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INTRODUCTION TO STORMS

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INTRODUCTION

Storms are fundamental to life on Earth. But their impacts on society (and environment) are not always welcome. While they bring the rains which make life possible, when extreme, they can take life as well. Worldwide, the societal impacts of storms as measured by lives lost and economic damages have yet to be tabulated on a systematic basis. Nonetheless, rough estimates are available which provide insight as to the magnitude of storm impacts on society. According to the International Federation of Red Cross and Red Crescent Societies, flood and wind disasters resulted in an average annual loss of more than US$56 billion (over the period 1990–94) and the average annual loss of more than 40,000 lives (over the period 1970–94, IFRCRCS 1996). Countless other impacts not counted as disasters would certainly add to these rough totals.

As a result of these impacts societies around the world have sought to reduce their vulnerability to storms. In some cases, society implements an explicit response to a perceived threat, as is the case in evacuation planning (e.g., Baker). Sometimes they are incorporated as part of an ongoing decision process, such as in the development of building codes (e.g., Cochran). But all too often, decisions are made without consideration of vulnerability to storms, leading to unnecessary loss of property and life, and in some cases to disaster (e.g., Anderson and Morrow). And in other cases, societal responses to storm impacts can serve to exacerbate vulnerability (e.g., Pilkey *et al.*). This broad spectrum of events, vulnerability and responses provides a rich body of theory and experience on which future decisions might benefit from. The overarching objective of this volume is to provide an overview of important themes in this spectrum.

This chapter provides a brief introduction to storms on planet Earth as a background to the more detailed chapters provided by this volume on storms, one of seven titles in the Routledge series on natural disasters. The overarching integrative focus that we asked authors to bring to this volume is "vulnerability" (see Anderson; also Pielke and Pielke 1997). Vulnerability has several definitions in the literature on natural hazards (e.g., see Pulwarty and Riebsame 1997 for an overview). We use the concept of vulnerability to distinguish the incidence of storms from the exposure of society in order to focus attention on those actions which can lead to reduction in vulnerability (Pielke and Pielke 1997). Anderson (this volume) provides a comprehensive overview of vulnerability.

A TAXONOMY OF STORMS

There are many valid ways to classify storms. For instance, meteorologists often differentiate atmospheric phenomena according to their scale (that is, microscale, mesoscale and synoptic scale) (Cotton). Natural hazards scholars have typically focused either on particular phenomena (hurricanes, floods, blizzards, etc.) or on decision processes of various actors (for example, warning and response), risk assessment, mitigation, etc. In structuring this volume we chose to use a combination of these approaches. We differentiate storms by their physical characteristics into tropical cyclones (Part II), extratropical cyclones

(Part III) and mesoscale convective systems (Part IV) (each of which is described below). Within each section, the volume focuses on particular phenomena and on certain decisions. We also chose to present case studies of events, impacts and responses within each section. Not all cases fit neatly into the classification of tropical cyclone, extratropical cyclone and mesoscale convective system. For instance, polar lows (Rasmussen) monsoons (Krishnamurti *et al.*), duststorms (Goudie and Middleton), and space weather storms (Maynard), each have unique characteristics and are included in Part V.

In addition to a broad focus on vulnerability, there are several other choices that we made in structuring the volume. One is that we chose to de-emphasize floods in recognition that the Routledge series includes an entire volume on floods (which are obviously closely related to storms). Floods are of immense importance to societies and environments around the world and we encourage the reader to consider the Floods volume as a close companion to this one. A second is that we asked each author to write for a broad, multidisciplinary audience using as little jargon as possible. We also asked authors to provide key references to the literature in their area to guide the interested reader in their further investigations. A third choice that we made was to include a number of cross-cutting chapters that spanned the phenomenological taxonomy we use in the bulk of the volume. These topics are presented in Part I and include, amongst others, forecasting (Wernly and Uccellini), social science (Carbone), insurance (Malmquist and Michaels) and climate variations (Trenberth).

STUDY OF THE SCIENCE OF STORMS

Scientists define large-scale storm features into two types: tropical and extratropical. Tropical systems derive their energy from clusters of thunderstorms. Tropical systems include loosely organized thunderstorm systems called "mesoscale convective systems" and tightly structured features such as tropical depressions, tropical storms and hurricanes[1] (Gray, and Powell, this volume; Neumann 1993). While the term "tropical" is used to define these features, clusters of thunderstorms actually occur at both mid and high latitudes (for example, polar lows; Rasmussen, this volume). Mesoscale convective systems occur as nearly circular thunderstorm clusters and also as linear features that are referred to as squall lines (Zipser 1977; Maddox 1980; Smull and Houze 1985; Houze 1994; see also Hjelmfelt, Ziegler, Garstang and Tyson, Silva Dias and Rodriguez, this volume).

Extratropical storms derive their energy from the juxtaposition of cold and warm air (Davis *et al.* Weaver, and Chakina, this volume; Gurka *et al.* 1995). The separation of the cold air (of mid and high latitudes) from the warmer air (of tropical origin) defines what is called the "polar front". The movement of cold air towards lower latitudes in one area, and the movement of warm air poleward in an adjacent area to the east, generates low pressure systems along the polar front. These low pressure systems become extratropical storms if they strengthen as the equatorial movement of cold air and poleward movement of warm air continues. The term "extratropical" is used because the polar front on which they form (and, therefore, the extratropical storm) almost always develops at latitudes poleward of around 30 degrees.

On a broad scale, the Earth's atmosphere has a region of low-level wind convergence near the equator that is called the "intertropical convergence zone (ITCZ)" and also the "equatorial trough" (since it is a region of relatively low sea-level pressure). At around 20–30 degrees of latitude (with this location tending to move poleward in the summer, and closer to the equator in the winter) is a region of persistent high pressure that is referred to as the "subtropical high". This region of subsiding air causes the vast desert regions of the Sahara, the Sonoran, the Kalahari, the Atacama and the Great Australian Deserts.

Between the subtropical high and the ITCZ, the low-level winds usually blow in from the northeast in the Northern Hemisphere and from the southeast in the Southern Hemisphere. These winds are called the "trade winds". In the upper troposphere (about 17 kilometers), the air that moves upwards in the ITCZ in thunderstorms is transported poleward before sinking at the latitude of the subtropical high. This poleward-moving air in the upper troposphere often occurs in well-defined corridors of air that are called the "subtropical jet streams". This flow transfers poleward vast amounts of heat, Earth's rotational momentum and moisture. The subtropical jet stream has a greater westerly component as it moves poleward because it carries with it some of the higher velocity movement towards the east that it obtained from the Earth's rotation closer to the equator. (In physics, this effect is referred to as the "conservation of angular momentum".) The result of this deflection towards the east is that the energy generated in the ITCZ cannot be directly transported north of the subtropical highs.

This tropical and subtropical region of wind circulation is called the "Hadley circulation" and is illustrated in Figure 1.1. It is a form of a direct heat engine in that warm air rising in the ITCZ drives the flow. It is the main mechanism by which heat, moisture and the Earth's rotational momentum are transferred poleward to the latitudes of the subtropical ridge. It has been suggested that the tropical depression, tropical storms and hurricanes develop when the Hadley circulation is unable to transfer all of this heat and moisture poleward by itself.

Further poleward, a different mechanism to transfer heat, moisture and momentum occurs. Extratropical storms become the primary exchange mechanism where cold dry air with smaller values of Earth's rotational momentum is moved equatorward behind cold fronts (that is, when the polar front moves equatorward) and warm, moist air with higher values of the Earth's rotational momentum is moved poleward behind warm fronts (that is, when the polar front moves poleward). The greater the contrast in temperature between the cold and warm air, the stronger the extratropical storm can become. This is the reason that winter extratropical storms are typically stronger than summer extratropical storms.

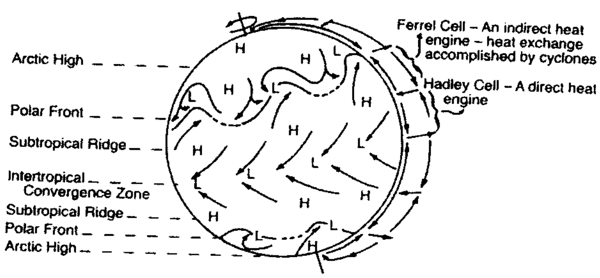

Figure 1.1 Schematic view of the general circulation of the Earth and associated names of the major circulation features

In the upper troposphere, the polar front is intimately coupled with the "polar jet stream". The polar jet stream develops because of the horizontal differences in pressure between the warm and cold air. This difference creates wind, which increases in strength with height through the troposphere when the temperature contrasts exist. Warm air toward the equator and cold air poleward creates a westerly polar jet stream. The larger the horizontal temperature contrast, the stronger the polar front and the polar jet stream. Figure 1.2 illustrates how the jet stream, polar front and extratropical cyclone development are interrelated.

In the winter in mid and high latitudes, continents tend to become lower tropospheric high pressure reservoirs of cold air as heat is radiated out to space during the long nights. In contrast, oceans lose heat less rapidly as a result of the large thermal inertia of water, its ability to overturn as the surface cools and become negatively buoyant, and the existence of ocean currents such as the Gulf Stream and Kuroskio Currents, which transport heat from lower latitudes poleward. The warmer oceanic areas, therefore, tend to be regions of relatively low surface pressure. As a result of this juxtaposition of cold and warm air, east sides of continents and the western fringes of oceans in middle and high latitudes are preferred locations for extratropical storm development. Over the Asian continent, in particular, the cold high pressure system is sufficiently permanent that a persistent offshore flow called the "winter monsoon" occurs.

An inverse type of flow develops in the summer as the continents heat more than adjacent oceanic areas. Continental areas tend to become regions of relative low surface pressure, while high surface pressure becomes more prevalent offshore. Persistent onshore winds which develop over large land masses as a result of the heating are referred to as the "summer monsoon". The leading edge of this monsoon is associated with a trough of low pressure called the "monsoon trough". Tropical moisture brought onshore by the monsoon often results in copious rainfall. Cherrapunji in India, for instance, recorded over 9 meters of rain in a month (July 1861) due to the Indian summer monsoon. The monsoon process is discussed in Krishnamurti *et al.*

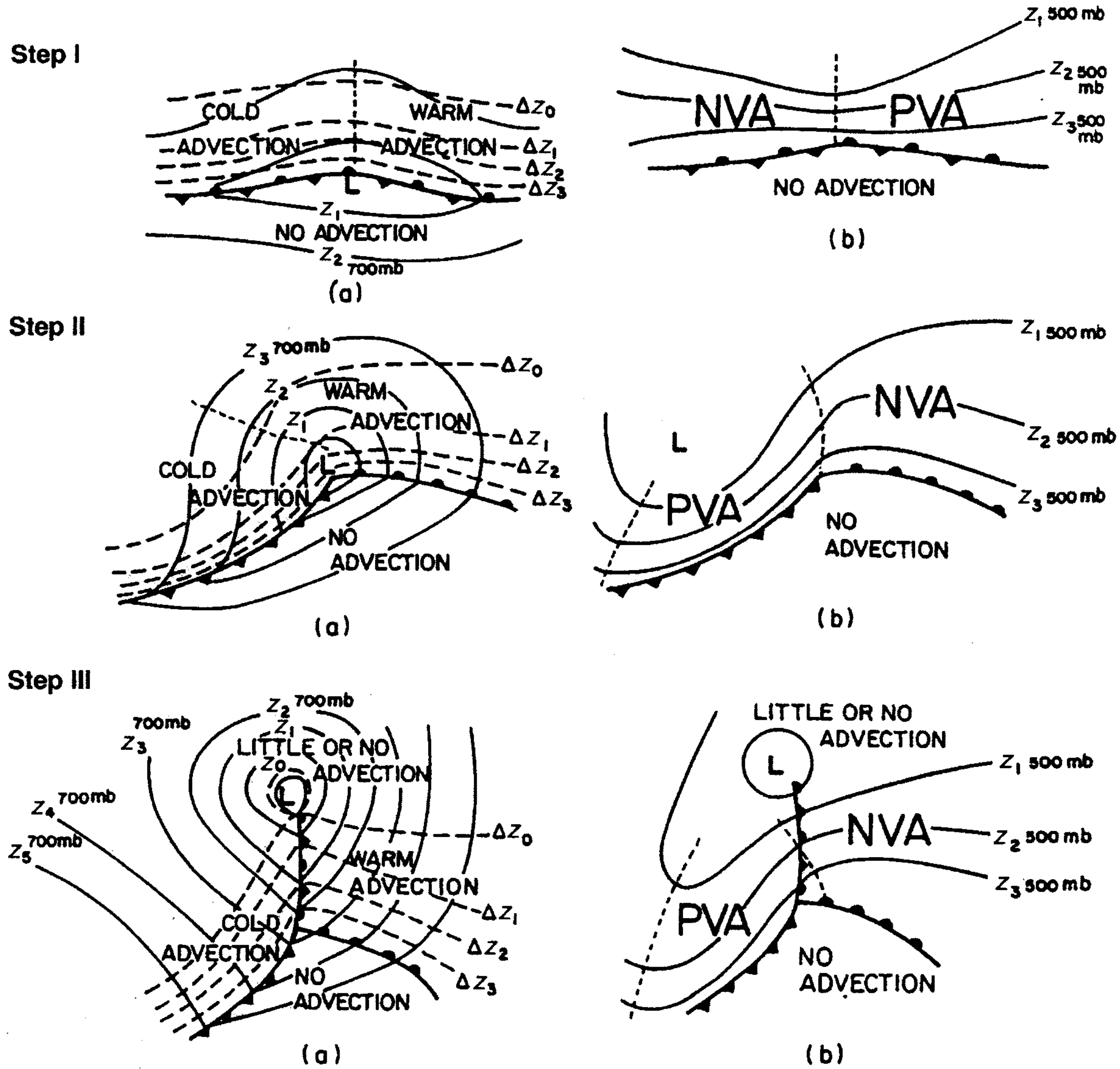

Figure 1.2 Schematic view of surface weather (a) and middle troposphere (b) features of the development of an extratropical cyclone. In (a) the values of z represent the height of the 700 mb pressure surface ($z_3 > z_1$), while the mean temperature of the 1000–500 mb layer (as represented by its thickness Δz) is shown by the dashed lines $\Delta z_3 > \Delta z_0$). The location of cold, warm and occluded fronts relative to the thickness gradient is presented. In (b), the height of the 500 mb pressure surface is shown ($z_3 > z_1$), along with regions of positive and negative vorticity advection (PVA; NVA). Positive vorticity advection causes an increase in the cyclonic curvatures to the height field shown in (a). The spacing between height contours is directly related to wind speed. In (b) the strongest jet stream at 500 mb occurs where the contour spacing is the tightest

Squall lines and mesoscale convective systems develop in the warm, tropical air ahead of approaching cold fronts. These systems are also part of the movement poleward of heat, moisture and the Earth's rotational momentum, on the poleward side of the subtropical ridge.

Tropical systems

Figure 1.3 illustrates how tropical systems of different intensities appear. The weakest systems consist of a loosely organized region of irregularly spaced thunderstorms and showers. It is evident in a satellite image because this region has a higher coverage of these rainy areas than the surrounding areas. Typically, there is a core of strong thunderstorms at the leading edge of the system and a much larger area of steady rain from stratiform clouds on the trailing side (Cotton 1990; Cotton and Anthes 1989; Zipser 1977).

Better organized tropical systems have a more

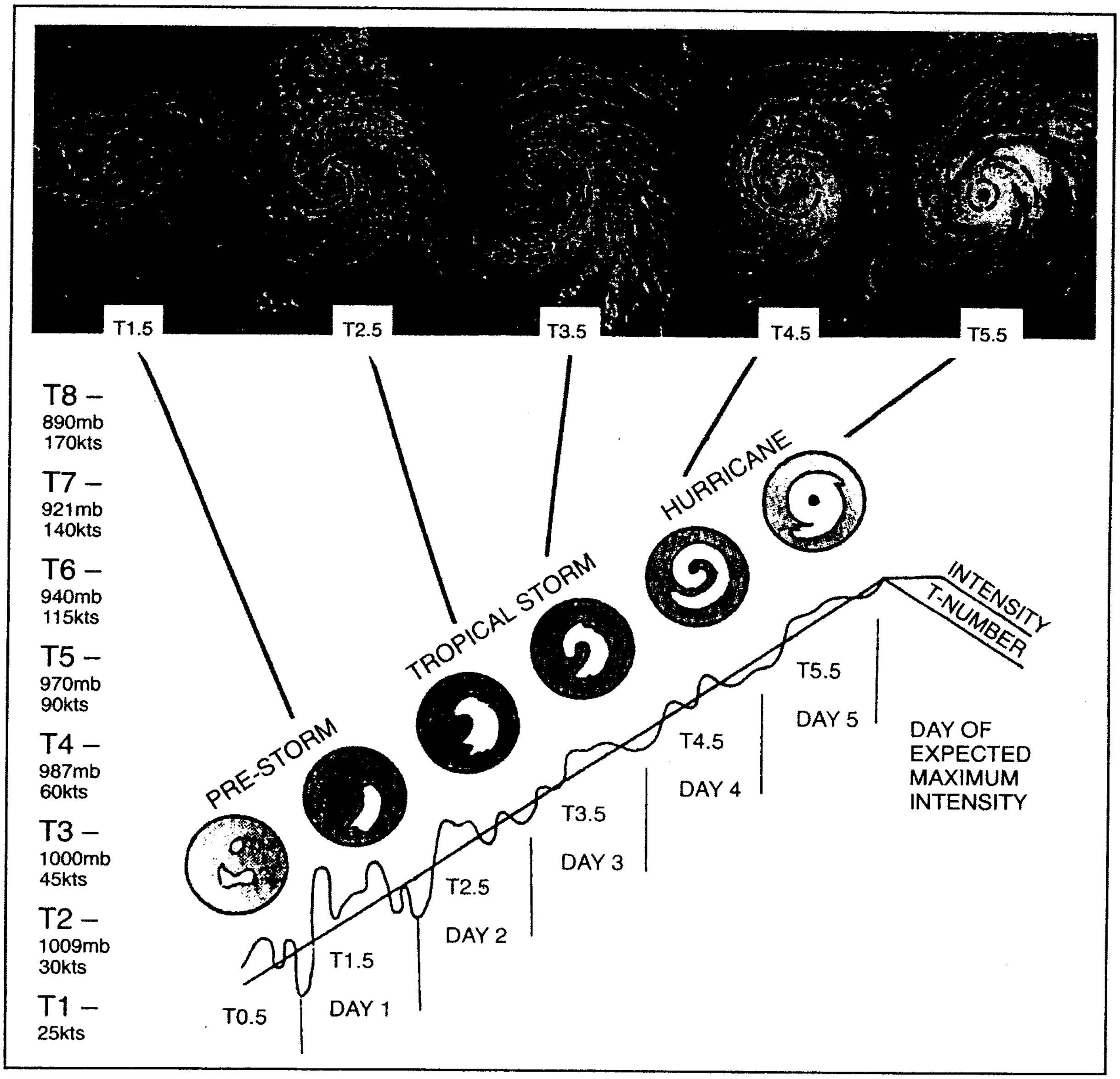

Figure 1.3 The organization of tropical cyclones as seen by satellites (from Dvorak 1984)

concentrated area of thunderstorms with a corresponding region of lower sea-level pressure. In the United States, tropical depressions are defined when there is a circulation of winds around these low pressure areas, but one-minute averaged winds are less than 39 miles per hour. Between 39 and 73 miles per hour, these systems are called tropical storms and are given names. At and above 74 miles per hour, they are called hurricanes. In the Pacific west of the dateline, such storms are called typhoons. At these speeds, the strongest winds occur in an annulus of intense thunderstorms called the eyewall which surrounds the eye. Sustained winds in the strongest hurricanes can reach 200 miles per hour. The coexistence of the thunderstorms over warm ocean waters at and near the center of these low pressure systems sustain and perpetuate them. Tropical cyclones and other types of tropical weather systems are discussed in texts such as Asnani (1993).

Extratropical storms

In a typical extratropical storm, there is a large cloud shield poleward of the warm front (as illustrated in Figures 1.4 and Plate 1.1) with steady rain or snow typically occurring. Along the cold front, a narrow band of clouds and precipitation, often of a shower or thunderstorm type, occur. In the warm section, between the cold and warm fronts, squall lines of thunderstorms often occur in the humid, warm tropical air.

Extratropical storms that undergo explosive deepening are referred to as bombs (Sanders and Gyakum 1980). Such storms achieve very low sea-level atmospheric pressures and, as a result, a strong horizontal pressure gradient develops between its center and the atmosphere at the periphery of the storm. This results in a very large-scale field of gale force (and occasionally near hurricane force) winds. "Nor'easters" are examples of this type of storm which develop along the east coast of the United States. Detailed texts on extratropical storms include Bluestein (1992, 1993), Carlson (1991), Barry and Perry (1973).

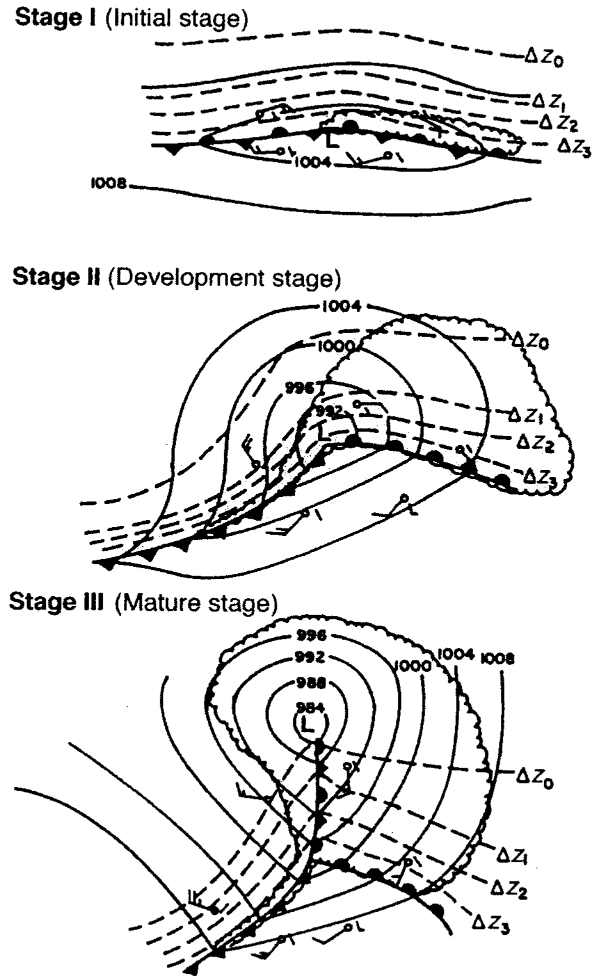

Figure 1.4 The extratropical cyclone development in Figure 1.2(a) is shown with respect to how its cloud field develops

THE STUDY OF STORM IMPACTS

In addition to the nature of storms, scientists also study their impacts and how societies prepare for and respond to those impacts. Impact researchers often distinguish climate from weather. There are several technical definitions of climate (e.g., Bryson 1997; Pielke 1998), but perhaps the most common is a statistical definition such as that adopted by the 1979 World Climate Conference: weather is associated with the complete state of the atmosphere at a particular instant in time, and with the evolution of this state through the generation, growth and decay of individual disturbances.

Climate is the synthesis of weather events over the whole of a period long enough to establish its statistical ensemble properties (mean value, variances,

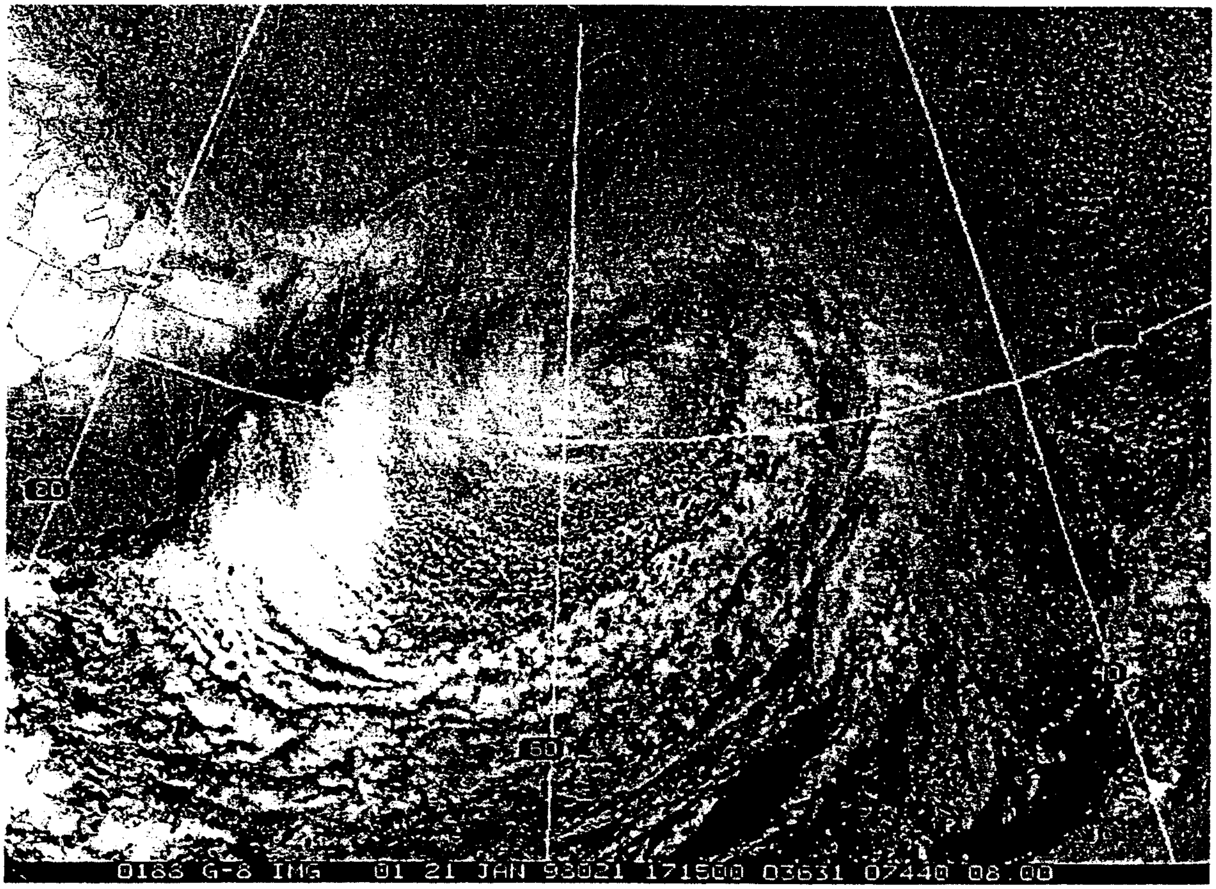

Plate 1.1 A satellite view of a mature extratropical cyclone (photograph reproduced by courtesy of Ray Zehr, NESDIS, NOAA)

probabilities of extreme events, etc.) and is largely independent of any instantaneous state. In this definition, climate is more than just "average weather" (Gibbs 1987). Climate is the distribution of weather events and their component properties (for example, rainfall) over some period of time, typically a few months to thousands of years. In general, climate statistics are determined based on actual (e.g., weather station) or proxy (for example ice cores) records of weather observations. For those who use weather and climate information, an old adage aptly summarizes the distinction between the two: "Climate is what you expect, weather is what you get."

Impacts research takes place across a broad range of time and spatial scales of weather and climate, from the use and value of current weather information in decision-making to the impacts of possible future climates on society centuries hence. The methodologies used by impacts researchers span the social sciences and the humanities. This volume provides an overview perspective on social science and weather warnings (Aguirre) as well as a range of cases on impacts which are illustrative of different social science methodologies (for example, Pielke, and Etkin and Myers).

The volume also contains a number of case studies of forecasts, impacts and responses to a range of phenomena around the world. The case studies presented in Parts II, III and IV focus on tropical cyclones extratropical cyclones, and on mesoscale convective systems. Cross-scutting themes such as vulnerability, forecasting and insurance are presented in Part I. Storm impacts are important to society and environment. With a better understanding of the physical, societal and environmental processes, decision-makers will be in the position to more effectively prepare for and respond to storm impacts. This volume is intended as a starting point for those who would like an introduction or a gateway to the vast knowledge that society has gained about storms on planet Earth.

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NOTE

1 Tropical cyclones are called variously cyclones, severe cyclones, typhoons and super typhoons.

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