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TECHNICAL REPORT

THE DISTRIBUTION AND CHARACTERISTICS OF SURFACE BIOLUMINESCENCE IN THE OCEANS

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ABSTRACT

Approximately 3,000 reports of bioluminescent displays on file at the U. S. Naval Oceanographic Office are charted by three-month periods. In addition, various aspects of bioluminescence, bioluminescent organisms, seasonal and geographic distribution, and displays are discussed. A separate chart and a discussion of the puzzling phenomena of the "phosphorescent wheel" and "wave" displays are included.

FOREWORD

Bioluminescence of the sea generally has been regarded as a mysterious phenomenon, and observations in the past for the most part have been fragmentary and unreliable. It is only in recent times that systematic observations and explanations of the phenomenon have become available.

In an effort to summarize the data already in existence, the U. S. Naval Oceanographic Office has undertaken an intensive literature search which included reports extending back almost a century. As expected, reports of displays for the most part came from shipping lanes and included very little information from less frequented areas.

This study is published as part of the Oceanographic Office program in marine biology. It is intended as a small contribution to a field that has been sadly neglected for a long time.

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HISTORICAL RESUME

A fully developed luminescent sea is one of the most striking natural phenomena that mariners or sea travelers can witness. Many reports in the form of log entries or as part of various written narratives in travel books or cruise reports have referred to luminescent seas since ancient times. During past centuries these strong displays of light often were viewed as having mystical meanings and were identified with the supernatural. In the South Seas, for example, islanders considered the fire they used on land as originating from the brilliant luminescent seas they often encountered during their travels among the numerous islands. Whatever ancient peoples thought of bioluminescence, they left little record of their observances, except for a few poetic references and some more disciplined records by Aristotle.

Descriptive reports of bioluminescent seas of a more scientific nature increased after the 15th century. Various sea captains, whether on exploring, military, or commercial ventures, made numerous records of luminous seas from almost all the oceans of the world. One of the earliest descriptive reports on file concerned a "burning and glittering light of the sea ... as though all the Sea ourer had beene burning flames of fire." This luminous condition of the water was observed by the explorer John Davis in the 17th century near Ascension Island. The terms "burning sea" and "milky sea" often appeared in the records. The ocean surface, when strongly lighted by the phenomenon, appeared to be burning, to give off flames as if on fire, and to contain what appeared to be "smoldering coals." Sailors to this day have called such manifestations "phosphorescent seas." We now know this term to be a misnomer; the luminescence of the sea is bioluminescence, or biological light caused by living organisms, rather than phosphorescence, which in the strict sense results only from the irradiation of inanimate substances by radiant energy.

"Milky seas" were observed in various oceans, mostly tropical, and were particularly intensive in the Indian Ocean, Arabian Sea, and the seas of the Indonesian Archipelago. Stavorinus (1798), a Dutch navigator on a voyage to the East Indies, described this phenomenon near the coast of southern Saudi Arabia.

> "On the 30th (January) we met at night a very singular appearance in the color of the sea. It assumed so great a degree of whiteness that it was perfectly like milk... as the evening twilight diminished, it became whiter and increased gradually in whiteness till nine o'clock when it was so white that the whole sea appeared as if covered with a white sheet, or exactly like the appearance in the night time of a flat country overspread with snow."

This resemblance to a snow-covered plain led the Dutch to call such appearances the "winter ocean" or "the white water," the latter term particularly suited in describing the snow-white luminescence often observed during late winter in the Banda Sea.

Systematic collections of reports concerning bioluminescent seas were not made until comparatively recent times. During the latter half of the 19th century, articles published by the Meteorological Offices of both England and Germany included records of bioluminescent displays, primarily in the Atlantic Ocean. More recently the incidence of bioluminescence in the Atlantic was charted by Smith (1931). His charts were based upon numerous observations of bioluminescence reported in the British publication "The Marine Observer." The seasonal distribution of displays in the Arabian Sea and adjacent regions was reported in the publication "Der Seewart" (1939). Turner (1965) has recently written a comprehensive report on the nature and occurrence of marine bioluminescence. This report was received as our publication was going to press.

LUMINESCENT MARINE ORGANISMS

Plankton organisms chiefly are responsible for bioluminescence in the sea. The smallest forms are luminescent bacteria which usually live on decaying matter or within various marine animals. However, with a supply of the proper nutrients, luminescent bacteria can develop in great masses in the sea, causing a general bluish green glow in the water. The glow is usually diffuse and barely detectable, although exceptionally bright displays caused by luminous bacteria occasionally are observed in coastal regions near the outflow of large rivers. The light given off frequently outlines the current front where the river and ocean meet. Soviet investigators believe that luminescent bacteria have a much larger role in producing bioluminescence than that considered by American or European scientists.

Most bioluminescence in the oceans is produced by one-celled organisms called dinoflagellates. Of these small luminescent organisms, members of the genus Noctiluca are associated most frequently with strong displays of light. Although individuals are just visible to the eye, they can develop in such prodigious numbers that they color the water pink or red by day. Noctiluca is particularly abundant in coastal waters and at night imparts a rather brilliant greenish glow to the water when mechanically disturbed. Fishermen in some regions have long used the cry of "Noctiluca!" to bring fiery illuminations to the attention of their fellow fishermen, regardless of the organism causing the luminescence. Holder (1887) observed a display caused by vast accumulations of Noctiluca. He reported:

> "On the 10th of April, in the evening, the sea in the roadstead of Simonstown, Cape of Good Hope, presented an extraordinary phosphorescence of a most vivid character. At whatever points the phosphorescence was greatest, the water was colored on the surface as red blood and it contained such an immense quantity of little globules (Noctiluca) that it had the consistency of syrup, the globules consisting of more than half the volume of the seawater."

Other dinoflagellates also impart luminescence to the ocean. Pyrocystis, often confused with Noctiluca, is responsible for many extensive displays on the high seas. Organisms such as Ceratium, Peridinium, and Gonyaulax cause rather bright surface luminescence. Gonyaulax also is one of the prime causes of "red tide."

Other organisms responsible for luminous waters include crustaceans, such as ostracods, copepods, and euphausiids. Most of the displays caused by crustaceans are seen in colder waters and only rarely in tropical waters. The light emitted appears to twinkle at a distance because of abrupt flashing by each individual and is usually blue or green.

Luminescent jellyfishes (Medusae) also cause many displays. Large shining round or oval spots of light may appear in the water and the resulting luminous sea can be very bright and cover a large area. One of the most spectacular forms is the large luminescent medusa Pelagia noctiluca. When touched lightly the whole surface of the organism starts to luminesce, first at the point of contact, then spreading out to the umbrella and tentacles.

Ctenophores (comb jellies) are almost all luminescent, giving off a greenish glow. Luminescent transparent tunicates such as Salpa or Pyrosoma are responsible for some of the most spectacular displays reported by mariners. The latter organism is abundant in warm waters, and the light produced by large concentrations of colonies has been described by Thomson (1877) while a member of the CHALLENGER Expedition.

> "After leaving the Cape Verde Islands and going south in August, between 14° and 22°W and 5° and 17°N, the sea had been every night a perfect blaze of phosphorescence, the unbroken part of the surface appeared pitch black, but wherever there was the least ripple the whole line broke into a brilliant crest of clear white light. Near the ship the black interspaces predominated, but as the distance increased the glittering ridges looked closer until towards the horizon as far as the eye could reach, they seemed to run together and to melt into one continuous sea of light. The wake of the ship was an avenue of intense brightness. It was easy to read the smallest print sitting at the after-port in my cabin; the bows shed on either side rapidly widening wedges of radiance, so vivid as to throw the sails and rigging into distinct lights and shadows. The first night after leaving San Iago, the phosphorescence seemed to be chiefly due to large Pyrosoma of which we took many specimens with a tow net, and which glowed in the water with a white light like that from molten iron."

The slightest touch at one end of a colony of Pyrosoma can cause blue light to advance along the structure, each individual organism lighting in turn, until the whole luminesces brilliantly. Two popular names for this organism are the "fire body" and "fire cylinder." Various colors of

Pyrosoma luminescence have been reported, such as red, orange, yellow, and white light, but these result when the organisms are overexcited or dying. The light normally given off in the sea is bluish green or green. In colder water luminescent salps often are in great abundance and may be present as individuals or in great chainlike aggregations. They luminesce blue or green.

Except for the above organisms, the majority of luminescent forms in the ocean rarely occur in great enough numbers to create marked surface displays. However, some of these may create displays at certain times and places. Some seaworms may luminesce during their spawning periods when they swarm in surface waters, and the resulting light may be very strong. The lights Columbus observed on the night preceding his landing on San Salvador may have been caused by the luminescent worm Odontosyllis. Other forms, such as the deep-sea squid Watasenia scintillans (Japanese firefly squid), may congregate in large numbers on the surface during the spring, causing displays. Microscopic radiolarians occasionally may impart a weak luminescence to the ocean.

TYPES OF BIOLUMINESCENT DISPLAYS

Bioluminescent displays may be classified according to their appearance. The observations presented in this report have been grouped into three general descriptive categories based, with some modifications, on the types proposed by Tarasov (1956). We have named these three: sheet type, spark type, and glowing-ball or globe type.

The sheet-type display is the most common type observed in coastal waters and is caused by masses of dinoflagellates or bacteria. Tarasov (1956) referred to this luminescence as spilled or "milky" bioluminescence. The water may appear dully luminescent, and the individual points of light are not resolvable; that is, they give a sort of luminous cloudlike appearance in the water. The color usually is green or blue and in many displays appears white when the organisms are present in great numbers. From this latter appearance the term "milky sea" has been derived. Dense and extensive concentrations of large organisms, such as Pyrosoma, luminescing at the same time, may appear as a sheet-type display, instead of the flashing appearance noted when they are less concentrated. The same effect is produced by large concentrations of euphausiids, as Murray (Thomson and Murray, 1885) reported in August 1880 while in the Faeroe Straits (Faeroe-Shetland Channel). He noted: "large spots and long bands of milk-white water." The luminescence was caused by countless numbers of Nyctiphanes norvegica, a luminescent euphausiid.

Spark-type displays are created by large numbers of luminous euphausiids or copepods. This kind of luminescence occurs most often in colder waters and only when the waters are disturbed. Luminescing of the organisms gives the ocean surface a scintillating appearance. The luminescence produced usually is brilliant blue or white, and the light flashes are just resolvable to observers from the deck of a ship.

Glowing-ball- or globe-type displays are seen most frequently in the warmer waters of the world. The ocean may appear as if full of balls or discs of light, some flashing brightly as they are disturbed and others dimming after the initial stimulus has ceased. The flashes or pulsations of light may range in size from a few centimeters to a number of meters in diameter, depending upon the size of the organisms. The light given off usually is blue or green; occasionally, displays of white, yellow, orange, or red have been reported. The light rarely is continuous and may be noted from afar by its flashing appearance.

Combinations of either two or all three types of displays often occur. The light given off may consist of flashing luminescence against a cloud-like luminescence in the water or a mixture of glowing-ball- and sheet-type luminescence. In some observations, especially in higher latitudes, the scintillations of luminous crustaceans may be seen as they graze on the edges of large concentrations of luminous dinoflagellates, that is, a spark-type display fringing on a sheet-type display.

Exotic light formations like "phosphorescent wheels," undulating waves of light, and bubbles of light appear to be separate and distinct from all three types discussed above. "Phosphorescent wheels" and "waves" of light are discussed in another section.

OBSERVATION REPORTS

In preparing the charts used in this report the writer had access to files in the Biological Section of the U. S. Naval Oceanographic Office containing approximately 3,000 individual reports of displays throughout most of the oceans of the world. These reports date primarily from the beginning of the 19th century to the present time; however, a few reports are many centuries old, and these have been included in the overall presentation where they were considered useful.

Most of the reports of displays have been obtained from publications such as the British "The Marine Observer," the "Hydrographic Bulletin" of the U. S. Navy Hydrographic Office, and the "Notices to Mariners" published jointly by the U. S. Coast Guard and the U. S. Naval Oceanographic Office. In addition to the above publications, numerous scientific cruise reports, especially narrative logs, provided many reports. Reports from books of ocean travels also were included. The works of Harvey (1952), Nicol (1960), and Tarasov (1956) were of special value.

As with many types of oceanographic and hydrographic data, a bias exists in the geographic distribution of bioluminescence observations, inasmuch as the majority of reports are from frequently traveled shipping lanes. Consequently, reports of displays were unavailable or few in number for many regions. When the available reports are all plotted, they may give an erroneous representation of the seasonal distribution of bioluminescence in many places. Therefore, additional information such as published general descriptions of bioluminescence, ecological factors, distribution of organisms causing bioluminescence, and many other types of miscellaneous data were used to provide a more comprehensive coverage of the phenomenon.

NORTH ATLANTIC OCEAN AND ADJACENT SEAS (FIGURE 1)

Coastal Waters of Eastern United States

Bright displays (mostly sheet- and glowing-ball types) have been observed in coastal waters of the eastern United States during spring and late summer. Euphausiids and copepods often appear in large concentrations capable of causing strong spark-type displays in the Gulf of Maine during the summer. Ctenophores, such as Pleurobrachia, the sea gooseberry, have been observed in large numbers in the Gulf of Maine and along the coasts of southern New England. Dahlgren (1915) reported some observations of a friend from Harpswell, Maine concerning bioluminescent water. The water luminesced because of large concentrations of ctenophores, which glowed with a green light as they were struck or entrapped within a towed net. Diffuse surface luminescence has been observed during the spring and late summer months in Long Island Sound and Narragansett Bay.

Farther south in Barnegat Harbor, New Jersey occasional displays have been observed. These often have been bright enough to attract the attention of observers on shore, as in the autumn of 1963 when large numbers of luminescent copepods and dinoflagellates were present in the water. Dahlgren (1915), while traveling in Chesapeake Bay, described the vivid "green fire" that occurred as his ship sailed through water containing large numbers of luminescent dinoflagellates. The light emitted was strong enough to come through the porthole and reflect from the ceiling of a stateroom.

Gulf of Mexico

The Gulf of Mexico contains a tropical plankton, including many bioluminescent forms. Displays are as intense as in more northern waters, although not as frequent. Most of the bioluminescence reported has been observed in coastal regions or over shallow depths as in the Straits of Florida. Agassiz (1888) noted both Pyrosoma and Salpa in coastal waters. The pyrosomes were not as common as in Indian Ocean waters, and the displays caused by these forms were much weaker. Salps, according to Agassiz, were larger in size than in more northern waters; the light given off by them was bright green, supplemented by a bluish light from other smaller salps.

"Red tides" often are noted along the west coast of Florida and in Texas coastal waters during the summer. Connell and Cross (1950) described the appearance of a "red tide" containing large numbers of a particularly virulent marine dinoflagellate, Gonyaulax. At night the water appeared luminescent. This condition has been observed in June and August, usually after rains along the coast. Noctiluca also has been observed in the gulf during March. This organism may be present in great numbers along the Mexican coast and over Campeche Bank in the spring.

Along the north coast of Cuba the ocean often is strongly illuminated. Fishermen make use of this bioluminescence for tracking fish as the fish swim through the water. In Havana Harbor the water often is bioluminescent during the cool December and January nights.

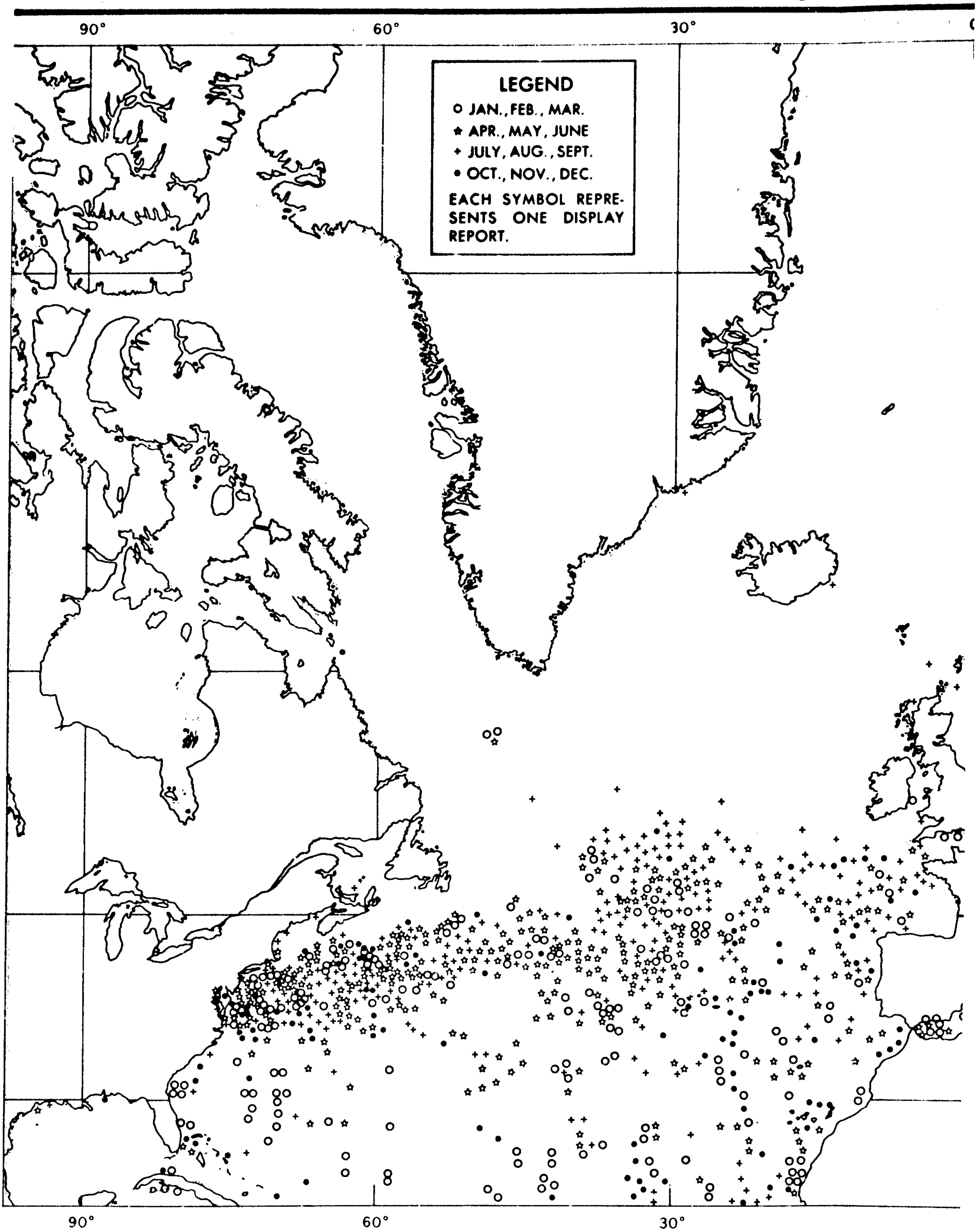
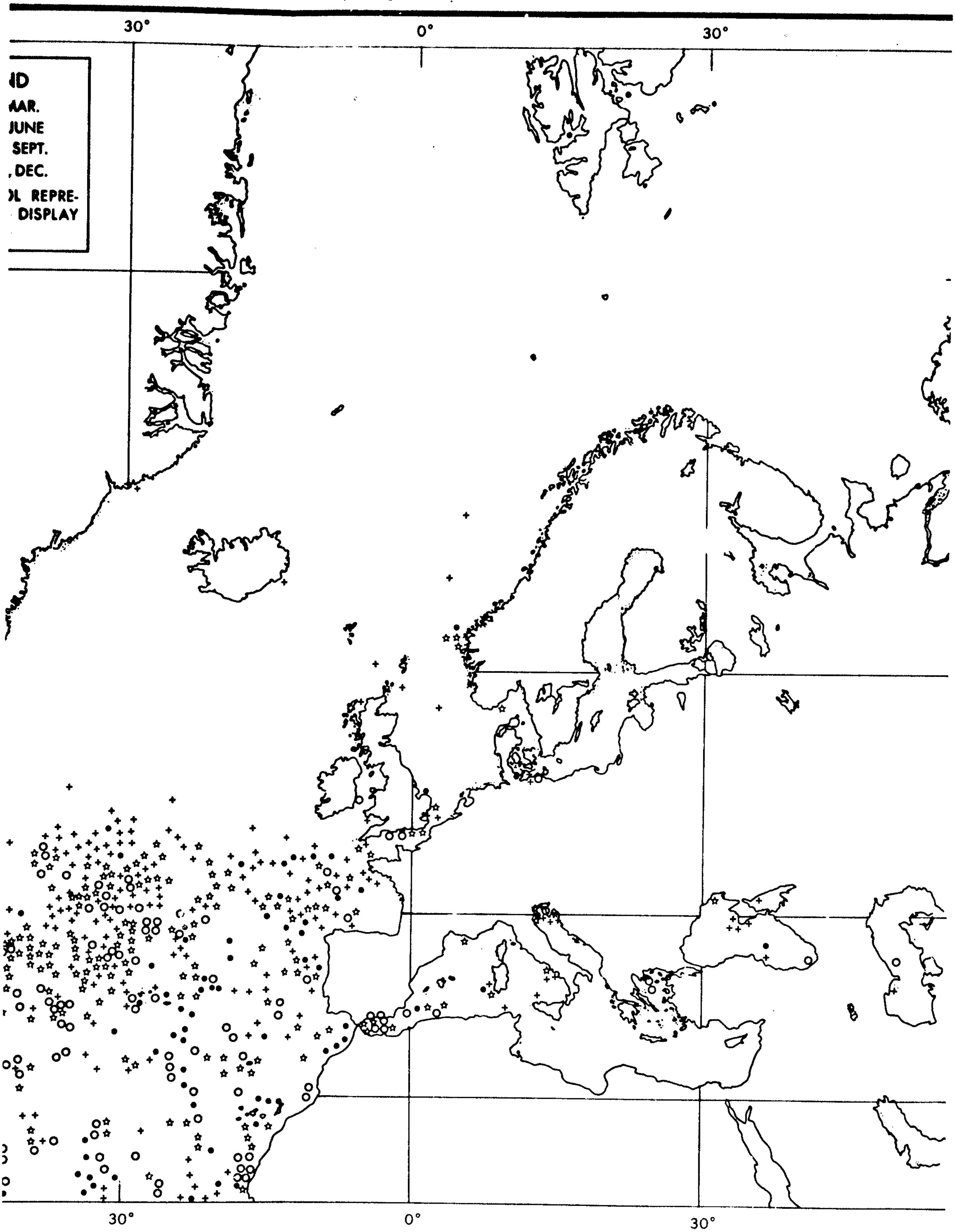


FIGURE 1 SEASONAL DISTRIBUTION OF BIOLUMINESCENT DISPLAY ATLANTIC OCEAN AND ADJACENT SEAS



ASONAL DISTRIBUTION OF BIOLUMINESCENT DISPLAYS, NORTHERN
'LANTIC OCEAN AND ADJACENT SEAS

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Open North Atlantic

The percentages of total observations of bioluminescence from the open ocean of the North Atlantic west of 30°W for three-month periods are as follows:

January through March-----	24%
April through June--------	38%
July through September----	27%
October through December--	11%

The percentages of total observations for the three types of displays in this region are as follows:

Sheet type----------------	52%
Spark type----------------	14%
Glowing-ball type---------	34%

The most luminescence occurs in close proximity to regions in which "mixing" occurs, such as the front between the Gulf Stream and the cold Labrador Current. Sheet-type bioluminescence predominates in the spring; both sheet- and glowing-ball luminescence occur with equal frequency in summer in the western North Atlartic.

Sheet-type displays, which are predominant in the region of "mixing," become less frequent eastward from 30°W, whereas glowing-ball displays gradually increase in this direction. Glowing-ball displays have been reported 54 percent of the time in this portion of the North Atlantic, most frequently in the spring. Sheet-type displays have been recorded about 27 percent of the time and are most often seen from April through September. Spark-type displays have been observed 19 percent of the time, mostly from July through December.

The Sargasso Sea, noted for its floating vegetation, is, however, an impoverished area with regard to other forms of marine life. As a consequence, very little bioluminescence has been observed there. About 65 percent of the few reported observations were made from January through June and 35 percent during the other half of the year. Although few in number, some very strong displays have been reported, especially on the fringes of this vast eddy. In 1905 observers on board the scientific yacht PRINCESS ALICE observed a bright luminescent wake as they sailed through the western portion of the Sargasso Sea. The luminescence was globular in form and was caused by large numbers of Pelagia noctiluca, a luminescent medusa noted for its green luminescence.

In the coastal waters of various island groups, such as the Azores and the Canaries, luminescent displays occur during all seasons. Most of the luminescence observed is caused by large shoals of jellyfishes and tunicates carried into the area by prevailing currents. Around the Canary Islands, bioluminescence has been observed most frequently during the spring and autumn, whereas in the vicinity of the Azores the majority of displays occur from April through December.

Atlantic Coastal Waters of NW Africa, Spain, Portugal, and France

Along the Atlantic coast of northwestern Africa and in the western approaches to the Strait of Gibraltar, displays occur during the spring and autumn months. On the Moroccan coast, in such places as the Bay of Agadir, there also is an abundance of luminescent organisms during the winter. In February 1960 these organisms luminesced brightly during the earthquake which caused so much destruction on land. In October and November 1955 moderately intense displays were noted near Casablanca, Morocco. The light was bright enough to cause a "milky" glow which extended 2 feet from the sides of various oceanographic instruments as they were raised and lowered into the water. These particular displays were due to large concentrations of luminescent protozoans primarily, although large flashes of light by ctenophores or jellyfish could be observed whenever an instrument jarred these organisms.

Some very spectacular displays occur in various bays of western Spain and Portugal. Pinto (1949) gave an account concerning intense luminescence and "red water" near Lourinha, Portugal in September 1944 caused by a bloom of the dinoflagellate Gonyaulax. The luminescence caused some panic among local fishermen according to Pinto. The light given off was blue-green, and the intensity increased when the water was disturbed. Displays such as these may occur along the western Iberian coast from April through December, although the most vivid displays are seen in the late summer and early autumn. One of a number of wartime reports concerning bioluminescence and submarine tracking comes from this region. In November 1918 the last German U-boat (U-34) to be destroyed during World War I was easily tracked because the water was so "phosphorescent" at the time that the submarine could be seen moving under the water "glowing" and outlined by "sea fire."

In the Bay of Biscay French and Spanish fishermen utilize summer bioluminescence to track fish at night. The trails left and the peculiar flowing movement of fish schools through luminescent waters provide them with evidence as to the type of fish present. Noctiluca, so common to most of the coastal regions of the world, causes bioluminescence in the various bays and inlets along the coast of France. Quatrefages (1850), a French naturalist, noted the intense luminescence of large concentrations of this particular pinkish organism in water near such ports as Dieppe, St. Malo, Bréhat, and Ostend (Belgium). These organisms appeared in the surface waters from July through September.

English Channel and North Sea

In the English Channel, bioluminescence is most evident from April through November; however, displays can occur during all seasons. Wintertime bioluminescence is not unusual in this region, especially along the English coast. For example, glowing forms of fishes and the long luminescent trails they leave in the water have been observed in the dark surface waters during February near Plymouth. "Brilliant green lines" and "balls of phosphorescence" were noted by observers on board the SS BEAVERGLEN in June 1957 off Beachy Head, England. Off Lands End, Cornwall very bright light has been noted in the late summer, when shoals of luminescent jellyfishes are brought in by currents.

Although many oceanographic and fisheries investigations have been conducted in the North Sea, very little information is available concerning bioluminescence in this region. As might be expected in temperate regions such as this, the greatest peak of bioluminescent activity appears to take place from April through June and a smaller peak from late August through November. Bioluminescence generally is restricted to shallow coastal regions or to the waters over the Dogger Bank, although some strong displays can occur some distance from the coasts over deeper regions.

The majority of the references are to spark-type bioluminescence. Murina (1954) observed very intense bioluminescence east of the Orkney Islands in August 1953. The surface water appeared to be full of "sparkling emerald dots." Further investigation showed that a luminescent copepod, Metridia lucens, was responsible for the light. Various species of luminescent euphausiids also contribute to the spark-type luminescence observed in late summer and early autumn. Euphausiids may be present in large numbers in the numerous inlets and firths along the Scottish coast, where they remain at depth during the day and migrate to the surface layers at night, creating displays of some brilliance.

Sheet-type luminescence occurs in the late spring and late summer. The light given off usually is produced by large numbers of luminous dinoflagellates, most prominently Ceratium, Peridinium, and Noctiluca. The last organism causes bioluminescence in coastal regions in late spring, and the other two organisms are responsible for late summer displays. Noctiluca develops in such great numbers at times that it constitutes up to 1/7 of the water volume.

Glowing-ball bioluminescence may be observed in such regions as the Thames Estuary when influxes of luminous medusae occur. Farther to the north great shoals of salps appear in late summer and early autumn at the northern entrance to the North Sea and at times extend into the central North Sea. Such large concentrations often create strong glowing-ball displays.

Ocean Waters West and North of the British Isles

Although no specific reports are on file it is known that many types of bioluminescent organisms cause displays in the ocean west of the British Isles. Displays have been observed in coastal waters during all seasons, although most of the bioluminescence appears during the late spring, late summer, and early autumn. Scott (1920) noted that although Noctiluca reached a peak of abundance in the coastal waters of the Irish Sea in late summer and early autumn during mild winters as in

1919, this organism could be found in the water within Barrow Channel, developing in great enough concentrations to discolor the water and to cause strong sheet-type bioluminescence. One observer noted that during the winter along the rocky coast of northwestern Scotland the sea was luminescent. Every stroke of an oar produced a myriad of "green sparks" in the disturbed water, and the wake luminesced for some distance astern. Shoals of jellyfishes, salps, and ctenophores are responsible for much of the summertime bioluminescence in the Irish Sea. Farther north along the Scottish coast some displays due to dinoflagellates and euphausiids often are observed in September. Swarms of herring create bright luminous trails off the Hebrides Islands as they swim through water containing luminescent copepods and dinoflagellates.

In the waters around the Faeroe and the Shetland Islands, displays are most frequently observed from May through late October. The displays often are caused by euphausiids, which are common and at times appear in dense concentrations throughout the region in spring, summer, and autumn. The first aggregations of Salpa generally are sighted inside the Faeroe-Shetland Channel in May and June. The water often is so full of these organisms that it appears opaque, and the luminescence given off at night can be very strong.

Norwegian and Greenland Seas

Strong displays can be expected during the year in the coastal waters of Iceland and Norway and in regions where the warm North Atlantic Current meets cold currents from the Arctic Ocean. The sea ice also may be luminous because of entrapped luminous organisms. Flashes of light have been seen when sea ice along the west coast of Norway was broken or jarred. This luminescence continues in the melt water. Copepods and dinoflagellates appear to be the organisms frozen, but not dead, within the ice.

In the offshore waters of the Norwegian and Greenland Seas, Russian observers have noted a considerable amount of bioluminescence in March and April. In June and July this bioluminescence becomes stronger and often extends over large regions. The organisms responsible probably are dinoflagellates, most likely Ceratium or Peridinium. They can create luminescence in ice-free waters along the coast of eastern Greenland during the year. In August Metridia lucens is abundant in Denmark Strait, and as a result displays of sparkling green light have been observed in the various ice-free fiords along the Greenland coast. Occasional displays also occur along the coast of Greenland and Iceland from early summer through early autumn. Reports dating back to the early 18th century make reference to the red discoloration of water in southern Icelandic fiords, which turned into "sea fire" at night. Displays such as these are unusual for regions in such high latitudes.

Mediterranean Sea

The western basin is the most luminescent part of the Mediterranean Sea except for the Adriatic Sea. Most of the displays observed in the western Mediterranean occur from October through June. Sheet-type displays predominate, with an occasional glowing-ball display. Luminescent salps, pyrosomes, and medusae are responsible for many of these displays. Pelagia noctiluca is especially plentiful in the surface waters of the western Mediterranean. Salps often almost fill the water; the organisms frequently form long chains and may emit long lasting and rather intense light when disturbed. Noctiluca may be present in great abundance, tinging the water red by day and luminescing brightly by night.

During one of the many cruises of the Norwegian research vessel MICHAEL SARS in April 1909, Murray (1912) noted that the sea surface for several nautical miles in the Sea of Alboran was full of "phosphorescent" Noctiluca. The concentration was so great that the water was like a "broth," and in the evening "the sea resembled a star-spangled sky, and the wires following the vessel looked like gleaming stripes." A more recent report from the SS EXANTHA in January 1951 bears out the fact that strong sheet-type luminescence can be expected in this region. The water was "phosphorescent" for several nautical miles along the coast of southern Spain. The ship created a "luminous sheet" so intense that it was possible to read by the light emitted. The cause of this luminescence was not ascertained; however, it was of the type produced by dinoflagellates such as Noctiluca. Very intense bioluminescence has been observed during the summer along the coast of Algeria.

Luminous euphausiids are responsible for many spark-type displays along the coast of southern France and northwestern Italy. During the winter months these organisms may appear in large swarms, coloring the water red. At night the light given off is sparkling and bluish white in color, and when the organisms all light, the water takes on a "blue radiance."

To the south, swarms of Noctiluca occur in the Bay of Naples in August and September. Ehrenberg (1859), a German biologist, noted the long luminescent wake created by these organisms as his boat traveled through the water of the bay. He also noted that the fronds of a common brown seaweed (Fucus) were covered by these tiny luminescent forms, the fronds appearing to glitter when disturbed. Bioluminescence occurs most frequently during the spring and summer months in the Bay of Naples.

In the northern Adriatic Sea, bioluminescent displays are observed more often than in any other part of the Mediterranesn. The luminescence observed in the coastal waters here is most pronounced from April through September. In April and May water near the mouths of the Po may become very luminescent; the development of luminous organisms is increased by the nutrients washed from land during the high springtime runoff. At times bioluminescence may be produced by bacteria or protozoa. Apparent bacterial luminescence usually is found in fiordlike inlets along the northern Yugoslavian coast, where much decomposition and stagnation occur.

In the Gulf of Trieste a luminescent slime often develops in the late summer. The slime is yellow and ropy and adheres to objects in the water. Therefore, it is not unusual to see pilings, rocks, and bottoms of anchored boats luminesce yellow-green when covered by this slime. The slime probably is produced by luminescent bacteria, although dinoflagellates also have been suggested as the causative organism.

Little information is available concerning bioluminescence in the eastern Mediterranean. Two reports indicate wintertime bioluminescence due to masses of copepods in the Aegean Sea. Some rather extensive sheet-type bioluminescence occurs along the Egyptian, Israeli, and Lebanese coasts in July, August, and September. Seaward from the Nile Delta, fishermen locate fish by the luminescence stimulated by the fish swimming at this time. Bioluminescence is most frequent during this period because of the large development of luminescent plankton triggered by the enormous quantities of nutrients carried seaward by the flooding Nile.

Black Sea, Sea of Azov, and Caspian Sea

Tarasov (1956) states that luminescence can be observed throughout the year in the Black Sea and that it reaches a maximum intensity during the autumn months. Near Sevastopol Gonyaulax frequently causes a red discoloration of the water. At night the waves are capped with brilliant bioluminescence, and the surf gives off vivid light as it breaks against the shore. In the Bay of Odessa very intense bioluminescence has been observed in the early summer, probably most frequently near the mouths of rivers such as the Dnieper and Dniester. Noctiluca is the dominant form in the summer plankton of the Black Sea. While normally a coastal form, it occurs in large concentrations in the open parts of the Black Sea. The light emitted by these protozoans is augmented somewhat by large numbers of luminescent ctenophores during the summer.

According to Zenkevitch (1963) the Sea of Azov is extremely productive. The production reaches a maximum in the summer and early autumn, and luminescent forms develop in such large concentrations that they create sheet-type luminescence at this time. Sea worms also develop in great numbers in the summer and create luminescence as they move through concentrations of luminescent dinoflagellates.

Bacterial bioluminescence has been reported from the northwestern part of the Caspian Sea. Zhirnov (1955) reported strong luminescence near Astara in July 1952. The bioluminescence was evident in the water for over a week and appeared to be due to tiny organisms visibly luminescing even during the daytime. The organism causing the luminescence was not determined.

Skagerrak, Kattegat, Belts, and Baltic Sea

In the Skagerrak considerable bioluminescence may be observed in the early spring. Observers on board the MV LAKSA reported a display off southern Norway in April 1963 which was determined to have been caused by luminous dinoflagellates. Pleurobrachia, a luminescent ctenophore, is very abundant in the Skagerrak in May. Numbers of this small transparent organism appear much like beads of green light when viewed in the water. This ctenophore is especially prevalent inside Oslo Fjord in the spring. Shoals of luminescent medusae may be encountered in the various fiords and inlets along the southwest coast of Sweden during the summer. Sheet-type bioluminescence has been observed in the various extensions of Oslo Fjord in August. Also, heavy concentrations of luminous dinoflagellates are common in this fiord during late summer. Euphausiids and copepods often create displays of some intensity within the Skagerrak during late spring and summer.

Extensive displays of light are not common in the Kattegat, Oresund, and the Belts. Some large concentrations of the tiny tunicate Appendicularia are responsible for green luminescence in coastal waters of the island of Laeso and along the Danish coast. Ctenophores cause bioluminescence inside Limfjord and Mariagerfjord. Noctiluca attains maximum abundance in the Belts and Kiel Bay in May and June. Luminescence is very intense during August in the various bays around Kiel, whereas in the open sea some distance from the coast it becomes intense in September and October. Michaelis (1830) observed that the blooming of Ceratium was most pronounced during windless, warm summer days leading to some rather strong sheet-type displays in Kiel Bay. Wintertime luminescence is rare, although sea light has been observed under the ice at Kiel.

Very little bioluminescence occurs in the Baltic Sea. Tarasov (1956) has indicated that some bioluminescence may be observed during July and August in the western and central Baltic. Large numbers of Pleurobrachia develop along the south coast of Finland in summer and autumn and are probably responsible for some glowing-ball displays in the Gulf of Finland. No significant bioluminescence has been reported from the Gulf of Bothnia. The extremely low salinity would seem to preclude the development of large numbers of luminous organisms.

SOUTHERN NORTH ATLANTIC AND SOUTH ATLANTIC OCEANS (FIGURES 2 and 3)

The percentages of total observations between 20°N and the Tropic of Capricorn for three-month periods are as follows:

January through March	27%
April through June	22%
July through September	29%
October through December	22%

The percentages of total observations for the three types of displays are as follows:

Glowing-ball type ---------- 50%
Sheet type ----------------- 27%
Spark type ----------------- 23%

The various types of displays are quite evenly distributed throughout the year, although there are some exceptions. A maximum number of glowing-ball and sheet-type displays occur from January through March, whereas glowing-ball displays are least frequent from April through June. Spark-type displays are least frequent from October through December.

South of the Tropic of Capricorn, data are relatively meager. Except for the shipping lanes from southwest Africa and southeast South America, large regions of open ocean are seldom traversed by vessels. Although intense displays probably occur south of this tropic, the frequency of the different types of displays is not known; glowing-ball displays probably predominate in the open ocean and sheet-type displays near the coasts. Spark-type displays might be expected to occur more often toward the south. The sparse data available appear to indicate that displays occur evenly throughout the year in this vast southern portion of the Atlantic.

In tropical waters containing the Equatorial currents, more bioluminescence has been observed east of the 30°W meridian, especially toward the bulge of Africa, than west of this meridian. A number of rather spectacular displays, principally glowing ball, have been observed in this region. Near Sao Tome, observers on board the whale catcher ENERM noted a display of blue light in which the wake glowed and the sea surface appeared as if fireworks were going off. The display was due to Pyrosoma, millions of which covered the sea surface to the horizon. The German research vessel METEOR, while sailing back and forth across the Equator in December, January, and February 1926, noted continuous bioluminescence in the water night after night. The principal organism creating the light also was Pyrosoma, often in great numbers.

Sheet-type displays occur most often in coastal regions, although some strong displays have been observed in oceanic equatorial waters. A typical sheet-type display was observed from the SS HERMINIUS in December 1931 while sailing toward Capetown. The sea appeared completely "phosphorescent," and it gave the "effect of the sea being illuminated by some unseen light underneath." The vessel

> "ran suddenly into a mass of pale, but intense green sea with silvery-white edges to the waves, somewhat similar in appearance to the illuminated dial of a wrist-watch, when observed in the dark, only of much greater intensity.

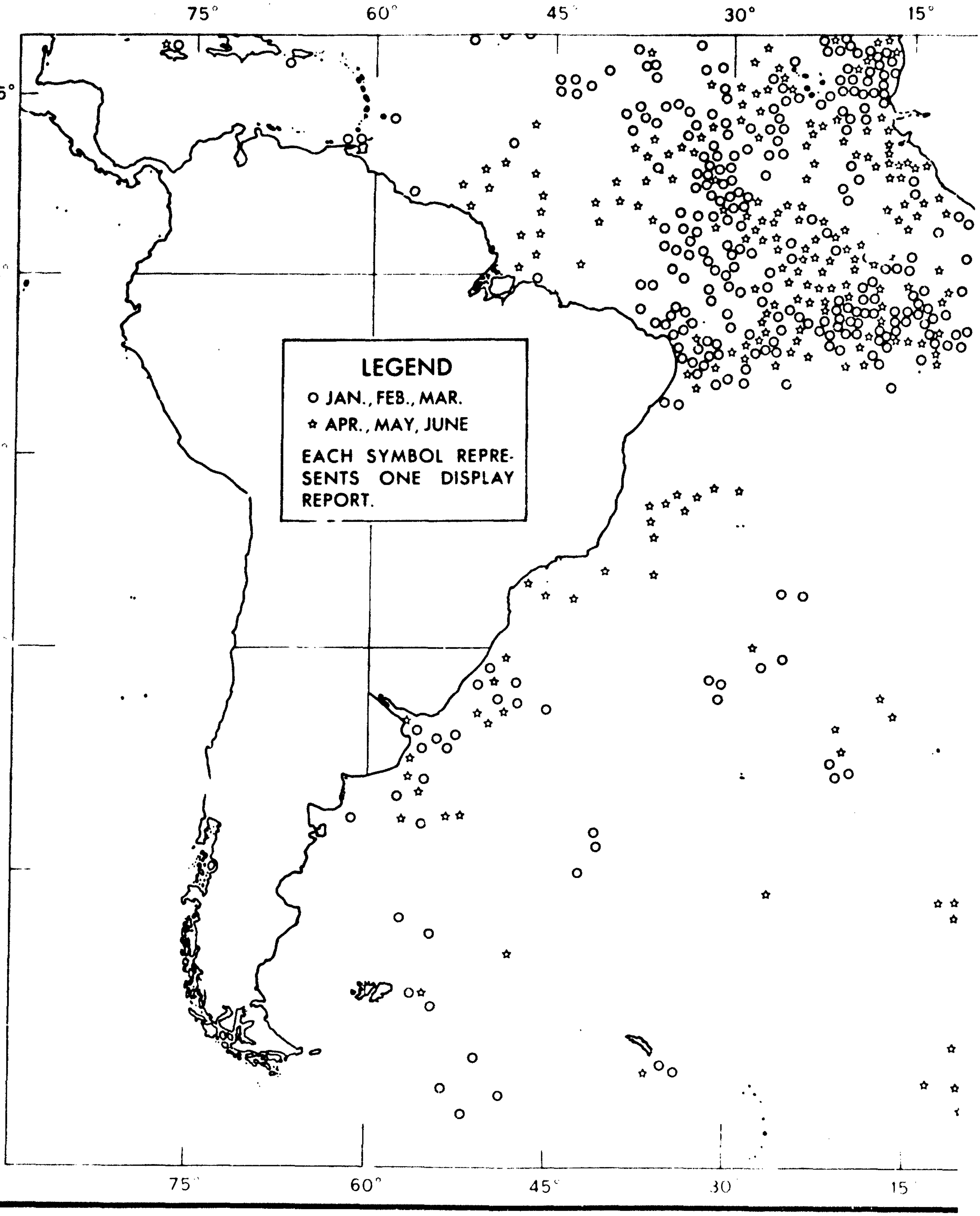
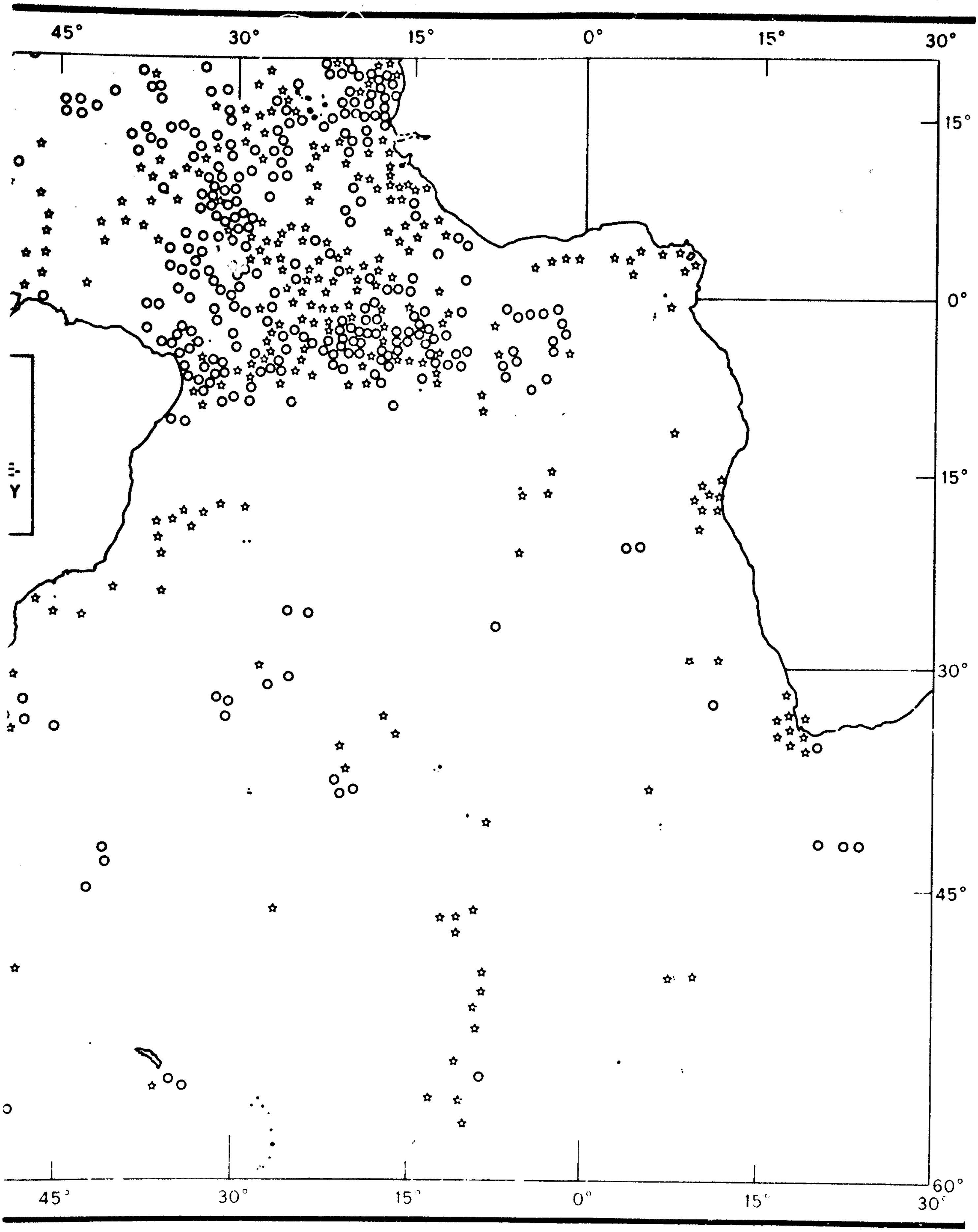


FIGURE 2 SEASONAL DISTRIBUTION OF BIOLUMINESCENT DISPLA
NORTH ATLANTIC AND SOUTH ATLANTIC OCEA



ONAL DISTRIBUTION OF BIOLUMINESCENT DISPLAYS, SOUTHERN TH ATLANTIC AND SOUTH ATLANTIC OCEANS (JANUARY)UGH JUNE)

B

The waves, breaking in the distance gave the appearance of the sails of a small yacht having a beam of light played upon them. As each bow wave broke, the white paintwork of the bridge and vessel's superstructure was brilliantly illuminated."

Sheet-type bioluminescence may resemble a "white sandy beach" in the distance, as was noted off Rio Para, Brazil.

Numerous displays occur along the coast of Africa, being most pronounced off the mouths of rivers. Discolored water from the Congo River has been observed some 300 miles from shore, and bioluminescence from rapidly developing bacteria and dinoflagellates may be seen through the region affected by this river. The METEOR sailed through this region in 1926, and observers noted a diffuse luminescence all along the coast of what was then French Equatorial Africa extending into the coastal waters of Angola. The light was continuous and rather intense in the vicinity of Mocamedes.

Farther south along the coast of southwest Africa, the incidence of bioluminescence increases markedly. Here, coastal waters are very productive because of abundant nutrients introduced by the upwelling Benguela Current. Walvis Bay, which is representative of many bays along this coast, is subject to periodic "red tides" and brilliant displays of bioluminescence. The "red tides," caused most frequently by Noctiluca, are accompanied by mass mortalities of marine life. As a result, luminescent bacteria develop on the decaying organisms, and the displays may range from dull to brilliant in the surface waters of the bay.

In False Bay, Union of South Africa, exceptional displays have been observed. One observer noted that the bay in November was covered by a "greasy" froth, variously colored, that gave the water an unclean appearance by day but caused it to resemble a lake of "molten gold" at night. Strong bioluminescence occurs in Table Bay in December and January, when dark red water develops.

In colder waters extending southward toward the Antarctic, an increased number of spark-type displays caused by euphausiids may be expected throughout the year. The usual displays caused by various jellyfishes and tunicates such as salps have been seen throughout the extreme southern portion of the South Atlantic. Harbors of the Isla de los Estados (Staten Island) often are filled in the early part of December with medusae which are said to cause brilliant bioluminescence at night. Salps cause some rather strong displays between southern Africa and southern South America. Dinoflagellates occasionally are abundant in waters near the Falkland Islands. Here the movements of large fishes have been observed by their bioluminescent tracks. Euphausiids have been observed luminescing both in the water and on floating ice in February near the South Orkney Island.

The incidence of bioluminescence increases northward along the east coast of South America. Many luminescent forms are carried north by the Falkland Current and develop in large numbers in regions such as the convergence zone to the east of the Rio de la Plata.

Strong bioluminescence occurs within and seaward of the Rio de la Plata. This region is one of the most bioluminescent parts of the South Atlantic. Here, Darwin (1845) observed

> "a sea that presented a wonderful and most beautiful spectacle ..... the vessel drove before her bows two billows of liquid phosphorus, and in her wake she was followed by a milky train. As far as the eye reached the crest of every wave was bright, and the sky above the horizon, from the reflected glare of the livid flames, was not so utterly obscure as over the vault of the heavens."

Commander Charles Wilkes (1845) on board the USS VINCENNES during the famous exploring expedition of the U. S. Navy in 1838-42 observed in this convergence zone "that the water was much discolored due to salps during the day, and as night closed in the sea became very luminous, the vessels passing through the water leaving long bright trains behind them." Just after noting this luminosity, the ship encountered a temperature drop in the water, probably due to the Falkland Current, but the sea remained luminescent on each side of this front.

Caribbean Sea

More luminescence occurs in the eastern Caribbean than in the western portion. Frequent displays occur along the coast of Venezuela, principally in the Gulf of Paria and in the Golfo de Venezuela.

Exceptional bioluminescence may be observed in the bays located along the coasts of various islands encompassing the Caribbean Sea. Bahia Fosforescente (Phosphorescent Bay), located on the south coast of Puerto Rico, is outstanding in this respect. In this bay sheet-type bioluminescence occurs year round because of a continuously abundant dinoflagellate community. The bay itself acts as a culturing vessel, complete with the proper nutrients, the right temperature, and other ecological factors needed to sustain a continuing rich community of dinoflagellates. Bioluminescence is intense when the water is agitated by boats or fishes. Bays, such as this, usually are bordered by mangroves, with continual drainage from the land into the bay.

Oyster Bay, near Falmouth, Jamaica is another bioluminescent bay, in which sheet-type bioluminescence occurs throughout the year. Harvey (1952) visited the region and found the water "marvellously beautiful, with every fish that moved outlined in fire and every wave looked as if it were aflame." He indicated two responsible organisms, the marine dinoflagellates Ceratium and Pyrodinium bahamense. Research concerning bioluminescence and bioluminescent organisms was conducted in this bay

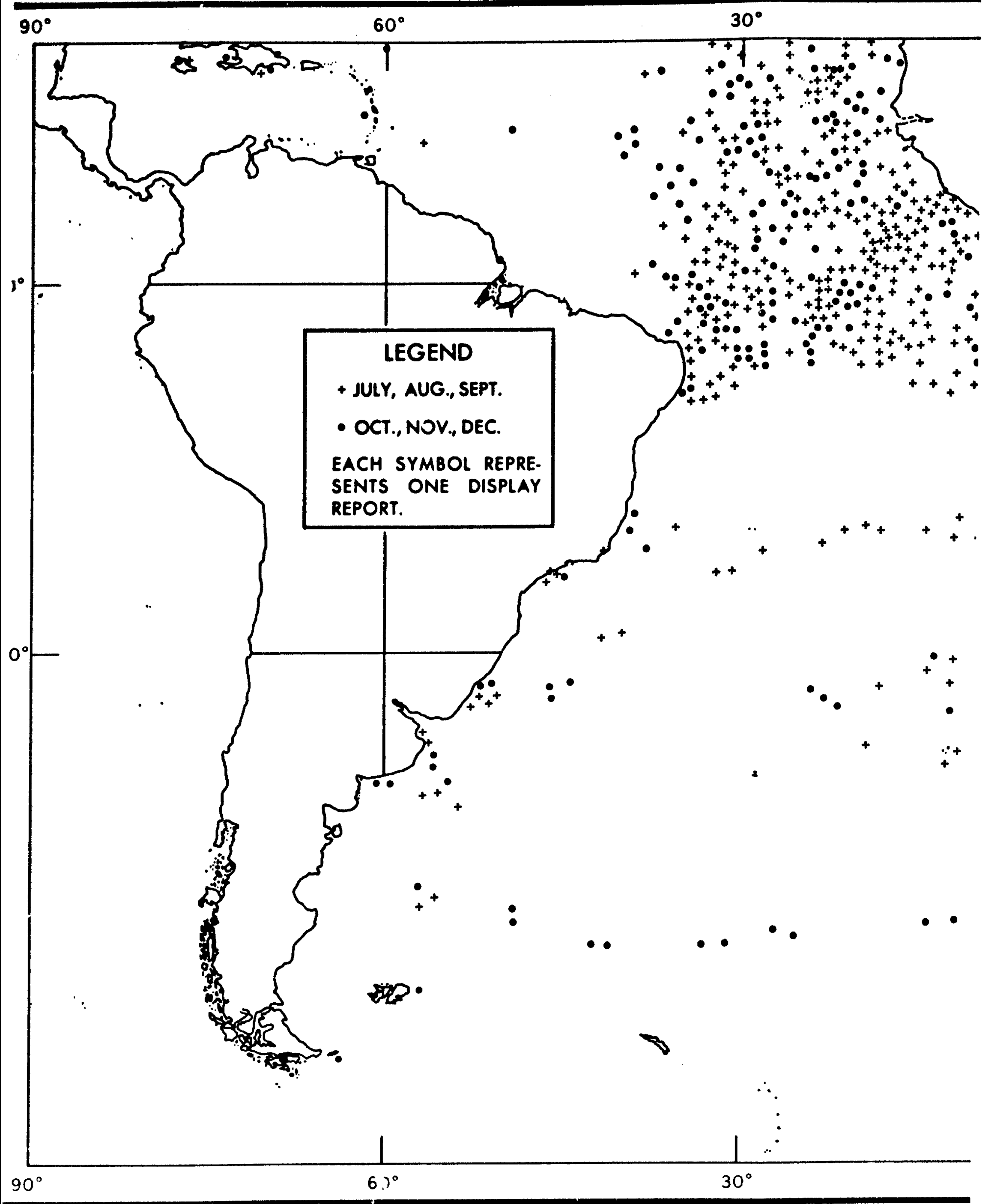
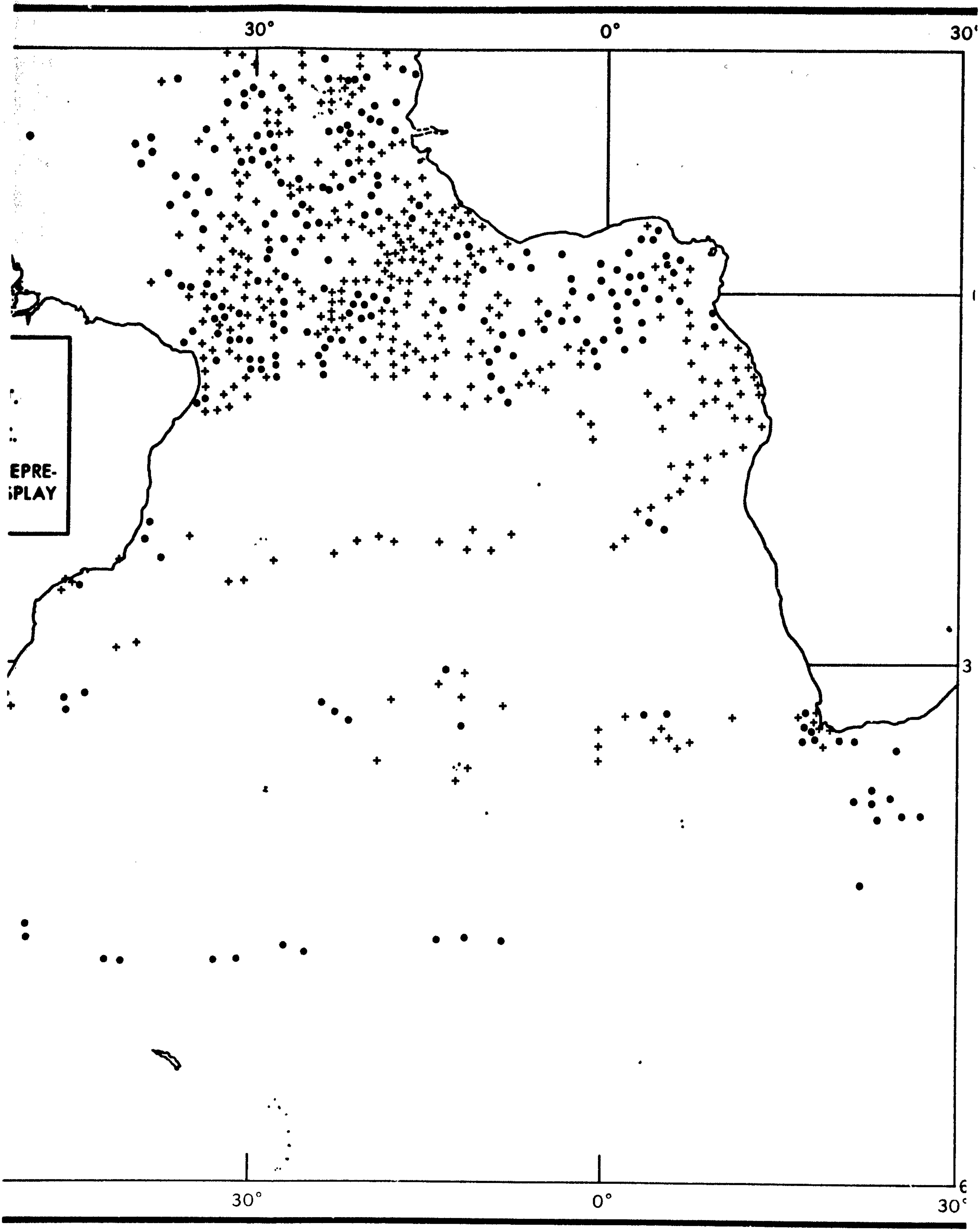


FIGURE 3 SEASONAL DISTRIBUTION OF BIOLUMINESCENT DISPLAY NORTH ATLANTIC AND SOUTH ATLANTIC OCEAN (JULY THROUGH DECEMBER)



ASONAL DISTRIBUTION OF BIOLUMINESCENT DISPLAYS, SOUTHERN
)RTH ATLANTIC AND SOUTH ATLANTIC OCEANS
LY THROUGH DECEMBER)

B

by a joint Johns Hopkins University-U. S. Naval Oceanographic Office team in February 1963. Further investigative efforts along this line are to be carried out by this group from July 1965 to June 1966.

Until the early 20th century, another spectacularly bioluminescent bay near Nassau, Bahama Islands was described regularly. However, the environment of the bay was changed by the dredging of a channel, and the water can no longer support large populations of luminescent organisms.

NORTHERN PACIFIC OCEAN AND ADJACENT SEAS (FIGURE 4)

Little information is available concerning the incidence of bioluminescence in the East China and Yellow Seas. Some displays occur in the summer and autumn, when Noctiluca and Salpa often appear in very large shoals; the former organism also may cause various degrees of luminescence in coastal waters in spring. The water may appear greenish and turbid by day because of masses of green-colored Noctiluca. This particular species of Noctiluca has been observed to luminesce brightly by Haneda (1955), although Ostrumoff (1924) and other workers consider the green variety as nonluminescent. Peridinium and Ceratium (luminescent dinoflagellates) have been observed in large concentrations near Nagasaki in October.

Bioluminescence may be very brilliant at times along the west coast of Kyushu and around some of its adjacent island groups. Observers on the SS LAOMEDON noted that much reddish brown discolored scum was floating in the water in April 1928 as they approached the Danjo Islands from the southwest. After sundown the patches gave off a bluish green glare. During the evening they observed long streaks of "phosphorescence"; the light from the individual streaks was so bright that lights from passing ships were obscured by the glare. This display lasted throughout the night. The streaks had an oily appearance indicative of concentrations of Noctiluca, in this case most likely the pink colored species.

The most prevalent type of bioluminescence in the Sea of Japan is the sheet type, generally caused by pink Noctiluca. This dinoflagellate is present throughout the year and is especially abundant in spring. It and other luminescent dinoflagellates may cause a "red tide" along the Japanese coast.

Luminescent dinoflagellates, particularly Peridinium, have been observed in large reddish blooms during late summer along the Soviet coast of the Sea of Japan. Luminescence in the water near Vladivostok is caused by dinoflagellates from the latter part of August until the first part of October. The light given off often is very intense. Euphausiids or copepods contribute to the overall bioluminescence in August and September. A diffuse luminescence consisting of sparkles often is noted in bays such as the Bay of Patrokl (near Vladivostok) at this time, evidence of the large number of euphausiids and copepods present in the surface waters.

Spark-type bioluminescence caused by swarms of euphausiids also may be observed in the Sea of Japan; it is blue and prevalent in the northern part. The light given off by these and other crustaceans is very intense in April and is used by fishermen to detect moving herring schools.

Although reports of glowing-ball bioluminescence are lacking for the Sea of Japan, this type of display probably occurs within the Tsushima Current. Both Pyrosoma and Salpa often are observed in the Sea of Japan, the former restricted to warm water regions in the south and east. Haneda (1955) noted that numerous individuals of Beroe (a luminescent ctenophore) often were mixed with specimens of the luminescent squid Watasenia scintillans in nets retrieved from the waters of Toyama Bay.

In the Sea of Okhotsk the spark type is the most commonly observed bioluminescence. The displays are frequent from August through December and often very intense, especially in September. According to Stukalin (1934), unusually bright greenish white light may be observed in August and September. The regions of cold water and the fronts of the cold water masses appear to be the most favorable regions for the development of many luminescent forms. Noctiluca occurs in large numbers in the surface waters of the Gulf of Terpeniya and off southern Sakhalin in spring. An influx of luminescent organisms, including ostracods, often occurs along the north coast of Hokkaido and east coast of Sakhalin in September. Copepods such as Metridia are responsible for displays during May and June.

Icebreakers in the Sea of Okhotsk have created some strong scintillating green bioluminescence as they crashed their way through icefields or bumped floating chunks. The light probably is given off by imprisoned luminescent organisms. These organisms occasionally make the ice appear red, from which the term "bloody ice" has been derived.

Certain other luminescent displays, the shapes and movement of which are unexplainable at this time, have been observed by observers in the Sea of Okhotsk. These displays are best described as large expanding circles of light which appear suddenly in the sea, or as waves of light, or strips of light extending in various directions. Occasionally these strips of light will rotate, resembling a "phosphorescent wheel" (see section on this subject). Observers from the Sakhalin Branch of the Russian Oceanological Institute on a research expedition noted such an appearance (Priroda, 1956) 14 miles east of Cape Aniva in September 1953. They reported as follows:

> "On the night of the 9-10 of September unexpected bright luminescence of the sea was observed across the stern of the ship, which progressed rapidly, forming a rather large ring in the center of which was the ship. It was very brilliant near the ship, and was strongly luminescent as it rapidly increased in size progressing from the ship to the invisible horizon. The luminescence was intense and

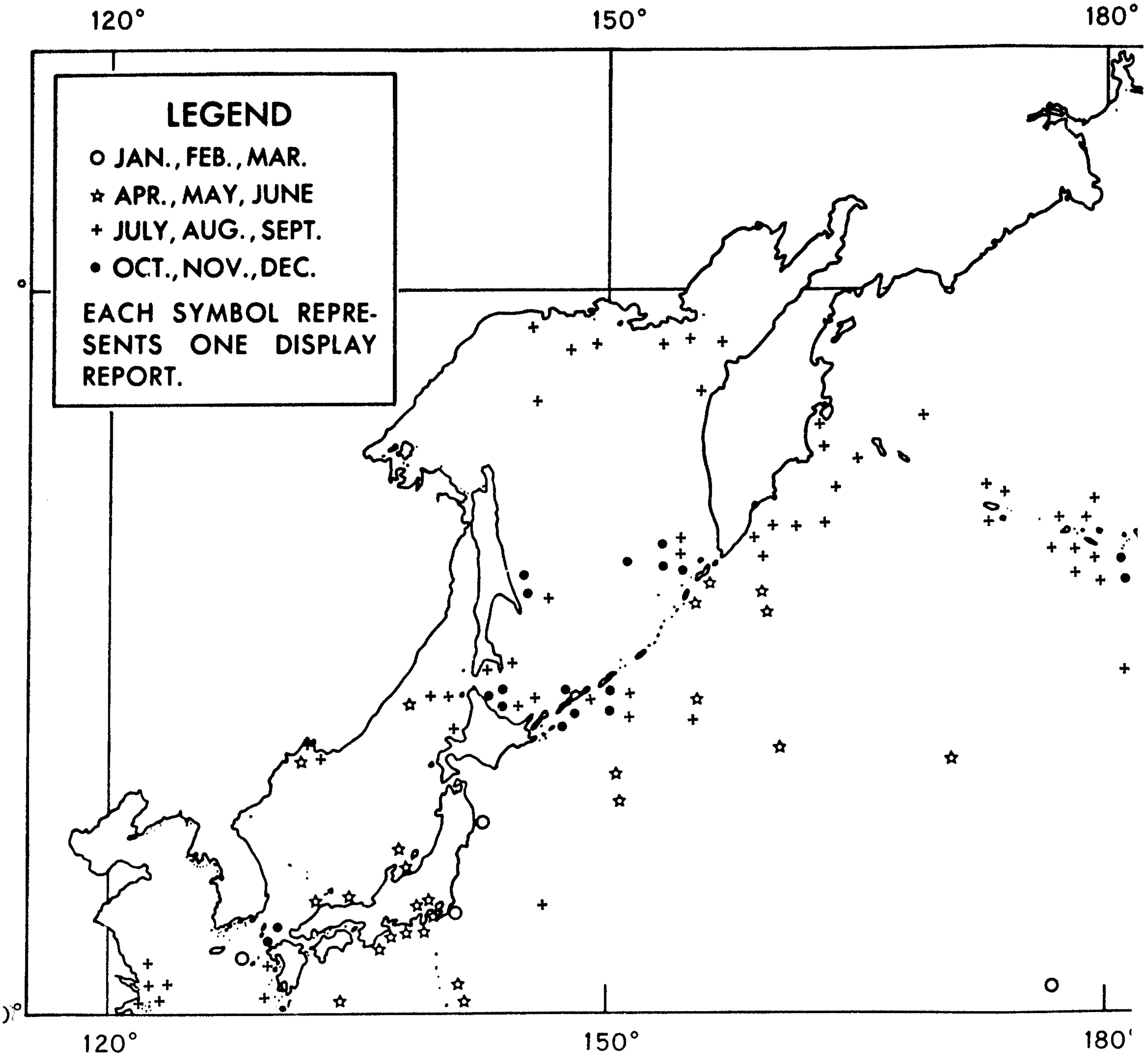
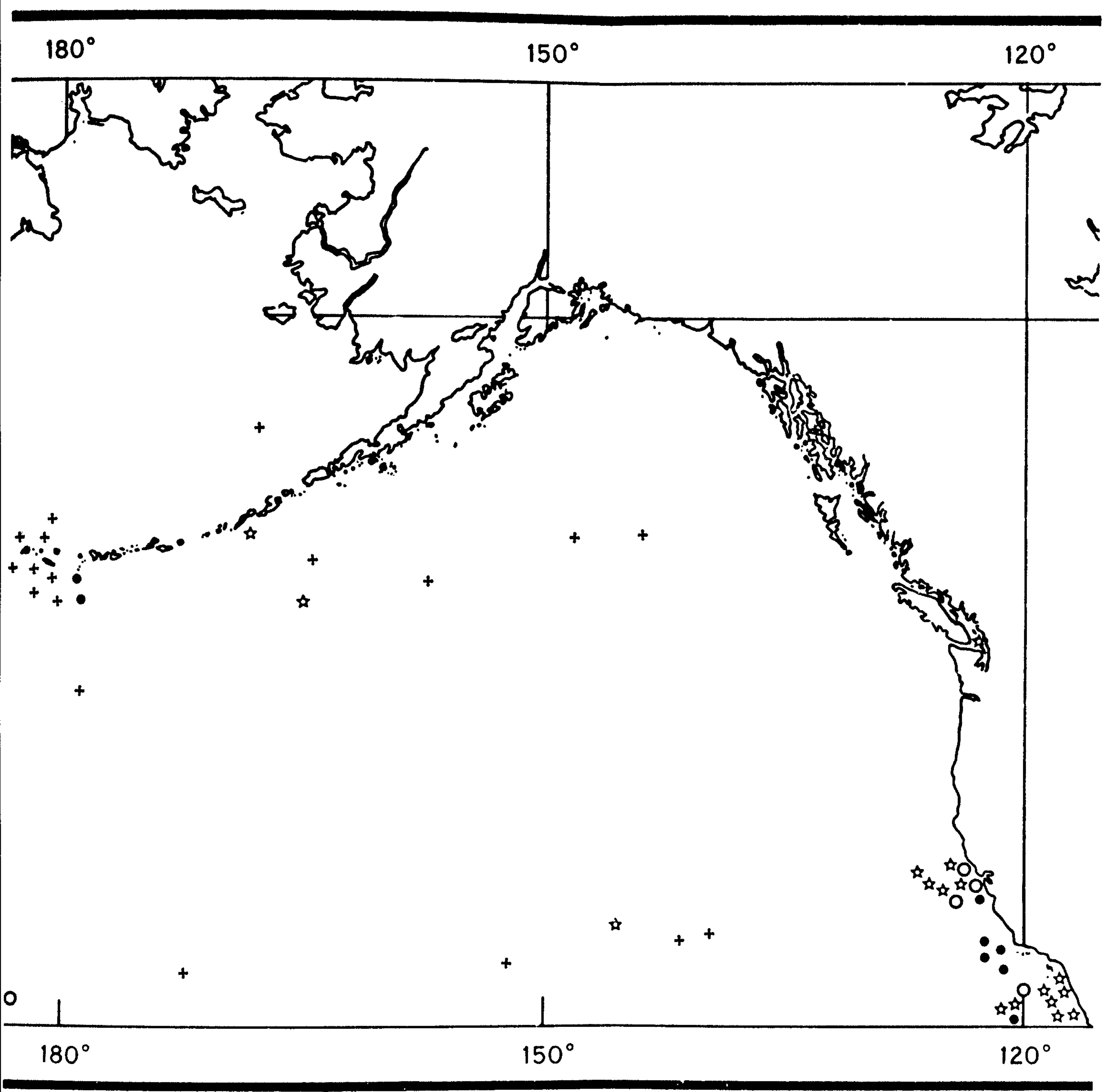


FIGURE 4 SEASONAL DISTRIBUTION OF
PACIFIC OCEAN AND ADJACEN

A



N OF BIOLUMINESCENT DISPLAYS, NORTH
)JACENT SEAS

B

moving fast. The water did not contain organisms visible to the eye. The intensity of the luminescence was sufficient to read by. It seemed the rapidly moving waves of light were accompanied by an unclear sound reminiscent of boiling water."

Another sighting of a luminescent display was reported in an article entitled "Huge Luminescent Mass Sighted in the Sea of Okhotsk" published in the Sapporo Edition of the "Asahi Shimbun" in August 1964. The article stated that just southeast of Cape Terpeniya, Captain W. Takada of the patrol ship TESHIO noted in August a spot of bright light which measured a few meters in diameter at first and then expanded quickly to 400 meters in diameter; it then contracted to 30 meters in diameter and disappeared into the sea in a whirling manner. The luminescence was as strong as an electric lamp but not the same as would occur when a ship broke seawater containing Noctiluca, for example.

Along the Pacific coast of Japan Noctiluca is particularly abundant in spring, when it occurs in such great quantities at times that the water, in addition to being discolored, becomes almost viscous in consistency. This extraordinary abundance has been observed in Aomori Bay and along the coasts of northeast Honshu and northeast Hokkaido. Spark-type displays occur very frequently in late summer and early autumn in the coastal regions as well as at some distance from the coast. These displays predominate in the more northern waters of Japan, whereas sheet-type and, to a lesser degree, glowing-ball-type bioluminescence appear most frequently farther south. Very dark brown or blood-red water caused by dinoflagellates has been observed in Tokyo Bay from January through March, and the sheet-type bioluminescence produced is brilliant at night. Many displays, often bright, have been observed in the Gulf of Sagami where warm water organisms of the Kuroshio and cold water organisms of the Oyashio are brought together.

Spectacular bioluminescence also has been observed during earthquakes. "Fiery" columns of light were observed in the Gulf of Sagami during the severe earthquake of 1923. The light was believed to have come from bioluminescent organisms violently stimulated by the strong shocks transmitted through the water. Near Sanriku, Honshu the sea receded during a tsunami. The exposed bottom was strongly luminescent with a bluish white light of such strength that land objects were visible as if in daylight. This display was attributed to the stimulation of the luminescent organisms coating the bottom.

On the Pacific side of the Kuril Islands and to the north along the east coast of Kamchatka, bioluminescent displays have been observed throughout the year wherever the water is free of ice cover. The luminescence is mostly sheet type and usually is seen in coastal waters in the spring; spark-type bioluminescence also has been observed in the spring, but generally some distance from the coast where large concentrations of luminescent euphausiids occur. Spark-type bioluminescence is the most common type observed during the autumn and winter months.

Only meager data are available concerning bioluminescence in the Bering Sea and northern part of the North Pacific Ocean. The few reports available indicate that the majority of displays occur from April through September, although the water probably is highly luminous at times during autumn and winter. Noctiluca and other luminous dinoflagellates are the principal light producers during summer, when maximum bioluminescence apparently occurs; copepods and euphausiids seem to cause the majority of displays during other seasons. Shoals of luminescent salps and medusae have been reported in the warmer waters of the North Pacific.

The maximum amount of bioluminescence in the region most probably occurs in the zone where the Oyashio and Kuroshio meet. One observer, while traveling across the front between the two currents, noted the sea as a tremendous arc of "phosphorescence" which lighted up the ship as though a green floodlight had been turned on.

In the western Aleutian Islands bioluminescence is pronounced during summer and early autumn (July through October). Both sheet and spark types have been observed during this period. The copepod Metridia has caused strong greenish bioluminescence in the coastal waters of the various islands of the Aleutians in the summer. Noctiluca reaches a peak of abundance in late summer and is responsible for displays in the surface waters off Attu, Kiska, and other islands.

Reports of bioluminescence are fragmentary in the northeastern part of the North Pacific. However, bioluminescence undoubtedly is much less frequent in the open ocean than near the coasts. Glowing-ball type bioluminescence increases in frequency southward to the Hawaiian Islands. Many species of luminescent medusae occur in the central Pacific.

Along the California coast many sheet-type displays occur during spring and summer when red water is produced by large numbers of luminescent dinoflagellates. Red water also may develop in winter when unusually warm water conditions occur. Luminous water observed just south of Monterey contained large numbers of dinoflagellates. The water may be highly luminescent off San Diego and San Francisco in November. This luminescence often is due to concentrations of salps or pyrosomes and at times to ctenophores.

Along the coast of southern California and Baja California, fish schools are located with the aid of bioluminescence. The kind of fish, depth, and direction of movement all are revealed by the bioluminescence created when they move through large concentrations of bioluminescent organisms. Nets drawn through the water often retrieve a very luminous slime made up of innumerable dinoflagellates.

EAST-CENTRAL AND SOUTH PACIFIC OCEAN (FIGURE 5)

Bioluminescence has been observed along the Pacific coast of Mexico and Central America throughout the year. The majority of displays are sheet type and glowing-ball type. Strong bioluminescence occurs in the Gulf of California during autumn. Beebe (1942) observed bioluminescence near Acapulco, Mexico during November. He described the display as "a mass of boiling turquoise foam" extending behind the ship and noted "a narrow intense curved line of pale green extending out from the side of the ship as if a luminous serpent were gliding with us over the surface." Brilliant displays of bioluminescence have been reported in Bahia Ballena, Costa Rica in March.

In the western approaches to the Panama Canal, bioluminescence occurs most frequently from January through June. The displays are primarily sheet type and glowing-ball type. Unusual displays of crescent-shaped "phosphorescence" and patches of pale green light often are reported. The crescent-shaped light apparently was not affected by the movement of a ship and most probably was caused by pulsations of the ship's engine, similar to incidents reported in Asian waters. Bright balls of "phosphorescence" are commonly observed in February.

In the vicinity of the Galapagos Islands, marine life is rich and includes a number of bioluminescent species. Beebe (1924) found the marine life very distinct at night, each organism "glowing from a phosphorescent silhouette." Copepods and medusae are the main bioluminescent forms in this region. Beebe also described concentrations of organisms capable of causing luminescent displays that he observed between Cocos Island and the Galapagos. He noted a gigantic current rip in April caused by two westward flowing currents; at the juncture of the currents the water was so full of plankton that it resembled soup. Single-celled organisms capable of lighting up the sea at night also were reported by him. Salps were present in great numbers. This enormous concentration of plankton continued for several nights. Noctiluca glowed in the water at night just south of Cocos Island in May.

The ocean off Peru and Chile within the Peru Coastal Current is highly luminescent. However, marine life farther offshore in the Peru (Humboldt) Current is meager, and only occasional displays of light have been observed. Along the coasts of Peru and Chile, bioluminescence has been known to occur most frequently from September through April.

The most intense sheet-type displays are said to occur along the Peruvian coast from December through April, when "aguaje" (sick water) develops in coastal waters. The water becomes greatly discolored sometimes bright red or various shades of brown and often, because of decomposing marine forms, gives off an offensive odor of hydrogen sulfide. At night the bioluminescence is often extremely brilliant. During periods when "El Nino" extends much farther south than normal, as into northern Chilean waters, the water becomes highly discolored

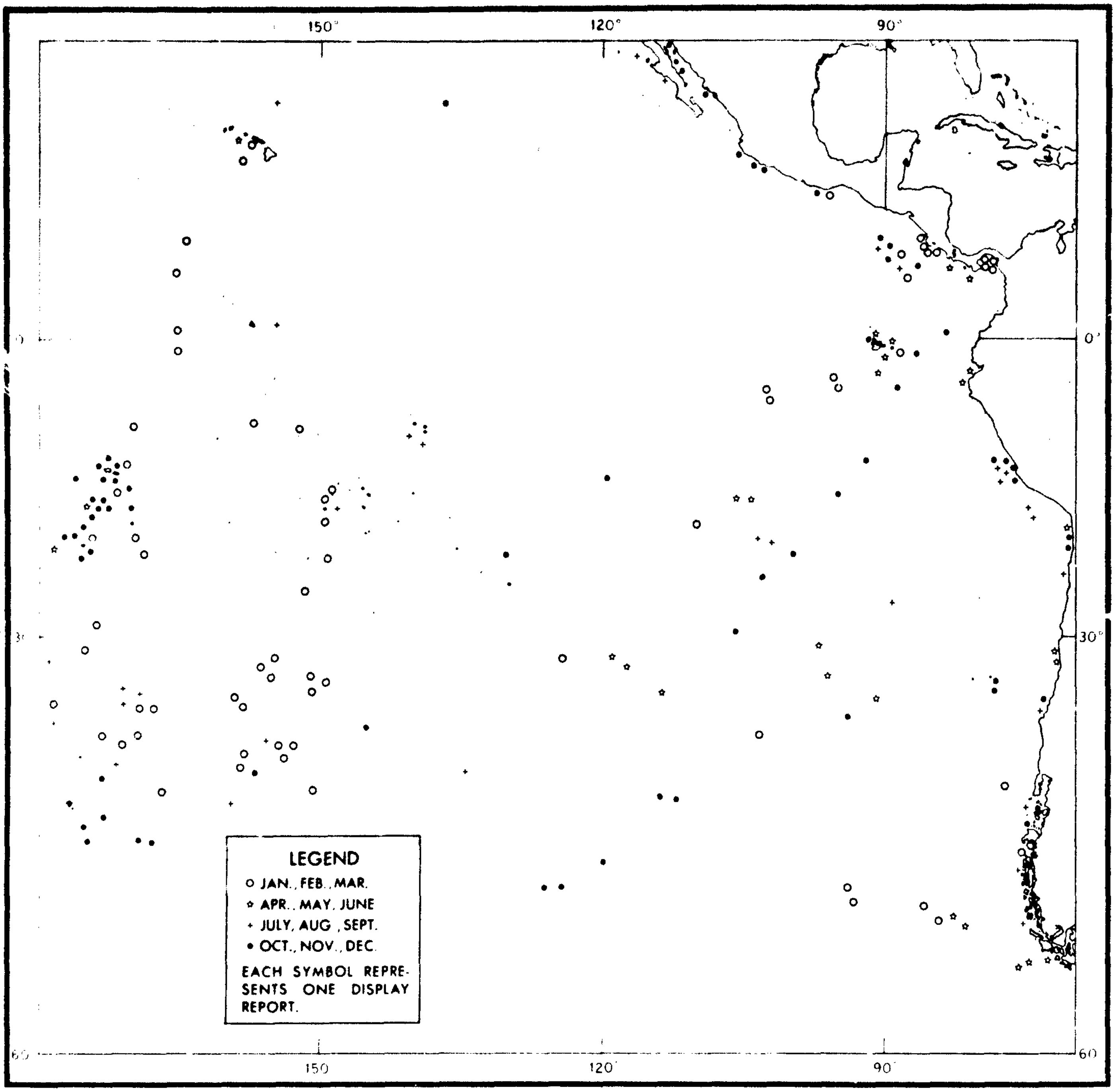


FIGURE 5 SEASONAL DISTRIBUTION OF BIOLUMINESCENT DISPLAYS, EAST-CENTRAL AND SOUTH PACIFIC OCEAN

because of massive blooms of luminescent and nonluminescent dinoflagellates. Murphy (1926) refers to an observer who noted during an "El Nino" disaster some years before that "after dark the sea broke out in phosphorescent lightings all along the coast," and during the day "the water was covered with blood-like patches many acres in extent."

One interesting report indicating a formation much like those observed in the south Okhotsk Sea and southeast Asian waters was made by Captain R. B. Bryant of the SS CURZCO sailing from Iquique, Chile to Tocopilla, Chile in September 1960. He noted "very marked phosphorescence in the form of lines which appeared to be spinning around in circular movement until dispersed by breaking waves." This appears to be a form of "phosphorescent wheel."

In the South Pacific north of 60°S over twice as many displays (about 69%) occur from September through January than during the rest of the year. Most of the displays in this region are glowing-ball type, usually produced by masses of salps, medusae, or Pyrosoma. A December report noted "globules of phosphorescent matter that would brighten momentarily when disturbed by the ship and cause sufficient light to illuminate an area of the sea surface about 8 feet in diameter." It also was observed that the breaking of waves some distance from the ship was sufficient to cause the same reaction. Shoals of bright red euphausiids often are noted in the southern regions of this area. The shoals luminesce at night and cause a scintillating blue light, which is quite striking to observers.

Bioluminescence probably occurs extensively throughout the year in ocean waters near the various island groups of the South Pacific. Although available data are inadequate, displays most likely occur with equal frequency throughout the year.

One interesting phenomenon may be mentioned. In the Samoan Islands the palolo worm swarms on the surface of the sea after dark in October and November. This swarming takes place near coral reefs, and the water is filled with vast numbers of threadlike worms which give out a pale-green "phosphorescent light."

WESTERN SOUTH PACIFIC AND EASTERN INDIAN OCEANS (FIGURE 6)

The percentages of total observations to the north of the Tropic of Capricorn for three-month periods are as follows:

January through March	16%
April through June	25%
July through September	39%
October through December	20%

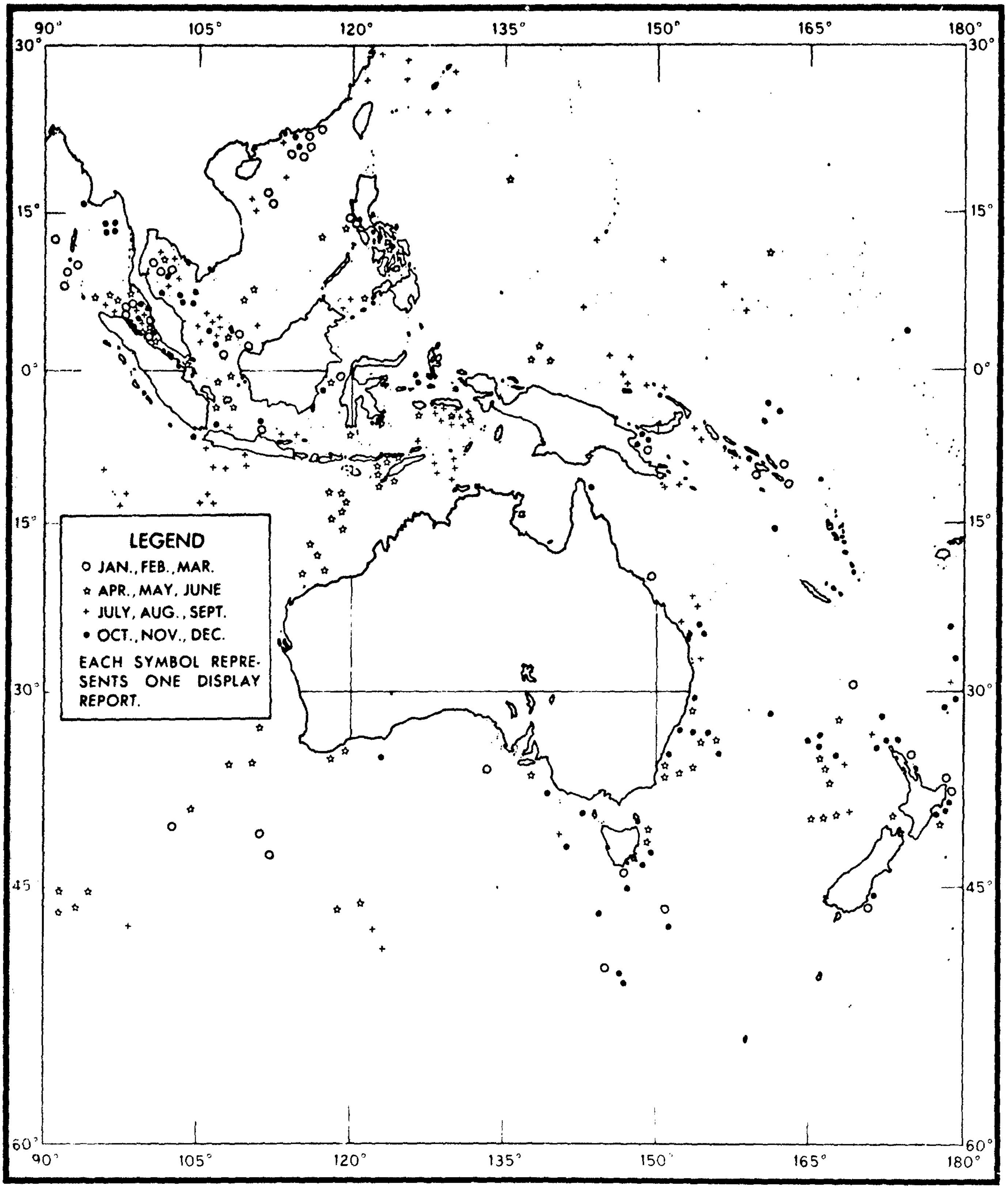


FIGURE 6 SEASONAL DISTRIBUTION OF BIOLUMINESCENT DISPLAYS, WESTERN SOUTH PACIFIC AND EASTERN INDIAN OCEANS

The percentages of total observations for the three types of displays in this region are as follows:

Sheet type ---------------	57%
Spark type ---------------	7%
Glowing-ball type --------	36%

Fewer displays have been reported to the south of the Tropic of Capricorn. The percentages of total observations for this region for three-month periods are as follows:

January through March ------------	13%
April through June ---------------	34%
July through September -----------	11%
October through December ---------	42%

Data are inconclusive as to the types of displays most frequently observed, although both sheet type and glowing-ball type bioluminescence appear to be more frequent than the spark type.

Pyrosoma (the fire cylinder) is responsible for the more spectacular glowing-ball displays throughout the year in this area. When luminescing, as observers aboard the USS VANCE noted in September 1961 in the Southwest Pacific, they were visible at a distance of 75 to 100 yards.

Large shoals of medusae also create brilliant displays of light in this area. In November 1950 observers on board the SS WAIHEMO noted a brilliant "phosphorescent" region as they steamed along in the western South Pacific. "Where the wash broke, the sea was brilliant blue, nearly as bright and the same color as the arc from a welding torch." Intense patches of light about the size of dinner plates also were observed. This reference to an arc light indicates the brilliance of some bioluminescence, sufficient to outline a ship in light.

Of special interest are the very brilliant snow white sheet-type displays which occur in the Banda Sea and have been observed most frequently during June through September. Because of these unusual displays the Banda Sea often is referred to as the "white sea." A characteristic of the displays is the suddenness with which they occur. The sea, normal in appearance, suddenly becomes "milky" as if a light switch had been thrown. The light is so strong that the sky may appear to be lighted, and the ocean may give the appearance of a snow covered land scene to observers. These exceptional sheet-type displays probably are due to large concentrations of dinoflagellates such as Noctiluca.

An article in the Washington "Sunday Star" of 9 February 1958 concerned recollections of an observer in the 1920's in Sandakan Harbor, British North Borneo. He stated:

The percentages of total observations for the three types of displays in this region are as follows:

Sheet type --------------- 57%
Spark type --------------- 7%
Glowing-ball type -------- 36%

Fewer displays have been reported to the south of the Tropic of Capricorn. The percentages of total observations for this region for three-month periods are as follows:

January through March ------------ 13%
April through June --------------- 34%
July through September ----------- 11%
October through December --------- 42%

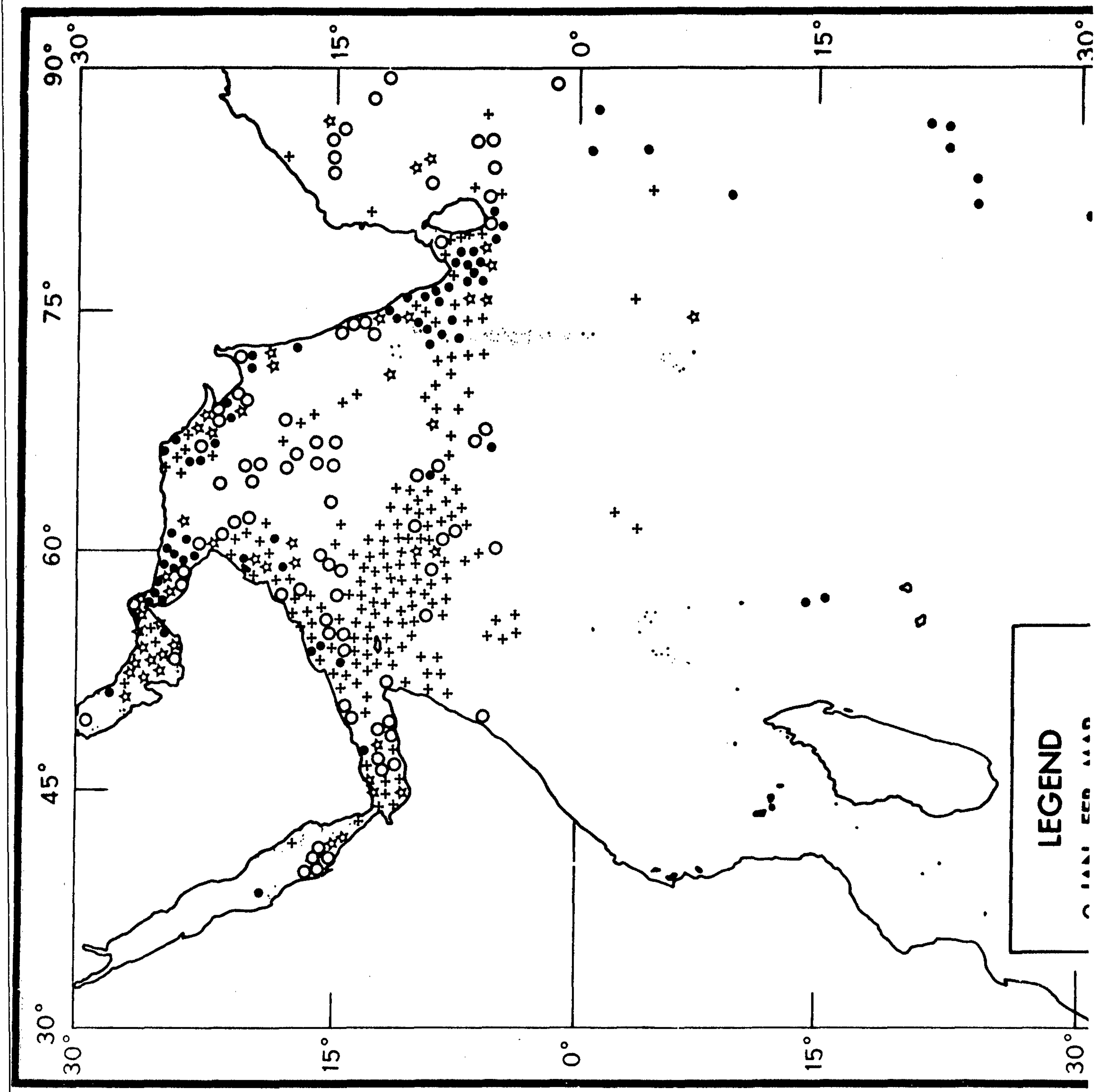
Data are inconclusive as to the types of displays most frequently observed, although both sheet type and glowing-ball type bioluminescence appear to be more frequent than the spark type.

Pyrosoma (the fire cylinder) is responsible for the more spectacular glowing-ball displays throughout the year in this area. When luminescing, as observers aboard the USS VANCE noted in September 1961 in the Southwest Pacific, they were visible at a distance of 75 to 100 yards.

Large shoals of medusae also create brilliant displays of light in this area. In November 1950 observers on board the SS WAIHEMO noted a brilliant "phosphorescent" region as they steamed along in the western South Pacific. "Where the wash broke, the sea was brilliant blue, nearly as bright and the same color as the arc from a welding torch." Intense patches of light about the size of dinner plates also were observed. This reference to an arc light indicates the brilliance of some bioluminescence, sufficient to outline a ship in light.

Of special interest are the very brilliant snow white sheet-type displays which occur in the Banda Sea and have been observed most frequently during June through September. Because of these unusual displays the Banda Sea often is referred to as the "white sea." A characteristic of the displays is the suddenness with which they occur. The sea, normal in appearance, suddenly becomes "milky" as if a light switch had been thrown. The light is so strong that the sky may appear to be lighted, and the ocean may give the appearance of a snow covered land scene to observers. These exceptional sheet-type displays probably are due to large concentrations of dinoflagellates such as Noctiluca.

An article in the Washington "Sunday Star" of 9 February 1958 concerned recollections of an observer in the 1920's in Sandakan Harbor, British North Borneo. He stated:



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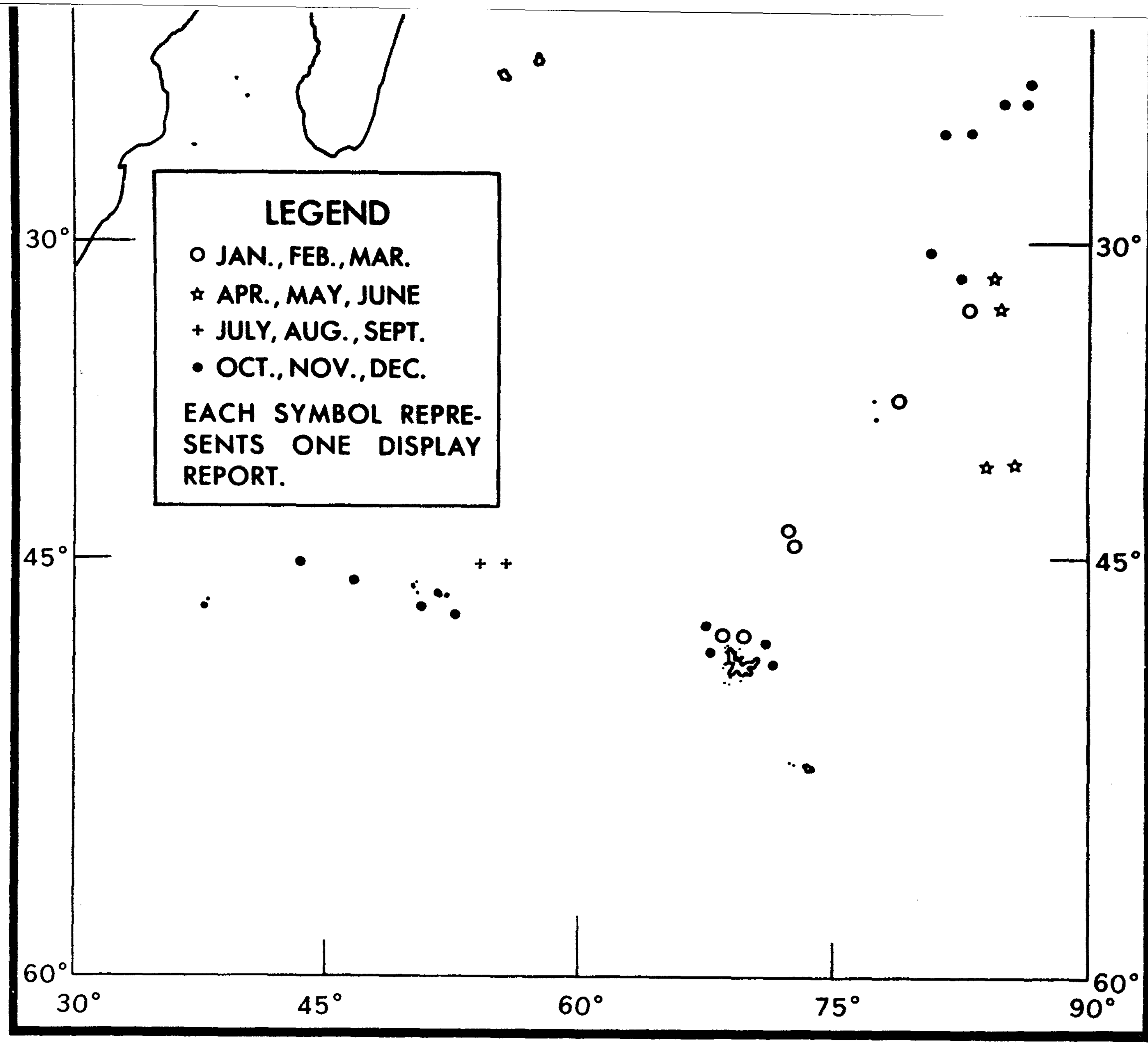

FIGURE 7 SEASONAL DISTRIBUTION OF BIOLUMINESCENT DISPLAYS, CENTRAL AND WESTERN INDIAN OCEAN AND ADJACENT SEAS

drift together or by which upwelling increases surface nutrients and thereby increases the production of marine forms capable of luminescing.

The percentages of total observations for the three types of displays in this region are as follows:

Sheet type	75%
Spark type	3%
Glowing-ball type	22%

The light given off by the sheet-type displays often is glaring in intensity and much more spectacular than any reported from other ocean areas of the world.

Some of the more unusual reports on surface bioluminescence are from the Arabian Sea. Numerous patches of vivid bioluminescence were noted on the surface of the sea by observers on the SS ELPHENOR in September 1931. The patches seemed to be arising from the depths of the ocean; the water swirled as if in an upward and spiral movement. Later in the evening, it was found that a ray of light from a flashlight could produce bioluminescence in the water wherever shown. Observers on board the USS DEVON in December 1929 noted small patches of bioluminescence which suddenly expanded from diameters of about 6 feet to diameters of 100 to 400 feet. In April 1956 observers on board the MV DAGMAR SALEN noted a similar appearance to that of the crew of the DEVON. The luminescence appeared to "bubble" up from below in the form of a cone of light, which eventually spread out to a diameter of 100 to 150 years. Those on board the DAGMAR SALEN also observed the water begin to "boil" because of thousands of mackerellike fish. One authority believes this occurrence to be a rare occasion when the Deep Scattering Layer broke through to the surface, as the mass appeared to be made up of luminescent plankton and the fish feeding upon them.

A "milky sea" display was noted by observers on board the Greek vessel SS IONNIS ZAFIRAKIS in August 1950 in the Arabian Sea. Second Officer M. Mariakis reported that the horizon commenced to whiten as the ship approached the luminous region, and then within the luminous region the water assumed a milky color. The discoloration of the water was considered different from "phosphorescence" by the reporter. The phenomenon lasted about $4\frac{1}{2}$ hours, and during that time the lower layers of the atmosphere acquired a very thin whitish appearance, reaching approximately 15° altitude and dimming the brilliance of the stars. The sea was rough until the ship reached the luminous area, where it became calm and glassy. This change may have been the result of concentrations of oil-bearing luminescent organisms such as Noctiluca. Captain A. Charasakis of the Greek vessel VERNICOS NICOLAS in the Arabian Sea during August 1949 observed that the "whole surface of the sea became brightly and deeply fluorescent" and "the surface appeared as if crystalline in nature, through which a high tension current of electricity passed, illuminating it brightly." Visibility was hindered by the light given off. That this condition can continue over a series of nights is indicated by the report of observers on board the SS PORT HUNTER during the nights of 18 - 21 August 1925.

"Extraordinary phosphorescence was noted in the sea. The sea became luminous from horizon to horizon each evening between 8:30 and 9:00 p.m., and disappeared in the morning about an hour before daylight. It gave the effects of the ship sailing in a sea of milk, at times very bright, and it was possible to read the Azimuth Tables on the bridge by the light, usually between the hours of 2 and 4 a.m."

Bioluminescence in this area appears to occur much less frequently south of the Equator than north of it. Reports south of the Equator make up only about 10% of all those available north of 60°S. All three types of displays have been observed, the glowing-ball and spark types of bioluminescence being predominant. Shoals of pyrosomes or salps are responsible for most of the glowing-ball bioluminescence in this region. The few reports available indicate that glowing-ball bioluminescence has been observed most frequently in the period April through June and again from October through December. Little is known about the incidence of spark-type bioluminescence, but there is probably an increased number of these displays in the direction of the Antarctic Convergence, where euphausiids and copepods reach peak abundance most likely in the same months as do the glowing-ball organisms.

"PHOSPHORESCENT WHEEL" AND "WAVE" DISPLAYS (FIGURE 8)

Reports of 85 "phosphorescent wheel" displays and 26 "wave" displays (not plotted) are on file at the Oceanographic Office. The category of "wave" displays includes such light formations as luminous undulating waves, luminous rays extending through the water, and various light patterns which cannot be categorized as "phosphorescent wheels."

Descriptive material concerning "phosphorescent wheel" and "wave" formations is both voluminous and variable. The complexities encountered in attempting to classify such appearances are illustrated by the following two reports from "The Marine Observer."

MV SCOTTISH EAGLE. Captain R. R. Baxter. Bandar Maahur to Kwinana. Observer, Mr. S. M. Grant, Chief Officer.

"23rd April, 1955, 1625 to 1635 G.M.T. When approaching Jazirat Tunb Island a bright flashing light was observed on the port bow, distant about 1 mile. Almost simultaneously another was observed on the starboard bow. On approaching it was seen that these were two revolving phosphorescent wheels. The ship passed between them, the centres being about ¼ mile distant on either side. The wheel on the port side appeared to revolve anti-clockwise, and that on the starboard side clockwise.

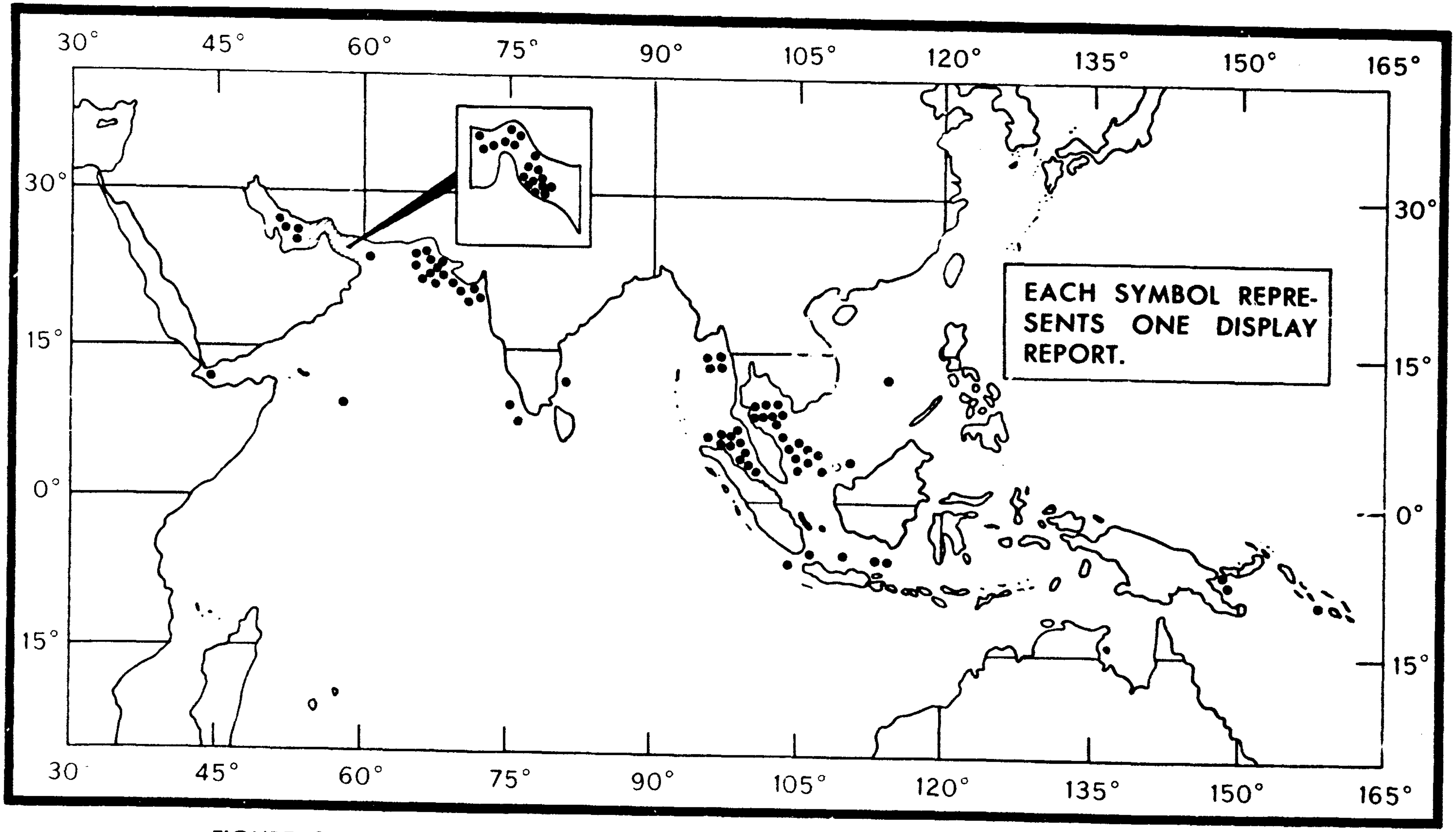

FIGURE 8 DISTRIBUTION OF "PHOSPHORESCENT WHEEL" DISPLAYS

The spokes of radius $\frac{1}{4}$ mile were from 6 to 12 feet broad at the tips with about 15 feet between them. They passed with a frequency of 1 $\frac{1}{2}$ sec. with a colour similar to that of a dull electric light. Immediately we had passed these two wheels, further phenomena were observed (.....). On the port side concentric circles were seen to radiate from a centre, with an effect similar to that of dropping something in still water. On the starboard side there appeared lines, apparently moving away from the ship in a manner similar to the wake. As the ship passed they gradually faded from sight astern and had been in sight 10 or 15 minutes. At 1700 a similar phenomenon was observed to the SE distant about 7 miles."

"The Master comments: 'The sky was overcast and the atmosphere appeared to have more than the usual amount of particles in suspension, but the all-round visibility was very good. Jazirat Tunb Light was about 20 miles away and its rotating beams were visible in the air throughout their complete revolutions. Above the sea surface their was apparently a layer of mist a yard deep.

"The bands of phosphorescent light appeared to float on top of this layer, but on closer examination of the beams as they passed vertically under the observer it could be seen that the sea was affected to a considerable depth. Each band was similar in colour and appearance to the Milky Way, myriads of particles of light dust with brighter and larger specks here and there. My impression, especially during the concentric ring phenomenon, was of shock waves causing the millions of organisms to light up as the wave passed through them, then going dark until the next wave struck them. I do not believe the organisms themselves were on the move. The effect on the onlookers seems to have been a feeling of weirdness, bordering on fear, similar to that experienced by people ashore during earthquake tremors.

"When the later distant phenomenon was observed it made a glow on the horizon and could be made out with binoculars but no shape or form. I believe this was another group of wheels covering more than a square mile.' Temperature, air 81°F, wet bulb 75.6°, sea 78°."

Position of the ship: 26°11'N, 54°55'E.

MV BRITISH EMPRESS. Captain A. Henney, O. B. E. Port Okha to Persian Gulf. Observer, Mr. P. M. Alderton, 3rd Officer.

"5th April 1953, 2125 Indian Standard Time. Commencing from about NNW, shafts of pale white diffused light appeared, apparently travelling on the surface of the water at a great speed. Each shaft was several feet wide and they stretched as far as the eye could see. At first they appeared in perfectly parallel lines, equally spaced, passing tne ship at about one every second, but after five minutes they wheeled round in perfect formation and approached the ship from all points of the compass. They came from only one compass point at a time and each change of direction was swift and definite, though not abrupt. The most frequent directions were from NNW and SSE.

"After about 15 minutes the shafts occasionally formed into a rotating radial movement in which they retained their equal geometrical precision and the frequency of about one per second. At this time the pattern was continually changing about every 20-30 seconds from the parallel lines to the wheel. The periods of transition were hardly noticeable, but they were not abrupt. Each time the wheel appeared it was in a different place. On one occasion there were two distinct wheels visible at the same time. Throughout the period the wheels appeared they varied in direction of rotation, some clockwise and some anticlockwise. Five minutes later the pattern became still more complicated but remained perfectly regular and at 2150 the light faded out over a period of 30 seconds.

"Although the light appeared to be on the surface of the water it was completely unaffected by the wind and no disturbance of the water was produced. The most notable feature of the phenomenon was the effortless speed and mathematical precision of movement. The only near analogy I think of is that of being placed in the middle of a large A scan when a large variable AC current is supplied. The whole effect was one of great weirdness and errieness, so much so that the look-out man came on to the bridge quite scared, believing that he was suffering from hallucinations.

"The ship's course was 290° (T), speed 10 kt and no alteration of either took place during the observation. The sea was that corresponding to Beaufort Scale wind force 2-3, swell negligible, sea temperature 78°F. The sky was cloudless, with perfect visibility, wind NW, force 2-3, air temperature 80°F."

Position of ship: 22°42'N, 68°03'E.

A simple "wheel" report appears to include the initial sighting of a spot or pulsation of light on, above, or just under the sea surface, sometimes observed at a great distance. This luminous spot usually broadens and forms a pyrotechnic pinwheel effect, with long curving luminous arms (spokes) that turn either clockwise or counterclockwise. More than one wheel may appear, sometimes very small (less than a meter in diameter) and at other times very large (covering the horizon). The hub of such a wheel often is a glaring and intense white luminescence, of such intensity at times that one observer noted it appeared "like magnesium burning."

The cause or causes of such phenomena are still unknown, although the luminescence created appears to be related directly to luminous organisms in the water. However, some theories have been advanced to explain these formations. Kalle (1960) has suggested that these appearances result from the action of submarine shock waves upon bioluminescent organisms. These shock waves, originating from submarine earthquakes, impinge upon bioluminescent organisms and cause them to light up. The light pattern perceived is due to the interference pattern created by shock waves and reflected waves. When in phase, the luminescence formed is intense; when out of phase, it is weak. Most of these formations have been observed in regions of shallow water where such interference patterns can occur. According to Kalle, the pattern created appears as a wheel or some closely allied appearance. He also indicates that "exploding" luminescence, noted most often in deep waters, is due to the arrival of submarine shock waves at the surface. The pattern occurring resembles a bubble of light which rises from the depths, bursts at the surface, and rapidly expands into a large circle of luminescence.

Nicol (1961) expressed doubts about this theory, giving as his reasons the patchiness of the distribution of bioluminescent organisms and the fatigue experienced by these organisms after continual stimulation. Both the symmetry and duration of the pattern would be greatly affected, the wheel and wave would be broken in appearance, and the intensity would gradually lessen after each shock. This occurrence has not been reported.

Hilder (1962) advanced the theory that "phosphorescent wheels" were caused by electromagnetic waves, such as would occur in magnetic fields. The distortion of the earth's magnetic field caused by a ship moving through a region, magnetic anomalies created by sunspots, and the ultrahigh frequency of radar are all implicated by him in the development of wheels or waves. He reported an effect in the Solomon Islands area in March 1955 in which luminescence of the sea was a function of the radar emission. When the radar was turned on, the luminescence appeared; when the radar was turned off, the luminescence weakened considerably. Except for one other report, no other observations, even during conditions of total blackout, have been reported concerning the above phenomenon. Nicol's argument is relevant to this theory also.

Both light and sound waves have been implicated in the stimulation of bioluminescence. The sound emitted by ship engines has been correlated with the pulsations of light observed, also, observers have noted that a beam of light on the surface of the sea activated bioluminescence. A bright green streak may be noted as the beam from a flashlight is moved across the surface of the sea. When the light is turned off, the bioluminescence disappears after a few seconds. In still other situations, pinpoints of light, much like the end of a lighted cigarette, flashed on when a light beam passed over and immediately disappeared as the light was removed.

Although most investigators believe that the luminescence during "wheel" displays is produced by marine organisms in the water, it is possible that some other type of luminescence may be occurring, if not exclusively, at least as an adjunct to the bioluminescence. Of the displays reported (Figure 7), most occurred in the following areas: southern Persian Gulf, Strait of Hormuz, seaward of the Mouths of the Indus, Strait of Malacca, Gulf of Thailand, and southern South China Sea. Displays occurred to a lesser extent in the northern Andaman Sea and along the north coast of Java. All of these regions are shallow, and rather extensive blooms of phytoplankton occur in all quite regularly. The water often becomes supersaturated with oxygen during these blooms.

Strong pressure waves passing through a solution of high gas content may cause an electroluminescence due to the breakdown of bubbles of gas within the solution. It is possible that this phenomenon may occur in the sea also. Shock waves (from submarine earthquakes or underwater volcanic activity), which often are strong enough to jolt a ship, might also be strong enough to cause luminescence in sea water containing a very high gas content such as may occur in this area.

Although the occurrence of "phosphorescent wheels" or "waves" is unpredictable at present and the reports are not numerous, the available records indicate that these phenomena are more frequent during particular months in four areas. In the southern Persian Gulf-Strait of Hormuz area about 67 percent of reported displays have occurred from April through June. Off the Mouths of the Indus and in the Strait of Malacca approximately 75 percent of reported displays have occurred from July through December, and in the Gulf of Siam and the southern South China Sea 75 percent of reported displays have occurred from April through June and from September through December.

POLAR REGIONS

Although little information is available concerning bioluminescence in the ocean surrounding Antarctica, some rather strong spark-type displays have occurred along the fringe of the Antarctic Convergence. Here massive concentrations of euphausiids have been noted. The light they give off may be intense at times but more often is weak.

More bioluminescence has been observed in the ocean areas adjacent to the Arctic Ocean, but information still is meager. Dinoflagellates produce luminescence in the waters around Svalbard (Spitsbergen); crustaceans also may create varying degrees of bioluminescence near these islands. Tarasov (1956) reported an observation by K. S. Badiginin in January 1940 at 81°11'N, 3°50'E of bright greenish "phosphorescence" lighting up the waves of an ice-filled ocean, reminiscent of light observed in the Indian Ocean at a previous time.

Snow and ice sometimes luminesce in these colder regions as a result of entrapped dinoflagellates and crustaceans. One observer noted his luminescent footprints in the snow as he walked along the edge of the sea after dark. He described very intense but quickly fading bluish white light outlining his footprints. Later investigations attributed this light to luminescent crustaceans washed in from the sea into the snow.

Isachenko (1914) stated that luminescence was a common phenomenon near Murmansk during autumn nights. Although the type of bioluminescence was not mentioned, certain luminescent dinoflagellates appear to reach a maximum development in the waters of the western Barents Sea in November and December. Other luminescent dinoflagellates are most abundant in August. All of the seas fringing the Arctic Ocean probably experience some spark-type bioluminescence due to crustaceans.

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