A brief survey of meteorology as related to the biosphere

by C.C. Wallén

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## CONTENTS

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Foreword</strong></td>
</tr>
<tr>
<td><strong>Summary (English, French, Russian, Spanish)</strong></td>
</tr>
<tr>
<td><strong>Chapter I — Introduction</strong></td>
</tr>
<tr>
<td><strong>Chapter II — Solar energy and the ecosystem</strong></td>
</tr>
<tr>
<td><strong>Chapter III — The atmosphere and the ecosystem</strong></td>
</tr>
<tr>
<td>1. Weather and climate</td>
</tr>
<tr>
<td>2. Studies of atmospheric processes in ecosystems</td>
</tr>
<tr>
<td>3. Atmospheric processes and climate in large-scale ecosystems</td>
</tr>
<tr>
<td>4. Atmospheric processes and climate in small-scale ecosystems</td>
</tr>
<tr>
<td>5. Atmospheric processes and climate in meso-scale ecosystems</td>
</tr>
<tr>
<td>6. Interrelation between climatic conditions in ecosystems of different scales</td>
</tr>
<tr>
<td>7. Changes of climate in ecosystems</td>
</tr>
<tr>
<td>8. Meteorology and the modelling approach to studies of ecosystems</td>
</tr>
<tr>
<td>9. WMO activities in relation to studies of ecosystems</td>
</tr>
<tr>
<td><strong>Chapter IV — Man’s impact on his atmospheric environment and global climate</strong></td>
</tr>
<tr>
<td>1. Introduction</td>
</tr>
<tr>
<td>2. Low-concentration pollution in the atmosphere</td>
</tr>
<tr>
<td>3. Man’s impact on global climates</td>
</tr>
<tr>
<td>4. High-concentration air pollution in local areas</td>
</tr>
</tbody>
</table>
### Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5. Meteorology and other detrimental effects of air pollution on the biosphere</td>
<td>22</td>
</tr>
<tr>
<td>6. Modification of weather</td>
<td>23</td>
</tr>
<tr>
<td>7. Modification of climates</td>
<td>25</td>
</tr>
</tbody>
</table>

**Chapter V — Meteorology and the aquatic parts of the biosphere**

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Introduction</td>
<td>27</td>
</tr>
<tr>
<td>2. Meteorology and the water cycle</td>
<td>27</td>
</tr>
<tr>
<td>3. Meteorology and the oceans</td>
<td>27</td>
</tr>
<tr>
<td>4. Meteorology and inland waters</td>
<td>28</td>
</tr>
</tbody>
</table>

**Chapter VI — Human biometeorology**

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Introduction</td>
<td>31</td>
</tr>
<tr>
<td>2. Assessment of reactions to changes in the atmospheric environment</td>
<td>31</td>
</tr>
<tr>
<td>3. Influence of meteorological elements on physiological processes</td>
<td>31</td>
</tr>
<tr>
<td>4. Influence of weather and climate on man</td>
<td>32</td>
</tr>
<tr>
<td>5. Requirements of man for modifications of climatic stresses</td>
<td>33</td>
</tr>
<tr>
<td>6. WMO activities related to human biometeorology</td>
<td>33</td>
</tr>
</tbody>
</table>

**Chapter VII — Animal biometeorology**

| References                                                                 | 37   |

**Appendix A — WMO activities in relation to monitoring and acquisition of scientific knowledge of the bio-physical environment**

| Appendix B — WMO statement on weather modification                       | 53   |
FOREWORD

Man is becoming increasingly aware that his environment must be protected. To understand the problems involved in the conservation of environmental resources it is necessary to appreciate how physical and biological processes interact in the creation and maintenance of these resources, and how man's impact on the various ecosystems that make up the biosphere may lead to their deterioration. Weather and climate are naturally basic elements in these complex systems and it is therefore important to know how meteorological and hydrological information can be used for their preservation and development. This publication, the fourth in the series of WMO special environmental reports, attempts to achieve this objective in pointing to the importance of meteorological and hydrological knowledge in solving environmental problems related to the biosphere. It also gives a brief review of relevant activities of WMO.

I am confident that this report will be welcomed by many scientists, technologists and students, who, in their efforts to improve their understanding of the current problems of the biosphere, wish to consider the role of meteorology and hydrology. The report is also relevant to the development of various projects within the Unesco Man and the Biosphere Programme in which such factors play a fundamental role.

This paper was prepared in the Special Environmental Applications Division, Meteorological Applications Department, of the WMO Secretariat by Dr. C. C. Wallén.

D. A. Davies
Secretary-General
SUMMARY

This publication reviews briefly for the non-specialist how meteorology is involved in studies of the biosphere. After defining the biosphere and the ecosystem, the note explains the importance of solar energy to all processes in the biosphere, particularly those connected with the formation of weather and climate.

The note then proceeds with the description of the dependence of ecosystems of various scales on meteorological processes and climates. The interrelationship between the meteorological processes and the climates in ecosystems of different scales is discussed and also the changes of climate occurring in these systems. A special chapter is devoted to the importance of meteorological factors which have to be included in mathematical models of ecosystems. The WMO activities related to studies of ecosystems are also referred to.

The note continues with the discussion of how man may influence his atmospheric environment by high-concentration air pollution in local areas and rising low-concentration air pollution all around the globe. A discussion on the possible impact of man's activities on regional and global climates presents recent views on this controversial subject. In connexion with man's influence on the atmosphere, the present stage of weather modification and climate modification is briefly considered.

A separate chapter describes briefly the involvement of meteorology with the biota in oceans and inland waters and in the concluding chapters reference is made to the present state of knowledge in the fields of human and animal biometeorology.
Cette publication examine brièvement, à l'intention du non-spécialiste, le rôle de la météorologie dans les études de la biosphère. Après avoir défini la biosphère et l'écosystème, l'auteur explique l'importance que l'énergie solaire revêt pour tous les processus dans la biosphère, notamment pour ceux qui sont liés à la formation du temps et du climat.

Le rapport contient ensuite une description de l'influence exercée sur les écosystèmes de diverses échelles par les processus météorologiques et les climats. L'auteur étudie les relations entre les processus météorologiques et les climats dans des écosystèmes de différentes échelles, ainsi que les changements de climat se produisant dans ces systèmes. Un chapitre spécial est consacré à l'importance des facteurs météorologiques, qui doivent être inclus dans les modèles mathématiques des écosystèmes. Il est également fait état des activités de l'OMM relatives aux études des écosystèmes.

Le rapport se poursuit par une étude de la manière dont l'homme agit sur son environnement atmosphérique en causant une pollution locale de l'air de forte concentration, ainsi qu'une pollution de faible concentration, qui cependant augmente sur l'ensemble du globe. Un exposé des conséquences que peuvent avoir les activités humaines sur les climats à l'échelon régional et mondial présente des points de vue récents sur cette question controversée. À l'occasion de l'étude de l'influence de l'homme sur l'atmosphère, l'auteur examine brièvement la situation actuelle en ce qui concerne la modification artificielle du temps et du climat.

Un chapitre distinct décrit brièvement les liens entre la météorologie et la vie dans les océans et les eaux intérieures ; dans le dernier chapitre, l'auteur fait le point de l'état actuel des connaissances dans les domaines de la biométéorologie humaine et animale.
РЕЗЮМЕ

В настоящей публикации приводится краткий обзор для неспециалистов о роли метеорологии в исследованиях биосферы. Дан определение биосферы и экосистемы, автор поясняет важную роль солнечной энергии для всех процессов в биосфере, в частности тех, которые связаны с формированием погоды и климата.

Затем в записке приводится описание зависимости экосистем различных масштабов от метеорологических процессов и климатов. Описывается взаимосвязь между метеорологическими процессами и климатами в экосистемах различных масштабов, а также изменения климата, происходящие в этих системах. Отдельная глава посвящена важной роли метеорологических факторов, которые должны быть включены в математические модели экосистем. Делается также ссылка на деятельность ВМО, связанную с исследованием экосистем.

Затем обсуждается изложение вопроса о влиянии человека на окружающую его атмосферную среду путем высокой концентрации загрязнения воздуха в локальных областях и повышения низкой концентрации загрязнения воздуха по всему земному шару. Описание возможного влияния деятельности человека на региональный и глобальный климаты отражает последние точки зрения по этому противоречивому вопросу.

В связи с влиянием человека на атмосферу кратко рассматривается существующее положение дел в отношении активных воздействий на погоду и климат.

В отдельной главе кратко описана роль метеорологии в жизни океанов и внутриматериковых вод, а в заключении главы говорится о существующем уровне знаний в области биометеорологии человека и животных.
RESUMEN

En la presente publicación se examina sucintamente para los no versados en la materia cómo la meteorología está relacionada con los estudios de la biosfera. Después de definir la biosfera y el ecosistema, en este documento se explica la importancia que para todos los procesos de la biosfera reviste la energía solar, particularmente para aquellos procesos relacionados con la formación del tiempo y del clima.

En el documento se describe a continuación de qué forma los ecosistemas de diversas escalas dependen de los procesos meteorológicos y de los climas. Se examina asimismo la interrelación que existe entre los procesos meteorológicos y los climas en los ecosistemas de diferentes escalas e igualmente los cambios climáticos que se producen en esos sistemas. Se consagra un capítulo especial a la importancia que revisten los factores meteorológicos que han de incluirse en los modelos matemáticos de los ecosistemas. También se alude a las actividades de la OMM relacionadas con los estudios de los ecosistemas.

Se analiza seguidamente la forma en que el hombre puede influir en el medio atmosférico que le rodea mediante una contaminación del aire de alta concentración en zonas localizadas, y provocando una contaminación de bajas concentraciones en el aire alrededor del globo. Al examinar las posibles consecuencias de las actividades humanas en el clima regional y mundial, se exponen las más recientes opiniones sobre este tema tan sujeto a controversias.

En lo que respecta a la influencia que ejerce el hombre en la atmósfera, se examina sucintamente el estado en que actualmente se hallan las actividades de modificación artificial del tiempo y del clima.

En un capítulo aparte se describe sucintamente la relación que existe entre la meteorología y los seres orgánicos de los océanos y de las aguas ubicadas tierra adentro, y en el capítulo final se alude a los actuales conocimientos que se tienen en materia de biometeorología humana y animal.
CHAPTER I

INTRODUCTION

An Austrian geologist, Eduard Suess, casually introduced the concept of the biosphere into the realms of science almost one hundred years ago. However, it was not until 1926 when a Russian mineralogist, Vladimir Vernadsky, published his concept of the biosphere, that the idea became established in the scientific world.

The biosphere may be defined as the boundary layer at the Earth’s surface where physical processes within the lithosphere, the hydrosphere, and the atmosphere interact with biological processes to form complex systems (ecosystems) constituting the portion of the Earth occupied by the various forms of life such as human beings, animals and plants. Each ecosystem is characterized by a well-defined soil/climate/water/flora/fauna complex having its own potential for adaptation and tolerance. As a result of various processes, many of the natural resources which are used by man are formed within the biosphere. In any appraisal of how these resources should be most efficiently used and protected by man, it is essential to understand thoroughly how the physical and biological processes interact both in their creation and destruction. In this context it is necessary to consider first how that part of the total environment which forms the physical milieu of organisms and the biosphere resources is created and maintained by physical processes.

The present report deals with the role of the physical processes of the atmosphere in its interaction with other physical and biological systems. In view of the influence of atmospheric processes and their climatic repercussions on the use and protection of the biosphere, modern society should be aware of how meteorological and climatological information should be applied for various planning and protective activities of mankind. This report therefore focuses attention on the importance of meteorological information and how meteorological knowledge is pertinent to many problems related to the conservation and use of natural resources. It also summarizes the relevant current work of the World Meteorological Organization and gives an outlook on future activities of the Organization in relation to these problems.

In view of the importance attached to the problems of ecosystems and to the role of meteorology in solving these problems, these questions are considered in Chapters II and III. Chapter IV deals first with how man may unintentionally influence the atmospheric part of the biosphere and the possible effects on the Earth’s climates. A discussion follows on the present state of the art of deliberate weather modification and on the possibilities for man eventually to influence intentionally the climate over considerable areas of the globe. In order to complete the picture of how meteorology is involved in the physical parts of the biosphere, the meteorological problems related to the aquatic part of the biosphere are briefly summarized in Chapter V. Finally human beings and animals are considered as components of the biosphere in their relation to weather and climate (human and animal biometeorology).

In preparing the report, various aspects and concepts in the FAO/Unesco report on “Conservation of the Human Environment”, submitted to the Conference on the Biosphere, Paris 1968, have been used. Furthermore, some basic concepts and approaches presented in connexion with the Man and the Biosphere programme, launched by Unesco in 1970, are pertinent and have also been applied (Unesco 1971).
CHAPTER II

SOLAR ENERGY AND THE ECOSYSTEM

The functioning of any ecosystem and, in fact, of the biosphere as a whole is characterized by a series of processes, the basic one being the transfer of the energy reaching the planet Earth as solar radiation. Other important processes driven by this energy input are the cyclic transformations of water, oxygen, nitrogen and carbon.

As solar radiation is transformed into other forms of energy through photosynthesis and the "nutritional chain", higher elements in the system are created, some of which eventually serve as food for man. Although the amount of solar radiation energy available to an ecosystem depends on latitude and atmospheric conditions and processes, it lies between basically defined limits. Therefore man must realize that any modification leading to diversion of energy from the building up of foodstuffs which may be introduced in the "nutrition chain" of an ecosystem (for instance by man's degradation of his environment) will lead to a decrease in the food supply found in the system. It follows that an increase of the productivity of an ecosystem can only be achieved by a more effective use of solar radiation.

To increase the productivity potential for foodstuff of an ecosystem often implies the introduction of new plants or animals which are more adaptable to the solar radiation and the related climates than the ones previously introduced. There are in fact many examples where through meteorological and climatological research man has been able to ascertain that certain plants or new varieties make better use of solar radiation than the ones previously cultivated in the same area. It should be recalled, however, that their introduction may change the delicate transformation cycles of basic elements in the system and lead to an environmental degradation. It is therefore necessary to study in detail these cycles and ascertain that the balance of the system will not be adversely affected by any change which is introduced.

Obviously it would be quite impossible to determine how efficiently solar energy is used in a particular ecosystem without knowing how much incoming energy is available. Thus measurements of solar radiation and observations of its modifications in the atmosphere and at the Earth's surface are a basic task of scientists interested in establishing the potentialities of a system. It is not surprising therefore that special needs are repeatedly voiced by ecologists for more and improved measurements of solar radiation all over the globe. It is the task of meteorologists to provide these observations and measurements as well as to analyse them, in co-operation with biologists, for the purpose of understanding how the available energy is transformed through micrometeorological and physiological processes. WMO is engaged in co-ordinating a network of radiation stations around the globe and in standardizing radiation measurements. These activities are carried out by special working groups of experts within the Commission for Instruments and Methods of Observation and the Commission for Special Applications of Meteorology and Climatology (see list of references).

The energy flow through an ecosystem is a complicated and often inefficient process. Only rarely is more than one per cent of the available total solar energy intercepted by vegetation and stored as energy for potential use. The basic reason for this inefficiency is that in any spontaneous transformation of energy some is inevitably lost to the system, being dispersed as unavailable heat energy. This explains further why any effort to increase the production potentialities of a system must rely on a thorough understanding of how solar radiation is transformed so that the efficiency of the system may be increased.

Solar radiation is not only of direct importance to the ecosystem by providing energy which is more or less directly used by vegetation for photosynthesis and evapotranspiration; it also has an important indirect influence by creating the environmental atmospheric conditions which appear as weather and climate, subject of the next chapter.
1. Weather and climate

It is generally accepted that the atmosphere is an integral and important element of the biosphere and therefore also part of any terrestrial ecosystem regardless of size or location. Its importance is not only in its passive presence as a mixture of gases, which provide a source of oxygen and carbon dioxide, but also in its active dynamic role in weather and climate. Unlike the soil, the atmosphere is not a relatively fixed part of the ecosystem; it is constantly in motion and its local properties are frequently modified as the great air masses move and interact. Physical processes beyond the confines of the ecosystem, as well as those within, have their influence.

Weather is the state of the atmosphere at a given time, as defined by the various meteorological elements. Climate, on the other hand, is a synthesis of the weather of a specified area over a specified interval of time, usually several decades. Weather can change rapidly over very short periods of time and may vary markedly from day to day and season to season. It often displays certain regular diurnal and annual rhythms. Climate, on the other hand, is relatively stable although in marginal areas small changes may have important practical consequences. Certain of its characteristics are determined, within somewhat flexible limits, by fixed factors in the local environment such as latitude, altitude, distance from the sea and topography. Locally, characteristics of climate may also be strongly influenced by more variable features of the ecosystem such as soil, moisture and vegetation. In some cases, in ecosystems where man is dominant, the climate may be further modified by man's activities, sometimes deliberately and sometimes inadvertently. Although climate may thus be influenced by the system itself, our main interest here is that climate has a decisive influence on various processes occurring in the system. Therefore, it has to be taken into consideration when dealing with the biosphere and its natural resources.

2. Studies of atmospheric processes in ecosystems

The basis for all studies aimed at improving our understanding of the atmospheric processes of an ecosystem and how they influence both organic and inorganic material in the system is the regular observation of the meteorological elements which constitute weather and climate. The most important and most frequently observed elements are the following:

Radiation (incoming shortwave including spectral composition, outgoing longwave and net),
Air temperature (including low-level lapse rates for special purposes),
Air pressure,
Wind direction,
Wind speed,
Air humidity (including low-level lapse rates for special purposes),
Clouds, amount and type,
Duration of bright sunshine,
Precipitation, amount and type,
Evaporation.

For special purposes within the biosphere, the following elements are often observed:

Evapotranspiration,
Soil temperature,
Soil moisture.
Observations of the above elements may be taken continuously on a routine basis for meteorological operational purposes or during special periods for research purposes. It is fortunate that national Meteorological Services have, for many decades, taken careful observations, primarily for their operational purposes. Long records of data from a national network of meteorological stations are now available in most countries (Gandin 1970). Thanks to the standardization work by the World Meteorological Organization and its predecessor the International Meteorological Organization, the observations are usually taken with scientifically acceptable instruments at regular times by specially trained personnel. The result is that the time series of data on the state of the atmosphere available in the archives of the national Meteorological Services probably from the most reliable existing data collections for studies of environmental conditions in the biosphere. It may be added that many services now use machine-processing which means that the data are readily available for use in computers together with other relevant information on the biosphere. The extensive activities of WMO in co-ordinating and standardizing methods of collection, storage and retrieval of meteorological data are of fundamental importance both for immediate research purposes and for future efforts to integrate meteorological information with other data relevant to problems of the biosphere.

The WMO activities in relation to monitoring and acquisition of data from the bio-physical environment are described in Appendix A with relevant references to WMO publications.

Consideration will be given later as to how such data may be used in various important applications of meteorology to the problems of the biosphere. First, however, it will be demonstrated in principle how the behaviour of an ecosystem is influenced by atmospheric processes and how operational and/or research observations can be applied for investigation of various problems of interactions.

3. Atmospheric processes and climate in large-scale ecosystems

Ways and means of studying ecosystems with regard to the implications of weather and climate depend on their scale. By definition, each ecosystem is characterized by a fairly homogeneous climate or at least by climatic conditions where a basic climatic element or parameter has a similar influence on the biosphere processes throughout the system. A fundamental category of ecosystems includes, for instance, the major types of world vegetation characterized by similarities in climate and soil conditions. In order to establish the general climatic characteristics of an area of the size of a world vegetational zone, it is usually possible to make use of observations from the networks maintained for operational purposes by the national Meteorological Services. The distances between the stations in such networks vary considerably from country to country but are recommended to be more than 10 and less than 100 kilometres. The major climatic characteristics which can be established from such scattered observations are necessarily approximate and general. They are usually derived by statistical methods and are often referred to as macroclimatic.

The classical approach to an investigation of the macroclimate of a large area is to study different climatic elements in their relation to general vegetational conditions, applying various statistical methods until those elements and parameters are found which give the best correlation and hence seem significant. Let us consider, for example, the semi-arid zones of the world as a prototype of a large ecosystem. The principal meteorological elements governing drought and aridity are precipitation and evapotranspiration. Other closely interrelated elements are soil moisture and surface run-off. The first assessments of arid zones were in fact based on precipitation criteria while evaporation and transpiration were not introduced until later, because they were more difficult to measure and calculate.

The precipitation criteria which were used in the past to establish climatic characteristics of the semi-arid zones were based on amounts only; these were compared with vegetation conditions to give an idea of the relation between the incoming side of the water balance and the outgoing. More explicitly, knowledge of vegetation types was introduced as a substitute for knowledge of evapotranspiration. In more recent investigations of arid systems, other precipitation parameters have been found to be applicable, such as variability (dependability), intensity,
CHAPTER III

seasonal occurrence and length of periods with reliable rainfall. Variability parameters have proved particularly useful owing to the close relationship between variability of rainfall and aridity (Perrin de Brichambaut and Wallén, 1963).

However, it gradually became clear that temperature data could also be useful in defining various degrees of aridity. Obviously, vegetation always reacts to very high and very low temperatures, and hence observations on extreme temperatures are essential in any attempt to determine the limits of arid zones. It was realized, however, that vegetation in fact reacts also to intermediate temperatures because evapotranspiration from a vegetative cover can be approximated as a function of temperature. Temperature data may thus — if suitably treated — be a moderately useful substitute for evapotranspiration data. Originally, only average and extreme temperatures were applied together with precipitation amounts and vegetation conditions. Recently more sophisticated temperature parameters have been used, such as annual and daily fluctuations, accumulated temperatures and length of periods above certain limiting values.

A very simple example of an assessment of climatic characteristics of an ecosystem where precipitation and temperature parameters are applied in relation to vegetation conditions will demonstrate how meteorological elements have been used to establish climatic boundaries of ecosystems. Köppen (1931), in his well-known system for classification of climates, concluded that the boundaries of the arid regions of the world could be established in terms of annual precipitation \( P \) and annual mean temperature \( T \). He found that the limit towards semi-arid ecological conditions (steppe) could in general be expressed in terms of annual precipitation and temperature as follows: \( P = 2 (T + 7) \) where \( P \) is expressed in centimetres and \( T \) in °C. With a typical annual mean temperature of 18 °C, semi-arid conditions would appear with less than 50 cm of annual rainfall, a value approximately confirmed by experience. Köppen, who was quite aware of the difference between aridity in areas where the rainfall comes in summer with high evaporation or in winter with low evaporation, went one step further to refine his system and amended his formula to read:

\[
\begin{align*}
P &= 2 (T + 14) \text{ for areas with summer rainfall;} \\
P &= 2 T \text{ for areas with winter rainfall.}
\end{align*}
\]

This relation indicates that the upper limit of semi-aridity is 64 cm of annual rainfall in areas with summer rainfall and 36 cm in winter rainfall areas.

There is no doubt that such methods for defining climatic criteria for the various major vegetational ecosystems of the world may be useful when considering the global picture, provided their limitations are clearly understood. However, in dealing with ecosystems on a regional scale, where sufficient data from a standard network of meteorological stations exist, a more thorough approach should preferably be applied. The following types of investigations are recommended from a practical viewpoint:

- Length of vegetation season in relation to radiation,
- Light, temperature and precipitation,
- 0 °C and other temperature limits in relation to crop development and distribution,
- Crop development during the vegetative season,
- Importance of precipitation during various periods of the vegetative season,
- Importance of evapotranspiration and water balance during various periods of the vegetative season,
- Frequency of wet and dry periods during the vegetative season,
- Statistical analyses of damage to vegetation caused by various climatic elements (frost, hail, excessive precipitation, etc.).

Some examples of the application of the above steps will be found in Perrin de Brichambaut and Wallén (1963), Brown and Cochemé (1973), Cochemé and Franquin (1967).
4. Atmospheric processes and climate in small-scale ecosystems

Every major ecosystem may be divided into smaller but still distinctive communities, each with a different type of vegetation or array of plant species (and animal association) occupying a different kind of soil and often characterized by different climatic (meso-scale) conditions. The details of these climatic conditions are masked in the overall pattern by the lack of sensitivity of the above-mentioned methods to determine the climate of a major system. It is therefore essential to apply increasingly sophisticated methods for investigations of the climate of ecosystems as their scale decreases.

Let us now consider at the other extreme a very small ecosystem, as for example a field or trial plot in which the same crop is grown in the same kind of soil. In such a small and homogeneous area it is possible to study in detail the small-scale atmospheric phenomena i.e. to investigate the micrometeorological processes and determine the so-called microclimate of the system. In the large-scale macroclimate case discussed earlier, processes related to the general circulation of the atmosphere determine the climatic patterns obtained, while the influence of the small-scale processes, although continuously contributing to the overall picture, cannot be detected. Studies of microclimate, as such, generally pertain to short periods of time.

The most important micrometeorological parameters governing the climatic pattern in a small ecosystem are vertical and horizontal eddies of turbulence; these create the momentum, heat, and moisture exchanges which take place continuously in the boundary layer between the atmosphere and the Earth. Turbulence, however, is notably influenced by the albedo of the Earth's surface and topography; hence the microclimate is very much determined by local characteristics and especially by the nature of the terrain upwind. Moreover, it must be emphasized that any microclimate of a small ecosystem is not only created by the small-scale local processes but is itself also influenced by the large-scale dynamics and physics of the atmosphere.

This may be illustrated by comparing two wheat fields which have similar soil conditions; one in a temperate latitude and the other in the subtropics. The micrometeorological conditions above the wheat may for short periods of time be essentially the same in the two fields depending upon the local conditions, but the microclimates as determined over days, months or the whole year are quite dissimilar because of the differences in latitude and atmospheric circulation conditions of the two major climatic zones where the fields are located. The influences are reflected in differences in the annual variations of incoming radiation, temperature and rainfall.

Unlike the situation in a large ecosystem, it is possible in a small ecosystem to combine the large-scale and the small-scale effects and to obtain a more adequate picture of the microclimate by considering the daily, monthly, and annual variations of different micrometeorological phenomena such as turbulence, energy balance, and water balance.

Unfortunately, turbulence parameters and the energy and water balances cannot be derived from the routine observations taken at stations in the conventional networks of Meteorological Services. For micrometeorological purposes much more sophisticated instrumentation and also more frequent observations are needed. Hence, investigations of a micrometeorological nature and assessments of the microclimate are usually carried out by microweatherists by means of observations from research stations which have been erected for this particular purpose, often expressly in connexion with investigations of biological processes.

In investigations of this nature the earlier mentioned concepts of energy- and water-balance have become indispensable. It was gradually realized that, while the micrometeorological processes per se are of great basic interest to the meteorologists, it is the availability of energy and water that is of importance to the biological components of the ecosystem. The importance of energy or water to the processes in a small-scale ecosystem varies with latitude and with the overall macroclimatic conditions. In high latitudes, where temperature conditions are usually limiting to biological processes, the energy may be of greater importance than the water but in the subtropics, of course, the reverse is true. Whatever the relative importance of the two, the energy balance
is always fundamental because the water balance, to a large extent, depends upon the availability of energy for evaporation and transpiration. This explains why observations of the radiation conditions (i.e. the balance between incoming, reflected, absorbed and outgoing radiation) are essential (see page 3) for studies of ecosystems.

Given the radiation conditions in a small ecosystem, it is equally important to observe how the energy available from radiation is used in turbulent eddies of motion, sensible heat transport, and moisture transformations. This requires observations of the relevant meteorological elements (wind, temperature and moisture) at various levels by rather sophisticated instrumentation. For accurate determination of the turbulent humidity transport in the air layers close to the Earth’s surface, for instance, measurements of the elements have to be made at intervals of only seconds or fractions of seconds, implying that even after a short interval an enormous amount of data has to be digested. Thus quite sophisticated systems must be applied for the collection and processing of data. It is therefore quite understandable that investigations of micrometeorological processes have to be carried out at well-equipped and well-staffed research stations.

It is important to remember that observations of some elements, such as temperature, heat flux and moisture content, should also be taken within the soil in order to give a complete picture of the micrometeorological conditions and in order to allow for computation of the complete energy- and water-balances. Soil temperature and soil moisture may therefore, in this sense, be considered as meteorological elements.

With the above-mentioned observations, various theoretical procedures for establishing the micro-conditions of the atmospheric processes of the ecosystem may be applied. Some approaches have been tried on the basis of the basic heat balance equation; others are related to turbulence theory. Unfortunately, none of the procedures so far applied is completely satisfactory and more research in this field is therefore necessary.

The energy balance equation used in studies of the interrelation between energy and evapotranspiration is often written as follows:

\[ LE = R_n \pm H + A - S_t \]

where \( L \) is the latent heat of evaporation and \( E \) the mass of water evaporated; \( R_n \) is the net radiation energy; \( H \) is the sensible heat gained from or lost to the air; \( A \) and \( S_t \) are, respectively, the quantities of heat directed upwards to the surface layer and stored therein. \( H/LE \) (the Bowen ratio) is often used to give an idea of what proportion of the incoming radiation is transformed into sensible and latent heat respectively. This ratio usually gives a good indication of the water balance conditions above a vegetative surface.

The basic concept used for calculating evapotranspiration from turbulence theory can be expressed as follows:

\[ LE = K_{(z_e)} \frac{de}{dz} \]

where \( K_{(z_e)} \) is the eddy diffusivity for water vapour at the height \( z \) (in the boundary layer) above the ground and \( \frac{de}{dz} \) is the gradient of vapour pressure. Under many conditions \( LE \) can be approximated by the following empirical expression \( LE = (b + cu_1) (e_0 - e_1) \) where \( e_0 \) is the vapour pressure at the evaporating surface, \( u_1 \) the wind velocity and \( e_1 \), the vapour pressure at some other level; \( b \) and \( c \) are constants. It is possible to use an analogous approach to calculate the sensible heat from convection theory, i.e.

\[ H = K_{(z_t)} \frac{dt}{dz} \]

where \( H \) is the sensible heat, \( K_{(z_t)} \) is the eddy convectivity for exchange of heat and \( \frac{dt}{dz} \) the temperature gradient. \( K_{(z_t)} \) is often considered equal to \( K_{(z_e)} \) but serious errors have resulted from this assumption on occasions when it does not hold, which is the rule rather than the exception. It should be stressed that the \( K \) coefficients vary with height above the surface.
Whatever results are obtained with the various approaches applied, it is essential to keep in mind that a complete picture of the atmosphere in a small ecosystem is not obtained unless the micrometeorological processes are interrelated with the biological processes. This can only be achieved if sufficient data on these processes are also available. At any research station where investigations of this kind are taking place, observations of the development and behaviour of the biological components must be taken. For many purposes only simple ecological and phenological observations of the developments of plants and behaviour of animals may be sufficient, but for a detailed analysis of the influence of the atmospheric elements and processes on the biological components it is also essential to collect data on their physiological activities. Such analyses are urgently required in various ecosystems of the world so that relationships can be established between physiological and micrometeorological processes for various important species of vegetation or typical crops.

5. Atmospheric processes and climate in meso-scale ecosystems

Let us now consider an ecosystem of intermediary size. As an example one may select an agricultural area of some 25 square kilometres. In such an area we must expect both local topography and soil conditions to vary considerably and hence we do not have the homogeneous environmental conditions assumed for the case of the small ecosystem. On the other hand, the variations in topography and soil conditions are not so big as those occurring in a large ecosystem. All environmental conditions, including the climate vary on a local (meso) scale and consequently the meteorological conditions averaged in time and space are referred to as the local (meso) climate of the system.

The local climate in such a limited area may often be assessed from data obtained from meteorological stations of a standardized type similar to those used by the Meteorological Services in their national networks. However, the local network of stations has to be more dense than for the macro-scale in order to allow for an understanding of the local variations. For an area of 25 km², the number of stations needed is of the order of 20 to 30 depending upon the local variations of the environmental conditions.

In view of the meso-scale variations in meteorological conditions, it is often necessary to take measurements also at ground level and in the soil, particularly in studies of the interrelation between frost conditions on one hand and topography and soil conditions on the other.

As the network of meteorological stations has to be denser than the permanent national network, investigations in local ecosystems are usually performed by special networks established over a limited period of time for this particular purpose. As in the micro-scale studies, it is essential to have biological, ecological, and/or phenological data on crops and vegetation from within the system in order to allow for the establishment of the interrelations between the atmospheric and the biological processes. As examples of important investigations on local ecosystems, one might mention the influence of topography on net radiation and frost conditions, frequencies of showers brought about by local variations in turbulence and local wind conditions. A thorough knowledge of such meteorological factors may lead to a better understanding of the balance between the atmospheric processes and those taking place in soil and vegetation. In this connexion the possibility should be mentioned of formulating mathematical models to treat the complicated interrelationship between the atmospheric and the biological processes in crops and vegetation. Mathematical models might be particularly useful in mesoscale ecosystems for the practical planning of the use of natural resources.

It should be emphasized, however, that a local system is always influenced on one hand by the macrometeorological processes typical of the overall ecosystem of which the local system forms a part and on the other by processes occurring on the micro-scale; for instance, local frost conditions depend on differences in vertical temperature distribution caused by local topography. Studies of local ecosystems therefore require first of all that the macro-climate of the larger system is known inter alia with respect to circulation and latitudinal type. It is also an advantage if micrometeorological data are collected from strategic points within the system during the period of operating the special network of standard stations at screen level.
CHAPTER III

Having reviewed how investigations of atmospheric processes and the resulting climate can be carried out in ecosystems of different scales, it is necessary to emphasize once more the important interaction between the processes of various scales.

6. Interrelation between climatic conditions in ecosystems of different scales

Theoretically one might expect that a macro-climate or meso-climate could be built up from a multitude of micro-climates and hence it has been argued that a macro-climate over a larger area could be established by areal integration of results from micro-climatic investigations at a large number of places. It is doubtful, however, whether it would be possible to distinguish through such investigations the large-scale latitudinal characteristics of the macro-climate as in micrometeorological studies the small-scale phenomena must be allowed to dominate the picture. Moreover, as such investigations are very expensive due to the sophisticated instrumentation needed at micro-meteorological stations, it is unlikely that we would ever obtain a sufficiently large number of such stations to establish in this way the macro-climates of ecosystems. Instead, some investigators have tried to develop empirical or approximate formulae by which it is possible to determine a key parameter for the micro-climate, such as evapotranspiration, from measurements at screen level of some simple meteorological parameters such as radiation, hours of day-light, temperature, humidity and wind, which are often available from ordinary climatological stations.

Thornthwaite (1948) was the first to attempt to establish the climates of ecosystems on the basis of a micro-climatic parameter: the potential evapotranspiration, i.e. the evapotranspiration that should occur from a vegetative surface provided sufficient water is available in the soil. His formula can be applied on a monthly and annual basis with data from any ordinary climatic station in the world where measurements are taken of temperature and where the day-length is known. His equation to calculate the annual potential evapotranspiration is as follows:

$$ETP = 1.6 \times d \left(\frac{10t}{T}\right)^a$$

where

- $a = 6.8 \times 10^{-7} \times I^3 - 7.7 \times 10^{-5} \times I^2 + 1.8 \times 10^{-2} \times I + 0.5$,
- $I = \text{an annual heat index } \sum_{i=1}^{n} i$,

and $i$ (the monthly heat index) = $(\frac{t}{3})^{1.514}$,

- $d$ = monthly duration of day-light,
- $t$ = monthly mean temperature.

Although nomograms may be applied, it must be admitted that this expression is very complicated. It sometimes breaks down completely, as for instance in areas of temperatures below 0°C, in very arid regions, on islands and in coastal zones. It is applicable, however, in studies of local ecosystems in climates similar to those where the empirical constants were derived on the basis of measurements. It has sometimes been used to establish the broad climatic zones of the world but obviously it is not very useful for such purposes due to the comparatively large areas where it is not applicable.

A more sophisticated formula for determining the potential evapotranspiration was developed by Penman (1948) and modified later by various scientists dealing with the biosphere:

$$ETP = \frac{2 \, R_n \, (de/dt) + E_a}{2 \, de/dt + 1/SD}$$

where $de/dt$ is the gradient of the saturation vapour pressure curve at air temperature $t$, and $E_a$ represents the evaporation from a hypothetical surface at a temperature equal to that at screen height, calculated from

$$E_a = (b + u_1) \, (e_a - e_d)$$

where $(e_a - e_d)$ is the saturation deficit at screen height.
\( R_n \) is the net radiation either observed or calculated and \( SD \) is an index depending upon the crop type; according to Milthorpe (1960), for ordinary grass vegetation \( SD = 1.3 \).

This formula has been found to be more applicable for determining large-scale variations in micro-climatic conditions than the one developed by Thornthwaite as it appears to be more or less valid in any area of the world. However, it does render only approximate values and accurate detailed information can only be obtained from special investigations. The formula is particularly useful for local areas or sub-regions of macro-climatic zones. Budyko (1951) developed a similar formula for the heat-balance and evapotranspiration which has been used to delineate the main world climatic ecosystems.

The establishing of local climates and macro-climates on the basis of potential evapotranspiration is particularly pertinent for application in biosphere problems, as evapotranspiration is of basic importance to biological and hydrological processes.

It is particularly useful in dealing with ecosystems in arid climates and in this connexion is much superior to the old Köppen system. It should be remembered however that, although the potential evapotranspiration calculated from the above formulae is a useful parameter in studies of the climates of ecosystems, the actual evapotranspiration would be even more useful. However, existing methods for the observation or calculation of actual evapotranspiration from vegetative surfaces are still not satisfactory. It must be stressed finally that much research is still needed, both for the development of improved methods to establish the microclimate in relation to physiological processes of plants, animals and man at various localities (see also chapters VI and VII) and for establishing approximate methods for determining the climate of large-scale ecosystems on the basis of micro-climatic parameters.

7. Changes of climate in ecosystems

Having outlined above how ecosystems can be studied with regard to atmospheric processes and the climate, we shall now discuss the extent to which the climate may be considered as stable over a period of time.

For macro-climatological studies there is an international agreement that the climatic assessments should be based on a 30-year period. In many areas of the world there are now continuous records of meteorological data covering more than three successive 30-year periods. From a simple comparison of the results obtained from these three periods it is obvious that the climate is not stable: in fact it must be considered to fluctuate considerably from time to time. These fluctuations or changes in climatic conditions are unfortunately not cyclic in nature but vary in amplitude, phase and period. When using 30-year averages and frequencies, fluctuations of a shorter time span in general become statistically insignificant. Nevertheless changes of climatic conditions with great practical implications for an ecosystem may occur over shorter periods, such as 10 years. On the other hand, climatic changes of much greater dimensions also occur, for instance over time spans of 100 and 1000 years (see WMO Technical Note No. 79).

Meteorological science has so far not been able to solve the problem of the natural causes of climatic changes. Variations in the solar radiation, due for instance to changing activity of the sun or to influences on the incoming radiation in the upper atmosphere, seem to be the most likely basic cause. It is also possible that many short-term fluctuations are statistically random. A ten-year period may very well be wetter or warmer than the preceding one just because of the random distribution of wet and warm years over a longer time span. It should also be kept in mind that feedback influences caused by the thermal properties of the oceans or the large ice-caps of the world play an important role in climatic changes.

Obviously there exists an important field for future research on the problem of climatic changes, both short-time and long-term. If the mechanisms involved were thoroughly known and if it transpired that random processes
were not dominant, it might be possible to make long-term forecasts of climatic trends which would be of great practical importance for planning many activities related to the efficient use of the resources of the biosphere.

An important problem on climatic changes in ecosystems is our present inability to separate variations due to natural causes from those due to man and his activities (see page 21). A local climatic trend in a given system is likely to be a combined effect of a gradual change of the general circulation and the influence of man by irrigation, deforestation, animal grazing, etc.

Nevertheless, an important first step in all investigations of climatic changes is to find out if and how the changes in temperature, humidity and precipitation are associated with changes in the general circulation pattern over the ecosystem under study. Changes in the general circulation of the atmosphere cannot up to now be attributed to human activities and hence, when such changes are found to have been the cause of altered climatic conditions, one has to presume that a natural change in basic meteorological conditions has taken place. Even if some distinction between natural and man-made causes can be made on the above lines, a clear picture of what is taking place can only be obtained by carefully comparing the developments in an ecosystem not subject to any human influence with those in a neighbouring area where such influences exist. It is therefore essential that "bench mark" ecosystems be established in various zones where the natural conditions should remain unchanged and where consequently the natural development of climate and other ecological conditions can be followed over long periods of time.

In studies of data from small-scale ecosystems it is often useful to apply the heat balance approach to investigate to what extent human influence may be responsible for a certain change of climate or of the water balance. If we consider the equation given on page 9

\[ LE = R_n \pm H + A - S_r \]

and neglect \( A \) and \( S_r \), we can make use of the Bowen ratio \( H/LE \) to study possible changes. In very humid areas this ratio becomes very small, between 0 and 0.5, indicating that the radiation energy is used mainly for evapotranspiration. In very dry areas where water is not available for evapotranspiration, the radiation energy is transformed into sensible heat and the Bowen ratio becomes quite large, sometimes between 5 and 10. It is obvious that the Bowen ratio can be considerably changed from its natural value through irrigation; it may in fact decrease from 5 to around 0 or may even become negative. The order of magnitude of man's impact on climate and water balance can thus be expressed in terms of changes of the Bowen ratio.

If man converts temperate-zone forest areas into agricultural land, comparatively small changes of the Bowen ratio are likely to occur. However, in tropical regions where deforestation is at present proceeding rapidly in many areas, changes in the Bowen ratio could be much larger and even dramatic. In the humid tropics on the margin of savannah areas, as for instance in Brazil, Indonesia and parts of Africa, deforestation might easily change the Bowen ratio from the order of magnitude of 0.3 to something like 5, which would indeed imply a complete change in the water balance over the area concerned. The replacement of large latent heat sources by sensible heat sources might also possibly affect the dynamics of the general circulation and, as suggested in the SMIC report (1971), it seems important that further studies of this possibility with numerical experiments and mathematical models be started as soon as possible.

It is also essential to remember that the cutting down of tropical forests is almost an irreversible process due not only to the overall change of heat and water balance but also because it is not possible for the soil moisture to be retained in the same way as before. The result is an increase in floods and soil erosion. It should also be mentioned that deforestation in the humid tropics makes the land more open to incoming radiation which in turn may increase the soil temperature above the level where the soil minerals are kept stable. In the overheated ground some minerals break down and are easily leached out of the soil or transported to lower levels by the abundant precipitation, leaving in the top layers only unfertile laterite soil.
Returning to man’s influence in semi-arid and arid lands, it is obvious that irrigation has a considerable impact on the heat and water balances. In Tunisia, Flohn (1972) has made some interesting comparisons between the Bowen ratio over an oasis and over semi-arid lands. Over the irrigated oasis this ratio becomes negative and amounts to — 0.3 while over the surrounding semi-desert the ratio is 5. If irrigation is increasingly applied in a marginal area between arable land and the desert, the imbalance between the amount of water available through precipitation and the actual evapotranspiration will steadily grow. Flohn calculated that a reasonable area-averaged increase of the actual evapotranspiration at present is at least 2.5 mm/year i.e. about 2 per cent of the water budget. In the long run this growing imbalance certainly affects the water budget of the whole area unfavourably. In all areas of this type a continuous degradation of the natural vegetation can also result from overgrazing.

8. Meteorology and the modelling approach to studies of ecosystems

Models, and particularly mathematical models, are becoming important tools in studies and control of both natural and man-made ecosystems. Although natural ecosystems are very complex, recent work of various scientific groups has demonstrated that mathematical models can be developed with which the events can be approximated by simulation.

In earlier studies of the behaviour of ecosystems, the approach was generally to attempt to understand each individual natural process in depth. Only recently has an attempt been made to approach the behaviour of an ecosystem through a simultaneous analysis of all the processes involved, followed by a prediction of the results of the combined effects of these processes. In the prediction process following such a system of analysis, the mathematical simulation model is a useful tool. When many different variables are included, representing the actual state within the system or the driving forces to change the system, the mathematical representation of the behaviour becomes extremely complex and the large sets of algebraic and differential equations included in the model can only be solved by using large, high-speed digital computers.

In formulating the mathematical simulation models of natural resource systems, one recognizes the existence of state variables, driving variables and output variables.

The state variables represent values of measurable properties of the system such as amount of biomass, plant conditions, numbers of animals, mineral concentrations and water content. It is the time variation of these variables that is the basic object of the analysis of the system. In order to create a dynamic model by which this time variation may be studied, it is necessary to add the driving variables to the basic analysis made of the state variables. In natural resource ecosystems the most important driving variables are the major climatological and meteorological factors. These factors are adequately described by data representing various meteorological elements of which, as discussed in earlier chapters, the most important are radiation, temperature, precipitation and evapotranspiration, although many others of secondary importance may also be applied. The state variables are coupled with the driving variables according to the various ecological, physiological and physical processes acting within the system and the dynamic model is created by expressing the coupling in mathematical terms, making use of our existing knowledge of these processes. The output variables represent the result when the complicated system of algebraic and differential equations is solved by use of the computer.

A very good example of a system analysis relevant to processes in the ecosystem has been presented by Landsberg (1968) in a simplified scheme showing the flow patterns for matter, energy and information which determine the efficient cultivation of agricultural crops. The scheme, which is reproduced in Figure 1, also shows the basic elements which are the essential components of the system.

The fact that weather and climate represent the basic driving forces within the system means that it is very important to understand the processes which couple the meteorological elements with the state variables of system. Hence it is obvious that for any modelling approach it is necessary to know thoroughly the processes
described in earlier chapters. It is also clear that, for such an approach to be successful, there are many remaining problems connected with these processes which must be solved through further research. Some of these have been pointed out in the preceding chapters. Unfortunately, it sometimes happens in modelling work that scientists, who do not have experience with the meteorological and physical processes involved in natural ecosystems, accept much too simplified mathematical expressions for their models.

A good example of the involvement of meteorological factors in a project where the approach of systems analysis and mathematical modelling is being applied, is provided by certain aspects of an International Grazing Land Project which has been drafted in co-operation between IBP, FAO, Unesco and WMO.

Some of the major tasks in this project are:

(a) To collect, organize, process and retrieve useful data from earlier grazing land research and surveys as well as from available operational monitoring sources such as existing networks of meteorological and climatological stations;

(b) To apply advanced techniques of analysis and synthesis for the development of mathematical models as a means of understanding the behaviour of grazing land ecosystems.

The most important data on state variables to be collected in the project are:

(i) Yield, its seasonal distribution and year-to-year variations;
(ii) Number of animals and its year-to-year variations;
(iii) Growth, reproduction and mortality of animals;
(iv) Distribution and adaptation of major native species;
(v) Response and adaptation of cultivated species in relation to management treatments;
(vi) Stocking rates and carrying capacity.
The essential driving variables data are:

(i) Meteorological data for radiation, temperature, precipitation and evapotranspiration;
(ii) Soil moisture data;
(iii) Phenological data on plant response to (i) and (ii);
(iv) Data on changes in extension of grazing systems, including data on the influence of man and animals.

The meteorological data will not only be important for the development of the mathematical models on the behaviour of the grazing land; they will also be needed for establishing the type of climate to which the various project areas are exposed. The first pilot phase of the project suggests a study of the grazing lands of the Mediterranean climates of the world. Climatological data will therefore have to be applied to determine areas suitable for such a pilot study.

The need for including meteorological data in the development of models is illustrated by existing models for grazing lands, which are only preliminary and not too sophisticated; temperature, precipitation and soil moisture were used in one case and temperature, precipitation and evapotranspiration in the other. As energy is a very basic factor in all processes involved in the dynamics of an ecosystem, it seems advisable in the future to apply radiation also as an important driving variable in the development of mathematical models for studies of ecosystems.

9. WMO activities in relation to studies of ecosystems

Various WMO constituent bodies are involved with different aspects of the application of meteorology to studies of ecosystems.

First of all, the Commission for Climatology, recently converted into the Commission for Special Applications of Meteorology and Climatology, is concerned, in view of its interest in the climatological characteristics of many large fundamental ecosystems of the world such as the humid tropics, the arid lands, the polar regions, etc. Several WMO Technical Notes have been prepared under the auspices of this commission on questions of general interest, such as The climatological investigation of soil temperature (T.N. No. 20), Climatic change (T.N. No. 79), Some methods of climatological analysis (T.N. No. 81), A note on climatological normals (T.N. No. 84), Data processing for climatological purposes (T.N. No. 100) etc. A recent Technical Note deals with the present saharization problems in Tunisia (T.N. No. 120).

Secondly, the Commission for Agricultural Meteorology has shown great interest in methods and problems related to studies of ecosystems under cultivation. Of general significance are studies on plant diseases and frost (T.N. Nos. 41, 51 and 99), Windbreaks and shelterbelts (T.N. No. 59), estimation of evaporation and evapotranspiration as well as discussion of soil moisture problems (T.N. Nos. 83 and 97). The overall problem of micrometeorology in relation to agricultural ecosystems is dealt with in Technical Note No. 119. Studies of larger ecosystems have been carried out in semi-arid climates in the Near-East and in the area South of Sahara (T.N. Nos. 56 and 86) in co-operation with FAO and Unesco.

Furthermore, the Commission for Instruments and Methods of Observation has paid close attention to the various instrument problems of ecosystem investigations. Two technical notes deal with measurement of evapotranspiration and humidity in the biosphere (T.N. Nos. 21 and 83).

With particular reference to the problem of climatic change, it should be mentioned that for some ten years WMO has urged Member countries to keep climatological reference stations in different climatic zones of their territories in order to allow for a continuous following of climatic trends; quite a number of such stations are now in operation. It would, however, be even more useful if such stations were established in ecosystems where not only the immediate area around the stations is kept unchanged as in the case of reference stations but where the whole local ecosystem is kept without influence of man. In this way the natural interaction between meteorological, hydrological, pedological, and biological processes could be followed through various stages of development.
CHAPTER IV

MAN'S IMPACT ON HIS ATMOSPHERIC ENVIRONMENT AND GLOBAL CLIMATE

1. Introduction

Any ecosystem, be it large or small, involves a continually changing atmospheric column which, under natural conditions, would contain a certain percentage distribution of chemical constituents. Today it is practically impossible to find any such system where the air column has not been influenced by contamination from human sources. Even in Antarctica and in Greenland evidence of the influence of human pollution has been found. It is therefore hardly possible to establish a so-called zero station where the air remains under absolutely natural conditions and where future trends in the chemical content may be followed. On the other hand, there are nowadays many industrialized areas and densely populated urban regions where pollutants become highly concentrated in the air, particularly under special meteorological circumstances.

In view of the very important implications that the increase of air pollution will have on the biosphere and on man's environment in general, be it in low concentration all around the globe or in high concentration in local areas, WMO has assumed various responsibilities for planning, organizing and co-ordinating the monitoring of general trends from the point of view of the changing composition of the atmosphere.

2. Low-concentration pollution in the atmosphere

It has long been realized that the chemical content of the Earth's atmosphere could be changed, both by natural causes such as volcanic eruptions and by human activities. During periods of frequent volcanic eruptions an increase in the amount of debris and in the content of CO₂ and SO₂ can be recorded. However, through self-cleaning effects the conditions usually return to "normal" during periods of low-volcanic activity. The influence of man's activity on the content of the atmosphere is different in as much as many activities, such as industrialization, are processes which lead to a continuous increase in the adverse effects upon the atmosphere. There is evidence that the contents of CO₂ and particulate matter in the Earth's atmosphere are gradually increasing in spite of the self-cleaning processes which are built into the atmosphere-ocean system. In fact, as mentioned above, the available observations indicate that there are no areas of the world left where the atmosphere has not been influenced by the chemical input from increased industrialization and urbanization.

At present we do not have precise knowledge about the effects of the increasing content of various chemical compounds and particulate matter in the atmosphere but it is logical to suppose that both an increase of CO₂ and particulate matter could influence the radiation balance of the atmosphere and gradually lead to changes in the general circulation of the atmosphere and consequently the climate. Increases of the sulphur compounds in air and precipitation might eventually lead to increased acidity of soil and water at the Earth's surface which could be harmful for agriculture and other human activities.

It is therefore obvious that there is a great need for the establishment of a monitoring system of low-concentration air pollutants all over the globe to enable scientists to follow the future trends. WMO is now assisting in the establishment of a global network of background stations, situated in areas sufficiently remote from industrialized regions, and not affected by daily variations in pollution. It has been recommended that each country should establish at least one so-called "regional" background station for measurements of chemical content of precipitation and turbidity conditions. In large countries, the number of stations should be one for every 500 000 km². At the moment, the temperate part of the northern hemisphere will thus be fairly well covered with regional stations and WMO is urging Members in lower latitudes and the southern hemisphere to join in this effort.
In addition to these regional background stations, WMO has proposed that Members establish a limited number of more sophisticated stations, the so-called "baseline" stations. These should be located in even more stringent conditions in remote areas which still have very clean air. Observations will be made at these stations not only of precipitation chemistry and turbidity but also of CO₂ and, on an optional basis, of air sample chemistry. It is hoped that the number of baseline stations around the world will ultimately reach about 20 (for details on monitoring background air pollution, see Appendix A).

Although techniques are available for measuring the chemical content of precipitation and for monitoring some important air pollutants in low concentrations, there is still a need for much research to refine these methods and to develop methods of monitoring compounds for which no sufficiently sensitive techniques are yet available. In some cases, this research may show that modern remote-sensing techniques could be applied. Several specialized laboratories and meteorological institutions are at present involved in such developments.

In this connexion, it should also be mentioned that WMO Members, in co-operation with IAEA, are already operating a network of about 100 stations around the world for studies of radioactive content of precipitation. The data from the WMO networks of regional and baseline pollution stations are being collected at two of the World Meteorological Centres of the World Weather Watch and will be published monthly by the U.S.A.

In view of the great potential influence of changes in the chemical content of the atmosphere on climate and health, meteorologists must not only monitor the trends but must also study both the dynamic and climatic implications. In fact the Global Atmospheric Research Programme, operated in co-operation between WMO and ICSU, will deal with some of the most important research problems. In addition, a modern climatology of the chemical content of the world's atmosphere should in fact be developed. The global network of background stations will provide the necessary data for such a programme.

3. Man's impact on global climates

Although final conclusions regarding man's possible impact on global climates through his various activities cannot be reached until more and better data have been collected by means of the above-mentioned networks, some of the possibilities can already be indicated.

From what has been said about the natural causes of climatic changes, it is obvious that the most likely of man's activities to have a significant impact would be his ever-increasing release of heat into the atmosphere through processes aimed at producing energy. The specialists who gathered in 1971 in Stockholm to study man's impact on climate (SMIC) estimated the release of heat from energy production in some of the most exposed areas of the world; the results are given in Table I. It is predicted that with the present trend the energy production by the beginning of next century will reach such a level that the release of heat in the large industrialized areas in the U.S.A., Western Europe and Japan will become of the same order of magnitude as the incoming radiation energy from the sun. At that time or even somewhat earlier, it is not impossible that such an amount of released energy could have an influence upon the general circulation of the atmosphere. As the areas with the largest releases of heat are all situated in the westerlies, it could result in considerable changes in the weather patterns.

Particulate matter enters the atmosphere from both natural sources and as a result of human activities. The most abundant natural sources include forest fires (sometimes man-made), the oceans, volcanoes and deserts. The man-produced particles arise from clearance of land, industrialization, burning oil for heating purposes, motor vehicles and aeroplanes. According to the SMIC report (1971) the natural sources produce 750-2,200 million tons of particles per year while man's activities produce between 200-400 million tons per year. About half of the particles produced by man consist of sulphates.
Table 1
Energy Consumption (EC) Density, Industrial and Urban Areas (SMIC 1971)

<table>
<thead>
<tr>
<th>Area</th>
<th>Population</th>
<th>EC density (W/m²)</th>
<th>EC per Capita, Eh</th>
<th>Average net radiation (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nordrhein-Westfalen</td>
<td>34 039</td>
<td>16.84</td>
<td>4.2</td>
<td>8.0</td>
</tr>
<tr>
<td>Same, industrial area only</td>
<td>10 296</td>
<td>11.27</td>
<td>10.2</td>
<td>8.9b</td>
</tr>
<tr>
<td>West Berlin</td>
<td>234</td>
<td>2.3</td>
<td>21.3</td>
<td>*</td>
</tr>
<tr>
<td>Moscow</td>
<td>878</td>
<td>6.42</td>
<td>127</td>
<td>16.8b</td>
</tr>
<tr>
<td>Sheffield (1952)</td>
<td>48</td>
<td>0.5</td>
<td>19</td>
<td>1.6</td>
</tr>
<tr>
<td>Hamburg</td>
<td>747</td>
<td>1.83</td>
<td>12.6a</td>
<td>5.0</td>
</tr>
<tr>
<td>Cincinnati</td>
<td>200</td>
<td>0.54</td>
<td>26</td>
<td>9.3</td>
</tr>
<tr>
<td>Los Angeles County</td>
<td>10 000</td>
<td>7.0</td>
<td>7.5</td>
<td>10.3</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>3 500</td>
<td>7.0</td>
<td>21</td>
<td>10.3</td>
</tr>
<tr>
<td>New York, Manhattan</td>
<td>59</td>
<td>1.7</td>
<td>630</td>
<td>21.0</td>
</tr>
<tr>
<td>21 metropolitan areas</td>
<td>87 000</td>
<td>33</td>
<td>4.4</td>
<td>11.2c</td>
</tr>
<tr>
<td>Fairbanks, Alaska</td>
<td>37</td>
<td>0.03</td>
<td>18.5</td>
<td>21.8</td>
</tr>
</tbody>
</table>

Note: The data for Montreal (Oke, 1969), showing 58 W/m² during summer, 156 W/m² during winter, are in agreement. Hannell (1969) has estimated that the energy output of a steel mill at Hamilton, Ontario, is 385 to 580 W/m² (sensible heat) and 48 W/m² (latent heat), equivalent to a total of about 430 to 630 W/m².

Source: Compiled by H. Flohn from numerous published and unpublished sources.

a Building area only.  b Related to industrial production.  c Eastern United States.

Clean air (i.e. air which is devoid of clouds or fog, or in some contexts air which is devoid of any solid or liquid particles which would reduce visibility) is supposed to have less than 10 $\mu$gm$^{-3}$ of particulates but this occurs rarely. On the average, continental air in rural areas has about 30-60 $\mu$gm$^{-3}$, urban air 60-100 $\mu$gm$^{-3}$ and highly polluted areas 200-1000 $\mu$gm$^{-3}$. Studies of the electric conductivity in air show that the number of particles in the atmosphere of the northern hemisphere has increased by about 100 per cent since around 1910. Locally, even higher increases seem to have occurred.

An increase in the number of particles leads to increased turbidity in the atmosphere and, as this parameter is fairly easy to monitor, it provides a good way to measure particle density. As mentioned in paragraph 2 of this chapter, this parameter is monitored at all WMO regional and baseline stations. Studies of the turbidity at stations operating since around 1910 show local increases of up to 50 per cent.

If then we must accept that more and more particles will enter the atmosphere what effects can be expected? We must presume that the global albedo (i.e. the proportion of the incoming radiation reflected back into space by the Earth and its atmosphere) will change both due to the increasing number of particles and to changes in the cloud amount. Unfortunately, it is extremely difficult to calculate how large the change due to the increasing number of particles will be because the refraction indices and the capacity for absorption of radiation with various types of particles are not known with sufficient accuracy. It is likely, however, that increased turbidity in the atmosphere at high levels would reduce the amount of incoming radiation reaching the Earth's surface, thereby tending to decrease the air temperature. As mentioned, the increased amounts of particles may also lead to an increase of the cloudiness on the globe, which must in turn have two consequences on climate working in opposite directions. Greater cloud amounts would lead to a greater absorption of long-wave radiation from the Earth's surface and at the same time to a reduction of the incoming short-wave radiation. The first factor would tend to increase
the air temperature at lower levels and the second to decrease it. Furthermore, more particles in the atmosphere would tend to increase the thickness of clouds, which again could have both the above-mentioned effects. One can readily see how complicated it is to predict the consequences of an increase of particulate matters in the atmosphere in as much as the secondary effects sometimes work in opposition to the primary ones. It seems reasonable however, to assume that most of the effects of increased turbidity would tend to cool the Earth's surface.

It is interesting to note, however, that Mitchell (1970) has found that the amount of particulate matter which currently enters the atmosphere from man's activities is still small compared to the amount which enters when volcanic activity on the Earth is fairly intense as seems to be the case in our times. Mitchell estimates that the current influence of man on the Earth's climate through emissions of particulate matter is small and of the order of 0.05° C per decade. He agrees, however, that, if the introduction of particulate matter into the troposphere continues to increase at the same rate as during the last 25 years, things might be altered after the year 2000. The input could then have risen to a level where it would be of the same order of magnitude as the amount emitted through volcanic activities and hence there would be a clear risk of an influence upon the global climate. In discussing the effect of an increased amount of aerosols on the Earth's heat balance, Mitchell (1972) is even more cautious; he considers that until we have a better knowledge of the refraction and absorption capacity of aerosols no definite conclusions regarding their influence on the Earth's temperature should be drawn.

A second very much discussed way by which man may influence the heat balance of the atmosphere and thereby cause changes of climate is by the continuously increasing input of carbon dioxide into the atmosphere from the burning of fossil fuels. It now seems reasonable to assume that there will be an increase in the use of fossil fuels of about 4 per cent per year until 1980 and that it will then continue at a somewhat slower rate. The evidence available indicates that about 50 per cent of the CO₂ which now enters the atmosphere will stay there. The observations of CO₂ made at Mauna Loa since 1958 indicate that the mean increase per year is about 0.64 ppm (Keeling, 1971). The increase seems to be slightly greater after 1969, around 1 ppm/year, but values are uncertain and a reasonable average increase is about 0.7 ppm/year.

Machta (1971) has predicted that by the year 2000 the CO₂ content of the atmosphere will be 375 ppm compared with the present 340 ppm. These figures are estimated to be accurate to about ± 10 ppm.

The next problem is to consider how the climate would be affected by an increase of CO₂. Discussion on this subject has in fact gone on for over a century. One of the most recent estimates by Manabe (1971) is that a doubling of the amount of CO₂ in the atmosphere would increase the temperature at the Earth's surface by 2°C. The main reason for this increase is the absorption of the long-wave radiation from the Earth's surface by the CO₂ but we must realize that, as in the case of particulate matter, secondary factors will also arise which in some cases have an opposite effect.

First of all an increase of CO₂ and the consequent warming of the atmosphere would lead to an increase of water vapour content. This would tend to increase the temperature still further through absorption of long-wave radiation. However, an increase of water vapour would also favour an increase of cloud amount, which in turn would cause an increase of temperature due to the absorption of outgoing long-wave radiation but could also lead to a considerable decrease of temperature due to a reduction of the incoming short-wave solar radiation. So the final result is extremely difficult to predict with our present state of knowledge. In Manabe's model, an attempt is made to include some considerations of secondary effects but not the effect of clouds. If we accept the increase of CO₂ up to the year 2000 calculated by Machta (i.e. from 340 ppm to 375 ppm) Manabe's model suggests a temperature increase for the Earth of 0.5°C by that year. This temperature change is of the same order of magnitude as the natural fluctuations of climate that we have experienced during the last century.

A recent investigation by Bischof (1973) on air samples collected by commercial airliners from 1962 to 1971 within the northern hemisphere shows an annual increase of CO₂ in the atmosphere of about 0.09 ppm/year, thereby confirming the order of magnitude of the increase found at Mauna Loa.
Another recent view is however that present evidence is not sufficiently compelling to relate completely the increased atmospheric CO₂ content with CO₂ from increased fossil fuel combustion, or to establish that such trends in atmospheric CO₂ content will continue. Future changes may not only depend on the activities of man but on secular changes in the radiative and dynamic properties of the atmosphere and in oceanic circulation, of which there is at present an incomplete understanding (Pearman and Garrat, 1972).

Another much discussed possible influence on climate by man is through high-altitude jet aircraft, particularly the supersonic transport (SST). Even with ordinary jet aircraft increasing in number, it has been suggested that the frequency and amount of cirrus clouds in the upper troposphere may increase and in fact there are some indications from observations above the Rocky Mountains that an increase of high clouds has taken place since the mid-1950's. In the case of SST very few observations are available and predictions of their impact are mostly speculative at the present stage. A fundamental difference of the problems which arise from SST from those so far discussed, is that SST aircraft deliver their input directly into the stratosphere, while in all other cases discussed the input is delivered in the troposphere.

The SST engines add a considerable amount of water vapour to the stratosphere and this could in fact change the water balance at these altitudes — the stratosphere is very dry and only a relatively small addition of water vapour could therefore be significant. In fact an increase in the humidity mixing ratio in the stratosphere has been observed from 1964 to 1969 (Mastenbrook 1971) but this is considered to be due to natural causes. The emission of water vapour and nitric oxides from SST aircraft might also change the ozone content in the stratosphere. It is not yet possible to say exactly how the ozone layer would be influenced but it is disturbing enough to know that an impact is possible because the present ozone layer protects man against excess of ultra-violet radiation from the sun. Any change in the composition of this layer could therefore have far-reaching direct effects on man; it could also affect the climate because the ozone layer is a secondary heat source in the atmosphere.

Another possible result of man's polluting the atmosphere could be that, although the increase of background pollution may not be sufficient to cause any direct harmful changes in climate, it might be large enough to release trigger effects in the delicate heat balance of the atmosphere, which might lead to undesirable consequences. It is well-known that the extent of the Arctic sea ice has a very important impact on the climate and on the general circulation of the atmosphere over the northern hemisphere. The basic reason lies in the difference in albedo between the ice and the oceans. If considerable changes in the boundaries of the sea ice occur as a result of fluctuations in climate, the resulting changes in albedo might have a considerable effect on the radiation balance. For example, a decrease in radiation from the sun of only one per cent would decrease the Earth's mean temperature by 1.5°C. It has been calculated by Budyko (1969) that the change in albedo incurred through the displacement of the limit of the sea ice due to this drop of temperature would be sufficient to cause the mean temperature to decrease by as much as 5°C instead of only 1.5°C. Under these circumstances, the Arctic sea ice would extend 8-13° of latitude further south than at present, a position similar to that of the quartenary epochs. An ice age would then be likely to develop. It is not impossible that man, by increasing further his input of particulate matters into the atmosphere, could incur a gradual reduction of the radiation from the sun by as much as one per cent causing thereby a decrease in temperature sufficient to trigger the above developments.

In the opposite case, if man's input of CO₂ caused a warming up of such magnitude that the Arctic Sea ice disappeared completely, the air temperature in high latitudes might increase by as much as 20°C in winter and 5°C in summer. This would easily lead to further disappearance of ice on Greenland, which in turn would cause a rise of sea level of up to six metres causing tremendous problems in many cities located near sea level.

4. High-concentration air pollution in local areas

Just as macro-climatic conditions are basically built up from an integration of local and micro-climatic influences, the increased low-concentration air-pollution in the atmosphere discussed in earlier chapters is a consequence
of increased high-concentration air pollution in local areas of industrialization and urbanization. These local areas may be considered as ecosystems created by man, the natural conditions of which are influenced by his activities. The atmosphere in these systems is more or less constantly very different from the natural conditions.

The measurement and monitoring of high concentration air pollution are often the concern of industrialists, engineers, and health experts. However, as the measurements relate to the atmosphere, meteorologists are also concerned with the development of observing techniques and are interested in providing technical advice on how to arrange for operational monitoring of air pollution in local areas, paying due attention to meteorological factors.

The meteorologist is also particularly concerned with the dispersion of air pollutants from local sources and in local areas. The concentration of pollutants at various distances and directions from a point source is basically a function of meteorological factors such as wind, stability (vertical temperature profile) and precipitation.

A large number of techniques have been developed recently for the study of local dispersion of air pollution. Although they are based in principle upon the general diffusion equations, these techniques are empirical in nature rather than theoretical and therefore have to be tested before they can be adopted for application. As climatological factors may influence their applicability, the methods to study dispersion, which have mainly been developed in temperate latitudes, must be tested before being used in other climates.

Nevertheless, it can be said that acceptable methods now exist for investigating dispersion of pollutants from point sources as regards the concentration in various directions and distances as well as the height of the stacks that should be used to avoid too high concentrations under special meteorological circumstances. The situation is different in relation to area sources from which dispersion is still difficult to identify clearly. For area sources of air pollution, modern techniques with mathematical models of the atmospheric behaviour over local industrialized areas may prove to be particularly useful not only in order to establish the actual concentration and dispersion conditions but also to make it possible to forecast such concentrations for local areas taking into account the foreseen development of weather conditions. The present state-of-the-art of applying meteorological concepts to the problems of dispersion and forecasting of air pollution has recently been summarized in WMO Technical Note No. 121. Other relevant WMO publications are Technical Notes No. 106 and No. 114.

5. Meteorology and other detrimental effects of air pollution on the biosphere

As far as the dispersion of pollutants in the atmosphere is concerned, it is necessary to consider also another scale than the local and world-wide scales so far discussed. There is considerable evidence that emissions of pollutants from highly industrialized areas may spread over comparatively large distances and have effects in other countries. In Scandinavia, for instance, some evidence has been found that increasing acidity in lakes and soils may be due to the effect of sulphur pollutants transported from the highly industrialized regions in central and western Europe. Obviously, the transport and transformation processes in the atmosphere determine the long-distance spread of pollutants. Methods used in meteorology to study trajectories are therefore very useful in this context. To follow changes in amounts of regional pollution it is also becoming increasingly important to acquire the necessary data on atmospheric content of pollutants. The WMO network of background stations will be useful for this purpose but these will have to be supplemented by national or subregional networks which as far as possible should be organized so that observations will become compatible with those from the global WMO network.

Air pollutants have also been found to be detrimental to plants and trees. In many agricultural regions adjacent to industries or industrial sections, severe damage to certain vegetable crops and tobacco have occurred.

In order to investigate in detail how such damages occur and from which sources the pollutants originate, similar methods to those used for studies of dispersion of urban and local spread of air pollution may be applied. In addition to WMO Technical Note No. 121 mentioned above, WMO Technical Note No. 96 on Air pollutants, meteorology and plant injury is relevant.
CHAPTER IV

6. Modification of weather

Artificial precipitation

Pollution of the atmosphere is a result of human activities which is not desirable and certainly not deliberately planned by man. On the other hand, man has tried for many years and particularly in the last few decades to influence his atmospheric environment so as to create desirable consequences, for instance to obtain more precipitation or to incur changes in climates of ecosystems.

Various attempts to increase precipitation were made in the first half of this century both in Germany and the U.S.S.R. and an institute for systematic studies was established in the U.S.S.R. in 1932. However, it was not until Schaefer, in 1946, discovered that dry ice (solid CO\textsubscript{2}) could produce ice crystals in large number in clouds of supercooled water drops that clear indications of how to induce artificial precipitation were found. In the same year Vonnegut found that silver iodide could also stimulate the formation of ice crystals.

There is no doubt that experiments both in laboratories and in the field have shown that the basic characteristics of certain clouds and specifically those including liquid drops at temperatures below 0°C can be changed. Practical results have also frequently been achieved in dissipating supercooled fog and low stratus clouds for short periods to allow landing of aircraft. In relation to precipitation, however, the practical results achieved by these techniques are still either contradictory or uncertain.

The reason for this situation is that the dynamic and the microphysical processes as well as their interrelationship in producing precipitation is not sufficiently known although research in cloud physics has concentrated on these topics for several years. Attempts to increase or decrease the amount of precipitation from clouds are based on the assumption that the precipitation process can be affected by introducing substances which should alter the microphysical processes in the clouds. It is difficult to get conclusive results of experiments to achieve this goal because what can be hoped for is not to change the cloud structure per se but to obtain indirect results through a chain of events.

Precipitation may be formed through two different processes: (a) collision and coalescence (warm rain process); (b) a three-phase process (the Bergeron process).

In the first case the clouds often have temperature above 0°C throughout and drops need not have gone through an ice stage. Larger drops fall faster than the smaller ones and in overtaking and collecting them they become gradually larger. Then they fall still faster and sweep up small drops even more rapidly. Drops of at least 20 microns in radius must exist in the cloud to start this process. Due to curvature effects there is also a vapour pressure difference between large and smaller drops causing the larger to grow at the expense of the smaller.

In the second case the temperature of the cloud is below 0°C at least in the higher levels but drops often remain liquid at temperatures considerably below 0°C. When ice crystals are formed in such clouds they are much fewer than the liquid drops. In a mixture of ice crystals and liquid drops below 0°C, the drops will evaporate and the ice crystals grow quite rapidly. Crystals which grow through this process will start to fall relative to the remaining drops and will tend to collect them. There is also a release of latent heat through freezing which will cause vertical motion and cloud growth.

The two processes may very well act together in cold clouds so that the second process initiates the first process.

In the case of liquid clouds, artificial inducement of precipitation is attempted by seeding with hygroscopic nuclei, such as common salt, or with water spray. The basic idea is that the introduction of large drops, which will grow sufficiently rapidly by collision and coalescence, will cause precipitation in clouds which either would have
produced no precipitation or would have done so at a later time. Recent computations and experiments indicate, for instance, that the amount of salt particles to be introduced in order to achieve results would have to be quite great, i.e. exceed $10^{-6}$ grammes per cubic metre. These indications are based on a very simplified model and both the theory and the method of computation still have to be improved considerably.

In the case of the three-phase process of precipitation, the introduction of ice-nuclei presents a more favourable possibility. Here the concept is that the introduction of a large number of ice-nuclei at lower levels and higher temperatures than where natural ice-nuclei exist, will produce precipitation which otherwise would not have occurred or at least earlier than under natural conditions. It should be kept in mind, however, that if natural conditions were sufficiently favourable for formation of precipitation, the artificial introduction of ice-nuclei could cause over-seeding which ultimately could lead to reduction of precipitation.

It is no exaggeration to say that there is still considerable controversy concerning the efficiency of the above-mentioned techniques of cloud seeding. One reason for this controversy has been the great difficulty involved in the objective evaluation of seeding operations. In most cases where the operations have taken place over a considerable period of time and some evaluation has been possible, there were clear cut effects on individual clouds but ambiguous conclusions with respect to increase of precipitation reaching the ground.

The results of those experiments where sufficient precautions have been taken to allow for a subsequent objective analysis are also ambiguous. Of 23 such experiments, only six showed increases of precipitation. Seven showed increases for some parts of the target area and decreases for others. The remaining 10 experiments showed a statistically significant decrease of precipitation.

It is obvious that there is a great need for considerably more research to be carried out regarding the physical and meteorological processes taking place in clouds and regarding the micro-physical structure of clouds before we can clearly understand under which circumstances the techniques applied in cloud seeding will lead to an increase of precipitation.

**Reduction of fog**

In recent years much work has been done on seeding stratus clouds in order to reduce fog. These efforts have in fact resulted in a considerable degree of success. Several airports in the world are now equipped with facilities to seed both warm and cold fogs on a routine basis. Results are generally more difficult to achieve with warm than with cold fogs. In the U.S.A. recently a new chemical seeding procedure (with poly-electrolytes) for warm fogs has been introduced and appears quite promising.

**Suppression of hail**

Attempts to prevent the occurrence of hail were made for example in Italy and France, long before seeding of clouds with dry-ice or silver-iodide. Most of them, however, were quite unsuccessful; at least there was no conclusive evidence that any success was achieved although this was often claimed. Nor has any clear scientific explanation been given that firing anti-hail rockets into the clouds would be successful.

Recently, however, experiments in the U.S.S.R. with rockets and shells carrying silver-iodide in the nosecone which spreads when the rocket explodes seem to have given promising results. This method is based on the assumption that the silver-iodide will create such a large number of small ice nuclei from the water available in the cloud that the formation of big hailstones will be prevented. Further statistical analysis of the experiments and more research on the effects of the silver-iodide on hailstorm formation is needed before any definite conclusions can be drawn about the usefulness of this technique.
CHAPTER IV

WMO activities

The WMO activities in relation to weather modification are centred within the Commission for Atmospheric Sciences (CAS), where a working group on cloud physics and weather modification deals with this field. On the initiative of the Secretariat Technical Note No. 105 was prepared and the text above is mainly a summary of the presentation in that publication. The WMO Congress, on the initiative of CAS, has accepted also a general statement on the present stage of development in the field of weather modification. This is given in Appendix B.

7. Modification of climates

In the chapter on climatic changes, we have already referred to modification of climates of ecosystems incurred by man. In that context we were particularly concerned with unintentional meso-scale and micro-scale modifications created by man's actions. In the chapter on air pollution we also discussed man's inadvertent impact on global climates. Some scientists are now speculating about the possibilities of changing deliberately the macro-scale climate on the Earth, i.e. by ecological regions or globally. Few modifications of the human environment could be more far-reaching in their consequences than large-scale modifications of climate.

It may be admitted that, for the first time in human history, mankind now has at his disposal the technological means and the energy resources necessary to attempt large scale influences on the world climates. However, our basic knowledge of the behaviour of the atmosphere is still insufficient to allow for a theoretical calculation of all the consequences pertaining to the world climates which would result from any major experiment of this kind. It is therefore generally agreed that such undertakings should wait until future research projects, such as GARP (GARP 1969) have made it possible to forecast the consequences of modifications on a large scale.

It should be kept in mind also that before embarking on projects concerned with large-scale climate modification, much more research is needed to understand the possible effects of weather and climate on plant and animal communities better than we do now. Without such wider knowledge, our actions to modify climate could very well lead to undesirable consequences within ecosystems.
CHAPTER V

METEOROLOGY AND THE AQUATIC PARTS OF THE BIOSPHERE

1. Introduction

In the earlier chapters we have dealt mainly with the meteorological aspects of the land and atmospheric parts of the biosphere while water has been considered only in some special contexts. It should be recognized, however, that water is by far the most abundant substance in the biosphere. No less than 1.5 billion cubic kilometres of water exist on the Earth in one form or another.

Water is biologically indispensable for many reasons connected with its physical and chemical characteristics. As part of the biosphere, water sustains life either in media where fish and other species are living or through various processes in man, animals and plants being dependent on water for their life functions.

Meteorology is connected both with the existence and formation of the water reservoirs (oceans, inland waters) on the globe and with the utilization of water by living organisms in their life functions. However, meteorology is primarily involved in the transfer of water from one physical state to another and hence should be discussed first of all in relation to the water cycle.

2. Meteorology and the water cycle

Water exists on the globe in liquid, solid and vapour phases. Oceans store 97 per cent of all the water on the globe, 2.25 per cent of the Earth’s water is stored in ice-caps and glaciers. Most of the remaining 0.75 per cent exists in the form of lakes, rivers and groundwater. Only a very small but quite important amount exists in the atmosphere in the form of vapour.

Meteorological factors connected with the energy cycle are basically responsible for any transition from one physical state to the other. The transition from the liquid state into ice or snow or into vapour is governed by energy processes which depend upon the availability of radiation energy. Similarly, condensation of water vapour into clouds which causes precipitation is due to a process by which energy and latent heat are released into the atmosphere. In order to understand the biological processes in any aquatic ecosystem, large or small, it is necessary to follow the transition of the water from one state to the other and to take into account meteorological factors. In the discussion of land-ecosystems we considered how the water balance at a vegetative surface may be studied by means of either the heat balance approach or by turbulence theory. An ocean surface or a fresh water surface can be treated in a similar way.

3. Meteorology and the oceans

In the case of the oceans it is necessary to understand how the salinity and temperature conditions are created in order to study the biological processes. This is important for instance in the areas around the tropics or in the Mediterranean Sea where the salinity is very high. These conditions are usually a function of the balance between evaporation and precipitation and meteorological observations of these parameters or other parameters that will allow them to be calculated are therefore essential. It should be emphasized in this context that precipitation is very difficult to measure at sea; there are in fact no accurate methods for such measurements today.
Another important factor for the biological conditions of the oceans is the wind, which along with temperature and salinity governs the ocean currents. These currents create substantial effects also on the land components of the biosphere. For example, the large differences in climate between the eastern and western coasts of the Atlantic is to a great degree caused by the ocean currents. Aquatic resources of algae and fish are dependent to a large degree on temperature and salinity conditions which in turn are related to the circulation and currents in the oceans. Circulation and currents, however, are governed, to a great extent, by wind and temperature at the sea surface. Meteorological factors hence tend to be fundamental to many problems related to aquatic resources.

Fishing opportunities in northern latitudes are often influenced by sea ice conditions which are related to seasonal variations in temperature and wind. Meteorological Services nowadays often contribute substantially to the understanding of ice conditions in these high latitudes both by climatological information and by forecasts of ice development.

Recently the marine pollution problems have further increased the needs for meteorological and chemical observations at sea in order to follow trends and the long-range transport of pollutants in the oceans. WMO co-operates closely with the IOC in the development of a system to improve observations over the oceans including both atmospheric parameters and physical and chemical properties of the sea (IGOSS) (WMO, 1970).

It should be added that one of the most interesting aspects of meteorology in relation to the oceans is the fact that the atmosphere acts as a very important source of marine pollution and it is therefore essential that methods be developed for monitoring more precisely the amount of pollution which enters the sea from the atmosphere. In fact many kinds of pollutants are transferred from the atmosphere into the ocean, in particular, pesticides and inorganic waste such as DDT, BHC, PCBs as well as mercury and lead. About 40 to 60 per cent of the annual production of organochlorine pesticides reaches the sea and 50 per cent of this amount gets there through transport from the atmosphere. As such pollutants are transported over long distances in the atmosphere before they enter the sea, there is a need for intensive research on long-distance transport mechanisms in the atmosphere.

Another pollution problem in the oceans which causes considerable damage to living species and biological processes and where meteorological considerations are relevant, is the oil slicks from tanker flushings and tanker accidents. The prediction of the movement and behaviour of oil slicks both on the surface of the oceans and beneath is, to a large extent, a problem of prediction of currents and winds, which opens a new area of research for meteorologists and oceanographers.

Some further discussion on meteorological environmental problems related to the oceans will be found in the articles presented in WMO Special Environmental Report No. 2.

4. Meteorology and inland waters

The discharge, the flow characteristics, the water quality including temperature and the nature and amount of material dissolved or suspended are all important factors for understanding the biological processes in rivers. Through erosion and accumulation, water in rivers and run-off in general form an important factor for changes of the terrestrial component of the biosphere.

Meteorology is closely related to all processes connected with inland waters. Evaporation and precipitation together with infiltration govern the discharge in rivers and surface run-off in general. Therefore, observations of river discharge should be accompanied by observations of meteorological parameters such as precipitation, evaporation, temperature and air-humidity. The effect of erosion and accumulation on the land component of the biosphere is related to runoff as affected by precipitation characteristics and to the stream velocity in rivers and again the basic hydrological and meteorological records mentioned above are essential.
In northern latitudes the freezing of lakes and rivers during the winter season have particular implications for the living conditions of fish and other species. In these areas it is the temperature conditions together with stream velocity that determine the length and regularity of the ice season. Reservoirs on rivers may influence greatly temperature of water in the stream and other conditions over the seasons and cause considerable changes in freezing conditions of both lakes and rivers thereby creating significant environmental problems in northern countries. Meteorologists in such countries may not only contribute to the solution of these problems but also to other problems related to changes of local climates caused by similar effects. They also contribute to the forecasting of spring and summer flow in rivers from predictions of air temperature.

From the point of view of the biosphere, the deterioration and destruction of many inland water ecosystems through pollution is particularly serious. Here again a thorough observation of changes in the river discharge as related to precipitation, evaporation and heat exchange between the water and the atmosphere is essential to a clear understanding of the harm to the biological processes caused by pollutants. Rivers may disperse and break down many pollutants — the more turbulent the flow the more rapid is the breakdown of some of the harmful ones. There is also a direct relationship between the discharge of the rivers and the concentration of pollutants. One way of minimizing the harmful effects of pollution is therefore by regulating the streamflow; on the other hand an efficient streamflow forecasting system may constitute an important component of this solution.

In relation to pollution conditions in big rivers, it is thus of primary importance to develop methods to forecast streamflow which in turn are closely related to meteorological forecasts. Through its Commission for Hydrology, WMO is active in developing standards for hydrological observations and also in co-ordinating studies for the purpose of developing forecasting systems both for normal fluctuations of rivers and for the occurrence of disastrous floods or droughts. The implications of meteorology in relation to inland water pollution may be particularly important at river outlets, coastal areas, deltas, marsh lands, etc. where pollution reaches high concentration and therefore the balance between precipitation and evaporation becomes very critical.

Pollution of lakes either through discharge from rivers or directly into lakes from land and air is also a serious problem of inland water ecosystems. Such a discharge may cause an increase of water temperature and the amount of nutrients which lead to eutrophication of the lakes. The adverse effect of eutrophication may be mitigated by controlling the outflow from the lake. Here again, as in the case of rivers, a thorough knowledge of the meteorological parameters such as evaporation, precipitation and temperature is essential for control purposes.

Hydrological forecasting may also play an important role in minimizing the level of pollution in a lake through various control activities at the outlet.

The following are some recent WMO publications which refer to the various aspects of hydrology in relation to the biosphere:

- Technical Note No. 90 — Measurement of peak discharge by indirect methods,
- Technical Note No. 92 — Hydrological forecasting,
- Technical Note No. 98 — Estimation of maximum floods,
- Operational Hydrology Report No. 2 — Automatic collection and transmission of hydrological observations,
- Technical Note No. 126 — Comparison between pan and lake evaporation.
CHAPTER VI

HUMAN BIOMETEOROLOGY

1. Introduction

The scientific field where man as part of the biosphere is studied in his relation to weather and climate is called human biometeorology. Man's dependence upon atmospheric conditions, as is well known, is not limited to his vital requirement for oxygen. Meteorological elements such as temperature, humidity, wind, radiation and atmospheric electricity are also of fundamental importance to man's health and well-being, not only in a direct sense but also in as much as changes in these elements may play a role in causing the onset of diseases. In studies of these interrelationships, human biometeorology also takes into account the fact that man, in contrast to animals, is able to adapt himself through clothing and technology to many climatic circumstances with which by nature he has difficulty in coping.

Although the importance of the influences of weather and climate on human well-being and health has been well-known since ancient times and many attempts have been made over the years to establish clear and definite relationships in this field, human biometeorology is still comparatively new as an interdisciplinary science. As such it now "joins biology, particularly ecology, and meteorology in the study of (the human body as) a system in which organism and environment interact" (Sargent and Tromp, 1964).

2. Assessment of reactions to changes in the atmospheric environment

The basic problem in human biometeorology is to try to assess how the human body reacts to changes in the atmospheric environment. These changes may be comparatively easy to establish by measurements of such physical parameters as radiation, temperature, humidity and wind, and the determination of certain complex variables combining these elements such as cooling power, wind chill and effective temperature.

The problem of assessing the physiological reactions of the human body to changes in the atmospheric environment is much more complicated than that of establishing the changes themselves. The most important reason for the difficulties involved is the large biological variability that characterizes the human body. Some of this variability is inherent in the organism and could be called system variability, while some of it, on the other hand, relates to changing environmental conditions. One important problem in human biometeorology is thus to establish how much of the overall biological variability is the result of changes in weather, climate and seasons.

Human biometeorological research may be divided into three main areas:
(a) Influence of meteorological elements on physiological processes;
(b) Influence of weather and climate (as combinations of meteorological elements) on man;
(c) Studies of requirements of man for modification of climatic stresses (through clothing, buildings, urban settlements, etc.).

3. Influence of meteorological elements on physiological processes

The fundamental reason why most of the effort in this area has been devoted to studies of the problems of the heat balance of the human body in relation to its meteorological environment is the necessity for the human
body to maintain a temperature at or near 37°C. The problem will be discussed further to show how complicated is the research involved in biometeorological studies. Among other factors the following are of concern:

- The metabolic rate of the body;
- Heat gained or lost by convection (depending upon temperature and wind);
- Heat gained or lost by conduction;
- Evaporation of sweat and of moisture from the lungs (depending upon temperature, humidity and wind);
- Short-wave radiation from sun and sky;
- Albedo and radiation balance of the body.

The main difficulty is that ordinary meteorological observations do not provide the data necessary for the above studies; this means that special measurements under laboratory conditions have to be organized both for the meteorological elements and the physiological reactions. The results of such experiments then have to be inferred for people in general, and hence the present situation implies that our knowledge is limited to empirical approximations.

The influence of atmospheric pressure on physiological processes are mainly connected with changes in the partial oxygen pressure. The human body is generally acclimatized to the particular partial oxygen pressure of the ambient air of habitat. It is particularly in relation to changes in altitude that the human body experiences difficulties in adaptation. Many investigations have shown that there is never an increased or decreased consumption of oxygen at a reduced partial pressure at the basic metabolic rate and therefore the difficulties that the body experiences in efficiency is due only to the poor availability of oxygen to the tissues. Due to the great importance of the problem of adaptation of human beings to different altitudes many investigations have been carried out on the influence of partial oxygen pressure. It is likely to become one of the most developed aspects of human biometeorology.

It should be noted that an area in this science of increasing importance to mankind is the impact of air pollutants on physiological processes and human health. As it is outside the aim of this survey to summarize the present stage of knowledge in this field, the reader is referred to various publications by the WHO for such a summary (see References). For the direct meteorological impact on concentration and distribution of air pollution the reader is referred to Chapter IV.

4. Influence of weather and climate on man

Climatic effects on healthy man are well manifested in acclimatization processes. Many differences in physiological functions between acclimatized and non-acclimatized people have been established, mainly through studies of seasonal variations in physiological functions and metabolism in people living in temperate latitudes.

In any attempt to relate a population rather than an individual to stress of weather and climate, the meteorologist must try to develop a method to relate the integrated effects of weather and climate to this stress. For this purpose meteorologists have often adopted an index developed many years ago by heating and air conditioning engineers, namely the “effective temperature”. It is defined as “a sensation in which for a given air temperature and humidity the state of comfort is equal to that experienced for an environment at a lower temperature with saturated vapour, i.e. when dry-bulb and wet-bulb temperatures are equal”. A place is said to have an effective temperature of 20°C if the ambient air feels the same as air at 20°C and 100 per cent relative humidity. This would correspond broadly to 22.5°C and 50 per cent relative humidity or 25°C and 10 per cent relative humidity. There are many investigations where the “effective temperature” has proved quite useful in establishing physiological reactions to atmospheric environment conditions.

The problem of establishing bioclimatic classifications for human requirements is closely related to attempts to find a simple meteorological index which may be related to physiological reactions. Various attempts have been made to arrive at acceptable classifications of world climates for this purpose and the effective temperature or
similar concepts have often been applied as useful basic indices. Since similar problems arise in classifying bio-
climates as in the case of other climatic classifications, it is not surprising that no completely satisfactory solution
has yet been found to this problem.

The classical monograph on the influence of weather and climate on human diseases was published by
Professor W. F. Petersen in 1938. Both before and since hundreds of research studies have been carried out in
this field, most of them of an empirical character. They have usually been based on statistical correlations but in
some cases they have penetrated deeper into the physiological mechanisms involved. However, it should be noted
that, although many physiological effects related to seasonal changes of weather or to climatic conditions are
fairly well established, the influences of daily changes of weather on the physiology and pathology of man have
proved to be extremely difficult to study and demonstrate with sufficient scientific accuracy. There are many
reasons for these difficulties but the main factor seems to be the genetically inherent variability in reactions of
different individuals to the often rather small fluctuations in meteorological conditions connected with changes in
daily weather. Therefore, statistical correlation is the only scientific approach which can be expected to yield
results in this area, and experiments or investigations involving a sufficiently large population to make possible
correlation studies are difficult to organize. Undoubtedly, there is a need for promotion of this kind of investiga-
tion to be carried out in collaboration between medical experts and meteorologists.

A list of reputed effects of the influence of weather and climate on diseases up to the early 1960’s is given in

5. Requirements of man for modifications of climatic stresses

Studies of man's needs for modifying his environmental climatic conditions by technological means include
in the first place urban biometeorology, which deals with the effects of town planning and architectural design on
the climatic environment of man. Another area is concerned with research on the need for various types of clothing.

It has often been claimed that a basic aim of planning for human settlements should be “to provide an
optimal external climate” and that a basic aim of building design should be “to provide an optimal internal
climate”. From the point of view of creating a suitable human environment these are important aims which need
further consideration by health experts, town planners, architects, engineers and meteorologists. In studying the
creation of an ideal internal climate, it must be remembered that the internal climate is, of course, closely inter-
related with the external climate and therefore the whole field of building climatology is a subject area for close
collaboration between the above experts.

As far as town planning is concerned, the following climatic elements should be considered: air pollution,
radiation and light, temperature and wind. Of particular interest are the effects of “green areas” upon the local
climate of a city.

In building climatology the main problem is to what extent available climatological data from meteorological
stations, which often are located far away from the building to be constructed, may be applied for the purpose of
design and construction in order to obtain an ideal indoor climate. This problem basically involves the interrelation
of the macroclimate derived from an ordinary meteorological station to the microclimate created in the immediate
surroundings of a building, and to the transfer processes taking place through the walls of a building. Little research
has so far been carried out about the microclimate within the “sheath” around buildings and this is the main area
for future activities in the scientific field of building climatology.

6. WMO activities related to human biometeorology

The Commission for Climatology of WMO, recently converted into the Commission for Special Applications
of Meteorology and Climatology (CoSAMC), is responsible for most of the WMO activities in the field of human
biometeorology. In the early 1960's the Commission requested a review of the present state-of-the-art in this field. Hence Technical Note No. 65: *A survey of human biometeorology* was prepared by F. Sargent II and S. W. Tromp and published in 1964. To review certain meteorological aspects of the field, Professor H. E. Landsberg, the president of the Commission, recently prepared Technical Note No. 123: *The assessment of human bioclimate — A limited review of physical parameters*, which was published early in 1972.

In addition CoSAMC recently established a Working Group on Human Biometeorology; one of the tasks of this group will be to outline a programme for further activities of WMO in this field.

As far as urban climates and building climatology are concerned WMO, in co-operation with WHO, arranged in 1968 a symposium on the subjects, the proceedings of which were published in WMO Technical Note No. 108 and No. 109.
CHAPTER VII

ANIMAL BIOMETEOROLOGY

For the sake of completeness it seems relevant to include in this survey some mention of the effects of meteorological and climatic factors and elements on the living conditions of animals and the environmental implications of such effects.

The impact of meteorological factors on wildlife protection has never, to the author's knowledge, been investigated. However, as climatic conditions have often been shown to have important effects upon the reproduction potentiality of animals, it is desirable that such factors be considered in establishing areas and zones of protection. The differences in behaviour and reaction of various wild animals in relation to climate and weather should be considered, a scientific field requiring further development in co-operation between international organizations such as IUCN, WMO and ISB.

The scientific basis of our knowledge of the impact of weather and climate on domestic animals is considerably more developed than that for wild animals. The impact on animals' health and productivity has been specially studied.

A basic factor which has long been recognized is that in the tropics and subtropics animal productivity is low compared to temperate latitudes. Temperature, humidity and thermal radiation conditions in the tropics and subtropics are in most cases more severe than can be tolerated with comfort by most domestic animals as well as for man. Through technological means, such as appropriate housing, extreme climate effects may be overcome but unfortunately the indirect influences of climate are often far more important than the direct impact and those are much more difficult to prevent. It should also be noted that, as in the case of the human being, it is often the interaction between several climatic elements such as radiation, temperature, humidity and air-movement that may have a negative impact on reproduction and productivity of animals.

The most important climatic element having a direct effect on domestic animals is temperature which, under extreme conditions, affects reproduction, health and productivity; ideal conditions for most species are found between 13 and 18°C while serious problems are met at temperatures above 28°C. Cold climates tend to have a dangerous effect on newborn animals and hence influence productivity. Light intensity and length of the photoperiod tend to influence reproduction in many species but are of particular importance through effects on plants which supply the food. Radiation tends to increase the temperature effect by providing additional heat to the animal. Indirectly radiation also has an important impact through its effects on the food supply. As far as wind conditions are concerned, it is generally agreed that in hot, humid climates, winds below 5 km per hour create discomfort to animals while in similar circumstances wind speeds above 35 km per hour may also create problems. Humidity plays a smaller role in animal than in human physiology but at altitudes above 3000 m problems may be encountered. Disease and parasitism are mainly influenced by interactions of the above elements.

In recent years several successful attempts have been made to establish and quantify relationships between weather and climate on one hand and incidence and intensity of animal diseases on the other. Unfortunately, not many diseases are well understood from the point of view of environmental influences. In some cases, however, where some basic principles of infection are known, it has been possible to obtain a lead as to which meteorological parameters might be involved in the incidence, intensity or spread of the disease. Such leads have warranted further micro-scale investigations of meteorological and physiological problems, which in turn have rendered information about how to apply available macro-scale data to establish a correlation between the relevant meteorological parameter and the incidence or spread of the disease. Diseases for which interrelations with various meteorological
parameters have been established include foot and mouth disease, pregnancy toxaemia, sway back in lambs, gastro-enteritis in cattle, parasitic bronchitis and red water fever. These relationships were all established in temperate climate but the methods used could also probably be applied to diseases in other climatic zones. For a closer study of these methods the reader is referred to WMO Technical Note No. 113: *Weather and animal diseases*, by L.P. Smith.

A better understanding of the meteorological observations needed to be made in animal experiments with an aim to improving productivity in animal husbandry may be obtained from a study of WMO Technical Note No. 107 on this subject, prepared by a special working group of the CAgM, and edited by C. V. Smith.
REFERENCES


GARP, 1969: An Introduction to GARP. GARP Publication Series No. 1.


REFERENCES


WMO, 1971b: *WMO operations manual for sampling and analysis techniques for chemical constituents in air and precipitation*. (Part I), WMO-No. 299.


REFERENCES


APPENDIX A

WMO ACTIVITIES IN RELATION TO MONITORING AND ACQUISITION OF SCIENTIFIC KNOWLEDGE OF THE BIO-PHYSICAL ENVIRONMENT

1. Introduction

The WMO and its predecessor, the IMO, have, for now more than 100 years, been the focal point of the national capabilities of all Members for monitoring atmospheric and related geographical parameters. Technical developments in communication and methods of measuring atmospheric parameters have permitted the extension and improvement of those monitoring systems to meet the increasing requirements.

Thus, for purely meteorological purposes, over a period of a century, a highly effective system has evolved for monitoring the atmosphere on a global scale. Having achieved such a monitoring system, it became apparent that meteorology had reached the state at which it could play a significant and increasingly useful role in support of man's relation to and use of the environment. This thinking led, firstly to the development of the concept of the World Weather Watch and more recently to the grouping of all WMO scientific and technical activities under four main programmes, namely:

- World Weather Watch Programme,
- The WMO Research Programme,
- The WMO Programme on the Interaction of Man and his Environment,
- Technical Co-operation Programme.

2. The World Weather Watch Programme

The World Weather Watch Programme constitutes the basic part of the WMO monitoring enterprises and involves three elements:

- Global Observing System,
- Global Telecommunication System,
- Global Data-processing System.

The first of these ensures that meteorological observations are made every few hours (generally every three or six hours) at fixed international times at a network of stations covering as far as possible the whole surface of the globe. At present, some 8500 stations throughout the world comprise the synoptic network of land stations. The map (Annex I) attempts to show the distribution of these stations but their density in some areas is so great that it is very difficult to identify each station on such a small map. In addition to the observations from land stations, the Global Observing System provides for data to be obtained from about 6,000 merchant ships at sea, from special ocean weather ships, from a large number of aircraft and, in recent years, a vast amount of world-wide data from meteorological satellites. In addition to synoptic observations of the common meteorological parameters (temperature, wind, precipitation, etc.) many other types of geophysical observations are made. A list of those other types of observations (made at synoptic stations) is given in Annex II. The last column of this annex (number of stations) refers only to those stations whose data are transmitted over the Global Telecommunication System.

To be of value for synoptic purposes, all these observations have to be exchanged within a few hours on a regional, hemispheric and even a global scale by certain centres. Thus, a complex global telecommunication system...
has to be maintained under the WWW plan. The schematic diagram in Annex III gives some indication of the main features of the WMO Global Telecommunication System.

The vast quantity of observational data now available, as well as the development of numerical forecasting techniques, makes it necessary for many centres to be equipped with modern data-processing equipment, including high-speed electronic computers. The World Weather Watch therefore includes a co-ordinated data-processing system of world and regional centres. The World Meteorological Centres are based in Melbourne, Moscow and Washington, and all have extensive computer facilities; the 21 Regional Meteorological Centres are distributed throughout the world and most of these are, or will shortly be, computer-equipped*. In addition, many national centres already have advanced data-processing facilities.

Thus, an extensive WMO programme for monitoring the atmosphere on a global scale for meteorological purposes is in routine operation. It is supported by extensive telecommunication and data-processing facilities. It is a programme which is based upon long experience in this field but which has, nevertheless, flexibility so that it can be adjusted to meet changing requirements.

3. Monitoring in support of the WMO Research Programme

One of the most significant responsibilities of the World Meteorological Organization is to support and encourage activities aimed at improving the scientific understanding of atmospheric processes. Such activities need large amounts of data from the natural environment often in addition to those available through the WWW. The additional data contribute to our knowledge of the environment as can be seen from the following examples.

**The Atmospheric Ozone Network** – The objective of this network, co-sponsored by the International Ozone Commission, is to monitor, in a co-ordinated manner, the variations in concentration of ozone in the atmosphere for studies of troposphere-stratosphere energy exchange processes and other energy balance research. Measurements made at 32 stations in the world and the regular publication of the data from this network are sponsored by WMO.

**The Atmospheric Electricity Network** – The measurements made at 19 stations in the world are co-ordinated by WMO through this network which has been initiated by the responsible body of IUGG. The aim of the network is to detect changes in the Earth's electrical field and to relate these changes to atmospheric processes.

**The Solar Radiation Network** – Several hundred stations around the world make measurements of incoming and outgoing radiative energy at the surface of the Earth. Through the WMO, the measurements from these stations have been co-ordinated to form a world-wide network. Working groups for studies of problems related to the density of the network, publication of data and methods of observation have been established by both the Commission for Special Applications of Meteorology and Climatology and the Commission for Instruments and Methods of Observation.

4. Monitoring in support of the WMO Programme on the Interaction of Man and his Environment

The WMO Programme on the Interaction of Man and his Environment embraces the activities aimed at applying meteorological knowledge to various human activities. In this connexion we can consider two types of monitoring networks — those gathering basic data on the environment for long-range application and those designed to meet the requirement of specific activities.

The following examples will demonstrate the nature of these networks which are aimed at broadening our knowledge of the environment.

*The products of the WMCs and RMCs are distributed by the GTS to all countries requiring them.*
APPENDIX A

BASIC ENVIRONMENT DATA NETWORKS

(a) The Basic Climatological Network — This system is fundamental to the WMO concept; its objective is to monitor the meteorological parameters which will permit the application of meteorology to economic activities and the human environment and also the identification of long-term trends in the climate of the world.

There are over one hundred thousand stations in this network measuring such elements as temperature, humidity, pressure, wind, precipitation and snow cover, evaporation and soil temperature. Some of these data are exchanged on WWW facilities.*

(b) The Network for Isotope Concentration in Precipitation — This network, which was conceived as a global system and consists of 155 stations, is operated jointly with IAEA. Its purpose is to determine on a monthly basis the concentration of deuterium, tritium and oxygen-18 in samples of precipitation collected from around the world.

(c) The Global Background Air Pollution Network — This monitoring system is truly global in concept and has as its aim to document long-term changes in the composition of the atmosphere. Two types of stations make up the network. Regional air pollution stations are intended to reveal long-term changes in atmospheric composition due to changes in regional long-use practices. Parameters to be measured at these stations are: turbidity and chemical composition of precipitation. Baseline air pollution stations are designed to document long-term changes in atmospheric environmental parameters of particular significance to weather or climate, with a minimum influence from local or regional factors. In addition to the above parameters, these stations will measure carbon dioxide and a number of other gaseous and metallic parameters. This network inaugurated in July 1970, contains 92 stations from 43 countries (1973). It is expanding and the number of stations making measurements of atmospheric composition is expected to reach 100 to 200 in the course of the next few years. A map showing the locations of the stations so far identified is given in Annex IV. The network is expected to cover the oceans as well as land areas. An Operations Manual giving guidance on how to site a regional station, what to measure and how to measure it, was recently published. A similar manual for operations at baseline stations will follow shortly.

NETWORKS FOR APPLICATIONS TO SPECIFIC ACTIVITIES

(a) Monitoring in support of marine activities — Meteorological observations in support of long-haul sailing vessels are at the origin of the systematic organization of meteorological oceanic monitoring systems, first by individual nations and shortly thereafter as a co-ordinated international system. Over the years, through the action of the Commission for Marine Meteorology, this network developed into a global oceanic observing system reporting world-wide in real time. The role of this system is to monitor a variety of physical parameters in the atmosphere over the oceans, including the ocean-atmosphere interface and the upper layers of the ocean. This monitoring system permits the preparation of forecasts and statistical information in support of a broad range of ocean activities for the purpose of safety and efficiency of these activities. It also enables the scientific community to study the evolution of the oceanic climate and of certain physical characteristics of the upper layers of the ocean.

The backbone of this system consists of some 6000 voluntary observing ships. To this should be added a small number of stationary meteorological ships, and more recently, automatic buoys and meteorological satellites.

With a view to expanding this monitoring system into the deeper layers of the ocean, IOC and WMO have recently engaged in the joint planning of a complementary oceanic monitoring system, known as the Integrated Global Ocean Station System (IGOSS), thus hopefully paving the way for the establishment of a comprehensive monitoring system of the physical characteristics of the ocean-atmosphere environment.

*Information about the availability of climatological records for research is to be found in the Catalogue of Meteorological Data for Research, WMO No. 174 TP 86, Parts I, II and III.
The parameters measured in the existing system are: atmospheric pressure, air temperature, sea temperature, sea ice, wind and wind waves, humidity, visibility and weather. The expanded system provides in addition for systematic measurements of sub-surface temperatures, salinity and ocean currents. Consideration is also being given to the possibility of securing through this combined scheme simultaneous observations of atmospheric and oceanic pollution.

(b) Monitoring in support of Air Transport – Whereas maritime meteorology was at the origin of the development of the international meteorological monitoring system, it is as a result of the pressures of aviation that the system went through its first major development stage during the first half of the 20th century. The need to service international air transport has led to the setting up of a specialized aeronautical meteorological monitoring system comprising some 3,000 stations, which make observations on an hourly or half-hourly basis. The planning of this network is being co-ordinated jointly by the WMO through its Commission for Aeronautical Meteorology and the International Civil Aviation Organization (ICAO). This special purpose monitoring system, combined with observations available through the WWW, enables the preparation of the meteorological forecasts and statistical information needed to support aviation activities, whether actual operations or development projects such as airport planning and design studies. Moreover, as a result of the privileged location of airport meteorological stations, the international programme of “Aeronautical Climatological Summaries” relating to surface and the upper air parameters constitute a source of information which is used for a variety of environmental purposes. The parameters measured comprise:

Visibility, wind (high-precision measurement), cloud, significant weather, temperature, humidity and pressure; instrumentation to measure low-level turbulence is under development.

(c) Monitoring in support of Hydrology – The aim of this monitoring system is to measure basic hydrological elements from networks of meteorological and hydrological stations, and to collect, transmit, process, store, retrieve and publish the basic hydrological data. This system also encompasses research on, and the development and improvement of methods, procedures and techniques in network design; specifications of instruments; standardization of instruments and methods of observation; data transmission and processing; and hydrological forecasting. These activities of the system are included in the activities known as operational hydrology. The role of WMO in promoting international co-operation within this system pertains (with particular reference to surface water) to precipitation; snow cover; evaporation from lakes, river basins and reservoirs; temperature and the régime of rivers, lakes and reservoirs; water level of rivers, lakes and reservoirs; water discharge of rivers; sediment discharge of rivers; soil moisture and depth of soil frost; quality of water; and groundwater.

(d) Monitoring in support of Agriculture – The network maintained by national meteorological and agricultural services in support of agricultural activities have been co-ordinated to create a data-gathering system of worldwide coverage. The objective of this system is to monitor and acquire data on atmospheric parameters (including the radiation balance of the Earth) of particular significance to agriculture. Parameters measured: temperature, humidity, radiation, soil temperature, soil moisture, precipitation and evapotranspiration.

S. Relationship between the operational and the environmental change monitoring programme

As can be seen from what has been said, WMO co-ordinates a variety of monitoring systems acting in support of human activities and welfare. These systems fall broadly in two classes:

A multi-purpose basic system collectively designated by the name WWW;

A series of specialized single-purpose systems each specifically tailored to the needs of given user communities or subjects.

By its very concept, the multi-purpose basic system acts in one way or another in support of all of the specialized single-purpose systems; in any given country, its constituent elements can therefore be considered to be part of any of the specialized systems, depending on the requirements for meteorological support services.
prevailing in that country at any one time. Thus one Member may require a WWW station to serve the specialized needs of agriculture and aviation and this station then becomes part also of the overall agriculture and aviation meteorological networks. At other times or in another country, a similar meteorological station may be required to support development projects in the field of hydrometeorology and tourism. There is one fundamental difference, however, between the WWW and the various special-purpose monitoring systems which is very significant in that it affects the GTS. This difference is that some of the systems operate on an immediate exchange basis whereas others operate on a delayed basis. The former are collectively known as the meteorological operational systems, while the latter are more particularly directed at monitoring the changes which occur, from natural or man-made causes, in the environment.

It is through the integration of the operational system and the environmental-change monitoring system and through their interaction with related monitoring systems and other relevant scientific fields that a comprehensive monitoring of the physical aspects of the total human environment will become possible.

Although WMO has come a long way to achieve its goal of monitoring the atmosphere for various purposes, several research problems are still to be solved, such as for example:

(a) Establishment of the optimum density of networks, specially in view of the introduction of automatic instruments;

(b) The possibilities of replacing surface observations with observations from satellites, aircrafts and other moving platforms.
The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of the Secretariat of the World Meteorological Organization concerning the legal status of any country or territory or of its authorities, or concerning the delimitation of its frontiers.
NOTE
The stations located in the higher latitudes tend to appear more widely dispersed than they are because of the projection (Mercator's) of the map.

LEGEND
- Observation existing and included in the regional basic synoptic network
- Observation not existing but included in the regional basic synoptic network
### OTHER TYPES OF GEOGRAPHICAL OBSERVATIONS MADE AT SYNOPTIC STATIONS IN THE WWW SYSTEM

<table>
<thead>
<tr>
<th>Abbreviation or symbol</th>
<th>Meaning</th>
<th>Number of stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGRIMET</td>
<td>Agrometeorological station</td>
<td>55</td>
</tr>
<tr>
<td>ATMEL</td>
<td>Atmospheric electricity measurements</td>
<td>15</td>
</tr>
<tr>
<td>ATMOS</td>
<td>Atmospherics location by narrow-sector direction-finder</td>
<td>7</td>
</tr>
<tr>
<td>AUT</td>
<td>Automatic station or observation made by automatic equipment</td>
<td>13</td>
</tr>
<tr>
<td>AUR</td>
<td>Visual aurora</td>
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<td>Station for which monthly climatological means of surface elements are transmitted</td>
<td>984</td>
</tr>
<tr>
<td>CLIMAT (T)</td>
<td>Station for which monthly climatological means of upper-air elements are transmitted</td>
<td>93</td>
</tr>
<tr>
<td>CLIMAT (CT)</td>
<td>Station for which monthly climatological means of both surface and upper-air elements are transmitted</td>
<td>306</td>
</tr>
<tr>
<td>EVAP</td>
<td>Evaporation measurements</td>
<td>1,117</td>
</tr>
<tr>
<td>H</td>
<td>Hourly observations The letters are followed by figures showing the hours during which the observations are made (e.g. H 00-24 or S 0630-1830)</td>
<td>3,275</td>
</tr>
<tr>
<td>S</td>
<td>Half-hourly observations</td>
<td></td>
</tr>
<tr>
<td>HU/FC</td>
<td>Hurricane, tropical cyclone or typhoon forecast centre</td>
<td>21</td>
</tr>
<tr>
<td>ICE</td>
<td>Ice observations</td>
<td>79</td>
</tr>
<tr>
<td>IONOS</td>
<td>Ionospheric observations</td>
<td>7</td>
</tr>
<tr>
<td>LIT</td>
<td>Lightning counter</td>
<td>18</td>
</tr>
<tr>
<td>MAGNET</td>
<td>Magnetic observations</td>
<td>17</td>
</tr>
<tr>
<td>METAR</td>
<td>Aviation routine weather report</td>
<td>105</td>
</tr>
<tr>
<td>M/B</td>
<td>Station making reports of sudden changes</td>
<td>1,252</td>
</tr>
<tr>
<td>MONT</td>
<td>Observations of cloud below the level of the station</td>
<td>92</td>
</tr>
<tr>
<td>NEPH</td>
<td>Nephoscope observations</td>
<td>414</td>
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<tr>
<td>NLC</td>
<td>Noctilucent cloud</td>
<td>58</td>
</tr>
<tr>
<td>NOCTRA</td>
<td>Nocturnal radiation measurements</td>
<td>10</td>
</tr>
<tr>
<td>OZONE</td>
<td>Ozone observations</td>
<td>32</td>
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<tr>
<td>PH</td>
<td>Phenological observations</td>
<td>252</td>
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<tr>
<td>RAD</td>
<td>Radiation measurements</td>
<td>52</td>
</tr>
<tr>
<td>RAREP</td>
<td>Weather radar report</td>
<td>9</td>
</tr>
<tr>
<td>RECCO</td>
<td>Aircraft reconnaissance flights</td>
<td>6</td>
</tr>
<tr>
<td>ROCOB</td>
<td>Rocket-sonde observations</td>
<td>9</td>
</tr>
<tr>
<td>RSD</td>
<td>Radar storm and meteorological phenomena detection</td>
<td>234</td>
</tr>
<tr>
<td>SEA</td>
<td>State-of-sea observations</td>
<td>275</td>
</tr>
<tr>
<td>SEA/SWELL</td>
<td>Sea and swell observations</td>
<td>75</td>
</tr>
<tr>
<td>SEATEMP</td>
<td>Seawater temperature measurements</td>
<td>106</td>
</tr>
<tr>
<td>SEISMO</td>
<td>Seismological observations</td>
<td>175</td>
</tr>
<tr>
<td>SFERIC</td>
<td>Atmospheric detection by cathode-ray direction-finder</td>
<td>29</td>
</tr>
<tr>
<td>SKYRA</td>
<td>Sky radiation measurements</td>
<td>48</td>
</tr>
<tr>
<td>SNOW</td>
<td>Snow survey</td>
<td>105</td>
</tr>
<tr>
<td>Abbreviation or symbol</td>
<td>Meaning</td>
<td>Number of stations</td>
</tr>
<tr>
<td>------------------------</td>
<td>------------------------------------------------------</td>
<td>--------------------</td>
</tr>
<tr>
<td>SOILTEMP</td>
<td>Soil temperature measurements</td>
<td>792</td>
</tr>
<tr>
<td>SOLRA</td>
<td>Solar radiation measurements</td>
<td>231</td>
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<tr>
<td>SPECI</td>
<td>Aviation selected special weather reports</td>
<td>193</td>
</tr>
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<td>SUNDUR</td>
<td>Sunshine duration measurements</td>
<td>1,610</td>
</tr>
<tr>
<td>SWELL</td>
<td>Swell observations</td>
<td>8</td>
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<tr>
<td>TIDE</td>
<td>Tide observations</td>
<td>92</td>
</tr>
<tr>
<td>TI/WA/FC</td>
<td>Tidal wave forecast centre</td>
<td>7</td>
</tr>
<tr>
<td>TOTRA</td>
<td>Total radiation measurements</td>
<td>211</td>
</tr>
</tbody>
</table>
The diagram shows the centres on the Main Trunk Circuit, which circles the Earth. The three centres denoted by the symbol are the World Meteorological Centres while those denoted by the symbol are Regional Telecommunication Hubs on the Main Trunk Circuit and on its branches. The telecommunication links between these centres and also the links to the respective regions are shown. In the space representing each region the Regional Telecommunication Hubs are shown by the symbol and the National Meteorological Centres by the symbol , the number of symbols in each representing the number of centres in that region.
PRESENT STAGE OF WMO NETWORK FOR MONITORING BACKGROUND AIR POLLUTION

REGIONAL AIR POLLUTION STATIONS
- in operation
- planned (located)
- proposed (non-located)

BASELINE AIR POLLUTION STATIONS
- in operation
- planned (located)
- proposed (non-located)
APPENDIX B

WMO statement on weather modification

PRESENT STATE OF KNOWLEDGE AND POSSIBLE PRACTICAL BENEFITS
IN SOME FIELDS OF WEATHER MODIFICATION*

1. General

It has been demonstrated that ice crystals may be caused to form in supercooled clouds by seeding them with dry ice, silver iodide and other nucleants. Ice crystals are known to play an important role in the formation of precipitation and therefore cloud seeding provides a means for modifying the precipitation process in supercooled clouds. Conversion of a supercooled cloud to ice by seeding releases latent heat which can have important dynamical effects. The varied and controversial results of seeding experiments appear to be due to the complexities of the dynamics and microphysics of the precipitation process. An encouraging beginning in the understanding of these processes has been made through the development of numerical models which incorporate both the dynamics and microphysics and their interactions. Such models and their successors can be expected to define more clearly the most favourable seeding situations and the observations needed for the evaluation of the results. Although some experiments have apparently yielded positive results, the possible practical benefits of weather modification can be realized only through an increased research effort. This research should be directed primarily at cloud dynamics and the interactions of the dynamics with the microphysics, since knowledge of the latter is relatively more complete.

Particularly in the case of rain stimulation, it appears that the most sophisticated statistical procedures are an inadequate substitute for more complete knowledge of the atmospheric mechanisms. However, statistical design and evaluation of experiments are necessary partners of increased physical understanding in the further development of weather modification, particularly in connexion with the evaluation of the practical results of experiments.

It is important to emphasize that weather modification is still largely in the research stage. For this reason, operational efforts should be undertaken only after the most careful study of the particular situation by experts and with the understanding that the desired end results may not always be achieved.

Brief summaries of the current status of weather modification in several categories are given below.

2. Stimulation of precipitation

Of the many experiments conducted in this field, only a few have clearly demonstrated that seeding has increased the precipitation; in some cases there is even evidence of a decrease in the precipitation. However, there is some evidence that orographic precipitation can be modestly increased by seeding, particularly during the winter, over the mountain ranges of the western U.S.A. There is also some evidence that certain sub-tropical convective clouds, selected on the basis of numerical models, become taller and larger when they are heavily seeded so as to release latent heat. In view of the high correlation between the size of convective clouds and the rainfall from them, the seeded clouds presumably give more rain than if they had not been seeded. Confirmation, however, is required from further suitably designed experiments.

*Annex to para. 3.3.6.2 of general summary of Congress-VI (1971).
3. **Dissipation of fog**

Supercooled fog and stratus can be dissipated by seeding them with ice nucleants or by means of cooling agents. This has been brought into operational use at several airports at which there is a relatively high incidence of supercooled fog. The more common warm fog may be dissipated by the use of heat, hygroscopic particles and the down-wash of helicopters. Successful experiments have been reported with each of these techniques but, in addition to other disadvantages, they have been considered too expensive for general use. Recent experiments, guided by numerical modelling and using carefully sized hygroscopic particles, offer some prospects for a more economical technique.

4. **Hail suppression**

After extensive experiments and the development of a model of hail growth, substantial successes in the reduction of hail damage have been reported from the U.S.S.R. Recent experiments in other countries have shown some reduction in hail damage with varying techniques, but more adequate numerical and physical models need to be developed.

5. **Hurricane modification**

Recent hurricane seedings off the eastern U.S.A. coast have been accompanied by reduced maximum wind velocities for short periods. Confirmation is required from further experiments. In view of the limited opportunities for hurricane seeding, there is need for improved numerical hurricane models to strengthen the scientific basis of the hypothesized hurricane modification and to provide guidance for future experiments.

*Note: A survey of several aspects of weather modification has recently been prepared by Professor M. Neiburger as WMO Technical Note No. 105 entitled *Artificial modification of clouds and precipitation.*