High-Resolution Paleoclimate Records from Monsoon Asia

Studying high-resolution climate records of the past 2000 years has been identified as a high research priority by the IGBP PAGES program (International Geosphere-Biosphere Program Past Global Changes) [*Eddy*, 1992] as well as by the U.S. Global Change research community [*Bradley et al.*, 1991]. Monsoon Asia, particularly south and southeast Asia, has great potential for expanding our understanding of climatic fluctuations over the past 2 millennia. However, relatively little is known about climatic changes in that area over the last 2000 years. The lack of information is particularly significant because of the area's very large population and its vulnerability to climatic anomalies. At the same time, a real opportunity exists to document climatic changes in monsoon Asia by analyzing a number of types of high-resolution paleoclimatic record.

To address these issues, an international group of scientists met in Taipei, Taiwan, from April 21 to 23 to discuss the opportunities for research on high-resolution records of past climate in the monsoon Asia area. Primary objectives of the meeting were to develop a scientific plan for future research in the region, stimulate discussion of collaborative research projects, and encourage more research on climatic fluctuations of the last 2 millennia. Discussions focused on well-dated reconstructions at the annual to decadal scale (at best) or decadal to century scale where finer resolution is not realistically possible. For the purpose of the meeting, the boundaries of the region were defined very broadly, from India to the Philippines, and from Indonesia to China and Japan. The meeting was sponsored by the IGBP PAGES Program and was financially supported by the National Science Council, Taiwan, and the National Science Foundation. The workshop was hosted by Academia Sinica, Taiwan.

The meeting brought together scientists with a very wide range of disciplinary interests, including historical documents, tree rings, corals, ice cores, loess and other terrestrial sediments, and marine sediments. After short overviews of the current status of research in each field, participants divided into six topical working groups to set research priorities for each subject and make recommendations. The resulting document has been published as an IGBP PAGES report [*Bradley*, 1993]. Papers on the current state of research in the region will be published in a special issue of *Terrestrial, Atmospheric and Oceanic Research*.

Workshop Recommendations

Here we summarize the primary recommendations of the working groups, which provide a scientific plan for how future research in the region could make the most rapid progress if appropriate resources were made available. Further details are found in the workshop report of *Bradley* [1993].

Historical Records: Historical records can provide very high-frequency information extending back several centuries in many regions and up to 2 millennia in some areas, providing a link between sedimentary and biological proxy records and instrumental records. To date, most historical research has been carried out in China, Japan, and Korea, though there has been only a limited effort to standardize the procedures concerned with converting historical records to climatic estimates and preparing the records in a computer-readable format. There appears to be good potential for similar studies in India, which could yield long records of major droughts, floods, cyclones, and the arrival of monsoon rains. Since the region has a long history of European colonial occupation, many records from this period reside in European archives, yet there has been no systematic evaluation of these sources for historical paleoclimatology. The International Council of Archivists, in collaboration with the World Meteorological Organization, currently is engaged in a survey of such records in major European archives, and further studies should follow from their findings. The working group recommended that the preparation of computer-readable files fully documenting the information used to derive paleoclimate estimates from historical records be given highest priority. To this end, an international workshop of historical climatologists and historians from China, Japan, Korea, and other countries will be held within a year to compare and standardize methodologies used in extracting paleoclimatic data from historical sources and to initiate procedures for creating computer-readable archives of climate-related historical data.

Tree Rings: Within the region of concern, both temperate and tropical species of trees are found. Tree-ring studies in temperate areas can build on the methodologies and experience gained from dendroclimatic research in other temperate regions, and the research may shed light on links between the intensity of monsoon rainfall and the extent of spring snow cover in the interior of continental Asia. In tropical Asia, tree-ring studies have shown potential in reconstructing precipitation in the transitional season (between the dry season and periods of monsoon activity) and hence may give information on the timing of monsoon rains. In some cases, it is also likely that records of monsoon intensity can be derived. They may also be used to reconstruct climatic conditions at the western end of the El-Niño-Southern Oscillation (ENSO) system. The working group strongly recommended that research be encouraged to develop climatically sensitive tree-ring chronologies in the low latitudes of monsoon Asia, for example, southeast Asia, India south of the Himalaya, south China, Indonesia, and the archipelagos to its east and south. This research should be carried out in conjunction with process studies to better understand the links between interannual variations of tree-ring properties and climate. The group also pointed to the urgent need for "rescue sampling" of old trees, which in many parts of the region are threatened by logging or other human activities.

Corals: The monsoon system is driven by seasonal contrasts between land and ocean; long-lived corals can provide high-resolution information on past seasonality in oceanic regions most affected by the Asian monsoon. A number of coral studies are already underway in the region, ranging from sites in northern Australia to the Gulf of Kutch, and from the Maldives to the Ryukyu archipelago, southern Japan. Many other potential sites are available, but research is needed to iden-

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tify sites where the strongest climatic signals are recorded. High-resolution, multi-parameter measurements are needed, together with environmental monitoring programs at many sites to clarify the interpretation of coral-based paleoclimatic records. In particular, further research on the physiology of coral growth and carbon dynamics is needed. Like the tree-ring group, the coral experts expressed concern that many coral reefs are in danger due to pollution and human disturbance; they urged that extensive reef surveys be undertaken and the results made public.

Ice Cores: In high-elevation areas of central Asia, many ice caps preserve annual records of monsoons over at least the last 2000 years. Ice-core studies can provide information on accumulation (net balance) and moisture sources, paleotemperatures, and aerosols, as well as changes in solar and volcanic activity. Three ice cores extending over more than the last 1000 years have so far been recovered—from the Dunde, Guliya, and Chongce ice caps in China (at 5325, 6530, and 6200 m respectively). A two-phase strategy is recommended for future drilling in the Tibetan Plateau area. Phase one would involve drilling a number of shallow (20 m) cores at twenty to thirty selected sites to obtain information essential to a subsequent comprehensive deeper drilling program. Because of the paucity of high-elevation meteorological records from the region, ten automatic weather stations should be deployed to monitor climatic conditions relevant to the paleoclimatic interpretation of ice-core records. This plan should be coupled with the collection of snow samples to develop appropriate transfer functions between modern processes and the ice-core archives. Phase two would involve drilling five deep ice cores to provide long time series from the best sites. This would be facilitated by the construction of a lightweight, modular ice-core drilling system, capable of drilling to a depth of 500 m in high elevation, remote ice caps, and glaciers.

Terrestrial Sediments: Discussions focused on loess and paleosols, lake and alluvial sediments, and glacial deposits. Persistent deflation and eastward transport of dust from desert basins of central Asia has led to the accumulation of thick deposits of loess in central and eastern China during the past 2.4 m.y. Throughout a major part of the Chinese Loess Plateau, the Holocene section is 1–2 m thick, representing an average Holocene sedimentation rate of 0.1–0.2 mm/yr; farther west, where the Holocene section reaches a thickness of 10 m, the average sedimentation rate is about 1 mm/yr. With a sampling interval of 2 cm, temporal resolution in high-sedimentation-rate profiles may approach 25 years, whereas in the main sector of the Loess Plateau it more commonly will be 100–200 years. Because of widespread human disturbance of the loess/paleosol record, the best high-resolution data are likely to come from the drier western areas where sedimentation rates are higher and disturbance is less prevalent. Priority should be given to locating the best high-resolution sites and to sampling along transects normal to monsoon frontal limits. More widespread sampling over a grid of sites across the Loess Plateau would enable regional trends and gradients to be analyzed. Optical dating techniques and Accelerator Mass Spectrometry (AMS) ^{14}C dating should be more widely applied to provide improved dating control on the sediments.

Lake sediments have the potential of yielding high-resolution records of paleomonsoon fluctuations. Meromictic lakes, which may have annual laminations (varves), have been reported in Sichuan Province of southwest China and may exist in the Qinghai-Xizang Plateau, northern India and Pakistan, and in the Himalaya. However, for most parts of the region, meromictic lakes are unlikely to exist and paleoclimatic records will come from holomictic lakes, where a temporal resolution of 100 years is more probable. Freshwater swamps in southeast Asia and northern Australia have been shown to offer potential where lake records are unavailable or suboptimal. Although studies have been done in Java, Sumatra, and New Guinea, climatic reconstruction is complicated at many sites by human disturbance of the lake catchments. This is likely to be a pervasive problem throughout the region. A further difficulty with many existing lake records is the lack of good dating control and the absence of an adequate surface-sampling network, which is essential for derivation of reliable transfer functions. In addition, there is a general lack of knowledge about modern ecology and the distribution ranges of major pollen-producing plants, especially trees. There is an urgent need for establishment of standard stratigraphies for each key region of monsoon Asia, containing a high density of dating control and multiple proxies (for example, pollen, isotopes, diatoms) from the same core or the same sites. Efforts should be made to develop transects incorporating these standard sites perpendicular to monsoon tracks or fronts. Priority should be given to climatically sensitive areas like the Qinghai-Xizang Plateau and the Loess Plateau, northwest India, and northern Australia, which mark important ecotones and modern monsoon limits, to produce sensitive and high-quality records.

Fluctuations in summer monsoon intensity may result in changes in stream regimen that produce a stratigraphic record in the form of flood alluvium, slackwater deposits, or stream terraces. However, a major problem in assessing the climatic significance of stream deposits in a tectonic region like eastern Asia is the possibility that alluvial regimes have been affected by tectonic movements. Furthermore, human impact on fluvial systems can obscure the climatic signal, requiring very careful analysis of land use in conjunction with studies of recent alluviation. Highest priority should be given to locating and dating alluvial records that hold promise for providing unequivocal evidence of climatic variation in areas where tectonic and human disturbance are minimal or lacking. As in the case of other climate proxy studies, sites located along transects perpendicular to fluctuating monsoon limits may provide the most useful means of assessing the magnitude and possible diachronous character of changing monsoon conditions in the recent past. Possible areas for this work include northern China, northwestern India, and northern Australia. To promote further research on these problems, a small workshop to discuss the extraction of paleomonsoon data from alluvial deposits should be convened. Small temperate alpine glaciers respond quickly and sensitively to climatic changes by advancing or retreating. Moraines formed during episodes of glacier

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advance, or of stabilization during overall recession, provide information from which discontinuous time series of glacier variations can be reconstructed. In monsoon Asia, glaciers are found mainly in the high mountains of western China, Pakistan, India, and Nepal. Documentary evidence for past glacier fluctuations is very limited, and relatively few field-based studies have been carried out. Detailed studies of promising sites, using all available dating approaches, should be encouraged to supplement the studies of more continuous paleoclimatic records.

Marine Sediments: Studies of sediments from ocean areas surrounding monsoon Asia are crucial to understanding the long-term dynamics of the monsoon and the influence of oceanographic changes on the monsoon. Marine sediments can provide information on sea-surface temperatures (SSTs), upwelling (and inferred wind-stress variability) sea-level changes, ocean circulation changes, terrestrial river run-off, and eolian activity changes. They can also provide information relevant to understanding possible linkages between the ENSO and monsoon systems. The group recommended that both long (160 ka) low-resolution records (one sample per 2–4 ka) and shorter (20 ka) high-resolution records (one sample per 200–400 years) be obtained from a number of important oceanic regions. A systematic search for areas with undisturbed very high accumulation rates (>50 cm/ka) and/or laminated sediments is needed, focusing on key regions (including downstream of river mouths, upwelling areas, and locations sensitive to circulation changes). Wherever possible, paleoclimatic reconstructions should be based on multiple independent proxy indicators (for example, paleontological, geochemical, sedimentological, or paleomagnetic). An expanded program of modern process and calibration studies is needed, using sediment traps and core-top sediment analyses. A multinational effort is needed to construct a much-expanded data base of modern core-top sediment data.

High-quality AMS ^{14}C chronologies are needed for the shorter records (one sample per 500 years), and where possible, other geochronological methods should also be used (for example, volcanic ashes of known age). The most common deficiency in current marine sediment studies of past monsoon dynamics is the lack of sufficient time control, especially AMS ^{14}C dates. A mechanism must be established to enable the international community to obtain the AMS ^{14}C (and other types of dates needed) at an affordable cost and with a rapid turn-around time; rapid information is often needed at the beginning of studies to guide sampling.

In closing, the meeting also endorsed the development of coordinated national and regional centers for data management and data archiving. All data from PAGES-related activities should be available (in digital form) for other scientists working both within and outside national borders. Data should be made available to the research community through the World Data Center for Paleoclimatology in Boulder, Colo. Both "raw" data (for example, original fossil counts versus depth, and radiocarbon date lists) and "derived" data (for example, records versus a preferred age model and quantitative reconstructions) need to be shared, as well as complete documentation of the sites and sources of data. Efforts should be made to share the technology needed for these activities, and an emphasis should be placed on making the international sharing of all data as easy and affordable as possible.

The groups also recognized the inevitable language and political barriers to paleomonsoon research. More international workshops, conferences, and scientist exchanges were recommended to facilitate better communication and promote the exchange of ideas, literature, and data. Scientists involved in PAGES-related research should promote more international interaction, and the IGBP START program (regional research centers) should take the lead on funding short courses and workshops for scientists and students working in the monsoon regions, with a focus on field and laboratory techniques and methods of data reduction and analysis.—*Raymond S. Bradley, Department of Geology and Geography, University of Massachusetts, Amherst; David Sheu, Institute of Marine Geology, National Sun Yat Sen University, Kaohsiung, Taiwan; and Weichyung Wang, Atmospheric Sciences Research Center, State University of New York at Albany*

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