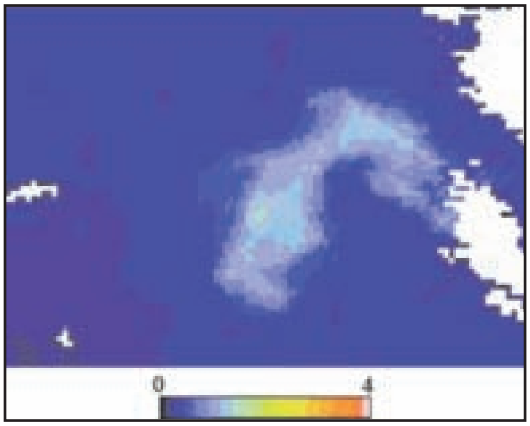
productivity

Nutrients

The basis of life in the upper ocean foodweb is light from the sun, carbon dioxide, and sufficient quantities of various other chemical nutrients for phytoplankton growth and reproduction. These nutrients include nitrogen, silicon (especially for diatoms that have an external casing made of silica), phosphorus, and several others. When the supply of any one of these becomes exhausted, growth and reproduction stop.

Throughout much of the subarctic North Pacific beyond the coastal regions, the limiting nutrient is iron. An open-ocean experiment, initiated by scientists of the PICES Advisory Panel on Iron Fertilization Experiment in the Subarctic Pacific Ocean demonstrated that supplementing the amount of iron in seawater in the central part of the Gulf of Alaska can increase phytoplankton abundance approximately fivefold. The increased abundance of chlorophyll was recorded by an orbiting ocean colour satellite 24 days after the application (Figure 4).



[Figure 4] SeaWiFS ocean colour image (mg chl m^{-3}) showing the phytoplankton bloom resulting from the addition of iron to seawater at Ocean Station Papa (50°N 145°W). The bloom covers an area approximately 1000 km^2. White denotes clouds that blocked the "view" of the satellite.[2]

There is a significant lack of quality long-term nutrient data for most regions of the North Pacific. Where they have been measured regularly, such as at Ocean Station Papa and in the California Current System, nutrient concentrations declined from the late 1970s to the late 1990s, but they have been increasing since 1999. The decline appears to have been due to increased stratification and a shallower thermocline in the Gulf of Alaska, increased stratification and a deeper thermocline in the southern California Current system that reduced the supply of nutrients to the upper layers. Increased nutrient supply in the Gulf of Alaska from 1999 - 2002 appears to be a result of a deepening of the upper mixed layer in the Alaska Gyre since 1999 but the re-emergence of a very shallow mixed layer in 2003 and 2004 will reduce the nutrient pool in the surface waters once again. In the California Current System, an increase in nutrients in 2002 was due to an intrusion of subarctic water and strong upwelling. Both processes may have been driven by atypical winds in the North Pacific since 1999. Winds were directed more strongly eastward towards the coast of North America.

Phytoplankton

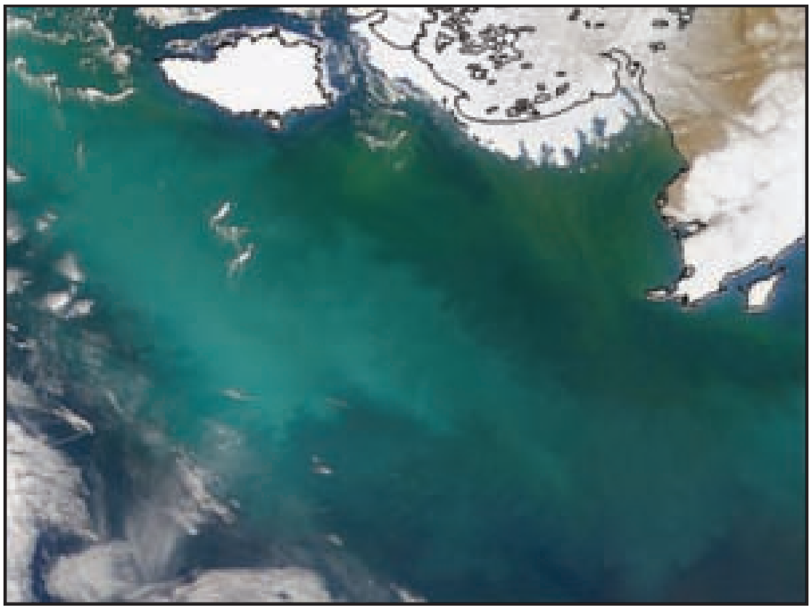
Annual rates of primary productivity are generally similar among regions of the North Pacific (Table 1), and are comparable to the North Atlantic. Changes in the methods used to determine primary productivity make it difficult to compare among years and regions. Ocean colour sensors on orbiting satellites are a relatively new tool for studying ocean productivity. They can provide unreliable results when ocean colour is affected by processes other than photosynthesis (e.g. suspended sediments). In the Yellow Sea, for example, shipboard samples are required to provide reliable chlorophyll data until the intercalibration issues are resolved.

Region	Primary Productivity ($gC\ m^{-2}\ yr^{-1}$)	Comments
Yellow Sea – East China Sea	150-200	
Okhotsk Sea	450	Includes phytobenthos
Bering Sea	225	In highly productive areas
Gulf of Alaska	80	In central gyre
	150-200	At Station Papa (50ºN 145ºW)
	300	On the Alaskan Shelf
Gulf of California	477	Estimated from satellites

[Table 1] Annual average primary productivity estimates for some regions of the North Pacific Ocean.

In general, the biomass of phytoplankton has been decreasing in the deep-water areas of the eastern and western North Pacific over the past 20 years. Since 1999, increases in phytoplankton have been seen in the Yellow Sea, off the west coast of Japan, in the Gulf of Alaska and off the west coast of North America. In the California Current System, higher nutrients in the upper layers in recent years were a result of an unusual intrusion of the subarctic water and enhanced upwelling. These contributed to a tripling of primary productivity off Oregon during summer of 2002 compared with the previous five years. Much of this phytoplankton production sank to the bottom and its decomposition created a large (>700 km^2) hypoxic zone over the continental shelf. In the Bering Sea the spring bloom occurred later in 2000-2002 than normal due to the early retreat of sea ice during these years. The central North Pacific Transition Zone was more productive during the cooler years and lower sea levels that occurred from 1977-1998, and has been less productive with the warmer temperatures and higher sea levels that have occurred since 1998. In recent years (1999-2003) the North Pacific chlorophyll front has not extended as far south as in previous years, so that presently it occurs at about 30°N latitude in winter.

Occurrences of unusual phytoplankton blooms have been increasing in the North Pacific Ocean. Large blooms of the coccolithophorid *Emiliana huxleyi* occurred in the Bering Sea (Figure 5) in 1997 and returned in later years.

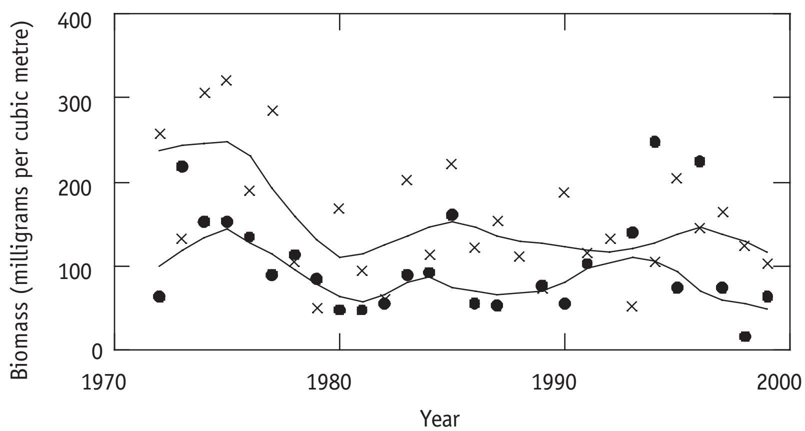


[Figure 5] Satellite image of a bloom of coccolithophores in the eastern Bering Sea in 1997.

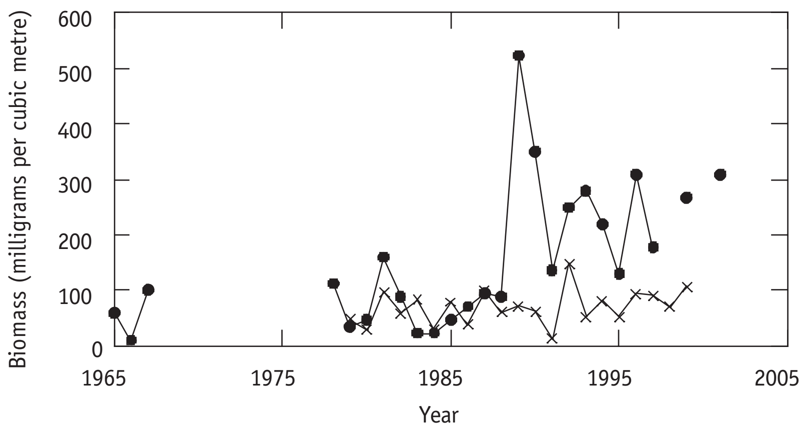
Phytoplankton species that produce toxic domoic acid (e.g. *Pseudo-nitzschia* spp.) have been increasing along the coastal portions of the California Current System and in the Gulf of California. These outbreaks have forced the closures of shellfish harvesting beaches, and led to the deaths of marine mammals. The Gulf of California is also experiencing increases in phytoplankton of tropical origin in these blooms. Severe harmful algal bloom outbreaks have been increasing in parts of the Yellow Sea and East China Sea. Severe outbreaks used to occur mostly along the southern coast of Korea, but now they also occur along the western coast of Korea.

Zooplankton

Estimates of annual rates of secondary productivity for the seas of the North Pacific are also generally similar to those in the North Atlantic. Annual zooplankton production rates in the Bering Sea range from 4 gC m^{-2} in the coastal domain to 64 gC m^{-2} at the highly productive shelf edge. In the Gulf of Alaska estimates range from 13 gC m^{-2} at Station Papa to 30-50 gC m^{-2} on the continental shelf and near shore. These compare with annual rates of 15-20 gC m^{-2} in the North Sea and 35 gC m^{-2} on Georges Bank.

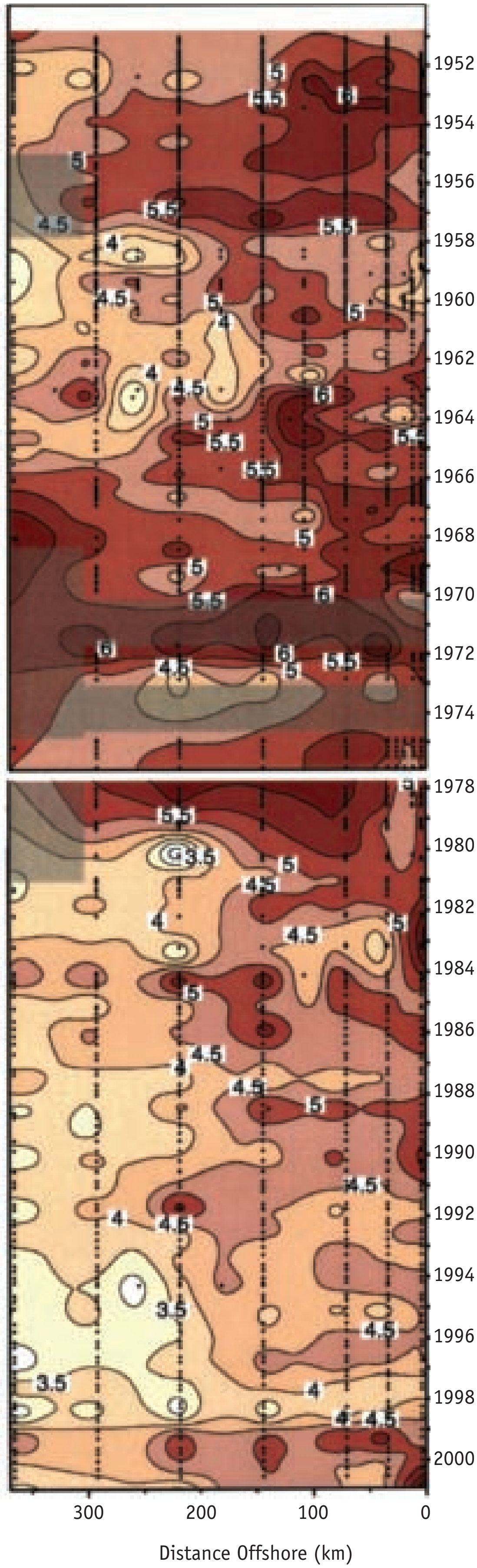


[Figure 6] Zooplankton biomass (mg m^{-3}) in spring (x) and summer (•) in the Oyashio Current.



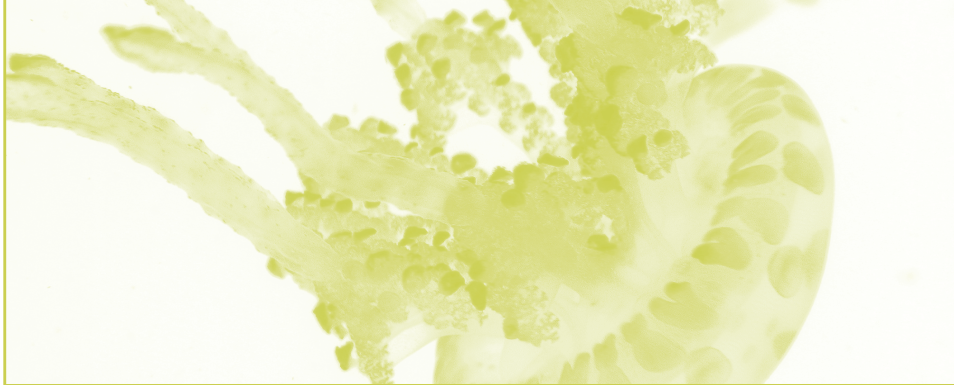
[Figure 7] Zooplankton biomass in the Yellow Sea in February (x) and August (•).

As with phytoplankton, zooplankton biomass has decreased in the northern part of the Oyashio Current (Figure 6) and in the southern part of California Current over the past 30 years (Figure 8), but increased in the Yellow Sea (Figure 7) and the coastal parts of the Gulf of Alaska. There are indications that zooplankton biomass in the California Current System increased after 1999 (Figure 8). In the Bering Sea, zooplankton biomass has remained similar to that observed throughout the 1990s.



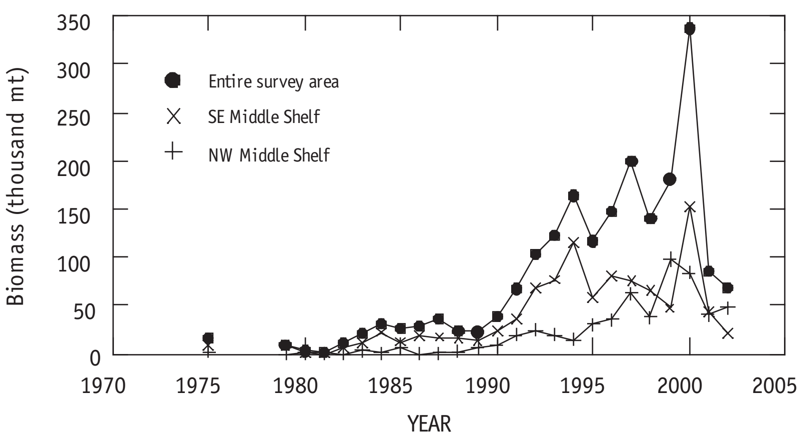
[Figure 8] Zooplankton biomass (displacement volumes - cm^3 $1000m^{-3}$ - log transformed) by year and location along line 80 of the CalCOFI sampling grid in southern California. Note the higher volumes in the late 1960s and the small volumes in the 1990s, with increases after 1999.[3]

Synthesis



Zooplankton species composition in coastal North America has varied with temperature, with previously uncommon southern species increasing in abundance during El Niño events. The seasonal timing of peak zooplankton biomass, which is due principally to the large copepods of the genus *Neocalanus*, occurred 30-60 days earlier in both the eastern and western subarctic North Pacific as a result of the warmer and shallower mixed layer. In the eastern North Pacific, the timing of the biomass peak has returned to near-normal since 1999.

As with the phytoplankton, there were unusual zooplankton blooms in the 1990s. In the Bering Sea in particular, large blooms of gelatinous zooplankton have occurred since 1989, peaked in 2000, but then declined markedly and have remained low (Figure 9).



[Figure 9] Biomass index (x 1000 t) of jellyfish caught in bottom-trawl surveys on the eastern Bering Sea shelf during 1975 and from 1979 to 2002. Also shown are the totals for the SE middle shelf and NW middle shelf only.