The Mesoscale Forecasting Process
Applying the Next Generation Mesoscale Forecast

Written by: Mr. Calvin C. Naegelin
Mr. Paul J. McCrone

**Air Force Weather Agency
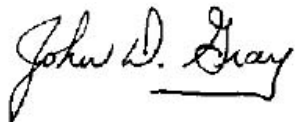106 Peacekeeper Drive, Ste 2NE
Offutt AFB, NE 68113-4039**

REVIEW AND APPROVAL STATEMENT

AFWA/TN-06/001, *The Mesoscale Forecasting Process: Applying the Next Generation Mesoscale Forecast*, has been reviewed and is approved for public release. There is no objection to unlimited distribution of this document to the public at large, or by the Defense Technical Information Center (DTIC) to the National Technical Information Service (NTIS).

RONALD P. LOWTHER, Colonel, USAF
Director of Operations

John D. Gray
Scientific and Technical Information
Program Manager

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to the Department of Defense, Executive Services and Communications Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

1. REPORT DATE (DD-MM-YYYY) 5 October 2006	2. REPORT TYPE Technical Note	3. DATES COVERED (From - To)

4. TITLE AND SUBTITLE

The Mesoscale Forecasting Process: Applying the Next Generation Mesoscale Forecast

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Mr.Calvin C. Naegelin
Mr. Paul J. McCrone

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Weather Agency
106 Peacekeeper Drive, Ste 2NE
Offutt AFB, NE 68113-4039

8. PERFORMING ORGANIZATION REPORT NUMBER
AFWA/TN-06/001

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The weather forecast effort has progressed a long way past its embryonic stage of the barotropic forecast. Both computer power and our knowledge of atmospheric processes have increased substantially over the years, allowing for the classification of many weather phenomena into scales, including the global/hemispheric scale, the synoptic scale, the mesoscale, and the microscale. These scales represent the cascade of energy that occurs in the atmosphere, with hemispheric features providing energy for the synoptic scale, synoptic features providing energy for the mesoscale, and so forth. Many observation and modeling tools exist to aid the forecaster along the way, including RAOB soundings, satellite imagery, wind profiler data, radar data, lightning data, and model data, and all are useful in mesoscale forecasting. When performing a mesoscale forecast, however, it is prudent to use a mesoscale model, such as the Air Force Weather Agency's (AFWA) Weather Research and Forecasting (WRF) model.

15. SUBJECT TERMS

NUMERICAL WEATHER PREDICTION, MESOSCALE METEOROLOGY, WEATHER RESEARCH AND FORECASTING MODEL

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON H. Gene Newman
a. REPORT	b. ABSTRACT	c. THIS PAGE			
U	U	U	U	39	19b. TELEPHONE NUMBER (Include area code) (828) 271-4218

Reset

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

ABSTRACT

The weather forecast effort has progressed a long way past its embryonic stage of the barotropic forecast. Both computer power and our knowledge of atmospheric processes have increased substantially over the years, allowing for the classification of many weather phenomena into scales, including the global/hemispheric scale, the synoptic scale, the mesoscale, and the microscale. These scales represent the cascade of energy that occurs in the atmosphere, with hemispheric features providing energy for the synoptic scale, synoptic features providing energy for the mesoscale, and so forth. The forecast process, in fact, can often be analogous to a funnel, in which the forecaster examines hemispheric phenomena in order to better forecast synoptic-scale phenomena, and synoptic-scale phenomena in order to better forecast mesoscale phenomena. Many observation and modeling tools exist to aid the forecaster along the way, including RAOB soundings, satellite imagery, wind profiler data, radar data, lightning data, and model data, and all are useful in mesoscale forecasting. When performing a mesoscale forecast, however, it is prudent to use a mesoscale model, such as the Air Force Weather Agency's (AFWA) Weather Research and Forecasting (WRF) model, which can describe atmospheric features on medium to small scales because of its finer resolution. In addition to many other products, the AFWA WRF may be used to produce forecast soundings for thousands of specific points on a given forecast map, as well as meteograms that illustrate forecast evolution with time, and cross-sections that enable the forecaster to diagnose vertical atmospheric structure. The forecaster must also use his or her knowledge of the local topography to determine how the topography will influence the mesoscale weather. All of these tools, in addition to the forecaster's knowledge of local climatology, will enable him or her to concoct a mesoscale forecast with a firm scientific basis.

Table of Contents

Figures

Tables

Acknowledgments

The Mesoscale Forecasting Process

"Great whirls have little whirls
That feed on their velocity,
And little whirls have smaller whirls,
And so on to viscosity"
L. F. Richardson, (Circa 1922)

1. Introduction

The weather forecast effort has progressed a long way past its embryonic stage of the barotropic forecast. In the late 1940's, this was the only model running because of limitations of computer power. As computer power increased, so did the complexity of the meteorological model, always pushing computer resources to their limit. The forecast methodology quickly changed from barotropic to baroclinic. As the limit was pushed, a greater wealth of prognostic information began to flow from the models. Model sophistication leads to more detailed (and assumedly) better forecasts. While initially chasing the weather-producing and extremely elusive energy packets at high levels, it became apparent that detailed didn't always imply a better forecast. Although most forecasters will agree that Rossby waves became more predictable throughout the 1960's and 1970's, there was still a gap that needed bridging as numerical weather prediction (NWP) modelers took the first shaky steps down from the heights of the hemispheric energy level to the synoptic energy level. That step seemed to work well; however, it would be beneficial for meteorologists to shrink the forecast net down to a smaller opening in an effort to catch the rest of the energy cascade that was obviously being missed.

The evolution of forecast models will no doubt continue. The fact that humans will continue to interpret the model output is also a forgone conclusion for the near and intermediate future. An understanding of the model and its juxtaposition in the energy spectrum is critical to understanding and interpreting the model's output. This is not an easy task, and requires an understanding of the basic meteorological fundamentals that underlie every meteorological setting. How does one slide from the hemispheric scale to the synoptic scale to the mesoscale to the microscale and on into the noise level without compromising meteorological integrity by leaving a signature trace on the model output? The fact of the matter is that there will be a signature trace in the model's output (regardless of level) because each iteration is a disturbance of the atmospheric continuum which, once broken, and much like Humpty Dumpty, can never be put back together again.

Another extremely useful forecaster capability is the ability to think in three dimensions (actually four, if one includes time.) Thinking three-dimensionally means a departure from the conventional xy-horizontal plane which is conventionally taught, to a fully developed data cube that occupies space in the atmosphere irrespective of the xy-plane orientation. Not everyone can master this technique; indeed, most military forecasters never reach that level of thinking but are content to stay at the level of "pattern identifier" that is taught at the technical training schools. There is nothing wrong with this approach and it works remarkably well. However, when interpreting a newer and more detailed model, this way of extracting information from the model needs refining because the emphasis shifts to vertical motion fields that must be analyzed on-the-fly in a three-dimensional mode.

Stepping down two levels from the primary energy level (hemispheric level) will impact a lower-scale model run. Since the mesoscale model runs two levels down, human intervention (the forecaster) will still be very much involved in the final interpretation and application of the model output. Initially, the Weather Research and Forecasting model (WRF) output will not look much (if any) different from MM5. That may change as the model evolves,

due primarily to new products. The desired outcome of this publication is to enable the AFW forecaster to properly understand the mesoscale forecasting process; and to visualize the movement of atmospheric energy as the means for generating and sustaining weather at the sub-synoptic scale (mesoscale, via WRF). See COMET Module: Mesoscale Meteorology Primer (http://meted.ucar.edu/mesoprim/index.htm)

2. The Scales of Motion.

Scale is frequently used in meteorology to allow comparison of atmospheric phenomenon of different size, e.g., an order of magnitude aid in estimating meteorological parameters (GOM). *Scale Analysis* is an analysis method using the non-dimensional equations to determine which terms are dominant for a particular phenomenon or situation so that the smaller terms can be neglected, resulting in a simplified set of equations. When a meteorologist speaks of a scale of motion, he is usually referring to a particular set of limits used to determine the extent of the event under scrutiny. Consider the breakdown of scale in Figure 1.

Figure 1 shows a breakdown of what is traditionally accepted meteorological scale from the largest to the smallest. One must be careful in specifying limits of the scales. Note that those limits will vary in the literature. The scale definitions used here are from the textbook "*Meteorology Today*" by Ahrens. A little flexibility in the definition may be required by the reader to accept these. The idea is not to quibble over a few kilometers or a few hours, but to present the idea that atmospheric scales do exist and do have approximate limits.

A discussion of scale would be incomplete without considering why scale is important in the first place. From a meteorological point of view, the scale is used to filter certain levels of energy and
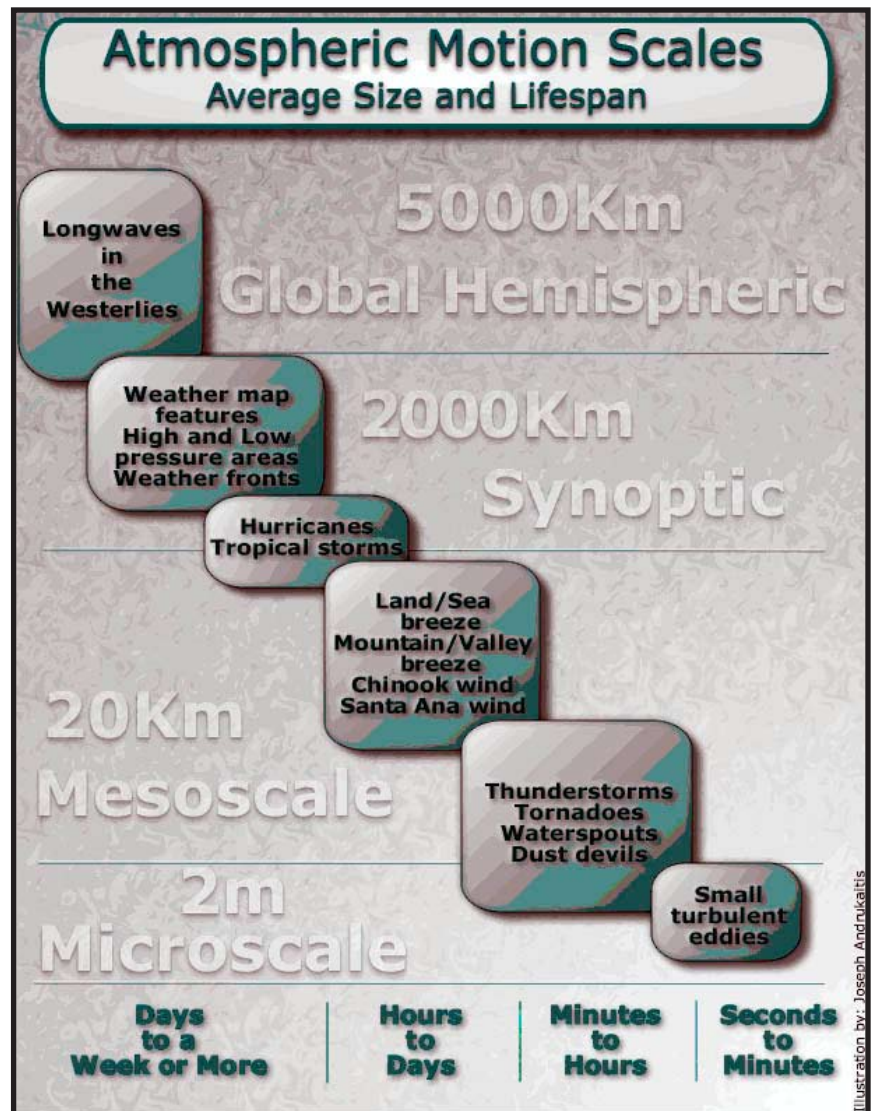
Figure 1. Atmospheric Motion Scales. These are the typically accepted scales of atmospheric motion. Note the extensive overlaps in most instances. Feature size will vary. (After Ahrens, *Meteorology Today, 7th Ed.*)

categorize them by how they drive atmospheric phenomenon, e.g., extra-tropical cyclones. With this in mind, one must hand-in-hand walk down the path of cascading energy as outlined by the Russian Mathematician/Physicist Kolmogorouf in the middle 1930's. Kolmogorouf envisioned energy cascading down through a spectrum of dissipation from maximum energy to the ultimate eddy dissipation region which is usually labeled as "noise" (Figure 2). With this energy cascade in mind, let us now revisit meteorological scale.

The atmospheric scientist lives by the presence (or absence) of energy. A professor at St. Louis

University used to fondly say: "Show me where the energy will be tomorrow and I will show you where the weather will be!" (Dr. Frank Lin). At the time, that comment was not fully appreciated. Now, it forms the basis for all meteorological understanding because indeed, a significant amount of time is expended diagnosing the current state of the atmosphere so that one can determine where the energy resides today. It is up to the model to move it to its projected location where the forecaster can use that energy analysis to interpret the face of the sky at some point and at some delta-t forward.

The largest scale is the *hemispheric scale* (Figure 1; Figure 2). This is the scale where most of the fundamental atmospheric energy resides. Temporally, it has dimensions of weeks to maybe a month; spatially, it has dimensions of hemispheric proportions—hence its name. Rossby waves reside here. The orientation of this flow (zonal or meridional) will go a long way toward determining the weather at a location for an extended period of time. These *long waves* move slowly, carrying their energy with them across oceans, continents, and even mountains. They establish what is known as the general circulation that is driven and oriented by the three cell model of the atmosphere. They are the basis for every drought or plunge of Arctic air. Based on this foundation, the remaining scales fall into place under the hemispheric long waves.

Following closely behind the hemispheric scale is the *synoptic scale* (Figure 1; Figure 2). This scale is considerably smaller than the hemispheric scale yet shares some of the characteristics of the
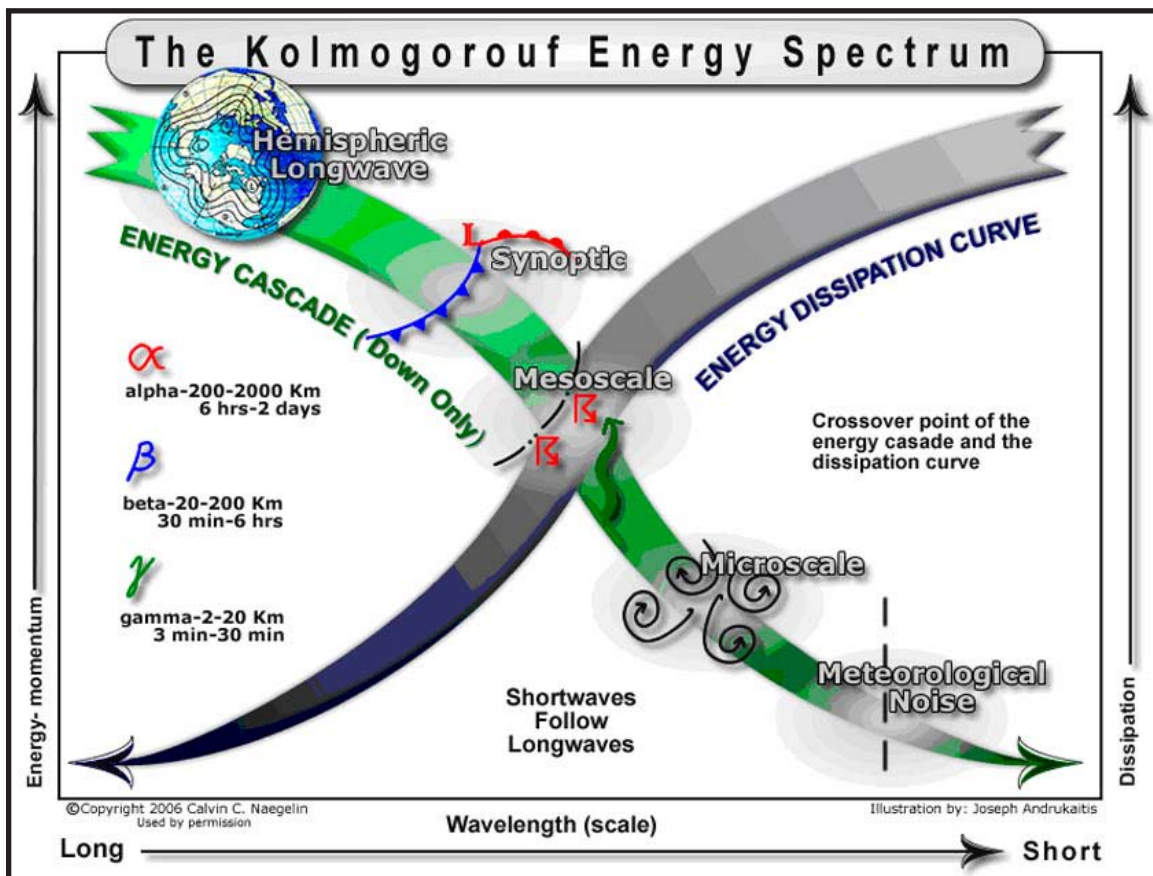
Figure 2. Kolmogorouf Energy Spectrum. The Kolmogorouf Energy Spectrum demonstrates the cascading of energy stored in the hemispheric longwaves with the corresponding levels of energy dissipation. It is evident that the mesoscale is a consumer and not a source of energy. By dividing the mesoscale into three regions, one can look at different features and how each uses the energy available in the cascade. Note that not all aspects of these three sub-scales are active all of the time.

long wave scale. For example, a series of short waves reside in the long wave flow and, to some extent, act independently of them throughout their life cycle. They are compact energy packets that maintain their identity for a period of several days to a week or more, serving as focus sources for upper-level divergence which ultimately results in the upward vertical motion that will serve as support for areas of deteriorating weather. If these areas of deteriorating weather organize they can metamorphose into extra tropical cyclones with a spatial extent of five to six hundred miles or more. A key element to the discussion is that some of the energy from the long wave system is used to drive the mechanics of the synoptic scale system. This is important, because for the first time it is apparent that energy from the larger scale is responsible for causing disturbances in the atmosphere at a smaller scale in an organized manner. In short, this scale adds no new energy to the energy spectrum but becomes the first true and wholly dissipative segment of the energy cascade. As a result, the energy cascade begins.

Below the synoptic scale one finally comes into contact with the *mesoscale* (Figure 1; Figure 2). This scale suffers from lack of a clear-cut definition because the spatial and temporal intervals quickly become smaller. Spatially, they can go from ten miles up to possibly a hundred miles or larger (squall line, mesoscale convective complex (MCC)). Temporally, these systems last from several minutes to several hours (MCC, squall line, super-cell thunderstorm). In addition, this scale is associated with the energy embodied in the hemispheric scale and the synoptic scale from which it draws its energy. This scale doesn't add new energy to the energy spectrum either, but continues the dissipative path of the energy cascade.

Many transitions, actions, and reactions are taking place in the mesoscale region of the atmosphere. In fact, there are so many and at so many different time/ space intervals that meteorologists have divided this region into several different meso regions. They are the meso alpha, the meso beta, and the meso gamma (Table 1). Note the mesoscale location on Figure 1 and Figure 2. The sub-scale mesofeatures are not discussed here because they are simply subsets of what is known as the mesoscale region of the atmosphere and are so designated for convenience.

The reason why the mesoscale is sub-divided into three categories is that each scale has different features associated with it. Note that this list is not exhaustive, but is meant only to provide a flavor for the features that may be encountered at each sub-scale. Any feature that is smaller or lasts less time than meso-gamma is considered in the microscale. Microscale features include almost all tornadoes.

Continuing the cascade, the next scale encountered is the *microscale* (Figure 1; Figure 2). This scale is also energy intensive and dissipative, drawing energy downward from its mesoscale counterpart. Spatially, meters to maybe a kilometer are considered representative of this scale. Temporally, seconds to a few minutes, possibly up to an hour is the rule. The example usually cited is rainshowers or the funnel portion of a tornado.

Table 1. Mesoscale Dimensions

Mesoscale Dimensions

Category	Spatial (Km)	Temporal
Meso Alpha	200-2000	6 hrs-2 days
Meso Beta	20-200	30 min-6 hrs
Meso Gamma	2-20	3 min-30 min

Features

Category	Features
Meso Alpha	Jet Stream (Jet Streak), anticyclones small hurricanes and less-intense tropical cyclones
Meso Beta	Some large-scale mountain winds, local winds, mesoscale convective complexes (MCC), large thunder-storms, Land/Sea breeze
Meso Gamma	Large cumulus, many thunderstorms, EXTREMELY large tornadoes

These highly dissipative energy intensive systems continue to draw their source of energy from the scales above. However, the ultimate boundary layer (the earth) is ready and willing to receive any momentum that may be transferring to its ultimate dissipation destination. One should also note that energy cascade with these dimensions can occur in the atmosphere without an organized energy source to draw from. Energy packets originating at levels other than the mesoscale may be included in this energy transfer, thereby making this part of the atmosphere slightly more chaotic than the previous three divisions.

Much below the microscale, meteorologists find it difficult to measure any of the sensible weather elements, such as pressure, temperature, winds, etc. This is the area in the energy cascade that is usually referred to as "*meteorological noise*". It is, if you will, the atmospheric sewer for spent meteorological energy.

The rules of hydrostatic equilibrium have long since broken down. That happened several scales ago. The hydrostatic approximation means simply that one neglects vertical accelerations in the vertical equation of motion when compared to gravitational acceleration. This is acceptable, as long as horizontal scales of motion are larger than the vertical scales. The added benefit of filtering sound waves is also realized. So how far down the scales can one go before the hydrostatic assumption is no longer valid? Most researchers agree that even into the mesoscale end of things where grid sizes of 10 km or larger prevail that one can use the approximation effectively. However, smaller scale phenomena that have vertical accelerations that are not negligible (e.g., a strong vertical pressure gradient in a thunderstorm inducing a strong updraft) require that equations be solved without the benefit of the hydrostatic approximation. The non-hydrostatic models (such as WRF) simulate mesoscale phenomena without the hydrostatic assumption, using anelastic equations, which is well outside the scope of this discussion. See COMET Module: How Mesoscale Models Work (http://meted.ucar.edu/mesoprim/models/index.htm).

Data are changing fast and furiously, with spatial scales on the order of centimeters to possibly a few meters and temporal scales in terms of tenths of seconds to maybe a minute (or five minutes). This is the region where dissipation rules supreme and all the rubber that the atmosphere can muster is put to bear on the surface of the earth's road. Turbulence (a dissipative process) is seen to exist in a wide variety of instances. Note that without a specific parental structure, this type of activity can take place just about any place and under any set of favorable circumstances. Hence interaction in the microscale region of the atmosphere need not be associated with a jet streak, energy maximum, MCC, etc. It can simply occur as a spin-off from a larger transient energy flux.

Establishing this scalar hierarchy allows the meteorologist to compartmentalize certain weather phenomenon. The danger is that each scale designation serves as a box with impervious sides that capture energy and consume it on the spot. We know this is not true and that energy flows through the atmospheric system from top to bottom. Hence when a forecast is built (in this case, WRF), there is a constant danger that the output will be viewed in total isolation from the remainder of the atmosphere's energy profile. That model is certainly not the beginning and end of atmospheric energy. Each level borrows the energy and consumes a part of it before passing it along to the next level down. It just so happens that our focus (WRF, mesoscale) provides forecasters with guidance information at the mesoscale. Brooks sums this up nicely by saying: "In general, numerical prediction models do not produce a weather forecast. They produce a form of guidance that can help a human being decide upon a forecast of the weather. Just as with any other information source, numerical models can help or hinder a forecaster, depending on his or her experience, understanding of the model and its shortcomings, and the weather situation." (Brooks, et al, 1991).

3. The Mesoscale. See (COMET Module: Definition of the Mesoscale (http://meted.ucar.edu/mesoprim/mesodefn/index.htm).

Defining the Mesoscale gives one the choice of several possibilities. A generic definition is offered by the Glossary of Meteorology and reads as follows: "Pertaining to atmospheric phenomena having horizontal scales ranging from a few to several hundred kilometers, including thunderstorms, squall lines, fronts, precipitation bands in tropical and extratropical cyclones, and topographically generated weather systems such as mountain waves and sea and land breezes. From a dynamical perspective, this term pertains to processes with timescales ranging from the inverse of the Brunt-Vaisala frequency to a pendulum day, encompassing deep moist convection and the full spectrum of inertio-gravity waves but stopping short of synoptic-scale phenomena, which have Rossby numbers less than 1." However, this definition does not allow for any specific variations that many believe to exist. As a result, others have sub-divided the mesoscale space into three distinct regions (Table 1). Note that each of the sub-scales has particular features associated with it. Be reminded that this list is not all-inclusive and is meant only to provide examples for the types of features found at each sub-scale. Also be aware that the definitions will vary from source to source. Be flexible.

Any features that are smaller than or last less time than the meso-gamma intervals are considered to be microscale. As a result, microscale features include virtually all tornadoes.

It is critical to understand these different scales, because each scale dictates different phenomena. One must be careful not to intermix scales. If an NWP model operates at the synoptic scale, one cannot expect to obtain actual meso-quality features. This is especially true when looking at a smaller model and comparing it to a larger model output. However, one may be able to identify atmospheric conditions in the larger model that are favorable for a smaller scale feature. In short, we can "model down" but we cannot "model up". The WRF model replaces the MM5 as AFW's mesoscale model of choice. Hence mesoscale models and their output are not new to AFW forecasters. The subtle changes in WRF are all internal. WRF is a mesoscale model that gives a tremendous boost to the capability of AFWA's mesoscale forecast effort.

4. The Forecasting Process, a.k.a., The Forecast Funnel.

The search for meteorological data to use in any forecast ends only when the transmit button is actuated. Getting to that point can be an arduous and excruciating task. Numerous checklists have been built and there are innumerable systematic, scientific, and efficient approaches to making sure all raw and processed meteorological information is at least looked at if not used in forecast production. Forecasters need to start thinking "mesoscale." One needs only to look at the Energy Cascade (Figure 2) to realize that this model may act differently from a synoptic scale model and certainly differently from a hemispheric one. This requires the forecaster to be more aware of model strengths and weaknesses—an experience base for WRF that will not be available to field forecasters for quite some time. In the mean time, in order to make up for the lack of this important experience data set, forecasters must apply the soundest physical reasoning to the application of the WRF mesoscale model.

The Air Force weather mission has not changed. Every forecaster is bound to put the best meteorological effort into each and every forecast effort. While this used to be at the synoptic level, that emphasis has now shifted to the mesoscale or one level down in the energy spectrum of the atmosphere. An emphasis on briefing and communicating and a reliance on NWP do not release the duty forecaster from his primary responsibility of issuing a horizontally consistent and vertically stacked forecast that flows cleanly over some delta-t. The crux of the matter is not what the machine thinks, but what do YOU, the forecaster, who is ultimately responsible for the issued product, think! Issuing a forecast for an air force base, a geographically separated unit (GSU), or a high-priority target, is the responsibility of the duty forecaster and not the model. "Modeling may give us scenarios, but not reality." (Roland List, University of Toronto). The model can help, but the responsibility rests on the human side of the

fence. A computer model is a tool, not a crutch. It is very bad practice to blindly forecast for the model's solution. Be sure you have sound meteorological reasons for your forecast, and can honestly justify your decisions to yourself, other meteorologists, and above all, the customer.

It takes an entire atmosphere to set the stage for a forecast. The atmosphere presents a unique entity in that it is continuous. As soon as it is interrogated and analyzed, that continuum is broken, and the troubles begin. The continuum is viewed (piecemeal) from top to bottom, from its widest expanse down to the point one is forecasting for. The entire atmosphere contributes to the forecast. The forecaster's job is to focus the atmosphere on the area in question, i.e., funnel every piece of meteorological information into its place in the puzzle of the final forecast. We do that with a concept known as "The Forecast Funnel."

This pictorial representation outlines the process a forecaster must go through to build a point or small area weather forecast. Note that all scales of motion are used, especially the Hemispheric and Synoptic scales. The atmospheric energy must be tracked from its origin in the broad scale flow to its dissipation in and below the small scale part of the spectrum. For practical purposes, the energy is not tracked once it passes through and out of the mesoscale.

The entire forecast process begins with the initialization phase. The model has already "initialized" so the forecaster must gather and assimilate as much data after model initialization as possible. Every scrap of data is eligible for initialization. There is a continual flow of satellite data (MetSat, Modis, plus others), surface and upper air observations, NEXRAD and PIREPs that must be integrated into the forecast. A systematic and efficient way to organize this post-model material is by applying the "Forecast Funnel" (Figure 3). Seemingly simplistic in nature, the Forecast Funnel reminds the forecaster of the position of WRF as a meteorological input and of the importance of organizing one's approach

to forecasting. Check, check, and recheck are the name of the game. Internal consistency is an absolute must. Just like in top-down structured programming, the forecast effort is also top-down in an effort to follow the energy from the long-waves to where it disturbs the atmosphere over the forecast area. One soon realizes that if one does not have a good handle on where the current weather-producing features are one will probably not have a good handle on where they are going. The Forecast Funnel makes a forecaster systematically assimilate data from the largest scale down to whatever scale is of interest, in our case, the Mesoscale. Each piece fits and builds on the other. This part of the analysis/forecast process cannot be overemphasized, if for no other reason than the organization it provides to the forecaster and his line of reasoning.
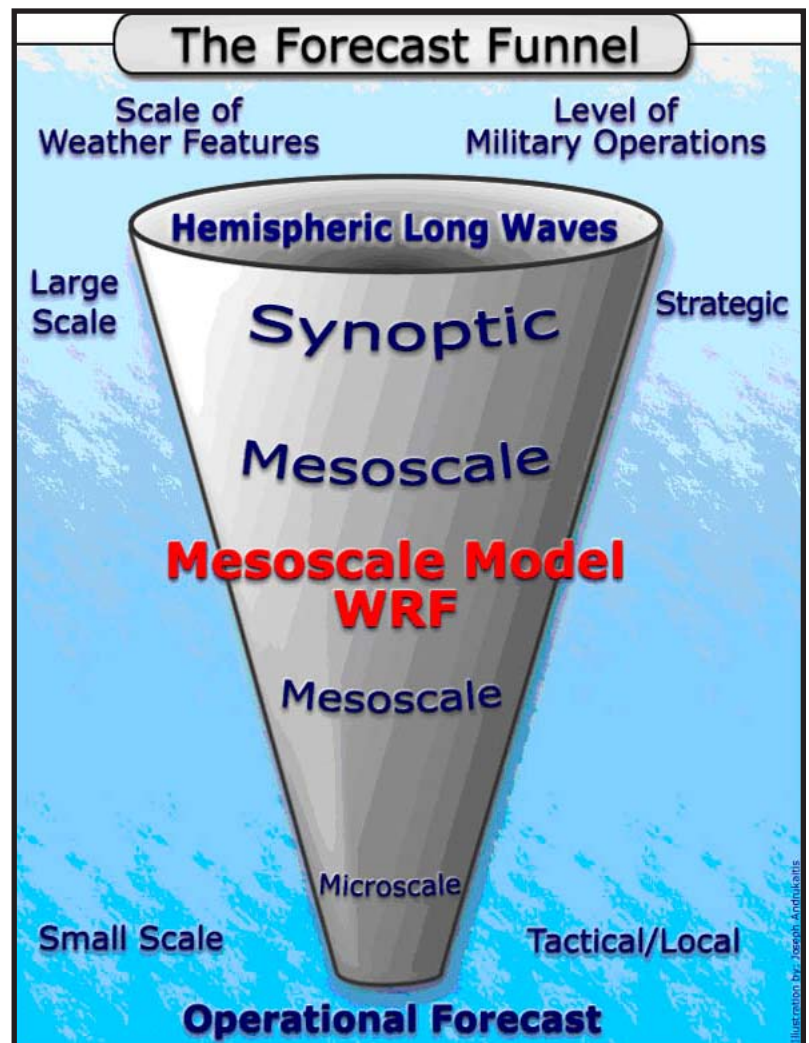

Figure 3. The Forecast Funnel.

14

a. The Hemispheric Scale. It all starts at the top, that is, at the hemispheric scale. This is where one determines where the energy resides. Working in the diagnostic mode allows one to determine where the railroad tracks of the upper air are going to steer its included energy. Determine the location of the long wave troughs and ridges. Are there any blocking patterns; is the flow split; what is the orientation of the features? This is the fundamental area to thoroughly examine because it forms the basis for everything else down-scale.

The pressure-height lines form the railroad tracks for the all-important polar jet stream. They also form the path for the smaller scale systems (synoptic features) to follow. With the general circulation being depicted by the long-wave flow, one can get a quick idea of the basic flow over an area of interest. Is it zonal or is it meridional? Is the area of interest in a trough or in a ridge axis? Where is the jet stream in relationship to the area under scrutiny? Is the forecast area on the left side of the jet stream or on the right side of the jet stream—as you stand with your back to the wind in the Northern Hemisphere? Where are the height falls and rises? Where is the vorticity curl? These are just a few memory joggers to get you started. The 250-mb, 300-mb and 500-mb (the meteorologist's friend) charts, et al, will help shape the forecast funnel as one heads toward a point or small area forecast. See Figure 4 and Figure 5.

This upper level flow can take on characteristics of its own. When the upper level flow is consolidated (a broad belt of westerlies), the primary concerns are the amplitude and propagation speed of the imbedded long wave troughs and ridges.

The term low zonal index is used to describe a hemispheric flow characterized by the presence of four or five large-amplitude waves. These long waves do not move very much nor very fast. Conversely, a high zonal index is characterized by a high speed, low amplitude long-wave pattern. In this situation, the long waves are usually progressive.

There are times when the upper level flow becomes very complicated. This occurs when there is a "split" in the flow, i.e., the flow is divided into two branches with both branches carrying a significant amount of the available energy. These episodes are called blocking patterns. There are
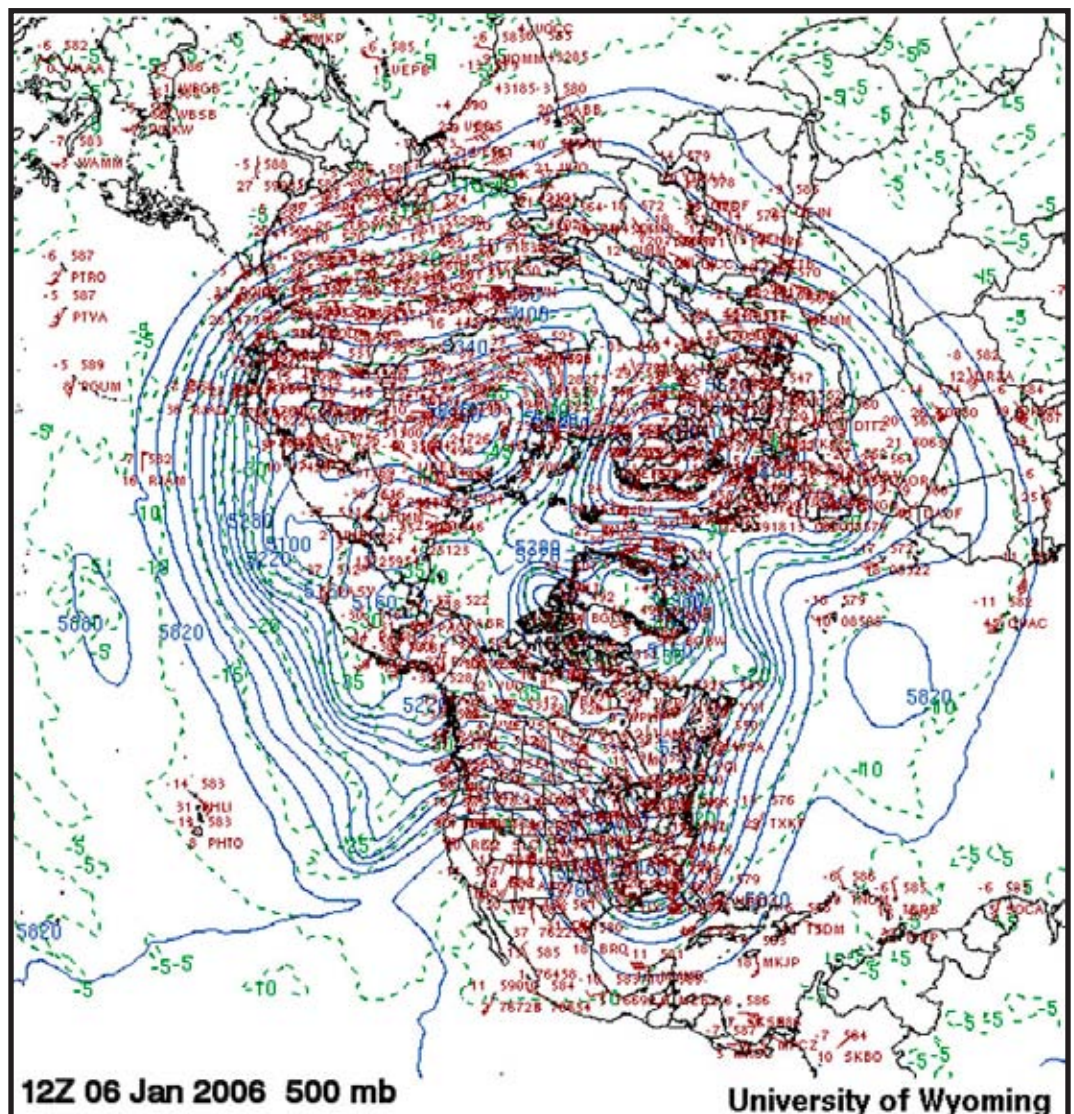

12Z 06 Jan 2006 500 mb   University of Wyoming

Figure 4. Standard 500-mb Plot.

15

various categories of blocks, and it is left to the reader to research these on his own. However, one should always remember that blocking patterns are always very persistent (greater than seven days) and result in the migratory systems (synoptic scale) being forced to circumnavigate the associated warm high or closed cyclone.

Examination of these levels will no doubt bring out favorite characteristics that a forecaster can 'hang his hat on' as the forecast process evolves downward in scale (Figure 4; Figure 5). Note: After a year or so of forecasting, you, as a forecaster, will find/discover some feature in one of your data fields that will stand out above all others, like a peg. Watch for this, because in time, this peg will become the place where you can "hang your hat on," i.e., the security blanket that you depend on to make your forecast. We all have one, whether we want to admit it or not. It's your focus from the Forecast Funnel.

Features do not change very fast at the hemispheric scale. A great diagnostic tool, one can successfully use persistence as a first guess for the twenty-four hour forecast. Forecasts made at this level are generally reliable from three to five days. One can easily determine the pattern of the westerlies (mid-latitude and above). A quick check of the animated 500-mb or 300-mb height chart along with a corresponding animated satellite chart will do much to help find weather-producing energy. This is especially true for the migratory systems that are active in the westerlies at any particular time. The cloud analysis (Figure 6) provides a means of determining how well the model is handling the major features by a straight comparison to the model output. It may not correspond exactly to
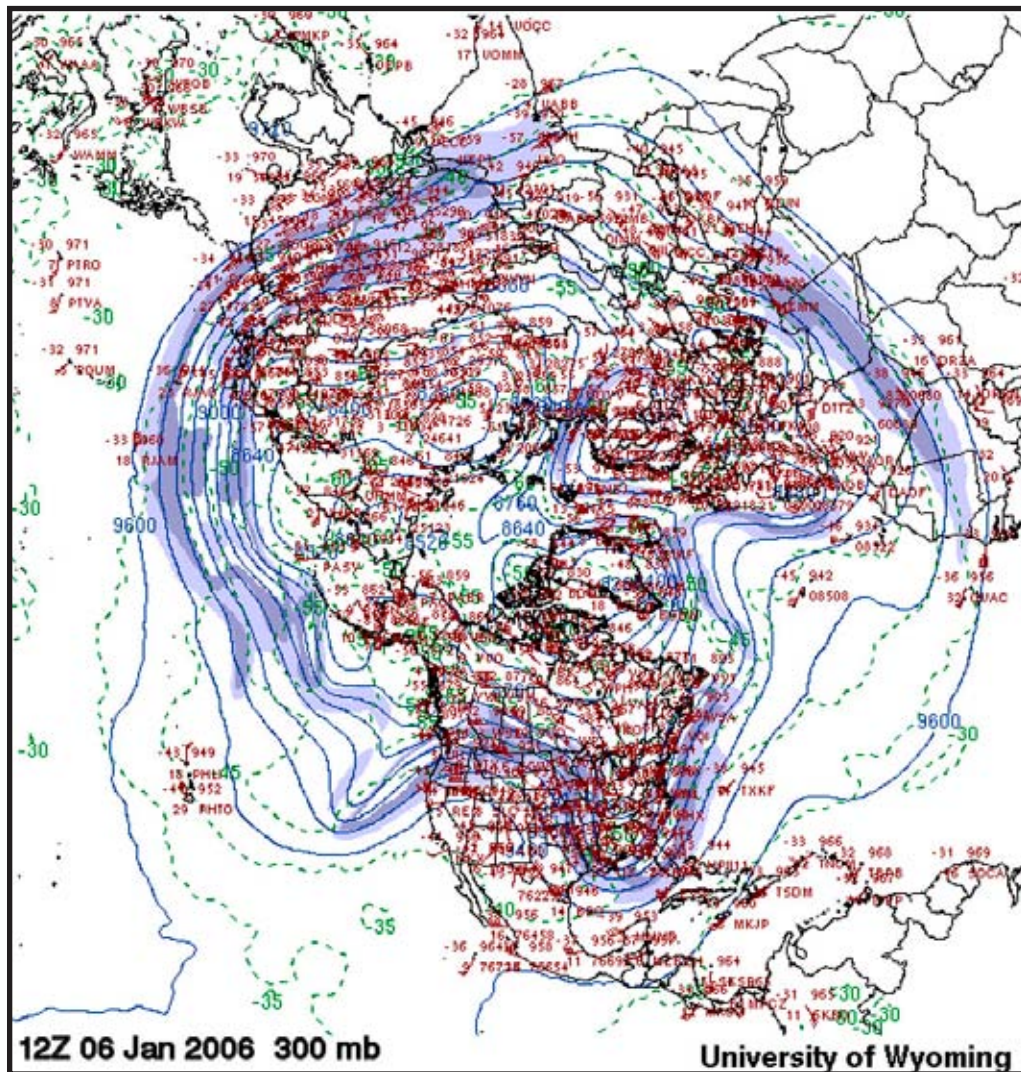
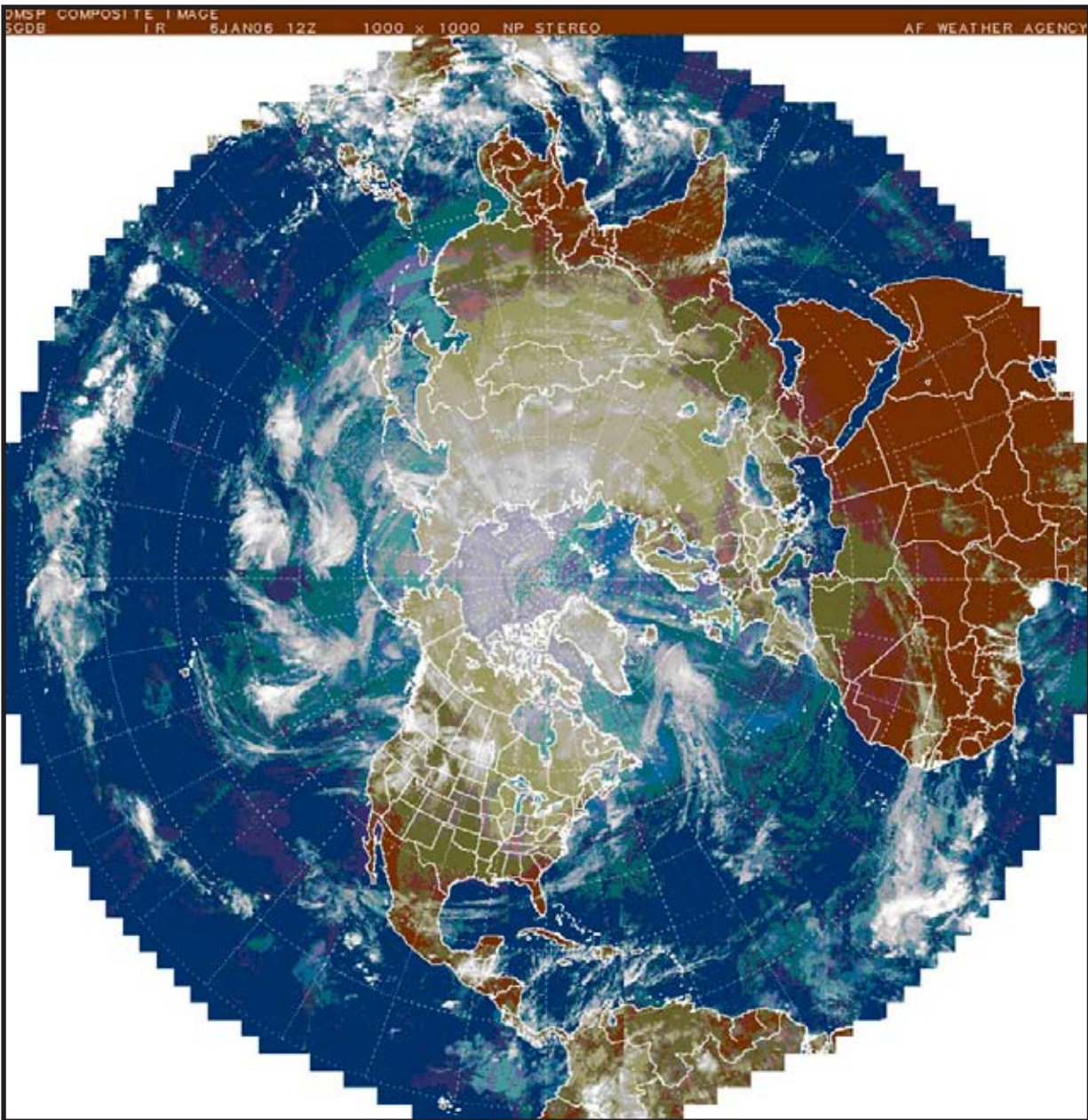

Figure 5. Standard 300-mb Plot.

Figure 6. Hemispheric Cloud Analysis. A "bowling ball" cloud analysis shot of the Northern Hemisphere. When animated, these can provide an excellent continuity for initialization purposes.

the time, but you should be able to find one that is close. Be flexible. Apply imagination and basic training—the clouds are where the energy is/was, depending on the time of the observed satellite shot.

One thing is for sure: change is inevitable. A stationary (actually quasi-stationary) pattern means not much movement in the near future. The upper air orientation over the point of interest won't change much so any energy producers will be synoptic scale transients in the hemispheric flow. These flow patterns can maintain themselves

for several days. Progressive waves move things forward across a forecast area of interest. Things happen when this occurs as the hemispheric waves move from west to east. The change in orientation can bring on troughing or ridging and the associated broad weather patterns that both bring. There will undoubtedly be a transition between the two as the inflection point moves across the forecast area. One must watch these transition zones for potential weather formation. Hemispheric waves will occasionally retrograde by moving from the east toward the west against the prevailing westerly flow. A tip-off that this will

17

happen is when a strong short wave (synoptic scale) transfers energy into the back side of the long wave, allowing part of the long wave system to move east while a new part of the long wave builds to the west. The new long wave position is west of the original position. A significant amount of energy is required to make this occur, hence there is plenty of energy to cascade down the energy pike and produce weather, in this case, frequently explosive cyclogenesis, as the upstream shortwave intensifies.

This first input into the Forecast Funnel is a very important one because it clearly identifies what is driving the synoptic scale feature and identifies the framework within which the migratory systems will evolve. It is a diagnostic process and requires careful consideration and study of all the atmospheric variables the forecaster can find!

b. The Synoptic Scale. Some of the devil in the details will begin to come out at this point. One can search for the migratory short wave troughs and ridges that are embedded in the hemispheric scale flow. Many surface features will become apparent at this point, including surface cyclones, anticyclones, frontal systems, squall lines, etc. Jet stream locations with their associated jet streaks are of primary interest to forecasters, because these are the energy packets that cause upper level divergence. This is a good place to fit the latest MetSat imagery satellite data into the equation. It will help you find the location of the jet stream and serve as a jumping off place for where the energy will be tomorrow. Analyze the satellite data as per the standard cyclone model—it is good enough until someone comes up with a better one.

It is at this point where one begins to drag some of the information from the larger scale down to the smaller ones. The Synoptic Scale is smaller than the Hemispheric Scale but can use a lot of the same data. For example, the suite of hemispheric upper air data can be analyzed for a continent/theater and further information extracted from them. The Synoptic Scale continues the boiling down and focusing process, always looking for the energy that is causing today's weather, where it is now, where it will be tomorrow. Features move somewhat faster at this level than at the

Hemispheric. Effective forecast time drops from several days to the 24- to 48-hour range.

Things to remember while preparing the Synoptic Scale part of your Mesoscale input are pretty well the same as they were for the Hemispheric Scale. Foremost is: "Where is the energy that is causing the weather today?" It doesn't hurt to go diagnostic for a while longer. Knowing the current location of weather-producing energy is crucial to figuring out where it will be tomorrow or the next day. Note that it is still fairly difficult to locate Mesoscale features, but the focus is sharpening. The *synoptic scale* features will tell a lot about how the atmosphere is shaping up over the next few days. Forecasters will want to look at things such as surface high and low pressure systems, frontal systems, extra-tropical cyclones, short-wave troughs and ridges (especially at the 500-mb level), wind shifts, cloud patterns, and the list goes on forever! There is a lot to look at! And the big question is: "How is it all going to evolve?"

One can't overestimate the importance that the diagnostic (initialization) portion of this forecast development plays. It started at the hemispheric scale and continues at the synoptic. The synoptic scale is rich in diagnostic tools, some of which have already been mentioned. Here are just a few:

- Surface and Upper-Air Objective and Subjective analysis
- Cross-section analysis
- Satellite imagery
- Soundings
- Wind Profiler data
- Lightning data and large area radar summaries

Note that the overlap between scales continues, and even at this point is starting to lean toward the smaller scale. One could even look at some numerical weather prediction (NWP) outputs at this level to get an idea of where numerical guidance would like to move some of these features. It is certainly necessary to relate the various weather features to the large scale pattern and determine if they will affect the forecast area. Remember the "peg" you identified earlier? Is it still a square peg/square hole fit? If so, press on!

And still the diagnosis continues. The information just keeps coming in the form of surface data and upper air data. Raw observations need to be processed (initialized) into the forecast data base. When time series of these products are examined, they provide an effective means for tracking the observed changes in fronts, jets, cyclones, cloud bands, etc.

This is the time to start checking the NWP analyses. They are, by definition, largely objective, and, for that reason, are a great input to your forecast. As mentioned before satellite data are very good and timely for this effort. However, don't make the assumption that the machine is always right. Challenge it! Do a hand analysis to determine if it has missed a few small kinks (mesoscale features) in its analysis. Even a partial hand analysis is useful. Make the time to do it. It will compensate for poor model initialization, difficulties with the physics in the model (such as flux rates, latent and sensible heat), and any other little glitches that may work themselves into the forecast process.

With all the weather data now digitized, it is a simple matter to overlay analysis, satellite data, PIREP data, and large-scale radar data, as a matter of building meteorological consistency. Forecasters will soon find out that there are too many products to successfully process manually and that they will have to turn to the machine for help at some point along the way. This is especially true of model initializations where the machine has ready access to many more observations than the forecaster has. They still need to be checked, and here is where the forecaster has a tremendous opportunity to determine if the model is headed in the right direction or not. If the diagnostics are bad, the output will be worse: Garbage in, garbage out, was never truer!

So what does one look at? That depends on the level of interest. At the Tropopause/Jet Stream level, one would look at the 300-mb (Figure 5), 250-mb and 200-mb levels. Most units would probably use the 300-mb level, but the other two levels are useful and contain a lot of jet stream information as well, especially in the subtropical and tropical regions. Things to look at on this level may include but are not limited to the following:

- Long wave troughs and ridges
- Jet axes (50kt or greater)
- Isopleths of geopotential height
- Pressure height falls and rises
- Areas of advection (cold or warm)
- Any tendencies toward ageostrophic flow

Moving on down to the 500-mb level (Figure 4), one comes to basically the middle of the atmosphere as far as mass is concerned. There are many features at 500 mb that can be useful in diagnosing the current state of the atmosphere. Things to look at on this level may include but are not limited to:

- Major troughs and ridges
- Short wave troughs and vorticity maxima (both positive and negative vorticity advection)
- Isopleths of geopotential height
- Areas of geopotential height change
- Jet axes (50 knots or greater)
- Isotherms
- Areas of moisture (can include relative humidity)

If you remember correctly from your dynamics classes, the 500-mb level also contains the all-important *level of non-divergence*. This is defined by the Glossary of Meteorology as: "A level in the atmosphere throughout which the horizontal velocity divergence is zero." Although in some meteorological situations there may be several such surfaces, the level of non-divergence usually considered is that mid-tropospheric surface that separates the major regions of horizontal convergence and divergence associated with the typical vertical structure of the migratory cyclonic-scale weather systems. Interpreted in this manner, the level of non-divergence is usually assumed to be in the vicinity of 500 mb. *The assumption of such a level in theoretical work facilitated the construction of early models in numerical forecasting.* The concept is still valid today and allows the forecaster to do a sanity check on any sized scale model.

More diagnostics can be accomplished for the 700-mb, 850-mb and 925-mb levels. Each can be

analyzed for the following:

- Isopleths of geopotential height
- Isotherms
- Isodrosotherms (Dew Point Isopleths)
- Areas of moisture/relative humidity
- Low-level jet (850 mb), 30 kts or greater

Data are data, and there is a lot represented at each of these levels. Ideally, one should use it all. Time constraints will limit the amount of time the forecaster has to spend on each of these levels. Remember, the machine has looked at these during its initialization process. However, artificial intelligence has not advanced far enough yet for it to draw conclusions about the advection of a moisture/thermal field at 850 mb.

Until recently, much of the information included with the surface analysis was lost during the modeling process. This has now drastically changed. The WRF is able to use surface data as part of its initialization effort and hence for the first time, inputs from the surface are coupled/integrated into the model. Some items to include from the surface analysis include but are not limited to:

- Fronts, troughs, and confluent zones
- Pressure centers and pressure value
- Dry lines/Squall lines
- Bubble highs/outflow boundaries
- Moisture ridges (including advection patterns)
- Thermal ridges (including advection patterns)
- Isallobaric analysis (surface pressure rises/falls—pressure tendency)
- Significant tropical features, such as tropical cyclone formation alerts, tropical depressions, tropical storms, hurricanes, typhoons
- Radiation/moisture fluxes (machine analyzed)

Cross-sections provide a superior means to assimilate data in the vertical. Weather features of interest that fall between the cracks of standard constant pressure and isentropic surfaces do appear in a coherent manner in vertical cross-sections. One of the more effective applications of the cross-section diagram is a plot of the constant potential temperature surfaces (also known as isentropic surfaces). These allow one to visualize the true three dimensionality of the atmosphere. Unlike isobaric surfaces, which usually represent a nearly constant altitude, isentropic surfaces can and do slope greatly. Since many atmospheric processes are approximately adiabatic (isentropic), airflow actually moves along isentropic surfaces. This can make it easier to infer three dimensional motions. For more information on the use of isentropic products, refer to AWS TN-87/002, *Isentropic Analysis and Interpretation.*

c. Satellite Imagery. Satellite Imagery was not always available to the forecaster. The strategic surveillance provided by these eyes in the sky probably marks one of the largest changes from old-school to modern meteorology. Satellites are relatively new, not coming into routine operational use until after 1982 or so. By animating the cloud series, one has an efficient way to quickly locate the *weather-making features* and obtain an initial sense of the intensity trends of weather systems. These almost ideal diagnostic tools allow for following continuity and can give forecasters a first guess for an otherwise data-denied forecast area such as a war zone. They also play an important role in the verification of model analyses and prognoses. By examining satellite imagery, a meteorologist can determine if features of concern are located properly and/or propagating and developing at the rate predicted by a model. Numerous examples abound every day. Be flexible. Be creative. Data denied areas may actually have more information than meets the eye because of the satellite coverage in that area.

d. Soundings (RAOBS). There is nothing more comforting than having a full suite of plotted RAOBS when one reports in for duty at the weather station each morning. By now, all forecasters should understand the importance of being able to think three-dimensionally. The meteorological world does not stop with the surface map. Indeed, the atmosphere is much like a puppy, with the upper air part being the body of the puppy and the surface sensible weather a manifestation of

the effects of the puppy's tail. The old cliché is that the puppy always wags the tail, and not the visa of versa. Hence if the tail is spreading a particular kind of weather, you can bet the puppy is wagging it accordingly! It's what happens aloft in the third dimension that comes around to bite us, be it a thunderstorm, hail, freezing rain, or any of the other nasty elements of weather that the atmosphere can throw our way.

At the present time, balloon soundings are a twice a day happening, once at 0000Z and again at 1200Z. The data are useful for all scales of analysis and forecasting, even though this particular observational mode is normally considered "synoptic". They are very helpful when locating fronts, determining atmospheric stability, finding the height of the tropopause, and determining vertical wind shear. The inputs that we receive from them are used to produce both the constant pressure and isentropic analyses. Sounding data are probably one of the (if not the) most important raw meteorological data input that is used by our models (irrespective of scale) to determine the future state of the atmosphere. Their value simply cannot be overstated.

Most meteorologists will see and use RAOB data in the most common form of the Skew T-logP diagram (Figure 7). The Skew T, as it is generally called, is an emagram (temperature and logarithm of pressure as coordinates) with the isotherms rotated 45 degrees clockwise to produce greater separation of isotherms and dry adiabats. From the Glossary of Meteorology, we read: "On some charts the area so enclosed is directly proportional to the work done in the process…" These are referred to as "thermodynamic diagrams."
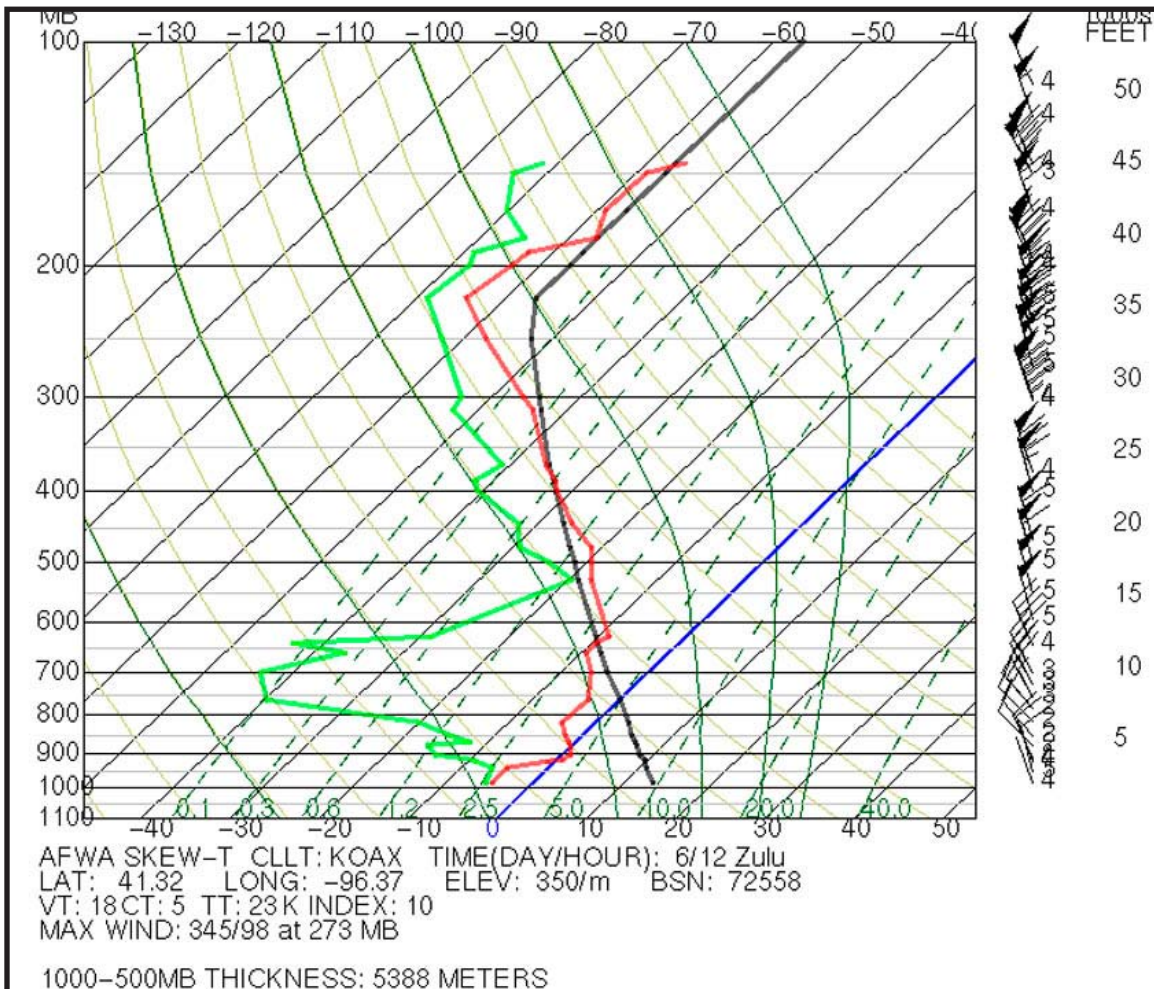

Figure 7. RAOB from Omaha, Nebraska.

Note how this representation provides an excellent summary of the atmospheric conditions in an atmospheric profile. In all actuality, however, the balloon path will fluctuate, and near the top of its path, it may be a considerable distance from its launch point.

As a tool for evaluating area stability, the Skew T is superb. Most stability indices such as the Lifted Index, K-Index, Total Totals, etc., utilize the information from the Skew T observation. By plotting this information across an area, one can obtain a good estimate of the stability of the various air masses one may have to deal with during a forecast period. (Figure 8) This product can then be used in conjunction with model data to compare the NWP model's instability (Figure 9 and Figure 10) with reality.
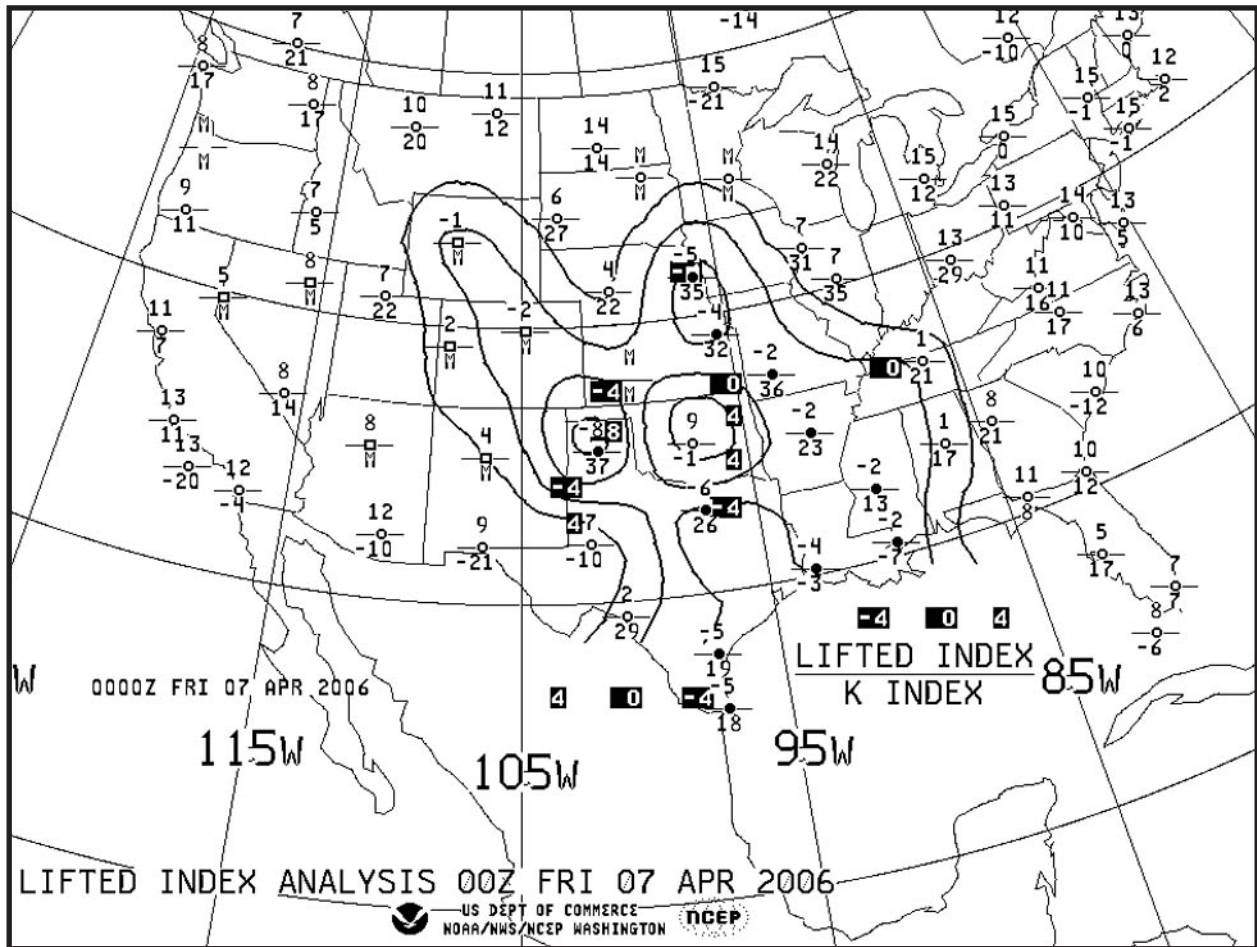

Figure 8. Lifted Index Analysis. Analysis of RAOB data for stability indices. In this case, the Lifted Index and the K Index are extracted from the RAOB data. This is an excellent sanity check on the model forecast.
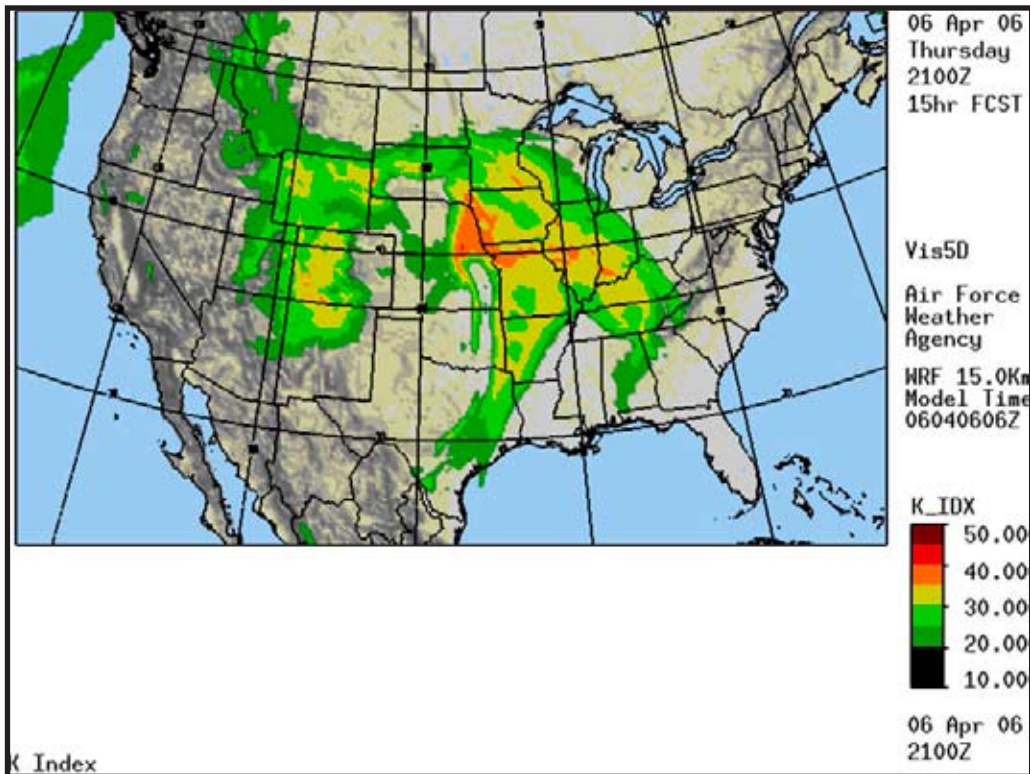
Figure 9. K Index Forecast. This is the WRF's version of how the K Index will change over time. This index can be "spliced" on to the analysis to get a logical progression of how the atmospheric stability will change over time.
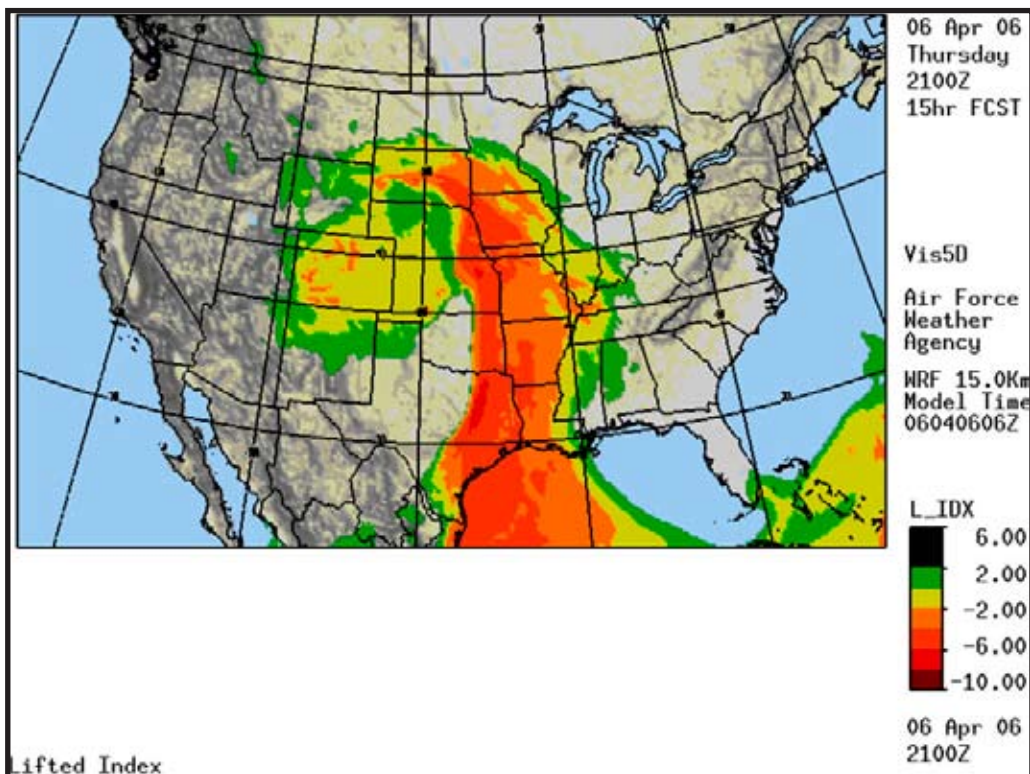

Figure 10. Lifted Index Forecast. The K Index and Lifted Index are forecast separately by the WRF. Color-coding helps bring out the details of the forecast very quickly. The model basically completes the forecast for designated time-steps. One can quickly focus in on the areas that are vulnerable to convective activity.

e. Wind Profiler Data. Wind profiler data is a relatively new and limited data source. See Figure 11. Its strength is that one has a vertical wind profile every hour. Utilizing Doppler radar and acoustic sounding techniques, these systems interrogate the atmosphere constantly, providing wind speed and direction in finite slices in the vertical. Their big advantage is that they can provide information of how the atmospheric flow is changing hourly. RAOBS can only provide this information every twelve hours. Unfortunately, once one travels outside of the central part of the United States, there are not many wind profiler sites available. Use them if they are available.
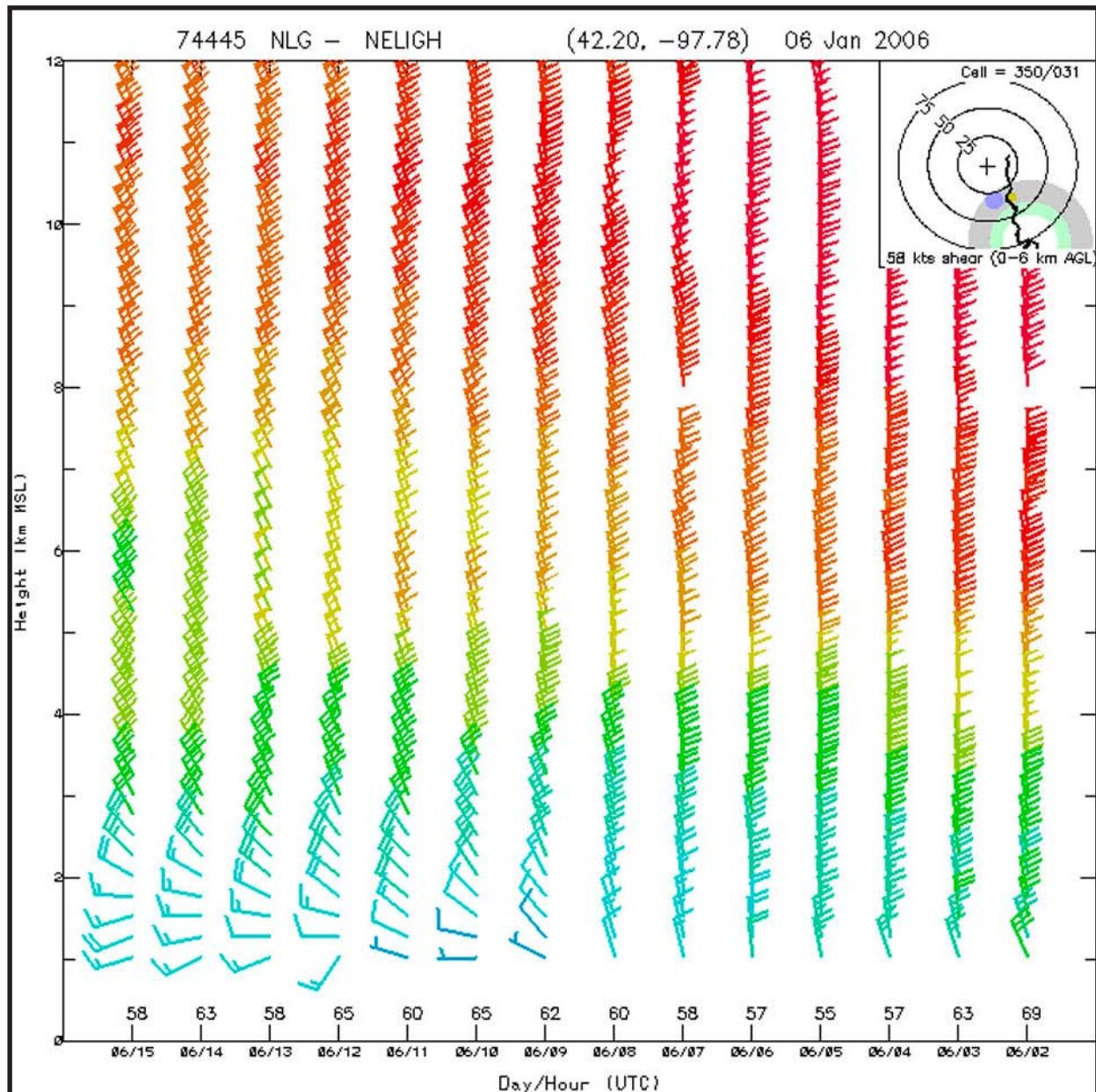

Figure 11. Wind Profiler Plot. A typical wind profiler output. Observations are taken on the hour. Equipment limitations preclude observations below 1Km. However, observations do provide a wind profile of the upper air between normal RAOB runs and are quite useful for tracking short wave features.

f. Lightning Data and Large Area Radar Summaries. In keeping with the Forecast Funnel tradition, it is always a good idea to look over as wide an area as possible for lightning strikes. These are available on the web (Figure 12) at many sites as well as JAAWIN. Large area radar summaries can show areas of potential stormy weather, especially when overlaid or cross-correlated with lightning strikes (Figure 13). Lightning and corresponding radar echoes show areas of instability—where they are now. Your job is to find out where they are going, once you get out of the diagnostic mode and into the prognostic mode.
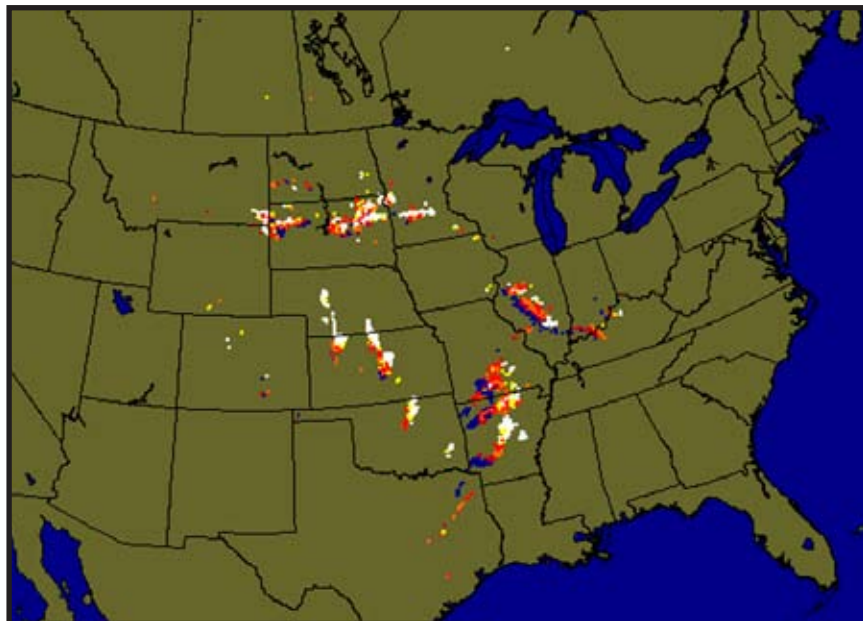
Figure 12. Lightning Plot. This diagram shows the real-time lightning strokes. It also can be animated and the resulting figure shows not only the duration/age of the storm cells but the movement of the storm cells as well. It is an extremely useful tool for mesoscale forecasting.

Figure 13. Large Area Radar Summary. The large scale radar reflectivity helps bring out the focus of what the upper air features are doing. An excellent mesoscale tool, this presentation will allow the forecaster to metwatch areas of potentially dangerous weather.

g. The Basic Conceptual Model **(Any scale).** Most of the models we use to express weather patterns are derived from the 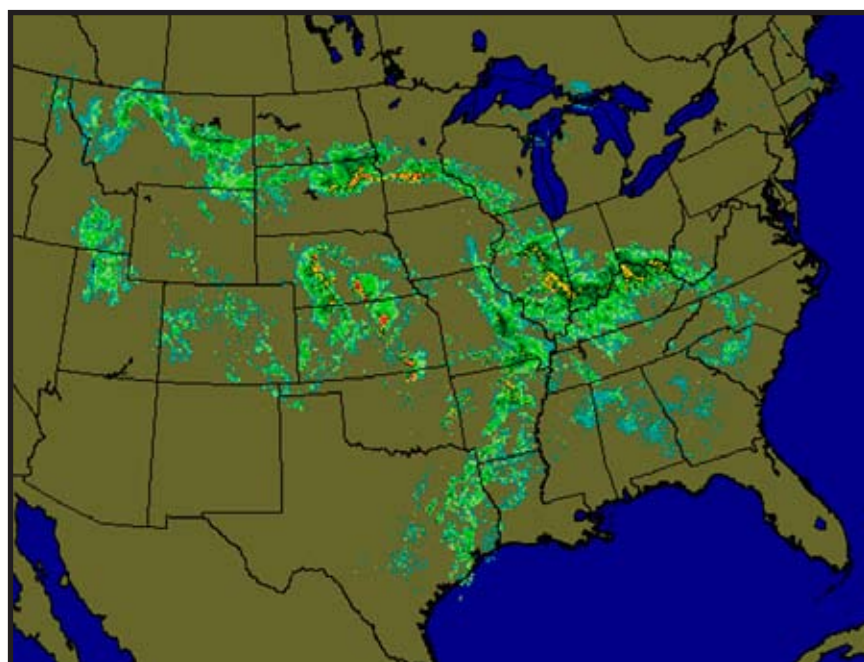Norwegian model proposed in the early 1900's. The amazing part of this model is that almost one hundred years after it was proposed, the meteorological community has done little to improve it, much less, replace it. Everyone agrees that "…it's no good…" (*Sic*), but it still waits for someone to come up with something better. Until meteorologists do come up with something better, go ahead and use it—it really works just fine! It is based on the hydrostatic assumption (discussed earlier) which, at the Synoptic Scale works just fine most of the time. It starts to break down at the mesoscale level and, indeed, WRF is an anelastic model. For the most part, the winds will adhere to geostrophic rules well into the mesoscale level. At any rate, meteorologists still have a full set of governing equations that help them understand the physical processes at work in midlatitude weather systems. They even allow us to capture some of the smaller scale features that a purely synoptic scale analysis and model would miss.

A stable wave (extra-tropical cyclone), for example, is certainly a synoptic feature. However, this system can harbor many mesoscale features (warm sector, squall line, MCC, derecho, etc.). Combine these with the juxtaposition of a jet streak (isotach max) and one has the three dimensionality necessary to apply divergence theory to cyclogenesis at any scale!

5. Mesoscale Forecasting.

We have very carefully defined the spatial and temporal extents of the Mesoscale Régime. This includes the divisions into its three subcategories as outlined in Table 1. Note that the list is not exhaustive but is meant only to give you a flavor for the types of features you will see at each sub-scale. Any feature you see that is smaller or lasts less time than meso-gamma is considered to be *microscale*. And, as mentioned before, microscale features include virtually all tornadoes.

It is critical to understand each scale, because each scale dictates a different phenomenon.

You can't mix scales! As mentioned before, you can model down, but you can't model up. Hence a mesoscale model will be able to identify atmospheric conditions that are favorable for the development of a smaller scale feature (such as a tornado); however, the model will not forecast for tornadoes. See COMET Module: How Mesoscale Models Work (http://meted.ucar.edu/mesoprim/ models/index.htm)

Knowing the horizontal resolution of the model is quite important. The word *resolution* here refers to the grid spacing in a model. Each NWP model computes a variety of meteorological parameters (such as temperature, pressure, winds, etc.) at evenly spaced or equi-distant points over a given region. Each of these points is referred to as a model *grid-point*. The grid-point spacing on AFWA's WRF is 15 and 5 kilometers. At this point, numerical prediction must accept a trade-off between the number of grid points and the available computer resources necessary to run a forecast for a certain time interval, say 72 hours. The more grid-points, the better the model resolution, and the longer it would take the model to run. Hence a grid system that has a mesh that is small enough to successfully forecast thunderstorms will, in all probability, not be small enough to forecast a tornado. With this in mind, we need to be careful to look at only weather events that are large enough to have sufficient grid points to provide adequate coverage. Which raises the very valid question: "How many grid points are enough?"

The first answer to this would be: "The more the merrier!" However, reality soon sets in when computer resources are purchased. This results in a model resolution that is a compromise between what the meteorologist would like to have and what resources will support. The area covered by the model (its *domain*) is a limiting factor that will continue to be an issue. We can make it very large with correspondingly large grid-point spacing; or, we can make it smaller with correspondingly smaller grid-point spacing. System limitations will be an issue for WRF planners for many years to come. For the immediate future, forecasters will have to keep the following in mind:

- What is the resolution (the grid spacing) of the model?

- What is the size of the smallest feature that the model can adequately depict?

•. What mesoscale features correspond to the size determined from Question 2?

Only when these questions are fully answered can you expect to obtain reasonable conclusions from the mesoscale model output.

As stated earlier, the AFWA WRF runs at 15 and 5 kilometer grid spacing. It uses the ½-degree GFS as the 15-kilometer Mother Domain. The vertical resolution is 41 levels and it is currently run out to 48 hours. These dimensions would certainly provide a forecast at the Mesoscale resolution. To get into the *microscale*, we would need a resolution of 400 meters (0.4 km) or less for grid spacing. Quite a difference requiring quite a boost in computer resources! Keep in mind that AFWA's WRF will have the ability to resolve only a certain level of detail. Hence there is a lower limit as to how detailed WRF will go.

Five Kilometer Coordinate Spacing   Fifteen Kilometer Coordinate Spacing

Five-fifteen Kilometer Coordinate Overlay
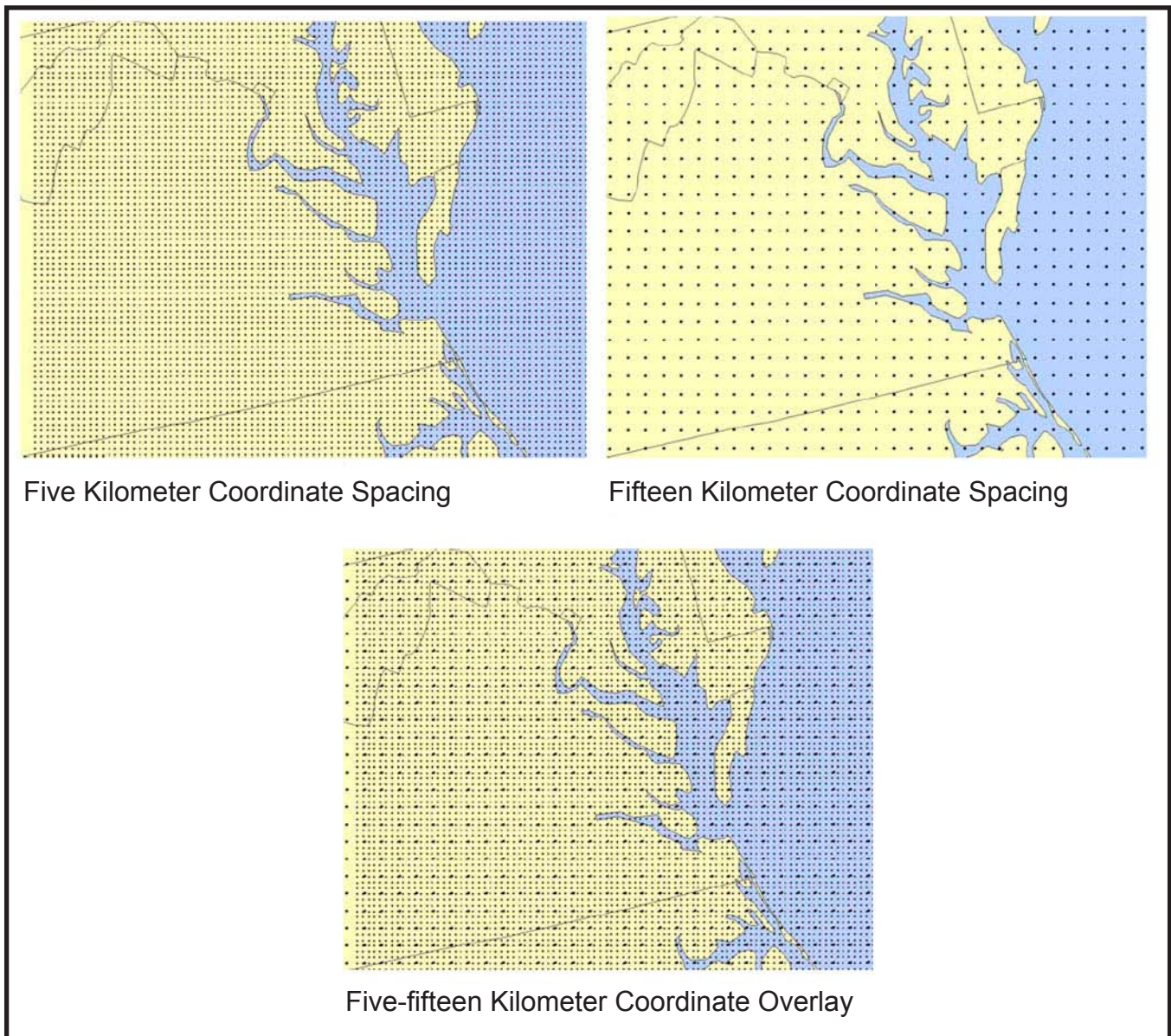
Figure 14. Comparison of Grid Spacings. This figure demonstrates the relationship between 5km and 15km domain size. Going from 15km to 5km will provide a much more dense network. as demonstrated by comparing coordinate spacing between five kilometer and fifteen kilometer. Note that such applications rapidly consume computer resources and will restrict the size of the domain substantially.

When you use model data, such as WRF, you need to know the horizontal resolution of the model data. The word *resolution* here refers to the grid spacing in a model. Each NWP model computes a variety of meteorological parameters at evenly spaced or distinct points over a given region. Each of these points is referred to as a model *grid point*. We always need to keep in mind to be careful to look at only weather events that are large enough to have sufficient grid points to provide adequate coverage.

This somewhat begs the quest of how many grid points is enough. For mesoscale weather phenomenon one would need a square area of 5 grid spaces by 5 grid spaces (25 square grid spaces) to cover a weather event at any time. Both the 5 km and the 15 km domains are therefore capable of resolving mesoscale phenomenon.

At 5 km, we can expect to resolve weather phenomenon that are 25 km by 25 km or smaller. This is getting to be a fairly decent resolution but it requires a lot of computer resources to run. At 15 km, the square expands to 75 km by 75 km, allowing us to resolve weather phenomenon that are larger yet still in the mesoscale (just barely).

Forecasters will need to keep all this in mind when making decisions regarding mesoscale model output. One must especially keep track of the following:

- What is the resolution (the grid spacing) of the model?

- What is the size of the smallest feature that the model can adequately depict (Remember to multiply the grid resolution by five)?

- What mesoscale features correspond to the size determined by question 2?

Only when you have answered all of these questions can you expect to obtain reasonable conclusions from the mesoscale model output. Take some time now to reflect on what this means in terms of the model's ability to identify different meteorological parameters.

6. Applying the AFWA WRF Model.

I am certain you have all heard the expression: "Software is software is software!" Although putting professional opinion at serious risk, much the same can be said for a numerical weather prediction mode…which is, indeed, software. There are differences in how data are handled, how computational instability is stymied, initialization schemes, grid spacing, etc. However, the intent of the model is to manipulate the atmospheric continuum in a CPU, project it into a future state, and reproduce it as a continuum. Every NWP works like this, there are no exceptions. Hence meteorological interpretation techniques that worked with the Global Spectral Model work with WRF. Vertical motion and moisture still produce cloudiness and rain. Wind shear still produces turbulence. Instability still produces thunderstorms and tornadoes. Granted, some of the products that the model generates may be different from what you remembered as a fledgling forecaster back in 1968, but the basic laws of the atmosphere have not changed since the days of Richardson's NWP effort back in the 1920's. The same energy equations apply; P still equals ρRT; the Coriolis parameter is still a problem; and upper-air divergence still causes rising air. Keep this in mind every time you examine a "new and improved" forecast package. The products produced can be interpreted just like the previous ones.

The basic question still requires that one finds **where the energy is now!** The diagnostic mode is often overlooked or slighted. However, it is during the diagnostic phase of the forecast that the all-important initialization takes place. And this initialization will tell the forecasters where the current weather-producing energy resides. After zeroing in at the synoptic scale, one can step down to the mesoscale region and begin looking for specific areas of upward vertical motion.

a. Determining Upward Vertical Motion (UVM).
Upward vertical motion is perhaps the single most important parameter a weather forecaster could look for. At the hemispheric scale, one can characterize broad-scale areas of UVM by locating the long-wave trough. Any areas to

the east of the trough (in the Northern Hemisphere westerlies) up to and including the apex of the ridge line are in an area of potential UVM. The atmosphere is certainly destabilizing in this area. But it is a very large area and other than serving as a flag for UVM potential, to attempt to nail down specific areas of overcast skies is very general at best. Enter the synoptic scale.

In the synoptic scheme of things, the short-waves, jet streaks, and areas of positive vorticity advection (PVA), just to name a few, become very important. They are the focus points for UVM and areas that will bear additional watching as these smaller migratory systems move through an area of forecast interest. They will intensify in the base of the long-wave trough, and de-intensify as they climb the ridge. But they are focal points for UVM

and for that reason are very important to watch. Enter the mesoscale.

The WRF will show focal points of UVM within the synoptic scale features (the energy cascade). The increased resolution will allow the forecaster to look closer at parts of the atmosphere that are rising more rapidly than ordinary synoptic scale action would suggest. An excellent product for this is available off JAAWIN (Figure 15).

This product shows isopleths of UVM (in cm/sec). Downward and/or neutral vertical motion is not shown to reduce clutter. This serves as a valuable tool in identifying those mesoscale locations where convection has the potential to develop. It also provides a picture of true upward and downward vertical motion, something that most previous
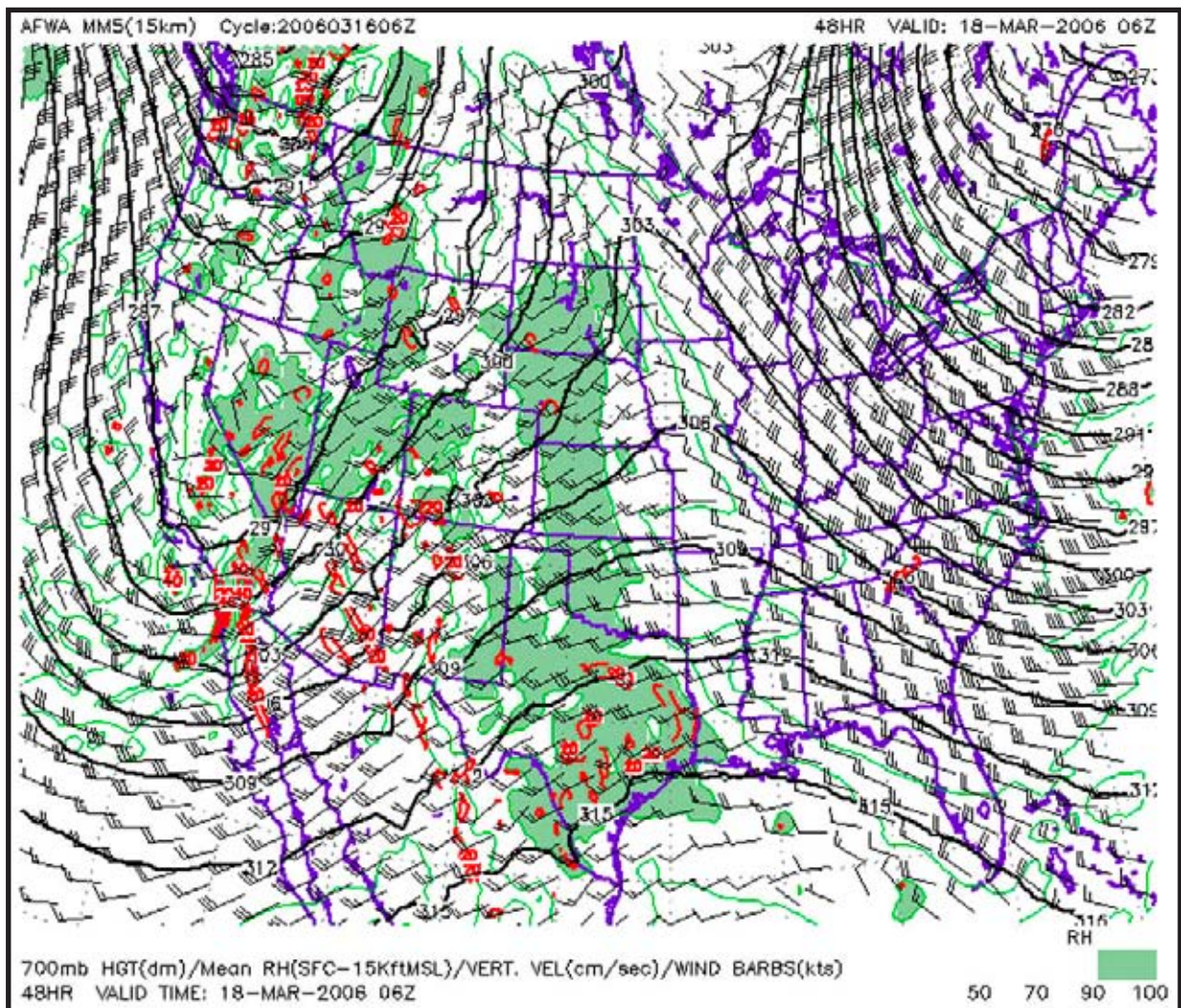

Figure 15. Wind Field, Moistue, and UVM. The wind field and the UVM will go a long way toward directing the forecaster's attention to areas of potential cloud/thunderstorm development.

29

synoptic scale models did not provide. The attempt here is not to calculate vertical motion indirectly but to show a direct representation of where the model thinks it will be happening.

Once one has determined the direction of airflow in the vertical and assessed its strength, the next important ingredient, that of moisture, comes into focus. Moisture is still one of the more difficult elements of weather to track. Moisture can be very discontinuous: if it rains, the moisture is gone out of the atmosphere, leaving behind large quantities of energy in the form of heat. The exact conversion is a matter of physics—how much is converted is a matter of atmospheric activity. Consulting precipitable water charts and analyzing satellite images for areas with water vapor content and/or areas of active cloud growth and decay can also be very useful.

There are follow-up questions that need addressing, e.g., will it rain? This age-old question will keep popping up again and again. Unfortunately, there are no hard-and-fast rules that one can apply. Most forecasters will look for the superimposing of UVM and moisture before they really start to look for rain. Note that this precludes showers and/or thunderstorms, which are entirely different genera. Sometimes, rules are made to be broken. Sometimes, there aren't any rules. An old rule-of-thumb for forecasting precipitation revolves around the 700/500-mb short wave pattern. Precipitation will begin when an area comes under the influence of the first third of uplift from the 500-mb trough, and the precipitation will end with the passage of the 700-mb trough. Clouds will break as the 500-mb trough passes through a region. This is a "peg" many forecasters "hang their hats on" when forecasting. If nothing else, the rule helps the forecaster logically assimilate all of the available information in an effort to make the best forecast possible.

b. Mesoscale Tools. Many of the tools that are important to rely on at the mesoscale level are some of the newer technology platforms for taking observations. Essential sources of data and information at the mesoscale include (but are not limited to) the following.

(1). Lightning data. Lightning data aid the forecaster in determining where the strongest vertical motion is located and are also helpful in assessing the movement, intensification, severity, and decay of any convection that may be present. (Figure 12). This product provides a near real-time display of lightning in the United States. Crosshairs plotted on the map indicate a lightning strike within a specified time range. This time range and total number of strikes in the current view are listed. The lightning strikes are time lapsed into six categories to assist in distinguishing lightning progression. The display can be "zoomed in" on specific areas of interest. When using this product, be cautious that the lightning strike product may be up to ten minutes old. Lightning sensors only detect up to 90% of cloud-to-ground strikes and no cloud-to-cloud strikes. The data are only provided over CONUS and have a spatial accuracy of 0.5 km.

Largely a diagnostic tool, lightning strikes can be followed and projected using simple persistence. The forecaster should have an idea where the thunderstorms are developing from the vertical motion outlined in the vertical velocity information above. With that in mind, here are some rules-of-thumb for using lightning data:

- 90% of all lightning strikes occur within 5 NM of the main storm cell.

- 9% of all lightning strikes occur between 5 and 10 NM of the main storm cell.

- 1% of all lightning strikes occur farther than 10 NM of the main storm cell.

Be especially on your guard when dealing with dissipating storms: they may no longer look threatening, but may contain residual electrification. Check the lightning chart for the last time there was a registered strike. The longer the time span the better! Wait for at least 30 minutes after lightning activity has ceased to be certain it is all out of your area.

(2). Doppler Radar. The WSR-88D is a marvelous mesoscale sensing tool to be sure. Running as a conventional radar or as a Doppler, this atmospheric interrogation tool provides diagnostic capability to the local area at the mesoscale. Rapidly updated information regarding the speed and direction of the local wind, along with detailed information on the areal extent and intensity of precipitation are a valuable input when building the local forecast. There are many available over the CONUS and the coverage is outstanding. Unfortunately, the remainder of the world does not enjoy such coverage. However, where available, the advantage of the copious radar data is that it can be compared with mesoscale model reflectivity forecasts. Note that the color scales of the WRF radar reflectivity forecast were designed to correspond directly to the WSR-88D base radar reflectivity products. Thus, the WRF forecasts of radar reflectivity can be viewed as a kind of forecast radar reflectivity image.

(3). Mesoscale Analyses and Prognoses. As the data gathering process continues, one is again faced by the age-old problem of putting it all together as a diagnostic so one can use it as a prognostic tool if by no other technique than simple persistence or advection. Both are valid, both work at the mesoscale. The analysis (objective or subjective) provides the means to organize the numerous observations available to the forecaster at the mesoscale. Using such analysis gives the forecaster an efficient method of monitoring patterns in the observed weather elements as well as producing derived fields. It is in the area of the derived fields that the mesoscale analysis
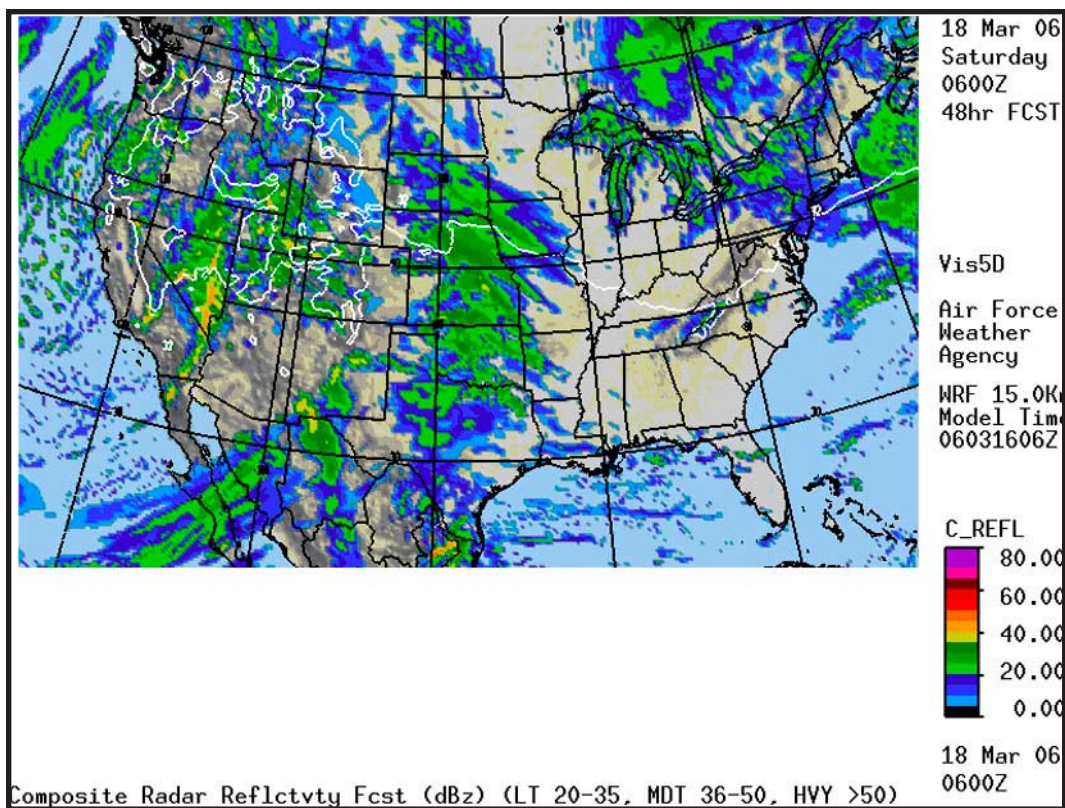

Figure 16. WRF Forecast Doppler Panels. The Composite Radar Reflectivity Forecast can be very useful in determining cloudiness for aircraft operations, e.g., refueling. When animated, this product can provide an idea of cloud progression that can easily be checked against corresponding satellite data.

and forecast really stand out. The forecaster can plot RAOBS for virtually any location in the area of forecast responsibility. The model can generate numerous stability analyses (indices), CAPE (Convective Available Potential Energy) fields, pressure tendencies, moisture and wind fields, etc. These analyses are extremely useful when monitoring rapidly evolving mesoscale weather events in the local forecast area.

The moisture and wind convergence (Figure 17) diagrams/plots are a great tool for alerting the forecaster to areas of potential vertical motion. The colorized regions indicate areas where there is a high combined value of both surface moisture and convergence in the surface wind field, giving the forecaster a best-guess location of unstable air. While this product is not a stability index (like Total-Totals), it has similar applications. Be aware

that this product only looks at the surface, and does not take into account the upper atmospheric parameters like inversions that would cause (provide) atmospheric capping.

There are a number of stability indices available through WRF. Old favorites such as the K Index, Storm Relative Helicity, Lifted Index, Total-Totals, etc., are there for the forecaster's use at the mesoscale level.

An interesting chart used to determine the potential for capping is the "Lid Strength" chart (Figure 18). In this product the higher values (>4.1) represent values that are expected to possess a stable layer; convection is not likely here. In regions that have a value from 2.1 to 4.0, convection is possible, but there is still a weak inversion in this area. Careful attention should be paid here
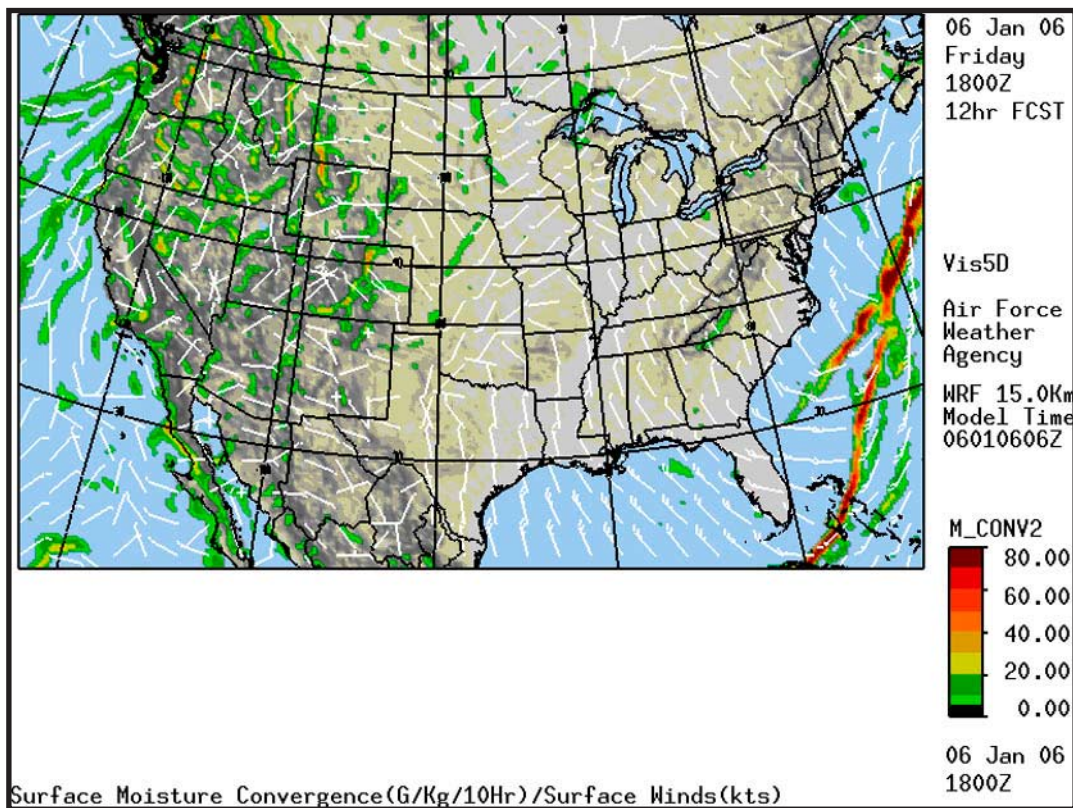

Figure 17. Surface Winds and Moisture Convergence. A combination of surface winds and moisture convergence serves as an excellent tool to alert the forecasters on areas of potential UVM.
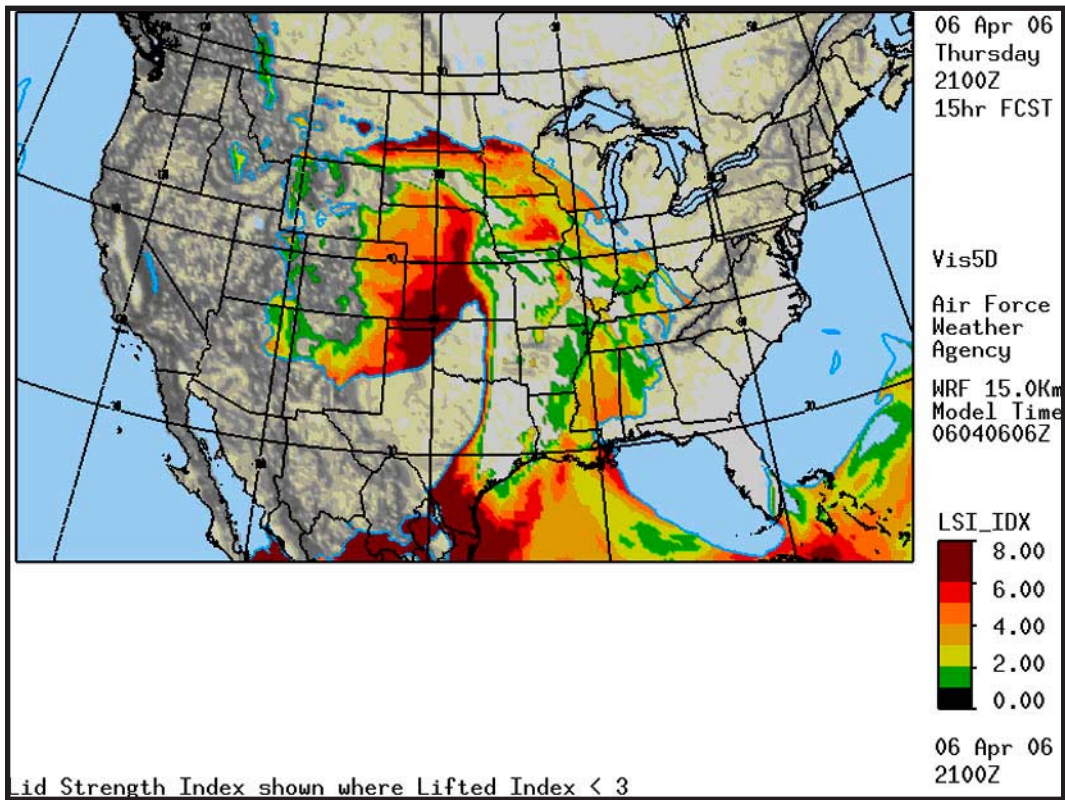
Figure 18. Lid Strength Index. The Lid Strength Index chart is yet another attempt to characterize an atmosphere in terms of its stability/instability. In this case, areas that are "capped" will not lend themselves to deep convection. Hence this is an excellent diagram for where deep convection should not occur.

since either a mechanical influence will be needed for convection to occur, or thermal advection (in the appropriate layers) is needed to break down the inversion. From 0 to 2.0, free convection is possible. A value between 0-2 Lid Strength is not a guarantee of convection preparing to take place because this product must be used in conjunction with a stability parameter. You must have an unstable air mass with a low Lid Strength to have free convection.

(4). Soundings. Perhaps one of the most important and primary tools in the forecaster's tool belt is the atmospheric sounding (Figure 7). Analyzing an atmospheric sounding (RAOB, radiosonde) will provide more information about the atmosphere and its vertical structure than any other piece of meteorological data. It is second to none and absolutely vital when assessing the current state of the atmosphere. WRF can

provide the forecaster with literally hundreds of these data points. They are extremely useful in the prognostic form because a forecaster can watch the atmosphere evolve right before his eyes. A quick check of the original data point will quickly tell you if the advection patterns make sense or not. Cold and warm air advection are quickly and clearly depicted in time. The amount of CAPE and/or CIN (Convective Inhibition) and their distribution, wind profiles, and the vertical distribution of moisture can all be determined from a single sounding. The conventional Skew-T diagram can be used to initialize other products from WRF, such as meteograms.

(5). Meteograms. Meteograms in WRF will look virtually the same as they did in the MM5 (Figure 19). No parameters will change. The forecast period is relatively short (48 hours). Anything past this time will have to come from an
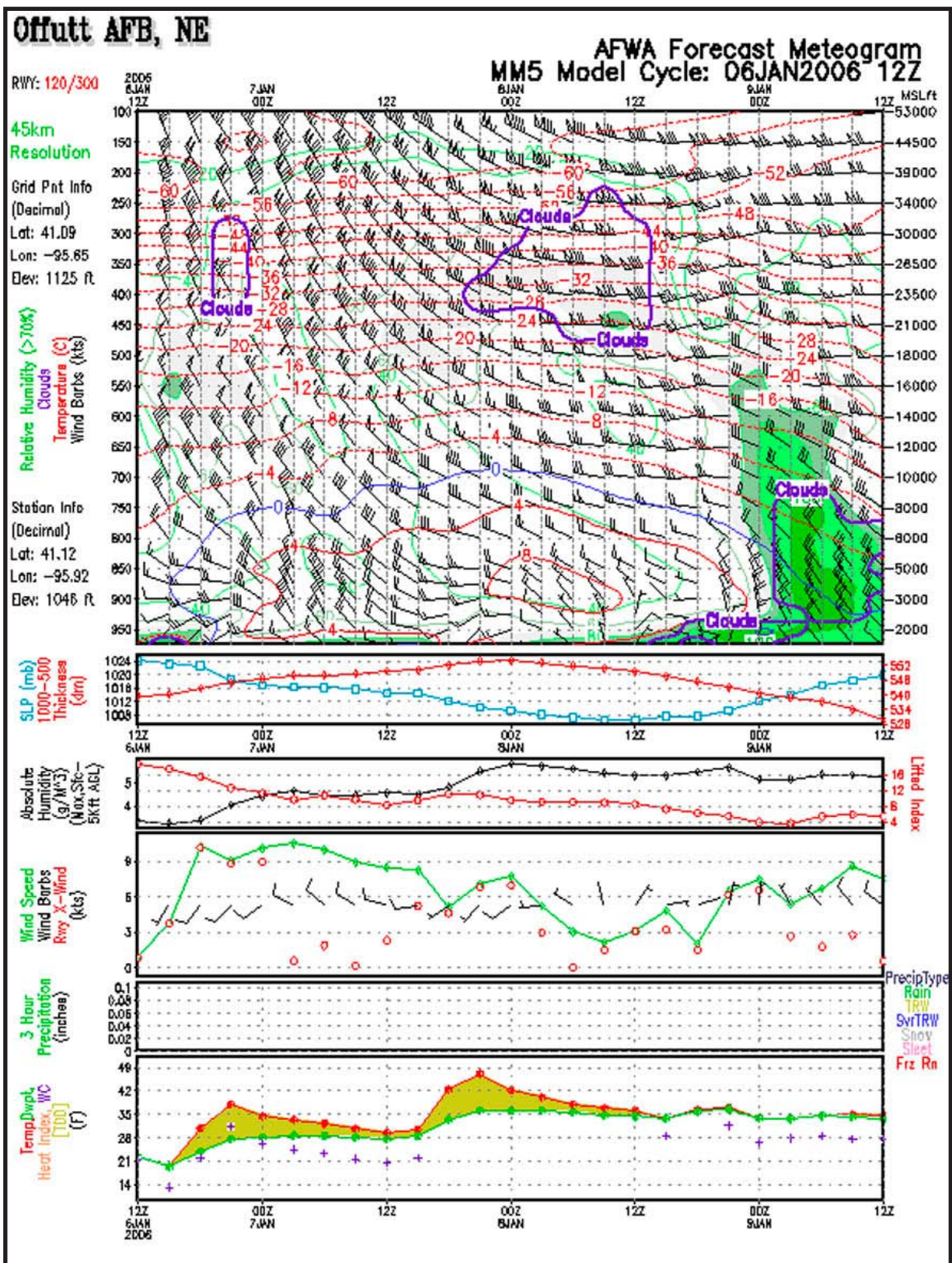
Figure 19. Meteogram. The meteogram contains a significant amount of information already boiled down and digested for the forecaster. The only problem is that its period of coverage only extends to 48-60 hours. At that point, if a longer forecast is desired, a forecast platform different from WRF will need to be consulted for extended coverage.

alternate model. The "stitching" process between WRF and the longer range model will present its own set of challenges. That issue will be covered in a future FYI and a COMET module. There are many meteograms available for locations worldwide. Most DoD sites already have a site specific meteogram.

(6). Wind Profiler Data. Some of the more interesting mesoscale data is, unfortunately, extremely limited. Wind profiler date (Figure 10) falls into this category. These data are taken by either Doppler radar or acoustic sounder and generate a vertical profile of winds through the atmosphere from near the surface to over 30,000 thousand feet. They provide hourly observations. As such, the wind information provided by profilers can be very useful when following the development and/or progression of mesoscale weather systems. Changes in the local vertical wind shear profile, as it relates to changing static stability and the possibility of severe convection, can also be followed with this tool. Wind profiler data can be used in conjunction with RAOB data to validate

the performance of the WRF meteograms that the forecaster uses to produce operational forecasts, since the meteogram gives a time series display of forecast winds. This comparison between the meteogram and the wind profiler information can be a quick and easy way of determining the accuracy of the model with respect to its handling of the dynamic state of the atmosphere.

(7). Local Topography. Knowledge of the local topography and its effects on sensible weather under various meteorological conditions is an important part of mesoscale forecasting. Proximity to mountains, hills, river valleys, deserts, and various bodies of water all have important consequences relevant to making a local forecast. Although topography is not a tool, it is an important consideration when forecasting due to its effect on the evolution of mesoscale weather events.

When considering topography, the forecaster needs to look at both the horizontal and vertical aspects of topography. **(**Figure 20**)**. This drawing demonstrates the impact of mountainous
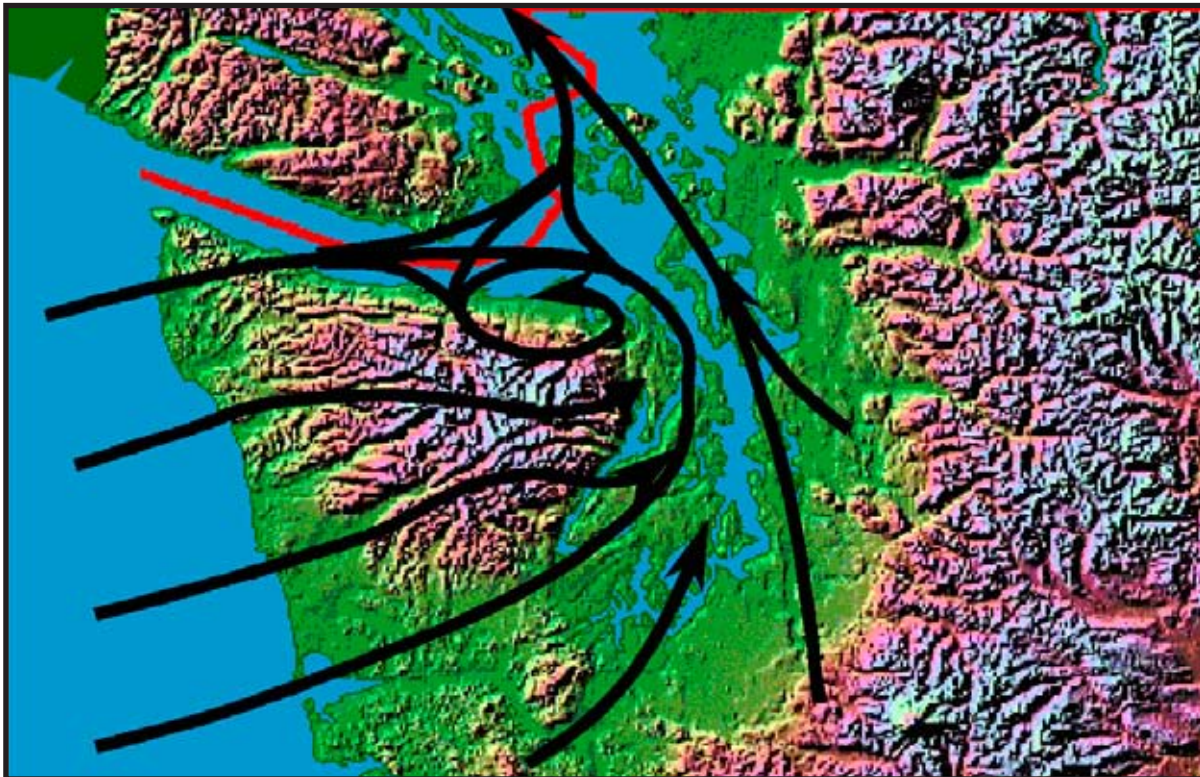

Figure 20: Surface Wind Flow, Puget Sound, Washington. This chart represents a conceptual streamline pattern over the Puget sound / Olympic Peninsula region under a prevailing southwesterly wind regime (Courtesy Angove, 1998).

topography on surface wind flow in Puget Sound in Washington. The effect of the mountains causes the wind to become south – southeasterly near Whidbey Island. In the vertical, mountains can cause radical variations in precipitation over short distances. Consider Figure 21 over the same area as the previous figure. On the windward side of the Olympic mountains, we see high relative humidity and precipitation, whereas the leeward side has drier air. This is due to the upward mechanical lift induced by the flow as it climbs the mountain-side. Clearly, a good knowledge of topography is a key towards a proper forecast at the mesoscale.

It is also important that the topographical database in the mesoscale model is accurate. For example,

a model can be run at 12 km resolution, yet only use a 36 km topographical database. If this is the case, then the model may likely fail to pick up on a key feature in the flow at the 12 km scale. The forecaster must be careful to ask these questions up front. Otherwise, incorrect conclusions will be drawn from the model output. See COMET Module: Flow Interaction With Topography (http://meted.ucar.edu/mesoprim/flowtopo/).

When considering topography, the forecaster needs to look at both the horizontal and vertical aspects of topography. The impact of topography on surface wind flow can be astounding. Winds can be channeled from one direction to another. In the vertical, terrain can cause radical variations
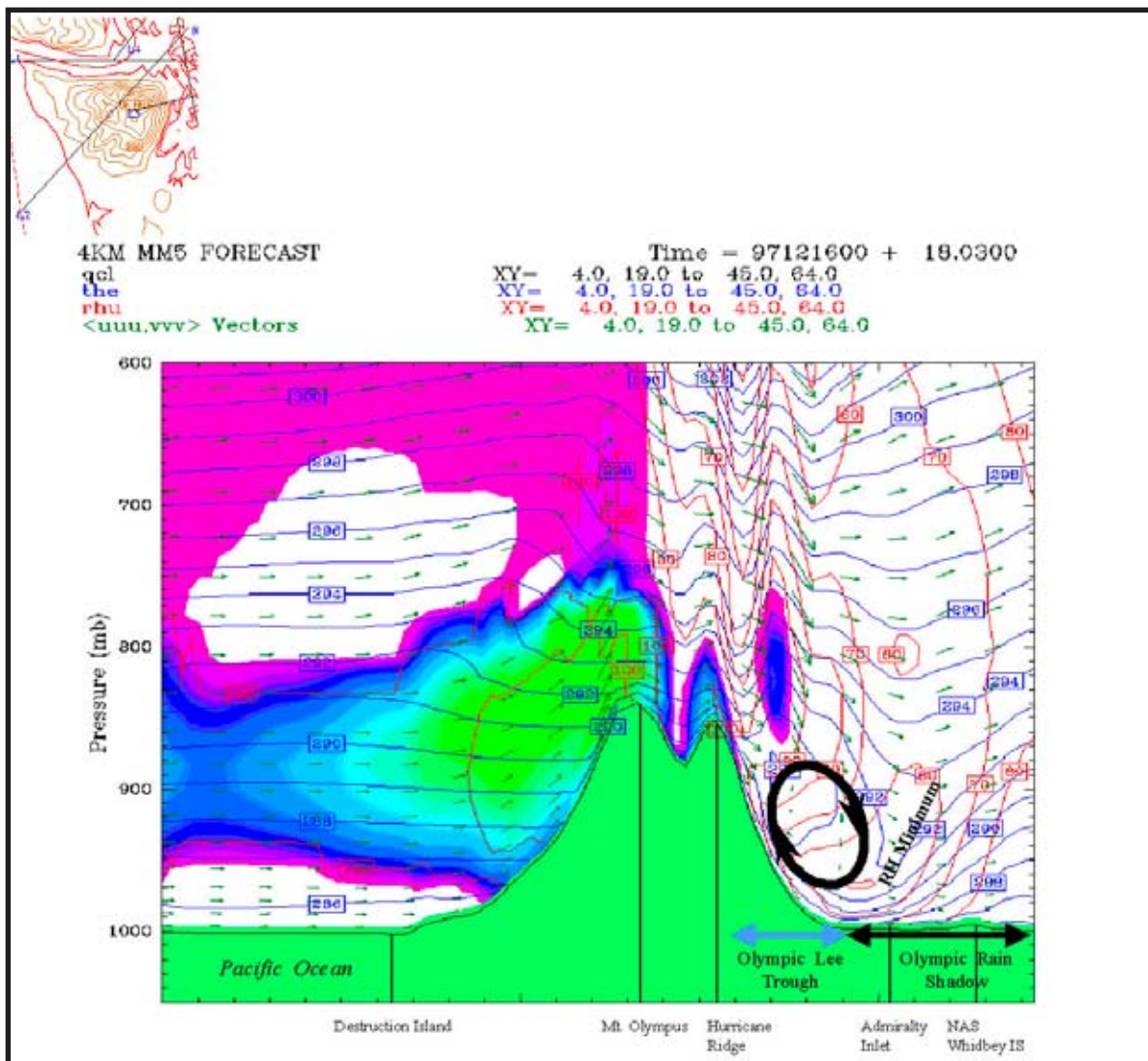

Figure 21: Example of Vertical Orographic Variations. Schematic depiction of the lee-trough and rainshadow effect of the Olympic Mountains during southwesterly low-level saturated wind flow. Gridded fields depict two-dimensional wind vectors, potential temperature and relative humidity. Shaded areas represent precipitation. Horizontal extent of the cross-section is shown in the insert immediately at the top of the figure. (Courtesy Angove, 1998).

in precipitation over short distances. Clearly, a good knowledge of topography is a key towards a proper forecast at the mesoscale.

c. Model Biases and Trends. It is still way too early to assess model biases and trends with the WRF. These will come with time. Biases can cause serious errors in forecast fields, e.g., stability indices. It will likely affect the location of fronts, precipitation, and other key parameters as well. Only time will tell.

d. Mesoscale Conceptual Models. There are numerous useful conceptual models at the mesoscale level. Some of the more common ones include (but are not limited to):

(1). Various thunderstorm structure models—Meteorologists classify thunderstorms as single cell, multi-cell, supercell, squall-line, etc. Each of these classifications implies certain characteristics, including the typical life cycle and the degree of severe weather likely to accompany the storm.

(2). Sea breeze circulation—The sea breeze and its associated land breeze are common phenomena that often play a significant part in the daily weather along coastlines and near large bodies of water. Grasping the conceptual models of onshore and offshore flows and their associated rising and sinking motions is vital to making a good forecast in such areas.

(3). Topographically forced flows and circulation—Many different conceptual models relate to the effects that mountains have on local weather. Examples include mountain waves, Chinooks, boras, canyons, and mountain and valley winds. Associated with each of these models are site-specific patterns of winds, clouds and precipitation.

(4). Banded precipitation—Banded mesoscale precipitation features are often observed in association with extratropical cyclones. Examples of such phenomena include cold-frontal and warm-frontal bands, warm-sector bands, and pre-frontal and post-frontal bands. Each of these precipitation band types can be related to the detailed conceptual models of the forcing and instabilities associated with extratropical cyclones. Significant rain bands are also observed with tropical features such as hurricanes.

(5). Mesoscale jets (includes low-level jets)—Two examples of mesoscale jets are the low-level jet that develops in the Great Plains in the warm sector of an extra-tropical cyclone, and barrier jets that develop along mountain ranges. The low-level jet is often instrumental in thunderstorm initiation in the Great Plains, and the barrier jets can play a significant role in the distribution of precipitation, especially snow.

(6). Local studies and flow—Insight into local weather phenomena can be obtained from on-station research projects. These studies can lead to the development of useful conceptual models pertaining to local forecast problems. One example of this might be studying the effects of different wind directions on ceilings and visibility at a particular site (Wind Stratified Conditional Climatology (CC) Tables).

7. Conclusion: A Concept of Operations (CONOPS) for WRF.

The WRF presents the military forecaster with a plethora of relevant and quite high-quality information. Forecasters actually have more information than they are capable of putting together into a useable package for their customer. How does the local forecaster squeeze/distill the maximum amount of pertinent information into a digested package of weather information that the customer uses for less than ten minutes to determine which weapons systems to use in an air strike? The following three-step package may be of use:

Step One: Properly analyze and forecast the hemispheric and then the synoptic environment. Where are the fronts in relation to the model analysis (Too fast? Too slow?). Are the analyses supported by satellite data? Does the flow match the general wind flow field? Are the model fields high or low compared to observational data? When, *and only when*, the forecaster is comfortable with the understanding of the hemispheric environment,

the synoptic environment, **and** has deduced the reliability of the synoptic models, then the forecaster may proceed to step two.

Step Two: Determine the mesoscale response. This is where the forecaster must transition into the mesoscale mode and must find the mesoscale solution to the synoptic scenario he has already deciphered. If not comfortable with the synoptic model depiction of the situation, this may be the final step before producing an operational forecast, since the mesoscale model output will be corrupt, and only serve to make the problem worse. However, if the forecaster is generally confident that the synoptic solution is reasonable, then proceed to step three.

Step Three: Compare expected mesoscale forecast with mesoscale model output; looking at the WRF output is the last thing the forecast does. More often than not, if the forecaster has done the first two steps correctly, WRF will only serve to confirm what the forecaster expects, and allow him to fine-tune some of the timing and structures as presented by the model. Occasionally, the model will introduce features that the forecaster might have missed in the first two steps, particularly in non-prevailing régimes. Again, the forecaster must be comfortable with the parent synoptic model before accepting the mesoscale structures, or modify that structure based on observed errors at the synoptic scale. This is a difficult and labor-intensive process, but it usually gets the "right" answer.

If correctly used, a mesoscale model can tremendously improve the quality of operational forecasts over complex terrain and other environments. Once the forecaster has become adept at mesoscale concepts (not a trivial issue), the key is to be able to confidently pick and choose when the model is going to hit. The forecaster must first invest in the understanding of the scales above the mesoscale environment before he can adequately use these tools to produce the desired product.

Bibliography

Ahrens, C. Donald. *Meteorology Today, 7th Ed.* Brooks/Cole, 511 Forest Lodge Road, Pacific Grove, CA 93950, 2000, p. 241.

Angove, M. D. *"A One-year Retrospective Analysis of the Mesoscale Modeling Initiative at the Naval Pacific Meteorology and Oceanography Detachment, Whidbey Island Washington"* (May 1998).

Brooks, Harold E., Doswell, C. A. III, and Maddox, R.A. Nov 1991. On the Use of Mesoscale and Cloud-Scale Models in Operational Forecasting. *Weather and Forecasting*, 7, 120-132.

Glickman, Todd S. *The Glossary of Meteorology, Second Edition*; 2000. American Meteorological Society, 45 Beacon St., Boston, Mass, 02108.

Kalnay, Eugenia. *Atmospheric Modeling, Data Assimilation and Predictability.* University Press, Cambridge. 2003.

Lin, Frank. St. Louis University, Class notes, CIRCA 1967.

List, Roland. University of Toronto, Quote. Date unknown.

Moore, J.T., "Isentropic Analysis and Interpretation: Operational Applications to Synoptic and Mesoscale Forecast Problems", *AWS TN-87/002*, Revised May 1989. Saint Louis University Department of Earth and Atmospheric Sciences, P.O. Box 8099 Laclede Station, St. Louis Missouri, 63156.

Ray, Peter. *Mesoscale Meteorology and Forecasting,* 1986, American Meteorology Society. Chapter 2: Mesoscale Classifications: Their History and Their Application to Forecasting. T. T. Fujita, pp 18-35.

Richardson, L. F., Quote, CIRCA 1922.