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Intercontinental Transport of Air Pollution: Will Emerging Science Lead to a New Hemispheric Treaty?

TRACEY HOLLOWAY*

Earth Institute, Columbia University, 2910 Broadway, New York, New York 10027

ARLENE FIORE

Department of Earth and Planetary Sciences, Harvard University, 20 Oxford Street, Cambridge, Massachusetts 02138

MEREDITH GALANTER HASTINGS

Department of Geosciences, Princeton University, B-78 Guyot Hall, Princeton, New Jersey 08544

We examine the emergence of InterContinental Transport (ICT) of air pollution on the agendas of the air quality and climate communities and consider the potential for a new treaty on hemispheric air pollution. ICT is the flow of air pollutants from a source continent (e.g., North America) to a receptor continent (e.g., Europe). ICT of air pollutants occurs through two mechanisms: (i) episodic advection and (ii) increasing the global background, which enhances surface concentrations. We outline the current scientific evidence for ICT of aerosols and ozone, both of which contribute to air pollution and radiative forcing. The growing body of scientific evidence for ICT suggests that a hemispheric-scale treaty to reduce air pollutant concentrations may be appropriate to address climate and air quality concerns simultaneously. Such a treaty could pave the way for future climate agreements.

Introduction

Past observations and modeling studies have established that one nation's pollutant emissions may affect the air quality of downwind regions (e.g., refs *1*−*3*). The late 1990s, however, brought a renewed focus on the potential role of air pollution transport between continents and its implications for air pollution mitigation efforts through traditional domestic controls. Awareness has grown in the climate, air quality, and policy communities that air pollutants are both transported on a hemispheric scale and climatically important. Here we examine the emergence of InterContinental Transport (ICT) of air pollution on the agendas of the air quality and climate communities and consider the potential for a new treaty on hemispheric air pollution.

Observations provide a clear indication that pollution emitted at the surface on one continent can contribute to ground-level pollution on downwind continents. Modeling studies of this intercontinental flow of pollutants suggest that it may be appropriate to manage air quality on a hemispheric scale. A treaty such as the 1979 Convention on Long-Range Transboundary Air Pollution (LRTAP) offers one mechanism to manage this air pollution transport between countries. If such a treaty were used to regulate non-carbon dioxide (CO_2) greenhouse gases and black carbon along with other species of interest for health and agriculture, it could pave the way for future CO_2 regulations.

Research on ICT is an ongoing example of feedbacks between scientific knowledge and policy awareness in which the science and policy communities influence one another. Atmospheric chemistry and climate researchers have convened in workshops to address the scientific questions of hemispheric air pollution transport and evaluate the growing evidence for ICT from both measurement and modeling studies. These workshops, outlined in Tables 1 and 2, are influencing the policy community, raising awareness of the issues, and increasing the priority of research funding for global scale air pollution research. To improve this process, both the science and the policy communities should create opportunities to foster the interaction needed for both communities to make progress in this area.

In March 2000, the International Global Atmospheric Chemistry Program (IGAC) launched the Intercontinental Transport and Chemical Transformation (ICTC) research activity, bringing together international measurement campaigns and modeling efforts contributing to ICT understanding. Later, U.S. EPA-sponsored meetings continued the objective of advancing ICT science while beginning to fulfill U.S. obligations under the most recent LRTAP protocol. Article 8 of the 1999 Gothenburg Protocol emphasizes the "improvement of the scientific understanding of the long-term fate of emissions and ... the potential for intercontinental flow of pollutants" (*4*). The ICT workshops represent the first cases of U.S. leadership on LRTAP-related science.

This paper is intended to introduce the recent scientific evidence for intercontinental air pollution to the policy community, with a particular emphasis on ozone (O_3) and aerosols and to suggest the policy applications of this evidence to the scientific community. As such, we do not offer here a detailed treatment of the policy issues surrounding intercontinental air pollution transport. Rather, we highlight the opportunity for joint advancement of science and policy developments related to ICT.

Evidence for ICT of Air Pollution

Overview. ICT is the flow of air pollutants from a source continent (e.g., North America) to a receptor continent (e.g., Europe), schematically shown in Figure 1. Here, we outline recent advances in our understanding of ICT from analyses of observations and models and discuss whether the evidence indicates that a global air pollution treaty could be supported by the science to date.

The distance over which ICT occurs is highly dependent upon meteorological conditions (e.g., wind speed, precipitation, frontal activity) and the properties of the pollutant itself (e.g., solubility, reactivity). Pollutants transported in the free troposphere will typically be carried further and faster than pollutants in the boundary layer due to stronger winds and fewer loss mechanisms. ICT of air pollutants occurs through two mechanisms: (i) episodic advection and (ii) increasing the global background, which enhances surface concentrations. We focus here on aerosols and O_3 to illustrate these mechanisms. Following the example set by the U.S. EPA for O_3 (*5*), we define background concentrations in surface air as those that would exist in the absence of anthropogenic emissions on the receptor continent. We mention here briefly the general emission sources associated with aerosol and O_3 production. For a more thorough discussion, the reader is

* Corresponding author present address: Gaylord Nelson Institute for Environmental Studies, University of Wisconsin—Madison, 1710 University Avenue, Madison, WI 53726; phone: (608)262-5356; fax: (608)265-4113; e-mail: taholloway@wisc.edu.

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TABLE 1. Policy-Relevant ICT Science Meetings

meeting	date	location	focus	sponsors
Intercontinental Transport and Chemical Transformation	March 2000	Tokyo, Japan	define objectives of multi-year research activity	International Global Atmospheric Chemistry Program (IGAC), National Oceanic and Atmospheric Administration (NOAA)
First International Conference on Trans-Pacific Transport of Atmospheric Contaminants	July 2000	Seattle, WA	trans-Pacific air pollution	Nautilus Institute and U.S. EPA
Workshop on Photooxidants, Particles, and Haze across the Arctic and North Atlantic: Transport Observations and Models	July 2001	Palisades, NY	trans-Atlantic and Arctic air pollution	EPA and European Monitoring and Evaluation Programme (EMEP)
Trends and Intercontinental Transport of Photo-oxidants, Particles and Their Precursors across the Northern Hemisphere: Observations, Models, Policy Implications	October 2002	Bad Breisig, Germany	ICT throughout the Northern Hemisphere, O_3, PM, mercury, and POPs	German Ministry of the Enviroment (BMU/UBA), EMEP, and U.S. EPA

TABLE 2. Interdisciplinary Climate–Air Pollution Meetings

meeting	date	location	focus	sponsors
Workshop on Global Climate and Air Quality	December 2001	Research Triangle Park, NC	climate and air pollution feedbacks	U.S. EPA
Air Pollution as a Climate Forcing Workshop, Honolulu, Hawaii	April/May 2002	Honolulu, HI	atmospheric chemistry, climate, public health, and energy issues of aerosols and non-CO_2 greenhouse gases	NASA, NOAA, NSF, Hewlett Foundation, California Air Resources Board, California Energy Commission, International Pacific Research Center, and East–West Center

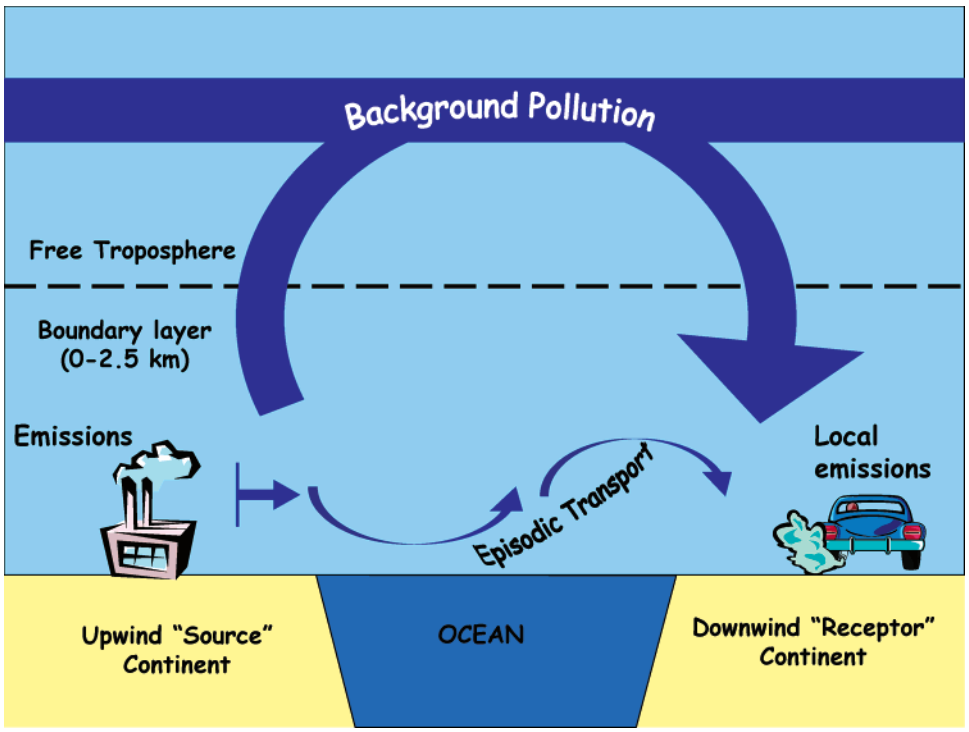

FIGURE 1. Cartoon schematic of intercontinental air pollution transport. Emissions from the upwind "source" continent are advected to the downwind "receptor" continent through episodic transport events and/or by enhancing the global background pollution concentration. Emissions may be mixed vertically into the free troposphere for rapid long-range transport or transported within the boundary layer. The degree of photochemical processing and deposition that occurs during transport controls the air pollutant concentrations that are ultimately detected on the receptor continent.

referred to appropriate chapters of the 2001 Report of the Intergovernmental Panel on Climate Change (*6*, *7*).

Aerosols, small particles suspended in the air, may be comprised of a range of different components, including black carbon (BC), organic carbon (OC), soil dust, sea salt, sulfate, and/or nitrate. The makeup of an aerosol is determined by its emission source as well as chemical reactions within the atmosphere. Directly emitted (primary) aerosols are released

TABLE 3. Surface Aerosol Enhancements at Northern Mid-Latitudes from Intercontinental Transport of Pollution

source region	receptor region	aerosol type	aerosol enhancement (μg m^{-3} unless stated otherwise)	method of estimate[a]	ref
Asia (mean)	U.S., yearly means	organic C	0.013 (western U.S.) 0.007 (eastern U.S)	sensitivity simulation with no anthropogenic emissions from source region	*44*
		elemental C	0.005 (western U.S.) 0.003 (eastern U.S.)		
Asia (events)	northwestern U.S., spring 1997	all	~200 particles cm^{-3}	obsd enhancements at Cheeka Peak Observatory in air masses of Asian origin	*45*
Asia (dust event)	western U.S., April 1998	all	40−63 (PM_{10}), 4−11 ($PM_{2.5}$)	obsd enhancements at a number of monitoring stations	*46*, *47*
Asia (dust event)	Lower Fraser Valley, BC, Canada, Apr 1998	all	18−26 (PM_{10})	attribution based on elemental composition at a umber of monitoring stations	*48*
Asia (dust event)	northwestern U.S., Apr 1993	all organic C elemental C	4−9 (PM_{10}) 0.4−0.7 0.03−0.1	obsd enhancements at three monitoring stations	*49*
Asia	western U.S., spring, summer, fall 1989−1999	all	0.2−1 ($PM_{2.5}$), rare exceedances of 5	attribution based on matching Asian source type (diagnosed from Apr 1998 events) via cluster analysis at a number of monitoring stations	*10*
Sahara (mean)	Florida, U.S.	mineral dust	0.8−16.3 (monthly mean; max in July) 10−100 (daily max during episodic events in summer)	long-term observations in Miami	*50*
Sahara (mean)	eastern U. S. (east of 106° W)	mineral dust	1 (annual mean), 4−8 (July)	attribution based upon Al/Si ratios at monitoring stations	*51*
Sahara (dust events)	Israel, Mar 1998	all	1000−1900 (PM_{10})	observations in Tel Aviv	*52*

[a] All estimates are from observations except for those from ref *44*.

by fossil fuel burning (BC and OC), biomass burning (BC and OC), ocean wave breaking (sea salt), and wind erosion (mineral dust). Aerosols may also be produced by heterogeneous chemical reactions (secondary aerosols). Precursors to secondary aerosols include non-methane hydrocarbons (NMVOC), sulfur dioxide (SO_2), and nitrogen oxides (NO_x). Aerosols can be produced from secondary oxidation in transit or be washed out of the atmosphere during precipitation events.

Tropospheric O_3 is not emitted directly but instead forms through a complex series of reactions that involve methane (CH_4), NMVOC, and carbon monoxide (CO) in the presence of NO_x and sunlight. These O_3 chemical precursors are emitted both from human activities such as fossil fuel combustion, industrial processes, agricultural practices, and biomass burning and from natural processes such as vegetation, wildfires, lightning, and microbial activity in soils. A direct source of O_3 to the troposphere is transport from the stratosphere, which naturally contains much higher O_3 concentrations from photolysis of oxygen molecules. O_3 produced in the boundary layer from precursors emitted at the surface can be directly transported to another continent. In addition, O_3 precursors can be exported and contribute to O_3 formation downwind of the region of emission. This chemical production in the free troposphere may be more important in contributing to the hemispheric background than direct export of O_3 out of the continental boundary layer (e.g., ref *8*). Ozone can also be removed from the atmosphere during transport, primarily via photolysis or dry deposition.

Both aerosols and O_3 have lifetimes of about 1 week, long enough to be transported over the 5−10-d trajectory from Asia to the United States (*9*) as well as the shorter distances across the Atlantic or Eurasian continent. The emission strength, transport duration, degree of photochemical processing, and wet and dry deposition during transit will ultimately determine the aerosol and O_3 concentrations that reach surface air over the receptor continent. Tables 3 and 4 summarize past studies documenting surface aerosol and O_3 enhancements at northern mid-latitudes from ICT. The aerosol studies (Table 3) have typically focused on episodic transport events that produce peak levels in measured surface concentrations on the receptor continent. VanCuren and Cahill (*10*), however, have recently shown that ICT of aerosols does occur persistently from Asia to North America at small background levels (Table 3). ICT of O_3 primarily occurs through increases in background concentrations that are difficult to detect as events on the receptor continent.

Observational Evidence. Evidence for aerosol transport to North America is summarized in Table 3. Observational aerosol ICT studies have focused on transport from Asia to western North America and from the Sahara to Israel and the eastern United States. In addition, ICT of other species has been detected in North America: pesticides in air masses from Asia in the Canadian Rocky Mountains, ecological indicators of possible trans-Pacific transport of POPs, and heavy metals in the Pacific Northwest and Arctic (ref *11* and references therein).

The observational evidence for ICT of air pollution from North America to Europe is less compelling. Observational

TABLE 4. Surface Ozone Enhancements at Northern Mid-Latitudes from Intercontinental Transport of Pollution

source region	receptor region	O_3 enhancement (ppbv)	method of estimate[a]	ref
Asia	northwestern U.S., spring	4 (mean), 7.5 (max)	sensitivity simulation with no anthropogenic emissions from source region	*53*
Asia	western U. S., spring	3−10 (range during Asian pollution events)	sensitivity simulation with no surface emissions from source region	*28*
Asia	Europe, U. S.	1.0 (U.S.), 0.8 (Europe)	annual mean enhancements from sensitivity simulations with 10% increases in emissions from source region; results were multiplied by 10 to estimate total effect of current anthropogenic emissions from source continent	*25*
Europe	Asia, U.S.	1.1 (Asia), 0.9 (U.S.)		
U.S.	Europe, Asia	2.0 (Europe), 0.8 (Asia)		
Asia + Europe	U. S., summer	4−7 (typical afternoon range), 14 (max)	sensitivity simulation with no anthropogenic NO_x and NMVOC emissions from source region	*54*
Europe	East Asia, spring	3 (daytime mean)	Ibid.	*29*
North America	Europe, summer	2−4 (daytime mean), 5−10 (events)	Ibid.	*29*
Europe	East Siberia	2 (annual), 3 (spring−summer)	difference between median obsd O_3 concentrations in 1997−1999 for air masses originating from Europe vs from Siberia and high latitudes	*55*
North America	Mace Head, Ireland	0.4 (winter), 0.2 (spring), −0.3 (summer), −0.9 (fall)	mean obsd difference in O_3 concentrations in 1990−1994 for air masses originating from U.S. and Canada vs from Iceland and Greenland	*13*
North America	Europe, yearly mean	18 (Atlantic fringes), 10−15 (central Europe)	ozone produced in tropospheric column over source region	*56*
Asia	Europe, yearly mean	9 (Atlantic fringes), 5−7 (central Europe)		
background (anthropogenic methane)	U.S., summer	6 (afternoon mean)	sensitivity simulation with anthropogenic CH_4 emissions reduced globally by 50%; O_3 enhancements from that simulation were doubled to estimate total enhancement from anthropogenic CH_4	*36*
background (1980−1998)	U.S.	3−5 (spring, fall)	obsd trend in lower quantiles of O_3 frequency distribution at rural sites	*20*
background (1984−2002)	U. S., west coast	10	obsd trend at surface sites and from aircraft missions (1984−2002)	57
Asia (future)	U.S.	2−6 (western U.S), 1−3 (eastern U.S.) highest in Apr−Jun	sensitivity simulation with tripled Asian NO_x and NMVOC emissions	*23*
Asia (future)	western U.S., spring	30−40 (max during Asian pollution events)	sensitivity simulation with quadrupled Asian emissions	*28*

[a] All estimates are from global 3-D models except those of refs *13*, *20*, *55*, and *57*.

evidence of North American emissions reaching the upper troposphere over Europe is well-documented (*12*). However, surface observations are inconclusive in detecting a significant North American contribution (e.g., ref *13*), except in the case of Canadian forest fires (*14*).

Limited measurements in Asia impede similar analyses of the contribution of European and North American emissions on air quality in Asia (*15*). Interest in Asia on assessing transboundary air pollution within the region has led to the establishment of two regional air pollution monitoring networks: Acid Deposition Monitoring Network in East Asia (EANET), parallel in structure and purpose to the LRTAP-sponsored monitoring program in Europe (EMEP, European Monitoring and Evaluation Program) (*16*), as well as a network for baseline studies of air pollution in South Asia under the Malé Declaration (*17*).

It is difficult to discern ICT influence on O_3 measurements since detection at the receptor continent reflects the source region, chemical transformations, mixing with other air parcels, and removal processes that may have occurred during transport. Observation-based studies of O_3, its precursors, and other tracers of continental emissions provide useful information on background levels as well as evidence of intercontinental influence on these concentrations (*2*, *13*, *18*−*21*). In fact, O_3 observations at mountain sites in Europe indicate that human activities over the past century have at least doubled tropospheric O_3 concentrations (*22*).

While these results suggest a problem of potential concern to domestic air quality in the United States and Europe as well as a global concern about Arctic haze, the observational evidence alone is not sufficient to determine source attribution. Such a determination would be an important precursor to emissions-limiting agreements. Although aerosol composition can be used to identify remote sources, the events with the most impact—Asian dust storms and Canadian forest fires—are not subject to direct controls. The evidence for direct ICT of pollution from Asia to North America is limited and from North America to Europe is inconclusive. However, when observations are considered in concert with simulations from computer models of ICT, the possible benefits of regulation may be assessed.

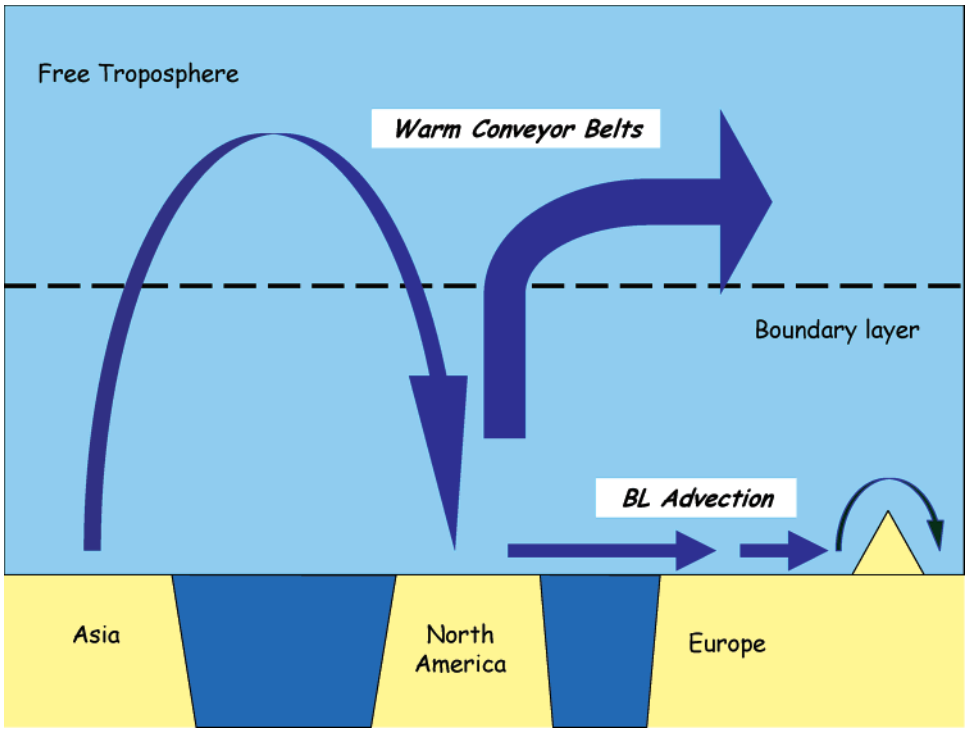

FIGURE 2. Cartoon schematic of specific intercontinental transport mechanisms, including warm conveyor belts (WCBs; warm moist air "belts" ahead of a cold front transport air from the boundary layer to the free troposphere). The trans-Pacific WCB carries air from the Asian boundary layer and subsides at the surface of North America. The trans-Atlantic WCB produces elevated levels of pollution in the free troposphere over Europe. Boundary layer advection is an important mechanism for trans-Atlantic ICT and the primary mechanism for Europe-to-Asia pollution transport.

Model Evidence. Current mathematical mathematical models of tropospheric chemistry are powerful tools for diagnosing the chemical and transport processes governing present and future distributions of air pollutants. The impact of future increases in hemispheric O_3 background on U.S. air quality was underscored by Jacob et al. (*23*), who calculated that a tripling of anthropogenic emissions from Asia (then projected from 1985 to 2010) could increase monthly mean surface O_3 over the United States by 1−6 ppbv (minimum in the east, maximum in the west in the spring). While the magnitude of this increase appears small, it would more than offset the benefits of 25% reductions in domestic anthropogenic emissions in the western United States (*23*). More recently, a modeling study by Li et al. (*24*) attributed 20% of violations of the 8-h average, 55 ppbv European Council O_3 standard to anthropogenic emissions from North America.

In addition to quantifying the magnitude of ICT transport of O_3 as summarized in Table 4, recent global modeling studies have advanced the understanding of the mechanisms for episodic ICT transport, emphasizing that the balance between various meteorological and chemical processes governing ICT of pollution varies considerably with season and region (e.g., ref 25). Lagrangian particle dispersion models have also been used to identify the various pathways and time scales by which pollution from each continent is exported (e.g., ref *15*).

Global modeling studies have shown that Asian pollution can be exported in the boundary layer (strongest at 30−45° N) and to the free troposphere by convection or by orographic forcing (*26*, *27*). Maximum ICT of Asian pollution tends to occur in spring when cold fronts sweep across eastern Asia, venting pollutants to the lower free troposphere where they are transported across the Pacific before subsiding to the surface over North America (see Figure 2) (*15*, *26*−*29*). The importance of transport by this warm conveyor belt mechanism was recently confirmed by extensive sampling during the TRACE-P aircraft mission off the Asian Pacific rim (*30*). The monsoon system largely controls the seasonal variability in the mechanisms for pollution transport in Asia (e.g., refs *27* and *31*).

Warm conveyor belts also carry pollution from the U.S. boundary layer to the upper troposphere over Europe (*32*, *25*). Global modeling studies have shown that another important pathway for ICT of pollution from North America to Europe is direct advection of pollution across the Atlantic in the boundary layer (*24*, *25*). Pollution from the United States is also lofted to the free troposphere by deep convection, particularly in summer over the southeastern and central states (*25*, *33*).

Export of pollutants from Europe is of greatest concern for the control of haze in the Arctic (ref *15* and references therein). Boundary layer advection is the typical pathway for export of European pollution, which predominantly flows north to the Arctic. Unlike North America and Asia, Europe lacks downwind storm tracks and the associated warm conveyor belts that efficiently transport pollutants from Asia to North America and from North America to Europe. Maximum European pollution influence on Asia occurs in winter and spring when pollution is transported around the Siberian anticyclone typically in the boundary layer (*27*, *29*, *34*).

Air Pollution Impacts on Climate

The case for controlling non-CO_2 greenhouse gases and BC aerosol (soot) was first presented by Hansen et al. (*35*). They argue that CO_2 accounts for less than half of the current radiative forcing and that a control strategy focused on CH_4, CFCs, O_3, and BC aerosols could offer a more tractable, short-term solution to slowing global warming. Although CH_4 is not currently regulated as an air pollutant, its role in controlling background O_3 in surface air (*36*) suggests that policies to reduce methane emissions may be appropriate under an air pollution agreement.

TABLE 5. LRTAP Timeline[a]

year	protocol	summary	signed	ratified
1979	Geneva Convention on Long-Range Transboundary Air Pollution (LRTAP)	initial framework convention	33	49
1984	EMEP Protocol, Geneva	established cost-sharing of program to collect emission data, measurements, and develop models	22	40
1985	First Sulfur Protocol, Helsinki	30% cuts in SO_2 emissions (or "transboundary fluxes")	19	22
1988	NO_x Protocol, Sofia	freeze NO_x emissions (or transboundary fluxes)	25	28
1991	VOC Protocol, Geneva	30% cuts in non-methane VOC emissions (or transboundary fluxes)	23	21
1994	Second Sulfur Protocol, Oslo	differentiated SO_2 emissions ceilings	28	25
1998	Heavy Metals Protocol, Aarhus	cadmium, lead, and mercury reduced below 1990 (or alternate 1985−1995 years)	36	14
1998	POPs Protocol, Aarhus	16 substances addressed: 8 banned, others limited to restricted use and/or scheduled for future elimination	36	15
1999	Multi-Pollutant Protocol, Gothenburg	differentiated 2010 emissions ceilings set for SO_2, NO_x, VOC, and ammonia	31	4
200?	Particulate Matter and Precursors?	?	?	?

[a] Information on signatories and ratification current as of June 23, 2003 (*4*).

The influence of aerosols on climate is an active area of research, as large uncertainties remain in quantifying the distribution and sources of all species. Identifying specific aerosol components is critical to link particulate matter pollution with climate goals. The sign of radiative forcing by aerosols is highly dependent upon chemical composition. Sulfate aerosol, the product of SO_2 emissions, exerts a negative radiative forcing whereas BC is an important warming constituent. All aerosol types contribute "indirect" forcing to the climate by serving as nuclei for cloud condensation, but the reflectivity of the resulting clouds depends in part on the type of aerosols around which they formed.

Because it would build on nations' domestic goals of improving air quality and reducing greenhouse forcing species simultaneously, a hemispheric treaty aimed at reducing intercontinental air pollution transport may serve as a precursor to climate commitments by the United States, China, and other major emitters in opposition of the current Kyoto Protocol. Hansen et al. (*35*) acknowledge the political benefits of their alternative scenario noting, "[A] focus on air pollution has practical benefits that unite the interests of developed and developing countries". Furthermore, they note that for ambitious emission reduction policies, such as those needed to control methane emissions, "global implementation of appropriate practices requires international cooperation" (*35*). While adoption of this alternative scenario (or a similar strategy) would present challenges to the international science and policy communities, the control of air pollution to meet climate goals offers a politically attractive approach to reduce greenhouse warming in the short term. Regulation could take shape without immediate reform of the domestic or international energy economy. Furthermore, energy savings implemented to achieve air quality goals could have the win/win affect of reducing CO_2 emissions as well.

Coordinating Global Air Quality and Climate Decision-Making

In this section, we sketch out a potential coordinated air quality and climate management regime. While a detailed analysis of such a framework is beyond the scope of this paper, we feel it is not too soon to begin dialogue on the possibilities for a hemispheric treaty addressing intercontinental air pollution transport and its impacts.

A global air pollution treaty would primarily pertain to countries in the mid-latitude Northern Hemisphere, where dominant winds from the west produce a northern mid-latitude pollution belt that traverses the entire extratropical Northern Hemisphere (Figures 1 and 2). Agreement may be facilitated as each country stands to benefit from upstream emission reductions. However, some countries will likely benefit more than others.

Because benefits from emissions reduction will be distributed unevenly, assigning specific emission reduction targets is not a straightforward task. A quantitative policy assessment would identify international air quality objectives and estimate intercontinental source−receptor relationships. A range of implementation mechanisms, such as uniform emission reduction guidelines or emission permit trading, would be evaluated, and each potential mechanism would be weighed in terms of ability to meet air quality objectives, cost, and political feasibility. Informed policy cannot move forward without quantitative policy analysis. However, often such analysis follows the emergence of an environmental issue on the political agenda. We intend here to place emerging scientific issues in a policy context and consider an overall structure that may be appropriate for an ICT treaty.

In considering the structure of a global air quality accord, an obvious starting point is the LRTAP Convention, which was initially drafted to address transboundary acid deposition in Europe. It has since been amended to cover a broad range of pollutants (see Table 5), and participants include countries from both Western and Eastern Europe as well as the United States and Canada. Broadly described, LRTAP is based on voluntary compliance with emission limits alongside ongoing reporting of emissions and ambient pollution concentrations (*37*).

The treaty fulfilled expectations of environmental protection primarily through indirect mechanisms. It put acidification on the national agendas of member countries; it increased national capacities for environmental science; and it provided a forum for ongoing regional negotiation, thus increasing political stability and encouraging stronger national emission reduction policies (*37*). Recent LRTAP protocols, particularly the Second Sulfur Protocol and the Gothenburg Protocol, were shaped by least-cost analyses from integrated assessment models, especially the RAINS model (*38*, *39*).

The key strength today of LRTAP is its broad geographic scope, including non-EU parties and stretching across the Atlantic. As such, LRTAP is well-poised to be a template for a flexible ICT treaty. As a European/North American treaty alone, however, LRTAP faces an uncertain future without some sort of incorporation into a larger scale accord. Where the treaty fulfilled multiple political and environmental objectives throughout the 1980s and early 1990s, its duties

are becoming partially redundant with the environmental directives of the EU, which include enforcement mechanisms.

Although the United States is currently party to LRTAP, it would have a greater incentive to participate in an agreement promoting emissions reductions in developing Asia, especially China. Heightened concern for pollution inflow from Asia is one major policy outcome of the emerging science−policy dialogue on intercontinental air pollution transport. China and other Asian countries may view the accord as a means of gaining international recognition for pollution emissions reductions already underway or planned, following the example of past sulfur dioxide emission reductions in China. China is already taking active steps to reduce domestic air pollution (e.g., ref *40*), and SO_2 emissions in China have been declining through the late 1990s (*41*, *42*). SO_2 exerts a cooling influence on the climate, so its regulation to date does not directly support the climate incentives of a potential treaty; however, the trends exhibited in SO_2 emission reduction suggest that China may be open to other policies to reduce local pollution impacts.

Given that the pollutant emissions fulfill domestic priorities in China and other Asian countries, leveraging these reductions to bolster national image could be a powerful incentive. It has been argued that the desire to project a favorable international image is a very real factor in determining a country's negotiating position, termed "tote board diplomacy" (*37*). A cooperative structure arguably has the greatest chance of success if it enhances China's national image and offers all parties an opportunity to pursue their environmental objectives.

Discussion

Research on ICT of air pollution in the Northern Hemisphere has recently been advanced by both atmospheric chemistry and climate communities. Overlapping interests in the science and policy communities on ICT are reflected in recent conference participation, new directions in ICT research, and science funding patterns. The convergence of interest around ICT of air pollution by these traditionally separate communities suggests that it is not too soon to discuss whether a new hemispheric treaty is appropriate for jointly managing air quality and greenhouse warming.

If a hemispheric or global air pollution treaty addressing pollutants contributing to ICT were implemented on a step-by-step basis, it could capitalize on characteristics contributing to the success of the trans-Atlantic LRTAP treaty. Initial efforts should be directed toward pollutants such as BC aerosols and O_3, which pose risks for health on local and regional scales, while contributing to large-scale climate forcing. As subsequent pollutants are regulated under such a framework, CO_2 could be addressed in a consistent manner. Thus, we suggest that multi-lateral air pollution regulation could pave the way for successful efforts to mitigate global climate change.

The momentum for growing interest in the connections between air quality and climate interest in ICT may be attributed in part to feedbacks between science and policy communities: the science community directs more research to hot questions needing further investigation; the policy community directs more funds to science identified as policy-relevant. Just as research output may be characterized as policy-relevant, the intersecting policy is often science-relevant. Advances in each field contribute to the evolution of the other. Within an ongoing science−policy framework, these feedbacks have been termed dependable dynamism (*43*), as exemplified by the interplay between science and policy during recent protocols to LRTAP.

Interactions among sectors of the scientific community and the policy stakeholders encourage developments within and across the separate disciplines. As such, we suggest that patterns of interdisciplinary exchange and agenda setting in ICT should be encouraged. An understanding of hemispheric air pollution and the consequences of its regulation will benefit by the continued interactions of the policy and science communities.

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Literature Cited

(1) Andreae, M. O.; Berresheim, H.; Andreae, T. W.; Krtiz, M. A.; Bates, T. S.; Merrill, J. T. *J. Atmos. Chem.* **1988**, *6*, 149.
(2) Parrish, D. D.; Hahn, C. J.; Williams, E. J.; Norton, R. B.; Fehsenfeld, F. C. *J. Geophys. Res.* **1992**, *97*, 15,883.
(3) Levy, H., II; Moxim, W. J. *Nature* **1987**, *328*, 414.
(4) United Nations Economic Commission for Europe. *1979 Convention on Long-Range Transboundary Air Pollution*; http://www.unece.org/env/lrtap (accessed 6/23/03).
(5) United States Environmental Protection Agency. Air Quality Criteria for Ozone and Related Photochemical Oxidants. Research Triangle Park, NC, manuscript in preparation.
(6) Penner, J. E. In *Climate Change 2001*: *The Scientific Basis*; Houghton, J. T., et al., Eds.; Cambridge University Press: Cambridge, U.K., 2001; Chapter 5.
(7) Prather, M. J.; Ehhalt, D. In *Climate Change 2001*: *The Scientific Basis*; Houghton, J. T., et al., Eds.; Cambridge University Press: Cambridge, U.K., 2001; Chapter 4.
(8) Liang, J.; Horowitz, L. W.; Jacob, D. J.; Wang, Y.; Fiore, A. M.; Logan, J. A.; Gardner, G. A.; Munger, J. W. *J. Geophys Res.* **1998**, *103*, 13,435.
(9) Wilkening, K. E.; Barrie, L. A.; Engle, M. *Science* **2000**, *290*, 65.
(10) VanCuren, R. A.; Cahill, T. A., *J. Geophys. Res.* **2002**, DOI: 10.1029/2002JD002204.
(11) Wilkening, K. E. *Water, Air Soil Pollut.* **2001**, *130*, 1825.
(12) Stohl, A.; Trickl, T. *IGACtivities Newsl.* **2001**, 24.
(13) Derwent, R. G.; Simmonds, P. G.; Seuring, S.; Dimmer, C. *Atmos. Environ.* **1998**, *32*, 145.
(14) Forster, C.; Wandinger, U.; Wotawa, G.; James, P.; Mattis, I.; Althausen, D.; Simmonds, P.; O'Doherty, S.; Jennings, S. G.; Kleefeld, C.; Schneider, J.; Trickl, T.; Kreipl, S.; Jäger, H.; Stohl, A. *J. Geophys. Res.* **2001**, *106*, 22,887.
(15) Stohl, A.; Eckhardt, S.; Forster, C.; James, P.; Spichtinger, N. *J. Geophys. Res.* **2002**, *107*, 4684; doi: 10.1029/2001JD001396.
(16) *Report of the Third Session of the Intergovernmental Meeting on the Acid Deposition Monitoring Network in East Asia.* EANET (Acid Deposition Monitoring Network in East Asia): Chiang Mai, Thailand, 2001; EANET/IG 3/12.
(17) *Implementation of the Malé Declaration on Control and Prevention of Air Pollution and Its Likely Transboundary Effects for South Asia, Phase I. Part I: Guidelines for the Preparation of Baseline Studies;* United Nations Environmental Programme: 1999.
(18) Trainer, M.; Parrish, D. D.; Buhr, M. P.; Norton, R. B.; Fehsenfeld, F. C.; Anlauf, K. G.; Bottenheim, J. W.; Tang, Y. Z.; Wiebe, H. A.; Roberts, J. M.; Tanner, R. L.; Newman, L.; Bowersox, V. C.; Meagher, J. B.; Olszyna, K. J.; Rodgers, M. O.; Want, T.; Berresheim, H.; Demerjian, K. L.; Roychowdhury, U. K. *J. Geophys. Res.* **1993**, *98*, 2917.
(19) Hirsch, A. I.; Munger, J. W.; Jacob, D. J.; Horowitz, L. W.; Goldstein, A. H. *J. Geophys. Res.* **1996**, *101*, 12,659.
(20) Lin, C. Y.; Jacob, D. J.; Munger, J. W.; Fiore, A. M. *Geophys. Res. Lett.* **2000**, *27*, 3465.
(21) Lefohn, A. S.; Oltmans, S. J.; Dann, T.; Singh, H. B. *J. Geophys. Res.* **2001**, *106*, 9945.
(22) Marenco, A.; Gouget, H.; Nedelec, P.; Pages, J. P.; Karcher, F. *J. Geophys. Res.* **1994**, *99*, 16,617.
(23) Jacob, D. J.; Logan, J. A.; Murti, P. P. *Geophys. Res. Lett.* **1999**, *26*, 2175.

(24) Li, Q.; Jacob, D. J.; Bey, I.; Palmer, P. I.; Duncan, B. N.; Field, B. D.; Martin, R. V.; Fiore, A. M.; Yantosca, R. M.; Parrish, D. D.; Simmonds, P. G.; Oltmans, S. J. *J. Geophys. Res.* **2002**, DOI: 10.1029/2001JD001422.
(25) Wild, O.; Akimoto, H. *J. Geophys. Res.* **2001**, *106*, 27,729.
(26) Bey, I.; Jacob, D. J.; Logan, J. A.; Yantosca, R. M. *J. Geophys. Res.* **2001**, *106*, 23,097.
(27) Liu, H.; Jacob, D. J.; Bey, I.; Yantosca, R. M.; Duncan, B. N.; Sachse, G. W., *J. Geophys. Res.* (in press).
(28) Yienger, J. J.; Galanter, M.; Holloway, T. A.; Phadnis, M. J.; Guttikunda, S. K.; Carmichael, G. R.; Moxim, W. J.; Levy, H., II. *J. Geophys. Res.* **2000**, *105*, 26,931.
(29) Liu, H.; Jacob, D. J.; Chan, L. Y.; Oltmans, S. J.; Bey, I.; Yantosca, R. M.; Harris, J. M.; Duncan, B. N.; Martin, R. V. *J. Geophys. Res.* **2002**, DOI: 10.1029/2001JD002005.
(30) Jacob, D. J.; Crawford, J. H.; Kleb, M. M.; Connors, V. E.; Bendura, R. J.; Raper, J. L.; Sachse, G. W.; Gille, J. C.; Emmons, L. *J. Geophys. Res.* (in press).
(31) de Laat, A. T. J.; Lelieveld, J. *J. Geophys. Res.* **2002**, DOI: 10.1029/2001JD001483.
(32) Cooper, O. R.; Moody, J. L.; Parrish, D. D.; Trainer, M.; Ryerson, T. B.; Holloway, J. S.; Hubler, G.; Fehsenfeld, F. C.; Evans, M. J. *J. Geophys. Res.* **2002**, DOI: 10.1029/2001JD000901.
(33) Horowitz, L. W.; Liang, J.; Gardner, G. M.; Jacob, D. J. *J. Geophys. Res.* **1998**, *103*, 13,451.
(34) Newell, R. E.; Evans, M. J. *Geophys. Res. Lett.* **2000**, *27*, 2509.
(35) Hansen, J.; Sato, M.; Ruedy, R.; Lacis, A.; Oinas, V. *Proc. Natl. Acad. Sci.* **2000**, *97*, 9875.
(36) Fiore, A. M.; Jacob, D. J.; Field, B. D.; Streets, D. G.; Fernandes, S. D.; Jang, C. *Geophys. Res. Lett.* **2002**, DOI: 10.1029/2002GL015601.
(37) Levy, M. A. In *Institutions for the Earth*; Haas, P. M., Keohane, R. O., Levy, M. A., Eds.; MIT Press: Cambridge, MA, 1993; p 75.
(38) Hordijk, L. *Water, Air, Soil Pollut.* **1995**, *85*, 249.
(39) Holloway, T. Ph.D. Dissertation, Princeton University, 2001.
(40) Pu, Y.; Shah, J. J.; Streets, D. G. *EM The Urban Environment*; June 2002, 32.
(41) Streets, D. G.; Tsai, N. Y.; Akimoto, H.; Oka, K. *Atmos. Environ.* **2000**, *34*, 4413.
(42) Carmichael, G. R.; Streets, D. G.; Calori, G.; Amann, M.; Jacobson, M. Z.; Hansen, J.; Ueda, H. *Environ. Sci. Technol.* **2002**, *36*, 4706.
(43) Eckley, N. *Global Environ. Change* **2002**, *12*, 15.
(44) Park, R. J.; Jacob, D. J.; Chin M.; Martin, R. V. *J. Geophys. Res.* **2003**, *108*, 4355; doi: 10.1029/2002JD003190.
(45) Jaffe, D.; Anderson, T.; Covert, D.; Kotchenruther, R.; Trost, B.; Danielson, J.; Simpson, W.; Berntsen, T.; Kalsdottir, S.; Blake, D.; Harris, J.; Carmichael, G.; Uno, I. *Geophys. Res. Lett.* **1999**, *26*, 711.
(46) Husar, R. B.; Tratt, D. M.; Schichtel, B. A.; Falke, S. R.; Li, F.; Jaffe, D.; Gassó, S.; Gill, T.; Laulainen, N. S.; Lu, F.; Reheis, M. C.; Chun, Y.; Westphal, D.; Holben, B. N.; Gueymard, C.; McKendry, I.; Kuring, N.; Feldman, G. C.; McClain, C.; Frouin, R. J.; Merrill, J.; DuBois, D.; Vignola, F.; Murayama, T.; Nickovic, S.; Wilson, W. E.; Sassen, K.; Sugimoto, N.; Malm, W. C. *J. Geophys. Res.* **2001**, *106*, 18,317.
(47) Vaughan, J. K.; Claiborn, C.; Finn, D. *J. Geophys. Res.* **2001**, *106*, 18,381.
(48) McKendry, I. G.; Hacker, J. P.; Stull, R.; Sakiyam, S.; Mignacca, D.; Reid, K. *J. Geophys. Res.* **2001**, *106*, 18,361.
(49) Jaffe, D.; McKendry, I.; Anderson, T.; Price, H. *Atmos. Environ.* **2003**, *37*, 391.
(50) Prospero, J. M. *J. Geophys. Res.* **1999**, *104*, 15,917.
(51) Husar, R. B. Presented at the U.S. EPA/EMEP Workshop on Hemispheric Pollution, Bad Breisig, Germany, October 2002.
(52) Alpert, P.; Ganor, E. *J. Geophys. Res.* **2001**, *106*, 18,275.
(53) Berntsen, T. K.; Karlsdottir, S.; Jaffe, D. A. *Geophys. Res. Lett.* **1999**, *26*, 2171.
(54) Fiore, A. M.; Jacob, D. J.; Bey, I.; Yantosca, R. M.; Field, B. D.; Fusco, A. C.; Wilkinson, J. G. *J. Geophys. Res.* **2002**, *107*, DOI: 10.1029/2001JD000982.
(55) Pochanart, P.; Akimoto, H.; Kajii, Y.; Potemkin, V. M.; Khodzher, T. V. *J. Geophys. Res.* **2003**, *108*, 10.1029/2001JD001412.
(56) Derwent, R. G.; Stevenson, D. S.; Collins, W. J.; Johnson, C. E. Presented at the U.S. EPA/EMEP Workshop on Hemispheric Pollution, Bad Breisig, Germany, October 2002.
(57) Jaffe, D.; Price, H.; Parrish, D.; Goldstein, A.; Harris, J. *Geophys. Res. Lett.* **2003**, *30*, 1613; doi: 10.1029/2003GL017024.

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