5-7-1979

Remote Sensing of Transfrontier Air Pollution in the United States-Mexico Border Region

Laurence Richard Shillito

THE UNIVERSITY OF NEW MEXICO
ALBUQUERQUE, NEW MEXICO 87131

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Laurence Richard Shillito
Candidate

Geography
Department

This thesis is approved, and it is acceptable in quality and form for publication on microfilm:

Approved by the Thesis Committee:

Stanley A. Morain, Chairperson

Richard E. Murphy

Albert Utton

Accepted: Bernard Spolsky
Dean, Graduate School

May 7, 1979
Date

REMOTE SENSING OF TRANSFRONTIER AIR POLLUTION IN THE UNITED STATES-MEXICO BORDER REGION

BY

Laurence Richard Shillito

B.S., The University of Arizona, 1972

THESIS

Submitted in Partial Fulfillment of the
Requirements for the Degree of

Master of Arts in Geography

The University of New Mexico
Albuquerque, New Mexico

May, 1979

ACKNOWLEDGEMENTS

This thesis represents the culmination of three years of study, which has benefited from the professional and personal resources of many persons. I wish to thank Dr. Stanley A. Morain, the chairman of my thesis committee, for his interested guidance, his valuable assistance in procuring the imagery evaluated in this study, and his detailed review of the initail draft. I also wish to thank Dr. Richard E. Murphy and Mr. Albert E. Utton for their informed comments and suggestions. To Drs. Howard G. Applegate, C. Richard Bath, Robert H. Schmidt, Jr., and Ellwyn R. Stoddard at the University of Texas at El Paso, I wish to extend my sincere appreciation for the information they provided and the time they freely gave to assist me. I hope this study will complement and add to their already extensive contributions to the understanding and resolution of United States-Mexico border region problems.

I must also express my gratitude to: the personnel of the Denver Regional Office of the National Cartographic Information Center, who aided me throughout a week-long search of the microform library; Jim Ebert at the Cultural Resources Center of the University of New Mexico, who's valuable assistance was necessary to the success of this study; and Mike White and Amy Komarek of the Technology Applications Center of the University of New Mexico for their part in ordering the imagery.

To those who volunteered their personal resources in the form of financial and emotional support, I wish to extend my sincerest gratitude.

It is to them that I owe the greatest debt. Despite aggravations that arose for both of us, Barbara Cunningham, as both a wife and a friend, shared, supported, complemented, and tolerated my intense interest in and love for geography. I wish to thank my good friend Dave Dorl, who, with Barb, helped in the preparation of the final manuscript. Finally, I must thank my family for having provided me with the confidence and ability to undertake and complete this endeavor, which I frevently hope will contribute to enhanced understanding and cooperation among all peoples and nations.

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ABSTRACT OF THESIS

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REMOTE SENSING OF TRANSFRONTIER AIR POLLUTION
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Laurence Richard Shillito
B.S., Business Adminstration, University of Arizona, 1972
M.A., Geography, University of New Mexico, 1979

A geographic perspective of the political, legal, and economic aspects of transfrontier air pollution is developed and the potential usefulness of remote sensing technology to enhance monitoring and control efforts is evaluated. The international border between the United States and Mexico is the principal reference area for examination and evaluation of 1) political considerations at international, national, and local levels, 2) principles of International Law, 3) legal and quasi-legal associations within the border region, 4) economic considerations relevant to transfrontier pollution as an international concern, and 5) fundamental economic relationships between the bordering countries. The need for international cooperative efforts toward resolution of transfrontier air pollution problems was apparent and is basic to the findings of this study.

A survey of environmental concerns, relative to air pollution in the United States-Mexico border region, was prepared and related to geographic characteristics affecting the intensity and distribution of air pollution problems. An evaluation of the potential contribution of the science and technology of remote sensing to aid pollution survey and control efforts was conducted by a review of pertinent literature, identification of demonstrated and feasible applications,

and detailed examination of several different types of readily accessible photographic and non-photographic imagery. Visual analysis, stereoscopic analysis, and electronic image enhancement was employed to determine the ability of selected imagery to detect air pollution, specifically, and environmental concerns, generally.

Results of the evaluation revealed that photographic images generated at aerial and sub-orbital altitudes possessed the best potential for reasonably acceptable mensuration of emission plumes and air pollution sources and/or source areas. Orbital photographic images yielded the best overall potential for evaluating air pollution dispersion patterns and defining the geographic scope of air pollution problems. Non-photographic imagery, specifically images generated by the Landsat MSS and the SMS and GOES satellites, exhibited potential for use in more sophisticated attempts within a controlled and well-funded program. Some suggestions for the future application of remote sensing imagery in evaluating transfrontier air pollution in the border region and elsewhere are noted. A summary of the potential usefulness of the different image types for surveying various environmental concerns, in addition to transfrontier air pollution, was developed.

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INTRODUCTION

Within the last two decades, there has developed an increased awareness of the earth's "global" environment. This heightened awareness has evoked a recognition of the ramifications for world health and economic well-being associated with degradation of the global environment. It is notable that even the less developed countries (LDC's) of the world have expressed concern about environmental matters. Unfortunately, because of the disparity of wealth and knowledge among nations, there is no general agreement concerning the importance of global environmental issues or the manner in which those issues may be resolved.

International recognition of and concern for degradation of the global environment was expressed most recently through the Declaration On The Human Environment, which was formulated at the United Nations Conference On The Human Environment held in Stockholm, Sweden, in June, 1972. The Declaration sets forth principles for guiding future international attentions to global environmental pollution matters. Several of these principles explicitly relate to problems clearly international in character, while others address problems common to all nations that are not manifested as direct impacts outside a nation's territorial limits. Urban deterioration is an example of the latter, while an oil spill is an example of the former. Problems manifested as impacts outside territorial limits are referred to commonly as transnational pollution. Transfrontier pollution is a special case of transnational pollution and is the subject of this thesis.

Problem Statement

Transfrontier pollution literally refers to the direct movement of pollution from the frontier area of one country into the frontier area of one or more adjacent countries. Because transfrontier pollution involves areal associations of countries or states, definitive boundaries, and a flow or movement, it is inherently a geographic problem. However, economic effects, political associations, social activity, and the legal status and rights of sovereign states are integrally interwoven with the geographic associations of bordering states. Broadly interpreted, transfrontier pollution means any degrading influence transported between sovereign states, including not only commonly recognized pollutants of the air and water, but also socioeconomic pollution (e.g., poverty or disease). Thus, there are many aspects of the transfrontier pollution question which impinge on its purely geographic character. The problems posed by transfrontier pollution involve the total interactions of bordering states, not just geographic proximity and spatial considerations. It is presumed in this thesis that transfrontier pollution can be properly evaluated and resolved as an international problem only with an understanding of the broader associations of bordering states.

Beyond understanding frontier region associations, there is the imperative of detecting, monitoring, and controlling transfrontier pollution occurrences. Often, frontier regions are literally "frontiers": large areas of uncharted, unsettled, and isolated land. It follows that there is a need to obtain information regarding pollution movement where in situ methods are not feasible. The chosen method must be reliable and reasonably acceptable to the bordering states affected. Reliability is necessary to protect the rights of states and provide the means for objectively evaluating activities in the frontier region. Protection of rights and objectivity should assist international efforts to preclude transfrontier pollution occurrences and/or mitigate potential effects. Acceptability is absolutely necessary to problem resolution and may involve the entire spectrum of political, legal, and socioeconomic relationships of states affected.

The problem of transfrontier pollution is, therefore, twofold. Understanding the political, legal, and economic associations of bordering states clearly is requisite to cooperation and coordination of each state's activities relative to transfrontier pollution. Cooperation and coordination is critical to the resolution of the fundamental cause of transfrontier occurrences: the geographic proximity of frontier region activities in bordering states. Secondly, an acceptable method or procedure for evaluating transfrontier pollution problems must be embraced by the bordering states. While this involves the sensitive diplomacy of affected states, relative to the institutional aspects of cooperation and coordination, it also requires that techniques for information gathering be developed and agreed upon. One such technique, examined in this thesis, is remote sensing.

Goals and Objectives

The primary goal of this study is to define the geographic perspective of the political, legal, and economic factors affecting the remote sensing of transfrontier air pollution. The United States-Mexico border region or "borderlands" serves as the reference area for defining this perspective. The choice of the United States-Mexico border region derives from its usefulness as a case study example and not from a desire to formulate any particular solutions to problems of the region. Neither is this study to be considered an exhaustive analysis of transfrontier pollution as an international problem, per se. Accordingly, this study has the following objectives:

- Define the relationship of transfrontier air pollution issues to global environmental concerns;
- Define some of the fundamental political, legal, and economic influences modifying what is essentially a geographic problem;
- Define, generally, global pollution distribution characteristics;
- Examine transfrontier pollution problems associated with the United States-Mexico border region; and,
- Examine the feasibility and practicality of detecting and monitoring transfrontier air pollution utilizing interpretations of remotely sensed images.

These objectives provide a fundamental basis for evaluating transfrontier air pollution as a geographic problem. Much of the material presented herein relates to specific situations or conditions associated with the United States-Mexico border region. However, not all aspects of the problems of this region will be applicable directly to problems elsewhere in the world, but the region does encompass many of the attributes associated with transfrontier pollution problem areas. It is geographically large; significant portions are unsettled; much of the area is remote and sparsely populated, although there are large urban centers and significant population pressures; political friction is an historical fact; and, finally, there is intensive social and economic interaction.

Sources of Information

The compilation of material for this study occurred over a two year period and derived from numerous sources, published and unpublished. Several publications have been produced by international organizations concerning transfrontier pollution, most notably the Organisation for Economic Co-Operation and Development (OECD). An excellent reference, regarding 1) international environmental regulation, 2) environmental quality control for pollutants and nuisances at the national and/or regional international levels, and 3) pollutants of international significance, is the United Nations Institute for Training and Research publication entitled "International Cooperation for Pollution Control" (UNITAR Research Reports, No. 9). Official United States Government publications by the National Aeronautics and Space Administration (NASA) also provided valuable information, especially regarding pollutants of global and regional concern and pollutant detection and monitoring technology.

Information specifically concerned with pollution problems and socioeconomic characteristics of the United States-Mexico border region was obtained from several persons at the University of Texas at El Paso, Texas, where the initial impetus developed for two international symposia concerned with air pollution along the United States-Mexico border. Other published and unpublished works, addressing environmental problems of the border region, the northern portion of Mexico, and the southwestern part of the United States, were useful also. Remote sensing products evaluated herein were secured through the Technology Applications Center (TAC) at the University of New Mexico, and from the EROS Data Center, Sioux Falls, South Dakota. Also, personal experimentation with standard photographic equipment was conducted in the El Paso-Cuidad Juarez metropolitan area.

PART ONE

POLITICAL, LEGAL, AND ECONOMIC ASPECTS OF TRANSFRONTIER POLLUTION

CHAPTER I

INTERNATIONAL ATTITUDES, PERCEPTIONS, AND POLITICS

The general and specific attitudes and perceptions of national governments will affect the manner in which problems of a transfrontier nature are integrated into national policy. This chapter outlines the present perceptions of the international community respecting transfrontier pollution. Only the obvious political nuances associated with the problem can be detailed, but the fundamental framework of the international community's concept of transfrontier pollution and the focus of its attention are defined.

Recognition of a "Global" Environment

Prior to initiation of action, there must be a perceived or recognized need to act. With regard to the global environment, it seemed necessary first for the human species (and/or its institutions of management and authority) to recognize that "it was becoming evident that the uncontrolled impact of human activity upon the biosphere could not long continue without endangering the basis of life itself" (Lynton K. Caldwell, 1972). The importance of ecological associations and the ramifications of uncontrolled human activity were recognized early in the latter half of the nineteenth century by many scholars and individual writers. Charles Darwin's The Origin Of The Species and George P. Marsh's Man and Nature, or Physical Geography

As Modified By Human Action, originally printed in 1864, are notable examples of learned discourses on the interactions of global environmental systems.

However, widespread recognition by the general populace of a "global" environment and its deterioration did not develop until quite recently. It is commonly suggested, and probably true, that the coming of the space age and, especially, manned space flight in the late 1950's and early 1960's manifested the first full realization of the earth as a self-contained and self-limiting complex of interdependent sub-systems. Even so, the statements and actions of today seem to be merely echos of the concerns voiced over one hundred years ago. Thus, there now is general recognition of the critical nature of human activity, but there is no general agreement as to the degree of criticalness. Notwithstanding national self-interest, the inherent philosophical undertones of such a question probably will prevent resolution of the man-environment dilemna in present times as it has in the past. Whether or not the environmental impact of human activity is indeed critical, it can at least be stated that a determination of impact has been perceived to be critical. This is clear from the magnitude of attention and effort devoted to the issues of the global environment in the last decade alone.

Perhaps the single most significant event recently focusing on the global environment, its deterioration, and the desire for enhancement was the United Nations Conference On The Human Environment held in Stockholm, Sweden, in June, 1972. The UN Conference On The Human Environment was truly international in participation, and four years were required for planning and preparation. Delegates and/or observers attended from 112 nations, 21 UN agencies, 16 intergovernmental organizations, and 258 non-governmental organizations with international constituencies (Paul S. Muther, 1973). The program developed for the Conference included consideration of a Declaration On The Human Environment and six substantive areas of concern dealt with by three committees, as noted below:

COMMITTEE I -

Human Settlements and
Education, Information Aspects;

COMMITTEE II -

Natural Resources Management and
Environment and Development; and,

COMMITTEE III -

Organization Implications and
Identification and Control of Pollutants.

Because the committees were dealing with the concerns of a global environment, the problems of transnational and transfrontier pollution were cardinal considerations.

Transfrontier Pollution in the Global Environment

Daniel Serwer (1972) identified several kinds of pollution problems requiring international cooperation for their resolution. The most obvious of these problems, and the specific concern of this thesis, is the release of pollutants into an environmental medium in such a manner as to affect large portions of the biosphere. This kind of pollution can produce undesirable effects outside the state of origin at regional and even global scale. Thus, radioactive fallout may be a pollutant of international significance and be considered transnational pollution, because of its characteristics and wide distribution. Likewise, an oil spill from a ship registered under the flag of one country (and, therefore, under that country's jurisdiction) would be considered transnational pollution when the spill occurred in the waters under the jurisdiction of another country.

Transnational pollution, therefore, encompasses any activity producing undesirable environmental effects without respect to national jurisdictions. Transfrontier pollution is a specific case of transnational pollution whereby pollution is transferred or transported directly across a defined international boundary. Because the area adjacent national boundaries is often referred to as the "frontier" region in the formal context of a state's political territory, the term transfrontier is appropriate. Transfrontier is also a more definitive term with respect to the fact that pollutant transport and dispersion can, and presumably does, affect large areas well beyond a narrow borderline.

Important aspects of the activities and results of the UN Conference On The Human Environment related directly to the issues raised by transfrontier pollution occurrences. The initial Draft Declaration On The Human Environment included a direct reference to transnational pollution problems. Draft Principle 20 read:

> Relevant information must be supplied by States on activities or developments within their jurisdictions or under their control whenever they believe, or have reason to believe, that such information is needed to avoid the risk of significant adverse effects on the environment in areas beyond their national jurisdiction (Muther, 1973).

Draft Principle 20 implicitly referenced transfrontier pollution. There was hard conflict on this Principle between Brazil and Argentina, due to political friction between the two countries concerning Brazilian activities on the Rio Parana. Ultimately, this reference to transnational and transfrontier pollution remained only in the form of a suggestion for cooperation. However, in subsequent actions by the UN General Assembly (October and November of 1972), a resolution was passed stating "that the providing of information about potentially harmful activities will further the Declaration's aims of international responsibility and cooperation" (Muther, 1973). This probably resulted from the fact that several Principles adopted in the final Declaration recognized, through strong inferences, that there was a need to deal with problems of transnational and transfrontier pollution.

The final Declaration On The Human Environment passed by the delegates at Stockholm contained Principle 21 stating:

> States have the sovereign right to exploit their own resources and the responsibility not to harm areas outside their territory (Muther, 1973).

This Principle clearly recognizes the extraterritorial effects, which can occur from transnational and transfrontier pollution, but does not have the strong language of Draft Principle 20 cited above. That "states have the sovereign right to exploit their own resources" seems obvious, but the statement of these rights in the form of a Principle apparently was important to the LDC's out of concern that the developed countries would impose restrictions by way of pollution standards. Assessing "responsibility not to harm areas outside their territory" infers a certain degree of international liability should harm occur. However, the final Principle 21 falls short of the demands of Draft Principle 20, which required communication of the potential for harm. Four other Principles of the final Declaration imply recognition of transnational and transfrontier pollution problems by the delegates to the Stockholm conference. These Principles, as cited by Muther (1973), are:

Principle 6. The spread of toxic substances must be controlled. The just struggle of peoples against pollution should be supported.

Principle 7. The pollution of the seas must be prevented.

Principle 22. The international laws of cooperation should be developed further.

Principle 23. The relative values of all countries must be considered in setting pollution standards.

Principles 22 and 23 are especially relevant to the application of international leverage to resolve recognized international environmental problems. Also, Principle 23 reflects the concern of the conference delegates, especially those from the LDC's, with the disparity of wealth and power that may exist between affected countries. It insures that economic status and social values will not be subordinated to the interests of the affluent, industrialized nations.

Three Principles contained in the Declaration On The Human Environment directly relate to research and planning. They provide the framework within which remote sensing may be employed in solving global environmental problems, including those which are transfrontier in nature. As cited by Muther (1973), these Principles are:

Principle 17. Countries should designate institutions to help environmental planning.

Principle 18. Modern technology should be used for environmental planning.

Principle 20. The free exchange of scientific and environmental information must be promoted. Environmental technology must be made available to developing nations.

Clearly, the science of remote sensing can contribute to the objectives these Principles represent. Not evident in any of the Principles (other than from their vague wording) is the hesitancy of the delegates, especially those of Committee III, to commit an international effort to the actual determination of pollutants of international significance. Apparently, there was also a strong aversion to the development of any standards. "The final draft of recommendations limited the [pollution control] agency to development of internationally accepted 'procedures' to identify the pollutants (Muther, 1973).

Although there was resistance to actual determination of pollution activities and pollutant standards, there was no resistance among the delegates to the acquisition and assessment of knowledge concerning various pollutants nor to proposals for research, monitoring, and information exchange. An important concern, in part explaining the resistance, was national sovereignty. This concern was manifested in efforts to prevent, postpone, or weaken the impact of the naming of 'specific' pollutants and pollution problems. Resistance can also be explained relative to the ultimate ramifications of any actual determination, which are a calculation of damage costs induced by transfrontier pollution and/or more costly production processes to reduce pollution discharges. Most nations might be resistant to the

the first result; however, the LDC's were especially resistant to the latter, because expensive pollution reduction processes threatened to negate a competitive advantage over nations imposing national pollution standards.

Thus, although the Stockholm conference succeeded in generating a Declaration On The Human Environment and a set of recommendations for action from each of the three committees, the content of all elements was broadly and delicately worded. While the existance of transfrontier pollution problems was implicitly recognized, conference delegates generally accepted the premise that much needed study of the problems was precedent to the establishment of any specific technique, standards, or means in fulfillment of the Principles. The needed study led the delegates to establish a Governing Council for Environmental Programs reporting to the Economic and Social Council (ECOSOC), a subsidiary organ of the General Assembly. Through this Governing Council, the now recognized global environmental problems are being considered, especially the relationships of environmental policies to overall economic and social policies. The Governing Council also oversees, by way of annual review, the Environmental Fund, which is maintained through voluntary contributions to

> . . . be used for financing such programs of general interest as regional global monitoring systems, environmental quality management, research, information exchange, public education and training, promoting research for industrial and other technologies, and such other programs as the Governing Council may decide upon, taking due account of the needs of developing countries (Muther, 1973).

Clearly, remote sensing systems are suitable subjects for study relative to this mandate to the Governing Council and purposes of the Fund.

CHAPTER II

INTERNATIONAL LEGAL AND INSTITUTIONAL CONSIDERATIONS

In providing the groundwork for discussions on transnational and transfrontier pollution matters, Serwer (1972) asserted that pollution viewed as an undesirable effect on the environment varies with the physical, legal, economic, social, and cultural context; "Accordingly, the discharge of pollutants is not viewed . . . as either illegal or immoral, and the control of pollution is viewed as a matter of choice rather than necessity." The question as to whether transfrontier pollution is illegal or immoral has been answered to some extent in rulings by international arbitration panels and the International Court of Justice (ICJ) at the Hague. The question as to whether transfrontier pollution occurs from choice rather than necessity yields more subjective answers. These answers, as indicated by Serwer, derive from the perceptions, goals, and objectives associated with the political, social, and economic objectives of each individual state. The discussion of this chapter attempts to highlight some of the fundamental aspects of these two questions respecting international legal precedents and institutional frameworks. In addition, it addresses two other aspects of the legal concerns related to transfrontier pollution: the legal definition of frontier limits and the acceptability of remote sensing data and/or imagery as evidence.

Precedents: Legality and Morality

The classic case concerning the legal responsiblity of a state relative to transfrontier pollution occurrences is the Trail Smelter Arbitration in which the United States obtained remuneration from Canada for damages sustained from smelter emissions transferred from Canada into Washington state. Gunther Handl (1975) refers to the Trail Smelter Arbitration in his analysis of the Nuclear Tests case, which involved Australia and France. In the Nuclear Tests case, Australia argued it had suffered a moral injury, a violation of its territorial sovereignty, because an atmospheric nuclear test by France resulted in radioactive fallout being deposited on Australian territory. In examining Australia's claim of moral injury, Handl was convinced that case law and state practice rejected moral injury as sufficient ground for international responsibility associated with actions lawful, per se.

Both the Trail Smelter Arbitration and the Nuclear Tests case expose a fundamental legal question associated with transfrontier pollution: the rights of a sovereign state. This is exemplified by Handl (1975) when he defines the rights of France and Australia in the Nuclear Tests case as

> . . . the right as France sees it to carry out activities lawful per se in its own territory as the essential consequence of its sovereignty; and the right . . . claimed by Australia to determine itself what acts may take place within its territory, based on the very same notion of sovereignty.

Sovereignty is a complex and sensitive question in state relations and "recent trends in customary international law have been in the direction of expanding rather than contracting the sphere of territorial sovereignty or jurisdiction of states" (Oliver James Lissitzyn, 1965). The Trail Smelter Arbitration is considered the "locus classicus" of international legal principles and state responsibility relating to transnational and transfrontier pollution. Although international law was not strictly the basis for judgement, the arbitration strongly inferred

> . . . that under international law a state has to tolerate the consequences of the activities of another state affecting its territory which are lawful per se so long as these extraterritorial effects do not amount to injury and the case is not of serious consequence (Handl, 1975).

The Trail Smelter Arbitration established a quasi-judicial precedent concerning state responsibility when clear and convincing evidence indicates an injury of serious consequence has occurred. Thus, courts may be expected to look for an injury in fact, which could include environmental or aesthetic injury, but not moral injury.

"State practice" is an important element in interpretations of state responsibility in international relations. However, in the highly decentralized international legal system, determining the existence of a specific rule of international law or a particular practice or custom among states is a formidable task. State practice is often identified as conduct customary among states or as agreements generally recognized through explicit and implicit actions. Thus, Handl (1975) asserts the Declaration On The Human Environment, although not a legal, binding document, has provided what must be considered ". . . a clear expression of 'opinio juris' and thus as having a binding effect." Principles 21 and 22 of the Declaration confirm that material damage from activities lawful, per se, is a precondition for international responsibility. Because the Declaration was adopted by an international body, it acts to establish "state practice" and these two principles are specifically applicable to transfrontier pollution occurrences. Handl's assessment of air pollution as an international legal question concludes that

> . . . state practice in the field has been fairly limited and probably would not yet in itself afford a basis upon which one could determine exactly the conditions in which states would generally be considered responsible for transnational air pollution originating from their territory.

Beyond the obvious questions of sovereignty and internal rights of self determination, there are questions relating to transfrontier air pollution that expose very real and critical socioeconomic issues, which fortify the barrier against international cooperation. While some social and economic issues may have no apparent legal aspects, it cannot be denied that the "choice" of a state to pollute or not to pollute will undoubtedly have legal overtones with respect to state responsibility to the world community and neighboring states. Several issues of concern raised by an official of the Pan American Health Organization indicate that the "choice" is inherently international. Guillermo H. Davila (1973), referring to shared air pollution problems of the United States and Mexico, noted the following characteristics of the region that act as barriers to air pollution control and health maintenance:

> Judicial and legal characteristics: due to the absence of legal mechanisms which would establish joint paritcipation between . . . countries, and to the public health legislation adopted by [countries] related strictly to national needs;

> Technological and scientific characteristics: related to standard procedures, techniques, instrumentation, etc., adopted and utilized by [countries];
>
> Economic characteristics: due to standards of living in [bordering countries], due to policies for economic development established [independently by countries], and due to the economic resources that each country can allocate to air pollution control activities; and,
>
> Urban planning characteristics: due to the standards and criteria for urban planning adopted by [bordering countries and applied to frontier region development regardless of the policies of the neighboring country].

The expressions of Davila have been freely modified in order to reveal that the issues are or can be common to the problem of transfrontier air pollution anywhere in the world. As indicated earlier, the United Nations and other international institutions have begun efforts to deal with transfrontier pollution as a potentially critical international problem. In the interim, cooperative agreements (or even unilateral action) in regions where transfrontier air pollution is already a problem must be or has been initiated. However, this ad hoc approach will not replace solution in an international forum, because the atmosphere cannot be reduced to national control. Unilateral action or inaction simply adds another echo to the voices of a century ago.

Institutional Aspects of Transfrontier Air Pollution

The atmosphere is what economists refer to as a "common property" resource. Therefore, it is a resource, ". . . which cannot, or can only imperfectly be reduced to private ownership" (Allen V. Kneese, 1977). Common property resources are, by the very meaning of the phrase, common to all: "Clean air is everyone's right; yet, as long as we fail to understand this and accord it proper priority, we shall continue to make the air we breathe intolerable" (Joaquin Telloz, 1973). This inherent characteristic of the atmosphere necessitates a unique institutional framework for coping with territorial activities leading to extraterritorial effects and deterioration of global environmental quality.

Robert E. Stein (1972) discusses several different approaches states can implement to resolve pollution problems of a transfrontier nature. In his discussion of the role of international arrangements between affected states, he stresses the need for an international pollution control institution. This institution might possess at least five functions: "planning, standard setting and apportionment, monitoring, contingency plans, and regulation." Similarly, Christopher Bo Bramsen (1972) asserts the need for states to cooperate between themselves and with international organizations to work out standards, working limits, and acceptable levels of pollution. Clearly, the objectives noted in relation to the Declaration On The Human Environment are aimed at accomplishing these goals. Serwer (1972), in his discussion paper prepared for the Stockholm conference, also recognized the need for an "international forum." Albert E. Utton (1973) stressed the need for the development of a "special" institutional framework for resolving transfrontier pollution problems.

It is evident that the solution to transfrontier pollution problems must be developed, ultimately, within institutional arrangements accommodating all states concerned. It is also evident that "the physical proximity of such concerned states, their trade relations, their political and economic systems, and their stage of development are likely to be important factors in determining the appropriate intergovernmental forum . . . " (Serwer, 1972). What is not evident is that which is necessary to gain participation in such institutional arrangements. Although another one hundred years may go by, it seems clear that "old habits of nationalism need to yield to new concepts embodying optimal utilization of shared resources" (Utton, 1973). The Declaration On The Human Environment is apparently one more step in a long process of perception and recognition leading to action.

Definition of Frontier Limits

An important factor in the legal question of transfrontier air pollution occurrences is the geographic or legal description of the border. By definition, a transfrontier pollution problem cannot exist until and unless the pollution originating in one country moves to the territory of another country. Therefore, the boundary between affected countries must be accurately defined and the fact that pollution was transferred across that boundary must be proven. The next section of this chapter will outline several bases upon which remote sensing data and/or imagery are acceptable as evidence. The concern of this section is the geographic or legal description of national boundaries.

The land boundaries between most of the world's states are fairly well described and accepted, although there remain many areas where disagreements still exist. When land boundaries are defined and have been surveyed and accepted, presumably there would be little difficulty in establishing the fact of a transfrontier pollution occurrence. This, of course, assumes that evidence is not debated. However, a principal problem may well emerge relative to boundaries in general. The political boundaries of states do not always terminate neatly at land's edge. There is, in fact, a significant body of international law dealing with the delineation of political and jurisdictional boundaries into adjacent waters of coastal states. As such, the geographic scope of transfrontier pollution as an international problem effectively extends to areas or "zones" in bodies of water, where states have asserted varying degrees of territorial and jurisdictional rights. While many of the problems arising in these zones (principally, the Territorial Sea, the Contiguous Zone, the Fishery Zone, and the Exclusive Economic Zone) will be of a transnational nature, it is clear that pollution occurrences of a transfrontier nature are likely or may be defined as such.

In examining this particular aspect of transfrontier pollution, it is informative to review the Law of the Sea Conventions. The Law of the Sea embodies principles of international law that have been tested over a great many years and it provides an indication of the probable future directions of international law respecting transfrontier air pollution: that the oceans of water and oceans of air are both common property resources is difficult to deny. The Law of the Sea Treaty, currently under consideration (and conventions currently in effect), embodies the concept that the seas are a common property resource of all states. This is such a strong concept that even states having no geographic proximity to the seas are guaranteed unrestricted access and use of the seas. However, as Lissitzyn (1965) noted, the trend is towards expansion of the sphere of sovereignty or jurisdiction by coastal states. Although the right of free passage is not affected, the coastal states have asserted what can be considered "property rights" over certain aspects of the marine environment. This trend is based on and supported by state practice; however, the trend is integral to the new Law of the Sea Treaty, which deals with all as aspects of marine pollution (Scty. Henry A. Kissinger, 1976). For example, the Informal Composite Negotiating Text of the 3rd United Nations Conference on the Law of the Sea (July, 1977) sets forth several principles of conduct relative to the environmental quality of straits:

> Article 39.2.(b) requires that ships in transit "comply with generally accepted international regulations, procedures, and practices for the prevention, reduction, and control of pollution . . . ";
>
> Article 42.1.(b) provides that states bordering straits may make laws and regulations in respect to "the prevention, reduction, and control of pollution by giving effect to applicable international regulations regarding the discharge of oil, oily waters, and other noxious substances . . . ";
>
> Article 43.(b) calls on states bordering straits and user states to "by agreement co-operate . . . for the prevention, reduction, and control of pollution from ships."

There are numerous other references to protection of the marine environment from pollution in the Negotiating Text. Significantly, with regard to questions of transfrontier pollution, Article 55.1.(b)(iii) provides coastal states explicit jurisdiction for the preservation of the marine environment within the "Exclusive Economic Zone." The Exclusive Economic Zone extends 200 nautical miles from the territorial base line. Therefore, the effective geographic extent of state boundaries, relative to transfrontier pollution, is 200 nautical miles seaward. Thus, territorial and jurisdictional boundaries and rights asserted by coastal states are potential legal questions. The fact that the "effective" border between coastal states may well extend 200 nautical miles seaward significantly alters the customary view of transfrontier pollution being associated strictly with the land based boundaries. Although this facet of the legal question of international boundaries and transfrontier pollution is primarily related to water pollution problems, an important point can be made with respect to air pollution. If and when ratified, the Law of the Sea will establish precedents amenable to the adjudication or arbitration of matters relating to the environmental quality of the atmosphere. In fact, state practice has already made many of the principles being negotiated an integral part of customary international law.

Acceptability of Remote Sensing Data in Legal Proceedings*

The permissibility to enter remote sensing imagery (or data) as evidence in legal proceedings involves complicated judicial aspects associated with the common rules of evidence. In general, legal acceptance of remote sensing data is fundamental to its usefulness respecting any transfrontier pollution occurrence and adjudication of

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*The following discussion is condensed from "Remote Sensing Evidence And Environmental Law" in California Law Review authored by Howard A. Latin, Gary W. Tannehill, and Robert E. White (pp. 1300-1446). Numbers in parentheses refer to pages in CLR. See List of References for complete cite.

consequent damage claims of bordering nations. It must be noted that this review is inadequate with respect to "international" litigation; however, it provides a basic framework for an understanding of the admissibility of remote sensing outputs as evidence. Probably the most significant aspect of using remote sensing outputs as evidence is the unique and highly technical principles and methods employed in obtaining the images or data. Therefore, expert testimony is usually required, a determination of reliability of methods is made, the certainty of acquisition procedures is evaluated, and the authenticity of the output or product is verified.

The novel and scientific nature of remote sensing requires that expert testimony, once allowed, 1) establish the reliability of the scientific theories and techniques employed, 2) document that instruments employed were "constructed and operated in a manner consistant with" these theories and techniques, 3) identify the output as derived from the instruments so employed, and 4) interpret the output (1366). There are two important caveats to these four requirements. The first is that one witness may or may not be considered qualified (i.e., expert) to react to all the requirements. The second is that one witness may or may not be considered qualified to testify with regard to different remote sensing devices employed and imagery (or data) offered in evidence. In fact, it is quite likely that the expertise of a witness will be narrowly confined to a very specific aspect of a particular remote sensing output or a particular theory or technique. For example, an expert witness may be qualified to testify with regard to image interpretation or system applications, but not be qualified to testify with regard to the physics and optics of the instrumentation employed. However, courts recognize they are most competent at interpreting the law and tend to defer to witness expertise.

Although courts tend to defer to witness expertise, there will be a determination of the reliability of evidence presented. "It is clear that the great majority of jurisdictions require a higher degree of reliability for the admission of scientific data than for most other forms of evidence" (1374). Courts will employ both predictive and normative criteria in determining the reliability of evidence. The issue at law affects the degree to which any one of these criteria is applied. Predictive criteria include concerns of the court relating to the validity of the methodology incorporated to obtain the evidence. Areas pursued by the courts in this regard often take the form of queries as to:

- whether the principles of a particular scientific methodology "have achieved 'general acceptance within the scientific community'" (1375);
- whether a specific scientific discipline or recognized field of expertise exists, which possesses recognizable standards for qualification;
- whether the principles involved are universally accepted and/or have widespread application to non-legal pursuits;
- whether independent, repeated applications have produced consistent and accurate results and conclusions; and/or,
- whether the extent and nature of the effect of uncontrolled variables on the output has been adequately defined.

Normative criteria employed by the courts "must decide, as a matter of law, whether [the] predicted level of reliability is adequate to support admission of the evidence in a particular case" (1375). Thus, the courts must decide whether or not to admit the evidence on the basis of the legal context of the proceeding and the relevant standard for admissibility. For example, criminal proceedings require proof "beyond a reasonable doubt," while challenges to administrative decisions require only that "there is substantial evidence" (1393). However, courts have demonstrated a liberal bent with respect to remote sensing evidence, partly because of the technical complexity of cases involving submission of remotely sensed information, partly because there is often a need for the wide area or "synoptic" perspective possible with remote sensing images (especially relative to environmental issues) and partly because "a substantial proportion of remote sensing submissions will be made in administrative proceedings" (1395). Other normative criteria include:

- the importance of the issue at law, which relates closely to that just described;
- the margin of error associated with the evidence, which relates closely to the tests of consistency and accuracy employed in determining reliability; and,
- the availability and comparability of results derived from alternative methodologies, techniques, or applications.

Given that the expertise of a witness and the reliability of a methodology (as defined by an archetypal model) are acceptable, the court still must decide " . . . whether a typical application of the process is capable of producing acceptable information in the normal course of events" (1403). Most importantly, the courts must determine not whether " . . . the process could yield trustworthy results, but . . . whether the application of that process in a specific case did yield the desired degree of trustworthiness" (1404), Thus, the acquisition procedure or, in other words, the proper conduct of the remote sensing technique must be verified. In the past, inquiry by the courts, as to the proper conduct of scientific processes, has considered:

- whether the methods incorporated in the application at hand conformed sufficiently to the approved archetypal model;
- whether the methods of the process were properly applied, including the correct and proper operation of the devices; and,
- whether the process was conducted by qualified individuals.

Notwithstanding admissibility of the evidence and the truth of its content on the basis of the three aspects outlined thus far, there is, ultimately, a requirement that the identity of the submitted imagery or data be established. This is an especially critical condition for remote sensing, because of the various manipulation techniques employed in the interpretative process (e.g., image enhancement, false-color composites, contrast stretching, and others). Thus, two essential issues for consideration are: " . . . 1) does the image actually portray what it purports to depict; and 2) is the image submitted in court legally equivalent to that which was initially obtained?" (1419). The court's satisfaction, respecting these two issues, is ideally based on the extrinsic facts relating to acquisition, testimony of the acquirer, and demonstration of a "chain of custody." The chain of custody substantiates the images or data as original products or outputs. "In view of the diversity of potential remote sensing techniques and the different formats in which remote sensing information may be introduced in court, the authentication procedures appropriate in any given case may range from a minimal showing of identity to an exhaustive demonstration of the complete chain of custody" (1421).

Given a spirit of international cooperation and good faith between nations and a common understanding of the transfrontier pollution problem, technicalities examined in this section may never be of concern. That remote sensing outputs are potentially useful as evidence in an international arena is demonstrated by the following:

> Landsat and Skylab imagery certainly have implications in this field . . . . An historic example is smelter smoke from the Douglas, Arizona smelter drifting into Mexico as recorded on Apollo 6 in 1968. The Governor of Sonora, Mexico reportedly showed this to the Governor of Arizona and shortly thereafter Arizona enacted some of the most stringent air pollution controls in the country (1351).

That remote sensing outputs are potentially useful in furthering the aims of both the United States and Mexico in detecting, monitoring, and controlling transfrontier air pollution problems in the border region remains a question of this thesis. However, no amount of demonstrated technical capability will override non-cooperative attitudes, conflicting government policies, and socioeconomic differences unless great effort is expended by both countries.

CHAPTER III

ECONOMIC CONSIDERATIONS

As noted earlier, Serwer (1972) indicated that not only geographic proximity, but also trade relations, the political and economic systems, and the stage of development of states would likely be important factors in determining the appropriate intergovernmental forum for resolution of transfrontier problems. There are many elements of an international control activity capable of illiciting economic effects. Effects on growth and development goals and trade relations seem to be basic to state concerns. The discussion in this chapter focuses on the inherent trade-offs that will surface when states seek to resolve a problem such as transfrontier air pollution and when an organization such as the United Nations seeks to strive for global environmental enhancement. Economic considerations also invoke the question of damage payments between states in cases where damages are of consequence. Therefore, a brief outline of one scheme for classifying damages is presented, which relates the nature of damages to the type of economic loss incurred. The chapter concludes with a discussion of the role of institutions in dealing with the economic aspects of transfrontier air pollution.

International Economic Effects

The distribution of air and water pollution is a manifestation of the use of earth's common property resources by sovereign, economically independent nations for the disposal of unconsumed by-products or residuals from internal socioeconomic activity. Therefore, external effects are experienced by all nations to some degree or another as the pollution is dispersed through the dynamic actions of the atmosphere and hydrosphere, respectively. As this means " . . . that there is an inadequate impediment to social damage and an inadequate return to the production of social benefits," it can be assumed that the general welfare of the world's population is not well served (William J. Baumol, 1971). From another viewpoint, environmental enhancement and/or prevention of environmental degradation may be considered an external effect, if the definition of external effects is accepted to include costs imposed on nations by way of organized influence and power. These costs are commonly referred to be economists as externalities in both instances.

Recognition by the LDC's of an imposed cost, resulting from influence exerted by the developed countries, is evident from the outcome of the Stockholm conference and the Principles and recommendations cited in Chapter I. The developed countries, experiencing the gravest pollution problems over-all, are sufficiently affluent to effect some degree of remedy. However, similar efforts by the LDC's are viewed as a luxury. LDC's have inadequate resources (financial and otherwise) to meet many of the immediate needs of their populations, such as food, shelter, and employment, let alone expensive pollution abatement processes. In a sense, LDC's must pursue development at any cost, although development compatible with a clean environment would probably be cheaper in the long term.

The complexities of understanding the characteristics of pollutant dispersion may be only minor compared with the complexities associated with international agreements for enhancement of the global environment. A key issue in the future will concern the question of comparative (or competitive) advantage between nations, especially between the less developed and developed countries. As the developed countries undertake costly efforts to reduce pollution, LDC's well may become "pollution havens" and be able to produce cheaper goods for the world market. Thus, they will acquire a comparative advantage over the developed countries. This poses a problem for international trade balances, which will be examined shortly. Paradoxically, this advantage is also a disadvantage for the LDC's, because, in effect, the developed countries will have exported some pollution generating activities.

The problem of comparative advantage is not limited to a dichotomy of developed and underdeveloped countries. There is also a question of geographic location. The Mediterranean Sea is a good example: " . . . with only one outlet through the narrow Strait of Gibralter, the Mediterranean requires much more expensive pollution controls than those needed on wide oceans" (Business Week, 10/31/77). This geographical aspect of pollution control is affecting both the developed and underdeveloped countries of the Mediterranean. It is affecting the competitive position of the developed countries relative to world markets (_e.g._, Italian Chemical giant Montedison). For the developing countries, the imposed pollution control requirements " . . . are a barrier to development that the developed countries did not have when they were at the same economic stage 20 years ago . . . " (Business Week, 10/31/77).

In addition to general questions of growth and development, many questions have been raised respecting the alteration of international trade relations induced by transfrontier pollution effects. Because of the peculiar complications inherent to externalities generated by transfrontier pollution occurrences, Baumol (1971) has suggested that the classical subscription to a world of free-trade may lose some of its form. By this he meant that the classical basis for free-trade between nations may be required to take a back seat to a new philosophy; a philosophy which recognizes the impact of transfrontier pollution externalities on economic interaction. Whether this is true or not remains a question. Nonetheless, three broad economic concerns, specifically related to transfrontier pollution problems, deal with 1) the balance of payments of nations, 2) the effect of unilateral abatement actions, and 3) the manifestation of implicit or explicit subsidies.

Each of the three concerns just noted is intricately interrelated, and it is necessary to evaluate each relative to the other. A further complicating aspect is that transfrontier pollution may be manifested as a physical transfer of pollution through an environmental medium or as a transfer of the polluting activity. This is to say, a polluting nation can export pollution in two ways: 1) introduce pollutants into an environmental medium that extends beyond its borders and 2) restrict, inhibit, or prohibit entirely the emission of pollutants thereby encouraging emigration of polluting activities to other nations. The most obvious result of the former is the external effects accruing to the receiving nations. Initially apparent is the damage incurred by the receipt of the pollutants. Significant efforts have been made to determine means for measuring damage in economic terms and establishing a framework for accounting for and collecting damage payments. But, in essence, the receiving nations also subsidize the source nation by being the depository for its wastes or residuals. This subsidy, which is an external benefit to the polluting nation, undervalues the cost of goods produced by the polluting process. Therefore, the undervalued goods, when exported, produce a distortion in the balance of payments between the exporting and importing countries. In effect, the nations receiving the pollution, generated in the production of the goods, will pay the additional cost of damages and the subsidy on top of the price of the goods. The complexity of this situation is clear, and considerable attention has been given to the development of economic adjustments to these distortions produced by transfrontier pollution (OECD, 1976b).

An even more complex problem involves the implications of a direct transfer of a polluting activity to another nation. The problem can no longer be dealt with in the form of simple cost functions. The problem requires an analysis of welfare functions and sociopolitical considerations. It is often noted that " . . . the growing concern with pollution problems in wealthier countries means that the poorer industrial countries may well begin to specialize more in polluting type industries" (Baumol, 1971). The rationale behind this concern is that polluting industries will incur higher costs in wealthier countries as stricter standards are imposed. This will result in the poorer industrial countries gaining a competitive advantage, because there will be less inclination to impose these costs and, therefore, production costs will be lower.

This same effect can result from outright prohibition of a polluting activity. Clearly, an occurrence of this type can have an effect on the balance of trade between the wealthier countries and the poorer industrial countries. However, it is not clear that the transfer of polluting activities will actually occur. The reason for doubt is that the acceptance of polluting industries amounts to " . . . a peculiar export subsidy that conceals more effectively than most others what the exporting country is giving away to its customers" (Baumol, 1971). Thus, in effect, the poorer industrial countries, while providing benefits to themselves in the way of jobs and income, provide benefits to the countries importing their new goods by absorbing the greatest burden of the pollution. It is important to note that the transferred polluting activity will, in turn, become a source of transfrontier pollution for the wealthier countries, which negates, to some degree, efforts to reduce pollution.

Whether or not the short-run balance of payments and employment benefits, derived by the poorer industrial countries by becoming pollution havens, will outweigh the longer-run consequences is in doubt. At present, it appears that LDC's with an established industrial base will subsidize the economic activity of the developed countries for some time to come, either as receivers of pollution or receivers of polluting activities. In this regard, it is apparent that an exchange of subsidies will be occurring: LDC's will subsidize the developed countries in the manner described above, while the developed countries will subsidize the LDC's through contributions to the Environmental Fund and contributions to independent technological research efforts, which are directed at the development of more efficient, cleaner processes.

Environmental Damage and Economic Losses

If damage costs are to be estimated, there must first be an estimate of damage effects. It is desirable to quantify the effects and potential consequences when and where practical. Effects may require measurement in different units, because of the physical character of the effects or the perceived nature of the effect, which may vary with cultural value systems. Therefore, to gain an appreciation of the total impact, it is necessary to attach an objective measure to each effect associated with a given pollutant. This objective measure is usually an economic value expressed in monetary terms. An intergovernmental forum or an international judicial or arbitration panel attempts to apply this knowledge in a pollution prevention and control program or in settlements of international claims, respectively.

There are no perfect classification schemes, but, generally, damage can be classified according to the receptor suffering the damage, the pollutant causing the damage, or the sources emitting the pollutant. Which is more effective, relative to an international situation, is unclear and, in fact, all may be useful. The Organisation for Economic Co-Operation and Development (OECD) classifies damage into six broad receptor categories. These six categories are schematically related to the type of loss incurred (Table 1). The type of loss incurred determines the manner in which settlements will be resolved, the difficulty

Table 1. Damage Classification Scheme with Examples

Damage Category	Type Of Loss Incurred: Financial	Amenity
Human Health	Productivity losses. Health care costs, including increased research costs to avoid pollution. Premature burial costs.	Risk Aversion. Cost of suffering. Cost of bereavement. Cost of limitations imposed upon an individual, his family and his society.
Fauna	Lost animal and fish production.	Risk Aversion. Reduced pleasure from fishing and hunting. Reduced wildlife populations.
Flora	Reduced crop production. Reduced forest growth.	Risk Aversion. Reduced pleasure from horticultural and forestry losses.
Natural Resources	Lost production from polluted water or soil.	Risk Aversion. Decreased recreation benefits.
Materials	Reduced life of a material. Reduced utility of a material. Cost of producing a material. Extra cost of a substitute.	Risk Aversion. Endurance of soiled or damaged materials. Damage to selected aesthetic monuments and objects.
Climate and Weather	Reduced agricultural output from decreased rainfall. Larger lighting expenses from decreased sunshine.	Risk Aversion. Decreased recreation benefits from decreased sunshine or increased rainfall. Decreased pleasure from reduced visibility.

Source: Adapted from OECD, 1976a.

of the computation, and the sensitivity of negotiations. Financial losses can be determined fairly objectively, though with complications. Generally, financial losses can be considered those " . . . changes in the level of expenditures resulting from environmental quality changes . . . " (OECD, 1976a). If sufficient data are avialable, then there are apparently relatively few obstacles to estimating the monetary value of financial losses. However, amenity losses are intangible and somewhat subjective. Amenity losses may well invoke feelings and sentiments deriving from cultural differences as well as social goals.

Institutional Aspects of Economic Considerations

The problem of externalities produced by environmental degradation is relatively new to international affairs. Thus, there has developed a need for a basic understanding of the role and purpose of institutional arrangement in resolving economic issues induced by transfrontier pollution. Several aspects, relating to the role of institutions in dealing with the economics of transfrontier pollution, in general, have been examined and identified by the OECD (1976b), as noted below:

- the essential role of multicountry agencies should be the " . . . production of technical, economic, and social data," which can be accepted by all parties without question;
- the institution or agency should provide a framework for the transfers, payments, or payments-in-kind, which will almost certainly be an integral part of most agreements;
- the institution or agency should provide a forum for formal bargaining on levels of pollution and payments;
- where reciprocal problems exist, such as on a lake, the role

of international cooperation is not to bring about a state which would not be achieved by independent actions, " . . . but to do so more quickly, with less uncertainty, and with greater equity";

- for each country, the best institution is one minimizing total costs of transfrontier pollution or maximizing the benefits of transfrontier pollution control;
- the best set of institutions and policies for a combination of two or more countries will minimize the total international cost with consideration given to distribution of those costs; and,
- on an international basis, the best agreement whould bring about a set of institutions minimizing the sum of all costs.

The term "costs," as used by the OECD, includes all expenses or losses resulting from abatement actions, actual damages, transportation, agreement to conditions, and compliance with agreements. These costs will be incurred between countries and between jurisdictions and private actors. The economist accepts as given that the best institutions or procedures will lead to a rational and equitable compromise between two extremes: high pollution with heavy damage and low pollution with heavy abatement costs. These two extremes are representative of the conflict of growth and development goals between the poorer industrial nations and the more affluent industrialized nations, as outlined earlier. The two extremes also reflect, to some degree, the economic relationship between the United States and Mexico.

The fact that Mexico possesses an industrial base has produced an institutional effect of a different type, which affects the role remote sensing will play in resolving transfrontier air pollution problems along the border. The United States Agency for International Development (USAID) has been restricted from assisting Mexico in capital intensive projects by a congressional mandate (Charles K. Paul, 1978). This mandate prevents the USAID from establishing a remote sensing center in Mexico and assisting in the training of personnel. Thus, it seems that institutional factors have precluded an important financial resource for Mexican development of a remote sensing program. This denial of direct financial aid is mitigated, perhaps by a cooperative research program between the National Aeronautics and Space Administration (NASA) of the United States and the Comision Nacional del Espacio Exterior (CNEE) of the United Mexican States, which was effected by an exchange of notes February 27, 1965 (TIAS* 5763; 16 UTS 620). This agreement was subsequently amended and extended June 15, 1972 (TIAS 7371). Amendments added responsibilies for NASA in developing Earth Resource Technology Satellite (ERTS, later renamed Landsat) data and training qualified Mexican personnel. Thus, through this program, Mexico is receiving aid or a subsidy to develop the technical expertise to utilize remote sensing information.

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*Treaties and Other International Agreements Series

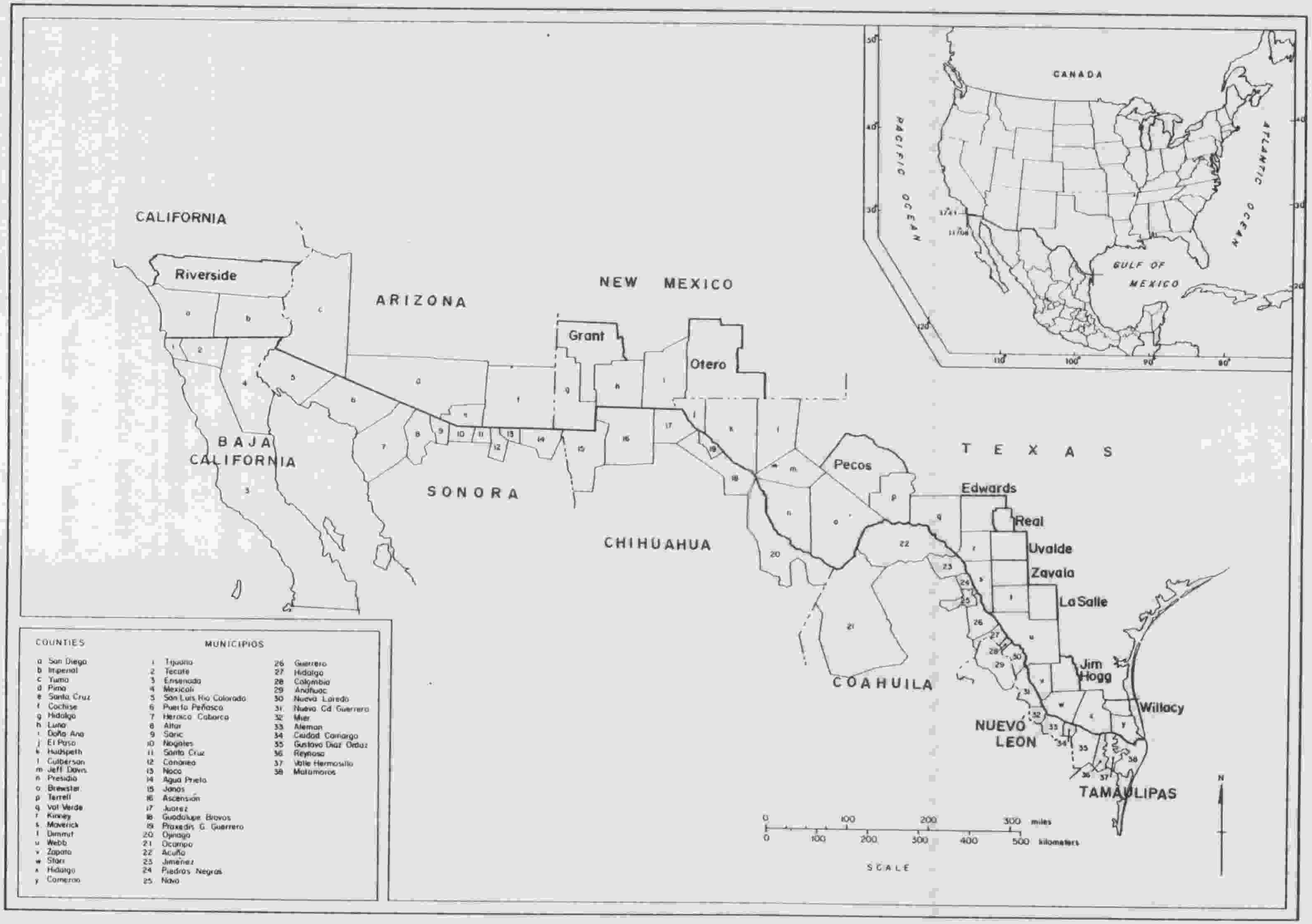
PART TWO

TRANSFRONTIER AIR POLLUTION PROBLEMS ASSOCIATED WITH THE UNITED STATES-MEXICO BORDER REGION

CHAPTER IV

TRANSFRONTIER AIR POLLUTION GEOGRAPHY: THE UNITED STATES-MEXICO BORDER REGION

This chapter focuses on the physical and social geography of the United States-Mexico border region, evaluating those elements deemed prominent in the generation and distribution of pollution throughout the region. If one assumes the definition of a region is based on a defined area in which there are recognizable relationships between a selected set of phenomena at a given time for a particular purpose, then there is no "border region" defined in the literature appropriate to the evaluation of transfrontier air pollution. In the United States, the border region has been formally identified by the Southwest Border Region Commission (a State/Federal coordinating body supported by Federal funds) as the counties adjoining the border and some counties that do not, as shown in Map 1 (Wayne Gyulae, 1978). Counties are convenient for purposes of statistical data gathering and analysis, and they provide a viable, in place, political structure for dealing with border associated issues. However, political units rarely reflect the realities of spatial associations, and this instance proves no exception. In Mexico, the area often identified with reference to border related problems and issues is the La Fontera (The Frontier); a zone delimited by a line drawn approximately 16 km (10 mi) from the border. This has been true especially with respect to air pollution problems

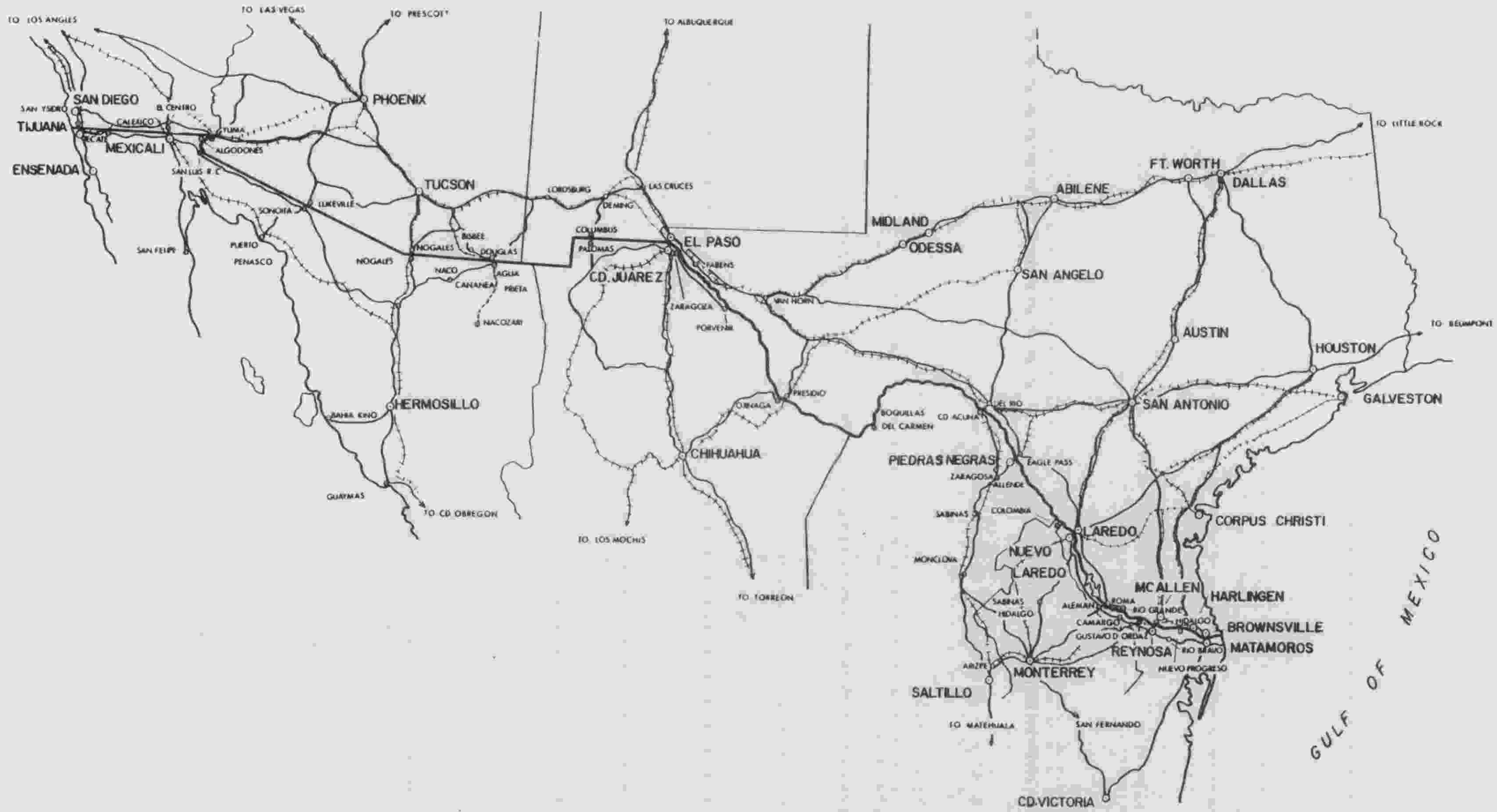


Map 1. United States-Mexico Border Region Counties and Municipios. Adapted from Schmidt (Forthcoming, a).

along the border, because present transfrontier air pollution problems of principal concern are, primarily, associated with urban centers adjacent the border (Howard R. Applegate and C. Richard Bath, 1974).

The need to define a border region, sensitive to the interplay of the spatial associations of physical, political, economic, and social factors, is apparent. To denote the land area associated with the United States-Mexico border, many writers have employed the term "borderland(s)." Richard L. Nostrand (1970), for example, incorporated "borderland" in his definition of the Hispanic-American culture region of the United States. Nostrand narrowed Herbert Eugene Bolton's original use of the term "Spanish Borderlands," which Bolton regarded as stretching broadly across the southern United States and including part of northern Mexico. Nostrand restricted the meaning of the term borderland to the land area north of the border. Ellwyn R. Stoddard (1975) employed the term "borderlands" more nearly as Bolton intended in 1921. Often the term is used to refer to an intuitive recognition of all land area having a recognizable relation to the border. For example, most of New Mexico and Arizona, the southern halves of Texas and California, and the six northern states of Mexico may be considered borderlands by some writers (Map 2).

Given the dynamics of atmospheric processes and a plethora of factors modifying the lifetime and, therefore, the distribution of pollutants, delimitation of a transfrontier air pollution region in association with the United State-Mexico border is probably a moot issue. In fact, the concept of an "air shed," which is an idealized region of the atmosphere often used for evaluating air pollution problems, has been



Map 2. United States-Mexico "Borderlands". Transportation linkages and relationships of urban centers are important factors defining the "Borderlands" geographically, From Schmidt (Forthcoming, c).

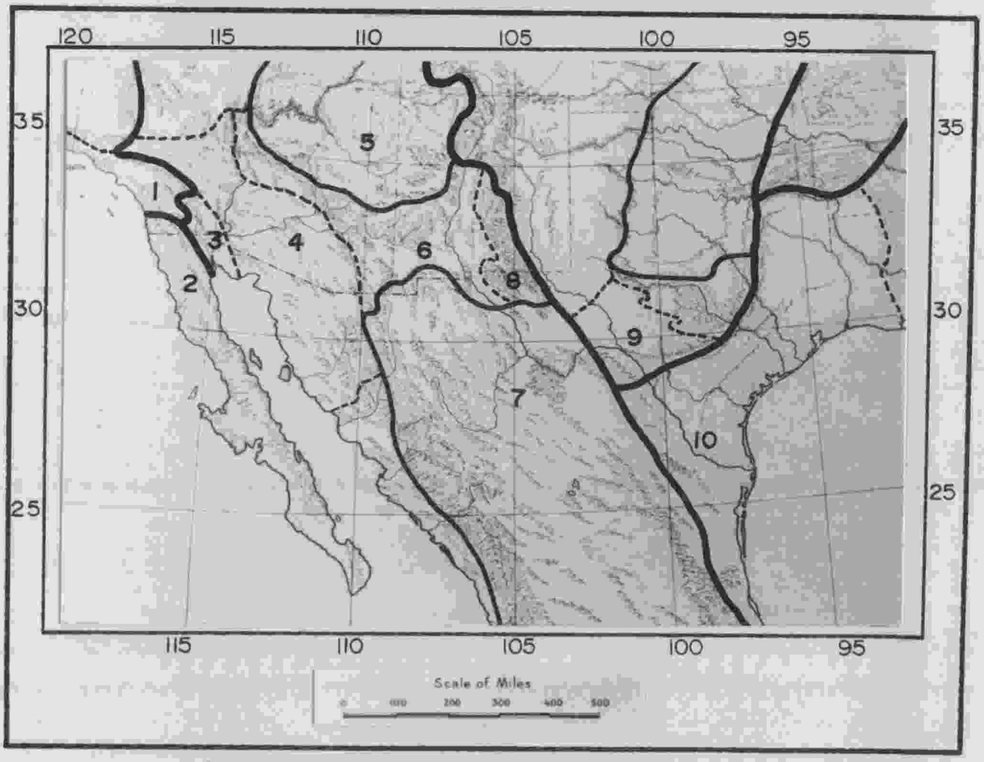
determined to be ineffective by the United States Environmental Protection Agency (Sabino Gomez, 1978). For purposes of evaluating environmental problems, especially air pollution and its detection utilizing remote sensing methods and techniques, precise delimitation of a border region is not necessary. It will become clear in the remainder of this thesis that transfrontier air pollution problems, associated with the border, can be manifested as local or widespread regional, even global, problems. Thus, the term "border region," as employed in this thesis is used to convey a focus on the borderlands: an area essentially undefined in terms of natural processes, but recognized as a unique geographical area of interface between the United States and Mexico. It must be noted that this definition of the border region is insufficient for the evaluation of specific concerns related to pollution distribution and measurement of effects.

Physical Geography

Two elements of the physical geography of the border region are prominent in the distributional character of air pollution: topography and climate. Both affect the transport and diffusion of pollutants and the transformation and removal of pollutants. Soil and vegetation characteristics of the border region are important in the generation of air pollution rather than modifiers of the distribution. Notwithstanding the distribution effects of physical characteristics, the imperative of familiarization with the physical geography derives from the need for "collateral information" in the interpretation of remotely sensed imagery. Also, climate, topography, soils, and vegetation affect scene radiance recorded by remote sensors, which is an important consideration in evaluating the usefulness of employing remote sensing methods and techniques in the border region.

Border region topography derives from the charactertistics of five Physiographic Provinces. However, the most characteristic topography within the border region is the NW-SE trending valley and ridge system of the Basin and Range Province (Map 3). The central portion of the border region is an area of isolated mountain ranges (largely dissected block mountains) separated by aggraded desert plains. This area is referred to as the Mexican Highlands Secion of the Basin and Range Province in the United States and the Mexican Plateau Province in Mexico. The detritus-filled basins or "bolsons" vary in elevation from 1,500 m to 2,000 m (4,900' to 6,600') and are the most extensive and conspicuous feature of the landscape (Robert Wauchope, 1964a). The higher mountain ranges rise above the adjacent basins to elevations of 2,000 m to 3,000 m (6,600' to 9,800') above sea level.

Westward from this central portion, toward the Colorado River, the topography is typified by " . . . a series of high parallel N-S ranges and narrow alluvium-filled basins forming a transitional area between the Sierra Madre Occidental and . . . the low, dry western plains and isolated ranges half buried by stream-borne alluvium" of the Sonoran Desert Section of the Basin and Range Province (Wauchope, 1964a). About 113 km (70 mi) east of the Colorado River, the low desert plains grade into the Salton Trough: the northward extension of the Gulf of California, a tectonic rift or trough. On the western margins of this low desert are the extensive sand dune fields of the Yuma Desert in the United States and the "Gran Desierto" in Mexico.



Map 3. Topography of the United States-Mexico Borderlands. Base map from D. E. Lee (1938). Physiographic regions from Nevin M. Fenneman (1930), Wauchope (1964a), and David Greenland and Harm J. De Blij (1977).

Physiographic Regions

Pacific Mountain System
- 1 - Los Angeles Range Section, Pacific Border Province
- 2 - Lower California Province

Intermontane Basins and Plateaus
- 3 - Salton Trough Section, Basin and Range Province
- 4 - Sonoran Desert Section, Basin and Range Province
- 5 - Colorado Plateaus Province
- 6 - Mexican Highlands Section, Basin and Range Province
- 7 - Mexican Plateau Province
- 8 - Sacramento Section, Basin and Range Province

Interior Plains
- 9 - Edwards Plateau Section, Great Plains Province

Atlantic Plains
- 10 - West Gulf Coastal Plains Section, (Gulf) Coastal Plains Province

The Salton Trough Section is an integral element of the border region's landscape, extending westward to the Laguna Mountains-Sierra Juarez of southern California and northern Baja California, respectively. The lowest elevations of the border region are in this section. As will be noted later, this section is also the driest area of the border region. Alluvial slopes, the delta plains of the Colorado River, and lateral depressions, such as the Laguna Salada in northwestern Baja California, characterize the landscape. The Laguna Mountains-Sierra Juarez on the west are part of the Lower California Province of the Pacific Mountain System. From elevations exceeding 2,000 m (6,000'), the land slopes gradually from these mountains to the Pacific Ocean.

East of the Basin and Range Province, the topography is characterized by low hills and dissected valleys of the Edwards Plateau Section of the Great Plains Province. The remainder of the border region eastward to the Gulf of Mexico is in the West Gulf Coastal Plains Section of the (Gulf) Coastal Plains Province. The land slopes gently to the Gulf Coast and the Rio Grande Embayment, transitioning from high plains and low mountain escarpments to low, coastal plains. The Rio Grande Embayment is an extensive alluvial plain, extending about 300 km (190 mi) inland from the Gulf Coast.

The topographic characteristics of the border region affect the potential for transfrontier pollution in three principal ways: 1) air descending into expansive basins warms to exaggerate the general aridity of the region; 2) up-valley and down-valley air movement occurs on a diurnal basis; and, 3) elevation affects temperature and precipitation. These topographical effects primarily are manifested as regional and local variations of climate and weather and as localized surface conditions, which contribute to the particulate load of the atmosphere. Figure 1 shows the relationship of the topography of the border region to the two principal components defining the climate of the border region: temperature and precipitation.

Map 4 reveals the United States-Mexico border region is dominated by two types of dry climates. Over fifty percent of the border region is a true Desert Climate (BW), where the average annual precipitation is less than 300 mm (12 in) as shown in Map 5. In these desert areas, mean annual temperature varies from 16°C (61°F) in the eastern portion to greater than 22°C (72°F) in the lower elevations of the Sonoran Desert and Salton Trough. Most of the remainder of the border region (43%) has a Steppe or Semiarid Climate (BS), where average annual precipitation ranges from 300 mm (12 in) at lower elevations to more than 500 mm (20 in) at higher elevations and near the Gulf Coast. The Gulf Coast area is affected by maritime influences, receiving greater than 550 mm (22 in) of precipitation per year average and having a mean annual temperature exceeding 22°C (72°F) (Wauchope, 1964b; and Robert H. Schmidt, Jr., Forthcoming-b).

The Pacific Coast has a Semiarid Climate most precisely described as a "West Coast Fog Desert" (Bn). Average annual precipitation is 200 mm to 300 mm (8 in to 12 in) and mean annual temperatures range between 15°C and 20°C (59°F and 68°F). Higher elevations of the interior Laguna Mountains-Sierra Juarez have a Humid Mesothermal Climate (C), receiving from 300 mm to greater than 400 mm (12 in to greater than 16 in) of precipitation per year average. Mean annual temperature in this region ranges between 16°C and 18°C (61°F and 65°F).

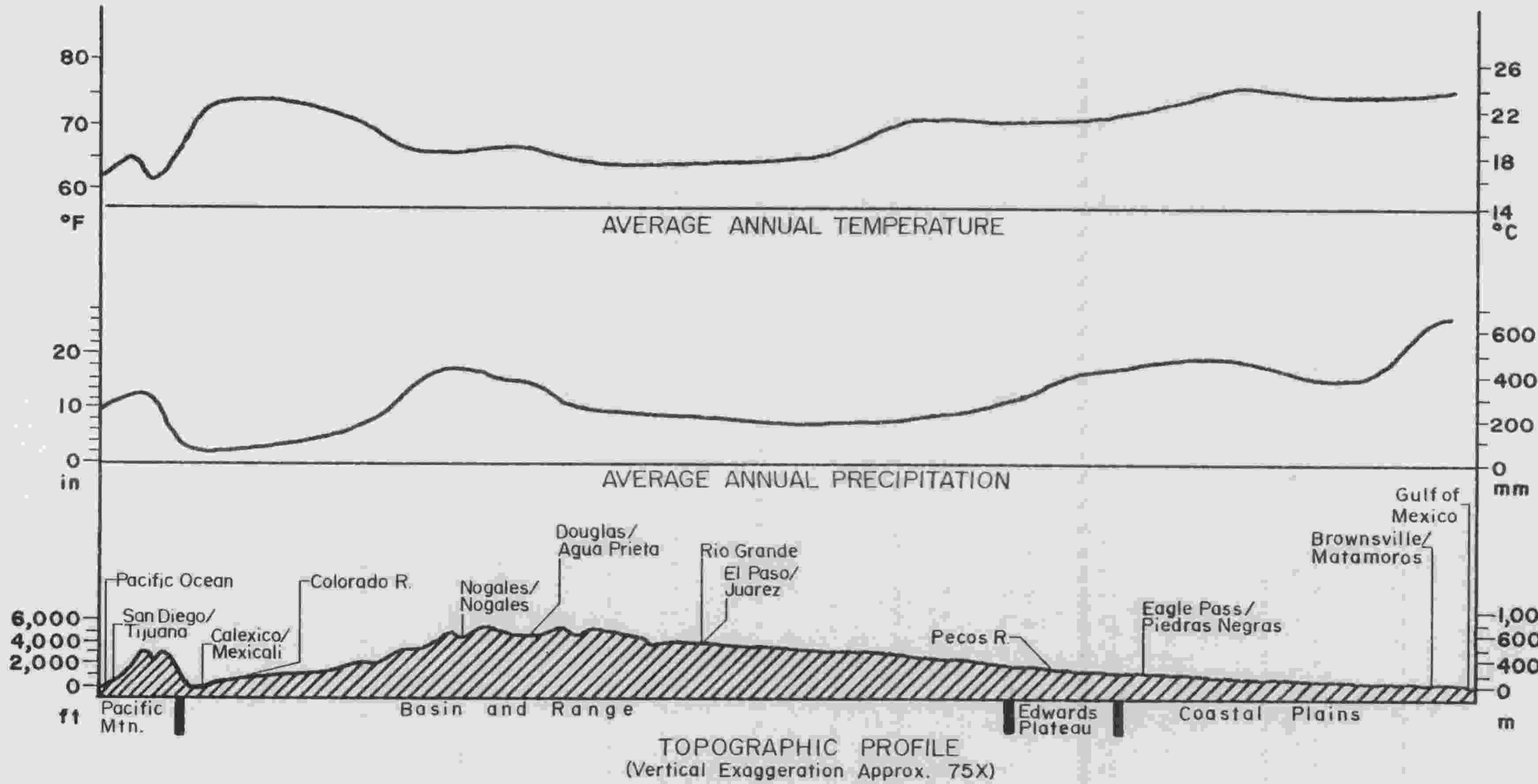
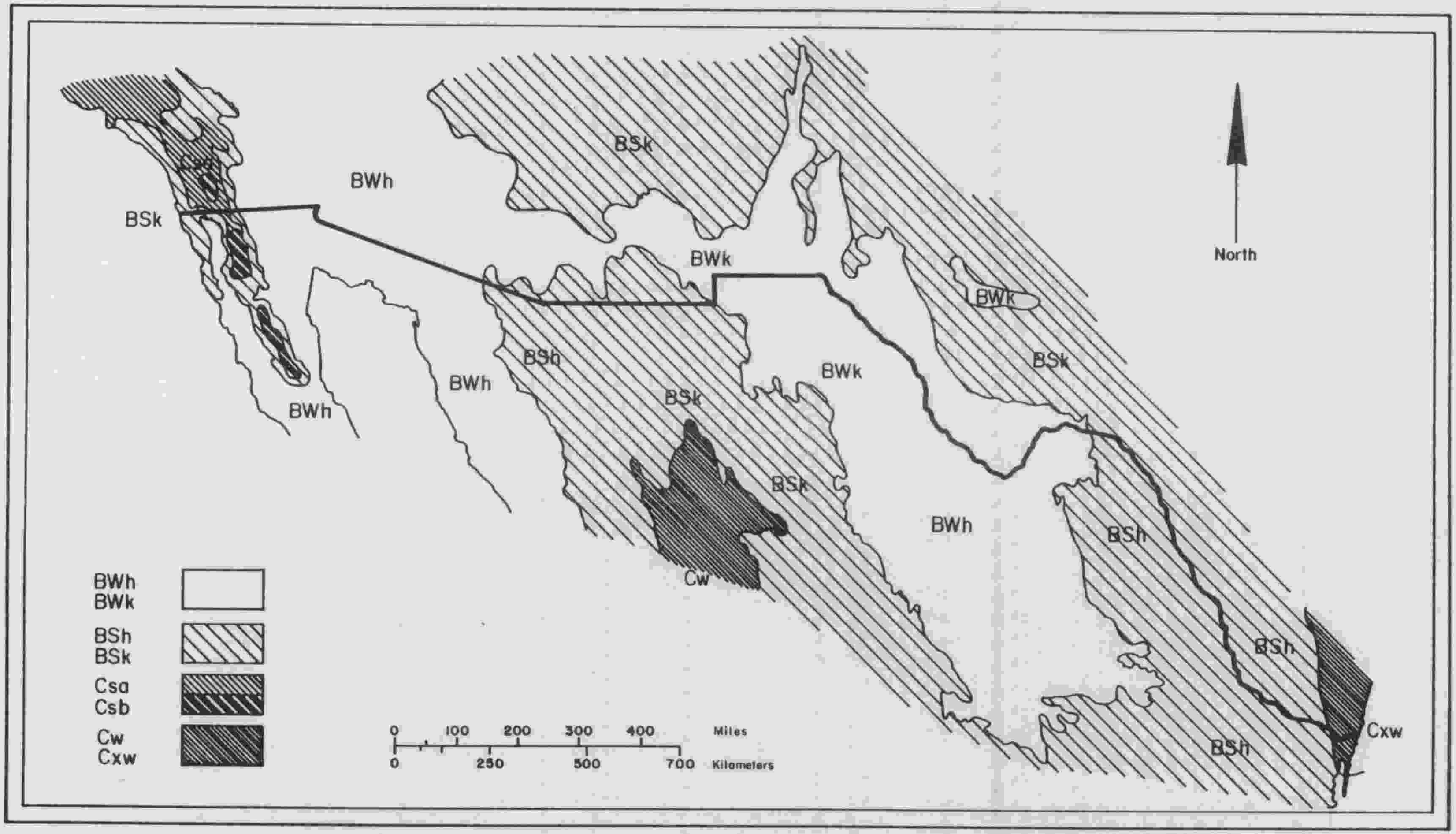
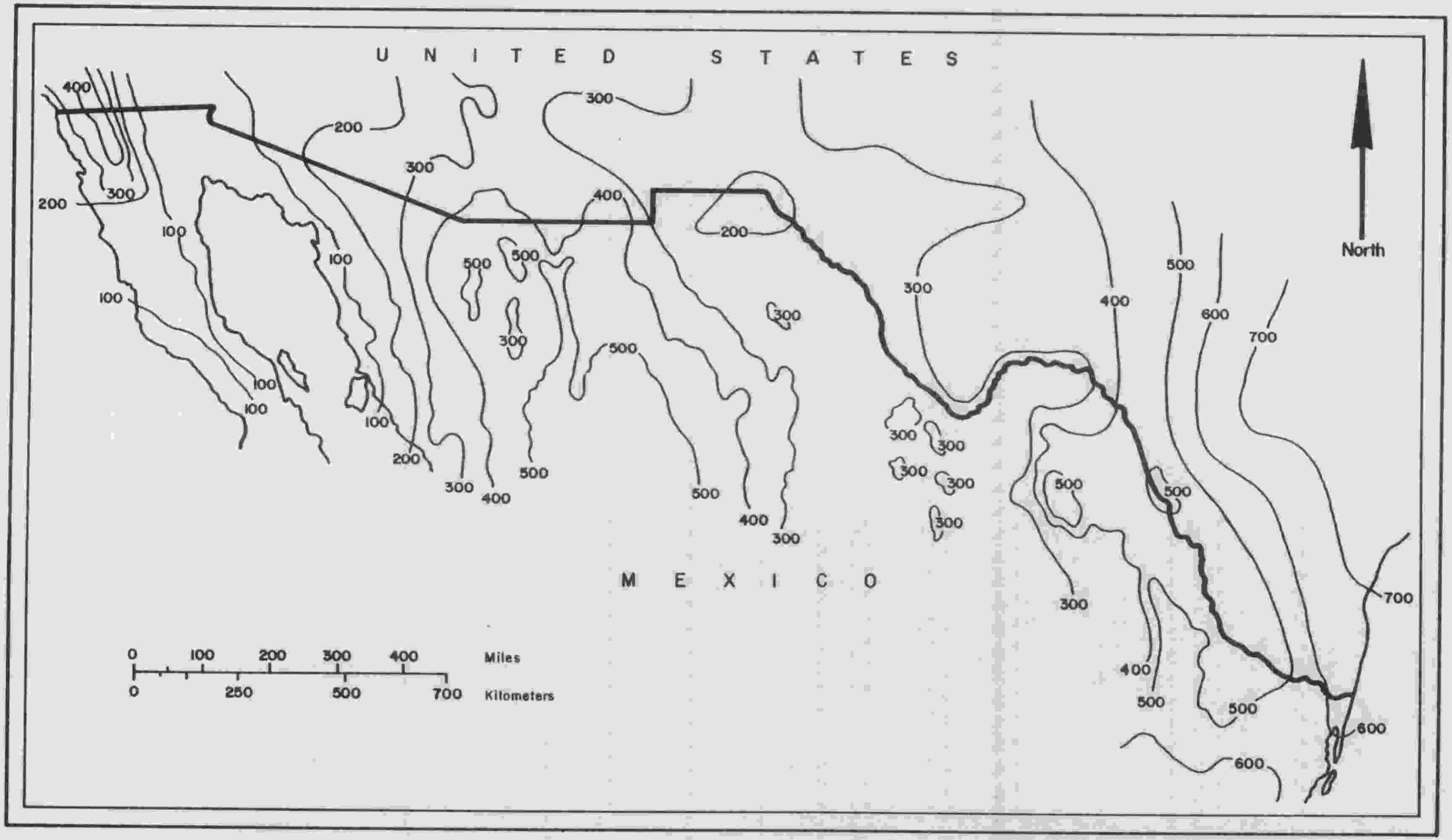


Figure 1. Temperature and Precipitation Related to Topography of the Borderline



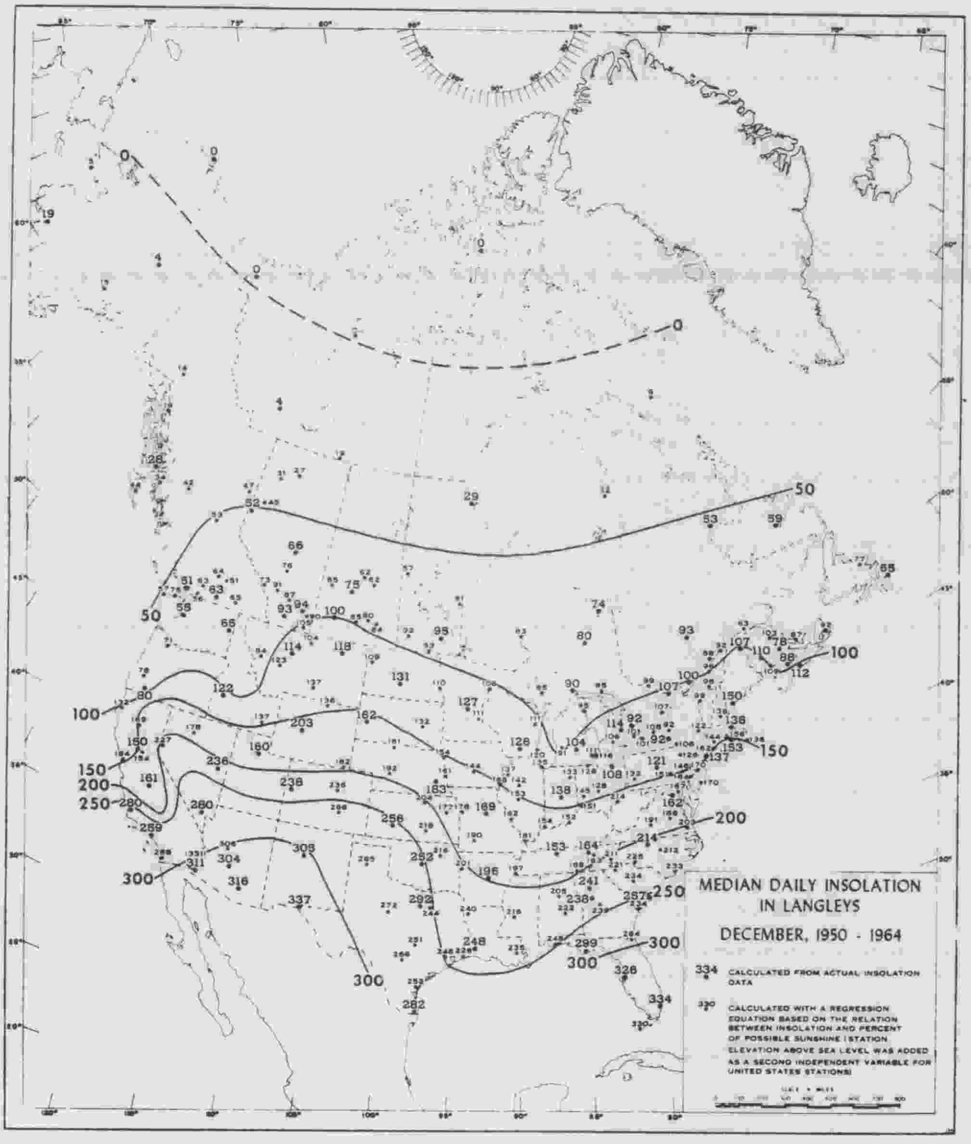
Map. 4. Climate Regimes of the United States-Mexico Borderlands. From Schmidt (Forthcoming, b).



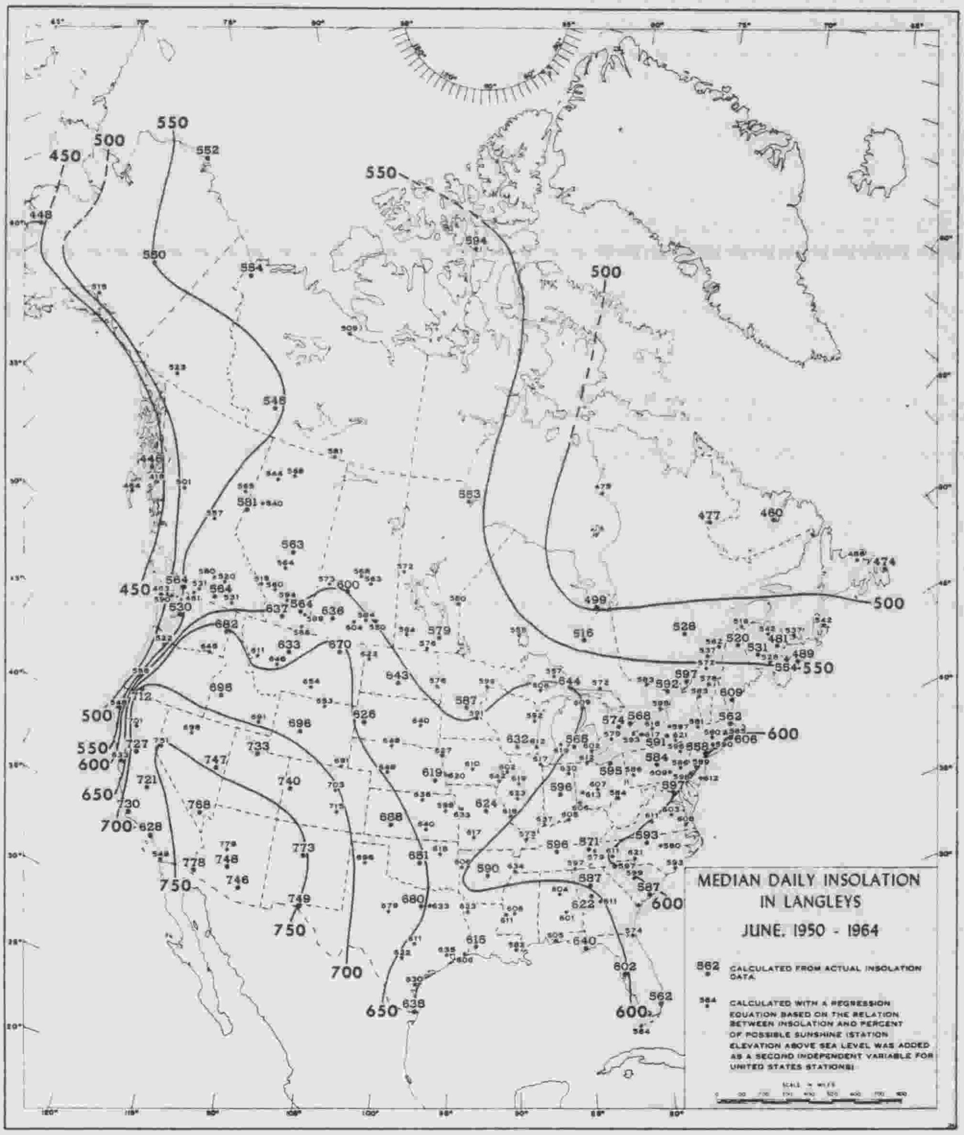
Map 5. Mean Annual Precipitation of the United States-Mexico Borderlands. From Schmidt (Forthcoming, b).

It is not within the scope of this study to analyze the climate of the border region in detail. Much work has been completed already in this regard, a summary of which has been developed by Schmidt (Forthcoming-b) for a "Border Region Source Book." However, several aspects of the climate of the border region play important roles in the transport, diffusion, transformation, and removal of pollutants and, therefore, are critical to the transfrontier air pollution question. Three climatological factors seem to be of primary relevance to potential transfrontier air pollution conditions; frequency of inversions; wind speed and direction; and, topography.

The aridity dominating the border region results from a number of climatic factors and significantly contributes to a prominent diurnal inversion cycle. Generally, the aridity results from dominance of much of the region by the dry, subsiding air of the subtropical belt of high pressure located at about 25° - 35° North Latitude. This high pressure dominance is most pronounced in the low-sun or winter season. Clear skies associated with high pressure dominance allow large amounts of insolation to be received at the surface, even during the low-sun season (Maps 6 and 7). Consequently, there is a high rate of evapotranspiration throughout much of the border region, during most of the year. The interior continental location of a large portion of the border region is a cardinal reason for the generally arid conditions. The area, quite simply, is too far removed from maritime sources of moisture. In addition, the topography of the region acts to produce local variations in precipitation. Expansive basin areas and associated high mountain ranges, characteristic of the central Mexican Highlands-Mexican



Map 6. From I. Bennett (1967).

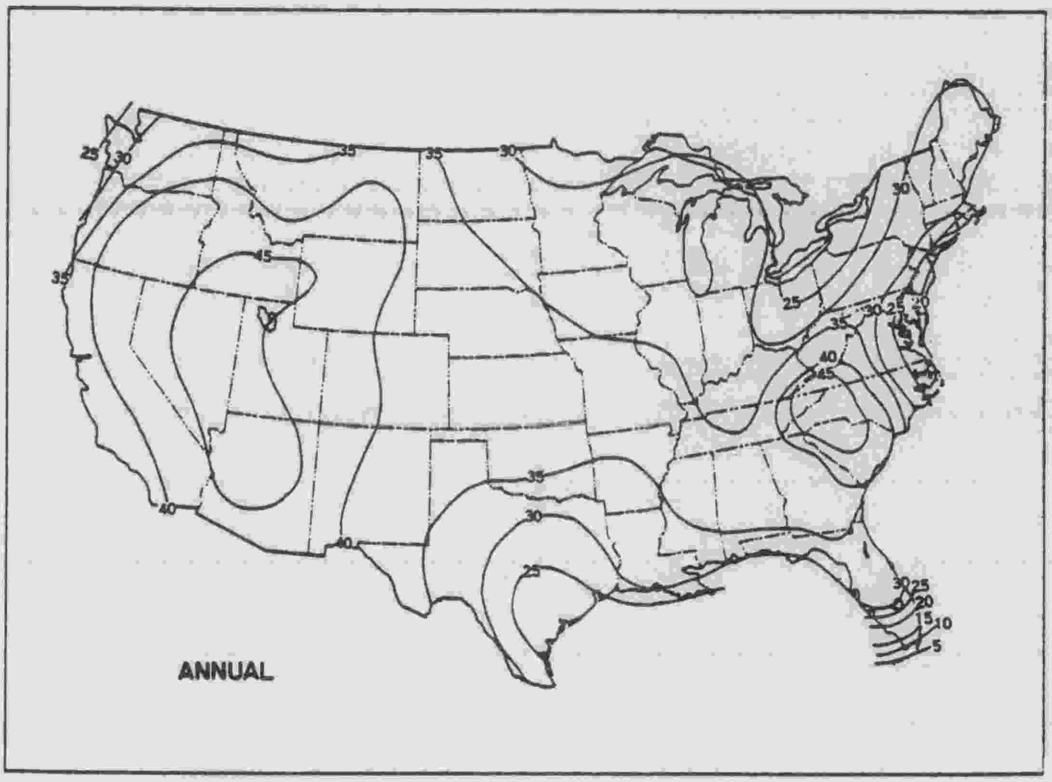


Map 7. From I. Bennett (1967).

Plateau, combine to reduce precipitation at lower elevations. As the generally westerly air flow moves across the border region and across the N-S trending ranges, air flowing into the basins warms adiabatically. Because warming increases the capacity of the air to retain moisture, this subsidence of the air into the basins inhibits precipitation at the lower basin elevations. Thus, differences of altitude and proximity to sources of moisture are the principal factors locally modifying the general aridity and clear skies of the border region.

The usually clear sky condition of the border region not only allows maximum receipt of insolation at the surface, but also allows maximum loss of daily heat input in the form of nocturnal ground radiation (Richard A. Kassander, 1970). Rapid heat loss from the surface (starting in the early evening) compared to less rapid heat loss from the air aloft produces an inversion of the normal temperature lapse, which is a decrease of temperature with an increase in altitude. This meteorological condition generates a stable atmosphere in which convective air movement is inhibited, because the air closest to the ground is colder, heavier, and denser than the air aloft. Low-level inversions of this nature are termed "ground radiation inversions."

The border region, as a whole, has a relatively high frequency of ground radiation inversions throughout the year (Map 8). Thus, inhibited mixing and diffusion of any pollutants introduced into the air is a fairly common occurrence. "In essence, the dilution efficiency of the atmosphere depends on the wind and temperature gradients, both of which vary vertically, horizontally, and with time" (C. R. Hosler, 1961). High pressure dominance favors a clear sky condition, and,

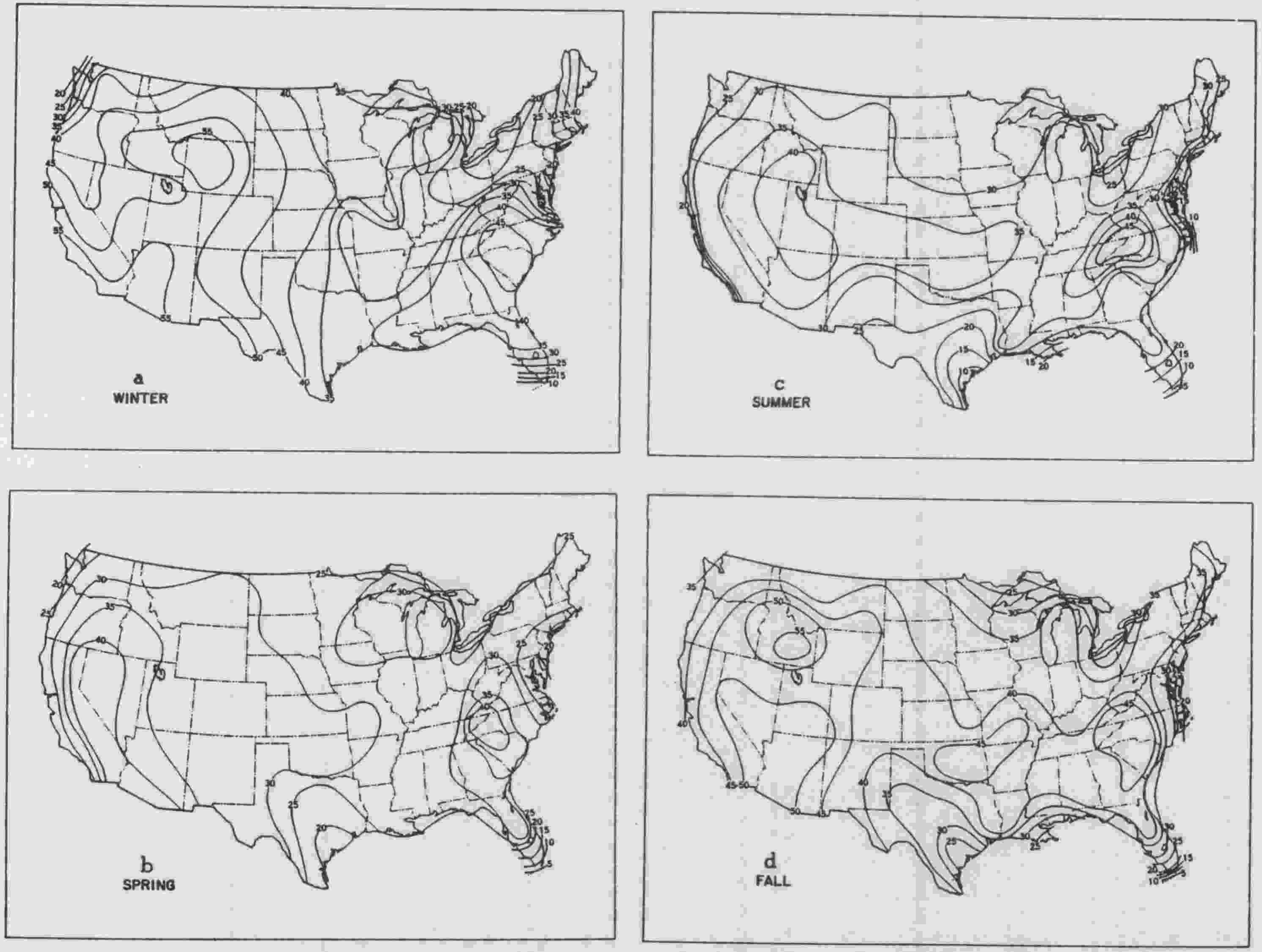


Map 8. Annual Low-Level Inversion Frequency of the Contiguous United States. Frequency interpreted as percent of total hours. Adapted from Hosler (1961).

generally, clear skies (less than 3/10 cloud cover) and surface winds of less than 11 km/hr (7 mi/hr) favor the formation of nocturnal radiation inversions over land.

From Map 8, it can be noted that, on an annual basis, the frequency of low-level inversions in the region varies from 25% to 30% of total hours on the Gulf Coast to greater than 40% of total hours in the interior desert areas of southern Arizona, southern California, and northern Sonora and northern Baja California. There is significant temporal (or seasonal) variation to this pattern. During the low-sun season of December, January, and February, about two-thirds of the border region has an inversion frequency of greater than 50% of total hours (Map 9a). This includes all of the areas west of the Sacramento Mountains-Sierra Madre Oriental alignment, i.e., the eastern margins of the Basin and Range Province and the Mexican Plateau Province, respectively. There is, in effect, a potential for the development of an inversion every winter night in the region.

The inversion frequency for the border region, as a whole, is lowest in the high-sun or summer season of June, July, and August (Map 9c). The frequency increases rapidly to approximately winter frequencies, during the fall season (Map 9d). On an annual basis, there is a lower frequency for the coastal areas (Map 8). Generally, the Gulf Coast has neutral stability during the day and inhibited inversion formation at night, due to air flow over adjacent warm waters. The Pacific coastal areas have a higher frequency of inversions than the Gulf coastal areas, particularly during daytime hours, due to the effects of the adjacent, cool California current. With respect to the



Map 9. Seasonal Low-Level Inversion Frequency of the Contiguous United States. Frequency interpreted as percent of total hours. Adpated from Hosler (1961).

California coastal areas, it is significant to note that " . . . locations only a few miles inland from the coast exhibit a continental-type frequency of low-level stability" (Hosler, 1961).

Although " . . . nearly all nocturnal inversions reported by inland radiosonde stations are based below 500 feet above the surface . . . ", inversions on the Pacific coast are often based between 150 m and 600 m (500' and 2,000') above the ground (Hosler, 1961). This phenomenon is associated with upper level subsidence of air on the eastern side of the Pacific subtropical cell of high pressure. This subsidence inversion aloft results in a semi-permanent stable layer throughout the spring, summer, and fall months. Because the frequencies shown in Maps 8 and 9 were developed on the basis of nocturnal inversions below 150 m (500'), frequencies indicated for Pacific coastal areas are probably conservative. According to Hosler, regional scale subsidence in this portion of the border region is an important contribution to the gross accumulation of air pollution in the coastal areas.

While vertical temperature inversions are an important factor in the determination of the vertical component of air movement in the region, the horizontal component, wind, is equally important in air pollution conerns. "Wind affects the dispersion of pollutants in three ways: 1) it carries the pollutants away from [the] source; 2) it dilutes the concentration downstream; and 3) if the wind is strong, or the air unstable, eddy currents are established which dilutes the concentration vertically, as well as horizontally" (Robert Orton, 1973). Obviously, in local and regional transfrontier air pollution occurrences, the horizontal component of air movement is an important factor to consider. Pollutants entrained in horizontal air movements will be transported, all or in part, from one country to another depending on seasonal, daily, and even hourly variations of wind direction.

Because of the high frequency of nocturnal ground radiation inversions and associated high winds in the border region, the daytime winds are the most significant transport mechanism. As nighttime inversions develop. " . . . the surface of the earth cools, which in turn cools the boundary layer of air near the surface. The air thus becomes stratified with the coldest, and more dense layer of air near the ground surface" (Orton, 1973). Due to surface friction, the colder, more dense layer slows down, and it is at wind speeds less than 11 km/hr (7 mi/hr) that air pollution problems are most likely to develop. This is because pollutants are not dispersed and are accumulated near the sources. Rapid daytime heating of the cold surface boundary layer causes the air at the surface to rise and mix with the layer above. Generally, this diurnal process occurs during the times of high inversion frequency in the region. Thus, by late morning or early afternoon, stronger surface winds develop as the cooler, faster flowing air aloft replaces the warming and rising air at the ground surface.

Orton (1973) has shown, however, that the El Paso-Cuidad Juarez metropolitan area experiences a frequency of calm or nearly calm winds in the afternoon that is approximately the same as in the morning, during the month of November. Because much of the border region is climatologically similar to the El Paso-Cuidad Juarez area, it can be presumed that these conditions apply to a large portion of the region. Relative to the potential transfrontier air pollution problems of the region, now and in the future, an important fact of air pollution must not be ignored. Pollutants accumulated as a result of nocturnal ground radiation inversions have the effect of attenuating the amount of insolation received at the surface. Therefore, the amount of pollutants accumulated will affect the rate at which inversions break down, and it can be assumed that as border region development proceeds and the amount of pollutants increases that the duration of inversions will increase accordingly, notwithstanding local atmospheric conditions.

With the break down of nocturnal inversions, stronger winds carry accumulated pollutants away from sources and/or source areas, diluting and dispersing the nighttime concentration downwind. It has been noted that there is both a horizontal and vertical component to air movement. These components affect the efficiency of dilution and dispersion and determine the area of ultimate deposition to some degree. In the border region, downwind is 1) the United States side of the border, 2) the Mexico side of the border, or 3) both sides of the border. Occasionally, as noted above, the process of surface heating does not result in sufficiently high winds to dilute and disperse pollution accumulated during the night. This results in a localized pocket of stagnated air. In some cases, such as in the El Paso-Cuidad Juarez metropolitan area, the pollution accumulation is shared almost equally by the populations of both countries. This condition is a relatively common occurrence in the many topographic basins characterizing the United States-Mexico border region.

Topographic air flow is the third important climatological aspect of transfrontier air pollution in the border region. As noted in the section on topography, much of the border region is characterized by Basin and Range systems. During the day, air in the lower troposphere literally flows over ranges and subsides into the basins. At night, a more rapid rate of surface cooling at higher elevations (including up-valley) results in colder, denser air flowing into the basins (and down-valley) in the form of katabatic winds. With daytime receipt of insolation, a more rapid warming of surface air temperatures at high elevations produces a reversal of air flow in the basins (and valleys), generating anabatic winds. Thus, air flow is up-valley and up-slope, during the daytime.

During winter months especially, " . . . this back and forth circulation is superimposed on a typically light wind situation" (Kassander, 1970). The potential result is a "sloshing back and forth" of pollution concentrations. Even when daytime break-up of a nighttime inversion occurs " . . . total wind passage during the 12-hour period may be only a few tens of miles before the inversion forms again and a reversal of wind direction occurs" (Kassander, 1970). The potential for Basin and Range topography to produce a build-up of pollution in this manner has been demonstrated for the Tucson and Phoenix, Arizona, areas, where inversions persist in fall and winter. The strength of inversions and the potential for build-up is influenced, also, by the soils and vegetation of the border region, which reflect both the climate and topography.

Soils and vegetation of the border region reflect the general aridity induced by climatological factors and topographic effects on air movement. A detailed discussion of the soils and vegetation is not necessary; this has been accomplished quite adequately by Wauchope (1964c & d), Schmidt (Forthcoming-a), and others. However, the soils and vegetation are important elements in the total transfrontier air pollution problems of the border region. The great majority of the vegetation is desert shrub and grassland. Although generally sparse, vegetation density varies directly with the amount and distribution of precipitation, which varies according to geographic location and elevation. Thus, the most luxuriant vegetation is found on the coastal plains of the Gulf of Mexico, where a deciduous forest occupies a small area of the Rio Grande Embayment and cord grass grows along the coastal littoral. In contrast, the interior desert area with its expansive, nearly flat basins has a very sparse vegetal cover dominated by creosote bush and bunch grasses. Higher elevations are forested with pine and juniper, grading upward into a large leaved, deciduous oak forest and small areas of fir forest at the highest elevations around 2,800 m to 3,500 m (9,200' to 11,400').

In the Sonoran Desert and Salton Trough " . . . little of the surface is actually shaded by the crowns of shrubs" (Wauchope, 1964c). West toward the Laguna Mountains-Sierra Juarez, vegetation zones evolve from the sparse desert xerophiles, to microphyllus shrubs and semi-succulents, such as the Yucca, to open woodlands of piñon and juniper, to oak forest at the highest elevations. The mountains are characterized by a chaparral forest interspersed with grass covered ranges and occasional arid valleys. The dominant vegetation of the Pacific coastal area is low microphyllus shrubs, leaf succulents, stem succulents. and semi-succulents.

The soils of the region reflect the climate, topography, vegetation complex. Except for the Rio Grande Embayment, the Laguna Mountains-Sierra Juarez, and isolated highlands of the central portion of the region, the soils are Aridisols, formed through the calcification process: a process dominant where evaporation exceeds precipitation. Most are of the Orthid suborder, which exhibits altered horizons, a hardpan, or an illuvial horizon composed of water soluble material. The kind and strength of pedogenic processes determines the classification of soil orders. However, relative to remote sensing and image interpretation, the Marbut System, as presented by Donald Steila (1976), yields valuable information as to soil color. Also, Wauchope (1964d) notes that in the cooler desert areas, such as the higher and drier parts of the interior, soils are primarily Gray Desert (or Sierozem), while in the warmer Chihuahua and Sonoran deserts " . . . greater dehydration of the iron compounds gives the soils a decidedly reddish tinge, hence the term Red Desert soils . . . " is applied.

Except for areas of alluvial soils, soils of the border region are sandy and exhibit moderate to severe erosion. A unique feature of the soils is the very shallow profile and low humus content. Commonly, a residual surface layer of rock and gravel is produced through the "deflation" of finer particulate matter. This residual surface is termed "Desert Pavement" (Steila, 1976). This peculiar aspect of desert soils is important relative to the air quality of the region. Deflation, and resulting dust particles, is generally recognized as an important contributor to the particulate load of the air of the border region. Clearly, particulates deriving from natural processes cannot be considered pollution, per se. However, when particulates act as a transport medium for various organic and inorganic pollutants, such as pesticides, a transfrontier air pollution problem could be deemed to exist. At the extreme, overgrazing, which exacerbates deflation processes, could be considered a valid concern relating to transfrontier air pollution.

Aside from generating particulate air pollution, the relation of sparse vegetation and overwhelmingly bare soils of the border region is important especially in the formation of nocturnal ground radiation inversions. The porous, sandy soils of the arid and semiarid portions of the region have a low heat conductivity; therefore, the daily receipt of heat energy in the form of insolation is lost more rapidly from these soils than from the darker soils of the coastal plains. Thus, rapid heat loss from the soil combined with sparse vegetation compounds the heat loss resulting from the generally clear sky condition of the region. Rapid heat loss from soils in basin areas serves to intensify the accumulation of cold air resulting from nighttime cold air drainage. Thus, the intensity of nocturnal ground radiation inversions in basins and valleys is greater than in areas of greater horizontal expanse.

Social Geography

The amount and type of pollution generated in the United States-Mexico border region is a direct reflection of its social and economic geography. Daily socioeconomic interaction in the borderlands, including trade, tourism, and employment commuting, is high at many points along the border. With increasing interaction has come a concentration of population, specifically in urban areas, and with the population has come increasing pollution. Population growth on the Mexican frontier has been phenomenal in the last two decades. Industrialization of the border region is relatively restricted to "dirty" extractive industries. There are other industries represented, but, whether "dirty" or "clean," there has been an effect on environmental quality. A third element of the social and economic geography of the region is agriculture. Agricultural activity is not extensive, but where it is highly developed and concentrated, it poses significant environmental problems related to dust particulate generation and pesticide use.

An examination of the social and economic geography of the region, while relevant, is beyond the scope and purpose of this thesis. However, the following survey of environmental problems is developed in the context of the social and economic geography of the border region. The survey stresses environmental problems related to air pollution with the understanding that transfrontier air pollution is potentially, if not in fact, a present condition. Environmental problems reasonably expected to engender transfrontier air pollution conditions are associated principally with 1) solid wastes, 2) open burning, 3) energy generation, 4) industrial activity, 5) agriculture and related activities, and 6) vehicular transportation. Thus, environmental problems in the border region stem from a growing population and activities associated with development of the region.

The formerly sparsely inhabited deserts and semi-deserts of the United State-Mexico border region are fundamental to one of the most rapidly developing international border regions in the world. Industrialization, corporate farming, and urbanization are playing an active, though localized, role in changing the character and status of these arid and semiarid environments. Employment opportunities, development of irrigation districts, intensified tourism and trade, an infusion of foreign capital, a "National Border Program," and influence and technology from the United States are doing likewise to the Mexican frontier. In the region as a whole, subsistence agriculture, irrigation agriculture, and cattle ranching are the dominant economic base and, of course, account for the greatest amount of land use (Schmidt, Forthcoming-c), However, extractive industries are becoming a significant element in the economic base. The trend in the economy is heavier dependence on the interchange of commercial transactions, tourism, and transfrontier employment (Howard R. Applegate, Forthcoming).

The relationship between population growth, socioeconomic development, and environmnetal problems is complex. Unfortunately, for many problems, the greater the population, the greater the problems, and the greater the difficulties in solving the problems. Respecting the border region, population growth seems to be an inescapable fact, especially in the Mexican frontier area. Table 2 shows the projected population growth for border counties of the United States from 1970 to the year 2000. In all states, except California, the border county population is expected to more than double by the year 2000. However, Table 2 does not indicate that the population is highly concentrated.

The combined population of the fifty-two border counties and municipios (Mexico) was approximately 5.8 million people in 1970. Of this population, slightly more than half (50.4% or 2.92 million people) was in the border municipios of Mexico, and, within these municipios, Cuidad

Table 2. Projected Population of Border Counties in the United States.

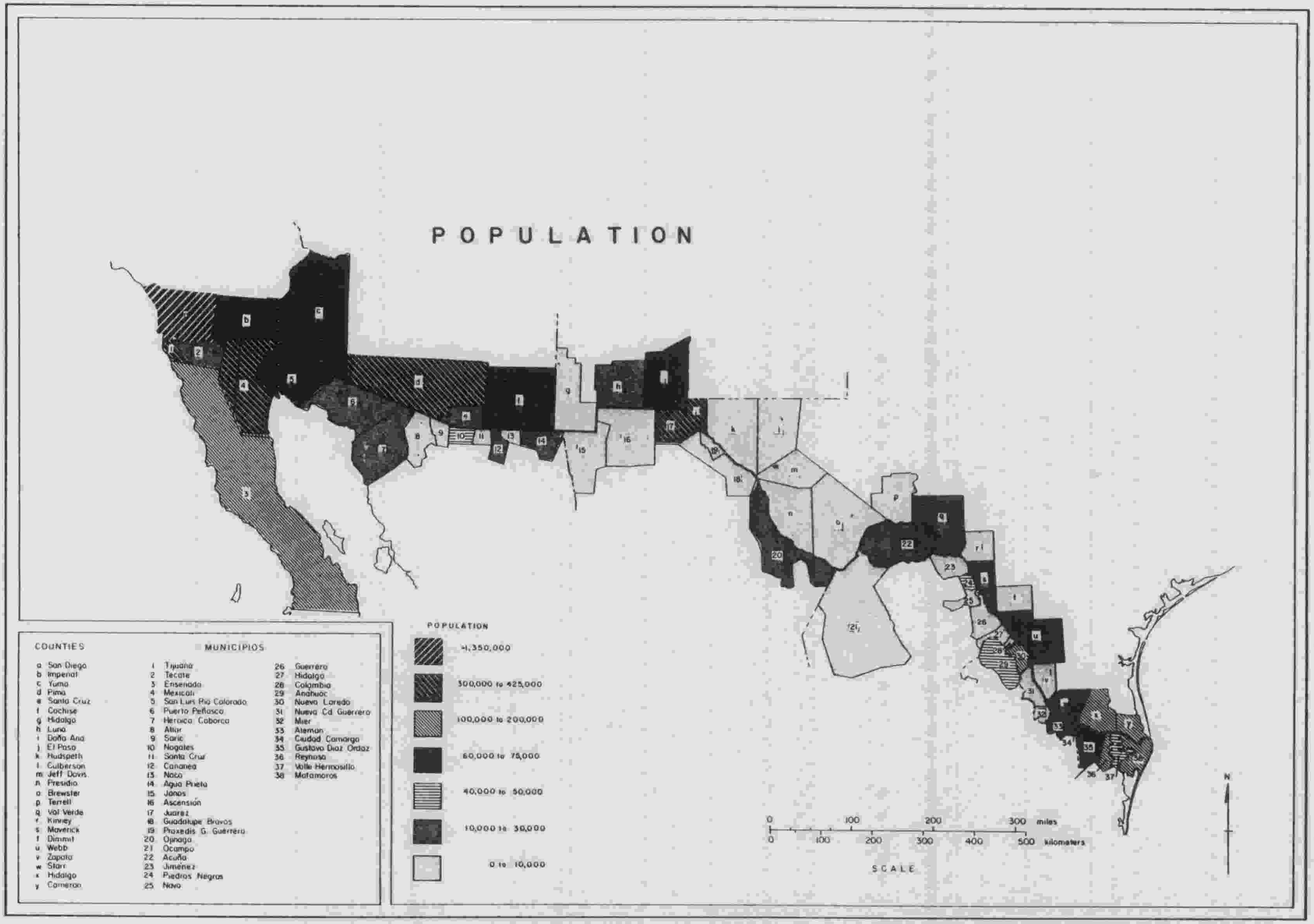
State	Year 1970	1980	1990	2000	% Change 1970-2000
Texas	1,066,589	1,243,860	1,448,530	1,500,530	41
New Mexico	149,340	251,000	312,500	413,800	177
Arizona	488,400	695,000	878,900	1,030,400	111
California	1,891,420	2,474,800	2,589,000	2,800,000	48

Source: Applegate, Forthcoming.

Juarez, Mexicali, and Tijuana accounted for 40% of the population (Map 10). Ensenada, Matamoros, Nuevo Laredo, and Reynosa accounted for another 40%. Thus, seven urbanized municipios accounted for 80% of Mexico's frontier population.

The distribution of population along the border in the United States in 1970 was even more concentrated. Approximately 72% of the frontier population was in the urbanized counties of San Diego, Pima (principally in Tucson and Nogales), and El Paso. "Nearly a third of the entire border population lived in the county of San Diego and the municipio of Tijuana" (Schmidt, Forthcoming-c). As of 1976, Mexico's frontier population was estimated at 3.5 million people by the Secretario de Industriary Comercio (1978), which was an increase of close to 20% in six years. If the past provides any indication of the future, most of the growth in population in the border region will occur in Mexico and in urban areas. This is reflected in Table 3.

The rapidly growing population generates a large quantity of solid wastes, and disposal is a concern with respect to general health and



Map 10. Population of Border Counties and Municipios: 1970. From Schmidt (Forthcoming, c).

Table 3. Percent Population Change for Selected Border Cities: 1940-1970.

United States		Mexico	
Brownsville, Texas	137%	Matamoros, Tamaulipas	1086%
Mc Allen, Texas	216%	Reynosa, Tamaulipas	1502%
Laredo, Texas	75%	Nuevo Laredo, Nuevo Leon	424%
Eagle Pass, Texas	137%	Piedras Negras, Coahuila	198%
El Paso, Texas	232%	Cuidad Juarez, Chihuahua	767%
Nogales, Arizona	74%	Nogales, Sonora	285%
Calexico, California	69%	Mexicali, Baja California	2011%
		Tijuana, Baja California	1965%

Source: Ellwyn R. Stoddard, 1974.

transfrontier air pollution. There is an important difference in solid waste handling and disposal between the United States and Mexico: burial in the United States (with some recycling) and open burning in Mexico (with some collection by municipios). Calculations by Applegate (Forthcoming), using Texas State Department of Health data, indicate that solid waste in the United States frontier will increase from 8,270 metric tons per day in 1970 to 25,270 metric tons per day in the year 2000. Most of this waste will end up in muncipal landfills, which, it is suggested, may become future resources, because the aridity of the region inhibits decomposition.

However, landfills are potential polluters of ground water aquifers, a critical resource in the arid border region. Respecting, transfrontier air pollution, there are several critical concerns. An extremely critical issue is the current debate concerning the burial of low-level radioactive wastes in the vicinity of Carlsbad, New Mexico. While this area of the border region is not in a county recognized by the Southwest Border Region Commission, it is no further away from the border than the northern end of Yuma County, Arizona, which is recognized. No conclusions can be drawn regarding this proposal; however, the potential entrainment and transport of radioactive materials into Mexico does exist and probably should be considered. Any burial operations, but especially landfills, are ready sources of loose earth, debris, and bacteria. Transfrontier movement of these by-products of landfill operations in high winds is clearly possible. In addition, landfills sometimes catch fire, a condition which has the potential of releasing an unknown quantity and type of organic and inorganic pollutants into the atmosphere (Applegate, Forthcoming).

"A 1969 study of the twenty-one Mexican [border] cities showed that the total garbage collected in all of these cities was 1,240 [metric] tons per day, or 384,400 [metric] tons per year" (Joaquin Telloz, 1973). Clearly, solid waste generation in the border municipios of Mexico is considerably less than in the United States border counties. However, a large portion of the solid waste is eliminated through a practice of sporadic open burning (with some regular control in only three cities). Compared to controlled incineration, open burning causes ten times more pollution and creates a significant air pollution problem, at least locally. According to Telloz (1973) particulate matter constitutes thirty percent of the total pollution produced in the burning process; "odors and gases offensive to the senses are released; a great variety of unsaturated hydrocarbons, some of which may be carcinogens for animals and man, may be released; and multiple generations over a relatively large area makes monitoring and control of emissions almost impossible." An important aspect of the open burning question concerns the use of almost any material to heat homes in the poorer areas of the Mexican frontier cities. This factor of open burning is apparently ubiquitous and, clearly, will not be resolved in the near future.

One cannot assume that the quantity of solid wastes in the United States will triple and the quantity of solid wastes in Mexico remain constant. Assuming a direct relation between population growth and solid waste generation, Table 3 can be used as the basis for estimatint future solid waste generation in Mexico's frontier cities. The data in Table 3 reveal that there was an average of 10 times more people in Mexico's frontier cities in 1970 compared to 1940. If it is assumed that this growth rate will continue (and there seems to be evidence that it might), then the solid waste generation of those same cities surveyed in 1969 could average 10 times more or 12,400 metric tons per day. This is still far less than the 25,270 metric tons per day in the United States border counties, but there are three important qualifications: 1) the multiplier effects of increased affluence in Mexico have not been taken into account, assuming, of course, that development efforts will succeed in the face of phenomenal population growth; 2) the ability or desire of the government of Mexico to deal with the problem has not been considered; and, 3) the amount of solid wastes in the United States border counties, which is estimated to increase only 3 times, has already become a matter of serious concern.

A second environmental concern associated with the United States-Mexico border region and transfrontier air pollution is power generation. In point of fact, a potential pollution problem exists " . . . whenever there is a boiler fed by basic fuels, whether gaseous, liquid, or solid" (Telloz, 1973). Imperfect combustion results in the release of sulfur and nitrogen oxides, unburned hydrocarbons, and particulate matter. In the border region, there are at least four power generation plants: one in Cuidad Juarez, Chihuahua; a second just north of El Paso, Texas; a third in Rio Bravo, Tamaulipas; and a fourth (and the largest) in Rosarito, Baja California, just south of Tijuana. Principal air pollutants produced by natural gas and coal fired generating plants, as identified by Hal B. H. Cooper (1974), are listed below in order of importance.

- Natural Gas - Nitrogen Oxides (Nitric Oxides & Nitrogen Dioxide)
  Hydrocarbons
  Particulate Matter
  Sulfur Oxides and Carbon Monoxide

- Coal - Sulfur Oxides
  Nitrogen Oxides (See Above)
  Particulate Matter
  Carbon Monoxide
  Hydrocarbons
  Trace Metals, such as Lead, Zinc, Selenium, Beryllium, and Mercury.

Some of the power generated in the border region is consumed by industrial activities, which contribute to environmental problems (especially air pollution) through both process and fuel combustion losses.

Jim M. Shoults (1973) estimated "point source process loss emissions" for the border counties of the United States. Shoult's summary of emissions is presented in Table 4. A very significant facet of the economic geography of the United States frontier is revealed by the very low emissions of sulfur oxides (SO_x) in California. While the greatest tonnage for any of the five pollutants is sulfur oxide, "most of the sulfur oxide emission occurs within a 600 kilometer or 360 mile linear distance of the border extending from El Paso, Texas, to Ajo, Arizona" (Shoults, 1973). Smelters are, the major contributors of sulfur oxides. At the time of Shoult's study, 18.56% of the total emissions of sulfur oxides in the United States originated in the border region (Table 5).

Particulates rank second among the pollutants in total quantity, originating from " . . . rock, gravel, and sand quarrying, concrete batching, asphaltic batching, and cement processing" (Shoults, 1973). In quantity, carbon monoxide (CO) is the third greatest contributor to environmental air pollution deriving from industrial sources. Petroleum refining, petrochemical, and chemical process industries are the most notable sources of carbon monoxide. A surprising statistic is the contribution of the border region to the total nitrogen oxide (NO_x) emissions of the United States. Both industrial and electric power generating plants are sources, accounting for 37.77% of the nationwide emission of NO_x. Chemical process industries and petroleum refining are principal sources of emissions of hydrocarbons. The 23,590 metric tons per year generated by sources in Texas, reflect the importance of these industries in the economy of Texas border counties.

Table 4. Summary of United States Point Source Emissions: United States-Mexico Border.*

Point Source Location	Pollutant (Metric Tons Per Year)				
	Particulates	SO_x	NO_x	HC**	CO
Texas	38,286	256,187	34,147	23,590	112,247
New Mexico	37,583	224,623	8,145	2,399	3,899
Arizona	35,294	525,345	6,215	642	4,033
California	59,568	7,649	19,503	5,838	3,037
TOTAL	170,731	1,013,804	68,010	32,459	123,216

*Border counties of the United States.

**Hydrocarbons.

Source: Shoults, 1973.

Table 5. Comparison: United States Nationwide Emissions vs. United States Border Counties.

Point Source Location	Pollutant (10^6 Metric Tons Per Year)				
	Particulates	SO_x	NO_x	HC*	CO
U.S. Nationwide	12.07	5.44	0.18	4.99	10.34
U.S. Border Counties	0.17	1.01	0.068	0.033	0.13
% of U.S. Emissions Nationwide	1.41%	18.56%	37.77%	0.66%	1.25%

*Hydrocarbons.

Source: Shoults, 1973.

Unfortunately, similar measurements are not available for the petroleum refining industry of the Mexican border municipios, which is concentrated around Monterrey and along the border near Reynosa. In fact, recent activities in Mexico, including a natural gas pipeline terminating 75 miles south of Reynosa, indicate that this sector of the Mexican economy will become even more important in the future (Business Week, 1/15/79).

In addition to the five principal pollutants studied by Shoults, other industrial pollutants are present in the border region, but they have not been adequately evaluated. These pollutants are lead, cadmium, and arsenic. Lead is significantly associated with smelting operations and, in fact, has been the subject of a law suit involving a large copper smelter located in El Paso (John C. Ross, 1973). One study of lead levels in the blood of 1 to 4 year old children, conducted in 1976 in El Paso, revealed a concentration of high levels directly northeast of the discharge stack of this smelter (Applegate, 1978).

Telloz (1973) stated that, in Mexico, "industrial pollution control developments in the thrity-six border cities are generally null and incipient." This was in contrast to the rather stringent controls imposed on industry and border cities in the United States by the Clean Air Act of 1970 (as amended 1977, Pub. L. 95-95). In specific areas, industrial activity in the Mexico frontier is estimated to be responsible for thirty percent or more of the air pollution problem. In general, however, there is not a great amount of large scale industrial activity in the Mexico frontier compared to the United States frontier. There is a considerable industrial complex at Reynosa-Rio Bravo, Tamaulipas, which includes a petroleum refinery and a pulp and paper mill. The metallurgical industry is well represented at Piedras Negras, Coahuila-Eagle Pass, Texas, and at Cuidad Juarez, Chihuahua-El Paso, Texas. Copper smelter operations are prominent at Ajo, Arizona; Douglas, Arizona; Agua Zarca, Sonora; El Paso, Texas; and southwestern Hidlago County, New Mexico. A survey of the types of pollutants produced by industrial operations in the states of California, Arizona, New Mexico, and Texas has been developed by Cooper (1974). A summary of Cooper's findings is presented in Appendix A.

Appendix A also presents the pollutant types associated with agriculture and agriculturally related activities of the border region. Cooper (1974) reports that "agricultural operations constitute probably the most significant category of air pollution in Mexico along the U.S. border in the general categories of agricultural field production, product processing, and chemicals manufacture." Environmental problems developing from field production result from land management methods. Overgrazing in some areas of the border region has bared the soil to wind erosion, which contributes particulate matter to the pollution load of the atmosphere. Also, some wind erosion is induced by field agricultural activities. With the increase in irrigation districts in the Mexico frontier, this problem could become more serious. Stephan J. Mech and Neil P. Woodruff (1967) studied the importance of wind erosion in irrigated lands and developed an equation to estimate average annual erosion potential, which might be applied in the border region.

"Because of the physical nature of the soil and conditions under which it is used, bare ground can cause dusty whirlwinds with strong winds. This situation occasionally occurs, especially in the Mexicali Valley of Baja California" (Nicolas Sanchez Duron, 1974). The Mexicali Valley is the Imperial Valley of Mexico, and the border certainly does not cause a differentiation of surface wind and pressure phenomena, such as whirlwinds. Therefore, it must be presumed that similar situations arise in the Imperial Valley of California. Although the precise magnitude of dust contributed to the atmosphere of the border region from naturally arid conditions compared to soil disturbances resulting from agricultural field activities is not known, dust is recognized as a major contributor to the particulate load of the air. The often brilliant sunsets in the arid and semiarid environments of the border region is sensible evidence of a large particulate load in the lower troposphere. In agricultural areas, there is a greater probability that dust is acting as a medium for the transport of organic and inorganic pollutants.

The open burning of fields, of vegetation along irrigation ditches, and of trash resulting from the ginning of cotton is another source of air pollution related to agricultural activities (C. Wayne Hanselka, 1974). Open burning of a different form is a major contributor to air pollution in the frontier of the State of Chihuahua: diesel fueled heaters to prevent late frost damage in fruit-growing areas. "This is an air pollutant of considerable importance for people living nearby, and under certain circumstances, a nuisance to distant areas as well" (Hanselka, 1974). Because burners are used in the periods in which the inversion frequency is highest, pollutants are added during the night in the fruit-growing areas in contrast to urban areas where the pollutants begin building up with morning activities. Incomplete combustion of diesel fuel used in the burners is the principal problem, endangering people, animals, and pollination of the fruit blossoms being protected. Currently, different protection methods, such as individual heaters with chimneys, diesel fuel burned under pressure, more efficient gas heaters, and spray irrigation, are being evaluated. However, the burners presently employed are the most economical.

Although open burning for various purposes is an important environmental concern and visibly conspicuous, there is greater concern with respect to the release of fungicides, herbicides, and pestcides into the air, during and after field spraying operations. Stringent requirements are attached to the use and application of agricultural chemicals in the United States; however, organochlorine insecticides are still employed under little, if any, control in Mexico. "In 1978 human adipose tissue from [persons of] Cuidad Juarez were found to contain very high concentrations of these compounds," specifically DDT, Aldrin, and Heptachlor (Applegate, Forthcoming). In another investigation of the agricultural chemicals problem, DDT residues in alfalfa fields of southern Arizona were found to have increased between 1964 and 1967, a period in which the fields were not sprayed with DDT. This is prima facia evidence that "the source of the compounds had to either drift from nearby fields [in Mexico], during spraying, or from wind blown dust from sprayed fields after spraying" (Applegate, Forthcoming). There is some debate on this issue and Duron (1974) asserts that pesticide use in Mexico may be a nuisance to villages surrounded by fields treated, but "in most cases the pesticides sprayed do not represent an air pollution factor affecting the urban population along the border." One important aspect of DDT is its very long lifetime in the environment. Thus, windblown DDT residues from spraying of several years ago must be considered in any conclusions as to source.

Within the border region, more total land is devoted to range cattle than any other single enterprise. The cattle on the range seldom cause environmental problems, due to the low density of the cattle population. Although overgrazing and wide area accumulations of bacteria cannot be overlooked as significant concerns, the prime concern respecting cattle and livestock, in general, is with feedlot operations and associated odors, insects, and disease carrying bacteria in concentrated areas. "There are five major cattle crossings in Arizona, one in California, two in New Mexico, and six in Texas" (Applegate, Forthcoming). Each crossing has feedlot operations immediately proximate to the border on both sides; therefore, solid wastes and insecticides used for dipping cattle are especially critical environmental concerns of a local nature. Wind borne transport of solid waste particulate matter and bacteria are critical transfrontier air pollution concerns of a regional nature. In addition to cattle feedlot operations, the odors, insects, and disease associated with dairy operations, poultry, swine, and sheep must also be noted. Border crossings are also a principal focus of the environmental problems related to vehicular transportation in the border region.

The internal combustion engines of automobiles and trucks have been established to be responsible for fifty percent of the pollution problems of Mexico's frontier. Telloz (1974) reports that typical pollutants resulting from internal combustion processes are: " . . . carbon monoxide; carbon dioxide; simple hydrocarbons; oxygenated and polynuclear hydrocarbons; nitrogen of oxide and sulphur [sic]; aldehydes; phenols; lead salts; and volatile particulates." Emission data is sketchy, at best, for the border region, unavailable for Mexico and very general for the United States. Table 6 is an emissions inventory of San Diego County, California, which reveals that " . . . mobile sources are the greatest contributor to air pollution . . . " (Applegate, Forthcoming). However, it must be noted that this is the case principally in urban areas and may not be so in rural and agricultural areas of the border region.

There are three principal concerns associated with vehicular transportation in the border region. The first of these concerns relates to the frequency, magnitude, and nature of border crossings. "Of all the international borders in the world it is said that the United States-Mexico border registers the most intense transit. In gross figures the number of people that cross the border per year is about 130 million, one fourth from the El Paso-Cuidad Juarez area" (Guillermo H. Davila, 1973). At border crossing points, the average wait to cross in a vehicle is 20 minutes, according to Applegate (Forthcoming). Thus, idling vehicles at border crossings are something unique to the border region, especially in urban areas.

A second concern is that "the average age of vehicles in Mexico is considerably higher than the average age of American automobiles" (Woody Russel, 1974). Thus, many, if not most, vehicles operated in the Mexico frontier lack air pollution control devices. The result is that old age

Table 6. Emissions Inventory for San Diego County, California

Emission Source	Kilograms/Day					
	CO	NO_x	SO_x	Total Suspended Particulates	Total Hydrocarbons	Reactive Hydrocarbons
Process Losses	3,102	15,039	37,947	33,510	167,860	112,944
Combustion						
Fuel	6,059	33,554	25,056	11,014	2,404	761
Wastes	1,487	9	0	362	2,866	145
Vehicles	92,847,384	217,565	233,890	27,209	211,558	144,314
Misc.	32,578	353	0	19,359	4,689	2,268

Source: Adapted from Applegate, Forthcoming.

and long idling time combine to create a very real air pollution problem at crossing points, because automobiles emit a greater amount of various pollutants during slow, erratic operation. Cooper (1974) cites a study conducted in 1973 by Hughes, Boyce, and Welling, which contained recommendations for "major corrective changes in the ventilation system . . . " at the border Customs Inspection Station at Laredo, Texas, because of " . . . occupational exposures to excessive levels of carbon monoxide to inspectors from motor vehicles." Clearly, the larger the number of automobiles and trucks involved and the greater the frequency of border crossings, the worse will be the air pollution problem.

Another aspect of the age question is the great number of Mexican vehicles lacking pollution control equipment, which operate in the United States on a daily basis. These vehicles contribute to the overall pollutant levels of the United States border cities: a prime example of transnational pollution rather than transfrontier pollution. Apparently, it generally has been agreed that this transnational pollution occurrence combines with excessive vehicle emissions in Mexico to elevate ambient concentrations of hydrocarbons, nitrogen oxides, and carbon monoxide in the cities of El Paso, Texas-Cuidad Juarez, Chihuahua, and other locations along the border (Russel, 1974; and Ing. Luis H. Barojas Weber, 1974). C. Richard Bath (1977) refers to an international meeting called by the city attorney of El Paso in an apparent attempt " . . . to use the failure of the resolution of air pollution at the international level as justification for El Paso not conforming with national ambient standards of the United States." Obviously, without clear and convincing evidence, the elevated levels of pollutants of El Paso cannot be attributed wholly to Cuidad Juarez. However, this example serves to reveal only one complication a transfrontier air pollution problem can raise.

A third concern related to vehicular transportation is the actual area of movement. Many miles of dirt roads exist in the border region. In rural or thinly populated areas, dust problems may be insignificant, although the over-all addition of particulate matter to the air of the border region cannot be ignored. Dirt roads become a critical problem in need of direct and maybe urgent attention in urban areas, such as Cuidad Juarez. The phenomenal (767%) population growth of Cuidad Juarez (Refer to Table 3) has resulted in the extensive and intensive development of the hill sides west and south of the original city. This area is serviced by miles of dirt roads so prominent as to show up in satellite photography. While dirt roads are a problem, this concern is clearly a sensitive matter, reflecting the over-all population pressures within Mexico and the generally underdeveloped economic resources.

Political Associations

Socioeconomic activity generates pollution, and the geographic distribution of that activity affects the distribution of pollution sources and source areas. The physical geography of the border region also has played, and will continue to play, a role in the distribution of both socioeconomic activity and pollution itself. In addition, physical processes in the region act to modify the distribution of pollution generated from socioeconomic activities. There are, however, political factors also acting to affect pollution distribution and/or its concentration. The relations between the two countries at the national, regional, and local levels have the potential to foster or inhibit 1) growth in the border region and 2) specific development patterns. Growth and development, in turn, affects the distribution and/or concentration of pollution and, ultimately, the nature and magnitude of transfrontier air pollution.

Norris C. Clement (1978) has provided a clear and succinct discussion of many of the aspects of binational coordination and planning efforts associated with the border region, specifically the California-Baja California area. Political institutions identified and described by Clement are slowly becoming an integral part of the decisionmaking structure of the region. However, the effectiveness of these insitutions seems dependent on a variety of political, cultural, and economic factors, both within the United States and Mexico and between the two countries. This complex of political, cultural, and economic relationships is nowhere more evident than in the associations established and abandoned over the past few years between El Paso, Texas, and Cuidad Juarez, Chihuahua, respecting air pollution. In 1972, a cooperative program was implemented between the air pollution control officials of the two cities. Air quality monitoring stations were established in both cities, and there began an exchange of data and technology. In addition, training in air quality monitoring was provided to Mexican nationals by the United States. However, a truly cooperative association prevailed little more than one year, and, in 1973, active participation by personnel of Cuidad Juarez began to ebb (Sabino Gomez, 1978).

Reduction of the cooperative nature of the monitoring program was apparently the result of a general increase in tension between the two cities, which also manifested conflict over the operations of an international bus system (Thomas J. Price, 1977). Although the joint monitoring effort suffered after 1973, data continued to be gathered in both cities until 1977 by air pollution control personnel from the Texas Air Control Board. In 1977, the air quality monitoring effort ceased in Mexico, because the city government of El Paso acted to prohibit city vehicles from entering Mexico, ostensibly because of insurance restrictions. However, this prohibition apparently was in retaliation to an official ban on mosquito control activities of the City of El Paso in Cuidad Juarez. The root cause of both bans may well have developed from a change of the national government of Mexico. An extensive discussion of the tenuous political associations between the City of El Paso and Cuidad Juarez with respect to air pollution control efforts has been prepared by Bath (1977).

Between 1972 and 1977, several actions were taken by both cities to reduce air pollution, principally because of new authority provided by the respective national governments (Bath, 1977; and Bill Enriquez, 1973). However, the actions taken essentially were independent of any formal cooperative arrangements. As of 1977, Mexican officials asserted their independent capability to meet the needs of the monitoring program, but data exchange with the Texas Air Control Board has been untimely and of doubtful accuracy (Gomez, 1978). An informal liaison is maintained, however, between the local air pollution control officials of the two cities.

The difficulties of resolving the air pollution problems of the El Paso-Cuidad Juarez international metropolitan complex, considered an "epidemiological unity" by Davila (1973), derives largely from the external influences of national politics. Also, there are constitutional limitations on the degree of cooperation that can develop at this local level. While the United States constitution allows "subgovernments," such as states and cities, to participate in joint quasi-governmental associations, the Mexican constitution does not (H. Marshall Carter, 1977). Thus, formal local associations and cooperative efforts, necessary to resolution of the El Paso-Cuidad Juarez air pollution problem, are inhibited not only by national political (and economic) interests, but also by constitutional restrictions. However, this has not completely eliminated efforts to develop informal, joint programs, nor has it eliminated cooperative ventures in the border region as noted by Clement (1978) and Michael Becker, et. al. (1976).

In the case of El Paso-Cuidad Juarez, an inter-university pact, including the four universities in the two cities, was formed in January, 1976, to conduct joint research on environmental problems (See Appendix B). Although this effort apparently is encumbered with less than enthusiastic cooperation among the participant institutions, it reveals the continuing realization by some persons that a shared problem must be solved by all parties affected. In addition, the unofficial liaison maintained by the air pollution control officials has probably been more important than might seem on the surface. Clearly, efforts toward ultimate resolution of environmental problems, such as posed by transfrontier air pollution, must be sanctioned by the national governments. Bath (1977), in his discussion of dependence, interdependence, or detachment in the relations of the United States and Mexico respecting air pollution control actions, concluded that " . . . both are following detached, separate policies." While there is a perception of interdependence between the two countries, stemming from the recognition that air pollution control is a joint problem requiring joint action, there is also an apparent stigma associated with the past dependence of Mexico on the United States for assistance. Thus, a "detached" relationship has developed, the ramifications of which were recognized by the City Attorney of El Paso.

Whether real or apparent, the El Paso City Attorney's threat of suit to exempt the city from the national ambient air quality standards may have provided the impetus for the signing of a "Memorandum of Understanding" in June, 1978, between the Subsecretariat for Environmental Improvement of Mexico and the Environmental Protection Agency of the United States (See Appnedix C). The Memorandum formalizes a procedure for coordinating environmental enhancement efforts by both countries, but does not establish a definite program for pollution control. It is important to recognize, however, that the Memorandum of Understanding is perhaps only the first step in a long-term, politically and economically sensitive process, which will encompass more than local border problems. There likely will be involved a delicate weighing of each country's political, economic, and social goals and objectives, relative to the border region and international responsibility. While the pollution problems of some of the border cities in both countries should receive direct and immediate attention in the minds of some persons, this type of international coordination, cooperation, and evaluation must evolve before programs to resolve local problems can be effectively implemented. Without such an effort, the benefits of technological applications and objective problem evaluation will remain beyond the grasp of local officials. It is, after all, necessary for the problem to be perceived before action will be taken, and there are extraordinary problems in the border region that may or may not subordinate transfrontier air pollution in the hierarchy of priorities for international concern.

CHAPTER V

REMOTE SENSING AS A TOOL FOR EVALUATING TRANSFRONTIER AIR POLLUTION PROBLEMS

The local, regional, and potentially global scale of transfrontier air pollution problems in the United States-Mexico border region is amenable to evaluation through remote sensing operations. Whereas, local, in situ monitoring would be warranted in certain circumstances, detection and monitoring of transfrontier air pollution in the region as a whole should be enhanced by the aerial, sub-orbital, and orbital perspective associated with certain remote sensing applications. In the geographic context, the problem is to identify the flow patterns of various pollutants, the areal extent of identifiable pollutant effects, the intensity of concentrations, and the area of ultimate deposition (even when effects are not readily apparent). In order to evaluate the usefulness of remote sensing applications to detect and monitor transfrontier air pollution, it is helpful to have an understanding of the fundamental factors or determinants of pollution distribution dynamics. The distributional dynamics of air pollution are integral to the inherent geographical nature of transfrontier air pollution problems and, therefore, integral to the evaluation of the overall usefulness of remotely sensed imagery. Also, it is beneficial to understand the basic framework within which remote sensing, as a science and a technology, may be employed as an analytical tool.

Fundamental Aspects of Air Pollution Distribution

There are four principal factors affecting the distribution and concentration of pollutants discharged into the atmosphere: quantity of emissions; transport and diffusion mechanisms; transformation and removal processes; and pollutant lifetime (Paul S. Muther, et. al., 1973). Conclusions as to the usefulness of remote sensing to detect and monitor transfrontier air pollution must be sensitive to these factors. The primary conclusion respecting the quantity of emissions in the international milieu is that the more "advanced" the civilization, the more pollution per capita will be generated and discharged into the environment. It follows that the developed countries are the major contributors of air pollutants. The relation of the socio-economic activity and total emissions in the United States frontier compared to the Mexico frontier supports this conclusion. A second conclusion is that the quantity of emissions, which can be released without doing harm to the receiving medium's environmental service function, is determined by the other three factors. Thus, while quantity of emissions is important to the ultimate effects of pollution, transport and diffusion mechanisms, transformation and removal processes, and pollutant lifetime are critical to the geographic distribution of air pollution and those effects.

There are several components associated with the transport and diffusion of discharged pollutants. Pollutants are transported with the movement of the air, and dilution of concentrations result from mixing. Mixing or diffusion occurs both vertically and horizontally. Horizontal mixing is a function of wind speed and direction, while vertical mixing is a function of 1) the adiabatic lapse rate of temperature and 2) air mass characteristics. Thus, the geographic variation of transport and diffusion components can be directly associated with the seasonal variation of temperature and pressure patterns, given the location and physical characteristics of a particular region. Selective and controlled remote sensing observations, therefore, have the potential for providing seasonal information for determining transport and diffusion mechanisms.

Selective and controlled monitoring also should aid in evaluating transformation and removal processes. True removal processes carry the pollutants out of the atmosphere, while transformation changes the original pollutant through chemical and/or physical processes. A transformed pollutant remains in the atmosphere to be removed. The removal process can occur through dry fall-out, impaction or reaction with surface features, and/or "rain-out" or "wash-out." The type of removal process characteristic in a region will be related to the transport and diffusion mechanisms and, therefore, should be roughly predictable. For example, arid lands and drought periods in semiarid lands, such as characterize much of the United States-Mexico border region, would experience a predominance of dry fall-out. Transformation poses extreme complications, due to the need to trace the transport and diffusion patterns of pollutants after they have been transformed. The transformation process, in fact, may occur several times in the lifetime of a pollutant, and very little currently is known respecting the transformtion processes associated with known pollutants. In addition, the lifetime of pollutants is altered when transformation processes occur.

Ultimately, determination of transfrontier air pollution effects must establish where the pollutant is removed. Because the lifetime of pollutants is a function of the first three factors (including pollutant type), it is clear that no unique lifetime exists for any given pollutant. The fact that no unique lifetime exists can present tremendous logistical and technological problems in identifying the fact of a transfrontier air pollution occurence in a particular instance for a particular pollutant. This is true especially of the more "exotic" pollutants, such as lead, cadmium, and others, Ultimate removal of pollutants and the processes by which pollutants are generated and discharged, therefore, may be the most important considerations relative to remote sensing operations. That is to say, detection of sources and source areas or pollutant effects on surface features may be more feasible than attempts to detect pollutants in any one of a variety of states.

Although the emphasis of this thesis is directed at air pollution, it is beneficial to understand certain relationships between air pollution and water pollution, respecting distributive characteristics. Generally, factors controlling the concentration and dispersion of pollutants in the air are applicable to pollutants discharged into the water. There are, however, important differences between air pollution and water pollution regarding the nature of the problems posed once distribution has begun. For example, water pollution " . . . can be controlled after the pollutants have entered the water," while the "control of air pollution must take place before the pollutants enter the air, and this means that control action must be taken at each separate pollution source" (J. Clarence Davies, III, 1970). Thus, a centralized body can actually provide the means for water pollution control through such means as treatment facilities or low-flow augmentation actions. In contrast, air pollution control allows a centralized body to act only as a regulator of the source's discharge; no control of the atmosphere is possible.

Another important difference between air and water pollution is that the geographic distribution of pollutants in the air differs from that in the water. Whereas, pollutants entering water are confined to relatively defined limits of a river, bay, or lake, pollutants entering the atmosphere may well be distributed over a widely varying geographic area, given daily and even hourly variations of atmospheric conditions. It seems apparent that control approaches must account for these differences. It is apparent also that the usefulness of remote sensing as an aid in monitoring and control must be evaluated in the context of the unique control requirements associated with air pollution. In the case of transfrontier air pollution, these requirements are compounded by the requirement for international cooperation.

Framework for Detection and Measurement

Basically, there are two inherent approaches to the utilization of remote sensing as an analytical tool. The first approach monitors the concentration of pollutants in an environmental medium, determining the "ambient" quality. There are at least three classes of measurement of the ambient quality. As noted in The Remote Measurement of Pollution, which was published by the NASA Langley Research Center (1971), these three classes are:

1. Those that identify a given species of pollutant or confirm its existence in the atmosphere or the oceans;

2. Those that measure the total amount of a pollutant over a given area, i.e., the total burden; and,

3. Those that measure the distribution or pollutants along some axis, such as the vertical or line-of-sight.

The second approach is to monitor the effects of the polluted medium upon some material contacted by the medium, such as the effects of lead emissions on vegetation near highways. Either of these approaches may be used independently depending on the information desired. For example, an agronomist may be interested in the effect of air pollution on the health of crops or on crop yield and have no particular interest in the ambient quality of the atmosphere. However, the principal remote sensing approach applied to air quality monitoring is that which is concerned with the ambient quality or concentration of pollutants.

Because of the scale of transfrontier air pollution problems, large area, synoptic observations will be necessary to analyze pollution transport and diffusion. As such, "orbital air quality surveys are difficult to duplicate using aerial observations, which are sufficiently local in nature to be insignificant in the study of region-scale phenomena" (Frank S. Wobber, 1969). However, as indicated by the information presented thus far, many conditions of transfrontier air pollution in the United States-Mexico border region are localized and may be discrete occurrences. Thus, "region-scale" surveys of the ambient air quality may fail to provide an adequate basis for decisionmaking analysis. In fact, in order to affirm the presence and degree of concentration and dispersion, low altitude aerial observations may be necessary. Orbital air quality surveys should not be neglected, however, because of the synoptic view provided.

As indicated earlier, the acceptance of data relating to pollutant types, concentrations, and distribution in the global environment is a critical issue. Inherent political, economic, and cultural differences between nations are linked to varying national goals and objectives. It was indicated also that "procedures" to be examined, in light of the Principles of the Declaration On The Human Environment, should include an investigation of remote sensing techniques. It is useful to outline the several attributes of remote sensing in this context.

- Environmental Impact: Remote sensing techniques are compatible with the objective of understanding, measuring, and preventing environmental pollution, because of the minimal effects on the environmental medium monitored.
- Repetition: Remote sensing operations, especially those conducted from orbital platforms, can be conducted on a regular basis at predetermined intervals. This yields a consistant data set or, in the case of photography, a regular pictorial history of a particular area. Clearly, repetitive ability is an important attribute for monitoring.
- Access To Isolated Areas: Remote sensing operations can provide regular access to areas where on site ("in situ") investigations would be costly and laborious tasks. For transfrontier air pollution problems, this is important, because 1) many frontier areas are inaccessible and 2) the need for joint (international) field teams could be minimized.
- Objectivity: Although "interpretation" of remote sensing products implies subjective judgements will be incorporated, the

logical and mathematical basis of the science of remote sensing strives for objective results.

- Consistency: Consistency in the remote sensing of phenomena or areas of interest over time is an extremely important attribute. Field or "in situ" investigations can easily result in instrument calibration or reading errors. Weather anomalies also can generate errors in the results obtained. Remote sensing instruments need fewer calibration adjustments over a given period of time and, in fact, can be automatically calibrated at regular intervals in some cases. Also, "known error factors" can be employed to correct the information once obtained. Consistency in remote sensing by photography can be maintained through the control of film and filters employed and control of processing and processing environments. Again, known error factors can be employed, based on known parameters associated with the camera, film, development process, and acquisition environment.
- Synoptic View: The synoptic view provided by orbital platforms and, to a lesser degree, aerial observation platforms yield broad-scale information concerning a variety of phenomena. Imaging devices, such as multiband cameras and multispectral scanners, can provide information for analyzing large areas affected by pollution with respect to several natural phenomena, e.g., vegetation, soils, water resources, landforms.
- Operational Economics: Satellite remote sensing provides the opportunity to obtain relatively inexpensive synoptic views on a global basis at regular intervals. "A principal reason for the

> importance of remote sensing is the need for the collection of data on a scale and with a coverage either prohibitively expensive or virtually impossible by conventional or direct means . . . " (Conrad F. Heine and F. Douglas Johnson, Undated). Real data reproduction also can be easily accomplished, allowing joint examination of the same data and eliminating separate collection activities. This attribute is particularly desirable with respect to transfrontier air pollution monitoring in the United States-Mexico border region.

It should be pointed out that many remote sensing techniques, such as "Side-Looking Airborne Radar" (SLAR) and "Multispectral Scanners" (MSS), can yield "real" images. However, photography has the distinct attribute of providing positive, direct images familar to persons unacquainted with the scientific basis of remote sensing and image acquisition. For example, in many cases, little or no "interpretation" is required to identify a discharge or emissions plume associated with industrial operations.

PART THREE

EVALUATION OF REMOTE SENSING METHODS AND PRODUCTS FOR MONITORING TRANSFRONTIER AIR POLLUTION

CHAPTER VI

LITERATURE REVIEW

Review of the literature yielded significant information regarding the attributes of various remote sensing methods and products. However, in reviewing the literature, it was found that very few published works were concerned with the remote sensing of transfrontier air pollution, per se. Considerable information on the state of the art in detecting air pollution was gleaned from the literature, although many of the works reviewed concentrated more on global problems and global measurement of pollutants than on regional or local conditions. Because transfrontier air pollution is inherently a question of origin, transport, and deposition, studies relating with these particular aspects of air pollution detection and measurement were considered relevant. Studies concerned with pollution damage associated with broad area dispersion of pollutants also were considered relevant. The following discussion attempts to synthesize a large amount of information, derived from numerous sources, in order to provide a workable technical framework applicable to the nature of the transfrontier air pollution problems apparent in the United States-Mexico border region.

Because the detectability and, therefore, usefulness of photographic images varies with respect to the platform employed, it is important to note the essential characteristics of images obtained at orbital altitudes and sub-orbital or aerial altitudes. With orbital photography, concentrations of undispersed pollutants or plumes can be detected. In fact, "air pollution plumes may be of such major proportions or so subtle in total that they cannot be detected without the large area overview and synthesis . . . " provided by orbital coverage (Wobber, 1969). Photography is effective in the visible region of the electromagnetic spectrum; however, very few molecular absorption or emission bands exist in this region for gaseous air pollutants. "The only colored gas that is a common pollutant is NO_2 [Nitrogen Dioxide], the gas that causes the so-called brown smog" (NASA Langley Research Center, 1971). Detection of NO_2 in the troposphere has been demonstrated, and total vertical resolution between the ground and the camera has been obtained. Detection of NO_2 in the stratosphere is feasible with a vertical resolution of a few kilometers. Although direct detection of specific gaseous pollutants with photography is limited, mega-scale phenomena, such as cloud drift, is detectable. Cloud drift reveals variations in the air wind structure. Because orbital photographs sometimes can detect pollution plumes, knowledge of air wind structure is beneficial to inferences as to transport and ultimate deposition of plume constituents when known.

The literature reveals that the geographical distribution and movement of certain types of pollutants, primarily particulates, can be monitored with orbital photography. "Orbital photograhs have been successfully used to define the scale of dust movement, which, like many man-made pollutants, probably could not have been detected using aircraft" (Wobber, 1969). William E. Shenk and Robert J. Curran (1974) reported that the visible reflected energy recorded by the Image Dissector Camera System (IDCS) on Nimbus 4 revealed a bright spot over the Atlantic Ocean west of Africa, which most likely resulted " . . . from the transport of the smaller particles [of a dust storm] over the water a maximum distance of about 200 kilometers offshore." Also, Frances C. Parmenter (1971) reported that "a large area of smoke, emanating from slash burning operations in Central America, was observed on Applications Technology Satellite 3 (ATS 3) photographs." The smoke was visible clearly for a 25-day period and the anticyclonic flow of the Gulf region carried the smoke " . . . northward and eastward as far as Tampa, Fla."

Thus, orbital photography and imaging systems operating in the visible region of the electromagnetic spectrum (which produce photographic-like images) can be useful in tracking particulate matter. In fact, particulate matter can be tracked over long distances through regular, repeated surveys at orbital altitudes, if surrounding atmospheric conditions provide sufficient contrast. A significant portion of the pollution load generated by natural processes and industry is particulate matter. Therefore, orbital photography provides a high potential use in monitoring occurrences of transfrontier air pollution in the United States-Mexico border region.

Generally, aerial photography provides the same potential detectability as orbital photography. However, the scale and detail of aerial photographs is vastly different. In addition to scale differences, compared with orbital photography, there is a large decrease in the mass of the atmosphere through which visible radiation is transmitted to aerial cameras. Thus, there is a considerable difference in spatial and spectral resolution between aerial and orbital photographs obtained in an identical manner. This does not imply that one method is better than the other. In fact, in an interstate pollution case between Vermont and New York, both orbital and aerial images were introduced as evidence and accepted by the court.

A good example of the use of aerial photography in detecting particulate pollution is a study conducted in the Kansas City-Topeka corridor. The study of air quality in this area was based on the assumption that monitoring of particulate matter could be conducted on the principles associated with the phenomenon of scattering (B. G. Barr, et. al., 1972). Utilizing multiband photography, Barr and his associates assumed that the intensity and polarization of scattered light could be recorded and density measurements employed to determine an optical extinction coefficient of particulate concentrations. The calculation of the optical extinction coefficients was accomplished; however, it was concluded that coefficients could not be relied upon as a sole indicator of atmospheric aerosol mass concentration. Additional information was deemed necessary, respecting: 1) the amount of water vapor in the air compared to the amount of water vapor emitted at the source; 2) the process producing the particulates; 3) the air temperature, which affects water vapor condensation on particulates; and, 4) the background aerosol level and emission of gases, which affects total aerial visibility. It was noted by the researchers that these factors also may be important to the dispersion characteristics of plumes.

A principal difficulty in the detection and measurement of pollution with aerial photography and calculation of an extinction coefficient relates to the lifetime of the particles according to size. All of the above factors will affect lifetime and the rate at which deposition occurs. Therefore, the change in optical extinction, progressively away from the source, must be measured. Clearly, the information derived from photography will not yield perfect knowledge about the phenomenon or phenomena under investigation. While the bulk of a pollutant concentration or the bulk of a pollutant's effects may be readily apparent, even to the untrained eye in some cases, the full extent of pollutant dispersion patterns and ultimate deposition tends to remain somewhat enigmatic. Factors, such as cloud cover, particulate scattering, absorption, solar angle, film quality, spectral response, photographic background, photographic medium, and the pollutant itself, act in concert to prohibit simple methods of identifying and measuring air pollution. Thus, it is imperative that the interpretation of photographic images must involve various logical methods, such as photo-interpretation keys, in conjunction with other remote sensing methods and ground based data gathering activities.

Thus far, there has been mention only of the detection and measurement of air pollutants: the utilization of photography to evaluate the ambient air quality. The second analytical approach to air quality monitoring, that of evaluating the effects of the polluted medium on material it contacts, has been demonstrated in, at least, two studies. In one study, aerial color photographs were obtained of national forest lands near Los Angeles (Steven L. West, et. al., 1970). Five different scales and four different film types were employed in a test to determine the usefulness of aerial photographic interpretation techniques in detecting and evaluating air pollution damage. The resulting interpretations of the photographs were verified by ground-based inspection of the forested lands photographed. The interpretation accuracy was considered acceptable as was the ground truth correlation. The study concluded that "aerial photography can be used to detect and evaluate affected trees within an acceptable limit of accuracy" (West, et. al., 1970).

In controlled, experimental photography of vegetation in the Kansas City-Topeka corridor, "vegetation stress" was determined to be possibly, if not likely, a direct result of air pollution (Barr, et. al., 1972). Although other factors, such as soil content, soil moisture, and slopes, were possible causes in most cases, the experimental tests indicated reason for continued investigation of the potential for photography to reveal vegetation stress. Tests clearly indicated that vegetation near the pollution source (e.g., roadway) was noticeably less vigorous. Relative to stress created by ambient air quality for the large metropolitan corridor, the less vigorous vegetation was noticed where concentrations were highest. Thus, the photography provided evidence of a correlation between pollution and vegetation stress, but Barr and his associates were unable to state without qualification that the stress was caused by the pollution. If soil and slope factors could be neutralized or held constant in a controlled manner, then the strength of this correlation may be better determined.

Clearly, orbital and aerial (or sub-orbital) photography can contribute significantly to the monitoring and evaluation of certain aspects of the air pollution problem. However, photography, as a remote sensing system, is limited to the narrow, visible portion of the electromagnetic spectrum, which is roughly between 100 nm and 1500 nm (1.5 micrometers). Non-photographic remote sensing systems operate over a larger portion of the spectrum between the ultraviolet (290 nm) and the microwave (20 m). Many non-photographic systems directly sense reflected or emitted electromagnetic radiation. Some devices compare the spectral qualities of an environmental sample with that of a known sample pollutant. Also, there are a great variety of products or outputs produced by non-photographic remote sensing systems. Some generate images and some do not. Due to the different spectral, spatial, and temporal aspects of the various "remote sensors," each system possesses inherent advantages and disadvantages with regard to monitoring pollutant flow and burden in environmental media.

The greatest ability of aircraft and satellite borne remote sensors in the lower atmosphere is in the determination of the "total" burden of a gaseous pollutant above a point on the surface. At the present state of the art, there are limitations on the measurement of concentrations at some point or the distribution of gaseous pollutants as a function of height. However, these limitations can be mitigated through the supplementary use of " . . . data on wind velocities and wind structure to quantitatively determine [sic] the total amount of pollutants present in a given region and to monitor the dissipation of each pollutant and its mass transfer between one region and another" (NASA Langley Research Center, 1971). Also, supplementing aircraft and satellite borne remote sensor data with concurrent ground-based measurements of meteorological conditions appears useful in making inferences on the vertical structure of pollution. In the upper atmosphere, limb scanning techniques, which scan the horizon plane, can independently measure vertical distribution with good height resolution.

The degree of accuracy appropriate for studying gaseous pollutants has been considered by the scientific community, and levels of desired accuracy have been established. Tables 7 and 8 are reproduced to provide a summary of the types of gaseous pollutants causing concern, the associated problems, and the level of accuracy considered to be appropriate. The tables display measurement requirements at both the global and regional scales. "Regional," in the context of this information, was taken as being an area of about 10^6 square kilometers or 384,400 square miles. If the United States-Mexico border region or the "borderlands" is assumed to incorporate an area roughly 160 kilometers (100 miles) on both sides of the border, then the border region would encompass approximately 826,000 square kilometers or 320,000 square miles. Clearly, the border region is a typical "regional" area defined by NASA. Although spatial and temporal factors were not directly considered in the formulation of the tables, it was generally held that a ground resolution of 100 square kilometers (38.4 square miles) was desirable. The tables are useful for general guidance, but for problems of localized transfrontier air pollution, a ground resolution of greater than 1 square kilometer will prove inadequate.

Airborne particulate measurement depends on an understanding of interactions resulting from scattering, rather than alteration of the "normal" or clean atmosphere, per se. Therefore, the prime determinants

Table 7. Requirements for Measuring Pollutants with A Recognized Environmental Impact

GLOBAL

Constituent & Region Of The Atmosphere	PROBLEM: Why are we concerned?	Accuracy
CO_2	Measure its increase, which is a factor in climate change	0.5 PPM
SO_2 - Upper Troposphere And Stratosphere	Formation of particles in the stratosphere from SO_2 carried upward from the troposphere or injected by volcanos and SST's	0.5 ppb
O_3 - Stratosphere	What causes the long term changes in distribution of Ozone? Is there a correlation with solar activity?	Total Content, 1%; Distribution With Height, 10%
H_2O - Stratosphere	(a) Determine effect on Ozone concentration (b) Determine effect on radiation balance of stratosphere (c) Determine influence on particle size distribution in the sulfate layer	Total Content, 20% for (a); Much less accuracy for (b); Distribution With Height 0.5 ppm (c)
NO_x - Stratosphere	Determine effect on Ozone concentration	NO_2 and NO, 10 ppb

REGIONAL

Constituent In Lower Layers	PROBLEM: Why are we concerned?	Accuracy
SO_2	(a) Damage to plants (b) Particle formation, which subsequently contributes to acid rain [Note: Generally not a problem in arid climates]	10 ppb
H_2S	(a) Oxidizes to SO_2 (b) Its natural source is uncertain	0.1 ppb (?)

Table 7. (cont.)

Constituent In Lower Layers	PROBLEM	Accuracy
NO_x	(a) Damage to plants and toxicity at PPM concentrations (b) Photo-oxidation of hydrocarbons and particle formation (c) Precursor of PAN's	0.1 ppm for (a); 10 ppb for (b) and (c)
$\langle HC \rangle$	(a) Lead to particle formation by photochemical processes (b) Lead to noxious and toxic products	>1 ppb (?); Necessary to distinguish species
O_3	Irritant and destructive; a product of photochemical processes involving $\langle HC \rangle$ and NO_x	10 ppb
PAN's	A class of toxic and irritant products of photochemical processes	1 - 10 ppb
Hg	Atmosphere transports Hg, which is toxic where it accumulates in the biosphere	10^2 ppb
Heat Released	A factor in regional climate change	-

Source: NASA Langley Research Center, 1971.

Table 8. Requirements for Measuring Pollutants for which Concern is Speculative or Long Term

GLOBAL

Constituent & Region Of The Atmosphere	PROBLEM: Why are we concerned?	Accuracy
CO - Troposphere and Stratosphere	(a) Is concentration changing due to man's burning of fossil fuels? (b) Determination of destruction processes in the stratosphere	10 ppb
HNO_3 - Stratosphere	(a) Determine effect on Ozone concentration (b) Does it influence aerosol formation?	1 ppb
$\langle HC \rangle$ - Stratosphere	Do they influence aerosol formation?	Not determined except for CH_4. $\langle HC \rangle$ have not been detected om the stratosphere
CH_4 - Troposphere and Stratosphere	(a) Participates in photochemical reactions in the lower atmosphere (b) What is its influence on stratospheric H_2O (and O_3) distribution?	Troposphere, 0.5 ppm; Stratosphere, 0.2 ppm
Fluorocarbons, Total	Probably accumulating due to man's release	$>$.001 ppb (?)
N_2O - Stratosphere	Determine its rate of photo-dissociation in the stratosphere	50 ppb

Table 8. (cont.)

REGIONAL

Constituent In Lower Layers	PROBLEM: Why are we concerned?	Accuracy
CO	(a) Determination of sources, sinks, and lifetime in lower atmosphere (b) Participates in photochemical reactions (c) Indicative of oceanic processes	10 ppb
H_2CO	(a) Participates in photochemical reactions (b) Irritant at concentration near 1 PPM	1 ppb
Halogens	(a) Toxic and damaging (especially fluorine and HF) (b) Bromine is indicative of bio-productivity of the oceans	1 ppb
NH_3	Combines with sulfuric acid to form $(NH_4)_2SO_4$ particles	10 ppb

Source: NASA Langley Research Center, 1971.

examined are the " . . . conductivity and size compared to the radiation wavelength" (NASA Langley Research Center, 1971). The principal concern is the size parameter (q), defined as the ratio of the circumference of the particles divided by the wavelength of radiation. Utilizing laser radar (LIDAR), the presence of particulate matter can be determined by deviations in echos that might be expected from a pollution free atmosphere. "Typical range resolution with presently available laser radar systems are of the order of 100 m" (NASA Langley Research Center, 1971). This resolution seems appropriate for transfrontier air pollution problems; however, a finer resolution may be desirable. "The ability to collimate the high intensity light source and the very narrow spectral line widths makes the laser very attractive for pollution measurements" (NASA Langley Research Center, 1971). It must be noted, however, that maintenance of collimation is a principal limitation of LIDAR systems, especially in the infrared portion of the spectrum, which is the "signature region." Also, LIDAR systems require an energy source, making them expensive to operate.

When passive systems are employed, the "signature" of a pollutant in the atmosphere usually arises due to molecular absorption. In active systems, such as LIDAR and RADAR, the "signature" may also arise due to scattering processes. Thus, the choice of a spectral interval will be dictated by " . . . the presence of a measurable molecular absorption coefficient in the interval or by the existence of a sensible spectrally dependent molecular scattering coefficient in the region" (NASA Langley Research Center, 1971). These coefficients are an indication of the pollutant's signature as a function of the signature of a "clean" atmosphere. However, the difficulties of data interpretation and the availability and sensitivity of instruments and detectors must be considered in any monitoring effort.

Spectroscopic techniques, whether in emission or absorption mode, offer the means for the direct and continuous detection of pollutants in the gas phase. The absorption or emission characteristics can serve to identify a pollutant and to measure its ambient concentrations. Furthermore, spectroscopy offers the means for direct observation of pollutants at a point or over an extended path without the need for any intervening sampling apparatus.

Specific techniques, methods, and systems, demonstrated to be useful in non-photographic remote sensing of air pollution, are summarized in the following paragraphs. In addition, Appendix D summarizes specific experiments conducted to evaluate the usefulness of Landsat MSS imagery in detecting air pollution. Landsat MSS imagery is readily accessible at a comparatively reasonable cost.

- The Non-Dispersive Infrared Spectrometer (NDIR), using a dual isotope fluorescence principle, senses Carbon Monoxide (CO) in the atmosphere to a sensitivity of 0.1 parts per million (ppm). Since its original incorporation in Skylab and subsequent commercialization, the technique has been greatly improved.
- A dispersive polychromator radiometer, used in conjunction with the Satellite Infrared Spectrometer (SIRS) on Tiros and Nimbus, yields reliable measurements that can be converted into a vertical temperature profile of the atmosphere. However, the instrument complex is not effective when cloud cover is present.

- The Vertical Temperature Profile Radiometer (VTPR) can obtain information when partly cloudy conditions prevail. The VTPR takes advantage of the spectral properties of ubiquitous Carbon Dioxide (CO_2).
- Densitometer scans of Landsat imagery have provided qualitative information on the character of aerosol plumes in the atmosphere. "By correlating ERTS [Landsat] imagery with known stack locations, actual emission data, and meteorological conditions, atmospheric diffusion coefficients can be computed and a model developed to predict surface emission concentrations" (Heine and Johnson, Undated). It also may be possible to determine stack emission rates using ERTS imagery in this manner.
- The Correlation Interferometer has been developed to a point where it can measure CO concentrations in the atmosphere with good sensitivity and specificity. Three sensors in the Nimbus 6 interferometer measure ozone, water vapor, nitric acid, methane, nitrous oxide, and nitrogen dioxide in the stratosphere, while a second remote sensor measures carbon monoxide, sulfur dioxide, ammonia, and methane in the troposphere. Also on board is a visible polarimeter that measures the composition, size, and distribution of particles in the atmsophere.
- Correlation spectrometers have been shown to be effective in determining sulfur dioxide (SO_2) and NO_2 profiles via airborne platforms. The instrument can be pointed up, down, or obliquely, enabling profile data to be obtained over an entire region,

depending on the flight path. Basically, the correlation spectrometer can be used to obtain measurements of "total" pollutant burden and pollutant mass flow. Measurement of burden can be obtained with the instrument pointed vertically upward, which results in values specified in parts per million meters. The measurement of mass flow can be obtained by combining burden with wind speed and direction, assuming the pollutant is transported by wind. Mass flow measurements are estimated only, unless the speed of the platform is taken into account. The resultant flow in grams per second can be converted into metric tons per day with this approach. Use of the correlation spectrometer requires knowledge of the mixing depth of the atmosphere and, therefore, the vertical temperature profile must be known. Vapor content of the atmosphere also is important in interpreting profiles obtained with the correlation spectrometer.

- The Kansas City-Topeka corridor study demonstrated the effect of atmospheric lapse rates on plume dispersion, utilizing a correlation spectromter (Barr, et. al., 1972). Plume dispersion (or dispersion of any pollutant released into the atmosphere) is affected by the meteorological conditions prevailing in the area. Pollution, in turn, affects these atmospheric conditions. Thus, as pointed out by Barr and his associates, factors, such as " . . . condition of release, wind speed, turbulence, stack height, and many other factors associated with terrain and aerodynamics . . . " must be considered.
- The application of active (radar) and passive (radiometer) microwave remote sensing systems to measure vegetative stress associ-

ated with air pollution also was investigated in the Kansas City-Topeka corridor study (Barr, et. al., 1972). The use of fine-resolution synthetic aperature radar (SAR) was reported to be promising.

- The use of radiometers for monitoring pollution in the atmosphere has provided measures of ozone and water vapor concentrations.
- With a spectral scanning capability and when used in the absorption mode, radiometers have been shown useful in contouring particulate atmospheric constituents and determining the distribution of molecules along the line of sight.
- The Visible and Infrared Spin-Scan Radiometer (VISSR) on the Synchronous Meteorological Satellite (SMS-1) has been shown to be useful in detecting ground radiation fog and low stratus clouds (John A. Ernst, 1975). The VISSR also has been shown useful in detecting large scale dust movement in the southern portion of the United States (Henry W. Brandli, et. al., 1977).
- The Temperature Humidity Infrared Radiometer (THIR) on Nimbus 4 proved useful in interpreting storm conditions and the over-all dimensions of an area of the western Sahara Desert in which a dust storm occurred between 20 and 23 April, 1970 (Shenk and Curran, 1974). The THIR was employed on the premise that there would be a detectable thermal contrast between areas where material is and is not being lifted. The thermal data obtained from the THIR was used in conjunction with the Image Dissector Camera System (IDCS) also on Nimbus 4.

- Two ESSA 8 photographs, analyzed by Tillmann Mohr (1971), were found useful in detecting " . . . areas of critical pollution potential (i.e., areas with existing low-level inversions)" in an area of western and central Europe.

Much work has been completed and continues in the development and use of photographic and non-photographic remote sensing for air pollution detection and monitoring. In addition to the specific examples cited above, a summary of NASA findings is presented in Table 9. Thus far, most systems employed are not strictly applicable to air pollution problems. This means, simply, that further work need only be oriented to experimentation with currently available instruments, in order to gain better understanding of interpretative techniques. Thus, this study is directed toward evaluating whether remote sensing applications and interpretation of outputs can be employed to produce meaningful inputs for global, national, regional, and local decisionmakers dealing with transfrontier air pollution concerns. Ultimately, the science of remote sensing, its theories, its instruments, and its interpretations must be oriented to enhance decisionmaking processes.

At present, the efforts of the science seem to be spread thinly over numerous areas of interest or concern. The focus of this study and the evaluations of imagery to follow are concerned with the potential contribution of the science to the problems of transfrontier air pollution. It should be noted that there was considerable difficulty encountered in determining the proper terminology for instruments, which should be established, if for no other reason than to allow understandable communication respecting techniques, methods, and applications. The

Table 9. Measurement Capabilities for Remote Sensing of Trace Gases

Measurement Approach:	I. Limb Scan	II. Vertical Scan
	1. Thermal Emission	1. Thermal Emission
	2. Absorption	2. Absorption

Constituent	Altitude Range Of Measurement	Altitude Resolution	Capability	Measurement Approach
CO_2	Entire	Total	Potentially Feasible	II.2 - SOLAR IR. Required accuracy will be very difficult to obtain.
$(C^{12}O_2/C^{13}O_2)$	Entire	Total	Feasible	II.2 - SOLAR IR. Not required measurement, but may be useful in distinguishing between sources.
CO	Troposphere	Total	Feasible	II.1 and II.2 - SOLAR IR and THERMAL IR
SO_2	Troposphere	Total	Demonstrated In Tests-Regional; Potentially Feasible-Global	II.2 - SOLAR UV. Demonstrated from a balloon, using a correlation spectrometer.
			Feasible-Regional; Potentially Feasible-Global	II.2 - THERMAL IR; and, II.2 - SOLAR IR
	Stratosphere	FEW km	Potentially Feasible	I.2 - SOLAR IR and THERMAL IR; and, I.1 - THERMAL IR

Table 9. (cont.)

Constituent	Altitude Range Of Measurement	Altitude Resolution	Capability	Measurement Approach
O_3	Stratosphere	2 km	Feasible	I.1 - THERMAL IR. Under development for NIMBUS F.
		0.5 km	Demonstrated In Tests	I.2 - SOLAR visible. Demonstrated on balloon. Under development for OSO-J.
		Total	Demonstrated In Tests	II.2 -SOLAR UV. Flown on NIMBUS 4. Accuracy of 10% achieved. Method can also give height distribution above O_3 maximum.
	High Strato-sphere And Mesosphere	1 km (?)	Demonstrated In Tests	I.2 - STELLAR UV. Results have been obtained, using OAO data, for altitude range - 60 km to 100 km.
	Entire	Total	Demonstrated In Tests	II.1 - THERMAL IR. Flown on NIMBUS 3 and 4. Accuracy - 5% achieved.
H_2O	Troposphere	?	Demonstrated In Tests	II.1 - THERMAL IR. Flown on NIMBUS 3 and 4. Does not meet accuracy requirement; measurement in high troposphere difficult.
	Stratosphere	2.5 km	Demonstrated In Tests	I.1 - THERMAL IR. Flown on a rocket, but required accuracy not achieved.
		1 km	Demonstrated In Tests	I.2 - SOLAR IR. Flown on a rocket. Potentially can extend to mesosphere.

Table 9. (cont.)

Constituent	Altitude Range Of Measurement	Altitude Resolution	Capability	Measurement Approach
NO_2	Troposphere	Total	Demonstrated In Tests	II.2 - SOLAR visible. Demonstrated on a balloon, using a correlation spectrometer.
			Feasible	I.2 and II.2 - SOLAR IR and THERMAL IR
	Stratosphere	FEW km	Feasible	I.2 - SOLAR VISIBLE
			Potentially Feasible	I.1 - THERMAL IR
NO	Troposphere	Total	Feasible	II.1 - THERMAL IR
	Stratosphere	FEW km	Feasible	I.2 - THERMAL IR
$\langle HC \rangle$	Stratosphere	FEW km	Potentially Feasible	I.1 or I.2 - If concentrations are in PPB range.
CH_4	Stratosphere	FEW km	Feasible	I.1 or I.2 - THERMAL IR or SOLAR IR
H_2CO	Troposphere	Total	Potentially Feasible	II.2 - SOLAR IR and SOLAR UV. Capable of measurements in PPB range, but required accuracy not known.
C_2H_2	Troposphere	Total	Potentially Feasible	II.2 - SOLAR IR. Capable of measurements in PPB range, but required accuracy not known.
C_2H_4	Troposphere	Total	Potentially Feasible	II.2 - SOLAR IR. Capable of measurements in PPB range, but required accuracy not known

Table 9. (cont.)

Constituent	Altitude Range Of Measurement	Altitude Resolution	Capability	Measurement Approach
H_2S	Troposphere	?	Not Currently Feasible	?
N_2O	Stratosphere	FEW km	Feasible	I.1 or I.2 - SOLAR IR or THERMAL IR
I_2	Troposphere	Total	Demonstrated In Tests	II.2 - SOLAR visible. Demonstrated from an aircraft over marine source.
HCl	Troposphere	Total	Feasible	II.2 - SOLAR IR
HF	Troposphere	Total	Feasible	II.2 - SOLAR IR
HNO_3	Stratosphere	FEW km	Demonstrated In Tests	I.2 or I.2 - THERMAL IR or SOLAR IR. Demonstrated in balloon experiment.
NH_3	Troposphere	Total	Feasible	II.2 - SOLAR IR
	Stratosphere	FEW km	Feasible	I.1 or I.2 - THERMAL IR or SOLAR IR
Fluorocarbons	Troposphere	Total	Not Currently Feasible	?
Hg	Troposphere	?	Not Currently Feasible	?
Heat Released	Surface	Total	?	Depends upon ability to measure surface temperature, air temperature change, wind, water vapor, etc., since heat released will take many forms.

Source: NASA Langley Research Center, 1971.

use of the terms radiometer and spectrometer interchangeably in the literature is unjustified, because there are inherent differences between these two types of devices. In fact, the lack of definition of many terms freely used in the literature and a general lack of standardization of terminology reveals the immaturity of the science.

Relative to the questions of transfrontier air pollution problems, it is apparent that remote sensing can provide significant information concerning CO, CO_2, NO_2, SO_2, and other pollutants. Additionally, remote sensing can provide valuable supplementary data necessary to the interpretation of pollutant species effects, especially temperature profiles, and/or variance of air and water temperature, circulation of water, air mass dynamics, water vapor content of the atmosphere, and oxygen content of water bodies. It appears that both spatial and spectral resolution can be attained appropriate to the scale of transfrontier air pollution problems. The remaining evaluations of specific imagery are aimed at determining the validity of this general conclusion.

CHAPTER VII

IMAGE SELECTION AND EVALUATION METHODOLOGY

Evaluating the contribution which remote sensing methods and products, specifically photographic and non-photographic images, can make to resolving transfrontier air pollution problems (and other environmental problems) involved 1) a determination of the potential usefulness of photographic and non-photographic systems to detect pollutants and 2) an examination of selected products and analytical techniques relative to images generated by those systems. Products were selected with respect to the United States-Mexico border region within the broad definition noted in Chapter IV. The determination of potential usefulness relied on the review of the literature in Chapter VI, evaluation of the nature and character of environmental problems in the border region as presented in Part Two, and a search and screening of accessible product files, such as microform and computer listings, maintained by public agencies (Dick Kroeck, 1976). The latter effort will be discussed more fully in later paragraphs.

Examination of selected products included fundamental interpretation techniques applied to a variety of images. Visual interpretation techniques, including stereoscopy, were employed initially. The spectral sensitivity and spatial resolution provided by the images was evaluated. Image enhancement techniques were then applied to some of the products to determine the usefulness of such methods in contributing to the evaluation of transfrontier air pollution occurrences. Finally, findings and conclusions, derived from evaluation of the selected images, were schematized. The scheme relates the type of image and image scale to potential use in evaluating transfrontier air pollution concerns of the border region. The findings and conclusions will be discussed in Part Four.

Image selection was intended to yield the greatest variety of images, based on spectral, spatial (or scale), and temporal differences. However, limitations were imposed on both the selection of products and the evaluation of analysis techniques, because financial resources were lacking, the most sophisticated analysis techniques were inaccessable, and a controlled program of observation and ground truth collection was impossible. These limitations are not considered fatal to the study, because an important premise is that the products be suitable for use by the United States and Mexico. Thus, the products should be 1) readily accessable, 2) amenable to fairly direct interpretation and analysis, and 3) reasonably inexpensive. The premise is based on the belief that accessability, analysis, and costs would be critical concerns in the establishment of joint efforts between the two countries. Considering the disparity of wealth and technological achievement between the two countries, this does not seem to be an unreasonable basis upon which to structure the study. Therefore, despite the limitations noted, it is believed that the methodology employed has served to 1) establish a firm basis for preliminary conclusions respecting the utility of remote sensing in transfrontier pollution monitoring in the border region, 2) provide adequate knowledge for initial attempts to integrate remote sensing methods and products into an international monitoring program, and 3) provide sufficient information to formulate directions for future study.

Remote sensing imagery readily accessible for a study of this nature include: Landsat images generated by the Multispectral Scanner (MSS) and Return Beam Vidicon (RBV) camera; photographs obtained by the Skylab Multiband Camera (S190A); photographs obtained by the Skylab Earth Terrain Camera (S190B); Apollo/Gemini photographs; NASA aircraft photographs; and visual and infrared images generated by the Synchronous Meteorological Satellite (SMS) and the Geostationary Operational Environmental Satellite (GOES) over the Pacific and Atlantic Oceans, respectively. All the products noted are in the public domain and can be obtained at a nominal cost for reproduction. The Landsat, Skylab, Apollo/Gemini, and NASA products are available directly from any one of several agencies established to provide the products to the public. Kroeck (1976) has prepared a comprehensive listing of sources of imagery, including a concise summary of image characteristics, platforms employed, and sensor features. SMS and GOES imagery is relatively easy to procure at principal United States Weather Service offices. In addition, an unknown number of local aerial photographic surveys have been conducted, but most of these are not in the public domain and, therefore, not catalogued nor as easily procured.

Prior to selecting remote sensing products for evaluation in this study of transfrontier air pollution, an attempt was made to determine the potential usefulness of the various products noted above. Therefore, listings of available photographs and imagery with cloud cover of 10% or less were requested for the United States-Mexico border region. Because of the large land area of this region (826,000 square kilometers or 320,000 square miles), an enormous amount of images have been obtained in recent years through a variety of means. Only the Landsat listing proved manageable with regard to a basic selection process. Even an analysis of Landsat usefulness had to be restricted: 1,349 accessions were listed for the paths and rows crossing the border. Therefore, imagery of the international metropolitan complex of El Paso-Cuidad Juarez was selected for evaluation. This international urban center exhibited most of the environmental problems contributing to transfrontier air pollution, meteorological information was easy to procure, it has been the subject of considerable debate already with respect to transfrontier air pollution problems, and the two cities were accessable to the author for purposes of field investigations and interviews with persons in the area.

The potential usefulness of Landsat images was evaluated on the assumption that the images had to be free of clouds (10% of less) to enable detection of air pollution. Analysis of the listing of Landsat images of the El Paso-Cuidad Juarez area revealed that there were potentially 168 images generated, during the period 09/06/72 and 08/06/78. Of these, 114 or 67.9% were characterized as having 10% or less cloud cover. Clearly, a high percentage of cloud free or nearly cloud free images would be expected for the arid climate. The listing indicated 50 out of 114 images (almost 30% of the total for the period) were high quality and 24 images (slightly over 14%) were high quality with 00% cloud cover. Thus, the gross potential for using Landsat images was apparently high, especially in the aird (and probably semiarid) portions of the border region. By way of comparison, only one image was reported to have 00% cloud cover for the Gulf Coast area and the Rio Grande Embayment, during the period 01/21/73 to 07/12/78.

The listing of Landsat images also was useful in determining the time of year cloud free images would be most probable. For the the El Paso-Cuidad Juarez area, it was expected that the time of year with the highest number of cloud free images would correspond to the time of the year with the highest frequency of inversions: late fall, winter, and early spring. Should this be true, there would be a high potential for any particular image generated during this time to reveal air pollution. Thus, the selection of images could be guided to the times of the year when the potential for detecting specific pollution sources or the total pollution burden would be highest. The fact that Landsat MSS images are generated at approximately 9:30 A.M. local time was added reason to believe that specific images might be useful. Generally, nocturnal inversions do not "break-down" until midday. Analysis of the listing revealed that October and May accounted for the greatest number of images having 10% or less cloud cover. In addition, 45.5% of the October images and 34.4% of the May images were listed as cloud free. The higher percentage for October correlates will with the higher inversion frequency at that time of the year compared with May.

In order to determine the usefulness of available non-Landsat images, the microform library at the regional office of the National Cartographic Information Center in Denver, Colorado, was searched. During a 4 day period, hundreds of photographic images (including Landsat images) were previewed for examples of air pollution in the border region. This search was directed at areas in the border region where industrial activities and other pollution sources (or source areas) were known to exist (e.g., Douglas, Arizona; Ajo, Arizona; El Paso, Texas; Cuidad Juarez, Chihuahua; and Rosarito, Baja California). The search was not based initially on temporal or spectral considerations. These considerations were fundamental, however, to the actual selection of products for evaluation.

A total of 54 separate images, generated by Landsat, Skylab, Apollo/Gemini, and NASA aircraft operations, were selected for detailed examination and evaluation, employing the following criteria.

- The image exhibits a readily apparent air pollution occurrence, such as a stack emissions plume, dust, or agricultural burning.
- The image exhibits an area in close proximity to the border or the area reasonably can be considered an integral part of the border region.
- The image was generated during the low-sun season when the inversion frequency is highest.
- The image adds to the variety of media and film type necessary for comparative analysis.
- It is possible to use stereoscopic techniques, because the subject of interest appears on a sequential series of images.
- The image differs in scale from a similar image of the same area.
- The image was generated at a different time of the year from a similar image of the same area.

In addition, SMS and GOES images for the month of January, 1979, were obtained without regard to the above criteria. The general utility of meteorological satellite images was evaluated, respecting the monitoring of atmospheric dynamics associated with the border region, especially wind patterns. A special example of air pollution was recorded by the SMS VISSR during the course of this study and has been incorporated in the general evaluation. A list of all images selected, identifying image type and time of year obtained, is provided in Appendix E. An evaluation of the selected products is presented in Chapter VIII.

A remote sensing device readily available, but as yet unmentioned, is the hand-held, land-based camera. In areas where pollution sources are in such proximity to the border that transfrontier air pollution is an immanent occurrence at any time, hand-held photography could be useful in documenting and even studying the occurrence. It was believed that the use of a polarizing filter, as suggested by Barr and his associates (1972), might aid in revealing some characteristics of plume dispersion. In order to test this remote sensing technique, the El Paso-Cuidad Juarez metropolitan area was observed and photographed over a three day period (November 8-10,1978). Several of the slides from this phase of the study have been incorporated into the general evaluations of the usefulness of remote sensing to detect and monitor transfrontier air pollution presented in the next chapter.

CHAPTER VIII

EVALUATION OF IMAGES

Selected remote sensing products, specifically photographic and non-photographic images, were evaluated by employing three interpretation techniques: visual evaluation of apparent information; interpretation and mensuration of stereo models; and image enhancement. The usefulness of the various selected images to detect transfrontier air pollution was determined on the basis of the evaluations presented in this chapter. All plates and slides referenced in the discussion are grouped at the end of the chapter.

Visual Evaluation of Apparent Information

Generally, photographs provided direct evidence of air pollution occurrences in the border region without any special interpretive aids. This was true at both orbital and aircraft (or sub-orbital) altitudes. Plates 1, 2, and 3 show the large open pit copper mine and Stargo Plant between Clifton and Morenci, Arizona. Plate 1 is a Skylab photograph obtained February 1, 1974, which exhibits a readily apparent plume with an east-southeast directional component. In contrast, Plate 2, obtained the previous summer (August 11, 1973) on a previous Skylab mission, exhibits no coherent plume. In fact, a very diffuse discharge is apparent over a very large area southwest of the plant site. Plate 3 was obtained November 21, 1972, by a high altitude NASA aircraft. The stack discharge is fairly concentrated near the plant site and has a directional component to the northeast.

These photographs, obtained at three different times of the year over a two year period, indicate the capricious nature of stack discharges. They also indicate that monitoring a point source, such as the Stargo Plant, is reasonable over a long period of time. With a knowledge of the quality and quantity of stack emissions and local atmospheric conditions, continuous monitoring with photography should prove useful in developing a model for predicting the probable area of ultimate deposition, given a selected set of variables. This conclusion applies only to normal black and white and color photographs, because the dispersed pattern so apparent in Plate 2 was not readily discernible in a color infrared (CIR) photograph taken simultaneously by the Skylab Multispectral Camera (S190A). Color infrared photographs of the New Cornelia Mine at Ajo, Arizona, also were deficient in revealing stack emissions. This probably results from the greater penetration of aerosol formations, such as plumes, by devices operating in the near infrared portion of the electromagnetic spectrum (700 nm to 1100 nm).

However, stack emissions or discharges were evident in both CIR photographs. Thus, it is reasonable to conclude that comparison may be useful, because infrared would be more sensitive to slightly larger particulate matter. The comparison of infrared photographs of stack emissions with photographs filtered for sensitivity to the shorter visible wavelengths might aid in developing information concerning the relative abundance of gases, aerosols, and particulates in stack emissions. The general principles of scattering should apply, which is supported by the studies of Barr and his associates (1972).

Visual analysis of a color infrared photographic series of the El Paso-Cuidad Juarez international metropolitan area revealed no atmospheric pollution. However, the detail of cultural features provided by this type of product should prove useful in identifying and evaluating some of the principal sources and source areas of pollution, such as bare soil, highway corridors, agricultural areas, and industrial areas (Plate 4). In fact, Norman J. W. Thrower (1970) indicated that several studies have attested to " . . . the use of infrared (CIR) film for delimiting socioeconomic areas in cities." This type of information should be helpful in assessing the total pollution potential for the metropolitan complex. Especially notable in Plate 4 is the large area of dirt roads flanking Cuidad Juarez on the west and south. Also, principal industrial areas are apparent as are the extensive agricultural areas of the Rio Grande Valley.

Visual analysis of Landsat MSS images yielded mixed results. It is clear from the literature that the detection of air pollution is possible with Landsat imagery. Color composites proved useful for identifying large scale industrial operations (Slide 2), assessing the areal extent of agricultural activity (Slides 1, 3, and 4), and evaluating natural landscape characteristics (Slides 1 - 4). However, the usefulness of Landsat imagery for visual confirmation of air pollution is limited, at best. The hypothesis that Landsat images would be useful at specific times of the year, when natural or man-made events are conducive to air pollution concentrations is invalid relative to the images selected.

This does not mean the hypothesis itself is invalid; there is insufficient information to prove or disprove it. A principal reason for an invalid result could be the climate of the United States-Mexico border region. The detection of air pollution, utilizing Landsat imagery, as reported in the literature, was associated with the considerably more humid northeast and east central portions of the United States. The aridity of the border region inhibits not only the magnitude of aerosol concentrations, but also the duration of existence.

Bands 4, 5, and 7 of the Landsat MSS were evaluated. The three bands were selected from March, June, and November scenes of the El Paso-Cuidad Juarez area. There was no discernible air pollution in any of the images. Data from Continuous Air Monitoring Stations (CAMS) in El Paso indicate that the wind speed was less than 7 mph at the time the November images were generated (Table 10). The CAMS data also indicate higher levels of all measured constituents (except ozone) in November compared with March and June. The November images (Plates 5, 6, and 7) reveal an essentially cloud free condition. Thus, given the low wind speed, the slightly elevated pollutant levels, and the clear sky, it can be concluded on the basis of Hosler's (1961) analysis that a low-level ground radiation inversion was probably in effect when the scene was recorded. While Band 4 (500 nm to 600 nm) is definitely darker than Bands 5 and 7, this is not conclusive evidence that the inversion is detected. Band 4 is especially sensitive to attentuation effects of the total atmosphere, which reduces the surface radiance received and recorded by the sensors of the MSS. Thus, Band 4 is the darker image for the March and June scenes also. "Darker" is really only a visual

Table 10. Continuous Air Monitoring Station (CAMS) Data: 1979 (0900-1000)

Atmospheric Quality Monitored	March 7		June 23		November 23	
	CAMS 6	CAMS 12	CAMS 6	CAMS 12	CAMS 6	CAMS 12
Ambient Temperature	56.3°F	56.6°F	89.7°F	86.7°F	57.2°f	61.1°F
Wind Speed (mph)	9.0	8.2	8.7	4.2	3.5	6.2
Ozone*	0.054	0.039	0.045	0.053	0.014	0.032
Methane*	N/D	1.4	1.4	1.5	1.8	1.7
Non-Methane Hydrocarbons*	N/D	0.0	0.4	0.0	1.6	3.0
Total Hydrocarbons*	N/D	1.4	1.3	1.3	3.4	5.7
Oxides of Nitrogen (NO_x)*	0.01	0.0	0.08	0.01	0.12	0.03
Nitrogen Dioxide (NO_2)*	0.0	0.0	0.01	0.0	0.05	0.02
Nitirc Oxide*	0.0	0.0	0.02	0.01	0.06	0.01
Hydrogen Sulfide*	0.0	0.0	0.0	0.0	0.0	0.0
Sulfur Dioxide (SO_2)*	0.0	0.0	0.0	0.0	0.12	0.0
Total Sulfur*	0.0	0.0	0.0	0.0	0.18	0.0
Carbon Monoxode (CO)*	N/D	0.2	1.6	0.0	1.7	0.3

*Parts Per Million (ppm)
N/D - No Data
Source: Gomez, 1978.

interpretation; Band 4 simply does not possess the scene contrast (or spectral response) of Bands 5 and 7. This is evident also in images of the San Diego-Tijuana area on the Pacific coast (Plates 8, 9, and 10).

The lack of natural contrasts in the predominantly arid and semi-arid environments of the border region reduces the usefulness of Landsat imagery in the high-sun season. On an annual basis, images generated in November offered the best scene contrast. A lower solar elevation, greater soil moisture, more vigorous vegetation, and other factors probably contributed to a better spectral response. The reflectance of the nearly barren desert environment within which El Paso-Cuidad Juarez are situated has a definite effect on image quality. The high reflectance saturates the detectors of the sensor, which leads to a condition analogous to "overexposure" in photography. This is not as true for the areas of the border region with greater vegetal cover. Thus, the Band 7 image of San Diego in late summer showed good scene contrast, whereas the Band 7 image of El Paso did not. Solar elevation varied only 3 degrees between the two images.

Landsat RBV images of the El Paso-Cuidad Juarez area did not reveal any apparent air pollution. The same holds true for RBV images of the Douglas-Agua Prieta area. Attempts to compare differences of RBV images on a seasonal basis failed because of poor image quality. It was assumed that the high-sun effect would also be associated with the RBV images. That is to say, a high solar elevation would saturate the RBV camera and result in an overexposed image being generated. The May image of El Paso-Cuidad Juarez had little scene contrast compared with the October image, which was generated when the solar elevation was several degrees lower. The images of the Douglas-Agua Prieta area were generated in April and August with solar elevation differing by only one degree. The April image had very poor scene contrast. Thus, it was concluded initially that the better spectral response of the August and October images was a result of increased vegetal cover, soil moisture, or some other factor(s). However, closer examination of the image generation data revealed that the April and May scenes were exposed for 4.0 ms (milliseconds) compared with 2.4 ms, which was the exposure of the August and October scenes. While a more thorough analysis of this matter would be desirable (using many more images), it seems apparent that the shorter exposure time will be necessary for good quality images of the arid and semiarid regions of the border region.

The SMS and GOES imagery for the month of January, 1979, did not reveal transfrontier air pollution in the border region. However, meteorological satellite imagery has proven useful in evaluating regional and seasonal air flow. The GOES imagery shown as Plates 11 and 12 reveals air flow across central Mexico northward and eastward toward the Florida panhandle. This air flow is similar to that revealed in the May, 1971, images generated by the Applications Technology Satellite used by Parmenter (1973) to study smoke movement from Central America. Plate 11 is a "visible" image generated at 3:01 P.M. MST and Plate 12 is a computer enhanced "infrared" image generated at 3:32 P.M. MST. Both images are useful in determining the areal extent of cloud cover, cloud height, and air circulation patterns.

Recent visible imagery from both the SMS and GOES has demonstrated the feasibility of detecting and monitoring regional scale air pollution movement. Brandli and his associates (1977) cited the detection by GOES sensors of dust movement from Texas to Florida. On several occasions, steamship plumes have been detected and recorded by satellite sensors. Plate 13 shows the most recent example of this detection capability. The detection of steamship plumes raises the question regarding the 200 nautical mile "exclusive economic zone." It is conceivable that point source air pollution standards may be enforced in the zone. However, legal enforcability would be less of a question than the political and economic ramifications of enforcement. Because the SMS and GOES images are generated every one-half hour and several "enhancement curves" are already developed, the usefulness of these images for continuous monitoring for transfrontier air pollution merits further and more detailed appraisal.

Experimentation with hand-held photography also appears warranted. During the month of November, 1978, photographs of the El Paso-Cuidad Juarez metropolitan area were taken by the author (Slides 5 - 11). In this experiment, there was an attempt to evaluate the use of a polarizing filter to enhance the definition of pollution concentrations. The tests were less than conclusive, because exposure setting apparently was a critical modifier of the images. The experiment did demonstrate, however, that hand-held photography is practical for documenting air pollution concentrations. There also is justification for believing that a polarizing filter will be beneficial in monitoring activites, if more sophisticated camera equipment is employed by trained personnel.

Good visual evidence of air pollution concentrations, resulting from inversion conditions, is exhibited in Slides 5 - 9. The top of a ground radiation inversion is faintly visible in Slide 5. Slide 6 reveals a ground radiation fog (or haze) forming before 5:30 P.M. over the two cities and extending northward into the Tularosa Valley. It was found that a panoramic series was useful in gaining insight into the full effects of the inversion process and pollution concentrations that develop. Slides 7, 8, and 9 form a panoramic series of the two cities, which was generated with a normal lens the morning after the evening Slide 6 was generated. The trapped pollutants are readily apparent as a haze with definite vertical limitations. Although the haze appears to be concentrated mostly over Cuidad Juarez, this may be an effect rather than a fact. Many photographs from many different angles would be necessary to substantiate this conclusion.

The polarizing filter seemed to prove more beneficial when photographing a specific target. Slide 10 shows the plume from the ASARCO smelter taken with a normal lens. Slide 11 shows the same plume taken with a polarizing filter. As already noted, exposure settings are critical to this type of remote sensing. However, these two photographs support the belief that a polarizing filter would be useful in gaining a better definition of plume dispersion characteristics. According to the Aeronautical Sectional Chart for the El Paso region (NOAA, 1979), the top of the taller stack is 825 feet above ground level. Comparing the plume behavior shown in Slide 11 with Figure 2 on page 142, it can be concluded that there is probably a weak lapse condition at this height above the ground with an inversion below, <u>i.e.</u>, a combination of (b) and (d). Although not a substitute for actual atmospheric data, Figure 2 is a good reference for evaluating plume behavior. For example,

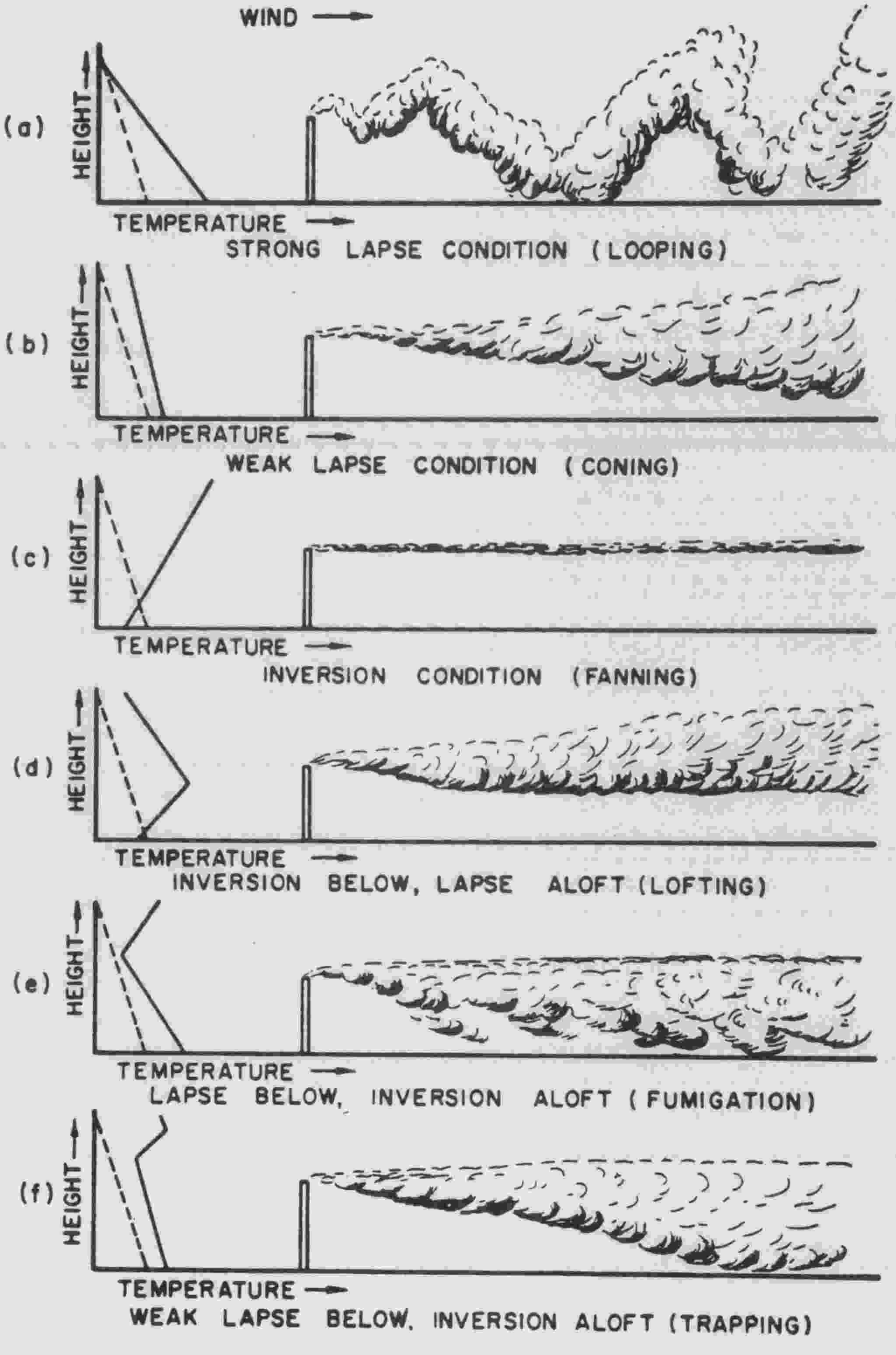


Figure 2. Six Types of Plume Behavior under Various Conditions of Stability and Instability. The broken lines at left are dry adiabatic lapse rates. The solid lines are existing lapse rates. From Fierly and Hewson (1962) in Kassander (1970).

Plate 14 shows the plume from the smelter in Douglas, Arizona, crossing the border into Mexico. This, in fact, is the photograph shown to the Governor of Arizona by the Governor of Sonora, referred to earlier (See page 30). Visually, the movement of the plume seems to reflect a weak lapse condition (b in Figure 2) with a strong south-southwest wind component. The plume from the Stargo Plant (Plate 1) indicates a weak lapse condition (b) and, possibly, an inversion aloft, producing the "fanning" effect (c). Plate 2, also showing a plume from the Stargo Plant, indicates either the "fumigation" (e) or "trapping" (f) of the stack emissions by an inversion aloft.

Stereo Model Interpretation and Mensuration

Several photographic series were obtained, which exhibited air pollution in the form of stack emissions. Plates 1, 4, 14, and 15 are images from three different series generated at orbital altitudes. Two photographic series were obtained, which were generated at a sub-orbital altitude (Plate 3). Each series yielded a stereo model, which was evaluated to determine the feasibility and practicality of utilizing stereo models to define and describe plume profiles and behavior. Four mensuration techniques were employed in attempts to develop quantitative descriptions of the plumes visible in the selected images: 1) direct measurement of parallax and measurement of parallax using the Michigan Parallax Wedge; 2) measurements using a measuring magnifier with 0.1 mm accuracy; 3) area measurements using random samples from an area grid; and 4) definition of vertical and horizontal dispersion of the plumes using a Form Line Grid in conjunction with a hand stereoscope.

Generally, stereo models of images generated at orbital altitudes are impractical for developing vertical profiles, due to the small scale and relative lack of depth of the model (Plate 1). Parallax measurements are not feasible, either through direct measurement or using the Michigan Parallax Wedge. The use of a Form Line Grid to develop a contour of plume dispersion is not practical either, due to lack of model depth. The stereo models did reveal the vertical displacement and directional components of the plumes examined, which was beneficial in understanding atmospheric conditions (Plate 15). It is possible that more sophisticated equipment and techniques, such as employed by W. Z. Sadeh and J. F. Ruff (1973), could yield accurate measurements of vertical displacement. However, Sadeh and Ruff employed aerial photographs from low-altitude, and it is not known whether any principles employed by them would be applicable to the problems of stereo models from images generated at orbital or even sub-orbital altitudes. Indications are that such models are generally not useful for detailed mensuration efforts (Robert G. Reeves, 1975).

Individual photographs generated at orbital altitudes, however, were useful in developing quantitative measurements of horizontal dispersion. A measuring magnifier was adequate to develop reasonable dimensions of the horizontal dispersion of plumes. It is important to note that horizontal dispersion measurements must relate to plume height, because the height of the plume is the actual plane of measurement for horizontal dispersion relative to the imaging system. Thus, while careful measurements can provide a horizontal dispersion profile, the magnitude of dispersion will be underestimated, if plume height is ignored. Therefore, in order to gain an accurate estimate of horizontal plume dispersion, the plume height must be determined. As plume height can not be determined from the stereo models formed from orbital photographs, some other method will be necessary to determine the required scale adjustment.

Sub-orbital photographs proved to be considerably more useful in determining the total plume profile (Plate 3). Although even the larger scale of sub-orbital photographs did not produce a stereo model with adequate depth for measurements of parallax with the Michigan Parallax Wedge and a hand stereoscope, precision instruments may be able to produce good estimates. Horizontal dispersion measurements were relatively easy to make; however, the limits of the plumes were not able to be defined accurately, due to diffusion at the margins. Measurement of the area covered by a dispersed plume was conducted and reasonable results obtained. Again, determining the limits of the dispersed plume was a critical factor, which was not totally resolved. A description of all plume measurements attempted and conclusions developed respecting the reliability and/or practicality of those attempts is presented in Appendix F.

Image Enhancement

A relatively inexpensive and direct process for the enhancement of photographic and non-photographic images is density slicing. The process employs a vidicon camera to scan an image placed on a light table. Analog techniques are incorporated to translate the amount of light transmitted through the image into values on a gray scale. Values of the gray scale can be read as the percentage of light transmitted through the image. Thus, black would be 00% transmittance and white would be 100% transmittance. The density slicer employed produced output in three forms: 1) a color enhanced image linked with a set of "crosshairs" for determining the transmittance percentage at any particular point on the image and producing a graph of percentage values across the width or length of the image; 2) a black and white image linked to contrast adjustments; and, 3) a three dimensional image translator, which generated a contoured image revealing the across the image light transmittance graph for each line scan of the vidicon camera.

Density slicing techniques applied to photographs were helpful in verifying the visual interpretations of plume dispersion patterns. Density slicing also proved useful in adding to the knowledge of the patterns. For example, Plate 1 shows the plume of the Stargo Plant oriented downwind toward the southwest face of the Big Lue Mountains on the border between Arizona and New Mexico. It is unclear from the photograph what occurs at the face of the mountains. There seems to be a piling-up of emissions and then extreme diffusion along the face of the mountains to the southeast.

Utilizing the density slicer to analyze the plume despersion pattern of the plume visible in Plate 1, the image shown as Slide 12 was generated. This "enhanced" image indicates that there apparently is a piling-up of emissions against the mountains. However, the presence of clouds directly north of this point makes a positive conclusion somewhat tenuous. It is possible that a cloud formation process not readily apparent in the photograph is accentuating the total whitness at this point in the plume dispersion pattern. Slide 13 shows a magnification of the area of the plume in question and tends to verify that the condition is produced through a piling-up of emissions rather than cloud formation processes. The path of movement of the plume and a distinction in form and color from the clouds to the north leads to this conclusion. Further evidence is provided by Slides 14 and 15, which provides a three dimensional visual separation of the apparent plume terminus and the clouds. An attempt to analyze the more dispersed emissions pattern of the August photograph of the Stargo Plant (Plate 2) was unsuccessful. The images generated by the density slicer provided little additional information regarding the extent of the dispersion. In fact, there was no distinction between the dispersed plume, the mine itself, and the apparent bare soils of the Gila River Valley to the west.

Slides 16 and 17 are enhanced images of the plume emanating from the smelter at Douglas, Arizona (Plate 14). Because of a strong contrast between the plume and the surrounding landscape, a strong, discrete image of the plume was generated by the density slicer. This experiment indicated that the density slicer may have utility in defining the limits of an emissions plume, a factor noted as critical in measurements of horizontal dispersion. Each slide reveals the percentage transmittance graph superimposed on the enhanced image. The location of the horizontal line determines the values of the graph. Thus, Slide 16 shows the line directly over the source and Slide 17 shows the line at the apparent terminus of the plume. Transmittance registered 80.9% to

81.1% over the source, which is reflected by the graph peaking at the top of the image. Transmittance registered about 33% at the apparent visual terminus of the plume.

The utility of analysis with the density slicer is debatable. It should be useful in defining the limits of a plume where there is sharp contrast between the plume and the surrounding background (or landscape), such as exhibited by Plate 14. A series of measurements of percentage transmittance along the length of the plume should reveal a sharp drop in transmittance values around its perimeter. In effect, the recording of these values produces a densitometric analysis and can yield a series of graphs (Reeves, 1975). However, there is no precise method for resolving these measurements with the original image being analyzed. That is to say, the process by which a point on the enhanced image is geometrically correlated with the actual point on the image is complex and subject to error. Estimations are feasible and should be useful in determining the limits of plume dispersion.

Density slicing may prove valuable in gaining knowledge of plume dispersion dynamics. The recording and plotting of values along and across the plume (or any pollutant concentration) could serve to aid in evaluating diffusion rates under varying atmospheric conditions and discharge rates. For example, Slide 18 shows the contoured transmittance values through the length of the Douglas plume: the higher the contour from the base, the greater the light transmittance and the whiter the image. From this image, there is evidence of a break in what has the appearence of being a coherent plume. This break is near the middle of the plume with respect to its length, and it is manifested as a reduction of "whiteness." In fact, Plate 14 and Slides 16 and 17 also exhibit this break in the downwind coherency of the plume. The cause is unknown, but some form of wind shear could be acting to affect the linear dispersion pattern.

Because density slicing is an analog process, the images generated by the Landsat MSS are considered more amenable to analysis. Band 4 of the Landsat MSS is the "green" band with a spectral range or bandwidth of 500 nm to 600 nm. This band would be sensitive to the "brown smog" (or "smust" in arid and semiarid regions: smoke and dust) produced by high concentrations of NO_x and particulates. Also, it is the band most sensitive to Mie scattering by aerosols and particulates having diameters ranging from 0.1 times the wavelength of radiation to 25 times the wavelength of radiation. Mie scattering is restricted, generally, to the lower troposphere, below 4,500 m (15,000'). Examples of particulates that could produce Mie scattering in the El Paso-Cuidad Juarez area are: sulfur and lead from the copper smelter; dust from bare soils and dirt roads; particulates from home fireplaces often burning bulk wastes; and organic and inorganic agricultural residuals. Measurements by F. L. Ludwig and Elmer Robinson (1968) indicated that the mass median equivalent diameter of sulfur compound particulates in the San Francisco area was approximately 350 nm with an approximate range of 100 nm to 1,000 nm (1 micrometer). A substantially higher mass median diameter was recorded during periods of high humidity. Due to the generally arid conditions of the border region, it would be expected that the mass median diameter of sulfur compound particulates would be nearly always toward the smaller diameters.

The density slicer was employed to analyze the difference between transparencies of Bands 4, 5, and 7 for the El Paso-Cuidad Juarez area generated November 23, 1976. CAMS data from the Texas Air Control Board (Table 10, page 137) reveal that inversion conditions were probable for this date: wind speed was less than 7 mph and there was less than 3/10 cloud cover, as verified by the imaged scene. Therefore, it was anticipated that the Band 4 transparency would have much lower light transmittance values than Band 5, which is the "red" band (600 nm to 700 nm), and Band 7, which is a near-infrared band (800 nm to 1,100 nm). Lower light transmittance values would result from sensor response to the high reflectance of the generally bare soils of the area, sparse vegetation, and possibly, increased reflectance and scattering induced by the inversion "smust."

In order to test for the presence of the inversion and associated "smust," it was presumed that pollution concentrations would be highest in the Tularosa Valley-Hueco Basin, wherein the City of El Paso and Cuidad Juarez are located. Also, during the winter months winds are generally from the north and northwest, which would keep air pollutants confined to the east side of the mountains (even a light wind). A third factor is the nocturnal down valley air flow of the Rio Grande Valley, which would also tend to confine air pollutants to the east side of the mountains. Seven sample points were selected as indicated by Plate 16, and light transmittance values were recorded at each sample point for each band, using the crosshairs referred to earlier. The recorded values shown in Table 11 seem to support the expectation that total reflectance in the "green" band is higher in the valley-basin

Table 11. Percent Transmittance of Light

	Density Slicer Values*		
Sample Point	Band 4	Band 5	Band 7
1	28.5	40.9	43.2
2	34.2	54.3	57.4
3	27.1	28.4	29.1
4	25.5	28.0	33.9
5	32.9	39.4	40.8
6	33.0	44.7	39.2
7	28.4	43.0	44.5

*All values plus or minus 0.1.

area compared to areas west of the mountains and the Rio Grande. Evident from the table of values is a relatively large difference in magnitude between Band 4 and Bands 5 and 7, except for points 3 and 4 located in the built-up portions of El Paso. These two points correspond roughly to the location of CAMS 6 (Downtown) and CAMS 12 (East), respectively, identified in Table 10 (page 137). Generally, it is recognized that Band 7 provides the best penetration of atmospheric haze. Thus, the strength or intensity of the probable effects of the haze associated with an inversion could be analyzed by comparing the discriminatory power of Band 7 with that of Band 4. Thus, Table 12 shows the relation of the eastern and metropolitan sample points to sample point 2 on the west for Bands 4 and 7. The conclusion drawn from Table 12 is that Band 4 has little discriminatory power, although

Table 12. Comparison of Sample Point Values by Band

	Percent of Sample Point 2		
Sample Point	Band 4	Band 5	Band 7
1	83.3	75.3	75.3
3	79.2	52.3	50.7
4	74.2	51.6	59.1
5	96.2	72.6	71.1
7	83.0	79.2	77.5

there are apparent and obvious differences between the sample point areas (Plate 16). Band 7, in contrast, strongly discriminates the densely developed downtown area and provides somewhat better discrimination of outlying areas.

Unfortunately, this test comparison of the MSS bands cannot be considered conclusive evidence of exaggerated reflectance produced by an inversion. However, it represents an approach that may yield a better understanding of the varying quality of the atmosphere throughout the year and under differing atmsopheric conditions. Controlled analysis of MSS digital data, using a greater number of sample points, a greater number of images, and better knowledge of the physical character of the area (e.g., soils, vegetation, slope, etc.) would be necessary. It would be expected that variations in air quality would cause variations in the relationships found in this sample analysis. The gap between bands would vary and the discriminatory ability of Band 4 would vary (See Experiments 7A PR135 and 7A PR173, Appendix D).

Image enhancement of the three bands revealed considerable similarity of patterns west of the two cities (Plates 17, 18, and 19). However, the eastern sector is entirely different in Band 4 compared with Bands 5 and 7, except in the lower right quadrant. Sample point 5 in this quadrant had a light transmittance value of 32.9% for Band 4. When compared with sample point 2 (34.2%) and sample point 6 (33.0%), there is an indication that sample point 5 is similar, and this is verified by the enhanced image. Thus, it could be concluded that the pollution build-up is more concentrated east and northeast of the two cities. It must be stressed that this is a tenuous conclusion also, and many more samples of many more images are necessary.

Relative to the equipment used in this test, it must be noted that there was no function to insure the same sample point was precisely located on the different transparencies. The value of each point was measured by placing the "crosshairs" over the sample point with reference to image features. Thus, errors of unknown magnitude are contained in the Tables 11 and 12. Sample point 6 exemplifies the unreliability of sample point location. While all other sample points show an increase in light transmittance from Band 4 to Band 5 to Band 7, sample point 6 does not. Therefore, location of sample point 6 was incorrect for either Band 5 or Band 7 or both. However, because of the consistency of the pattern of increasing values among all other sample points, it is presumed that some degree of accuracy was obtained.

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PLATES

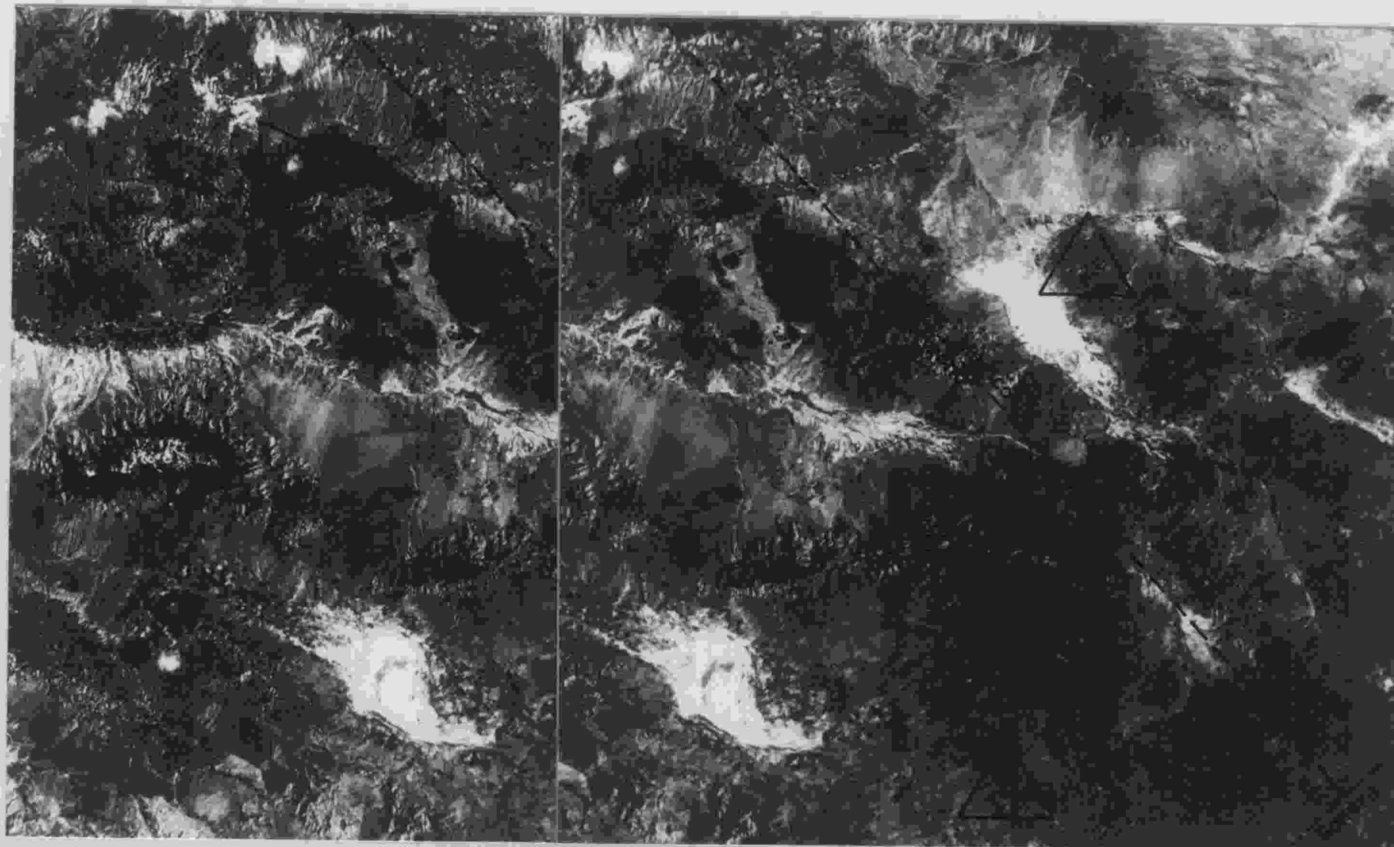

Plate 1. Stereo Model of Skylab 4 Color Photographs, Stargo Plant, Clifton-Morenci, Arizona. Plume is readily discernible in the upper left corner. Directly below is the Gila River Valley and definite agricultural patterns. Note, also, the Wilcox Playa (bottom center) and the South Alkali Flat (upper right) west of Lordsburg, New Mexico. Interstate 10 can be seen near the center of the photographs. Triangles indicate areas where mining and quarrying are evident. Scale, 1:1,332,168.

Plate 2. Skylab 3 Color Photograph, Stargo Plant, Clifton-Morenci, Arizona. Plant and mine are located in the lower right corner of the photograph. Plume is dispersed over the ridges and valleys between the plant site and the Gila River Valley where Safford, Arizona is located. The San Carlos Reservoir is visible in the upper left center of the photograph. Directly above the reservoir on the edge of the photograph is Globe, Arizona, another large mining center. Directly to the left of the reservoir (in the next valley) is Hayden and Winkleman, another area of mining activity. No visible emissions were discernible in these two mining areas. Scale, 1:1,431,932.

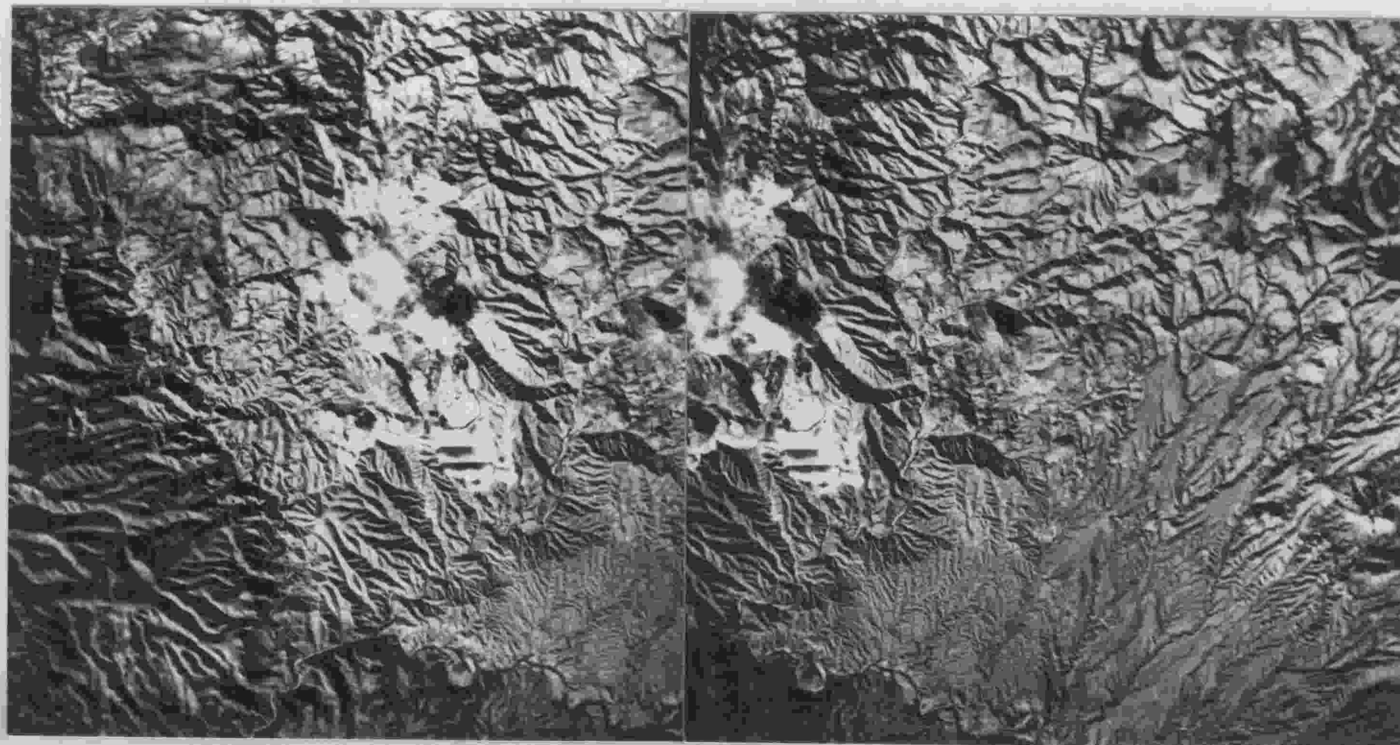

Plate 3. Stereo Model of NASA Aircraft B&W Photographs, Stargo Plant, Clifton-Morenci, Arizona. Stack and plant are faintly visible at the base of the plume. Dispersion of the plume between photographs causes difficulties in taking accurate measurements; however, Sadeh and Ruff (1973) described a technique for using stereo models to monitor pollutant concentrations and mixing. The stereo model reveals considerable information about the mine structure and towns developed nearby. Clifton is near the mouth of the very prominent canyon of Chase Creek to the right of the mine and plant. Morenci is obscured by the plume and Plantsite is to the southwest (to the left of the tailings piles). Scale, 1:239,133.

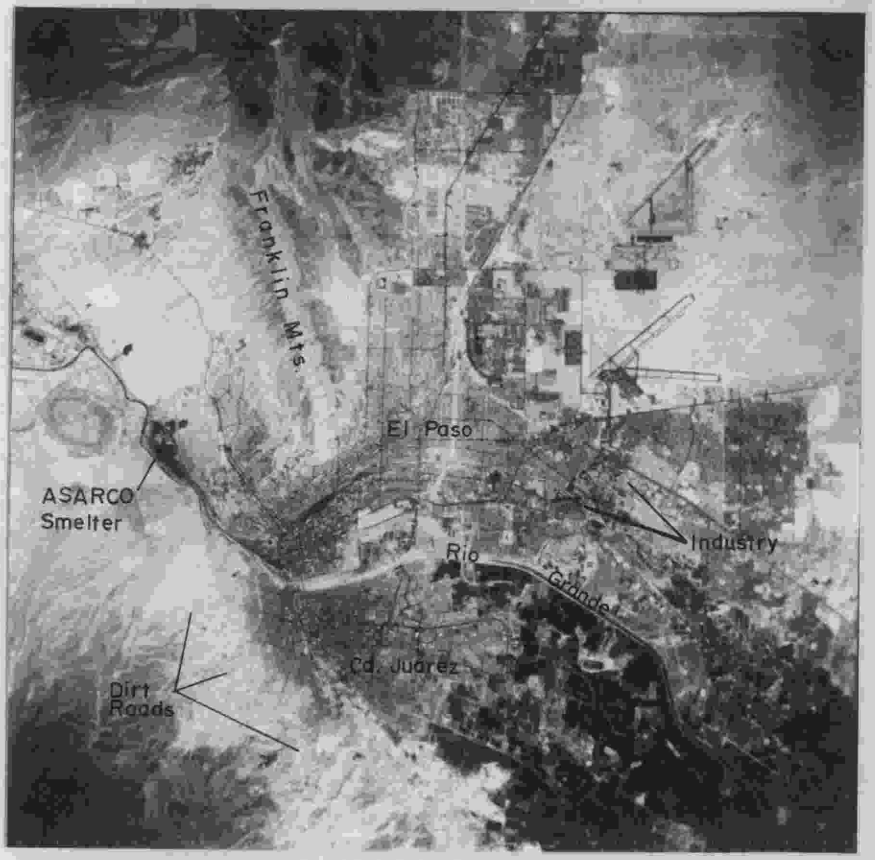

Plate 4. NASA Aircraft Color Infrared Photograph of El Paso, Texas, and Cuidad Juarez, Chihuahua. Cultural patterns and prominent cultural features are readily identifiable. Large areas of bare soil are evident, especially to the west (left) of the mountains and circumscribing the more densely developed center of Cuidad Juarez. The prominent dark area at the left center of the photograph is the site of a copper smelter. Just to the north are a cement plant and a power generating plant. High lead levels in the blood of children 1 to 4 years of age were recorded by Applegate (1978) in a 1976 study and were attributed to the smelter. Highest levels were recorded in the residential area directly to the east of the smelter at the base of the Franklin Mountains. This photograph is one in a series of the greater metropolitan area of these two cities. Scale, 1:196,358.

Plate 5. Landsat 2 MSS, Band 4, El Paso-Cuidad Juarez, 11/23/76.

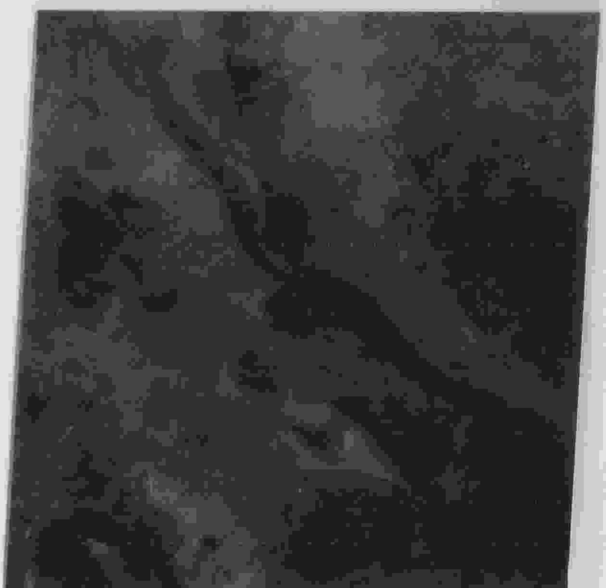

Plate 6. Landsat 2 MSS, Band 5, El Paso-Cuidad Juarez, 11/23/76.

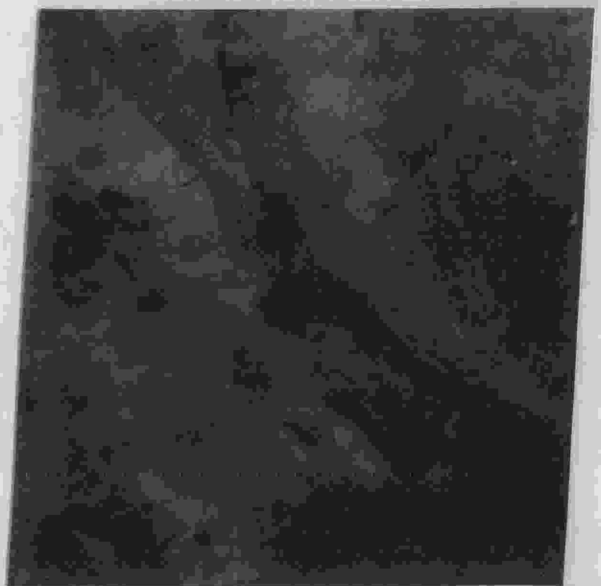

Plate 7. Landsat 2 MSS, Band 7, El Paso-Cuidad Juarez, 11/23/76.

Plate 8. Landsat 2 MSS, Band 4, San Diego-Tijuana, 9/2/76.

Plate 9. Landsat 2 MSS, Band 5, San Diego-Tijuana, 9/2/76.

Plate 10. Landsat 2 MSS, Band 7, San Diego-Tijuana, 9/2/76.

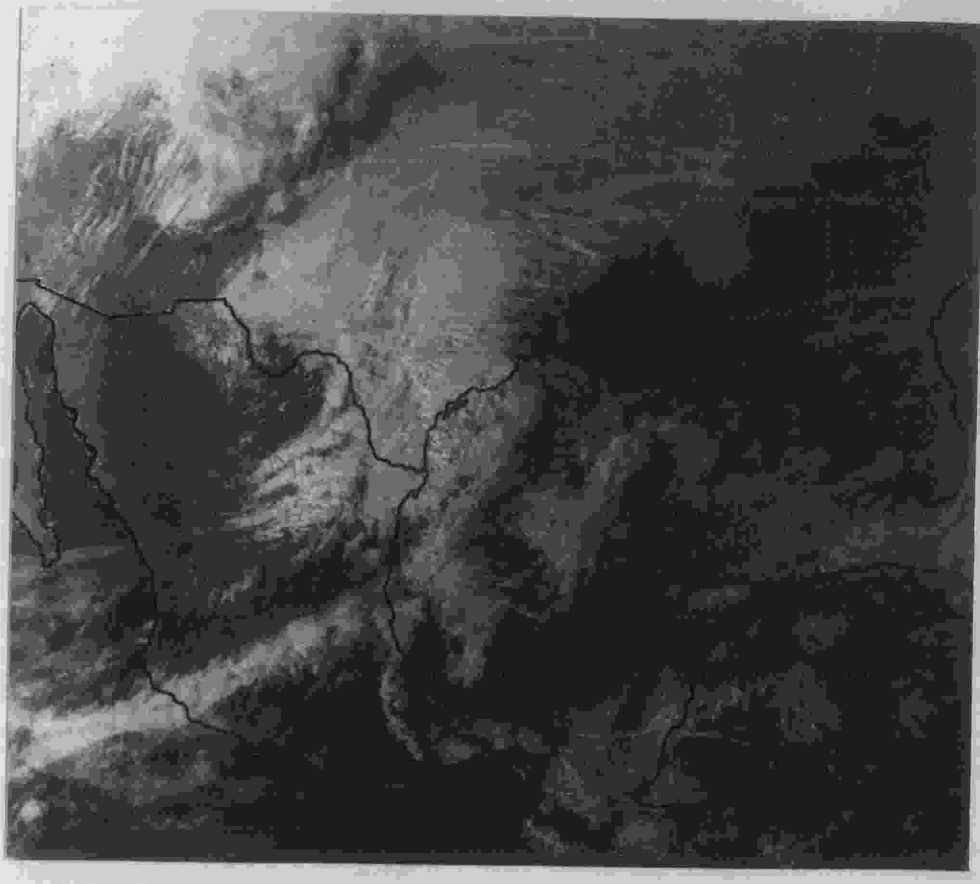

Plate 11. GOES "Visible" Image of Southern U.S. and Mexico, 1/10/79. Image Generated at 2201Z (3:01 P.M., MST). Enhancement Code 14A-1. Image ID 02441 12902 KB4. Nominal resolution is 1 nautical mile. Spectral resolution is 0.5 nm in a range of 550 nm to 700 nm. Scale, 1:17,800,000 at the Arizona/New Mexico border.

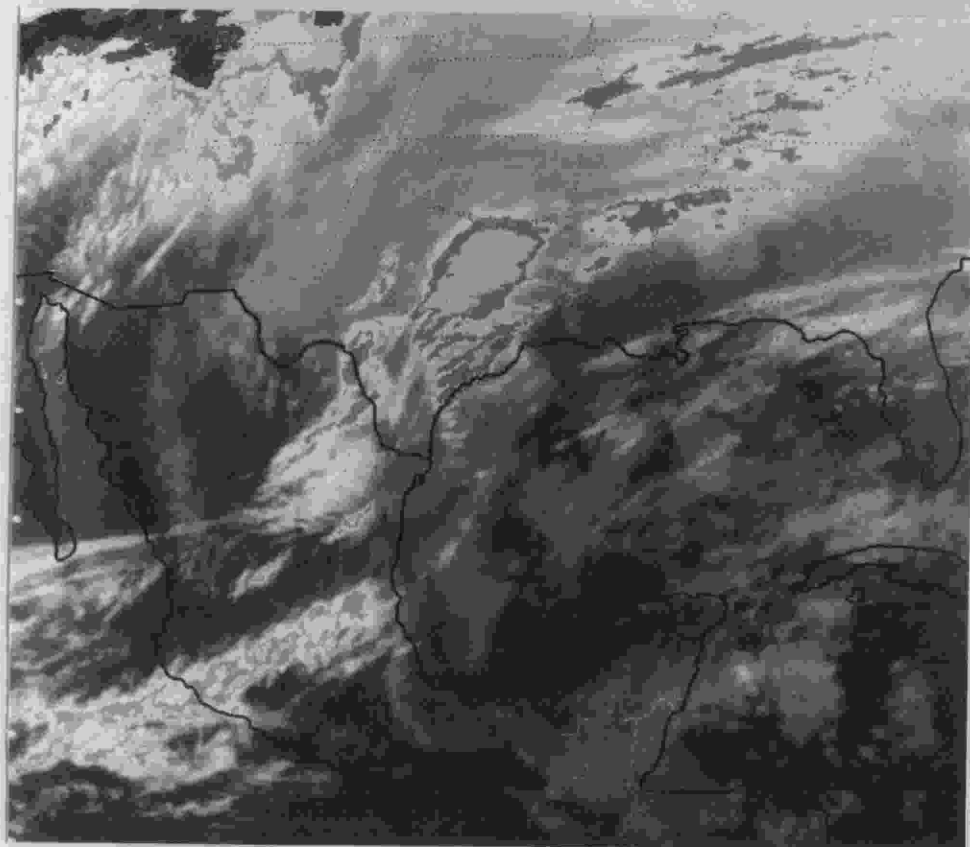

Plate 12. GOES "Enhanced Infrared" Image of Southern U.S. and Mexico, 1/10/79. Image generated at 2232Z (3:32 P.M., MST). Enhancement Code 14E-1MB. Image ID 02441 12902 KB4. Nominal resolution is 1 nautical mile. Spectral resolution is 4.85 nm in a range of 10.5 to 12.6 micrometers. Scale, 1:17,800,000 at the Arizona/New Mexico border.

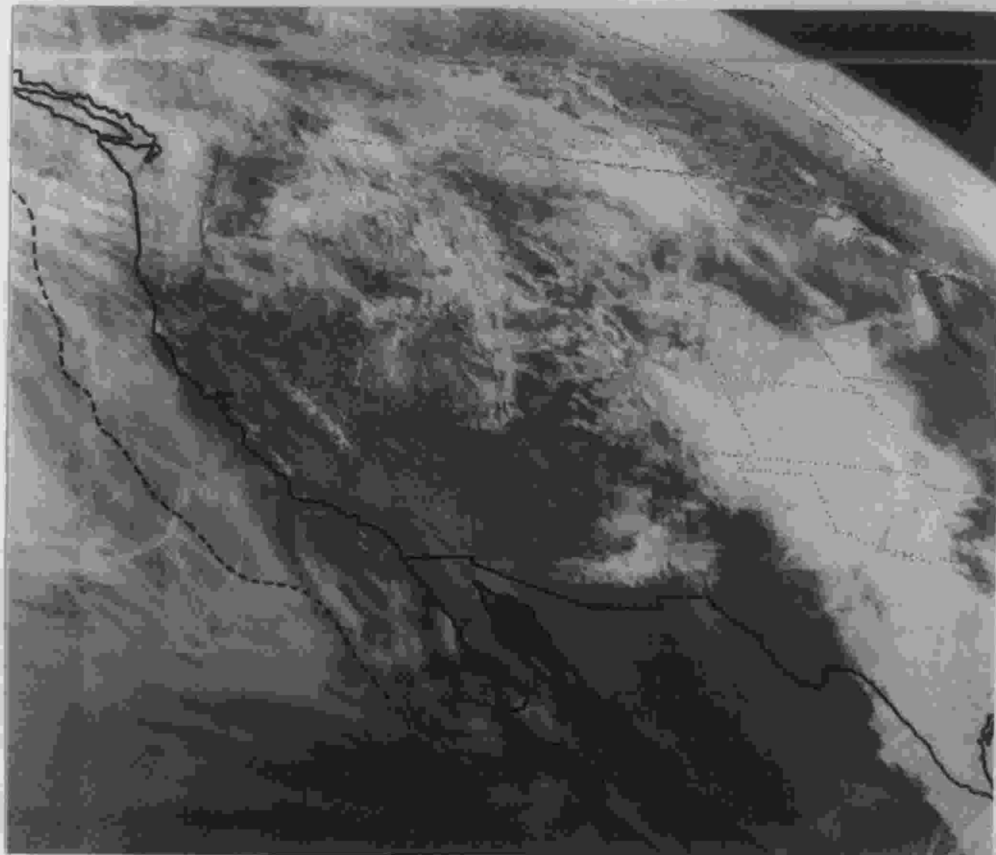

Plate 13. SMS "Visible" Image of Western U.S. and Northwestern Mexico, 4/3/79. Image generated at 1545Z (8:45 A.M., MST). Enhancement Code 35A-2. Image ID 01232 25221 KB7. Nominal resolution is 2 nautical miles. Spectral resolution is 0.5 nm in a range of 550 nm to 700 nm. Dashed line approximates the limit of the 200 nautical mile "exclusive economic zone." Scale, 1:17,800,000 at the Arizona/New Mexico border.

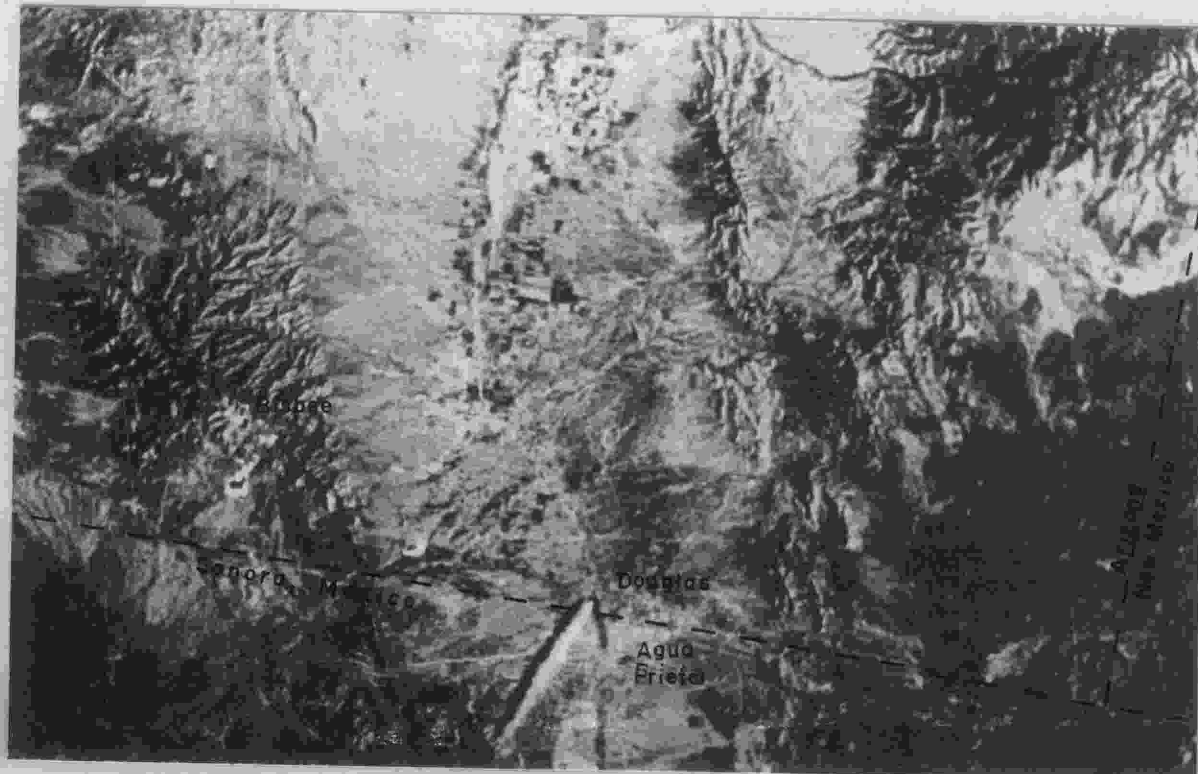

Plate 14. Apollo 6 Color Photograph, Copper Smelter, Douglas, Arizona. Plume from smelter is readily apparent at bottom center of photograph and is an obvious case of transfrontier pollution. Note the break in the plume near its center, which may indicate a wind shift or wind shear. Lavender Pit copper mine at Bisbee, Arizona, is visible to the west (left). Mining activities at the Lavender Pit ceased in 1974. Agricultural activity in the Sulphur Springs Valley is a prominent feature in the photograph. Scale, 1:669,643.

Plate 15. Apollo 6 Color Photograph, Copper Mine, Hurley, New Mexico. The mine and stack plume are visible in the upper left corner. Other discernible environmental concerns are: extensive areas of bare soil; urban/rural development patterns (Deming, New Mexico, is at the left center of the photograph); and extractive industrial activities indicated by triangles. Interstate 10 is the linear element apparent across the center of the photograph. Scale, 1:1,565,481.

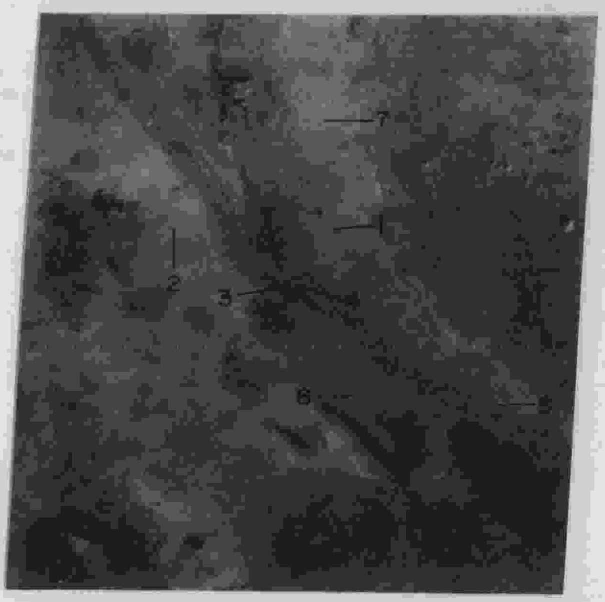

Plate 16. Location of Sample Points Employed in Evaluating Band Density Differences. Point 3 is the approximate location of CAMS 6, Downtown, and Point 4 is the approximate location of CAMS 12, East. Band 4 had little discriminatory power relative to Band 7, which here reveals clear differences between the points selected. Compare Plates 5, 6, and 7. Scale, 1:2,983,872.

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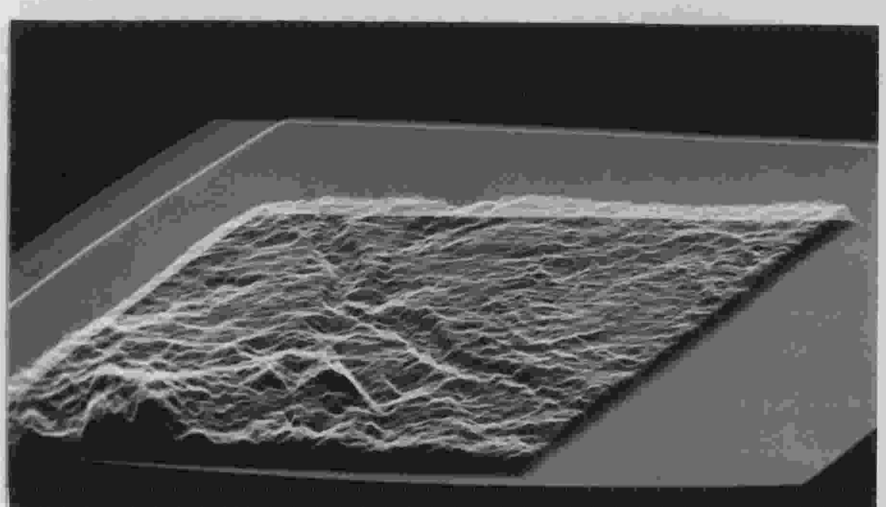

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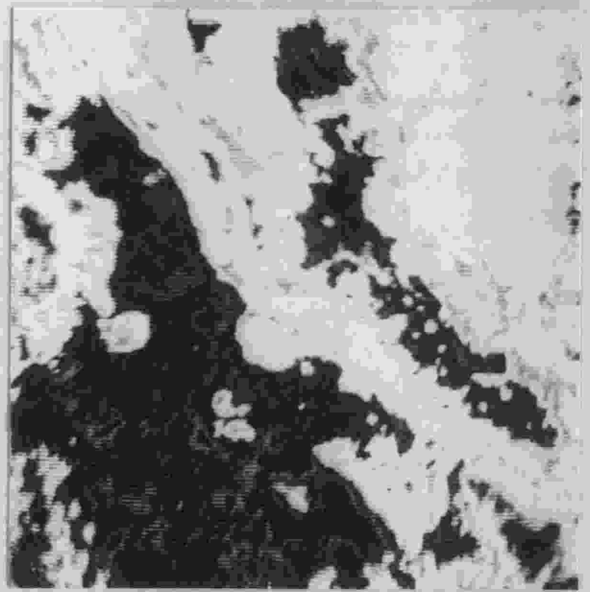
Plate 17. Image Enhancements of MSS Band 4, El Paso-Cuidad Juarez. Color enhancement (a) reveals darkest tone where light transmittance is greatest, e.g., black areas at the bottom left of the image are nearly white sand dunes. Three dimensional image (b) shows peaks at dune locations and little variance of light transmittance elsewhere.



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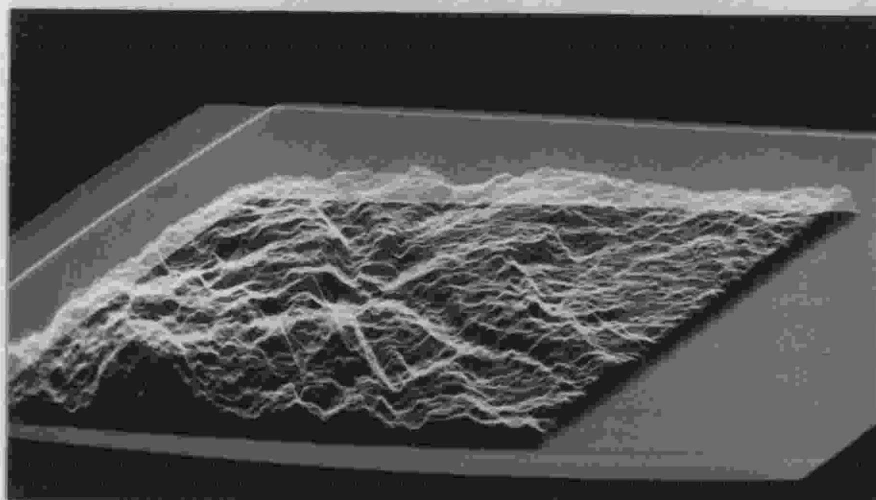
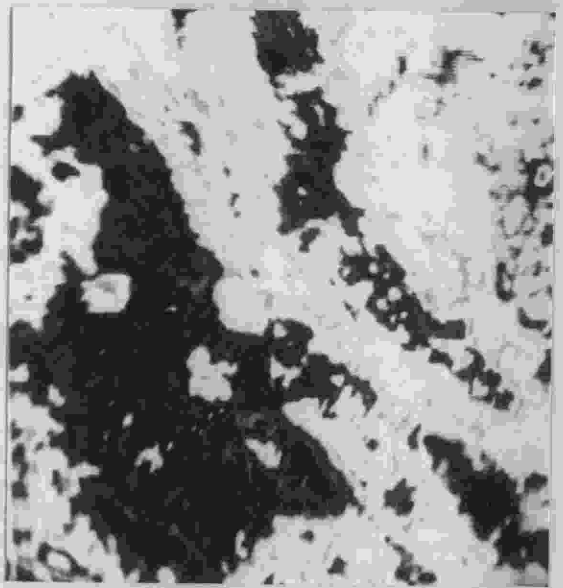


b

Plate 18. Image Enhancements of MSS Band 5, El Paso-Cuidad Juarez. Color enhancement (a) shows a very dark region east of the Rio Grande in contrast to Band 4 (Plate 17). This is an area of sparse vegetation and generally bare soil as to the west. Three dimensional image (b) shows greater discrimination of surface radiance when compared to Band 4.



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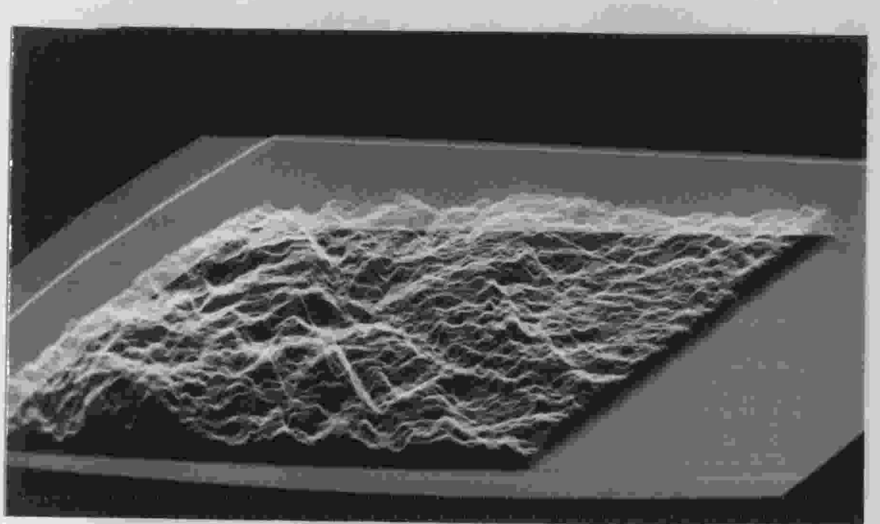

b

Plate 19. Image Enhancements of MSS Band 7, El Paso-Cuidad Juarez. Little variance from Band 5 (Plate 18) can be noted. There is a slight improvement of discrimination where surface radiance differences may be subtle (a). The three dimensional image (b) reveals a general, but slight, increase in light transmittance and, therefore, image brightness.

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SLIDES 1 - 18

SLIDE INDEX

1. Landsat MSS Color Composite, December 12, 1972. California-Baja California. From left corner diagonally: Coachella Valley, Salton Sea, Imperial Valley, Borderline, Mexicali Valley, Laguna Salada. San Diego-Tijuana visible in the lower left corner. Note the difference in the landscape east and west of the snow-capped mountains. Dense, vigorous vegetation is red.

2. Landsat MSS Color Composite, September 6, 1973. Arizona-Sonora. Yuma Desert at top, Gran Desierto at center, Gulf of California at bottom. New Cornelia Mine is visible in the upper right corner. Dense, vigorous vegetation is red.

3. Landsat MSS Color Composite, June 23, 1973. Arizona/New Mexico-Sonora/Chihuahua. Image Shows the Wilcox Playa and South Alkali Flat west and east of the Chiricahua Mountains, respectively. Agriculture of Sulphur Spring Valley, south of Wilcox Playa, and Animas Valley, south of South Alkali Flat, is visible. Note the ability to identify the borderline, due to differences in land use and land use practices. Dense, vigorous vegetation is red.

4. Landsat MSS Color Composite, June 21, 1973. Texas/New Mexico-Chihuahua. El Paso-Cuidad Juarez international metropolitan complex is in center of image. Agriculture of the Rio Grande Valley is readily apparent. Large landforms, such as the sand dunes in Chihuahua, are easy to identify. Dense, vigorous vegetation is red.

5. El Paso-Cuidad Juarez Morning Inversion, 11/9/78. Early morning (8:30 A.M.) photograph looking west at El Paso-Cuidad Juarez from approximately 25 miles east along Highway 62/180 [f/4-5.6, 1/125, w/polarizing filter and 2x telephoto converter]. Inversion haze is apparent and obscures the northern end of the Juarez Mountains and southern end of the Franklin Mountains.

6. El Paso-Cuidad Juarez Evening Inversion, 11/9/78. Early evening (5:30 P.M.) photograph looking west at Cuidad Juarez and Juarez Mountains from I-10 at Horizon Blvd., 12 miles southeast of the city [f/1.4, 1/60, w/normal lens and 2x telephoto converter]. Ground radiation fog or haze is shown developing as a result of rapid heat loss from the ground surfaces.

7. El Paso-Cuidad Juarez Morning Inversion, 11/10/78. Early morning (8:30 A.M.) photograph looking south southeast at eastern El Paso-Cuidad Juarez and Rio Grande Valley [f/11-16, 1/125, w/normal lens]. Inversion haze is readily apparent. Extinction of the haze seems to occur near the left side of the image; however, this could be an effect rather than a fact. Easterly drift seems to be evident. See Slides 8 and 9.

8. El Paso-Cuidad Juarez Morning Inversion, 11/10/78. Same as above, but looking south. Concentration of haze seems apparent on the east side of the Juarez Mountains. See Slides 7 and 9.

9. El Paso-Cuidad Juarez Morning Inversion, 11/10/78. Same as above, but looking south-southwest. Easterly drift seems more evident in this image. See Slides 7 and 8.

10. Photograph of ASARCO Stack and Plume w/Normal Lens. Afternoon (4:00 P.M.) photograph looking north-northwest at stack and plume from Rio Grande [f/8, 1/250, w/normal lens].

11. Photograph of ASARCO Stack and Plume w/Polarizing Filter. Same as above [f/5.6, 1/250, w/polarizing filter]. Compared with Slide 10 the plume is far more distinquishable, although Slide 10 may have been slightly overexposed.

12. Image Enhancement of Skylab 4 Photograph of Stargo Plant (Plate 1). Two dark spots on the right are clouds. To the left of the clouds, the plume from the Stargo Plant is revealed as a linear element oriented to the bottom right corner of the image. Note the apparent accumulation south of the plant. Also note that the plant and plume are not distinquished from the slopes of the Gila River Valley on the left side of the image.

13. Enlarged Image Enhancement of Skylab 4 Photograph (Plate 1). Note the difference in configuration and color between the two clouds and the mass of the plume to the south.

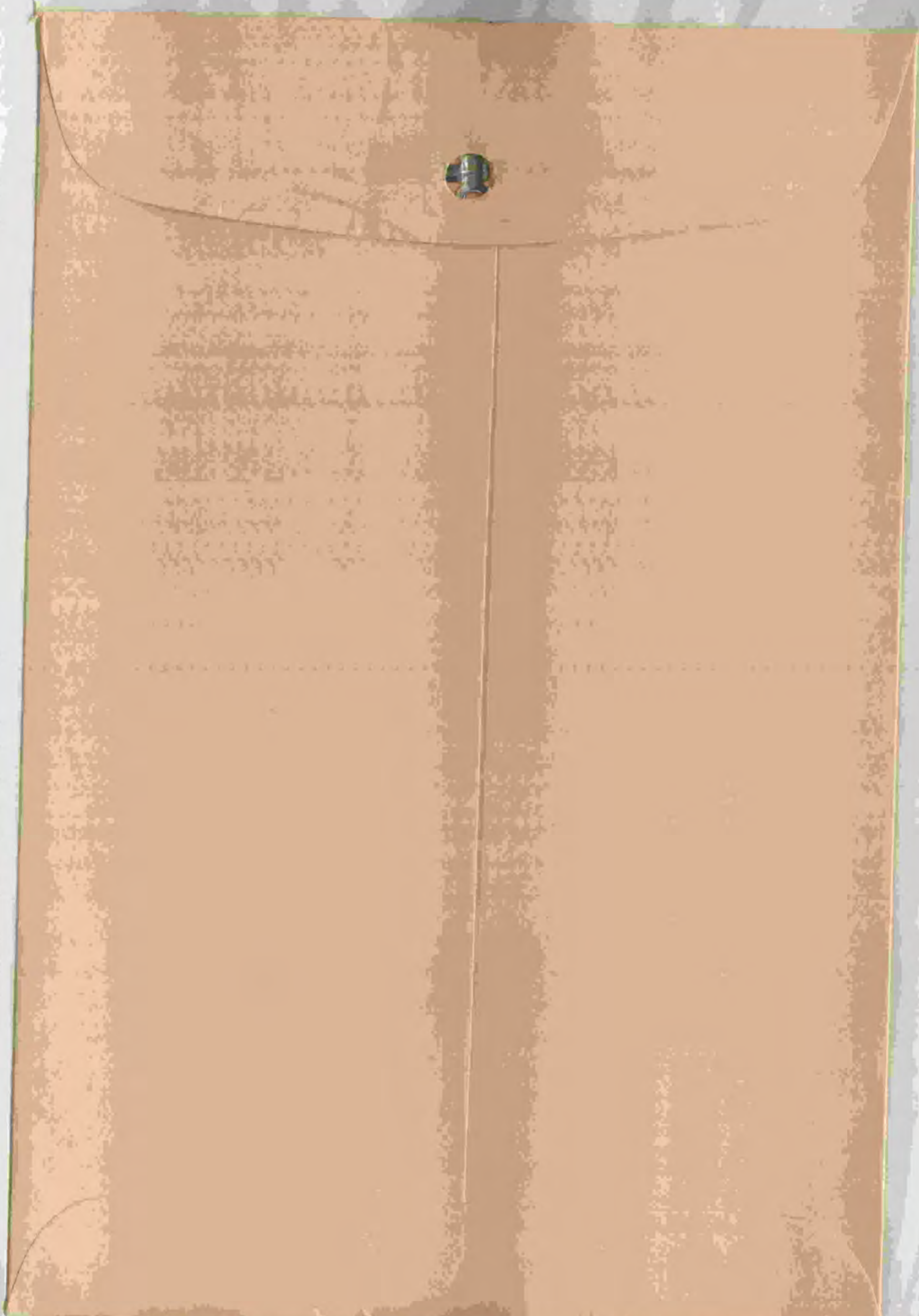
14. Light Transmittance Contours of Skylab 4 Photograph (Plate 1). Two dome-like forms on the right are the clouds. Note the difference between the clouds and the apparent terminus of the plume, which is the linear, ridge-like element directly to the left of the clouds.

15. Enlarged Light Transmittance Contour Image of Skylab 4 Photograph (Plate 1). Note the coherent forms of the contours which indicate the clouds on the right. Compare them with the plume and the apparent piling-up of emissions south of the clouds.

16. Color Enhancement of Plate 14. See text, page 147.

17. Color Enhancement of Plate 14. See text, page 147.

18. Light Transmittance Contour of Douglas Plume (Plate 14). See text, page 148. It should be noted that the contrast is so great between the plume and its background in the photograph that the light transmittance contour exhibits few surrounding contours. Compare with Slides 14 and 15.

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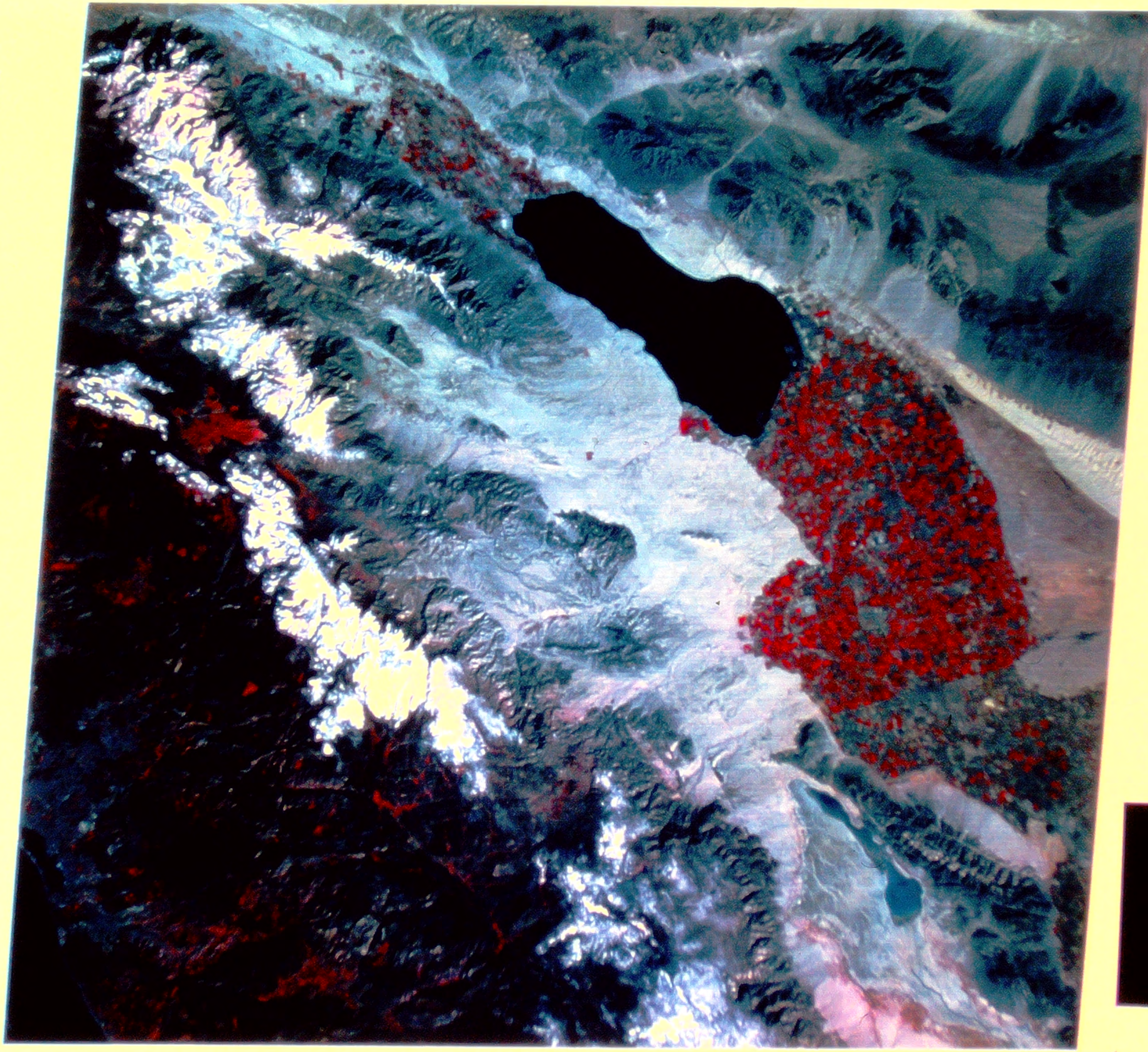

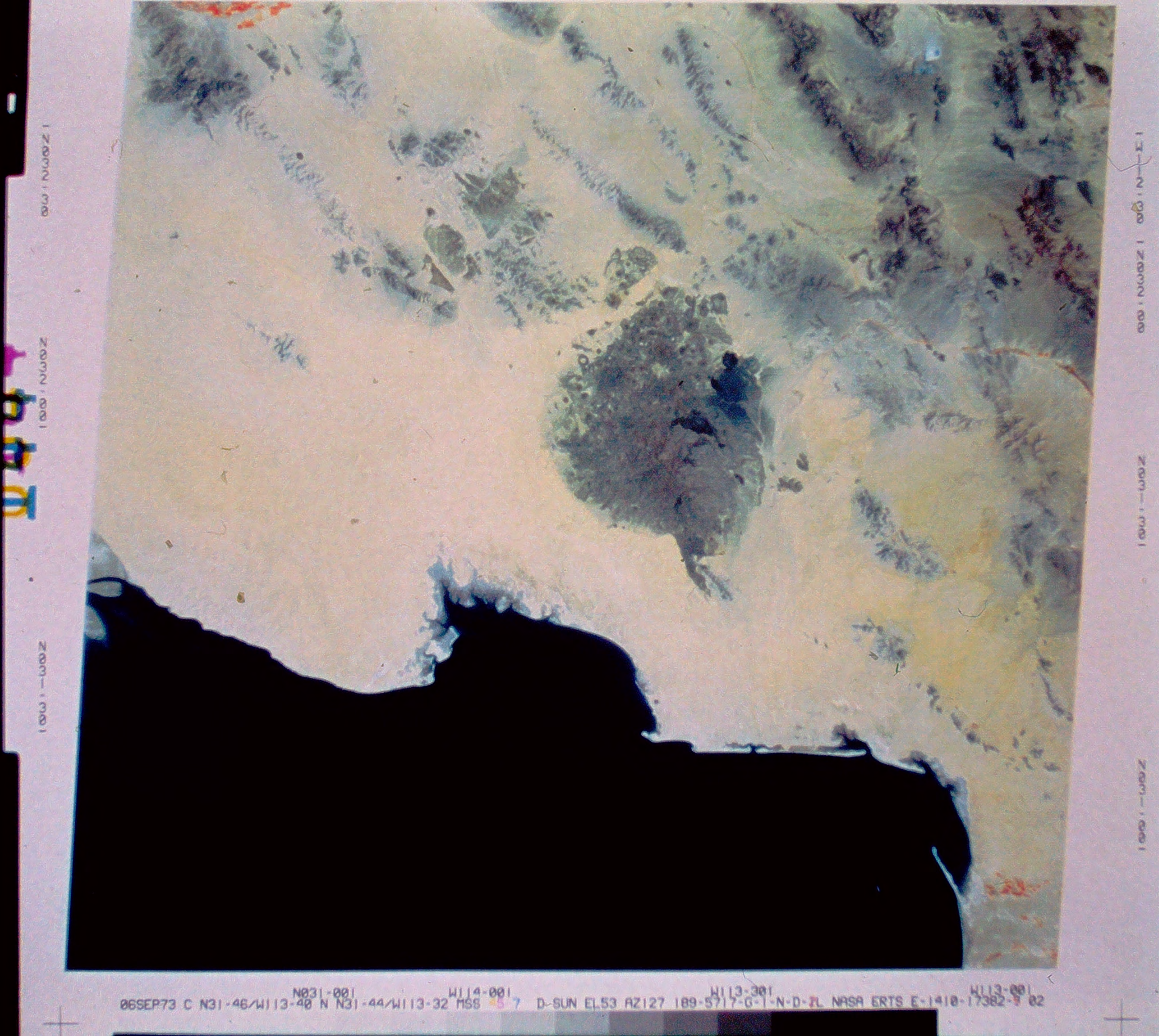
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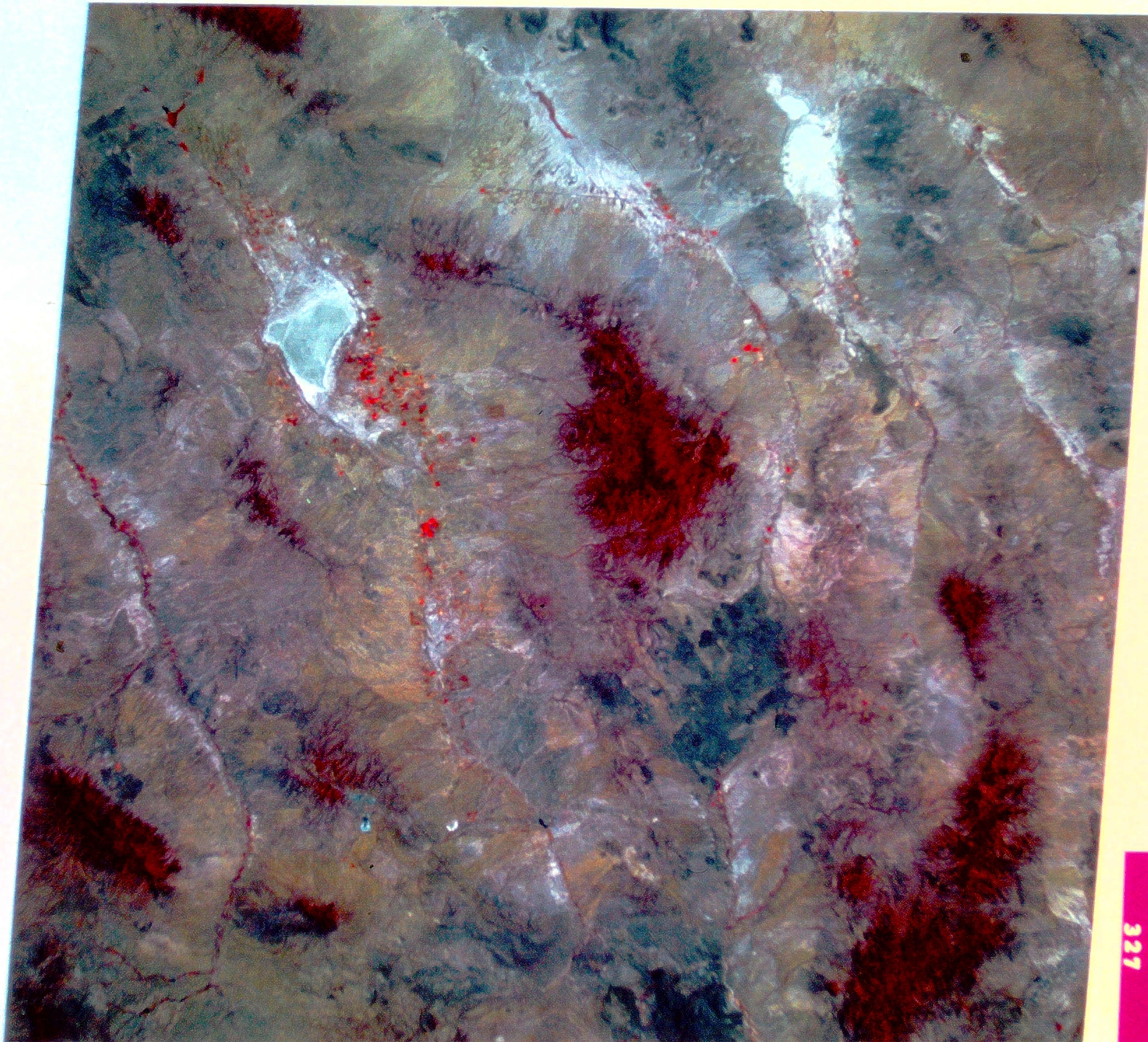

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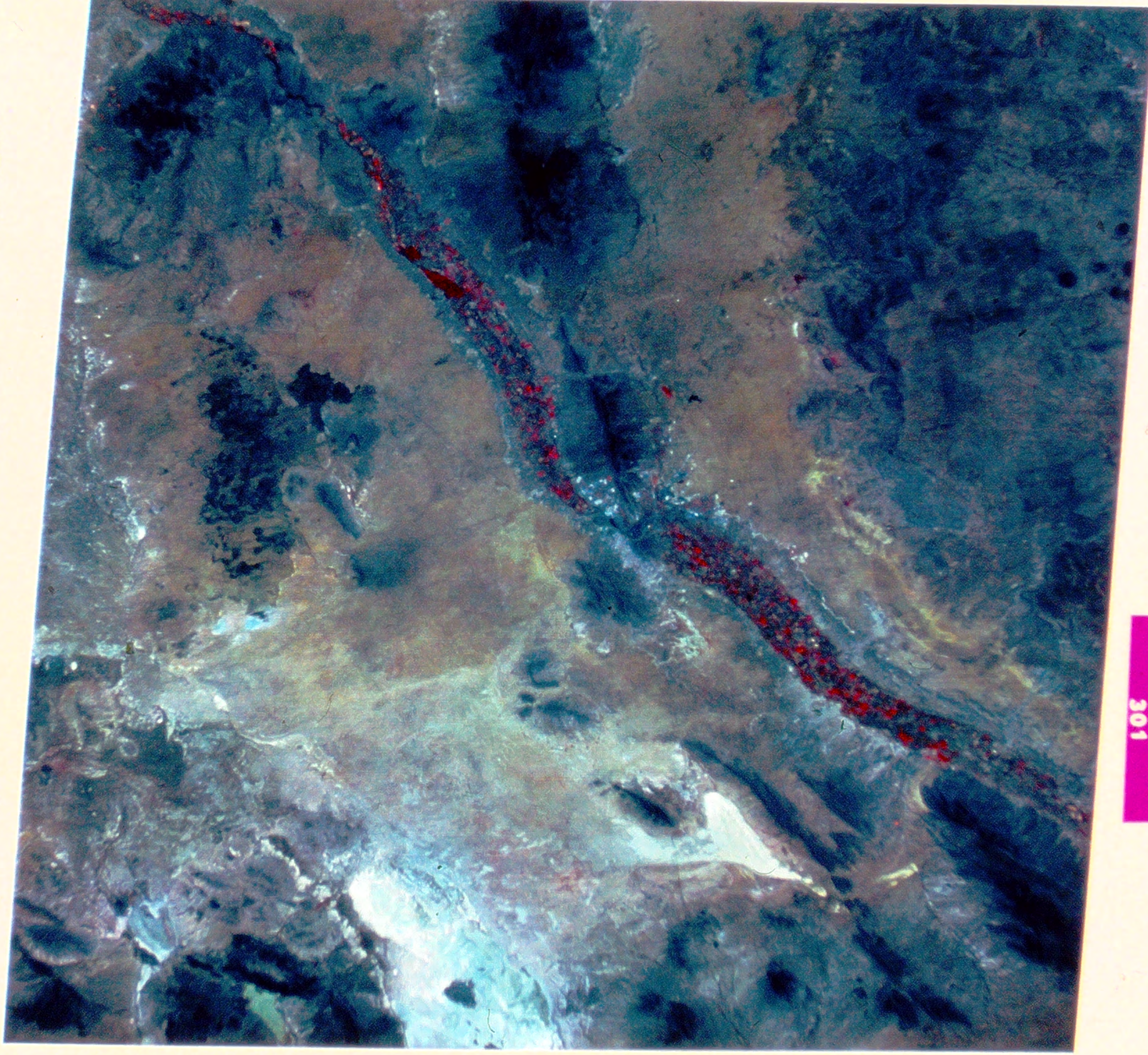

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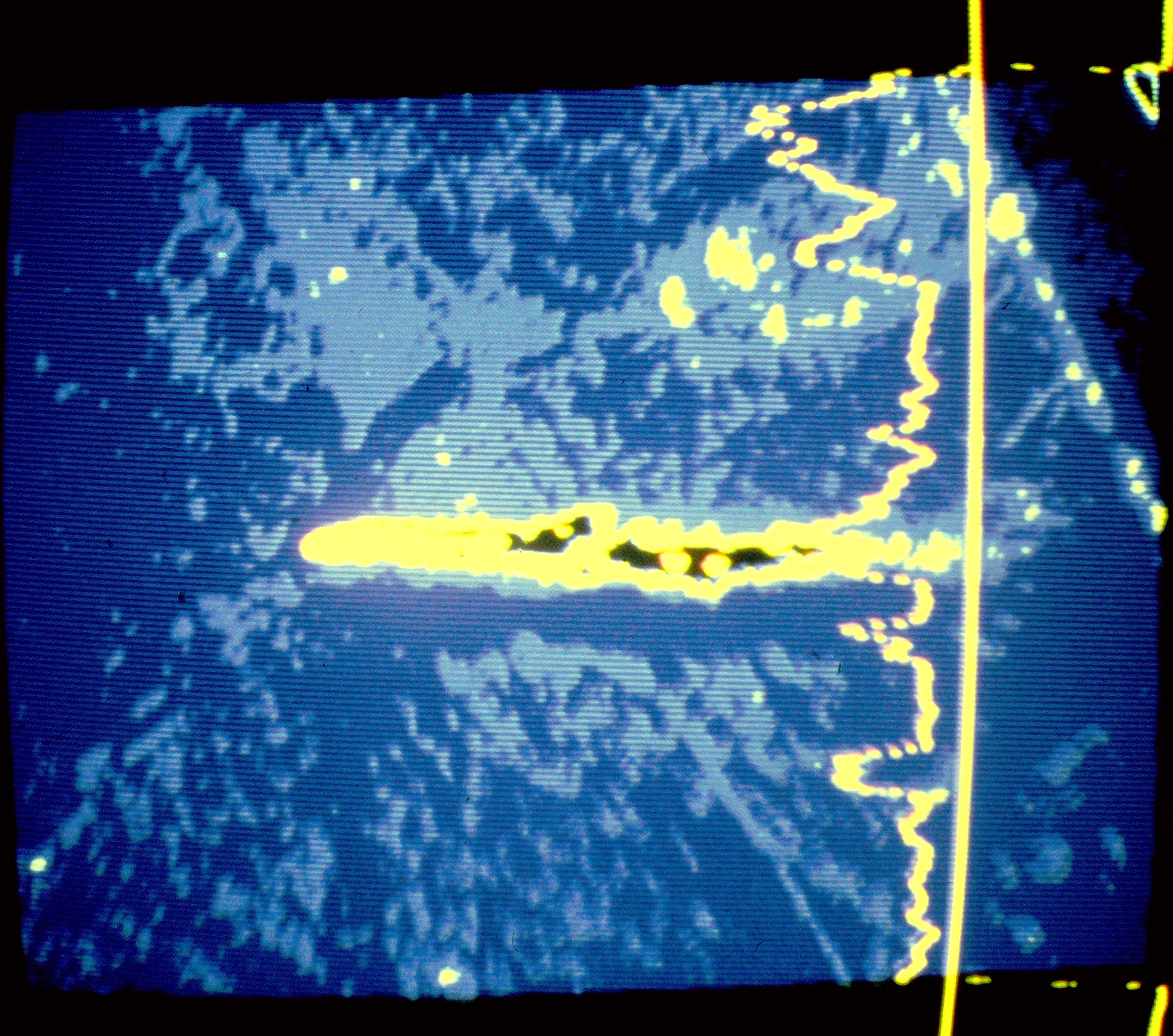

FINDINGS AND CONCLUSIONS

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Transfrontier air pollution presents problems, which inextricably link the geographic realities of the political, legal, and economic relationships of neighboring countries. As such, the problems manifested by the movement and consequent external effects of air pollution from one country to another requires resolution in an international forum. Affected countries must implement acceptable means for developing cooperative compromises regarding air pollution levels, given their respective national goals. Relative to the United States-Mexico border region, environmental problems associated with transfrontier air pollution are being identified. The principal efforts are being expended by individuals, either independently or within informal cooperative arrangements involving persons of both countries. However, simple identification of the transfrontier air pollution problems will not lead to the resolution of those problems.

As yet, a formal cooperative program with explicit objectives for air quality control and/or enhancement has not been developed relative to the United States-Mexico border region. National efforts to deal with transfrontier air pollution in the border region have been characterized as "detached." It seems apparent that the political and economic relations of the United States and Mexico, in general, can be characterized as being based on "detached" policies, reflecting only national interests. The Clean Air Act of 1970 (as amended in 1977) is the United

States' response to national air pollution problems. The "Federal Law for the Prevention and Control of Environmental Contamination" is its counterpart in Mexico. These are national reponses to national problems, neither of which directly address the transfer of air pollution between the two countries. The United Nations Conference On The Human Environment addressed the questions relating to international pollution transfers and established Principle 21, which calls on all nations to act responsibly with regard to the external effects of pollution imposed on other nations. While the Declaration On The Human Environment is not a binding, legal agreement, the effect of the Declaration is to identify state practice (or state intentions) relative to environmental degradation and/or enhancement. Thus, each nation must consider its international responsiblities within the scope of the Declaration. A first step in the recognition of these responsibilities by the United States and Mexico was the signing of a Memorandum of Understanding between federal agencies responsible for environmental concerns.

Political and legal responsibilities of nations with respect to global environmental concerns are compounded by economic considerations. The economic status and, therefore, economic goals of the United States and Mexico differ. These differences are reflected by differing priorities with respect to national growth and development objectives. In turn, the differing priorities between the two countries reflect, almost epitomize, the disparity of wealth and technological achievement of industrialized countries compared with less developed countries. The choice of the United States to direct USAID funds to the poorest nations, eliminating Mexico as a recipient, neglects the geographic reality of the proximity of Mexico to the United States (and vice versa), and the socioeconomic reality that there is an intense interchange of people and goods occurring between the two countries on a daily basis. Mexico, for its part, is strained to keep pace with a rapidly increasing population and the need for supporting economic development. Thus, pollution control, which in and of itself is a non-productive activity, is a luxury for Mexico. It seems clear that Mexico will have little interest in promulgating strict air quality standards, while a large portion of its population is living at subsistence levels.

The border region of the United States and Mexico is an area of interface between the two countries. It is possible that a focus on specific problems associated with the border region has prevented people in both countries from seeing the area simply as an interface. The reality of history testifies to unresolved tension between the two countries. This tension seems to focus on the border region, especially the "border," even when the border region is not germane to the issue. The "border" is essentially an arbitrary division of land by two conceptual entities: nation-states. Political separation of the land has not retarded socioeconomic interaction, maintenance of cultural ties, or transfrontier air pollution, which is the reality of the present. The reality of the future must include recognition of human and natural interactions between the two countries. It must also include recognition of the consequences of future population growth and socioeconomic development in the border region. At this time, environmental problems in the border region are considered serious by some persons, who echo the concerns for the environment and modification of it by humankind expressed over one hundred years ago. Others perceive environmental problems in the border region as unavoidable consequences, resulting from productive activities necessary to sustain a rapidly growing population. Clearly, this basic economic dilemna, which possesses deep philosophical roots in questions respecting man and nature interactions, will not be resolved through unilateral or "detached" action by the two countries.

Environmental problems, associated with transfrontier air pollution in the United States-Mexico border region are already evident. Soild waste disposal, open burning, power generation, industrial processes, agricultural activities, and vehicular transportation are prominent activities generating the constituents of transfrontier air pollution. Because of the great expanse of the border region, it is unclear, thus far, as to the seriousness of any one of these polluting activities. In urban areas, such as the El Paso-Cuidad Juarez international metropolitan area, pollution problems have become an obvious and identifiable concern. However, conclusions as to the seriousness of pollution throughout the border region certainly are not justified at this time. The activities of the United States and Mexico reflect the findings, conclusions, and recommendations of the Stockholm Conference. The prime concern, at this time, is the determination of effects, resulting from human modification of the physical environment and not the determination of specific pollution standards.

While air quality monitoring in urban areas is well advanced and providing significant information regarding the effect of growth and development activities, air quality monitoring in geographically large frontier regions has not been a concern until quite recently. Concern did not develop until there was a general recognition that localized activities affected the global environment. Efforts to determine the state of the global environment have relied heavily on the information gained through the deployment of remote sensing devices capable of monitoring large areas of the earth and its atmosphere. Attention to the matter of transfrontier air pollution necessarily leads to an investigation of these efforts to monitor the global environmental quality. Thus, attention is focused on aerial, sub-orbital, and orbital platforms carrying remote sensing devices.

Examination of the usefulness of aerial, sub-orbital, and orbital remote sensing systems and outputs from those systems revealed that remotely acquired imagery could contribute to a better understanding of the problem of transfrontier air pollution. The ability to inventory sources and source areas, related to the enviornmental problems of the border region, is feasible using orbital photography. Specific sites or sources are distinquishable and can be mapped, which will provide the geographic perspective necessary to evaluating transfrontier air pollution flow patterns. In the United States-Mexico border region, mining and smelter sites are dectectable, and principal agricultural areas can be identified. Although the literature reveals that the detection of vegetative stress with photography could be a valuable tool in determining the areal effects of pollution, attempts to confirm this were not initiated. It is likely, however, that such experiments will not be appropriate using orbital photographs of the border region, because of the generally sparse vegetal cover.

Attempts to measure actual air pollution occurrences, specifically stack emission plumes, indicated that orbital photography should be useful in determining the regional dispersion potential of such emissions. However, precise measurements were inhibited by the small scale of orbital photographs. There seems to be some potential for the use of enhancement processes to contribute to quantitative and qualitative knowledge of air pollution detected by orbital photography. However, sharp contrast between the pollution concentration and the surrounding landscape is necessary. Sub-orbital photography appears to have greater potential use for direct measurement of pollution dispersion patterns. The development of acceptable vertical profiles was unattainable with images generated at sub-orbital and orbital altitudes.

Evaluation of Landsat imagery revealed that the scale is too small to detect ordinary air pollution occurrences associated with the environmental problems reviewed in this study. However, the imagery should prove useful in determining the extent of large scale surface phenomena, which contribute to transfrontier air pollution, such as agricultural areas, range land, and areas of bare soil. There is an apparent potential for the use of Landsat imagery to determine the magnitude and intensity, in relative terms, of pollutant concentrations produced by nocturnal ground radiation inversions and subsidence inversions. Pollutant concentrations, developing as a result of inversions, are a current, recognized problem for many of the international urban areas situated on the border and many other urban areas in the border region. Further examination of the use of Landsat imagery to evaluate this problem seems justified.

Although emphasis has been on the detection and monitoring of transfrontier air pollution, the evaluation of photographic and non-photographic remote sensing outputs (i.e., imagery) has provided a good basis for determining image usefulness relative to other environmental problems in the United States-Mexico border region. Thus, Table 13 is a summary of the potential usefulness of images evaluated in this study, relative to 1) efforts to understand and control environmental problems and 2) actions and decisions affecting future development patterns. Whether or not such information will enable the implementation of long-term pollution prevention actions, such as source sitings, emission timing regulations, and cooperative regional planning, remains a question which must be answered within the total political, legal, economic, and social context of the United States and Mexico in particular and all countries in general. Notwithstanding national associations, remote sensing outputs examined in this study clearly are effective and available aids to evaluating environmental problems in the border region, including transfrontier air pollution.

Table 13. Potential Usefulness of Photographic and Non-Photographic Images in Detecting and Monitoring Border Region Environmental Problems Related to Air Pollution

Potential Usefulness:

1 - Definitely Useful

2 - Possibly Useful

3 - Definitely Not Useful

Image Type, Working Scale	Environmental Problems: Natural Pollutants	Solid Wastes	Open Burning	Power Generation	Industrial Activities	Industrial Air Pollution	Agricultural Operations	Agriculture and Related Activities	Transportation Facilities	Urban Growth and Development	Atmospheric Dynamics
High Resolution Aerial Color, 1:440,000	2	3	3	2	2	2	3	2	2	1	2
Panchromatic, 1:118,000	2	2	2	2	1	1	2	2	2	2	2
High Definition Aerial Color, 1:666,287	2	3	3	2	1	1	3	2	3	3	2
Color Infrared, 1:666,287	3	3	3	3	2	3	3	1	3	3	3
Color, 1:113,144	3	3	3	3	1	2	2	2	1	2	3
Color Infrared, 1:96,464	2	2	2	2	1	2	2	1	1	1	3
High Resolution Aerial Color, 1:669,643	2	3	3	2	1	1	3	2	3	3	2
Landsat False Color Composite (35mm Slide)	2	3	2	3	1	1	3	2	2	2	2
Landsat RBV 3-Band B&W Composite, 1:241,514	3	3	2	2	2	2	3	1	2	1	3
Landsat B&W Transparency Band 4, 1:994,624	2	3	2	3	3	2	3	3	3	3	3
Landsat B&W Transparency Band 5, 1:994,624	2	3	3	3	3	3	3	2	3	1	3
Landsat B&W Transparency Band 7, 1:994,624	2	3	3	2	2	2	3	2	1	1	2
VISSR, SMS and GOES (Visible), 1:9,154,000	2	3	2	3	3	3	3	3	3	3	1
VISSR, SMS and GOES (Visible), 1:17,800,000	2	3	2	3	3	3	3	3	3	3	1
VISSR, SMS and GOES (Visible), 1:35,000,000	3	3	3	3	3	3	3	3	3	3	1
VISSR, SMS and GOES (Infrared), 1:9.154,000	2	3	2	3	3	3	3	3	3	3	1
VISSR, SMS and GOES (Infrared), 1:17,800,000	2	3	2	3	3	3	3	3	3	3	1
VISSR, SMS and GOES (Infrared), 1:35,000,000	3	3	3	3	3	3	3	3	3	3	1

APPENDIX A

INDUSTRIAL AND AGRICULTURAL ACTIVITIES

AND

ASSOCIATED POLLUTANTS

IN THE

UNITED STATES-MEXICO BORDER REGION

POLLUTANTS ASSOCIATED WITH INDUSTRIAL ACTIVITY

METALLURGICAL OPERATIONS

Iron and Steel Mills	- Large quantities of particulate matter, sulfur oxides, hydrocarbons, carbon monoxide, nitrogen oxide, hydrogen sulfides, volatile organics (ammonia & organic tars), phenol compounds, polycyclic aromatic hydrocarbons
Nonferrous Metal Smelting	- Sulfur oxides, particulate matter, trace metals (lead, zinc, arsenic, selenium, mercury)
Aluminum Reduction	- Particulate and gaseous fluoride compounds
Iron Foundaries	- Particulates
Metal Casting Operations	- Particulates
Metal Fabrication Plants	- Particulates
Secondary Lead & Zinc Recovery	- Particulates
PETROLEUM REFINING	- Hydrocarbons, particulate matter, sulfur oxides, nitrogen oxides, carbon monoxide, ammonia, hydrogen sulfide, organic sulfur compounds, other odorous gases, aldehydes
PULP AND PAPER (Kraft Process)	- Hydrogen sulfide odors, organic sulfur compounds, particulates
MINERAL PROCESSING Asphalt Batching Cement Manufacturing Ceramic Clay Production Lime Production Brick and Clay Production	- Dust particulates, sulfur oxides, nitrogen oxides, carbon monoxide

POLLUTANTS ASSOCIATED WITH AGRICULTURAL OPERATIONS

PROCESSING	- Particulate matter, odorous gases
Alfalfa Dehydration Cotton Gining Cottonseed Oil Production Coffee Roasting Feed Grain Milling/Storage Peanut Shelling Suger Cane Production	
FEEDLOT OPERATIONS	- Particulate matter, odorous gases (organic acids, nitrogen-containing amines and ammonia, reduced sulfur compounds), disease carrying bacteria
CHEMICAL PRODUCTION	- Sulfur dioxide, sulfuric acid mist, nitrogen dioxide, nitric acid mist
NITRATE FERTILIZER PRODUCTION	- Particulate matter, oxides of nitrogen, ammonia
PHOSPHATE FERTILIZER PRODUCTION	- Particulate matter, hydrogen fluoride, fluoride particulates

APPENDIX B

BASES OF COLLABORATION ON INTER-UNIVERSITY PROGRAMS

CONCERNING

ENVIRONMENTAL IMPROVEMENT IN THE EL PASO-JUAREZ AREA

BASES OF COLLABORATION ON INTER-UNIVERSITY PROGRAMS CONCERNING ENVIRONMENTAL IMPROVEMENT IN THE EL PASO-JUAREZ AREA

PARTICIPATING INSTITUTIONS

Universidad Autonoma de Cd. Juarez

Instituto Tecnologico Regional de Cd. Juarez

Escuela Superior de Agricultura "Hermanos Escobar"

University of Texas at El Paso

1. DEFINITION OF GOALS

The goals to be achieved by this plan are the following:

1.1 To promote local student awareness of the need for studying and preserving the environment by using the resources of the four participating Universities.

1.2 To complement the professional training of graduate students in this field.

1.3 To contribute to the institutional development of the Universities in the environmental field.

1.4 To contribute to environmental improvement in the region by collaboration with competent authorities.

2. STATEMENT OF ACTIVITIES FOR THE ACHIEVEMENT OF THESE GOALS

2.1 To investigate the need and the possibility of establishing the required curriculum in order to conduct courses on environment improvement.

2.2 To interchange information, publications, and experiences.

2.3 To utilize in a mutually advantageous manner joint facilities and services devoted to these activities.

2.4 To conduct seminars, workshops, and lectures.

2.5 Faculty interchange.

2.6 Student interchange.

2.7 To conduct studies and research in order to define and to resolve the environmental problems of the region.

2.8 To offer services, advise, and technical orientation to the competent organizations.

3. The activities of this plan will be implemented in accordance with the adoption of semester programs which will run in the common academic sessions already established by all the participating institutions.

Source: Applegate, 1978.

APPENDIX C

MEMORANDUM OF UNDERSTANDING

BETWEEN

THE SUBSECRETARIAT FOR ENVIRONMENTAL IMPROVEMENT OF MEXICO

AND

THE ENVIRONMENTAL PROTECTION AGENCY OF THE UNITED STATES

FOR

COOPERATION ON ENVIRONMENTAL PROGRAMS AND TRANSBOUNDARY PROBLEMS

MEMORANDUM OF UNDERSTANDING*

between

The Subsecretariat for Environmental Improvement of Mexico

and

The Environmental Protection Agency of the United States

for

Cooperation on Environmental Programs and Transboundary Problems

Whereas, the Governments of Mexico and the United States share many environmental problems related to large and expanding urban populations, substantial industrial activity, and a common border between the two countries; and both countries possess many areas of natural and man-made scenic and recreational value; and

Whereas, the Subsecretariat for Environmental Improvement of Mexico (SMA) and the Environmental Protection Agency (EPA) of the United States share a concern for protecting and improving the human and natural environments of their respective nations, and a common interest in the cause of global as well as common border environmental protection and improvement; and

Whereas, the Governments of Mexico and the U.S. have pledged increased cooperation through the Consultative Mechanism set up by the two Presidents to include environmental cooperation;

It is Hereby AGREED that:

1. The SMA and EPA will initiate a cooperative effort to resolve environmental problems of mutual concern in border areas as well as any environmental protection matter through exchanges of information and personnel, and the establishment of parallel projects which the two parties consider appropriate to adopt.

2. The SMA and EPA will accomplish parallel activities, while allowing for the possibility that, at any given time, through special agreement, joint actions tending to resolve specific problems, may be conducted.

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*Reproduction of signed original obtained from files of the Teaxas Air Control Board, Region 11, El Paso, Texas.

3. SMA and EPA senior officials will meet annually, unless they mutually agree otherwise, to discuss overall policies, programs and problems which are of common concern. The annual meeting will be held, alternately in each country, at a mutually agreeable time and site.

4. Experts designated by SMA and EPA will meet periodically or as necessary to review technical issues and plan parallel projects, including pollution abatement and control, regulations, quality assurance, research, and monitoring, that are of common interest or concern to both Mexico and the United States. An annual meeting of designated experts will be held at a site mutually agreed to by both parties and may coincide with the U.S./Mexico Border Health Association annual meetings or with other meetings. The SMA and EPA experts may make policy recommendations for consideration by the respective heads of SMA and EPA.

5. The meetings of the SMA and EPA representatives will not be limited to consideration of border problems alone but may include discussions of all areas of environmental protection and enhancement. It is understood that the Water Treaty of 1944 between the two Governments entrusted the solution of border sanitation problems to the International Boundary and Water Commission.

6. Each Party will name one person to act as coordinator to facilitate exchanges of information and other cooperation under this Memorandum of Understanding. The coordinators will establish procedures and details for the meetings of the senior officials as well as experts, including the time, place and agenda.

7. The coordinators may invite representatives of federal, state and local government agencies, international organizations, members of private organizations or other private citizens to participate in meetings, conferences, and other parallel activities as deemed appropriate.

8. Parallel activities may be conducted when approved by appropriate authorities of the respective governments and may include but will not be limited to the following:

-- Development of pollution abatement and control programs directed toward specific pollution problems affecting either or both countries along the border.

-- Development of an early warning system to alert the two Governments to potential environmental problems.

-- Review and consultation regarding national environmental policies and strategies of Mexico and the United States.

-- Development of data gathering, processing and mechanisms for the exchanges of information of common interest.

9. The coordinators will be responsible for the general management of programs, workshops, projects and activities undertaken pursuant to this Memorandum of Understanding. This includes definition of each program, workshop or project as to scope, priority, and completion schedules. The coordinators may delegate work on a special problem area to a special subcommittee which shall examine the problem in detail and make recommendations to the Governments through the SMA and EPA, respectively.

10. Unless otherwise agreed, each Party will bear the cost of its participation, including personnel costs, in activities undertaken pursuant to this Memorandum of Understanding.

11. Work under this Memorandum of Understanding is subject to the availability of funds and other resources to each Party, and to the laws and regulations of Mexico and the United States.

12. Results of work accomplished under this Memorandum of Understanding will be fully available to both parties and either Party may release information in its possession to the public on 10 days notice to the other Party.

13. This Memorandum of Understanding will enter into force when signed by both Parties and approved by the two Governments through an exchange of notes. The Memorandum of Understanding will remain in force indefinitely until either Party notifies the other of its intent to terminate the agreement, with 90 days notification.

Done in duplicate at Mexico City on the 6 of June 1978 in the Spanish and English languages, both texts being equally authoritative.

For the United States Environmental Protection Agency	For the Mexican Subsecretariat for Environmental Improvement
Administrator for Environmental Protection Agency	Subsecretary for Environmental Improvement

APPENDIX D

SELECTED EXPERIMENTS IN AIR QUALITY MONITORING UTILIZING LANDSAT (ERTS) MSS IMAGERY

The following report of four experiments testing the air quality monitoring capabilities of Landsat (ERTS) MSS imagery has been extracted from Appendix A, Detailed Review of Experiment Results in Appendix 6, An Analysis of the Benefits and Costs from the Use of ERS Data in Environmental Analysis in Earth Resources Survey Benefit-Cost Study prepared by the Earth Satellite Corporation and the Booz-Allen Applied Research Corporation for the U.S. Department of the Interior/Geological Survey, Contract Number 135-19, November 22, 1974. The selected experiments relate only to air pollution concerns; however, the publication includes several examples of successful use of Landsat MSS imagery in detecting water pollution in coastal areas, which falls within the scope of transfrontier pollution concerns.

EXPERIMENT TITLE: DETERMINATION OF AEROSOL CONTENT IN THE ATMOSPHERE FROM ERTS-1 DATA (7A PR135)

PRINCIPAL INVESTIGATOR: M. Griggs/C. B. Ludwig (Science Applications Incorporated)

EXPERIMENT OBJECTIVES:

- Determine aerosol content in the atmosphere using ERTS-1 data based on contrast reduction and radiance.

SUMMARY OF RESULTS:

- A linear relationship as predicted by theory, has been shown to exist between the MSS radiance over water surfaces and the aerosol content of the atmosphere. This suggests that this technique is suitable for sensitive monitoring of aerosol content. The linear relationship was obtained using ERTS-1 digital data. The relationship will enable the atmospheric aerosol content to be monitored on a global basis, once it has been verified with further measurements and should provide the information with considerable cost savings over a ground based photometer network.

EXPERIMENT TITLE: STUDY TO DEMONSTRATE THE FEASIBILITY OF, AND DETERMINE THE OPTIMUM METHOD OF REMOTE HAZE MONITORING BY SATELLITE (7A PR173)

PRINCIPAL INVESTIGATOR: E. H. Rogers
Aerospace Corp.

EXPERIMENT OBJECTIVES:

- Measure loss of scene contrast and relate it to haze as measured by ground truth.
- Compare ratio of brightness of dark areas to average brightness with previous ratios for the same wavelength and same area, by comparing contrast with clear air content a measure of haze will be obtained.
- Compare apparent contrast at 0.5-0.6 micrometers to contrast measured at same time in another band (0.6-0.7 micrometers) less affected by haze. [Note: Spectral limits identified correspond to MSS Band 4 and MSS Band 5, respectively.]

SUMMARY RESULTS:

- A general purpose flexible computer program for the analysis of ERTS MSS data has been written for the Control Data 7600 computer. Preliminary results indicate that a slight reduction in contrast and some distortion of spectral signatures are caused by heavy haze. This effect is thought to be sufficient to determine the presence of moderate haze without the benefit of ground truth data. No quantitative cost benefits described.

EXPERIMENT TITLE: THE USE OF ERTS-A [Landsat 1] SATELLITE DATA IN GREAT LAKES MESOMETEOROLOGICAL STUDIES (6A UN144)

PRINCIPAL INVESTIGATOR: Walter A. Lyons
Energetics Department
University of Wisconsin

EXPERIMENT OBJECTIVES:

- Detect meteorological phenomena occurring at the low end of the mesoscale motion spectrum (1-100km) e.g., convective cloud phenomena, internal wave patterns, air pollution, snow squalls, etc.

SUMMARY OF RESULTS:

- Detection of cumulis clouds to clearly mark the inland penetration of cooler lake air and its updrafts at the frontal convergence zone. Now can determine what size identation or bay in the shoreline produces detectable variations in the inland penetration. Detection of large point sources of suspended particulates possible. Can study interregional pollution transport by combining ERTS imaging, computer simulation and actual aircraft measurements. An aid in inadvertent weather modification detection, e.g., downwind increases in precipitation from large cities.

- Quantitative cost benefit includes: (1) monitoring of interregional pollution transport; (2) snow squall cloud monitoring might be of inestimable value in upcoming years when operational cloud seeding of lake snows becomes a reality. ERTS provides a unique source of data for meteorological studies and thus cannot be compared to any other source. ERTS data will be of immense value in directing future research efforts and greatly help in wisely utilizing federal research monies.

EXPERIMENT TITLE: CORRELATION OF SATELLITE AND GROUND DATA IN AIR POLLUTION STUDIES (7A UN672)

PRINCIPAL INVESTIGATOR: G. E. Copeland
Old Dominion University,
Research Foundation

EXPERIMENT OBJECTIVES:

- Collect particulate matter samples.
- Determine metal concentrations.
- Monitor gaseous pollutants.
- Relate ground truth to ERTS imagery.
- Use of both photogrammetric and densitometric examination of ERTS-1 MSS imagery.

SUMMARY OF RESULTS:

- The general suitability of ERTS imagery in detecting ground originated air pollution has proved to be excellent. In some cases, point sources located to within a thousand feet. Positive identification of plumes less than a quarter mile in length is possible. Identification and surveying of fixed particulate emitters is, therefore, feasible. Quantitative monitoring of smoke stacks from orbital altitudes over state-size regions appears possible when tied to realistic plume models and minimal ground truth. Project appears to have little immediate practical application, although it may be quite valuable for basic scientific research.

APPENDIX E

PHOTOGRAPHIC AND NON-PHOTOGRAPHIC IMAGES

SELECTED FOR EVALUATION

The images identified in this appendix were selected and evaluated in the course of this study. Known technical information, concerning the image, is presented, including the photo/scene identification number (ID). If the image has been presented in the body of the text, the Plate or Slide number has been referenced. The general area covered by each photo/scene and the "working" scale for this study is presented, also.

NASA AIRCRAFT PHOTOGRAPHS

- New Cornelia Mine, Ajo, AZ (1:124,000); ID 5730012810056, Frame 59; BIR 2.2" (Poor Quality) and CIR 2.2".
- New Cornelia Mine, Ajo, AZ (1:113,144); ID 5720003700106, Frames 114-116; Col. 2.2".
- El Paso-Cuidad Juarez (1:96,464); Plate 4; ID 6201000500008, Frames 9-14; ID 6201000500017, Frames 19-23; ID 6201000500024, Frame 24; CIR 9.0"; May 13, 1972.
- Clifton-Morenci, AZ, Stargo Plant (1:118,000); Plate 3; ID 5720008176277, Frames 6280-6282; B&W 9.0"; November 21, 1972.

APOLLO/GEMINI PHOTOGRAPHS

- SE AZ, SW NM, N MX (1:669,643); Plates 14 and 15; Apollo 6, ID 7A06000201442-1446; 70 mm High Resolution Aerial Ecktachrome; April 4, 1968.

SKYLAB

- SE AZ, SW NM, N MX (1:664,336); Plate 1; Skylab 4, Frames 044-045; 70 mm High Definition Aerial Ektachrome (400 nm to 700 nm); February 1, 1974.
- E Central AZ (1:666,287); Plate 2; Skylab 3, Frame 28-063; 70 nm High Definition Aerial Ektachrome (400 nm to 700 nm); August 11, 1973.
- E Central AZ (1:666,287); Skylab 3, Frame 27-063; 70 mm CIR (500 nm to 800 nm); August 11, 1973.
- Central AZ, E Central AZ, SE AZ (1:633,600); Skylab 2, Pass 3, Frames 200-202; 70 mm High Definition Aerial Ektachrome; June 3, 1973.

SKYLAB (cont.)

- El Paso-Cuidad Juarez (1:440,000); Skylab 4, ID G408092023000-25000 (three images); 4.5" High Resolution Aerial Color; January 11, 1974.

LANDSAT

Color Composites: 35mm Slides, 1 - 4, respectively

- San Diego-Tijuana, Imperial-Mexicali Valley; ID 8114217504500; December 12, 1972.
- SW AZ, N MX; ID 8141017382500; September 6, 1973.
- SE AZ, SW NM, N MX; ID 8133517221500; June 23, 1973.
- El Paso-Cuidad Juarez; ID 8133317104500; June 21, 1973.

9.0" B&W Transparencies, MSS Bands 4, 5, and 7 (1:994,624)

- El Paso-Cuidad Juarez; November 23, 1976;
  ID 8267116471401, Plate 5;
  ID 8267116471501, Plate 6;
  ID 8267116471701, Plate 7.
- El Paso-Cuidad Juarez; March 7, 1976;
  ID 8532316314401;
  ID 8532316314501;
  ID 8532316314701.
- El Paso-Cuidad Juarez; June 23, 1976;
  ID 8543116241401;
  ID 8543116241501;
  ID 8543116241701.
- San Diego-Tijuana; September 2, 1976;
  ID 8258917353401, Plate 8;
  ID 8258917353501, Plate 9;
  ID 8258917353701, Plate 10.

Return Beam Vidicon (RBV), 3-Band Composites

- El Paso-Cuidad Juarez (1:497,312); ID 83011816590A, B, C, & D; 9.0" B&W Transparencies (Poor Quality); July 1, 1978.
- El Paso-Cuidad Juarez (1:241,514);
  ID 83006416583A0; 18" B&W Print (Poor Quality); May 8, 1978;
  ID 83022617001A0; 18" B&W Print; October 17, 1978.
- SE AZ, N MX (1:241,514);
  ID 83015617110C0; 18" B&W Print; August 8, 1978;
  ID 83004817095C0; 18" B&W Print (Poor Quality); Apr. 22, '78.

SMS and GOES

January, 1979, Visible and Infrared

- Eastern Pacific, Western North America (UC2); 1:35,000,000.
- Pacific and Western U.S.-Mexico (KB7); 1:17,800,000.
- South Central U.S., Mexico (KB4); 1:17,800,000; Plates 11 and 12 (GOES).
- South Central U.S., Northern Mexico (KA4); 1:9,154,000.

April, 1979, Visible

- Pacific and Western U.S.-Mexico (KB7); 1:17,800,000; Plate 13 (SMS).

APPENDIX F

MENSURATION OF STEREO MODELS

Four measurement techniques were employed in an attempt to develop quantitative description of plume profiles apparent on some of the selected image series: 1) direct measurement of parallax and measurement of parallax using the Michigan Parallax Wedge; 2) measurements using a measuring magnifier with 0.1 mm accuracy; 3) area measurements using random samples from an area grid; and 4) definition of vertical and horizontal dispersion using a Form Line Grid. Plume height measurements were developed using the basic formula for determining object heights from parallax measurements as described in Avery (1977):

$$\text{Height of Object } (h_o) = (H) \frac{dP}{P + dP}$$

where: H is the height of the aircraft [or any platform] above the ground datum;
P is the absolute stereoscopic parallax at the base of the object being measured; and,
dP is the differential parallax.

<u>Plate 15. Copper Mine at Hurley, New Mexico</u>

Plume Height Measurements:

Measurement 1 - H = 218 km (135 mi)
P = 106.5 mm
dP = 11 mm
therefore, h_o = 20 km (12.4 mi or 65,472')

Measurement 2 - H = 218 km
P = 106.5 mm
dP = 2.3 mm
therefore, h_o = 4.6 km (2.86 mi or 15,086')

Plume Dispersion Measurements:

Directly above the source (*i.e.*, stack), the plume was dispersed .44 km (.27 mi).
At a distance of 1.68 km (1.04 mi) from the stack on an azimuth of 195°, the plume dispersion had almost doubled to .84 km (152 mi) and the directional flow reversed to an azimuth of 295° with hori-

zontal and vertical dispersion continuing.
At a point 1.74 km (1.08 mi) from the point of reversal, horizontal dispersion of the plume was 1.17 km (.73 mi).

Conclusions:

Accurate parallax measurements are not feasible with the Michigan Parallax Wedge and a hand stereoscope. A plume height of 20 km (65,472') would have indicated the plume was in the stratosphere. The error between the two measurements is considerable. The orbital photograph had no depth as a stereo model; however, this does not mean that more sophisticated methods will prove infeasible. The stereo model did reveal the vertical displacement of the plume, which was beneficial in understanding atmospheric conditions: initial downwind forces to the south accompanied by a reversal of wind direction aloft at an unspecified altitude.

Measurement of horizontal dispersion, utilizing the measuring magnifier, yielded reasonable results; however, it must be noted that varying heights within the plume will require different scales, due to a change in the value of H. Because the plume height could not be measured accurately, the horizontal dispersion measurements are underestimated.

Attempts to profile the plume, utilizing a Form Line Grid, failed, because there was not adequate depth to the stereo model. Again, more sophisticated techniques could prove useful.

An estimate of area coverage was not attempted.

Plate 1. Stargo Plant, Clifton-Morenci, Arizona

Plume Height Measurements:

Plume height measurements were not attempted, given the conclusions derived from measurement attempts of Plate 15. However, an estimate of plume height was developed. The top of the stack is 1,482 m (4,940') above sea level (NOAA, 1979). The local elevation of the ridge at the visual end of the plume is 2,241 m (7,470') above sea level (U.S. Army Topographic Command, 1974); therefore, estimated vertical displacement of the plume is 759 m (2,530').

Plume Dispersion Measurements:

Directly above the source, the plume dispersion is .4 km (.25 mi) not adjusted for a change in H, due to altitude.
The plume is fairly distinct to the Big Lue Mountains, a distance of 20.9 km (13 mi) from the source. At this point, horizontal dispersion is greater than 2.5 km (1.6 mi), but plume diffusion makes measurement difficult.

The dispersion rate of the plume from the source to the ridge is approximately one-tenth of one kilometer (100 meters) for every one kilometer or 327' per mile.

Conclusions:

Height measurements are not feasible utilizing the Michigan Parallax Wedge with millimeter intervals.

Horizontal dispersion of the plume was estimated by careful measurement along its length, using the measuring magnifier. Diffusion of the plume made these measurements increasingly difficult.

The Form Line Grid was not useful, because of the lack of depth of the stereo model. The model was useful in interpreting the dynamics of the dispersion pattern of the plume.

Area coverage measurements were not attempted.

Plate 3. Stargo Plant, Clifton-Morenci, Arizona

Plume Height Measurements:

Measurement 1 - Direct measurement of differential parallax between the stack base and a point in the plume

H = 18.08 km (11.2 mi or 59,187')
P = 90.85 mm
dP = 2.4 mm
therefore, h_o = 470 m (1,539')

Measurement 2 - Measurement of differential parallax using the Michigan Parallax Wedge w/0.1 mm intervals

H = 18.08 km
P = 90.85 mm
dP = 1.7 mm
therefore, h_o = 330 m (1,080')

Measurement 3 - Direct measurement of differnetial parallax between the stack base and top of stack

H = 18.08 km
P = 90.85 mm
dP = 0.2 mm
therefore, h_o = 40 m (133')

Measurement 4 - Direct measurement of differential parallax between the top of the stack and the point in the plume used in Measurement 1

$$H = 18.08 \text{ km}$$
$$P = 90.85 \text{ mm}$$
$$dP = 1.3 \text{ mm}$$
therefore, $h_o = 260$ m (851')

Plume Dispersion Measurements:

Assuming the mass of the plume directly above the source was 300 m (1,000') above the surface, the scale was adjusted to 1:113,928 for measurements of plume dispersion. The working scale of the image was 1:118,000 (Appendix E).
The horizontal dispersion of the plume directly above the stack was estimated to be 1,210 m (3,960').
At a distance of 3.5 km (2.2 mi) from the stack, in a northerly direction, horizontal dispersion was 3.7 km (2.3 mi).
The greatest dispersion visible is 8.0 km (4.9 mi) at 7.9 km (4.9 mi) from the stack. The dispersion rate at this point was equivalent to 1 km per 1 km (1 mi per 1 mi).

Area Coverage Measurements:

An estimate of the areal extent of plume dispersion was based on four random samples with an area grid. Each grid cell represented 0.26 square kilometers (0.1 square miles) at the adjusted scale. The total areal coverage of the dispersed plume was approximately 15.6 square kilometers (6.0 square miles).

Conclusions:

This larger scale photograph, taken by a NASA aircraft, is much more amenable to mensuration techniques. Plume height measurements were checked against base elevations indicated on maps of the area (U.S. Army Topographic Command, 1974) and the stack height determined from an Aeronautical Sectional Chart of the area (NOAA, 1979). According to the chart, the top of the stack is 180 m (600') above ground level. Thus, Measurement 3 is grossly in error, probably due to the inability to identify properly the stack base. Photographic scale is still too small for accurate and reliable measurements with a hand stereoscope. If a stack height of 180 m (600') were added to the estimated height of the plume above the top of the stack (Measurement 4), the height of the plume above ground level at the selected point would be 435 m (1,451'), which compares favorably with Measurement 1, indicating 462 m (1,539'). Thus, it seems reasonable to conclude that relatively reliable measurements could be obtained at this scale with precision instruments. Horizontal dispersion measurements and estimates of areal coverage also could be developed. A principal difficulty is the determination of the precise limits of the plume.

LIST OF REFERENCES

Applegate, Howard G. "Environmental Problems Along The Border." In Border Region Source Book. Edited by Ellwyn R. Stoddard. Department of Sociology, University of Texas at El Paso, Texas. Forth coming.

Applegate, Howard G. Professor of Environmental Engineering, University of Texas at El Paso, Texas. Interview, November 8-9, 1978.

Applegate, Howard G. and Bath, C. Richard, eds. Introduction to Air Pollution Along The United States-Mexico Border [Contaminacion del aire a lo largo de la frontera Mexico-Estadounidense]. El Paso, TX: Texas Western Press, 1974.

Avery, Thomas Eugene. Interpretation of Aerial Photographs. 3rd ed. Minneapolis: Burgess Publishing Company, 1977.

Barr, B. G.; Eagleman, J. R.; Eastmond, R. J.; and Morain, S. A. Atmospheric Pollution And Its Effects In The Kansas City-Topeka Corridor. Lawrence, KA: The University of Kansas, Center for Research, Inc., 1972.

Bath, C. Richard. "Air Pollution Regulation Between the Two Cities." In "Dependence, Interdependence, or Detachment?: Three Case Studies of International Relations Between El Paso, Texas and Cuidad Juarez, Mexico." Paper presented at the Third World Conference, Omaha, Nebraska, October 28, 1977.

Baumol, William J. Environmental Protection, International Spillovers And Trade. Wicksell Lectures 1971. Uppsala: Almqvist and Wiksells Boktrycheri AB, 1971.

Becker, Michael, et. al. "San Diego-Tijuana: Plans Across The Border." Cry California 2, Summer, 1976: pp. 29-35.

Bennett, I. "Frequency of Daily Insolation in Anglo North America During June and December." Solar Energy 11(1), 1967: pp. 41-55.

Bramsen, Christopher Bo. "Transnational Pollution and International Law." In Problems In Transfrontier Pollution, pp. 257-284. Paris: Organisation for Economic Co-Operation and Development, 1974.

Brandli, Henry W.; Ashman, Jerome P.; and Reinke, Donald L. "Pictures of the Month, Texas Dust Moves Into Florida." Monthly Weather Review 105(8), 1977: pp. 1068-1070

Business Week. "A Campaign To Cleanse The Mediterranean." October 31, 1977: pp. 32-33.

Business Week. "International Report: Mexico's Reluctant Oil Boom." January 15, 1979: pp.64-74.

Caldwell, Lynton K. In Defense Of Earth: International Protection Of The Biosphere. Bloomington: Indiana University Press, 1972.

Carter, H. Marshall. "Law Enforcement in the El Paso-Juarez Region: The Crime of the Border." In "Dependence, Interdependence, or Detachment?: Three Case Studies of International Relations Between El Paso, Texas and Cuidad Juarez, Mexico." Paper presented at the Third World Conference, Omaha, Nebraska, October 28, 1977.

Clement, Norris C. "Binational Coordination and Planning on the California-Baja California Border." Occasional Papers No. 5. San Diego: Institute of Public & Urban Affairs Press, 1978.

Cooper, Hal B. H. "Industrial Air Pollution Problems in the United States and Mexico." Paper presented at the Fourth Joint Conference of Mexican and American Engineers, San Antonio, Texas, April 13, 1974.

Davies, J. Clarence, III. The Politics of Pollution. Introduction by Senator Edmund S. Muskie. Preface by J. Clarence Davies, III. Studies in Contemporary American Politics. Edited by Richard E. Morgan. New York: Pegasus; reprint ed., Western Publishing Company, Inc., 1970.

Davila, Guillermo H. "Air Pollution Control on the United States-Mexico Border: International Considerations." In Pollution and International Boundaries, pp. 66-71. Edited by Albert E. Utton. Preface by Albert E. Utton. Albuquerque, NM: University of New Mexico Press, 1973.

Duron, Nicolas Sanchez. English Summary of "Contaminacion del aire por actividades agricolas en Mexico a lo largo de la frontera" [Air Contamination from Agricultural Activities in the Frontier Zone of Mexico]. In Air Pollution Along the United States-Mexico Border [Contaminacion de aire a lo largo de la frontera Mexico-Estadounidense], pp. 22-27. Edited by Howard G. Applegate and C. Richard Bath. El Paso: Texas Western Press, 1974.

Enriquez, Bill. "International Legal Implications of Industrial Development Along the Mexican-U.S. Border." In Pollution and International Boundaries, pp. 88-98. Edited by Albert E Utton. Preface by Albert E. Utton. Albuquerque, NM: University of New Mexico Press, 1973.

Ernst, John A. "Picture of the Month, Fog and Stratus 'Invisible' in Meteorological Satellite Infrared (IR) Imagery." Monthly Weather Review 103(11), 1975: pp. 1024-1026.

Fenneman, Nevin M. "Physical Divisions Of The United States." In cooperation with the Physiographic Committee of the Geological Survey. United States Department of the Interior Geological Survey, 1930.

Gomez, Sabino. Regional Supervisor, Air Quality Control Region 11, Texas Air Control Board, El Paso, Texas. Interview, November 9, 1978.

Greenland, David and De Blij, Harm J. The Earth In Profile: A Physical Geography. San Francisco: Canfield Press, 1977.

Gyulae, Wayne. Planning Director, Southwest Border Region Commission. Pioneer Plaza, Tucson, Arizona. Interview, December 27, 1978.

Handl, Gunther. "Territorial Sovereignty and the Problem of Transnational Pollution." The American Journal of International Law 69, 1975: pp. 50-76.

Hanselka, C. Wayne. "Air Pollution Potential from Agriculture Along the Texas-Mexico Border" (with Resumen). In Air Pollution Along the United States-Mexico Border [Contaminacion del aire a lo largo de la frontera Mexico-Estadounidense], pp. 15-21. Edited by Howard G. Applegate and C. Richard Bath. El Paso: Texas Western Press, 1974.

Heine, Conrad F. and Johnson, F. Douglas. Application Of Aerospace Technology In The Public Interest: Pollution Measurement. Denver: Denver Research Institute, University of Denver, Undated.

Kassander, A. Richard. "A Bit of Smokestack Meteorology." In Proceedings of the Conference on Mining and Ecology in the Arid Environment, March 22 to 27, 1970, Tucson, Arizona, pp. 89-100. Edited by W. C. Peters. Preface by W. C. Peters. Tucson: Department of Mining and Geological Engineering, College of Mines, University of Arizona, 1970.

Kissinger, Secretary Henry A. "The Law of the Sea: A Test of International Cooperation." Speech before the Foreign Policy Association, U.S. Council of the International Chamber of Commerce, and the U.N. Association of the U.S.A., New York City, NY, April 8, 1976.

Kneese, Allen V. Economics and the Environment. Geography and Environmental Studies. Edited by Peter Hall. New York: Penquin Books, 1977.

Kroeck, Dick. Everyone's Space Handbook. Foreword by Robert Rudd. Arcata, CA: Pilot Rock, Inc., 1976.

Latin, Howard A.; Tannehill, Gary W.; and White, Robert E. "Remote Sensing Evidence and Environmental Law." California Law Review 64(6), 1976: pp. 1300-1445.

Lee, D. E. "Base Map For American History." Houghton Mifflin Company, 1938.

Lissitzyn, Oliver James. International Law Today and Tomorrow. Dobbs Ferry, NY: Oceana Publications, 1965.

Ludwig, F. L. and Robinson, Elmer. "Variations in the Size Distribution of Sulfur Containing Compounds in Urban Aerosols." (Atmospheric Environment 2(1), 1968: pp. 13-23). In Meteorological & Geoastrophysical Abstracts 19(7), 1968: p. 1656.

Mech, Stephan J. and Woodruff, Neil P. "Wind Erosion on Irrigated Lands." (In: Hagan, R. M.; Haise, H. R.; and Edminister, T. W., eds., Irrigation of Agricultural Lands. Madison, Wis., American Society of Agronomy, 1967. p. 964-973) (Agronomy, Madison, Wis., No. 11). In Meteorological & Geoastrophysical Abstracts 19(7), 1968: p. 1595.

Mohr, Tillmann. "Picture of the Month, Air Pollution Photographed by Satellite." Monthly Weather Review 99(8), 1971: p. 653.

Muther, Paul S., et. al. "The Stockholm Conference: A Synopsis and Analysis." Stanford Journal Of International Studies 8, Spring, 1973: pp. 31-78.

NASA Langley Research Center. Remote Measurement Of Pollution. Washington, D.C.: Scientific and Technical Information Office, NASA SP-285, 1971.

NOAA (National Oceanic and Atmospheric Administration). Phoenix and El Paso Aeronautical Sectional Charts. Washington, D.C.: NOAA, U.S. Department of Commerce, 1979.

Nostrand, Richard L. "The Hispanic-American Borderland: Delimitation Of An American Culture Region." Annals of the Association of American Geographers 60(4), December, 1970: pp. 638-661.

OECD (Organisation for Economic Co-Operation and Development). Economic Measurement of Pollution. Paris: OECD, 1976.

OECD (Organisation for Economic Co-Operation and Development). Economics of Transfrontier Pollution. Paris: OECD, 1976.

Orton, Robert. "Meteorology Of Air Pollution." Paper presented at The First Binational Symposium on Air Pollution held on the Campus of The University of Texas at El Paso [Memoria del Primer Simposio-Binacional Sobre Contaminacion Atmosferica al lo largo de lo frontera Mexico-Estados Unidos], September 27-28, 1973.

Parmenter, Frances C. "Picture of the Month, Smoke from Slash Burning Operations." Monthly Weather Review 99(9), 1971: pp. 684-685.

Paul, Charles K. "The USAID Program in Remote Sensing." In Proceedings On The Second Conference On The Economics Of Remote Sensing, Janary 15-18, 1978, pp. 11-19. Edited by K. B. Craib and T. H. Wat-

Paul, Charles K. (cont.)
kins. San Jose, CA: Department of Economics, San Jose State University, 1978.

Price, Thomas J. "International Transportation and Integration: Evidence for the El Paso/Juarez Microcosm." In "Dependence, Interdependence, or Detachment?: Three Case Studies of International Relations Between El Paso, Texas and Cuidad Juarez, Mexico." Paper presented at the Third World Conference, Omaha, Nebraska, October 28, 1977.

Reeves, Robert G., gen. ed. Mannual of Remote Sensing. 2 Vols. Foreword by Joe E. Steakley. Preface by Robert G. Reeves. Falls Church, VA: American Society of Photogrammetry, 1975. Vol II: Interpretation and Applications. Preface by Leonard W. Bowden, ed.

Ross, John C. "Environmental Law: Air Quality Litigation in the El Paso-Juarez Area." In Pollution and International Boundaries, pp. 72-84. Edited by Albert E. Utton. Preface by Albert E. Utton. Albuquerque, NM: University of New Mexico Press, 1973.

Russel, Woody. "Vehicular Air Pollution In The United States Along The Border" (with Resumen). In Air Pollution Along the United States-Mexico Border [Contaminacion del aire a lo largo de la frontera Mexico-Estadoundense], pp. 42-49. Edited by Howard G. Applegate and C. Richard Bath. El Paso: Texas Western Press, 1974.

Sadeh, W. Z. and Ruff, J. F. "Remote Sensing of Pollutants by Means of Stereo Analysis." In Pollution Engineering and Scientific Solutions, Proceedings of the First International Meeting of the Society of Engineering Sciences held in Tel Aviv, Israel, June 12-17, 1972, pp. 453-468. Edited by Euval S. Barrekette. Preface by Euval S. Barrekette and Ervin Y. Rodin. New York: Plenum Press, 1973.

Schmidt, Robert H., Jr. "Physical Characteristics of the Border." In Border Region Source Book. Edited by Ellwyn R. Stoddard. Department of Sociology, University of Texas at El Paso, Texas. Forthcoming.

Schmidt, Robert H., Jr. "Climate Of The Borderlands." Professor of Geography, Department of Geology, University of Texas at El Paso, Texas. Forthcoming.

Schmidt, Robert H., Jr. Economic Characteristics of the Border Region." In Border Region Source Book. Edited by Ellwyn R. Stoddard. Department of Sociology, University of Texas at El Paso, Texas. Forthcoming.

Serwer, Daniel. International Cooperation For Pollution Control. UNITAR Research Reports, No. 9. New York: United Nations Institute for Training and Research, 1972.

Shenk, William E. and Curran, Robert J. "The Detection of Dust Storms Over Land and Water With Satellite Visible and Infrared Measurements." Monthly Weather Review 102(12), 1974: pp. 830-837.

Shoults, Jim M. "Air Pollution from United States Industrial Sources Along the United States-Mexico Border" (with Resumen). In Air Pollution Along the United States-Mexico Border [Contaminacion del aire a lo largo de la frontera Mexico-Estadounidense], pp. 28-33. Edited by Howard G. Applegate and C. Richard Bath. El Paso: Texas Western Press, 1974.

Steila, Donald. The Geography of Soils. Englewood Cliffs, NJ: Prentice-Hall, Inc., 1976.

Stein, Robert E. "Legal and Institutional Aspects of Transfrontier Pollution Control." In Problems In Transfrontier Pollution, pp. 285-298. Paris: Organisation for Economic Co-Operation and Development, 1974.

Stoddard, Ellwyn R., ed. "The Status of U.S.-Mexico Borderlands Studies: A Symposium." Social Sciences Journal 12/13, October 1975/ January 1976: pp. 1-112.

Stoddard, Ellwyn R. "Impact of Mexican Migration on the U.S.-Mexico Border." Paper presented at the International Conference on Contemporary Mexico, Cuidad Juarez, Chihuahua, Mexico, September 13, 1978.

Telloz, Joaquin. "Sources of Atmospheric Pollution at the U.S.-Mexican Border." In Pollution and International Boundaries, pp. 85-87. Edited by Albert E. Utton. Preface by Albert E. Utton. Albuquerque, NM: University of New Mexico Press, 1973.

Thrower, Norman J. W. "Annals Map Supplement Number Twelve: Land Use In The Southwestern United States - From Gemini And Apollo Imagery." Annals of the Association of American Geographers 60 (1), June, 1970: pp. 208-209.

U.S. Army Topographic Command (BEEE). Clifton, Arizona; New Mexico, NI 12-9, Series V502, 1954. Revised by U.S. Geological Survey, 1971. Reston, VA: Interior-Geological Survey, 1974.

Utton, Albert E. Preface to Pollution and International Boundaries. Edited by Albert E. Utton. Albuquerque, NM: University of New Mexico Press, 1973.

Wauchope, Robert, gen. ed. Handbook of Middle American Indians, 16 vols. Austin, TX: University of Texas Press, 1964. "Surface Configuration and Associated Geology of Middle America," Robert C. West. In Vol. 1: Natural Environment and Early Culture, pp. 33-83. Edited by Robert C. West.

Wauchope, Robert, gen. ed. Handbook of Middle American Indians, 16 vols. Austin, TX: University of Texas Press, 1964. "Weather and Climate of Mexico and Central America," Jorge A. Vivó Escoto. In Vol. 1: Natural Environment and Early Culture, pp. 187-215. Edited by Robert C. West.

Wauchope, Robert, gen. ed. Handbook of Middle American Indians, 16 vols. Austin, TX: University of Texas Press, 1964. "Natural Vegetation of Middle America," Philip L. Wagner. In Vol 1: Natural Environment and Early Culture, pp. 216-264. Edited by Robert C. West.

Wauchope, Robert, gen. ed. Handbook of Middle American Indians. 16 vols. Austin, TX: University of Texas Press, 1964. "The Soils of Middle America and their Relation to Indian Peoples and Cultures," Rayfred L. Stevens. In Vol 1: Natural Environment and Early Culture, pp. 265-315. Edited by Robert C. West.

Weber, Ing. Luis H. Barojas. English Summary of "Contaminacion del aire por vehiculos en Mexico a lo largo de la fronter" [Contamination of the Air by Vehicles in the Frontier Zone of Mexico]. In Air Pollution Along the United States-Mexico Border [Contaminacion del aire a lo largo de la frontera Mexico-Estadounidense], pp. 50-57. Edited by Howard G. Applegate and C. Richard Bath. El Paso: Texas Western Press, 1974.

West, Steven L.; Miller, Paul R.; and Larsh, Robert N. "Color Photos Detect Smog Injury To Forest Trees." Journal of Forestry 68(9), 1970.

Wobber, Frank S. "An Appraisal of the Contribution of Orbital Photography to Problems of Environmental Quality." ASP-SPSE Proceedings, 1969.