CONTRIBUTION OF CANADA-UNITED STATES TRANSBOUNDARY TRANSPORT TO WET DEPOSITION OF SULPHUR AND NITROGEN OXIDES – A MASS BALANCE APPROACH

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1. INTRODUCTION

The five-year-average integrated emission and deposition values for sulphur (S), shown in Figure 1, indicate that a major imbalance exists between emissions and wet deposition in eastern Canada (EC).

Acid wet deposition in EC is therefore attributed to both local emissions and long-range transport (Fig. 2) of eastern Canadian and eastern US (EUS) emissions of SO_2 (Fig. 3) and NO_x.

The primary cause of this imbalance is hypothesized to be the long-range transport into and subsequent wet deposition of EUS emissions in EC. A set of mass balance equations was developed from Figures 1a and 1b to investigate this.
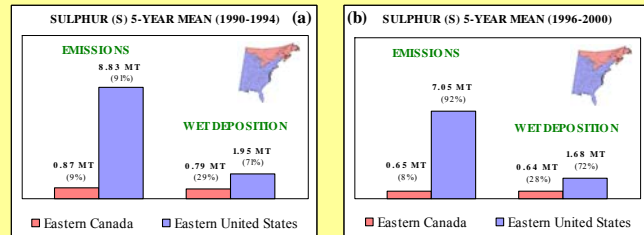

SULPHUR (S) 5-YEAR MEAN (1990-1994) (a)

EMISSIONS — 8.83 MT (91%)
WET DEPOSITION — 1.95 MT (71%)
0.87 MT (9%) — 0.79 MT (29%)

(b) SULPHUR (S) 5-YEAR MEAN (1996-2000)

EMISSIONS — 7.05 MT (92%)
WET DEPOSITION — 1.68 MT (72%)
0.65 MT (8%) — 0.64 MT (28%)

■ Eastern Canada ■ Eastern United States

Figure 1. *Integrated S-SO_2 emissions and integrated S-non-sea-salt-SO_4^{2-} (S-nssSO_4^{2-}) wet deposition over EC and the EUS averaged over the 5-year periods (a) 1990-1994 and (b) 1996-2000 expressed as megatonnes (MT) of S per year. The area of integration is shown in the map inserts.*

2. MASS IMBALANCE and TRANSBOUNDAY TRANSPORT

In Figures 1a (1990-1994) & 1b (1996-2000):

- EC emitted only 8-9% of eastern North American (ENA) S emissions but received 28-29% of ENA wet deposition of S.

- In light of the fact that the southern portions of EC are predominantly downwind of the major EUS SO_2 emission areas (see Fig. 2 & 3), the most reasonable explanation for the disproportionately high deposition in EC is the long-range transport and subsequent wet deposition of SO_2 from EUS sources into EC.

- S emissions and deposition decreased significantly between the two periods as shown in the table below:

S (MT/yr)	in EC		in EUS	
	Emissions	Deposition	Emissions	Deposition
1990-94 (Fig. 1a)	0.87	0.79	8.83	1.95
1996-2000 (Fig. 1b)	0.65	0.64	7.05	1.68
Decrease	0.22	0.15	1.78	0.27

- As was the case with S, EC received a disproportionately large amount (32%) of ENA NO_3^- wet deposition, given its low percentage (7%) of ENA NO_x emissions.

3. MASS BALANCE EQUATIONS

- The mass balance equations state that the total amount of wet S deposition in EC must be equal to the total S emissions multiplied by the fraction of emissions that is wet deposited in EC plus the total EUS S emissions multiplied by the fraction of emissions that is wet deposited in EC.

The mass balance equations are shown in the table below.

1990-1994	1996-2000
$WD_1 = 0.87A + 8.83B_1$ (Eq. 1)	$WD_2 = 0.65A + 7.05B_2$ (Eq. 2)
$F_1 = 1 - 1.10A$ (Eq. 3)	$F_2 = 1 - 1.02A$ (Eq. 4)

WD = the integrated S-nssSO_4^{2-} wet deposition in EC;

$_1$ and $_2$ indicate the 5-year-average values of the periods, 1990-94 and 1996-2000, respectively;

0.87 and 0.65 = the 5-year-average emissions of S-SO_2 in EC (in MT S/yr).

A = the fraction of EC S-SO_2 emissions that is wet deposited in EC. **A** is assumed to be constant because the 5-year-average precipitation rates are approximately equal for the two periods in EC (107.41 and 107.18 cm/yr). **A** is set between 0.2 and 0.4 (substantiated by the results of Galloway and Whepdale, 1980, Galloway et al., 1984). Calculations were made here for the two extreme values of **A** (i.e., 0.2 and 0.4).

8.83 and 7.05 = the 5-year average emissions of S-SO_2 in EUS (in MT S/yr).

B = the fraction of EUS S-SO_2 emissions wet deposited in EC. Since the large emission reductions that occurred in the EUS between the two periods depended strongly on location (i.e., the % reductions were not constant across the entire domain), the assumption could not be made that B was constant between periods.

F represents the fraction of EC wet S-nssSO_4^{2-} deposition attributable to EUS S-SO_2 emissions (e.g., $F_1 = (WD_1 - 0.87A)/WD_1 = 1 - 1.10A$).

4. CONCLUSIONS

- The mass balance results indicate that SO_2 and NO_x emission sources in the EUS contributed 56% to 83% of the nssSO_4^{2-} and NO_3^- wet deposited in EC during the 1990s.

- Due to extreme sensitivities in the mass balance equations, our method could not be applied with confidence to calculate the contribution of EC emissions to wet deposition in the EUS. However, our results did corroborate previously-published modelling results suggesting that this contribution is very small.

- The large contribution of EUS emissions to wet deposition in EC implies that future emission reductions in the EUS will play an important role in reducing wet S and N deposition in EC.

Figure 2:

The general pattern of air movement across North America (Source: (1) redrawn by NARSTO, 2003 from (2) Bryson and Hare, 1974).

South-to-north-or-northeast transport direction is typical for eastern North America.

nssSO_4^{2-} **20** & **30** kg/ha/yr

Figure 3:

Superposition of 1990 wet nssSO_4^{2-} deposition isopleths on a map of the 1990 SO_2 emissions to compare high emission and deposition areas.

The high wet deposition in the low emission areas of northern Ontario and Quebec is due to the long-range transport of SO_2 from the high emission areas.
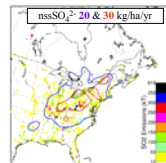
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