Defining the mesoscale: Qualitative Analysis Perspective

We start at exactly the same place as the first lecture for WAF I, but this time to focus on the mesoscale within the continuum of atmospheric motion.

Continuum of scales	Examples
Microscale < 1 km, < 1 h	Atmospheric turbulence, PBL
Mesoscale 1 – 1000 km Hours, day	Thunderstorm, sea breeze
Synoptic 1000 – 6000 km several days, week	Mid-latitude baroclinic waves
Global > 6000 km weeks to months	global circulation structure, Hadley cell, polar jet

Synoptic: Coincident in time. "General view of the whole" (Greek derivation)

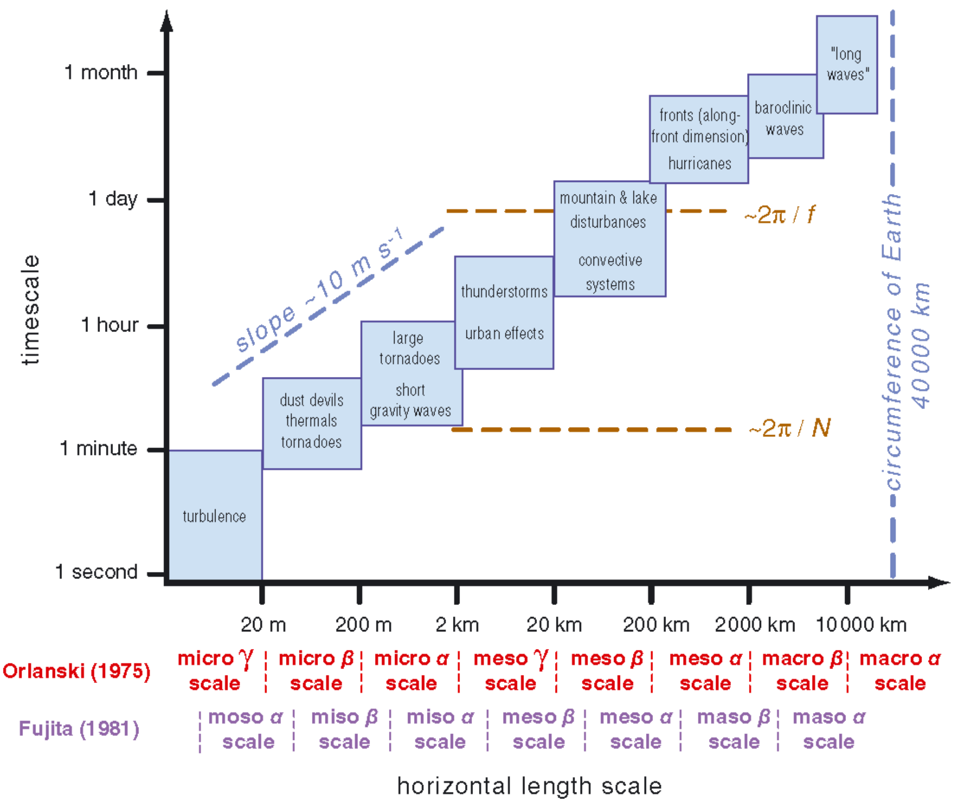


Figure 1.1 Scale definitions and the characteristic time and horizontal length scales of a variety of atmospheric phenomena. Orlanski's (1975) and Fujita's (1981) classification schemes are also indicated.

Mesoscale : Scale smaller than the spatial and temporal resolution of radiosonde network (Pielke definition). For this reason the term wasn't used until the advent of Wx radar.

Another way to think about demarcation of mesoscale vs. synoptic scale is via Rossby number (R_0), conceptually

$$R_0 = \frac{\text{Advective terms}}{\text{Rotational (Coriolis) terms}}$$

Synoptic $\sim$ 0.1 or below
Mesoscale ~ 1

From standpoint of Weather Analysis and Forecasting

Synoptic scale
- Dealing with continental-scale mid-latitude cyclones, with a life cycle on the order of several days to a week
- Quasi-geostrophic balance mostly applies : Vertical motion caused by the advective effects of geostrophic wind.

- A coarse-resolution global model is sufficient to get the majority of dynamics (e.g. 1°-2° lat/lon)

Meso-α, Meso-β scales: 10s to 100s km.
- Convection must be parameterized via a column model that removes atmospheric instability, warms & dries the atmosphere, generates precipitation
- Okay for representing warm season storm environments, but not the individual storms themselves.
- Typical scale of global numerical weather prediction models (e.g. GFS, ECMWF)

Meso-γ scale: 1 to 10 km.
- Convective precipitation is represented exclusively by microphysical parameterization in NWP. Convective allowing ≤4km grid spacing, non-hydrostatic (e.g. WRF-HRRR)
- For NWP, microphysical parameterization incorporates some treatment of ice phase processes.
- Convective-allowing models allow step improvements in representation of convection, particularly organized forms
- Must rely on satellite, radar as sources for observational data, or mesonets

Microscale: Less than 1 km.

- Need to explicitly represent turbulent motions, instead of parameterizing them in PBL
- Requires eddy-resolving simulation to explicitly represent ~~[illegible]~~ turbulence
- Virtually no observations at this scale
- ~~Be~~ Beyond the scale of current NWP capability.
- Probably matters for extreme weather phenomena (e.g. tornadoes, hurricanes)

The mechanisms for inducing mesoscale motion are very different from the synoptic scale, but broadly fit into two categories:

thermodynamic: Related to gradients in surface heating, buoyancy

- Sea breeze
- Mountain-valley circulations
- Circulations resulting from differences in land surface properties (e.g. soil moisture, vegetation)

<u>Dynamic</u> : Related to atmospheric waves, dynamic instabilities, inertial oscillations

- gravity waves
- Symmetric instability
- Shearing instability (barotropic)
- low-level jets.

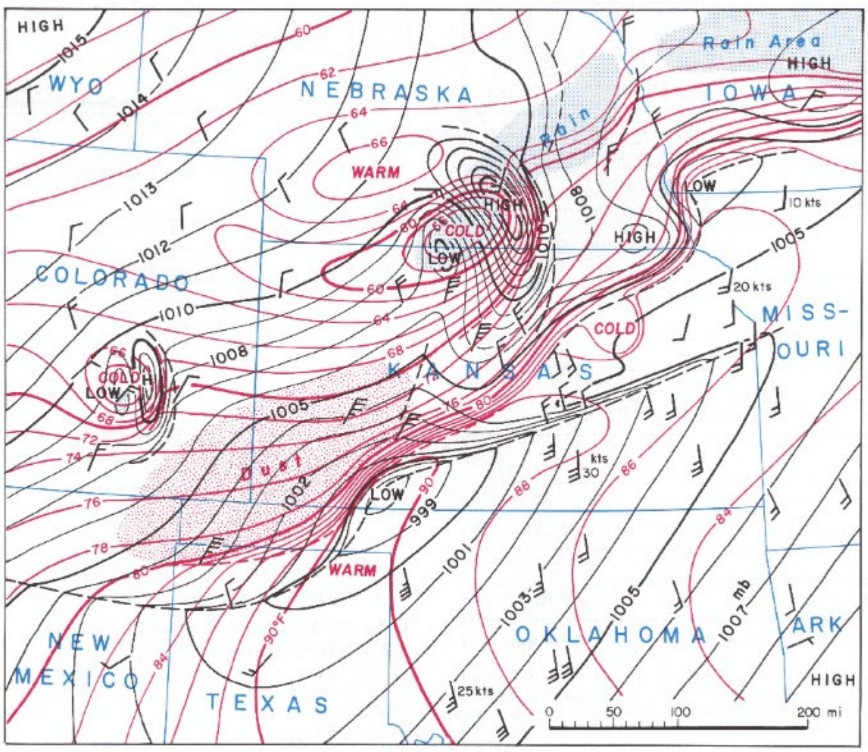


Figure 1.2 Sea-level pressure (black contours) and temperature (red contours) analysis at 0200 CST 25 June 1953. A squall line was in progress in northern Kansas, eastern Nebraska, and Iowa. (From Fujita [1992].)

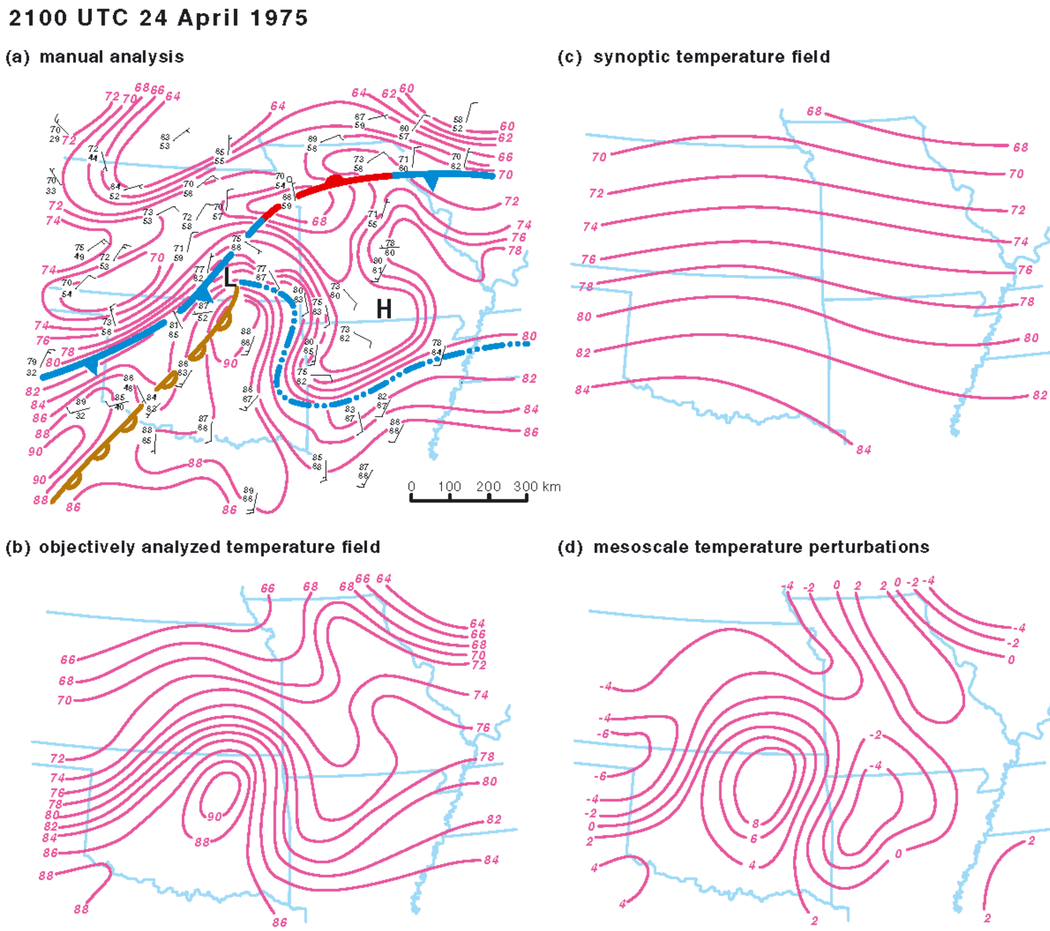


Figure 1.3 (a) Manual surface analysis for 2100 UTC 24 April 1975. Isotherms are drawn at 2°F intervals and fronts and pressure centers are also shown. A thunderstorm outflow boundary is indicated using a blue dashed line with double dots. The brown boundary with open scallops denotes a dryline. (The symbology used to indicate outflow boundaries and drylines has varied from analyst to analyst; different symbols for outflow boundaries and drylines appear in other locations within this book.) (b) Computer-generated ('objective') analysis of the total temperature field, i.e., the sum of the synoptic-scale temperature field and the mesoscale temperature perturbations. The objectively analyzed total temperature field is fairly similar to the manually produced temperature analysis in (a), although some small differences can be seen. (c) The synoptic-scale temperature field (°F). This was obtained using a low-pass filter that significantly damped wavelengths smaller than approximately 1500 km. (d) Mesoscale temperature perturbation field (°F). This was obtained using a band-pass filter that had its maximum response for wavelengths of 500 km, and damped wavelengths much longer and much shorter than 500 km. (Adapted from Maddox [1980].)

Defining the mesoscale: Quantitative Analysis Perspective

Vertical momentum equation:

$$\underbrace{\frac{dw}{dt}}_{\text{Vertical acceleration}} = \underbrace{-\frac{1}{\rho}\frac{\partial p}{\partial z}}_{\text{Vertical PGF}} \underbrace{- g}_{\text{gravity}} \underbrace{+ \hat{f}u}_{\text{vertical Coriolis}} \underbrace{+ F_W}_{\text{Friction (viscosity)}}$$

$$\hat{f} = 2\Omega \cos\phi$$

where $\Omega = 7.29 \times 10^{-5}\ 1/s$

ϕ = latitude.

In Synoptic Meteorology world of WAF I we basically assumed hydrostatic balance applied to most everything.

- Assumes vertical accelerations relatively small
- Neglect rotational, viscous effects.

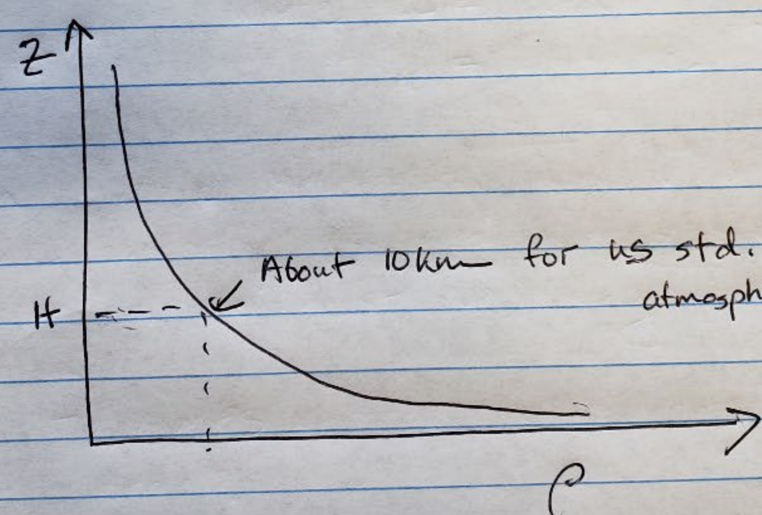
Hydrostatic equation

$$\underbrace{\frac{\partial p}{\partial z}}_{\text{vertical PGF}} = -\rho \underbrace{g}_{\text{gravitational accel.}}$$

As discussed in WAF I, can use hydrostatic equation to solve for pressure and density as a function of height.

The solution is that pressure and density decay exponentially with height. The scale height, or e-folding distance is order ~ 10 km. (H)

$$H = \frac{RT}{g} \quad \text{(for isothermal atm)}$$



A hydrostatic assumption + QG assumption is generally sufficient to explain synoptic scale dynamics associated with mid-latitude cyclones.

Using these simplifications, consider we are able to derive

- QG omega equation
- Height tendency equation
- Q-vectors, Q-vector convergence (i.e. frontogenesis terms)

That's actually a LOT of "mileage" we get from the WAF perspective before we even have to worry about the mesoscale! Keep that in mind...

Moreover, in numerical atmospheric modeling there is actually not much difference in hydrostatic vs. non-hydrostatic solutions until we hit meso-γ scale, and then only for the more interesting, extreme convective weather phenomena. Another reason meso-γ scale is a "step transition" in terms of NWP.

What matters in vertical momentum equation for mesoscale?

Full form of vertical momentum (neglecting rotation + friction) Numbers ref. text of eqns.

$$\frac{dw}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g \quad (1.4)$$

Introduce mesoscale perturbation

$$p = \bar{p} + p' \quad (1.6)$$

$$\rho = \bar{\rho} + \rho' \quad (1.7)$$

"Bar" = Synoptic base state

"Prime" = Mesoscale contribution.

The synoptic base state is in hydrostatic balance, so

$$0 = -\frac{\partial \bar{p}}{\partial z} - \rho g \quad (1.8)$$

Incorporating these definitions
- Multiply 1.4 by ρ
- Subtract 1.8, divide by $\bar{\rho}$
- Use definitions in 1.6–7

$$\frac{dw}{dt} = -\frac{1}{\bar{\rho}}\frac{\partial p'}{\partial z} - \frac{\rho' g}{\bar{\rho}}$$

Vertical acceleration

Perturbation pressure gradient in vertical

Buoyancy term.

A note on buoyancy ...

For convective dynamics this relates to the buoyancy of a parcel of air (e.g. in a cloud) relative to its surrounding environment

Jumping ahead... a parcel can be positively buoyant in a conditionally unstable environment.

"Condition" = latent heat release due to condensation, as parcel rises moist adiabatically

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Consider scale analysis of terms in the vertical momentum equation.

1) Vertical PGF

$$-\frac{1}{\rho}\frac{\partial p'}{\partial z} \underset{\text{"Scales as"}}{\sim} \frac{\delta p'}{\rho D}$$

D = vertical depth.

Now how do we get scaling for $\delta p'/\rho$?

For horizontal momentum

$$\frac{du}{dt} \approx -\frac{1}{\rho}\frac{\partial p'}{\partial x}$$

Basically horizontal acceleration same order of magnitude as PGF_x

Scales as

$$\frac{V}{T} \sim \frac{\delta p'}{\rho L}$$

V = horizontal velocity
T = time
L = Horizontal length

So...

$$\frac{\delta \rho'}{\rho} \sim \frac{VL}{T}$$

Back to scaling for vertical PGF, substituting for $\delta\rho'/\rho$.

$$\boxed{-\frac{1}{\rho}\frac{\partial p'}{\partial z} \sim \frac{VL}{TD}}$$

2) Scaling for vertical acceleration.

From continuity

$$\frac{\partial w}{\partial z} \sim \frac{\partial u}{\partial x}$$

Scaling for vertical motion (w)

$$\frac{w}{D} \sim \frac{V}{L}$$

Scaling for vertical acceleration

$$\boxed{\frac{dw}{dt} \sim \frac{VD}{LT}}$$

Can define ratio of vertical acceleration to vertical PGF.

$$\frac{\frac{dw}{dt}}{-\frac{1}{\rho}\frac{\partial p'}{\partial z}} \sim \frac{\frac{VD}{LT}}{\frac{VL}{TD}} = \left(\frac{D}{L}\right)^2$$

Ratio of vertical depth to horiz. length

Two possibilities in terms of this ratio.

$$\frac{D}{L} \ll 1$$

Vertical acceleration small compared to PGF_z

$\Rightarrow$ Hydrostatic

Generally synoptic, meso-α, meso-β.

$\frac{D}{L} \sim 1$ Vertical acceleration similar magnitude to PGF_z

$\Rightarrow$ Non-hydrostatic : meso-γ

AND ONLY significant dynamic effects may contribute to pressure perturbations that would induce large vertical accelerations (e.g. in a thunderstorm)

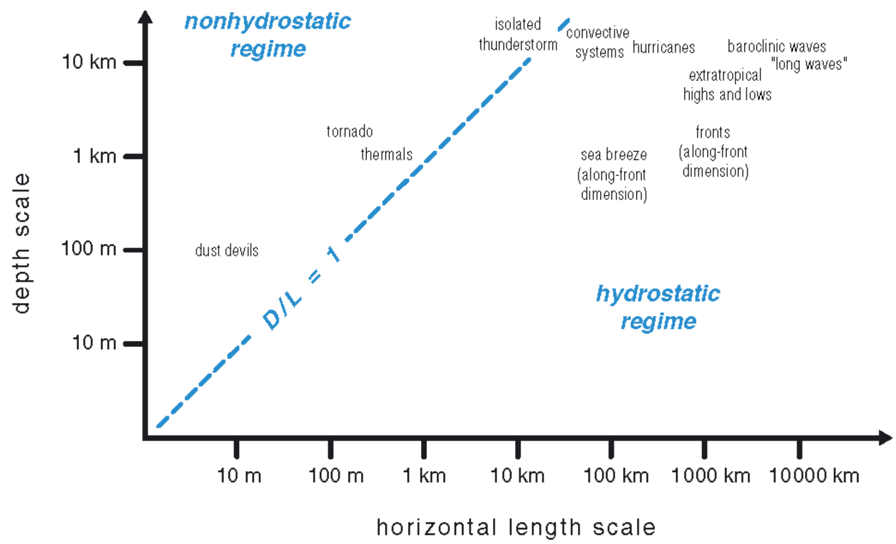

Figure 1.4 We can infer that a phenomenon is hydrostatic when its horizontal length scale is significantly larger than its vertical depth scale. Shown above are some examples of nonhydrostatic and approximately hydrostatic phenomena plotted as a function of depth versus horizontal length (i.e., width) scale.