Overview

(continued from page 5)

from about 70 countries to define a 20-year environmental and developmental agenda for the natural, social, engineering, and health sciences. The conference was organized into three sections dealing with the problems of environment and development; scientific understanding of the Earth system; and the contributions of science to environmental and developmental strategies. Although the conferees developed many strong specific recommendations, the conference statement's executive summary distilled their work into the following:

The participants at ASCEND 21 stressed a new commitment on the part of the international scientific community as a whole to work together so that improved and expanded scientific research and the systematic assessment of scientific results, combined with a prediction of impacts, would enable environmental and developmental policy options to be evaluated on the basis of sound scientific facts. Furthermore, the participants forcefully asserted the responsibility of science to provide independent explanations of their findings to individuals, organizations, and governments. In this context, ASCEND 21 underlined the central importance of the precautionary principle, according to which any disturbances of an inadequately understood system as complex as the Earth system should be avoided.

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Members of the scientific community participating in ASCEND 21 also agreed on the nature of the major problems that affect the environment and hinder sustainable development, and they identified a number of specific areas through which the scientific community could begin to tackle those problems they consider to be of the highest scientific priority: population and per-capita resource consumption; depletion of agricultural and land resources; inequity and poverty; climate change; loss of biological diversity; industrialization and waste; water scarcity; and energy consumption. To tackle these problems, the ASCEND 21 participants recommended

- intensified research into natural and anthropogenic forces and their interrelationships, including the carrying capacity of the Earth and ways to slow population growth and reduce overconsumption;
- strengthened support for international global environmental research and observation of the total Earth system;
- research and studies at the local and regional scales on the hydrological cycle, the impacts of climate change, coastal zones, the loss of biodiversity, the vulnerability of fragile ecosystems, and the impacts of changing land use, waste, and human attitudes and behavior;
- research on the transition to a more efficient energy supply and more efficient use of materials and natural resources;
- special efforts in education and in building up scientific institutions, as well as involvement of a wide segment of the population in environmental and developmental problem solving;
- regular appraisals of the most urgent problems of the environment and development and communication about these problems with policymakers, the media, and the public;
- establishment of a forum to link scientists and development agencies and a strengthened partnership with organizations charged with addressing problems of environment and development; and
- a wide review of environmental ethics.

The conference statements from which these recommendations were excerpted are available from

Sigma Xi, The Scientific Research Society
99 Alexander Drive
P.O. Box 13975
Research Triangle Park, N.C. 27709
USA
(telephone: 1-919-549-4691)

and from

ICSU Secretariat
51, bld de Montmorency
75016 Paris
FRANCE
(telephone: 33-1-45-25-03-29).

CLIMATE

Growing Halophytes to Remove Carbon from the Atmosphere

Edward P. Glenn, Carl N. Hodges, Helmut Lieth, Roger Pielke, and Louis Pitelka

One of the few viable options for mitigating carbon dioxide (CO_2) accumulation in the atmosphere from burning fossil fuels is the assimilation and sequestering of carbon into biomass. Two recent strategies that have received considerable attention involve planting new forests on currently unforested land and enhancing the growth of phytoplankton in the oceans.[1] One problem with reforestation is that much of the same land required to grow trees (from 200 million to 500 million hectares) may be needed for food production and other uses as the world's population continues to grow. A second problem is that forests can continue to store carbon only if the biomass is periodically harvested and the forests replanted. Moreover, the harvested biomass must be permanently stored so that the carbon is not returned to the atmosphere as a result of decomposition.[2] The potential for sequestering carbon in marine phytoplankton remains uncertain because the factors that currently limit phytoplankton reproduction are not completely understood by scientists. In addition, the extent to which dead phytoplankton would sink to the ocean floor without decomposing and releasing the carbon back to the air remains uncertain.

An alternative approach for removing atmospheric CO_2 that has received less attention involves increasing the productivity of desert areas. Deserts are currently underexploited for both biomass and food production and could act as biospheric sinks for carbon given novel water sources

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to enhance the productivity of adapted plants. For example, scientists have been investigating the feasibility of growing wild, salt-tolerant plants, or halophytes, to sequester carbon on desert lands. The land resources available for halophyte plantations include coastal deserts, inland saline basins, and regions of secondary salinization in arid-zone irrigation districts. Globally, these regions occupy areas of 294 million, 427 million, and 65 million hectares, respectively.[3] In many important respects, the case for planting halophytes in the desert compares favorably to the case that has already been made for reforestation.

Field experiments have recently been conducted by the authors using seawater and brackish water to grow halophytes in the deserts of Saudi Arabia, the United Arab Emirates, and Mexico.[4] The authors used ground-based data supplemented by visits to the experiment sites to estimate potentially usable land for halophyte plantations in 36 coastal deserts, 19 saline basins, and 9 arid-zone irrigation regions.[5] To be considered usable for halophyte plantation, coastal desert land had to be at an elevation below 100 meters to facilitate pumping of seawater; to have level topography to facilitate irrigation; to have suitable soil substrate; to have low natural productivity; and to be presently unused for development or agriculture. Inland saline areas also were considered under the same constraints with two exceptions: Elevation above sea level was not considered important, and the amount of surface or groundwater for irrigation was considered to be a limiting factor.

Unlike coastal deserts, for which the sea serves as an unlimited irrigation source, inland saline basins have a finite internal irrigation supply. The amount of land that can be irrigated from internal sources depends on the rainfall, the area of drainage, and the amount of saline water already stored in the basin. In most cases, these quantities are not accurately known. However, the authors assumed that areas with permanently water-logged soil could be used for halophyte plantations after the installation of irrigation and drainage systems. (In the Caspian Sea region, however, the water supply was considered to be unlimited based on the area of salinized seashore that could be irrigated directly from the sea.) The area available for halophyte plantations within or adjacent to desert irrigation districts was determined to be limited by the amount of saline drainage water that can be generated within the districts to irrigate the plants. Also, it was assumed that an additional area equivalent to 20 percent of existing arid irrigation districts could be planted with halophytes using that water source.[6] Moreover, in less efficient irrigation districts around the world, as much as 40 percent of the irrigated land has become salinized and could be used to grow halophytes.[7]

The area of usable coastal desert land was estimated to be 49.5 million hectares. The largest of these areas, the Ranns of Kutch in northeast India and southeast Pakistan, are vast coastal plains consisting of barren, salinized soil. Other large areas include the salt deserts of the lower Indus River in Pakistan and the extensive *sabkha* (salt) flats along the Persian Gulf and Sea of Oman. The area of usable inland desert was estimated to be 61.6 million hectares, and the saline soils of the Caspian and Aral seas and the Lake Eyre basin in Australia are the largest such areas. An additional 13.0 million hectares of land in or adjacent to arid irrigation districts were estimated to be usable. These amounts are significant both in terms of the land area that is considered necessary to mitigate carbon accumulation and in comparison to estimates of the land areas available for reforestation. (Studies have indicated that land availability for reforestation is a major problem.)

Of the world's coastal desert and inland saline land, 15.4 percent was estimated to be usable for planting halophytes. It is impossible to verify the accuracy of the individual area estimates without detailed site surveys, but the aggregate estimate appears to be conservative in comparison with other estimates of this sort. For example, an estimated 22.5 percent of the world's arid regions have no inherent soil constraints for growing crops except lack of water.[8] Furthermore, 65 million hectares of desert are already under irrigation, representing just 2 percent of the total desert land.[9] Therefore, it appears conservative to conclude that, if water were available to more desert areas, the amount of desert land under irrigation could triple. The authors' estimate is lower than that made by in-country experts of the amount of saline land suitable for rangelands improvement (150 million hectares) using halophytes in just 20 countries.[10]

All of the land areas considered usable are classified as arid or extremely arid desert in terms of their climate and vegetation, and most had hot temperatures. The majority of desert soils are already salinized but can be reclaimed for use in conventional agriculture if nonsaline water is available for leaching salts. However, extensive subsurface drainage systems may be needed to reduce salt levels to those tolerated by conventional crops, as is done in the Nile Delta.[11] On the other hand, halophytic vegetation often appears early in the reclamation process of such soils—even before surface drainage is installed—and is considered a valuable step toward reclaiming the land for conventional crops because of its beneficial effects on soil properties.[12]

One problem with reforestation is that much of the same land required to grow trees may be needed for food production and other uses as the world's population continues to grow.

High rates of biomass production are necessary for efficient carbon sequestration. The productivity of halophytes has been reported for a number of species grown in field trials using brackish water and seawater at different locations and in different soil types (see Table 1 on page 42). Annual biomass yields of the best performing species have ranged from 9 to 20 tonnes per hectare over a wide range of soil, water, and climatic conditions. For example, the annual rate of carbon storage by the oilseed halophyte *Salicornia bigelovii*, whose straw (at 25-percent carbon content) would be used for carbon storage and seeds for food, is 3.2 to 6.2 tonnes per hectare. (The annual rate for tree plantations and other biomass crops is 5 tonnes per hectare.[13]) If the usable world area were planted with halophytes with a net productivity of 5 tonnes of carbon per year, the total carbon accumulation would be 0.6 billion tonnes per year, which equals approximately 10 percent of all fossil fuel carbon releases and 20 percent of the carbon burden that remains in the atmosphere. Thus, halophytes, like trees, could play a significant role in an overall biomass strategy for climate change mitigation, but they could not be used alone to solve the problem.

The usefulness of halophytes will depend on how their costs and benefits compare to those of other biomass crops. Although the costs of halophyte carbon production are site-specific, they are driven in part by the expense of irrigation. Halophytes grown with brackish water, for instance, have approximately the same irrigation requirement as have conventional crops grown in a similar climate. However, halophytes grown with seawater have a greater irrigation requirement because they need more water to control salt levels in the root zone. Using typical U.S. farming costs, the scientists estimated the production costs of *Salicornia bigelovii* from the initial land preparation, prorated over 10 years, to the annual harvesting, baling, and delivery of the biomass to the edge of the field.[14] The cost estimates were \$44 and \$53 per dry tonne of biomass (\$175 and \$211 per tonne of carbon) for brackish water and seawater irrigation, respectively. By comparison, other high-productivity energy crops are estimated to cost between \$30 and \$45 per dry tonne.[15] Hence, the cost of halophyte biomass would be somewhat higher than that of other forms of biomass, but not prohibitively so. However, halophytes can be grown on land that has not been forested or farmed, whereas other biomass crops must be grown on arable land.

The carbon emissions produced by fossil fuel-burning pumps and farm equipment that are used to grow halophytes add an additional "cost." If the energy is assumed to be supplied by diesel fuel containing 85 percent carbon, then the fossil fuel carbon needed to grow, harvest, bale, and deliver a tonne of halophyte carbon to the edge of the field is approximately 225 kilograms in a brackish water halophyte plantation and 300 kilograms in a seawater plantation. Other cellulosic biomass crops, which are less dependent on irrigation, require from 130 to 180 kilograms per tonne of carbon, while corn grown as an energy crop requires from 330 to 970 kilograms per tonne.[16]

There remains the question of what to do with the biomass once it is produced. Removing CO_2 from the atmosphere requires the use of biomass with a long carbon storage lifetime, such as wood, peat, or biomass deposited in deep-sea or wet sediments. CO_2 incorporated into biomass for food and fodder has a residence time of only one to two years and is of no value for atmospheric CO_2 reduction. Therefore, halophyte biomass must be either stabilized for long-term storage or used as a replacement for fossil fuels to make a direct contribution to removing CO_2 from the atmosphere. Halophyte biomass has about the same heating value as lignite B coal and could be a useful fuel.[17]

Additionally, growing halophytes for food and fodder crops could make an indirect contribution to atmospheric carbon mitigation by reducing the need for deforestation to create new cropland. Estimates of how much new cropland will be needed to support the world population that is expected to exist in 75 years are on the order of 200 million hectares, most of which must come from the remaining undisturbed tropical forests or from forest fallow if conventional crops are to be grown.[18] But if the 124 million hectares of available saline land identified by the scientists were planted with halophytes to produce such products as animal feed and vegetable oil suitable for human consumption,[19] the existing forest land could be spared, leaving the stored carbon in the standing crop of trees rather than releasing it into the atmosphere by land clearing.

Mangrove plantations offer a special case for carbon storage in halophyte tissues. Because they are extremely long lived, mangroves can be used as a more permanent form of carbon storage than other halophytes. Mangroves once thrived in many coastal desert environments but have been eliminated by shoreline modifications. Replanting mangroves in these areas and extending mangrove habitats by irrigating new coastal land with seawater is one possibility for enhancing carbon storage. One species of mangrove in the Arabian Gulf, *Avicenia marina*, tolerates salinity levels as high as 4.5 percent and soil temperatures as high as 50°C.[20]

In any massive vegetation scheme, secondary effects must be evaluated carefully because they may cause environmental problems greater than those they are intended to solve. For instance, halophyte plantations may cause increased salinization of the soil as a result of inadequate drainage, reduction of biodiversity in planted areas, and eutrophication from fertilizer run-off into the sea. In general, the same problems that have occurred with conventional irrigation projects can also occur with halophyte plantations if the projects are not well planned and executed.

There are beneficial side effects of halophyte plantations, too. For example, halophytes can aid in revegetating bare coastlines that formerly supported estuarine and delta halophytes in arid regions. Also, it is possible that revegetated desert areas will experience enhanced rainfall and lower temperatures. Mesoscale cli-

TABLE 1
ANNUAL YIELDS OF HALOPHYTES IN FIELD TRIALS CONDUCTED BY THE ENVIRONMENTAL RESEARCH LABORATORY

Location and species	Yield (dry tonnes per hectare)	Soil type	Irrigation water salinity (grams per liter)
Safford, Arizona			
Atriplex lentiformis	14.7	loam	0.6
Atriplex nummularia	12.3	loam	0.6
San Joaquin, California			
Atriplex barclayana			
subspecies *sonorae*	11.1	clay	1.0
subspecies *barclayana*	9.2	clay	1.0
Tucson, Arizona			
Salicornia bigelovii	17.3	sand	1.0
Puerto Penasco, Mexico			
Atriplex lentiformis	17.9	sand	4.0
Batis maritima	17.4	sand	4.0
Atriplex canescens	17.2	sand	4.0
Salicornia bigelovii	15.4	sand	4.0
Kalba, United Arab Emirates			
Salicornia bigelovii	20.4	silt	4.0

SOURCES: M. C. Watson, J. W. O'Leary, and E. P. Glenn, "Evaluation of *Atriplex lentiformis* (torr.) S. Wats. and *Atriplex nummularia* Lindl. as Irrigated Forage Crops," *Journal of Arid Environments* 13 (1987):293–303; M. C. Watson, "*Atriplex* Species as Irrigated Forage Crops," *Agriculture, Ecosystems and Environment* 32 (1990):107–18; E. P. Glenn and J. W. O'Leary, "Productivity and Irrigation Requirements of Halophytes Grown with Sea Water in the Sonoran Desert," *Journal of Arid Environments* 9 (1985):81–91; E. P. Glenn et al., "*Salicornia bigelovii* Torr.: An Oilseed Halophyte for Seawater Irrigation," *Science* 251 (1991):1065–67; and C. Mota, *Kalba Farm Report, 1989* (Tucson, Ariz.: Planetary Design Corporation, 1989).

mate models of and observational data from arid and semi-arid regions show higher atmospheric moisture levels, lower temperatures, and, in some cases, increased convective rainfall in regions that are vegetated and irrigated, compared to those of barren areas.

In northeast Colorado, for instance, aircraft flying between irrigated and nonirrigated land have documented substantially cooler and moister air over the irrigated cropland.[21] Also, it has been shown that the atmosphere over a surface is substantially more favorable to the formation of large cumulus clouds than is that over adjacent natural short grassland.[22] Satellite imagery of surface temperatures indicates that the alteration of surface conditions through irrigation is a common occurrence and would be expected wherever halophytes are planted over sufficiently large areas. Furthermore, the establishment of open spaces between halophyte plantations could help focus convective rainfall by generating organized, thermally forced mesoscale circulations between the dry land surface and the wetter land.[23] Thus, in the most optimistic scenario, halophytes could improve the local climate in deserts where they are planted for the purpose of mitigating global climate change.

Scientists continue to investigate the possible benefits of halophyte plantations at the field stations. At Zayed International Farms in the United Arab Emirates, scientists are studying the production rates of mangroves and other halophytes under brackish water irrigation. Methods of carbon storage, such as the incorporation of biomass into desert soils, are under evaluation for several halophyte species at the sea water test plots in Puerto Penasco, Mexico. In Jubail, Saudi Arabia, scientists are evaluating methods of soil and water management to determine whether saline agriculture can be used as a sustainable commercial enterprise. Two proprietary, improved selections of oilseed *Salicornia* are grown at that location. Also, an experiment to reduce irrigation requirements is under way using center-pivot overhead irrigation instead of flood-irrigation. One of the goals of these field tests is to enlarge some of the plantings to up to 1,000 hectares or more to test the hypothesis of weather modification and to test the economics of seawater biomass production with halophytes.

NOTES

1. J. L. Kulp, *The Phytosphere as a Sink for CO_2* (Palo Alto, Calif.: Electric Power Research Institute, 1990); G. Marland, *The Prospect of Solving the CO_2 Problem Through Global Reforestation* (Washington, D.C.: U.S. Department of Energy, Office of Energy Research, 1988); R. A. Sedjo, "Forests: A Tool to Moderate Global Warming?" *Environment*, January/February 1989, 14; J. R. Trabalka et al., "Human Alterations of the Global Carbon Cycle and the Projected Future," in J. R. Trabalka, ed., *Atmospheric Carbon Dioxide and the Global Carbon Cycle* (Washington, D.C.: U.S. Department of Energy, 1985), 247–88; P. Vitousek, *Reforestation to Offset Carbon Dioxide Emissions* (Palo Alto, Calif.: Electric Power Research Institute, 1990); J. H. Martin, R. M. Gordon, and S. E. Fitzwater, "Iron in Antarctic Waters," *Nature* 345 (1990):156–58; and T. H. Peng and W. S. Broecker, "Dynamical Limitations on the Antarctic Iron Fertilization Strategy," *Nature* 349 (1991): 227–29.

2. For a full discussion of reforestation, see Sedjo, note 1 above.

3. P. Meigs, *Geography of Coastal Deserts* (Paris: United Nations Educational, Scientific and Cultural Organization, 1966); I. Szabolcs, *Salt-Affected Soils*, (Boca Raton, Fla.: CRC Press, 1989); and H. Fukuda, *Irrigation in the World: Comparative Developments* (Tokyo: University of Tokyo Press, 1976). Arid irrigation districts were considered to be those areas receiving less than 250 millimeters of precipitation annually.

4. The field experiments in Jubail, Saudi Arabia, are directed by C. N. Hodges of the University of Arizona, under the sponsorship of the Royal Commission of Saudi Arabia. The experiments in the United Arab Emirates are directed by A. Lieth of Zayed International Experimental Farms, Al Ain, United Arab Emirates, under the aegis of United Arab Emirates University, Desert and Marine Environment Research Center. The experiments in Puerto Penasco, Mexico, are directed by E. P. Glenn of the University of Arizona and sponsored by the Electric Power Research Institute. Further descriptions are in C. N. Hodges, "Environmental Technologies: Ordering Biological Development," *Journal of Social and Biological Structures* 13 (1990):83–92; E. P. Glenn et al., "*Salicornia bigelovii* (torr.): An Oilseed Halophyte for Seawater Irrigation," *Science* 251 (1991):1065–67; H. Lieth and H. Barth, "Untersuchungen uber die Moglichkeit zur Einrichtung von Mangrovenplfanzugen in Kustenwusten," *Verhandlungen der Gesellschaft fur Okologie (Festschrift Ellengerg)* 11 (1983):265–76; and E. P. Glenn, K. J. Kent, T. L. Thompson, and R. J. Frye, *Seaweeds and Halophytes to Remove Carbon from the Atmosphere* (Palo Alto, Calif.: Electric Power Research Institute, 1991).

5. Estimates were made from speciality maps of the regions. Elevation above sea level and areas of waterlogged soils in saline basins and along coasts were determined from the *World Map, 1: 2,500,000 Series* (Berlin: Department of Geodesy and Cartography, 1964). Slope classes and soil classifications were determined from *Soil Map of the World* (Paris: United Nations Educational, Scientific and Cultural Organization, 1974). Usable areas were slope class "a," level to gently undulating slope. For areas where a mixed slope class was given in *Soil Map of the World*, the percentage of flat land was estimated by subtracting out hill areas shown on the topographical maps. Areas of dunes, shifting sands, or stoney areas were considered unusable. Present land use and vegetation cover was determined from *World Atlas of Agriculture*, (Navaro, Italy: Istituto Geographico de Agostini, 1976). Other usable areas included those classified as nonagricultural or nonagricultural with rough grazing. Areas of higher agricultural use and areas of mangrove swamps were excluded. Areas of settlement were determined from *Time Atlas of the World* (New York: *Times Books*, 1980). Additional information on specific regions came from D. H. Amiran and A. W. Wilson, eds., *Coastal Deserts: Their Natural and Human Environments* (Tucson, Ariz.: University of Arizona Press, 1973); V. J. Chapman, *Salt Marshes and Salt Deserts of the World*, (Lehre, Germany: Springer-Verlag, 1974); A. Poljakoff-Mayber and A. Gale, eds., *Plants in Saline Environments*, (New York: Springer-Verlag, 1975); V. A. Demkin, I. V. Ivanov, and G. P. Maksimyuk, "Soils of the Northern Caspian Semi-Arid Zone and Their Changes Under Irrigation," *Problems of Desert Development* 4 (1986):9–17; M. Evanari, I. Noy-Meir, and D. W. Goodall, eds., *Ecosystems of the World: Hot Deserts and Arid Shrublands*, vols. 12A and 12B (Amsterdam: Elsevier, 1986). Site visits were made in the course of conducting field experiments and in collecting halophyte germplasm. For a list of individual desert areas and further references, see Glenn, Kent, Thompson, and Frye, note 4 above.

6. Glenn, Kent, Thompson, and Frye, note 4 above.

7. Szabolcs, note 3 above.

8. A. L. Hammond and M. E. Paden, *World Resources 1990–91* (New York: Oxford University Press, 1990), 287–90.

9. Fukuda, note 3 above; and W. G. McGinnies et al., eds., *Deserts of the World* (Tucson, Ariz.: University of Arizona Press, 1977).

10. E. G. Barrett-Lennard, C. V. Malcom, W. R. Stern, and S. M. Wilkens, eds., *Forage and Fuel Production from Salt Affected Wasteland* (New York: Elsevier, 1986).

11. J. H. Boumans and A. M. Mashali, "Seepage from Lake Burullus into the Reclaimed Mansour and Zawia Polder Area," *Agricultural Water Management* 7 (1983):411–24.

12. P. Wagret, *Polderlands* (London: Methuon, 1968); and B. Knights and A. J. Phillips, eds., *Estuarine and Coastal Land Reclamation and Water Storage* (Westmead, Great Britain: Saxon House, Teakfield, 1979).

13. Sedjo, note 1 above.

14. Irrigation rates and individual farm operations needed to grow *Salicornia bigelovii* were expressed in terms of energy and dollar costs using farm data for Yuma County, Arizona. S. Hathorn, D. R. Howell, B. Tickets, and J. C. Wade, *Arizona Field Crops Budget: Yuma County* (Tucson, Ariz.: University of Arizona, Department of Agricultural Economics, 1987). Growing costs in Mexico are much lower, whereas costs in the United Arab Emirates and Saudi Arabia are higher. Details of the farm operations and methods of calculations are in Glenn, Kent, Thompson, and Frye, note 4 above.

15. L. R. Lynd, J. H. Cushman, R. J. Nichols, and C. E. Wyman, "Fuel Ethanol from Cellulosic Biomass," *Science* 251 (1991):1318–23. The energy inputs were converted into carbon inputs by assuming that energy was supplied by diesel fuel.

16. Ibid.

17. Glenn, Kent, Thompson, and Frye, note 4 above.

18. P. A. Sanchez, D. E. Bundy, J. H. Villachica, and J. J. Nicholaides, "Amazon Basin Soils: Management for Continuous Crop Production," *Science* 216 (1982):821–27; and J. P. Lanly, *Tropical Forest Resources*, FAO forestry paper no. 30 (Rome: FAO, 1982).

19. Glenn et al., note 4 above.

20. Lieth and Barth, note 4 above.

21. M. Segal et al., "The Impact of Crop Areas in Northwest Colorado on Mid-Summer Mesoscale Thermal Circulations," *Monthly Weather Review* 117 (1989):809–25; and R. A. Pielke and R. Avissar, "Influence of Landscape Structure on Local and Regional Climate," *Landscape Ecology* 4(1990):133–35.

22. R. A. Pielke and X. Zeng, "Influence on Severe Storm Development of Irrigated Land," *National Weather Digest* 14 (1990):16–17.

23. H. Yan and R. A. Anthes, "The Effect of Variations in Surface Moisture on Mesoscale Circulations," *Monthly Weather Review* 116 (1988):192–208; and Z. Xian and R. A. Pielke, "The Effects of Width of Land Masses on the Development of Sea Breezes," *Journal of Applied Meteorology*, forthcoming.