ON TRANSPORT OF SULPHUR OVER THE NORTH ATLANTIC

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SUMMARY

The sulphur content in the precipitation collected on ocean weather ships in the North Atlantic has been analysed. From these data and from results of trajectory computations it is concluded that considerable amounts of anthropogenic sulphur are transported from North America towards Europe. The dry deposition of sulphur over the Atlantic, except close to the emitting sources, must be very small. The amount of sulphur in the precipitation from air coming from the high pressure area near the Azores is very small and thus one can say that the normal value of natural sulphur in precipitation cannot be much larger than 0.1 mg/l.

SAMMANFATTNING

Svavelinnehållet i nederbörden har uppmätts på väderskepp i Nordatlanten. På grundval härav och av trajektorieberäkningar visas att betydande mängder antropogent svavel transporteras från Nordamerika mot Europa. Torrdepositionen av svavel över Atlanten på långa avstånd från källan måste vara mycket liten. Värdena på nederbördsutfallet av svavel ur luft som kommer från det azoriska högtrycksområdet är mycket låga och man kan därför säga att det naturliga svavlet i nederbörd i allmänhet högst är av storleksordningen 0.10 mg/l.

ON TRANSPORT OF SULPHUR OVER THE NORTH ATLANTIC

While studying the long range air-born transport of sulphur in Europe, Nyberg (1972), I concluded that a considerable amount of sulphur must be transported from the North-American continent eastwards over the sea and that it might fall down with precipitation even so far to the east as at the European weatherships Alpha, India, Juliet, Kilo and Mike.

Some experiments were started in order to collect amount of precipitation on board ships. Collectors were equipped with a shield and placed in a position slanting to windward to increase the collected amount of precipitation. The primary purpose was not a correct measure of the precipitation but to obtain its concentration of sulphur.

It was not always feasible to obtain a large enough sample of precipitation as to be able to make satisfactory analyses of the sulphur concentration. After some preliminary experiments collectors were set up on the weatherships mentioned above with the cooperation of the Norwegian Meteorological Institute, the Royal Meteorological Institute of the Netherlands and the U.K. Meteorological Office. The collectors were placed rather high on the ships in order to avoid sea water spray. However, as expected, analysis of Na and Cl showed that sea salt content often was very high and many samples had to be rejected. Another problem was the smoke from the stack. The collectors were placed forward in the ships but smoke was still sometimes found in the samples which in such cases had to be rejected. In most cases, however, the engine was stopped during the sampling and no smoke was noticeable in the samples.

The collecting activity went on for about two years during which time the total number of usable samples

numbered 26.

The time of precipitation was recorded and trajectories for the air at the level 850 mb during the proceeding 5 days that ended at the weatherships at that time were computed. The trajectories were computed by Miss Ann-Beate Henrikson as described in Henrikson (1974).

The first experiments were made on some Swedish merchant ships without any success. An improved sampler was then set up on the Norwegian-Swedish weathership Polarfront but the collected samples then regularly contained too much sea salt. Later on improved collectors were put on board the Dutch weathership Cumulus which took samples from stations Alpha, Kilo and Mike, and finally on the U.K. weatherships on the stations India, Juliet and Lima.

Analysis of several chemical compounds in the samples were made at the International Meteorological Institute in Stockholm. Of main interest was the sulphur content. In order to check any pollution caused by sea spray the analysis of Cl and Na was studied. If the concentration of Na surmounted 10 mg/l the sample was rejected. If it was less than 10 mg/l and amount of 0.084 mg/l sulphur was deducted for each mg Na as originating from the sea and the rest was called the excess sulphur. In general the amount of Cl corresponded well to the Na content. In one case the Cl content was considerably higher which may have been caused by an error in the Na analysis, case 16. The material is presented in Tables I and II.

Tabell I Data regarding precipitation collected on U. K. ships

Ship station and nr	Collection time	Position N	Position W	Course	Wind Dir.	Beauf	Origin of trajectory N	Origin of trajectory W	Trajectory position 2 days before sampling N	Trajectory position 2 days before sampling W	Analysis mg/l S	Cl	Na	Excess S mg/l
J 1	29.4-74 07.45 13.30	52° 25′	19° 30′	Engine Stopped	170° 300°	5 5	58	60	53	30	0.97	19.00	8.40	0.26
I 2	30.4 06.49 12.42	59° 05′	19° 13′	140° 120°	130° 120°	7 6	56	8	54	18	1.70	19.90	10.68	0.81
I 3	29.5 14.20 18.07	59° 07′	19° 13′	Stopped	130° 140°	4 4	66	53	60	30	0.96	12.00	6.42	0.42
I 4	29.5 19.30 30.5 00.20	59° 08′	19° 18′	Stopped	130° 130°	5 6	41	23	52	30	0.75	15.00	7.86	0.09
J 5	30.5 07.43 12.40	52° 26′	20° 13′	230° Stopped	230° 260°	6 4	39	66	46	44	1.36	18.80	10.20	0.50
I 6	5.8 10.23 16.00	59° 05′	18° 56′	Stopped	110° 180°	5 5	44	36	41	27	0.65	11.80	7.38	0.03
I 7	7.8 06.00 18.00	59° 18′	18° 43′	Stopped	180° Calm	4 0	55	58	48	30	0.13	1.27	0.62	0.07
I 8	11.8 22.00 12.8 04.00	58° 49′	19° 23′	Stopped	100° 80°	4 5	53	47	52	26	0.67	8.84	5.32	0.17
J 9	14.8 00.05 04.20	52°32′	20° 20′	Stopped	110° 120°	5 4	35	57	41	23	0.90	17.16	10.08	0.06
J 10	18.8 15.20 20.35	52° 32′	20° 20′	Stopped	150° 180°	4 4	30	72	38	46	0.40	8.70	5.52	- 0.05
J 11	24.12 18.00 23.50	52° 34′	20° 18′	Stopped	190° 90°	5 7	62	34	48	34	1.34	19.80	10.50	0.46
J 12	9.1-75 09.30 15.30	52° 43′	20° 07′	Stopped	10° 60°	5 5	40	16	39	22	0.66	10.90	5.70	0.18
J 13	9.1 15.30 21.30	52° 43′	20° 09′	Stopped	60° 60°	5 6	29	18	38	18	0.53	9.45	5.19	0.10
J 14	9.1 22.00 10.1 02.00	52° 39′	20° 55′	Stopped	90° 90°	4 5	41	19	36	25	0.24	3.81	2.03	0.07
J 15	4.6 13.30 19.30	52° 32′	20° 02′	Stopped	110° 110°	4 4	33	49	38	28	0.74	7.57	5.00	0.28
L 16	17.7 08.59 14.59	57° 09′	19° 52′	Stopped 216°	180° 190°	5 5	48	73	51	42	1.48	9.73	3.00	1,1
L 17	17.7 15.00 21.00	57° 07′	19° 59′	216°	190° [illegible]	5 [illegible]	44	73	52	45	0.56	8.81	3.54	0.35
L 18	19.7 00.00 06.00	57° 00′	20° 24′	Stopped 180°	130° 180°	5 6	45	84	48	52	0.54	7.47	3.44	0.25

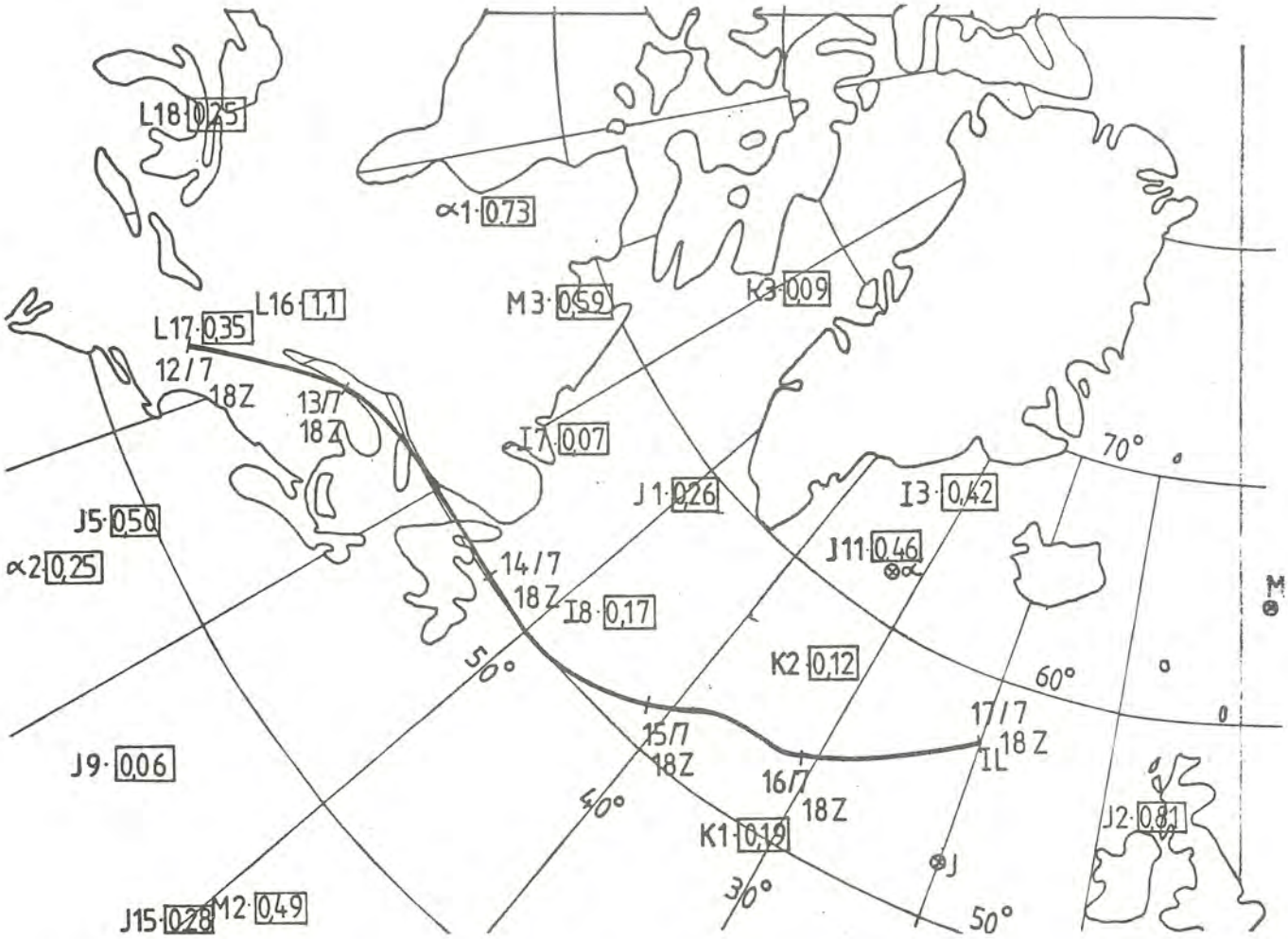

Fig 1 The trajectory at the 850 mb level on 12-17 July 1975 ending at the weather ship station I or L. The value 0.35 in the square at the origin of the trajectory is the content of sulphur measured in the precipitation collected at station L on July 17th. Other starting points of 5 day trajectories ending at weather ship stations I,J,L and K or M are indicated with the number given in table I or table II and, within each square, with the content of sulphur in mg/l as measured in the samples collected at the weather ships.

In fig. 1 is shown, as an example, the 120 hours trajectory for air at the 850 mb level arriving at ocean weather station Lima on 17th of July 1975. With . are marked the beginning of all trajectories starting in the western areas and ending at stations India, Juliet or Lima at times of the fall of collected precipitation. In squares is given the concentration of sulphur in mg/l as analysed in the precipitation. The numbers corresponding to Table 1 are also indicated close to the square.

The values from the samples J 15 and M 2 are rather high although the trajectories start in the subtropical high pressure area. Trajectories are not computed for longer periods than 120 hours, however, by studying weather maps for preceding days it is possible to give an indication of the previous flow of the air in question. Thus in both the two cases mentioned it appears that the air has come from the area of the north-eastern U.S.

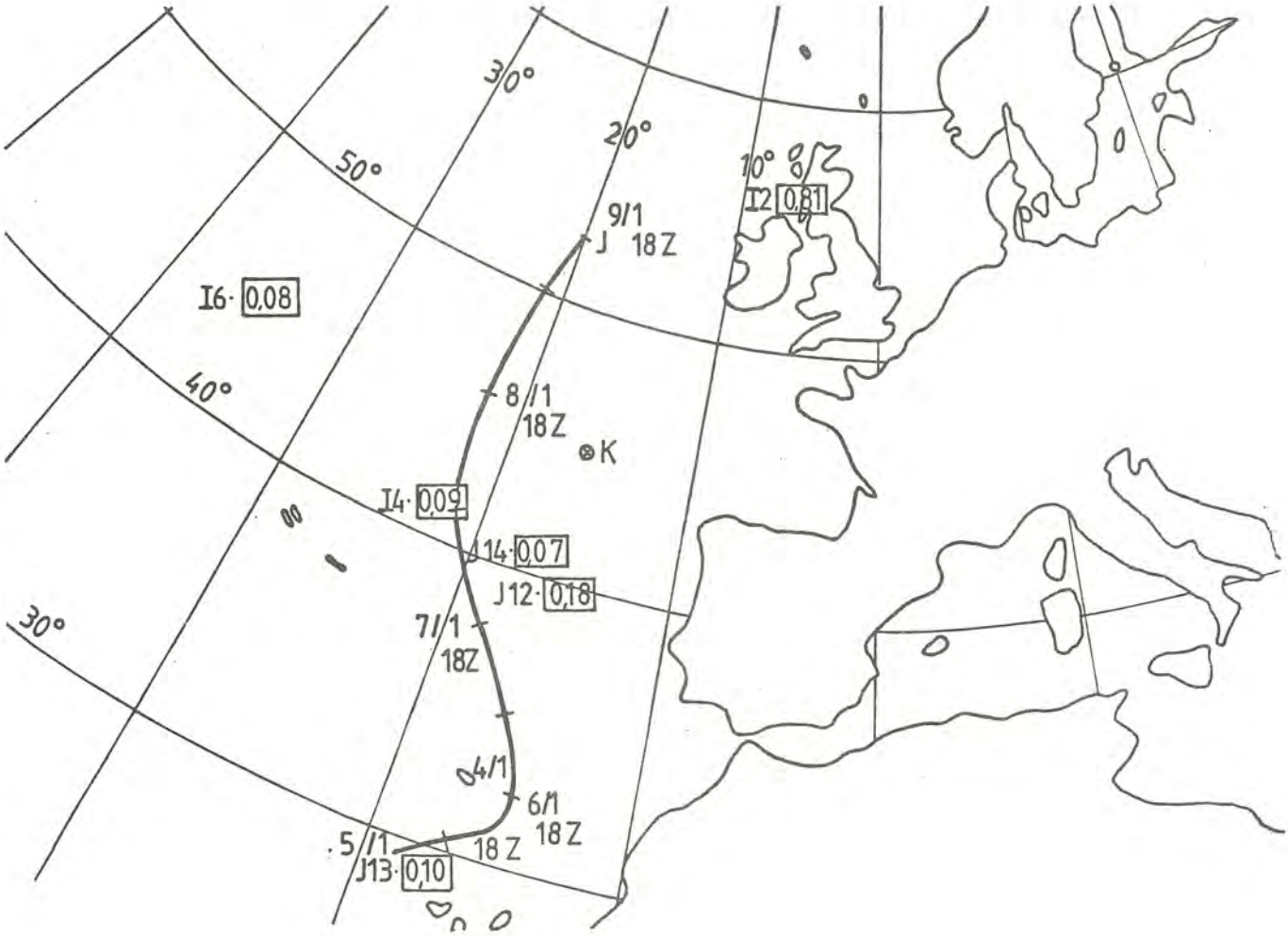

Fig 2 The trajectory at the 850 mb level on 5-9 January 1975 ending at weather ship station J.
The value 0.10 in the square at the origin of the trajectory is the content of sulphur measured in the precipitation collected at station J on January 9th. Other starting points of 5 day trajectories ending at weather ship stations I and J are indicated with the number given in tables I and II and, within each square, the content of sulphur in mg/l as measured in the samples collected at the weather ships.

In fig. 2 is shown the 120 hours trajectory for air at the level 850 mb arriving at ocean weather station Juliet

on 9 January 1975. With · is marked the beginning of all trajectories starting in the Azores area and ending at stations India or Juliet. In squares is given the concentration of sulphur in mg/l as analysed in the collected precipitation. The numbers corresponding to Table I are also indicated close to the square. Comparing figs. 1 and 2 we find that the air coming from the high pressure cell near the Azores gave a very small amount of sulphur in the precipitation. The maximum value is 0.18 mg/l and the mean value is 0.10 mg/l whereas the air coming from the North American Continent in general had a considerably higher content. The maximum concentration obtained was 0.59 mg/l, or even in a doubtful case 1.1 mg/l and the mean value was no less than 0.33 mg/l. The absolute reliable maximum recorded at station I was 0.81 obtained when the trajectory started close to the British Isles.

The observations from the Netherland ship Cumulus on three different stations confirmed these results.

Tabell II Data regarding precipitation collected on Dutch ships

Ship station and nr	Collection time Year 73		Position N	Position W - E	Course	Wind Dir.	Beauf	Origin of trajectory N	Origin of trajectory W - E	Trajectory position 2 days before sampling N	Trajectory position 2 days before sampling W - E	Analysis mg/l S	Analysis mg/l Cl	Analysis mg/l Na	Excess S mg/l
∝ 1	23.10	11.45 14.35	62° 00′	32° 30′W	Stopped	110°	5	56°	76° W	49°	46° W	1.28	11.42	6.54	0.73
∝ 2	28.10 29.10	09.55 03.00	62° 00′	32° 59′W	Stopped	210°	5	25° 40°	70° W 106° W	36° 54°	73° W 58° W	0.34	1.78	1.02	0.25
K 1	11.9	09.50 19.00	45° 07′	16° 06′W	Stopped	180°	2	58° 49°	34° W 33° W	42°	26° W	0.67	10.20	5.70	0.19
K 2	11.9	20.20 20.35	45° 06′	16° 18′W	Stopped	50°	2	57°	34° W	42°	21° W	0.20	1.78	0.97	0.12
K 3	19.9	18.45 19.40	44° 36′	15° 36′W	Stopped	310°	3	67°	61° W	53°	27° W	0.20	2.30	1.30	0.09
M 1	7.7 8.7	20.50 08.30	64° 50′	02° 55′E	Stopped	120°	3	58°	38° E	51°	11° E	3.04	10.70	5.94	2.54
M 2	28.7 29.7	23.15 09.30	65° 38′	03° 06′E	Stopped	190°	4-5	34°	49° W	55°	20° W	0.70	4.94	2.52	0.49
M 3	30.7	16.15 23.15	65° 56′	04° 30′E	Stopped	200°	5	59°	67° W	58°	33° W	0.30	6.13	3.42	0.59

At station Alpha about 62°N, 33°W, only 2 acceptable observations were obtained. One trajectory originated

near the Great Lakes in North America. The sulphur content was 0.73 mg/l. The other trajectory is not well defined because there was a great change in the flow pattern between the beginning and the end of the precipitation period. However, most of the time the air seems to have originated not far from the point 35°N, 65°W. The sulphur content was 0.25 mg/l.

At the station Kilo about 45°N, 15°W, we obtained 3 usable samples. The first trajectory originated in the area 55°N, 35°W and the precipitation gave a sulphur value of 0.19 mg/l. The second trajectory started at 65°N, 60°W and the sulphur content in the precipitation was 0,09 mg/l. The third trajectory started at 58°N, 35°W. The sulphur content was 0.12 mg/l.

At station Mike about 65°N, 50°E there were only 3 acceptable observations. 2 trajectories started west of 50°W one in Canada giving the sulphur value 0.59 mg/l and one at 35°N, 50°W giving the value 0.49 mg/l. The third trajectory started in the western part of Russia but then passed down over Central Europe and arrived 2 days later directly from there to the station. Fig. 3. The sulphur concentration value reached the top value of 2.54 mg/l.

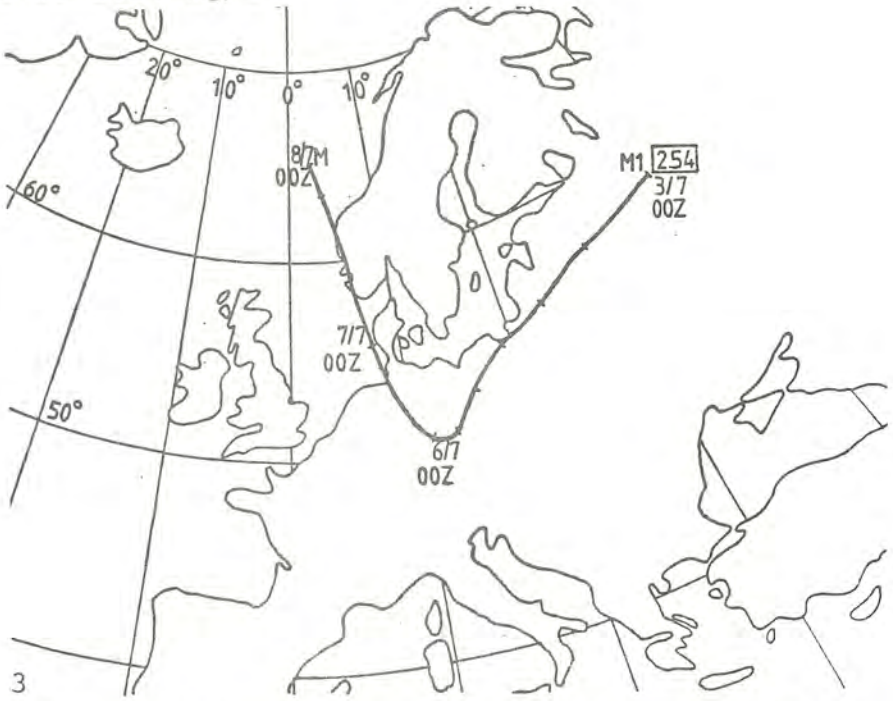

Fig 3
Trajectory at the 850 mb level on 3-8 July 1973. The value of the content of sulphur in the precipitation collected at weather station M on July 8th is given at the starting point of the trajectory as 2.54 mg/l.

Although the data material is rather limited the following observations, considered reliable, are summarized.

1. Air starting west of 50°W and north of 30-35°N five days before the precipitation in stations I and J normally had a content of excess sulphur of 0.2 - 0.6 mg/l. In exceptional cases values of 0.07 and 1.1 were recorded.

2. In one case air starting near the British Isles had the maximal value at station India of 0.81 mg/l.

3. Air starting in the high pressure cell near the Azores and giving precipitation at stations I and J gave precipitation values of about 0.1 mg/l.

4. Observations at stations A, K and M confirm the results obtained from observations at stations I, J and L.

5. Air passing over Central Europe and giving precipitation at station M gave a sulphur content value of 2.54 mg/l.

The following conclusions are drawn.

1. The air coming from North America will probably often contain a certain amount of sulphur (excess sulphur) when arriving in Europe and more so than is contained in air coming from the area of the Azores.

2. The fall out of sulphur with precipitation in central Europe is depending on emission in North America to a small extent, say about 10 % or even less, whereas in Northern Scandinavia where the total content of sulphur fall out is about 0.5 mg/l the North American contribution may raise to as much as about 30 %. This is not only "long range" transport but we have here a true hemispherical transport.

The sulphur content naturally varies with the history of the air. Air involved in precipitation loses its sulphur rapidly whereas air can move long distances

without passing rain or shower areas and in such cases the decrease of sulphur in the air is slow. Bolin and Persson (1975) have discussed the dry deposition and state that this deposition at the earth's surface may be an equally important sink mechanism for atmospheric pollutants. This may be true. However, as the precipitation contains rather large quantities of sulphur at the weather stations India and Juliet it is clear that the dry deposition of sulphur - over the ocean and at least at large distances from the sources - must be very small.

One experience from the sampling of precipitation is that the amount of precipitation collected over the ocean is rather small. Although the collector was set up in order to get as much rain as possible the collected amount was never very large. The disturbances of the circulation of the air created by the ship in its own vicinity may of course reduce the obtained precipitation. Nevertheless, it is difficult to believe that this is the sole reason for the fact that only a small amount of rain is collected. This question, which certainly is important, calls for active research on the intensity of precipitation at sea using radar or other methods independent of the disturbances of the flow of air around the ship.

The low value of sulphur content obtained in the samples collected at station K indicates that the amount of natural sulphur as a matter of fact must be low, probably only of the order 0.10 mg/l which is considerably less than generally assumed. However, this result agrees with the conclusions drawn by L. Prahm et. al. 1975, based on observations of concentrations of sulphur in the air at the Faroe Islands.

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