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Atmospheric Thermodynamics

J. V. Iribarne and W. L. Godson

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ATMOSPHERIC THERMODYNAMICS

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PREFACE

The thermodynamics of the atmosphere is the subject of several chapters in most textbooks on dynamic meteorology, but there is no work in English to give the subject a specific and more extensive treatment. In writing the present textbook, we have tried to fill this rather remarkable gap in the literature related to atmospheric sciences. Our aim has been to provide students of meteorology with a book that can play a role similar to the textbooks on chemical thermodynamics for the chemists. This implies a previous knowledge of general thermodynamics, such as students acquire in general physics courses; therefore, although the basic principles are reviewed (in the first four chapters), they are only briefly discussed, and emphasis is laid on those topics that will be useful in later chapters, through their application to atmospheric problems. No attempt has been made to introduce the thermodynamics of irreversible processes; on the other hand, consideration of heterogeneous and open homogeneous systems permits a rigorous formulation of the thermodynamic functions of clouds (exclusive of any consideration of microphysical effects) and a better understanding of the approximations usually implicit in practical applications.

The remaining two-thirds of the book deal with problems which are typically meteorological in nature. First, the most widely-used aerological diagrams are discussed in Chapter V; these play a vital role in the practice of meteorology, and in its exposition as well (as later chapters will testify). Chapter VI presents an analysis of a number of significant atmospheric processes which are basically thermodynamic in nature. In most of these processes, changes of phase of water substance play a vital role – such as, for example, the formation of fog, clouds and precipitation. One rather novel feature of this chapter is the extensive treatment of aircraft condensation trails, a topic of considerable environmental concern in recent years.

Chapter VII deals with atmospheric statics – the relations between various thermodynamic parameters in a vertical column. In the final (and longest) chapter will be found analyses of those atmospheric phenomena which require consideration of both thermodynamic and non-thermodynamic processes (in the latter category can be listed vertical and horizontal motions and radiation). The extensive treatment of these topics contains considerable new material, which will be found especially helpful to professional meteorologists by reason of the emphasis on changes with time of weather-significant thermodynamic parameters.

The book has grown out of courses given by both of us to students working for a degree in meteorology, at the universities of Toronto and of Buenos Aires. Most of these students subsequently embarked on careers in the atmospheric sciences – some in academic areas and many in professional areas, including research as well as forecasting. As a consequence, the courses taught, from which the present text originates, emphasized equally the fundamental topic and practical aspects of the subject. It can therefore be expected to be of interest to engineers dealing with atmospheric problems, to research scientists dealing with planetary atmospheres and to all concerned with atmospheric behavior – either initially, as students, or subsequently, in various diverse occupations.

PREFACE TO THE SECOND EDITION

It is now eight years since we commented that we had produced a text book on atmospheric thermodynamics to fill a rather remarkable gap in the literature related to the atmospheric sciences – namely, a general-purpose concise text in English on thermodynamics applied to the atmosphere. We have been extremely pleased with the wide acceptance of our text, and have realized that it would be worthwhile improving on this contribution to atmospheric science teaching and research by producing a revised edition. In so doing, we have taken advantage of many helpful comments made by students and colleagues.

The general subject of atmospheric thermodynamics must be regarded as extremely stable, so that there were few new concepts that we felt deserved inclusion in this edition. However, there were some topics that we considered required a more detailed treatment; moreover, it was decided that the thermodynamic aspects of cloud microphysics should now be incorporated. Thus a new chapter on equilibrium with small droplets and crystals was added, more attention was given to polytropic processes (Ch. 2, Section 8 and Ch. 7, Section 11), a section was included on the variation of latent heat along the equilibrium curve (Ch. 4, Section 9) and the last section on available potential energy was expanded; minor corrections and improvements are also to be found in many places throughout the text. This was complemented by a list of Symbols, a rather extensive Bibliography and new additional problems; for some of the latter, we acknowledge use of the WMO publication by Laikhtman *et al.* (see complete reference in Bibliography, Section 6; their problems 2-12, 24, 33, 39, 5-17 and a 'sample problem' – p. 38 – were used as such or modified for our problems VII-12, VIII-5, IX-9, 10, 11, 12).

While we were working on this revised edition, we were saddened to learn of the death, on 31 August 1980, of Prof. Jacques van Mieghem. Prof. van Mieghem was a true pioneer in atmospheric dynamics and thermodynamics, and the textbook on atmospheric thermodynamics which he co-authored (in French) is a model of elegance and precision. As a tribute to his contributions to atmospheric science, we would like to dedicate this edition to his memory.

In closing, we would like to express our thanks to all who have helped with the two editions and to express our particular gratitude to our publisher, D. Reidel, for excellence in both printing and publishing.

LIST OF SYMBOLS

Roman Letters	
a	Work performed on the system by external forces, per unit mass.
A	Work performed on the system by external forces, per mole or total. Available potential energy.
c	Specific heat capacity. Number of components.
C	Molar heat capacity.
d	Exact differential.
D	Virtual differential.
e	Water vapor pressure.
f	Specific Helmholtz function. Correction coefficient.
F	Helmholtz function, molar or total.
g	Specific Gibbs function. Gravity.
G	Gibbs function, molar or total.
h	Specific enthalpy.
H	Enthalpy, molar or total.
k	Compressibility coefficient.
K	Kinetic energy.
l	Specific heat of phase change.
L	Molar heat of phase change.
m	Mass.
M	Molecular weight.
n	Number of moles. Polytropic exponent.
N	Molar fraction.
p	Pressure.
P	Potential energy. Rate of precipitation.
q	Heat received by the system, per unit mass. Specific humidity.
Q	Heat received by the system, molar or total.
r	Mixing ratio.
R	Specific gas constant.
R^*	Universal (molar) gas constant.
s	Specific entropy.
S	Entropy, molar or total.
$\mathcal{S}$	Surface.
t	Time. Temperature, on Celsius scale.

T Absolute temperature.
u Specific internal energy.
U Internal energy, molar or total. Relative humidity.
v Specific volume.
V Volume, molar or total.
$\mathscr{V}$ Volume of a drop.
z Any specific property, derived from Z. Height.
Z Any extensive property.

Greek Letters

α Thermal coefficient.
β Lapse rate, referred to actual height.
γ Lapse rate, referred to geopotential.
δ Non-exact differential. Geometric (as opposed to process) differential.
Δ Finite difference.
ε Ratio of molecular weights of water and dry air.
η Ratio of heat capacity at constant pressure to heat capacity at constant volume.
θ Potential temperature.
$\varkappa$ Ratio of gas constant to molar heat capacity at constant pressure.
λ Rate of temperature change dT/dt.
μ Chemical potential.
ν Frequency. Variance of a system.
π Length ratio of circumference to diameter.
ϱ Density.
σ Surface tension. Interfacial tension.
Σ Area on a diagram.
τ Period.
φ Latitude. Number of phases.
ϕ Geopotential.
ω Angular velocity.

Subscripts

a Adiatic (as in T_{aw}).
c Condensed phase. Critical.
d Dry air. Dry adiabatic. Dew point (in T_d).
e Equivalent (as in T_e).
f Fusion (in l_f). Final. Frost point (in T_f).
g Gas phase.
i Ice. Initial. Referred to ice (in U_i). Saturation with respect to ice (as in e_i). Isobaric (as in T_{iw}).

l	Liquid.
m	At constant composition (when using mass units). Moist.
n	At constant composition (when using number of moles).
p	At constant pressure.
s	Sublimation (in l_s). Solid. Saturation. Surface.
t	Triple point. Total.
v	At constant volume. Vaporization. Water vapor. Virtual (as in T_v).
w	Water. Referred to water (in U_w). Saturation with respect to water (as in e_w). Wet bulb (as in T_w).
Bar	Average (as in $\bar{T}$). Partial molar or specific property (as in $\bar{G}_v$, $\bar{g}_v$).
Prime	Parcel (as in T').