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THE PACIFIC OCEAN[1]

By Dr. H. U. SVERDRUP

SCRIPPS INSTITUTION OF OCEANOGRAPHY, LA JOLLA

THE Pacific Ocean can be discussed from a number of different points of view. One could deal with the history of its discovery and exploration from the time of Magellan's long and perilous journey up to the present day when clippers of the air cross and recross the ocean in a few days, or one could discuss its importance as a highway of the sea carrying trade between large surrounding countries, or one might consider it as determining the routes for the migration of man and the spreading of culture from island group to island group and from continent to continent. I shall not attempt to discuss the Pacific Ocean from any of these points of view, but shall, instead, deal with the water masses themselves and with the systems of prevailing currents, and shall indicate how the ocean influences the climate and the weather of the surrounding land and how the productivity of the sea, which is becoming increasingly important to the economy of man, varies from one region to another because of the character of the currents.

As a starting point let us examine the distribution of surface temperature over the Pacific Ocean in the month of August. The striking features are, in the first place, the vast extent of the tropical areas in which the surface temperature is very high, above 24° C. (75° F.), and, in the second place, the tongues of low temperature which extend towards the Equator along the western boundaries of the ocean, that is, along the coasts of North and South America. Due to the intrusion towards the Equator of these cold

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waters the width of the tropical region is much smaller on the American side than on the Asiatic-Australian side. This contrast between west and east is closely related to the character of the currents, and we shall later on return to this relationship. The point which will be emphasized now is that the surface waters of the Pacific Ocean are very warm over large areas in the tropics, moderately warm over smaller areas in middle latitudes, and cold only in high northerly and high southerly regions.

Observations of the temperature at subsurface levels show, however, that only a relatively thin surface layer is heated and that the enormous water masses which fill all the deep basins of the Pacific Ocean are cold, having a temperature which lies less than 2° C. above freezing. Thus, to the south of the Aleutian Islands the very surface waters in summer are moderately warm, but below a depth of 60 meters the temperature varies between 3° and 1.6° only. In the trade-wind region in the North Pacific high surface temperatures are encountered, but below a thin top layer the temperature decreases rapidly with depth and below 1,500 meters again remains below 3°. In the region of the trade-winds of the Southern Hemisphere a similar temperature distribution is found. In 50° S near the center line of the South Pacific, the temperature is above 5° down to a depth of 900 meters, but below 1,500 meters is nearly the same as that observed in the other localities.

Below a depth of 2,000 meters the salinity of the Pacific waters is nearly constant, the salt content varying only between 34.6 and 34.7 parts per thousand (per mille), that is, only by about 0.1 gram in one kilogram of water.

The deep water of the Pacific is of greater density than the waters near the surface, and in the Pacific as well as in all other oceans we find the water masses arranged in stable stratification, that is, we always find the denser waters near the bottom and the lighter water masses at the surface. Now, the density of the ocean waters is changed only when the water is in contact with the atmosphere where it may be heated or cooled or where the salinity may be increased or decreased by evaporation or precipitation. In general, we therefore find certain regions where the surface waters attain a great density, and from where they sink to the level at which the density attained at the surface prevails. These are regions in which the subsurface water masses are formed. The formation of the uniform deep water of the Pacific was, however, for a long time puzzling to oceanographers because no region in the Pacific Ocean could be found in which such water was formed at the surface and sank towards the bottom. Over wide areas in the northwestern North Pacific the temperature is in winter as low or lower than the temperature of the deep water but the salinity remains so low that the water is much lighter than the deep water and can not sink towards the bottom. Similarly, in the Antarctic part of the South Pacific no sinking of cooled surface water takes place. The puzzle was solved when it was realized that the deep water of the Pacific is not formed in that ocean but originates mainly from the Atlantic Ocean, where sinking of surface water takes place both in high northerly and high southerly latitudes.

In the Atlantic Ocean deep water of high salinity ($34.9^0/_{00}$) and relatively high temperature (2.5° C.) is formed to the north where the high salinity water of the Gulf Stream is cooled in winter and attains such a high density that it sinks to great depths. The salinity of the North Atlantic deep water over large areas is increased by addition of high salinity water flowing out from the Mediterranean. In the Antarctic region to the south of the Atlantic the density of the water is increased by cooling and freezing of ice, leading to the formation of a bottom water of low temperature (− 0.6° C.) and moderate salinity ($34.6^0/_{00}$). These two types of deep water spread south and north, respectively, and the spreading can be recognized in vertical sections showing tongue-like isotherms and isohalsines. Mixing takes place and, due to this, a fairly uniform body of water is formed to the north of the Antarctic Continent within the region of the circumpolar Antarctic Current which circles the Antarctic Continent as the greatest current of all oceans. Within the greater part of this body the temperature varies only between 2.5° and 0°, and the salinity between $34.65^0/_{00}$ and $34.75^0/_{00}$. In the Atlantic and Indian sectors the influence of the warm and saline deep water of the northern seas and the cold and less saline bottom water of the Antarctic is evident, but otherwise the striking feature is presented by the very small differences in temperature and salinity within the entire region. The water is particularly uniform in the Pacific sector and it is this uniform circumpolar water which spreads north and fills the entire basins of the Pacific, being slightly diluted by low salinity water from higher levels. In the South Pacific a vertical circulation provides for exchange of water with the Antarctic circumpolar water mass, but in the North Pacific such circulation is lacking. There the small inflow of deep water from the south appears to be compensated by an outflow to the Indian Ocean between the islands of the East Indian Archipelago.

A vertical section showing the distribution of temperature and salinity in the Pacific Ocean clearly demonstrates the point that on the whole the waters of the Pacific are very cold and that only a relatively thin surface layer is heated. Between the deep water and the warm surface layers intermediate water masses of low salinity are present. These are formed partly in the Antarctic and partly in the Arctic regions of the Pacific Ocean and have their counterparts in the Atlantic.

Let us now return to conditions near the surface of the ocean in order to examine how the general distribution of temperature in the surface layers is related to the prevailing currents. Keeping in mind the picture of the distribution of surface temperature it is readily recognized that the regions of low temperature off the coasts of North America and South America are regions in which the general currents flow from higher to lower latitudes bringing water of low temperature closer to the Equator. In contrast the regions in the western part of the Pacific where extensive warm water masses are found are regions where the general direction of the current is from lower to higher latitudes such that warm water is carried away from the Equator.

The direction of the surface currents corresponds more or less to the direction of the prevailing winds over the different parts of the ocean, with such exceptions as must be expected because of the coast lines. Thus, the relatively narrow and swift Kuroshio off the coast of Japan is not directly related to the local winds but runs in winter partly against the wind, but this current must be considered as the necessary continuation of the North Equatorial Current which flows from east to west under the influence of the prevailing trade winds.

Among the surface currents of the Pacific Ocean there is, however, one which is not obviously related to the prevailing winds nor to the character of the coast lines, and that is the Equatorial Counter Current which is embedded as a narrow and swift current towards the east between the west-flowing North and South Equatorial Currents. The nature of the Equatorial Counter Current has only recently become clearly understood. It is explained as follows by Montgomery and Palmén: The prevailing trade winds exert a stress on the sea surface which, besides contributing towards maintaining the equatorial currents, also lead to a piling-up of light surface water against the western boundaries of the ocean. From oceanographic observations it is evident that such a piling-up takes place because off the American coast the thickness of the warm surface layer is as little as 20 meters, whereas off the Philippines and New Guinea the corresponding thickness is 200 meters or more. As a consequence of this piling-up the sea surface actually rises from east to west, the rise amounting to about 65 centimeters. This sloping surface has not been determined, of course, by precision leveling, but conclusions as to its existence are based on convincing oceanographic evidence. The slope in the trade-wind regions is balanced by the stress which the wind exerts on the sea surface, but between the trade wind regions lies the equatorial belt of calms where no wind stress acts on the sea surface. Therefore within the calm belt the water must flow downhill from the western to the eastern side of the ocean and the counter current represents this downhill flow. Frictional forces prevent the water from attaining as high velocities as would correspond to a free fall of 65 centimeters. If there were no friction a counter current should reach a velocity of nearly seven knots, that is, seven nautical miles per hour, when approaching the American coast, but the maximum velocity lies between 1 and 2 knots only.

Owing to the friction, a transverse circulation must develop within the counter current, which is quite shallow and confined to movement of the warm surface waters. Theoretical examinations by Defant lead to the result that this transverse circulation should have such character that water is drawn towards the surface at the northern boundary of the current and at the Equator, and sinks at the southern boundary of the counter current. Such a transverse circulation evidently exists in the Pacific, where detailed measurements of temperature, salinity and chemical constituents were made by the *Carnegie* in 1929. This circulation also has an effect on the distribution of organisms because wherever subsurface water is drawn towards the surface, conditions for development of organisms are favorable. The subsurface waters are rich in plant nutrients such as phosphates and nitrates and, when brought near the surface where there is light such that photosynthetic activity can go on, a rich crop of plants will develop followed by large populations of animals. During the crossing of the Equator by the *Carnegie* in 1929 net hauls were made for examination of the microscopic organisms, and according to these the variation in total plankton agreed perfectly with the above reasoning. Maximum amounts of plankton were found at the northern boundary of the counter current and near the Equator, where subsurface water was drawn towards the surface.

The counter current does not appear in the distribution of surface temperatures because it is a feature of the surface layers only, it is a shallow current which is found completely within one uniform climatological area, the Tropics. The other major currents are evident in the distribution of the temperature, as has already been pointed out, but from a chart of the surface temperature and also from a chart showing the character of the surface currents it appears as if all transitions in the ocean are gradual, as if the change in the character of the water when passing from lower to higher latitudes or from west to east takes place in such a gradual manner that no boundary regions between different currents can be recognized. Examination of subsurface conditions reveals, however, that this impression is quite erroneous and that, on the contrary, well-defined water masses are present separated by relatively narrow regions of transition.

In order to recognize these water masses it is necessary to plot the data from the sea, particularly the temperature and the salinity, in a special manner. The procedure is best illustrated by means of a diagram (Fig. 1). In this diagram are shown the vertical distribution of temperature and salinity at two stations in the Gulf Stream off North Carolina. Examining these curves only there appears to be little similarity between the conditions at the two stations. Thus, at the one which was closest to the coast a temperature of 15° was encountered at a depth of 300 meters, whereas at the station at greater distance from the coast the same temperature was encountered at the depth of 650 meters. The discrepancy between conditions at the two stations disappears, however, if the observed temperatures are plotted against the observed salinity, as has been done in the diagram to the right. From this diagram it is seen that the water which at the one station was found to be between the depths of 277 meters and 461 meters is of exactly the same character as that found at the other station between 490 and 790 meters. Or, in other words, a definite relation exists between the temperature and the salinity such that within the same water mass the corresponding values of temperature and salinity fall on a well-defined curve. Therefore, by plotting the observed temperatures and salinity in a diagram one can recognize a given water mass of different character.

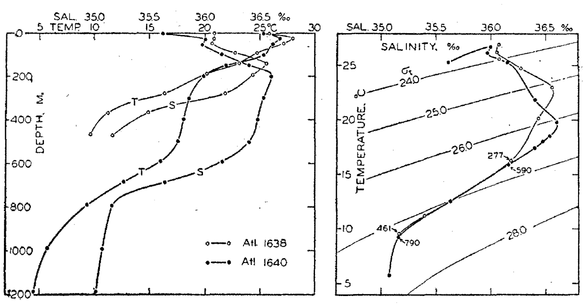

FIG. 1. *Left.* Temperature (T) and salinity (S) at two stations off Onslow Bay, N. C., plotted against depth. *Right.* Temperature and salinity at the same stations plotted against each other.

Applying this examination to the South Pacific, one finds there several well-defined regions within which typically different water masses are present (Fig. 2), the Subantarctic which occupies the southern part of the ocean and extends along the coast of South America to about 15°S, the eastern and western Central Water Masses and the Equatorial Water Mass, which is wide in the east and narrow in the west. The character of these water masses is shown in Fig. 3.

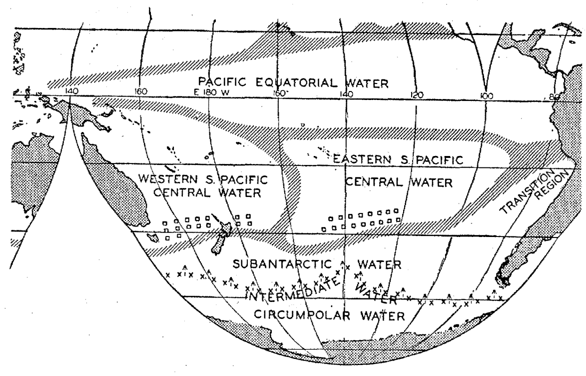

FIG. 2. Regional distribution of the water masses of the South Pacific. Areas in which the central water masses are formed are indicated by squares, area in which intermediate water is formed is shown by crosses.

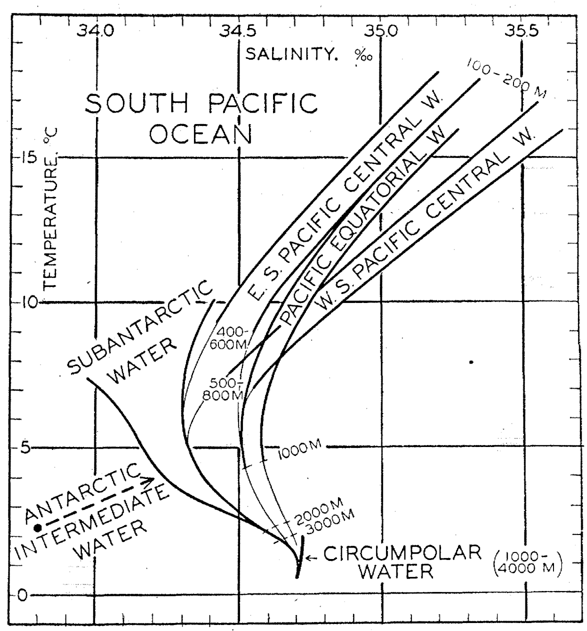

FIG. 3. The water masses of the South Pacific shown in a temperature-salinity diagram.

In this diagram no single T-S curves are entered but, instead, bands are shown, the significance of which is that corresponding values of temperature and salinity fall inside of the lines which represent the boundaries of the bands.

In the diagram the uniform circumpolar water appears as a short piece of a curve because the salinity of that water is nearly constant at $34.7^{0}/_{00}$ and the temperature varies only between 2° and 0.5°. The deep water below the other water masses is nearly similar to the circumpolar water, as is evident from the fact that all curves converge at their lower ends. Above the deep water the Antarctic Intermediate Water shows up by its low salinity values and above this again are found the other water masses. The Central Water Mass of the Western South Pacific is similar to the corresponding water masses of the Indian and Atlantic Oceans, being formed in a similar manner under similar external conditions. The Eastern Water Mass has a somewhat lower salinity, probably because of admixture of Subantarctic water, and the Equatorial Water Mass is intermediate between the two and must, therefore, mainly originate in the South Pacific.

Turning to the North Pacific, we encounter a similar distribution of water masses. Again two Central Water Masses are present (Fig. 4), one small eastern

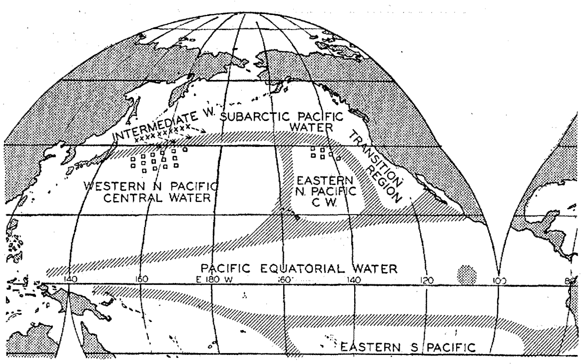

FIG. 4. Regional distribution of the water masses of the North Pacific. Areas in which the central water masses are formed are indicated by squares, area in which intermediate water is formed is shown by crosses.

and one large western, and to the north of them is found a large body of Subarctic water. It may be mentioned here that in the North and South Atlantic and Indian Oceans only one Central Water Mass is present, but in the North and the South Pacific Oceans two are found, probably because these oceans are very wide and because frequently two areas of atmospheric high pressure are present over these seas.

The character of the water masses can be illustrated by a diagram similar to that used for showing the water masses of the South Pacific (Fig. 5). Again, the uniform nature of the deep water is evident from the convergences of the different curves. Above the deep water intermediate water is present, but the formation of this intermediate water is more complicated and in some regions two salinity minima appear. The Central Water Masses are of much lower salinity than the corresponding ones in the South Pacific, indicating that the Equatorial Water Mass must originate in the South Pacific as was already pointed out. The Subarctic Water has a low temperature and a low

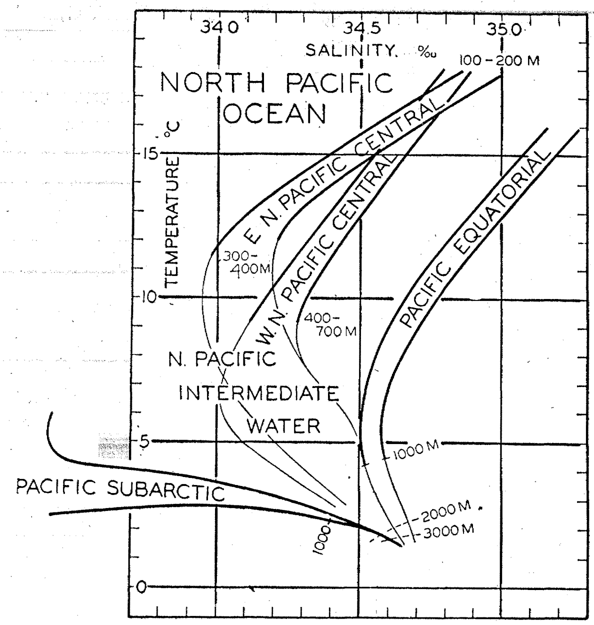

FIG. 5. The water masses of the North Pacific shown in a temperature-salinity diagram.

salinity which increases with depth until the values of the deep water are reached. The one feature to be stressed is that, except for the Eastern North Pacific Central Water Mass, these different water masses are all well defined and all are separated by relatively narrow regions of transition.

The circulation of the North Pacific can now be presented in a more definite manner than by maps showing the surface currents, because a chart can be prepared showing the general direction in which water is transported by the ocean currents and the amounts of water carried by the different branches. Such a chart is shown in Fig. 6 in which the transport by the different branches of the current system is given in millions of cubic meters per second. Thus the maximum transport by the Japan Current is as high as 65 million cubic meters per second, whereas the California Current carries about 10 million cubic meters per

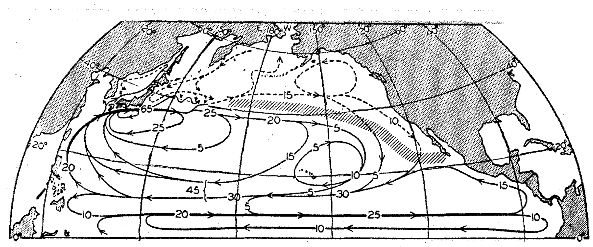

FIG. 6. Transport by the currents of the North Pacific. Lines indicate direction of transport and numbers give volumes of waters expressed as millions of cubic meters per second.

second. As a comparison it may be mentioned that the Mississippi River carries on an average 120,000 m^3/sec.

The chart shows the equatorial currents between which the counter current is embedded. It shows the intense Kuroshio, which is part of a big gyral in the western Pacific; it shows the presence of a smaller gyral between the Hawaiian Islands and North America, and it also shows how water of the Kuroshio becomes mixed with the cold water of the south-flowing Oyashio such that in the Northwestern Pacific a new water mass, the Subarctic Water Mass, is formed by intensive cooling and by dilution owing to excessive precipitation. This water flows to the east as a cold current, the Subarctic Current of the Pacific, part of which bends south and follows the west coast of the United States and Lower California, until it meets and becomes mixed with the Equatorial waters.

It is not possible to prepare a similar map for the South Pacific because sufficient data are not available, but from the information at hand it is certain that, in general, the currents of the two parts of the ocean are mirror images of each other. The California Current is a counterpart of the Peru Current, which is even more conspicuous and exerts a greater influence upon the distribution of organisms in the sea and upon the climatic conditions.

I have attempted to give a brief review of the structure of the water masses of the Pacific and the relation of prevailing currents to this structure. In conclusion a few words may be added as to the meteorological significance of our increased understanding of ocean circulation and as to the relation of the productivity of the sea to the water masses and currents. It has long been recognized that the oceans exercise a thermostatic control on the climate. The sea receives in summer a great surplus of radiation from the sun and the sky which in that season is mainly used for raising the temperature of the water, and in winter is given off to the air when cold winds blow from the continent, or is used for evaporation. Only recently has it been possible to examine more closely in what regions the heat is given off to the atmosphere and where the maximum evaporation takes place. According to a study which is now in progress, the warm waters of the Kuroshio give off in winter enormous amounts of heat as they flow north, whereas only small amounts are released over the eastern part of the ocean.

Off Japan the maximum amounts of heat given off are greater than 240 gm cal/cm^2/day, that is, about half the amount which in that region is received in summer. Similarly, the evaporation from the waters of the Kuroshio reaches in winter values greater than 0.8 cm/day, corresponding to a transfer of about 480 gm cal/cm^2/day of latent heat, or about as much as is received in summer. Evidently, the exchange of heat and the evaporation from the sea surface is closely related to the oceanic circulation and is very localized. Therefore, in winter the energy for the atmospheric disturbances in middle latitudes is supplied *by the sea in restricted areas*. These very areas have long been known to be those in which the atmospheric disturbances, the traveling cyclones, are formed, and the present results serve therefore to illustrate the close interaction between the atmosphere and the oceans.

As far as the productivity of the sea is concerned it should be borne in mind that the sea can support large populations of plants and, consequently, provide food to large numbers of animals only in regions where phosphates, nitrates and other plant nutrients are available in the surface layer where so much light penetrates that photosynthesis is possible. Phosphates and nitrates are present in relatively high concentrations in the subsurface layers where organic remains are decomposed, but in the surface layers the available amounts are depleted, owing to the activity of the plants, particularly the microscopic floating plants which represent the main animal food. In order to provide for continued production of plants, water from subsurface depths must be brought to the surface and this takes place in regions of intense mixing, in regions where in winter excessive cooling of the surface layer occurs such that convection currents reaching to considerable depths develop, and in regions where upwelling of subsurface water takes place. Upwelling of subsurface water is particularly conspicuous along the west coast of the United States and off the west coasts of Chile and Peru, and the waters off these coasts are known for their large fisheries. It may be enough to mention that during the last few years an average of about 500,000 tons of sardines have been caught off the American west coast and that according to estimates the amount of fish caught by the guano birds off Peru probably passes 3,000,000 tons a year. Regions of winter cooling and consequently thorough mixing to considerable depths are found in the Gulf of Alaska, around the Aleutian Islands, and in Bering Sea, where again fisheries of the greatest importance take place, and regions of intense mixing and partly of winter cooling are found around Japan, where probably the most intensive fishing in the Pacific is undertaken. The large open ocean areas are not devoid of life, but the populations do not reach such density that fishing operations can be undertaken with success. In the regions which have been mentioned and in regions adjacent to islands where considerable stirring occurs detailed and intensive work has to be carried out in order to learn more about the factors which control the productivity of the sea and which place a limit on the extent to which the sea can be exploited. At the Scripps Institution of Oceanography we shall for some time to come continue an intensive study of the productivity of the waters off southern California as one of our major objects.

Many of the conclusions which have been presented here are based on meager data, and many features of the picture which has been developed may have to be modified. Only the average state of the ocean has been dealt with because oceanography has not advanced far beyond the descriptive stage and because the understanding of the processes which maintain the average conditions is still incomplete. The field before us is enormous and it is my hope that in the future increasing efforts will be directed towards further exploration of the largest but least known of all oceans, the Pacific Ocean.

OBITUARY

DR. EDWARD KREMERS

ON July 9, 1941, Dr. Edward Kremers, director emeritus of the School of Pharmacy of the University of Wisconsin, died of a heart attack after having undergone some operations (intestinal cancer) with good success. He was seventy-six years of age.

Kremers was born at Milwaukee, Wisconsin, on February 23, 1865, as the scion of one of the German families coming to this country in order to escape the events around 1848. At the School of Pharmacy of the University of Wisconsin he earned his Ph.G. in 1886 and his B.S. in 1888. During his study at Madison Kremers enjoyed the fortune to have as his teacher one of the greatest scientists American pharmacy has presented to the world, Frederick B. Power. Working with Power on the chemistry of volatile oils he learned of the classical investigations executed in the field of phytochemistry by the German chemist Otto Wallach.

In the fall of 1888 Kremers went abroad and became a student with Wallach first at Bonn and later at Goettingen. In Bonn he attended also the lectures on structural chemistry delivered by Kekulé, of benzene ring fame. These two branches of chemistry, *i.e.,* phytochemistry and structural chemistry, have remained the two main fields of Kremers's scientific endeavor throughout his life, and it was in them that he gained world-wide reputation. The dissertation with which he fulfilled the requirements for his Goettingen doctor's degree in 1890 dealt with "The Isomerisms within the Terpene Group" and laid the ground for many later investigations. Returning to Madison, Kremers was instructor in pharmacy from 1890–1892, professor of pharmaceutical chemistry and director of the course in pharmacy at the University of Wisconsin from 1892–1935, succeeding Power.

Being a pharmacist by choice and by destiny Kremers attempted to make pharmacy a profession standing on the same educational level as the other academic callings and to give the pharmacist and the service rendered by him the advantage of special knowledge as well as of a broad general horizon. That is the reason for the fact that he already in 1902 introduced a four-year course in pharmacy, the first of this kind on American soil, and was likewise the first to establish graduate work for students of pharmacy in America leading to the Ph.D. with pharmacy as a major. In 1913 Kremers initiated the first "Pharmaceutical Experiment Station" in the United States, thus demonstrating the possibilities and usefulness of academic pharmaceutical research. Furthermore, it was Kremers who initiated the organization of a Historical Section of the American Pharmaceutical Association in 1902 and created in that way the first organized pharmaceutico-historical group not only in the U. S. A., but in the world. It is likewise very probable that the courses in history of pharmacy as well as of chemistry, announced by Kremers for the first time in 1907–08, were the first of their kind to be held as recognized subjects of instruction at an American university.

Finally, tribute has to be paid to the editor and the author Kremers. From 1896 to 1909 he edited, first together with Frederick Hoffmann and from 1901 alone, *The Pharmaceutical Review.* In 1898 Kremers created another journal restricted exclusively to the publication of scientific originals. This journal, bearing the title *Pharmaceutical Archives,* was discontinued in 1903 and revived in 1936. In 1912 Kremers published his classical brochure on "The Classification of Carbon Compounds," which was reprinted in 1924. He collaborated on the National Standard Dispensatory (1909) and translated Gildemeister-Hoffmann's work on "The Volatile Oils" from the German original into English (1900 and 1913). The pharmaceutico-historical collections of Kremers have formed the main basis for the "Kremers-Urdang History of Pharmacy" published in 1940, the first book containing a systematic survey on the development of American pharmacy.

Kremers served the United States Pharmacopoeia Committee as chairman of the Committee on Volatile Oils from 1900 to 1910 and the American Pharmaceutical Association as chairman of the Scientific Section and as historian. He refused the suggestion to become president of the association, but was made its