

Ocean Systems

Lecture 16 & 17

Hydroclimate, heat budgets and stratification

For plants to thrive in oceans and lakes they need sunlight and nutrients. But thermal stratification tends to separate nutrients and light.

These profiles of temperature, density and nutrients as a function of depth illustrate the nature of stratification. Light, less dense, water floats on top of colder, less dense water. Plankton (and dead fish, etc. are slightly heavier than water and tend to sink out of the lighted surface water, carrying nutrients with them. Stratification tends to separate nutrient rich from light rich waters.

Fig. 5.13. Distribution of nitrate (a) and phosphate (b) with depth in the three major ocean basins. From H. U. Sverdrup, Martin W. Johnson, and Richard H. Fleming, *THE OCEANS: Their Physics, Chemistry, and General Biology*, © 1942, renewed 1970. By permission of Prentice-Hall, Inc. Englewood Cliffs, New Jersey.

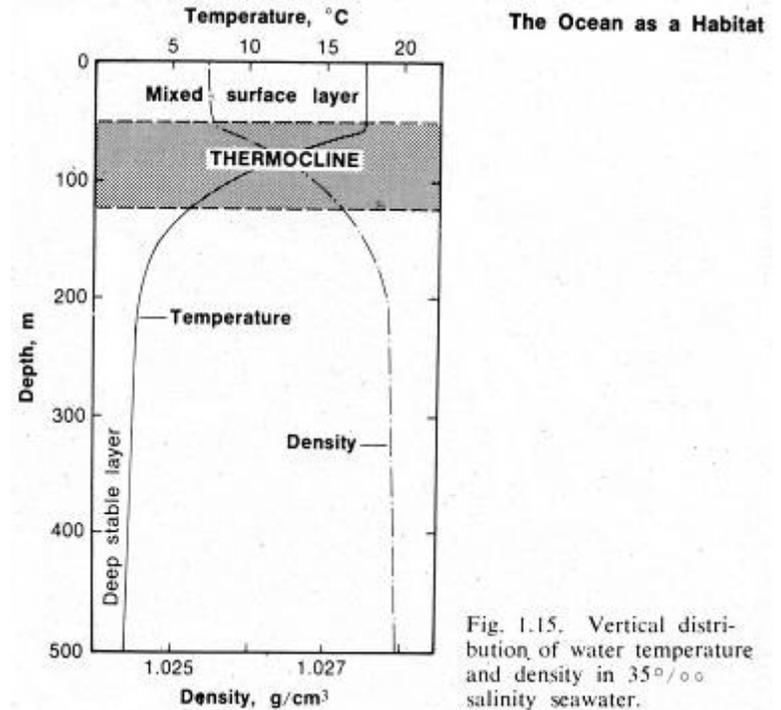
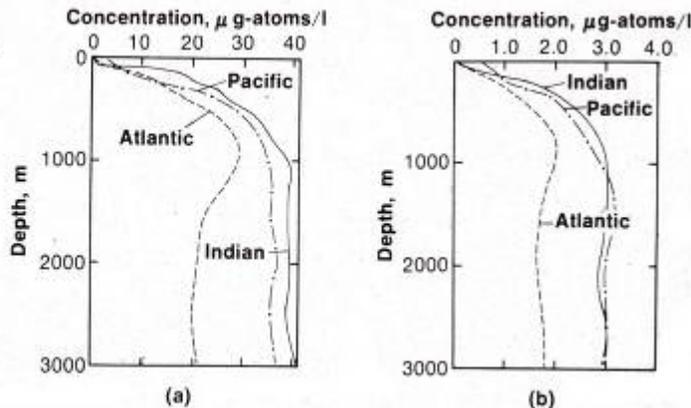


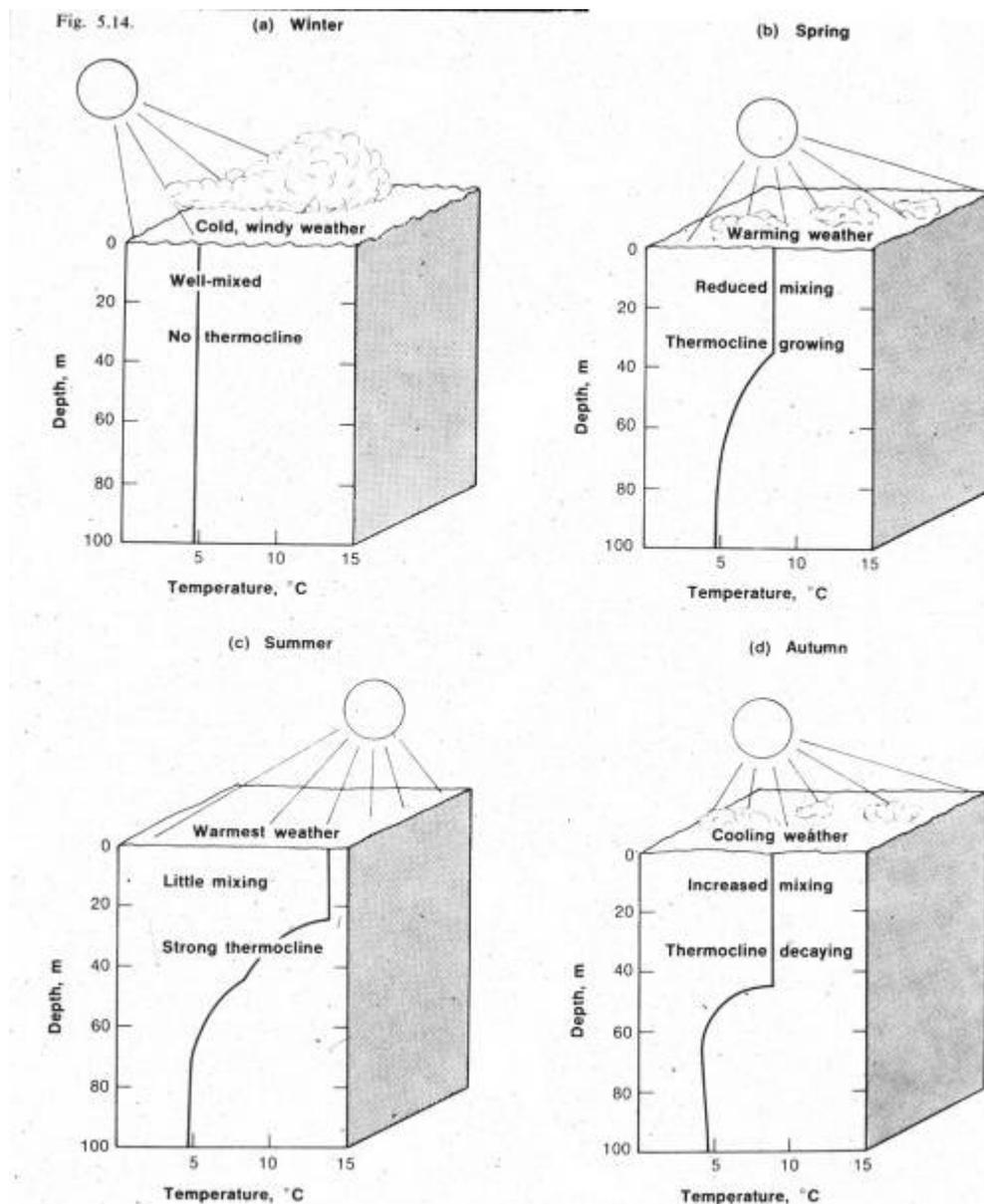
Fig. 1.15. Vertical distribution of water temperature and density in 35‰ salinity seawater.

At high latitudes, the oceanic thermocline is built and broken down down seasonally

Seasonal heat budget and stratification.

The picture at right shows how the stratification of the Transitional Biome in the ocean or large temperate lakes (like Tahoe) works. In the Winter evaporation, IR radiation to the cold sky, and conduction to the atmosphere result in dense water forming at the surface, deeply mixing the water column. In Spring, heat income from shortwave solar radiation increases sharply as the sun angle increases. The surface starts gaining more heat each day than it loses each night, mixing is reduced at the warm epilimnion forms. By mid to late Summer, the epilimnion (mixed layer) reaches its greatest extent and a temporary balance is achieved in which heat gain and loss balance. In Autumn, solar input drops and the surface starts losing more heat each night than it gains during the day. Nocturnal plumes of heavy cool water start to erode the thermocline. Finally, the thermocline becomes so weak that turbulent mixing in a big storm erases it entirely.

During the winter light is very low especially because the plankton are mixed very deeply. In the spring, light levels are high, mixing depth is limited, nutrients have been mixed upwards and the phytoplankton bloom. As the summer goes on, the mixed layer becomes stripped of nutrients, and productivity declines



Productivity in a seasonal ocean or deep lake

- In winter, mixing is deep and plenty of nutrients are mixed to the surface
- But phytoplankton are also circulated deeply, and light is dim in the winter; phytoplankton are light limited.
- In spring a thermocline is established, limiting deep mixing; phytoplankton bloom on the nutrients mixed to the surface in winter
- As summer progresses, nutrients stripped from water column by settling of biomass; primary production becomes nutrient limited
- Fall sees an erosion of the thermocline and the onset of winter light limitation

An aquatic version of a climograph. Sub-Polar Biome. In the Sub-Polar Biome the water column mixes in winter to depths far deeper than the photic zone, the zone with enough light for photosynthesis. Algae are light limited. In late spring and early summer, the mixed layer comes up to the same depth as the photic zone and primary production explodes. Note that the increase in biomass does not reflect the increase in production. That is because zooplankton grazers become very active and keep the crop of phytoplankton mowed down. Already by mid summer, nutrients are depleted and productivity begins to drop. It drops further in fall as the mixed layer deepens adding light to nutrient limitation. Note that DCM production is not very important. After AR Longhurst.

Key to abbreviations:

MLD = mixed layer depth

temp = temperature

sigma = density

Pt = rate of photosynthesis

profile = integrated over water column

DCM = in deep chlorophyll maximum

Chl-a = concentration of the main chlorophyll pigment in algae, a measure of algal biomass.

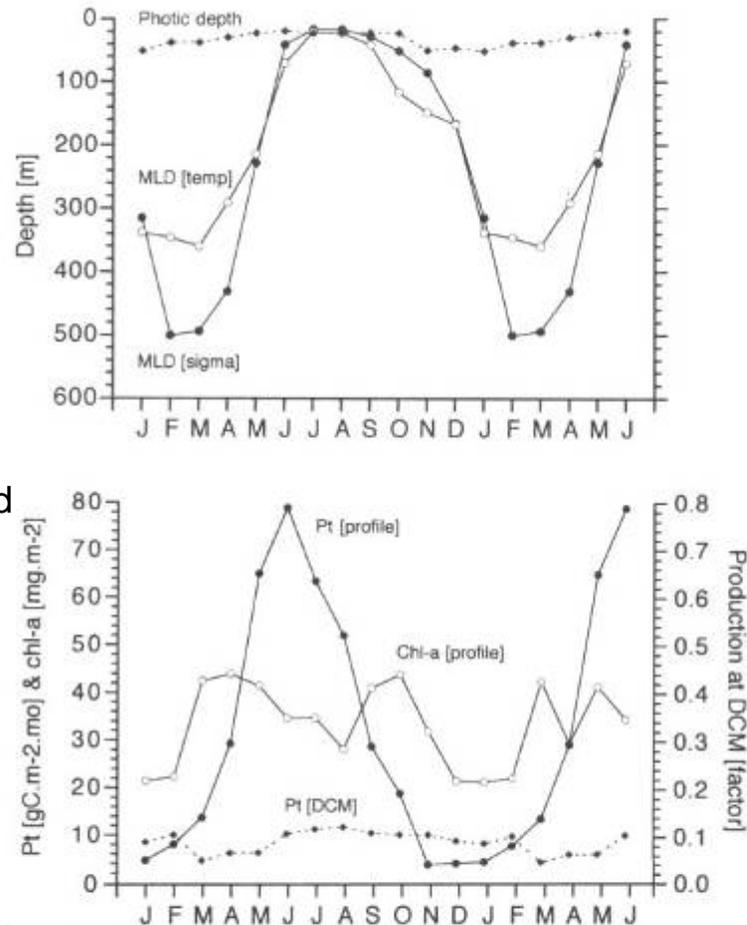
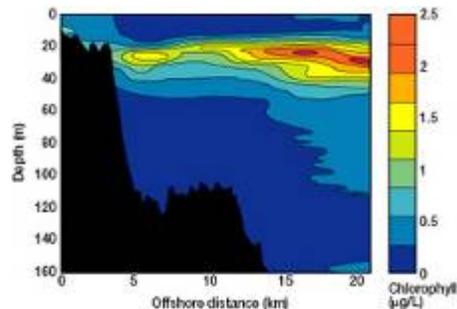


FIGURE 7.2 ARCT: characteristic seasonal cycles of monthly averaged mixed layer and photic depths, chlorophyll at the surface, and rate of primary production both depth-integrated and at the DCM. Data sources are discussed in Chapter 1.

Transitional Biome Climograph. California Current. Note the high and seasonal productivity. Even in winter, production is not too shabby. Upwelling tends to produce clear water and relatively deep euphotic zones, plus winters are fairly bright. In summer, upwelling is forcing water upwards. The thermocline is weak but shallow, established after the cool deep water upwells. Note that a respectable fraction of the production is in the Deep Chlorophyll Maximum in summer. Summer grazing by copepods keeps the algal biomass well cropped.

Section with pronounced DCM



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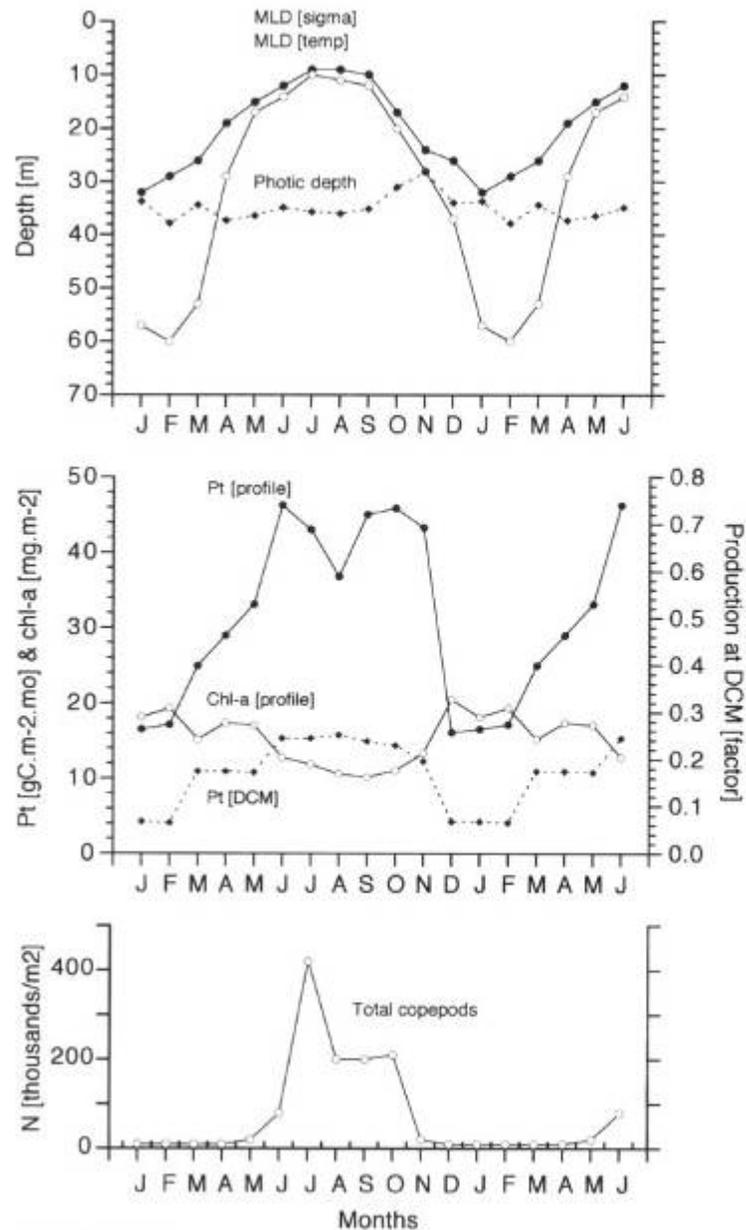
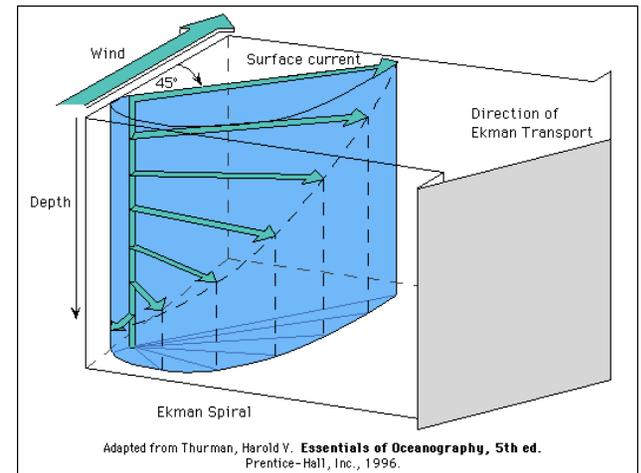
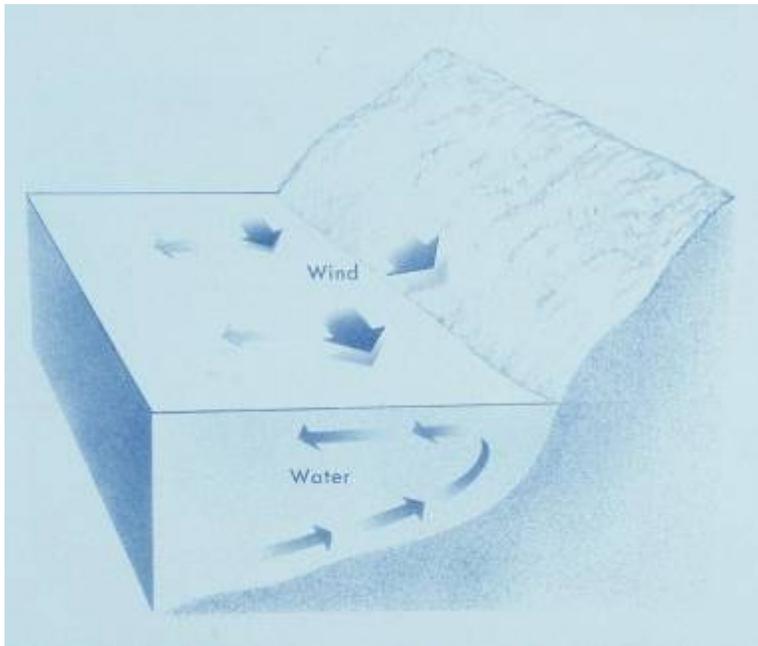
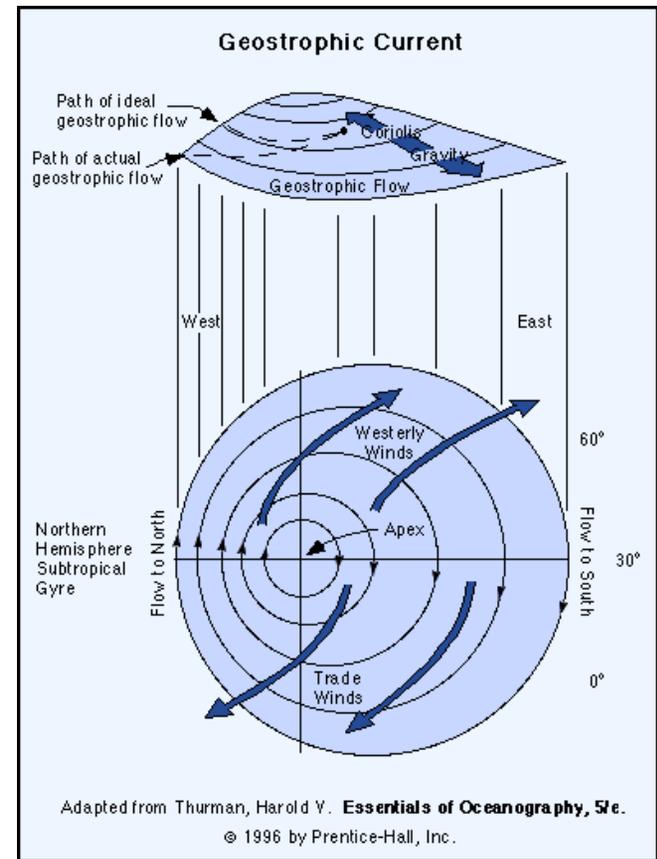
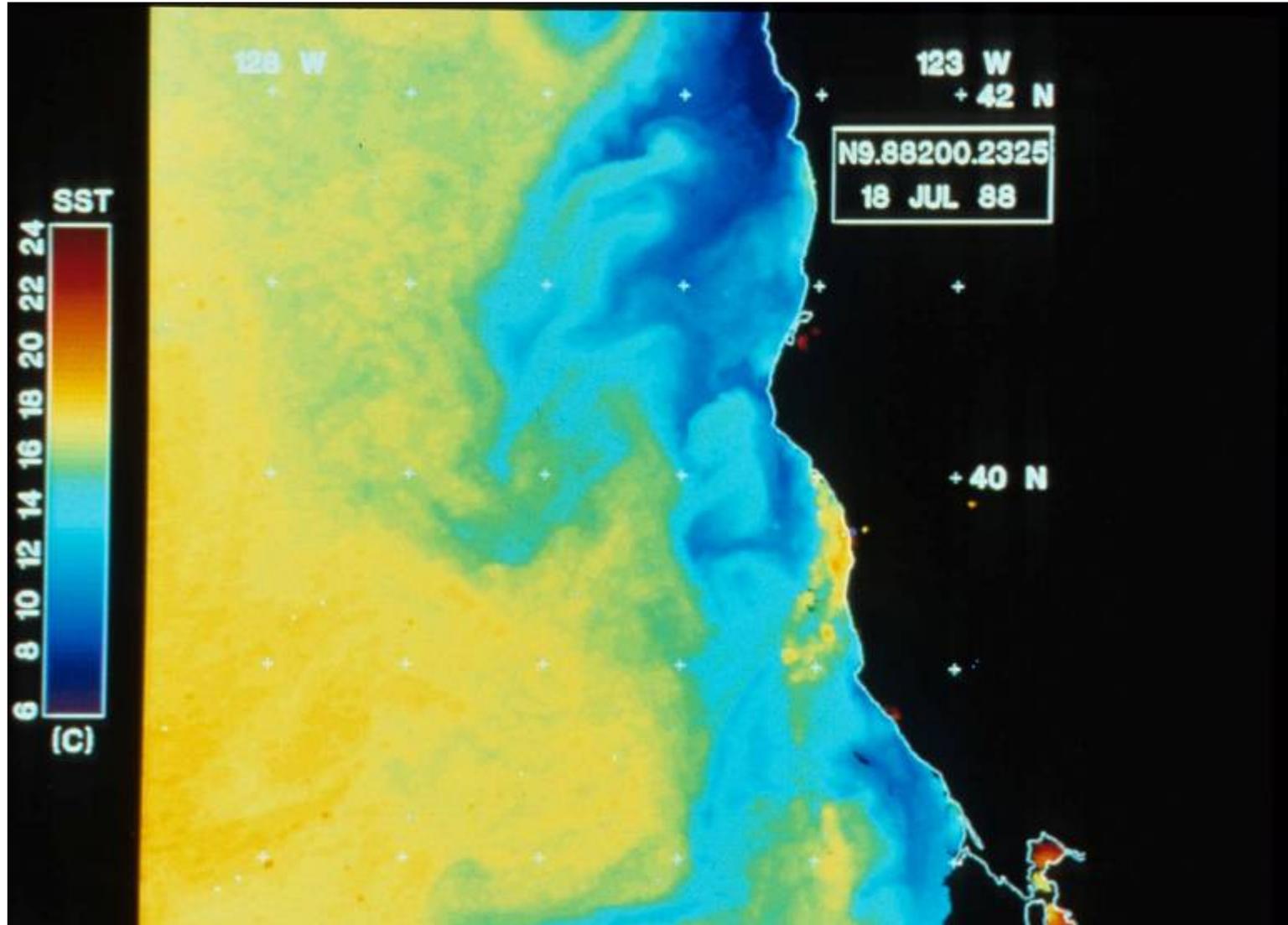


FIGURE 9.16 CALC: characteristic seasonal cycles of monthly averaged mixed layer and photic depths, chlorophyll at the surface, and rate of primary production, both depth-integrated and at the DCM. Data sources are discussed in Chapter 1.

Explaining upwelling. First, you need to understand the concept of “geostrophic flow.” The ocean currents are to a first approximation in equilibrium with gravity and Coriolis’ force, hence approximately geostrophic. The oceans are huge and have enormous momentum. The winds have strong average patterns. The oceans are “spun up” as the hydrodynamicists say; average current speeds reflect average winds speeds, roughly. See diagram right. The central gyres of the oceans are very gentle hills about a meter high. As a component current of the gyre, like the California Current, flows around the gyre, Coriolis’ force tugs it it toward the center of the gyre. The effect of Coriolis’ force is illustrated by the Ekman Spiral diagram below right. At equilibrium tho, enough water has piled up in the gyre to zero out the effect of Coriolis’ force. But the equilibrium is only approximate. Whenever a strong NW wind comes up along the California Coast, as it tends to do every few days, the California Current is accelerated, and it swings right, offshore, and colder, deeper water upwells right along the beach. It helps that the California Current is already fairly cold, so the thermocline is weak and relatively little energy in needed to push the thin surface current westward. See diagram below and real picture on the next slide.



California Coastal Upwelling. In midsummer a big blob of upwelled water has reached the surface at 42 N, and smaller ones at 40 N and 39 30 N, just north of San Francisco Bay in the lower right. Note that the core of the upwelled blobs are about 7° C or about 45 F. This is why swimming in the ocean is so rigorous in Northern California. Even in midsummer, the upwelling makes the water very cold. Notice the rather warm water right along the coast between 39 and 40 N. That is probably a bit of warm offshore water swept onto the coast when the current decelerated before the current upwelling episode.



Aquatic climograph for Central Biome. North Pacific Gyre. This is blue water; note the relatively great depth of the photic zone. Generally, the mixed layer is shallower than the photic zone. Plenty of light, scant nutrients! Note that photosynthetic productivity is aseasonal but at the same levels as the winter minima in the Sub-Polar Biome. What is going on here? The answer is a strong permanent thermocline.

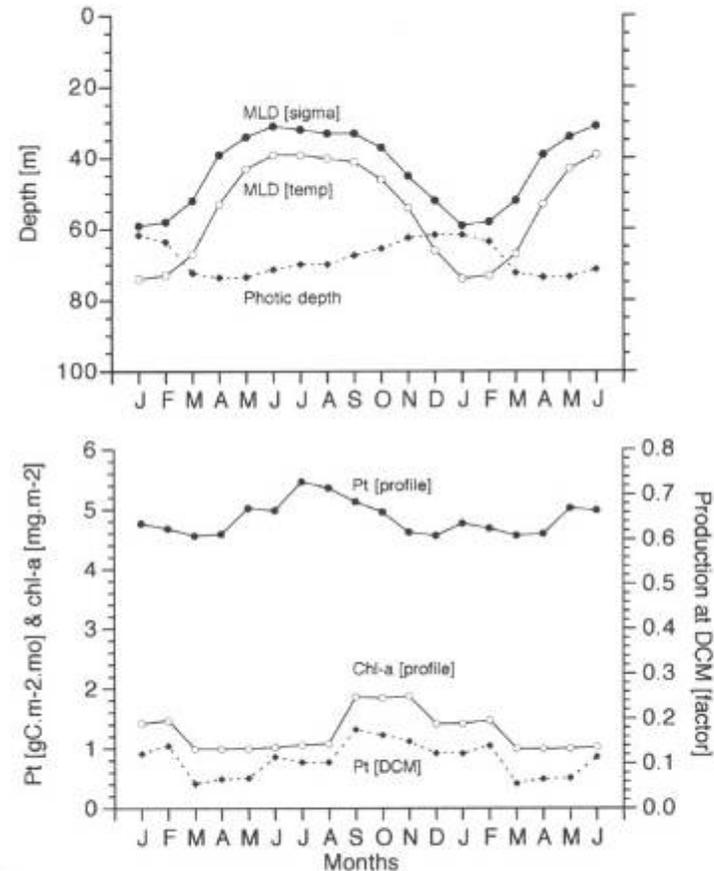


FIGURE 9.8 NPTG: characteristic seasonal cycles of monthly averaged mixed layer and photic depths, chlorophyll at the surface, and rate of primary production, both depth-integrated and at the DCM. Data sources are discussed in Chapter 1.

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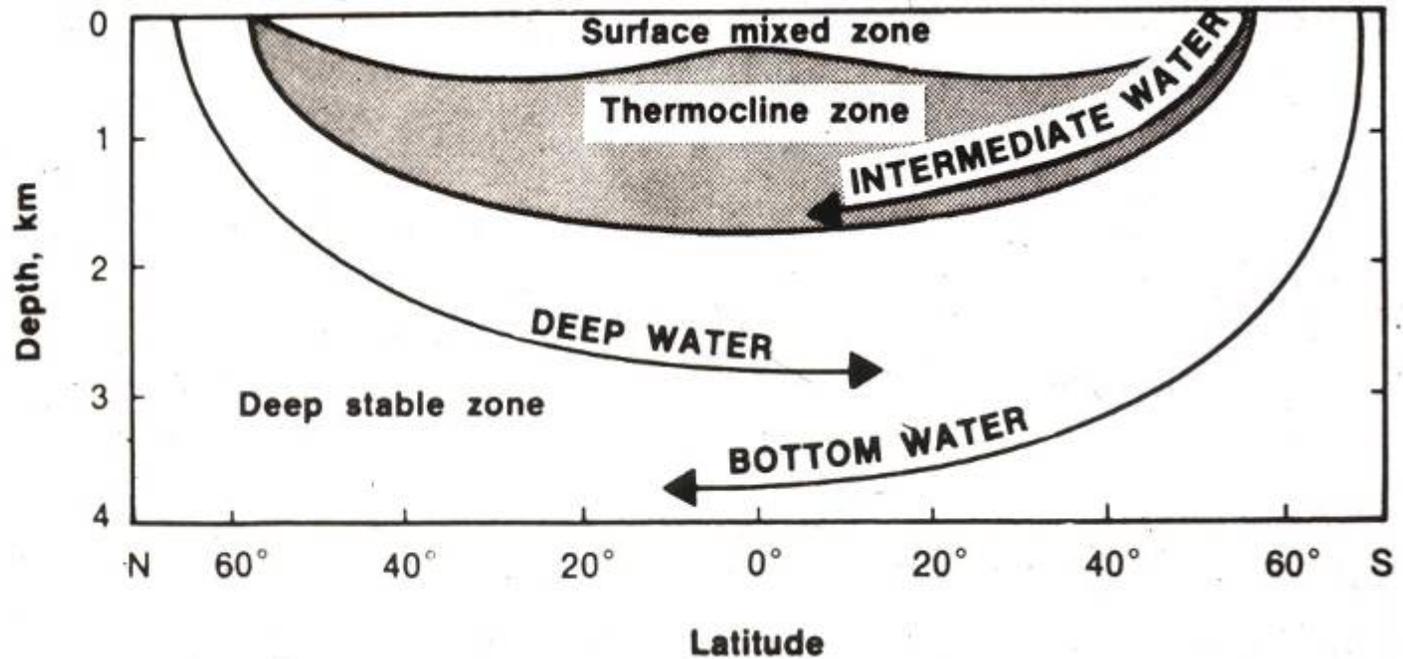
profile = integrated over water column

DCM = in deep chlorophyll maximum

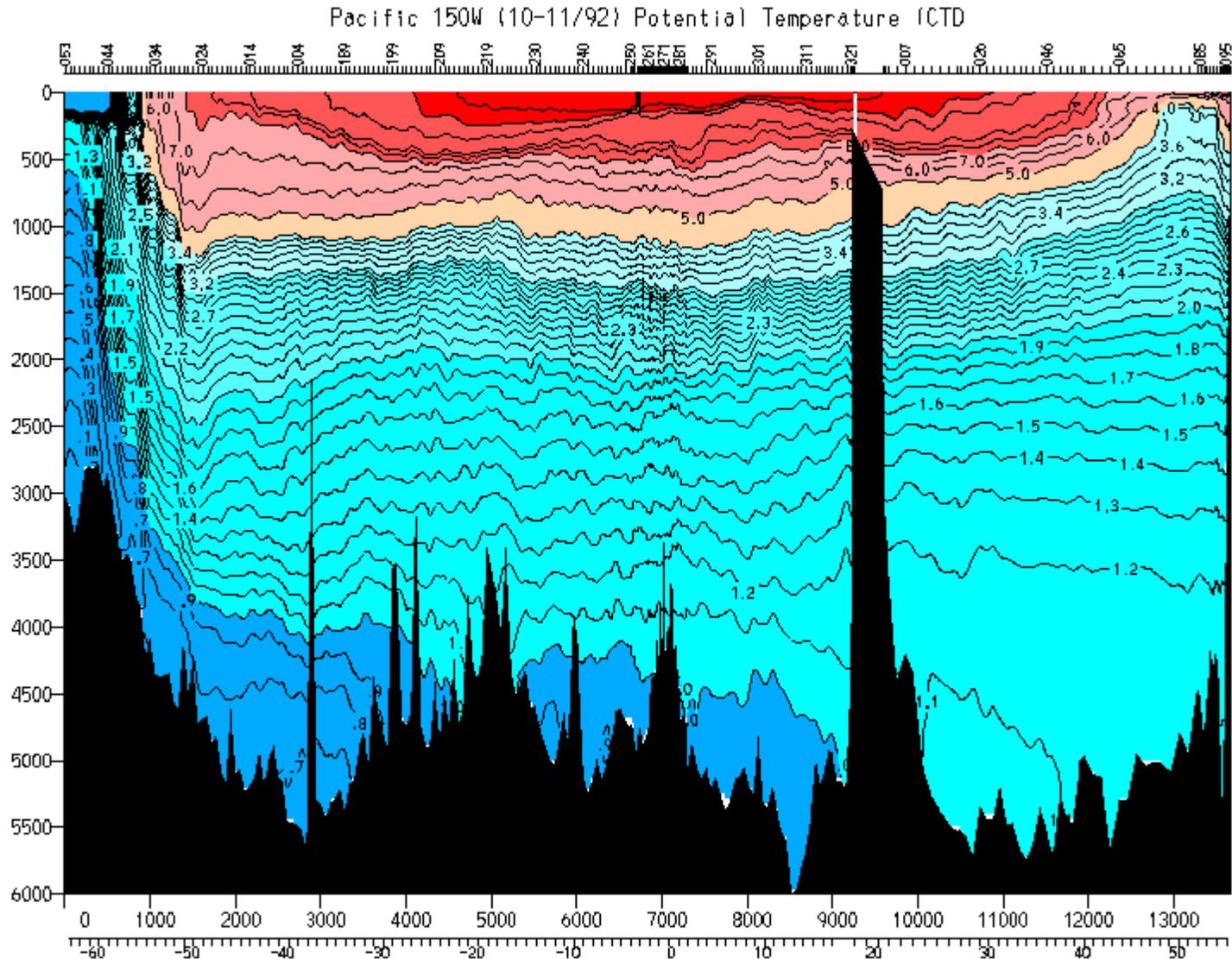
Chl-a = concentration of the main chlorophyll pigment in algae, a measure of algal biomass.

Idealized section of the Pacific Ocean. Cold water flows into the deep ocean from the Sub-Polar regions. The burning tropical sun floats warm water on top of this very cold water, creating a strong permanent thermocline that reduces the upward diffusion of nutrients to a slow trickle.

Fig. 1.28. The general pattern of deep-ocean circulation, shown in a north-south profile.



A real section through the middle of the Pacific. Note that s is on the left here. The deep currents of the ocean cause it to be stratified on a global scale. Very cold water from the North Atlantic and from the shores of Antarctica plunge to the bottom of the ocean. The moderate to slight seasonality in the temperate and tropical regions cannot generate enough winter mixing to break down the permanent thermocline. Note however, the slight shoaling of the thermocline around the equator. This is the basic explanation for why the Central Biome has such low productivity. The permanent thermocline is very tight and lets few nutrients mix upwards through the thermocline. Strong thermoclines very strongly suppress mixing.



Tropical Biome climograph. Equatorial Pacific. Along the equator, the North and South Equatorial Currents have a weak tendency to diverge when they accelerate. Stratification weakens somewhat, and primary productivity is about twice the levels in the Central Biome.

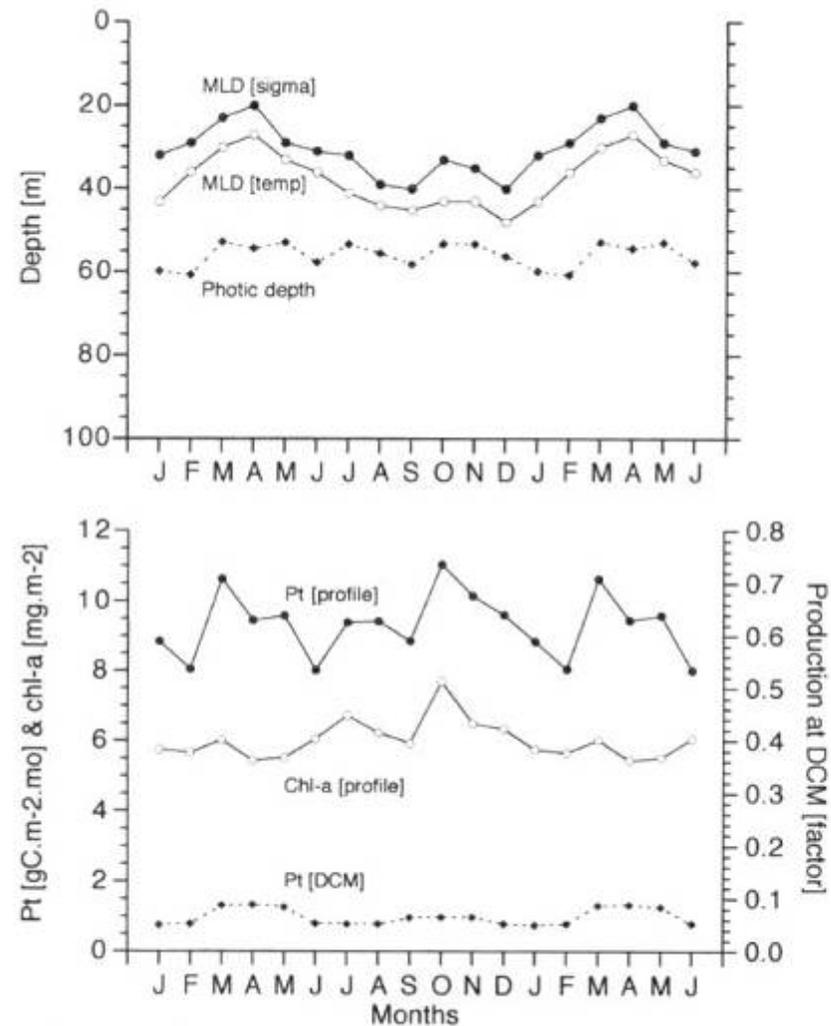
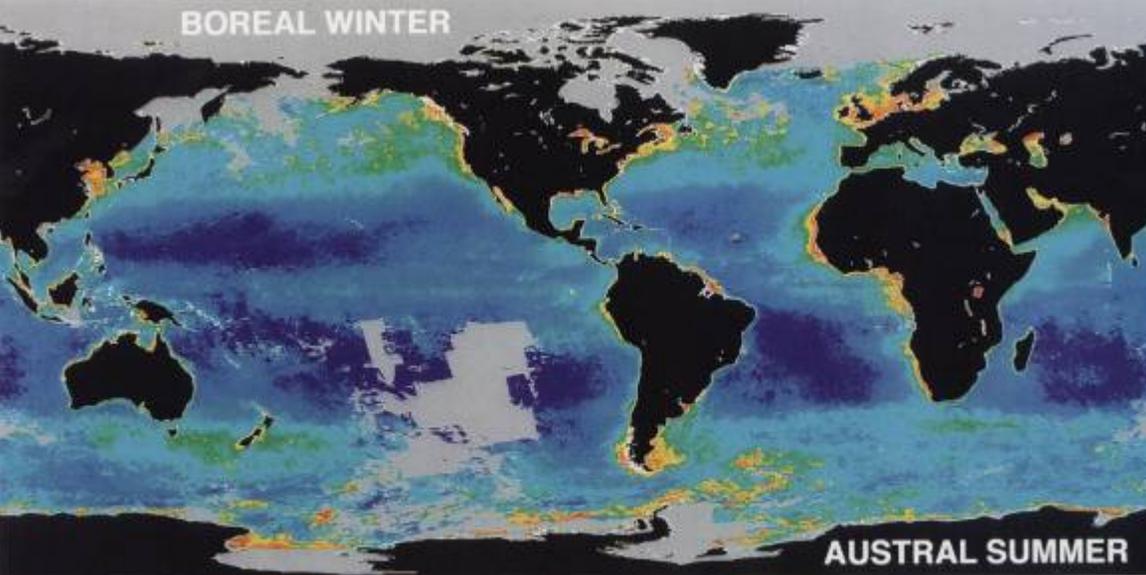


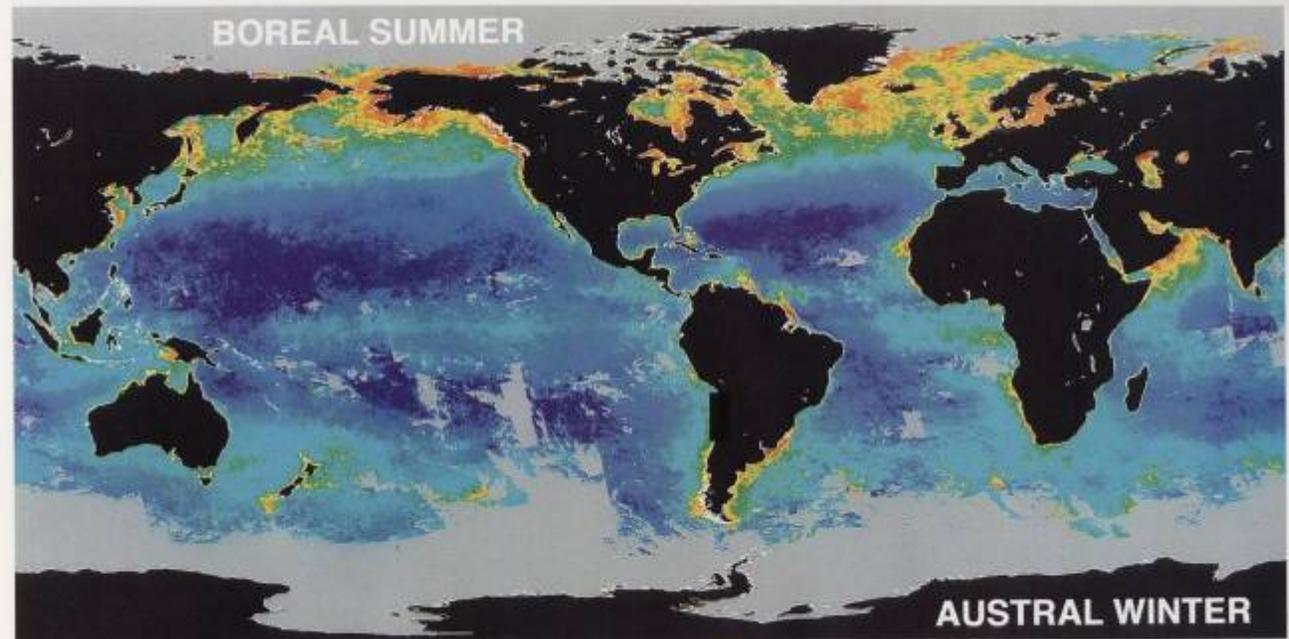
FIGURE 9.10 PEQD: characteristic seasonal cycles of monthly averaged mixed layer and photic depths, chlorophyll at the surface, and rate of primary production, both depth-integrated and at the DCM. Data sources are discussed in Chapter 1.



COLOR PLATE 3 Climatological (1978–1986) seasonal sea surface chlorophyll field obtained with Coastal Zone Color Scanner sensor for boreal winter (December–February). Color is a log scale for chlorophyll: purple = $< 0.06 \text{ mg Chl m}^{-3}$, orange-red = $1-10 \text{ mg Chl m}^{-3}$. Provided by NASA/Goddard Space Flight Center.

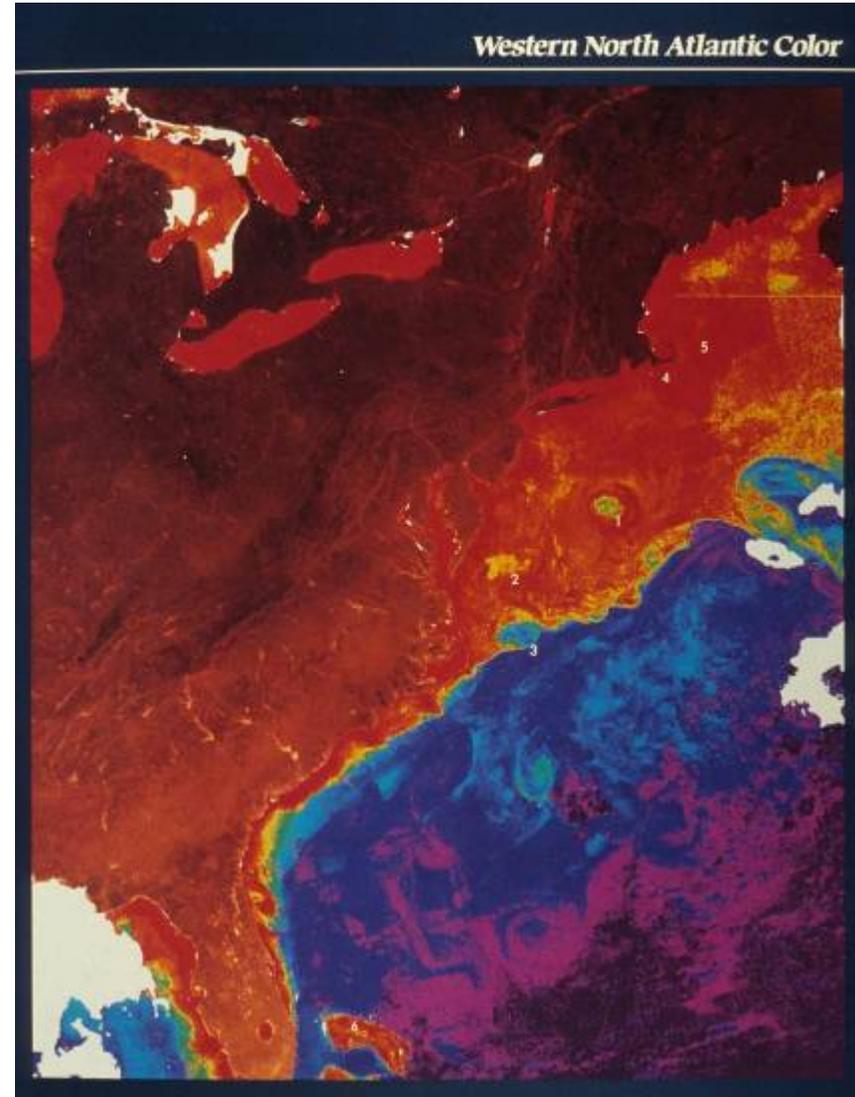
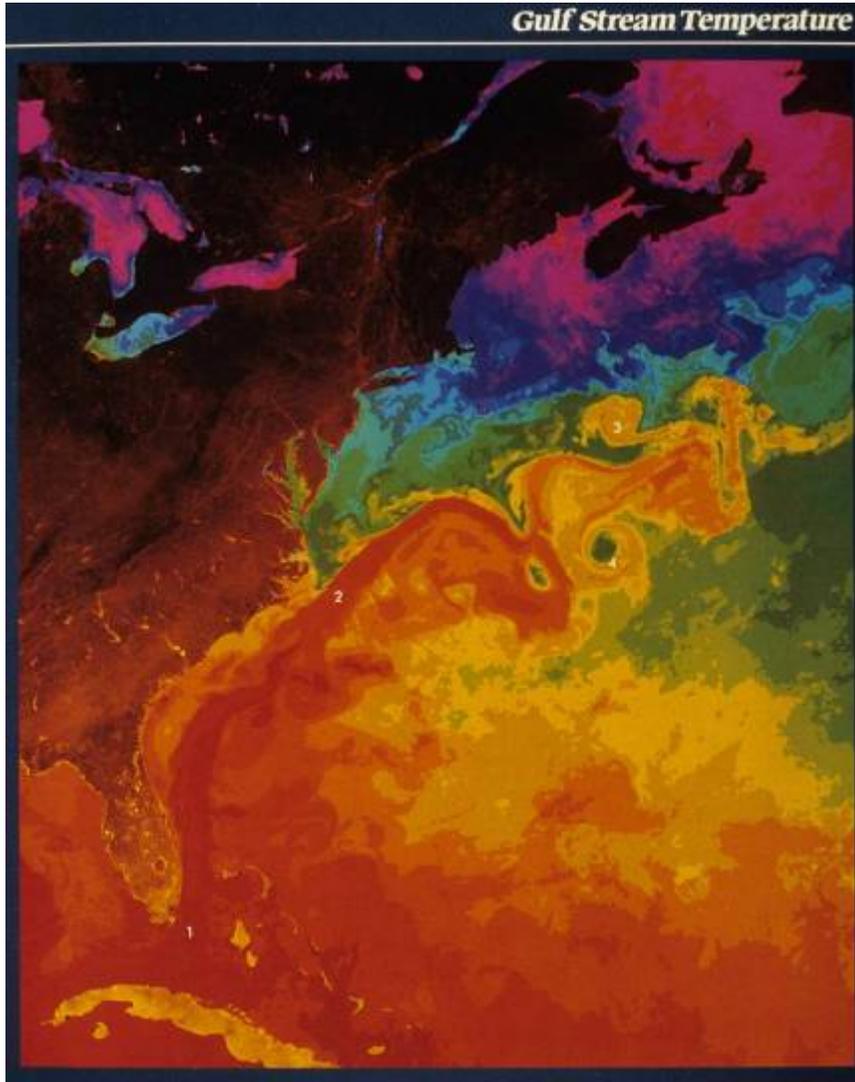
Chlorophyll false color visualization. Let's try our hand! With the concepts of seasonal stratification, the permanent thermocline, and upwelling, you should be able to account for most of what you see here. Remember the gray areas are insufficient data (Mostly due to dark cloudy winter days).

Some puzzlers remain. The North Sea and the Baltic are always productive. The summer upwelling off the coast of Arabia is impressive. The Mediterranean is rather unproductive. The Gulf of California is highly productive in winter.

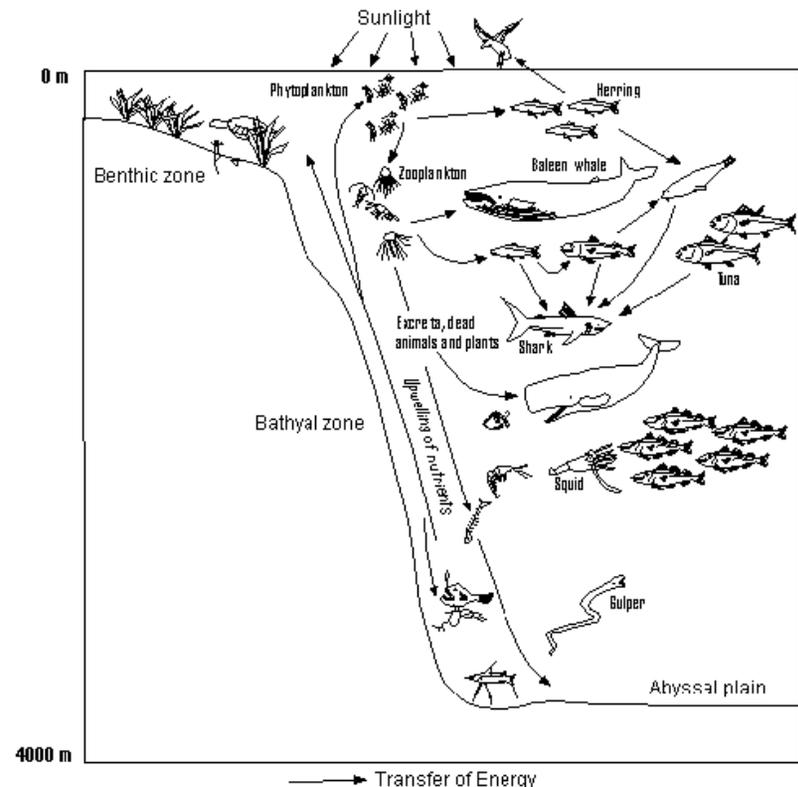
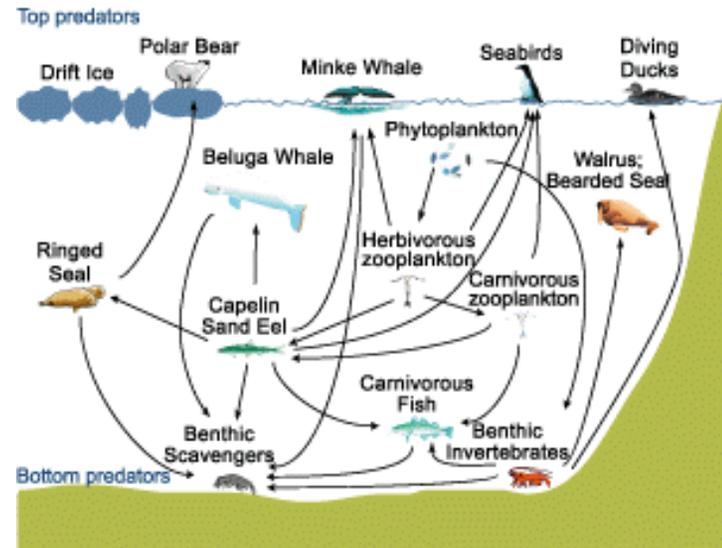
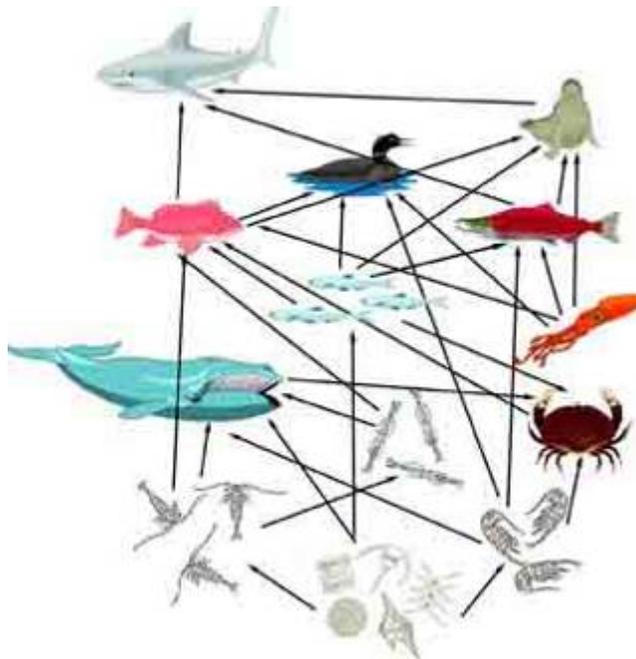


COLOR PLATE 1 Climatological (1978–1986) seasonal sea surface chlorophyll field obtained with Coastal Zone Color Scanner sensor for boreal summer (June–August). Color is a log scale for chlorophyll: purple = $< 0.06 \text{ mg Chl m}^{-3}$, orange-red = $1-10 \text{ mg Chl m}^{-3}$. Provided by NASA/Goddard Space Flight Center.

Let's try to figure out what is going on here, off the East Coast of the US in summer. On left, red is warm, purple cold. On right purple is low chlorophyll and red is high chlorophyll. Which state will have the richer fisheries, Maine or Florida? Why does the warm Gulf Stream separate from the US coast about North Carolina? Note the complex eddies the flow of the Gulf Stream. These were just noise until satellite instruments began to resolve them in the 1980s.



Marine food webs. Below, generalized. Right, North Polar. Right below, Australia. Note that these diagrams are oversimplified. Many marine organisms feed at more than one level in the food chain. For example small fish larvae may feed on phytoplankton while the adults eat zooplankton. A microbial food chain based upon bacteria that consume dissolved and particulate organic matter is missing from these pictures. DNA sequencing techniques have demonstrated that a huge variety of bacteria exist in the sea, most of which have never been cultured by bacteriologists. Marine food chains tend to be long: phytoplankton eaten by zooplankton, eaten by small fish, eaten by large fish, caught by humans. Contrast this with terrestrial food webs where people harvest mainly plants and herbivores. Thus, altho the total primary production of the ocean is similar to that of the continents, the total human harvest from the sea is far less than from land. Interesting, the biggest animals in the sea, baleen whales, mostly feed on zooplankton leading to a shorter than usual food chain.



Marine food webs do not seem to be very stable, even in the absence of human exploitation. High amplitude cyclical or quasi-cyclical variation seems to be the rule not the exception. The importance of endogenous cyclicity versus varying environmental factors is a matter of debate.

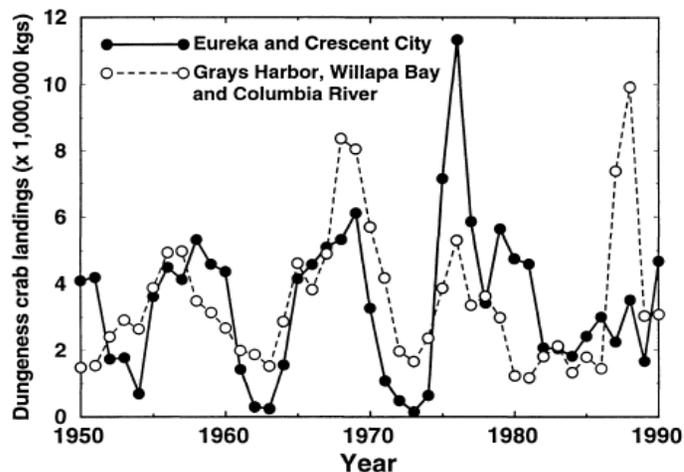


FIG. 1.—Time series for Dungeness crab catch at Eureka and Crescent City, California, and Grays Harbor, Willapa Bay, and Columbia River.

Left, Cyclical fluctuations in Dungeness Crab catch. Below, fluctuations in three widely separated sardine populations. The tendency of these populations to cycle together suggests that some Pacific-wide process is driving the cyclicity. Right, In the Gulf of California a century-long cycle with Anchovies (*Engraulis*) alternating with Sardines (*Sardinops*) seems to exist. Scomber and Myctophids seem to cycle with Sardines.

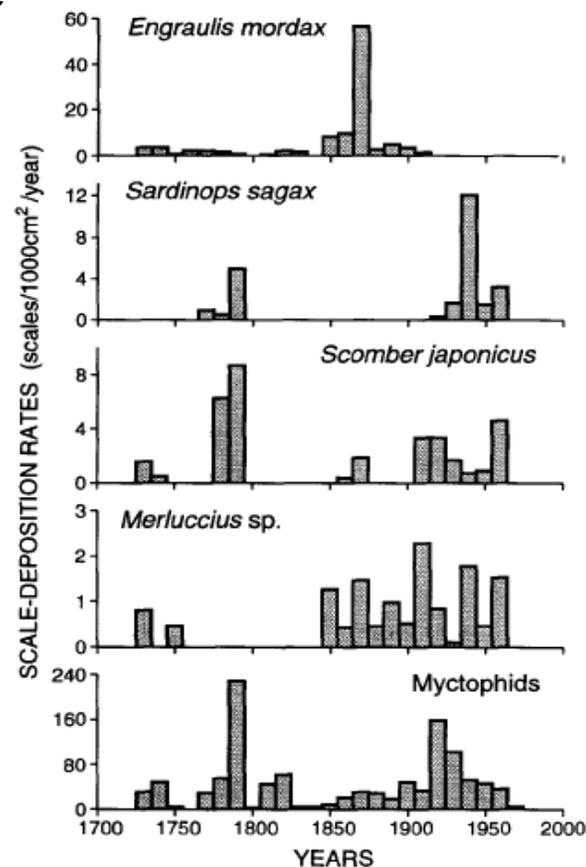


Figure 2. Time series of scale-deposition rates of *Engraulis mordax*, *Sardinops sagax*, *Scomber japonicus*, *Merluccius* sp., and the myctophid group reconstructed from box core 7807-1305 collected from the Guaymas Slope in the central Gulf of California. The time series covers the period from 1730 through 1980 and is resolved into 10-year intervals. Note that the chronology below 1910 is preliminary and has an associated uncertainty of approximately ± 10 years.

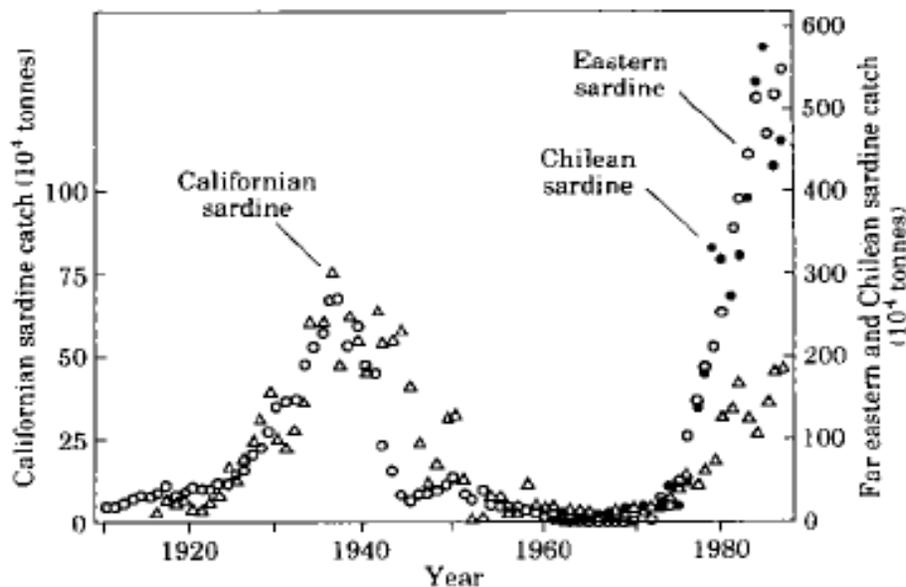


Figure 9. Catches of sardines from three stocks: the Far Eastern, the Chilean, and the Californian, 1910–1988. From Kawasaki (1992).

Figure from a paper arguing that the ecology of the whole Pacific sets up in a Sardine regime and then switches to an Anchovy regime and back again. Don't try to understand this figure in detail. Your brain might melt! It does give you some idea of all the balls oceanographers have to try to keep in the air to account for things like Sardine-Anchovy cyclicality.

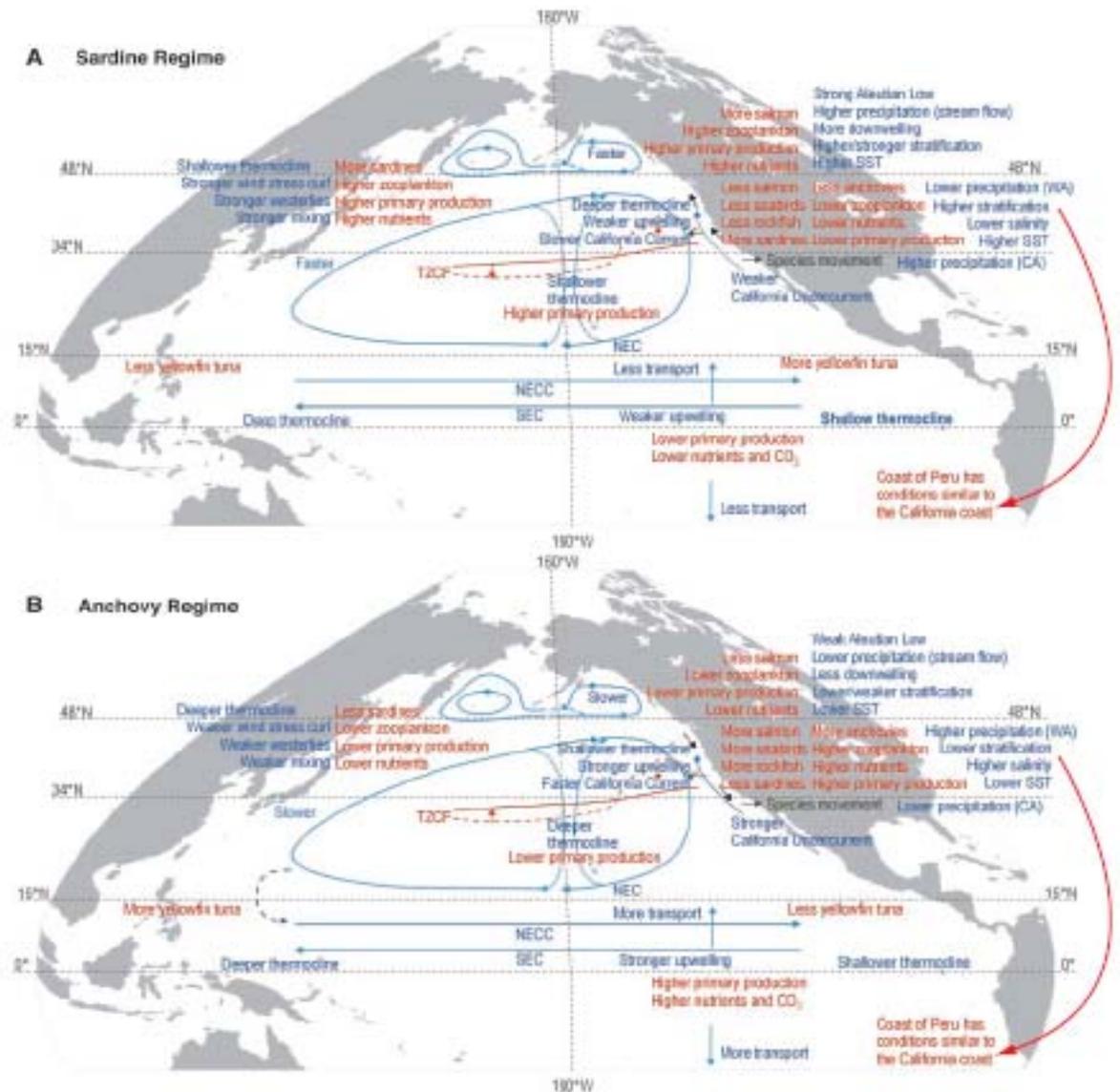


Fig. 3. Synthesis of Pacific conditions during the (A) sardine and (B) anchovy regimes. Physical changes are in blue, and biological and chemical changes are in red.

Diatoms. Glass box algae. These are perhaps the single most important group of primary producers in the sea. Size and shape of the different species are very diverse. The function of most of these form differences are poorly understood. Size is best understood. Large cells or colonies sink faster than small cells, but slow sinking cells deplete the nutrients in their vicinity. Large cells predominate in strongly mixed high nutrient waters and small ones under eutrophic conditions. That said, any given water sample typically contains species of vastly different sizes. Recently, oceanographers have discovered that ultra-tiny eukaryotic green algae and bluegreen algae (cyanobacteria) are major primary producers in the sea. Size: the small chains below right are perhaps 5 microns wide and the larger ones approximately 25 microns

Fig. 4.9. Some common temperate-water planktonic diatoms.

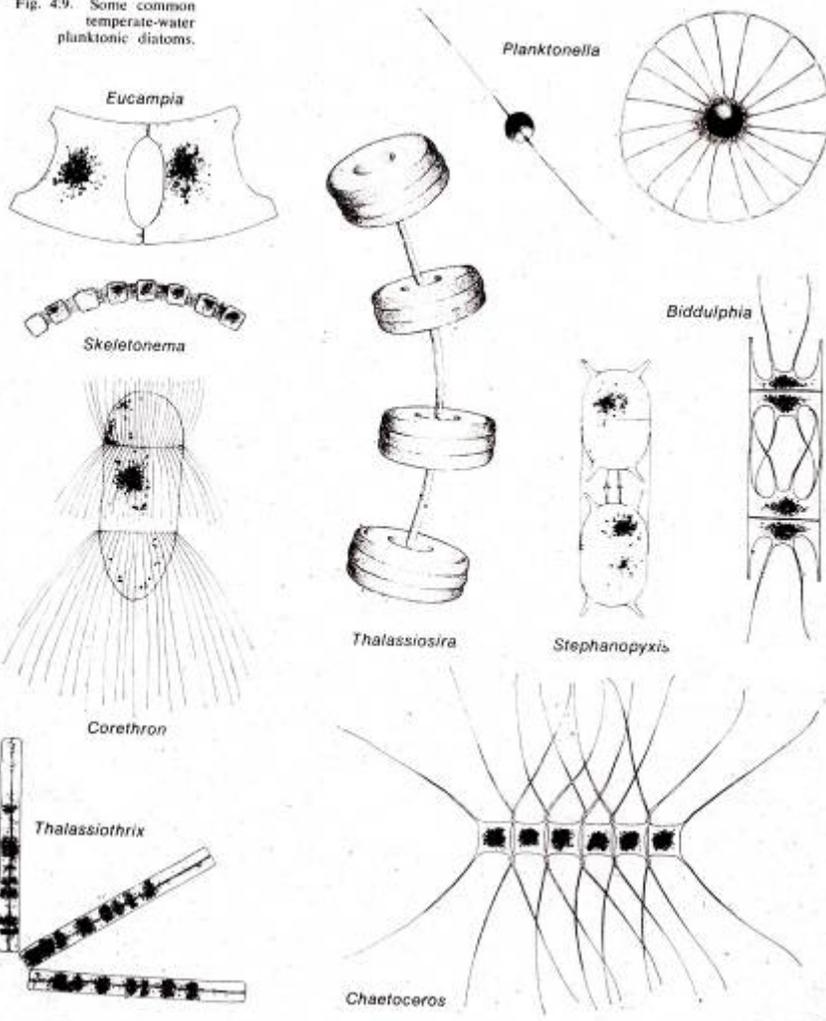
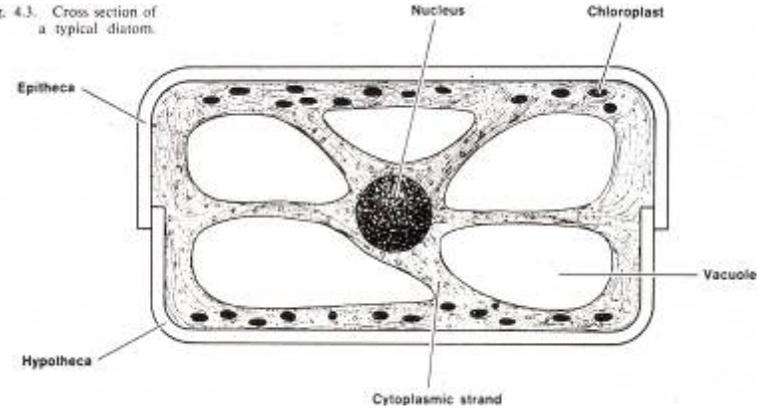


Fig. 4.3. Cross section of a typical diatom.



Dinoflagelates. Another group of important marine phytoplankton. They usually have two flagella and hence are motile. These species typically have a brownish rather than green color. This is due to the presence of “accessory pigments” that absorb light in the middle of the light spectrum where chlorophyll does not absorb light. Most plants have such pigments, tho in terrestrial plants the seldom mask the green of chlorophyll. See figure bottom left. These are sometimes called “antenna pigments” because they physically transfer the photons they capture to chlorophyll which is in turn physically connected to “reaction centers” where the photochemical part of photosynthesis begins. Size scale: the long slim cell below is about 5 microns wide by 100 microns long. The long horns on these species are interpreted as devices to deter zooplankton grazers.

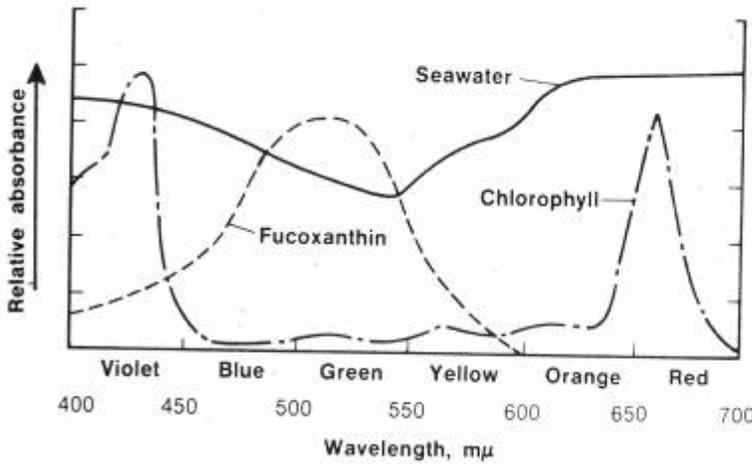
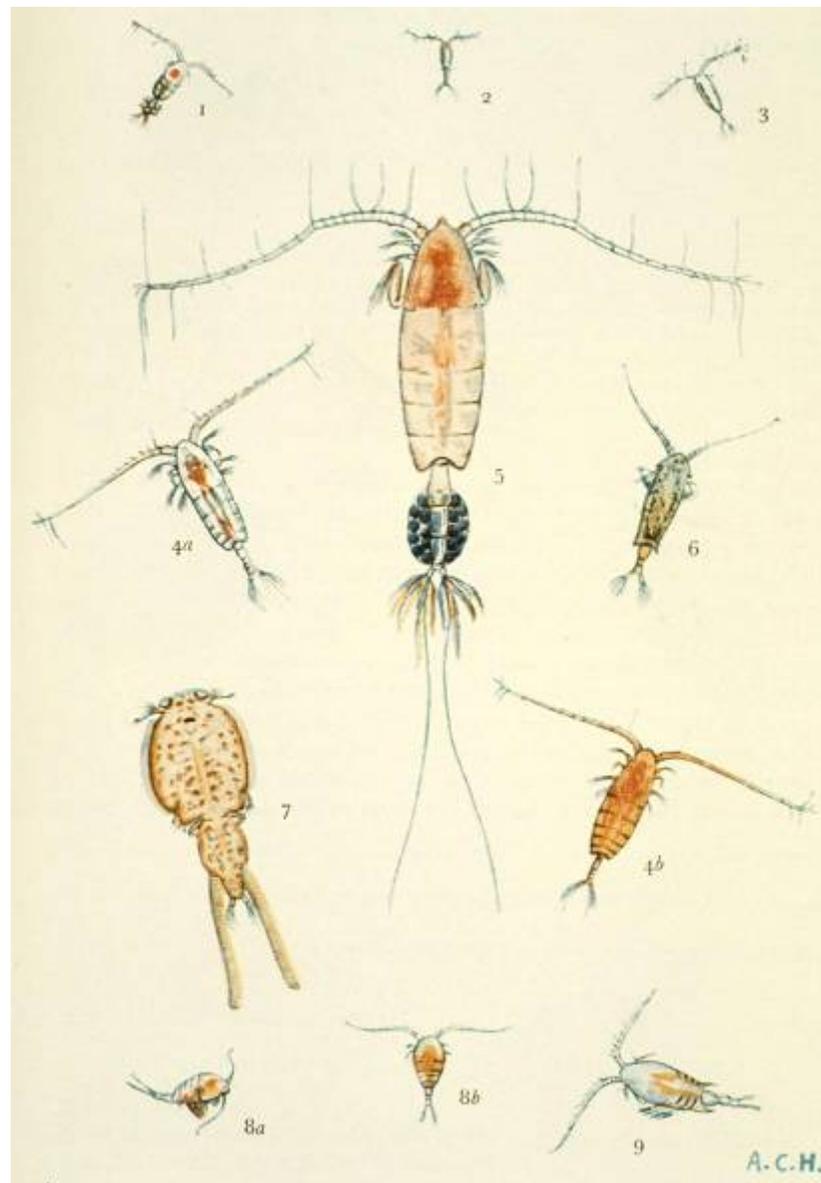
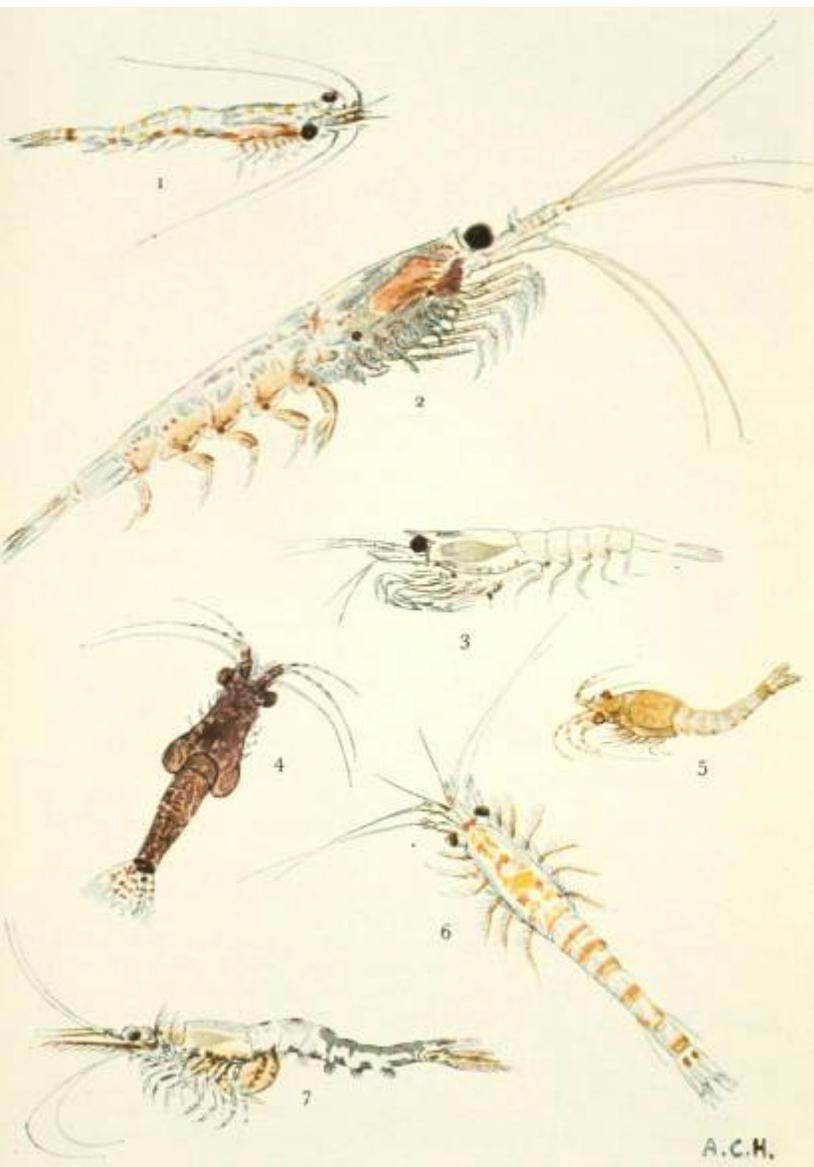


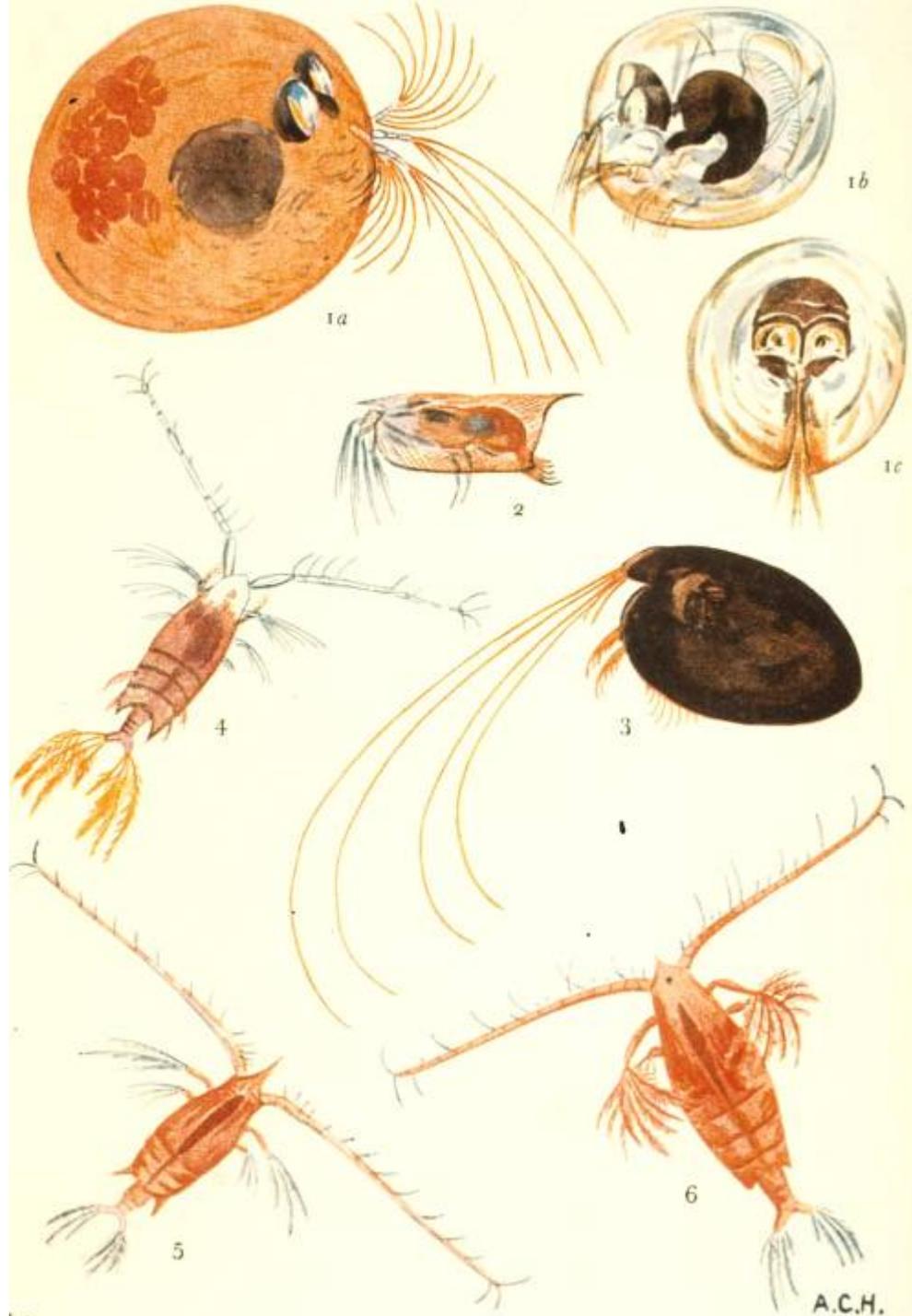
Fig. 5.10. Light absorption by seawater (—) reduces the energy available to chlorophyll (— · —). Accessory pigments such as fucoxanthin (---) greatly enhance a plant's light-absorbing capabilities in spectral regions where chlorophyll is inefficient.



Copepods (right) and Euphausiids any Opossum Shrimp (left). These crustaceans are the analog of the ungulates on land. They are often the dominant grazers on phytoplankton. Oceanographers originally imagined them to use their hairy appendages to create unselective filters. Actually, they use chemosensory organs to pick and choose from the algal community; they are rather selective grazers not unlike terrestrial herbivores. Larger specimens will also prey on smaller zooplankton. Copepods normally range in size from ½ mm to 5mm, Euphausiids and Opossum Shrimp from from 1-4 cm. Copepod #7 is an anomalous fish parasite.



Giant Bean Shrimp and large copepods from below the photic zone. Note large reflective binocular eyes on the upper 3 specimens. Red coloration at these depths with very little light at all and no red light to speak of is tantamount to black. I have seen specimens from the Eastern Pacific resembling 1 the size of golf balls. What is going on at this depth? Little work beyond collecting has been done. The eyes of the Giant Bean Shrimp use a mirror instead of a lense to direct light onto the retina.



The plankton includes lots of ciliated dispersing larvae of benthic organisms, such as clams and various worms (right). On the left are the larvae of crabs, lobsters and shrimp

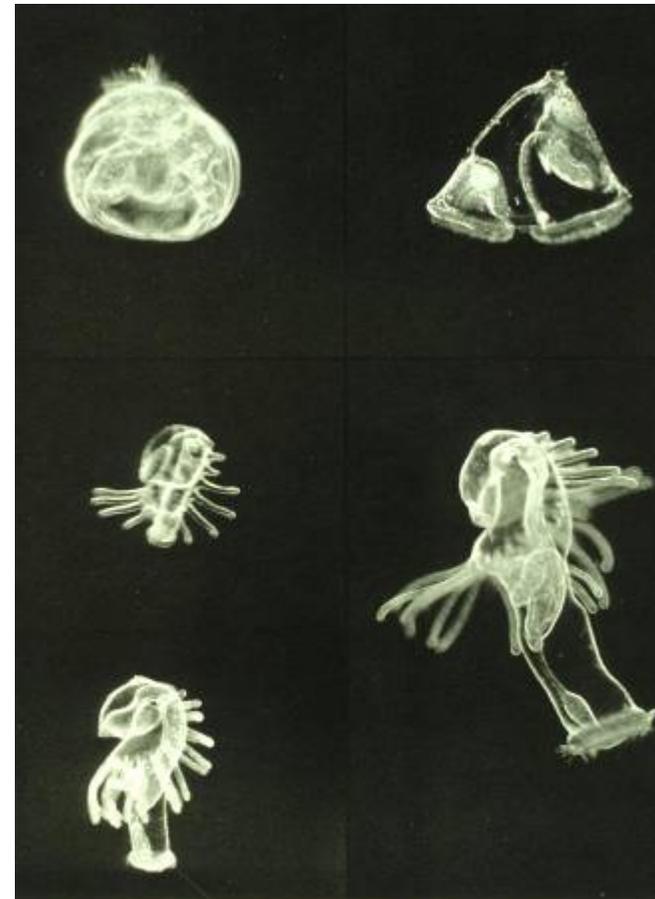
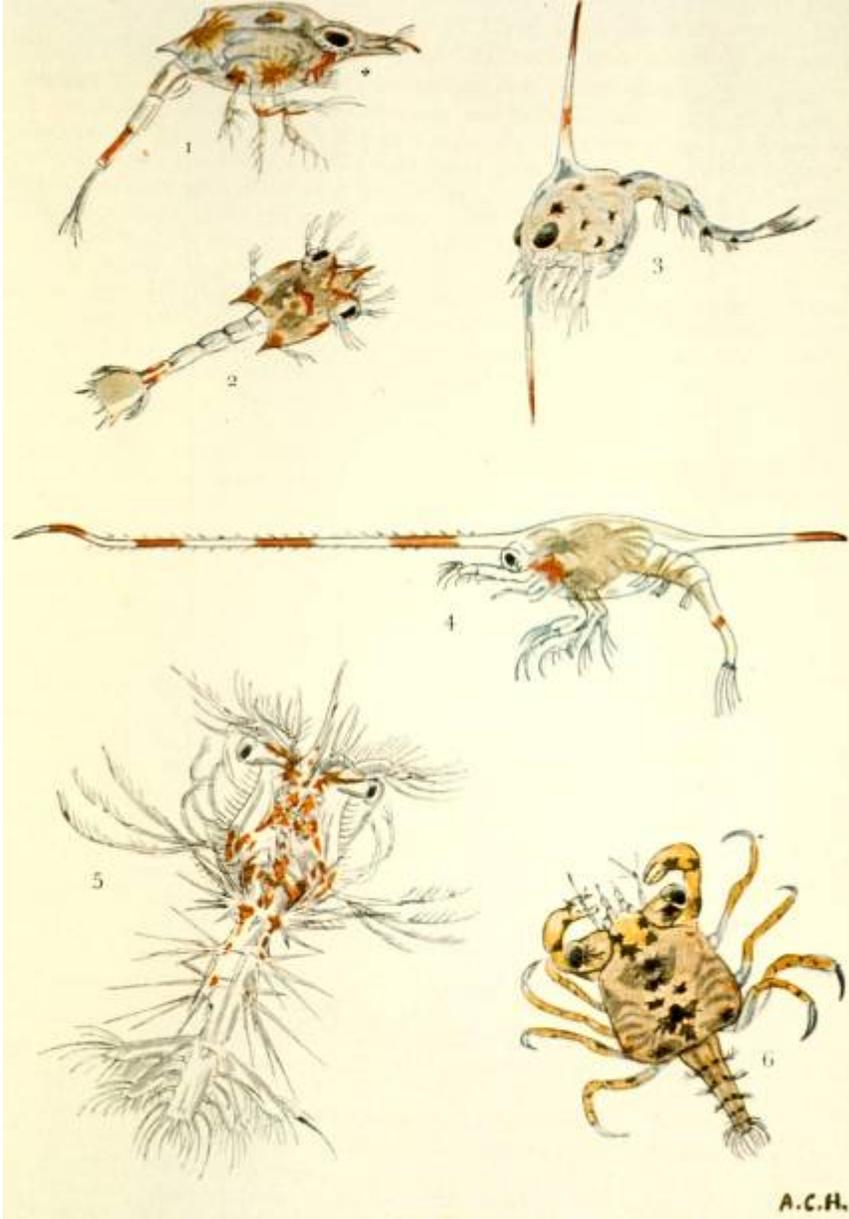
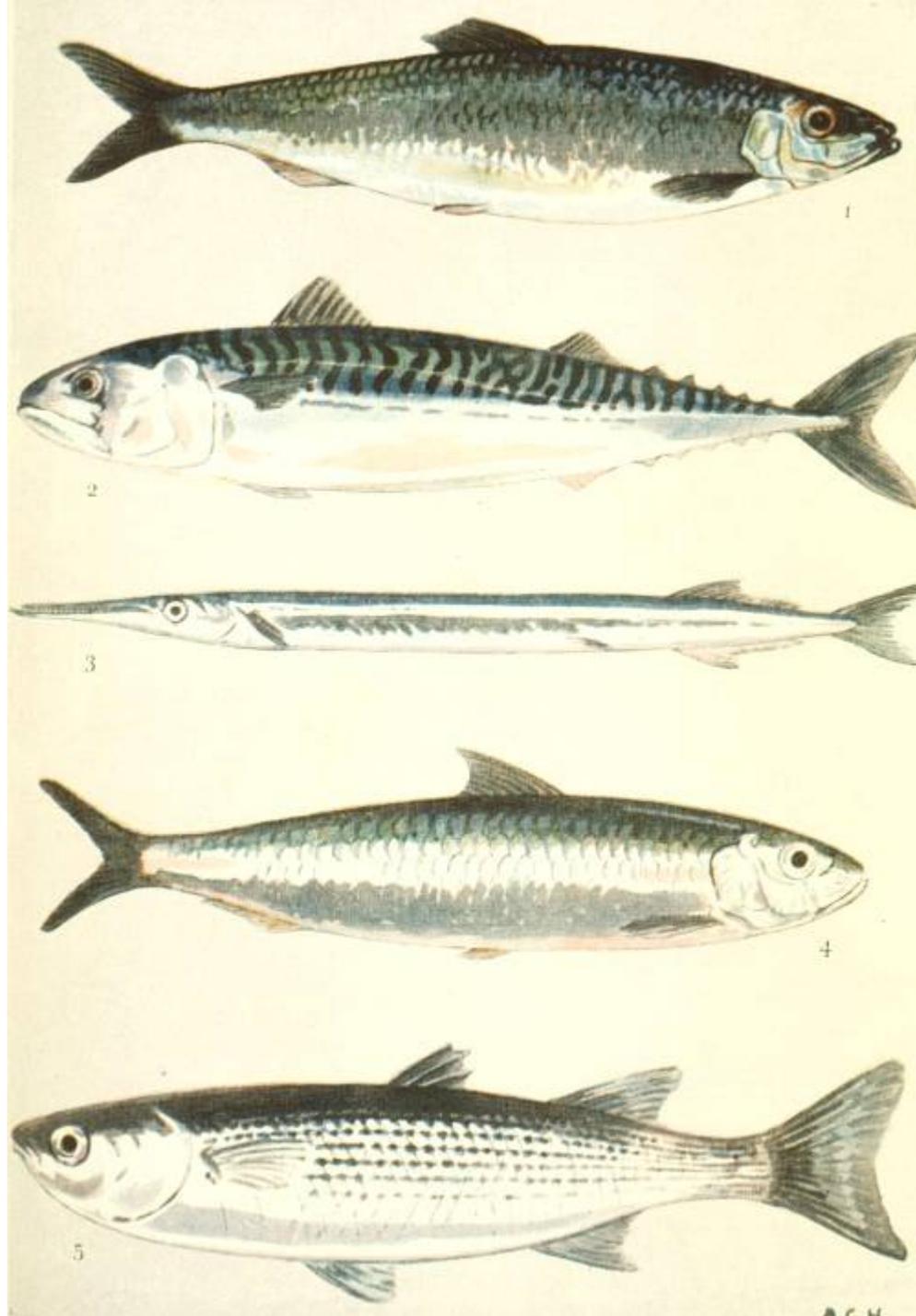
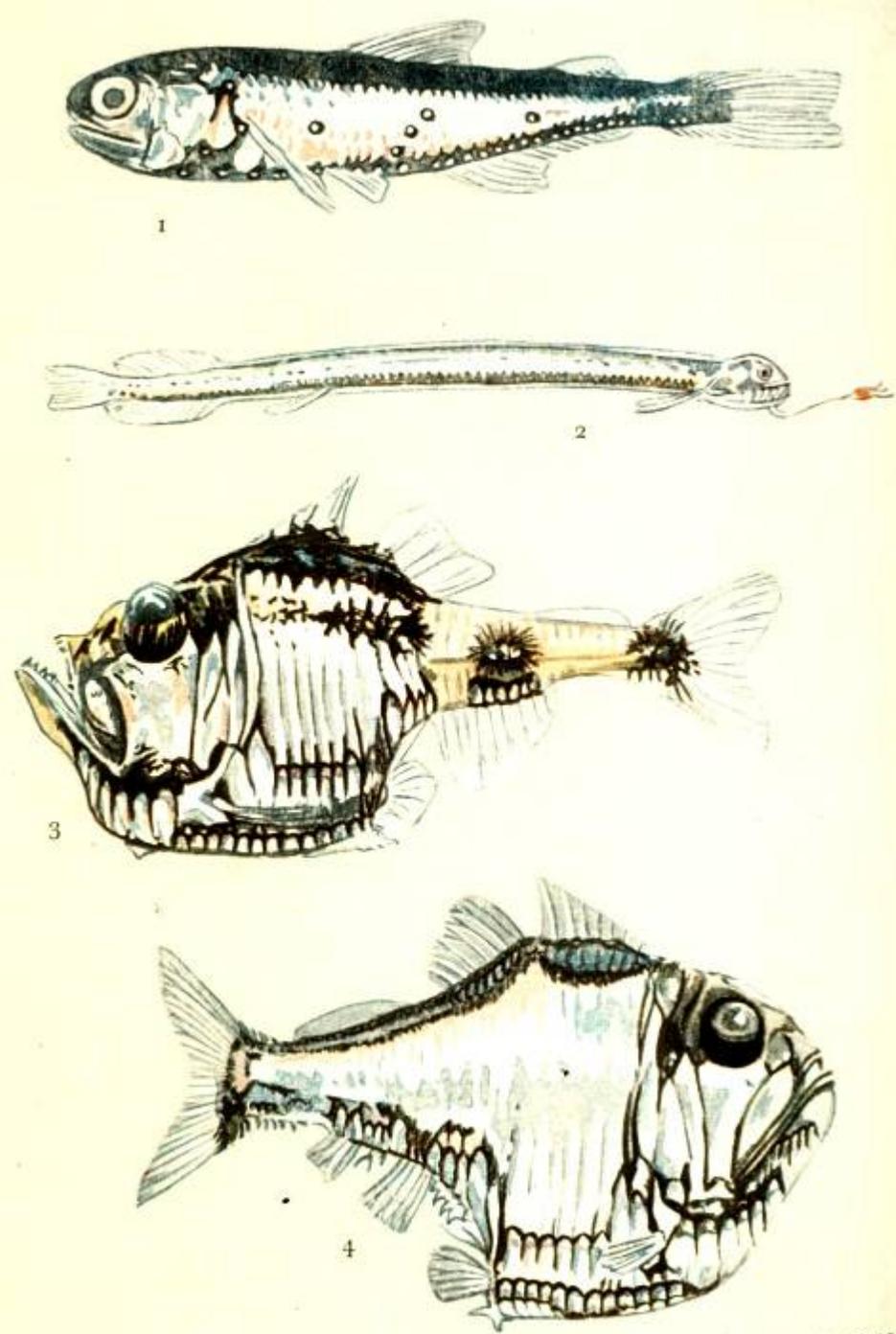


Plate NTIII. Various planktonic larvae, all living. (top left) a. Young stage of the razor shell *Eusis*, x 150. (top right) b. *Cyphomantes* larva of a polychaete, x 60. c, d and e. Three stages in the development of the actinotrocha larva of *Phoronis*, x 40. (a, c and e by electronic flash.) (Douglas Wilson)

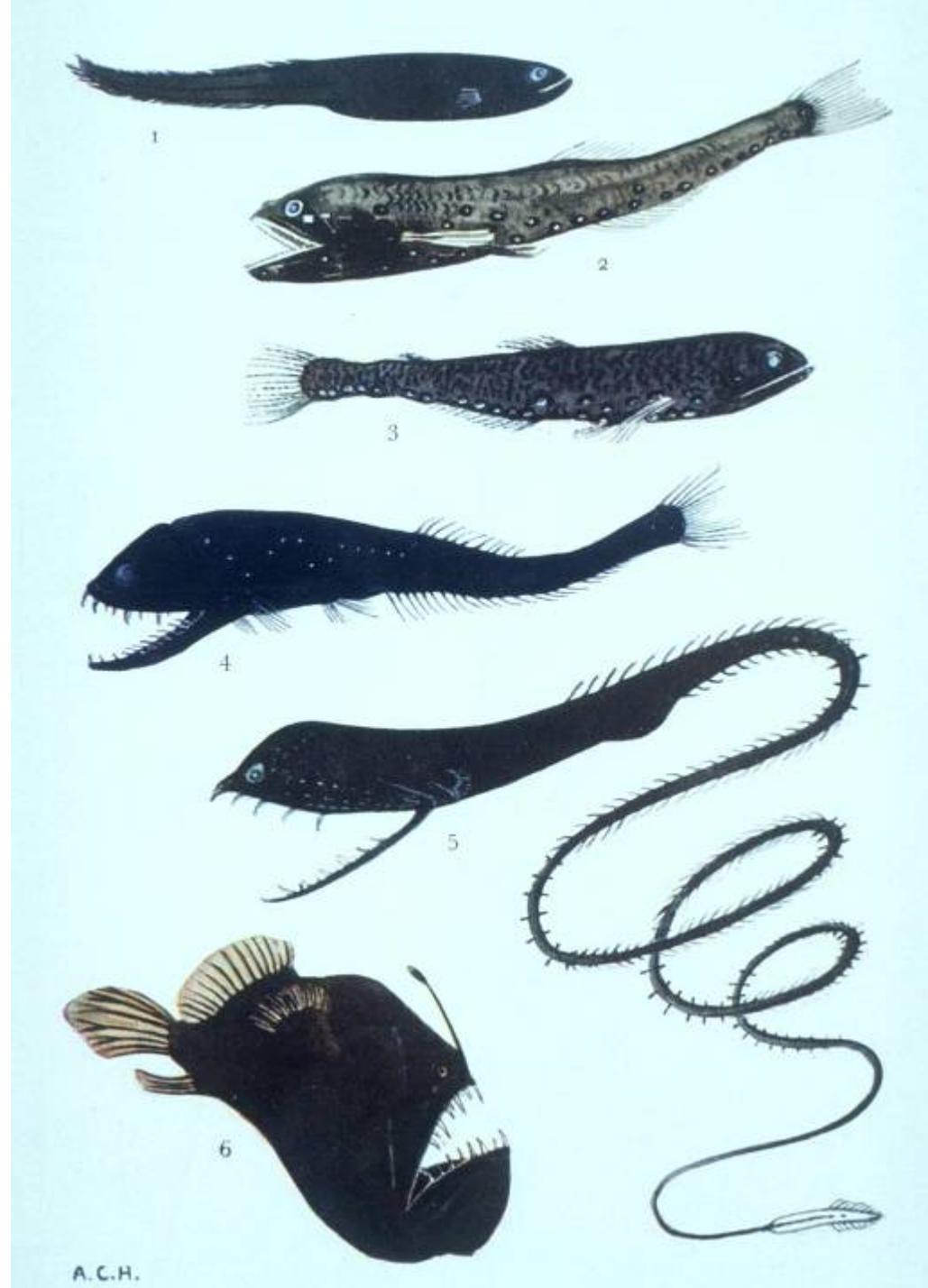
Fishes of the lighted waters are typically torpedo shaped with silvery bellies and dark backs, called “countershading.” They are typically predators on anything much smaller than themselves and prey to anything significantly bigger. It is a fish eat fish world out there in the pelagic! They are streamlined to achieve fast swimming speeds to catch prey and avoid becoming prey. From above the dark backs are viewed against the dark ocean depths and they do not stand out. From below the light bellies fade into the light downwelling from above and again a countershaded fish does not stand out. 1, Herring. 2, Mackerel. 3, Garfish. 4. Pilchard. 5. Mullet



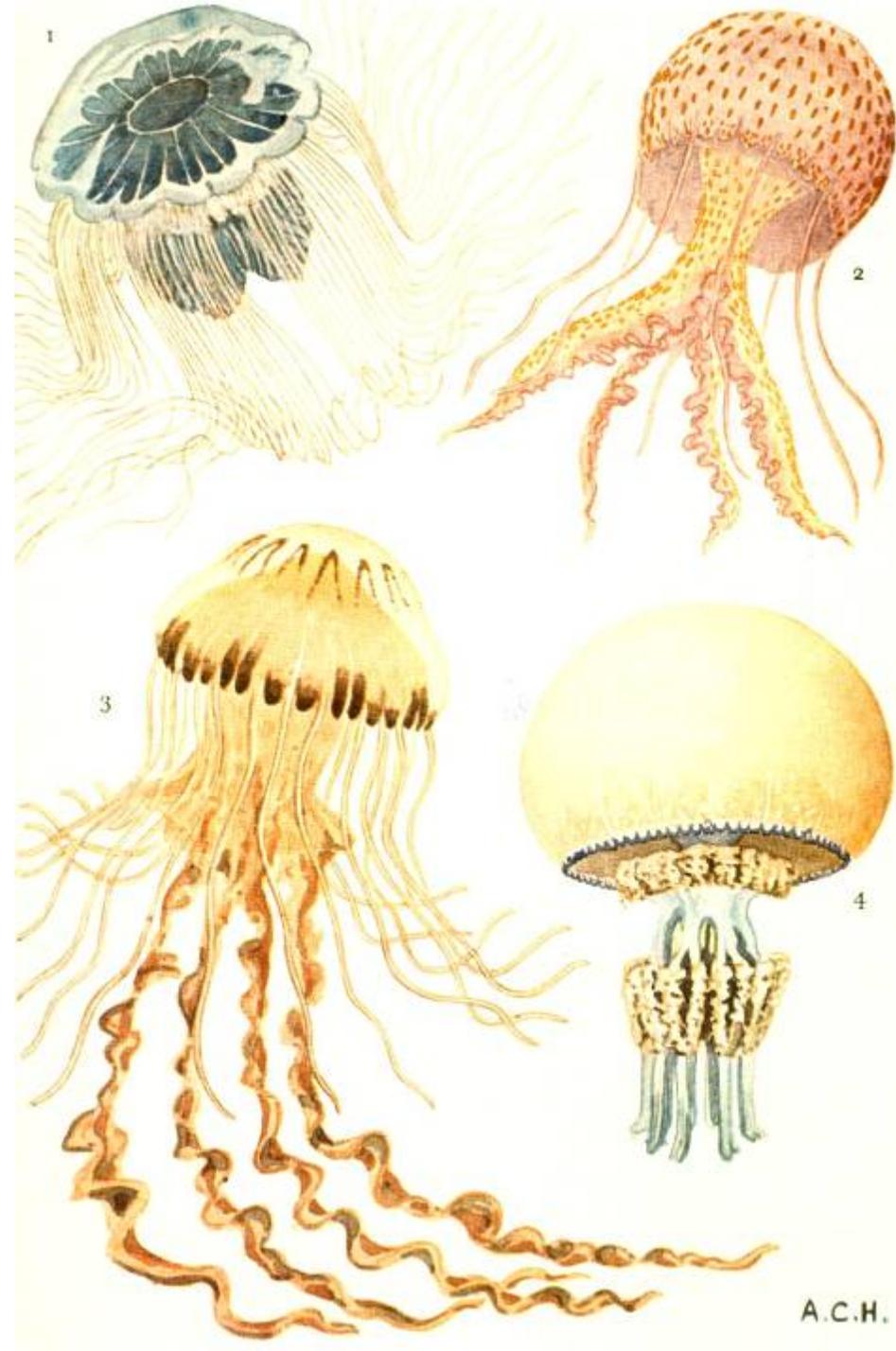
Strange fish from below the photic zone. Top, a Myctophid. The small silvery spots on its body are luminescent. The slim anglerfish has a copepod-mimicking lure attached to its chin. Hatchetfish below look as if they approach prey silhouetted by the weak downwelling light at these depths. Myctophids and Hatchetfish are often present in considerable numbers. When abundant their swim bladders reflect sound from echosounders, creating a “deep scattering layer.” The deep scattering layer rises at night and falls during the day. Many plankton also migrate on a daily cycle like this, hiding in the dark depths during the day and swimming up into the photic zone during the night to feed. These fishes hunt for zooplankters that are a little slow in getting down in the morning or too greedy in the evening. Likewise, submariners play cat and mouse with their pursuers by trying to hide beneath deep scattering layer so as to defeat surface sound-based detection systems. The Office of Naval Research supports a lot of biological oceanography because they want to know the nature of all the sound making and sound reflecting organisms in the sea.



The black fish of the very deep sea. Who knows exactly what goes on at these depths. Why are they black? It is as dark as a deep cave here. Many of these fish have luminescent spots. Presumably for communicating with potential mates. Ones like 4 and 5 seem to be delicate to be predators, despite the great teeth. Perhaps they seize dead or nearly dead fish falling from above? It is not too hard to catch a few of these fish, but they are dead when they reach the surface and no one has thought up a practical way of studying them in their natural habitat.



A sample of jellyfish. These are the simplest of animals. Generally their tentacles are lined with stinging, sticky cells that explode on contact with prey. A few have toxins strong enough to affect humans, but not very many.



Various odd and interesting plankters. Ctenophores, the comb jellies, have their own phylum. Portuguese Man-of-War and the little Sailor-by-the-Wind below are colonies composed of many anatomical individuals that cooperate to make rather complex organisms. The Siphonophores on the right are related but swim in the water column rather than float at the surface. They are Jellyfish relatives. The purple snail below, *lanthina*, floats on its bubble raft until it runs into a Sailor-by-the-Wind. Then it eats the Sailor, blows another bubble raft and goes hunting again. The "ctenophore", #5 on right is a highly modified snail that swims in the plankton.

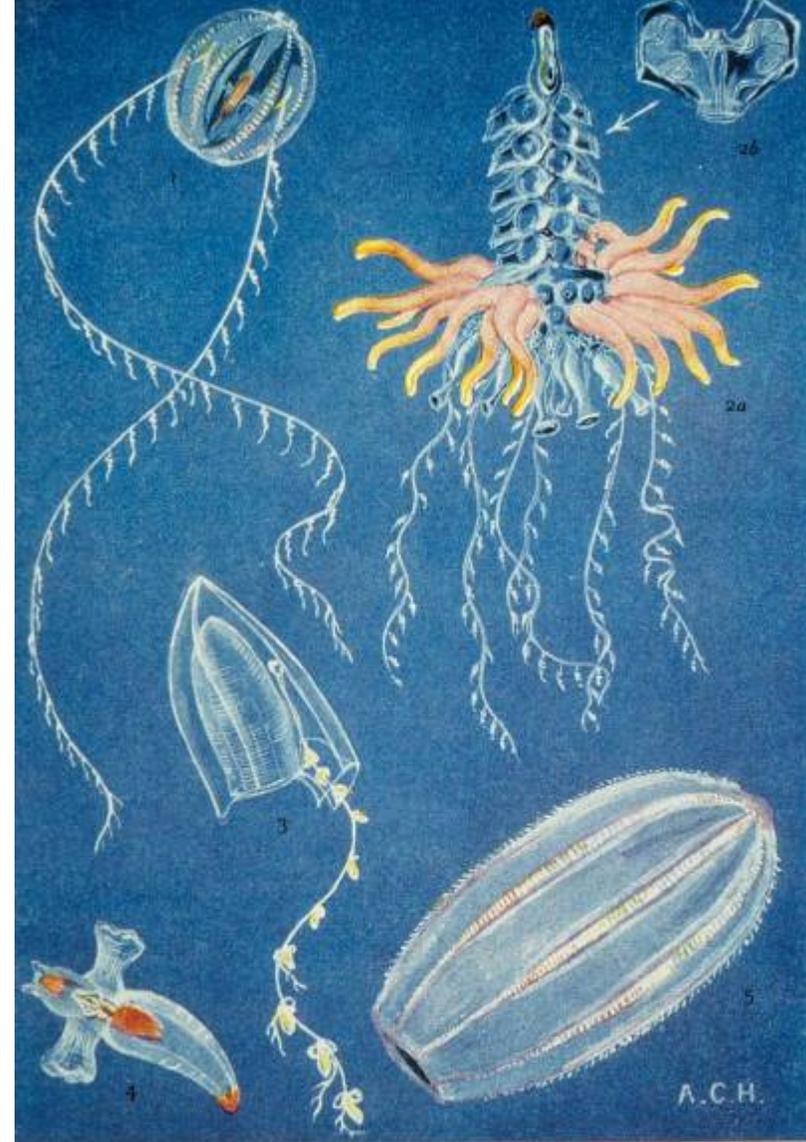
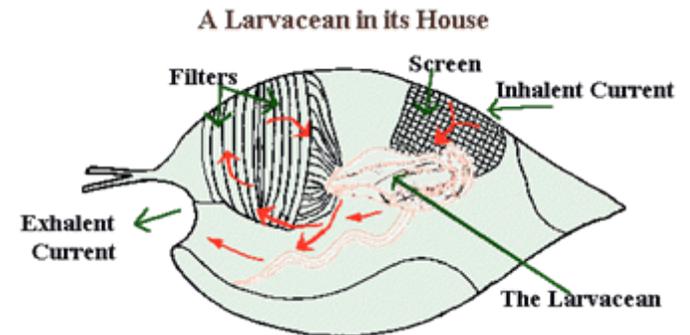
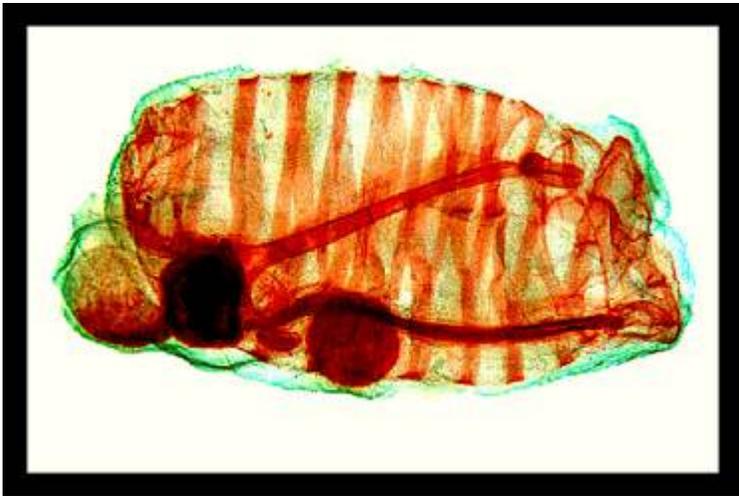


Plate 9. A PLANKTONIC MIXTURE: SIPHONOPHORES, 'COMB-JELLIES' AND A 'SEA-BUTTERFLY' (PTEROPOD)

1. The ctenophore *Pleurobrachia pileus* (nat. size). Lowestoft, August 1954
2. The siphonophore *Physophora hydrostatica*: a, whole animal natural size, b, one of the swimming bells enlarged. Drawn on the R.R.S. *Discovery* in 1925
3. The siphonophore *Muggiea atlantica* ($\times 3$), from a preserved specimen from Plymouth
4. The pteropod *Clione limacina*, a young specimen ($\times 4$), drawn at Cullercoats, November 1954
5. The ctenophore *Beroe cucumis* (nat. size) Lowestoft, August 1954

Primitive chordate zooplankters distantly related to ourselves. Left, a Salp. Salps are a hollow muscular tube that moves by a kind of jet propulsion. It uses mucous nets to trap particulate matter. Salps can reproduce by budding and build up large populations in a hurry, like springtime Aphids. On the right is a Larvacean. These little tadpole like animals secrete a great mucous house. They undulate their tail to create a current that moves the house about and from which they can filter out good stuff to eat. At least in some places, abandoned Larvacean houses are a major component of organic carbon transport to the deep sea. Larvaceans, like humans, may be a significant player in the earth's climate via their role in the carbon budget.



Squids. Squid are fast-moving highly visual fish-like predators. These are deepwater forms, two of which are liberally supplied with luminescent spots. Note that animal #1 is asymmetrical with more luminescent spots on one side compared to the other. The eye structure is also asymmetrical. Hardy spends a chapter in his book discussing the many theories about the luminescent organs of deep ocean creatures.



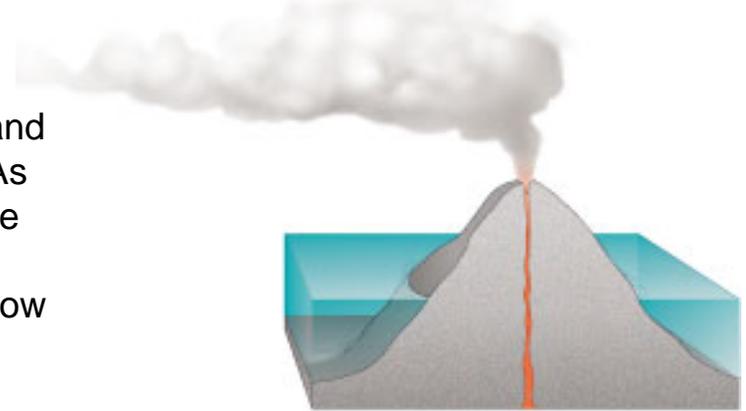
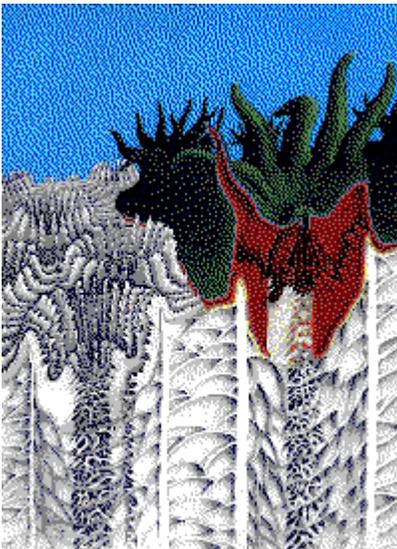
Benthic fish. Benthic fish are often more colorful and more variably shaped than pelagic fish. They use rocks, seaweed, coral, and other bottom obstacles for cover. They are often flattened side to side which makes for quick turns rather than sheer speed. Benthic fish communities are generally much more diverse than pelagic ones.



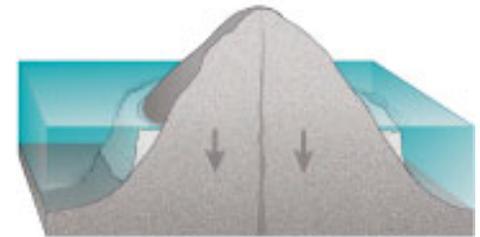
Coastal Ocean. Coral Reefs. How coral reefs evolve.

Generally volcanoes will form where the crust is relatively hot and buoyant, say near a spreading center or intra-plate hot spot. As the plate moves away from the spreading center or hot spot, the crust will cool and sink. Volcanic islands will tend to submerge over time for this reason. In the coral reef latitudes coral can grow fast enough to keep up.

Corals are simple animals, upsidedown Jellyfish. But they are ecologically plants. They harbor algal symbionts that produce most of the reef's carbon. Like carnivorous plants, the polyps do good work catching zooplankton mainly for a nitrogen supply. They are slow growing and cannot tolerate much grazing. Remember the Central and Tropical Biomes are nutrient poor. Hence they secrete a limestone pillbox topped by barbed-wire like crenulations to live in. Snorkeling on coral reefs you wear a wet suit not so much for the cold as for protect from the sharp coral.



Volcanic Island



Fringing Reef



Barrier Reef



Atoll

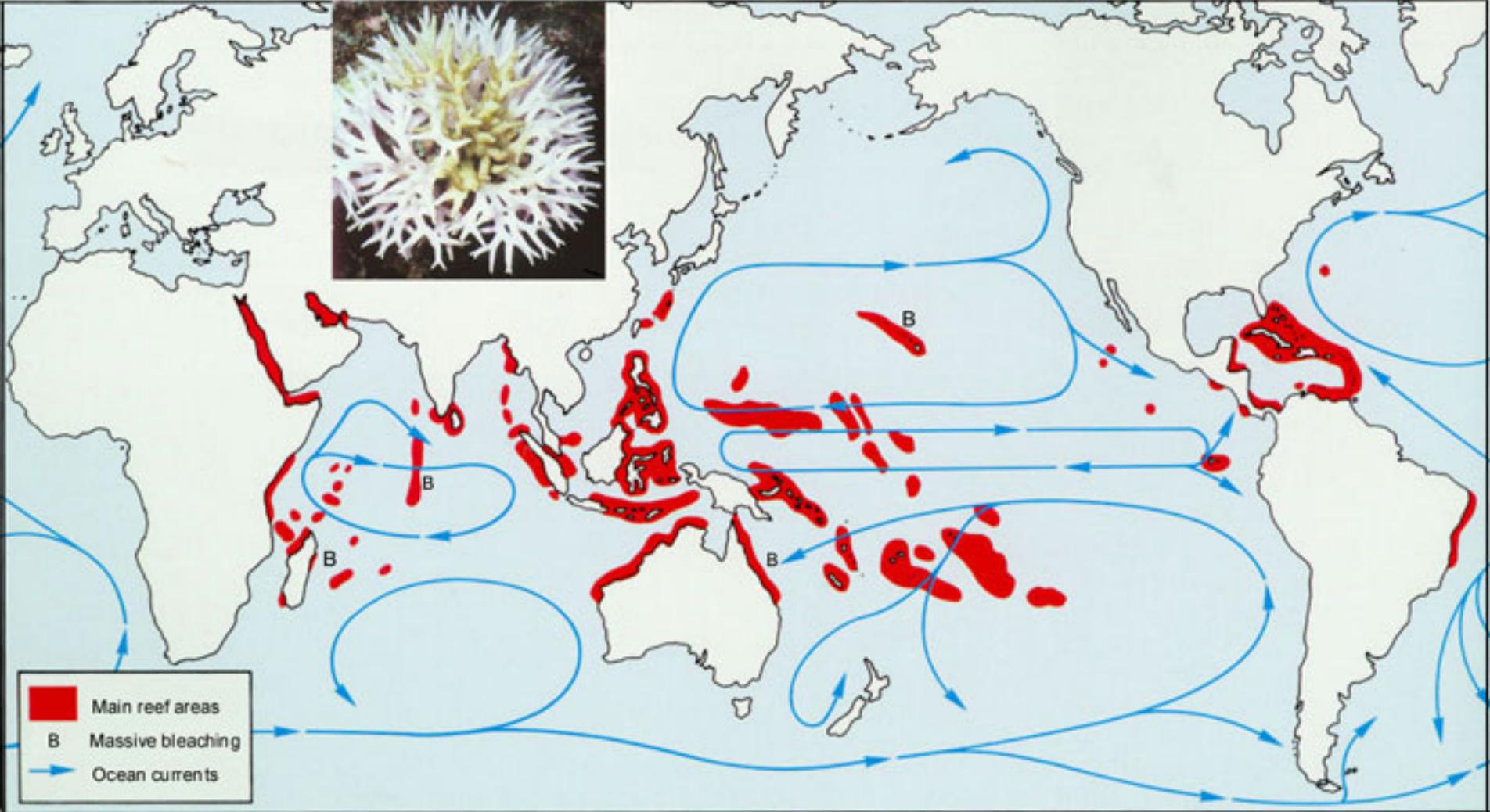
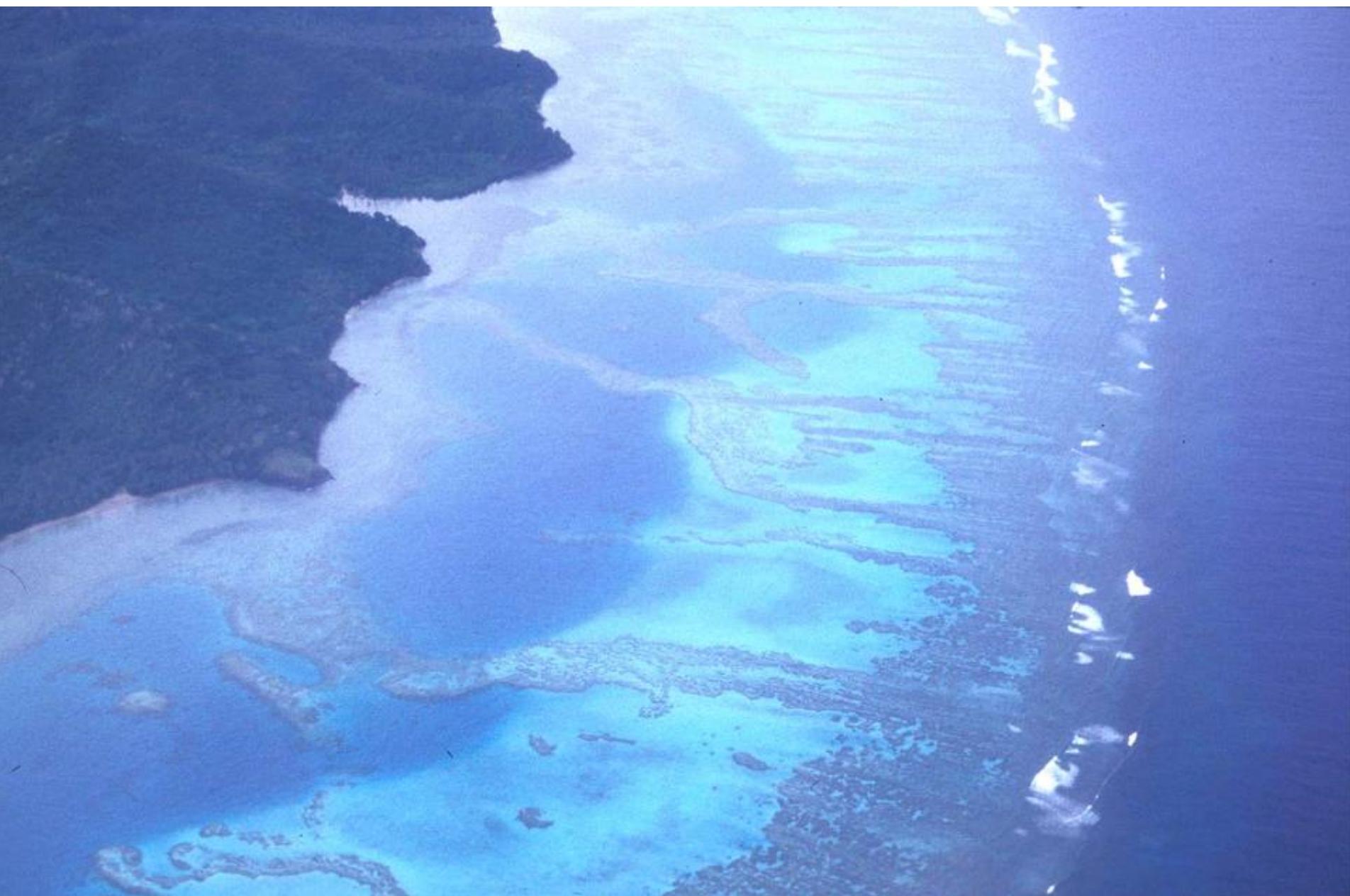


Fig.17 Coral reefs are found in warm, shallow, and clear waters of the tropical sea. Upon excessive heating, UV-radiation, and other factors, branching corals like *Acroporidae* (inlet) are the first to bleach. Bleaching is characterized by the expulsion of the dinoflagellated (zooxanthellae) from the coral tissue. Branching corals may regrow within a few years, while boulder corals may take several 100 years to reach the original size.

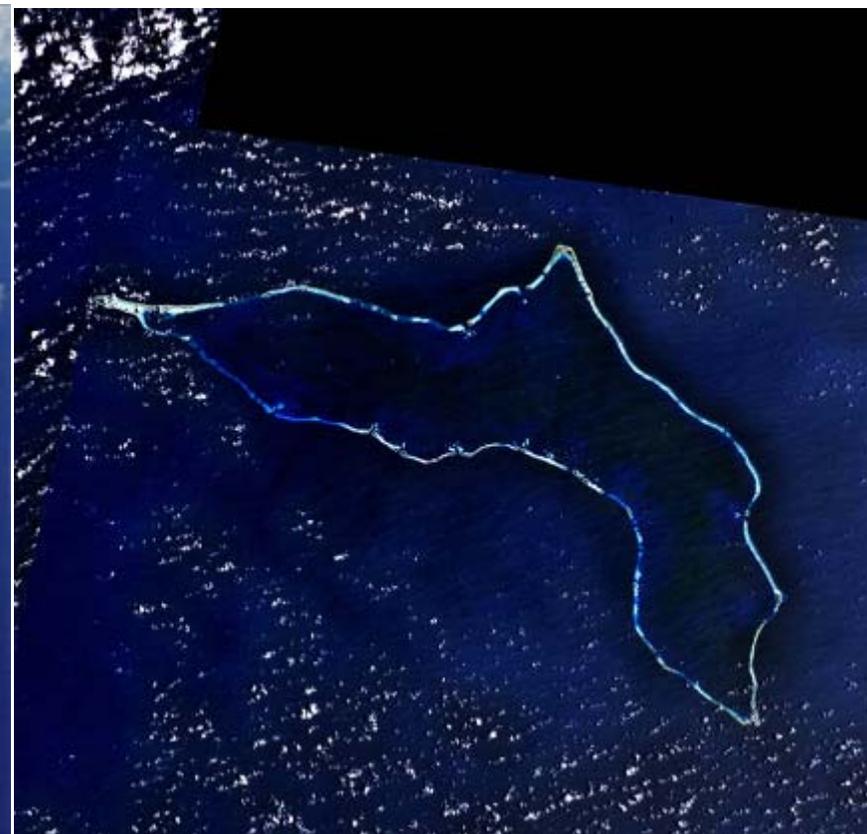
Fringing/Barrier reef. A lagoon is forming between the reef and the island shore but coral growth in the lagoon is still extensive. Note the breakers along the seaward side. During storms, the seaward edge of the reef takes a terrific beating. The light green band landward of the active reef is mainly coral detritus pounded to sand.



Section of barrier reef off the coast of Belize, Central America. The islets below are coral debris islands composed of the detritus from storm smashed coral.



Kwajalien Atoll. A very big atoll with a chain of tiny coral rubble islands embedded in the reef. Huge deep Lagoon.



Coral reefs rival Tropical Evergreen Forest in species diversity.

