Climate and Weather in the Tropics

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Preface

The years since 1950 have seen the propulsion of tropical countries around the globe into positions of prime importance in relation to world politics, economics and the future development of countries outside the tropics. Air communication and space observations have closed vast distances on earth, so that an increasingly coherent understanding of the world's climate and weather has been achieved, and it has become more and more clear that tropical atmospheric regimes, with their internal convolutions, affect not only areas within the tropical boundaries but eventually the entire earth. Our expanded understanding of the tropics along with their enhanced political importance, then, are the chief reasons for the appearance of this volume. Furthermore, my earlier book "Tropical Meteorology" (1954) needed to be updated and actually replaced.

The atmospheric scientist is now asked to stop the encroachment of deserts, create more water in arid areas, move hurricanes away from populated shores and, in general, make life easier for everyone. Progress within the quarter century since my previous publication means that some of these demands can now be achieved. This volume draws together new and old information from many sources to present a coherent picture of our current comprehension and to suggest, overtly as well as by implication, some of the needed directions for further advance, so that the science of weather can achieve the exalted goals set for it. It will be of particular use to atmospheric science students, provided that they are already familiar with the basics of the subject, including elementary theory, and it will also serve as a handbook for professionals in atmospheric science and in related fields such as physics and engineering. This by no means excludes those working in the social sciences who may also find it necessary to improve and update their knowledge of the tropics.

The information explosion in this, as in other fields, has created an urgency for a comprehensive new volume on the subject. Even the usually quiescent tropics have proved to be not at all sleepy in this area of research during the last quarter century. Advances have been most evident in techniques of weather analysis, now largely objective, and in the analysis of convective processes. Emphasis in the book is on the presentation of facts and their interpretation; a solid body of factual information underlies all twelve chapters. However, controversial interpretation and uncertainties of observations are by no means glossed over. Certain topics are caught in a state of rapid transition, such as weather modification through cloud seeding. Subjects such as these should be pursued through texts and articles dedicated to the problem alone; as nothing would be gained for tomorrow by attempting to present the whole of today's highly conflicting state of speculation within the confines of a single book. On other topics such as the high atmosphere and air-sea interaction, speciality textbooks exist to which the reader is referred.

New technology—satellite, radar, computer—has greatly furthered the advance of atmospheric science. I have been fortunate in obtaining the collaboration of Professor Ferdinand Baer who contributed Chapter 11, a thorough discourse on numerical weather prediction. His specific subject is tropical hurricanes, but the methods he has outlined are relevant to all attempts to apply advanced numerical methods to the problems of the tropics and their relation to other latitude belts. Satellite and radar information has been woven into the text in many places; this greatly enhances the pictorial presentation.

A decision had to be made regarding the inclusion of references literature. Although the number of references does not fall far short of one thousand, it was impossible to include a fully comprehensive literature survey without altering the main purpose of the book. The reader will find that most references are to widely disseminated journals which are accessible in most parts of the world. Much useful material is contained in monographs and articles which even I have had difficulty in locating and, while a few such references were unavoidable—largely for historical reasons—I am aware that they are practically useless to the general student. Regional and local investigations likewise have been mostly omitted except in Chapter 6 which is dedicated to the local scene. An apology is due to all friends and colleagues whose works were not included, some, no doubt, inadvertently.

Professor Hermann Flohn, Bonn, was especially active in encouraging the writing of this volume and its publication through Academic Press, London. Permission by several publishing houses to reproduce copyrighted illustrations is acknowledged, as is the contribution of numerous illustrations by friends and professional acquaintances. Editorial and manuscript assistance was generously provided by J. M. Van Valin.

30 March, 1979

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Symbols

All mathematical symbols are explained the first time they appear. Frequently used symbols are listed here, rarely used ones are defined *throughout the text.*

A	Area
a	Radius of earth
C	Unit in Celsius temperature scale
C	1) Propagation speed (or vector) or
	2) Circulation about closed curve
C_d	Drag coefficient
c_p	Specific heat at constant pressure
D	Thickness between isobaric surfaces
E	Evaporation
e	Vapour pressure
F	1) Latent heat of fusion
	2) Frictional force
F_l	Flux of latent heat
F_s	Flux of sensible heat
F_z	Vertical flux
f	Coriolis parameter
g	Gram
g	Acceleration of gravity
h_p	Height of constant pressure surface
h_s	Sensible heat content per unit mass
J	Joule, kJ kilojoule
K	Unit in absolute temperature scale
K	1) Kinetic energy ($V^2/2$)
	2) Exchange coefficient
K_h	Eddy transfer coefficient for heat
K_m	Eddy transfer coefficient for momentum
K_v	Eddy transfer coefficient for water vapour
L	1) Latent heat of vaporization;
	2) Wave length
M	Mass
M_r, M_ϕ	Horizontal mass flow
M_z	Vertical mass flow
m_d	Molecular weight of dry air

m_v	Molecular weight of water vapour
P	1) Precipitation 2) Potential energy
p	Pressure
Q	Thermodynamic heat content of air
Q_e	Latent heat exchange between ground and air
Q_s	Sensible heat exchange between ground and air
q	Specific humidity
q_{as}	Specific humidity of surface air
q_s	Saturation specific humidity
q_w	Specific humidity over water surface
R	Gas constant for air
R_a	Atmospheric radiation
r	1) Radius in cylindrical coordinates 2) Distance from earth's axis
s, n	Natural horizontal coordinates; s points along wind
T	Temperature
T_{as}	Surface air temperature
T_v	Virtual temperature
T_w	Water temperature
t	Time
U	Basic zonal current
u, v	Horizontal velocity components in Cartesian coordinates
V	Wind speed
$\mathbf{V}$	Wind vector
v_θ, v_r	Horizontal velocity components in cylindrical coordinates
W	Watts, kW kilowatts
W	Mechanical work
w	Vertical motion
x, y	Horizontal Cartesian coordinates; x points east, y north
z	Vertical coordinate

β	Variation of Coriolis parameter with latitude
δ	General difference symbol
Δ	Finite difference
γ	Lapse rate of temperature
ζ	Relative vorticity about vertical axis
ζ_a	Absolute vorticity
η	Vorticity about horizontal axis
θ	Angular measure in cylindrical coordinates
θ	Potential temperature
θ_e	Equivalent potential temperature
λ	Longitude
$\acute{\mu}$	Coefficient of eddy viscosity

ϱ	Density of air
ϱ_v	Density of water vapour
τ	Horizontal shearing stress
τ_s	Surface stress
ϕ	Latitude
ω	1) Earth's angular rotation rate
	2) Individual pressure change dp/dt
Ω	Angular momentum
Ω_r, Ω_ϕ	Lateral momentum transport
Ω_z	Vertical momentum transport
div ( )	Divergence of
$\nabla \cdot \mathbf{V}$ or $\text{div}_2 \mathbf{V}$	Horizontal velocity divergence
$\overline{}$	Time or line average; primes denote deviations
$\sim$	Area average; asterisk denotes deviations
$\wedge$	Vertical average (caret)

Note on Experiments

Several large tropical experiments, which have been conducted are mentioned frequently in the text. The ship array for three expeditions employing research fleets is shown in Fig. 5.2. The acronyms, periods and locations of the major experiments are as follows:

LIE	Line Islands Experiment, north central equatorial Pacific, March-April 1967.
ATEX	Atlantic Tropical Experiment, February 1969 in central equatorial Atlantic.
BOMEX	Barbados Oceanographic and Meteorological Experiment, May-July 1969 in the western tropical Atlantic east of the Lesser Antilles.
VIMHEX	Venezuela International Meteorological and Hydrologic Experiment—Northern Venezuela, June-October 1969, May-September 1972.
GATE	GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment, off West Africa, June-September 1974.

Contents

1

Wind Systems of the Tropics

The tropics straddle the earth's equator, but where are their limits toward the middle latitudes in both hemispheres? With the meaning of the Greek-derived word "Tropics" (i.e. turning) in mind, the encyclopedia strictly positions the Tropics of Cancer and Capricorn near 23·5° north and south. At these latitudes the zenithal position of the sun in the sky turns or reverses in the course of its annual "march". Another definition would be the latitudes 30° north and south; these then divide the global surface into two halves, tropics and extra-tropics. So bounded, the tropics are the source of all momentum and most heat for the atmosphere.

From the viewpoint of atmospheric science, one might define the tropics as that part of the world where atmospheric processes differ decidedly and sufficiently from those in higher latitudes, so that one is justified in writing a separate book on tropical weather and climates alone (see 28a for the geographer's viewpoint). If this is accepted, a dividing line between easterly and westerly winds in the middle troposphere (700 mb) may serve as a useful guide for the boundaries. This fluctuating line allows for seasonal variations and for differences between one part of the world and another, within the same season.

The "tropics" so outlined will be the major concern in this book. One knows, of course, that weather does not stop at any arbitrary boundary, neither that between two countries nor an imagined one between sources and sinks, or a change in predominant physical mechanisms. Indeed, we are very interested in the connections between tropical and extratropical zones. No part of the atmosphere exists alone or can be understood without examining wider regions. Therefore, "excursions" from any narrow definition of the tropics into the higher latitudes will be made throughout this volume.

The low-level general circulations: an overview

Mean zonal winds

A remarkable feature catches the eye at a cursory glance over the average surface wind systems of the globe. By and large, easterly winds (from east) prevail equatorward of latitudes 30°, and westerly winds (from west) over the middle and higher latitudes. Why this remarkable division of tropical and extratropical wind belts? The roots for understanding date from antiquity.

From measurements in the Nile Valley, the Ancients were able to prove that the earth was round as early as 500 B.C.; they suspected that it moved and rotated around the sun. When these concepts won general acceptance, from the sixteenth and seventeenth century onward, dynamical theory was not slow in developing. In the minds of early explorers, the quest for observation coupled with understanding was always uppermost. One of the valuable concepts to emerge was that of conservation of *angular momentum*.

Consider a basin with radius r rotating around the centre with angular velocity ω. The velocity of the rim, then, is $r\omega$ (Fig. 1.1 left).

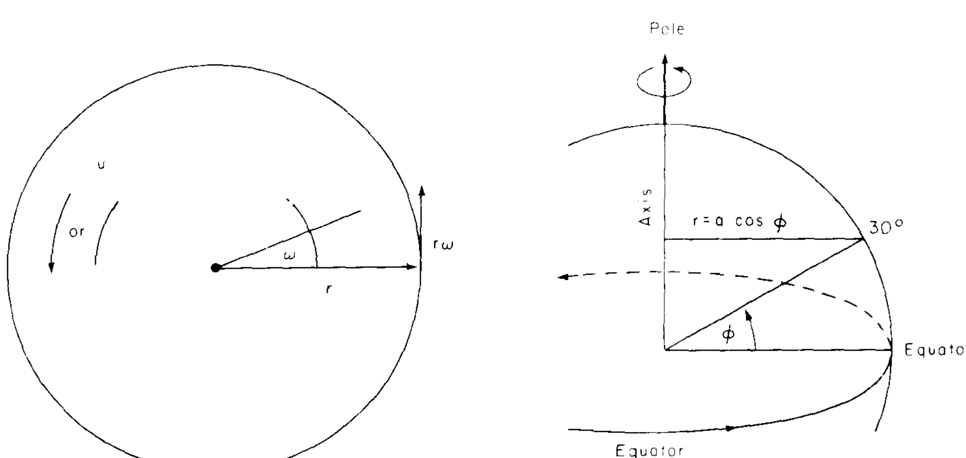

Fig. 1.1. Illustrating angular momentum for rotating basin (left) and for globe (right).

Multiplying again with r the length of the arm, the angular momentum of the basin per unit mass Ω is ωr^2. If fluid, such as water, moves at a different velocity u (the wind in the atmosphere) around the pan, the additional or *relative angular momentum* of the water is ur so that the total or *absolute angular momentum* of the water per unit mass $\Omega = ur + \omega r^2$. The farther toward the centre of the pan a measurement is made, the smaller ωr^2 is, which decreases with the radius.

Passing now to the earth and its atmosphere, the angular momentum of the surface about the rotating earth's axis will also be denoted by ωr^2. Now $\omega = 2\pi/86\,400$ rad s^{-1} or $7{\cdot}29 \times 10^{-5}$ s^{-1}. The arm $r = \cos\phi$ (Fig. 1.1 right); by convention, the symbol a is used for the earth's radius and ϕ is latitude. The value of ω, of course, is constant everywhere, but r varies from $r = a$ on the equator to $r = 0$ at the pole, so that the earth's angular momentum decreases poleward from the equator as $\cos^2\phi$. The relative angular momentum is given by the east-west or zonal component of the wind and will again be denoted by ur, always per unit mass.

The total or absolute angular momentum of earth plus atmosphere must take the masses into account. The mass of the earth is about 6×10^{21} tons and that of the atmosphere is 5×10^{15} tons (about one-millionth of the earth's mass). The momentum $\Omega = ur + \omega r^2$ integrated over the masses of earth plus atmosphere will be conserved in the absence of outside forces acting on the system; these need not be considered.

The conservation theorem may be applied not only to the total mass of earth and atmosphere but also to an individual column or parcel of air if it is not subject to any forces. Then

$$\frac{\mathrm{d}}{\mathrm{d}t}(ur + \omega r^2) = 0 \qquad (1.1)$$

along the trajectory where $\mathrm{d}/\mathrm{d}t$ is the time change following an individual mass. Air moving toward higher latitudes should acquire westerly relative velocity as ωr^2 decreases; for equatorward-moving air the winds should become easterly. Surface wind charts show easterly winds in the tropics and westerly winds at higher latitudes; therefore, momentum is less than that of the earth's surface in the tropics and higher beyond latitudes 30°. The suggestion is that the air in the tropics has moved equatorward and the air of the middle and high latitudes, poleward.

As the reader may compute from Eq. (1.1), the mean zonal wind distribution given by average seasonal profiles (Fig. 1.2) does not show nearly so large an equatorward increase of east winds as is demanded by conservation of momentum. The air, in contrast to the combined system earth-atmosphere, is subject to forces acting on it. Moving

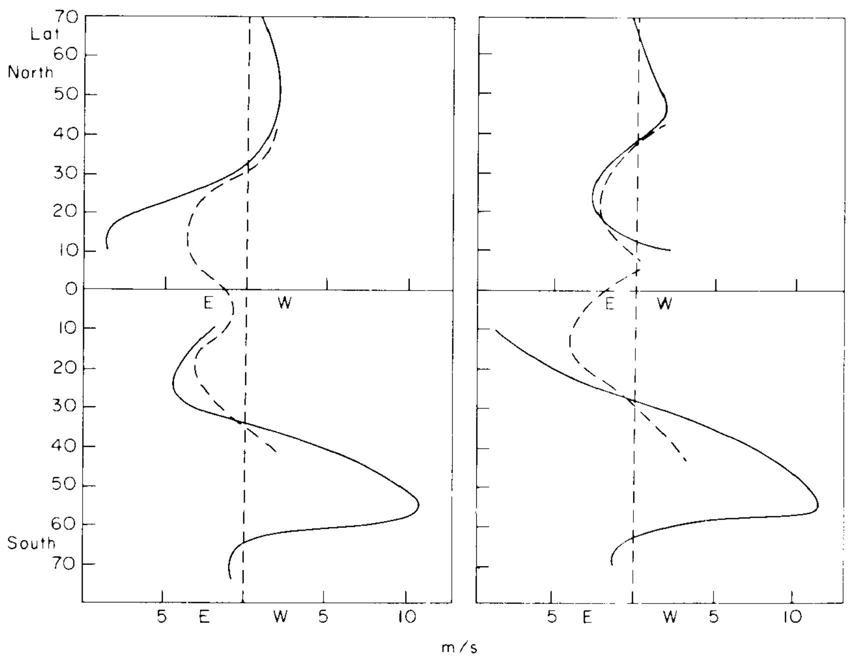

Fig. 1.2. Mean zonal winds (m/s, broken) and geostrophic wind (solid) for January (left) and July (right) over the oceans (23).

toward lower latitudes, air is slowed through ground friction so that very strong east winds in a belt around the globe will not develop; also, air moving toward higher latitudes is retarded so that the westerlies increase more slowly toward the pole than would be demanded by Eq. (1.1). In spite of the retardation, however, a basic tendency toward conservation of momentum is apparent; this tendency is unmistakeable and dominates the mean global wind field at the surface.

Mean meridional circulation

The mean zonal wind profiles imply north-south or meridional motions. These motions indeed exist (Fig. 1.3); they are directed predominantly toward the equator within latitudes 30° north and south (7, 43, 49). Such motions can exist only if some force accelerates the air in that direction, and the only force in the atmosphere known to produce accelerations of large-scale windfields is the pressure force.

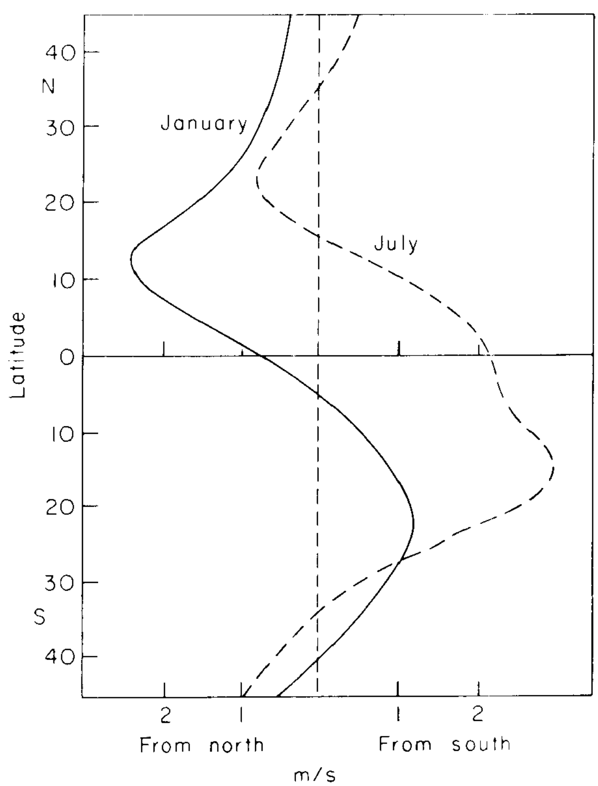

Fig. 1.3. Mean meridional winds at the surface for January and July over the oceans (43).

Therefore, one should expect to find high pressure in the subtropics and low pressure in the equatorial zone associated with the equatorward air motion. Such a pressure distribution does prevail (Fig. 1.4); a