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Fundamentals of Meteorology

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Library of Congress Cataloging in Publication Data

BATTAN, LOUIS J
Fundamentals of meteorology.

Bibliography: p. 293
Includes index.
1. Meteorology. I. Title.
QC861.2.B38 551'.5 78-7799
ISBN 0-13-341131-1

FUNDAMENTALS OF METEOROLOGY
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Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

Editorial/production supervision by *Karen J. Clemments*
Cover/interior design by *Mark A. Binn*
Page layout by *Georgina Ottaviano*
Manufacturing buyer: *Trudy Pisciotti*
Cover photograph supplied by the *National Oceanic and Atmospheric Administration*

PRENTICE-HALL INTERNATIONAL, INC., *London*
PRENTICE-HALL OF AUSTRALIA PTY. LIMITED, *Sydney*
PRENTICE-HALL OF CANADA, LTD., *Toronto*
PRENTICE-HALL OF INDIA PRIVATE LIMITED, *New Delhi*
PRENTICE-HALL OF JAPAN, INC., *Tokyo*
PRENTICE-HALL OF SOUTHEAST ASIA PTE. LTD., *Singapore*
WHITEHALL BOOKS LIMITED, *Wellington, New Zealand*

Preface

THE WEATHER AND CLIMATE AFFECT LIFE on the earth in many important ways—some direct and obvious, others indirect and subtle. Violent storms, dealing death and destruction, clearly fall into the first category. The results of droughts in distant places sometimes are not as readily discernable, even though their consequences to society can be profound. For example, an extensive drought in the Soviet Union in 1972 caused that country to buy large quantities of wheat from the United States. As a consequence the price of bread increased for all Americans and for the citizens of many other countries as well.

One of the purposes of this book is to help students perceive the role of the atmosphere in human affairs. The chief goal is to introduce college students to meteorology and climatology.

This volume is designed primarily for those with little training in mathematics, physics and chemistry. For this reason, there are few mathematical formulations in the main body of the text. A number of the more significant equations of meteorology are given in footnotes for those individuals who are interested. Since they are not essential in an introductory course, readers who are not fond of equations are invited to ignore these footnotes.

After a survey of meteorology a student should have a better understanding of the atmosphere—what we know and what still remains to be learned. It should be possible to look at the sky with a greater appreciation of the nature of clouds and storms and associated phenomena. A student should be in a better position to see how the weather and climate are related to his or her particular area of interest. We hope some individuals will be inspired to learn more about this challenging subject and perhaps make a career of the atmospheric sciences.

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CHAPTER 1

Introduction

BEFORE LAUNCHING into a detailed discussion of the science and practice of meteorology, we believe that for students exposed to this subject for the first time, it would be helpful to give a brief overview of what is to come. In reading this introductory chapter, we advise that you skim through it rapidly. There is no need to underline or try to memorize anything. The purpose is to introduce you to the entire subject in a general way, to give you an understanding of the uniqueness of the earth's atmosphere, and to impress you with the challenges of weather and climate. It is hoped that this chapter will make you aware of how the atmosphere affects life on earth and will make you eager to learn more about it.

The planet earth is unique in many important ways. It has expansive oceans and a substantial atmosphere made up of those gases which have allowed life, as we know it, to evolve and continue to exist. Only the earth, among the heavenly bodies orbiting the sun, has these properties. In view of the countless millions of other suns in the universe, most or all of which may have their own planets, it has been speculated that there may be many other civilizations, some much more advanced than our own. Astronomers have begun to listen for radio signals from outer space proving the existence of humanly creatures in the great beyond among the distant stars. The detection of such signals would be an event of immense importance.

Science fiction writers long have written about space travel and colonization of the moon and the planets. Not too many years ago such stories seemed farfetched and surely not likely to be achieved in this century. But on July 20, 1969, Neil Armstrong set foot on the moon and space travel became a reality.

Space vehicles have observed the properties of the nearby planets—Venus, Mars, Jupiter in particular. In a few instances, instruments have descended through the faraway planetary atmospheres and telemetered back measurements of gaseous composition, temperature, pressure, and wind. More often, specialized telescopes and cameras have observed and photographed the surfaces and atmospheres as spacecrafts passed relatively close to the planets. We know that the ones in our solar system have environments hostile to the life thriving on the earth.

The atmospheres of Venus and Mars are mostly carbon dioxide while that of Jupiter is mostly hydrogen. Oxygen, that crucial gas on which life depends, is almost a stranger in the atmospheres of these astronomical neighbors. The temperatures on these planets are hostile to living creatures. Venus is too hot while Mars and Jupiter are too cold.

Someday people will travel to nearby planets as they have to the moon, but it will be necessary to live within complicated life-supporting cocoons. Proposals dealing with space cities circling the earth and with immigration to other planets are fascinating, but it is certain that for a long time into the future, the earth will be home for the human race.

When the world's population was small, the supplies of clean air, water, and food and the mineral resources in the ground seemed limitless. There appeared to be little need to be thrifty in the use of these necessities; inefficiencies became a way of life, particularly in the more advanced countries of the world. In the last few decades it has become increasingly clear that the earth's resources are not inexhaustible.

An examination of factors governing the supplies of food and water and the use of fuels brings into immediate focus the vital parts played by weather and climate. Prolonged droughts over the grain belts of the world lead to shortages of food and in some cases widespread starvation. Dry spells existing over several years can deplete the water supplies of large cities and of hydroelectric operations. Extremely cold winters mean heavy fuel demands that sometimes exceed available supplies leading to cold homes and interrupted industry and commerce. Hot, humid summers strain the electrical capacities of most regions because of the widespread use of air conditioning, particularly in modern skyscrapers.

As everyone knows, heavy concentrations of air pollution or the occurrence of violent storms can lead to tragedy. Every year thunderstorms, lightning, tornadoes, and hurricanes account for huge losses of property and, more important, they injure and kill large numbers of people. At the same time, thunderstorms and hurricanes bring rainfall to nourish farm lands and fill reservoirs.

Clearly, the atmosphere affects the lives of everyone. We must know more about it. What are its properties? What causes the wind, the clouds, rain, snow, hail, and lightning? How can we more accurately predict the weather? Can we change or control it? There are a great many other questions that you could ask. The aim of this book is to supply the answers where they exist and to note those problems still awaiting solution.

A BRIEF LOOK AT THE REST OF THE BOOK

Composition of the Atmosphere

Chapter 2 deals with the composition of the earth's atmosphere. The substance we call air is actually a mixture of gases. Nitrogen and oxygen constitute most of the atmosphere, but there are a great many other gases in small but important amounts. Particles of dust, smoke, and mists, which in combination with air are called aerosols, are commonly present in the atmosphere. When particles are abundant, the sky loses its blue color and distant objects become indistinct or disappear. Certain types of atmospheric particles play crucial roles in the formation of clouds, rain, and snow.

The concentration of atmospheric contaminants depends on the quantity emitted into the atmosphere, the chemical and physical processes that affect them, and the volume of air through which they are mixed. In order to estimate this last factor it is necessary to know the structure of the atmosphere, i.e., the variations of such properties as temperature, pressure, and wind.

Energy Transfer

Chapter 3 discusses the nature of energy transfer with particular emphasis on radiation. It is known that the energy to drive the winds and generate storms comes from the sun in the form of shortwave radiation, most of it being visible light. At the same time, the land, water, and air emit long-wave radiation, much of it escaping, and carrying heat, to outer space. Since the average temperature of the earth as a whole remains essentially constant, the incoming solar energy and outgoing terrestrial radiation must be essentially in balance. Most solar energy falls over the equatorial regions. It is transported toward the poles by atmospheric and oceanic currents. If this did not occur, there would be progressively higher temperatures at low latitudes and progressively lower ones at higher latitudes.

The Winds

The atmosphere is a restless medium. The motions of the air range from barely discernible, feathery breezes to the turbulent blasts of a tornado or hurricane.

As shown in Chapter 4, in order to account for the winds, it is necessary to recognize that the air is a fluid responding to the physical laws of motion. As specified by Newton's second law of motion, force equals mass times acceleration. If you can specify the forces at work, you can calculate the acceleration of the air and hence its velocity. The principal wind-driving forces arise because of variations of atmospheric pressure from place to place. The pressure forces serve to accelerate air from regions of high to regions of low pressure. Once the air begins to move, frictional forces act to slow it down. Finally, because the air moves over a rotating, nearly spherical earth, the air is subject to a deflection effect known as a Coriolis force. As a result of the various forces, in the Northern Hemisphere air tends to move counterclockwise around centers of low pressure and clockwise around centers of high pressure. For example, in a hurricane approaching the United States, the winds blow counterclockwise around the eye of the storm.

Vertical Air Motions

The air not only moves horizontally; it rises and sinks, and in so doing, it affects the state of the sky. Descending air has the effect of inhibiting cloud formation, while ascending air, if it rises enough, causes clouds. Sometimes there are weak upward air motions over large regions and as a result cloud layers cover the entire sky. At other times, particularly in the summer, violent updrafts and downdrafts accompany the formation of thunderstorms. The variable air motions over small distances account for the turbulence experienced by airplanes flying through thunderstorms.

Strong vertical air motions usually occur because warm air rises and cool air sinks, a type of air circulation called convection. When the temperature decreases markedly with height, the atmosphere is unstable. In such a circumstance strong convection currents can develop, particularly if the air is humid.

The rate at which air pollution accumulates depends on the degree of convection near the ground. When the atmosphere is stable, with little vertical air motion, pollutants are trapped in a shallow layer of air. As a result there can be a build up of contaminants and heavily polluted air.

Winds over the Globe

Because of the distinctive features of the earth, the configuration of land and seas, its atmosphere and its rotation, the average patterns of high and low pressure and of the wind currents are unique characteristics of this planet. Chapter 6 notes that among the well-known air streams are the trade winds at low latitudes and the westerly winds at middle latitudes.

The term general circulation is used when referring to the average air motions over the entire earth between the ground and the upper reaches of the atmosphere. In considering the general circulation, the atmosphere can be regarded as a giant heat engine. Radiant energy from the sun, absorbed mostly in the equatorial regions, is the source of power to drive the engine, i.e., the wind currents. By means of a set of equations of fluid motion, and assuming that energy and mass are conserved, it is possible to construct mathematical models of the general circulation of the atmosphere.

Air Masses and Fronts

In order to describe and forecast the weather, it is important to understand the concepts of air masses and fronts. As noted in Chapter 7, huge bodies of air, covering regions thousands of kilometers in diameter, are found to have fairly uniform thermal and humidity properties. For example, air masses originating over the tropical Atlantic and the Gulf of Mexico are warm and moist. When such an air mass encounters a cold, dry one moving southward from Canada, the two bodies of air do not mix readily. Instead, the cold, heavier air slides under the warm, lighter air and a transition zone develops between the two air masses. This zone is called a front. When humid air moves up a sloping front, clouds and precipitation are the usual result.

Frontal zones are favorable locations for the development of cyclones. This term, often used in meteorology, refers to centers of low pressure around which the winds blow. Cyclones are common features on weather maps. Most cyclones, particularly those associated with fronts, produce widespread clouds, rain, or snow. Cyclones frequently observed over hot, dry deserts in the summer are often free of clouds.

Clouds and Precipitation

The processes of cloud formation are described in Chapter 8. Everyone knows, from looking at the sky, that there are many types of clouds. Some are associated with fair weather, others yield rain, snow, or hail. Over the years, a number of cloud classifications have been developed. The one used by the weather services around the world depends mostly on the appearance of the clouds.

It is well known that most clouds are made up of huge numbers of minute water droplets formed as water molecules condense on particles in the atmosphere. High clouds are made up of small ice crystals.

Knowing cloud types and properties, it is sometimes possible to anticipate the arrival of fair or stormy weather. In some circumstances, for example, during the approach of a well-developed cyclone, there is a regular sequence of clouds signaling that a storm is on its way.

Contrary to the belief of many people, most raindrops are not grown by condensation. Instead, they are produced either by the collision and merging of cloud drops or by the melting of snowflakes or ice pellets. Snowflakes are aggregates of ice crystals that have collided and stuck together. Hail represents a spectacular class of frozen precipitation resulting when ice particles remain in the upper part of a thunderstorm long enough to accrete large amounts of ice. On rare occasions hailstones may be the size of oranges, but most damage is done by heavy downfalls of hail less than a centimeter in diameter.

The quantity of water substance on the earth is essentially constant. Water evaporates from oceans, rivers, and lakes and transpires from humans, animals, and plants. In the atmosphere, water vapor is converted to rain and snow that carry the water back to the surface of the earth. The movement of water through the geophysical system is called the hydrologic cycle.

Severe Storms

Thunderstorms range in intensity from those producing only a single flash of lightning and no rain at the ground to those yielding a great deal of lightning, torrential rains, damaging hail, and deadly tornadoes. These storms, discussed in Chapter 9, are dramatic examples of convection at work. When the atmosphere is moist and unstable, strong thunderstorm updrafts can extend to altitudes exceeding 15 km.

Although Florida experiences more thunderstorms than any other state, the Great Plains region of the United States is the most prolific in the world for the production of hail and tornadoes. They are most likely to occur when a shallow layer of warm, humid air from the Gulf of Mexico is surmounted by a layer of fast moving, dry air from the west.

Tornadoes occur frequently over the area extending from Texas through Oklahoma to Illinois and Indiana. They also are observed in other countries but not with the high frequency or intensity experienced in North America.

Hurricanes are much larger and longer lasting than tornadoes and as a consequence do more damage. Hurricanes occur over many tropical oceans, particularly in the Northern Hemisphere. In the western Pacific these violent tropical storms are called typhoons. In southeast Asia they are called cyclones. As hurricanes approach land, they cause a rise in ocean level and a surge of seawater over low-lying coastal areas. This destructive flooding is augmented by heavy rain and strong winds.

Meteorological satellites and radar are widely used for observing the development and movement of severe storms. Improvements of these detection techniques are leading to better forecasts and the saving of a large number of lives.

Sights and Sounds

The distinctive features of a thunderstorm are the lightning and thunder that define its existence. There are many other acoustical and optical phenomena in the atmosphere that are the source of wonder and pleasure. The roaring sound of an approaching tornado signals that disaster is on the way. On the other hand, a rainbow or a halo can be sights of unmatched beauty. Mirages produce images that sometimes defy the imagination. These interesting subjects are examined in Chapter 10.

Climate

In recent years there has been a resurgence of interest in the study of climate, which, for most purposes, can be defined as the average state of the weather elements of a place or region. The tabulation of weather reports has been going on for a long time, for more than 200 years in some localities. These data have been used to calculate the climatological characteristics of many places. As you would expect, there is an important relationship between climate and native vegetation. For this reason, vegetation types have been used by various climatologists in constructing climatic classifications of the world.

Ingenious methods are being used in the study of the climate of the entire earth. From geological evidence it is clear that over the several-billion-year history of this planet, temperatures have changed markedly. There have been ice ages interspersed with relatively warm interglacial periods. The patterns of cool and warm eras of various lengths have been found to continue up to the present time.

Climatic variations over the last hundred years are of particular interest. From about 1880 to 1940 there was a general increase of average air temperatures near the earth's surface, followed by a cooling trend. Recent evidence shows a leveling off of global temperatures. It still is not clear how to account for this sequence of events. Have human activities such as the emission into the atmosphere of gases and particles been contributing significantly to climate fluctuations on a global or regional scale? This question is addressed in Chapter 11.

Applications

Chapter 12 deals with the many ways that a knowldege of weather and climate can be used to benefit people. The design of airports, the industrial zoning of cities, the planning of agriculture are just a few functions that should take into account the statistical properties of temperature, rainfall, and wind.

Accurate weather forecasts, made as long in advance as possible, have great value for almost everyone, but particularly for those engaged in weather-sensitive occupations—farmers, builders, operators of motor vehicles and airplanes, just to name a few.

Accurate predictions of violent storms, particularly tornadoes, hurricanes, and those producing flash floods, can lead to the saving of lives even in cases in which little or nothing can be done to prevent property damage.

Recent advances in observational techniques have made it possible to obtain a much better knowledge of the temperature, pressure, and wind distribution in the atmosphere at any instant. Having such information, mathematical models of the atmosphere can be solved by means of electronic computers in order to calculate future states of the atmosphere. These numerical techniques have converted weather forecasting from an art to a science. The quality of forecasts has been improving over the last few decades and continued improvements are expected in the years to come.