very sparsely over long periods. On the other hand, presentations of the ocean currents should only indicate which current direction and velocity are most likely to be observed over large areas (and can be expected with the highest probability). For practical purposes, charts showing current arrows have more reality and value than the charts of current vectors, but for teaching and as a basis for pure scientific discussions they also seem to be quite as useful. Moreover, it is more likely that the current pattern, given by current arrows, sometimes really appears over large areas simultaneously. " The current vectors include too much of the random distribution of currents and are not significant for the characteristic current distribution, while the use of the most frequent directions gives a picture of the significant current pattern. Thus, the main purpose of scientific current charts is the derivation of a complete and logical pattern of the surface circulation, showing the formation, flow, and disappearance of the different branches of currents.

Here no reference is made to current charts derived directly from dynamical computations, nor to those showing the fine structure of ocean currents, which normally give a quasi-synoptic picture of a very unstable and variable current pattern. Only those current presentations which present the average circulation may be discussed. Two different techniques are normally applied, the one showing current arrows, the other stream lines.

Scientific current charts, showing current arrows, are usually similar to those presented in figures 3 and 4. The arrows are arranged to cover the region most conveniently, without regard to the density of the observations. The velocity of the currents is indicated by the thickness and the feathering of the arrows. Often also a measure of the constancy of the currents is given. These measures, however, have been the subject of many discussions, and many different methods have been tried, but no mathematical method could really be successful owing to the paucity of observations, which do not satisfy the requirements of statistical analysis.

Nowadays the constancy of ocean currents is usually indicated by the percentage of observed directions, which fall into an octant or quadrant, extending to both sides of the most frequent direction. This gives a certain idea of the probability of current directions, but for nautical requirements and for detailed information, current roses must be preferred. Often current charts are correlated with charts showing distribution of other factors to derive conclusions about the distribution of certain water masses. An example of such an investigation is the presentation given by NEUMANN and SCHUMACHER (1944) for the region off the east coast of North America, comparing currents and density distribution in different seasons.

The presentation of ocean currents by means of stream lines, on the other hand, implies many theoretical assumptions, which often lead to rather complicated and sometimes doubtful pictures of the circulation, especially in the boundary regions of current systems. Among others, SCHUMACHER (1943) has drawn stream lines of the flow of surface water

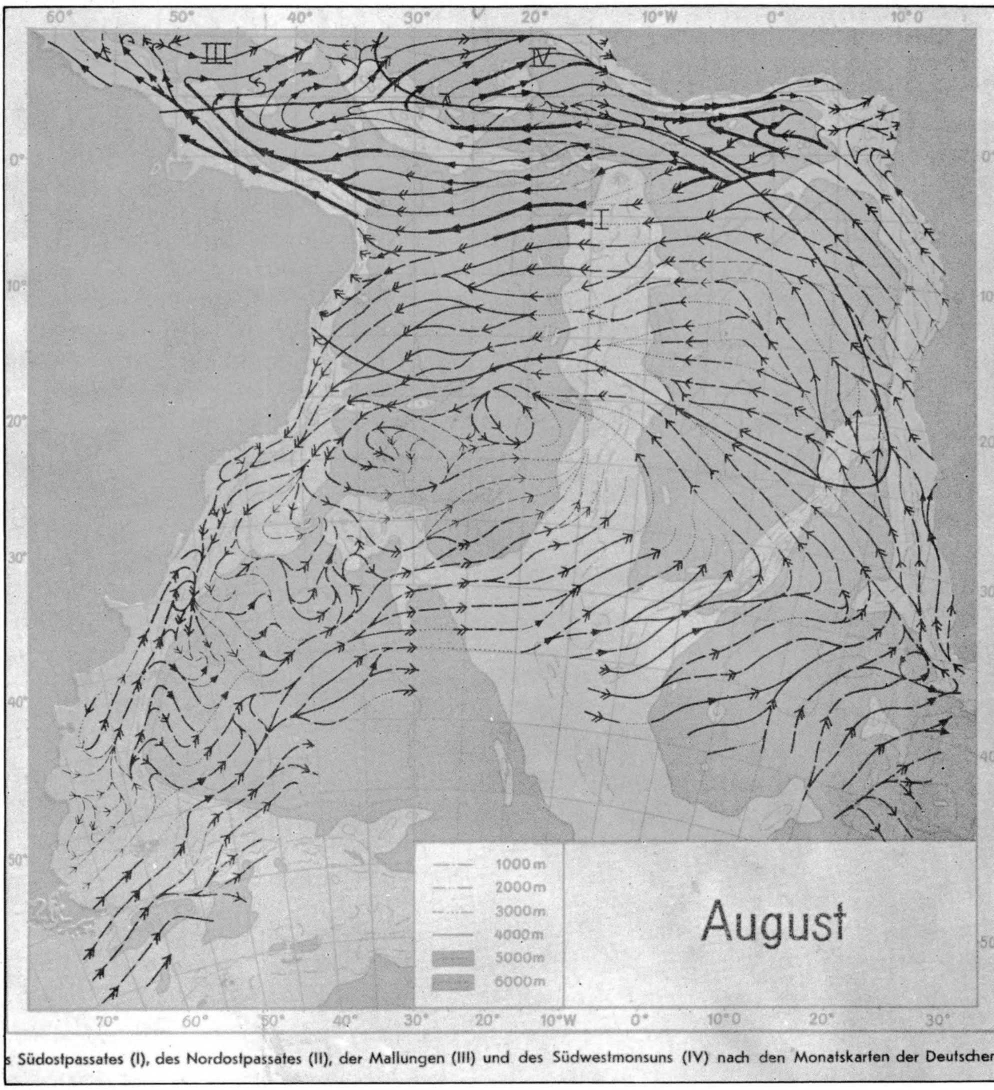

FIG. 5. — Chart of stream lines for the South Atlantic Ocean in August, after Schumacher (1943). Arrows indicate velocity, thickness of the stream lines indicates constancy of the currents.

for the South Atlantic Ocean, and one of his monthly charts is presented as figure 5. This chart demonstrates clearly the complexity of the flow, the appearance of divergences and convergences over almost the entire ocean, and the presence of other fairly complicated flow structures. It must, however, be borne in mind that these stream lines present only the flow at the surface, and that the complicated structure of the flow results partly from variations in the thickness of the moving layer, which can vary between 50 and several hundred metres, and partly from variations of the current velocity. Vertical movements, the sinking and upwelling of water masses, present over nearly the entire ocean, contribute to this complexity. In addition many subjective assumptions are encountered in these stream line charts, which, in the end, do not really satisfy because of their artificial appearance. Moreover, it must be mentioned that considerable labour is necessary for compiling such charts from the basic data.

Summarizing, it can be stated that two kinds of current presentations are normally used for nautical purposes : the average current vector charts and the current rose charts. The first have considerable disadvantages, because of the paucity of observations now available in most parts of the oceans, and because of the obscuring of the information by the mathematical process of vector averaging. The current roses, on the other hand, comprise the most valuable information which can be given to navigators. They permit us to find the expected current in different directions and in relation to the wind conditions, and to gain a picture of the frequency distribution of directions. These presentations are easily understood.

Two other kinds of current presentations in scientific use are current arrows and stream lines. Charts of stream lines are often difficult to understand, especially for the layman; construction involves considerable work and they usually show a fairly complicated structure of flow. Therefore they are not very numerous and have not found general application. The charts most suitable for all purposes are those indicating currents by means of current arrows, showing the prevailing current pattern.

REFERENCES

Von Arx, W. S., 1950. An electromagnetic method for measuring the velocity of ocean currents from a ship under way. *Pap. Phys. Oceanogr.* 11 : 3.

Barlow, E. W., 1939. The charting of ocean currents. *Mar. Obs.* 16 : 135.

Deutsches Hydrographisches Institut, 1943, Weltkarte der Meeresströmungen. No. 2802.

Deutsches Hydrographisches Institut, Monatskarten (for various parts of the oceans), No. 2419-2422.

Great Britain. *Admiralty*, 1949. General surface current circulation - the World. Adm. Chart No. 5310.

Great Britain. *Meteorological Office*, Marine Division. Ocean Currents. Various publ.

Koninklijk Nederlands Meteorologisch Instituut, 1957. Middellandse Zee. Publ. 138.

Koninklijk Nederlands Meteorologisch Instituut. Oceanografische en Meteorologische Gegevens. Various.

Meyer, H., 1923. Oberflächenströmungen des Atlantischen Ozeans im Februar. *Veroff. Inst. Meeresk. Univ. Berl.* 11.

Neumann, G. and Schumacher, A., 1944. Strömungen und Dichte der Meeresoberfläche vor der Ostküste Nordamerikas. *Ann. Hydrog. Berl.* 72 : 10.

Schott, G., 1939. Die äquatorialen Strömungen des westlichen Stillen Ozeans. *Ann. Hydrog. Berl.* 67.

Schott, G., 1942. Die Grundlagen einer Weltkarte der Meeresströmunger. *Ann. Hydrogr. Berl.* 70, 11.

SCHUMACHER, A., 1940. Monatskarten der Oberflächenstromungen im Nordatlantischen Ozean. *Ann. Hydrogr. Berl.* 68, 4.

U.S. Navy Hydrographic Office, 1945. Currents in the South China, Java, Celebes and Sulu Seas. H. O. Publ. No. 236.

U.S. Navy Hydrographic Office. Atlas of surface currents (for various parts of the oceans). Various.

U.S. Navy Hydrographic Office, 1957. Oceanographic Atlas of the Polar Seas, Antarctic. H.O. Publ. No. 705.