

Chapter 1. Introduction

Mesoscale phenomena include, but are not limited to

- thunderstorms
- squall lines
- supercells
- tornadoes
- mesoscale convective complexes
- inertia-gravity waves
- mountain waves
- low-level jets
- density currents
- land/sea breezes
- heat island circulations
- clear air turbulence
- jet streaks
- fronts
- hurricanes

In this class, we will study some of these phenomena, with emphasis on the physical understanding of these phenomena, and use dynamic equations to explain their development and evolution.

From the dynamical perspective, mesoscale concerns processes with timescales ranging from

- the buoyancy oscillation ($2\pi / N$, where N is the buoyancy (Brunt-Vaisala) frequency) to
- a pendulum day ($2\pi / f$, where f is the Coriolis parameter), encompassing deep moist convection and the full spectrum of inertia-gravity waves
- but stopping short of synoptic-scale phenomena which have Rossby numbers less than 1.

First, we will start with the definition of MESOSCALE.

1.1. Definition of Mesoscale

We tend to classify weather system according to their intrinsic or characteristic time and space scales.

Often theoretical considerations can also enter into the definition.

Two commonly used approaches for defining the scales: Dynamical and scale-analysis approach.

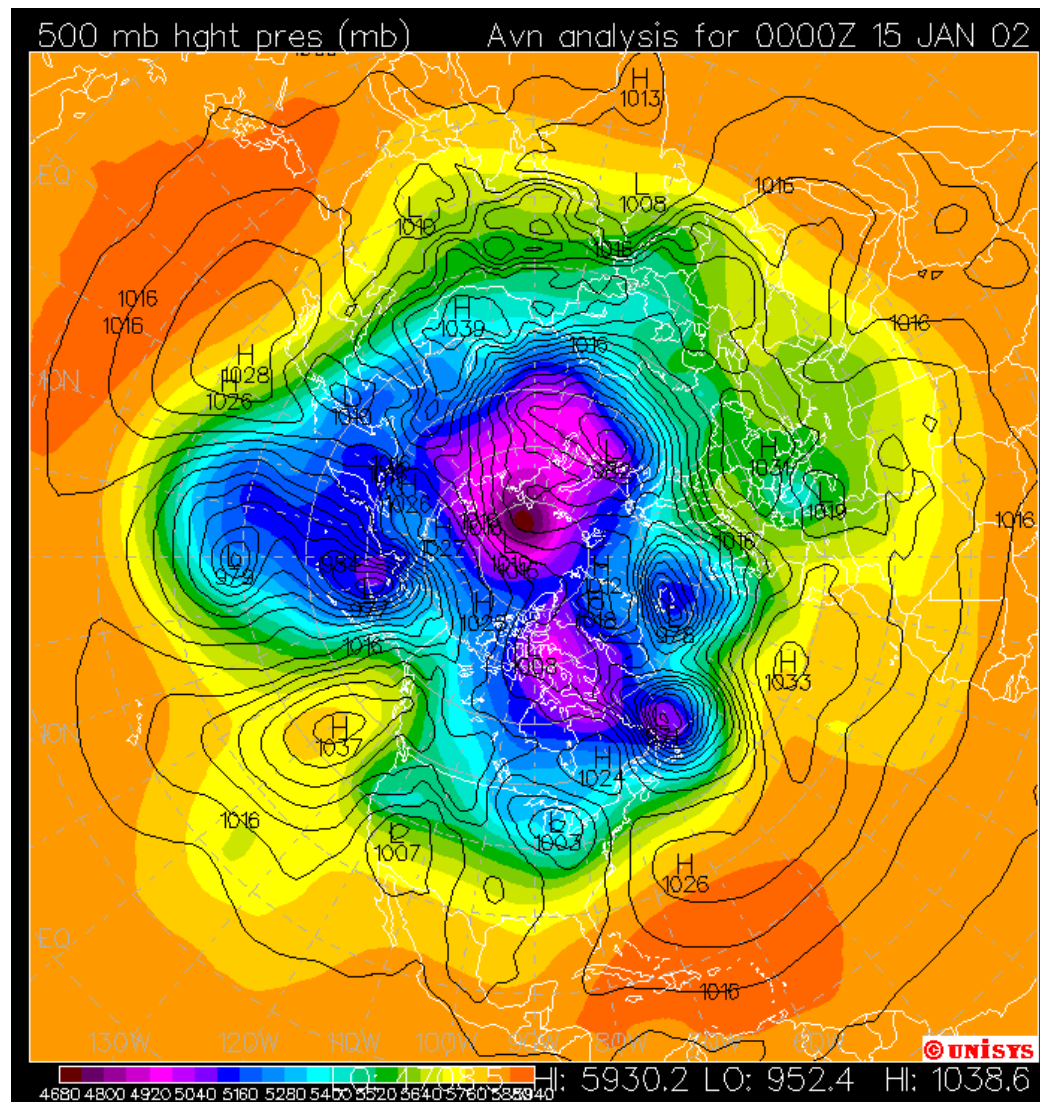
Dynamical:

The dynamical approach asks questions such as the following:

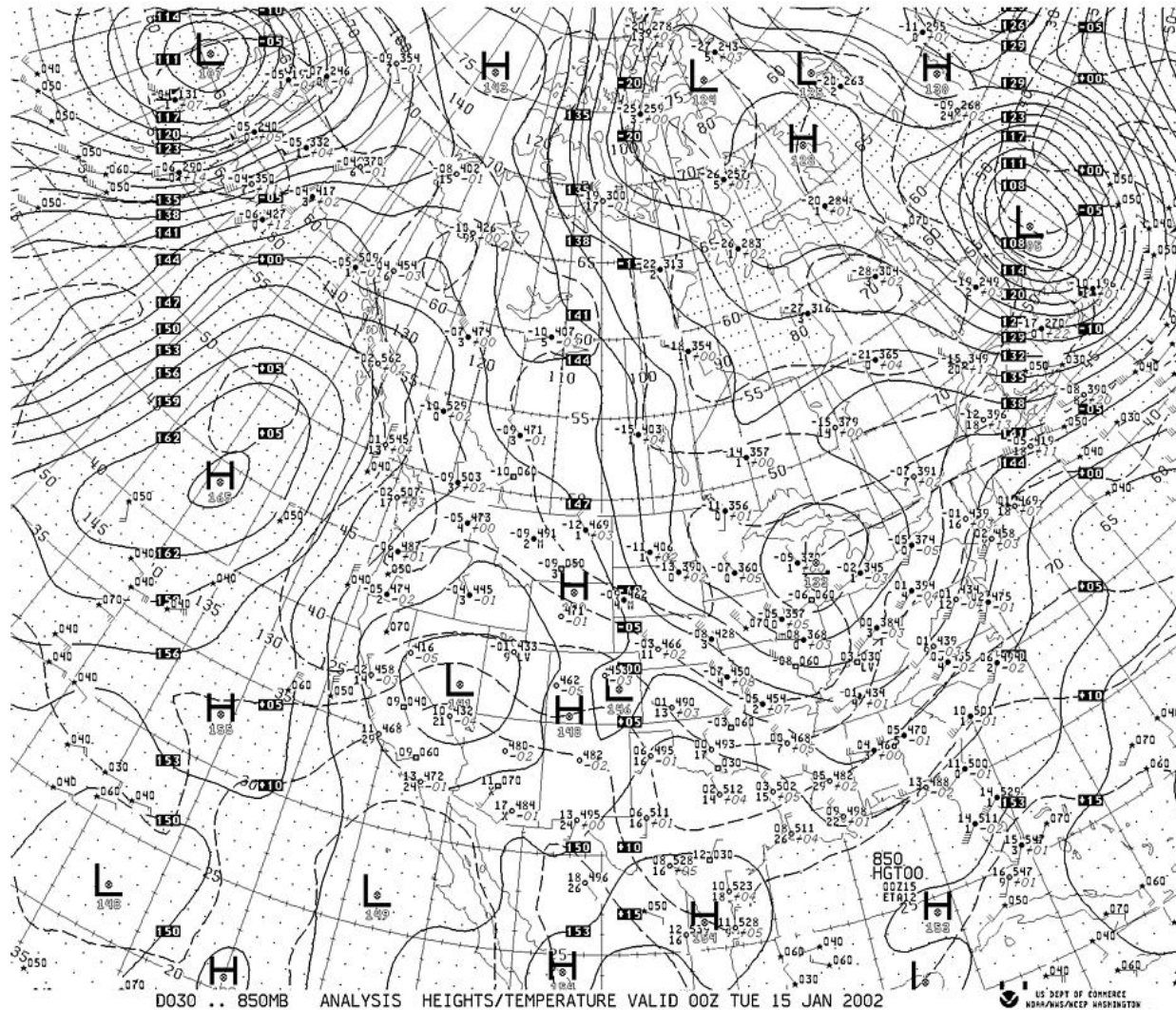
- What controls the time and space scales of certain atmospheric motion?
- Why are thunderstorms a particular size?
- Why is the planetary boundary layer (PBL) not 10 km deep?
- Why are raindrops not the size of baseball?
- Why most cyclones have diameters of a few thousand kilometers not a few hundred of km?
- Tornado and hurricanes are both rotating vortices, what determine their vastly different sizes?

There are theoretical reasons for them!

There are many different scales in the atmospheric motion. Let look at a few examples:



Hemi-spherical plot of 500mb height (color) and MSL pressure (contours) showing planetary scale waves and surface cyclones (lows).

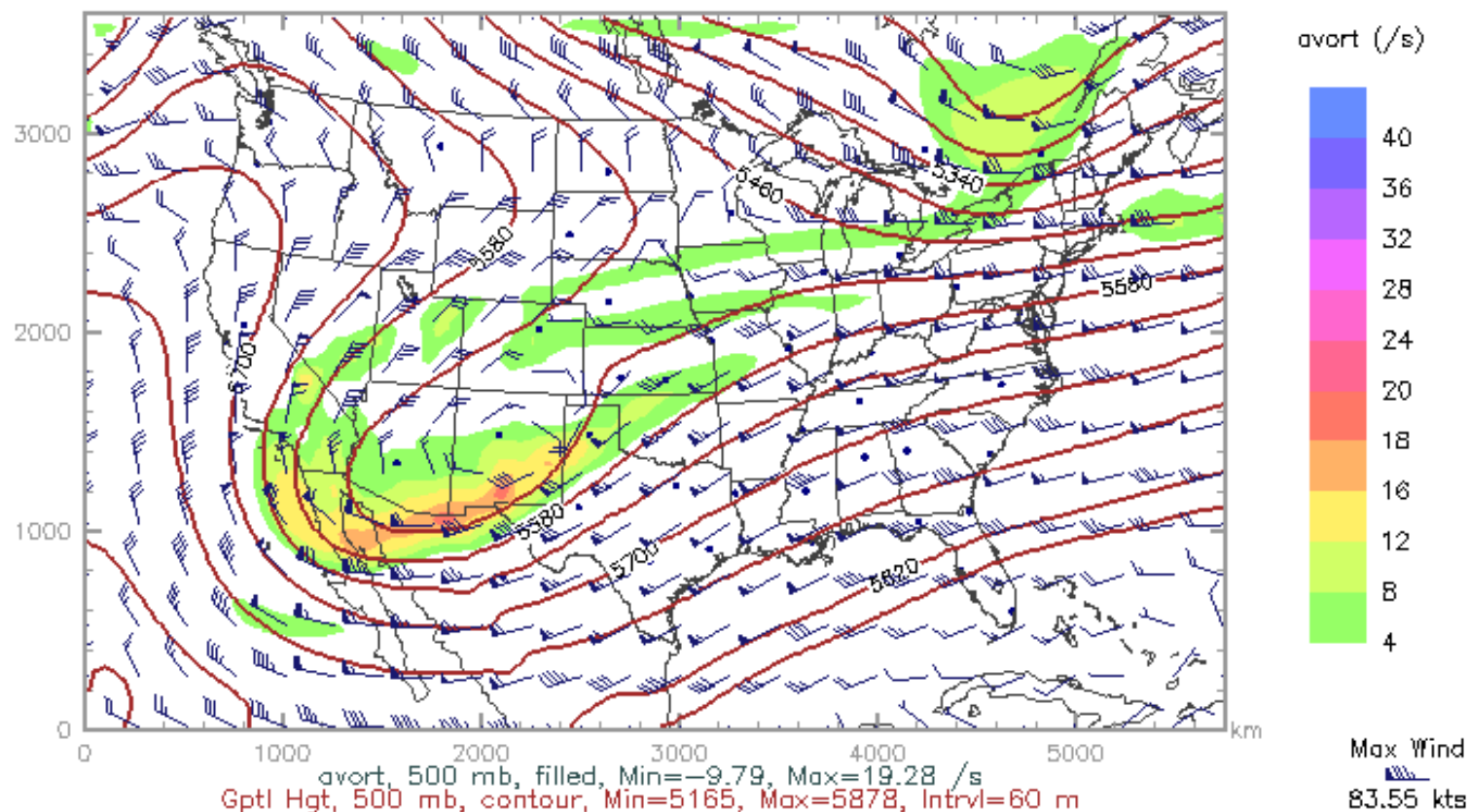


National Weather Service 850mb (synoptic-scale) weather chart for northern America. A cyclone/low is located over eastern U.S. Most features shown are considered synoptic scale as fine scale features are often missed by standard upper-air observation network.

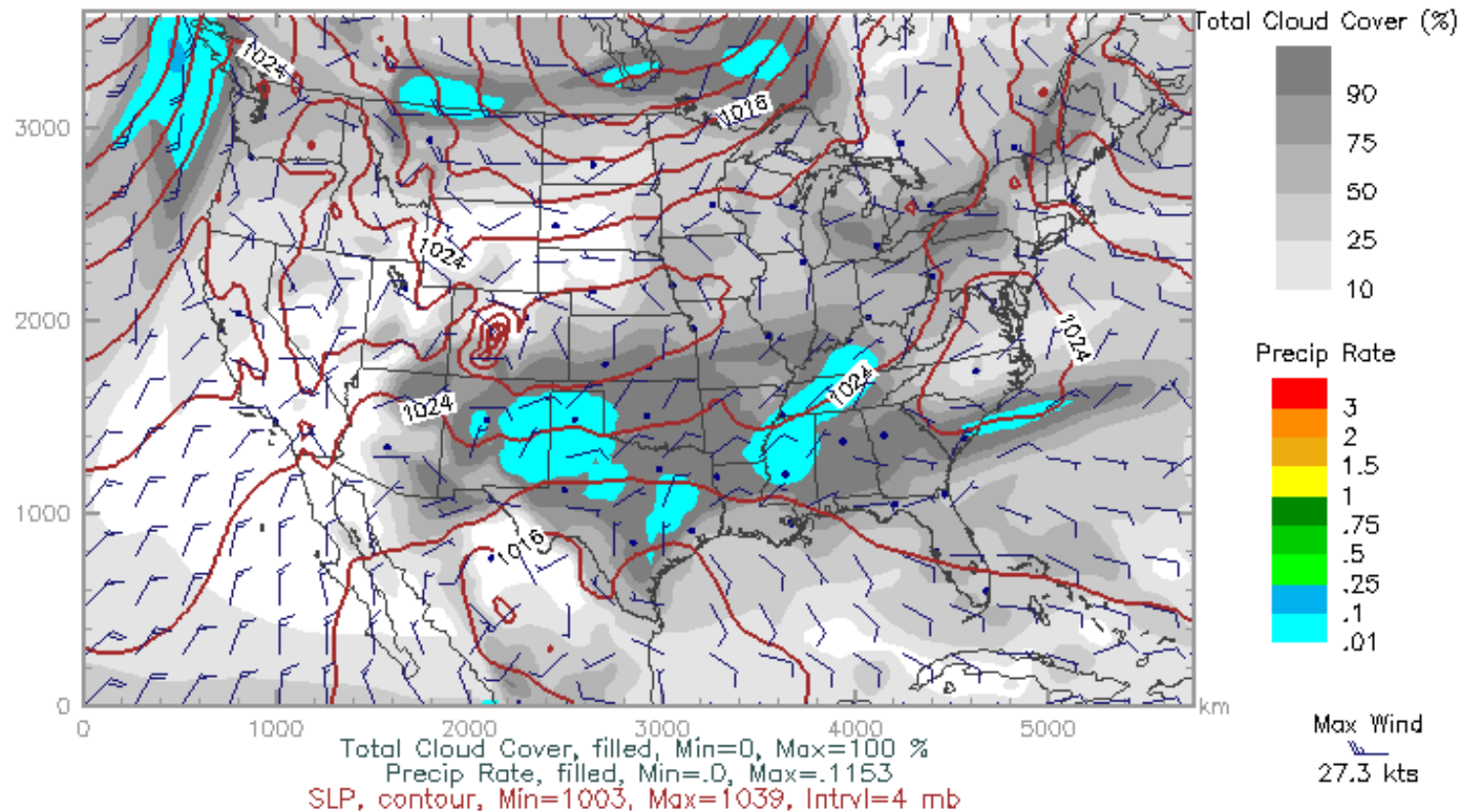
ARPS (<http://www.caps.ou.edu/ARPS>) Continental Scale Forecast (dx=40km)

Similar forecasts can be found at <http://www.caps.ou.edu/wx>.

15 hr forecast valid Wed, 17 Jan 2001, 9 am CST (15Z)
500 mb Height, Abs Vorticity

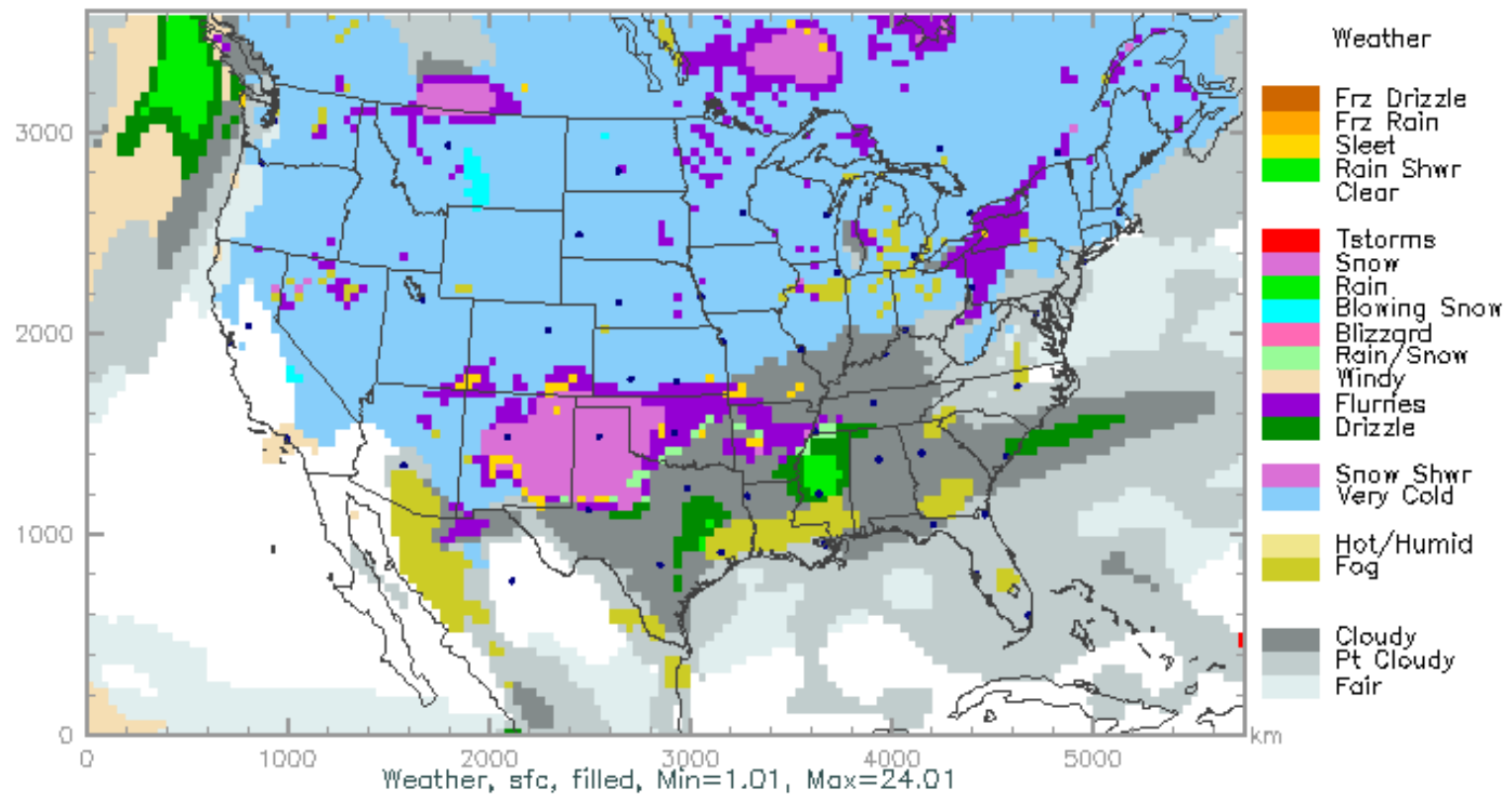


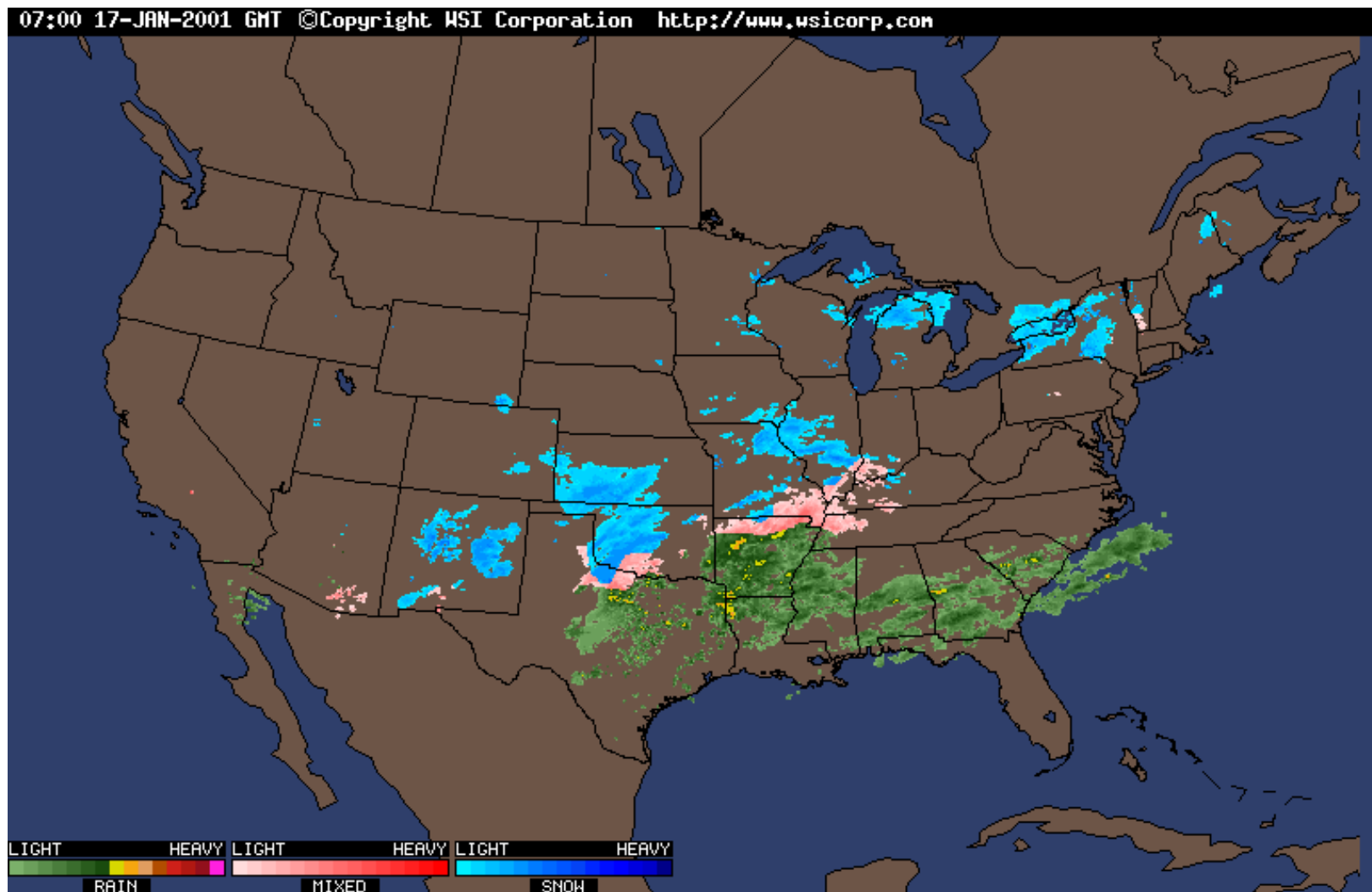
15 hr forecast valid Wed, 17 Jan 2001, 9 am CST (15Z)
Sea-Level Pressure, Clouds, Precip Rate



15 hr forecast valid Wed, 17 Jan 2001, 9 am CST (15Z)

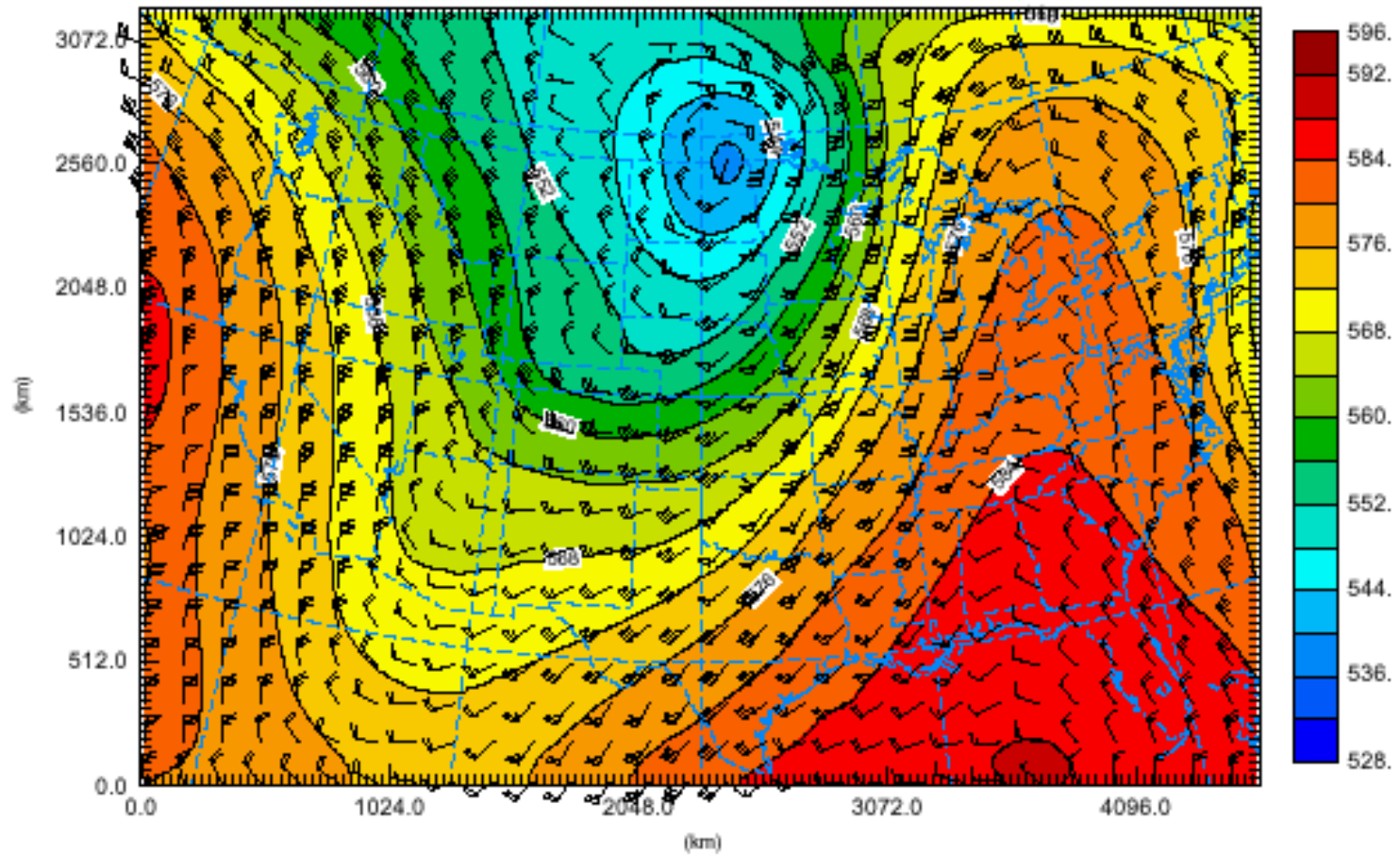
Weather





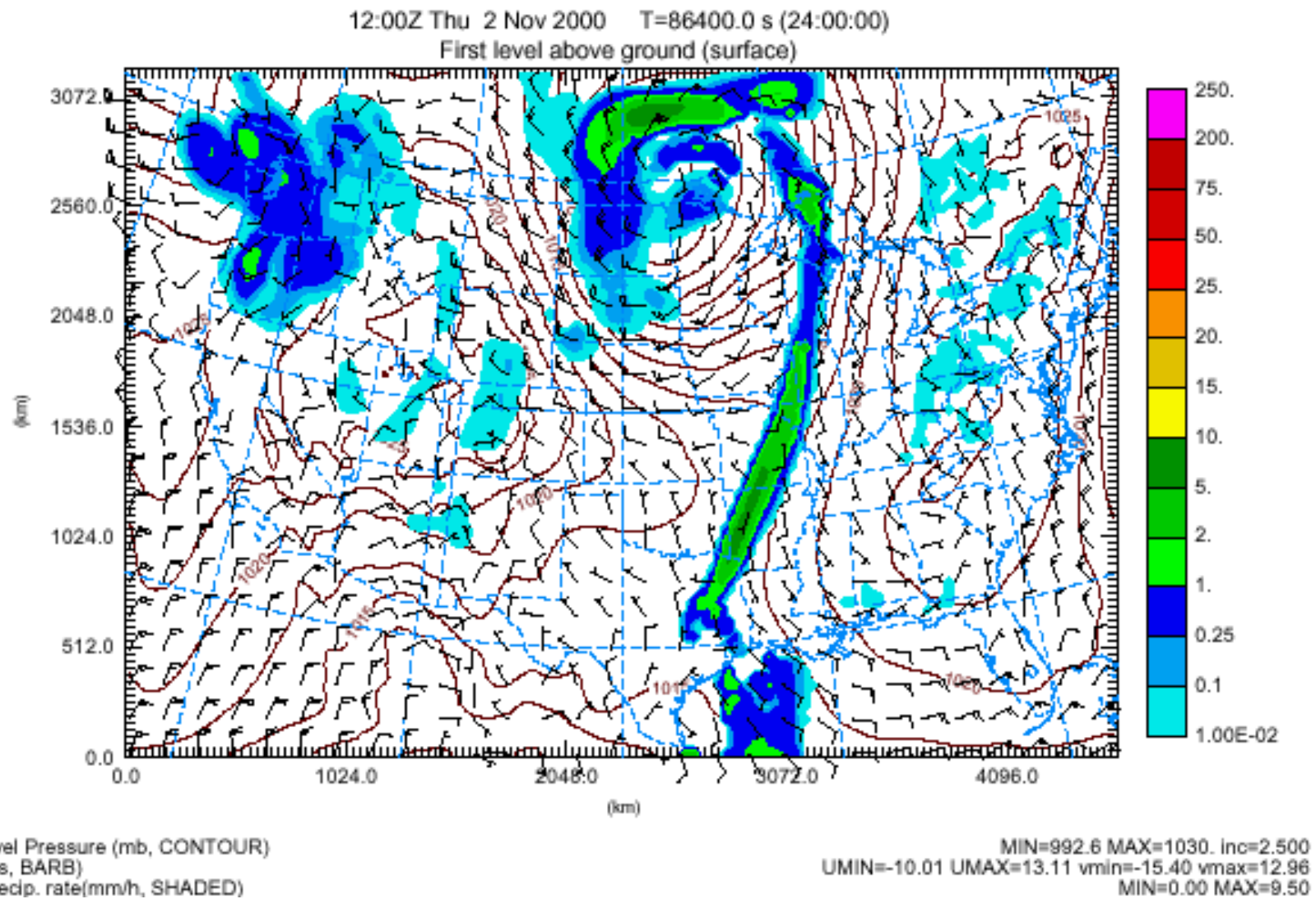
1am CST, January 17, 2001

12:00Z Thu 2 Nov 2000 T=86400.0 s (24:00:00)
P=500.00 MB



h (10m, SHADED/CONTOUR)
U-V (m/s, BARB)

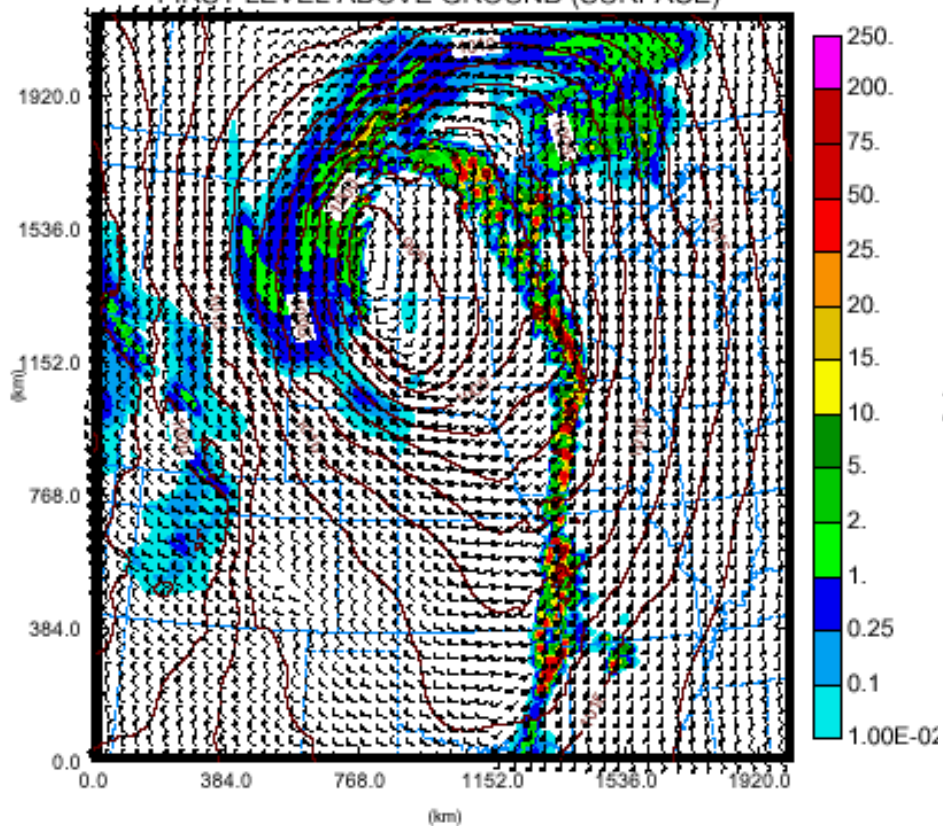
MIN=539.6 MAX=588.3 inc=4.000
UMIN=-17.66 UMAX=29.03 vmin=-30.32 vmax=43.46



24 h forecasts by ARPS for November 2, 2000, at 32-km resolution.

00:00Z Thu 2 Nov 2000 T=43200.0 s (12:00:00)

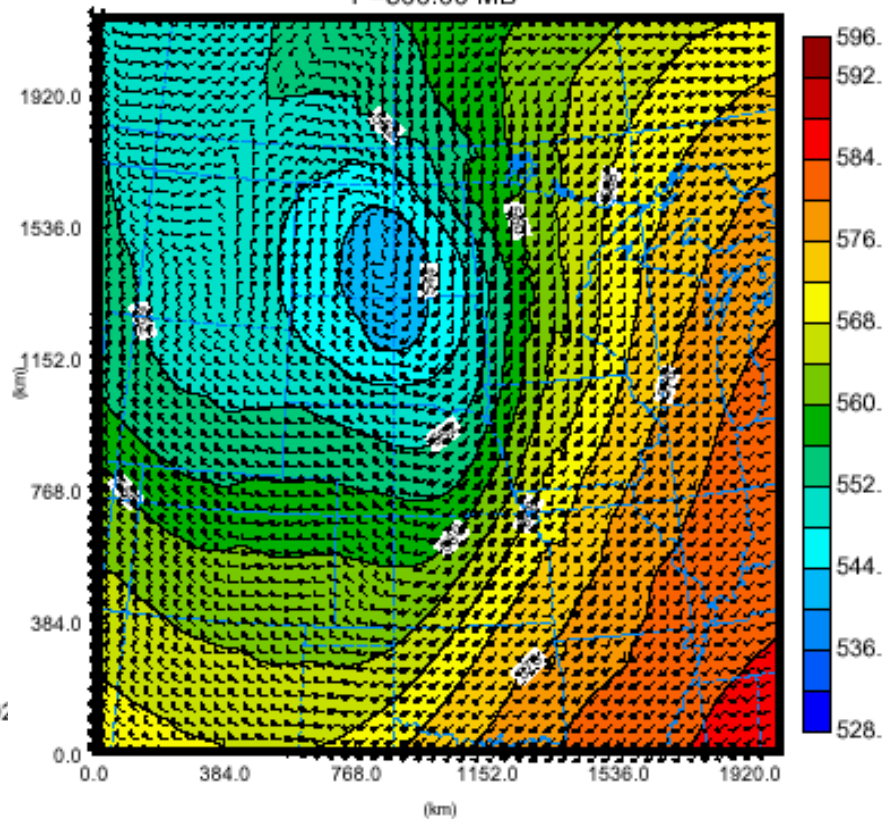
FIRST LEVEL ABOVE GROUND (SURFACE)



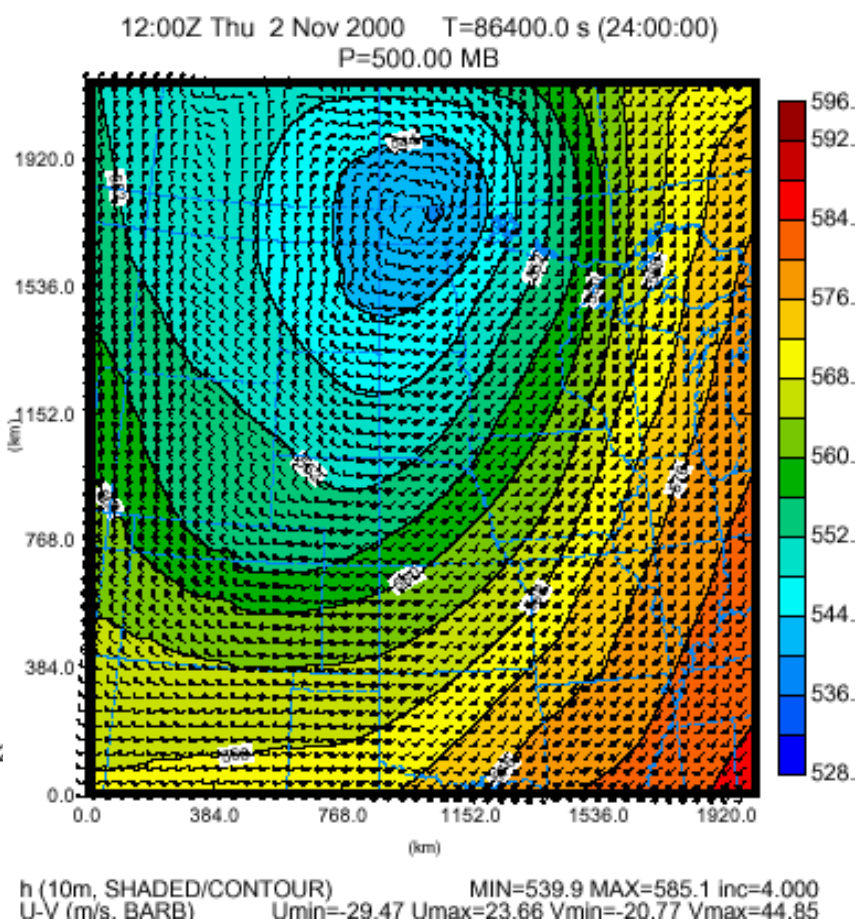
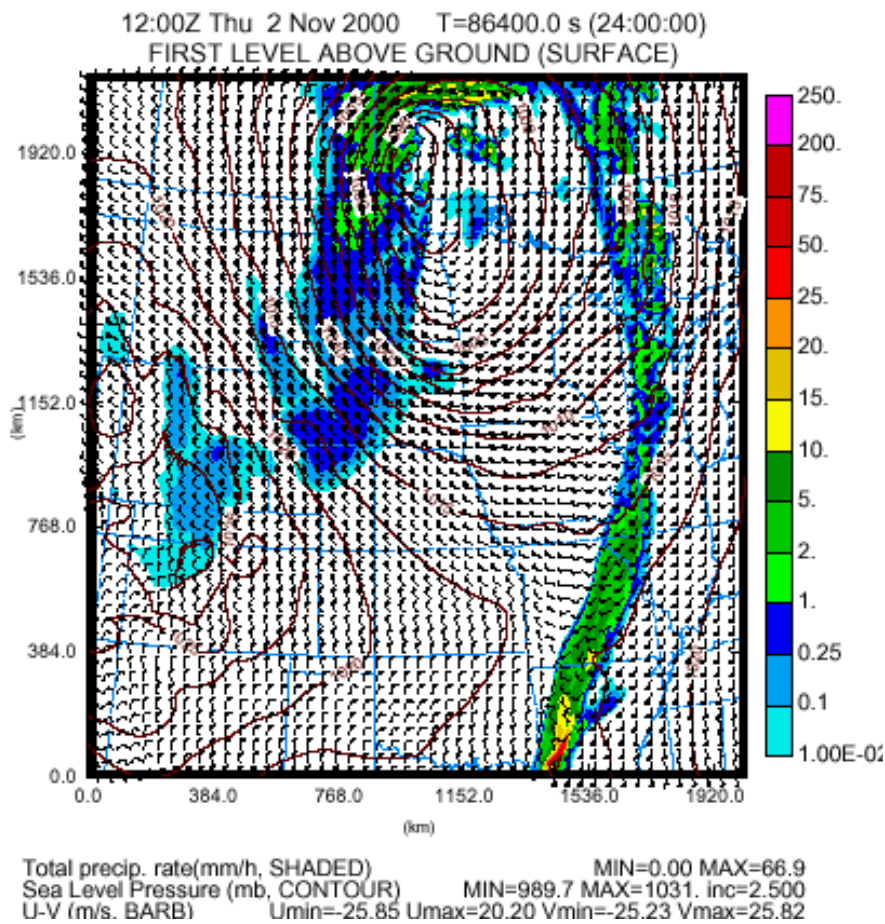
Total precip. rate(mm/h, SHADED) MIN=0.00 MAX=209.
 Sea Level Pressure (mb, CONTOUR) MIN=992.9 MAX=1025. inc=2.500
 U-V (m/s, BARB) Umin=-19.59 Umax=22.85 Vmin=-27.49 Vmax=29.67

00:00Z Thu 2 Nov 2000 T=43200.0 s (12:00:00)

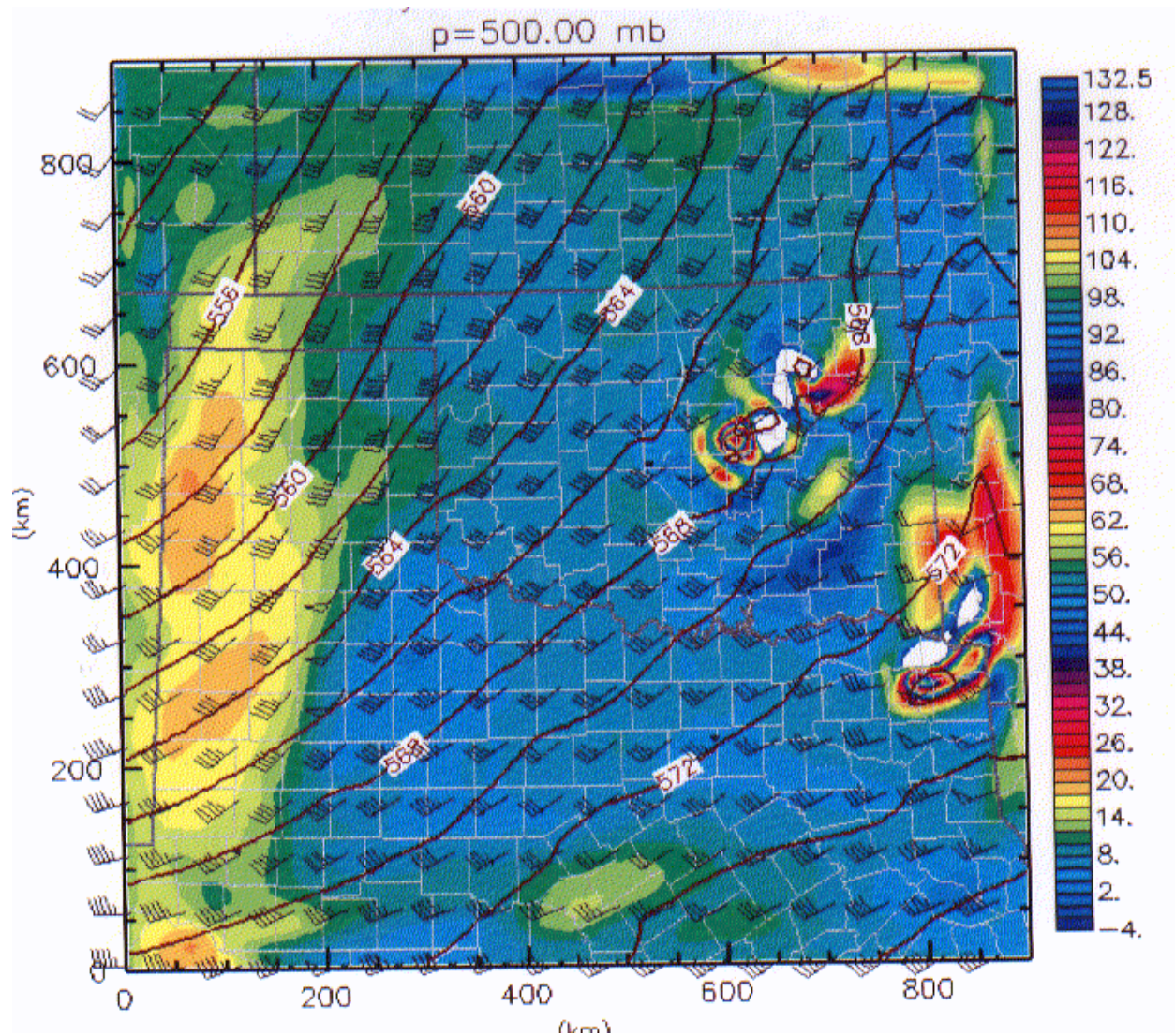
P=500.00 MB



h (10m, SHADED/CONTOUR) MIN=541.5 MAX=585.7 inc=4.000
 U-V (m/s, BARB) Umin=-25.54 Umax=26.12 Vmin=-25.25 Vmax=52.08



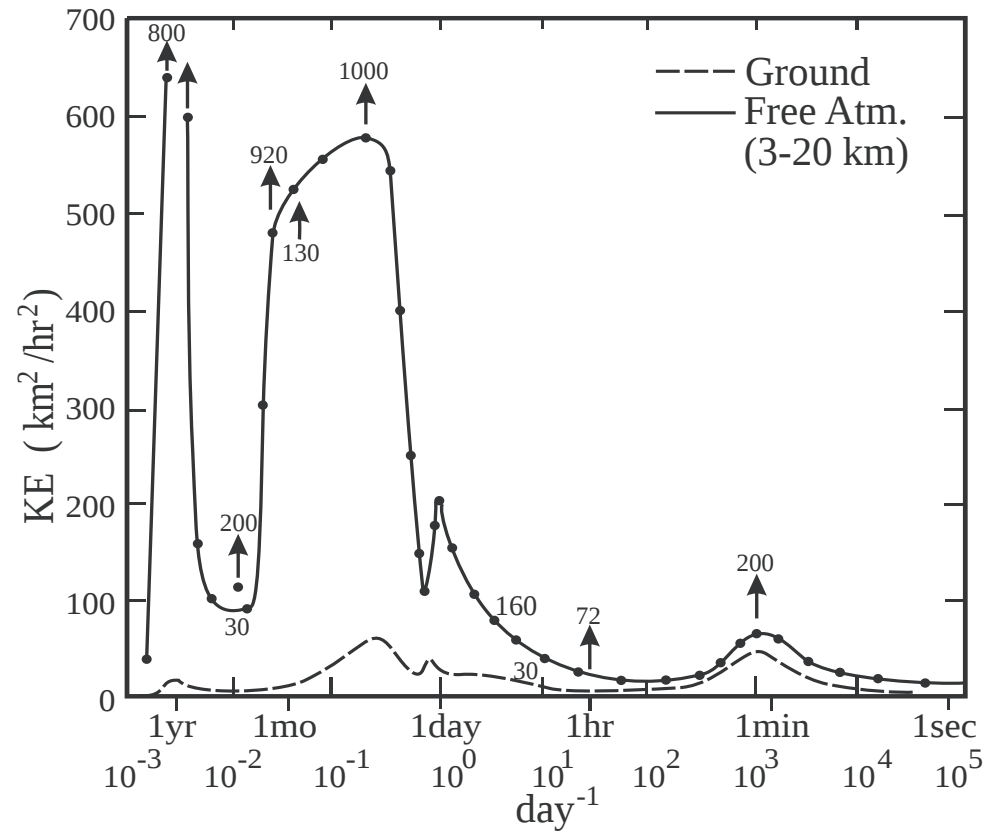
12h and 24 h forecasts by ARPS for November 2, 2000, at 6-km resolution. An intense squall line is shown, with embedded convection at even smaller scales.



A 500mb plot showing small-scale disturbances associated with thunderstorms, in the 9km-resolution forecast of ARPS.

Atmospheric Energy Spectrum

There are a few dominant time scales in the atmosphere, as is shown by the following plot of the kinetic energy spectrum plotted as a function of time:



Average kinetic energy of west-east wind component in the free atmosphere (solid line) and near the ground (dashed line). (After Vinnichenko, 1970). See also Atkinson Chapter 1.

There is a local peak around 1 day – associated with diurnal cycle of solar heating, and a large peak near 1 year – associated with the annual cycle due to the change in the earth's rotation axis relative to the sun. These time scales are mainly determined by forcing external to the atmosphere.

There is also a peak in the a few days up to about 1 month range. These scales are associated with synoptic scale cyclones up to planetary-scale waves. There isn't really any external forcing that is dominant at a period of a few days – this peak must be related to the something internal to the atmosphere – it is actually scale of most unstable atmospheric motion, such as those associated with baroclinic and barotropic instability.

There is also a peak around 1 min. This appears to be associated with small-scale turbulent motion, including those found in convective thunderstorms and planetary boundary layer.

The figure also shows that energy spectrum of the atmospheric motion is actually continuous!

There appears to be a 'gap' between several hour to half an hour – there remain disputes about the interpretation of this 'gap'. This 'gap' actually corresponding to the 'mesoscale' that is the subject of our study here.

We know that many weather phenomena occur on the 'mesoscale', although they tend to be intermittent in both time and space. The intermittency (unlike the ever present large-scale waves and cyclones) may be the reason for the 'gap'.

Mesoscale is believed to play an important role in transferring energy from the large scale down to the small scales.

Quoting from Dr. A. A. White (of British Met Office) "at any one time there is not much water in the outflow pipe from a bath, but it is inconvenient if it gets blocked". It's like the mid-latitude convection – it does not occur every day – but we can not do without it – otherwise, the heat and moisture will accumulate near the ground and we will not be able live at the surface of the earth!!

Energy Cascade

As we go down scales, we see finer and finer structures. Many of these structures are due to certain types of instabilities that inherently limit the size and duration of the phenomena. Also, there exist exchanges of energy, heat, moisture and momentum among all scales.

Example: A thunderstorm feeds off convective instabilities (as measured by CAPE) created by e.g., synoptic-scale cyclones. A thunderstorm can also derive part of its kinetic energy from the mean flow. The thunderstorm in turn can produce tornadoes by concentrating vorticity into small regions. Strong winds in the tornado creates turbulent eddies which then dissipate and eventually turn the kinetic energy into heat. Convective activities can also feed back into the large scale and enhancing synoptic scale cyclones.

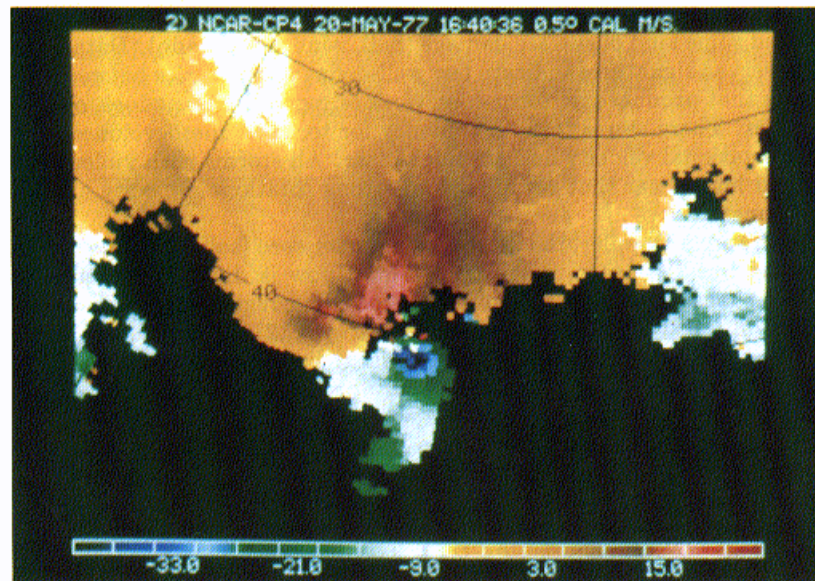
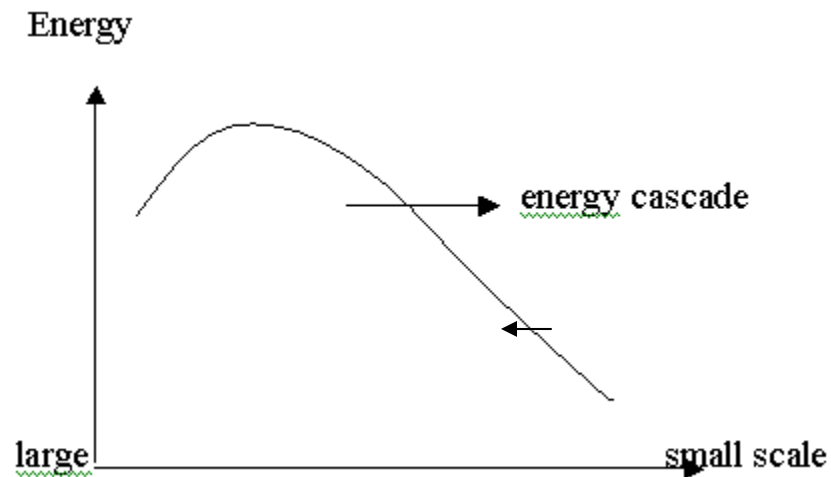


Figure 6.8. Display of Doppler radar data from a tornadic storm that occurred near Fort Cobb, Okla., 20 May 1977: (Top) reflectivity; (bottom) Doppler velocity. Elevation angle is 0.0° and radar is located at the figure top. Data are from NCAR's 5 cm wavelength CP-4 radar. The display was generated from the ATD/FOF RDSS display.

Most of the energy transfer in the atmosphere is downscale – starting from differential heating with latitude and land-sea contrast on the planetary scales. (Energy in the atmosphere can also transfer upscale).

We call the energy transfer among scales energy cascade.



What does this have to do with the mesoscale?

It turned out that the definition of the mesoscale is not that easy. Historically, the mesoscale was first defined as the scale between the visually observable thunderstorm scale and the scale that can be observed by synoptic observation network – i.e., it is a scale that could not be observed (read Atkinson Chapter 1, in particular page 5).

The mesoscale was, in early 50's, anticipated to be observed by the weather radars.

Rough Definition of Mesoscale:

The scale for which both ageostrophic advection and Coriolis parameter f are important – which is smaller than the Rossby radius of deformation ($L = NH/f \sim 1000\text{km}$).

For now, let's use a more qualitative definition and try to relate the scale to something more concrete.

Consider that the word mesoscale defines meteorological events having spatial dimensions of the order of one state, not an individual thunderstorms or cumulus clouds, and not a synoptic-scale cyclones (whose scale is on the order of several thousands of km).

Typical thunderstorms are actually sub-meoscale scale, that we call the convective scale.

Orlanski's classification of scales

(see more discussions on this table in Atkinson Chapter 1)

$L_s \backslash T_s$	1 MONTH $(\beta _R)^{-1}$		1 DAY $(f)^{-1}$	1 HOUR $(\frac{g}{\theta} \frac{d\theta}{dz})^{-\frac{1}{2}}$	MINUTE $(\frac{g}{H})^{-\frac{1}{2}}, (\frac{L}{U})$	1 SEC
10,000 Km	STANDING WAVES	ULTRA-LONG WAVES	TIDAL WAVES			MACRO $\propto$ SCALE
2,000 Km		BAROCLINIC WAVES				MACRO β SCALE
200 Km			FRONTS & HURRICANES			MESO $\propto$ SCALE
20 Km			NOCTURNAL LOW LEVEL JET SQUALL LINES INERTIAL WAVES CLOUD CLUSTERS MTN. & LAKE DISTURBANCES			MESO β SCALE
2 Km				THUNDERSTORMS I.G.W. C.A.T. URBAN EFFECTS		MESO γ SCALE
200 m				TORNADOES DEEP CONVECTION SHORT GRAVITY WAVES		MICRO $\propto$ SCALE
20 m					DUST DEVILS THERMALS WAKES	MICRO β SCALE
					PLUMES ROUGHNESS TURBULENCE	MICRO γ SCALE
C.A.S.	CLIMATOLOGICAL SCALE	SYNOPTIC PLANETARY SCALE	MESO SCALE	MICRO-SCALE		PROPOSED DEFINITION

Horizontal Scale	Lifetime	Stull (1988)	Pielke (2002)	Orlanski (1975)	Thunis and Bornstein (1996)	Atmospheric Phenomena
10 000 km	1 month	Macro	Synoptic Regional	Macro- α	Macro- α	General circulation, long waves
				Macro- β	Macro- β	Synoptic cyclones
2000 km	1 week	Macro	Synoptic Regional	Meso- α	Macro- γ	Fronts, hurricanes, tropical storms, short cyclone waves, mesoscale convective complexes
200 km	1 day			Meso- β	Meso- β	Mesocyclones, mesohighs, supercells, squall lines, inertia-gravity waves, cloud clusters, low-level jets, thunderstorm groups, mountain waves, sea breezes
20 km	1 h	Meso	Meso	Meso- γ	Meso- γ	Thunderstorms, cumulonimbi, clear-air turbulence, heat island, macrobursts
2 km				Micro- α	Meso- δ	Cumulus, tornadoes, microbursts, hydraulic jumps
200 m	30 min	Micro	Micro	Micro- β	Micro- β	Plumes, wakes, waterspouts, dust devils
20 m	1 min			Micro- γ	Micro- γ	Turbulence, sound waves
2 m	1 s	Micro- δ	Micro		Micro- δ	

Atmospheric scale definitions, where L_H is horizontal scale length proposed by Thunis and Bornstein (1996)

Definition of scales via scale analysis on equations of motion

(Read Chapter 1 of Atkinson. Fujita also has a chapter on this topic in book edited by Ray 1985).

Some (time and spatial) scales in the atmosphere are obvious:

Time scales:

- diurnal cycle
- annual cycle
- inertial oscillation period – due to earth rotation – the Coriolis parameter f .
- advective time scale – time taken to advect over certain distance

Spatial scales:

- global – related to earth's radius
- scale height of the atmosphere – related to the total mass of the atmosphere and gravity
- scale of fixed geographical features – mountain height, width, width of continents, oceans, lakes

Scale analysis (you should have learned this tool in Dynamics) is a very useful method for establishing the importance of various processes in the atmosphere and terms in the governing equations. Based on the relative importance of these processes/terms, we can deduce much of the behavior of motion at such scales.

Let's look at a simple example:

$$\frac{du}{dt} = \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + fv$$

What is this equation? Can you identify the terms in it?

With scale analysis, we try to assign the characteristic values for each of the variables in the equation and estimate the magnitude of each term then determine their relative importance.

For example,
$$\frac{du}{dt} \sim \frac{\Delta u}{\Delta t} \sim \frac{U}{T}$$

where U is the velocity scale (typical magnitude or amplitude if described as a wave component), and T the time scale (typical length of time for velocity to change by Δu , or the period for oscillations). It should be emphasized here there it is the **typical magnitude of change** that defines the scale, which is not always the same as the magnitude of the quantity itself. The absolute temperature is a good example, the surface pressure is another.

For different scales, the terms in the equation of motion have different importance – leading to different behavior of the motion – so there is a dynamic significance to the scale!

Synoptic Scale Motion

Let's do the scale analysis for the synoptic scale motion – since we know pretty well about synoptic scale motion (correct?).

$V \sim 10$ m/s (actually the typical variation or change in horizontal velocity over the typical distance)

$W \sim 0.1$ m/s (typical magnitude or range of variation of vertical velocity)

$L \sim 1000 \text{ km} = 10^6 \text{ m}$ (about the radius of a typical cyclone)

$H \sim 10 \text{ km}$ (depth of the troposphere)

$T \sim L/V \sim 10^5 \text{ s}$ (the time for an air parcel to travel for 1000 km)

$f \sim 10^{-4} \text{ s}^{-1}$ for the mid-latitude

$\rho \sim 1 \text{ kg/m}^3$

Δp in horizontal $\sim 10 \text{ mb} = 1000 \text{ Pa}$ (about the variation of pressure from the center to the edge of a cyclone – note that it is the typical variation that determines that typical scale, not the value itself, as in this example. Using the scale of 1000mb will give you wrong result!!)

$$\begin{array}{rcccl} \frac{\partial u}{\partial t} & + & u \frac{\partial u}{\partial x} & + & w \frac{\partial u}{\partial z} = & - \frac{1}{\rho} \frac{\partial p}{\partial x} & + & f v \\ \rightarrow & & \frac{V}{T} & & \frac{VV}{L} & & \frac{WV}{H} & & \frac{\Delta p}{\rho L} & & fV \\ & & \frac{10}{10^5} & & \frac{10^2}{10^6} & & \frac{0.1 \times 10}{10^4} & & \frac{10^3}{10^6} & & 10^{-4} \times 10 \\ & & 10^{-4} & & 10^{-4} & & 10^{-4} & & 10^{-3} & & 10^{-3} \end{array}$$

It turned out that the time tendency and advection terms are one order of magnitude smaller for *synoptic scale flows*. The pressure gradient force and Coriolis force are in rough balance – what kind of flow do you get in this case?? - The quasi-geostrophic flow.

Similar scale analysis can be performed on the vertical equation of motion.

Δp over vertical length scale $H \sim 1000 \text{ mb} = 10^5 \text{ Pa}$

$$\begin{array}{cccccc}
\frac{\partial w}{\partial t} & + & u \frac{\partial w}{\partial x} + & w \frac{\partial w}{\partial z} = & - \frac{1}{\rho} \frac{\partial p}{\partial z} & - g \\
\frac{W}{T} & & \frac{VW}{L} & & \frac{WW}{H} & & \frac{\Delta p}{\rho H} & & g \\
\frac{0.1}{10^5} & & \frac{10 \times 0.1}{10^6} & & \frac{0.1 \times 0.1}{10^4} & & \frac{10^5}{1 \times 10^4} & & 10 \\
10^{-6} & & 10^{-6} & & 10^{-6} & & 10 & & 10
\end{array}$$

Clearly, the vertical acceleration is much smaller than the vertical pressure gradient term and the gravitational term, which are of the same order of magnitude. The balance between these two terms gives the hydrostatic balance, and this balance is a very good approximation for synoptic scale flows. Also, the vertical motion is much smaller than the horizontal motion. We can deduce the latter from the mass continuity equation ($\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \approx 0$).

Therefore, we obtain, based on the scale analysis alone, the following basic properties of flows at the synoptic-scale flows: such flows are **quasi-two-dimensional, quasi-geostrophic and hydrostatic**.

We saw a good example of horizontal scale determining the dynamics of motion!

In summary, synoptic (and up) scale flows are

- quasi-two dimensional (because $w \ll u$)
- hydrostatic (we can see it by performing scale analysis for vertical equation of motion)
- Coriolis force is a dominant term in the equation of motion and it is in rough balance with the PGF, the flow is quasi-geostrophic

Mesoscale Motion

What about the mesoscale? We said earlier we define the mesoscale to be on the order of hundreds of kilometers in space and hours in time. Repeat the scale analysis done earlier:

$$\begin{array}{cccccc}
 \frac{\partial u}{\partial t} & + & u \frac{\partial u}{\partial x} + & w \frac{\partial u}{\partial z} = & -\frac{1}{\rho} \frac{\partial p}{\partial x} & + f v \\
 \frac{V}{T} & & \frac{VV}{L} & \frac{WV}{H} & \frac{\Delta p}{\rho L} & fV \\
 \frac{10}{10^4} & & \frac{10^2}{10^5} & \frac{1 \times 10}{10^4} & \frac{10^2}{10^5} & 10^{-4} \times 10 \\
 10^{-3} & & 10^{-3} & 10^{-3} & 10^{-3} & 10^{-3}
 \end{array}$$

we see that the all terms in the equation are of the same magnitude – none of them can be neglected – we no longer have geostrophy! For the vertical direction, the hydrostatic approximation is still reasonable good for the mesoscale.

In the vertical direction:

$$\begin{array}{ccccc}
\frac{\partial w}{\partial t} & + & u \frac{\partial w}{\partial x} + & w \frac{\partial w}{\partial z} = & - \frac{1}{\rho} \frac{\partial p}{\partial z} - g \\
\frac{W}{T} & & \frac{VW}{L} & & \frac{WW}{H} & \frac{\Delta p}{\rho H} & g \\
\frac{1}{10^4} & & \frac{10 \times 1}{10^5} & & \frac{1 \times 1}{10^4} & \frac{10^5}{1 \times 10^4} & 10 \\
10^{-4} & & 10^{-4} & & 10^{-4} & 10 & 10
\end{array}$$

Therefore, mesoscale motion is not geostrophic (i.e., ageostrophic component is significant – see earlier definition), the Coriolis force remains important, and hydrostatic balance is roughly satisfied. The motion is quasi-two-dimensional ($w \ll u$ or v). This can be a dynamic definition of the mesoscale, or in Orlanski's definition, the meso- β scale.

In summary, **meso- β scale flows are**

- quasi-two dimensional
- nearly hydrostatic
- Coriolis force is non-negligible

When we go one step further down the scale, looking at **cumulus convection or even supercell storms**, $L \sim 10$ km, $V \sim 10$ m/s, $T \sim 1000$ s, we get

$$\begin{array}{cccccc}
\frac{\partial u}{\partial t} & + & u \frac{\partial u}{\partial x} & + & w \frac{\partial u}{\partial z} & = & -\frac{1}{\rho} \frac{\partial p}{\partial x} & + & fV \\
\frac{V}{T} & & \frac{VW}{L} & & \frac{WV}{H} & & \frac{\Delta p}{\rho L} & & fV \\
\frac{10}{10^3} & & \frac{10^2}{10^4} & & \frac{10^2}{10^4} & & \frac{10^2}{10^4} & & 10^{-4} \times 10 \\
10^{-2} & & 10^{-2} & & 10^{-2} & & 10^{-2} & & 10^{-3}
\end{array}$$

Now we see that the Coriolis force is an order of magnitude smaller, it can therefore be neglected when studying cumulus convection that lasted for an hour or so. Again, the acceleration term is as important as the PGF.

The scale analysis of the vertical equation of motion, based on the Bousinessq equations of motion (see e.g., page 354 of Bluestein) is as follows:

$$\begin{array}{cccccc}
\frac{\partial w}{\partial t} & + & u \frac{\partial w}{\partial x} & + & w \frac{\partial w}{\partial z} & = & -\frac{1}{\bar{\rho}} \frac{\partial p'}{\partial z} & + & \frac{\theta'}{\bar{\theta}} g \\
\frac{W}{T} & & \frac{VW}{L} & & \frac{WW}{H} & & \frac{\Delta p}{\bar{\rho} H} & & \frac{\Delta \theta}{\theta_0} g \\
\frac{10}{10^3} & & \frac{10^2}{10^4} & & \frac{10^2}{10^4} & & \frac{10^2}{0.5 \times 10^4} & & \frac{1 \times 10}{300} \\
10^{-2} & & 10^{-2} & & 10^{-2} & & 2 \times 10^{-2} & & 3 \times 10^{-2}
\end{array}$$

Here we are using the vertical mean density as the density scale in PGF term. The Bousinessq form of equation is used because it is the residual between the PGF and buoyancy force terms that drives the vertical motion, therefore we want estimate the terms in terms of the deviations/perturbations from the hydrostatically balanced base state.

Clearly, the vertical acceleration term is now important therefore hydrostatic approximation is no longer good. According to Orlanski's definition, this falls into the meso- γ range, sometimes it's referred to as small scale or convective scale. At this scale, the flow will be ageostrophic, nonhydrostatic, and three dimensional ($w \sim u$ and v).

In summary, **meso- γ , small or convective scale flows are**

- three dimensional
- nonhydrostatic
- ageostrophic and the Coriolis force is negligible

As one goes further down to the micro-scales, the basic dynamics becomes similar to the small scale flows – the flow is

- three dimensional
- nonhydrostatic
- ageostrophic and the Coriolis force is negligible.

Summary

There are more than one way to define the scales of weather systems. The definition can be based on the time or space scale or both of the system. It can also be based on certain physically meaningful non-dimensional parameter (for example, Rossby number based on Lagrangian time scale as advocated by Emanuel 1986).

The most important is to know the key characteristics associated with weather systems/disturbances at each of these scales, as revealed by the scale analysis. The scale analysis can lead to non-dimensional parameters in non-dimensionalized governing equations. Physically, the last approach (that based on non-dimensional parameters) makes most sense.

Reference

Emanuel, K. A., 1986: Overview and definition of mesoscale meteorology. In: P.S. Ray (Editor), *Mesoscale Meteorology and Forecasting*. American Meteorological Society, Boston, 1-17.

In the course, we will focus on the meso- β (or classical mesoscale) and meso- γ (or small or convective scale), with some coverage on meso- α (hurricanes) and micro- α scale (e.g., tornadoes).