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A Rational Subdivision of Scales for Atmospheric Processes[1]

Isidoro Orlanski, *Geophysical Fluid Dynamics Laboratory/NOAA, Princeton University, Princeton, New Jersey 08540*

Abstract

Some atmospheric scale definitions are reviewed and a proposed new subdivision of scales that covers the entire spectrum is described.

[1] This paper is part of an invited paper presented at the meeting of the Geophysical Fluid Dynamics Laboratory, November 1973, that originated the SESAME project (Severe Environmental Storms and Mesoscale Experiment).

1. Introduction

Meteorologists have historically tended to study atmospheric dynamics from two points of view which are characterized by greatly differing space and time scales. In trying to explain the detailed behavior of the immediate surface environment in which Man lives, they have developed the science of micrometeorology which deals with atmospheric dynamics having space scales of several meters and time scales on the order of a minute. Similarly, in order to predict the evolution of weather patterns in the atmosphere, meteorologists have devoted much attention to the behavior of large-scale dynamics having space scales greater than one thousand kilometers and time scales of the order of a week.

Yet although macro- and microscale meteorology encompasses many atmospheric processes, there is still a large number of important phenomena occurring in the atmosphere whose spatial and temporal scales are intermediate between these two categories. The slowness with which our understanding of these intermediate scales has developed has been caused, not by their lack of importance, but rather by the difficulty involved in obtaining useful observational data concerning them. However, the recent surge of interest in the urban environment and in severe storm weather conditions has reversed this trend and seems to be leading to a more rapid advancement of our understanding of these important meteorological processes.

The wide range of atmospheric phenomena with scales between the macro- and microscales necessitates the further division of processes according to time and space scales. The term mesoscale, as it is used today, defines all of the intermediate states between the macro- and microscale. Through this definition, mesoscale represents motions of the order of 1000 km on the horizontal scale and several days on the time scale. Hurricanes and fronts are such examples. In addition to this, it also includes processes with scales on the order of 10 km and a few Brunt-Väisälä periods such as thunderstorms, small orographic effects, etc.

Because of the wide range of phenomena which this definition covers, various groups in the scientific community have come to use the same name for markedly different processes as well as different names for the same processes. Now, in particular, when a major experiment is planned (SESAME [2]) it is important to be precise about the different atmospheric phenomena and scales of interests. For instance, some groups consider "fronts" to be on the intermediate scale, some define them to be on the synoptic scale, and many others consider them to be on the mesoscale. An illustration of the various definitions appears in Fig. 1 in which the central box shows the different processes with characteristic time and horizontal scales. The list is by no means complete but is used merely for illustrative purposes here, nor is it meant to imply that processes with similar times and horizontal space have any dynamic similarity. The terms in parentheses along the time scale row are physical parameters known to be controlling each particular range of time scales. Scales between one month and one day are governed by a time scale which is the inverse of the product of the Rossby radius of deformation, $L_R = (H/f)[(g/\theta)d\theta/dz]^{\frac{1}{2}}$, and the variation of the earth's rotation with latitude, β. The local effective period (f^{-1}) of the earth's rota-

[2] SESAME: (NOAA, Boulder, Colorado, May 1974.

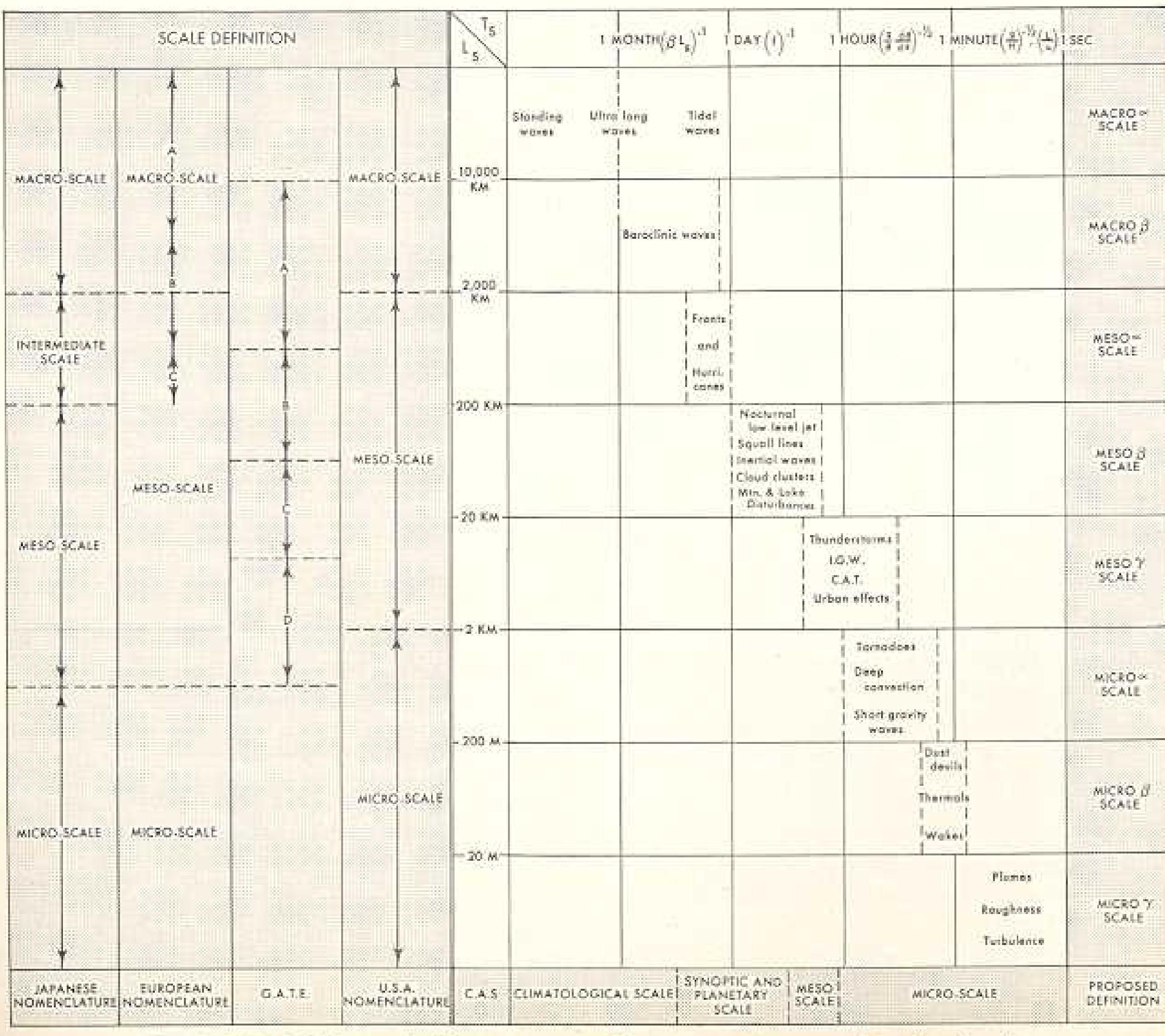

FIG. 1. Scale definitions and different processes with characteristic time and horizontal scales.

tion is a controlling factor for motions with scales of one day to a few hours. The static stability of the atmosphere, or the Brunt-Väisäla period, is the time scale for motions between a few hours and $N^{-1} = [(g/\theta)\ d\theta/dz]^{-1}$. For shorter time scales, there could be two characteristic parameters depending on the scale of the motion: $(g/H)^{-\frac{1}{2}}$ for external gravity waves or L/u which is the advective time for turbulent motion.

On the left side of the figure we indicate the definitions used by a few groups;[3] these definitions relate to the horizontal scale of the motion. The bottom row shows the definitions as given by the Committee of Atmospheric Science of the National Academy of Sciences (CAS) in which the scales are defined according to the time extension of the processes. In particular, this latter use of time scales for delineating mesoscale categories is not good. For in fact, the observed frequency ω_{obs} for any wave processes is determined by combining the intrinsic frequency ω_i with the Doppler shift frequency $\omega_D (= u/L)$ such that $\omega_{obs} = |\omega_D \pm \omega_i|$. In the global-scale motions $\omega_{obs} \approx \omega_i$. The Doppler frequency ω_D is the most important for small-scale processes ($L < 10$ km) so $\omega_{obs} = \omega_D$. However, in intermediate scales, the intrinsic frequency is of the same order as the Doppler frequency. Therefore, intermediate-scale processes will exhibit quite different observed time scales ($2\pi/|\omega_D \pm \omega_i|$) depending on whether they are propagating in the direction of the mean flow or against it. Therefore, the CAS definition would allow the same physical process to be classified in several different scale categories.

For practical reasons the horizontal scale of motion seems to be the better quantity to use for classifying atmospheric processes. In order to define an observational or numerical experiment, it is of fundamental importance to determine the proper horizontal scale which is most representative of the particular event. Clearly the choice of the horizontal extension plays an important role in the design of any atmospheric research problem so that scientists can optimize the use of input resources to generate meaningful results. Lately the tendency of scientists has been to design field experiments emphasizing observations of phenomena having a common scale range rather than singling out one phenomenon in particular. This approach seems more desirable and rational since a limited amount of initial investment in a well designed experiment can provide meaningful observational data of different processes that populate a certain spatial scale.

[3] A review of some of the scale definitions is given by Fujita (1963) and WMO (1972).

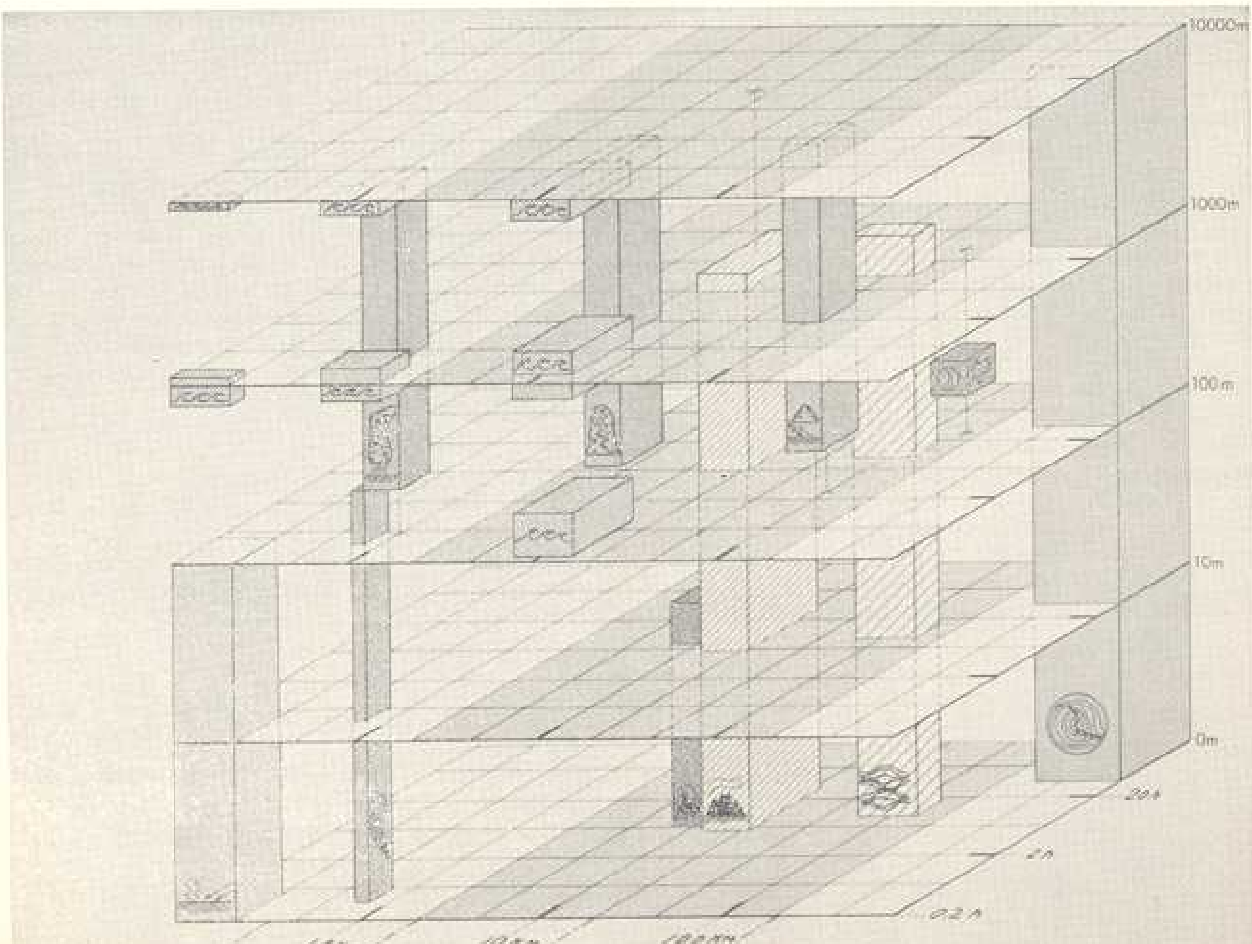

FIG. 2. The meteorological log scale frame.

As was previously discussed, we can identify intrinsic time scales for most of the processes that affect weather, and in addition we can relate these time scales to some geophysical parameters such as gravity, buoyancy, earth rotation, etc. Unfortunately, in most atmospheric processes a relationship between geophysical parameters and the intrinsic spatial scale derived from empirical results is not known. (A relation is known in certain cases, for example: ultra-long waves associated with the radius of the earth, baroclinic waves with the Rossby radius of deformation, mountain waves with orographic scales.) This fact makes any horizontal scale division somewhat arbitrary and ill-defined. However, as discussed previously, the use of time scales is less desirable than spatial scales because Doppler effects make time scale classification ambiguous. On the other hand, space scales can be rationalized if one approaches the scale division in a probabilistic sense. According to this approach we postulate that we can find some scale interval which has a maximum probability of containing the phenomenon we are trying to classify. Of course this subdivision cannot be refined more than to an order of magnitude of the scale length. Because "macro," "meso," and "micro" (the Greek equivalents of "large," "intermediate," and "small") have been used, according to general consensus, for classifying the atmospheric processes, it is proposed here to use these names in conjunction with the Greek suffixes α, β, and γ [Fujita (1963) subdivided the mesoscale network in a similar way] in order to subdivide the atmospheric horizontal scales and thereby to make them more precise and more useful. These definitions are located on the right-hand side of the box in Fig. 1. This type of definition was accepted for the planning of the SESAME project.

In order to more clearly emphasize the processes which belong to the mesoscale range and their vertical extension, I have included Fig. 2 which shows a three-dimensional structure (like a building frame) having the horizontal space scale (in kilometers) as one coordinate, a time scale (in hours) as another, and the vertical space coordinate (in meters) as the third. The graph shows five horizontal planes (time and horizontal scales) at different heights: ground, 10, 100, 1000, and 10 000 m. Starting from the right, the large column extending from the ground to the tropopause level represents all of the motions in the meso-α scales—fronts, hurricanes, etc. Close to the column on the border of the meso-β scale we have the nocturnal low-level jet which has an extension of a few hundred kilometers. This phenomenon occurs at a height of about 300–400 m and is a very important dynamic effect in the boundary layer. The tall hatched column next to it represents slow internal gravity waves with periods on the order of 1 day and extends practically to the top of the boundary layer. Next to that in the same 100 km range but with a shorter period (the order of a few hours) we have squall lines which extend from 300–10 000 m. Moving to the left, we find a medium height hatched column in the range of 20–30 km which represents orographic effects such as mountains, lakes, and land-sea breezes. The time scale is on the order of the diurnal period and extends from the ground to a few thousand meters in height. The urban-effect column seen close to it is very shallow and extends to only a few tens of meters and has a horizontal scale of 10 km. In the same range but of shorter duration (the order of 2 h) we find the column representing thunderstorms as well as the squall lines extending from 300 m to the tropopause. The small boxes which intersect the upper three planes, 100, 1000, and 10 000 m respectively, show internal gravity waves with horizontal scales of 10 km and time scales on the order of a half hour. These waves are believed to be the primary cause of clear air turbulence. Outside of the meso-γ scale in the range of 1 km, the upper part of the figure shows a column representing cumulus clouds and deep convection whereas the column below, which extends from the ground to the cloud base, represents tornadoes. Again, the small boxes intersecting the planes show internal gravity waves induced mainly by penetrative convection. Finally, to the extreme left in the micro-β scale are very short gravity waves, thermals, and turbulence, which extend from the ground to a 100 m in height.

The purpose of intensive mesoscale experiment SESAME will be focused on meso-β and meso-γ scales (central area of Fig. 2).

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