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Authors

Hunt, GL
Baduini, CL
Brodeur, RD
[et al.](#)

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The Bering Sea in 1998: The Second Consecutive Year of Extreme Weather-forced Anomalies

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In 1998, anomalous conditions in the Bering Sea included elevated heat content of the water, cross-shelf advection of zooplankton and larval fish, major changes in the structure of the zooplankton community, and an unprecedented second observation of a large-scale bloom of the coccolithophorid phytoplankton, *Emiliania huxleyi*. Some of these anomalies appear to be related to the unusual weather patterns of 1997 and 1998, while the causes of others remain unknown.

The Bering Sea is located in the northernmost part of the North Pacific Ocean, and its broad eastern continental shelf constitutes approximately 44% of its area. Because Pacific water must pass through the Bering Sea before entering the Arctic, climatic events in the Bering affect heat and biogeochemical transport to the Arctic. The Bering Sea, in particular its broad eastern shelf region, is also the site of some of the world's major fisheries. It contributes over half of the U.S. fishery production, with a commercial catch worth one billion dollars in 1997.

Two Major Investigations

During 1998, two major scientific programs were active on the southeastern Bering Sea shelf. One, the NSF-sponsored Inner Front Project, focused on a series of sites near the 50 m isobath (the inner front) from Slime Bank to Nunivak Island. The other, the NOAA-sponsored Southeastern Bering Sea Carrying Capacity (SEBSCC) project, concentrated on conditions conducive to fisheries production over the middle and outer shelves. In 1998, these two studies used a combination of shipboard measurements (9 cruises between February and October), moorings (11 sites), and satellite imagery to measure physical properties, nutrient concentrations, and biological parameters, including standing stocks and production of phytoplankton, and the distribu-

tion and abundance of zooplankton, fish and seabirds (Napp & Hunt, accepted).

Variation in the extent, duration, and timing of sea-ice cover over the continental shelf of the eastern Bering Sea is important in determining both physical properties and biological processes subsequent to ice melt [Stabeno *et al.*, 1999; D. A. Stockwell *et al.*, submitted manuscript, 1999]. Events in 1998 indicated that weather-driven interannual differences in winter sea ice cover can

influence the heat content of water exported from the eastern Bering Sea shelf to the Arctic.

Usually, cold northerly winds and ice melt remove residual heat from water column over much of the Bering Sea shelf. However, in 1998, northerly winds advected ice over the southeastern shelf for only a brief period in February. In addition, weak winter winds failed to mix these melt-cooled waters to the bottom (Figure 1). Thus, spring 1998 began with unusually warm bottom water. This residual heat, coupled with summer warming, resulted in the water column over the middle domain having higher heat content in summer 1998 than has been observed in recent years [Stabeno *et al.*, 1999].

The northward movement of this warm water could be traced in the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) images by its association with a bloom of minute phytoplankton cells, the coccolithophorids, that pro-

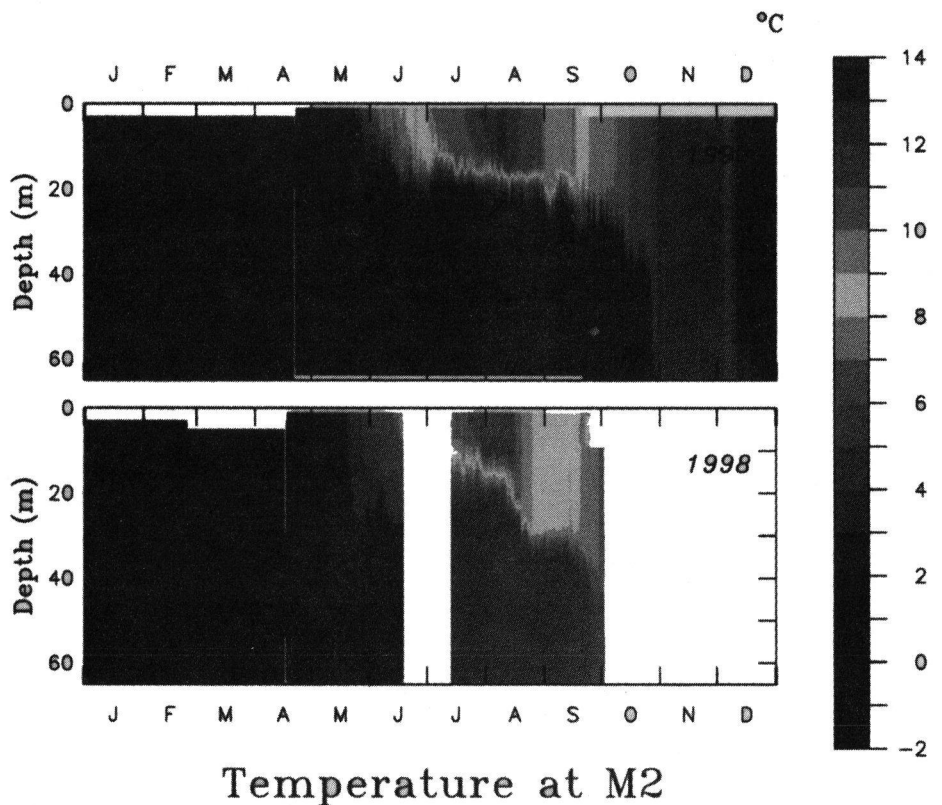


Fig. 1. Contours of temperature over the middle shelf of the southeastern Bering Sea in 1997 and 1998. Measurements were made at Mooring 2, at 56.9°N, 164°W [Stabeno *et al.*, 1999]. Original color image appears at the back of this volume.

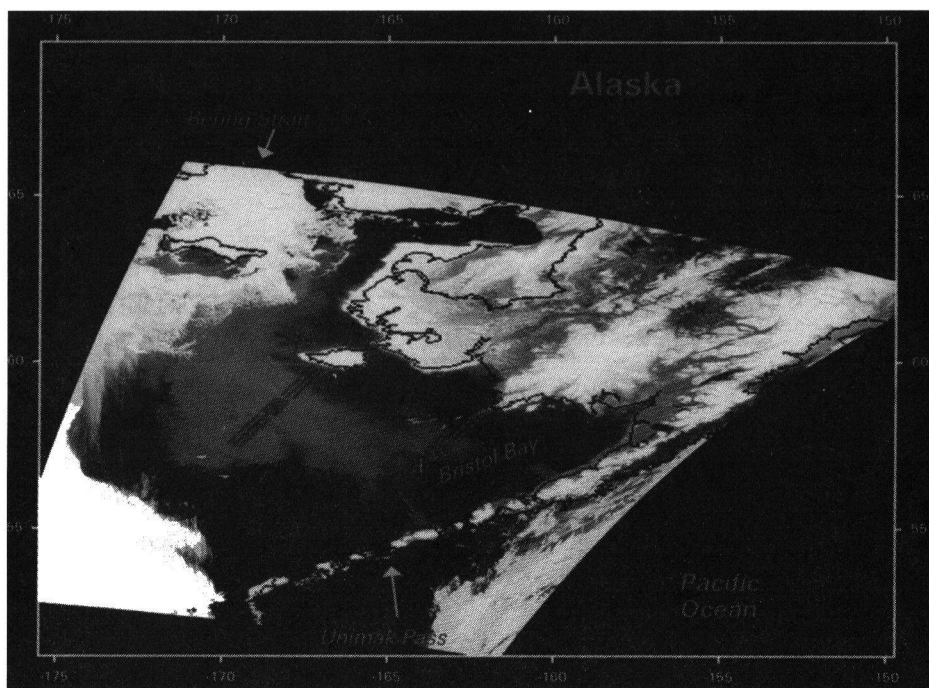


Fig. 2. Sea-viewing Wide Field-of-view Sensor false color IR image from April 25, 1998, showing the coccolithophorid bloom and its advection northward through Bering Strait. The reddish color along the coast is due to suspended sediments. The study grids are marked in red (clockwise from the top left: Nunivak Island, Cape Newenham, Port Moller, and Slime Bank grids). The position of Mooring 2 is marked with a yellow X. Original color image appears at the back of this volume.

duce calcium carbonate plates. These plates reflect light in a characteristic way that allows easy detection by satellite remote sensing. SeaWiFS images from July show the bloom being advected northward east of St. Lawrence Island and through Bering Strait into the Arctic (Figure 2).

Temperatures 2°C above Normal

Export of heat to the surface waters of the Arctic Ocean can increase ice melt and sea surface-atmosphere heat exchange in the Arctic. Recent studies have shown that the ice in the Arctic Basin is thinning [Wadhams, 1995]. Although we have no measurements in 1998 of the temperature of the water flowing from the eastern Bering Sea into the Arctic, average temperatures on the shelf were ~2°C above normal.

When the average heat content of eastern Bering Sea shelf waters is elevated and the typical northward flow of this water occurs, there will be changes in the surface heat content of the Arctic Ocean. A change of this nature could have important implications for Arctic Ocean circulation and heat budgets.

The early retreat of the ice in 1998 was followed by an unusually stormy spring that lasted into mid-June. A variety of biological tracers suggested that strong southwest winds associated with the spring storms resulted in transport of warm surface waters from the shelf break near Unimak Pass to the inner shelf, then northward to the Arctic.

For instance, in spring, we observed substantial quantities of bull kelp (*Nereocystis luetkeana*) floating near the inner front southwest of Cape

Newenham and off Nunivak Island (Figure 2). This species has its northernmost and westernmost distribution in the Gulf of Alaska and eastern Aleutian Islands.

Unusual Observations

During June, oceanic and outer shelf species of zooplankton, particularly copepods (*Neocalanus spp.* and *Metridia pacifica*) and euphausiids (*Thysanoessa inermis*) were found along the 50 m isobath at Port Moller, Cape Newenham and Nunivak Island (D.A. Stockwell et al., submitted manuscript 1999). These observations of onshore and northward transport of organisms are unusual in that previous studies have found cross shelf advection and northward flow in the southeastern Bering Sea to be weak [Stabeno et al., 1999].

This advection also affected the distribution of early life stages of walleye pollock (*Theragra chalcogramma*), the most important component of the Bering Sea commercial fisheries. In June 1998, we found larval pollock in abundance off Port Moller, and in August, young-of-the-year pollock were abundant off Cape Newenham. These observations suggest transport of larvae along the 50 m isobath from spawning areas near Unimak Island. Surveys in July and September, 1998, in the southeastern Bering Sea and around the Pribilof Islands encountered far fewer pollock than in previous years (R. Brodeur, unpubl. data), possibly because their distribution had shifted to the northeast.

A model of wind-generated surface currents has shown that the strongest year classes of wall-

eye pollock occurred when surface winds favored advection of larvae inshore, away from cannibalistic adults and older juveniles [Wespestad et al., 1999]. The conditions in 1998 were similar to those hypothesized for strong survival of young-of-the-year pollock. The effects of transport of larval and juvenile pollock on the strength of the 1998 year class will not be known until surveys of the distribution and abundance of these fish are concluded in 1999 and subsequent years.

More Anomalies

Coincident with the warm sea temperatures, other anomalies were observed in both 1997 and 1998, but their connection to the unusual weather is yet to be determined. For example, images from SeaWiFS from February through October 1998 revealed that cells from the previous year's extensive coccolithophorid bloom [Vance et al., 1998] had overwintered (Figure 2) and bloomed again. The duration of the 1998 bloom, on the order of 9 months, was much greater than the more usual duration of a few weeks to 3 months seen in the North Atlantic Ocean [Holligan et al., 1993].

Coccolithophorids are some of the smallest of phytoplankton species (about 10 microns), and they are not grazed as efficiently as larger phytoplankton cells are by large species of zooplankton [Nejstgaard et al., 1995]. Thus, coccolithophorids are likely to sustain a food web that is initially cropped by microzooplankton, thereby creating a longer, less efficient food chain for the transfer of energy from plant cells to upper trophic level organisms such as fish, seabirds, and marine mammals.

Also found in 1997 and 1998 were changes in the relative abundance of zooplankton components of the inner shelf ecosystem. This suggests significant changes since the 1970s and early 1980s (D.A. Stockwell et al., submitted manuscript, 1999). In particular, the euphausiid *Thysanoessa raschii*, a krill-like organism, was one to two orders of magnitude less abundant in 1997 and 1998 than earlier, and copepods were an order of magnitude more abundant.

Many Shearwaters Died

The decrease in the abundance of euphausiids in the surface waters of the Bering Sea may have affected at least one species of top predator. The short-tailed shearwater (*Puffinus tenuirostris*), a species of seabird that migrates from Australia, has in the past foraged almost exclusively on euphausiids in the southeastern Bering Sea (Baduini et al., accepted). In 1997, high numbers of these birds died in the southeastern Bering Sea, apparently of starvation.

In 1998, though no unusual mortality was seen, birds were underweight. In both years, shearwater diets were broader than in previous years, with fish becoming a dominant prey in 1998. Major changes in the components of the zooplankton community will be likely to affect other higher trophic level species including fish and whales.

Other ecosystem anomalies in 1997 and 1998 included a surprisingly low return of sockeye salmon (*Oncorhynchus nerka*) to Bristol Bay, the world's largest wild sockeye salmon fishery. The catch was approximately half of that forecasted in each year, and both years were well below the average over the last 25 years. In addition, salmon runs to the Yukon River, Kuskokwim River, and other Bering Sea rivers were well below the levels that were predicted for 1998. The Yukon River chum salmon (*O. keta*) catch in 1998 was only about 4% of the mean catch since 1974. The fish that did return were later and smaller than normal. The decrease in abundance and size was noted across several age groups, which suggests that the causative factor was likely to be of marine origin [Kruse, 1998].

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G. L. Hunt Jr., C. L. Baduini, R. D. Brodeur, K. O. Coyle, N. B. Kachel, J. M. Napp, S. A. Salo, J. D. Schumacher, P. J. Stabeno, D. A. Stockwell, T. E. Whittedge, and S. I. Zeeman

For more information, contact G. L. Hunt Jr., Department of Ecology and Evolutionary Biology, University of California at Irvine, CA 92697 USA; E-mail: glhunt@uci.edu

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FALL MEETING PREVIEW

AGU Session Explores Digital Earth and Digital Libraries for Earth System Education

PAGES 561-562

Imagine hyperlinking on your personal computer's Internet connection to delve into an interoperable, global mosaic of geospatial information systems that spouts seamless fountains of data from what otherwise might be a crazy quilt of sources: geoscientific studies, Earth and space-based monitoring instruments, local zoning details, and other geodata relating to the past, present, or future.

Imagine, too, the educational opportunities and social implications when this data is manipulated. Perhaps this digital system could help predict climate change, improve community planning, increase agricultural productivity, conduct emergency rescue missions, facilitate virtual diplomacy, or even help to plan a vacation.

It would be a kind of "digital library of Earth information" or maybe a more encompassing "Digital Earth": frameworks for geo-referenced data as well as intriguing models for helping to better understand the complex nature of Earth systems—including the atmosphere,

hydrosphere, biosphere, and solid Earth—and their interactions.

With the convergence of advances in the geosciences and observational and information technologies, a growing group of educators, computer experts, and policy makers is pursuing the goal of a national digital library for science education and a Digital Earth. Along the way to creating these models, the visionaries, bureaucrats, and technocrats are also trying to work through some technological and cultural issues such as ensuring interoperability between data systems, access, privacy, and e-commerce.

The upcoming AGU Fall Meeting in San Francisco, California, features a session on "digital libraries for Earth system education."

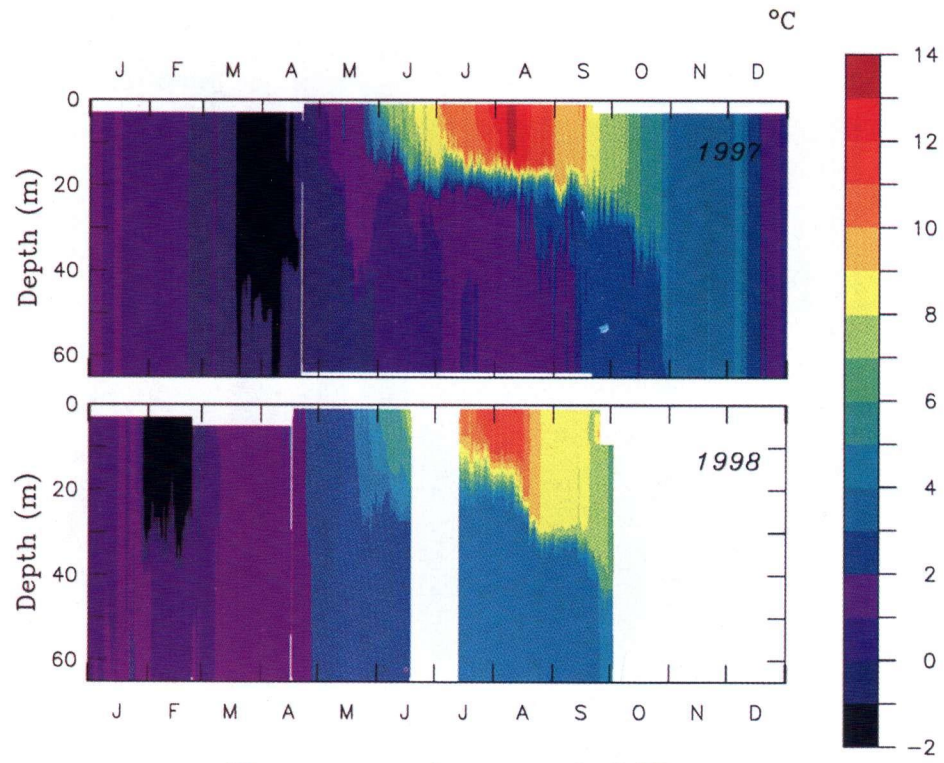
Creating a Digital Earth is also the topic of a series of meetings of the ad hoc U.S. Federal Digital Earth Interagency Working Group—which includes NASA, the U.S. Geological Survey (USGS), the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), and other agencies.

At a November 10 strategic planning session at USGS headquarters in Reston, Virginia, the group discussed a smorgasbord of projects already underway and possibilities related to developing a Digital Earth. Those presenting updates on their efforts included experts from federal agencies and from public and private organizations.

Dan Dubno, a producer with CBS News, urged the group to integrate the news media in developing a Digital Earth, in part because the media is where so many people turn to for their information. Dubno said media concerns about a Digital Earth include the reliability of information, freedom of the press issues about access to uncensored geospatial data, and the need for experts to help interpret the material. "You are storytellers," he told the group. "You are going to have to contextualize this."

Jay Feuquay of the USGS Earth Resources Observation Systems (EROS) Data Center in South Dakota, which archives images from a number of satellites including Landsat 7, approaches the Digital Earth concept from the perspective of a data provider. "I am looking for Digital Earth to solve my problem," he said. "I have a satellite beaming down a terabyte-and-a-half of information every week. I need to get it out to people. I need to make it available."

Joel Halvorson of the Science Museum of Minnesota added that he muses about Digital Earth concepts constantly from his center's new site on the banks of the Mississippi. "We will be involved" with creating a Digital



Temperature at M2

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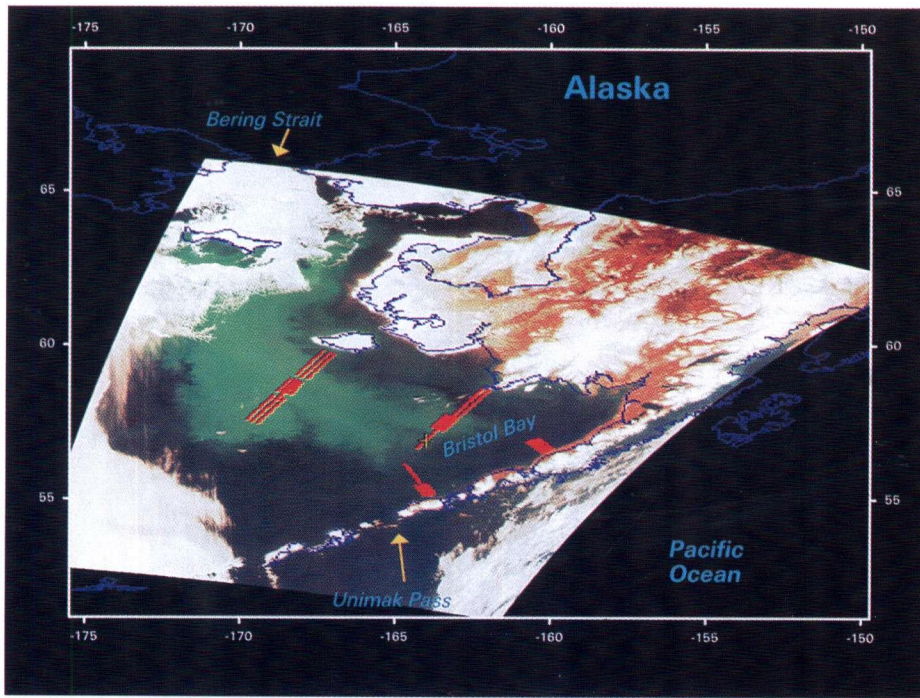


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