PERGAMON

Atmospheric Environment 34 (2000) 4425–4439

ATMOSPHERIC ENVIRONMENT

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The growing contribution of sulfur emissions from ships in Asian waters, 1988–1995

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Received 21 October 1999; accepted 6 March 2000

Abstract

International shipping is a major source of sulfur emissions in Asia. Because the fuel oil used by ships is high in sulfur, the resulting emissions of SO_2 are large and contribute as much as 20% to the atmospheric loading in the vicinity of ports and heavily traveled waterways. Because of the rapid growth of Asian economies in the 1980s and early 1990s, it is estimated that shipping trade grew by an average of 5.4% per year between 1988 and 1995; in particular, crude oil shipments to Asian countries other than Japan grew by an average of 11.4% per year. The emissions of SO_2 from shipping are estimated to have grown by 5.9% per year between 1988 and 1995, rising from 545 Gg in 1988 to 817 Gg in 1995. This study uses the ATMOS atmospheric transport and deposition model to study the effects of these emissions, both in absolute terms and relative to land-based emissions, on wet and dry deposition of sulfur. Southeast Asia is most heavily affected by emissions from ships, particularly Sumatra, peninsular Malaysia, and Singapore, which routinely receive in excess of 10% of their deposition from ships. A strong seasonal component is also observed, with large areas of Southeast Asia and coastal Japan receiving sulfur deposition that exceeds $10\,\mathrm{mg\,S\,m^{-2}\,season^{-1}}$. Deposition is at least 25% higher in summer and fall than in winter and spring. Peak values of $25–50\,\mathrm{mg\,S\,m^{-2}\,season^{-1}}$ are calculated for winter in the Strait of Malacca. This work suggests a need to introduce policies to reduce the sulfur content of marine fuels or otherwise reduce emissions of SO_2 from ships in Asian waters.

Keywords: Sulfur; Shipping; Emissions; Asia; Wet deposition; Dry deposition

1. Introduction

In the mid-1990s, concern arose over the high rate of emissions of sulfur dioxide (SO_2) from shipping in international waters (Corbett and Fischbeck, 1997). Traditionally, the cheapest grades of residual fuel oil, containing as much as 5% sulfur, have been used to fuel the commercial fleets of the world. The average sulfur content of marine fuel oils worldwide is about 2.8%. Ship emissions affect global and regional background air pollution and can be significant contributors to local pollution in areas of high shipping volume along congested waterways. In addition, ship emissions of sulfur have recently been identified as important contributors to sulfur cycling and radiative forcing over the oceans (Capaldo et al., 1999). However, only in the last few years have any policies been proposed to reduce shipping emissions.

In 1997, the International Convention for the Prevention of Pollution from Ships (commonly known as the MARPOL Convention) approved a global cap of 4.5% on the sulfur content of marine fuel oils. This is generally considered to be a weak provision, however, as only about 0.02% of marine fuel oils exceeded 4.5% sulfur in 1996 (Cullen, 1997). Stronger measures were instituted for Europe. The Convention declared the Baltic Sea an "Emission Control Area", with a requirement to limit the sulfur content of marine fuel oils to 1.5% or to apply exhaust-gas emission controls. Pressure to declare the

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1352-2310/00/$ - see front matter
PII: S1352-2310(00)00175-8

entire North Sea an Emission Control Area was unsuccessful. The new regulation must be ratified by several countries that control international merchant shipping fleets (such as Liberia and Panama) before it can take effect. Subsequently, Sweden introduced a sulfur charge of 0.9 krona (about 11 cents US) per gross ton for ships burning oil of sulfur content greater than 0.5% (passenger and railway vessels) or 1.0% (all other vessels) each time they enter a Swedish port (Elvingson, 1998).

A detailed examination by the European Monitoring and Evaluation Programme (EMEP) of SO_2 emissions from shipping in the North Sea revealed that annual emissions were more than 1 million metric tonnes in the early 1990s, which represented 3.5% of the total European SO_2 emissions in 1995 (Tsyro and Berge, 1997). Marine emissions were demonstrated to be responsible for more than 10% of the total sulfur deposition in southern England, northern France, and coastal regions of Belgium, the Netherlands, Denmark, and southern Norway.

Despite this rising awareness in Europe of the dangers of SO_2 emissions from international shipping, little action was taken in the period 1988–1995 to reduce SO_2 emissions in Asian waters. In an earlier paper (Streets et al., 1997), we reported the high levels of SO_2 from shipping in Asian waters in 1988 and the particularly high levels in the Strait of Malacca. Ecosystems in Sumatra and neighboring land areas were believed to be at risk of damage from acid deposition due to sulfur emissions from shipping. Since that time, we have become aware that shipping traffic increased dramatically in the early 1990s. We therefore decided to investigate the growth in shipping traffic that occurred from 1988 to the year of latest record, 1995, in order to estimate the increases in SO_2 emissions and the changed patterns of sulfur deposition to surrounding water and land areas. Several enhancements to the earlier estimation method were made at the same time.

2. Approach

The approach used in this paper is the same as that reported previously (Streets et al., 1997), with certain elaborations and expansions. The earlier version of the Asian shipping inventory examined 1988 shipments of the two major types of commodities, crude oil and dry bulk goods. The sulfur content of bunker oil burned in shipping fleets in Asia in the late 1980s was assumed to be 3%. All sulfur in the oil was assumed to be released as SO_2. Emissions of SO_2 were calculated on an annual basis for each $1^\circ \times 1^\circ$ grid cell corresponding to the particular routes and commodity volumes. Routes within grid cells were approximated to either diagonal, horizontal, or vertical transects. Emissions in each grid cell were summed for each of the routes. Six major routes within Asia were examined in this earlier work, as well as 12 of the major ports. The inventory was assembled as part of the RAINS-ASIA project, a comprehensive examination of SO_2 emissions in Asia from all sources (Arndt et al., 1997; Streets et al., 1999).

In this present work, the method of calculating emissions from individual vessels is unchanged, but several enhancements are made to the number and routes of vessels. First, the quantities of crude oil and dry bulk shipments are expanded to include *all* shipments to and from Asia, as reported in annual issues of *Fearnley's World Bulk Trades* (Fearnresearch, 1988–1995). This necessitated expanding the region of coverage toward the northeast, so as to include shipments between Japan/South Korea/other Asian countries and the Americas; coverage was therefore extended to the limiting northeast cell of 45.5°N/150.5°E. (The previous inventory ended coverage at the southern tip of Japan.) In this way, we have added to the earlier inventory emissions in all Japanese and Korean coastal waters, as well as the Yellow Sea and the Sea of Japan. In addition, more routes have been added from Australia to the Philippines and Japan, and the route in the Indian Ocean has been redrawn to more accurately reflect the actual routes taken by crude oil tankers from the Gulf. We now have 12 major routes for crude oil and dry bulk goods, instead of six. These routes are shown in Fig. 1(a).

In the previous work, we included only bulk trade vessels, presuming that this accounted for about 75% of the total traded volume (United Nations, 1984). However, in researching this question further and using more recent data, we found that bulk trade comprised 50–60% of the total trade in the 1990s (ISEL, 1988–1996). Because our primary objective in this work is to characterize total sulfur deposition from shipping, we would underestimate sulfur generation and deposition by ignoring these smaller vessels that carry miscellaneous cargo. However, we do not know the routes for these smaller vessels. Therefore, we have estimated their contribution by extrapolating their emissions from breakdowns of worldwide total cargo data for each year (ISEL, 1996) and distributing the emissions evenly over the waters between Japan, Indonesia, the Philippines, and the mainland – as shown by the shaded area in Fig. 1(b). This forms something akin to a "shipping emissions background". In this way, we take into account all the smaller vessels plying between minor ports such as Bangkok, Haiphong, and Manila. We term this contribution "miscellaneous cargo". The emissions contributions from miscellaneous cargo are large but dispersed, as opposed to the emissions from bulk shipments that are concentrated along international shipping lanes.

In the previous method, we assumed typical vessel sizes of 200,000 deadweight-ton (DWT) tankers and 70,000 DWT dry bulk carriers. As Corbett et al. (1999) point out, these values are at the high end of the range of

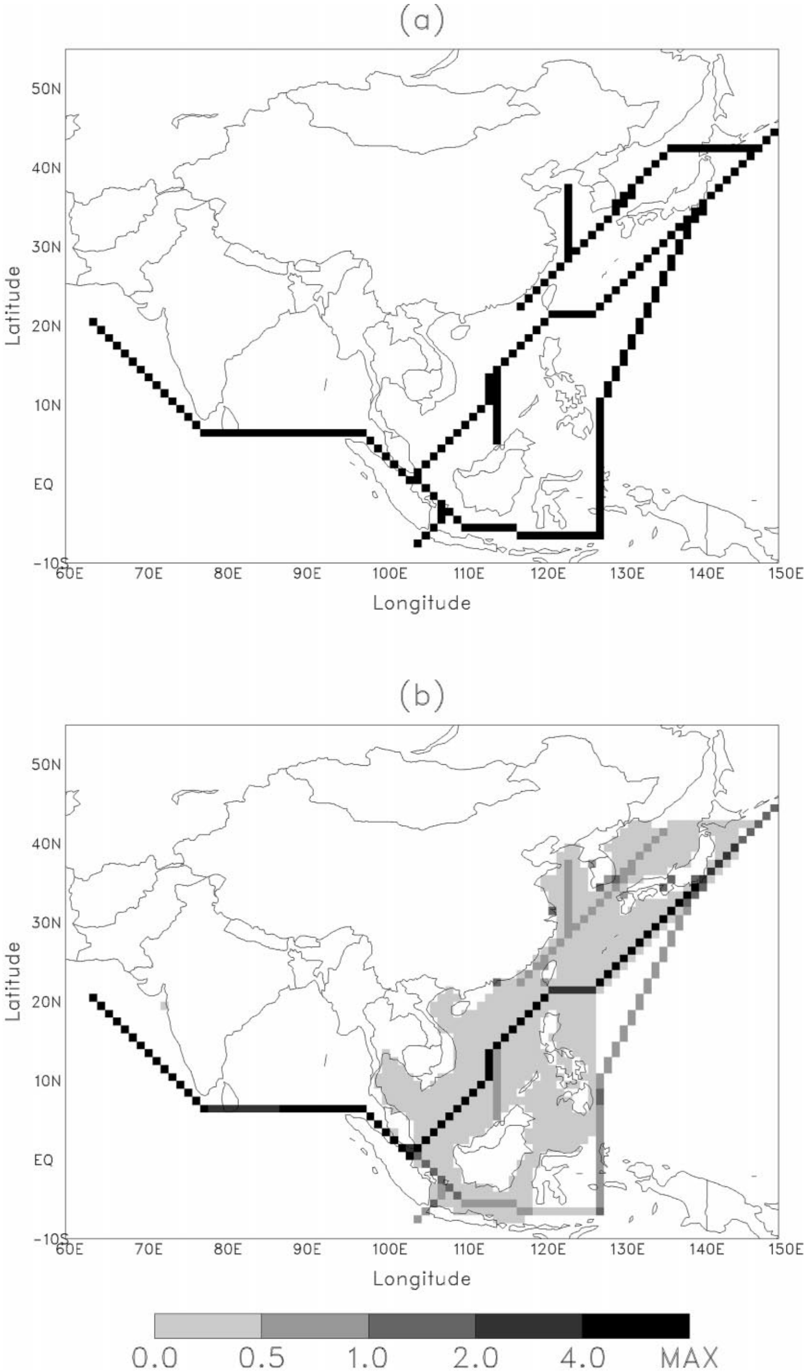


Fig. 1. (a) Major international shipping routes in Asian waters; (b) SO_2 emissions for 1995 from ships in Asian waters (Gg).

the actual vessel sizes. We have retained the use of these average sizes in the present work, but acknowledge that this may tend to underestimate the number of ships carrying a given amount of cargo and thus underestimate emissions, even though the lengths of the Asian routes may engender the use of vessels that are larger than the global averages.

We have also expanded the number of ports in this present work to include all those ports that handled more than 30 million tonnes of cargo in any of the years of our study period. This increased the number of ports from 12 to 19 and introduced some new high-volume ports, such as Chiba and Ulsan, which were not present in earlier statistical summaries. The methodology for calculating emissions from vessels entering and leaving ports is the same as in the previous work.

Emissions are estimated for five years: 1988, 1990, 1993, 1994, and 1995. Estimates for 1993, 1994, and 1995 are developed to fulfill a need of the RAINS-ASIA Phase II project, in which an intercomparison among different atmospheric transport models is being undertaken for these three years. The year 1988 is included as a point of comparison with the previous work, and 1990 is included because it is the base year for the present version of the RAINS-ASIA model. The year 1995 will be the base year of the new version of the model, presently under development. The entire seven-year period illustrates the remarkable growth in shipping volumes, in ship emissions, and in sulfur deposition that occurred as the economies of Asia grew in the early 1990s.

3. Asian shipping trade

As the economies of Asia expanded dramatically in the 1980s and early 1990s, there was increasing demand for raw materials and fossil fuels to drive industrial manufacturing, power generation, transportation, and higher standards of living. Additionally, increased quantities of finished goods were being shipped within Asia and exported to the West. During the period 1985–1995, the following average annual growth rates (AAGR) for GDP were recorded: China (9.6%), Thailand (9.0%), South Korea (8.4%), Singapore (7.9%), and Malaysia (7.4%) (World Resources Institute, 1998). Though their economies are large, India (5.2%) and Japan (2.9%) grew more slowly during this period. Though GDP will not precisely track the quantities of seaborne trade without account being taken of imports and exports, it gives a good indication of which countries were requiring large quantities of fuel and were exporting large quantities of finished goods, due to prosperous domestic economies. The single commodity shipped in greatest volume was crude oil from the Middle East to Japan and the other industrialized Asian countries. There was also a considerable amount of crude oil shipped within Asia, from such oil exporting countries as Indonesia, Malaysia, China, and Brunei. Dry bulk goods were dominated by shipments to Asia of iron ore from Australia and South America and coal from Australia and North America.

Table 1 summarizes the volumes of seaborne trade in Asia during the period 1988–1995. The most dramatic increase was in shipments of crude oil to destinations other than Japan, which more than doubled in the seven-year period (AAGR = 11.4%). In contrast, oil shipments to Japan grew at a much more modest rate (AAGR = 3.3%), slightly higher than the growth in GDP. Shipments of dry bulk goods to destinations other than Japan almost doubled (AAGR = 10.0%). In sum, the data show that seaborne trade in Asia grew by an average of 5.4% per year between 1988 and 1995.

The mix of commodities seems to have stayed fairly constant during this seven-year period, but the destinations have clearly shifted away from Japan. It should be expected that SO_2 emissions from ships would increase over time as the volume of trade increases – presuming no change in the average sulfur content of fuel oil – though the spatial distribution of emissions will depend on the cargo volumes shipped along each of the routes. It is possible, however, that emissions increases lagged trade increases over the period of this study, due to such factors as improved energy efficiency of vessels, higher

Table 1
Seaborne trade in Asian waters (10^6 tonnes yr^{-1})

Year	Crude oil		Dry bulk		Miscellaneous cargo	Total
	To Japan	To other Asia	To Japan	To other Asia		
1988	184.2	146.6	225.9	138.2	858.4	1553.3
1990	219.9	171.7	233.7	149.1	912.4	1686.8
1993	213.0	281.0	235.0	219.9	1051.2	2000.1
1994	238.8	296.1	237.4	230.6	1093.8	2096.7
1995	230.7	312.9	248.9	268.6	1177.1	2238.2
[AAGR][a]	3.27%	11.44%	1.39%	9.96%	4.61%	5.36%

[a]Average annual growth rate over the period 1988–1995.

Sources: Miscellaneous cargo data for each year are from *Shipping Statistics Yearbook 1996*, Institute of Shipping Economics and Logistics, Bremen, Germany (1996); detailed origin/destination data for crude oil and dry bulk goods for each year are from *Fearnley's World Bulk Trades, various years*, Fearnresearch, Oslo, Norway. Data from these two sources are consistent with each other.

cargo capacities, and more efficient terminal operations. The present method does not capture these factors.

4. SO_2 emissions from shipping

Using the method described in Streets et al. (1997), modified as described in Section 2, SO_2 emissions were estimated for crude oil and dry bulk shipments in each $1^\circ \times 1^\circ$ grid cell comprising the 12 selected routes for bulk goods shipments within Asia. Table 2 summarizes the new emission estimates for each route in each of the five years examined. For completeness, the emissions from miscellaneous cargo and major ports are also included in Table 2. The two routes with the highest emissions are from the Gulf through the Indian Ocean (Route #1) and from Singapore to Taiwan across the South China Sea (Route #3). This is a reflection of both the volume of traffic and the length of the routes. By 1995, emissions along both of these route segments had risen above $100\,\mathrm{Gg\,yr^{-1}}$ (1 Gg = 1 gigagram = 10^9 g = 1 thousand metric tonnes). The increase in emissions was particularly large along Route #1, reflecting the tremendous surge in demand for crude oil by the industrializing Asian economies.

Table 3 shows the estimates for SO_2 emissions in the vicinities of the 19 largest ports; recall that these ports were selected on the basis of having trade greater than 30 million tonnes in at least one of the years of the study period. Seven of the ports are in Japan and five in South Korea. Several relatively new ports, such as Chiba and Ulsan, have emerged on the scene and, in some cases, established a significant market share at the expense of neighboring ports. The SO_2 emissions in these 19 ports are estimated to have grown from 14.1 Gg in 1988 to 17.9 Gg in 1995 (AAGR = 3.5%). The average growth in emissions in these ports is lower than the growth in emissions along the shipping routes, because not all of these ports are involved in the transshipment of goods like crude oil. By 1995, Singapore had clearly consolidated its position as the largest volume port in Asia, in which SO_2 emissions are estimated at about $2.6\,\mathrm{Gg\,yr^{-1}}$.

Total SO_2 emissions, partitioned into the four major components, are summarized in Table 4. Note that the revised methodology, with its expanded geographical coverage and its inclusion of all trade vessels, has raised the estimate for 1988 from 236 Gg (Streets et al., 1997) to 545 Gg. Emissions are estimated to have grown to 817 Gg by 1995 (AAGR = 5.9%). This growth rate is consistent with the growth rate for cargo shipped (5.4%) that was shown in Table 1. Emissions from the transport of crude oil grew by an average of 8.2% per year, from 173 Gg in 1988 to 299 Gg in 1995.

Corbett et al. (1999) have developed a global inventory of sulfur emissions from oceangoing ships using a very different methodology to spatially assign emissions, namely, the use of ship sightings recorded in the logs of merchant and naval vessels. We have been able to compare our emission estimates for Asian waters with the inventory of Corbett et al., using the raw $2^\circ \times 2^\circ$ data on their web site. We calculated the emissions in an area that corresponded approximately to our area, by summing all emissions in the Corbett et al. inventory enclosed within the following longitude/latitude coordinates: 63°E/45°N to 63°E/5°N to 95°E/5°N to 95°E/7°S to 131°E/7°S to 131°E/17°N to 139°E/17°N to 139°E/33°N to 151°E/33°N to 151°E/45°N to 63°E/45°N. This

Table 2
Emissions of SO_2 ($\mathrm{Gg\,yr^{-1}}$) along major shipping routes

No.	Route	1988	1990	1993	1994	1995
1	Gulf/Indian Ocean	56.6	69.1	90.6	101.2	106.8
2	Indian Ocean/Singapore	43.5	51.5	67.5	75.3	80.0
3	Singapore/Taiwan	66.0	77.2	92.9	99.9	108.3
4	Taiwan/Japan	50.9	59.5	58.6	67.9	69.0
5	Australia/Singapore, from the S	2.6	2.8	4.6	4.3	5.2
6	Australia/Singapore, from the SE	5.7	6.2	10.1	9.5	11.4
7	Australia/Philippines	12.6	14.0	14.9	15.1	15.5
8	Philippines/Japan	19.9	21.8	21.6	22.1	22.3
9	Americas/Japan	17.2	17.1	17.9	18.1	21.0
10	Americas/South Korea	3.6	3.8	4.0	4.6	5.7
11	Other Asia/Japan	4.4	4.8	6.8	8.0	7.5
12	Other Asia/other destinations	1.8	2.1	3.5	3.6	3.5
	Miscellaneous cargo	246.7	262.6	300.8	322.8	342.7
	Major ports	14.1	14.8	16.8	17.6	17.9
	Total	545.4	607.2	710.5	770.4	816.8

Table 3
Emissions of SO_2 ($Mg\,yr^{-1}$) in major Asian ports[a]

Lat	Long	Port	1988	1990	1993	1994	1995
19.5N	72.5E	Bombay, INDI	253	251	255	254	282
35.5N	140.5E	Chiba, JAPA	1449[b]	1463	1371	1493	1514
22.5N	114.5E	Hong Kong, CHIN	699	765	943[b]	1088[b]	1248[b]
37.5N	126.5E	Inchon, KORS	433	518	727	807	904
22.5N	120.5E	Kaohsiung, TAIW	677	670	663	650	695
33.5N	130.5E	Kitakyushu, JAPA	806	818	800	794	834
34.5N	135.5E	Kobe, JAPA	1432	1474	1450	1469	788
34.5N	127.5E	Kwangyang, KORS	437	553	792	862	931
35.5N	136.5E	Nagoya, JAPA	999	1108	1155	1180	1225
34.5N	135.5E	Osaka, JAPA	742	837	793	783	775[b]
36.5N	129.5E	Pohang, KORS	278	279	327	324	363
3.5N	101.5E	Pt. Kelang, MALA	137	190	265	291	344
35.5N	128.5E	Pusan, KORS	510	545	602	702	803
31.5N	121.5E	Shanghai, CHIN	1143	1200	1512	1425	1426
1.5N	103.5E	Singapore, SING	1329	1614	2352	2493	2625
24.5N	120.5E	Taichung, TAIW	99	144	266	292	309
35.5N	139.5E	Tokyo, JAPA	605	681	633	669	662[b]
35.5N	129.5E	Ulsan, KORS	574[b]	643[b]	803	907	1094
35.5N	139.5E	Yokohama, JAPA	985	1065	1063	1102	1130
Total Emissions			14,089	14,815	16,771	17,586	17,875

[a]Cargo handling data are from *Shipping Statistics Yearbooks, various years,* by the Institute of Shipping Economics and Logistics, Bremen, Germany. All Asian ports are included that handled more than 30 million tonnes of cargo in any of the five years.
[b]Data were estimated on the basis of trends, because values were missing from the yearbooks.

Table 4
Emissions of SO_2 ($Gg\,yr^{-1}$) from all ships in Asian waters

Year	Oil	Dry bulk	Misc. cargo	Ports	Total
1988	172.6	112.1	246.7	14.1	545.4
1990	211.3	118.5	262.6	14.8	607.2
1993	257.7	135.2	300.8	16.8	710.5
1994	284.3	145.7	322.8	17.6	770.4
1995	298.8	157.5	342.7	17.9	816.8
[AAGR][a]	8.16%	4.98%	4.81%	3.47%	5.94%

[a]Average annual growth rate over the period 1988–1995.

generated an annual emissions estimate of 4.10×10^{11} g S or 820 Gg SO_2 (for the year 1993). The estimate for 1993 from this work is 710 Gg SO_2 (Table 4). The agreement is really quite good, considering the completely different methodologies used. Without going into the advantages and disadvantages of each method, one simple explanation for our lower estimate is that we do not include the non-transport vessels (fishing, military) that are contained in the Corbett et al. inventory. Globally, Corbett et al. estimate that non-transport vessels contribute 27% of SO_2 emissions; it is not unreasonable to think that the 13% difference between the two inventories could be largely explained by a smaller proportion of these non-transport vessels in Asian waters.

5. Sulfur deposition

5.1. Model description

Sulfur transport and deposition is studied using the ATMOS model, a three-dimensional, multi-layered, Lagrangian model with $1^\circ \times 1^\circ$ horizontal resolution. The study domain includes the whole of Asia between 60°E and 150°E and between 10°S and 55°N, excluding Afghanistan and the former Soviet Union. This analysis uses 1990, 6-hourly meteorological fields, with horizontal winds and temperatures from the National Climate Data Center, NCDC (1992) and 6-hourly ECMWF precipitation fields (NCAR, 1992). A detailed description of the model and the meteorology is provided elsewhere (Arndt, 1997; Arndt et al., 1997, 1998; Guttikunda et al., 1999). Emissions from land-based sources are derived from Arndt et al. (1997), using country-, fuel-, and sector-specific growth rates to obtain emissions for other years.

The calculation of sulfur deposition due to shipping activities requires that the emissions be allocated at $1^\circ \times 1^\circ$ grid resolution. SO_2 emissions from ships along the major routes, shown in Fig. 1(a), are calculated for each grid cell covered by a particular route. Emissions from miscellaneous cargo shipments are divided equally among the grid cells along the coastal areas of Indonesia, Malaysia, Philippines, Vietnam, China, Taiwan, the Koreas, and Japan. Emissions from the 19 major ports are assigned to their actual locations (see Table 3). The resulting gridded SO_2 emissions for 1995 are presented in Fig. 1(b).

For modeling purposes, shipping emissions are considered as surface-based, located at the center of a $1^\circ \times 1^\circ$ grid cell, and released into the well-mixed layer during the day and the surface layer at night. Five different runs are performed for the five different years, namely: 1988, 1990, 1993, 1994, and 1995. Both sulfur deposition and SO_2 concentration values are analyzed over the whole domain for all the years. The model's ability to create source–receptor relationships was used in the analysis of deposition and concentration fields, according to various source categories (Arndt et al., 1998).

5.2. Annual deposition

Figs. 2(a)–(e) present the modeled total annual sulfur deposition from shipping activities in $mg\,S\,m^{-2}\,yr^{-1}$ for the years of 1988–1995. Total annual sulfur deposition values of 207, 230, 270, 293, and 310 Gg are estimated for the years 1988, 1990, 1993, 1994, and 1995, respectively, over the entire study domain. More than 60% of the sea area included in the model domain receives sulfur deposition higher than $1\,mg\,S\,m^{-2}\,yr^{-1}$. Deposition levels exceeding $30\,mg\,S\,m^{-2}\,yr^{-1}$ are predicted around the major ports and in 2–5 degree bands centered along the major shipping lanes.

The increasing trade and transport among the small islands of Indonesia, Philippines, Taiwan, from and to Japan, the Koreas, the coastal areas of Sri Lanka, and portions of the Arabian Sea, between 1988 and 1995, is reflected in the deposition patterns. For example, peak sulfur deposition increased from 66 to $112\,mg\,S\,m^{-2}\,yr^{-1}$ in the coastal areas of the Strait of Malacca and from 23 to $43\,mg\,S\,m^{-2}\,yr^{-1}$ in the coastal areas of Sri Lanka over this seven-year period of study. Moreover, the average deposition values increased 50% over the ocean regions between the Philippines and Vietnam. Regions already under the threat of acid deposition in Sumatra also exhibited dramatically increased deposition over this period, with more of the terrestrial areas receiving sulfur deposition exceeding $30\,mg\,S\,m^{-2}\,yr^{-1}$ from shipping activities. Results from global simulations of the impact of sulfur emissions on oceans for the month of July (Capaldo et al., 1999) predict similar contributions of ships – as high as 60% in the Arabian Sea and the Indian Ocean and 10–30% in Southeast Asian waters.

Corresponding changes in the percentage contribution of sulfur deposition from ships to annual total deposition from all surface sources, including land-based anthropogenic sources and volcanoes, are presented in Figs. 3(a) and (b) for 1990 and 1995, respectively. For many ocean regions – especially Southeast Asia, the Indian Ocean, the North China Sea, and the western Pacific Ocean – shipping is the largest contributor to sulfur deposition. An average of 16% and 20% of the total deposition below 20°N is estimated to be from ships for the years of 1990 and 1995, respectively, which gives a strong indication of the importance of increasing shipping trade in this domain. A significant increase in the fraction of sulfur deposition due to shipping occurred over the Arabian Sea, due to the growing crude oil trade with the Middle East. Regions of the western Pacific Ocean receive 5–20% of their sulfur deposition from ships, and the average contribution from ships in this area increased significantly from 1990 to 1995. The average contribution also went up in the southern Indian Ocean from 20–50% to more than 50% during this period of study. Not only is sulfur emitted from ships the dominant contributor to sulfur deposition to many oceanic regions, but the sulfate aerosol that results from the oxidation of the emitted SO_2 is believed to represent a substantial fraction of the radiative forcing that occurs over the oceans (Capaldo et al., 1999).

A more detailed look at the contribution of shipping activities to sulfur deposition is presented for Southeast Asia. Figs. 4(a) and (b) present the annual deposition due to ships and the percentage contribution of ships to total sulfur deposition from all sources in the region for the year 1995. Most of coastal Sumatra and the southern tip of Malaysia and Singapore experience heavy deposition due to ships. A percentage contribution from ships of more than 20% to the total sulfur deposition can be observed throughout the region.

Figs. 4(c) and (d) present the percentage change experienced over the period of five years from 1990 to 1995 in sulfur deposition and in the percentage contribution from ships in the region. In 1995, more of the coastal areas of Sumatra and the Philippines faced the threat of acid deposition. From 1990 to 1995, an increase of 50% in the sulfur deposition is estimated in the region of the

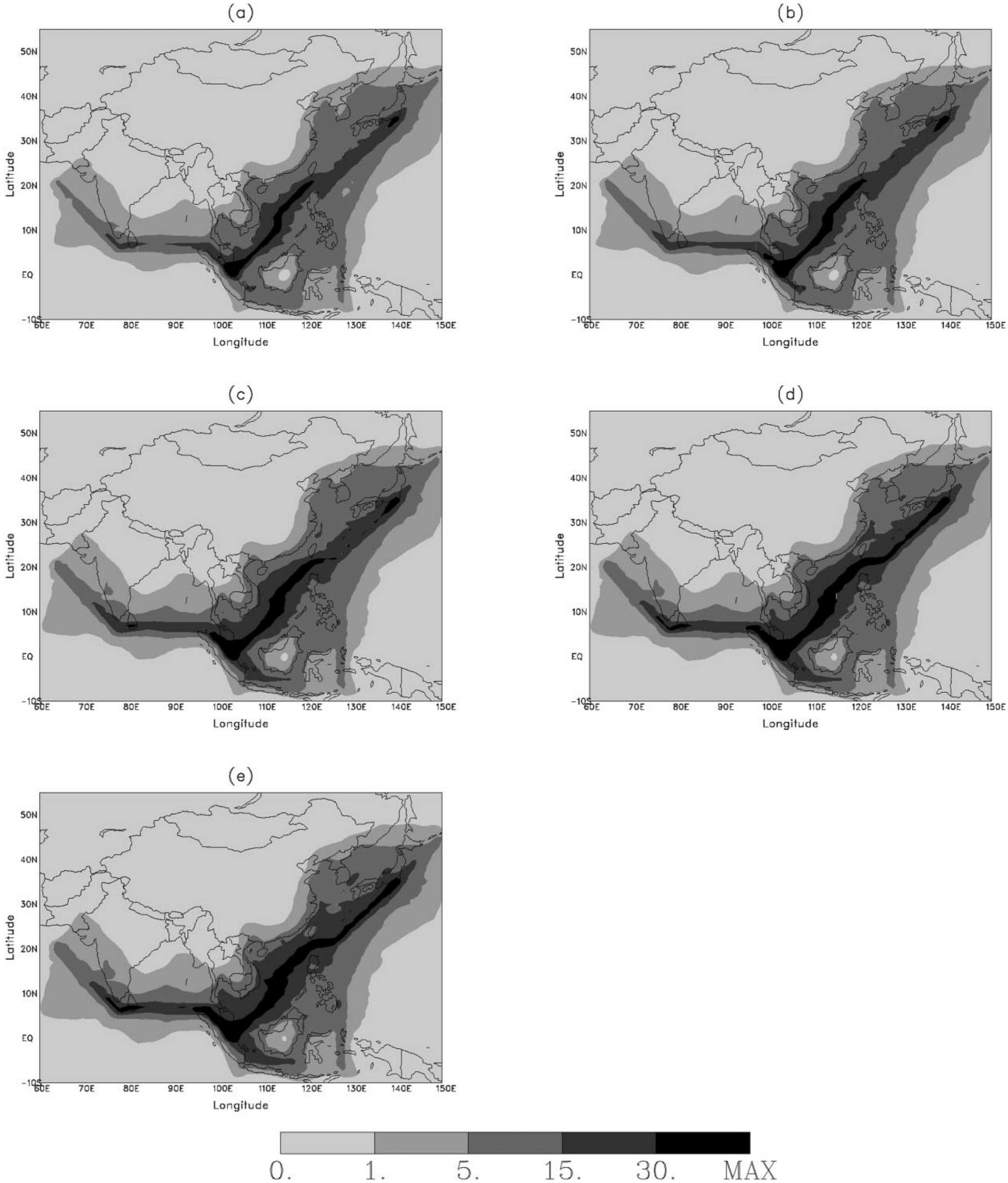


Fig. 2. Annual sulfur deposition due to shipping activity in Asia ($mg\,S\,m^{-2}\,yr^{-1}$): (a) 1988 (b) 1990 (c) 1993 (d) 1994 (e) 1995.

Strait of Malacca, peninsular Malaysia, and Singapore. Over the full seven-year span, an average increase of 20% in the percentage contribution from ships occurred in the region, which makes it extremely important to study the impact of shipping activities in detail. Fig. 4(d) shows that the percentage contribution from ships increased

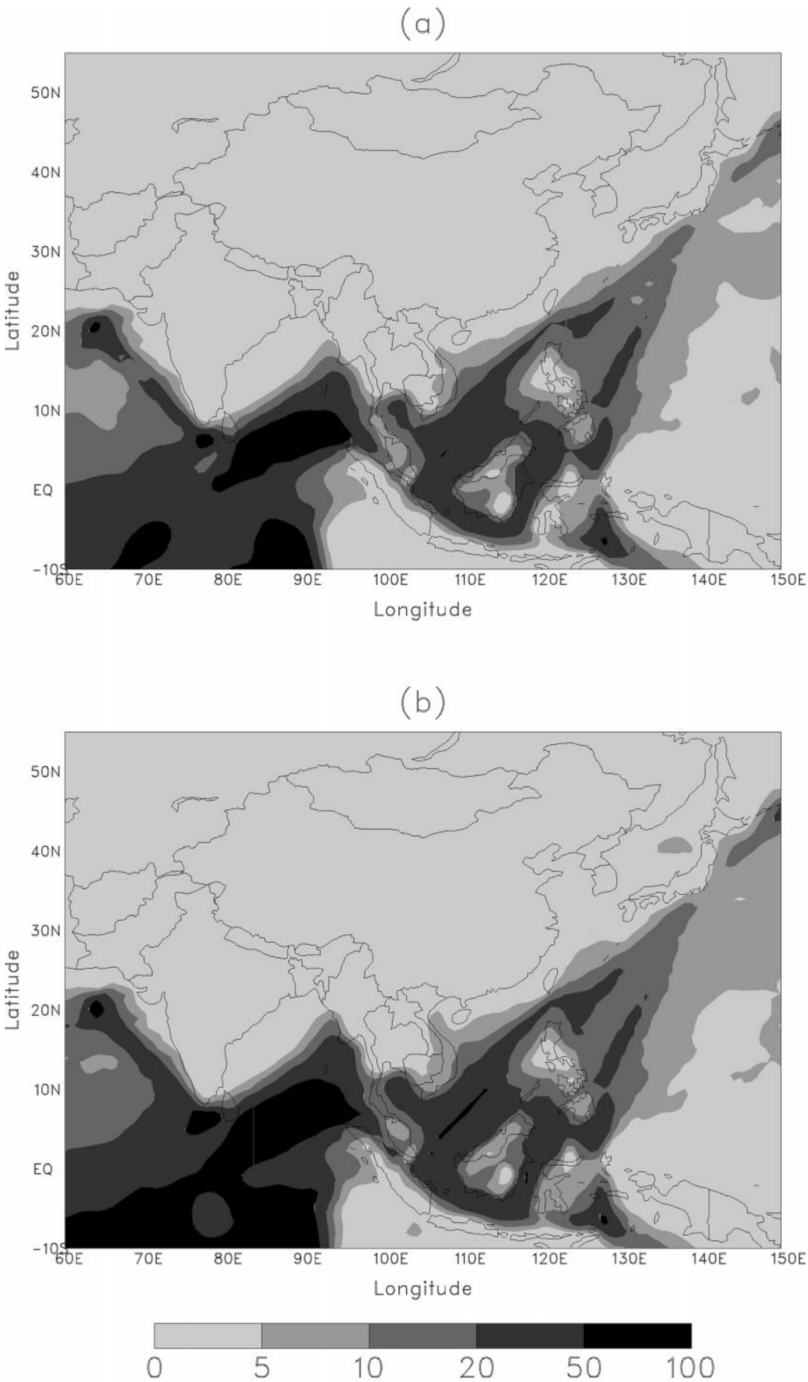


Fig. 3. Annual percentage contribution of emissions from ships to total sulfur deposition in Asia: (a) 1990 (b) 1995.

substantially over Sumatra, Java, northern Malaysia, Cambodia, and southern Vietnam, emphasizing the important role of ship emissions to deposition on land in these areas.

5.3. Seasonal sulfur deposition

Figs. 5 and 6 present the seasonal variation of wet and dry sulfur deposition from ships, for the years of 1988 and

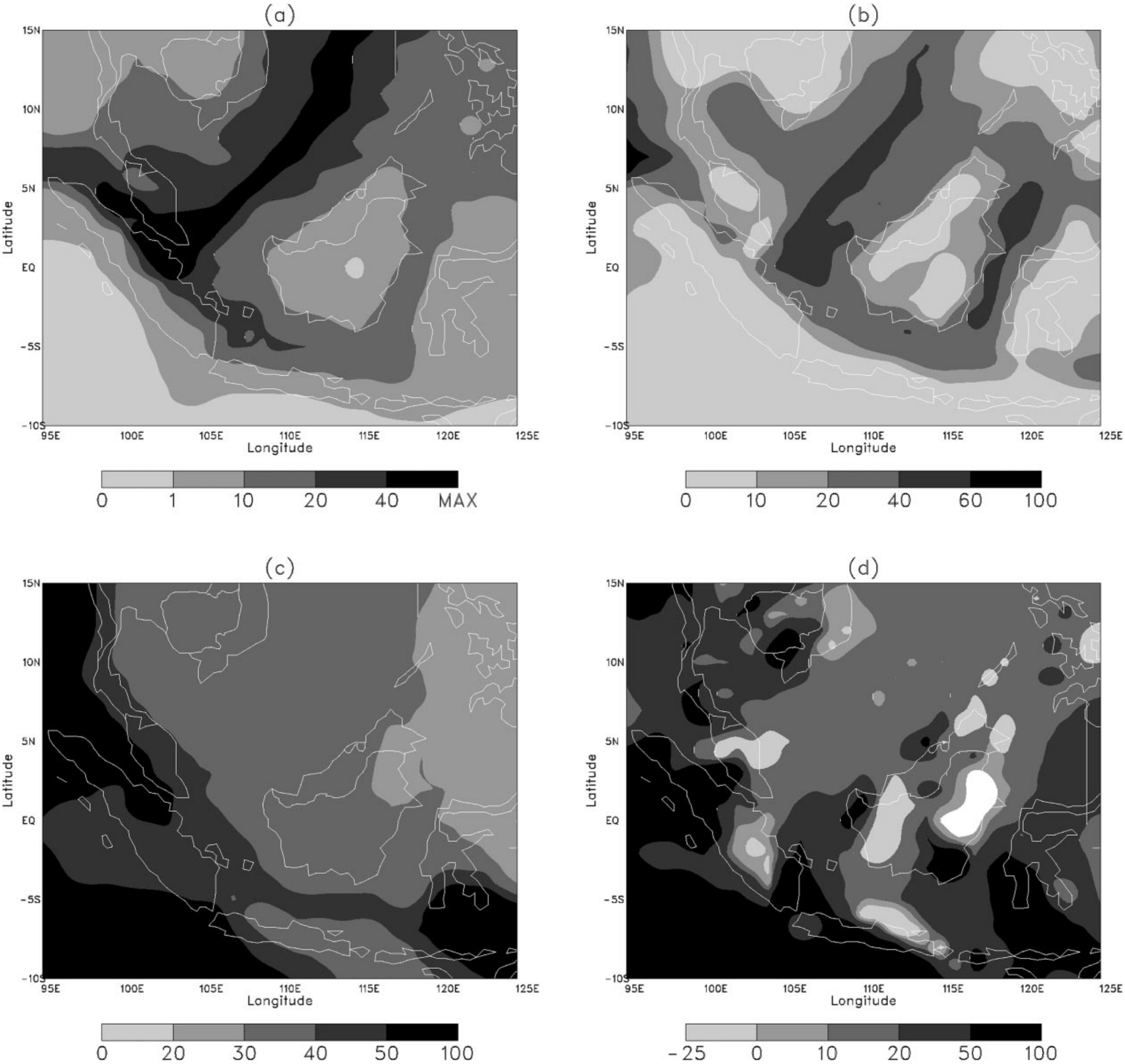
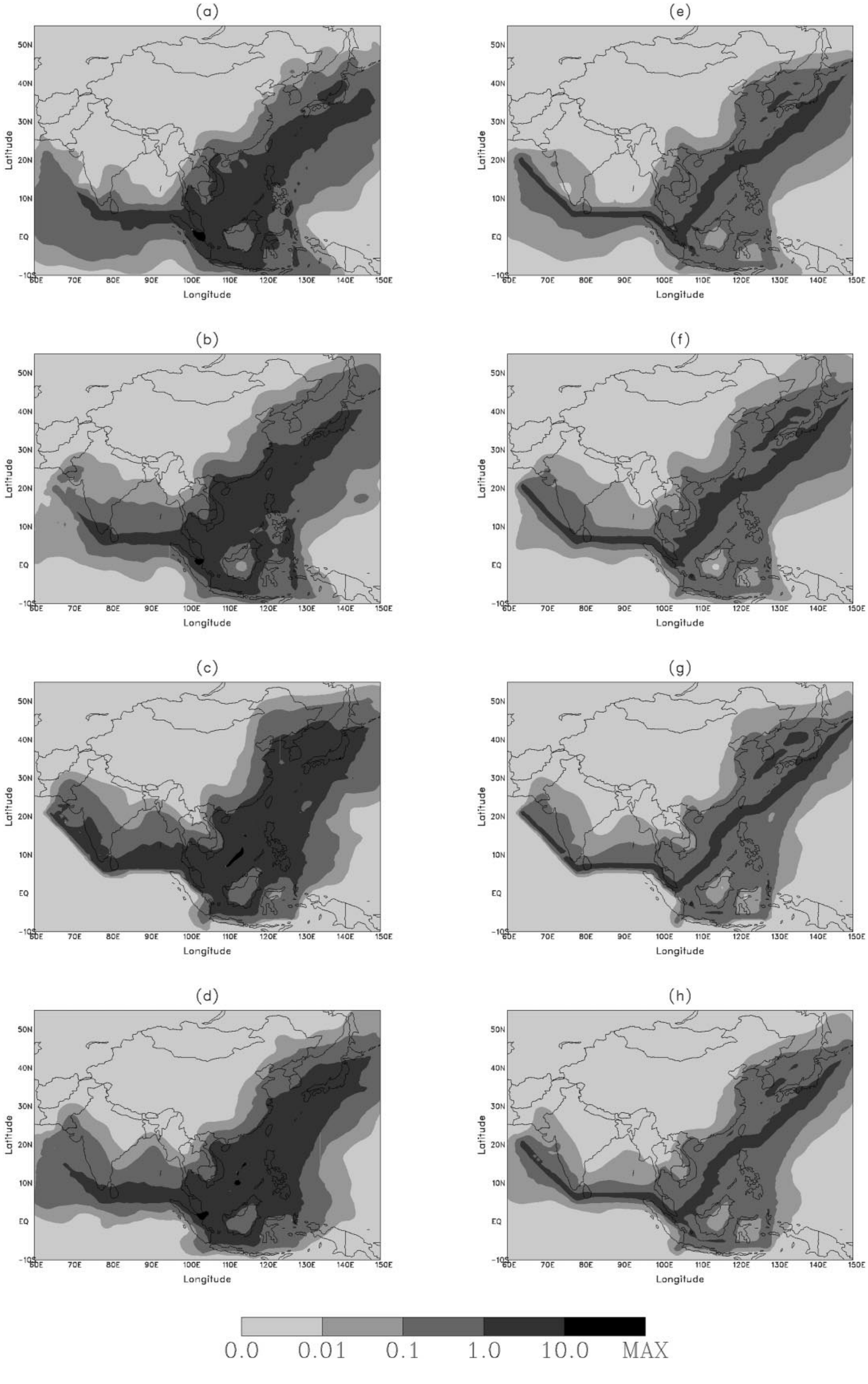


Fig. 4. Sulfur deposition in Southeast Asia due to ships: (a) annual total sulfur deposition due to ships in 1995; (b) percentage contribution of ships to annual total sulfur deposition in 1995; and percentage change from 1990 to 1995 in: (c) annual total sulfur deposition; (d) percentage contribution of ships to annual total sulfur deposition.

1995, respectively. Both wet and dry deposition patterns are analyzed for each season and each year, to help understand the importance of the seasonal component associated with the shipping trade. In general, wet deposition is 25% higher in the summer (JJA) and fall (SON), compared to spring (MAM) and winter (DJF). Dry deposition is equally important for all the seasons. Fig. 7 presents the seasonal average wind fields and precipitation for summer and winter of 1995 (NCEP, 1999). From Fig. 7, higher wet deposition during the summer and fall (not shown) can be attributed to heavy precipitation levels over the Indian Ocean and Southeast

Fig. 5. Seasonal total sulfur deposition in Asia due to ships for 1988 (mg S m^{-2} season^{-1}): (a) DJF/wet (b) MAM/wet (c) JJA/wet (d) SON/wet (e) DJF/dry (f) MAM/dry (g) JJA/dry (h) SON/dry.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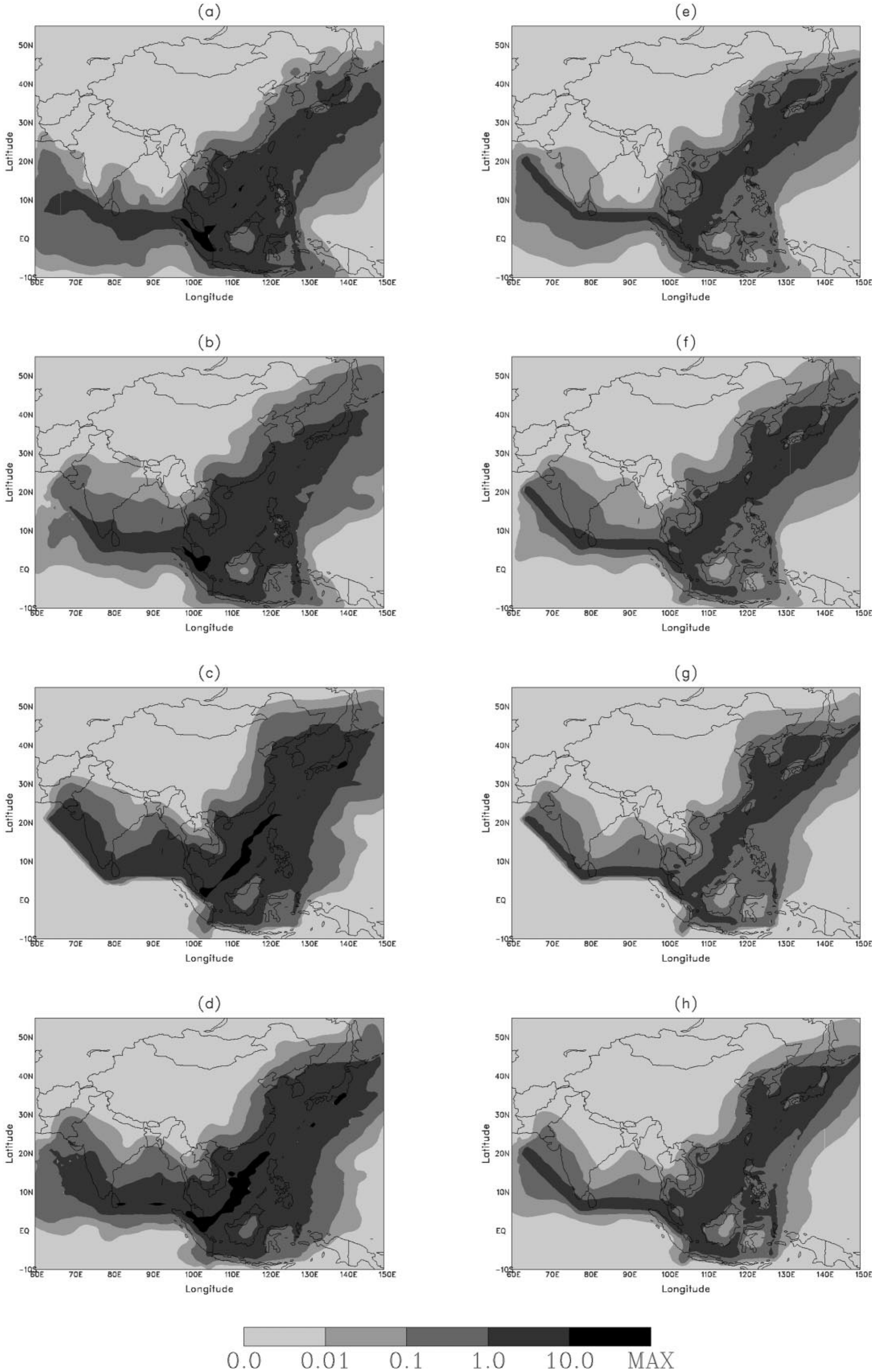
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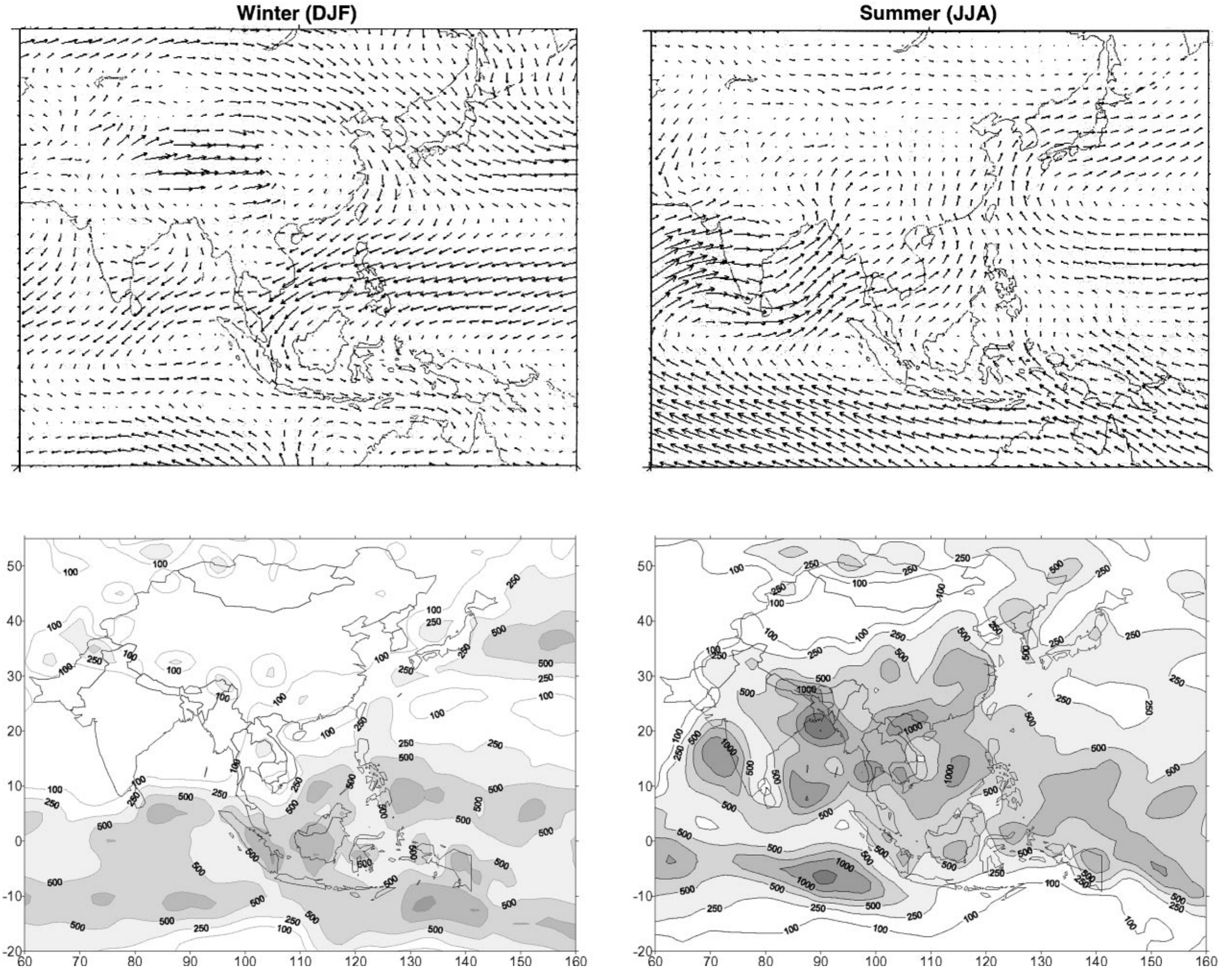

Fig. 7. Seasonal averaged flow fields (upper) and accumulated seasonal precipitation (mm) (lower) for 1995: winter (DJF) and summer (JJA).

Asia, where the major source of sulfur deposition is ships. A peak total sulfur-deposition value of 27 mg S m^{-2} is simulated in the region of the Strait of Malacca for the winter of 1988 and 47 mg S m^{-2} for the winter of 1995.

Over the period of seven years, more land area came under the threat of sulfur deposition from ships. For example, more regions of northern coastal Sumatra, coastal areas of Japan and Taiwan, Singapore, and most of the sea regions in Southeast Asia received total sulfur deposition exceeding 10 mg S m^{-2} season^{-1} in summer and fall, representing the increasing trade during this period. Strong on-shore winds, moderately high precipitation levels, and heavy shipping traffic are responsible for the peaks in the winter months around the Strait of Malacca, coastal Malaysia, Singapore and the Philippines. Most of coastal China, Taiwan, the Philippines, Vietnam, and the Koreas receive wet sulfate deposition of 1–10 mg S m^{-2} throughout the year. The western coast of India receives most of its sulfur deposition from ships in the summer months, due to prevailing southwesterly winds and heavy precipitation. Similarly, the western coast of Japan receives more than 60% of its wet sulfur deposition from shipping in summer and fall.

Dry deposition closely follows the sulfur emission pattern, with most of the deposition occurring over oceans

Fig. 6. Seasonal total sulfur deposition in Asia due to ships for 1995 (mg S m^{-2} season^{-1}): (a) DJF/wet (b) MAM/wet (c) JJA/wet (d) SON/wet (e) DJF/dry (f) MAM/dry (g) JJA/dry (h) SON/dry.

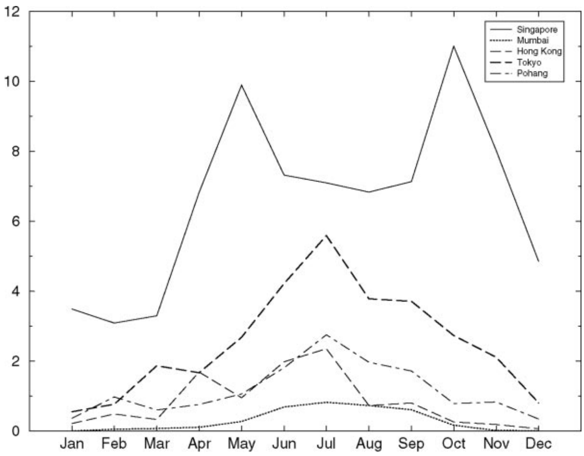

Fig. 8. Monthly total sulfur deposition for five major ports in Asia for 1990 ($mg\,S\,m^{-2}$ $month^{-1}$).

and seas. For 1988, peak values of 6 $mg\,S\,m^{-2}$ $season^{-1}$ of dry deposition are simulated for both winter and summer seasons, with most of the coastal areas of China, Vietnam, Taiwan, Japan, and the Philippines receiving a little less than 1 $mg\,S\,m^{-2}$. During the spring, dry deposition ranged from 1 to 10 $mg\,S\,m^{-2}$. For 1995, peak values of 11 $mg\,S\,m^{-2}$ are simulated for summer and winter, respectively, with most of the coastal areas, oceans, and seas receiving dry deposition of greater than 1 $mg\,S\,m^{-2}$. Overall, it is clear that there is a strong seasonal component associated with sulfur deposition around the major shipping lanes.

Apart from the deposition over the oceans and seas, shipping also contributes significantly to sulfur deposition in the coastal areas and the major ports. Fig. 8 presents the monthly averaged sulfur deposition for five major ports of Asia for the year of 1990: Singapore; Mumbai, India; Hong Kong, China; Tokyo, Japan; and Pohang, South Korea. A monthly deposition rate of more than 3 $mg\,S\,m^{-2}$ is predicted throughout the year for Singapore, with peaks in the spring and autumn months of around 10 $mg\,S\,m^{-2}$. The percentage contribution from ships reaches its peak in the winter months at around 50–70%, due to the prevailing northeasterly winds, and for the rest of the months it stays at around 15%. For Mumbai, the monthly contribution from ships is estimated to be less than 0.5 $mg\,S\,m^{-2}$; most of the urban and coastal area of Mumbai is affected much more by transport and industrial sources on land than by the shipping sector. Tokyo is estimated to experience a pronounced peak in July of about 5–6 $mg\,S\,m^{-2}$ from shipping. Pohang receives a monthly average deposition of 1 $mg\,S\,m^{-2}$ from shipping; percentage contributions are also low in this region, as most of the deposition is attributed to industrial activities.

6. Conclusions

The rapid growth of Asian economies during the late 1980s and early 1990s led to a dramatic increase in SO_2 emissions from shipping. Between 1988 and 1995, we estimate that emissions in Asian waters grew by an average of 5.9% per year, with emissions from crude oil shipments growing by a remarkable 8.2% per year. Total emissions from shipping increased from 545 Gg in 1988 to 817 Gg in 1995. Annual and seasonal sulfur deposition and concentration fields due to shipping activities in Asia were investigated for the seven-year span from 1988 to 1995 using the ATMOS model and 1990 meteorology. Sulfur emissions from ships were found to be a dominant source over the Indian Ocean, the North China Sea, the western Pacific Ocean, and most of Southeast Asia. The average contribution from ships to deposition in these areas increased by at least 5% in the seven-year period. Growing trade with the Middle East resulted in a dramatic increase in the contribution of ships to sulfur deposition in the Arabian Sea. The impact of shipping emissions on coastal areas and major ports is increasing rapidly. Southeast Asia is affected the most from ships, as most of the areas of Sumatra, peninsular Malaysia, and Singapore receive in excess of 10% of their sulfur deposition from ships.

A strong seasonal component is observed over the period of study, with more and more regions of Southeast Asia and coastal Japan receiving sulfur deposition above 10 $mg\,S\,m^{-2}$ $season^{-1}$. At least 25% more deposition occurs in the summer and fall than in the winter and spring. Peak values of 25–50 $mg\,S\,m^{-2}$ $season^{-1}$ are estimated for winter in the vicinity of the Strait of Malacca. In this work, we have not used the RAINS-ASIA or similar computer model to assess the kinds of ecological damage that might result from these elevated levels of deposition on land – for example, by comparing them with critical loads for particular ecosystems. Some of this kind of analysis was performed in the previous study (Streets et al., 1997), and the reader is referred to that paper and others for sulfur damage assessments. The results of this study suggest a need to institute policies to reduce the sulfur content of marine fuels used in Asia or otherwise reduce the emissions of SO_2 from international shipping in this region.

Acknowledgements

This work was partially supported by the US Department of Energy, Assistant Secretary for Fossil Energy, under contract W-31-109-Eng-38. It was also partially supported by the World Bank, as a contribution to the RAINS-ASIA Phase II project. The opinions expressed in this paper are those of the authors alone and should not be construed as representing the official positions of

Argonne National Laboratory, the University of Iowa, the US Department of Energy, or the World Bank.

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