TROPICAL ATMOSPHERIC ACIDITY : WHAT NOW AND WHERE TO?

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Our current understanding of acidification in tropical countries is briefly reviewed, and set within the context given by the growing recognition that the tropics are of great importance for the atmosphere globally as a major source of reactive atmospheric chemicals. Key issues are identified, and specific scientific goals for study of tropical atmospheric acidity are outlined, with special reference to relevant parts of the International Global Atmospheric Chemistry (IGAC) program.

INTRODUCTION

Acidification of the atmosphere and acidic deposition to the earth's surface are well known phenomena in Europe and North America, as are the range of adverse environmental consequences thought to result (Goreham, 1989; Cowling, 1989; Falkengren-Grerup, 1989; Likens, 1989; Tamm, 1989). Much effort has been expended in these two major, industrialised regions over the last two decades in order to define the extent, causes and consequences of this atmospheric acidification and resultant deposition : it is now very clear that activities such as generation of electricity from fossil fuels, use of liquid fuels for transportation, and smelting/refinement of metals are major sources of the atmospheric oxides of nitrogen and sulfur that are involved (Mohnēn, 1988; Galloway, 1989; Schwartz, 1989). The emission of these gases on a large scale is a natural consequence of the energy-intensive styles of living enjoyed by many of theindustrialised nations. The occurrence of acidification as a very serious environmental problem is now seen to be an equally predictable consequence (Mohnen, 1988; Galloway, 1989; Rodhe, 1989; Schwartz, 1989). Table 1 gives an insight into the extent which human activities have perturbed the global sulfur and nitrogen cycles.

The question of the extent of acidification in other parts of the globe naturally follows (Rodhe and Herrera, 1988; Galloway, 1989; Rodhe, 1989). However, regions outside Europe and North America have received little scientific attention until recently, so answers have been unsatisfactory or unavailable. For this reason the SCOPE project, Acidification in Tropical Countries, was initiated in 1984, culminating

TABLE 1: Estimated Source Strengths for the Global Atmospheric Sulfur and Nitrogen Cycles [Summarised from Moller (1983) and Liu and Cicerone (1984)] [The figures shown are uncertain, and must be considered to be indicative only; units are Tg/yr]

Source	S	N
Anthropogenic	75	25
Natural	72	30

in a workshop in Caracas in 1986. The outcome of the project was publication of the book SCOPE 36 (Rodhe and Herrera, 1988), containing a range of papers summarising what was known about acidification in several tropical countries. It was clear that the question of acidification was very relevant to the tropics—some areas of acidification were identified (for example southwestern China) as were some areas for which the soil/water system was assessed as highly susceptible to acidification. However, a common feature of all the areas investigated was a profound lack of relevant data outside the industrialised countries of Europe and North America.

The purpose here is to continue the focus on acidification in tropical countries initiated by the SCOPE project. The tropical region contains a large population and is the area of the globe where changes in population, energy usage, industrial capacity and agricultural practices are currently most rapid. Table 2 gives an indication of the importance of the tropical region as an area of human habitation, and underscores

TABLE 2: List of Cities between 30°N and 30°S with Population Exceeding 4 Million

Country	City	Population (millions)	Date
Mexico	Mexico	18.0	1986
China	Chongqing	13.9	1983
	Guangzhao	6.8	1983
	Nanjing	4.6	1983
UAR	Cairo	12.0	1984
India	Calcutta	9.2	1981
	Bombay	8.2	1981
	Delhi	5.7	1981
	Madras	4.3	1981
Brazil	Sao Paolo	7.0	1980
	Rio de Janiero	5.1	1980
Indonesia	Jakarta	6.5	1980
Pakistan	Karachi	5.1	1981
Hong Kong	Hong Kong	5.0	1981
Colombia	Bogota	4.3	1982
Peru	Lima	4.2	1981
Nigeria	Lagos	4.0	1980

the expectation that rapid industrialisation and development of tropical regions must lead to large increases in anthropogenic atmospheric emissions of all types. It is essential that the present levels and future likelihood of acidification be assessed so that tropical countries may avoid the acidification problems now so evident at the northern mid-latitudes. What follows is a brief review of the current understanding about acidification in tropical countries, leading on to discussion of areas where further work is required.

INITIAL PERSPECTIVES

The region under consideration encompasses a considerable range of environments, ranging from the borders of the continental, mid-latitude temperate regions, to sub-tropical and tropical deserts, to humid, equatorial-continental, and maritime (island) regions. Thus overall the tropics cannot be considered to be in any sense homogeneous, and we must expect to confront atmospheric chemical questions differently in differing environments within the region. Furthermore, given the peculiarities of the region scientific understanding gained already in the well-studied mid- to high-latitude areas of the northern hemisphere cannot be assumed a priority to be directly transportable to tropical regions.

The need for a broad perspective when considering the tropics can be illustrated by highlighting just a few features peculiar to particular parts of the region. First, we can note examples of particular geographical features, one being that active vulcanism can be found for example in the Indonesian archipelago, which clearly may have local atmospheric significance. Another geographical feature is that acid-sulfate soils occur naturally in the tropics (for example 40% of the world's acid-sulfate soils occur in the Asian region), so that acidification phenomena such as aluminium toxicity leading to fish kills are already experienced in fish farms where pond walls leach high levels of acidity, sulfate and aluminium when subject to heavy rain (Singh, 1982).

Meteorologically, in addition to temperate climates at the mid-latitude extremes the region also includes areas of the wet-dry tropics and humid tropics, plus the ITCZ (Inter-Tropical Convergence Zone). Clearly atmospheric composition may well differ according to whether air masses originate in the northern or southern sides of the ITCZ, or whether rain falls on practically every day, or does not occur at all for months at a time. At some times of the year in some locations the winds have remarkable persistence in direction (e.g. the various trade wind regimes) which may profoundly influence such things as source-receptor relationships.

Given large populations in many countries, the anthropogenic contribution to air chemistry in the tropics must be expected to be very significant, particularly in certain regions, for exmple southwestern China where acidic deposition has been well documented (Rodhe and Herrera, 1988; Zhao *et al.*, 1988; see Table 3). About half the global population resides in the Asian region, for example, and anthropogenic pressure on atmospheric composition and chemistry is likely to increase rapidly with time in regions such as this as population growth rate overall is 3 times that of the US/Europe/Western-OECD countries.

TABLE 3: Precipitation pH Data (Monthly Means) from Four Locations in Guizhou Province, China, in 1984 [Data from Zhao and Xiong, 1988]

Month	Guiyang (urban)	Luizhang (rural)	Keyang (rural)	Shisun (rural)
Jan.	3.9	4.3	4.3	5.9
Feb.	4.0	4.4	4.1	4.3
March	3.8	4.4	4.2	3.9
April	4.1	4.2	4.6	4.7
May	4.0	4.5	4.6	4.3
June	4.5	4.9	5.4	5.1
July	4.5	4.9	5.1	4.7
Aug.	4.1	4.6	4.5	4.5
Sep.	3.7	4.8	4.5	4.4
Oct.	3.8	4.3	4.6	4.5
Nov.	3.7	5.4	4.5	4.7
Dec.	3.4	5.4	4.3	4.7

Compounding increased pressure on the atmospheric environment from population growth, we can expect additional increased pressure from changes in lifestyle, as less developed tropical countries seek economic development and increased standards of living (see Hameed and Dignon, 1988; Dignon and Hameed, 1989, for perspectives on increasing energy use and emissions from the tropics in comparison with other regions). For example tropical Australia as an example of a developed country has per capita atmospheric emission of reactive nitrogen in the form of NO_x from controlled combustion sources (largely power generation and transport) of 14.5 kg/y. For three representative countries of southeast Asia (Thailand, Malaysia and Vietnam) the figure is an order of magnitude less at an average of 1.4 kg/y, similar to India at 1.1 kg/y (Galbally and Gillett, 1988).

Finally, pressure on the environment may be compounded yet again if fertilizer usage in Asia generally increases towards that of developed countries. Again in per capita terms, fertilizer usage as N stands at 59 kg/y for tropical Australia, an order of magnitude above the figures of 4.4 and 5.7 kg/y respectively for the three southeast Asian countries and for India (Galbally and Gillett, 1988).

ATMOSPHERIC COMPOSITION : WHAT WE KNOW

Consider first the local scale/acute-level of pollution, in other words the major urban/industrial centres and their immediate vicinities. The tropical region can probably be considered to have at least some of these localities moderately well-served by observation networks, data bases and quantitative or semi-quantitative understanding of local atmospheric chemical processes : urban smog is a well known phenomenon in a number of places in the region. Bangkok would be an example of such a site. Much of the data gathered by the Environmental Protection authorities or equivalent bodies in such places does not find its way quickly into the international scientific literature, but with appropriate personal contacts can be accessed and perhaps could provide a useful perspective on photochemical pollution in cities across the whole region. It is important that this information be accessed, as photochemical conversion of the acid precursors NO_x and SO_2 is likely to be an important acid production pathway in the tropical atmosphere. As well, however, there also must be many centres with little or no information yet available on even the local scale atmospheric composition.

At the other extreme, that is from the mesoscale up to the scale of the whole region, not very much is known at a quantitative level. However, we can make some general observations.

Tropical regions are characterised by agricultural activities and practices such as rice farming and biomass burning, which provide sources of CH_4, NMHC, CO, NO_x and N_2O to the atmosphere [see 24 papers in *J. Geophys.* (D), Feb. 1988; Clairac *et al.*, 1988; Suman, 1988; Talbot *et al.*, 1988]. In some regions, such as parts of China (see Table 4), large quantities of fuel are also burned in numerous, widely distributed, low level sources giving consequently large area source strengths for SO_2 (Rodhe and Herrera, 1988; Zhao *et al.*, 1988). If the source strengths for all these activities are large enough, then the lower troposphere in such locations may be an important source region for greenhouse gases and acid precursors, as well as exhibiting a high potential for photochemical reactions involving ozone, NO_x and NMHC.

TABLE 4: Energy Produced from Coal in China [from Zhao and Xiong, 1988] [Total energy in tonnes-coal-equivalent]

Year	Total energy	% from coal
1953	54	94.3
1962	165	89.2
1970	293	80.9
1975	454	71.8
1982	619	73.9

In a number of areas the tropics include extensive regions of tropical rainforests where active exchange of gases and aerosols between the atmosphere and the biosphere takes place as a natural process (Ayers and Gillett, 1988a; Zimmerman *et al.*, 1988; Clairac *et al.*, 1988). Further poleward the desert areas, central Asia for example, are a source of soil dust particles, which are transported by prevailing westerlies at certain times to places far afield such as the northwest Pacific region. These soil dust particles also participate in rainwater chemistry along the way, and are thought to be major contributors to the alkaline rainfall that has been observed in parts of India, Bangladesh and perhaps Thailand (Huebert *et al.*, 1988; Khemani *et al.*, 1989 a, b; Mahadevan *et al.*, 1989; Varma, 1989), as may be inferred from Table 5.

TABLE 5: Data from Ten BAPMoN Precipitation Composition Stations in India and one in Thailand; Monthly Volume-weighted Means [Source: World Meteorological Organisation]

BAPMoN site	Mean pH	Length of record
Allahabad	6.82	10/06/77 - 27/12/85
Jodhpur	7.25	01/05/74 - 08/10/85
Kodaikanal	6.02	04/02/77 - 01/12/85
Minicoy	6.50	01/09/77 - 03/12/85
Mohanbari	6.11	01/10/74 - 19/12/85
Nagpur	6.12	05/06/77 - 16/12/85
Pune (weekly)	6.60	12/02/84 - 10/11/85
Port Blair	6.12	27/02/75 - 01/11/85
Srinagar	7.06	05/01/77 - 08/12/85
Visakhapatnam	6.42	03/05/77 - 19/11/85
Kosichang	6.54	15/11/83 - 31/07/85

There are also some highlights from a few individual studies. Examples are the fact that routine measurements of greenhouse gases are now underway at several sites in the tropics, and at least at one tropical site in northern Australia the strong seasonal influence of biomass burning on CO appears in the data record. Other data are available to show that at least in specific instances tropical fires are also strong sources of C_2-C_5 hydrocarbons (Ayers and Gillett, 1988a and refs therein), while tropical vegetation is a strong source of the very reactive hydrocarbon isoprene (Ayers and Gillett, 1988a; Zimmerman *et al.*, 1988; Jacob and Wofsey, 1988).

There are many examples of rainwater studies from the Indian sub-continent (Khemani *et al.*, 1989a,b; Mahadevan *et al.*, 1989; Varma, 1989) consistently showing rainfall to have relatively alkaline pH values of 6 or above are common), while at the other extreme independent studies in northern Australia yield acidic rain, with pH values at the start of the wet season near or below 4 (Galloway *et al.*, 1982; Ayers and Gillett, 1988b). However, in these cases sulfate and nitrate concentrations are each only a few μ equivalents/L, with simple organic acids contributing most of the acidity. The sources of these organic acids remain uncertain (see also Sanhueza *et al.*, 1989).

There have also been a number of studies in southeast Asia looking at the cycling of N through fertilised and unfertilised rice paddies. These have demonstrated clearly the emission of reactive gases from these systems, including large losses of ammonia in Chinese experiments where ammonium bicarbonate is used as fertilizer.

Finally we can note again from Chinese studies that the widespread combustion of coal in low level sources leads to very high atmospheric levels of SO_2, sulfate and ammonium. In the southwest of the country where alkaline substances are not so prevalent in the atmosphere, rainfall acidity is very high, and corrosion, vegetation damage and soil acidification have all been documented (Rodhe and Herrera, 1988; Zhao *et al.*, 1988; Huebert *et al.*, 1989).

KEY ISSUES

Since data on the spatial distributions and temporal variations of trace gases and aerosols are so limited in the tropics a wide variety of key issues may be identified. The emphasis here is on atmospheric acidity, however all the key atmospheric chemistry issues are inter-related, so discussions such as that here need to explicitly acknowledge this fact by at least mentioning all the issues. Indeed the justification for choosing particular issues above others, or for addressing them at all, must be discussed so that priorities may be arrived at and clearly articulated. We simply begin the discussion here by suggesting that the possible influence of atmospheric chemistry in the tropical regions on (a) climate (via effects on radiative transfer); and (b) biological productivity (via direct effects on vegetation of atmospheric oxidants, etc. or via acidic deposition) underpin the following suggested list of key issues.

Thus we suggest that in the tropics there is a lack of quantitative knowledge or understanding as to:

(i) Urban/industrial source strengths of SO_2, NO_x and NMHC;

(ii) Biomass burning source strengths of SO_2, NO_x and NMHC, as well as a range of other gases (e.g. NH_3, CO, aldehydes and acids, etc.) and aerosols (e.g. elemental carbon, etc.);

(iii) Natural emissions of S, N, C and hydrocarbon species;

(iv) The effect on atmospheric composition of agricultural practices (and changes in these practices), including wetland farming, fertiliser use and deforestation;

(v) Regional scale atmospheric photochemistry in the light of (i)-(iv);

(vi) Influence on climate (greenhouse gases, etc.) in the light of (i)-(iv);

(vii) Meteorological control on atmospheric chemistry (note that tropical meteorology itself remains an understudied subject), including such things as consequences of seasonality in persistence of wind flow, and occurrence of precipitation; the role played by strong vertical transport associated with strong convective activity in and outside clouds in parts of the region;

(viii) The role played by tropical oceans as sources and recipients of atmospheric constituents (for example: Is there any connection between the enormous biological productivity of the region's extensive, tropical coral reefs and the atmosphere?); and

(ix) Acidic deposition and the current state of environmental acidification throughout the different parts of the region.

FUTURE DIRECTIONS

Having set the scene and put the question of tropical atmospheric acidity within the wider context of tropical atmospheric chemistry in general, the focus is now returned specifically to the question of what can be done immediately to further our knowledge of current levels of tropical atmospheric acidity and their causes. Four specific directions are proposed as follows:

(i) Development of a comprehensive anthropogenic emissions inventory for NO_x, SO_2 and NMHC covering all countries in the region, just has been carried out for CO_2 on the global scale by Marland *et al.* (1985);

(ii) Detailed experiments leading to a comprehensive understanding of the role played by biomass burning as a source of reactive trace gases and aerosol;

(iii) Observational and modelling studies of photochemical processes and reactivity in tropical air; and

(iv) observational studies (a comprehensive, tropical precipitation chemistry network) leading to a regional workshop on acidification, perhaps modelled on the framework provided by the global SCOPE Acidification in Tropical Countries Project.

The implementation of these suggestions will be best carried out by international co-operation between scientists from the countries in tropical regions, in partnership with experts from the industrialised countries. An example of a concrete framework for achieving such co-operation is given by the International Global Atmospheric Chemistry Program, although other avenues (e.g. via SCOPE or other such sources of international support, or via bilateral/multilateral scientific agreements) should also be pursued.

A summary of the appropriate parts of the IGAC Program is particularly illustrative as that Program is right now at the initiation stage. The relevant parts of IGAC are the two major foci : Natural Variability and Anthropogenic Perturbations of the Marine Atmosphere, and Natural Variability and Anthropogenic Perturbations of Tropical Atmospheric Chemistry.

The first of these foci has as its third project the East Asian/North Pacific Regional Study (APARE) for which the goals are: to assess the transport and chemical transformation of air pollutants over the East Asian region both over land and over the north-western Pacific Ocean; and to determine the deposition of primary and secondary pollutants (sulfate, nitrate and organics) in the East Asian region. While much of this project would be concerned with the northern mid-latitudes, its coverage of southern China and Taiwan ensures that it also has relevance to the question of tropical atmospheric acidity.

The second of these major foci, Natural Variability and Anthropogenic Perturbations of Tropical Atmospheric Chemistry, more obviously deals with issues related to tropical acidity. All four projects under this heading are relevant to the acidification question, particularly the second. The projects and goals are:

Project 1 : Biosphere-Atmosphere Trace Gas Exchange in the Tropics (BATGE)

Goals

- To determine the fluxes of chemicals between representative tropical biological environments (biomes) and the troposphere.
- To determine the factors that control these fluxes.
- To develop the ability to predict the impact on these fluxes of both climatic and land use changes.

Project 2 : Deposition of Biogeochemically Important Trace Species (DEBITS)

Goals

- To determine the rates of deposition from the atmosphere of a range of biogeochemically important chemical species.
- To identify the factors which regulate these deposition fluxes.

Project 3 : Impact of Tropical Biomass Burning on the World Atmosphere

Goals

- Characterise the fluxes of chemically and radiatively important species (especially carbon monoxide, nitrogen oxides, methane and other hydrocarbons, sulfur compounds, and cloud condensation nuclei) from biomass burning into the global atmosphere.
- Assess the consequences of biomass burning emissions on chemical and physical climate. Particular emphasis will be placed on the photochemical formation of tropospheric ozone in the tropics and on other perturbations of the oxidative characteristics of the atmosphere.

Project 4 : Chemical Transformation in Tropical Atmospheres and their Interaction with the Biosphere

Goal

- To understand the photochemistry of the tropical atmosphere and how this is affected by changing gaseous emissions from changing industrial and agricultural developments.

Project 2 has as its initial activity an experiment on the Composition and Acidity of South-East Asian Precipitation (CAAP). This experiment will be based on a precipitation chemistry network in the SE Asian region, from India through China, to south of Australia and the Pacific islands.

The goals of CAAP are:

- To quantify the wet deposition component of the atmospheric cycles of nutrient/reactive species (S, N, C, P and sea-salt species).
- To assess the current state of rainwater acidity across the region and identify the acid/base species involved.

The first year of CAAP will involve identification of appropriate scientists and sites in the Asian region. Emphasis will be placed on sharing or otherwise co-operating with existing facilities in many countries, in particular sites already part of the World Meteorological Organization BAPMoN network, and other sites run by local institutions for nutrient accession studies. Other avenues for support will also be explored; however a strong commitment to utilising existing local resources is intended.

Clearly CAAP or other studies like it, along with additional work of the types outlined in the IGAC projects, is essential if the current extent and future possibility of significant acidification in the tropics is to be assessed.

CONCLUSIONS

Tropical acidification has been identified, especially by the SCOPE project Acidification in Tropical Countries, as a potentially serious consequence of changing patterns of industrialisation and land use in tropical regions. However, the information necessary to assess the current levels of environmental acidification across the whole of the tropics is lacking, although some specific regions have been the subject of intense work in the last few years.

As the importance of tropical emissions and tropical atmospheric chemistry for global atmospheric chemistry has been realised in recent times, it has become clear that considerable effort is needed to provide an understanding of factors affecting the chemistry of the tropical atmosphere at the quantitative level now available for the atmosphere at mid-latitudes. Studies of tropical atmospheric acidity and environmental acidification sit properly within this perspective. Concrete proposals for action in this area are needed now, and possibilities have been illustrated here with reference to appropriate parts of the International Global Atmospheric Chemistry Program, which is currently being implemented.

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