The Three Important Processes Involved

During the later part of the workshop the group was divided into three working parties, each concentrating on one of the three processes:

Mobilization
Transport, and
Deposition

These three sections of this report are based on the findings of the three working parties. It is inevitable, therefore, that there is a certain amount of overlapping between the contents of these three sections.

1 MOBILIZATION

1.1 Introduction

The generation of dust in the Sahara has not been studied extensively. Yaalon and Ganor (1979), in their description of dust emission in Israel, state that desert dust originates from wind erosion of alluvial deposits in desert mountain valleys. Thus fine dust material would be ultimately produced by chemical weathering of primary minerals in mountains. On the other hand, Junge (1979) suggested that some of the desert dust may be produced by crystalline breakage of saltating grains. This latter possibility is supported by evidence of Krinsely and Doornkamp (1973). The generation of fine air-borne particles from semi-arid soils has been described by Gillette (1979) who showed that the ratio of vertical flux of fine particles to horizontal flux of all air-borne particles (roughly equivalent to the saltation flux) is variable with respect to soil mineralogy and wind speed but that in general it was much less than 1%. The production of dust was related to variables of surface soil texture, wind speed, vegetation, vegetative residue, surface roughness, soil aggregate size distribution and soil moisture.

To determine larger scale patterns of dust production in the Sahara, a compilation of Dubief (1952, 1979) on the frequency of occurrence of dust storms in different areas provides a valuable foundation for future studies. Discussions by Dubief (1979) and Kalu (1979) established that there are different kinds of disturbances affecting different parts of the Saharan area during different seasons. In the winter they are connected with the Mediterranean polar front and/or with strong upper tropospheric troughs. In summer they are related to the easterly waves associated with the Intertropical Convergence Zone.

The impact of human action can considerably increase wind erosion through: cultivation (for subsistence and market economy), improper grazing, unsuitable trampling by animals, cutting wood for fuel or other use, certain types of tourism, etc.

There are also many means for human action to limit wind erosion: exclusion from grazing (seasonal or pluriannual), scattering of numerous wells with small water discharge fitted to the grazing capacity of the land, limitation of cultivation to cover nutritional needs (only in areas with high erodibility), preferably limitation of settlement to a reasonable level, watershed management, and appropriate soil conservation techniques.

1.2 Research aspects

A. Surface Conditions

Aside from the aerodynamic conditions which are partially determined by the surface, the generation of dust is determined by surface conditions. The conditions listed below are the primary factors effecting erodibility for a given surface wind stress and the threshold velocity for raising dust.

Disintegration of soil aggregates and discrete particles into suspendible dust particles. Experiments should be undertaken to determine the amount of crystalline breakage and production of fine particles from coarse particles. This study, along with quantitative estimates of generation of fine particles from dunes and from alluvial deposits with fine material available will be helpful in estimating the relative importance of these processes for the production of fine particles.

Soil. The chief condition determining erodibility is the size distribution of surface soil aggregates. These aggregates, which may be in the form of a surface crust, large clods, or small pellets of soil, largely determine the threshold velocity and intensity of erosion. The stability of the aggregates determines future erodibility if more soil moisture is not forthcoming. Thus we should know the relationship of the size distribution of soil aggregates with physical properties, surface texture, modulus of rupture, soil moisture and compaction, and with chemical properties such as soil mineralogy and organic content. Organic studies should include organic films generated by soil microorganisms which tend to stabilize soil aggregates.

Vegetation. Vegetation exerts an influence in various ways: by the stabilization of soil by roots, by the absorbtion of some momentum flux to the soil surface, by alteration of the moisture and heat exchange to the soil, and by decay, which adds organic material to the soil. Soil erosion produces a negative effect on vegetation through the sand blasting effect of saltating sand grains on the plant leaves and stems. Studies should be undertaken to develop species of plants that are more resistant to this hazard. Studies should further be undertaken using a systematic approach to determine vegetation-desert soil interactions.

Plant litter. This material protects the surface by covering the soil. Upon decomposition, humus is added to the soil. Studies of plants that provide the best protective litter should be undertaken.

Rocks and boulders. These elements provide the surface with non-erodible elements which absorb part of the wind stress. They also disturb the wind field in general and can concentrate the wind in certain regions. This alteration of the wind should be studied.

Microscale roughness. Roughness of the soil traps sand grains and inhibits saltation. The distribution and cause of this surface roughness should be surveyed.

B. Geomorphological and Topographical Surface Conditions

Wind velocity is greatly modified either by single topographical components such as hills, mountains or large watersheds (in which valleys exert an influence), the (even slight) degree of slope of embankments, the cliffs (leeward or windward), pediments and alluvial fans. For this reason typical erosion and deposition patterns may be associated with geomorphological forms. Study methods should be based upon:

- statistical study of the frequency of 'dust-winds' in meteorological stations located at the pediment base;
- information provided by the indigenous population and by local geographical names;
- aerial photographs and ground checks;
- satellite images.

C. Wind Conditions

Measurements of wind profiles indicate wind stress which along with such factors as soil, vegetation, plant litter, rocks and boulders and microscale roughness, permits estimates of erodibility in most circumstances. Studies of how surfaces affect the wind flow, concentrating the wind in certain regions, should be carried out. Studies should also be made of threshold values for wind velocities with regard to dust mobilization under different surface conditions.

D. Large Scale Weather Mechanisms

The logical way to study such mechanisms is to make synoptic meteorological case studies of typical dust-storm conditions at the surface and upper levels of typical disturbances during different seasons. Satellite images of dust-storms are highly desirable for these studies. The weather maps should encompass a sufficiently large area to permit studies of the relation of disturbances to the general weather situation, and to permit investigations of dust transport from the Saharan area into other areas, particularly westward over the Atlantic, northward over the Mediterranean or eastward across the Red Sea.

*E. Statistical Studies of Air-borne Dust Over the Saharan Area Based on SYNOP and METAR Reports.**

The SYNOP and METAR reports contain valuable information on air-borne dust, permitting a study of frequency distribution in space and time. Such studies may reveal sources and sinks of desert dust.

An important factor in relation to air-borne dust is the critical wind speed for the raising of dust. Apart from wind-tunnel experiments and similar research, these SYNOP and METAR reports could be utilized for studying this problem, particularly through the information they provide concerning wind speed, present weather and visibility. Such studies should, however, be done only after a careful evaluation of the reliability of the reports in different regions of the Saharan area.

Several studies have indicated that there is a relationship between the visibility and the mass concentration of dust in certain particle size ranges even if this relation is fairly vague. A statistical study over the Saharan area of the visibility, as included in the SYNOP and METAR reports, could contribute to the knowledge of the distribution of air-borne dust in this area. Such a study should be supplemented by a systematic comparison of visibility and dust load at a few selected sites.

1.3 Monitoring aspects

As regards monitoring of air-borne dust in Africa, the group concluded that it is essential that some immediate steps be taken. The following action is proposed:

- initiating further studies of the best methods for observation of dust deposition, including comparisons between different methods;
- adding regular observations by high volume samplers of suspended particulate matters at all regional stations and at a selection of climatological stations in Africa north of the Equator. Analysis of content of suitable mineral and organic trace elements and of particle size distribution;
- adding wind observations as necessary at suitably distributed stations over Africa north of the Equator for establishment of the relationship with air-borne dust frequency;
- encouraging the establishment of further WMO regional air pollution stations in the area with the specific purpose of monitoring particulate matter.

2 LONG RANGE TRANSPORT

2.1 Introduction

The problem of the long-range transport of Saharan dust consists of two major parts:

The documentation of dust in the air, both for the area within and outside the

*SYNOP and METAR are coded routine reports on weather observations.

Sahara, and the possible impact of this dust on both the ecology of the adjacent areas and the regional and global climate.

To evaluate any possible effect of Saharan dust on the ecology and on climate not only within but also beyond the area of the Sahara, it is necessary that the phenomenon of this dust in the atmosphere, its transport, and its short and long term variations be much better documented and understood.

2.2 Dust in the Sahara

Essential for any understanding of the phenomenon of Saharan dust in the atmosphere is an adequate knowledge of the source areas, their location and strength and the seasonal and more long-term variations. Such information will enable more reliable estimates to be made of the fluxes leaving the Sahara, their further fate in the atmosphere and their composition. A suitable starting point to obtain such data is provided by the statistics compiled by Dubief (1952, 1979), which cover a period of over 20 years from 1929 to 1950. This information should be supplemented by a thorough statistical evaluation of available weather observations which have accumulated in the meantime. For the purpose of studying long-range transport, a spatial resolution of $5^\circ \times 5^\circ$ of sources of air-borne dust in the Saharan area and its surroundings is considered sufficient. The time resolution should be in accordance with the variability of the observed dust concentration, but for most global considerations monthly mean values would seem sufficient.

As mentioned in Section 1.2 E, it would be desirable to make a statistical investigation on weather data based on SYNOP and METAR reports.

These simple statistics should be supplemented by synoptic studies based on weather maps. Such investigations should cover a period of a few years in order to obtain sufficient representative information on the origin and behaviour of the dust storms and the resulting direction of the dust transport. This would certainly be a major undertaking and it could best be carried out by a synoptic meteorologist visiting the various meteorological services in the affected areas, and making use of the locally available material and expertise. Such a study should be facilitated by the cooperation of WMO.

Two-dimensional horizontal flow patterns, based on mean monthly winds over Africa, are available and were discussed during the workshop (Newell and Kidson, 1979). There are significant differences in the flow patterns between the 1958–63 moist period and the 1969–73 dry period and there are corresponding differences in the global general circulation. It is more difficult to appraise the vertical motion field through the continuity equation and the uncertainties make deduced year-to-year variations unreliable.

While the question of the dust transport by the mean circulation versus that by the transient features was not resolved at the workshop it is highly likely that the two aspects of the circulation are inter-related.

Another aspect of investigation of the Saharan dust phenomenon is the chemical and mineralogical composition of the soil material as a function of particle size, as well as the same information for the aerosols during dust-storms at the same locations. Such information is at present almost completely lacking for the source areas. It would also give important information about fractionation processes between soil and aerosol as a function of environmental conditions and particle size.

The analysis of the dust samples should be made according to both elemental and mineral composition because only this double analysis will permit understanding of fractionation with particle size. It is very desirable also to identify major biological components in the samples, since they may serve as useful tracers.

In addition, it is considered desirable to have aircraft data on the vertical distribution of dust over the Sahara.

The sample collection should cover all areas of the Sahara that may function as dust sources and should be made in such a way as to constitute a representative and unique data bank. It is essential that in all cases sufficient reserve samples should be stored for future research and follow-up studies. It is most essential that the sampling be done by scientifically trained personnel and that it should be supplemented by mapping expeditions carried out by a team of soil scientists, geologists and mineralogists. Again, this program should be organized in such a way as to obtain maximum support from the appropriate international organizations.

For study of the possible ecological and climatological impact, it is essential to have information on the long-term trends of the strength, location and composition of the Saharan dust sources. From the available evidence it is clear that considerable changes have occurred on all time-scales, including the ice ages. It is most likely that both natural changes of the climate and man-induced modifications of the ecology are involved, but these processes are very difficult to separate. Any attempt to clarify these questions should involve the most complete compilation of all available evidence from geology, sedimentology, hydrology, archeology, etc. Some of this evidence is already available in meticulous studies, such as those by Nicholson (1976) and Street and Grove (1976), but further studies of this type should be made in other fields of research.

Changes in source strength over periods of, say 10–20 years may also be significant. There have been suggestions that an observed three-fold increase in the dust concentration in Barbados between 1965 and 1976 might be due to an increase in source strength in the Sahara, possibly associated with the drought in the Sahel (Prospero and Nees, 1977). However, the observed increase could also be due to changes in the circulation pattern and the real cause has yet to be determined. Furthermore, some measurements (Jaenicke and Schütz, 1977) close to the Sahara indicate that no major change in source strength occurred in recent years.

2.3 Dust outside the Saharan area

There are several well-documented cases where an atmospheric transport of Saharan dust over distances of up to several thousand kilometres has been evident.

Probably the best known such situations refer to the transport westwards across the Atlantic at a latitude of about 10°N to 25°N (Carlson and Prospero, 1972), and the transport north-east to Israel (Yaalon and Ganor, 1979). These transports have been documented by measurements of turbidity and of dust concentration in the air (Prospero *et al.*, 1979) and have also been confirmed by satellite images.

There is also no doubt that a considerable transport of dust takes place from an area southwest of the Tibesti region of the central Sahara into the countries along the northern coast of the Gulf of Guinea (Kalu, 1979). Occasional intrusions of Saharan dust into Europe as far north as Scandinavia have also been documented. Our knowledge about possible transports of Saharan dust towards the east and south-east is very limited. However, satellite images have shown several cases of dust-storms moving in an ESE direction over the Red Sea. No significant transport of dust into the southern hemisphere has been observed and there are good reasons to believe that such a transport is effectively hindered by the precipitation scavenging associated with the intertropical convergence zone (ITCZ).

Regarding the meteorological processes that give rise to the mobilization and long-range transport of dust it is important to know whether they are more or less continuous processes or if they take place only under very special circumstances. In the former situation it would be pertinent to concentrate the study on the mean circulation pattern. In the latter case, we should of course concentrate our study on those particular occasions. From the information available it seems that there is a rather continuous transport of smaller dust particles (less than 1 μm) out over the Atlantic but that the transport of larger particles is more discontinuous. This is reflected in the relatively small variation of turbidity out over this area in contrast to the relatively larger day to day variations of total particle load (Prospero *et al.*, 1979; Jaenicke and Schütz, 1977). The transport in the north-easterly direction is probably a less continuous process. The conclusion is that we need to study both the mean circulation and the typical circulation patterns for situations when the transport is augmented. By getting to know the weather patterns that are conducive to long-range transport and by studying the variations of their frequency of occurrence, we might be able to establish whether changes in the observed dust concentrations can be explained by such variations.

2.4 Possible climatic effects of Saharan dust

It has been estimated that the contribution of Saharan dust to the total burden of tropospheric aerosols is about 60–200 million tons per year (Junge, 1979). This should be compared with other sources of mineral dust in the world estimated at roughly 200 million tons per year. It is clear that the Sahara is a very important source and that appreciable variations in its strength could have significant implications on the regional and global burden of mineral dust. This implies that changes in the dust output from the Sahara (be they natural or man-made) is of potential significance for the regional and global climate. However, quantitative estimates of such impacts have yet to be made. Among specific mechanisms of such impact on climate, one may mention:

- radiation effects in cloud-free air;
- effects on cloud albedo and
- effects on the formation of clouds and raindrops (condensation and ice nuclei).

A better understanding of these possible impacts does not depend so much upon the collection of more observations of the aerosols as upon a better understanding of the physical processes involved. However, it is imperative that reliable vertical profiles of the aerosol concentration are available.

2.5 Measurement and monitoring aspects

Appropriate techniques

There are two principal methods for measuring soil dust concentrations in the atmosphere which can be recommended at the present time. For areas with relatively high concentrations of soil dust (within the Sahara, or in dust plumes outside the Sahara) the desert derived insoluble fraction dominates and can be determined with high volume samplers by weighing filter samples. If the concentrations are less there may be significant fractions of aerosol components other than mineral dust present. In this case the total aerosol no longer represents soil dust and it is recommended to use more sensitive and specific methods, such as to analyse filter samples for silicon, iron, aluminium, or other elements which originate exclusively from crustal sources and to subsequently correct for average crustal composition. If the samples contain considerable fractions of particles larger than 10 μm radius, care should be taken to make the sampling isokinetic. The techniques mentioned have been used successfully in a variety of research projects and are well documented in the literature.

Monitoring of soil derived dust in the WMO network

Since rather large variations of the global production of soil dust occur and can be expected to continue in the future, it is recommended to monitor the soil dust component of the aerosol at the baseline and regional stations with an extended program of the WMO network of monitoring stations all over the globe.

For long range monitoring, weekly or monthly sampling is generally satisfactory but daily observations would be desirable for certain specialized research programs, for example, when the relation to transport trajectories is investigated. The samples should be analysed by a central laboratory to ensure comparability and high quality. The most suitable technique of choice is the elemental analysis of filter samples discussed above.

3 DEPOSITION

3.1 Introduction

Loess and other eolian deposits in soils of the desert fringe area present an excellent record of past rates and variations in dust deposition and could help in understanding natural trends or the influence of man on deposition. Saharan dust is the source for loess deposits in places such as Israel, the Nile Valley and the Cape Verde Islands (Matznetter, 1960). It has even been suggested that it also may be the origin of some soils on islands in the western Atlantic such as Bermuda, the Bahamas and the West Indies (Bricker and Prospero, 1969).

Studies, like those carried out in Israel, should be extended to circum-Saharan regions, with particular attention to the distribution of loess and to the eolian contribution to quaternary soils. As the rate of dust deposition seems to be a function of the distance and nature of the desert source, such studies would indicate past cycles of extension or recession of the desert. Detailed stratigraphic studies on carefully selected sites – e.g. from Tunisia and Israel – should be correlated with similar studies of deep sea cores off the West African coast, Barbados, the Mediterranean and other places where a fairly complete stratigraphic record is available. Recent studies have shown that many soils in desert fringe regions, in addition to the obviously loessial ones, have received considerable supplements of desert dust. Each case requires a specific analysis because of the slow but steady deposition the dust becomes totally assimilated in the soil forming environment. It seems desirable to carry out studies of dust contribution to soils, e.g., in northern Nigeria, the delta area of Egypt, the Sudan and Tunisia. Such studies would reveal not only the past extent of dust deposition but would also assess the posssible contribution of dust to the fertility of the soils and hence its ecological function. The studies should be made in conjunction with monitoring of the present rate and nature of dust deposition in desert fringe areas.

The ecological impact of dust transport in desert fringe areas may have been beneficial in the past; however, this process could easily be reversed by inappropriate land use, causing the desert fringe region to become a dust source rather than a dust accumulator. Careful attention must be given to dust generation processes during development projects whether agricultural or industrial in such areas, – particularly since the effects of the dust on human health are unknown.

3.2 Possible ecological effects of Saharan dust

There appears to be no reliable data, collected systematically over an adequate number of years, on the quantity, periodicity and chemical composition of dust received by soils of natural and agricultural ecosystems in oases, desert fringes and more distant peripheral vegetation. Such deposition is of particular importance with respect to the possibility of dry-flushing effects of dust with macro-nutrients (e.g. K, P, Ca, Mg, S) and with micro-nutrients (e.g. B, Mn, Co, Cu, Zn, Mo) in an oasis.

Studies are needed on the nutrient regimes of such soils and the dynamics of nutrient inputs via dust in order to determine whether air-borne deposition represents a significant percentage of the 'total', 'plant-available' and 'supplying-power' for nutrients in different soil-types.

It is also important to investigate whether the dust deposition (including any organic materials) enhances the physical soil structure for plant growth, possibly in conjunction with soil micro-biological investigations designed to relate dust receipt to micro-organism activity. Consideration should also be given to similar studies in different vegetation types in peripheral areas of deserts. Such studies would necessitate an experimental review of available inexpensive deposition gauges.

The ecological impact of dust deposition on marine life off near-shore and coastal deserts also requires attention and investigation. The deposition of nutrients associated with Saharan dust into ocean waters may under certain conditions contribute significantly to the productivity of the surface waters, for example, off the coast of West Africa (Lepple, 1975; Lundholm, 1979). Since phosphorus is probably the most important element in this connection we recommend that measurements of this element be made in different particle size ranges. This will enable the deposition to be quantitatively estimated. The importance of deposition of phosphorus on terrestrial ecosystems also needs to be investigated.

There is little doubt that, in the tropical and subtropical Atlantic east of the mid-Atlantic ridge, a major part of the non-biogenic sediment is of Saharan origin.

Saharan dust most likely also gives significant contributions to the sediments in the Mediterranean and in the western parts of the equatorial Atlantic. Study of these sediments may provide useful information about the past climate of the desert regions (Parkin and Shackleton, 1973).

There is also evidence that the dusty environment with its different components may affect human health. Attention should be drawn to the transport of potentially toxic elements from surface-mining and other human activities in the desert situation and to their possible bioaccumulation in food-chains, bearing in mind the ease with which a deposited pollutant may be resuspended under arid conditions. This latter item is of special importance for the Sahara, which is surrounded by grazing lands.

3.3 Measurement aspects

In order to understand the importance of atmospheric dust deposition and its effect on soils and organisms at different ecological sites, we recommend the collection and analysis of soil deposition from deserts and surrounding dry-land fringes.

A generally accepted standard method for measuring dry fall-out or dust deposition does not exist (cf. conclusions from the Report of the WMO Expert Meeting on Dry Deposition, Gothenburg, April 18–22, 1977) (WMO, 1977). However, for specific research purposes where only relative measurements are needed, several methods can give acceptable results.

In order to obtain as valuable data as possible with deposition gauges it is necessary that:

- the terrain be characterized with respect to surface roughness and 'filtration efficiency' of vegetation cover;
- the aerosol be characterized with respect to its particle size distribution and mean horizontal velocity;
- calibration studies be carried out where the deposition of an aerosol to a gauge in different types of terrain is correlated to the deposition on the ground. The calibration curve so obtained could then be used to estimate actual deposition so long as there is no major change in the aerosol or terrain type.

Several types of dust deposition collectors which are in use elsewhere are recommended for testing in desert and semi-arid areas, namely:

- dust collectors with beads of glass or plastic for collection of dry and wet fall-out (Yaalon and Ganor, 1979);
- buckets with water, as used in dust pollution studies;
- moss bags or other retentive surfaces, used until now mainly in highly polluted areas, may prove useful also for the analysis of the chemical composition of desert dust.

3.4 Research aspects

Because of the close inter-relationships between meteorological, pedological and biological studies in these proposals, it is desirable to develop a carefully co-ordinated integrated programme at each of the field sites under investigation.

– A careful study should be undertaken of all loess deposits and their stratigraphy on the northern and southern fringes of the Saharan desert. Stratigraphic analysis and dating of the sedimentary and pedogenic cycles should be made, using all of the modern techniques of radioactive, paleomagnetic and archaeologic dating.

– Specific pedologic studies should be undertaken to identify dust contribution in the soils of northern Nigeria, the Nile delta and Gezira, using geochemical, mineralogical and biological methods. These studies should be made in conjunction with monitoring the present rate and nature of dust deposition for purposes of comparison.

– To identify more accurately the actual sources of long distance transport of dust from the desert, a field study of suspected desert areas should be undertaken and samples collected from representative surfaces which characterize the source area. As clay minerals seem to be particularly sensitive to climatic influences, special attention should be given to these components in dust, soils, oceanic cores etc.

– A comprehensive nutrient budget of a selected typical oasis should be carried out over a period of several years.

– Methods of dust collection used in various places should be tested for their applicability on the desert and desert fringes and made more widely known. Particular efforts should be made to standardize methods and thus improve comparisons.

– Historical records of dust deposition have been provided by analysing the content of eolian dust in cores from glaciers in the Caucasus. This method could also be tried for suitable glaciers in other areas, e.g. the Alps for the dust plumes from North Africa.