SECTION 1

DYNAMIC METEOROLOGY

Contributing Editor: Joseph Tribbia

CHAPTER 1

OVERVIEW—ATMOSPHERIC DYNAMICS

JOSEPH TRIBBIA

The scientific study of the dynamics of the atmosphere can broadly be defined as the attempt to elucidate the nature and causes of atmospheric motions through the laws of classical physics. The relevant principles are Newton's second law of motion applied to a fluid (the atmosphere), the equation of mass continuity, the ideal gas law, and the first law of thermodynamics. These principles are developed in detail in the contribution by Murry Salby. Since the empirical discovery and mathematical statement of these laws was not completed until the middle of the nineteenth century, as defined above, atmospheric dynamics was nonexistent before 1875. Nonetheless, attempts at applying dynamical reasoning using principles of dynamics appeared as early as 1735, in a work discussing the cause of the trade winds. Hadley's contribution and a complete history of theories of the atmospheric general circulation can be found in the monograph by Lorenz (1967).

The recognition that the laws enumerated above were sufficient to describe and even predict atmospheric motions is generally attributed to Vilhelm Bjerknes. He noted this fact in a study (1904) detailing both the statement of the central problem of meteorology (as seen by Bjerknes), weather prediction, and the system of equations necessary and sufficient to carry out the solution of the central problem. The chapter by Eugenia Kalnay describes the progress toward the solution of the central problem made since 1904 and the current state-of-the-art methods that marry the dynamical principles spelled out by Bjerknes and the computational technology brought to applicability by John von Neumann, who recognized in weather prediction a problem ideally suited for the electronic computer.

If Bjerknes' central problem and its solution were the sole goal of dynamical meteorology, then the chapters by Salby and Kalnay would be sufficient to describe

---

Handbook of Weather, *Climate*, *and Water: Dynamics*, *Climate*, *Physical Meteorology*, *Weather Systems*, *and Measurements*, Edited by Thomas D. Potter and Bradley R. Colman.
ISBN 0-471-21490-6

both the scientific content of the field and its progress to date. However, as noted above, atmospheric dynamics also includes the search for dynamical explanations of meteorological phenomena and a more satisfying explanation of why weather patterns exist as they do, rather than simply Force = (mass)(acceleration). The remaining chapters in the part demonstrate the expansion of thought required for this in three ways. The first method, exemplified by Paul Kushner's chapter, is to expand the quantities studied so that important aspects of atmospheric circulation systems may be more fully elucidated. The second method, exemplified by the chapters of Gerry Meehl and Kyle Swanson, develops dynamical depth by focusing on particular regions of Earth and the understanding that can be gained through the constraints imposed by Earth's geometry. The third method of expanding the reach of understanding in atmospheric dynamics is through the incorporation of techniques and ideas from other related scientific disciplines such as fluid turbulence and dynamical systems. These perspectives are brought to bear in the chapters of Jackson Herring and Jeffrey Weiss, respectively.

The focus of the chapter by Kushner is vorticity and potential vorticity. Anyone familiar with the nature of storms, e.g., both tropical and extratropical cyclones, will note the strong rotation commonly associated with these circulations. As Kushner shows, the local measure of rotation in a fluid can be quantified by either the vorticity or the related circulation. The recognition of the importance of circulation and vorticity in atmospheric systems can be traced at least as far back as von Helmholtz (1888). However, the most celebrated accomplishment in the first half of the twentieth century within atmospheric dynamics was the recognition by Carl G. Rossby (1939) that the most ubiquitous aspects of large-scale atmospheric circulations in middle latitudes could be succinctly described through a straightforward analysis of the equation governing vorticity. Rossby was also one of the first to see the value of the dynamical quantity, denoted by Ertel as potential vorticity, which, in the absence of heating and friction, is conserved by fluid parcels as they move through the atmosphere. The diagnostic analysis and tracking of this quantity forms the basis of many current studies in atmospheric dynamics, of both a theoretical and observational nature, and Kushner's chapter gives a concise introduction to these notions.

The chapters by Meehl and Swanson review the nature of motions in the tropics and extratropics, respectively. These geographic areas, distinguished from each other by their climatic regimes, have distinctive circulation systems and weather patterns that necessitate a separate treatment of the dynamics of each region. The dominant balance of forces in the tropics, as discussed by Meehl, is a thermodynamic balance between the net heating/cooling of the atmosphere by small-scale convection and radiation and the forced ascent/descent of air parcels that leads to adiabatic cooling/heating in response. This thermodynamic balance is sufficient to explain the mean circulations in the equatorial region, the north–south Hadley circulation and east–west Walker cell, the transient circulations associated with the El Niño–Southern Oscillation (ENSO) phenomenon, the monsoon circulations of Australia and Asia, and the intraseasonal Madden–Julian Oscillation. Meehl also explains the interactions among these circulations.

In contrast to the tropics, the main focus in the extra-tropics are the traveling cyclones and anticyclones, which are the dominant cause of the weather fluctuations seen at midlatitudes in all seasons except summer. These variations, which are symbolized on weather maps with the familiar high- and low pressure centers and delimiting warm and cold fronts, are dynamically dissected by Swanson and explained in terms of inherent instabilities of the stationary features that arise due to the uneven distribution of net radiative heating, topography, and land mass over Earth's surface. In the process of dynamically explaining these systems, Swanson makes use of the quasi-geostrophic equations, which are a simplification of the governing equations derived by Salby. This quasi-geostrophic system is a staple of dynamical meteorology and can be formally derived as an approximation of the full system using scale analysis (cf. Charney, 1948, or Phillips, 1963). The advantage of such reduced equations is twofold: the reduction frequently leads to analytically tractable equations as shown by Swanson's examples and, with fewer variables and degrees of freedom in the system, it is almost always easier to directly follow the causal dynamical mechanisms.

The chapters by Herring and Weiss bring in paradigms and tools from the physics of fluid turbulence and the mathematics of dynamical systems theory. The entire field of atmospheric dynamics is but a subtopic within the physics of fluid dynamics. The study of fluid motions in the atmosphere, ocean, and within the fluid earth is frequently referred to as geophysical fluid dynamics (GFD), so it is not surprising that ideas from fluid turbulence would be used in atmospheric dynamics, as well as in the rest of GFD. What is different in the application in the large-scale dynamics of the atmosphere is the notion of viewing the atmosphere as a turbulent (nearly) two-dimensional flow. The perspective given by Herring was conceived in the late 1960s by George Batchelor and Robert Kraichnan, and further developed by C. Leith, Douglas Lilly, and Herring. Prior to this time it was thought that two-dimensional turbulence was an oxymoron since turbulence studied in the laboratory and observed in nature is inherently three dimensional. As Herring shows, the two-dimensional turbulence picture of the atmosphere has enabled a dynamical explanation of the spectrum of atmospheric motions and elucidated the growth in time of forecast errors, which initiate in small scales and propagate up the spectrum to contaminate even planetary scales of motion. This notion of forecast errors contaminating the accuracy of forecasts was first investigated by Philip Thompson (1957) using the methodology of Batchelor's statistical theory of homogeneous turbulence. Herring's chapter is a summary of subsequent developments using this methodology.

A seminal study by Edward Lorenz (1963) is the predecessor of the review given by Weiss, detailing the use of a dynamical system's perspective and deterministic chaos in quantifying the predictability of the atmosphere. Lorenz' study was the starting point for two research fields: the application of dynamical systems theory to atmospheric predictions and the mathematical topic of deterministic chaos. Weiss' chapter summarizes the scientific developments relevant to atmospheric dynamics and climate and weather prediction since 1963.

In any brief summarization of an active and growing field of research as much, or more, will be left out as will be reviewed. The chapters presented in this part are to be viewed more as a sampler than an exhaustive treatise on the dynamics of atmospheric motions. For those intrigued by works presented here and wishing to further learn about the area, the following texts are recommended in addition to those texts and publications cited by the individual authors: *An Introduction to Dynamical Meteorology* (1992) by J. R. Holton, Academic Press; *Atmosphere-Ocean Dynamics* (1982) by A. E. Gill, Academic Press; and *Geophysical Fluid Dynamics* (1979) by J. Pedlosky, Springer.

REFERENCES

Bjerknes, V. (1904). Das problem von der wettervorhersage, betrachtet vom standpunkt der mechanik un der physik, *Meteor. Z.* **21**, 1–7.

Charney, J. G. (1948). On the Scale of Atmospheric Motions, *Geofys. Publik.* **17**, 1–17.

Hadley, G. (1735). Concerning the cause of the general trade-winds, *Phil. Trans.* **29**, 58–62.

Lorenz, E. N. (1963). Deterministic Nonperiodic Flow, *J. Atmos. Sci.* **20**, 130–141.

Lorenz, E. N. (1967). The Nature and Theory of the General Circulation of the Atmosphere, World Meteorological Organization/Geneva.

Phillips, N. A. (1963). Geostrophic motion, *Rev. Geophys.* **1**, 123–176.

Thompson, P. D. (1957). Uncertainty of the initial state as a factor in the predictability of large scale atmospheric flow patterns, *Tellus* **9**, 257–272.

von Helmholtz, H. (1888). On Atmospheric motions, *Sitz.-Ber. Akad. Wiss. Berlin* 647–663.