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Is the Climate of the Bering Sea Warming and Affecting the Ecosystem?

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Observations from the Bering Sea are good indicators of decadal shifts in climate, as the Bering is a transition region between the cold, dry Arctic air mass to the north, and the moist, relatively warm maritime air mass to the south. The Bering Sea is also a transition region between Arctic and sub-Arctic ecosystems; this boundary can be loosely identified with the extent of winter sea-ice cover.

Like a similar transition zone in the eastern North Atlantic [*Beaugrand et al.*, 2002], the Bering Sea is experiencing a northward bio-geographical shift in response to changing temperature and atmospheric forcing. If this shift continues over the next decade, it will have major impacts on commercial and sub-sistence harvests as Arctic species are displaced by sub-Arctic species. The stakes are enormous, as this rich and diverse ecosystem currently provides 47% of the U.S. fishery production by weight, and is home to 80% of the U.S. sea bird population, 95% of northern fur seals, and major populations of Steller sea lions, walrus, and whales.

A biophysical oceanographic mooring (M2) that has been maintained since 1995 at a depth of ~70 m provides insight into the shifting temperatures on the southeastern Bering Sea continental shelf. Depth-averaged temperatures for 15 July to 15 September are warmer by 2°C for the mean of 2001-2003 compared with the mean of 1995-1997 (Figure 1; location chart in Figure 2). Note the warm temperatures at the beginning of April for 1998, 2001, and 2003. In contrast to the coldest years, these recent warm ocean temperatures could result in a two-fold or greater difference in zooplankton production [*Hunt and Stabeno*, 2002], as well as direct physiological impacts on upper trophic level species.

The climate record for the Bering Sea can be extended using surface air temperature (SAT) from St. Paul Island (Figure 2, left) and sea-ice observations (Figure 2, right). Monthly SAT anomalies are computed using a 1961-1990

base period. The primary pattern is a transition in 1976 from predominantly cold anomalies (blues) to warm anomalies (yellow-red). The period 1971-1976 was cold from January through September, with the largest anomalies (<-6°) occurring in February and March. This is followed by a warm period (1977-1981) with anomalies (> 4°) occurring from January through April. Also apparent is that 1976 marked a transition to warmer summers (May-August) for virtually all years after 1976. Beginning in 1996, spring consistently arrives earlier, as evident in warm April SAT anomalies, although several earlier springs were also warm: 1989, 1990, and 1993. Starting in 2000, warm anomalies generally extend from February through November.

Several shifts are evident in ice concentration. Percent ice cover is calculated for a 1° rectangle of latitude (57°–58°N; Figure 2, lower right); data are from National Ice Center and National Weather Service Alaska region ice charts. The first shift (Figure 2, upper right) occurred in 1977, with a decrease in the mean number of days from 1971-1976 (130 days) to 1977-1989 (67 days) in which there was more than 5% ice cover after 1 January. A second marked decrease occurred in 2000 to almost an absence of sea ice in this latitude band. The presence of sea ice is directly related to the timing of the spring phytoplankton bloom. During years when ice is present near M2 after mid-March, there is an early, ice-associated phytoplankton bloom that consumes the available nutrients in the upper mixed layer. During years of no ice cover after mid-March, the spring phytoplankton bloom does not occur until May or June with the onset of insolation-driven upper layer stratification. Because maximum zooplankton growth is delayed until later in the season when ocean temperatures are warmer, primary production from an early ice-associated bloom generally falls to the bottom, supporting benthic
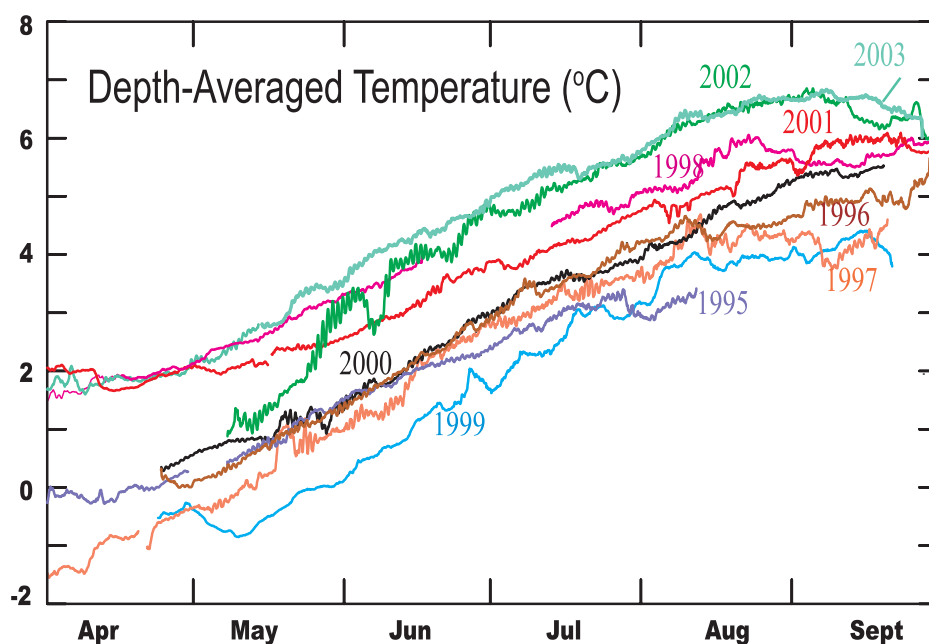

Fig. 1. The evolution of depth-averaged sea temperatures from an oceanographic mooring at site M2 (56.8°N, 164°W) for spring and summer in different years [Stabeno et al., 2002]. The previous 3 years (2001-2003) show consistently warm temperatures for 15 July to 15 September compared with 1995-1997; here 1995 temperatures for 15 August to 15 September are extrapolated. See Figure 2 for location map.

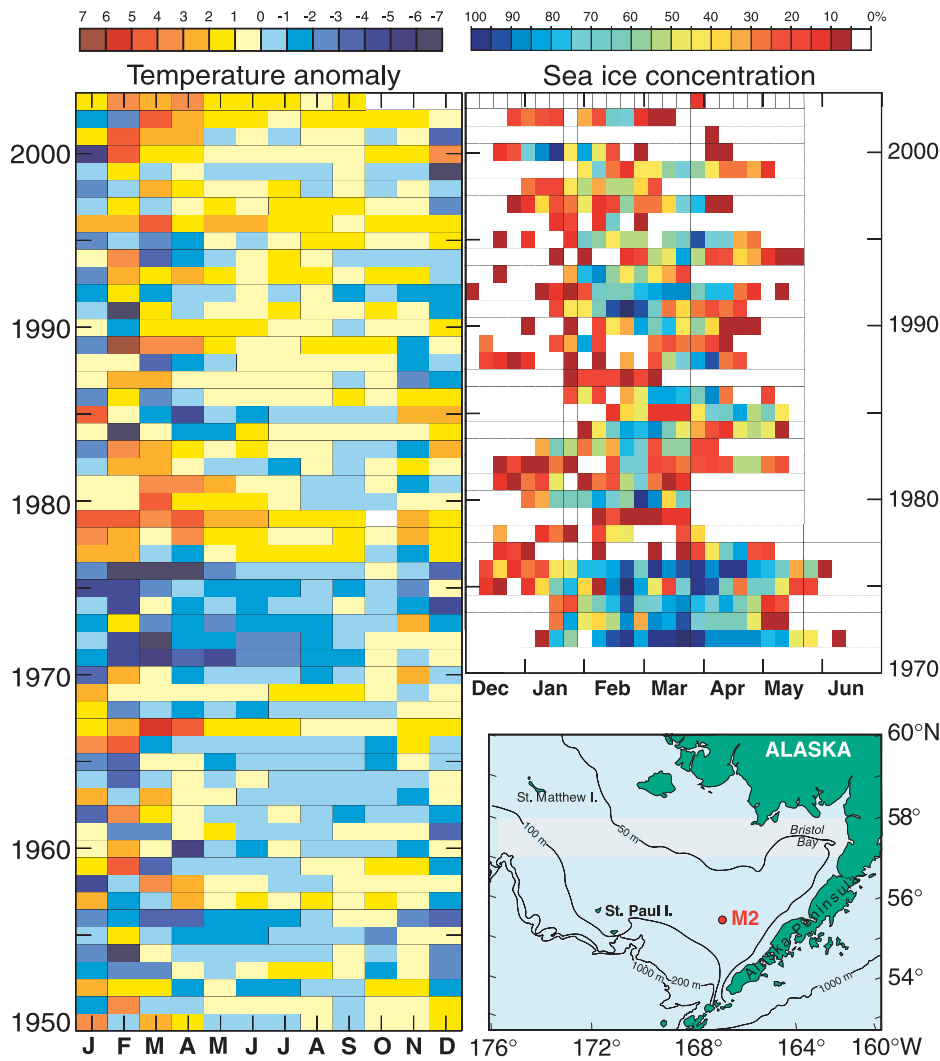BY JAMES E. OVERLAND AND PHYLLIS J. STABENO

Fig. 2. (Left) Monthly air temperature anomalies at St. Paul Island as a function of month and year. The base period is 1961-1990. Note the shift to warmer temperatures both after 1976 and for the previous 4 years. (Right) Concentration (% cover) of sea ice over the southeastern Bering Sea beween latitudes 57°N and 58°N. Location chart at lower right.
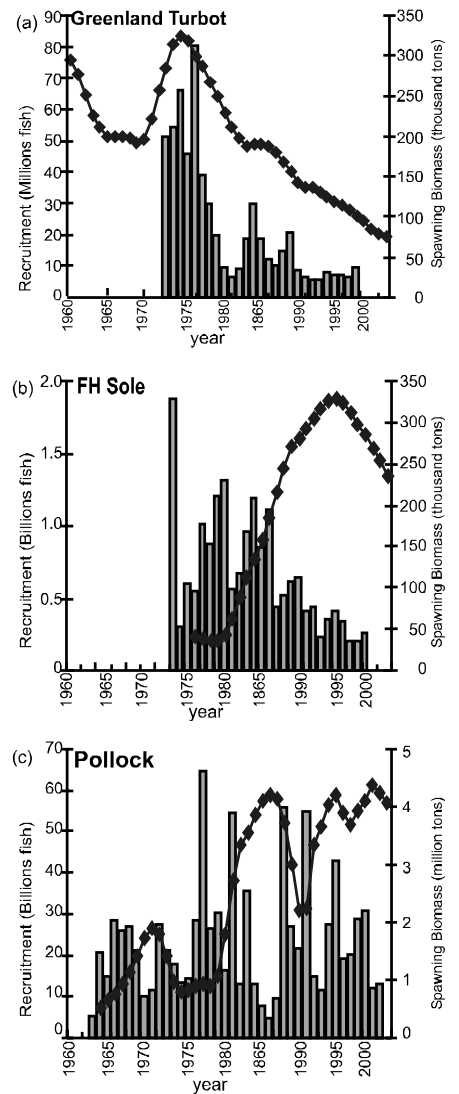

Fig. 3. Spawning biomass (diamonds) and recruitment (yearly addition in millions of fish to the stock) for representative Bering flatfish and gadids: Greenland turbot (Reinhardtius hippoglossoides), flathead sole (Hippoglossus elassodon), and walleye pollock (Theragra chalcogramma). Data are from the National Marine Fisheries Service net trawl surveys and recruitment models based on these observations [North Pacific Fishery Management Council, 2003].

communities, while a later bloom favors the pelagic ecosystem.

Ecosystem Reorganization

There is a preponderance of evidence that the ecosystem of the Bering Sea is shifting in response to a northward retreat of cold ocean temperatures. Annual fisheries surveys conducted on the southeastern Bering Sea shelf by the National Marine Fisheries Service track the status of major species in terms of estimated recruitment (addition of young fish to a stock) and spawning biomass [North Pacific Fishery Management Council, 2003]. Greenland turbot, a flatfish that prefers cold temperatures (1–3°C), had good recruitment in the cold years before 1977 (Figure 3a), but spawning biomass has decreased steadily since the mid-1970s; its current level is 18% of its pre-1977 maximum. Other flatfish, such as arrowtooth flounder, rock sole, and flathead sole (Figure 3b), all had above-average recruitment in the 1980s based on favorable larval drift [Wilderbuer et al., 2002], but have had decreasing spawning biomass

since the mid-1990s. In 2003, these primarily benthic flatfish make up 26% of the total groundfish of the Bering Sea [North Pacific Fishery Management Council, 2003]. The more pelagic walleye pollock, which currently accounts for 56% of the groundfish biomass, increased nearly 400% after 1978 (Figure 3c).

The last decade is characterized as having rather stable, high pollock biomass and low recruitment per spawning fish. The spawning biomass of Pacific cod, the other major pelagic groundfish, declined in the late 1980s and 1990s, but has increased in 2000-2003. One caveat for these trends is that the survey area is limited north of 60°N; declining numbers could indicate a northward shift rather than an absolute decrease in population. Other decadal changes are a decrease in snow crab in their southern range from 1990 to 2002 [Otto and Stevens, 2003], a northward shift in the feeding grounds of walrus due to thinner ice in the southern Bering Sea [Kelly, 2001], and a northward shift in grey whale feeding grounds to north of the Bering Strait [Moore et al., 2003]. Typical Bering Sea species, such as salmon and horned

puffins, are now reported on the Arctic coast of Alaska (G. Divoky, personal communication, 2004).

The sensitivity of pollock to ocean temperature is illustrated in Figure 4. For 6 of the 7 previous years (including 2003), the survey area had bottom temperatures in excess of 2°C; pollock concentration based on catch per unit effort (CPUE, in units of tons per hectare swept with fishing trawl nets) was high throughout the southeast Bering Sea [Ianelli, 2003]. In contrast, during 1999—a cold summer—pollock were limited to regions south of the 0°C isotherm. Continued warm conditions in the Bering would likely favor pollock.

At St. Paul, the warmest temperatures in the last half of the twentieth century occurred during the last 2 decades (Figure 2).
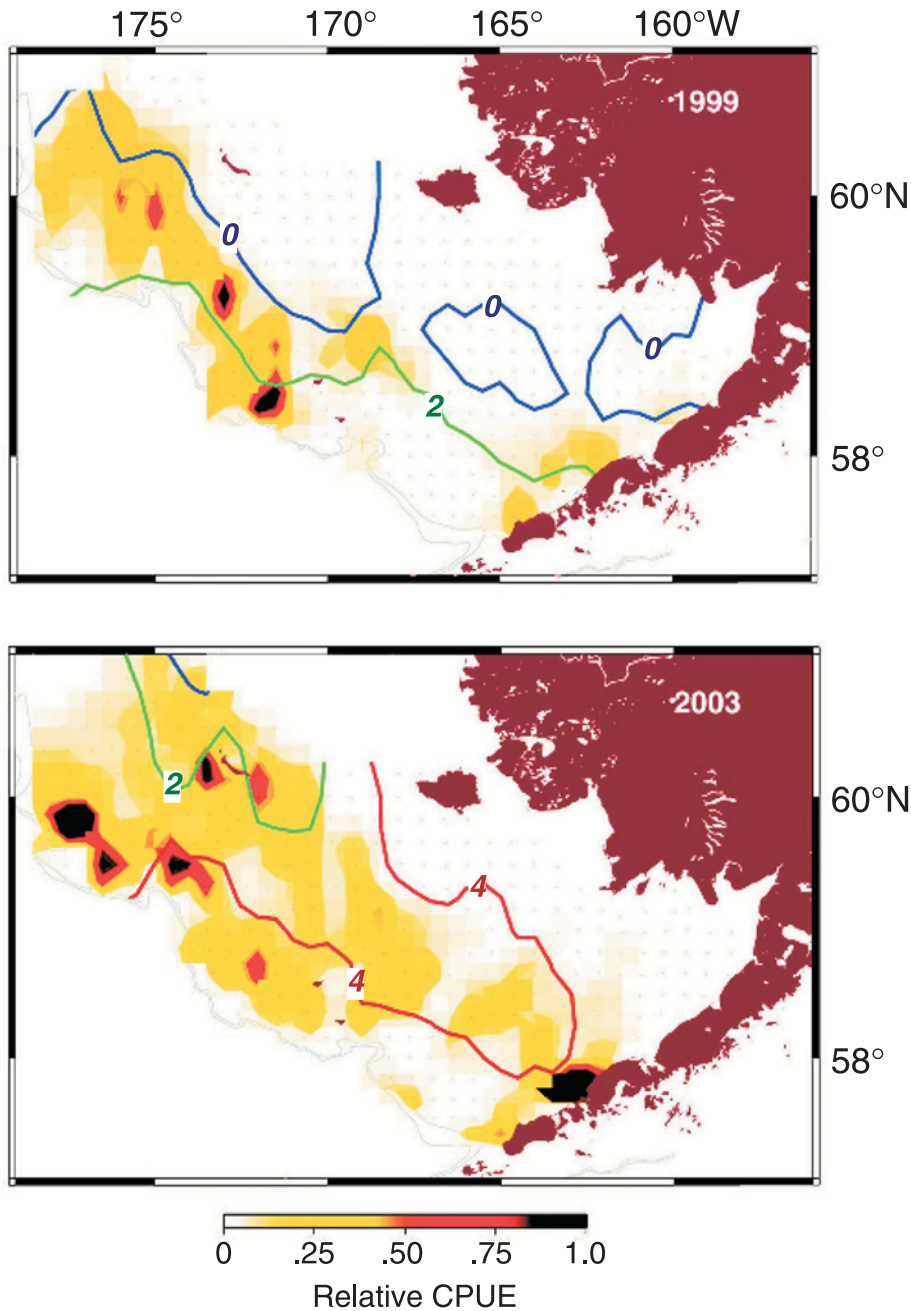
Fig. 4. Bottom temperatures and walleye pollock catch per unit effort (tons/hectare) observed during the 1999 and 2003 National Marine Fisheries Service bottom trawl survey [after Ianelli, 2003]. The geographic range of pollock was limited in years with cold bottom temperatures on the Bering Sea shelf.

The complete St. Paul air temperature record shows cool temperatures from 1917 to 1976, except for a brief warm interval in the 1930s. Tree-ring records from the Seward Peninsula show that warm season temperatures in the nineteenth century were colder than those of the twentieth [D'Arrigo et al., 2004]. These records suggest that cold air masses have been dominant for almost two centuries over the Bering Sea; hence, Arctic-adapted, long-lived species such as rockfish/flatfish and marine mammals should have predominated. During the 1950s to 1970s, there was large-scale exploitation of shelf flatfishes, slope rockfishes, and whales by non-U.S. fisheries [National Research Council, 1996], although historical fisheries data are limited. A decline of these species could have increased the availability of lower trophic level prey, and together with an expanded geographic range of warm bottom temperatures and other climate changes after 1976, may have allowed pollock, an opportunistic species, to become the dominant fish species biomass (>50%) in the Bering Sea. The ecological literature refers to this shift as a transition from "K-select" species associated with long-term stability to "r-select" species associated with rapid colonization [Francis et al., 1999]. There are additional factors besides direct temperature that support the biological shift in the recent decades. As previously mentioned, earlier ice retreat promotes a later spring phytoplankton bloom and increased coupling to the developing zooplankton; thus, much of the production remains in the pelagic system. This later bloom supports pollock at the expense of more benthic species [Palmer, 2003].

The change in the climate of the Bering Sea after 1976 was part of a larger North Pacific shift, with lower sea level pressures in the winter Aleutian low, and a switch to the positive phase of the Pacific Decadal Oscillation (PDO) with warmer sea temperatures along the west coast of the United States. An additional mode of climate variability influencing the Bering Sea is the Arctic Oscillation (AO), which contributed in the early and mid-1990s through a weakening of the Aleutian low and warmer air temperatures in early spring [Stabeno and Overland, 2001]. The conceptual model for PDO and AO often associates changes with rapid shifts between two quasi-stable states.

Although Bering Sea environmental data show some of these rapid shifts, the main characteristic of the last 4 years is a year-to-year persistence in lack of sea ice, warm bottom temperatures, and warm air temperature anomalies in late winter through summer, even though the AO and PDO have shown large interannual variability. Unlike the conceptual model of climate modes which would postulate that the next change in the Bering Sea would be a rapid transition to a previous cold state, the Bering Sea is behaving more like other high-latitude systems with multi-decadal trends; for example, tundra area and Arctic sea ice extent have decreased by 15% since the early 1980s [Overland et al., 2004]. Indeed the eastern North Pacific shifted after 1998 to conditions similar to those occurring before 1976, but the northern North Pacific, Bering Sea, and Sea of Okhotsk have not returned to a pre-1976 state, as would have been predicted from a PDO shift [Bond et al., 2003].

With the transition toward less ice cover for most years since the early 1990s and the 3 sequential years (2001-2003) of warm Bering Sea ocean temperatures, no strong argument is seen against a possible continued northward trend in the location of the cold water curtain in the Bering Sea, and thus the predominance of pollock and a worsening environment for Arctic K-select species. Bering Sea indicators should be watched closely over the next 5 years to confirm or reject this hypothesis.

References

Beaugrand, G., P.C. Reid, F. Ibañez, J. Alistair Lindley, and M. Edwards (2002), Reorganization of North Atlantic marine copepod biodiversity and climate, *Science, 296*, 1692–1694.

Bond, N.A., J.E. Overland, M. Spillane, and P. Stabeno (2003), Recent shifts in the state of the North Pacific, *Geophys. Res. Lett., 30*, 2183, doi:10.1029/2003GL018597.

D'Arrigo, R., E. Mashig, D. Frank, G. Jacoby, and R. Wilson (2004), Reconstructed warm season temperatures for Nome, Seward Peninsula, Alaska, *Geophys. Res. Lett., 31*, L09202, doi:10.1029/2004GL019756.

Francis, R.C., K. Aydin, R. L. Merrik, and S. Bollens (1999), *Modeling and management of the Bering Sea ecosystem in Dynamics of the Bering Sea*, edited by T. Loughlin and K. Ohtani, pp. 409–433, Univ. of Alaska Sea Grant, Fairbanks.

Hunt, G.L., Jr., and P.J. Stabeno (2002), Climate change and the control of energy flow in the southeastern Bering Sea, *Prog. Oceanogr., 55*, 5–22.

Ianelli, J. (2003), *SAFE Report, Appendix A*, p. 95, North Pacific Fishery Management Council, Anchorage, Alaska.

Kelly, B. P. (2001), Climate change and ice breeding pinnipeds, in *"Fingerprints" of Climate Change: Adapted Behavior and Shifting Species' Ranges*, edited by G.-R. Walther et al., pp. 43–55, Kluwer Academic/Plenum Publishers, Dordrecht.

Moore, S. E., J. M. Grebmeier, and J. R. Davies (2003), Gray whale distribution relative to forage habitat in the northern Bering Sea: Current conditions and retrospective summary, *Can. J. Zool., 81*, doi:10.1139/Z03-043, 734–742.

National Research Council (1996), *The Bering Sea Ecosystem*, 307 pp., National Academy Press, Washington D.C.

North Pacific Fishery Management Council (2003), *SAFE Report, Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands regions*, 846 pp., Anchorage, Alaska.

Otto, R., and B. Stevens (2003), *SAFE Report Appendix C*, pp. 180-181, North Pacific Fishery Management Council, Anchorage, Alaska.

Overland, J. E., M. C. Spillane, and N. N. Soreide (2004), Integrated analysis of physical and biological pan-Arctic change, *Clim. Change, 63*, 291–322.

Palmer, M. C. (2003), *SAFE Report Appendix C*, pp. 133–137, North Pacific Fishery Management Council, Anchorage, Alaska.

Stabeno, P.J., and J. E. Overland (2001), Bering Sea shifts toward an earlier spring transition, *Eos, Trans., AGU, 82*, 317, 321.

Stabeno, P.J., N. B. Kachel, M. Sullivan, and T. E. Whitledge (2002), Variability of physical and chemical characteristics along the 70-m isobath of the southeastern Bering Sea, *Deep-Sea Res. II, 49*, 5931–5943.

Wilderbuer, T. K., A. B. Hollowed, W. J. Ingraham Jr., P.D. Spencer, M. E. Conners, N.A. Bond, and G. E. Walters (2002), Flatfish recruitment response to decadal climatic variability and ocean conditions in the eastern Bering Sea, *Prog. Oceanogr., 55*, 235–247.

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Synoptic Monitoring of Water's Return to Mesopotamian Marshlands

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The Mesopotamian Marshlands are a recorded element of Sumerian culture since 5000 B.C. [*Thesiger*, 1964], and have withstood multiple impacts over the centuries until the twentieth century development of dams on the Tigris-Euphrates systems and greater water demand in Turkey, Syria, and Iraq [*Gruen*, 2000] increased their vulnerability to human impact. Devastation of > 90% of ~20,000 km² of the marshlands [*Partow*, 2001] occurred over a remarkably short period of time near the end of the twentieth century, when the majority of the area was drained beginning in 1991.

The late twentieth century barren landscape showed little hope of a return to its aquatic character until a 2003 military strategy, implemented March through May, resulted in return of water to areas that had not been inundated for >10 years. Ali Shaheen, chief of the Iraqi Irrigation Department in Nasiriyah, reported that the tactic of flooding the marshes was designed to interfere with military advances from the south [*Dixon*, 2003].

Dramatic changes in this aquatic landscape are quantified using a newly-developed technique for mapping inundation based on data from the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) Terra and Aqua instruments. The analysis uses daily surface reflectance products to map open water and inundated vegetation with a statistical technique [*Mertes et al.*, 1993; *Mertes*, 1997] that decomposes the image data into relevant landscape components. Spectral mixture analysis [*Adams et al.*, 1995] relies on statistically significant gradients in image spectral data. The spectral gradient from open water to wet vegetation is pronounced for the wavelengths of bands 1 (620–670 nm) and 2 (841–876 nm) of MODIS. The constraint on analysis for MODIS is the 250-m grain size of the pixels. The error image is then used to delineate the boundary between open water and vegetated areas (a water mask; see Figure 1A) in order to quantitatively map (Figure 1B) these features at the spatial resolution of 250 m.

Analyses from 59 MODIS images for 2002, 2003, and 2004 through July are compared to Landsat data from six images spanning mid-1976 to mid-1977. The open-water data alone do not indicate the entire inundated marsh area. However, classification of open water from this technique yields the greatest certainty in classification accuracy. The six Landsat data points demonstrate the climate-driven pattern of hydrology that shows the maximum extent of open water (high water) in April–May of 1977. The impact of managed releases from newly constructed dams on the Tigris-Euphrates systems was to shift maximum flow to mid-February [*Partow*, 2001]. These managed, earlier "floods" can be observed as slight increases in open water during February of 2002 and 2003.

The areal cover of open water in 1976–1977 is 6 times greater (~3000 km²) than the areal cover of open water (<500 km²) recorded in February of 2002 and 2003. The military releases from mid-March 2003 through early May 2003 resulted in a tripling of the area of open water (~1500 km²). At this same time, the first journalistic reports appeared [e.g., *Dixon*, 2003] documenting the return of residents to their former marsh settlements. From May 2003 until the end of 2003, the pattern of releases is inconsistent. Then, at the end of 2003, the open-water area dramatically increases, resulting in an aquatic landscape that includes a comparable amount of open water (2000– 3000 km²) as was estimated for 1976–1977. Although the areal cover of open water in 2004 is similar to that of 1976–1977, the landscape pattern of open water is unmistakably altered due to the drainage engineering.

Therefore, while marshland recovery would not be possible without the water's return, restoration is not merely a function of returning water. Use of these MODIS monitoring tools (Web site: http://www.geog.ucsb.edu/%7Erivers/as/mesomarsh-web/) can facilitate the recovery of these marshlands to a semblance of their former ecological health by providing the international community with a synoptic view of the recovery and fostering momentum toward an intentional restoration.