N91-21594

SECTION V.

REPORT OF THE PANEL ON THE LAND SURFACE: PROCESSES OF CHANGE

CONTRIBUTORS

John B. Adams
Eric E. Barron
Arthur A. Bloom
Carol Breed
J. Dohrenwend
Diane L. Evans
Thomas T. Farr
Allen R. Gillespie
L. B. Isacks
Richard S. Williams

SECTION V.

TABLE OF CONTENTS

I. SUMMARY

The land surface has been modified throughout geologic history by climatic and tectonic processes. Today a third process, human activity, is changing the Earth's surface. If we are to assess the future impact of human activities on the Earth's ecosystem we need to know how these processes work and how they interact with one another. We not only need to know how climate, tectonism and human activities are affecting the Earth's surface today, but also how climatic and tectonic processes have modified the Earth in the geologic past. The geologic record shows us a "noisy" background of natural changes over millions of years to decades. The potential changes in the Earth's climate that are a subject of concern today must be detected against this background. The past also may be the most important key to understanding what happens to the Earth's surface as a result of changing climate. The record of past changes in climate is preserved in such places as sea and lake sediments, ancient ice, soils and chemical weathering deposits, eolian deposits and in landforms. To read this record we must integrate astute field and remote-sensing observations with knowledge of present physical and chemical processes, along with models that describe different rates and interactions over time.

The processes that we wish to understand not only extend back in time, they also impact large regions of the Earth. Field studies alone are not feasible for the whole Earth or even for large regions, especially under conditions of rapid change. To extend observations over large areas and to a global scale the inevitable choice is to use satellite remote-sensing measurements in conjunction with detailed knowledge from a few well characterized field sites.

NASA has a clear role in obtaining remote-sensing data of the Earth. Through its Solid Earth Science (SES) program, NASA has the potential to provide scientific leadership in studies of the land surface by conducting key research projects and by coordinating research activities with a broad spectrum of US and foreign agencies. The panel defined three main areas of study that are central to the SES effort: climate interactions with the Earth's surface, tectonism as it affects the Earth's surface and its climates; and human activities that modify the Earth's surface. We envision four foci of research: 1) process studies with an emphasis on modern processes in transitional areas; 2) integrated studies with an emphasis on long-term continental climate change; 3) climate-tectonic interactions; and 4) studies of human activities that modify the Earth's surface with an emphasis on soil degradation.

Research in these areas will involve field and laboratory measurements of morphometric, chronometric, textural and other physical, chemical and mineralogical properties of the land surface. Repeated observations will be needed to study processes that operate on time scales of decades or less. These field studies will need to be integrated with studies of remotely sensed images acquired from aircraft and satellites, and with studies that emphasize modeling. The scope of research is such that it can only be achieved if there is broad support from different federal agencies and international organizations.

The panel attached high priority to studies of changes to the land surface that affect life-systems. A special opportunity exists for NASA SES to take a leadership role in research on how climate change affects soil resources.

To achieve the ambitious goals of understanding the changing land surface, the panel emphasizes that it will be necessary to move quickly toward a research environment in which remote-sensing data are readily accessible in terms of cost and ease of handling. In anticipation of the EOS era it also is critical to expand the base of trained personnel who understand how to use remote-sensing technology, and at the same time can integrate remote observations with field data and theoretical models.

The panel concluded that there is a clear requirement for global coverage by high-resolution stereoscopic images and a pressing need for global topographic data in support of studies of the land surface. The requirement is common to all researchers, but does not by itself meet all their remote-sensing needs.

II. OUTLINE SUMMARY OF SCIENCE GOALS

Understand the processes that produce changes in the Earth's surface

- key to the past climatic and tectonic record
- key to present climatic and human impacts

CLIMATE interactions with the Earth's surface

TECTONISM as it affects the Earth's surface and its climates

HUMAN ACTIVITIES that modify the Earth's surface

Understand the interactions of climate, tectonic and human processes

SHORT AND LONG TERM

LOCAL TO GLOBAL SCALES

III. SCIENCE PLAN

1) Modern Processes in Transitional Areas

Introduction. To observe, understand, and ultimately to predict global change - especially changes to the Earth's land surface - the best place to start is in the transitional areas of our planet. Transitional zones are especially responsive to changing climatic interactions with the Earth's surface, because their surface geologic materials or landforms (eolian sand deposits, glaciers, floodplains, etc.) are exceptionally sensitive to variations in climate-driven geologic processes and respond relatively rapidly to any such variations. Many such areas are particularly sensitive indicators of change because they are located within present climatic zones that are subject to shifting boundaries. The surfaces of transitional regions tend to be metastable; they are in tenuous equilibrium with the present-day climate, and they typically exhibit evidence of past changes in response to multiple climatic variations. These regions include, but are not limited to, the semiarid to subhumid margins of the extremely arid core deserts, margins of the polar regions (including permafrost), margins of glaciers, alpine glacial and periglacial terrains, the shorelines of lakes and coastal areas (including barrier islands, deltas, and wetlands), and many drainage basins.

Environmental changes in transitional regions have historically had severe impacts on flora and fauna (including humans), and environmental changes resulting from the predicted future global warming are expected to exert their greatest impact on humans and their facilities in these regions. In the context of NASA's Mission to Planet Earth and the U.S. Global Change Research Program, transitional areas are considered to be of the highest priority.

Process studies of the land surface are needed in order to study changes in the transitional environments. Studies must be tied closely to the technology for gathering real-time data on such climatic variables as precipitation, wind and temperature. A multidisciplinary effort is needed to gather and interpret data on such factors as vegetation cover, soil characteristics and hydrology, in addition to standard stratigraphic and topographic studies. Especially important are measurements that will add to the presently inadequate geochronology of geologic surficial units and landforms. Both radiometric and relative dating are badly needed to define sequences of events better, in order to help establish the rates of present processes and processes that operated under past climatic conditions.

Analysis of modern, on-going processes can greatly benefit from the satellite remote sensing record acquired over the 17-year period of the Landsat program. However, the geomorphic and stratigraphic indicators of climate change still need to be defined more reliably than is possible with the Landsat record alone.

Margins of Arid Regions. The transitional zones between the core deserts and adjacent semiarid to subhumid zones are particularly sensitive to changes in climate manifested by variations in precipitation, wind regimes, and vegetation cover. One of the first signals of disequilibrium between land surfaces and changing climatic conditions is a change in the relative effectiveness of running water *vs.* eolian (wind) activity. Typically, increased wind erosion occurs in areas formerly stabilized by vegetation which had been supported by runoff or directly from precipitation or from high groundwater levels. Reduction of soil moisture and loss of vegetation allow exposure of bare, dry and loose surface materials to wind, which winnows out the fine particles (e.g., soil nutrients) as dust, with consequent soil coarsening and loss of fertility. Continued wind erosion leads to segregation of sand-size particles into fields of mobile sand dunes, which can migrate into agricultural areas and settlements. Commonly, this degradation is exacerbated by increased runoff during the rainy season, leading to flash-floods, sedimentation in lakes and estuaries, and gullying. Frequently, such changes are attributed to "desertification" caused or influenced by human activity, but the evidence of repeated changes predating human occupation is also found in most areas. Wind erosion accounts for the generation of some 500 million tons of dust per year worldwide, but the prediction of damage to natural surfaces from wind erosion relies, at present, on models based on calculations for farm fields in agricultural regions. These models are not relevant to wind erosion on natural surfaces such as the desert scrubland used primarily for grazing purposes in much of the southwestern U.S, Central Asia, and arid regions of Africa, South America, and Australia.

Remote sensing by NOAA's weather satellites has made possible the global tracking of dust storms generated by wind erosion in the arid continental interiors -- from the U.S. High Plains to the Atlantic Ocean, from the arid steppes of China to Hawaii, and from the Sahara to the Caribbean and Florida. However, models that predict the generation of dust from natural surfaces are only beginning to be developed on the basis of systematic field observations and laboratory experiments. The convergence of improved satellite remote-sensing capabilities with new technologies for obtaining real-time ground measurements thus offers an opportunity to define eolian processes on the basis of data that was not previously obtainable. A spin-off of such studies would be the capability to include the generation of dust (aerosols) from the world's arid regions in General Circulation Models of climate (GCM's), and to investigate possible feedback effects of dust on climate.

Other processes that are particularly diagnostic of climate changes in areas along the margins of arid regions include changes in vegetation type and abundance (e.g., as recorded in packrat middens), and changes in the discharge, sedimentation, and distribution patterns of stream systems, including changes in lake levels.

Permafrost and lakes. The polar regions of the Northern Hemisphere, especially in North America and Asia, have extensive concentric regions of discontinuous and continuous permafrost (frozen ground which seasonally thaws only in a thin active surface layer). Permafrost is one of the four major components of the cryosphere, all of which are extremely sensitive to climate warming. Thermal anomalies have been measured in abandoned wells in Alaska which represent a warming signal during the last century of at least 1°C as recorded in the permafrost. Permafrost also contains enormous quantities of methane, bound interstitially in ice as a clathrate which, if released in the atmosphere under global warming conditions, could add significantly to the atmospheric loading of greenhouse gases. Methane is 15 times more effective than carbon dioxide in its greenhouse effect. Periodic *in situ* and remote-sensing measurements of areal changes in permafrost, in association with estimates of the volume of methane contained, may allow predictions to be made of the amount of methane being released to the atmosphere from this source.

The times of freezeup and thaw of lakes are sensitive indicators of climate change in temperate and polar regions. There is an opportunity to combine the satellite image observation records with historical field data records to compile a long-term history of the times of freezeup and thaw of many lakes in North America, Europe, and Asia. These histories could be correlated with available climatological data. The wide geographic monitoring capability of satellite remote sensing would also permit the assessment of inter-annual variation of lake ice freezeup and thaw with latitude. These data sets would be another important addition to long-term assessment of the effect of global climate warming.

Glaciers. Glaciers originate on the solid Earth and, except for floating ice shelves along the coast of Antarctica and small ones off Ellesmere Island (NWT, Canada), glacier ice is generally restricted to the land. Changes in the areal extent and volume of glaciers affect sea level. For example, if the volume of glacier ice presently stored in Antarctica (91%), Greenland (8.3%), and all other ice caps and valley glaciers (0.7%) were to melt, sea level would rise about 100 m. This would be equivalent to the rise in sea level 10,000 years ago following the end of the ice age.

Two key scientific questions are: (1) what is the rate of rise of sea level, and (2) how are the world's glaciers responding to global climate warming? The technology exists to answer these questions, using a combination of *in situ* measurements and remote sensing. For example, the U.S. Geological Survey has, for the past 10 years, been compiling a Satellite Image Atlas of Glaciers of the World based on Landsat multispectral scanner (MSS) images acquired in the mid-1970's. However, the high cost and lack of regional data coverage in the present Landsat program has precluded monitoring changes in most areas imaged in the 1970's, except for Antarctica. An interagency consortium of the USGS, NASA, and Scientific Committee on Antarctic Research (SCAR) Committee on Glaciology has funded the continuing acquisition of Landsat images of Antarctica to provide another data set in the late 1980's for comparison with the mid-1970's data set.

Coastal zones. The low-lying coastal zones of our planet are especially sensitive to climate-driven changes in the sea level. Sea level changes can result from fluctuations in glacier ice volume, changes in the shapes of ocean basins, and temperature changes in the oceanic water column. Sedimentation rates and transport patterns can be altered by climate-driven changes, changes in river position, and alterations in coastal geometry. Tectonic forces, isostatic rebound following deglaciation, and sediment compaction also can produce changes in the land surface with respect to sea level, and withdrawal of groundwater and of oil and gas in coastal areas can cause subsidence.

Satellite images provide a unique means of monitoring and measuring changes in coastal environments on a global basis. The Landsat MSS data provide a good record of changes over the past 17 years, but a continuing record is necessary as anthropogenic changes accelerate with increasing population and industrialization. If satellite data were available at a reasonable cost, changes in barrier islands, wetlands and other coastal features could be measured in a time-lapse sense to increase our understanding of the processes causing the observed changes. It may also become increasingly important to be able to predict coastline changes, in order to facilitate economic and social planning. A future rise in sea level may have the greatest global economic impact of all the forecast consequences of global change, as coastal areas worldwide have traditionally been the locus of human settlement and activity.

Fluvial Systems. Running water collected from precipitation or melted from the snowpack or from glaciers accounts for most erosion and sedimentation of the land surface, except in parts of the extremely arid core deserts. Even there, former river systems accomplished most of the lowering of the land surface and left their imprint on the topography and in widespread alluvial deposits. Rivers respond to changes in climate by altering their hydraulic gradient and consequently their geomorphic patterns and rates of sedimentation. In extreme cases, as when climate in the headwater region becomes extremely arid, or when capture or beheading occurs in response to tectonic or volcanic events, streams may dry up or even reverse their courses. A sequence of climatic or tectonic events that influenced the evolution of stream systems may be recorded by erosional features such as flights of terraces, or by stream network and channel characteristics (e.g., gullying and arroyo cutting) and by depositional features (e.g., floodplains, lake beds and terrace gravels). River systems integrate the response of the land surface throughout the entire drainage system to changes such as removal of vegetation (due to natural or human causes) or to uplift and subsidence.

2) The Continental Record of Climate Change

Introduction. Current predictive models of future global change are based primarily on modern climatological observations. Modern observations unfortunately lack any sense of climate change. The long-term record of climate change is preserved by the land surface and by terrestrial and marine sediment cores, ice cores, and other deposits. This record is the necessary link to understand how the land surface and associated distributions of life and life resources will respond to global change in the future.

Historical quantitative observations of weather and climate rarely extend back over a century. Older climate records covering hundreds of years to the entire Holocene come from cores in ice caps and tree rings. Recently, the COHMAP project integrated paleoecological, palynological, pluvial and other data to describe climatological reconstructions for the period since the latest glacial maximum: the last 18,000 years.

Other proxy records of climate extend much farther back in time. The Vostok ice core from Antarctica covers 120,000 years, and foraminiferal records from sea-floor cores span several glacial cycles. These data provide insight into global sea-level and temperature fluctuations, but they do not provide specific information on the land surface, where most human activity occurs. There, our knowledge of the climate record before 18,000 B.P. is sketchy and incomplete. Yet if we are to understand and predict the natural and anthropogenic climate changes in the future, it is essential that we have a detailed knowledge of an entire glacial cycle, especially the interglacial/glacial transition. The previous 18,000 years spans the glacial/interglacial transition, which has already occurred.

Landforms. The terrestrial landscape is a dynamic surface that evolves through the interaction of internal processes (generally constructional, except for gravity) and external processes (generally erosional). Erosional processes are strongly controlled by climate, although the rate of landscape evolution is slow enough so that most landscapes record the impact of multiple processes related to global climatic changes over the past few million years. Landform interpretation forms the link between geodynamic solid-Earth processes and the external climate-induced oceanic and atmospheric processes. Landscapes are highly amenable to analysis on a regional scale by remote sensing from orbit, and thus are a central link in "Earth-systems science." In spite of this pivotal role, analysis of landscapes has received little attention compared to the explosion of activities in the atmospheric sciences, geophysics and geochemistry. The new technology of remote sensing has had little impact so far on the traditional field of geomorphology, although the potential exists to integrate the study of internal tectonic processes with an understanding of external climatic processes.

Soils The continental climate history has been impressed on the land surface of the Earth as landforms and as chemical weathering products, including soils and rock coatings. Whereas the regional distribution of landforms charts paleoclimatic zones, the degree and type of chemical weathering can be used to infer paleoenvironmental conditions, including precipitation and temperature regimes. Multispectral remote sensing has been shown to be useful in estimating soil type and development. Remote sensing is especially valuable because the extensive coverage and closely-spaced measurements distinguish different soil units and detect subtle or diffuse gradients. Coupled with age data for different surfaces weathering in the same fluvial or other geomorphic unit, remotely sensed information can be used to help reconstruct a continental climatic history. Because geologic surfaces dating from times throughout the previous glacial cycle (the last ~ 130,000 years) are locally well preserved, regional studies of soils and landforms are expected to yield information on the spatial variability of climatic history on a scale sufficient to test paleoclimate reconstructions made using the General Climate Models.

Even where remotely sensed spectra or other types of data are not directly applicable to soils mapping they may be used indirectly to map over large areas the units that have been defined at specific sites by conventional field methods. Soils develop in response to climatic factors, but also in response to a host of local tectonic, microclimatic and other influences that introduce considerable variability into soil profiles. One way to circumvent this problem is to study regional patterns of soil types that reveal large-scale patterns, devoid of local complications. Recent studies have confirmed that some soil units as defined in trenches or pits have distinct surface spectra that permit the discrimination and mapping of the defined unit over large areas.

Arid Lands. The spatial patterns and surface characteristics of arid regions change through time in response to variations in the amount and distribution of rainfall, which is controlled primarily by the interaction of topography with the movement of air masses by the global circulation system. Major changes in the land surface in response to climate change include shifts in the boundaries between core deserts and their less-arid margins, shifts in the amount and type of vegetation cover relative to bare rock and soil, variations in stream erosion, discharge (including lake levels) and sedimentation, variations in the relative effectiveness of wind erosion and resulting redistribution of surface materials, and variations in the chemical and mechanical characteristics of the materials, including soils.

Proxy evidence for these climatically induced changes is preserved in the distribution of erosional and depositional patterns on the land surface and in the chemical and mineralogical composition of the surface materials. Cores in desert basins (dry lakes) have long been a source of critical data on past climates. More recently a rich source of data on climate change in desert areas has come from paleovegetation records from ^{14}C-dated packrat middens. It is now important to be able to compare the paleovegetation record with the present regional distribution of desert vegetation, which can be mapped using new multispectral remote-sensing techniques. New stable-isotope analyses of desert varnish suggest that paleovegetation and paleoclimate information can be inferred from rock coatings in arid regions. Rock coatings to a large extent are controlled by the stability of the rock substrate to weathering and spallation, and also can be measured by remote sensing.

One of the most important links between arid landforms and climate is knowledge of surface "exposure ages." Until recently the main data available were radioisotope dates of volcanic flows and tephras. However, volcanic features are not present in all deserts, and they rarely are distributed conveniently in space and time for dating. New techniques are now under development that date carbonate deposits (travertine, tufa and shells), rock coatings (desert varnish), and rock surfaces containing chlorine or beryllium created by cosmic-ray bombardment. With continued dating of the exposure ages of sparsely vegetated desert surfaces and with better understanding of how surfaces evolve under different climatic conditions, it is likely that it will become possible to interpret more remotely sensed data in terms of geomorphic processes and time scales. Both spatial and multispectral remotely sensed data will needed to support regional analysis of arid regions. Combinations of data from different sensors will have to be used synergistically (for example Landsat TM merged with imaging radar) to investigate simultaneously the spatial and spectral characteristics of surfaces, and of the shallow substrate.

Glaciers. During the glacial maxima about as much ice accumulated on land as is present today in the Greenland and Antarctic ice sheets. A doubling of glacier ice volume occurred, sufficient to lower sea level about 100 m. Glacial geologists have been active for years, principally in North America and Eurasia in field mapping the maximum extent of the ice sheets, ice caps, ice fields, and valley glaciers. Various types of glacial deposits provide information about the former glacier, and terminal moraines provide accurate information about the position of the former margins of the above types of glaciers. Although the former areal extent of glaciers is well known in North America and Eurasia, such is not the case in the mountainous regions of Asia and South America. High-resolution (less than 5-m pixels) stereoimages (less than 10-m contours) would permit the delineation of moraines in such regions. With appropriate assumptions, models of ice volume could then be constructed for these mountainous regions.

Glaciers contain a continuous record of past atmospheric composition which can be accurately measured and dated through an entire interglacial-glacial cycle by analysis of ice cores. Ice cores also contain a datable record of pronounced volcanic and eolian activity, especially events which have had a global impact. Studies of the ice-core record of well-known, large historic volcanic events and dust storms from geographically diverse glaciers will provide a basis for interpreting older ice-core records of prehistoric volcanic eruptions and their probable effect on climate.

Accurate modelling of the areal and volumetric extent of past accumulations of glacier ice must be correlated with the sea-level record to determine the rate of sea-level fall and rise as it relates to the accumulation and ablation of ice sheets. The relationship of fluctuations of sea level to variations in global ice volume also can be linked to climate change (warming and cooling) by inferred sea-surface temperatures recorded by organisms in marine sediments (foraminiferal studies), and by the atmospheric-composition record from ice cores. Ice cores from Antarctica (Vostok core) have provided a record back to the last interglacial. A deep continuous ice core from central Greenland is being recovered in 1989 under a program supported by NSF.

Large volumes of glacier ice on Earth (Greenland and Antarctica) probably have fluctuated widely over geologic time because of plate motion and mountain-building episodes. The onset of a major ice buildup in Antarctica probably began about 40 million years ago, as Antarctica was moving to its present location. Major ice buildups in North America and Eurasia had to await the opening of the North Atlantic, movement of the North American and European plates, sufficient continental elevations, and proper orientation of mountain ranges. Any modelling of past climates by models of global climate or by GCMs must take these geological, geophysical, and glaciological factors into account. The past geologic record provides the actual evidence of the effect of past climate change on the oceans and continents needed to confirm or reject the predictions of the GCMs. In particular, the geologic record of the most recent global warming interval (about 2.2 million years B.P., in the Pliocene Epoch) can provide us with an understanding of the probable response at different geographic locations of the predicted global warming by GCMs under an atmosphere enriched in CO_2 compared to today. Transitional areas are of greatest importance, because these regions are where GCMs predict the greatest change from present-day conditions (e.g., the temperature increase predicted for polar regions is 3-5 times that predicted for lower latitudes).

Lakes and oceanic shorelines. Shorelines of lakes and the continents can vary considerably over long periods of time in response to global climate change. Such changes, especially if recorded above present-day lake or sea levels, are present in the landscape. Lakes respond to changes in precipitation and evaporation on both the short and long term. For example, since the launch of Landsat in 1972, fluctuations in the volume of Lake Chad, north-central Africa, have been recorded on a sporadic basis. The Great Salt Lake of Utah in recent years has experienced a significant increase in volume in response to greater precipitation and less evaporation, resulting in the highest historic lake levels recorded. During the late Pleistocene and early Holocene, Great Salt Lake was the site of an enormous lake, "Lake Bonneville", the shorelines of which are preserved in the landscape. Numerous other intermountain lakes existed all over the western U.S., but of these pluvial lakes now small remnants or playas (dry lake beds) are found. Evidence of the former lake levels is commonly preserved in the landscape, and in many cases is readily detected in Landsat images. Other parts of the world in which lakes form by internal drainage also respond to climatic change by infilling or evaporating. Examples are found in Africa, the Middle East, South America, Asia, and Australia.

Oceanic shorelines of continents shift in response to a rise and fall in sea level from melting of glacier ice or accumulation of ice sheets, respectively, one of the major impacts of global climate change. Because rivers meet the ocean "at grade," any shift in the sea level has a profound impact on fluvial erosion and deposition in the lower reaches of the river, the coastal plain, and associated delta system. Low-lying coastal areas are most affected by rising or falling sea level.

If greenhouse-gas loading (especially CH_4 and CO_2) of the atmosphere can be correlated with global temperature and the response of global ice volume to such conditions, then future sea levels can be predicted. Atmospheric CO_2 concentrations can be determined from glacier ice-core analysis and dated. If multiple stillstands of sea level can also be dated and correlated with CO_2 concentrations occurring at the same time, the rate of sea level rise can be calculated. The problem with predicting future sea levels from such an analysis is that the present-day rate of global warming and greenhouse-gas loading of the atmosphere is many times higher than the rate due to natural processes, so that the historic and geologic record yields only imperfect analogs for current conditions. Therefore, it is difficult to predict the response of the planet to this human-induced acceleration of natural processes. It is the interaction of the atmosphere (global warming) on glacier ice volume and the addition of glacier meltwater to the ocean that is the key process that must be understood before a predictive technique becomes possible.

3) Climate-Tectonic Interactions

Introduction. The surface of the Earth is the product of dynamic interactions between internal processes and external or solar-driven processes. An integrated approach to climate and tectonics can form a foundation for a comprehensive, physically based understanding of the interactions and feedbacks between the two major sources of energy which define the Earth system. This foundation, combined with improved models of the atmosphere and of the internal dynamics of the Earth, will facilitate predictive models of future changes in the land surface.

Traditionally, land topography has been used in geophysics mainly to analyze gravity. However, topography itself is a major tectonic signal that is little exploited. The causes for the regional elevation of western North America, for example, remain a major unsolved problem, and the morphologies of the Tibetan and Andean plateaus provide some the most important clues about the origins of these still enigmatic features. In contrast, regional and global scale morphology of the ocean floor and other planets has from the beginning been a primary and fruitful focus of tectonic study.

Tectonic Geomorphology. Climate-tectonic interactions are most evident where tectonic processes create landforms that interfere with the global atmospheric or oceanic circulation. This includes major uplifts, such as the Sierra Nevada, Andes, and the Tibetan Plateau. In these areas, we must understand the spatial and temporal distribution of the processes that have been involved, including constructional (e.g., uplift, volcanism) and erosional (physical and chemical weathering, fluvial, glacial) processes and the linkages between them. Using this understanding, we can then model the interacting system in space and time, with special attention to feedbacks and sensitivity of the system to variations in individual processes. The models can then be used in reconstructions of the history of global climate as well as of entire mountain ranges.

Neotectonic landforms such as fault scarps and coastal terraces are often relatively short-lived (on the order of 10^3 - 10^5 years.). At the other end of the feature-stability (residence) time scale are extremely ancient landforms (paleoforms), the recognition of which is rapidly increasing our understanding of continental paleogeomorphology. Ancient high-level erosion surfaces are present in many of the Earth's orogenic belts. These hold important clues about the development of orogenic topography. A significant percentage of the Earth's land area is represented by convergent margins, rift zones, and zones of transform motion. Within these areas, tectonism exerts a primary control on landform evolution, and studies of the landforms yield important information on the nature and processes of lithospheric deformation. On the other hand, landform evolution within the relatively quiescent shield areas of the continents is more closely related to changes in climatic geomorphology and the evolution of the continental drainage systems. Even in "stable" shield areas, the landforms are affected by subtle vertical movements that reflect poorly understood mantle processes such as the movement of lithospheric plates over "hot spots." Spaceborne platforms offer the most effective means of gathering data with sufficient regional coverage of all these landscapes.

Critical problems that can be addressed by satellite observations are the spatial patterns of surface deformation and the redistribution of mass by erosion, transport and deposition. An adequate continental topographic database combined with planned new Visible and Near-Infrared (VNIR), Thermal Infrared (TIR) and Radar imagery, linked to climate and climate history, will provide new insights into the role of denudation rates in the tectonic evolution of mountain ranges, the role of sedimentary budgets in defining the characteristics of sedimentary basins and the potential feedbacks between topographic evolution and global atmospheric circulation patterns.

Volcanism. Volcanism and climate are linked in several ways. It is well known from historical and geological records that gases and dust produced during major eruptions change the global atmosphere and can influence climate. Less well understood are the effects of large ocean-floor eruptions on ocean currents and temperatures, which in turn can influence climate. On land, volcanoes and volcanic features are important parts of some mountain belts; and, as discussed above, mountains affect atmospheric circulation, and thereby climate. In addition, volcanic landforms, many of which can be radiometrically dated, show climate-dependent erosional dissection. Measurements of volcanic growth and dissection in accessible regions under known climatic conditions can be used to estimate the ages of less accessible volcanoes that are imaged from space.

The Volcanology Panel science report should be consulted for a more comprehensive treatment of the interaction of volcanic activity with the oceans and atmosphere and the use of orbital and airborne remote sensing techniques in the study of volcanic processes.

4) Human Activities that Modify the Earth's Surface

Introduction. The human aspects of climatic change include not only the effects of changes on prehistoric migrations but also on the later rise of great civilizations. For example, recent work indicates the presence, in the surficial geologic materials of the Sahara, of a record of climatic change spanning more than 200,000 years, which is closely related to human prehistory. Presently there are population pressures on many desert margins, with attendant problems of desertification (loss of vegetation, soil erosion, waterlogging and salinization). The impact of future changes, whether due to variations in climate or human activities (or both), cannot be assessed in the absence of regional analyses of the record of past changes recorded by the land surface.

During the past century both the rate of change on the Earth's surface and the area impacted by human activities has increased, so that anthropogenic changes now have a significant influence on the global system. The most obvious change has been deforestation and even devegetation in the most severely affected regions. Water impoundment and diversion projects are so widespread that few major river systems on the planet remain unmodified. Soil degradation, erosion, and transport are increasingly serious global problems.

Soil Degradation. Together, water and soil form the basis for life on the land surface. Since the beginning of permanent settlements, human activity has had an increasingly profound impact on soil degradation and associated changes in vegetation. Major human activities have been agriculture -- especially irrigation agriculture -- grazing of livestock, damming rivers, and deforestation. Today these activities have reduced the fertility of vast food-producing areas.

Soil degradation in some areas is now occurring so rapidly that its progress is difficult to measure using conventional ground-based mapping techniques. NASA's remote-sensing technology is uniquely capable of assisting ground-based programs to measure soil degradation globally and on a repetitive basis. Key capabilities of satellite remote-sensing technology include: synoptic coverage at useful map scales; estimation of chemical composition and abundance; and linkage to conceptual and quantitative soil-development models. Soil degradation includes aeolian and fluvial erosion and transport, waterlogging, and changes in chemical composition including salinization and acidification. Soil degradation is both a cause for and the result of changes in the type and amount of vegetation. Each process leaves tell-tale traces on the chemistry, soil texture, and morphology of the Earth's surface. The major changes on the Earth's surface resulting from agricultural activities and deforestation are sufficiently widespread that they may affect regional and even global climate.

Eroded soil is ultimately redistributed as wind-blown dust, as silt in reservoirs, as fields of sand dunes, and as alluvium in flood plains and deltas of river systems. Changes in the rate of fluvial erosion, transport, and deposition of sediment can have profound effects on human facilities and natural systems. The effect of increased sedimentation in estuaries, deltas, and other coastal environments is especially amenable to study with remotely sensed data.

Because of the special importance of the problem of soil degradation to life on Earth and because it is possible to measure key aspects of changes in soils by remote sensing, the panel recommends that the SES program explore the possibility of taking a leadership role in coordinating research on changing soil resources. Soil research is conducted by many US and international agencies, and any program would require close coordination; however, NASA uniquely is able to supply the broad perspective of remote sensing which will be necessary to treat soils on a global scale and in the context of global climate change.

IV. DATA REQUIREMENTS

1) Types of Measurements

Investigations of land surface processes that produce changes in response to climate, tectonism, and human activities require systematic, repetitive measurements (*in situ* at representative selected sites, and globally) of physical and chemical conditions of the Earth's surface at several spatial and temporal scales. This is best accomplished by a coordinated program of field and remote-sensing observations from aircraft and Earth orbit.

Physical characteristics important to land surface processes include geometry and distribution of landforms, surface roughness, thickness and distribution of eolian mantles, particle-size distribution, soil moisture and density, development of hardpan and caliche, and vegetation type and density. Chemical conditions of interest include rock type, weathering products, rock coatings and soil development. Most of these quantities may be derived from remote-sensing data: 1) visible and near-infrared data are sensitive to composition of surficial materials such as rock type and weathering products and to vegetation; 2) thermal infrared sensors are sensitive to rock type as well as bulk properties; 3) radar can be used to derive surface roughness, bulk properties, and potential subsurface horizons; 4) high-resolution (5-m) panchromatic images depict morphology in two dimensions (three dimensions if in stereo); and 5) topographic data quantitatively delineate landforms.

The areas covered by these investigations range from small and intensively studied "anchor sites" to large continental regions. Spatial and temporal resolution generally follow the spatial scale, with higher-resolution rapid-repeat measurements required in the smaller areas, and lower-resolution coverage acquired less often for continental-scale regions.

Ground data will be required at intervals ranging from seasonal (for vegetation cover, glaciers, and snowpack) to daily (for stream discharge and sedimentation) to hourly or less for soil moisture and temperature gradients, to a few minutes for wind speed and direction, peak gusts, precipitation , and eolian flux (sand and dust in transit), and for solar radiation studies (thermal brightness and reflectance measurements). Some measurements are best collected by individual teams, and others by sensors on automated platforms.

Measurements from aircraft and satellite sensor systems will require high-resolution spatial and spectral data. Both panchromatic stereo imagery (10-m contour interval) and multispectral imagery with a pixel resolution of 5 and 10-m, respectively, are desirable. An L-band, HH Synthetic-Aperture Radar (SAR) system, with a minimum 30-m resolution is essential for imaging shallow subsurface topography and geologic structures in arid regions obscured by wind-blown sand sheets and low dunes.

Imaging spectrometer data coregistered in the visible, near IR, and thermal IR with a pixel resolution of about 30 m are required for investigations of the chemical and minerological composition of surficial geologic units, including soils, and for discriminating vegetation cover from bare soils, especially in arid regions. The interdisciplinary nature of many investigations will require that the bands chosen (for example, on the HIRIS) meet the needs of mineralogists and soil chemists as well as of botanists and field geologists.

Space-based measurements of precipitation (or soil moisture) and wind systems over the land surface, including aerosols of dust and volcanic origin, are greatly desired if the technology can be developed. Detection and tracking of airborne dust is best achieved from geostationary satellites with a continent-wide field of view and round-the-clock coverage, but detailed observation of dust-source areas requires archiving of daily local area coverage such as is provided by the polar orbiting NOAA AVHRR LAC system.

Although it is difficult to choose between spectral and spatial needs for studies of change on the Earth's surface, the one global data set which is lacking and is most needed by the Earth science community is global stereoimage and digital topographic data. The panel recommends, therefore, that a high priority is for NASA to launch a stereoimage mapping satellite at the earliest opportunity to acquire a global data set.

2) Remote-Sensing Data

The complexity of the Earth's surface is such that most investigative strategies closely couple intensive field work at critical sites and along transects ("anchor sites") with the more general regional perspective afforded by remote sensing. Thus, data must be acquired in the field and laboratory, as well as from spacecraft or aircraft.

NASA collects images from a variety of sensors aboard aircraft and spacecraft. Currently, NASA's airborne imaging program involves a C-130, ER-2, DC-8, and Lear Jet operating from Ames Research Center and Stennis Space Center. The terrestrial spacecraft program has centered on the Landsat series, Seasat, Shuttle, and Eos (yet to be launched). Additionally, NOAA routinely collects small-scale images for weather prediction. The images collected by sensors aboard these platforms forms an historical record extending back to 1972, and this record allows us to study phenomena and processes at the two-week to ten-year time scale.

Image requirements in terms of sensitivity and resolution are specified below (Tables I and II). These requirements are cast in terms of existing, planned, and future sensors. The requirements for studying land surfaces are unusual in that there is a heavy emphasis on compositional analysis requiring hyperspectral imaging spectral data.

TABLE I

Required Data

Elevation images (digital elevation models) for morphometric analysis.

$\Delta x = 30$ m　$\Delta z = 20$ m (absolute), 2 m (relative)

- Topographic data for gradient images for analysis of radiance images.

  $\Delta x = 50$ m　$\Delta z = 1$ m (relative)

- High-resolution images for morphometric measurements.

  Panchromatic, low sun

  $\Delta x = 5$ m　SNR> 100　swath width = 60 km

  Stereo images

Base/height > 0.5 (10-m contours) SNR > 100 swath width: 60 km
fore/aft preferable (near-simultaneous)

- VNIR data for compositional analysis (hyperspectral or imaging-spectrometer data).
    - Spectral region: 0.45 - 2.4 mm
    - Number of channels: > 24 (if band centers selectable)
    - Bandwidths: > 10 nm Swath width: > 100 km SNR: > 100
    - Dynamic range: > 100 utilized gray levels

- Thermal infrared data
    - Two times of acquisition: noon and predawn
    - Spectral region: 3-14 mm
    - Number of channels: 4 (3-5 mm),12 (8-14 mm)
    - NEΔT< 0.1 K at 300 K Δx=60-90 m swath width = 100 km

- SAR data
    - LHH with Δx = 30 m Sensitivity: 30-40 dB Swath width:> 30 km
    - Multifrequency (C- and P-band) data are highly desirable
    - Multipolarization and multiangle images are useful

- Continental-scale images

Continuous coverage, low spatial resolution

Frequent coverage, moderate spatial resolution

TABLE II

Match of Data Requirements and Remote-Sensing Systems

- Topographic elevation and slope data
    - Currently unavailable from NASA systems

- High-Resolution, low-sun panchromatic data
    - Currently unavailable.

Large Format Camera, SPOT, and Soyuzkarta are the closest approximations to required system.

Imaging Spectrometer Data

HIRIS (Eos) and AVIRIS (ER-2) are the closest approximations. The HIRIS spatial resolution (30m) is acceptable; the SNR may be too low; and the swath width (12 km) is too small. AVIRIS sensitivity is too low (SNR=25 at 2 mm). MODIS does not have all the required bands and the spatial resolution is too low.

Multispectral Data

TM spatial resolution and swath width are excellent. Sensitivity is too low (dynamic range is generally 5 bits) and the number of bands is too low.

Multispectral thermal IR data

TIMS (C-130) has too few channels but does have the required sensitivity. ITIR (Eos) has too low sensitivity (0.3 K) and too few channels, but the same instrument acquires VNIR data. The ITIR swath width (30km) is too small. A planned TM upgrade that would have included three thermal IR channels has been postponed indefinitely. No other instruments are currently planned. Satisfactory data collection thus requires an ITIR upgrade or a new sensor on an Earth Probe mission.

SAR Data

Eos SAR would give the required data, but its future is now uncertain. ERS-1, JERS-1, and Radarsat are acceptable, except for duty-cycle constraints, but the lack of SES input into priorities for coverage make acquisition of the needed data problematical.

Continental-scale images

GOES/METEOSAT (geosynchronous satellites) provide continuous images of most areas on the Earth with resolution of 4 km. The NOAA polar-orbit satellites provide frequent AVHRR coverage at 1-km nadir resolution. AVHRR images must now be requested in advance. For most applications, these data are sufficient, but for covering short-term unpredictable events (e.g, dust storms) AVHRR data should be available retrospectively.

3) Data Volume

In studies of land-surface processes the data volume utilized will be controlled mainly by the manpower available for interpretation, and less by the scope of the projects or the number of images that can be acquired. Considering the availability of technically trained personnel in 1989, we anticipate that a realistic beginning program would require a data-equivalent on the order of ten new TM scenes. As an example, there might be four regions under study, each region initially requiring four TM-equivalents. The number of "TM-scene-equivalents" per region might be expected to increase by about two per year. In addition it is expected that it will be necessary to add one new region each year at the four TM-scene beginning data volume.

The actual data for each "TM-scene-equivalent" would not be restricted to TM, but would encompass any of the data types listed above. At least initially most of the data would be required for only one or two times per year (e.g., summer/winter). In order to integrate data from the variety of available sensors with each other and with topography, the data would need to be mosaicked and registered to a common base. Proper geocoding of all image data would automatically produce this result.

It is important to appreciate the magnitude of a truly global-scale remote-sensing research program designed to study global change. At the minimum, intensive study areas would need to be established in areas representing each of the types of sensitive geographic provinces -- for example, deserts in North Africa, central Asia, and the western United States, tropical and temperate rainforests, boreal forests, tundra, and so forth. These intensive local studies need to be coupled to regional-scale remote-sensing studies requiring both high-density data over many local sites similar in scale to those studied on the ground, as well as lower-resolution data of the region as a whole. The People's Republic of China is covered by 543 Landsat MSS images; this volume of data is of the same order of magnitude required for each regional study involving modern hyperspectral data (e.g., HIRIS) and data from the different spectral windows (e.g., VNIR and radar). Studies of this scope have not yet been attempted.

4) Accessibility and Cost of Data

There is a growing need, in support of two large national/international research programs (U.S. Global Change Research Program/International Geosphere-Biosphere Programme and NASA's "Mission to Planet Earth Program"), to: 1) provide easy access for all scientists, to past, present, and future satellite image/photographic data; 2) acquire a basic high-resolution (less than 5-m pixels) global dataset of the topography of the Earth (stereo images and digital terrain models); and 3) acquire on a continuing, long-term and systematic basis, repetitive coverage of the land and shallow-sea areas of our planet with a medium-resolution (30-m pixels) Landsat-type sensor. All satellite image/photographic data must be readily accessible to all scientists and affordable (cost of reproduction only), if adequate use of this data resource is to be made.

Landsat. The single most important quasi-repetitive global data set capable of monitoring changes on the Earth surface are Landsat 1-5 multispectral scanner (MSS) and Landsat 4 -5 Thematic Mapper (TM) images. Landsat MSS images comprise the longest set of medium-resolution coverage of our planet, beginning in July 1972. Since the recent commercialization of Landsat, image acquisition has been based on commercial rather than scientific reasons, hence the coverage has become sporadic. To measure processes of change on the land surface it is essential to have access to all of the existing Landsat data and to improve the continuity of coverage in the future. It is well known that Landsat data today are too costly to be fully utilized by most scientific investigators, including those supported under the Solid Earth Sciences program.

To achieve the objectives of the program where the Earth is truly to be viewed as a planet, we recommend that existing data (including all Landsat and NOAA AVHRR data) and future remotely sensed data be processed to a common reference base, and made available to all program-funded investigators. A precedent for this type of data support has been established by NASA's Planetary Program for the processing and provision of data (in hard-copy, map and image- mosaic form as well as in digital form, on disks) to its investigators of the other planets.

The civilian scientific community only has access to a small amount of high-resolution, stereoscopic image/photographic data. These data are from the Large Format Camera (U.S.) and the Metric Camera (ESA) -- both flown one time only on the Space Shuttle -- Soyuzkarta (U.S.S.R.), and the SPOT instrument (French-ESA). There is a significant need for global high-resolution (5 m), stereoscopic (10-m contour) satellite image data. In addition to the use of such a dataset for stereoscopic imaging and topographic mapping of the land shallow-sea areas of our planet, the data could also be used to compile a global digital topographic data base. Alternatively, digital topographic data could be obtained by a laser altimeter.

It is notable that in NASA's exploration of other planets, investigators started out with a global approach, with global data sets to match, and only later concentrated on smaller areas and localities as more detailed, higher resolution data became available. In the case of Earth, because of political sensitivities between countries, comprehensive topographic and image data sets today are seldom available, even on a regional scale for areas outside the U.S., Europe, and Australia. For example, most of North Africa is very poorly mapped, with contour intervals of 100 m or more and inadequate representation of the surface topography. Many parts of Mars are mapped in more detail! Obviously, a serious study of global change will require adequate global data.

5) Ground-based Data Collection

Field and laboratory data need to be acquired with three main goals in mind:

- radiometric calibration of the remotely sensed images
- spectral and chemical characterization of the scene to calibrate and verify the image analysis
- input to predictive models

The first category consists of radiance and reflectance data, radar measurements of standard targets, and surface temperatures. The second category includes high-resolution field and laboratory spectra. Also included are radar scattermeter data, and such data as vegetation type and cover, lithologic and mineralogic information, and morphometric information. The third category includes isotopic dates and exposure ages, topography, soil type and development. Ground-based data collection should rely heavily on the expertise and facilities available through cooperative efforts with agencies such as USGS, NOAA, and USDA, which have operational responsibilities to obtain many types of field measurements.

The panel notes, however, that while there is increasing emphasis on studying the land surface at regional and global scales, at the same time budgetary restrictions threaten to limit the expanding participation of skilled field observers. The panel emphasizes that a strong program of on-going field studies in close cooperation with remote-sensing measurements is essential to be able to test models of global change.

6) Role of Other Agencies

The multidisciplinary aspects of the work envisaged in this program will require cooperative arrangements with other Federal agencies including NOAA and USGS, as well as participation by scientists from several agencies and academic institutions as co-investigators and collaborators on individual projects. Collaborative efforts that utilize data collected from established ground stations by other agencies would save unnecessary cost and efforts of duplication, and should be encouraged. Similar encouragement should be given to cooperation with foreign groups who can assist in the logistics required for field work overseas.