Tropical Cyclone Physics

1. Introduction

The climate of the tropics is at once the most benign and the most dangerous on our planet. Most of the time the weather, as Christopher Columbus described it, is like May in Seville. Yet this salubrious climate, the placid subject of travel agency brochures and dream source of snowbound northerners, begets the most violent storms on earth. How and why does this happen? What physics determines the genesis, intensification, structure, and ultimate power of tropical cyclones? What role do they play in Earth's climate? This book addresses these and other fundamental questions.

Beside its intrinsic interest as a natural phenomenon, the tropical cyclone is a nearly perfect laboratory for geophysical fluid dynamics and thermodynamics, encompassing such concepts as balanced flow, potential vorticity conservation and inversion, dry and moist convection, boundary layer physics, frontogenesis, inertial, symmetric, and Kelvin-Helmholtz instabilities, Rossby waves, Carnot cycles, irreversible entropy production, interaction of longwave and shortwave radiation with clouds and water vapor, and upper ocean dynamics and mixing processes. As such, the content of this book is designed for the student with a firm background in classical physics, integral and differential equations, and geophysical fluid dynamics at the first-year graduate level. Some preparation in the physics of radiative and convective energy transfer will also be helpful.

To reach a viable understanding of tropical cyclones, it is first necessary to set them in the context of the tropical atmosphere-ocean system as a whole. Thus we first turn to the subjects of radiation and convection, which together form the two main elements of radiative-convective equilibrium, which we take to be a useful and natural starting point in describing the tropical atmosphere and ocean surface. Progressing from one spatial dimension to two, we inquire whether and to what extent the existence of meridional gradients of solar radiation perturbs our one-dimensional picture, leading us to an exposition of Hadley circulations. The existence of continents breaks the symmetry of the response of ocean currents to wind stresses imposed by the Hadley circulation, creating strong east-west gradients in ocean surface temperature which in turn lead to zonal atmospheric circulations. So, too, do continents provide the setting for seasonal monsoonal circulations. Besides these phenomena, there is a rich variety of more time-dependent organized structures, from squall lines and cloud clusters to equatorially trapped and African easterly waves, to the massive and mysterious planetary wave known as the Madden-Julian Oscillation. In addition to being of inherent interest to us, all these circulations play a role in the formation and behavior of tropical cyclones.

Then we arrive at our true destination: a comprehensive description of the physics of tropical cyclones as best we know them today. After reviewing the observed characteristics of tropical cyclones, we begin with perhaps the best known problem, the dynamics and energetics of the steady, circularly symmetric tropical cyclone vortex. While clearly an idealization, it has proven a useful one even though it is unlikely that the outflow region at the top of the storm is ever very symmetric or steady in time. We then tackle the time-dependent problem of the intensification of tropical cyclones, retaining the idealization of circular symmetry. Finally relaxing this assumption, we examine the nature of departures from circular symmetric, including spiral rainbands and outflow jets, and time-dependent phenomena such as secondary eyewall cycles.

Tropical cyclones are powered by turbulent enthalpy fluxes from the sea and retarded by turbulent dissipation in the atmospheric boundary layer owing ultimately to frictional stress with the underlying surface. But these exchanges are complicated by the complex physics of the air-sea interface at the extraordinary wind speeds of tropical cyclones. The ocean is far from a passive source of heat and sink of momentum; it reacts strongly to the passage of tropical cyclones. Surface waves carry off a surprising fraction of the energy generated by the cyclone, and the storm-generated surface stresses can resonate strongly with near-inertial currents in the upper ocean. The turbulent breakdown of such currents leads to mixing to the sea surface of colder waters in the seasonal thermocline, producing strong negative feedback on the storm itself. The role of ocean feedback and the importance of the air-sea interface are the central subjects of Chapter 8, as are the hydrodynamics of storm surges, tsunami-like phenomena generated by wind stresses but strongly affected by local bathymetry and astronomical tides. Surges are the main cause of loss of life in tropical cyclones globally.

The large-scale atmospheric environment also exerts strong influences on tropical cyclones. Vertical shear of the horizontal wind interacts in complex ways with tropical cyclones, stretching and separating the vortex's potential vorticity anomaly, leading to such phenomena as precession and re-alignment. Chapter 7 describes these interactions as well as the thermodynamic consequence of injecting large quantities of low entropy air from the environment into the vortex core, an effect akin to throwing buckets of water on a fire. But as tropical cyclones move into higher latitudes, they often interact with extratropical potential vorticity anomalies and large-scale horizontal temperature gradients, leading to fascinating and not fully understood evolutions, which can include re-intensification of the storm long after it has left its feeding grounds deep in the tropics. We also take the opportunity to describe tropical-cyclone like phenomena outside the tropics, including certain classes of polar lows that paradoxically favor arctic oceans in winter, medicanes…hurricane-like storms that form over the Mediterranean Sea… and agukabams, which develop over land under special circumstances.

Of all the mysteries that confront the tropical cyclone physicist, the nature of the processes by which these storms are generated remains the most enigmatic. In Chapter 9 we delve into this problem, examining in detail the sequence of events leading to the genesis of individual storms but also looking at the physics by which tropical storms emerge spontaneously from the chaos of radiative-convective equilibrium as simulated by contemporary numerical models that explicitly simulate cumulus clouds. This may provide clues about what controls the frequency of tropical cyclones on our planet in our current climate.

Which leads to the last topic of our treatise: How does tropical cyclone activity respond to climate change, and are these magnificent and terrifying storms incidental to our climate or integral elements of the climate machine, providing important feedbacks that stabilize climate or accelerate its change? Here we leave our reader with a perplexing unsolved mystery, but one which he or she should by then be well equipped to tackle.