EVALUATION OF CONCURRENT THERMAL IR ATMOSPHERIC PROPAGATION AND AEROSOL PARTICLE SIZE DISTRIBUTION MEASUREMENTS AT GOTLAND, SWEDEN

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SUMMARY

Measurements of spectrally resolved (2-14 µm) thermal infrared atmospheric transmission were made at the Swedish island of Östergarnsholm in the Baltic. The 908 meter horizontal path was located a few meters above the ocean surface. Concurrent measurements of meteorological parameters and aerosol particle size distribution were also made. The site on the island provides fetches ranging from about 3 km up to several hundreds of km, while very short fetches are provided when the wind is over the island. A variety of meteorological conditions were encountered during the experiments.

A preliminary comparison of the transmission measurements with the bulk meteorological parameters showed some of the expected dependence upon relative humidity, mainly in the 3-5 µm region. A preliminary analysis of the data shows qualitatively a good agreement with both the variation in the meteorological conditions and the variation of the aerosol concentrations for 6 out of 7 of the measurement periods.

1 INTRODUCTION

The imaging geometries of submarine and surface vessel sensors in the littoral zone are not adequately presented in atmospheric propagation models such as LOWTRAN 7 and MODTRAN. As a result, the SPAWARSYSCEN, San Diego, Atmospheric Propagation Analysis (APA) program initiated a series of atmospheric propagation measurements in the coastal atmospheric marine boundary layer (Ref 1,2,3). The most recent of these measurements were made in the Baltic off the east coast of Gotland, Sweden in May 1997. These atmospheric transmission measurements were coordinated with the European Air Sea Exchange Process Studies (ASEPS) program (Ref 4). This program is organized to measure and evaluate processes near the air-sea interface involving air-sea exchange of gaseous species and aerosols as well as the physical and chemical interactions between gasses and aerosols (Ref 5). In particular, TNO-FEL (The Hague) provided measurements of aerosol particle size distributions and meteorological parameters at both ends of the 908 meter transmission path. A range of meteorological conditions were encountered during the measurement period, including high wind speed, long sea fetch conditions which created high sea spray conditions. In this paper, temporal correlations are described between the atmospheric transmission measurements, meteorological parameters, and aerosol particle size distributions.

2 SITE DESCRIPTION

The measurements were made on the island of Östergarnsholm, a low-lying uninhabited island in the Baltic, located 3 km off the East coast of Gotland, Sweden. A 30 meter meteorological mast maintained by the University of Uppsala is located at the southern tip of the island. This site provided a variety of conditions including long fetch (>100 km) open ocean conditions and short fetch with land effects.

The measurement towers at the south end of the transmission path are shown in Figure 1. A view of the transmission path looking south is shown in Figure 2.

The Östergarnsholm site was evaluated for its similarity to U.S. Navy submarine and surface ship operational areas. A study of historical meteorological data for this area was performed and it was found that Östergarnsholm provides conditions similar to typical U.S. Navy operational areas above 50° North.

3 MEASUREMENT TECHNIQUE

Atmospheric propagation measurements were made along a horizontal over-water path from 3 to 13 May, 1997. These measurements were made in the thermal infrared region from 2 to 15 µm. The path length was 908 meters and at a height of approximately 2 meters above the sea surface. The

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measurement path extended across the southwest facing side of the crescent moon shaped island.

The APA technique for measuring transmittance involves measurement of the signal across a long path then quickly realigning the detector to measure the signal along a short path. Atmospheric transmission is then calculated from measurement of the infrared signal received over both a short path and a long path using the definition of transmittance (T) derived from Beers Law.

$$T = e^{-\sigma(R2-R1)} = \frac{S_{long} \text{ at } R_2/\Omega_2}{S_{short} \text{ at } R_1/\Omega_1} \quad (1)$$

σ = attenuation coefficient
S_{short} = Signal Response from the short path source
R_1 = short path length
S_{long} = signal response from the long path source
R_2 = long path length
Ω_1 = solid angle of long path source
Ω_2 = solid angle of short path source

The above calculation includes the ratio of the long path signal to a reference short path. The reference short path (50.4 m) signal was made during a period of low wind speed (5 m s^{-1} from the north and low relative and absolute humidity (50% and 3.7 g m^{-3}) on 4 May.

Due to errors caused by this technique, some transmission measurements are greater than one. A short path laboratory measurement is under investigation which will allow a more accurate calculation of transmittance. In the data presented here, all transmittances will simply be relative to the short path measurement made at the lower humidity. Although this is only a relative technique, it is still useful for finding relative trends over the measurement periods until an adequate laboratory short path measurement can be made.

A CI Systems Model SR-5000 infrared spectrometer is used to measure the signal from the IR source. The spectral resolution of the measurements is an average of 0.0152 µm from 1.3 to 5 µm and an average of 0.061 µm from 8 to 14.5 µm with the use of a circular variable filter wheel. A complete spectral scan is accomplished in approximately 13 seconds. Five spectral scans were taken every eight to ten minutes and then averaged.

The IR source includes a CI Systems Model SR-9 5-inch diameter, clear-aperture collimator with a 38-inch focal length optical system. This collimator system incorporates a two-optical element Newtonian telescope system with a 5-inch diameter, off-axis, parabolic mirror and a 1.5-inch focusing secondary mirror. The CI Systems Model SR-2-33 Blackbody Source is operated at 1000 °C (±1.5 ° C). Emissivity of the source is 0.99.

Aerosol particle size distributions were continuously measured with optical particle counters from Particle Measuring Systems (PMS, Boulder, Colorado). A PMS type CSAS-100-HV probe (PMS3) measuring particles in the diameter range from 0.5-47 µm was placed in a box at a height of about 3 meters above sea level at the south end of the transmission path. This box automatically aligned itself with the prevailing wind. A PMS type CSASP-200 (PMS2) was located in the scaffolding shown in Figure 1 at the south end of transmission path at a height of 10m above sea level. Another PMS type CSASP-200 (PMS4) was placed at the North end of the transmission path, also at a height of about 3 meters above the sea surface. PMS2 and PMS4 measured particles in the diameter range from 0.2-20 µm. The PMS2 and PMS4 were manually rotated into the wind during transmission measurement periods.

Meteorological parameters were measured using automatic recording weather stations places at the south end of the island at about 13m above sea level and at the north end of the transmission path at about 4 m above sea level. Data on wind speed and direction, relative humidity, air temperature and solar radiation were continuously recorded.

4 RESULTS AND DISCUSSION

Concurrent transmission, aerosol and meteorological measurements were made under a wide range of conditions during the campaign. The transmittance data was evaluated for correlation with meteorological parameters and aerosol particle size distributions.

Examples of transmittance and aerosol data are shown in Figures 3, 4 and 5 for the 10 May measurement period. Figure 2 shows a photograph of the waves in the transmission path during the 10 May measurement period. This particular day shows the sensitivity of the transmittance to sudden changes in meteorological conditions and aerosol concentrations.

Figure 3 shows the spectral transmittance data collected during the measurement period. Figure 4 shows a temporal plot of the transmittance data averaged over the three dominant transmission bands including 2.8 to 4.3 µm, 4.3 to 5.5 µm and 7.3 to 13.5 µm. Trends in the transmittance will now be described along with associated meteorological and aerosol parameters.

Figure 4 shows a sudden drop in transmittance at 11:00. The effect was more prominent in the shorter wavelengths. This decrease in transmittance correlates with the sharp increase in particle concentrations (Figure 5) due to the appearance of marine haze and increased humidity at this time. Transmittance then increases again during the next 1.5 hours. Around 1330 another decrease is observed after which the transmission fluctuates around a more constant value.

The above observations can be qualitatively understood from the meteorological conditions and the aerosol concentrations. Variations in relative humidity and atmospheric pressure (not shown) indicate passage of a low pressure front before noon. The wind speed increased to a value of more than 10 m s^{-1} with a long sea fetch (which still must be confirmed by air mass trajectories).

The data in Figure 5 shows an increase of the particle concentrations in both the large and giant aerosols during the high wind speed periods. The increase in the concentrations of the large particles is likely due to the advection of polluted air from industrialized areas in Western or Central Europe (which again has to be confirmed by air mass trajectories). The increase in the concentrations of the giant particles is conjectured to be caused, at least in part, by surface generation of sea spray due to the interaction between wind and waves at wind speed of around 10 m s^{-1} and occasionally higher. The increase in wind speed may give rise to the formation of young waves which break easier than in a well-developed wave field, while the frontal activity may have caused a confused wave field with waves coming from different directions and thus interfering and breaking.

It can also be seen in Figure 5 that the maximum concentration of giant particles was reached before noon and then decreased. The concentration of the large particles continued to increase. With a slightly decreasing relative humidity, the larger particles may be shrinking due to evaporation, thus causing a shift in the size distribution to the smaller particles.

Limitations on paper length preclude including such detailed analysis of all data sets. However, general trends in all the data sets may be found in Tables 1 through 3. A comparison of transmittance in each of the three prominent transmission bands is compared to LOWTRAN 7 predictions and the trends in relative and absolute humidity, wind speed and direction, and the concentration of large (2.2 to 2 μm diameter) and giant (>2 μm diameter) aerosols.

There are a few preliminary trends worth noting. Transmittance in all bands was highest on 3 May when the lowest relative and absolute humidities were measured, as well as the lowest concentrations of both large and giant aerosols. Although the wind speed of 6-14 m s^{-1} is quite high, the NNW wind direction caused the transmission path to be sheltered from the wind by the bulk of the island of Östergarnsholm. This sheltering effect reduced the amount of white caps and sea spray which would be expected at this range of wind speeds. LOWTRAN 7 predictions are also the highest for this date even though the model cannot take into consideration the sheltering effect of the topography.

All data measured and modeled during periods of long sea fetch (S to SSE) show lower transmittance than the sheltered fetch on 3 May. Transmittance does not seem to correlate with any single meteorological or aerosol parameter. For example, transmittance was lowest in all bands on 8 May. However, the relative and absolute humidities were not the highest encountered, the wind speed was very low, and the concentration of aerosols was relatively low. Under these conditions, a relatively high transmittance would be expected compared to other measurement periods.

5 DISCUSSION

Spectrally resolved transmission, measured over a path of 908 m across the bay of Östergarnsholm, was averaged to obtain the transmission in the three dominant transmission bands in the mid- and far IR windows. The trends in the band-averaged transmission has been qualitatively explained in terms of the local meteorological situation and the resulting aerosol particle size distributions. In general, the transmission follows the trends in the relative humidity and aerosol size distributions, with some exceptions. LOWTRAN 7 predictions are also somewhat consistent with measured data.

The observed discrepancies between the aerosol particle size distributions and the observed transmission may be due to effects that cannot be caught in a simple model based on only meteorological parameters. This is illustrated with the example presented in Figure 6 which shows the wind speed dependence of the fine aerosol fraction (particle concentrations integrated over sizes smaller than 1 μm), for wind directions between 110 and 180 degrees (long sea fetch). Clearly, two groups appear with quite different concentrations. In spite of the common meteorological conditions, the air masses are quite different, possibly with different origins. Indeed, the weather maps indicate two different air masses, one originating in clean arctic regions, the other coming from more polluted areas in Europe.

Consideration of the history of the air masses involved and chemical composition will further help to identify the aerosol behavior. This example clearly illustrates that consideration of only the local situation is not sufficient to explain the observed aerosol and transmittance behavior.

Finally, it is emphasized that the measured transmission is relative to signal measured over a 50 m path in clear weather. Hence the transmission values are not absolute, although it is not expected that they will change significantly with laboratory calibration. A final qualitative analysis will be made once the transmission values have been calibrated based on a short-path transmission measurement in the laboratory (in preparation).

6 ACKNOWLEDGMENTS

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7 REFERENCES

1. Law, D.B., Tong, R., Hintz, R., Terpening, L., Edwards, G., Csanadi, C., Tessmer, S., Johnson, C., "Atmospheric propagation analysis program", Technical Report 1577, Naval Command, Control and Ocean Surveillance Center RDT&E Division, San Diego, January 1993.

2. R. Carlson, D.B. Law, C. Csanadi, G. Edwards, and R. Tong, "Thermal infrared transmission through the marine atmospheric boundary layer and LOWTRAN 7 predictions", *Proc. SPIE*, vol 2828, pp. 532-541, August 1996.

3. Carlson, R., Law, D.B., Csanadi, C., Edwards, G., Tong, R., "Thermal Infrared Propagation Across the Surf Influenced Marine Atmospheric Boundary Layer", Proc. SPIE, vol 3125, pp 192-202, July 1997.

4. L.L.S. Geernaert, H. Bergstrom, A.M.J. van Eijk, T. Ellermann, P. Fritz, G.L. Geernaert, J. Hojstrup, B. Jensen, G. de Leeuw, J. Nielsen, B. Pedersen, and A.-S. Smedmann, "Micrometerological Process Study of Gaseous Reactive N-Compounds, BASYS-Workshop, Warnemunde, (Ge), 29-31 Sept., 1997

5. G. de Leeuw, A. van Eijk, and E. Vignati. Aerosol Particle Size Distributions on Östergarnsholm (Sweden). Proc. Nordic Aerosol Symposium NOSA 97, Chalmers University of Technology, Göteborg, Sweden, 23-24 October 1997.

Figure 1. Instrument towers and south end of transmission path on Östergarnsholm, Sweden, 10 May 1997.

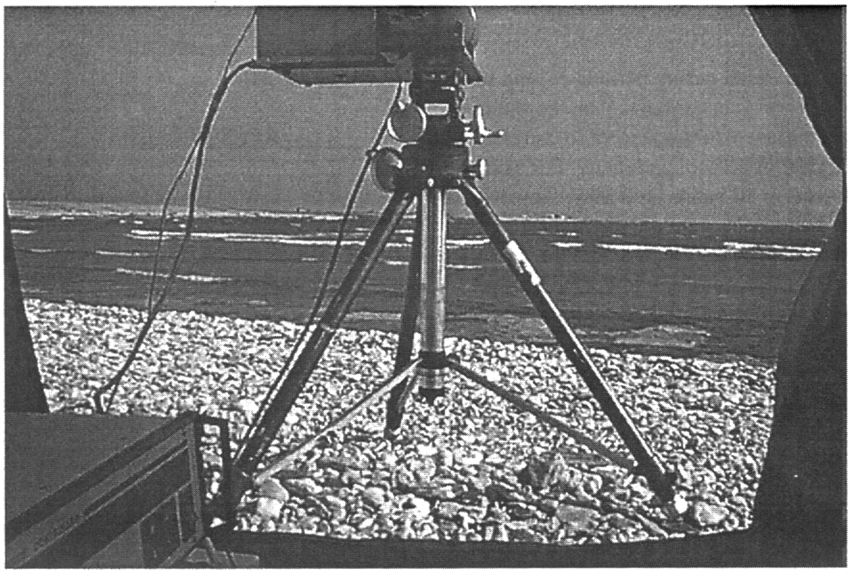

Figure 2. Whitecaps and waves in transmission path under high wind conditions on 10 May 1997. Looking south from IR source.
source.

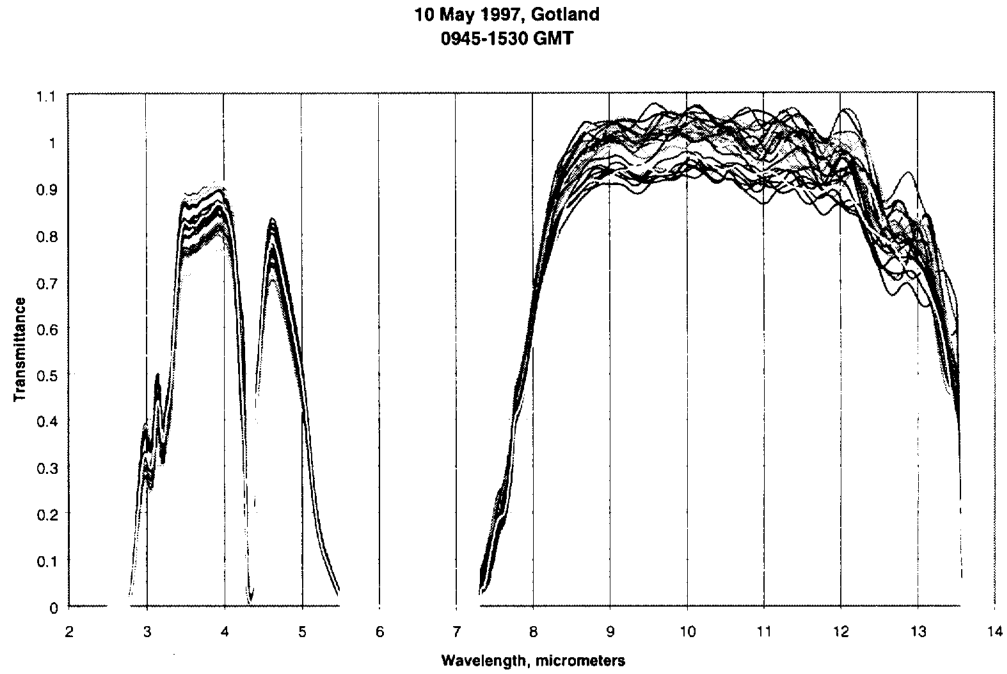

Figure 3. Spectral transmittance measured on 10 May 1997.

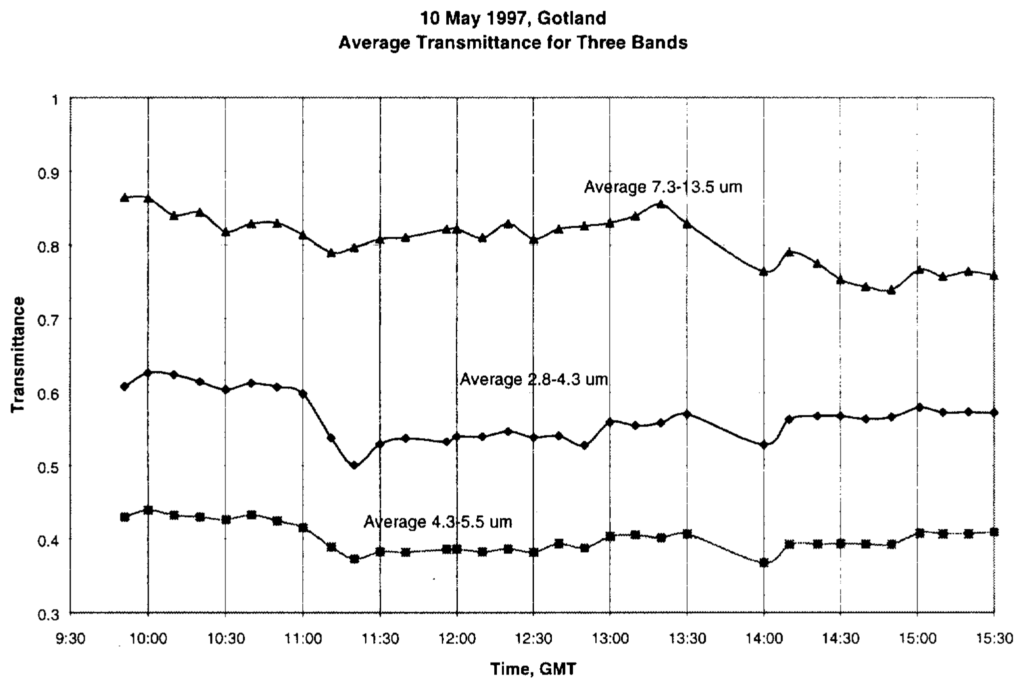

Figure 4. Average transmittance for three prominent band passes plotted over time for 10 May 1997. Note drop in transmittance due to marine haze at 1100.

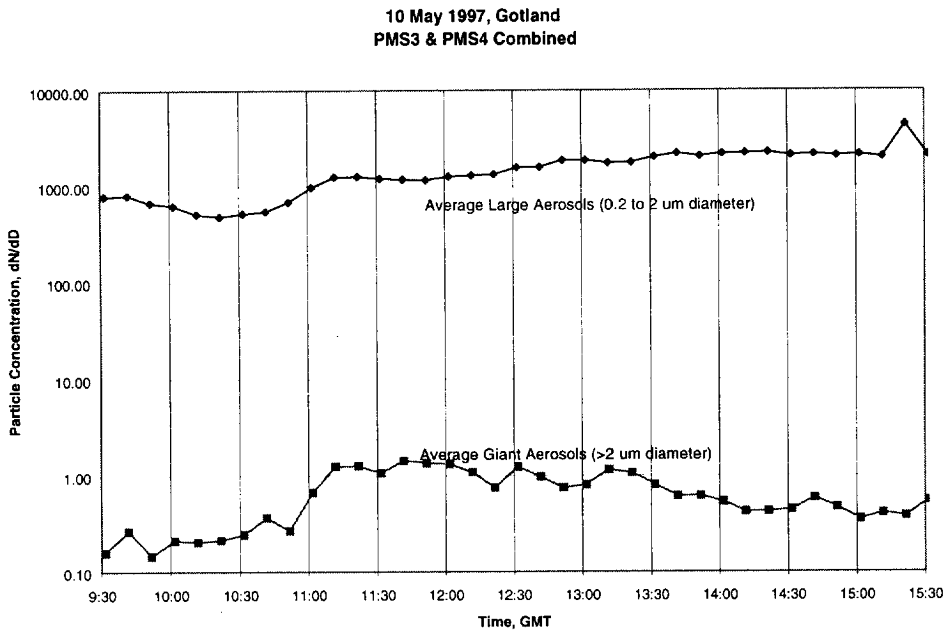

Figure 5. Large and Giant aerosols plotted over time for 10 May 1997. Note the increase in aerosol concentrations due to marine haze at 1100.

Date 1997	RH% avg.	Absolute Humidity gm m-3	Wind Speed m s-1	Wind Direction	**% Trans., 2.8-4.3 μm average**	**PC-TRAN 7** Avg. % Trans., **2.8-4.3 μm**	Large Aerosols 2.2-2 μm diameter dN/dD	Giant Aerosols >2 μm diameter dN/dD
8 May	**65-80**	**5-6**	**2-5**	**SSE**	**50**	**57**	**200**	**0.1**
10 May	85+	6.5	10-15	S	55	53	1000	1
13 May	80	10	2-5	S to SE	55	53	1000	0.1-1.0
11 May	85+	6.3	6-10	S	60	53	900	0.2
12 May	80+	6	2-8	SSE	60	56	1000	0.15
4 May	55-75	4-5	3-7	SSE	65	61	30	<0.1
3 May	**35-40**	**3.5**	**6-14**	**NNW**	**75**	**63**	**30**	**<0.1**

Table 1. Transmittance in 2.8-4.3 μm region sorted in ascending order and compared to LOWTRAN 7 predictions and measured meteorological and aerosol parameters.

Date 1997	RH% avg.	Absolute Humidity gm m-3	Wind Speed m s-1	Wind Direction	**% Trans., 4.3-5.5 μm average**	**PC-TRAN 7** Avg. % Trans., **4.3-5.5 μm**	Large Aerosols 2.2-2 μm diameter dN/dD	Giant Aerosols >2 μm diameter dN/dD
8 May	**65-80**	**5-6**	**2-5**	**SSE**	**35**	**36**	**200**	**0.1**
13 May	80	10	2-5	S to SE	35	32	1000	0.1-1.0
10 May	85+	6.5	10-15	S	40	34	1000	1
11 May	85+	6.3	6-10	S	40	34	900	0.2
12 May	80+	6	2-8	SSE	40	34	1000	0.15
4 May	55-75	4-5	3-7	SSE	45	39	30	<0.1
3 May	**35-40**	**3.5**	**6-14**	**NNW**	**55**	**41**	**30**	**<0.1**

Table 2. Transmittance in 4.3-5.5 μm region sorted in ascending order and compared to LOWTRAN 7 predictions and measured meteorological and aerosol parameters.

Date 1997	RH% avg.	Absolute Humidity gm m-3	Wind Speed m s-1	Wind Direction	**% Trans., 7.3-13.5 μm average**	**PC-TRAN 7** Avg. % Trans., **7.3-13.5 μm**	Large Aerosols 2.2-2 μm diameter dN/dD	Giant Aerosols >2 μm diameter dN/dD
8 May	**65-80**	**5-6**	**2-5**	**SSE**	**60**	**74**	**200**	**0.1**
13 May	80	10	2-5	S to SE	65	69	1000	0.1-1.0
4 May	55-75	4-5	3-7	SSE	75	77	30	<0.1
11 May	85+	6.3	6-10	S	75	72	900	0.2
12 May	80+	6	2-8	SSE	75	72	1000	0.15
10 May	**85+**	**6.5**	**10-15**	**S**	**80**	**71**	**1000**	**1**
3 May	**35-40**	**3.5**	**6-14**	**NNW**	**90**	**79**	**30**	**<0.1**

Table 3. Transmittance in 7.3-13.5 μm region sorted in ascending order and compared to LOWTRAN 7 predictions and measured meteorological and aerosol parameters.

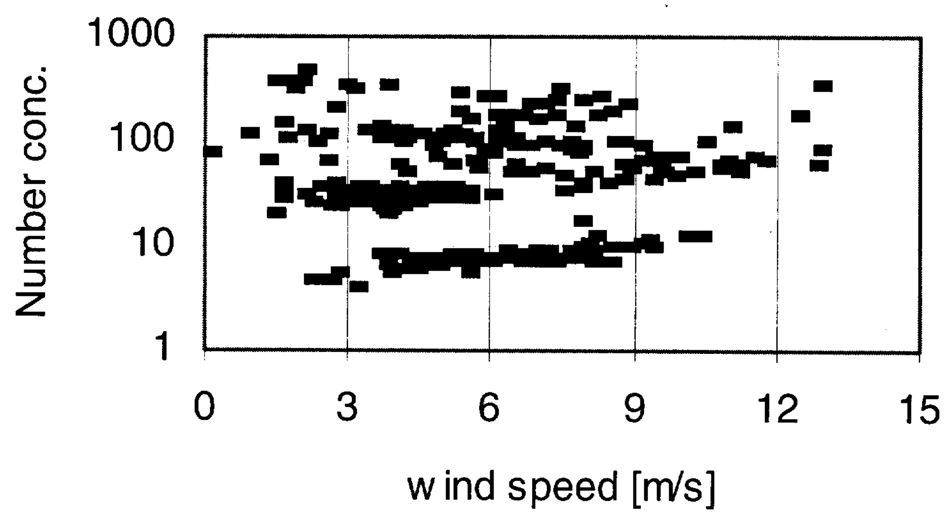

Figure 6. Number concentration of aerosols < 1 μm diameter as a function of wind speed, for wind directions between 110 and 180 degrees (long sea fetch).

PAPER No. 35

DISCUSSOR'S NAME: G. Anderson

COMMENT/QUESTION:

MODTRAN should have full prior capabilities of LOWTRAN aerosols. We will assure that any problems will or have been corrected.

AUTHOR/PRESENTER'S REPLY:

The remark that MODTRAN did not accept the wind speed input referred to the pc version.

PAPER No. 35

DISCUSSOR'S NAME: D. Dion

COMMENT/QUESTION:

In your Mic scattering calculations have you considered a different refractive index for the different air mass origins?

AUTHOR/PRESENTER'S REPLY:

In our Mic calculations we take into account a continental component and a marine component with a different refractive index.