OUR PRESENT KNOWLEDGE OF THE INTERACTION BETWEEN THE ATMOSPHERE AND THE OCEANS*

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1. Introduction

TILL recently, the atmosphere and the oceans were generally treated more or less as two separate systems and the fact that they could, from many points of view, be considered as a very intimately coupled single system came to be realised by meteorologists and physical oceanographers only within the last decade or so. Consequent on this recognition, a considerable volume of literature has grown during the last 10 or 12 years on the subject of interaction between the atmosphere and the oceans, and this newly-acquired knowledge is bound to have a far-reaching effect on the future development of meteorology as well as oceanography.

The subject can, broadly speaking, be discussed under the following heads:

(1) Energy exchange between the atmosphere and the oceans,
(2) Mechanical interaction between the atmosphere and the oceans,
(3) Chemical interaction between the atmosphere and the oceans.

It will be impossible to attempt a detailed survey of these three aspects in this short article. The author will therefore only very briefly summarise here a few recent contributions relating to energy exchange and mechanical interaction. The chemical interaction problems will be dealt with in a later article.

2. Energy Exchange between the Atmosphere and the Oceans

One of the first objectives in the study of the exchange problem is to delineate at least the broad patterns of seasonal and regional variations in the major components of the energy exchange. Woodrow C. Jacobs[1] has, in a good measure, achieved this objective by publishing the annual and seasonal charts and tables for various components of exchange in respect of the north Atlantic and north Pacific Oceans. In this article, we shall discuss only his evaluation of two important components of exchange, namely, the rate of exchange of sensible heat Q_h and the rate of energy loss from the sea surface through evaporation, Q_e. For this purpose, he has mainly made use of the equation derived by Sverdrup[2]

$$E = K_a (e_w - e_a)\ W_a$$

Where E is the rate of evaporation, K_a is the evaporation factor at a height 'a' above the sea surface, e_w and e_a are the vapour pressures at the sea surface and at the height 'a' above the sea surface respectively and W_a is the wind speed at height 'a'. While using this equation, Jacobs adopted a mean evaporation factor K which he computed by a semi-empirical method. From the evaporation value E, he obtained the corresponding energy equivalent Q_e by multiplying it by L_t, the latent heat of vaporisation at temperature 't'.

The rate of exchange of sensible heat Q_h has been computed by Jacobs by using the equation (Jacobs[1]) $Q_h = RL_tE$ cal. cm.$^{-2}$ day^{-1} where R, known as the Bowen ratio, is given by the expression

$$R = 0 \cdot 64\ \frac{P}{1000} \left(\frac{t_w - t_a}{e_w - e_a}\right)$$

where t_w and t_a are the sea surface and air temperatures respectively, e_w is the vapour pressure at the water surface, e_a is the vapour pressure in the air and P is the atmospheric pressure (Jacobs[1]).

The upper diagram in Fig. 1 shows the annual values of Q_h and the lower diagram in the same figure shows the annual values of Q_e. An examination of these annual diagrams and the seasonal diagrams (not reproduced here) of Q_h and Q_e shows the following:

(a) The isolines for Q_h show roughly the same configuration as those for Q_e. There are however no tropical areas of maximum Q_h within the trade wind regions as we have for evaporation in those areas.
(b) The atmosphere is directly heated by the sea surface at significant rates only in the middle and high latitudes along the eastern sides of the continents. Such heating occurs principally during the winter. During summer, large areas of the sea are actually receiving some energy by conduction from the atmosphere.

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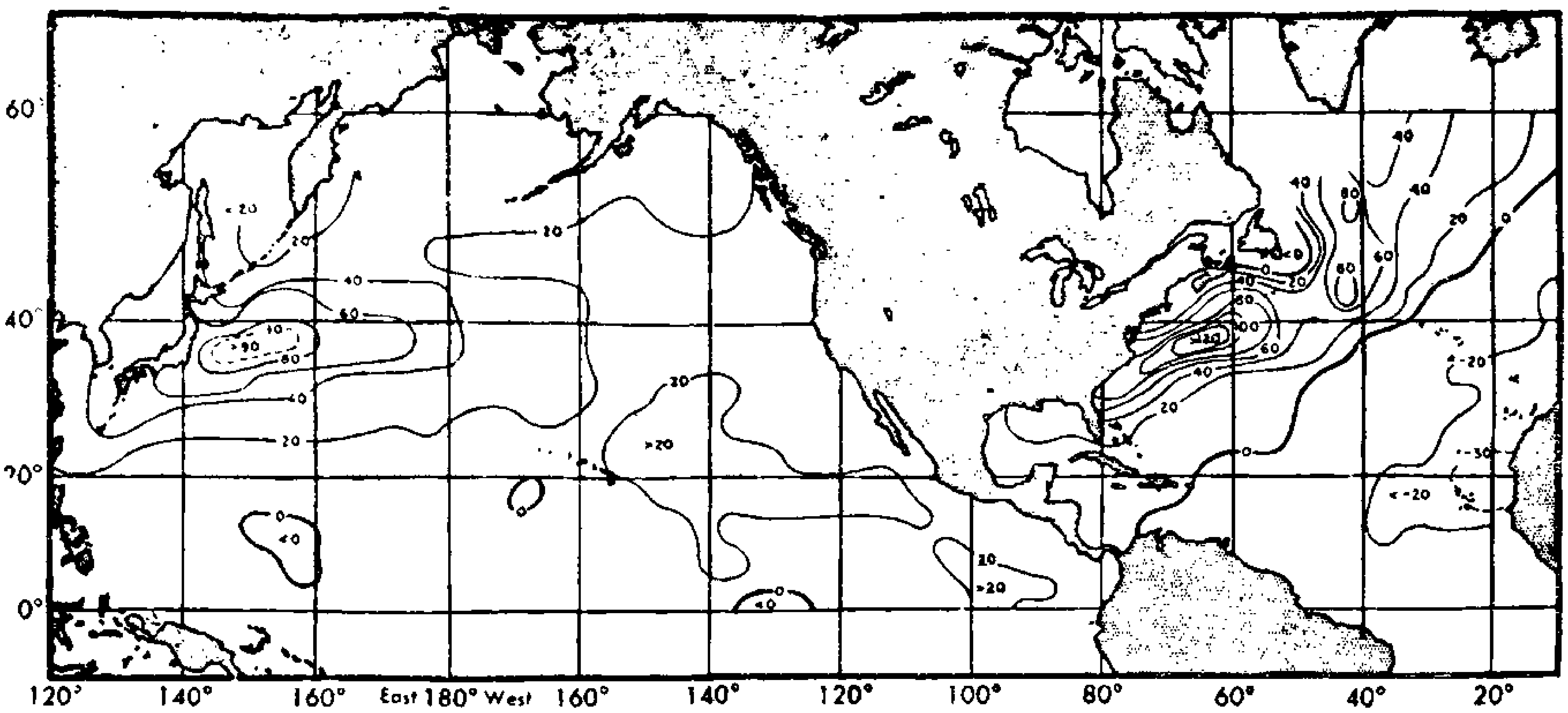
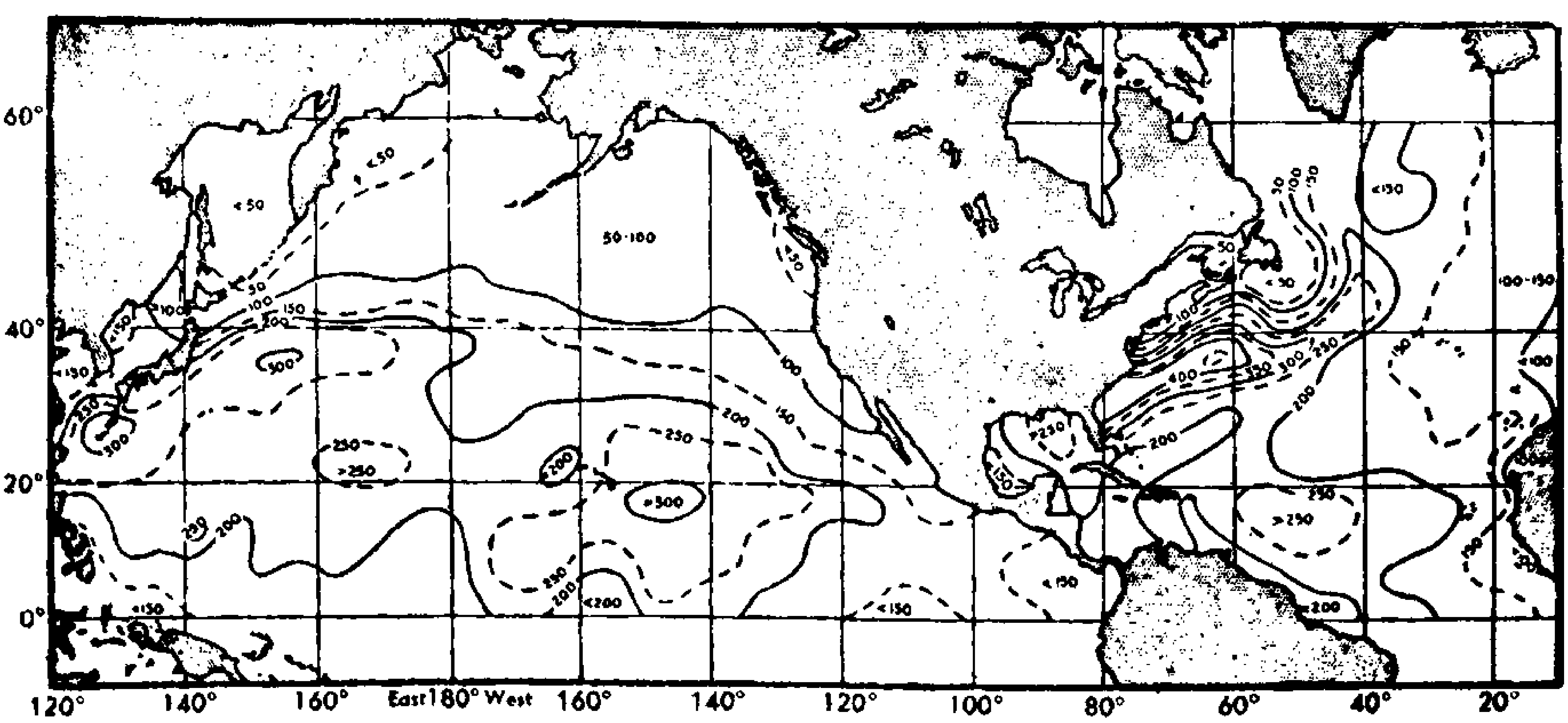
(c) The atmosphere is receiving moisture principally in the middle and lower latitudes.



(a)



(b)

FIG. 1. (*a*) The annual values of the rate of exchange of sensible heat between ocean and atmosphere Q_h over the North Atlantic and North Pacific, expressed in calories per square centimetre per day.

FIG. 1 (*b*). The annual values of the rate of energy loss from the sea surface, through evaporation Q_e over the North Atlantic and North Pacific expressed in calories per square centimetre per day. (The values above can be converted into rough evaporation rates by considering that the isometric interval of 50 cal. cm.$^{-2}$ day^{-1} is approximately equivalent to an evaporation rate of 12 in year^{-1}.) (From W. C. Jacobs, 1951, "Large-scale aspects of energy transformation over the oceans," *Compendium of Meteorology*, T. F. Malone, Editor, Published by American Meteorological Society through contractual support of the Air Force Cambridge Research Laboratories.

(d) There are significant maxima of Q_h as well as Q_e within the Kuroshio and the Gulf-stream.

Investigations on evaporation more or less on the same lines have been carried out by S. V. Venkateswaran[3] in respect of the Indian Ocean. Combining his seasonal charts for evaporation with the precipitation charts of Jacobs, he has mapped out the excess of evaporation over precipitation (E – P) in the Indian Ocean. He has also made use of similar E – P data for other oceans and drawn a composite diagram for 'all oceans'. Figure 2 which has been reproduced from his paper shows his comparative analysis. If we remember that neither E nor P is at present directly measured, the agreement between the zonal averages for "all oceans" arrived at by independent methods must be considered as satisfactory at latitudes which are not very close to the equator.

Another outstanding contribution which should be mentioned in this connection is the synoptic survey of the interaction between the sea and atmosphere over the north Atlantic by J. Bjerknes. Making use of the records for a 50-year period, Bjerknes[4] has shown how the long trend of cooling of the sea surface north of

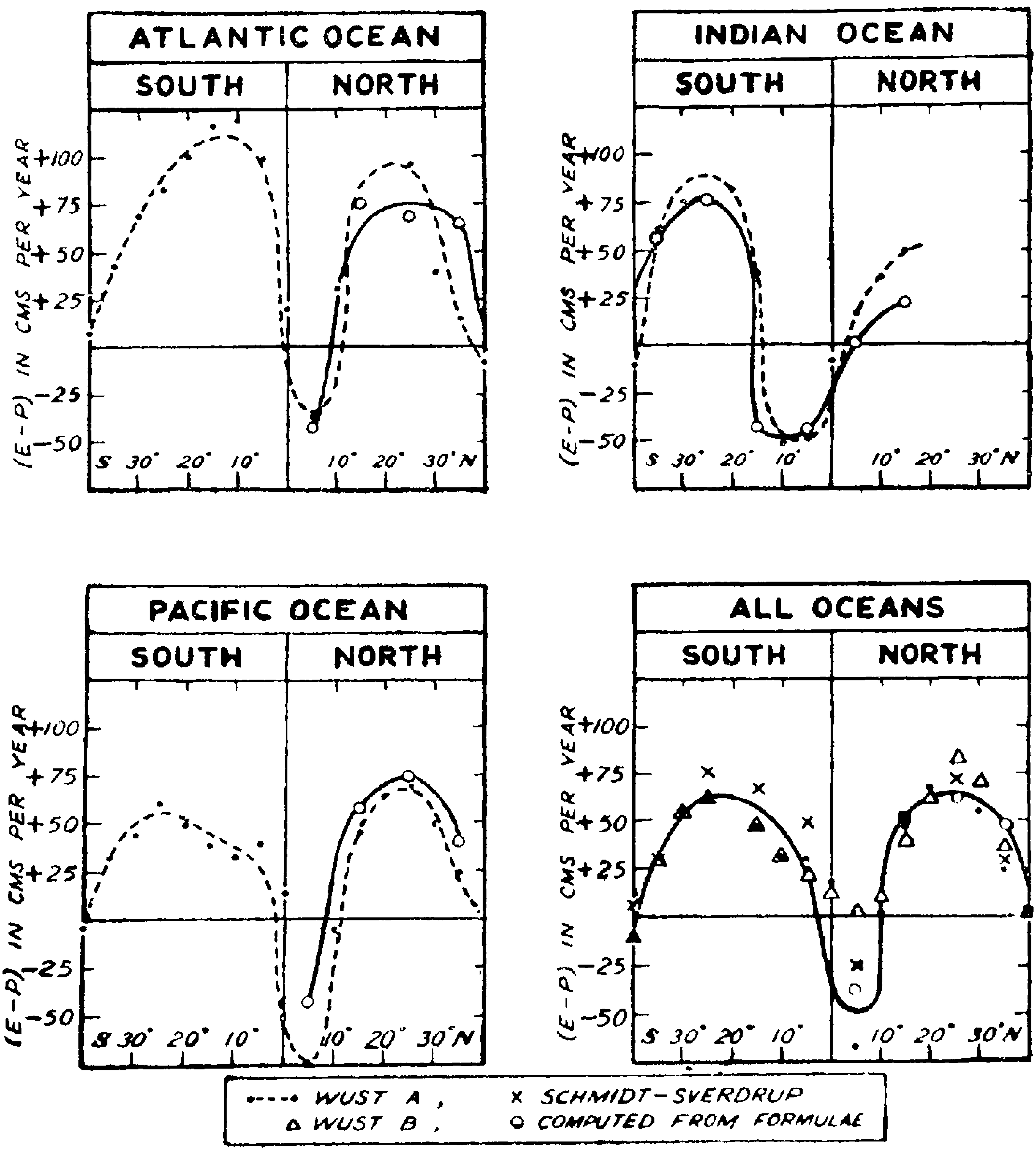


FIG. 2. Annual excess of evaporation over precipitation at different latitudes over the oceans. For the North Atlantic and North Pacific, the "computed" values are those of Jacobs while for the Indian Ocean they have been taken by the author from his own results. [From Venkateswaran, S. V., *Indian Journal of Meteorology and Geophysics*, 1956, 7 (3).]

50° N. was associated with a deepening of the semi-permanent meteorological low over the Iceland region. This deepening increased the cyclonic wind stress over that area causing thereby upwelling of the waters and lowering of the temperatures of the surface waters. Bjerknes has also shown how the intensification of the sub-tropical high during the same period, warmed up the jet-stream part of the Gulf-stream and how along with other contributory causes it intensified the jet-stream itself. These changes in the ocean produced a *feed-back* effect on the atmosphere and thereby prolonged the one-way trend. Bjerknes' study has clearly brought out that the climatic trends for a couple of years to two decades can be better understood by studying the interaction of the atmosphere and the oceans.

be seen from the diagram that there is a significant warming in the Jet-stream part of the Gulf-stream. The zone roughly between 50° N. and 60° N. shows a net temperature fall with maximum intensity east of 30° W. This is exactly the region where there was a net increase in cyclonic wind stress and which may have caused increased upwelling and consequent cooling of the sea surface.

In a very recent article, Gunnvald Boyum[6] has made use of the observations from the Ocean Weather Station 'M' at 66° N. and 2° E. collected during a period of 10 years and derived a semi-empirical expression connecting the rate of change of air temperature to the temperature difference between the sea and the air. According to his results, there should be *no* exchange of heat between the atmosphere and the oceanic

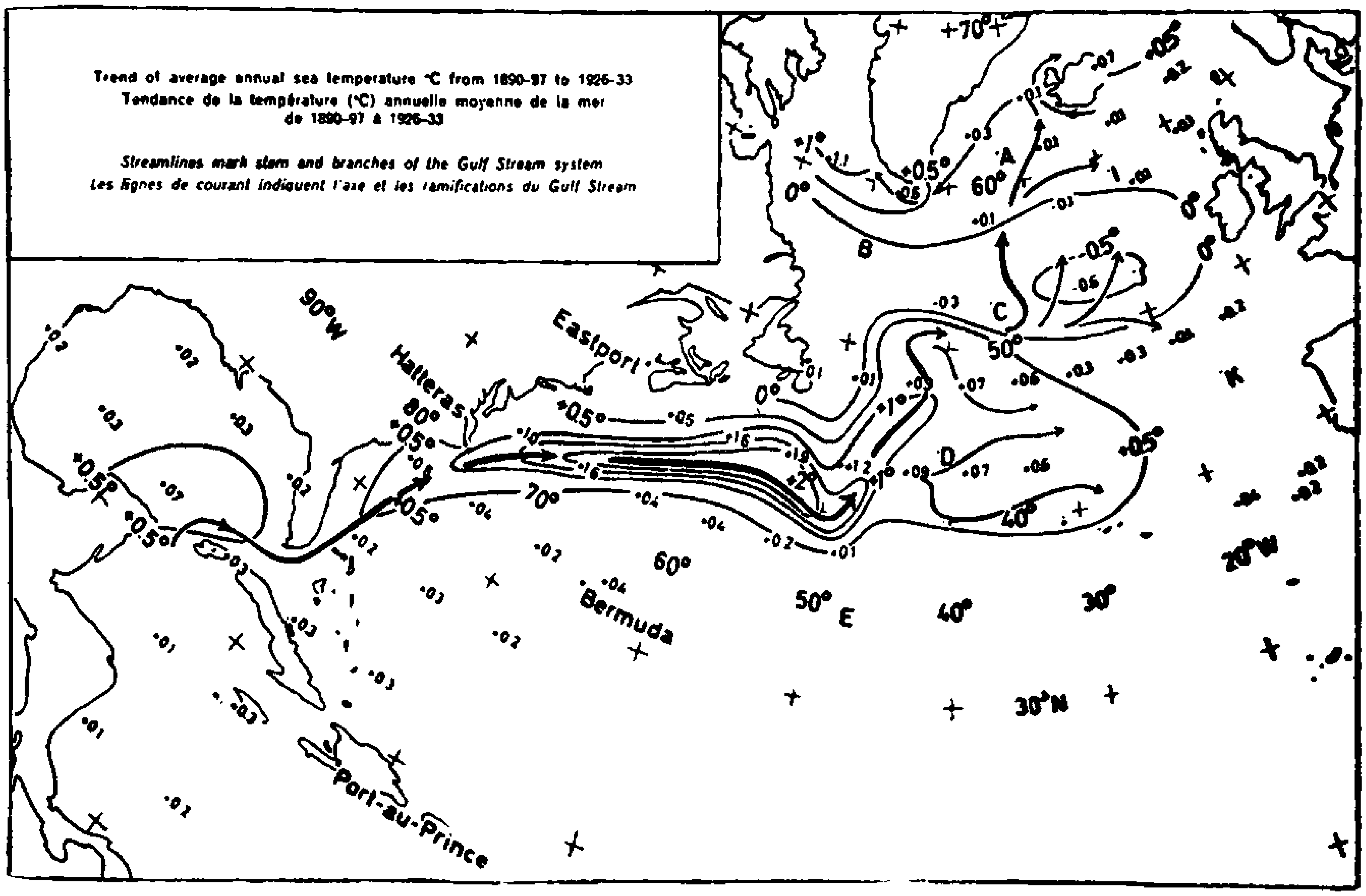


FIG. 3. The long trend of average annual sea temperature. [From Bjerknes, J., *W.M.O. Bulletin*, July 1960, 9 (3) and G. Dietrich, *Deutsche Hydrographische Zeitschrift*, 1957, Band 10, Heft, 2, pp. 39-61. Positions of present weather ships in Capital letters].

Figure 3 is a diagram reproduced from one of Bjerknes'[5] papers. The streamlines in the diagram refer to the Gulf-stream near North America. The continuous lines represent the lines of equal differences between the average annual sea surface temperatures during the two eight-year periods 1890-97 and 1926-33. It will

surface if the difference in the temperature between the sea surface and the air is less than 0·7° C. This conclusion has received support from a recent measurement made by Ewing and McAlister[7] of the long wave infra-red radiation from the top 0·1 mm. of the evaporating ocean. These radiometric observations which appear to be free from doubt show the existence of a cool surface layer characterised by departures of as much as 0·6° C. from the temperatures of the sea surface determined by conventional methods. Ewing and McAlister[7] conclude that the cold layer may be expected from evaporation effects and also from long wave radiation from the surface.

3. Mechanical Interaction between the Atmosphere and the Oceans

Gravity Waves.—Among the wind-generated waves which are not appreciably influenced by the deflecting force of the earth's rotation, special mention will be made here only about gravity waves. In the last decade an entirely new approach which may be referred to as the *wave-spectrum* approach has been made in regard to this problem of wind-generated gravity waves. In this approach, waves are studied by means of probability models and wave-records are analysed by statistical techniques. The sea surface disturbed by the wind is regarded as the sum of an infinite number of classical sine waves of small amplitudes extending over an infinite frequency spectrum with a specified spectral distribution of energy and having all directions of propagation. The phases of these waves are completely at random and consequently the wave-recording is completely unpredictable. "However" to quote Schule,[8] "the statistical properties of a recording are predictable even though the recording itself is unpredictable." The wave-recording approximates to what is known as a Gaussian process if a linear process is assumed. Based on this approach which we owe to many scientists, notably Pierson and Neumann,[9] a vast amount of empirical work has been done by the U.S. Navy Hydrographic Office which enables us to predict the wave characteristics in the open sea under idealised meteorological conditions.

Wind-Driven Ocean Currents.—Even a casual glance at any world map of ocean currents will reveal that the surface circulations in the oceans are strongest in the west. It was only about a decade ago that it was quantitatively explained by Munk[10] that this pronounced asymmetry with the strongest currents squeezed into a narrow belt on the western side of the oceans was a dynamical necessity for enhancing the frictional and planetary vorticity tendencies (*i.e.*, spinning tendency due to the rotation of the earth) to orders of magnitude greater than the wind stress. According to Munk, this is the way by which we can achieve balance between the vorticity tendency in the western as well as on the eastern sides of the oceans and obtain a steady state. This vorticity theory of the wind-driven ocean currents does not however account for several other important features of these currents, especially in the southern Hemisphere.

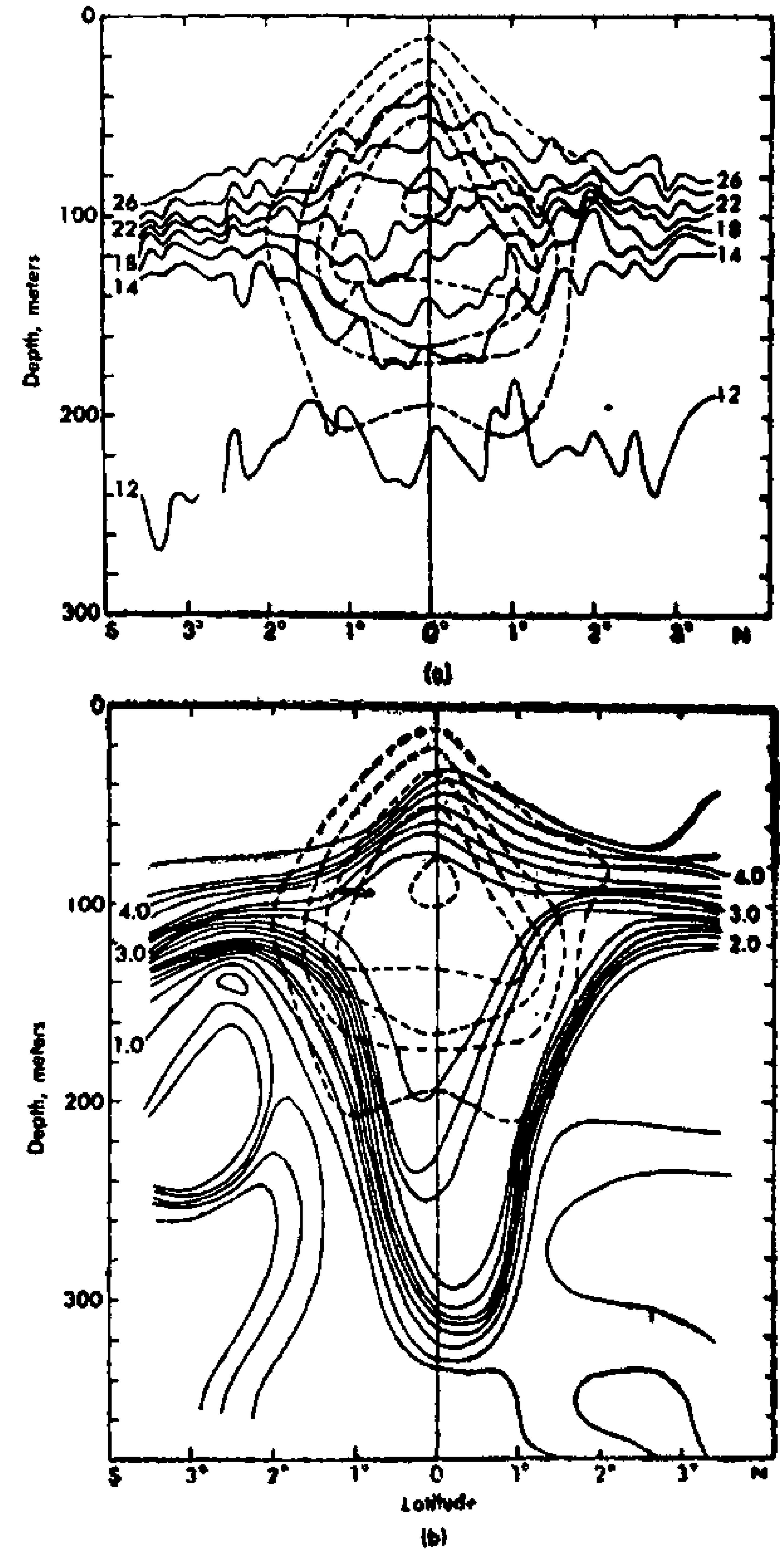


FIG. 4. Temperature and oxygen sections in the Cromewell Current in the Equatorial Pacific (Cross-section at 140° W., 20–22 April 1958). Velocity cross-section (dashed lines) superimposed on temperature and oxygen sections. Velocity contours 25–125 cm./sec. Temperature (upper diagrams) is in degrees centigrade. Oxygen (lower diagram) is in ml./litre: (From John A. Knauss, *Deep Sea Research*, 1960, **6**. Published by Pergamon Press.)

These difficulties have led to the formulation very recently of a yet another new circulation regime known as the *thermohaline* circulation. We shall not discuss this here except to state that the general circulation of the oceans as known today consists of a wind-driven gyre under the zonal wind belts and a pattern of thermally excited transport systems which extend over the whole globe and deep down to the bottom of the oceans and which work in the same sense as the wind-driven circulations in the northern Hemisphere but, on a broad basis, oppose them in the southern Hemisphere.

The Cromwell Current.—One of the very recent important discoveries which has baffled Physical Oceanographers and stimulated considerable amount of thinking among dynamical oceanographers and meteorologists is the Cromwell Current known by the name of its discoverer. This sub-surface undercurrent flows eastward in the equatorial Pacific extending symmetrically on either side of the equator (Knauss[11]). It is considered as a major current and is characterised by low temperatures and high oxygen values (*see* Fig. 4). There is evidence (Gerhard Neumann[12]) that the equatorial Atlantic has also such a current. Neumann[12] concludes that one may expect to find this undercurrent in the Atlantic strongest west of 20° W. longitude and weaker towards the east.

No completely satisfactory explanation for the Cromwell Current has yet been given. Knauss[11] believes that upwelling "will be a necessary part of any explanation of the current". Robert S. Arthur,[13] Henry Stommel,[14] Jules G. Charney,[15] Allan R. Robinson[16] and G. Veronis[17] have formulated various types of theoretical models to account for the existence of this remarkable sub-surface current. All these models associate this current with the surface wind stress. Special mention should be made here of the contribution by Jules G. Charney. He has shown that for the range of parameters applicable to the Cromwell Current, the inertial forces are as important as the frictional forces. He calculates the motion for several values of the coefficient of eddy viscosity. His calculation gives an undercurrent whose intensity increases with decreasing values of the coefficient of eddy viscosity. For sufficiently small values of eddy viscosity, the undercurrent resembles the Cromwell Current in intensity, in width and in horizontal and vertical velocity variations with depth.

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4. Bjerknes, J., *Geofys. Publ.*, Joner, 1962, **24**, 115.
5. — *W.M.O. Bull.*, 1960, **9**, 151.
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12. Neumann, G., *Ibid.*, 1959–60, **6**, 328.
13. Arthur, Roberts. S., *Ibid.*, 1959–60, **6**, 287.
14. Stommel, Henry, *Ibid.*, 1959–60, **6**, 298.
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16. Robinson, Allan, R., *Ibid.*, 1959–60, **6**, 311.
17. Veronis, G., *Ibid.*, 1959–60, **6**, 318.

SOME ASPECTS OF THE SEASONAL AND DIURNAL CHANGES OF CIRCULATION OVER INDIA AND NEIGHBOURHOOD*

R. ANANTHAKRISHNAN

1. Seasonal Variations

THE ultimate source of energy for all weather processes is the Sun. The working substance for the atmospheric heat engine is water vapour which is transported to the atmosphere from the oceanic surface as a result of sea-air interaction. Along with it the water vapour also transports heat energy in the form of latent heat from the great oceanic reservoir to the atmosphere.

Consequent on the apparent annual movement of the Sun between the Tropic of Cancer and the Tropic of Capricorn, the solar insolation intercepted by the latitudinal belts of the two hemispheres undergoes corresponding variations. While this is the primary cause for the seasons, the seasonal changes of weather are profoundly dependent on the distribution of land and sea masses over the earth's surface because of the differences in the physical properties of soil and water in respect of their response to incident solar radiation. This differential response sets up temperature contrasts between land and sea which in turn give

* This is a summary of the talk given at the 28th Annual Meeting of the Indian Academy of Sciences at Bombay in December 1962.