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1

The Atmospheric Mesoscale

1.1 Introduction

It is fitting to begin this exploration of mesoscale-convective processes with a definition of the *atmospheric mesoscale*. Likely, the reader has at least a vague idea of atmospheric phenomena that are normally categorized as mesoscale. Thunderstorms and the dryline are common examples. What the reader might not yet appreciate, however, is that devising an objective and quantitative basis for such categorization is nontrivial. Indeed, even the more basic practice of separating the atmosphere into discrete intervals can be difficult to rationalize universally, because the atmosphere is, in fact, continuous in time and space in its properties.[1]

Consider the atmospheric measurements represented in Figure 1.1. These have been analyzed to reveal a frequency spectrum of zonal atmospheric kinetic energy.[2] Although the spectrum is continuous, it does exhibit a number of distinct peaks. Conceivably (and arguably), the intervals centered about the peaks represent atmospheric scales. The relatively narrow peak at a frequency of 10^0 (/day) is compelling here, because it indicates the existence of energetic eddies with a diurnal cycle. Dry and moist convective motions that grow and decay with the daily cycle of solar insolation are the presumed manifestations of such eddies, and would fall generally within the atmospheric mesoscale.

The spectral analysis technique used to generate Figure 1.1 involved a transformation of the *temporal distribution* of zonal kinetic energy to a distribution in terms of *frequency* space. A similar technique can be used to transform the *spatial distribution* of some variable to its distribution in *wavenumber* space. The wavenumber spectra in Figure 1.2 are from independent measurements, but similarly reveal continuous, yet separate, regions.[3] Here, the region distinction is given by the slope of statistical fits to the data in wavenumber space. At wavelengths greater than a few hundred kilometers, which includes the *synoptic scale*, the spectral curves have slopes near –3. At wavelengths of a few kilometers to a few hundred kilometers, which spatially

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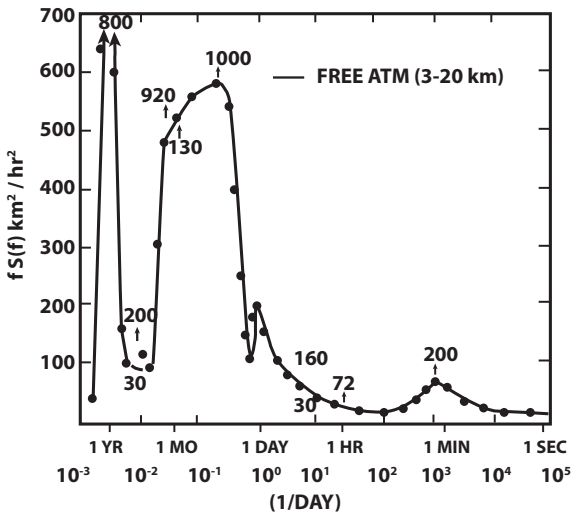

Figure 1.1. Average kinetic energy spectra (spectral density) of the free-atmospheric zonal wind as a function of frequency. Numbers show maximum kinetic energy at particular periods. After Vinnichenko (1970).

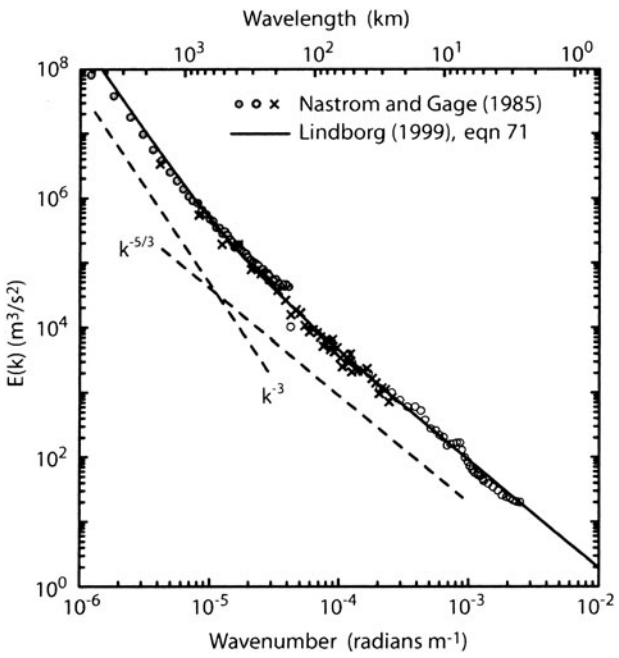

Figure 1.2. Kinetic energy spectra as a function of wavenumber, derived from the measurements of Nastrom and Gage (1985). The solid curves are from Lindborg (1999), which are fits to a separate set of measurements. The dashed lines indicate the slopes discussed in the text. From Skamarock (2004).

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will be shown to correspond to mesoscale structures, the slope of the spectral curves is near –5/3. Thus, the spectral slopes help to distinguish between these two scales; we will learn in Chapter 10 that these slopes also have implications on the limits of atmospheric predictability.

Though valuable, the information in Figures 1.1 and 1.2 is still a bit incomplete for the purposes of this chapter, because it discloses nothing explicit about other structural characteristics, such as the variations in temperature, pressure, humidity, and wind intrinsic to the various phenomena. As will be demonstrated in Chapters 2, 3, and 4, respectively, knowledge of these characteristics is paramount to choosing appropriate forms of the dynamical equations, planning observation strategies, and designing numerical simulation and prediction models.

History, as it turns out, was critically influential in how these remaining characteristics were determined and assigned. Technological advances played an obvious role, but so also did the geo politics and events of the time. Let us digress briefly to examine some of this history.

1.2 Historical Perspectives

We begin with the historical origin of the synoptic scale, because in most classification schemes the synoptic scale places an upper limit to the mesoscale. The modern definition of the synoptic scale is usually given in terms of the size of migratory high- and low-pressure systems (midlatitude anticyclones and cyclones), which range from several hundred to several thousand kilometers.[4] Interestingly, the quantitative values attached to the synoptic scale actually arose out of the size of the observing networks in the late 1800s and early 1900s. This is the period when synoptic weather maps were first constructed routinely and the study and prediction of air masses began.[5] Synoptic weather observations were – and still are – made nearly simultaneously, to give a snapshot of the state of an otherwise evolving atmosphere.[6] Hence, the synoptic length scales we accept today effectively came from the practical area of such simultaneous observations as of the late 1800s and early 1900s, as limited by communication technology, and perhaps complicated by geopolitical boundaries.

Meteorological features smaller than these length scales, and therefore not well represented by the synoptic observations, were deemed "noise" or subsynoptic disturbances.[7] As demonstrated in Figure 1.3, at least some of this noise is attributable to the surface outflow of thunderstorms. Nonetheless, thunderstorms effectively kept their status as noise until the hazards they were imposing on the rapidly expanding air transportation industry around1930 (and presumably on military interests, around 1940) were recognized. Indeed, efforts to observe subsynoptic-scale motions – and to describe the associated phenomena – were motivated in part by the rise in weather-related accidents.

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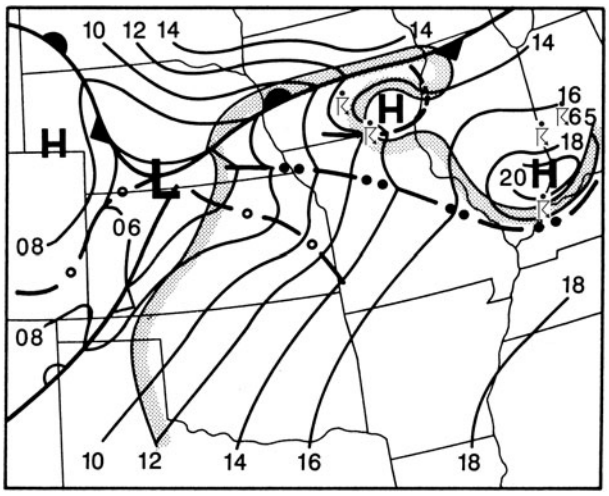

Figure 1.3. Analysis of sea-level pressure (millibars – 1000) and surface fronts at 0000 UTC 24 June 1985. The bold "H"s in southeast Iowa and southeast Illinois show convectively induced mesohigh pressure. Convective-storm outflow boundaries are indicated by lines with a dash-dot-dot pattern, and wind shifts by lines with a dash-dot pattern. The shaded line outlines the region where dewpoint temperatures exceeded 65°F. From Stensrud and Maddox (1988).

One result of such an effort was the subsynoptic observational network deployed during the *Thunderstorm Project*[8] in 1946. Compared with other experimental networks at about this time (see Figure 1.4), the Thunderstorm Project network had surface-station spacings as fine as 2 km, over a domain spanning several tens of kilometers.[9] The surface observations were supplemented with upper-air data collected using radiosondes, multiple coordinated aircraft, and even gliders.[10] When combined, these novel data helped to form a conceptual model of convective-storm evolution that still holds today (see Chapter 6).

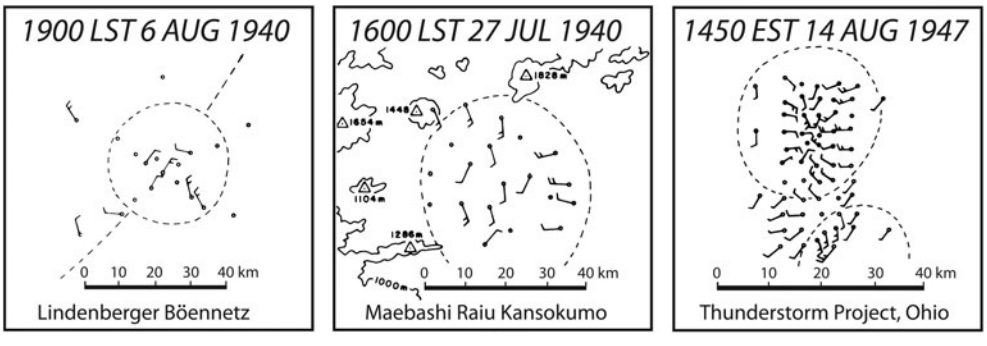

Figure 1.4. Examples of subsynoptic observing networks in the 1940s. The dashed lines indicate locations of thunderstorm outflow boundaries. From Fujita (1986).

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In terms of interests specific to the current chapter, the Thunderstorm Project data have been used to quantify the characteristics of deep moist convection in the continental extratropics. The typical updraft length, depth, and vertical speed of $\sim$10 km, $\sim$10 km, and $\sim$10 m s^{-1}, respectively, form the basis of the (sub)classification schemes discussed later; they also allow for interesting comparisons (in Chapter 5) with tropical oceanic convection, as quantified in part during the Global Atmospheric Research Program's Atlantic Tropical Experiment (GATE) almost thirty years after the Thunderstorm Project.[11]

Weather radar was another observing tool used during the Thunderstorm Project. Developed out of a military application in World War II, weather radar was still in its relative infancy during this time. Yet, sufficient data had been collected by 1950 to allow M. G. H. (Herbert) Ligda to posit the mesoscale as an intermediate between the synoptic scale and the microscale:[12]

> It is anticipated that radar will provide useful information concerning the structure and behavior of that portion of the atmosphere which is not covered by either micro- or synoptic-meteorological studies. We have already observed with radar that precipitation formulations which are undoubtedly of significance occur on a scale too gross to be observed from a single station, yet too small to appear even on sectional synoptic charts. Phenomena of this size might well be designated as mesometeorological.[13]

This recognition of the importance of weather radar and precipitation structure helped father the term *mesoscale*, but did not really help quantify it.[14] However, there was another recognition at this time (c. 1950–1960) that did: the importance of surface pressure measurements. This apparently was motivated by observations of abrupt changes in pressure at and just after the onset of thunderstorms (and thunderstorm systems). We will learn in subsequent chapters that pressure jumps – and, in particular, the spatially continuous pressure-jump lines – represent the leading edges of *meso-highs* generated beneath downdrafts, and are now commonly known as *gust fronts* (see also Figure 1.3). Pressure-jump lines were thought to play a vital role in tornado formation, especially when two lines intersected.[15] Although other mechanisms of tornadogenesis have since been established (see Chapter 7), this astute deduction (by M. Tepper) is viewed now as early evidence of tornadogenesis via storm-boundary interaction (see Chapter 9).

To better observe pressure-jump lines and related characteristics in pressure, a network of microbarograph stations was established in the United States (Figure 1.5).[16] This network, which subsequently was operated by the National Severe Storms Project (NSSP), the precursor to the National Severe Storms Laboratory (NSSL), is an early example of the more fully equipped surface mesonetworks now in place in several U.S. regions (see Chapter 3). It consisted of 210 stations in Kansas, Oklahoma, and Texas, and had a station spacing of $\sim$60 km. Because the NSSP network was much coarser than that used during the Thunderstorm Project, yet

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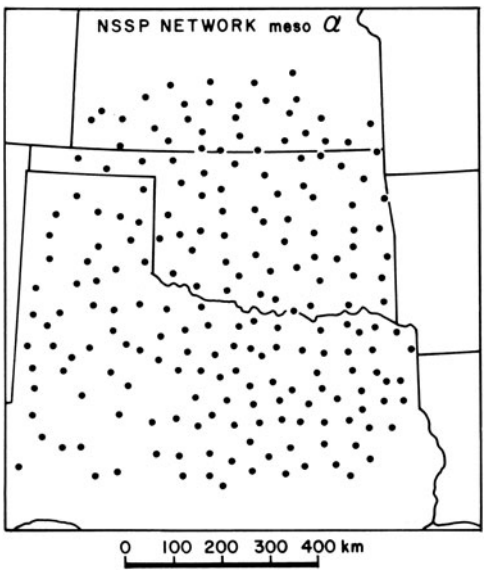

Figure 1.5. The National Severe Storms Project (NSSP) microbarograph network in the early 1960s. From Fujita (1986).

much larger in spatial extent, it served a useful purpose in describing the mesoscale "environment" as well as relatively larger mesoscale phenomena (see Chapter 8). In particular, such mesonetworks led to quantification of the characteristics of mesoscale-convective systems (MCSs), with typical lengths of ∼100 km and durations of ∼3 h.

Numerical weather prediction (NWP) was also advancing during this period, coincident with the technological advances of digital computing. Although the initial goal of NWP was prediction of planetary- and synoptic-scale waves, it was soon realized that the mesoscale could not be ignored if accurate predictions were to be made. This is especially true in the tropical latitudes, where deep moist convection is essential in redistributing energy and contributing to the global energy balance (Chapter 9). A representation of the effects of convection and other mesoscale processes in terms of relatively larger-scale variables is the premise of *parameterizations* (Chapter 4). Thus, the need to describe and understand the mesoscale goes beyond the hazards of convective weather.

1.3 Atmospheric-Scale Classification Schemes

Ligda's statement was followed by a number of proposals for atmospheric-scale classification schemes that accounted for the mesoscale. An example of a relatively simple three-class scheme of F. Fiedler and H. Panofsky is as follows:[17]

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	Synoptic-	Meso-	Micro-
Period	>48 hr	1–48 hr	<1 hr
Wavelength	>500 km	20–500 km	<20 km

Here, wavelength is an average distance, such as that between updrafts or pressure minima, and similarly, period is an average time between wind gust or temperature maxima. The rationalization is as follows: (1) "synoptic scale includes all scales of motion which can be analyzed on the basis of a weather map" (i.e., no discrimination between planetary scale and synoptic scale); (2) "all systems in which the vertical and horizontal velocities are of the same order of magnitude are 'microscale' systems"; and (3) the "mesoscale occurs between the microscale and synoptic scale."[18]

The scheme of I. Orlanski accounts for the characteristic times and lengths, includes examples of phenomena, and also has scale subdivisions, as designated by the Greek letters alpha (α), beta (β), and gamma (γ) (Figure 1.6).[19] T. Fujita's alternative to the Orlanski scheme has five divisions (using the vowels a-e-i-o-u), and each of these has an α and β subdivision (Figure 1.7).[20]

A survey of the literature suggests that Orlanski's scheme is employed fairly widely, particularly when a distinction within the mesoscale (i.e., meso-α, meso-β, or meso-γ) is deemed necessary. Fujita's scheme appears to have been adopted mostly for the characterization of a specific class of vortex, a *miscocyclone* (see Chapter 5), and for the convectively induced, near-surface outflows known as *microbursts* and *macrobursts* (Chapter 6). Herein, we will strive for consistency with the common uses of both schemes, but will have a preference for the Orlanski scheme when reference is made to scale ranges and subdivisions.

1.4 Mesoscale-Convective Processes

Our treatment of the atmospheric mesoscale, as guided by the preceding sections, will include processes with horizontal lengths of ∼10 to ∼100 km, times of ∼1 hr to ∼1 day, and speeds of ∼1 to ∼10 m s^{-1}.

The range of phenomena that possess these characteristics is quite broad. Although it includes mechanically forced flows, such as mountain waves, the discussions herein will be limited largely to flows that arise from buoyancy-driven, or convective, motions. Accordingly, "convective" will be used as a qualifier, to distinguish such motions from those that are mechanically forced.

The convective clouds, precipitation, and associated phenomena have characteristic lengths, times, and speeds that can extend below the lower end of the mesoscale, but can be initiated and forced by mechanisms at or above the upper end of the mesoscale. Subsequent chapters will offer a treatment of the processes that span this spectrum,

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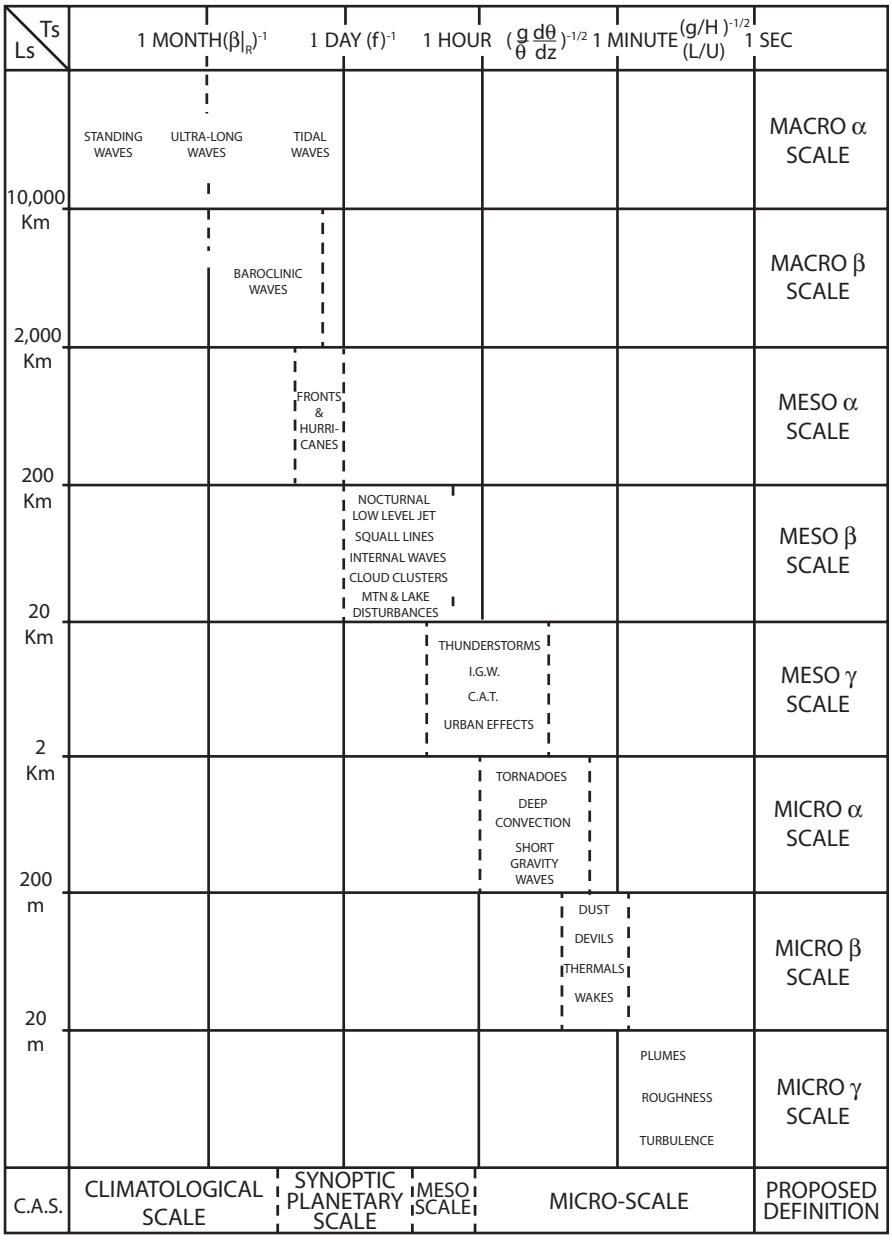

Figure 1.6. Atmospheric-scale classification scheme proposed by Orlanski (1975).

including convection initiation, the subsequent organization and morphology of the clouds and precipitation, and the interaction of these processes with those at the synoptic and larger scales. Other chapters will provide the mathematical theory behind the mesoscale-convective processes, describe how these processes are observed and

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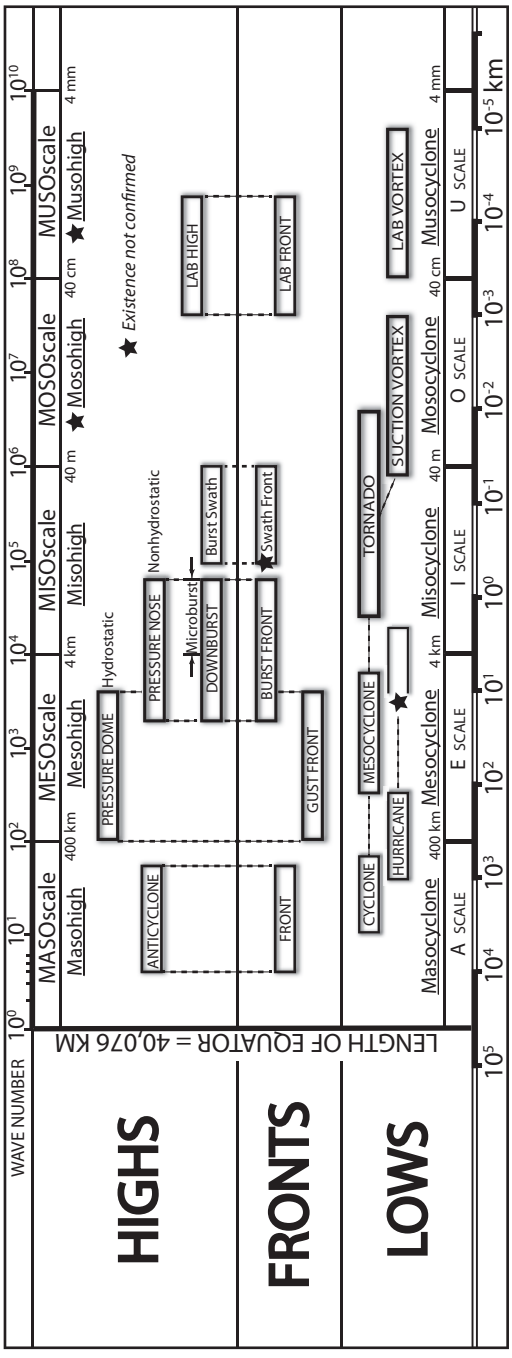

Figure 1.7. Atmospheric-scale classification scheme proposed by Fujita (1981).

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numerically modeled, and supply information about the observing and modeling techniques themselves.

Notes

1 The discussion in this section draws from Emanuel (1986).
2 Vinnichenko (1970).
3 Nastrom and Gage (1985); Gage and Nastrom (1986).
4 *Glossary of Meteorology* (Glickman 2000).
5 The discussion in this section is based on Fujita (1986).
6 This practice is consistent with the more general meaning of the word *synoptic* – presenting a general view of the whole – as derived from the Greek *synoptikós*. See *Webster's New World Dictionary of the American Language* (Guralnik 1984).
7 Fujita (1986).
8 Byers and Braham (1949).
9 As compiled by Fujita (1986).
10 This is a configuration that has been copied, and envied, by subsequent field-program designers!
11 A historical perspective of GATE can be found at www.ametsoc.org/sloan/gate/.
12 The atmospheric microscale is typically inclusive of the atmospheric motion referred to as turbulence. Note that this usage of *mesoscale* is based on the Greek *mesos*, which means middle. See *Webster's New World Dictionary of the American Language* (Guralnik 1984).
13 Ligda (1951).
14 Quantitative uses of weather radar will be demonstrated in subsequent chapters, and indeed are now critical in refining the mesoscale.
15 Tepper (1950).
16 See Galway (1992) for more details about the timeline and historical context.
17 Fiedler and Panofsky (1970).
18 Ibid.
19 Orlanski (1975).
20 Fujita (1981).

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