SCIENCE FOCUS: Ocean Optics

The Blue, Bluer, and the Bluest Ocean

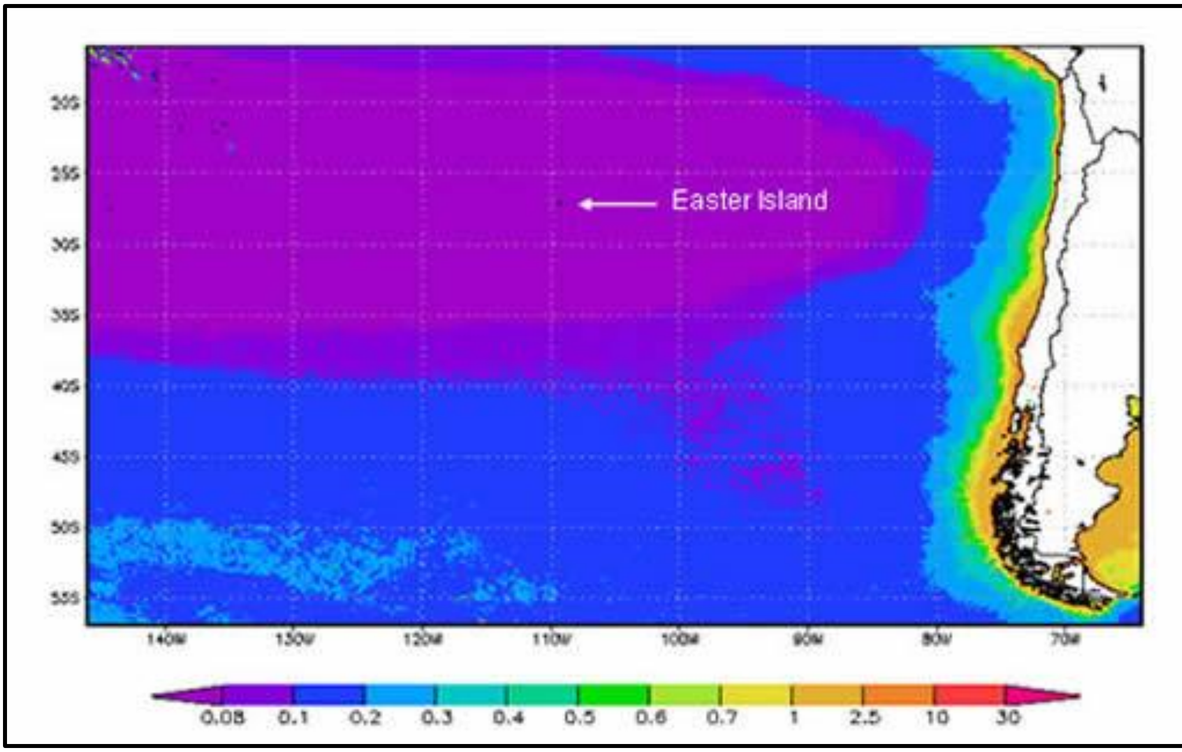
One of the most commonly asked questions about the ocean and its color – which we have had many chances to answer – is ***"Why is the ocean blue?"*** There are many Web sites and Web pages available that provide answers to it, in various ways, from differing perspectives (oceanographers, physicists, chemists), and in varying levels of detail.

This *Science Focus!* article will address a slightly different question – "Where is the ocean bluest?", or, alternatively "Where in the ocean is the most intense blue color of the ocean surface found – and why is it so blue?" Answering the "where?" aspect of that question is actually pretty easy – but the "why?" part requires a thorough examination of what makes the ocean appear blue. This article will do that, starting with the view of the global ocean from space, and ending with a single molecule of H_2O.

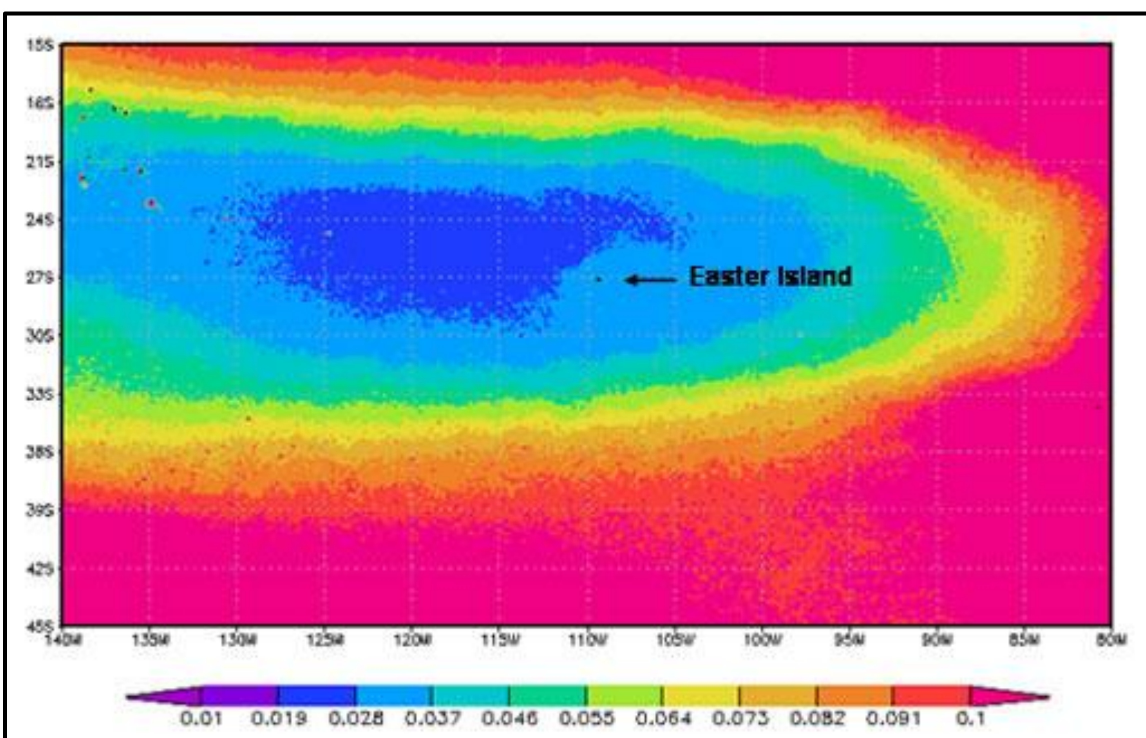
The observational record of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) was over eight years long when this article was written. During that period of time, SeaWiFS provided nearly continuous observations of the Earth, and particularly the Earth's oceans. One interesting aspect of these observations is that they indicated a region of the ocean where chlorophyll concentrations were lower than anywhere else, over the entire length of the mission. This area happens to be in the Pacific Ocean, just to the north and west of isolated Rapa Nui, which is more commonly known as Easter Island.

To take a closer look at this area, the data analysis tool Giovanni will be used. Giovanni allows an examination of SeaWiFS (or MODIS-Aqua) data for any time period and region of the ocean. We'll use Giovanni to "zoom in" on the low productivity region in the Pacific Ocean.

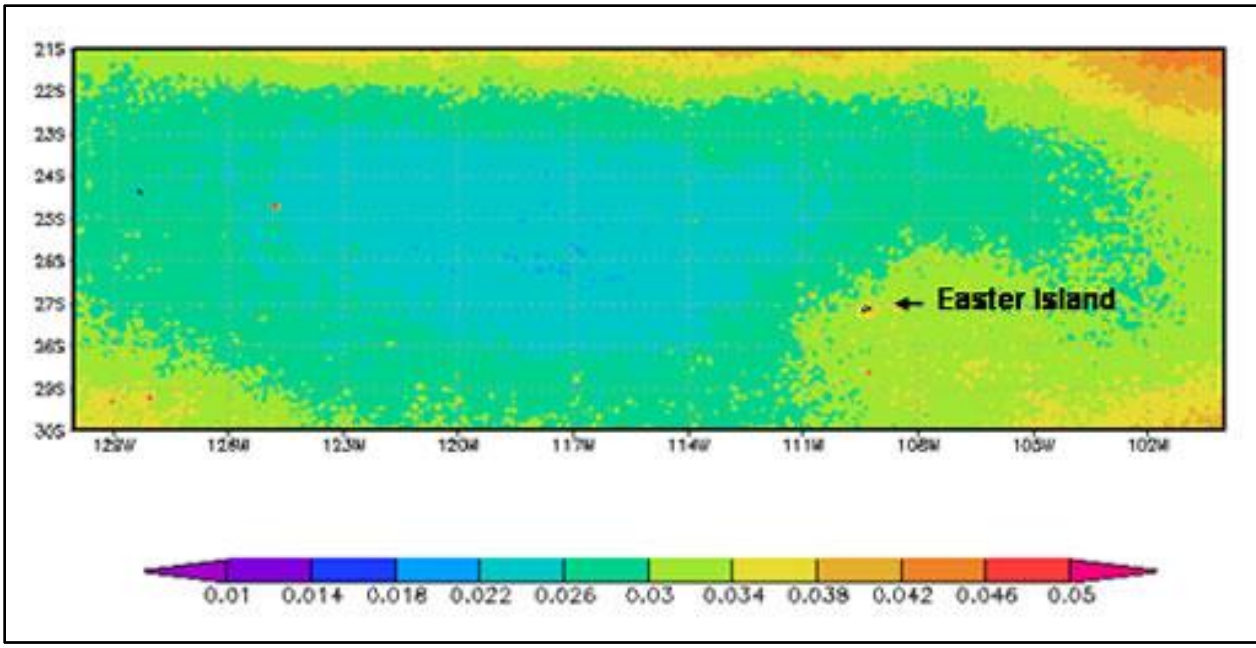
The first view of the data will help to locate Easter Island and the general area of low productivity. At the top of the next page is a view of the data averaged over the entire period of January 1998 to December 2004.



The second view moves closer to the center of the low productivity zone. The color palette is adjusted to the range of chlorophyll concentration values that occur here. In the first image, the color palette was the "standard" colors for the range of concentrations found in the entire ocean, starting with 0.08 milligrams of chlorophyll per cubic meter (mg chl m^{-3}) and ending with 30 mg chl m^{-3}. The new palette has a range of 0.01 to 0.1 mg chl m^{-3}.



It is clear from the previous image that although Easter Island is surrounded by ocean waters with very low chlorophyll concentrations, the area with the absolute lowest concentrations does indeed lie to the northwest of the island. How low can the concentrations go? The next image answers that question with a different color palette, ranging from 0.01 to only 0.05 mg chl m^{-3}. This image also "zooms" in a little closer to this region.



This image demonstrates that near the center of this region, the chlorophyll concentrations (averaged over seven years) are as low as 0.018 mg chl m^{-3}. Because there is so little chlorophyll (or anything else) in the water here, this is the most transparent surface ocean water in the world. So the next questions to answer are:

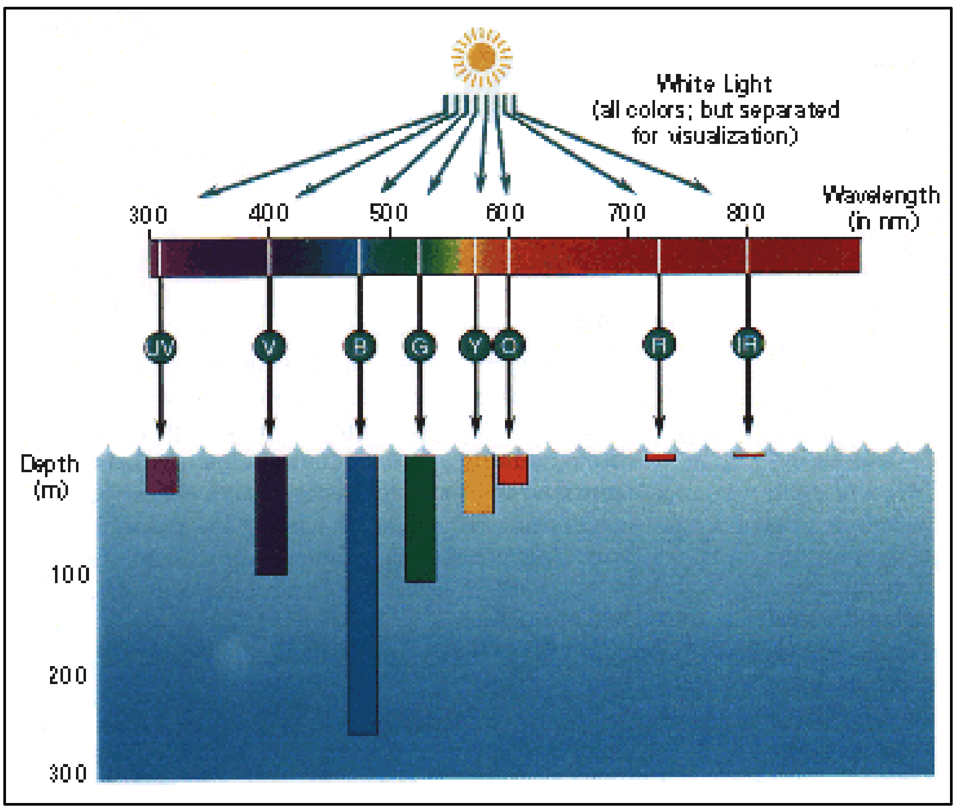
Why is this transparent ocean water the bluest ocean water?

and:

Why is it located here?

Why is this transparent water the bluest ocean water?

There are two major optical processes by which ocean water, and substances dissolved or suspended in ocean water, interact with incoming light from the Sun. The two processes are absorption and scattering. In the atmosphere, the main reason that the sky is blue is due to the scattering of light (more about this process can be found in the *Science Focus!* article "It's Not Easy Being Normal", in the section on Rayleigh scattering). In the ocean, the primary way that water interacts with light is absorption, and water absorbs different colors of the visible spectrum better than others. Water preferentially absorbs red light, and to a lesser extent, yellow and green light, so the color that is least absorbed by water is blue light.



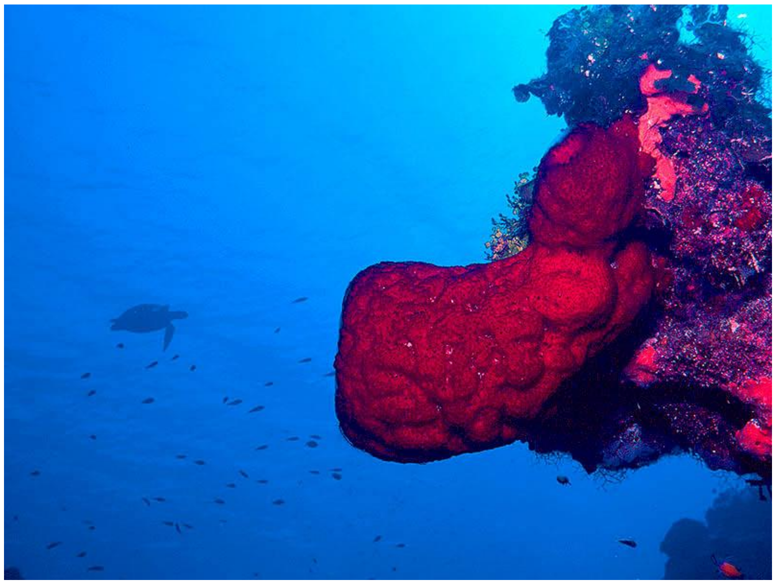
This diagram shows the depth that light will penetrate in clear ocean water. Because red light is absorbed strongly, it has the shallowest penetration depth, and blue light has the deepest penetration depth.

Underwater photographers have to deal with the absorption of light with every picture they take. In the natural light found in the ocean, a brightly colored tropical fish can look like this:

However, if the underwater photographer takes a picture of the same fish with a strong and bright flash unit, the fish looks a lot more colorful!

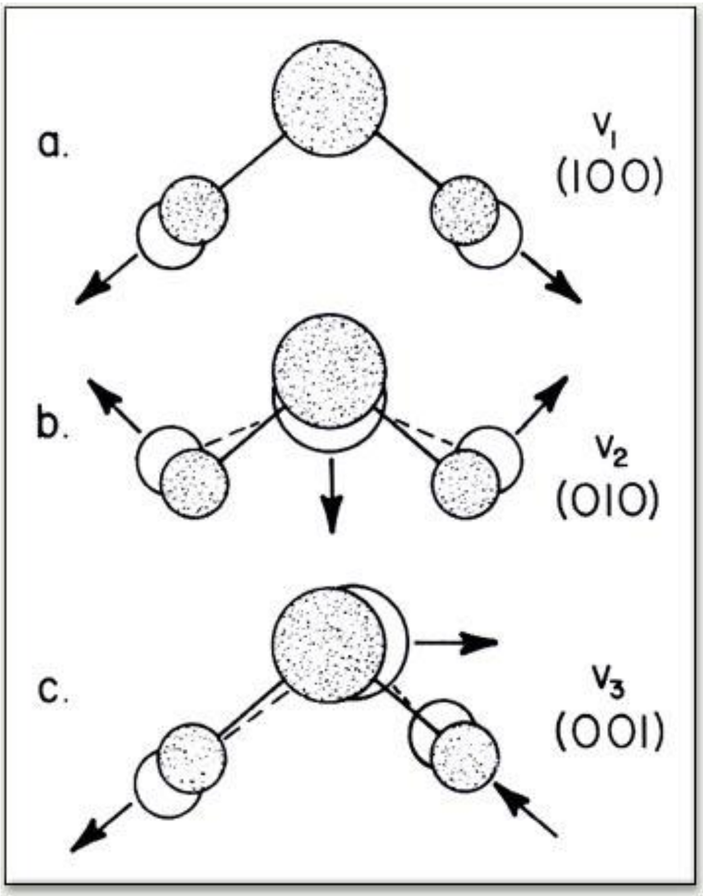
Photo Credits: Copyright David Knight, Technical Director, Cameras Underwater Ltd., http://www.camerasunderwater.co.uk/, used with permission of photographer.

Note in the natural light picture how the red and orange colors of the fish appear black, due to the nearly complete absorption of red and orange wavelengths by water. There is a species of sponge called the “strawberry sponge” (shown below) that is a deep ruby-red color, but unless divers have a light or a bright camera flash, the beautiful strawberry sponge merely looks like a black blob.



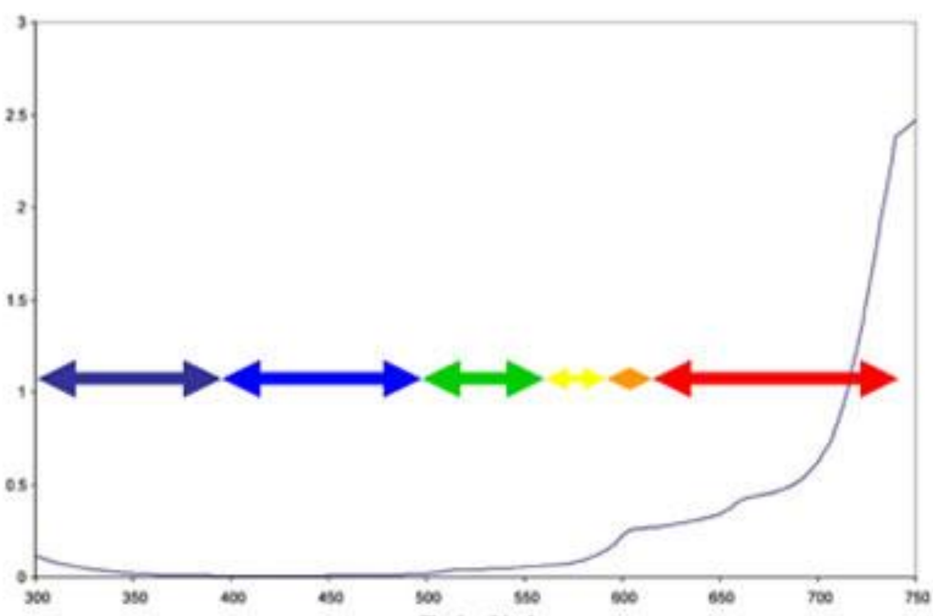
So clear ocean water appears blue because blue is the only color that is not strongly absorbed by water. As you might guess, that provokes another question to answer: Why does water absorb light strongly at some wavelengths, and not so strongly at other wavelengths? The answer to that question is found in water’s light absorption spectrum.

Water’s molecular formula, H_2O, means that each molecule of water consists of two hydrogen atoms that are connected (bonded) to an oxygen molecule. The atoms are in constant motion within the molecule, but their motion is restricted by the bonds. So there are only a few types of motion that are permitted, as shown in the diagram on the next page.



The various atomic motions are called vibrational modes, but water molecules can also have rotational modes. Each of these movements occurs at specific frequencies (for music lovers, there is a fundamental frequency and higher energy overtones). When a photon of light encounters a water molecule, the molecule can absorb it if it has the correct amount of energy to "excite" the vibration to a higher frequency overtone. Red light photons have the correct amount of energy, and blue light photons don't, so the molecules selectively absorb the red light photons.

The resulting spectrum of light absorption looks like this (the color range of the arrows is approximate!):



An additional interesting aspect of water in the liquid state is that the closely-packed, highly mobile water molecules also form hydrogen bonds – which, stated simply, means that hydrogen molecules in water are attracted to each other. Hydrogen bonds give water a somewhat defined structure (which is more apparent in ice – hydrogen bonds in ice are the reason that ice floats in liquid water – but we won't pursue that aspect of this subject). The hydrogen bonds in water actually make it absorb blue light less efficiently by changing the vibrational frequency of the hydrogen atoms. That change means that clear water would appear an even deeper blue if hydrogen bonding didn't occur.

So that is the reason that clear water appears blue, if there is enough of it to absorb the other colors of visible light. Clearer water means bluer water, because if there is anything else in the water to absorb or reflect or scatter the incoming light, the apparent color of the water will be altered.

Why is the ocean northwest of Easter Island so clear (or blue, if you prefer)?

There are several reasons that the surface waters of the ocean northwest of Easter Island are so clear and devoid of chlorophyll.

Reason 1: This area is near the center of the South Pacific Gyre, so there is very little water movement – vertically in the water column, or the horizontal circulation of ocean currents – to provide nutrients which promote phytoplankton growth. The South Pacific Gyre is roughly defined by the westward flow of the South Equatorial Current on the north side, the northward flow of the Peru Current on the eastern side, the southward flow of the East Australian Current on the western side, and the eastward flow of the Antarctic Circumpolar Current defining the southern boundary. In the center of the South Pacific Gyre, there are no strong currents, and the surface winds are also very light. Only a tiny population of phytoplankton can survive on the low concentrations of nutrients in these still, calm, and clear waters.

Reason 2: The area is a long, long way from any major land areas, so that nutrients derived from the land, either delivered by rivers to the ocean or by dust (which is an important source of iron) are scarce. A paper by Behrenfeld and Kolber (1999) indicates that the availability of iron may be the main reason for the low phytoplankton productivity within the South Pacific Gyre. The distance from land also means that there are no sediments from rivers available to cloud the waters, either.

Reason 3: It's very sunny here, and because it is in the tropics, the sunlight is particularly strong. The phytoplankton found here have to adapt to the intense sunlight by a process called "photo-acclimation" (or "photo-adaptation", or "photo-inhibition"). These photo-processes mean that the phytoplankton produce other pigments, instead of chlorophyll that shade them internally from strong sunlight. This protective reaction reduces the chlorophyll concentration in each phytoplankton cell. Not all the chlorophyll escapes; some of it is destroyed by the powerful sunlight, in the same way that a color photograph will fade if it is left in the sun too long. And strong sunlight will also fade and destroy any remnants of colored organic matter in the water, making the water even more transparent.

Bottom line: Low nutrients + low phytoplankton + low chlorophyll = very clear, very blue water.

Final question: Where in the world can the deep blue of the ocean be seen without traveling to Easter Island?

If traveling to Easter Island is out of the question – for most of us, it is! – there is a unique place in the United States that provides a window on the clear blue of the ocean. That place is Crater Lake in Oregon. Crater Lake is the deepest lake in the United States, and it fills the caldera created by the immense ancient volcanic explosion of Mount Mazama. Because it is so deep, and the water is clear because of the limited amount of runoff that enters the lake from the sides of the caldera, Crater Lake has a blue color that rivals the open ocean.

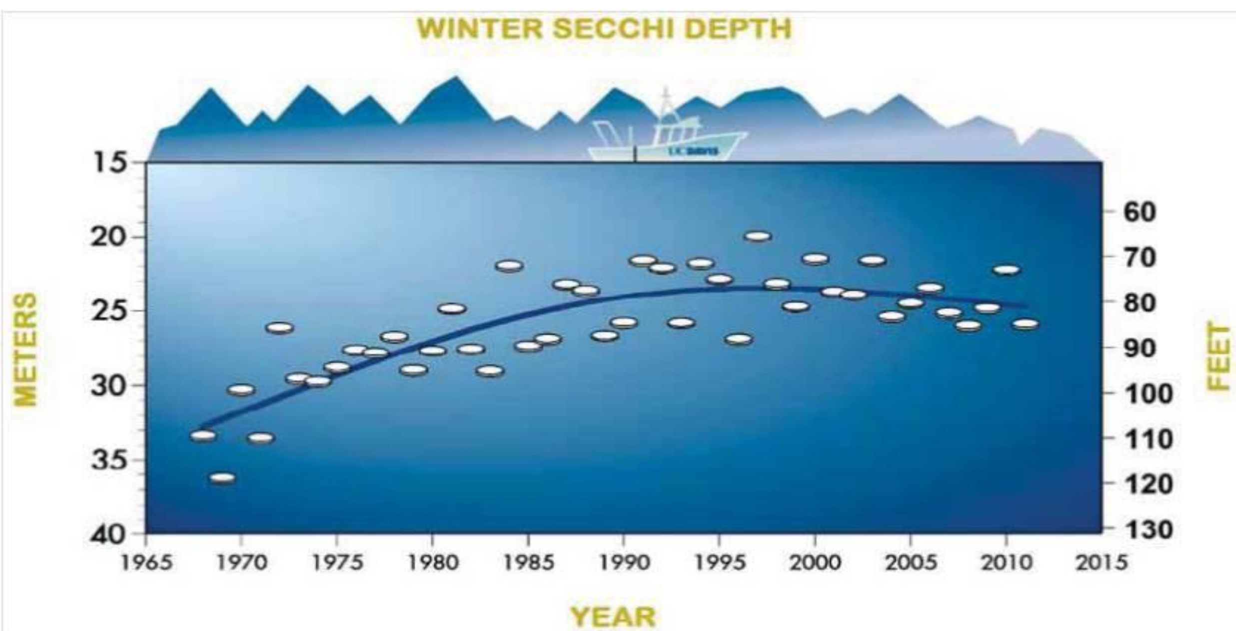
It's not easy to find pictures of Crater Lake that demonstrate its true blue color, because most pictures of the lake taken on a calm clear day will capture beautiful reflections of the sky and forested caldera rim on the surface. However, photographer Barry Haynes was high on the caldera rim one day, looking down, and captured this idyllic picture of a tour boat on the surface of Crater Lake:

Photo Credit: Barry Haynes, ©2004, Barry Haynes, All Rights Reserved, http://www.barryhaynes.com/, used with permission of the photographer.

So if your travel plans are unlikely to include Easter Island, but you still want to see how blue the ocean can get, Crater Lake can provide a sense of the oceans' blues.

Lake Tahoe: Out of the Blue and into the Green

There is another notable deep blue lake in the western United States—Lake Tahoe, which is on the border of California and Nevada. Unlike Crater Lake, which is surrounded by a volcanic rim and national park lands, Lake Tahoe's shores host homes, communities, casinos, and even some nearby ski areas. There has been a notable decline in the clarity of Lake Tahoe's water, presumed to be due to an increasing amount of nutrients (nitrate and phosphate) flowing into the lake, and possibly an increase in suspended matter. The image below shows the reduction in the Secchi depth (the depth at which a standard target, the Secchi disk, is no longer visible) over time in Lake Tahoe. Reductions in stormwater runoff may be helping to preserve the clarity of the lake, but it is still not as clear as it was decades ago.



The reduced clarity of Lake Tahoe illustrates that even small changes in the environment of lakes and oceans can significantly affect the characteristics of a large volume of water. Pure, transparent, deep blue water is an unusual condition for lakes or oceans; like other areas that are remote and pristine, the clear waters of the world can be recognized as vital natural resources.

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Acknowledgment
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Links
Satellites guide ships through South Pacific's watery desert
Why is water blue?

References

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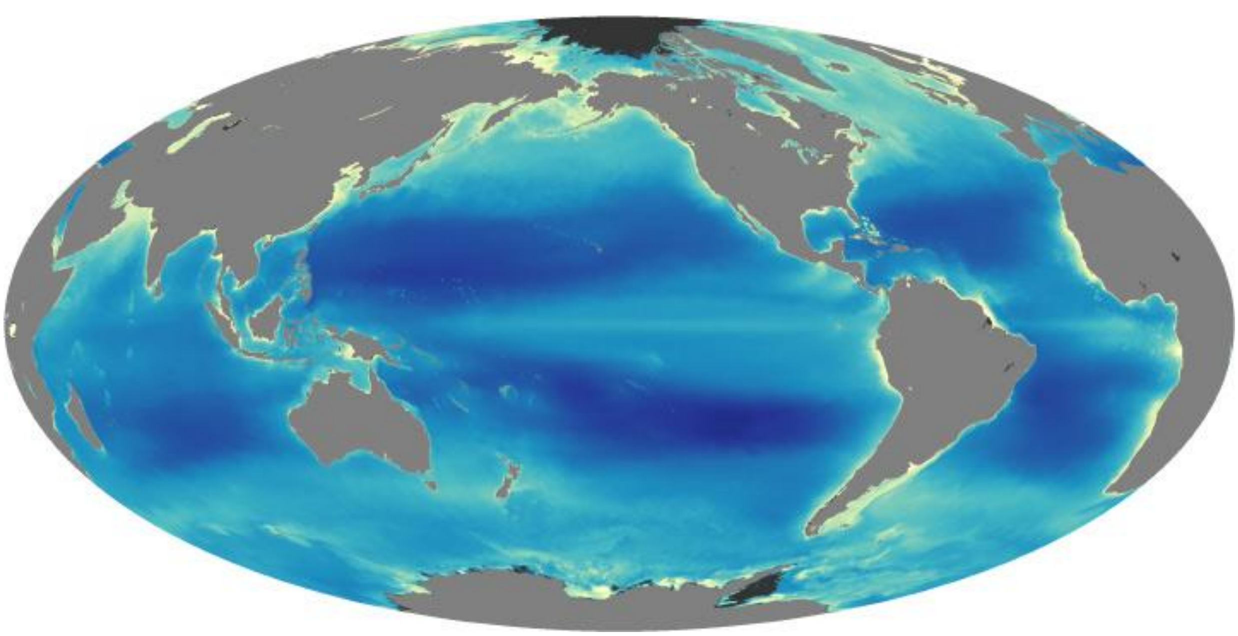

Image of MODIS-Aqua global chlorophyll, 2002-2010, from NASA Earth Observatory.