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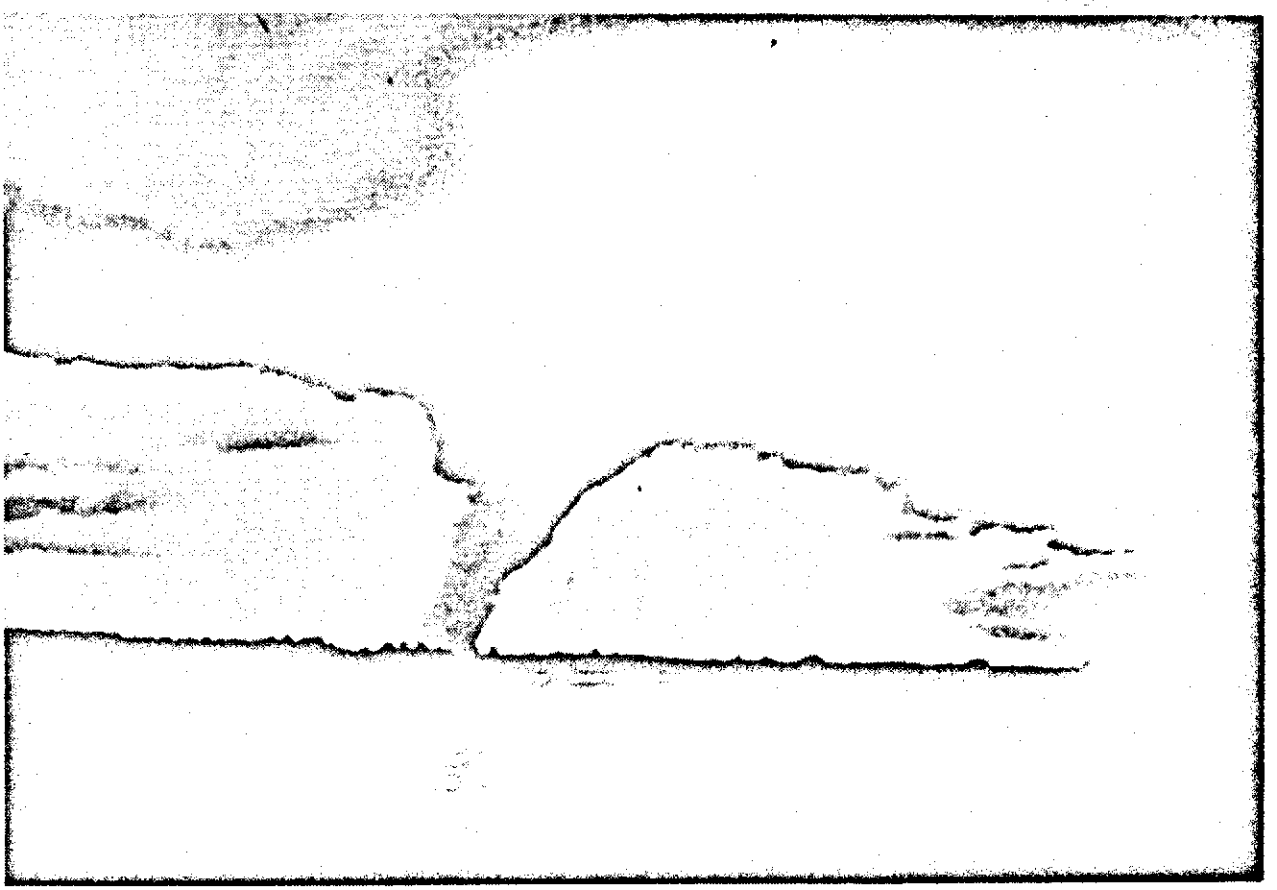

meteorological uses of the Synchronous Earth Observatory Satellite

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(NASA-CR-132937) A STUDY TO DEFINE METEOROLOGICAL USES AND PERFORMANCE REQUIREMENTS FOR THE SYNCHRONOUS EARTH OBSERVATORY SATELLITE (Wisconsin Univ.) ~~167~~ 170 p HC $11.50 CSCL 22B G3/20

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A STUDY TO DEFINE METEOROLOGICAL USES AND PERFORMANCE REQUIREMENTS FOR THE SYNCHRONOUS EARTH OBSERVATORY SATELLITE

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FOREWORD

With the proposal of the Synchronous Earth Observation Satellite (SEOS) by NASA, we at SSEC see an exciting opportunity to make a significant advance in mesoscale meteorology. It would be too optimistic for us to state that a large increase in the quality or quantity of data (which SEOS could provide) will produce a revolutionary improvement in the accuracy of forecasts. Progress in forecasting the weather is a gradual process. On the other hand, we can be certain that today's forecasting techniques coupled with better data will result in significant improvements. Further, we believe that with better data new analysis techniques, which we cannot now foresee, will be developed just as in the past.

Today a great gap exists in the area of forecasting the weather 0 - 6 hours ahead. We cannot acquire all of the pertinent data, we cannot assimilate what we have, and we cannot disseminate weather information effectively to the public. SEOS can fill much of this gap. SEOS has an enormous potential for mesoscale weather prediction.

If we are ever to improve our knowledge of the mesoscale, a start with an observing system such as SEOS must be made, just as the advent of TIROS and NIMBUS led to great improvements in macroscale meteorology. As GATE and FGGE begin to fill out our understanding of synoptic meteorology, interest must shift to the mesoscale. It is too important to ignore. Demand for data of the type SEOS can provide is evident now and will continue to grow. This demand will come from the meteorological science community and from the general public, which is most strongly affected by our lack of forecasting knowledge.

We wish to thank the many contributors to this report who provided such generous portions of their time and effort on short notice. Special acknowledgement should be given to Helen Loeb for the typing of this manuscript and to Sjef Vandenberg of the SSEC publications staff who was instrumental in its final production.

Verner E. Suomi

I. Introduction and Summary of Principal Findings

In the spring of 1973 NASA requested the Space Science and Engineering Center to study potential meteorological uses of a newly conceived earth satellite called SEOS, or Synchronous Earth Observatory Satellite. The basic system is depicted in Figures 1 and 2 taken from a recent SEOS feasibility study (Itek, 1973). The satellite consists of a 1.5-2.0 meter telescope in geosynchronous orbit, operated to make continuous observation of transient phenomena on earth. The basic purpose of the system would be to detect and predict hazards to life, property, or the quality of the environment, and promote proper exploitation and conservation of resources. The conceptual design envisions high resolution imaging in both the visible and thermal IR. Table I lists some of the anticipated uses of SEOS.

TABLE I

SEOS USES

- Forest fire patrol
- Crop disease watch
- Tornado watch
- Coastal shipping watch
- Coastal fog watch
- Ice packs on Great Lakes
- Iceberg patrol
- Location of forest perimeter
- Weather pattern observations
- Frost hazard watch

A document entitled "A Plan for the Observation, Study and Amelioration of Transient Environmental Phenomena" (NASA, 1971) describes the rationale behind the SEOS system. The point is made that the advent of weather satellite imaging significantly improved the detection and tracking of hurricanes, resulting in earlier warnings to affected areas and sharply reduced associated deaths. Similar technology, it is pointed out, is now available for observing smaller and more short-lived phenomena. These phenomena tend to undergo rapid changes, or are detectable only against a time variable background, so that they require nearly continuous monitoring with repetition rates from a few minutes to a few hours, and spatial resolution perhaps as good as 100 meters. One of the primary tasks of SEOS, for example, would be to monitor severe local storms and develop new methods of forecasting their movement and intensity changes. Such observations require a geosynchronous satellite containing a very large telescope ahead of the usual remote sensing devices.

SEOS CONCEPT

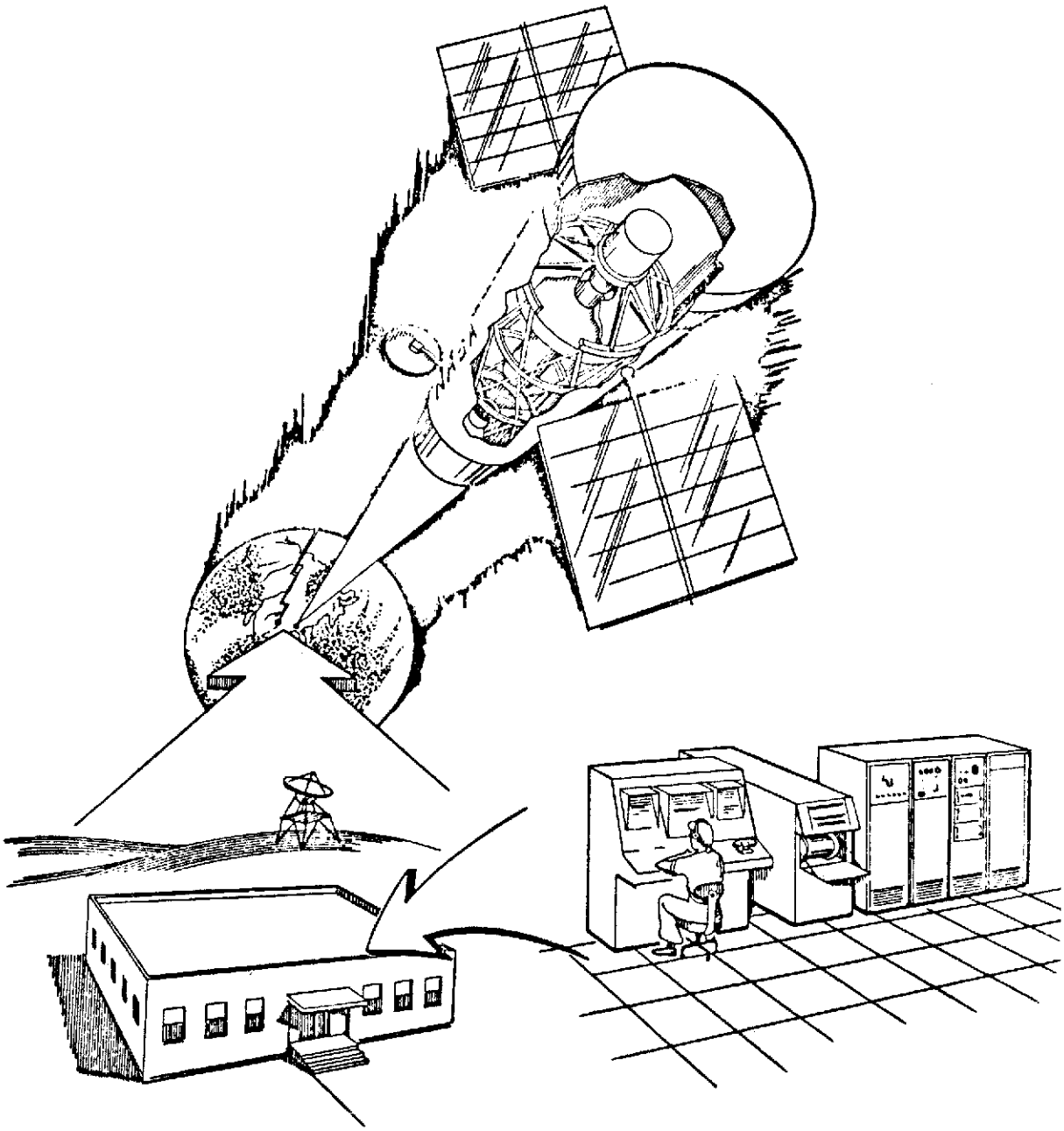
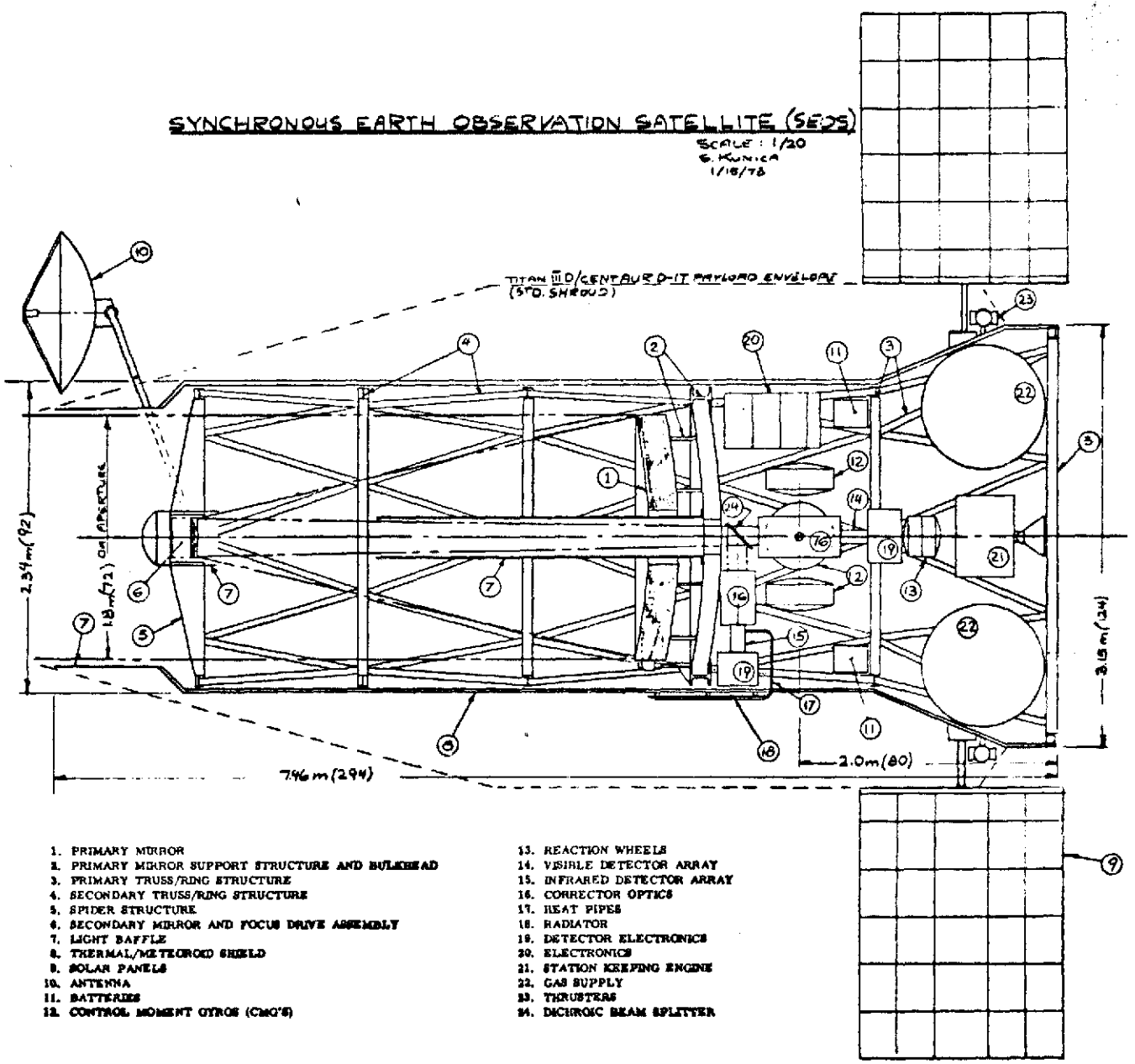


Figure 1

SEOS CONCEPT LAYOUT



1. PRIMARY MIRROR
2. PRIMARY MIRROR SUPPORT STRUCTURE AND BULKHEAD
3. PRIMARY TRUSS/RING STRUCTURE
4. SECONDARY TRUSS/RING STRUCTURE
5. SPIDER STRUCTURE
6. SECONDARY MIRROR AND FOCUS DRIVE ASSEMBLY
7. LIGHT BAFFLE
8. THERMAL/METEOROID SHIELD
9. SOLAR PANELS
10. ANTENNA
11. BATTERIES
12. CONTROL MOMENT GYROS (CMG'S)
13. REACTION WHEELS
14. VISIBLE DETECTOR ARRAY
15. INFRARED DETECTOR ARRAY
16. CORRECTOR OPTICS
17. HEAT PIPES
18. RADIATOR
19. DETECTOR ELECTRONICS
20. ELECTRONICS
21. STATION KEEPING ENGINE
22. GAS SUPPLY
23. THRUSTERS
24. DICHROIC BEAM SPLITTER

Figure 2

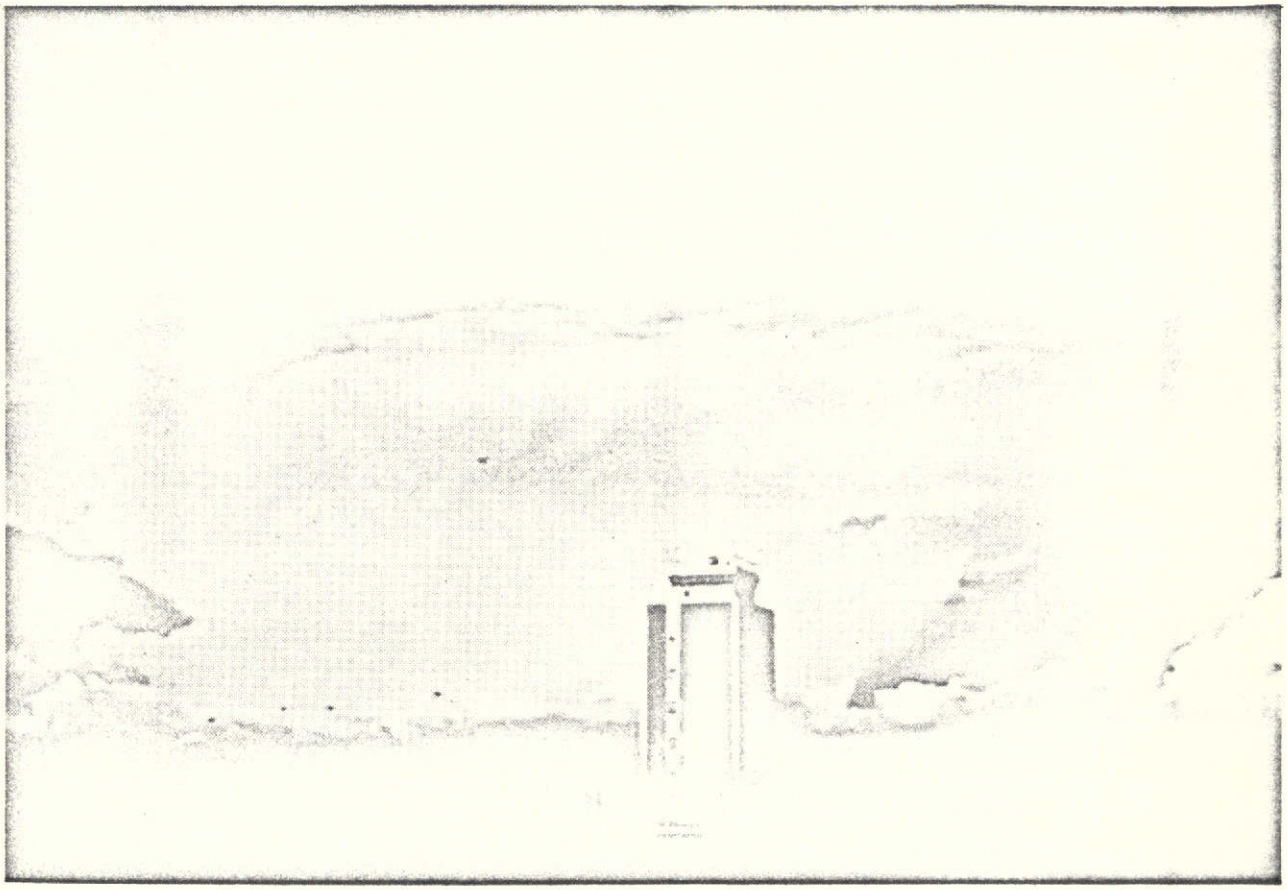


Figure 3. A well developed thunderstorm.

The 1971 NAS Report entitled "The Atmospheric Sciences and Man's Needs" concisely states the problem and points out the means of solution:

> Despite the fact that little predictive capability can be claimed for time scales less than 12 h ..., a significant fraction of atmospheric variability occurs on these smaller time and space scales. Tornadoes, thunderstorms, and other destructive storms are included here, but predictions are rarely sufficiently specific in terms of intensity, location, and time of occurrence. Terminal forecasts are made for aircraft, and probability forecasts are issued for severe storms expected to occur in large regions.... There are theoretical bases for understanding at least some of the important phenomena. Why then has short-range prediction not advanced as rapidly as has prediction on the synoptic and planetary scales? Two factors explain the situation.
>
> The first concerns the basic physics of mesoscale and microscale phenomena. There are severe mathematical and theoretical difficulties in developing general prediction models for these smaller scales. The time scales, are, of course, so short that the quasi-geostrophic relation between wind velocity and pressure

is not valid. Furthermore, many of the weather systems are fully three dimensional, so that the hydrostatic approximation which is essential to general circulation theory cannot be applied to the smaller scales. Gravity waves are ubiquitous, and their effects must be accurately represented. Change of phase in clouds must be included. Also, the boundary layer plays a crucial role in many weather phenomena, so that the effects of turbulence must be incorporated in successful models.

The second difficulty concerns the observations required to describe mesoscale and microscale phenomena. In many cases, differences are small and the required accuracy of the observations is correspondingly high. Also, the data required to describe these small-scale features are numerous, and the time available for processing, interpretation, and dissemination of results is short.

In the face of all these difficulties, can one realistically hope to improve short-range prediction? Indeed, there are several avenues that should lead to major improvements. For periods extending from a few minutes to perhaps 2 h some mesoscale features can be successfully predicted by simple extrapolation of present conditions and rates of change. In order for extrapolation to be useful, the characteristic time scale for significant changes of the phenomenon must be larger than the time period of extrapolation. Thus, an individual wind gust whose time scale is a few minutes could not be reliably predicted for longer periods by simple extrapolation.

The crucial need is to apply modern technology to describe the local weather as it occurs and to communicate the desired information immediately to users. At the present time, critical minutes or even hours often elapse between the time of observation and dissemination to the user. High-resolution satellite pictures often cannot be transmitted from data centers to users until days have passed. An important secondary benefit of a proposed Local Weather Watch would be to provide detailed quantitative data for use in research on mesoscale and microscale phenomena.

At the upper end of the short-range prediction scale ..., improvements can be made by adapting present numerical models to the mesoscale region. This has been done to some extent using models that admit internal gravity waves. They physics of these (mesoscale) weather features, especially their interaction with phenomena of other scales, remains largely unknown, and promising ideas are needed.

A third avenue along which increased effort should be channeled is the detailed analysis of mesoscale phenomena in their relation both to smaller-scale features and to the synoptic features in which they are imbedded. Technology provides measurement capability which has not been adequately employed on this problem.

The development of SEOS will stimulate activity in all areas of approach to the understanding and prediction of the mesoscale.

It was apparent to us, when asked to make the present study, that it would be impossible to investigate SEOS applications with either the depth or breadth desired. An indication of this can be seen in the number of contributors on the title page. We drew on a wide variety of talents and interests to save time. Nevertheless, despite a perhaps uneven result, we reached important conclusions concerning the worth of SEOS, and its unique application to monitoring mesoscale weather phenomena.

The mesoscale phenomena chosen for investigation in this study are not intended to constitute an exhaustive set of SEOS applications. Other areas deserving of study are listed in section IV-B, and more could probably be added. What has been selected, however, constitutes what we consider to be most important in the sense of the economic, social, and scientific benefits SEOS can provide to the public. Consideration of these mesoscale phenomena and their implications should in itself constitute sufficient justification for further development of both the SEOS satellite and the equally important ground support system. In our estimation, the question is not <u>if</u> SEOS should be built, but <u>when</u>.

Next to the climatic condition of prolonged draught, more total economic loss and disruption of people's lives and activities is probably caused by destructive storms and associated rain, hail, flood and tornadoes than any other kind of weather. Improved and accelerated warnings would permit greater protection of lives and property, eliminate waste, and generate more efficient utilization of resources. It would be possible, for example, in the areas of construction, agriculture, recreation, aviation, transportation, and personal activities of the general public, to achieve considerable savings of time, labor, money and materials. In the absence of adequate warning, these resources are now often wastefully committed to weather-disruptable activities. In addition, an accurate short-term forecast would allow savings in time and labor which ordinarily would be committed to unneeded protection of crops and property from the elements. It is difficult to put a dollar value on such savings, because it depends so much on the effectiveness of communication channels which must be developed and on the improved accuracy of short-term weather prediction. We can already see progress being made in both of these areas.

When SEOS is built, it will fit into a ready-made niche in the system, providing a source of information not now available through any existing or planned sensor system. When SEOS arrives, it will provide data of such improved quality and resolution, that forecasting and communication will be even further improved. There is no doubt that if such improved localized weather information were available through SEOS, people would put it to their considerable material advantage. From an aesthetic sense as well, improved quality, predictability, and control of environmentally associated human activities yields better and more satisfying lives. Ultimately, the decision to proceed in this direction rests with the wishes of the people, but in order to make wise decisions, they must know what is possible. We are confident that, as people become aware of what is technologically feasible, a strong demand for SEOS will develop.

In addition to the above-mentioned weather phenomena whose observation requirements justifiably occupy a large portion of this report, we

have added other socially and economically significant mesoscale phenomena: frost, clear air turbulence, lake and sea breezes, and local air pollution. These all have observation requirements necessitating higher space and time resolution than existing systems can supply. Yet the needed observations are surprisingly similar to those needed for severe storms. All the mesoscale phenomena examined here require good vertical resolution of the physical state of the atmosphere and a strong emphasis on measurements in the atmospheric boundary layer. SEOS has the unique capability to make such measurements, and to measure at the higher temporal and spatial resolution appropriate for dynamic description of the developing mesoscale phenomena.

Table II lists four important attributes of SEOS in regard to mesoscale meteorology. Because of these attributes, SEOS will permit prediction of small scale, fast developing weather phenomena in addition to monitoring.

TABLE II

UNIQUENESS OF SEOS FOR MESOSCALE FORECASTING

1. Improved Access to the Vertical Dimension
2. Fills Observation Time and Space Gap
3. Provides Accurate and Timely Forecasts
4. Complements Polar Orbiter and SMS Measurements

1. Vertical Dimension

The most important use of SEOS may not be xy, but z-axis resolution. SEOS should include an IR vertical temperature and moisture sounding capability in addition to daytime and nighttime imaging. The combination of imager and sounder, both of high resolution, is much more powerful than either capability alone. Adding the sounder obtains the temperature field (the driving force) along with the motion field. Thus it is possible to get at the dynamics of the atmospheric motion as well as the kinematics and to thus better identify regions of potential or developing danger before the hazards actually come into being.

Most large scale weather phenomena such as highs, lows, and fronts, are characterized by slowly developing horizontally moving air masses. These air masses change significantly only over periods of a day or two. The motion is practically all horizontal and along with the pressure field can be rather accurately predicted. The small scale weather phenomena such as squalls, thunderstorms, and tornadoes, derive from stresses developing from wind shears, localized solar energy absorption, sources of moisture, and the like, which tend to produce an unstable layering effect in the vertical direction in the atmosphere. In relieving those stresses, large quantities of air can move vertically and large quantities of energy can

be locally released. The energy density of such local phenomena can be very much greater than that of the large scale air masses, and thus we find that the localized atmospheric phenomena are often much more destructive of property and disruptive of our lives.

We must be able, with greater accuracy, to quantitatively determine the conditions in the vertical (the factors governing vertical stability) before we can predict if these localized phenomena will occur and whether large amounts of energy will be released in the atmosphere. Once this vertical development starts, we must be able to determine if the storms will intensify or diminish. SEOS, with the high radiometric accuracy which can be achieved by integrating as long as necessary from a geosynchronous orbit, can make soundings of high vertical resolution--especially in the lower troposphere, which is the crucial "trigger" region for most mesoscale phenomena. Polar orbiting satellites are not as efficient in collecting data such as this because they under-sample some areas, oversample others, and cannot continually observe a small spot on the earth for as long as necessary to observe the continual growth and development of small scale weather phenomena when they occur. High radiometric accuracy to better resolve the vertical structure plus the ability to continuously monitor changes in time is a fundamental observational improvement over what is available at present.

2. Time and Space Gap

The large scale air masses, because they develop over a period of days, are adequately parameterized by radiosonde soundings twice a day and averaging 300 km. between sounding stations. Planned or existing weather satellites such as ITOS, Nimbus, and SMS will continue to emphasize such synoptic scale observations by producing 300-400 km averages at 4-6 hour intervals. They are well suited to giving the large overall picture, and can identify regions of potential mesoscale activity, but are not designed to concentrate on small areas to obtain information needed to predict the location of actual storms, frost or heavy rain.

A substantial portion of severe or potentially hazardous mesoscale activity requires observations of much the same type and accuracy as is needed to model synoptic systems, but observation must be done at time and space resolution appropriate to baroclinic development of mesoscale systems. Mesoscale phenomena can develop, intensify, and die out in periods of one hour. To parameterize them requires observations in their immediate vicinity on time scales of 5-15 minutes, with ground resolutions of 20-50 km, and with quantitative instruments (such as IR sounders and high accuracy IR imaging) designed specifically to access the boundary layer and get very high vertical resolution. SEOS is uniquely suited for this purpose.

3. Accurate and Timely Forecasts

Use of diagnostic models for prediction is severely limited by the inadequacy of data. The models exist, but without data of the appropriate time and space density, the models cannot be used to full capability. SEOS is of greater potential worth than previously anticipated because it can be used to significant advantage in quantitative prediction as well as monitoring of the mesoscale. This is due primarily to inclusion of IR sounding

as well as imaging, which may permit identification of developing situations several hours earlier and increase the accuracy and lead time from prediction to the actual weather phenomenon.

With SEOS data, local forecasts of greater accuracy can be made, and at the same time the models can be refined and improved because SEOS also offers the means for comparison of the predicted weather with the actual weather. In addition, development of this mesoscale forecasting ability coincides with the development of the National Weather Service's Automation of Field Operations and Services (AFOS) and also of cable TV. The potential thus exists to disseminate the benefits of SEOS improved local forecasts to the general public in a timely fashion, i.e., in time to allow people to make decisions based on the information presented to them, and thereby reap the economic, social, and scientific benefits which justify SEOS.

A risk is involved here, however. When the public becomes aware of the fact that the technology for improved forecasting exists, the demand will exceed any that the science community could impose for research. The simultaneous development of both cable TV and AFOS will provide an information sink which could easily exceed SEOS' ability to collect data. The need to cover several hundred targets at once at 15 minute intervals per target imposes a measuring time of 5 seconds per target. Failure to account for this imminent change in public needs in the SEOS design greatly increases the risk of obsolescence before launch. Even if SEOS-A is planned for purely research purposes, it would appear incredibly foolish not to design it with its eventual public use in mind.

Lastly, it would seem, always comes ground data handling. For mesoscale forecasting, real time ground data reduction is absolutely crucial. Data gathering may in many cases depend on indirect inferences from other measurements and other systems, and be more of a data management problem than a data reduction problem. In addition, achieving adequately short recognition and response time in light of the many duties, complexity, and necessarily selective operation of the SEOS system is an area requiring much more detailed study. The value of SEOS depends on the data links to the ultimate user being effective. Furthermore, the information presented must be accurate, relevant, and timely, or the public will not use it. At the very least, we know that the job is complex and costly. There is little need for the SEOS satellite if we are not willing to spend the money to make SEOS benefits available to the public.

4. Complementarity

Polar orbiters have greater sensitivity because they are closer to the subject they are measuring. They must, however, measure when they are over the target, and then they are gone for 12 hours before they can look in the same place again. They can do a better job near the poles, which are passed more often. On the whole, however, a polar orbiter sees a mesoscale phenomenon once, if at all, and cannot follow its evolution in time. SEOS, in equatorial orbit, samples the equator well, but cannot see the poles. Being farther away from the earth, it needs a bigger collecting optic and longer integration time. It can, however, look as long as necessary to

achieve adequate signal to noise ratio. Furthermore, only the geosynchronous orbit permits the continual observation that gives access to the time domain at 5-15 minute intervals instead of 6-12 hour intervals. Thus, only a geosynchronous satellite like SEOS can give the correct combination of individualized target selection, high vertical resolution, and proper time and space sampling to adequately parameterize the developing mesoscale. It is therefore the ideal complement to the global coverage obtained by other satellite systems.

TABLE III

Instrumentation for SEOS

- Visible and IR Imaging
- IR Sounding
- Microwave Sounding
- In-situ Platform Interrogation

The instrumentation we recommend for SEOS is not unique. The techniques are tested and operational. They are shown in Table III. The instrument complement is perhaps a bit surprising -- especially the last two items. Visible and IR imaging were originally proposed. We feel that a single wavelength in the visible or near IR is adequate for high resolution (100 meter) and medium resolution (500 meter) imaging, and should have a variable format to utilize the information bandwidth efficiently. We desire IR imaging in several bands to get good altitude resolution of clouds, primarily to assist wind measurements from cloud motion.

The need for quantitative imaging must be stressed. After years of effort spent in analyzing weather satellite imagery, we have reached the stage where it is painfully obvious that the satellite sensors acquire data of quite high precision, but that we do not end up with the same high precision. In sending the data to the ground station, handling it, and storing it, the general method used in many cases is to run through several A/D and D/A conversions, enhancement curves, arbitrary and varied gain settings, and so forth, and then the final indignity of storage on photographic film, which combines the attributes of poor signal to noise, poor dimensional stability, and poor dynamic range. Since the end result desired is to use a computer for quantitative measurement and prediction, and since it is easy to calibrate and digitize on the satellite, and to store data on digital slant track tape, all the intermediate processes are superfluous as well as damaging. SEOS should be all digital and calibrated to yield the superb geometry and radiometry needed for accurate cloud motion and temperature measurements. One can always generate a time lapse motion picture film from the digital data. It is impossible to generate high quality digital data from film.

The need for IR soundings arises from the lack of any observing system now existing to provide a measurement of the temperature and moisture fields to high enough spatial and temporal resolution to permit mesoscale forecasting. The emphasis in satellite sounders up to now has lain in providing synoptic scale measurements for GARP. Mesoscale forecasting

needs far denser data point input than global atmospheric models do. The need for an extensive array of IR sounder channels is primarily due to the requirements for high vertical resolution of the temperature field in the lower portions of the troposphere. The determination of vertical stability --the presence of inversion layers and the identification of radiative or convective equilibrium--is crucial to parameterizing the development of many mesoscale phenomena.

It is important to identify the value of an IR sounding capability more precisely. With imaging, one can monitor storm development very well and keep track of what is happening. With adequate care taken during system design to preserve image geometry, pointing knowledge, and radiometric accuracy, one can obtain good quantitative knowledge of atmospheric motions and storm development. One can measure winds from cloud motion, storm development from cloud growth rates, and get altitudes from cloud top temperatures. Ground temperatures would also be well defined. One might, by use of such a monitoring system, gain 30 minutes warning time over what we now get from ground observations and radar. Imaging still deals with developed weather systems, however, and consequently observes things already happening.

In order to gain warning time we need to better understand the dynamics of mesoscale phenomena. Because these phenomena tend to be non-hydrostatic - non-geostrophic, "closed loop" numerical modelling of these phenomena has not yet been achieved. However, detailed information on the mass field, motion field, temperature field and moisture field in and about mesoscale phenomena make the use of "open loop" diagnostic models possible. As we gain a better understanding of the behavior of the atmosphere on the mesoscale, and through this gain a better qualitative predictive ability, we will also be in a better position to synthesize the behavior of the atmosphere on this scale and ultimately impose the quantitative aspects of the prediction process as well. Thus SEOS must be configured to give as much information on the structure and motion of the atmosphere on this scale as possible.

The addition of a microwave sounder arises from the need to determine the temperature field beneath cloud decks, as for instance in frontal systems or hurricanes. It turns out that a 2-3 meter antenna can provide 100-200 km ground resolution soundings beneath clouds in a time scale the same as that of IR sounding (a few seconds per point). If deployable solar panels that size can be built as part of SEOS, why not also a dish antenna boresighted with the telescope? The microwave soundings fill the time and space gap between radiosondes where IR soundings cannot reach.

The fourth "instrument" needed on SEOS is a capability to sample ground based sensors for P, T, ground moisture, water levels and humidity in data poor regions where ground stations either do not exist, are not close enough together, or simply do not make measurements often enough. The single most important tool to the mesoscale forecaster is the surface chart, because it is the most up-to-the-minute information he has. A platform interrogation capability could improve surface charts to the timeliness and resolution of the sounding and imaging systems. This sort of platform interrogation is a part of the ERTS and SMS systems

now. It does not have to be a part of the SEOS satellite if the data can be made available in real time through other satellite systems. It would be easier however, to control the sampling intervals and points by means of the SEOS ground station.

SEOS cannot waste its time making surveys or even spend much time moving from point to point. There is simply not enough time available. Thus, for instance, SMS or GOES should provide all large scale searches for cloud cover and active areas. The 30 minute time resolution and 1 km space resolution of SMS are quite compatible for observation of large weather patterns.

Most of the synoptic situation should be available in the form of digital upper air and surface charts from which those segments of the large scale weather data needed for mesoscale monitoring can be selected. Such data may be made available largely through the National Weather Service AFOS (Automatic Field Operations and Services) system. The SMS/GOES imaging data in the visible and IR would come from the National Environmental Satellite Service SFSS (Satellite Field Service Station). Satellite sounder data may come either from NESS or NWS depending on the form SEOS will use in setting up its own mesoscale situation monitor.

Figure 4 shows the relation of the proposed system functions. Four problem areas are indicated. The first three need to be worked on in ground station design. The fourth is being solved now in the form of "nowcasting."

1. SEOS must be able to access data from a wide range of sources, implying both a means of access and criteria for selection.

2. SEOS must maintain monitoring of the mesoscale situation in the form of diagnostic models which both detect and predict trends. We have to know what data is needed and how to use it.

3. Recognition of danger, to be useful, requires a short response time. We need to achieve this with reasonably simple criteria.

4. Getting the message to the public requires a more effective communication system than now exists. AFOS plus cable TV will provide this means of communication.

Mesoscale phenomena grow up and die in an hour. If we cannot design the system to output accurate information to the public within 30 minutes, there may be no time left to react to the message. Today, the local weather service office sits at the end of a teletype line highly subject to disruption by severe weather or flood, and must often relay its crucial warning sequentially by phone (also highly disruptable) to radio stations and offices of emergency government. Tornado warnings are often conveyed by means of sirens, which tend to alarm without communicating, generally fail by giving false warnings, and are tested often enough to generate apathy and distrust.

Meteorology is in the midst of its third "revolution," brought about by the coincidence of three technologies: the geosynchronous weather satellite, the computer, and cable TV. From work done in the Multidisciplinary Studies Group at SSEC (1972, 1973) the logic of future development appears almost inescapable. The technology of

SEOS GROUND SUPPORT CONCEPT

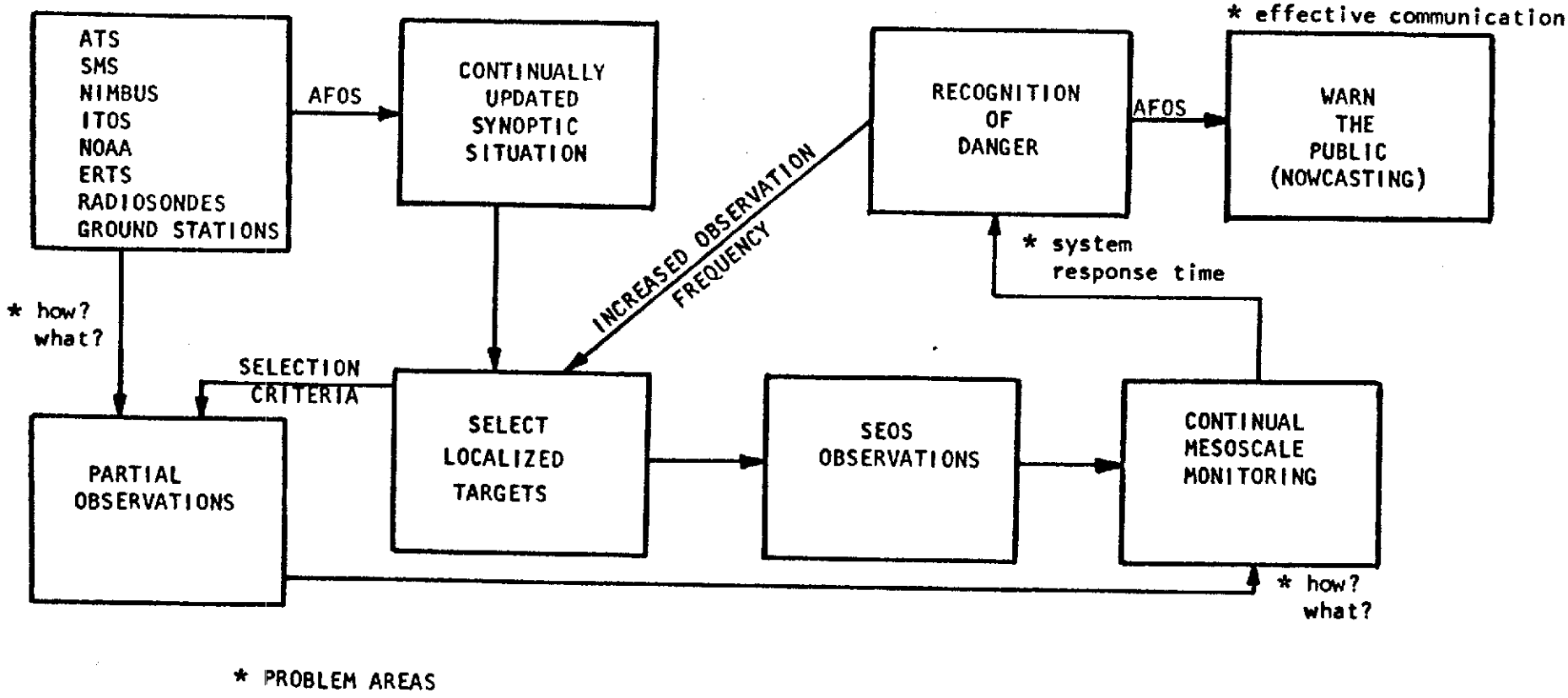


Figure 4

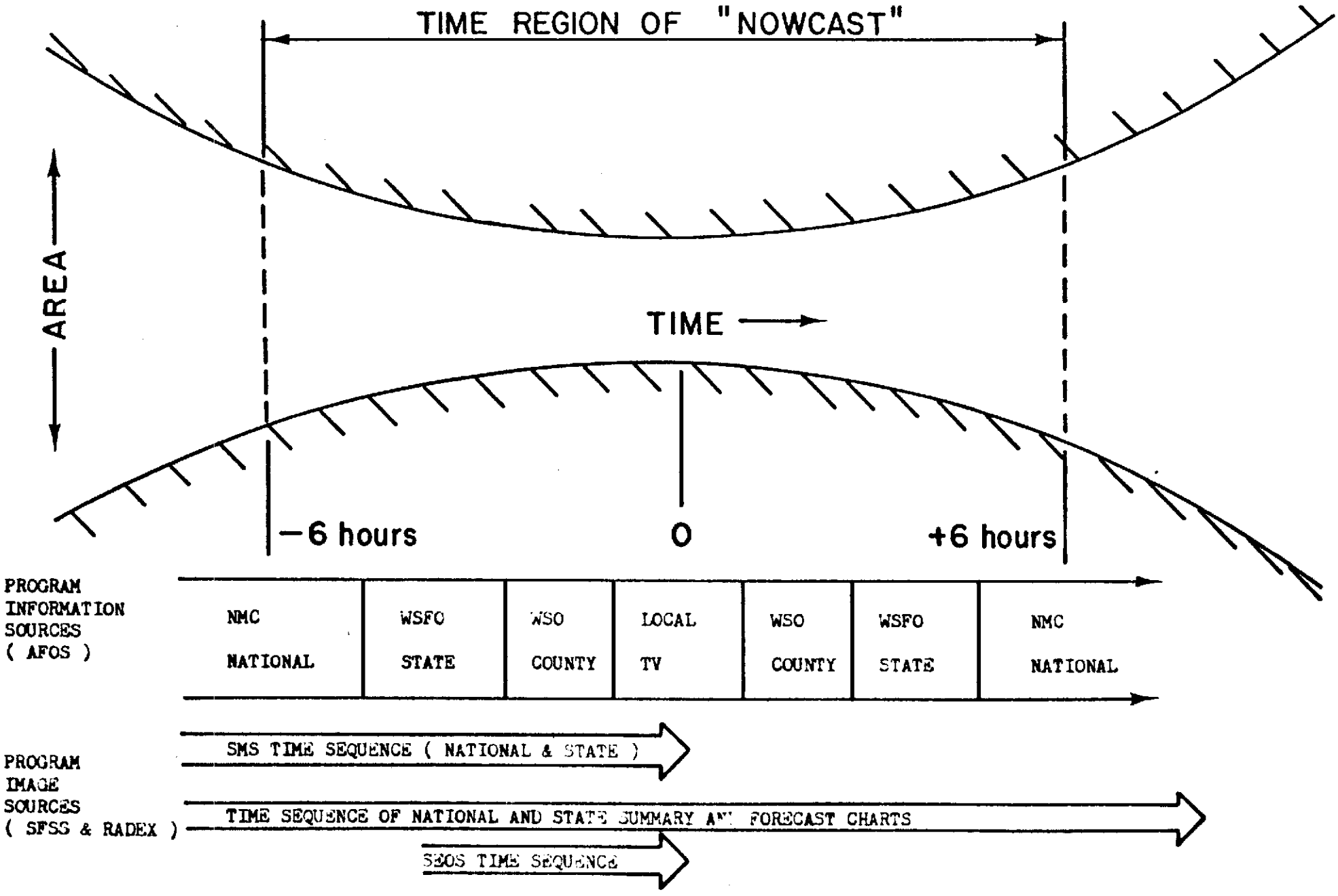

TIME REGION OF "NOWCAST"
AREA
TIME
−6 hours
0
+6 hours
PROGRAM INFORMATION SOURCES (AFOS)
NMC NATIONAL
WSFO STATE
WSO COUNTY
LOCAL TV
WSO COUNTY
WSFO STATE
NMC NATIONAL
PROGRAM IMAGE SOURCES (SFSS & RADEX)
SMS TIME SEQUENCE (NATIONAL & STATE)
TIME SEQUENCE OF NATIONAL AND STATE SUMMARY AND FORECAST CHARTS
SEOS TIME SEQUENCE

Figure 5

cable TV is the final element which will become in the next few years perhaps the most important driving force behind weather satellite development, which up to now has satisfied only the scientist's desires. People will demand the type of prediction SEOS can provide.

Another interesting fact emerging from the SSEC study was that people prefer continuity in weather prediction. Figure 5 shows the region of interest. For nowcasting, people are interested in local, county sized information. It should, however, be placed in the context of transition in time. Also, it was found that the further forward or backward in time the information was, the larger the geographic area should be. Thus, people wanted to know what things were like in the entire country this morning, what happened in the state a couple hours ago, what is happening in the county now, what will be likely to happen in the state in a few hours, what will the U.S. weather picture be like tonight and tomorrow. The predictions need not even be right 100% of the time, provided the forecaster admits his doubts. If people feel that they are getting all of the relevant information on which to base their imminent decision, they will have confidence in the nowcasting service. This sort of individualized attention is what a national weather service geared to regional forecasting cannot provide. It cannot account for local conditions.

The preference for continuity has other interesting aspects. The synchronous orbit satellite pictures, preferably in a time lapse sequence, convey more information, better, easier to the user than any other single format. People identify much more readily with a picture than a diagram, and with the ATS pictures even place themselves in the image geographically. The weather image has meaning because a person can see himself in it. If one now adds the diagram to bring in the quantitative information, information transfer is further improved. The key factor though is "weather-in-motion," and the geosynchronous satellite images have the right coverage, the right resolution, and the right time repetition rate for the mesoscale.

Figure 5 identifies time and space coverage required by nowcasting with the information sources added. As the weather data arrives at each link in the AFOS chain, new information is added in a block. Image data is acquired over image grade circuits from SFSS in a continuing sequence, so that the latest pictures are available. The local TV station adds the final countywide data and organizes the updated presentation. No link in the data chain is required to produce special products aside from its normal functions. All stations in the country will carry the same NMC summary. State by state, the WSFO, forecasts will vary. The individualized data is very small in quantity and easily updated. This is where the SEOS images of one or two counties will be especially valuable, since they show how a storm is approaching, how big it is, how far from a person's home the storm is.

On an average day in the U.S. we might have some 6-8 large scale weather features, each with 20 - 30 possible danger areas deserving of attention. Assuming we wish to look in 200 places with SEOS at 15 minute intervals in the average, that means that 13 times per minute--once

every 4-5 seconds--SEOS must move to a new pointing position, stabilize, and collect data. SEOS has the information bandwidth (at 500 meter resolution covering a 100 - 200 km square area for each mesoscale feature) and the necessary sensitivity to function as an imager and sounder under these constraints. The currently predicted mechanical operation of the telescope movement and sensor scanning is nowhere near such performance. Moreover, the figures above do not take into account the fact that SEOS will be used for other purposes besides meteorology and will not be available 100% of the time. Moving the entire telescope in a sweep mode will be a very efficient way to cover area. It will accomplish some, but not all sensing goals. It seems evident that in order to get both imaging and sounding without smearing resolution elements, some sort of two-dimensional mechanical or electronic scanning and/or pointing may be necessary in the sensor focal plane.

In Table IV we outline a recommended SEOS sensor system. It is a compromise between all of the observing requirements specified in Chapters III and IV, but is a surprisingly good compromise, primarily because the time and space resolution needed to parameterize one mesoscale feature is generally adequate for another where physical processes are similar and occur at the same rate. We desire more resolution in the IR imaging than can probably be obtained with diffraction limited optics. Consequently we have specified a dynamic range in the visible imaging system similar to that of the DAPP Air Force weather satellite, so nighttime imagery at high resolution is still possible.

In considering tradeoffs and relative values of the sensing bands, the primary conclusion is that on SEOS, IR sounding, IR imaging, and visible imaging capabilities are essential.

It is possible that a report as comprehensive appearing and as positive in outlook as this will be interpreted as a ringing endorsement for immediate construction of SEOS and as a statement that all relevant problems have been solved or are trivial. Careful reading will show that such an interpretation is incorrect. The mesoscale is too complicated for the prediction problem to be solved quickly or uniformly with or without SEOS. The ideas and expectations of a number of contributors to this study were used to achieve a description of what SEOS could be and how it can be used. Some hopes will die and others will succeed beyond our expectations. At this time, individual details are not as important to the future of SEOS as is the overall picture, which is indeed very positive. SEOS offers an opportunity, unlike any other yet proposed, to obtain improved mesoscale knowledge and forecasting ability through improved data. Taking advantage of that opportunity demands further planning and preparation since improved data alone is not enough.

This study must be considered as a first look, which will require careful consideration and reevaluation in the light of ongoing research on the mesoscale and changing national needs and priorities. The ideas and conclusions presented here should be a foundation to be examined, criticized, expanded, clarified, and modified to take full advantage of the experience and planning of government agencies such as NASA and NOAA. We welcome future discussion and participation in the SEOS program.

Table IV

SEOS Sensor Requirements

A. Visible Imaging:

Ground resolution (two imaging modes not necessarily simultaneous)	100 m 500 m
Spectral Bands	0.6-1.0μm ~0.4μm (optional)
Dynamic range	$>10^7$ (for nighttime imagery)
Signal to Noise Ratio	>150:1 @ 100% albedo
Gray scale digitizing	≥128 levels (linear)
Raster geometry	uniform, picture to picture determinable to <1/2 pixel
Raster shape	frame and/or strip (TV format compatible)
Raster size	variable line length and number >100 km square >600 lines
Area coverage (varies with scale of phenomenon)	10^4 - 10^6 km^2
Picture interval (per target)	10 min - 4 hours (4-5 sec/target)
Frame time	<4 sec/600 lines
Information bandwidth (constant)	~3 Megabits/sec.
Data type	digital
Pointing knowledge	20μr

B. IR Imaging:

Ground resolution	500 m desired (1-1.5 km acceptable)
Spectral Bands	6.7μm ($\Delta\nu$=150 cm^{-1}) 11.5μm ($\Delta\nu$=160 cm^{-1}) 13.8μm ($\Delta\nu$=100 cm^{-1})
NEΔT	0.5°C @ 225°K
NER	0.1 mW/($m^2 cm^{-1}$ ster.) 0.05 mW/(m^2 cm^{-1} ster.) [at 6.7μm]
Raster geometry	uniform picture to picture or determinable to 1/2 pixel
Raster shape	frame and/or strip
Raster size	variablé line length and number >200 km square >600 lines
Area coverage (varies with scale of phenomenon)	10^4 - 10^6 km^2
Picture interval (per target)	10 min - 4 hours (4-5 sec/target)
Frame time	<4 sec/600 lines
Information bandwidth	~500 kbps
Data type	digital
Pointing knowledge	20-30μr

C. IR Sounding

Ground Resolution - 35 km

	Channel	$\nu(cm^{-1})$	$\Delta\nu(cm^{-1})$	α(mr)	NER[1] $mW/(m^2 cm^{-1} ster.)$	P(mb)[2]
15μ CO_2	(1)	669	5	1.0	0.05	30
	(2)	680	5	1.0	0.05	65
	(3)	690	5	1.0	0.05	100
	(4)	700	5	1.0	0.05	200
	(5)	705	5	1.0	0.05	350
	(6)	715	5	1.0	0.05	500
	(7)	740	5	1.0	0.05	700
	(8)	750	5	1.0	0.05	900
4.3μ CO_2	(9)	2360	40	1.0	0.002	1
	(10)	2310	40	1.0	0.0004	60
	(11)	2290	40	1.0	0.0004	130
	(12)	2250	20	1.0	0.002	600
	(13)	2230	20	1.0	0.002	700
	(14)	2210	20	1.0	0.002	800
	(15)	2185	20	1.0	0.002	900
11.5μ window	(16)	900	32	1.0	0.05	1000
3.7μ window	(17)	2700	200	1.0	0.0002	1000
H_2O	(18)	1490	60	1.0	0.02	-300
	(19)	430	40	1.0	0.1	-600
	(20)	507	80	1.0	0.1	-750
	(21)	1225	60	1.0	0.02	-1000

(1) Proposed RMS maximum

(2) Location in pressure of weighting function maximum

D. Microwave Sounding (ref. Nimbus E Microwave Spectrometer)

Antenna size		2-3 meters
Frequencies	H_2O	22.235 GHz 31.40
	O_2	53.65 54.90 58.80
Bandwidth		250 MHz
Sensitivity		same as on Nimbus E
Ground resolution		<200 km

E. Ground Sensors and In-Situ Measurements

Surface temperature	±0.5°K
Surface pressure	±0.1 mb
Mixing ratio	±0.5g/kg
Surface wind	±1 m/s, ±10°
Frequency of observation	$(10\ \text{min})^{-1}$ to $(3\ \text{hr.})^{-1}$
Precipitation type, intensity, duration	--
River and lake levels	--
Watershed soil conditions	--

II. Study Objectives and Approach

In defining objectives for this study we felt that the SEOS concept, in its current state of development, could profit most from a detailed look at potential meteorological applications which emphasized SEOS' economic, social, and scientific value to the public. We especially wanted to identify applications for which SEOS is uniquely capable. The applications needed to be well justified scientifically with both strong and weak spots thoroughly exposed.

Two approaches were considered. The first was to develop a broad and comprehensive "shopping list" of applications which would be minimally developed and then run through a computer "sieve" program. The computer would correlate, organize, and compare the measurement requirements and yield a smaller set of technical requirements and data to serve as a basis for final analysis. Then, where desired, certain SEOS applications would be expanded upon in more detail if they had particular significance or were representative of a broad class of observations. The alternative approach (which we finally adopted) minimized the data put into the "sieve" by choosing only a small set of mesoscale activities already known to have significant impact on the general public. This approach runs a risk of overlooking potentially valuable uses, but has the advantage of achieving more immediate and substantial returns. Considering the time constraints on the study, this seemed particularly appropriate. Still available is the option, at some later time, to broaden the study and develop the full shopping list. A start in this direction is made in section VI-B.

TABLE V

SEOS Study Objectives

1. Identify uses of particularly great benefit to which SEOS can significantly contribute.

2. Define science requirements and the range of meteorological observations possible from SEOS. Especially delineate those observations unique to SEOS.

3. Define technical requirements for SEOS instrumentation and sensor specifications.

4. Identify observation systems in which SEOS can participate or interface to.

5. Define characteristics which ground data system must have.

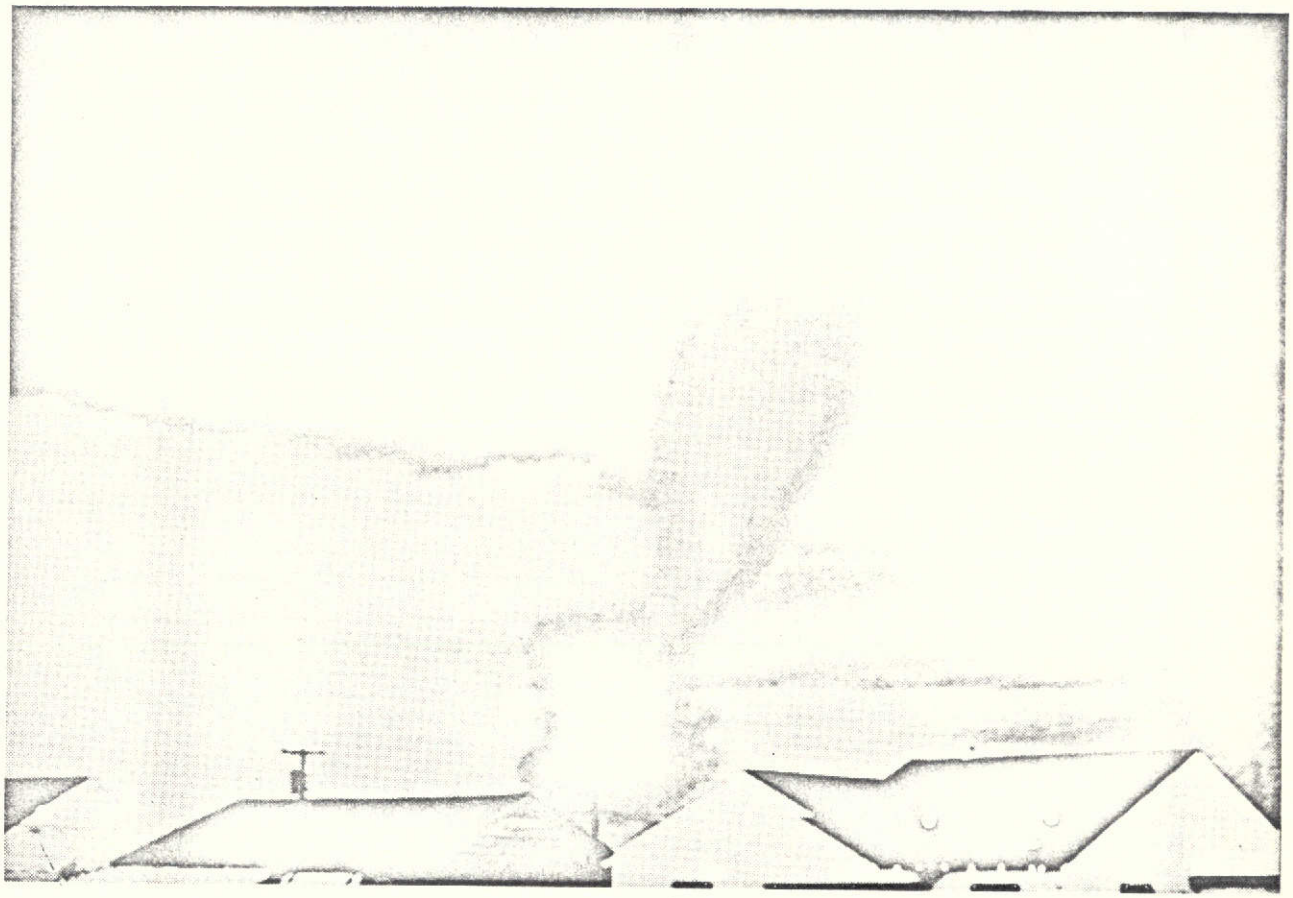


Figure 6. Tornadoes are the most intense mesoscale phenomena

The final reason for attacking a limited set of applications first was the work of a spring 1973 graduate seminar on "Mesoscale Monitoring and Prediction" conducted by Professor V. E. Suomi. The seminar concentrated on meteorological phenomena whose monitoring and prediction was of such obvious benefit and so directly applicable to measureing by SEOS that further searching for beneficial applications seemed unnecessary. Thus, five study objectives were defined. They are listed in Table V in order of priority.

At the end of the university semester in mid-May, the seminar participants, in two days of briefings presented their conclusions to the SSEC scientists who were to develop this report. Table VI lists the phenomena originally studied. The topics were chosen with the intent of covering those mesoscale weather phenomena having greatest social and economic impact on the general community. As such, they formed an ideal basis for a SEOS study, even though SEOS was not the intent of the course. The topics of fog, frost, and air pollution were added later in the SSEC study to make a more complete set of applications.

TABLE VI

Phenomena Studied in Mesoscale Monitoring Seminar

1. Tornadoes
2. Hurricanes
3. Heavy snow swaths
4. Lake and sea breeze
5. Thunderstorms
6. Flash flood
7. Clear air turbulence

The seminar was concerned primarily in identifying what observables need to be monitored and then applying those observations to improving local weather communication to the general public in Madison (see Figure 7 below). What was still needed for the SEOS study was to refine the results of the seminar group, to define how the necessary measurements should be made, and to consider the impact of these requirements on possible sensors for SEOS. Knowing what must be observed, we needed to find the best way to do it. It was evident immediately that SEOS would often be a "best" way because of its unique attributes of high resolution, high signal to noise ratio, continual temporal coverage, and large area coverage.

SEOS STUDY APPROACH

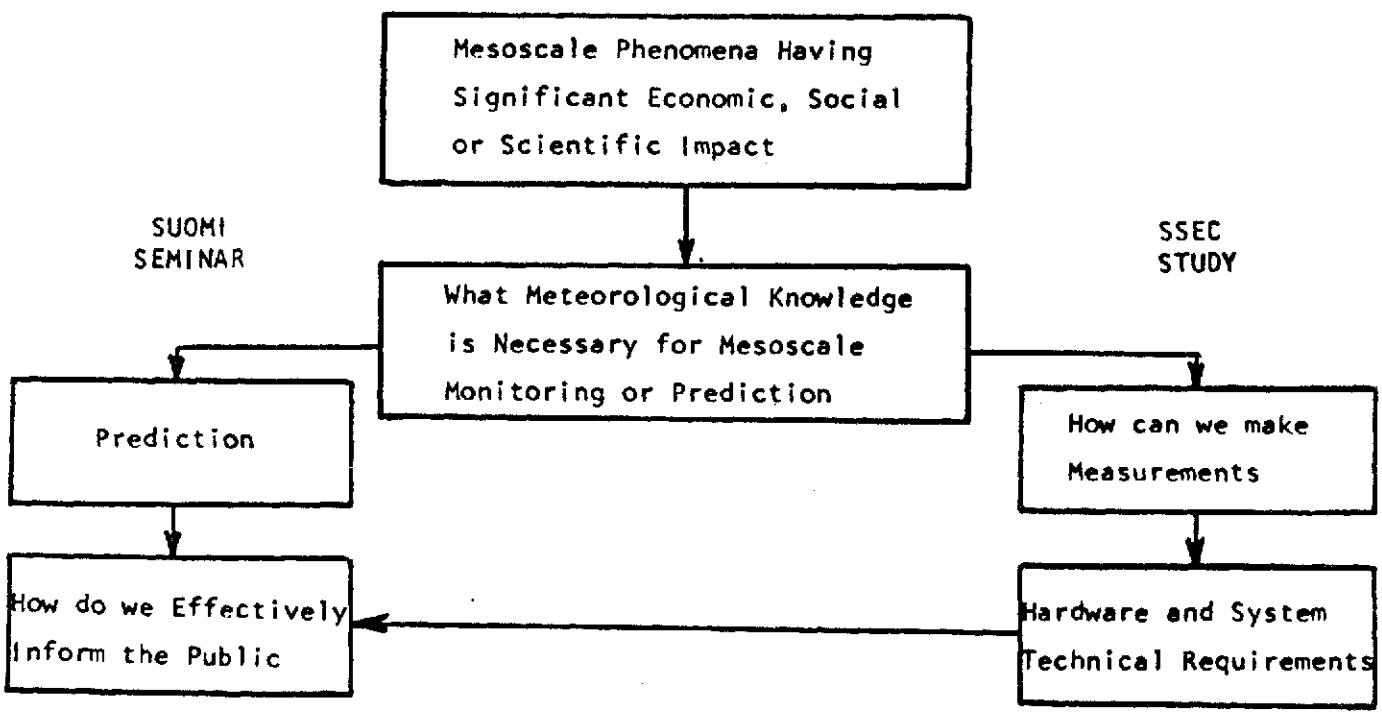


Figure 7.

To provide an orderly and comprehensive collection of observations and measurement requirements for translation into technical requirements of SEOS instrumentation, we developed a set of data sheets like the form shown on the next page (Figure 8). The seminar had identified items on the top half of the sheet. We had a set of major problems or needs: the seminar topics in Table IV. Suomi's group had basically defined what meteorological knowledge was necessary to monitor and predict the phenomena, and also what physical observables would provide such knowledge. SSEC scientists were to check the knowledge requirements for completeness and fill in the lower half of the sheets dealing with the quantitative measurement requirements.

The information on the sheets could be rapidly transferred to computer cards and reduced to correlation plots and histograms which would permit rapid segregation of different kinds of measurements. In this way it could be determined where tradeoffs were required to fit within constraints on performance, observing time, system complexity and the like. The computer sieve program could be configured to provide output from the data cards to answer most of such questions. Furthermore, the data card approach lends itself to easy addition of data to the "sieve". The analysis program, already modified to provide the pertinent information, would be able to easily point out where modifications of the SEOS sensors would be required to make the additional observations.

The analysis of the top half of the sheets led to significant findings which determined the eventual shape of this study. Rather early, we were led to concentrate on those areas of observation most beneficial to eventual definition of the SEOS system. This was accomplished by means of the frequency analysis explained in section IV-A. Analysis of the bottom half of the sheets proved difficult for three reasons:

1. The physical description of a developing mesoscale phenomenon requires a complex set of measurements. Omitting a single measurement degrades the physical picture, to be sure, but compensatory information is often available indirectly from other sources which may mitigate the loss. Furthermore, depending on the availability of such data and the physical conditions in existence at the time of observation, the value of a particular measurement may change. It is impossible to accurately program the "ifs" and "buts" without first knowing how the whole system (SEOS satellite and ground support) will operate. Thus, the sheets were too rigidly structured for our purposes and would work well only if the measurements were completely independent. Of course, because of the interrelation and similarity of the phenomena studied, it became easy to define the hardware requirements. Everything tended to occur in similar time and space frames. So, in that sense, a sophisticated tradeoff analysis was also unnecessary.

2. Imaging and sounding had such obviously high value as techniques that they could not be traded off against each other or anything else. The only real options were tradeoffs among the imaging channels themselves, and among the invividual sounding channels.

3. Tradeoffs in the imaging channels are hard to make because information bandwidth, frequency of observation, area coverage, and spatial

PLEASE USE PENCIL

MEASUREMENT REQUIREMENT

Figure 8.

☐ MAJOR PROBLEM OR NEED

SCIENTIFIC VALUE → ☐
ECONOMIC VALUE → ☐
SOCIAL VALUE → ☐
OTHER VALUE → ☐

☐ KNOWLEDGE REQUIREMENT
↳VALUE → ☐ → (IN SATISFYING MAJOR PROBLEM)

☐ OBSERVATION REQUIREMENT
↳VALUE → ☐ → (IN SATISFYING KNOWLEDGE REQUIREMENT)

20 ☐ INVESTIGATOR

DON'T KNOW → ↓ NO VALUE ↓ LOW HIGH ↓ HIGHLY SIGNIFICANT (ONLY SOURCE)

0 1 2 3 4 5 6 7 8 9
VALUE SCALE

HYPOTHESIS → 1 PROVEN THEORY → 2 MEASURED IN LAB → 3 MEASURED IN FIELD → 4 MEASURED REMOTELY → 5
DEVELOPMENT STATUS

PLATFORM USED ☐
1-SEOS
2-Geosynchronous Satellite
3-Low Orbit Satellite
4-Airplane
5-Balloon
6-Ship
7-Buoy
8-Land Based
9-Other: _____

SPECTRAL BAND ☐
1-UV < 0.35 μm
2-Visible .35-.75 μm
3-Near IR .7-3.5 μm
4-Thermal IR 3.5-20 μm
5-Far IR 20 μm-100 μm
6-Microwave .1 mm-50 cm
7-Radar, TV, W .5-100 m
8-Long Wave 7.1 km
9-P, T, other: _____

MEASUREMENT PARAMETERS: (PLEASE USE STANDARD UNITS)

1- BAND CENTER: _____ 24 S/N 29
2- BAND WIDTH: _____ 30 37 39
3- TEMPORAL FREQ.: _____ 40 47 49
4- SPATIAL RESOL.: _____ 50 57 59
5- S/N & RMS ERROR: S/N % | RMS _____ 60 67 69
6- ☐ AREA COVERAGE — KM → 10 50 250 1000 10000 — 1 2 3 4 — 70 RMS 77 79 80
7- ☐ TIME COVERAGE — <1h 1-10h 10h-1d 1d-1wk >1wk — 1 2 3 4 5
8- ☐ MEAS. DEVELOPMENT STATUS

SPECIAL REQUIREMENTS: _____

1 4 6 9 10 11 15 17 18 19 20 21 23

MEASUREMENT IS:
☐ PRIMARY
☐ SUPPORTING
21

PLATFORM IS:
☐ PART OF SYSTEM
☐ COMPLETELY SEPARATE UNIT
22

MEASUREMENT IS:
☐ UNIQUE TO SEOS
☐ NOT UNIQUE
23

resolution are all tied to the scale of the atmospheric phenomena, so are similar for all channels. The geometric and radiometric accuracy requirements cannot be relaxed. The 100 meter visible channel is perhaps weaker in terms of present day uses, but it has such high potential for studying small cloud growth rates and measurement of 850 mb winds it cannot be downgraded too far. Visible and thermal IR at 1/2 km resolution are both desirable, especially the visible with high dynamic range since 1/2 km resolution in the thermal IR is not likely to be attainable. The three thermal imaging IR bands are all needed because of the stringent altitude resolution requirements, and work best in conjunction with good vertical temperature and moisture soundings. Tradeoffs among the many sounding channels require a complete similation utilizing realistic error introduction, varied physical conditions, and simultaneous inversion of all channels to determine how well the vertical profiles can be reconstructed. An arbitrary value judgment, no matter how well informed, cannot accurately reflect the interplay of the multiple variables in the inversion process.

The chief value of the "sieve" thus lay in its frequency analysis of the knowledge requirements given in section IV-A. We were able to determine that the motion field at all levels was crucial and that vertical temperature and moisture sounding were also of high importance. Somewhat of a surprise was the very high proportion of measurements needed in the boundary layer. The importance of low level convergence to storm genesis has always been recognized, so it was planned to give some attention to the boundary layer in our study. The increased relative importance of the boundary layer in all mesoscale phenomena we studied required a change in emphasis. The number of sounding channels, for instance, needed to be increased to improve sounding accuracy at low levels. The need for <u>in-situ</u> measurements greatly increased when we looked at the time and space requirements for adequate physical knowledge of developing weather phenomena.

A common thread was found running through the phenomena analyzed, and that is vertical stability, the potential for vertical motion. Synoptic scale weather is almost entirely horizontal mass motion. Vertical motion in global atmospheric models is considered a neglibible perturbation, a view justified by the success of barotropic models in predictions of weather 24-48 hours in the future. Yet most of the influence weather has on us is due to these "negligible perturbations." Many a forecast has been ruined because of these negligible perturbations, in spite of their small time scale. We cannot predict 4-12 hours into the future with any great accuracy because we are not now able to determine the onset of conditions conducive to vertical instability. The problem is a combination of never having the information available, or if available, not getting it quickly enough to use it. Either it has not been gathered, or it takes too long to process. For instance, afternoon tornado warnings are based on morning balloon soundings. (Fortunately a strong correlation exists between morning conditions and afternoon tornadoes. For some phenomena, we do not have a 12 hour warning.) SEOS, besides monitoring storm tracking and cloud system development, can provide information on the time rate of change of the temperature field and moisture field in 3 dimensions. Those fields are the key determinants of conditions leading to vertical instability.

Two major sequences of events are involved: a preparation of the troposphere, mainly through horizontal motion of the mass field and temperature field; and a trigger mechanism, generally in the boundary layer. While previous studies of SEOS have centered on its ability to image at high resolution in space and time--an important feature of any program to monitor development of severe weather--the major new benefit suggested by the seminar work is the ability to quantitatively measure the rate of change of vertical stability. SEOS will be able to detect the onset of conditions leading to severe weather, besides showing where severe weather is occuring and to where it is moving.

The major problem appears to be adequate quantitative monitoring of the boundary layer. As Section IV details, the problem is exceedingly difficult, and as Table VIII shows, information on the boundary layer is needed almost everywhere: for storm prediction, sea and lake breezes, air pollution, hurricane development, tornadoes, fog and frost.

Thus, the frequency analysis of the knowledge requirements outlined in Section IV-A showed that SEOS observations must emphasize winds, vertical temperature and moisture sounding, and observations in the boundary layer. These are the chief topics of Chapter IV and serve as the basis of the final analysis. In addition, a need was felt to further detail severe storms, hydrometeors, and cloud observations more quantitatively because of the importance of obtaining the right match between these physical processes and the SEOS observation parameters.

Professor Suomi's seminar was asked where to spend a million dollars to improve communication of weather information to Madison residents. The responses were within the bounds of existing systems and provided no really original ideas. The participants recognized that the existing system of teletypes and phones is inefficient and easily disrupted during emergencies, that sirens are often misunderstood and that radio and TV stations, at the end of the warning chain, warned sequentially by phone from the local weather Service Office, are often too late to be of much help. Mostof the million was proposed for improving existing communications links - better radar, more foolproof teletype, closed circuit TV links, more effective use of local radio and TV, etc. Without the benefit of the SSEC Multidisciplinary study report and knowledge of the planning now going on for AFOS, they missed discovering nowcasts as an effective tool for communicating both forecasts and warnings.

In the end, defining the hardware requirements turned out surprisingly easy because all the phenomena investigated have the same physical scales. Consequently, the observations should be defined to similar ground resolutions and observation frequencies. The chief hardware problem involves how to combine the imaging and sounding sensors to meet the targeting reqirements imposed by nowcasting. We also need to determine the real extent of the improvement in our knowledge and forecasting ability once better data is available through SEOS. We give in the last section of this report a list of tasks we can start on in the coming year in order to aid in answering remaining questions.

III. Mesoscale Phenomena: Definition of the Observables

A. Clear Air Turbulence

As the name indicates, Clear Air Turbulence (CAT) is turbulence in the clear air and hence invisible to the human eye. This turbulence is normally experienced at upper levels of the atmosphere and is of special importance to the safety of high flying aircraft. Fortunately, extreme turbulence is experienced only rarely. At any one time, about 5 to 10 percent of the volume of the atmosphere at jet plane levels contains turbulence which can affect aircraft, and that is generally not severe enough to affect control or cause structural damage.

The fact that clear air turbulence is not generally associated with clouds means that the pilot cannot see the turbulence and take appropriate evasive action. Pilots can avoid storms by means of radar, but a similar aircraft-borne turbulence-sensing device has not yet been developed.

Since CAT is an atmospheric phenomenon, its cause can be traced to an existence of particular atmospheric conditions, the probability of occurrence of CAT can be estimated. The main problem is to identify the particular atmospheric conditions that are conducive to CAT.

CAT can be described as a rapid variation in space and time of strong vertical motion, typically extending over a few hundred kilometers in a thin, relatively narrow layer. CAT is also often experienced in the lee of mountains where the mechanism of occurrence is probably slightly different. This type of CAT generally occurs at a lower level. In any case, CAT is found only in a thermally stable atmosphere.

It has been surmised that the CAT, in most cases, owes its existence not to the buoyant forces, but to the Kelvin-Helmholtz instability, i.e., to a strong vertical shear of the horizontal wind in a stable atmosphere. There is now considerable circumstantial evidence that most CAT occurs at "interfaces" in the atmosphere across which wind speed and temperature change.

When fast winds are adjacent to slow winds, small fluctuations in the air flow can grow by extracting energy from the wind shear. Thus, it is in the wind shear that the source of CAT's energy lies.

Consider an interface in the atmosphere, with slow winds below the interface and fast winds above. Because of the wind shear, a pattern of waves can start forming at the interface (see Figure 9). As the waves break, the flow becomes turbulent, and an aircraft flying through the waves can be tossed about.

High-powered radars can often observe the visually transparent waves going through their life cycle of formation, growth, and breaking.

Occasionally, some cloud patterns are associated with CAT, and satellite

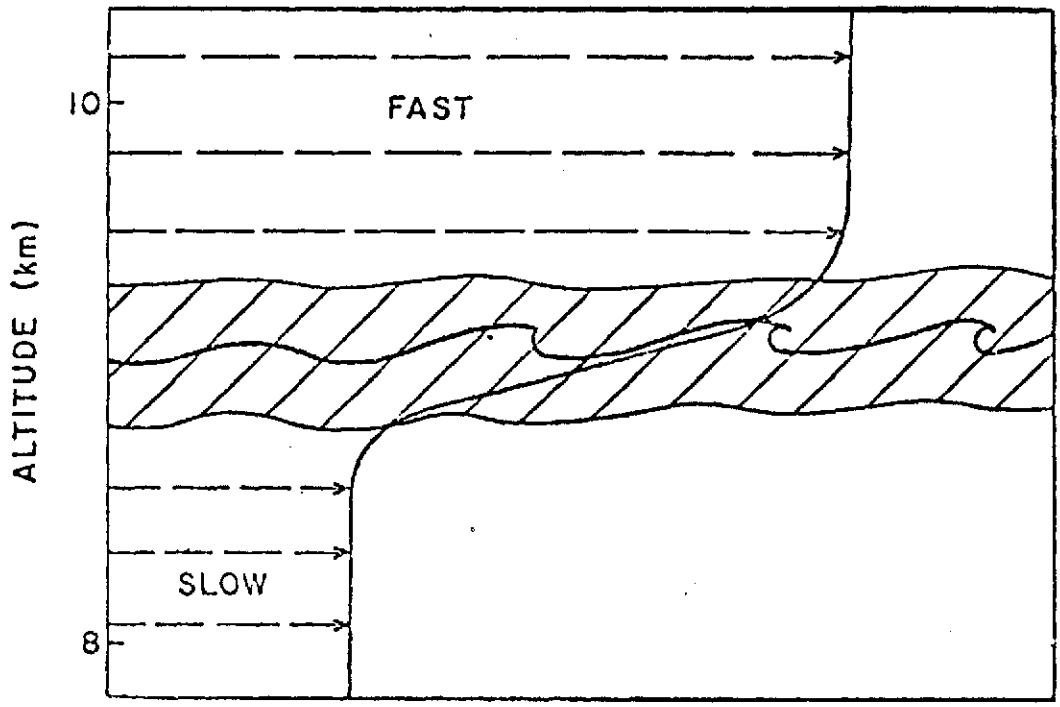


Figure 9. This schematic cross-section through an interface (crosshatched) which separates fast winds above from slow winds below shows waves at various stages of development forming at the interface. (after Woods, 1973)

photographs can be used to find these clouds. Cirrus clouds associated with currents of strong winds at high levels (jet streams) occasionally cast a shadow on lower clouds, which can be seen in enhanced satellite photographs. A method of CAT detection using satellite measurements of atmospheric variables is called for, but this type of detection must include some other form of sensing in addition to visible imaging.

Since CAT grows by drawing kinetic energy from the vertical wind shear, it might be possible to predict whether severe turbulence will occur, and whether it will grow, by monitoring the vertical changes that take place in the horizontal wind field. This can be done directly, where cloud motion is measureable, and also through the thermal wind relationship. A knowledge of the vertical stability of the atmosphere is also essential, however.

With the recent developments in applications of satellite sounding technology in meteorology, it has now become possible to obtain, on a continuous basis and on a global scale, the kinds of temperature profiles through radiance measurements that can be utilized for the forecasting of CAT. Through the thermal wind relationship it is possible to derive the vertical shear of the horizontal geostrophic wind. By looking at the horizontal temperature gradients at various atmospheric levels the wind shear field can be constructed. The stability of the atmosphere can be inferred from the temperature profile information and water vapor distribution. The latter is also obtainable from satellite measurements, though at lesser accuracy than the temperature measurements.

Since CAT occurs normally in the upper layers of the atmosphere (<500 mb), only this portion of the atmosphere needs to be examined. Measured radiances in two or three channels which tell about the upper levels of the atmosphere would be valuable in identifying the vertical variation of the temperature in that region. For example, channels 3, 4 and 5 of SIRS-B (see Figure 10) provide information about the 500-200 mb layer of the atmosphere and a ratio of radiances measured in channels 3, 4 and 4 and 5 respectively should indicate the stability of the atmosphere in that layer.

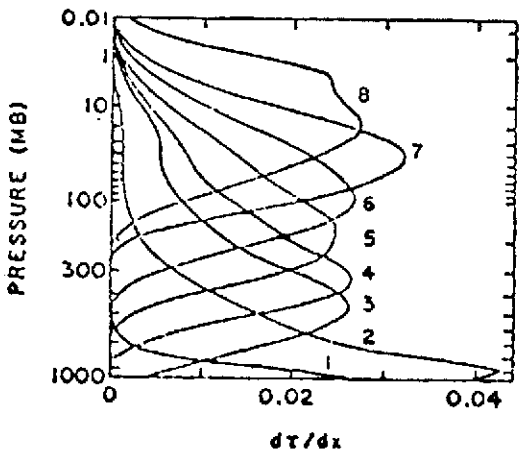


Figure 10. Weighting functions for the SIRS, with the curves showing the relative contributions from different levels in the atmosphere that make up the radiation received in each of the eight channels of the satellite-borne instrument. Thus, the radiation received in channel 4 originates predominantly at levels centered in the vicinity of the 300-mb pressure level about (9.2-km altitude).

Woods (1973), studying the CAT phenomenon utilizing SIRS-B data, determined that the probability of encountering CAT (as determined from pilot reports) increased substantially in regions of large horizontal temperature gradients. He did not, however, use the vertical gradients of temperature and moisture to measure vertical stability.

From a knowledge of the horizontal temperature gradient (hence vertical shear of the wind), and of the stability of the atmosphere (lapse of the potential temperature) the Richardson's number can be derived. Richardson's number (R_i) is directly related to the turbulence, and predicts substantial turbulence if:

$$R_i = \frac{g}{\theta} \frac{\frac{\partial \theta}{\partial z}}{\left(\frac{\partial \mu}{\partial z}\right)^2} < \frac{1}{4}$$

where $\frac{\partial \theta}{\partial z}$ is the potential temperature lapse rate or stability: $\frac{\partial \mu}{\partial z}$ is the vertical shear of the horizontal wind; and g is the acceleration of gravity.

The satellite information about the three-dimensional thermal structure and moisture content of the atmosphere can thus be reduced in real time to global CAT probability maps for use in charting aircraft flight

plans so as to avoid regions with highest probability of occurrence. The scheme outlined here for monitoring and forecasting of CAT is unique in the sense that it is the only one which gives some prior indication in terms of probabilities of occurrence. A Richardson number decreasing toward 0.25 warns of probable CAT; a Richardson number increasing from 0.25 suggests no CAT.

Almost all CAT observations are routinely reported by aircraft pilots in three categories: light, moderate, or severe turbulence. Quantified observations and measurements are very difficult to attain and even then if attained, difficult to analyze. Certain remote sensing methods for detecting CAT from the ground have been proposed (radar and LIDAR for example). They are based on the fact that the severe turbulence affects the physical properties of the atmosphere, e.g., changes in the index of refraction. Such ground based methods suffer from the drawback that they can sense the turbulence only when it is almost directly overhead, thus limiting the monitoring time span and spatial coverage of any ground stations.

Even though clear air turbulence occurs in the upper layers of the atmosphere, it can be expected to cause relatively rapid fluctuations in the surface pressure. A network of sensitive pressure sensors might also prove to be useful in locating CAT (at least the direction) by examining the phase of the pressure changes over the network. Such a network might supplement the satellite oriented technique for forecasting Clear Air Turbulence.

KNOWLEDGE REQUIREMENTS

(Clear Air Turbulence)

Determine surface pressure field, tendency, fluctuations.

Catalog and interpret pilot reports of CAT.

Moisture lapse rate (mixing ratio).

Monitor output of numerical models.

Locate jet streams.

Richardson number tendency (500-200mb).

Temperature lapse rate.

Potential temperature field (500-200 mb).

Locate regions of dynamic instability (advection - K.E.).

Identification of cloud patterns associated with jets.

Location of transitional layers or boundaries.

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B. Hurricanes

The two main forecasting problems of hurricanes are: (1) their formation, and once formed, (2) their movement. Hurricanes form from cyclonic disturbances over tropical oceans. These disturbances typically contain convective areas apparent as cloud clusters in satellite photographs. Clusters result when low level wind convergence produced by the disturbances triggers organized convection. Every year a few of these disturbances intensify to tropical storm or hurricane strength. This intensification depends in part on a complicated instability mechanism called CISK (Convective Instability of the Second Kind). The CISK mechanism involves two factors: (1) a conditionally unstable atmosphere and (2) forced synoptic scale boundary layer convergence and ascent proportional to the vorticity of the boundary layer geostrophic wind. Low level wind convergence in the wave disturbance provides the lifting necessary to trigger convection if instability is present. The CISK mechanism thus initiates, organizes, and fuels convection on a subsynoptic scale. The upper level outflow necessary to maintain the boundary layer convergence in the face of mass accumulation at the center of the disturbance is provided by an upper tropospheric anticyclone. The presence of such an anticyclone allows efficient transport of ascended air away from the storm, without disruption of its spiral organization. Upper level outflow greater than low level inflow produces a pressure fall at the surface. Heating by condensation in spiral bands and subsidence at the core of the storm enhances this pressure fall at the surface. Winds strengthen as the pressure gradient steepens, increasing the surface flux of moisture and convergence into the storm. With the formation of an eye, the storm achieves the essential structure of a hurricane.

Many of the key parameters in predicting the formation of hurricanes are associated with the CISK process. Although we do not fully understand CISK, much less its role in hurricane formation, the following conditions are known to be important:

1. Convective instability--an abundance of low level moisture in the atmosphere and a conditionally unstable lapse rate.

2. A disturbance to produce low level convergence to trigger the instability.

3. A warm ocean surface, $T_{sfc} \geq 27°C$.

4. Little vertical wind shear.

5. A non-zero Coriolis parameter, necessary to initiate rotation. (Hurricanes have never been observed to form on the equator.)

6. Upper tropospheric anticyclonic flow superimposed on a low level disturbance.

Some of these conditions can be monitored by a satellite. The sea surface temperature, lapse rate and low level moisture could be sensed using infrared or microwave channels. The wave disturbances are detected and tracked through the clouds associated with them. Wind convergence around the clusters can be measured by low level cloud motion. Upper

level divergence is also of interest and possibly could be measured if sufficient upper level clouds are present in the area. Vertical wind shear might also be measured.

In spite of much effort, the forecasting of hurricane movement remains a major problem. Present forecasts are based on the following four techniques or combinations thereof:

1. Climatological analog, based on hurricane tracks of the past;

2. Regression equations which use a combination of variables such as sea surface temperature, wind patterns, and the present movement of the storm;

3. Barotropic numerical models of the upper level flow;

4. Multiple level primitive equation models.

Because hurricanes always develop over the oceans, sometimes at great distances from land, the primary uses of satellites have been in locating the hurricane, in monitoring its strength, size, and movement, and in vectoring aircraft for additional, more precise measurements. In these roles, the satellite serves all forecast techniques both for initialization and for verification. Higher resolution providing improved monitoring would particularly benefit techniques based on climatology and regression equations. Forecasts by the regression technique might also be improved through satellite measurements of sea surface temperature, and IR soundings returning geopotential heights of pressure surfaces. Height and wind observations obtainable from satellites could be very useful to barotropic and multiple level primitive equation models. Undoubtedly, a more thorough review of forecast techniques would disclose additional uses.

KNOWLEDGEMENT REQUIREMENTS

(Hurricanes)

Convergence and divergence (1000-800 mb).

Convergence and divergence (800-100 mb).

Moisture lapse rate (mixing ratio).

Temperature lapse rate.

Vertical stability (1000-800 mb).

Vertical stability (800-100 mb).

Locate and track severe local storms, squall lines.

Location of regions of strong convective activity.

Detect wind veering (friction, gradient wind, thermal wind).

Vertical wind shear (800-100 mb).

Atmospheric motion field (1000-800 mb).

Atmospheric motion field (800-100 mb).

Surface temperature.

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Atlantic Hurricanes by G.E. Dunn and B.I. Miller

C. Flash Floods

Flash floods are probably the most destructive and devastating of all weather related phenomena. As opposed to other mesoscale phenomena which can be identified as a particular circulation system in the atmosphere, flash floods are a result of certain meteorological conditions rather than the conditions per se. Flash floods occur as a result of precipitation of such great intensity as to cause rapid overflow of rivers or streams and innundation of adjacent areas. Both in terms of property damage and loss of life, the toll taken by flash floods is enormous: last year's Agnes floods caused $3.5 billion in destruction and claimed 111 lives.

Flash floods, as the name implies, strike typically with great suddenness--thus the "lead time" for any forecast of their occurrence is very small. In certain valley locations flash floods can inundate inhabited areas within 1 hour. The scale of flooding varies. Sometimes isolated individual valley streams are involved, while in other cases, e.g., the Agnes floods, whole states or regions can be affected. In the case of most flash floods the crisis will have come and gone within a matter of hours, but persistent rains can cause recurrent flood crests. Amounts of precipitation needed to cause flash floods vary widely, depending on the type and condition of the ground, its immediate history, drainage patterns of the affected region, and the time period involved.

It is often difficult to issue forecasts of floods far in advance because they are often associated with very slow moving, or stationary convective cells. This slow movement is dependent on tropospheric winds. Predicting just where and when (if at all) sufficiently intense convective cells will stall over any given area is an almost impossible problem for long-range forecasting. Caution must always be used in issuing flood warnings. If the situation does not warrant it, the public will soon lose confidence in the credibility of the forecasts.

Parameters of importance in appraising a potential flood are:

1. Precipitable water.

2. Vertical motion and instability--amount of convective activity.

3. Rainfall intensity and duration--stationarity of convective cells.

4. Physical features of area in question:
   a. Topography--valley or low-lying area.
   b. Soil condition--with or without frost, saturated or unsaturated.
   c. Presence of absence of meltable snow cover.
   d. Present river stage.
   e. Previous flood history of area.

Monitoring tools which could be used are:

1. Radar: very important for determining intensity and movement of cells.

2. Satellite observations: can be used to verify data received through other channels; can be useful in monitoring moisture inflow into storm.

3. River gauge system: often inoperative during crisis situations; system needs upgrading.

4. Radiosonde data and associated NMC computer output: one way of attacking the problem, recognizing the scarcity of time for warning in actual situations, is to have continually updated "contingency tables" prepared for all river basins--"what-if" situations. For instance, what would happen (how high would water go) if too much rain fell in a given period of time. Danger areas could then be easily flagged as each new weather forecast is generated.

5. Local community warning system is essential as time is the key factor.

KNOWLEDGE REQUIREMENTS

(Flash Floods)

Extent and state of surface water.

Snow and ice cover and depth.

Monitor output of numerical models.

Precipitable water.

Vertical stability (1000-800 mb).

Vertical stability (800-100 mb).

Atmospheric motion field (1000-800 mb).

Atmospheric motion field (800-100 mb).

Determine precipitation extent, type, and intensity.

Monitor surface conditions and past history.

Moisture inflow.

Locate and track severe local storms, squall lines.

Location of regions of strong convective activity.

REFERENCES

The Agnes Floods, Report by National Advisory Committee on Oceans and Atmosphere, November 22, 1972.

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Compendium of Meteorology, p. 987, p. 1051.

D. Severe Convective Storms and Tornadoes

The subject of severe local storms forms the most important application of SEOS to mesoscale forecasting. Consequently, we found it necessary to pursue this area in greater detail than the student seminar output. This section briefly introduces terminology and subject matter dealt with at greater length in the next chapter.

Intensive research of thunderstorms and associated tornadoes conducted over the past 25 years has shown that both synoptic and mesoscale processes interact to prime areas for convective activity. While the scale interaction may occur differently in different parts of the country, the overall effect should still be the same; that is, to lower the stability by having moist air overlain by dry air.

Outbreaks of severe convection have been linked with the position of the jet stream. Sinking motion near the jet core provides a source for dry air which may be advected over very moist air, given the differential thermal advection and wind shears associated with jet stream regimes. In the southwest sector of the U.S., however, the jet stream is not the only mechanism which provides for the dry air needed for severe convection. Sinking motion off the Rocky Mountains and horizontal advection of dry air from the arid southwest are also important. The eastward trek of the dry air eventually leads to collision course with moist air moving north and west from the Gulf of Mexico. Convection develops along or near the boundary of the air masses.

Thus one must consider the different circumstances in which the generation of severe convection may occur. It is foolish to consider only one mechanism, whch combines different air masses in a manner suitable for convective instability, and completely ignore the others, and hope to successfully predict the occurence of thunderstorms. Four parameters have been found to have general applicability to strong convection:

1. Equivalent Potential Temperature

One parameter which is an effective measure of the low level energy supply available for thunderstorms is the equivalent potential temperature.

where $\theta_e = T_{ae}\left(\frac{1000}{p}\right)^{.286}$

T_{ae} = adiabatic equivalent temperature

$T_{ae} = T \exp(LW/C_pT)$ L = heat of vaporization
W = mixing ratio
T = temperature

Thus θ_e accounts for latent heat release and sensible heat available for thunderstorm activity. The greater θ_e is at or near the surface, the greater the energy source available for the development of severe convective activity.

A positive difference between θ measured at the tropopause and θ_e at the surface has been used to predetermine the areas of probable tropopause penetration by convective cells (Barber 1973). Thus:

$$\theta_e \text{ (surface)} - \theta \text{ (trop.)} > 0 \equiv \text{tropopause penetration}$$

These cells are usually the most severe.

In monitoring the outbreak of convection, one should search for the area where dynamic destabilization coincides with the region of maximum low level θ_e.

2. Stability Factor

Since dynamics and thermodynamics are important for thunderstorm activity, "θ" (Isentropic) coordinates were found to be convenient for this study.

We define:

$$(2)\ \sigma = -\frac{\partial\theta}{\partial p} \equiv \text{stability parameter}$$

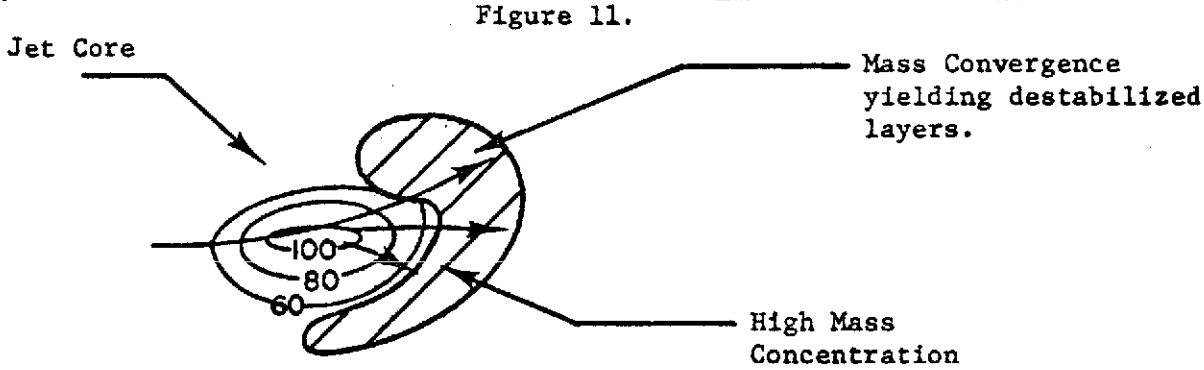
Note that for an adiabatic lapse rate $-\frac{\partial\theta}{\partial p} = 0$. As the lapse rate decreases (stability increases) $\left|-\frac{\partial\theta}{\partial p}\right|$ becomes large.

Mass is related to temperature and pressure and thus can be expressed as a function of σ.

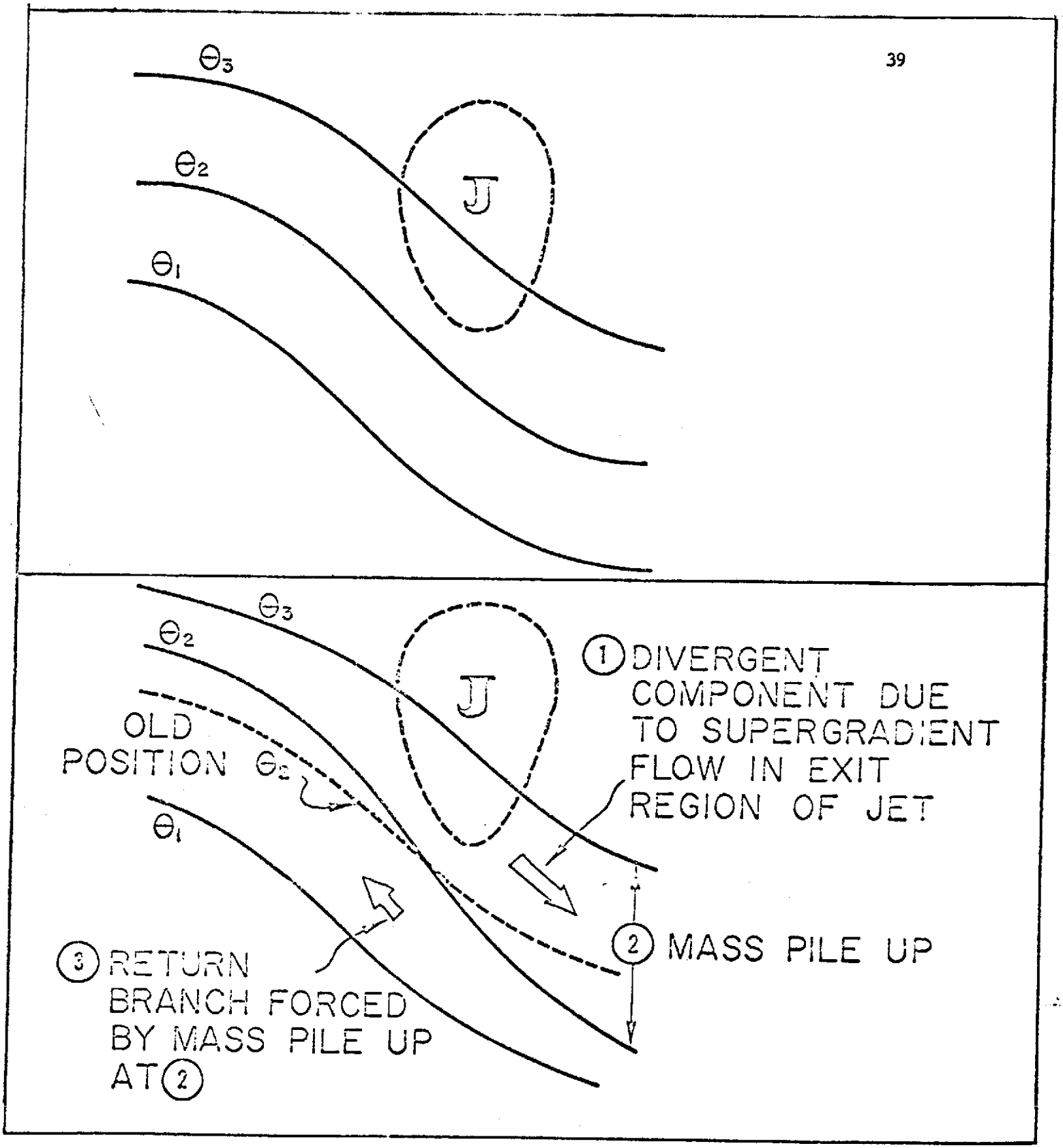
$$\rho_\theta = \frac{1}{g\sigma}$$

Therefore if mass is increased between two "θ" surfaces the stability must decrease. This happens in the outflow region of the jet stream (Gall 1972) since air decelerates as it exits the core region. A typical pattern of mass redistribution at the jet stream level looks like:

Figure 11.



While emphasis upon dynamical destabilization may be justifiable, other aspects of thunderstorm development must also be considered. An extreme amount of mass convergence will yield no thunderstorms if the heat and moisture needed for convective storms is not available.



MECHANISM FOR GENERATING THE BAROCLINIC SUPPORT FOR A PROPAGATING JET

3. Surface Convergence

Another aspect which is also important is the initiating factors which act to trigger thunderstorms by either destroying low level inversions typical of convectively unstable air (Newton 1963) or just lifting parcels beyond their level of free convection. While the mechanisms need not be explicitly known, their effects upon surface convergence (a measure of upward vertical motion) should be carefully monitored. Convective systems tend to develop in areas of pre-existing surface convergence with maximum cell intensity coinciding with the zone of maximum convergence (Uccellini 1971, 1972). Sub-synoptic scale wind measurements should be used to calculate the convergence, preferably on an hourly basis.

4. Terrain

Finally, the effects of terrain should be noted, especially near mountain and plateau ranges. This may be especially important in eastern Colorado where severe hailstorms frequently occur. An east to southeast wind from Oklahoma and Texas will lift parcels nearly 3,000 feet. This lift may be sufficient to trigger the storm development.

The above parameters have the primary advantage of being observable, through constant and careful monitoring, well before the convection has developed. The relative intensity of the convective system should be predictable given these variables. However, careful monitoring of certain variables during the life span of thunderstorms may yield telltale signs of impending (or almost immediate) catastrophic weather such as hail, windstorms, and tornadoes. Some of these parameters may be:

1. Development of a meso-low usually associated with the most severe convection. Therefore look for areas of rapidly falling pressure where convection is already in progress (Fujita 1963, Miller 1967).

2. Anvil growth as viewed from a geostationary satellite may yield insight into the intensity of individual cells (Auvine and Anderson 1972, Sikdar et. al. 1970, Sikdar 1972).

SEVERE CONVECTIVE STORMS

PRINCIPAL FINDINGS:

To monitor: lapse rate $\frac{\partial \theta}{\partial p}$, $\frac{\partial \sigma}{\partial t}$ $\sigma = -\frac{\partial \theta}{\partial p}$

Before the convection starts:	During storm development
θ_e	pressure tendency
surface convergence	anvil growth
terrain effects	

1. Radiosonde network supplemented by satellite soundings to determine: mass field, winds, temperature and moisture (note that the vertical structure of the soundings is very important).

2. "In situ" (surface temperature, winds, pressure and dewpoint), to measure low level convergence, θ_e, terrain effect and pressure tendency.

3. Radar and satellite to monitor thunderstorms as they develop and measure the intensity of each system.

KNOWLEDGE REQUIREMENTS

(Severe Storms)

Vertical stability (800-100 mb).

Vertical wind shear (800-100 mb).

Determine surface pressure field, tendency, fluctuations.

Locate and track severe local storms, squall lines.

Locate jet streams.

Identification of rapid growing cumulonimbus and cirrus anvils.

Location of regions of strong convective activity.

Locate inversion layer(s).

Locate regions of dynamic instability (advection - K.E.).

Locate regions of thermodynamic instability (convection - pot. temp.).

Locate dry air above 800 mb.

Locate regions of subsidence.

Locate thermal tongue.

Detect steep temperature and moisture gradients.

Detect wind veering (friction, gradient wind, thermal wind).

Detect difluent areas.

Potential temperature field (1000-800 mb).

Potential temperature field (800-100 mb).

Monitor location and quantity of precipitation.

Terrain effects on motion field (valleys, mountains, sea breeze, etc.).

Monitor output of numerical models

Convergence and divergence (1000-800 mb).

Convergence and divergence (800-100 mb).

Convective cell intensity.

Pressure field (1000-800 mb).

Atmospheric motion field (1000-800 mb).

Atmospheric motion field (800-100 mb).

Precipitable water.

Temperature lapse rate.

Vertical stability (1000-800 mb).

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E. Frost

Of all the weather related concerns of agriculture, perhaps only rain is more important than frost.[1] Crop damage from frost is endemic, a threat through all but the warmest months of the growing season. Although losses most often are small, they can be disastrous: in Oregon on 6 May 1968 damage to the fruit crops totalled several million dollars (Anon., 1969).

Frost may occur with or without surface wind.[2] In the former case, sub-freezing temperatures are principally a result of advection, as in an outbreak of arctic air. Because of the massiveness of such cooling, little can be done to prevent damage. Frost occurring under conditions of light surface wind or calm results principally from radiational cooling. Stagnation of the air and the limited vertical extent of the cooling make prevention of damage in this case very much easier; hence, it is this type of frost about which we shall be most concerned.

Radiation frost most typically occurs in the centers of cool, dry anticyclones and anticyclonic ridges. The rapid surface cooling needed for frost production is favored there by the clear skies and weak surface winds that typically prevail. Temperatures drop until sunrise brings a reversal in the balance of net radiation; however, an hour or two after sunset the rate of fall begins to decrease as radiating surfaces become colder (Figure 12). It also may decrease if condensation occurs on exposed surfaces, and may stop altogether if the air becomes saturated and fog forms. Cooling stops with the formation of fog because part or all of the outgoing radiation is intercepted and reradiated back. Cloud decks and moist layers act similarly. The effectiveness of fog, clouds, and moist layers as radiation shields depends both on their thickness (opacity) to longwave radiation and on their height (temperature). (Clouds, because of their generally greater opacity, are far more important than fog and moist layers.) Advection of a low or middle cloud layer overhead often reverses the temperature fall (Figure 13). Since surface temperature depends upon conduction as well as radiation, the occurrence of frost depends also on how fast heat is conducted to the cold radiating surface. This heat comes both from the air above and from the ground below. The conductivity of soil increases with increasing moisture content. Therefore soil moisture can be a factor of significance. Although air at rest is a poor conductor, in turbulent motion it transports heat very well. Since the air 10 to 20 meters above a cold radiating surface often is 10 to 14 F degrees (6 to 8 C degrees) warmer than the surface itself, forced mixing by, for example, a gust or pulse of wind can stop or even reverse a temperature fall; initially, through what might be considered a very local downward advection of warm air, and subsequently, through turbulent transport of heat to the radiating surface (Figure 14).

Short term frost protection measures are aimed at keeping plant tem-

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[1] In this discussion the term "frost" will include freezing conditions, both with condensation (hoarfrost) and without (blackfrost).

[2] Except where otherwise noted, the discussion which follows is based principally upon the 1963 WMO report, "Protection Against Frost Damage."

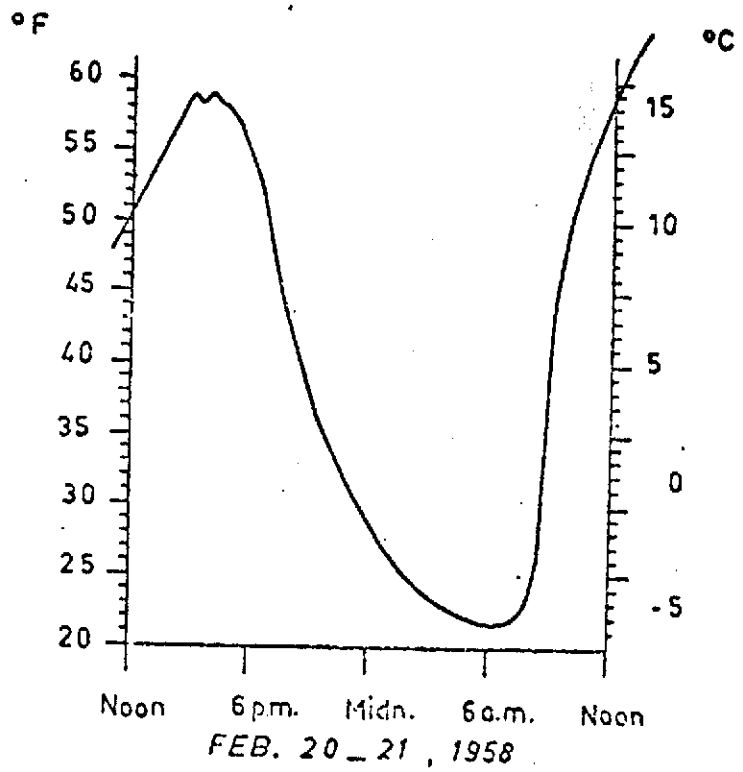

Figure 12 Radiational cooling, Polk City, Florida

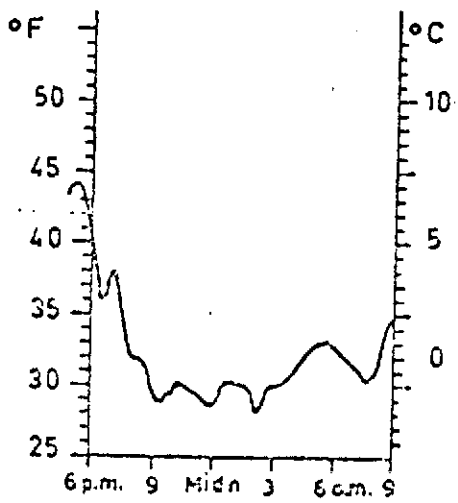

Figure 13 Effect of passage of clouds on temperature. Lake Garfield, Florida. Jan. 17-18, 1959 (from Georg)

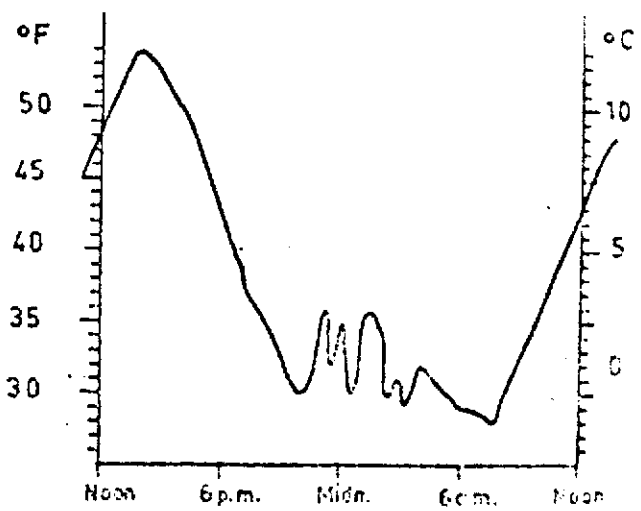

Figure 14 Effect of wind gusts on minimum temperature. Passadena, Florida. Jan. 22-23, 19[illegible]

peratures above the critical level at which destructive freezing of tissue begins (typically 1 to 3 F degrees or .5 to 2 C degrees below freezing). Methods most commonly used include covering, wind machine mixing, irrigation, and heating.

Covers act as radiation sheets preventing direct loss of heat to space. Materials in use range from soil--sometimes turned over young tomato plants in Florida--through water--the flooding of cranberry bogs in Wisconsin--to wooden troughs, boxes, baskets, screens and caps.

Mixing may be successful under conditions of strong low level inversion. It employs tower mounted fans or helicopters.

Irrigation is widely used because it employs ordinary irrigation equipment. Warm water is sometimes run into furrows between threatened plants, but more often plants are sprinkled through the vulnerable period. Freezing of liquid water on the plant surface releases latent heat of fusion. So long as liquid water is available for freezing, tissue temperatures are held at 32° F (0°C) and will not freeze.

Heating as a method of frost protection dates back at least 2000 years. Fires, ignited from wood, coal, charcoal, oil, or other fuels, heat the cold air layer below the inversion, preventing a drop below the temperature required for freezing plant tissue.

One additional measure may be available to agriculturalists threatened by frost--forced harvest. Of course, this presumes the crop is at a harvestable stage, and that sufficient labor and equipment are available to do the harvesting.

The lead time needed by growers on a forecast of frost depends on the crop, methods available for protection and the local supply of labor and materials--especially fuel. In Wisconsin, protection of cranberries until fairly recently was accomplished by flooding the bogs, a process which takes 5 to 8 hours (Tibbits and Meier, 1971). Nowadays, most growers use sprinklers, substantially cutting the needed lead time (Rosendal, 1973). In Florida, where protection for citris groves is provided by heaters, the lead time needed by growers is longer: arrangements must be made for fuel and labor, heaters must be checked and filled, densities and distributions of heaters sometimes need changing to better meet the threat. Considering these and other factors, the time required to respond to a frost forecast requires a lead time, if the forecast is to be useful, of 6 to 8 hours for a cranberry grower, at least 12 hours for a citrus grower (Georg, 1973). But issuance of the forecast is not the end of it. Especially if the frost threat diminishes, the grower can act to lessen his loss, for example, by releasing crews if a changing situation eliminates the danger of frost. Therefore, the Florida frost warning service issues, in addition to its main bulletin at 10:00 A.M., two updates, at 4:15 P.M. and 10:15 P.M. (Georg, 1973). The savings to be gained here are so large, and the lead time on such decisions is so short, that Florida growers are clamoring for an additional update at 1:00 A.M. (Georg, 1973).

Improvement in frost warnings through SEOS would come primarily through refinement and updating of forecasts and advisories based upon conventional data sources. Visible and infrared sensors would monitor clouds, including coverage, thickness, level, and movement. Knowing when a cloud deck will move in might save an agriculturalist thousands of dollars in operating costs; knowing that a cloud deck will break up or move out might save him his crop. From window infrared measurements of the surface rate of cooling in and adjacent to vulnerable areas forecasters could update and refine forecasts of minimum temperature and frost timing; subsynoptic-scale features such as cloudless wind shift lines, cols, and gust fronts should also be apparent from such measurements. The importance of such features as controls on surface temperature is apparent in Figures 13 and 14.

A sounder offering good resolution in the boundary layer would much improve this potential, by measuring, for example, the strength and level of the surface inversion, the presence of moist layers in and above the boundary layer, and the presence of low level baroclinic zones with associated circulations that could disrupt the surface inversion.

An additional role for SEOS, suggested by Mr. James Georg of the Lakeland, Florida National Weather Service frost warning service, is verification and evaluation of forecasts. Fields of surface temperature deduced from the infrared radiometer would provide information of enormous value: in the short term for identifying and explaining discrepancies between forecast and actual temperatures, in the long term for locating frost sensitive crops in frost-free areas or possibly reducing risks, where movement of a crop is impractical, by diverting or channeling cold downslope flows.

KNOWLEDGE REQUIREMENTS

(Frost)

Cloud cover.

Cloud thickness.

Cloud altitude.

Surface wind speed.

Moisture content of surface air.

Soil moisture.

Moisture content of the free atmosphere.

Surface Temperature

Boundary layer mean temperature

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F. Lake and Sea Breeze

Lake and sea breezes are localized and very shallow phenomena. They occur entirely due to differences in temperature between land and water. Their importance to us lies in the fact that many industrial cities are located near water and are greatly affected by local circulation patterns. Since these local patterns are often quite different from the larger scale wind patterns which might exist 10-15 miles inland, they can significantly affect the local distribution of smoke, fog, and temperature. Accurate prediction of the intensity of these breezes could permit the few hours needed for decisions not to fire up factory boilers or incinerators or to move a picnic from a lakeshore park further inland.

One of the conditions needed to start these circulation patterns is a minimal amount of cloud cover so that the sun can heat the land. The air becomes less dense above the land and a pressure gradient force develops directed from the land toward the water. The resulting transfer of air raises the sea level pressure off the coast. Cooler sea air then moves inland near the surface and replaces the air which was removed from the land area. Figure 15 illustrates how the circulation is dependent on temperature-induced pressure forces.

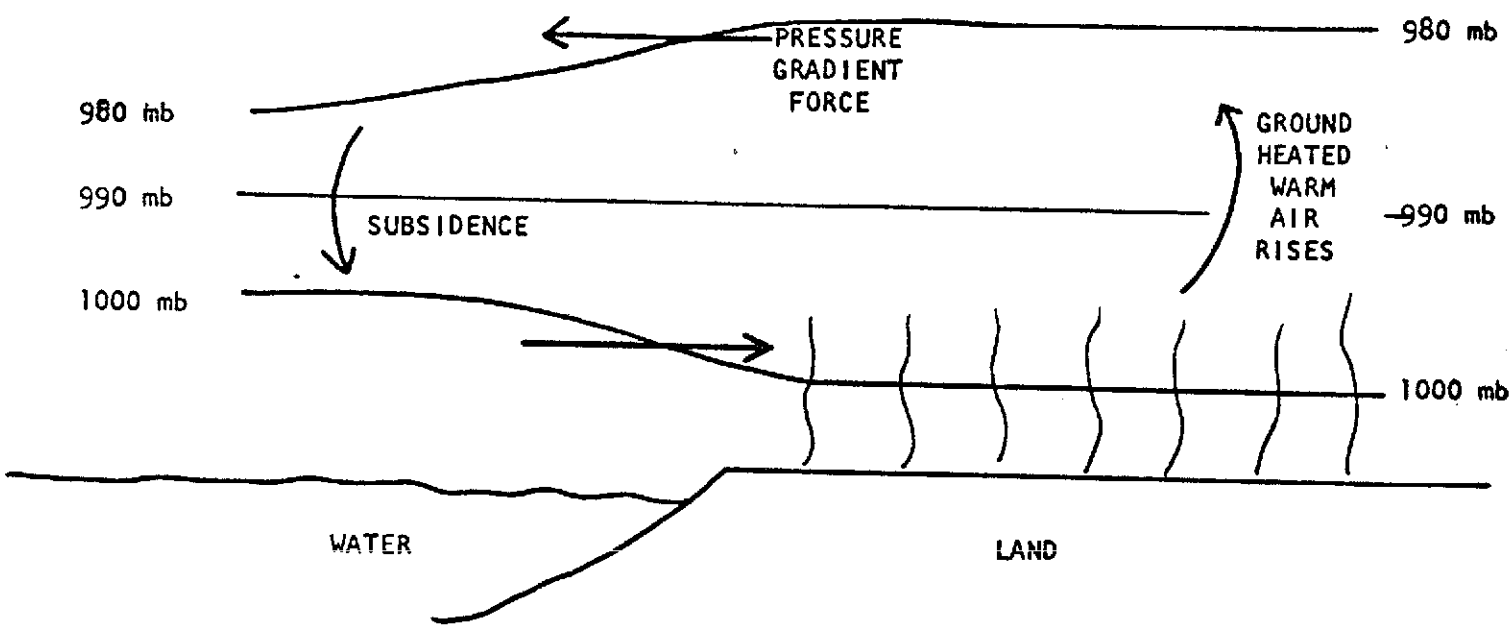

Figure 15. Source of the lake and sea breeze.

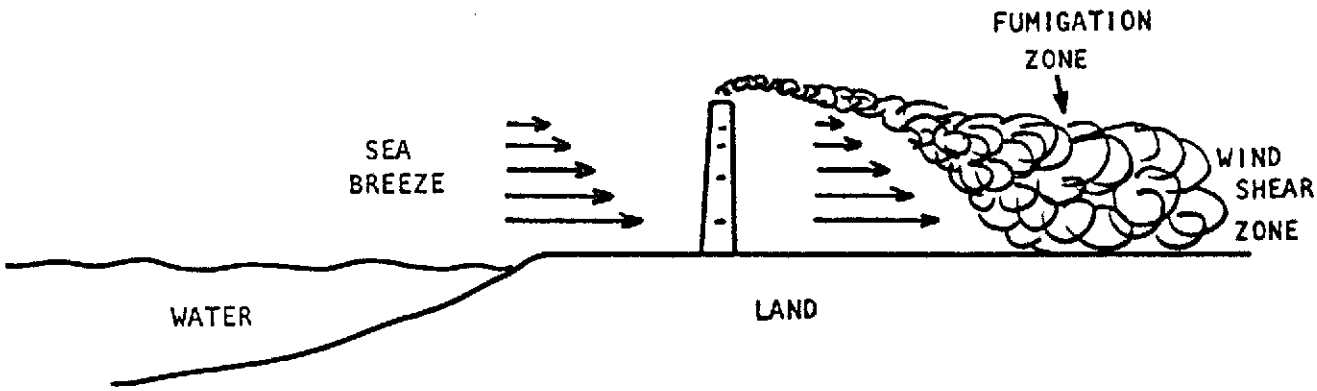

Figure 16. Source of the "Fumigation Zone".

The effect of such shallow circulation is illustrated in Figure 16. Cooling smoke from a chimney drifts down until it encounters the sea breeze. If the velocity gradient (shear) is large enough and the wind is strong enough, turbulent mixing will occur downstream. The velocities and gradients are smaller here, but the phenomenon is the same as that producing clear air turbulence. If the Richardson number is small enough, turbulence occurs. The result is called the "fumigation zone," a phenomenon well known by those living a mile or so from a large smokestack.

At night the land cools faster than the water, and the breeze phenomenon is reversed. The smoke blown inland during the day is sent out to sea. The next morning it reappears as the land warms and the circulation reverses once more.

Good models of the sea breeze circulation exist. Parameters needed to accurately describe the extent and intensity of local winds are the water and land surface temperatures. Regional wind patterns must be well-known, for the sea breezes are superimposed upon them. If the regional wind is too strong, the effect of the sea breeze is nullified. On the other hand, if the conditions are right, the effects are quite spectacular. High resolution imagery from satellites can trace smoke, indicate wind speed and direction, and locate lake breeze fronts. The surface temperatures are measured using IR imagery and radiometry.

KNOWLEDGE REQUIREMENTS

(Lake and Sea Breezes)

Determine extent and state of surface water.

Monitor smoke plumes, size, spread, and direction.

Determine land temperatures.

Atmospheric motion field (1000-800 mb).

Vertical stability (1000-800 mb).

Determine surface pressure field, tendency, fluctuations.

G. Air Pollution

Ecologists and environmental scientists have long been aware that pollution, far oftener than not, is more than just a local phenomenon. During the past few years there has been a growing demand for an observation technique that would permit the course and extent of a specific pollution phenomenon to be traced on a regional, and even global, basis, if necessary.

The deleterious effects of air pollution on human health depend on both the kind and the amount of pollutants present in the atmosphere. There is strong evidence that combinations of pollutants cause adverse health effects. Pollutants of major importance are the oxides of sulphur and nitrogen, carbon monoxide, particulate matter, and hydrocarbons.

Combustion of sulphur-containing fuels is the primary source of sulphur oxides in the atmosphere. Contributors of these pollutants range from the individual consumer by home heating to industry by combustion of coal for power generation, smelting, sulphite pulping operations, oil refining, and other processes. High concentrations of sulphur oxides, usually in the presence of particulate pollutants, appear to increase the risk of lung cancer and intensify distress from chronic respiratory diseases, resulting in increase in deaths and morbidity rates.

Aerosols of many types, especially those in the sub-micron size range that are particularly capable of penetrating deep into the respiratory system, serve as carriers of gaseous pollutants by both absorption and adsorption. Many other pollutants have been identified in urban and industrial communities, but only limited evidence is available concerning the health hazards involved.

The importance of meteorological factors in the transport and diffusion stage of the air pollution cycle is well recognized, and the literature is relatively voluminous on the subject; see, e.g., Pasquill, 1962, Slade 1968, and Scorer, 1968, for complete and informative treatments, and Air Pollution Control Association, 1968, for a recent annotated bibliography on air pollution meteorology. Not quite so obvious, but equally significant, is the importance of meteorological factors in the emission and reception (or immission) stages. Emissions from combustion of fossil fuels for space heating are related to air temperature. Aero-allergens such as ragweed pollen are released into the atmosphere only within certain limits of temperature and humidity. The entrainment of dusts into the air from ground surfaces is related to wind speed. The effective stack height of hot effluents emitted from chimneys depends upon the ambient air temperature, stability and wind speed.

The formation of secondary (photochemical) pollutants over urban areas is controlled not only by the rate of emission of the reactants into the air, primarily from automobiles, but also by wind speed, turbulence level, air temperature and solar radiation. Other atmospheric reactions may also depend upon the ambient humidity, as in the conversion of gaseous SO_2 to sulphuric acid droplets. The atmospheric scavanging by natural precipitation is an important cleansing mechanism, but it can cause contamination

problems at ground level.

Satellite measurements of air quality and meteorological elements are made generally in urban areas, for one or more of the following purposes:

1. To survey the distribution or dispersion of effluent from a particular source or source complex in anticipation of possible abatement action;

2. To collect data for forecasting purposes, usually in connection with atmospheric transport and dispersion processes; or

3. To document the conditions and climatology of the atmosphere over a community.

No single observational array will satisfy all requirements. The survey and research activities deal with specific three-dimensional space frameworks and particular time scales. Pollutant distributions in the vertical on the scale of meters to 1 or 2 kilometers (i.e., the depth of the mixing layer) are usually the critical factors to be determined in quantitative terms. Hence a capability for three-dimensional "soundings" in the mixing layer is imperative, for instance, in delineating the geometry of dispersion of individual pollutant plumes. Statistics of dispersion geometry are required on scales of a few hundred meters to tens of kilometers and also on time scales up to several hours.

SEOS can especially contribute in important ways to air pollution control activities including research, surveys, and operational programs. These can be categorized in the following areas:

1. Evaluating the effectiveness of individual control or abatement measures for a polluting source or a complex of sources.

2. Providing the basic analytical framework for development of control schemes and strategies yielding the optimum ratio of benefit to cost where these are related to atmospheric processes. Meaningful interim abatement schemes cannot be derived without regard to atmospheric transport and diffusion processes and their variability.

3. Forecasting concentration distributions of air pollutants on significant time and space scales under "normal" conditions of pollutant emissions, and with designated levels of control.

On a climatological basis the normal progression of diurnal and annual cycles of weather conditions and the diurnal, weekly, and annual cycles of pollutant emissions results in reasonably orderly and predictable diurnal patterns of air pollution in cities. The mass of data and literature on this subject (see Stern, 1968, for the most recent comprehensive survey on all phases of air pollution) indicates that most primary pollutants, e.g., SO_2, CO, oxides of nitrogen, and particulates, usually show two diurnal peaks, one occurring sometime after sunrise between 0700 and 1000 local standard time (LST), and the other in the evening between 1900 and 2200 LST.

On a day-to-day basis, however, departures from the climatological "normality" can be very great--as much as three orders of magnitude or more in the concentration of some pollutants. Except for accidental releases of large quantities of a pollutant, this variability is almost entirely due to the variability in meteorological elements that influence the production of pollutants and govern both transport and dispersion in the urban environment, as well as the transformation of pollutants in the atmosphere after they have been emitted.

The structure of the boundary layer over an urban area is often greatly modified from the structure observed in an upwind rural area. It is not surprising, then, that urban diffusion models based on a description of dispersion derived for steady conditions over smooth homogeneous terrain would hardly give satisfactory results. Advances in satellite observations of urban area dispersion will be directly tied to increasing our knowledge of the structure of urban atmospheres and incorporating this knowledge into models of atmospheric kinematics.

The urban-induced modification of the structure of the boundary layer is readily apparent in mesoscale observations of the near-surface air temperature; the urban area is usually warmer than adjacent rural areas, especially at night hours.

Four obvious factors contribute to the urban temperature excess: urban-rural differences in the thermal characteristics of the surface, evaporation rates, amount of heat produced by artificial sources, and long-wave radiation back to the surface from polluted layers in the urban atmosphere. The magnitude of the urban temperature excess appears related also to the lapse rate in the planetary boundary layer upwind of the city. The increasing depth of the mixing layer and, consequently, the urban temperature excess from the upwind edge to the center of the city can be determined as a function of the lapse rate of the planetary boundary layer upwind from the city, the heat sources within the city, and the average wind speed within the boundary layer.

Clearly, urban temperature fields are indicative of the potential dispersion characteristics of the urban atmospheric environment. The vertical temperature structure relates directly to urban dispersion. The atmospheric processes favorable for the establishment of a strong heat island (i.e., clear skies, light winds, and anticyclonic conditions) are also favorable for high concentrations of atmospheric pollution.

It is obvious that knowledge of the mean and turbulent structure of the wind field over urban areas is also fundamental to understanding urban pollution transport and dilution. In principle the measurement of wind is deceptively simple, but in practice measurement of even the horizontal component is notoriously difficult since it varies in three dimensions and in time and is radically affected by location and sensor characteristics.

The tetroon (tetrahedral plastic balloon) follows horizontal air motions with almost complete fidelity and also gives a good approximation

of vertical velocity (Booker and Cooper, 1965). Perhaps the most striking result from such experiments has been in showing the extreme complexity of the paths of air parcels under conditions when the surface winds are light or the flow is influenced by mesoscale phenomena. Figure 17 shows how a difference of only 2 hours in the release of the tracer (tetroon) resulted in dramatically different trajectories separated by more than 120 degrees in azimuth and more than 50 kilometers in distance over a period of only 16 hours.

In contrast, analyses of surface-wind data under conditions of moderate to high wind speeds with a well-mixed lower atmosphere show that surface trajectories deduced from the surface-wind observations correspond quite well with those obtained from upper atmosphere tracer experiments.

In the mean, however, the surface data always underestimate the speed of transport. This, of course, is to be expected. The trajectory directions are also significantly different. In the Los Angeles data the upper-level directions were shifted counter-clockwise from surface directions.

For a number of decades experimental work has been performed to assist in describing diffusion and its relationship to meteorological parameters. As there is no adequate theory describing the urban effect, experimental studies have been initiated in several places to specifically depict the turbulent structure and attendant diffusive characteristics of the urban atmosphere. The results show that irregular terrain has a strong channelling effect, the tracer clouds are noticeably and predictably deflected by the sea-breeze flow, and the tracer clouds are held below inversion bases except over hills whose crests are above the inversion base.

The potential for high air pollution is defined as a set of large-scale meteorological conditions that would lead to the widespread occurrence of high concentrations of pollutants that are typically emitted by myriad sources in most communities. This definition is in terms of meteorological conditions only, regardless of whether a city or industrial district is actually located in the geographic area of concern.

The meteorological criteria for issuance of a forecast of high air pollution potential in the United States were initially specified by Niemeyer (1960):

1. Surface winds less than 8 knots;
2. Winds aloft to 500 mb, 25 knots or less;
3. Subsidence below 600 mb;
4. The above conditions occurring over an area at least as large as a 4-degree longitude-latitude rectangle, and forecast to persist for at least 36 hours.

These conditions are recognized as commonly occurring with quasi-stationary warm-core anticyclones, which have been associated with episodes of high air pollution (Schrenk et al., 1949; Douglas and Stewart, 1953;

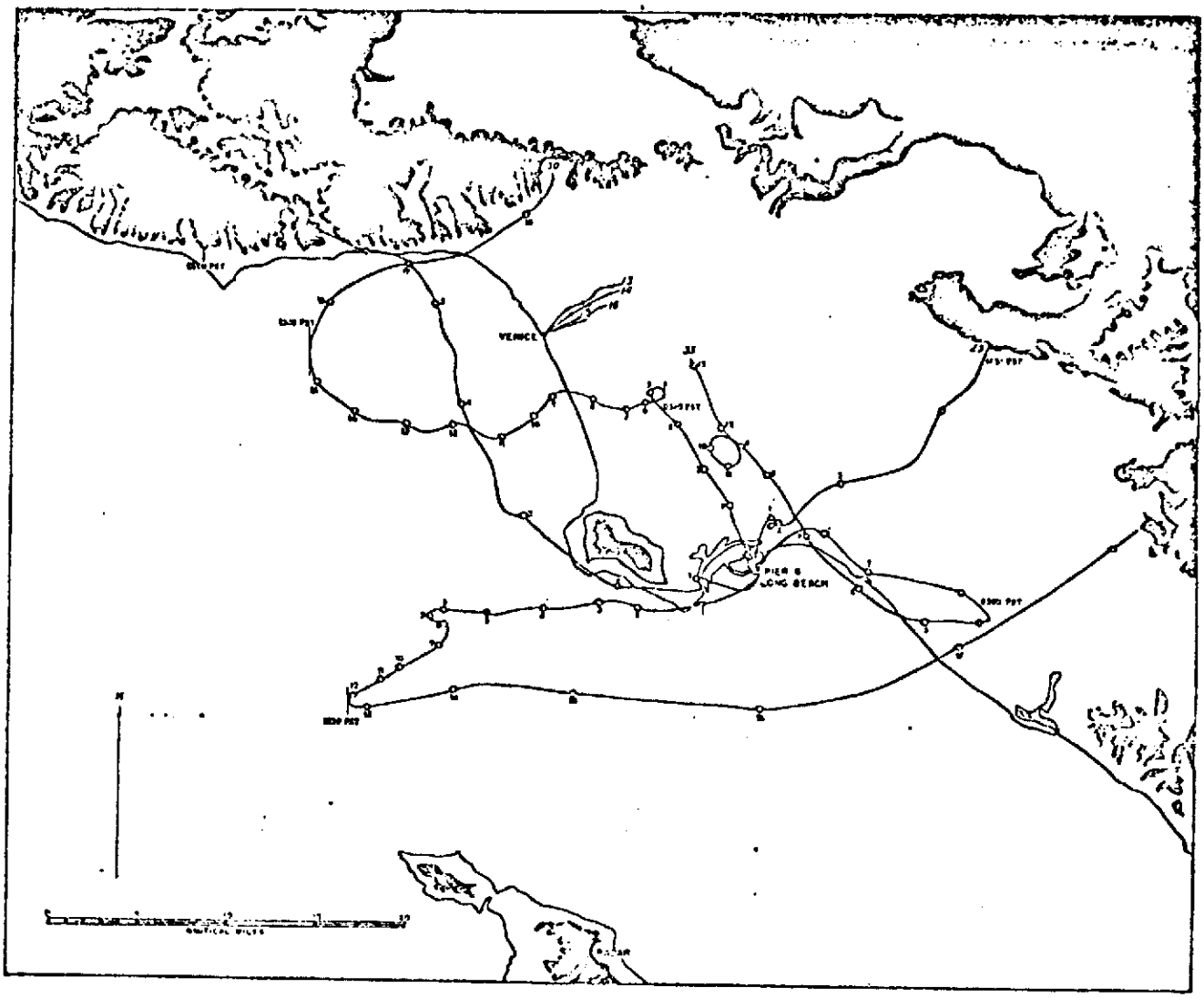

Figure 17. Series of tetroon trajectories originating at Long Beach showing land and sea breeze effects, and a series originating at Venice Marina (positions at hourly intervals, PST) showing veering of sea-breeze flow with time. (Pack and Angell, 1963)

Lynn et al., 1964).

At present the main parameters in the forecasting technique are mixing height and average wind speed through the mixing-height layer. The afternoon mixing height is estimated as the height above the surface at which the dry adiabatic extension of the surface maximum temperature intersects the vertical temperature profile observed in the early morning. Mean values of mixing height and vertically averaged wind speed for several locations have been given by Holzworth (1967, 1969). Figure 18 presents an example of the spatial occurrence of exceptionally limited afternoon mixing heights and average wind speeds during an extended episode of severe air pollution (Lynn et al., ibid.). The afternoon hours usually represent the diurnal time of greatest mixing heights and wind speeds; during this period, however, a large stagnating anticyclone was centered over the Great Lakes and extended southward to the Gulf of Mexico.

The current criteria for forecasting high air pollution potential (Stackpole, 1967) are as follows:

I. Observed this morning and subjectively forecast for tomorrow morning:
   A. Average wind speed through the mixing height 4.0 m sec^{-1} or less;
   B. Urban mixing height 500 meters or less.

II. Forecast for this afternoon and tomorrow afternoon:
   A. Average wind speed through the mixing height 4.0 m sec^{-1} or less;
   B. Ventilation (mixing height x average wind speed) 6,000 m^2 sec^{-1} or less.

III. Forecast throughout the 36-hour forecast period:
   A. Small values of 500-millibar vorticity and its 12-hour changes;
   B. No significant precipitation.

As might be expected, operational evaluation of the mixing-layer data has shown that the concept is valid only in large areas of nearly steady-state conditions, e.g., warm-core anticyclones. Fortunately, it is in just such situations that a "threat" of high air pollution potential usually exists. Conditions over these areas will be objectively forecast for 12-hour intervals out to at least 36 hours and will provide a basis for increasing the lead time of the pollution potential forecasts.

The most important use of a SEOS instrumental satellite toward forecasting air pollution would be to observe the development of the mixing-height layer and the motion of the temperature inversion layer. The primary advantage of SEOS observations over those of other satellites would be that SEOS could monitor the <u>local</u> urban atmospheric parameters, possibly at very high spatial resolution. Conditions of high pollution potential imply clear skies, which means that SEOS temperature soundings would be at their best.

The following measurement parameters are desirable:

a. Time: from the SEOS satellite, it must be possible to make soundings as required by changing atmospheric conditions, often

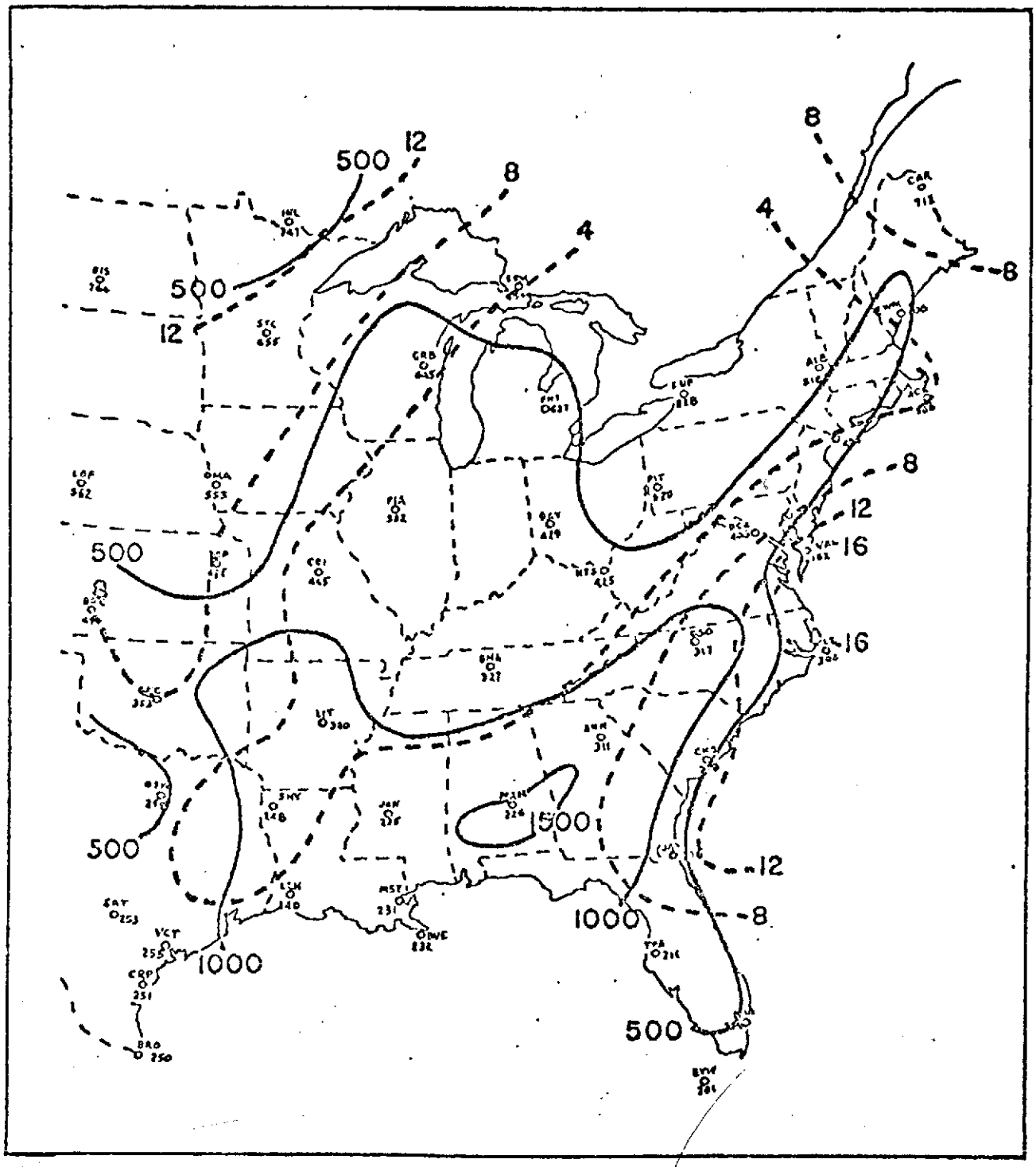

Figure 18.- December 1, 1962 isopleths of afternoon mixing height (m) above surface, solid lines, and vertically averaged wind speed (m sec^{-1}) through the mixing layer, dashed lines. Based on upper-air observations at stations shown, maximum surface temperatures, and assumption of dry adiabatic lapse rate in mixing layer. (Holzworth, 1969)

at regular time intervals for extended periods.

b. Spatial resolution: due to the many small urban regions in which air pollution can occur, many soundings should be made as close to every 2 km to 3 km over limited areas, and on the average at 10-20 km intervals.

c. Vertical resolution: in order to locate temperature inversions and moisture layers in the lower troposphere, the vertical resolution should approach 500 m at the boundary layer.

d. Accuracy: the sounding error averaged over the vertical resolution length should be $\leq .5°K$ in temperature and $\leq 10\%$ in relative humidity for the lower troposphere.

e. Spatial coverage: due to the development of air pollution at a number of geographic locations at the same time of day, it should be possible to make soundings over an area 30 km x 50 km within a period of 20 to 30 minutes.

KNOWLEDGE REQUIREMENTS

(Air Pollution)

Measure depth of mixing layer.

Determine land or surface temperature.

Determine extent of cloud cover.

Temperature lapse rate (1000-800 mb).

Locate inversion layers (1000-800 mb).

Monitor smoke plumes, size, spread, and direction.

Terrain effects on motion field.

Determine land temperatures.

Atmospheric Motion Field (1000-800 mb).

Location of transition layers or boundaries.

Surface turbulence.

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IV. Measurement of the Observables

A. Classification and Analysis of the Meteorological Knowledge Requirements

The knowledge requirements for phenomena discussed in Chapter III were tabulated to determine the frequency with which each requirement appeared. Table VII lists, in order of importance (as defined by frequency of use in Chapter III), the most commonly needed pieces of information. Over half of the mesoscale phenomena studied required this information for proper monitoring and forecasting of their development. The knowledge requirements cluster in areas of the motion field, the moisture field, and the thermal field. The less frequently used physical observations concerned mainly hydrometeors and assorted surface measurements. This, then, forms a useful classification of the physical "fields" for further study. The complete frequency of use list is given in Table VIII.

The physical fields define to a large extent, the type of measurement SEOS should make. Thus, we see fromTable VIIIthat IR sounding and wind inferences from cloud motion measurement should form an integral part of a viable SEOS system.

In order to determine if we could assign some special characteristics to the type of measurements to be made with SEOS, we made a classification of knowledge requirements by location in the atmosphere. Table IX shows the results, again in order of importance. Unlike other meteorological satellite systems now flying or planned, SEOS must strongly emphasize the monitoring of the earth's surface and the atmospheric boundary layer in addition to the usual tropospheric soundings. As the following sections of this chapter show, this means we must maximize vertical resolution of soundings below 800 mb and, in conditions of strong baroclinic activity, maximize time and space resolution of the measurements in the lower atmosphere. Table X details the relation of the physical field measurements and their location.

The influence of the analysis summarized in Table X guided further SSEC efforts toward regions of highest density in the Table. Special consideration was given to the physical conditions during which measurements would be made, since we could foresee a definite need to optimize the SEOS operational system and one optimizing technique is to fit the measurements to the scale of phenomenon. The failure of the "sieve" (mentioned in Chapter II) to further analyze and categorize measurements, and thereby aid our final choice of instrument parameters, was actually a blessing in disguise. It pointedly emphasized important facts which we were able to stress in the consideration of SEOS system characteristics.

1. Because we are considering complex interrelationships of physical fields described by means of non-linear coupled differential equations, much can be accomplished in an operational sense by means of indirect inferences. To be useful, SEOS need not gather all its information directly, as the following sections point out.

Table VII

Knowledge Requirements with Highest Frequency of Use

(Key Parameters in Order of Importance)
1. Boundary Layer Motion Field.
2. Vertical Stability.
3. Temperature Lapse Rate and Surface Temperature
4. Regions of Strong Convective Activity.
5. Middle and Upper Troposphere Motion
6. Pressure Field in Boundary Layer.
7. Moisture Field.
8. Convergence and Divergence.
9. Wind Shear, Jet Stream.

2. Because the situation is complex, we treated the monitoring in light of the general classifications defined by Table X. The following sections of this chapter show, however, a definite tendency to look at similar observing requirements from different viewpoints, reflecting the fact implied earlier that the problem of gaining meteorological knowledge is not one-dimensional. We cannot untangle all the observing requirements into a small set of unqualified measurements good everywhere under all conditions. Yet, until we have SEOS, the lack of data perpetuates our lack of understanding.

3. Because of the complexity of the mesoscale phenomena in a physical and mathematical sense, we must conclude that anything but a cursory approach to recognition, response, and forecasting by the SEOS system must involve substantial planning in the area of ground control. This includes full use of GATE acquired results concerning the boundary layer.

The following pages give some insight into both the complexity we refer to and also the great potential of SEOS. We follow with a description of the system characteristics needed for data processing and information dissemination to the public. The measurement requirements will then be used to define the SEOS hardware specifications and modes of operation.

Table VIII

Knowledge Requirement Frequency of Use Table

3	Determine extent and state of surface water.
1	Determine snow and ice cover and depth.
1	Catalog and interpret pilot reports of CAT.
2	Monitor location and quantity of precipitation.
2	Monitor smoke plumes, size, spread, and direction.
4	Terrain effects on motion field (valleys, mountains, sea breeze, etc.).
1	Monitor surface conditions and past history.
4	Monitor output of numerical models.
4	Convergence and divergence (100-800 mb).
3	Convergence and divergence (800-100 mb).
1	Dew point, humidity, mixing ratio.
5	Determine land temperatures.
2	Convective cell intensity.
1	Temperature and moisture fields inside and under clouds.
4	Pressure field (1000-800 mb).
8	Atmospheric motion field (1000-800 mb).
4	Atmospheric motion field (800-100 mb).
1	Moisture inflow.
2	Moisture lapse rate (mixing ratio).
3	Precipitable water.
6	Temperature lapse rate.
7	Vertical stability (1000-800 mb).
4	Vertical stability (800-100 mb).
2	Determine precipitation extent, type and intensity.
1	Determine electric field.
3	Vertical wind shear (800-100 mb).
4	Determine surface pressure field, tendency, fluctuations.
4	Locate and track severe local storms, squall lines.
3	Locate jet streams.
1	Identification of cloud patterns associated with jets.
2	Identification of rapid growing cumulonimbus and cirrus anvils.
4	Location of transition layers or boundaries.
5	Location of regions of strong convective activity.

4	Locate inversion layer(s).
3	Surface turbulence.
3	Locate regions of dynamic instability (advection - K.E.).
2	Locate regions of thermodynamic instability (convection - pot., temp.).
2	Locate dry air above 800 mb.
2	Locate regions of subsidence.
2	Locate thermal tongue.
3	Detect steep temperature and moisture gradients.
3	Detect wind veering (friction, gradient wind, thermal wind).
2	Detect difluent areas.
4	potential temperature field (1000-800 mb).
1	Potential temperature field (500-200 mb).
2	Potential temperature field (800-100 mb).
1	Richardson number tendency (500-200 mb).
1	Measure Depth of MIxing Layer
1	Determine extent of Cloud Cover

Table IX

Predominant Knowledge Requirement Locations

1. Boundary Layer (and Surface)
2. Middle Troposphere
3. General (unspecified)
4. Upper Troposphere

Table X

Location of Knowledge Requirements

Physical Field / Location	Mass Field	Motion Field	Thermal Field	Moisture Field	Hydrometeors	Other Quantities
Earth Surface and Boundary Layer 48	2	13	13	4	5	11
Middle Troposphere 28	1	11	7	4	1	4
Upper Troposphere 10	0	6	2	0	0	2
Stratosphere 1	0	0	0	0	0	1
Extra-terrestrial Regions 2	0	0	0	0	0	2
General Atmosphere 14	0	2	3	0	0	9
TOTALS	3	32	25	8	6	29

B. Monitoring the Earth's Surface and Boundary Layer

Of the nine most frequently needed meteorological knowledge requirements which Suomi's seminar students identified, seven came from the boundary layer. Of the 103 separate pieces of knowledge required, 48 (about 45%) must be gathered from the boundary layer. The reason for this is that we are considering weather phenomena affecting people's lives and property, and these destructive phenomena occur primarily in the mesoscale in the form of storms, fogs, floods, and wind. They occur on scales of tens to hundreds of kilometers in space and 1-6 hours in time. Synoptic scale air masses influence us climatologically as heat and cold or rain and drought, but it is the smaller, narrow frontal zones between the large air masses which contain most of the phenomena posing a physical threat. At present, prediction of localized disturbances is statistical only, because the type of information required for more precise short term forecasts cannot be collected often enough or with adequate spatial resolution. It is this type of phenomenon which SEOS is uniquely suited to observe and for which SEOS is needed in order to predict with greater accuracy. A large proportion of the high space and time resolution observations must be made in the boundary layer.

In atmospheric dynamics, the boundary layer (often called the Ekman layer) is considered to be the lower 10% of the atmosphere where the vertical viscous force is comparable in magnitude to the pressure gradient and Coriolis forces. The mean height of the boundary layer varies from 2-3 km, bounded at the top by the altitude where vertical transport of horizontal momentum by turbulent eddies becomes negligible. At this altitude, friction with the earth's surface no longer can produce low level convergence or cross-isobar flow and the wind becomes approximately geostrophic.

Synoptic models generally ignore the effect of the boundary layer except in the mean, because our atmosphere is so highly stratified that the predominant motion is horizontal. Yet, many of the mesoscale phenomena we seek to monitor are closely related to baroclinic disturbances. These disturbances are induced by activity in the boundary layer, developed by conditions further aloft, perpetuated by their own energy release, and vitiated by the stresses they eventually relieve in the atmospheric continuum.

In disturbed weather conditions there can be strong mass exchange between the boundary layer and the overlying cloud layer. The updrafts inside clouds transport heat, water vapor, and momentum from the subcloud layer while the compensating downward motion outside the clouds brings down and warms by compression the relatively dry upper air. Because of this mixing, the mean structure of the boundary layer is determined jointly by the action of turbulent and macro-scale dynamical processes. Models and parameterization schemes have been proposed which take into account these interactions in terms of large scale variables. For short term prediction, there are also smaller scale models which can be effective if properly parameterized. Much effort is now going into determining the correct parameters for such models, which are different over land and ocean. The results of the GATE

experiments, while mainly for the ocean, should shed more light on the needed density scales and tolerable errors in the measurements needed for input into small scale models. Clodman (1971) in Meteorological Challenges: A History (Information Canada) presents an excellent bibliography and summary of the existing situation.

> The general problem of the interaction between large-scale wind and topography to produce a wide range of smaller scale circulations is one of the most pervasive meteorological problems of today. Although it is important in terminal forecasting, pollution forecasting, forecasting for construction, forest fire hazards and in a host of other weather-sensitive activities, it has received relatively little attention.... It is clear that some aspects of the mesoscale information may be inherently unpredictable for conventional synoptic-scale forecast periods, particularly where the small-scale aspects depend on the precise position and shape of synoptic-scale features. However, where the larger scale flow is reasonably stable for a significant period of time, the terrain forcing effects should be dominant and predictable. In fact, over the years, weather forecasters have been empirically predicting some simple aspects of the latter type of mesoscale phenomena over relatively lengthy forecast periods. Thus, the challenge resolves itself to studying in more detail the interaction between terrain and macroscale flow to be able to predict many aspects of the local weather for days into the future.

We shall need a capability for defining the mean flux distributions and mean flow structure in the boundary layer, with the appropriate space and time variations. This means measuring the fields of surface pressure and temperature. Ideally, we also want the temperature field defined every 500 meters altitude in order to obtain improved measurement of vertical stability; but the least we need is the mean "thickness" of the boundary layer. We need horizontal velocity vectors good enough to compute horizontal convergence (and hence vertical motion), and horizontal advection of latent heat, sensible heat, and momentum.

Because turbulent stresses can be induced both mechanically (friction with snow, grass, buildings, hills) and thermally (solar heating of lower atmosphere and ground), the localized effects of the boundary layer can be significant and strongly dependent on topography, ground cover, and moisture content of the air. Since most solar energy is absorbed at the earth's surface, the amount of cloud cover is also highly significant. Localized thermal and mechanical stresses can be relieved most readily by convection, so the boundary layer is generally well mixed and supports an adiabatic temperature lapse rate. On cold, still, and dry winter nights, however, radiative equilibrium or a negative radiation balance prevail and the boundary layer could be highly stable and stratified.

Finally we need to develop surface charts of adequate detail and time resolution so the storm forecast computer has access to the latest conditions: up to the minute surface temperatures, pressures, winds, humidity trends, radar maps, and identified areas with high probability of significant weather. Some information can be less current, such as ground moisture content, river levels, regions of saturated soil and high flood potential. The more time variable the data, the more current and detailed the parameter tables must be.

In the remainder of this section on the earth's surface and atmospheric boundary layer, we shall identify the measurements which must be made as well as their accuracy, resolution, and frequency. Distinctions will be made to show what physical measurements are unique to SEOS and what can be done using other systems.

1. Physical Processes in the Boundary Layer

For convenience we will separate the boundary layer into three layers with somewhat differing physical properties and processes which influence the choice of what to measure and the tactics of making the measurement. These distinctions are depicted schematically in Figure 19. They are:

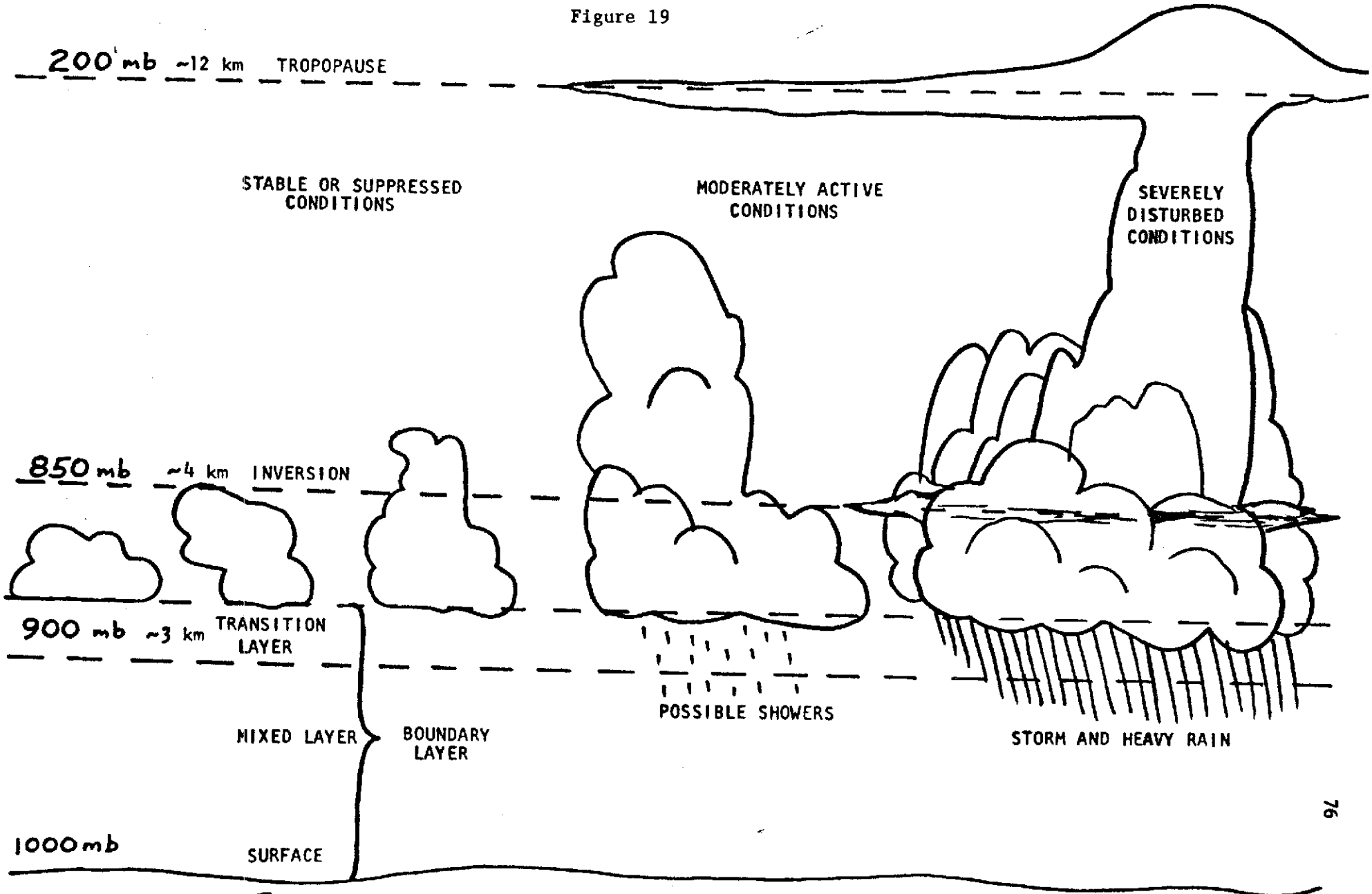
a. The surface layer, the lower bound of the boundary layer where temperature and pressure form a good datum for remote sensing and serve as indicators of trends higher up. The evaporation of water from ocean and land surfaces is a major source of energy for baroclinic disturbances. Surface winds can be modified significantly by friction and localized pressure gradients. The wind magnitude and direction is a key indicator of developing activity, because it shows where convergent/divergent regions are, and defines the amounts of advected sensible and latent heat and vorticity.

b. The subcloud or mixed layer is a region of decreasing eddy stress with altitude and rather uniform composition. Turbulent mixing of moist air in a relatively thick layer provides a large source of latent heat energy for storm development. Vertical motion is inhibited by stable stratification so if the vertical temperature profile in this layer is less than adiabatic or if inversions exist above the ground, convection and turbulence may be minimal. On the other hand, an intense thunderstorm, once started, acts like a chimney and generates quite a bit of horizontal air flow in this layer to replace the upward moving air inthe storm and maintain mass continuity. Vertical updrafts and downdrafts near the storm may generate severe turbulence. Most important of the physical processes occurring in the mixed layer are vertical and horizontal mass fluxes and the mixing of moist and dry and cold and warm air.

c. The transition layer is composed of cloud and subcloud regions across which mass, energy, and momentum are exchanged between boundary layer and the middle troposphere. This layer can be of great importance as an indicator of the many interactions and exchanges taking place near 900 mb. The downdrafts associated with deep cumulus clouds can penetrate into the subcloud layer and may enhance or inhibit later generation of clouds. The enhancement of cumulus may occur if there is a horizontal velocity field with a maximum in the cloud layer. Induced mixing then produces a downward transport of horizontal momentum, creating shears and turbulence and possibly generating convergence patterns leading to further cumulus development. If on the other hand, the downward moving air is sufficiently dry or warm, stratification and dilution of the subcloud air may occur so that a given level of convergence which initiated cumulus convection may no longer be able to gen-

THE BOUNDARY LAYER

Figure 19



RELEVANT SCALES OF OBSERVATION				
	TIME:	4 - 6 hours	30 minutes	5 - 15 minutes
	SPACE:	50 - 200 km	20 - 50 km	5 - 20 km

erate clouds where the stratification or dilution took place because the mean equivalent potential temperature of the subcloud air is reduced. The size, number, density, shape and growth rates of cumulus clouds in this region and just above, help to indicate the sign of vertical mass flux and also its intensity provided we also know the mean equivalent potential temperature of the boundary layer and the extent of mixing. One can distinguish inversion layers by the shape of the clouds. A developing storm cloud will often suck air away from under its neighbors and grow at their expense. The motion of small cumulus clouds, particularly their ageostrophic component (in the absence of strong baroclinicity) can be a measure of the net upward flux of horizontal momentum from the boundary layer.

Thus, at the earth's surface, we shall need to keep statistics on ground condition and cover, water area and depth, and critical areas delineated by a convergence of certain physical conditions at a point in time which could form a basis for later threats such as flash floods if certain atmospheric events occur as predicted. For the atmospheric models, we need definition of scalar fields such as surface temperature, pressure, mixing ratio, and their tendencies. We need surface wind magnitude and direction and preferably mean horizontal motion in the entire boundary layer. In the mixed layer, we need wind, moisture content, vertical stratification and temperature lapse rate. Moisture can be measured on the surface if the boundary layer is well mixed, but as with wind, a mean value throughout the mixed layer is more meaningful. At the top of the boundary layer we need data on cloud motion and statistics as indicators of conditions below, especially of convergence and vertical mass flux and the extent of mixing and dilution.

Another naturally appearing division influences the time scale on which meteorological observations should be made. We can separate atmospheric conditions into three classes:

1. Stable or suppressed, where inversions, subsidence, cloudy overcast, or lack of moisture may limit eddy stresses and convection. Conditions in this case tend to change slowly in time and also vary slowly on a horizontal scale. Observations made 200 km apart with a frequency of once every 4-6 hours are generally adequate to detect the onset of dangerous conditions.

2. Moderately active, where conditions have developed to being right for damaging weather. Cumulus towers may have started to grow, and showers may have begun. We are looking for the disturbance that will continue to grow and develop. Such local storms have a mean lifetime of one hour. At present, they cannot be identified until they are well developed and radar echoes appear. If these storms can be caught in their early incipient stages by satellite cloud imaging and inferences from boundary layer observations, perhaps another hour or two could be added to the warning time. In such unsettled conditions, observations every 30 minutes to one hour are desirable. Horizontally, conditions are varying over distances of 20-50 km.

3. Severely disturbed, the period of storm and heavy rain. The size and motion of the storm are easily detected by radar, but the shape,

altitude, and growth rates of the storm and its cirrus anvil, and the secondary developing cumulus towers are keys to predicting the storm intensity during the next 30 minutes, and indicating if tornadoes are likely to occur. Observations every 5-15 minutes are necessary to monitor storm development, which occurs in a limited area of 5-20 km extent.

One fact stands out above all others. If we are to make prognostically useful measurements, the observations must always be made at the correct spatial and temporal frequency for the physical phenomena under observation. To look too often or to look longer than absolutely necessary reduces the SEOS system capability for multiple observations. To look too seldom, or with poorer spatial resolution or signal-to-noise-ratio than necessary, severely reduces the short term predictive value of the system.

In this context, we should draw some comparison with the GATE program, since the results from the boundary layer observations during GATE will strongly influence SEOS design. The GATE Planetary Boundary Layer Program will make detailed studies relating to mass flux, turbulence, ocean surface and sub-surface conditions, pressure and temperature gradients. The accuracy and resolution will be much better than anything which can be done remotely by SEOS, since GATE will use a large number of in situ ships, buoys, balloons, and planes. On the other hand, mesoscale organization is such that we do not need to know in great detail about strongly localized interactions of the order of hundreds of meters in order to recognize an incipient storm. We need to know not so much about individual clouds and their interaction with the transition layer, but more about the statistics of a set of clouds in an area and the rate of mass transfer through the transition layer. The required scale, density, and accuracy of observations required for SEOS is different from that required for GATE. The parameterization of models that would work best with SEOS, however, remains to be defined. Observations made in GATE will authoritatively define the parameters to be measured and the time and space scales on which SEOS observations should be made to make most efficient use of the system.

2. Observations in the Boundary Layer

Tables XII, XIII, and XIV list the major meteorological observations required. In each case, a combination of satellite imaging, radiosonde measurements, and surface radar echo distributions will define the "state of cloud convection:" stable, moderately active, or severely disturbed. This will determine the density of measurements to be made in space and time, as shown in Table XI.

In practice, of course, one would hope the distinctions would be more subtle than shown in the table in order to make most efficeint use of the SEOS system. The most important thing to note is that the area coverage and time between observations are proportional in cases 2 and 3, but that

Table XI

Space and Time Density of Boundary Layer Measurements

Cloud Convection State	Frequency of Observation	Ground Resolution	Area Coverage
1. Stable	$(300\ \text{min})^{-1}$	200km	$40{,}000\text{km}^2$
2. Moderately Active	$(60\ \text{min})^{-1}$	50km	$2{,}500\text{km}^2$
3. Severely Disturbed	$(10\ \text{min})^{-1}$	20km	400km^2

the area increases faster than the time between observations in case 1. Thus, it becomes much harder for SEOS to monitor stable conditions assuming it gathers data at a constant rate, whatever the resolution. Fortunately, other geosynchronous sounders, such as that planned for GOES, or a set of polar orbiters such as Nimbus or NOAA will, together with conventional NWS observations, be able to provide adequate low resolution sounding at the 4-6 hour intervals. The imagers on GOES will be able to provide daytime and nighttime imaging on a synoptic scale which, with the sounding data, will permit definition of the disturbed regions which SEOS must cover. The resolution and accuracy of the other systems is not adequate in cases 2 and 3. Consequently SEOS must be a part of the larger system of weather satellites.

Table XII

Surface Measurements

1. Surface temperature distribution (±0.5°C)
2. Surface wind speed and direction (±1 m/s, 10°)
3. Surface pressure (±0.1 mb)
4. Mixing ratio (±0.5 g/kg)
5. Delineation of hydrometers falling on surface (type, intensity, duration)
6. River and lake levels
7. Watershed soil conditions, saturation points, soil moisture

Items 1-5 are generally measured hourly at all National Weather Service stations, but SEOS probably would require added in situ sensors systems such as planned for use with SMS and ERTS. The U.S. Forest Service is now testing such a system with ERTS for monitoring forest conditions for fire prevention and control. Depending on the predictive accuracy desired, such stations could be denser in those regions in the central and eastern U.S. where a longer warning time may be desirable. In less populated or mountain-

ous areas, the sensors could be spread more widely, and more emphasis could be placed on imaging rather than predictive models.

Item 5, besides direct measurements, can be measured remotely using ground or ship borne radar, enhanced satellite images, or passive microwave sensors. Intercalibration of the systems could be a sizeable problem.

Daily tables of items 5-7 are produced as a matter of course by various government agencies for a variety of reasons. The information is probably not adequate or in the proper form for use by the SEOS system. This area needs more study. It may be possible to measure some of these parameters directly with multispectral imaging from SEOS.

Table XIII

Measurements in the Mixed Layer

1.	Vertical temperature profile, preferably three measurements (surface, middle, and top) separated by 500 m to detect changes in stability. An average temperature throughout the mixed layer is tolerable. (±0.5°C)
2.	Mixing ratio averaged over entire mixed layer. Some slight vertical resolution desirable to detect dilution by downdrafts and subsidence (±0.5-1.0 g/kg)
3.	Horizontal and vertical wind profiles at 500 m vertical resolution, and 5 km horizontal resolution. (±1 m/s ±10°)
4.	Depth of the mixed layer. (±200 m)
5.	Detection of inversion layers between 700-1000 mb (1°C/500 m)

The vertical temperature profiles will be obtained primarily by means of high spectral resolution, low noise infrared sounding, for which SEOS is uniquely qualified by its fixed position relative to earth and its large aperture. A ground resolution of 35 km has been chosen as a compromise between the scales of observation required for moderately active and severely disturbed. The problem of cloud contamination must be balanced against the greater time needed to make the soundings at higher resolution. We have elected to compensate for contamination by adding more channels. Another serious question concerns exactly what increase in vertical resolution one can achieve by going to very narrow observation bandwidths. In principle, one should get an improvement, and indeed, improved vertical resolution is desirable to detect low level inversions and variations in mixing ratio. It will be necessary to use the a.m. and p.m. NWS soundings to fill gaps in the SEOS observations. SEOS will provide the improved time and space resolution we need, but only in limited regions of high activity. This involves an inter-calibration problem.

Wind shear measurements in the mixed layer are crucial to understanding mass flux and defining the convergence field. If the temperature field is well defined, we can derive the geostrophic wind component from thermal gradients. The convergence field cannot, of course, be derived from the thermal wind relationship, but we will have indications from surface winds as well as the 850 mb cloud motions and growth rates measured from high resolution images. Any ageostrophic component we can identify should be an indicator of baroclinicity, although, here again we would desire other indirect observations for verification.

Items 4 and 5 may be measured from high resolution images in addition to definition of the physical parameters (temperature and moisture fields) from sounding.

Table XIV

Transition Layer Measurements

1.	Identification of discontinuities in temperature, humidity, and horizontal wind velocity. (best estimates)
2.	Volume growth rate of active clouds (100 m resolution)
3.	Vertical velocity of cloud tops (3-5 m/s)
4.	Diameter of active clouds (100 m resolution)
5.	Fraction of sky covered by active clouds (5%)
6.	Height of cloud bases and change in time and space (200 m, 1 m/s)
7.	Cloud velocities and vertical wind shear (1 m/s, 1 m/s/100 m)
8.	Cloud top temperatures (2°C, 500 m resolution)

Item 1 will be inferred by all techniques at our disposal, mostly high resolution imaging and sounding Items 2-7 are all related to imaging at high resolution and all seem to cluster around 100 meters per resolution element. The velocity measurement of 1 m/s implies post facto pointing accuracy (with 5 minutes between observations) of 300 meters. At geosynchronous altitude, this requirement is a stringent 10^{-5} radians or better (<2 arc seconds) in celestial coordinates. If the subsequent images cannot be aligned to better than 300 meters, the measured velocities may not be sufficiently accurate. It may in most cases be possible to measure winds at 10 minute intervals, in which case 600 meter pointing knowledge is adequate. The alignment process also requires that all images have the same geometry. Moderate distortion is permissable, since locally it is small and will not affect measurement of volume or displacement if it is the same in both images. If, however, distortion is different from picture to picture, it adds the geometry change to the velocity error. SEOS is unique because

it should be able to track very small cloud tracers ahead of storm formation. Since there is a fairly good relation between size and depth it may also be possible to infer winds at different altitudes.

Finally, item 8 can be done best by IR imaging in the 11.5 μm window channel. It may be desirable to image in 2 spectral regions in the visible, say 400 and 700 nm to see effects of low level haze or moisture, but this is of low priority. What we do desire is the same 100 m resolution both day and night, Recently declassified Air Force weather satellites have imagers with 10^7 or better dynamic range. With this potential, it would be foolish to operate only at degraded IR resolution at night. It is doubtful we could observe any boundary layer convergence with poorer than 500 meter resolution imaging.

Table XV lists the desired SEOS performance for boundary layer measurements.

Table XV

SEOS Characteristics Defined by
Boundary Layer Performance Requirements

Imaging:		
(visible)	Resolution	100 m
	Spectral band	$0.7\mu m < \lambda < 1.0\mu$
		($\lambda \approx 0.4$ nm optional)
	Dynamic range	$>10^7$
	Signal-to-noise	>250:1
	Raster geometry	fixed
	Raster shape	frame or strip
	Raster size	50-400 km per scan line
(IR)	Resolution	500 m
	Spectral band	10.5 - 12.5μm
	Dynamic range	250:1
	NEΔT	0.5°C @ 250°K
	Raster geometry	fixed
	Raster shape	frame or strip
	Raster size	same as visible
Sounding:	Resolution	35 km (IR)
		100-200 km (microwave)
	(see section IV-D for added specifications)	
In Situ:	Capability to interrogate selected in situ sensors for P, T, q, v, ground moisture, water levels.	

The basic message we wish to impart is that there is a lot of information we could use, and that depending on conditions in existence at any point of observation, some pieces of information are more important than others. Many inferences can be made indirectly, which while not conclusive, may be justified by a preponderance of the data.

C. Severe Thunderstorm and Tornado Monitoring

1. Introduction

Tornadoes associated with severe thunderstorms kill an average of 118 persons in the United States each year (Pearson and Miller, 1971), while lightning accounts for another 180 deaths (Viemeister, 1961). Effective forecasting of these storms both on the time scale of severe weather watches (one to six hours) and on the time scale of warnings (one hour or less) is a prime concern of the National Weather Service. In spite of dramatic increases in our understanding of storm dynamics in recent years, the forecasting of severe convective storms remains an acute problem. This is so mainly because of lack of both adequate synoptic and meso scale data.

While a thunderstorm may have horizontal dimensions of 40 km., the distance between surface observing stations is at least five times larger and upper-air observations are more than ten times farther apart. Furthermore, while the giant severe thunderstorm may persist for upwards of six hours most storms are born, mature, and die in a fraction of that time; regular surface observations are at hourly intervals and the upper-air is sounded only once each twelve hours. The actual timing of the upper-air soundings while excellent for research is not optimal for forecasting. Figure 20 (from Winston, 1956) illustrates that soundings taken at 6:00 AM CST are six hours old before the frequency of tornadoes begins to rise to its early evening peak. During that six hour period significant synoptic-scale changes in the air mass structure take place which are difficult to predict. Soundings taken in the late morning and rapidly processed would alleviate this difficulty. This point is emphasized by House (1963) using verification statistics for tornado forecasts which show a sharp drop from 1957 to 1958 when soundings at six hour intervals over the midwest were dropped in favor of a twice daily schedule. The SEOS satellite has the potential of revolutionizing this picture.

It will be assumed in the following discussion that SEOS will be equipped with temperature and moisture sounding devices. Provided SEOS does have such sounding capability, it will provide temperature and humidity data of high spatial and temporal resolution, while observing storm structure and development in both the visible and infrared portions of the spectrum. Thus, SEOS will provide useful information at both the watch and warning stages of the severe weather forecast. Detailed proposals for application of SEOS data to the tornado and severe thunderstorm forecast problem will be found below following a brief background survey of recent research on storm structure and the synoptic-scale processes leading to storm development.

2. The Severe Thunderstorm

Excellent reviews of research on severe convective storms may be found in Palmen and Newton (1969) and Ludlum (1963), while detailed storm models based on a combination of their own case study results with the work of others are presented by Fankhauser (1971); Browning and Fujita (1965); and Browning and Donaldson (1963). These studies depict the severe thunderstorm in quasi-steady state with a tilted updraft, the core of which suffers negligible entrainment, a separate downward circulation branch extending from middle

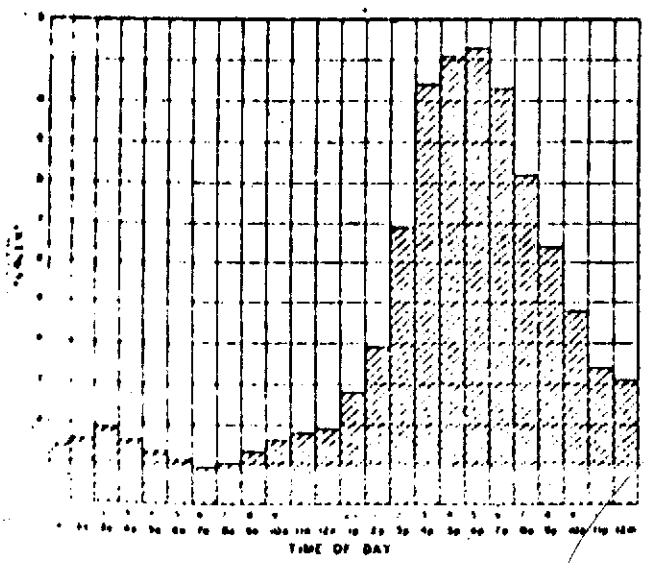


Figure 20.

troposphere to the ground, and strong flow relative to the storm both near the ground and at higher levels. These features are shown in Figure 21 after Fankhauser (1971). The structure and dynamics of these models place certain restrictions on the environment that can support such storms and allow one to deduce a model environment (Barber, 1968).

3. The Severe Storm Environment

There are four main requirements for the development of intense convective storms. a) The severe thunderstorm environment must be conditionally unstable to a high degree. To a first approximation parcel theory may be used to measure the degree of instability or what might be termed the available thunderstorm energy (ATE). Large amounts of ATE are associated with warm, moist air in low levels and cooler air aloft. b) The downdraft circulation is most well-developed when dry (potentially cold air) lies over warm air. Evaporative cooling from falling rain is then able to initiate and help sustain the downdraft. c) Relative inflow of warm, moist air in low levels to feed the updraft and cool, dry air in midlevels to feed the downdraft is facilitated by strong vertical wind shear in the environment. The existence of such shear is well documented for severe thunderstorms (see, for example, Marwitz, 1972 and Togstad, 1971). d) A mechanism is needed to initiate the processes which convert ATE into the kinetic energy of storm circulation. This mechanism may consist of a localized heat source which eliminates the low level stability commonly observed prior to severe convection (Fabush and Miller, 1954) or a lifting mechanism which lifts air to its level of free convection in the face of some stability.

In summary, the severe thunderstorm syndrome of the atmosphere is characterized by great available thunderstorm energy, dry air in midlevels and strong vertical wind shear. The storms themselves have unusually intense up and down drafts and appear to be remarkably persistent when compared to non-severe thunderstorms.

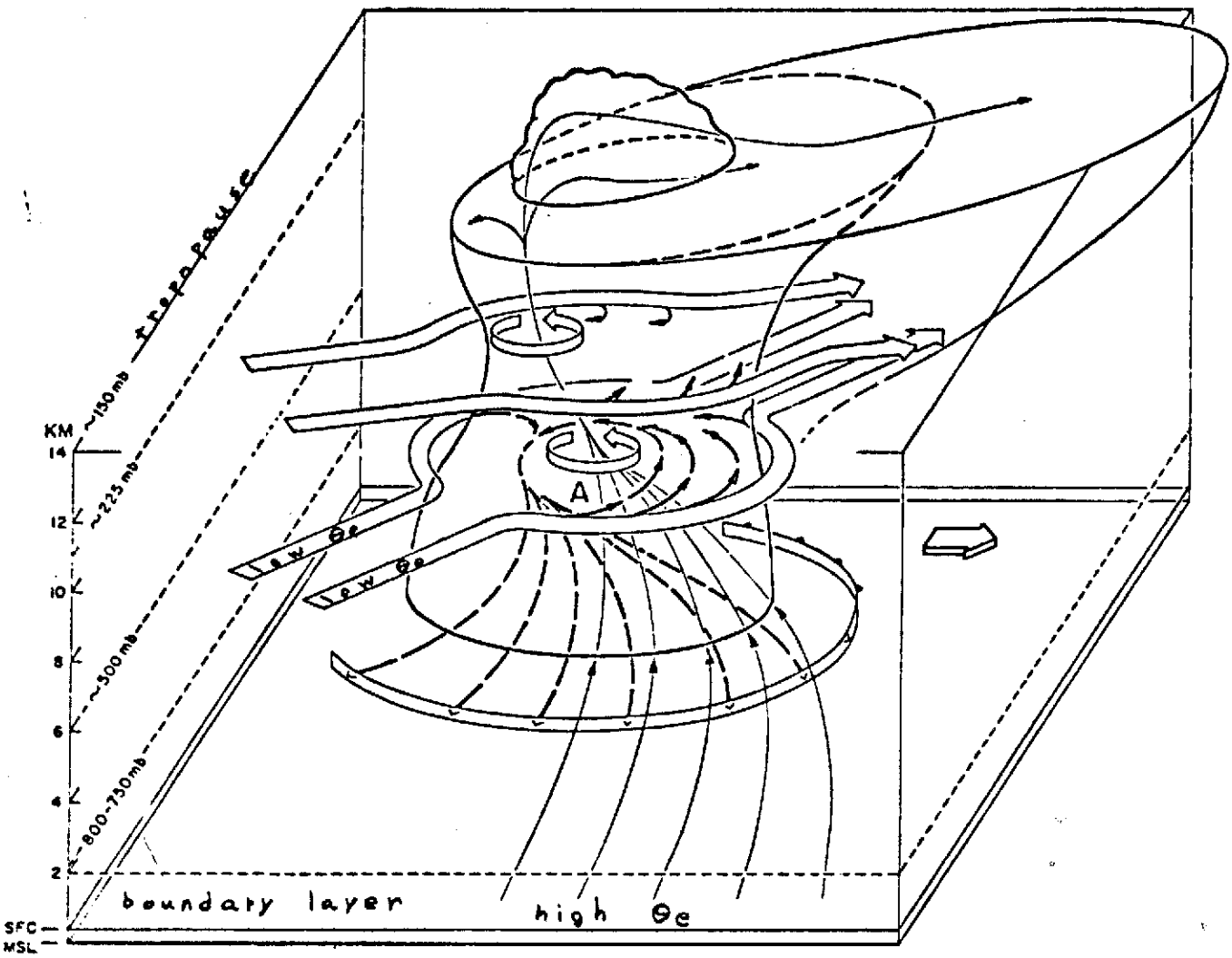


Figure 21.

It should be noted that there now exist no reliable techniques for distinguishing between days on which tornadoes will occur and days on which severe, but non-tornadic thunderstorms will occur. It is, however, well established by forecasting experience that the probability of tornado occurrence is directly related to the forecast intensity of severe thunderstorms. SEOS can play a crucial role in improving predictions of expected storm intensity.

4. SEOS Observations of Storm Precursors

Integration of the buoyancy force equation for parcel convection results in

$$E = R\int_{P_1}^{P_2} T^* d \ln P - R\int_{P_1}^{P_2} T^{*\prime} d \ln P \qquad (1)$$

where E is the energy gain (or work done) as a parcel moves from P_1, upward to P_2, P is pressure, R is the specific gas constant for dry air, and T* is

the virtual temperature. The primed value refers to the parcel. More simply we may write

$$E = f(T_a^*) - g(T_b^*, W_b) \tag{2}$$

where f and g are functions, w is the mixing ratio, 'a' refers to "aloft" and 'b' to the boundary layer. Most studies of destabilization have indirectly focused on (2) or the local derivative of (2). Darkow, Suomi, and Kuhn (1958) related details in the boundary layer temperature field to tornado occurrence. Winston (1956) and Miller (1967) are among those who have emphasized the boundary layer moisture distribution and its change with time. SEOS observations of boundary level temperature and moisture can be used to monitor, essentially continuously, the second right hand term in (2) with better time and space resolution than the radiosonde network, while providing more representative values of boundary layer moisture and temperature than the surface observations.

At the same time the SEOS sounding capability will provide high resolution fields of the first right hand side term of (2) by measuring mean upper level temperatures. Thus, the potential energy available for convective storms and its generation will be followed in detail.

Studies based on radar observations of severe thunderstorms have demonstrated that the probability of severe weather, including tornadoes, increases with the height of the storm top above the ground. Of greater significance, though, is the distance by which the storm penetrates into the stratosphere (see, for example, Donaldson, 1965). A penetration of 10,000 feet is considered to be highly significant. In order for air to penetrate that far into the stable stratosphere it must possess great momentum when it reaches the tropopause. This is only possible if it arrives at the tropopause with a temperature no lower than that of its surroundings.

The temperature difference between a rising parcel of air and its environment at the tropopause is given by

$$T' - T_t = (\theta' - \theta_t)\left(\frac{P_t}{1000}\right)^{\kappa} \tag{3}$$

where T' is the parcel temperature at the tropopause, T_t is the environment temperature at the tropopause, θ' and θ are the parcel and environment potential temperatures at the tropopause, P_t is the pressure at the tropopause, $\kappa = R/c_p$, R is the specific gas constant for dry air, and c_p is the specific heat at constant pressure for dry air. Figure 22 illustrates a parcel of air rising upward from near the ground in an adiabatic process. The <u>initial</u> equivalent potential temperature, θ_e, for such a parcel is conserved as it moves upward. Furthermore, the difference between the parcel θ_e and its θ becomes negligible in the high troposphere ($\theta_e - \theta \approx 2.8w$ where w is the mixing ratio in g/Kg), because nearly all of the water vapor has been condensed out. That is $\theta' \doteq \theta_e$; therefore, to a good approximation

$$T' - T = (\theta_e - \theta_t)\left(\frac{P}{1000}\right)^{\kappa} \tag{4}$$

It may be seen from (4) that if a parcel is to be buoyant when it reaches

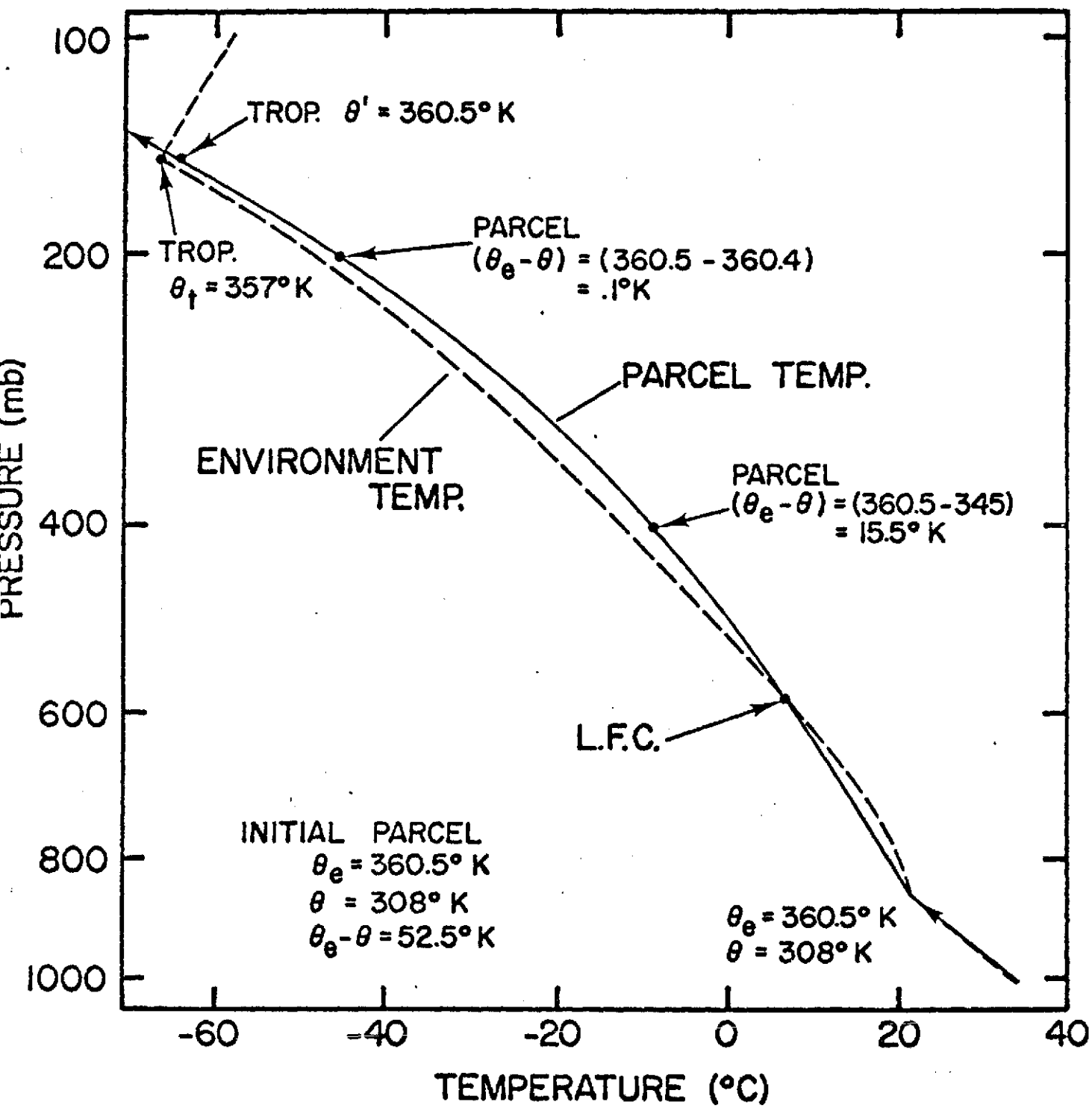

100
200
400
600
800
1000
PRESSURE (mb)
-60
-40
-20
0
20
40
TEMPERATURE (°C)
TROP. θ' = 360.5° K
TROP.
θt = 357° K
PARCEL
(θe - θ) = (360.5 - 360.4)
= .1°K
PARCEL TEMP.
ENVIRONMENT
TEMP.
PARCEL
(θe - θ) = (360.5 - 345)
= 15.5° K
L.F.C.
INITIAL PARCEL
θe = 360.5° K
θ = 308° K
θe - θ = 52.5° K
θe = 360.5° K
θ = 308° K

Figure 22

the tropopause with $T' > T$, then

$$\theta_e > \theta_t \tag{5}$$

SEOS will be capable of observing the boundary layer θ_e values by obtaining low level moisture and temperature profiles; concurrently it will monitor the potential temperature at the tropopause thus obtaining a high resolution check on the potential for tropopause penetration by growing cumulonimbus clouds.

Satellite cloud observations have revealed the existence of a tongue of clear dry air immediately upstream from the location of severe convective storm development (Fugita, Bradbury, and Van Thullenar, 1970). It has been shown that this air descends over the surface cold front and moves out over the moist air in the boundary layer (Wash, 1969) producing a convectively unstable air mass. Lifting of this air mass occurs in regions of low level convergence and the lapse rate is steepened. In addition to the production of convective instability this dry air provides a supply of potentially cold air for the downdrafts of individual convective storms. The SEOS will follow the progress of this dry air both visually and through the use of high resolution moisture soundings.

It was noted in the section on the severe storm environment that strong vertical wind shear increases the efficiency and organization of storm circulation. Such shear is maximized near the jet stream which has long been an observed feature of the severe thunderstorm environment (Fawbush, Miller, and Starrett, 1961). The jet, however, plays a dual role; besides providing vertical wind shear, the jet has been shown by Beebe and Bates (1955) and, more recently, by Gall (1970) to produce vertical motions which reduce the stability. SEOS observations will track the upper level jet stream using the motion and form of high clouds (Fujita and Bradbury, 1969) as well as through the use of temperature soundings to locate the thermal support for the jet (Togstad, 1972). The motions of small cumulus clouds will aid in locating the low-level jet.

Such trigger mechanisms as meso-high boundaries and pre-existent squall lines can be observed with visible and infrared data (Purdom, 1973). In addition it is possible that such disturbances as gravity waves which have been shown to trigger convection (Uccellini, 1972) may produce a characteristic image which would be tracked by SEOS.

Following this survey of mainly synoptic-scale features which are important in the preparation of severe weather watches, we focus next on the meso scale features observable from geostationary altitude that might be used in the preparation of warnings.

5. Direct Observation of Thunderstorms

Sikdar, Suomi, and Anderson (1970); Purdom (1971); and Sikdar (1972) have demonstrated that the horizontal expansion rate of cumulonimbus anvils observed in the visible is related to storm intensity. SEOS will observe

such changes in detail while adding the third dimension; high resolution infrared observations at frequent time intervals will provide direct information on the vertical growth rate of convective cells. Both horizontal and vertical growth rates are related to storm intensity and should be related to the probability of severe weather as well as sferics count rate. The form of such relationships could be investigated using SEOS data for great scientific as well as practical benefit.

Potential tropopause penetration was discussed in the preceeding section. Continuous monitoring of storm tops together with tropopause height will allow measurement of actual penetrations. Such measurements will provide verification of earlier forecasts and, more importantly, it will identify potentially severe storms for short-range warnings. It is acknowledged that radar may be used to great advantage to measure storm tops, but it does so in a cumbersome storm-by-storm fashion while the satellite can monitor the whole field of storms simultaneously.

A characteristic of many severe storms is their persistence over upwards of six hours. Such persistence has led many researchers to believe in the efficacy of a steady-state approach to storm dynamics, while others argue against it. Recent work by Darkow (1971) demonstrates the dialectical nature of our concept of the severe storm circulation. He examined persistent severe thunderstorms seen as single cells on radar demonstrating, by their very existence, a steady character. However, he found that such storms produced multiple tornadoes in many cases, with periods of 15 to 150 minutes between successive tornadoes, indicating a remarkable unsteadiness in the storm circulation. The storms are both steady and unsteady at the same time in rough analogy to a radio signal which has a basically steady carrier signal which is modulated to carry information. Darkow found that the period of tornado production is a constant for a given storm. SEOS observations of top height and anvil size could lead to increased understanding of this highly significant modulation of storm circulation and the factors which determine the period for each storm.

Fankhauser (1971) has reviewed the observations of and theories for the characteristic motion of severe thunderstorms to the right or left of the mean winds in the storm layer; less intense sotrms move mainly with the mean wind. Such deviant movement should be observable by SEOS and might be used for warning purposes on a very short time scale.

The high resolution of SEOS observations should be useful in studying the early history of severe storms before radar echo is detectable. Such photographic histories are not feasible with aircraft or from the ground because it is not possible to identify potential severe storms when they are in the cumulus stage. Such observations would be scientifically interesting and in the long run might be useful in forecasting.

6. Combination of SEOS with Conventional Data

There are many possibilities for improving conventional analyses using SEOS data. At this point it will merely be noted that high resolution sounding data could produce frequently updated thickness analyses. Combi-

nation of these with surface pressure analyses based on the relatively dense network of hourly surface observations would provide a continuous picture of constant pressure surface topography. Analyses of such severe weather precursors as positive vorticity advection (Miller, 1967) would then be continuously available to the forecaster.

Table XVI

KNOWLEDGE REQUIREMENTS

I. Accuracy

A. Boundary layer environment

1. Mean temperature to ±.5 °K
2. Mean mixing ratio to ±1g/kg.
3. Winds at top of boundary layer, ±1m sec^{-1}; ±10°
4. Mean pressure in boundary layer (for thermodynamic computations) ±5 mb.

B. Environment aloft.

1. Mean temperature from top of boundary layer to near tropopause ±.5 °K
2. Mean mixing ratio 700 mb to 400 mb ±1 g/kg.
3. Tropopause temperature ±1 °K.
4. Tropopause pressure ±5 mb.
5. Winds ±2 m sec^{-1}; ±10°

C. Thunderstorms

1. Tops ±.5 km

D. Visible and Infrared Imagery

Location and tracking of clear tongue, frontal bands, and jet stream clouds as well as observations of individual cumulonimbi.

II. Resolution

A. For watch purposes, soundings of temperature and moisture - 100 km and 1 hour.

B. For forecasts of tropopause penetrations, tropopause potential temperature and boundary layer equivalent potential temperature. About 50 km and .5 hour. Most of these soundings could be in clear areas.

C. Infrared imaging for defining thunderstorm tops, 1-2 km and 10 minutes.

D. Winds - 50 km and 1 hour.

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D. Vertical Temperature and Moisture Sounding

1. Introduction

A major conclusion to be drawn from the studies discussed in Chapter III is that atmospheric temperature and moisture soundings are essential to the prediction of transient mesoscale weather phenomena. Specifically, it was found that the vertical profiles obtained from these soundings should satisfy the following conditions:

1. Timeliness--it should be possible to make soundings at a moment's notice as required by changing atmospheric conditions, and to make soundings almost continuously in time when required.

2. High spatial resolution--for many phenomena soundings are required every 20 km to 30 km over limited areas; in order to maximize the chance of making measurements in the presence of broken cloud cover the instrumental IFOV should be of the order of 10 km to 20 km.

3. High vertical resolution--in order to locate inversions, lapse rate changes, and moisture layers in the lower and middle troposphere, vertical resolution should approach 1 km to 2 km in these regions.

4. High accuracy--the sounding error averaged over the vertical resolution length should be $\leq 1.0°K$ in temperature and $\leq 10\%$ in relative humidity for the lower and middle troposphere.

5. Spatial coverage--it should be possible to make soundings over an area approximately 400 km x 1000 km within a period of 10 minutes to 15 minutes at a frequency of once per hour.

Since the results of the best satellite sounding instruments to date do not meet any of these requirements, the sounder required for SEOS represents a very significant advance in the state of the art. However, the combination of 2 meter optics and a geosynchronous orbit presents substantial opportunities for improvement. It is our objective here to determine from past experiments where improvements are required and with the help of theoretical investigations to determine how SEOS' capabilities can be applied to make these improvements.

2. Results from Nimbus

The Satellite Infrared Spectrometer (SIRS) experiment flown on Nimbus 3 and Nimbus 4 serves as an example of the techniques and potential of remote atmospheric sounding. SIRS is a downward (nadir) viewing instrument with a 200 km FOV. Radiation leaving the atmosphere is measured 14 narrow spectral intervals, seven spanning the 15μ CO_2 absorption band, six distributed over the 20μ H_2O absorption band, and one at the 11.1μ atmospheric window. Since the vertical distribution of CO_2 in the atmosphere is known, the measured radiances can be interpreted as temperatures of atmospheric

layers. Near the center of the CO_2 absorption band (region of strongest absorption) observed radiation emanates from the upper atmosphere since emission from lower levels is absorbed. Near the wing of the absorption band (a region of weak absorption) the observed radiation emanates mainly from the lower atmosphere. The atmospheric layer sensed by each spectral interval is more precisely described by the weighting function for each wavelength. These are shown in Figure 23 for the SIRS B CO_2 channels. In this figure the weighting function for the 706 cm^{-1} channel shows that although the maximum sensitivity is to radiation emitted from the 350 mb level, there is still considerable sensitivity (>50%) from about 200 mb to about 550 mb, spanning an 8 km range of altitude. This lack of vertical resolving power in the weighting functions is characteristic and accounts for the inability of SIRS profiles to show sharp changes in lapse rate over small altitude intervals.

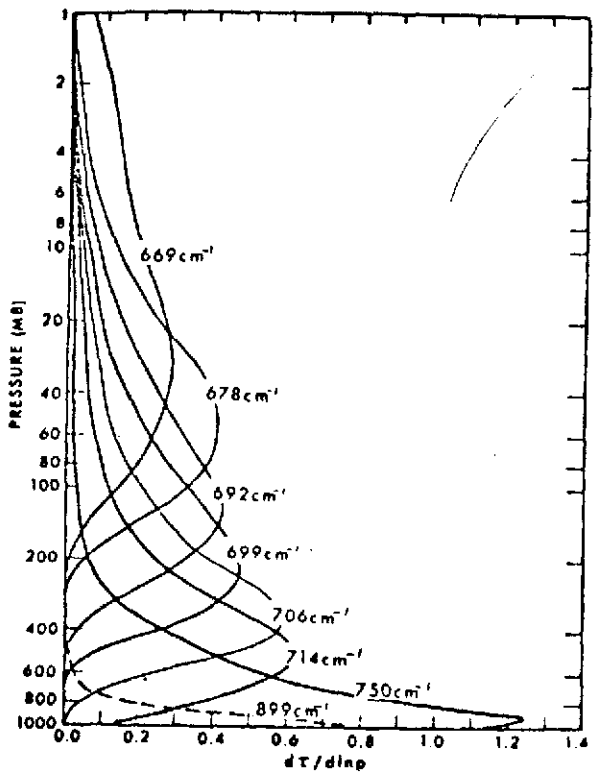


Figure 23. The derivative of transmittance with respect to the logarithm of pressure. These functions approximately describe the relative sensitivity of the eight SIRS radiance observations to temperature variations in various altitude layers of the atmosphere. (Smith, 1970.)

When the temperature profile is known and the vertical distribution of the absorbing molecules is not known (the case for water vapor) the measured radiances are interpreted to obtain constituent densities for various atmospheric layers. The weighting functions for the SIRS B H_2O channels are shown in Figure 24 for standard atmospheric conditions. Each curve represents the approximate sensitivity of a channel to variations of water vapor in different atmospheric layers.

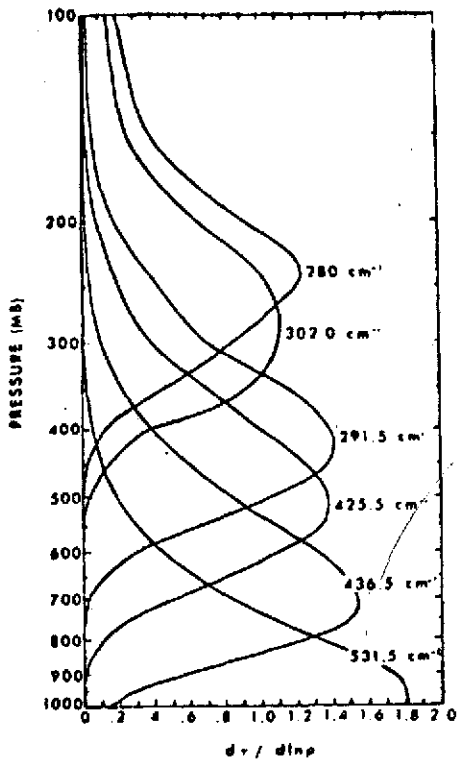


Figure 24. The derivative of transmittance with respect to the logarithm of pressure. These functions approximately describe the relative sensitivity of the six SIRS radiance observations to water vapor variations in various altitude layers of the atmosphere. (Smith, 1970.)

Examples of the profiles derived from SIRS measurements are presented in Figure 25(temperature profiles from SIRS A) and Figure 26(water vapor profiles from SIRS B). These examples indicate what is found to be the case generally, i.e., gross features (say 10 km. averages) retreived accurately, while fine structure in the profiles is often missed altogether. Theoretical calculations which closely simulate SIRS observations show that over a large sample of soundings the average absolute temperature error is approximately 1.5°K except near 800 to 900 mb and 200 mb where the absolute average error rises to 3.5°K and4°K. The latter results from sharp inversions which are well below the resolving power of the weighting functions. Studies by Smith and Howell (unpublished) indicate that errors in the SIRS-derived relative humidity in the middle troposphere (400-600 mb) are less than 20%, and in the lower troposphere (600-1000 mb) are less than 30%. They suggest that the latter error could be reduced by measuring upwelling radiation in more transparent spectral intervals of a water vapor band.

A major problem with the SIRS instrument, in addition to that of vertical resolution, is the large FOV which very often is contaminated by the presence of clouds. Since most clouds are opaque to IR radiation they seriously interfere with derivations of profiles, in many cases preventing any determination at all. This latter problem has been greatly alleviated by the Infrared Temperature Profile Radiometer (ITPR) flown on Nimbus 5.

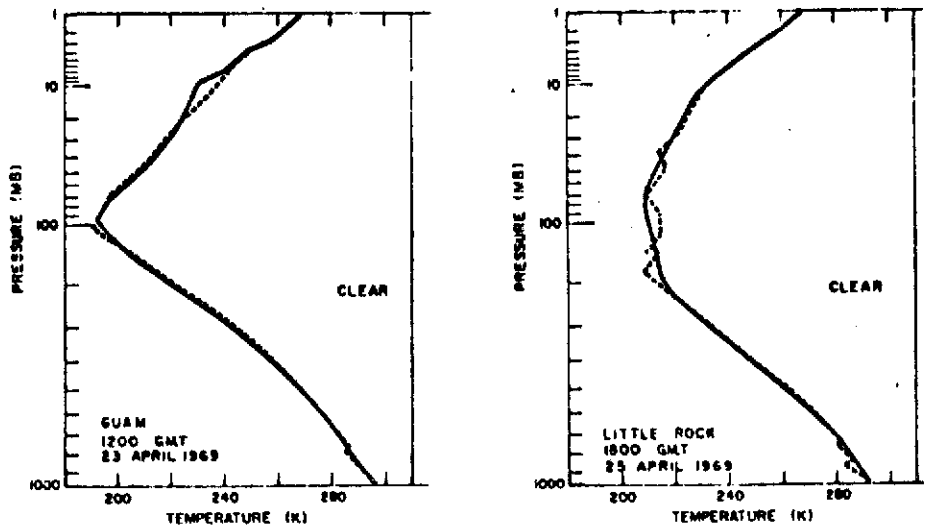


Figure 25. Examples of SIRS retreivals (Wark, 1970).

The ITPR instrument makes use of a relatively high spatial resolution (≃30 km FOV) to increase the opportunity for observing in the clear regions between clouds and two window channels (one at 11μ and one at 4μ) whose greatly different dependence on temperature makes it possible to correct radiation measurements when partial cloud contamination is present. Weighting functions for the seven ITPR spectral channels are shown in Figure 27. Only four of these channels are in the 15μ CO_2 absorption band. The one water vapor channel (507.4 cm^{-1}) is used only to correct the CO_2 transmission functions and not to determine H_2O profiles. An example of an ITPR derived temperature profile is shown in Figure 28. Generally, the ITPR profiles have the same characteristics as the SIRS profiles. The main contribution of the ITPR instrument is greatly improved spatial coverage even under cloudy conditions.

The Nimbus E Microwave Spectrometer (NEMS) experiment flown on Nimbus 5 demonstrates another technique for improving spatial coverage under cloudy conditions. The NEMS instrument neasures microwave radiation at three wavelengths near the 5 mm oxygen resonances and at two wavelengths near the 1.35 cm water vapor resonance. Since most clouds are quite transparent to radiation near 5 mm in wavelength, temperature profiles can be obtained down to the surface even under 100% cloud cover. Although relatively dense clouds, say 0.1 gm / cm^2 of water, can produce errors of 2°K over land and 1°K over oceans, the actual errors are much less because such clouds rarely fill the 200 km field of view of the radiometer. Measurements in the two channels near 1 cm make it possible to estimate atmospheric water vapor content with approximately 0.1 gm/cm^2 accuracy and liquid water vapor content with approximately 0.04 gm/cm^2 accuracy.

3. Possible Improvements

The main deficiency of the SIRS, ITPR, and NEMS profiles is the lack of vertical resolution. It is obvious that a small number of radiance measurements (4 to 6) are insufficient to determine arbitrarily complex temperature structures such as that produced by inversions. However, the solution is not merely to increase the number of spectral channels. Although this may be necessary, it is not sufficient. For a given level of radiometric

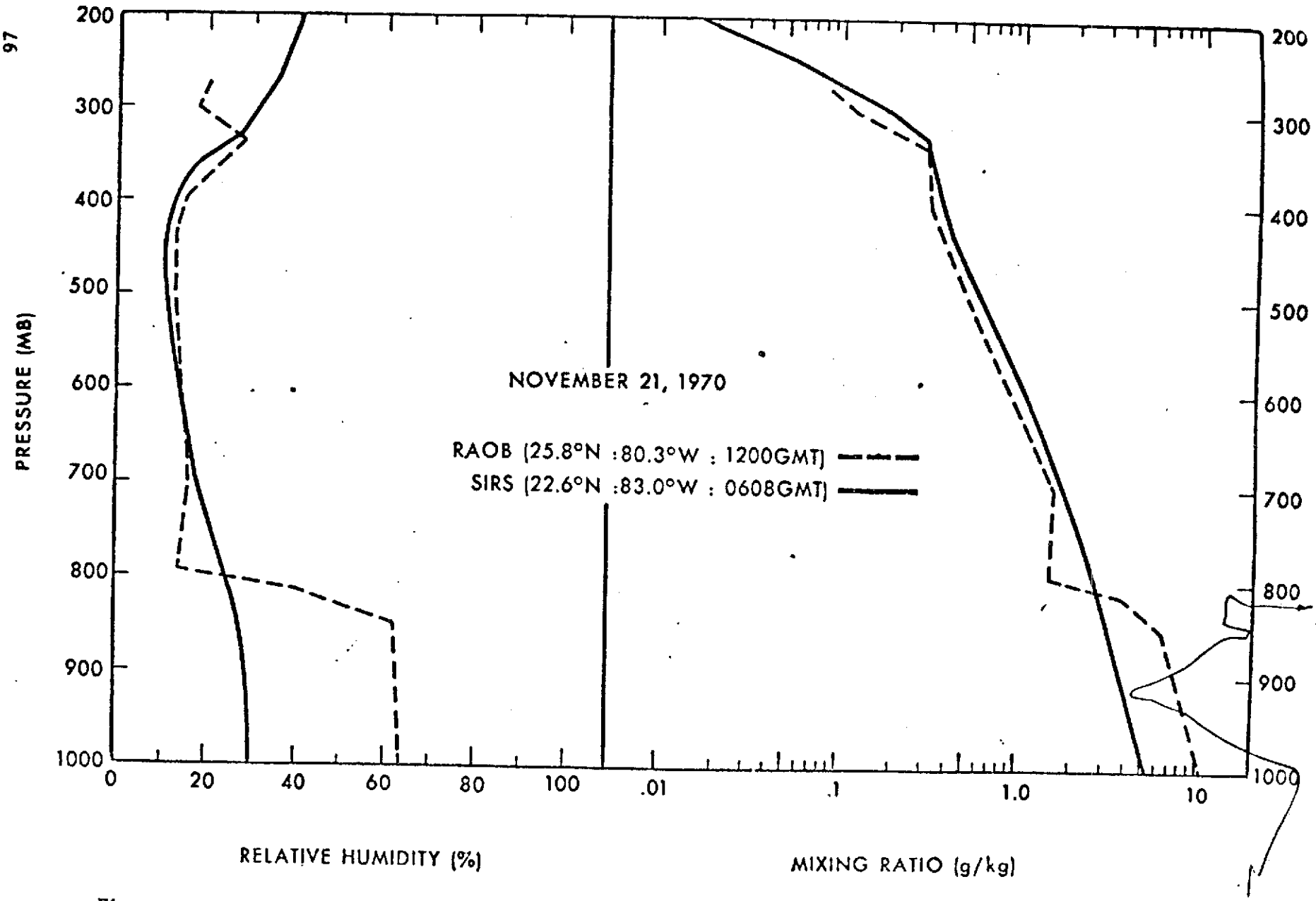


Figure 26. An example of SIRS-B water vapor retrievals.

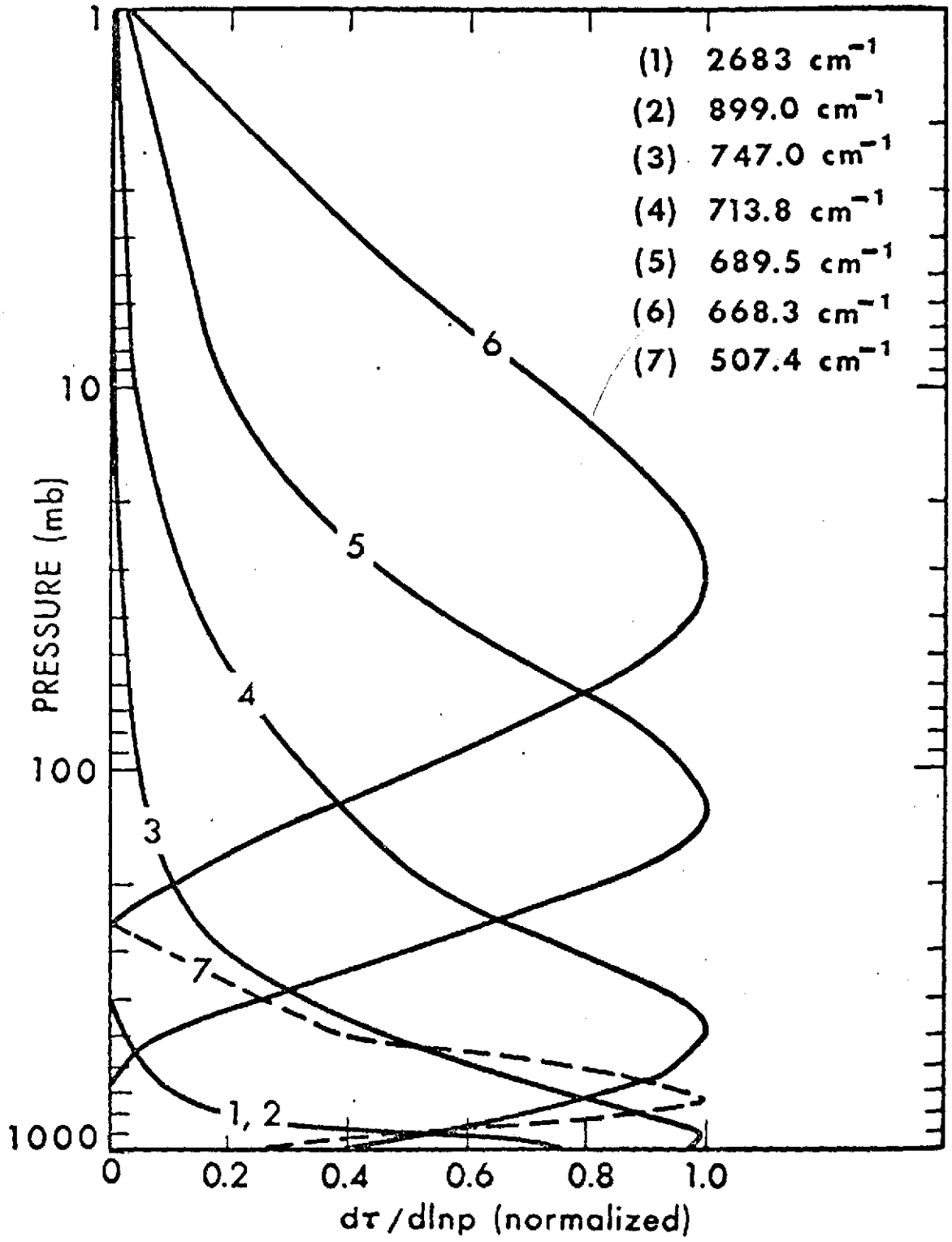


Figure 27. Atmospheric Weighting Functions for ITPR Spectral Channels

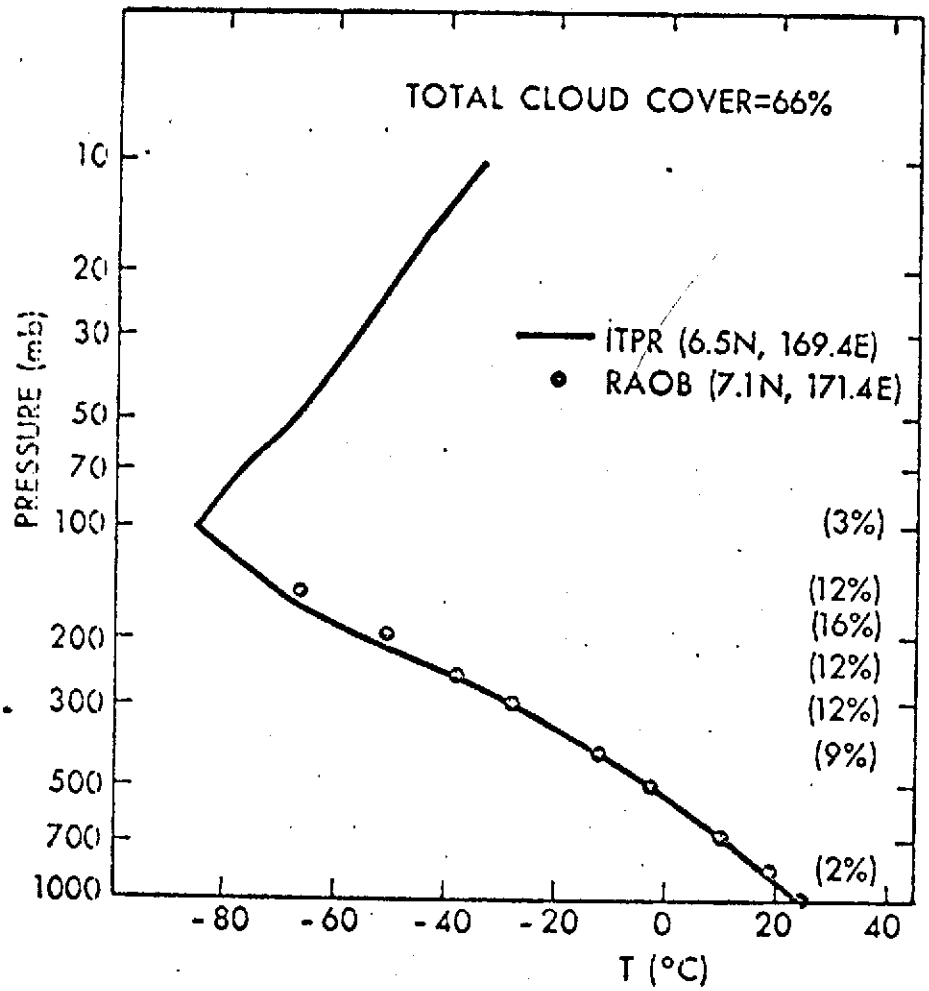


Figure 28. An example ITPR retreival in the presence of clouds (Smith, 1972).

errors increasing the number of channels beyond a certain point produced no measurable improvement. The weighting functions typical of the 15μ CO_2 band are so broad that only 4 to 6 channels can provide independent information when radiometric errors are of the order of 0.2 to 0.4 $mW/M^2\ cm^{-1}$ ster). Measurements in additional spectral channels would be redundant.

The question of the relation between optimum channel number and radiometric accuracy can be put in perspective by some results of Strand and Westwater (Westwater, 1968) concerning inversion of microwave emission by oxygen. Figure 29 displays a plot of RMS deviation of the solution temperatures from the actual temperatures as a function of the number of channels used for several different brightness temperature measurement errors. The behavior indicated is relevant to inversion of radiances measured in the 15μ CO_2 band as well. For a fixed number of channels, inversion accuracy remains finite no matter how much measurement errors are reduced. In fact, there is a finite error level which is, for all practical purposes, just as good as zero error. For example, if 3 O_2 channels are used, there is no advantage to reducing measurement error below 0.1°K. On the other hand, for a fixed brightness temperature error, inversion error remains finite no matter how many channels are used. For example, for the measurement errors 1.0°K, 0.5°K, and 0.1°K, no useful improvement in inversion accuracy results from increasing the number of channels from three to five. A much

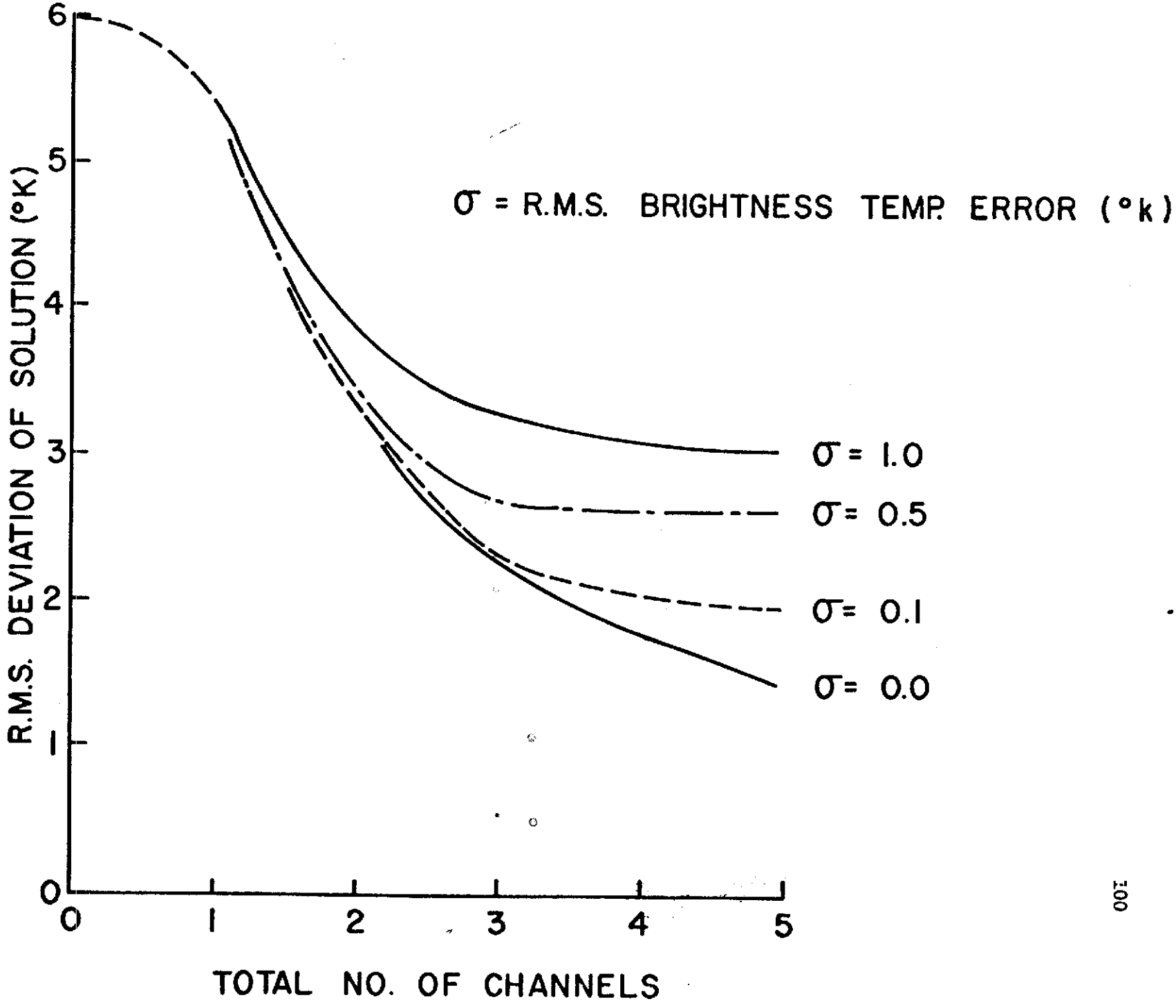


Figure 29. Sounding accuracy as a function of channel number and measurement error (Westwater, 1968).

smaller error is required before additional channels result in an improved inversion, as would be the case for zero measurement error.

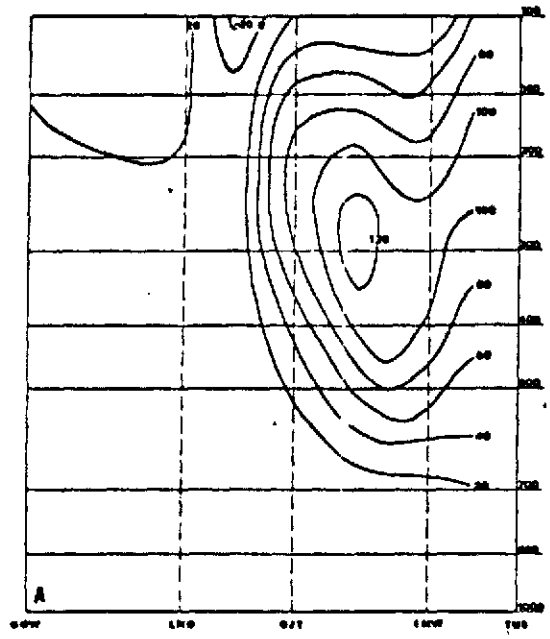
The implication of the Strand and Westwater study for 15μ CO_2 band sounding is that additional channels might be useful if radiometric errors can be reduced substantially below the level of 0.25 mW/(M^2cm^{-1} ster.). Supporting evidence for this contention is provided by work done by Togstad (Togstad, 1972). Togstad used synthetic SIRS soundings with simulated measurement errors of 0.25, 0.1, and 0.05 mW/(M^2cm^{-1} ster.) and the thermal wind relationship to determine the wind structure of a jet streak. His results, presented in Figure 30 show that the smallest error yielded substantially improved structural detail in the wind field. This suggests that the six channels (SIRS) might be fewer than the optimum number at this low value of measurement error.

Thus the first possibility of improvement is an increase in the number of spectral channels with a substantial decrease in the radiometric errors of measurement. Quantitative estimates for these changes cannot be made at this time and will await further investigations. In order to derive significant benefits from improved radiometric accuracy, atmospheric transmission functions must also be well known, including effects due to aerosols and trace constituents which could limit the degree of possible improvement.

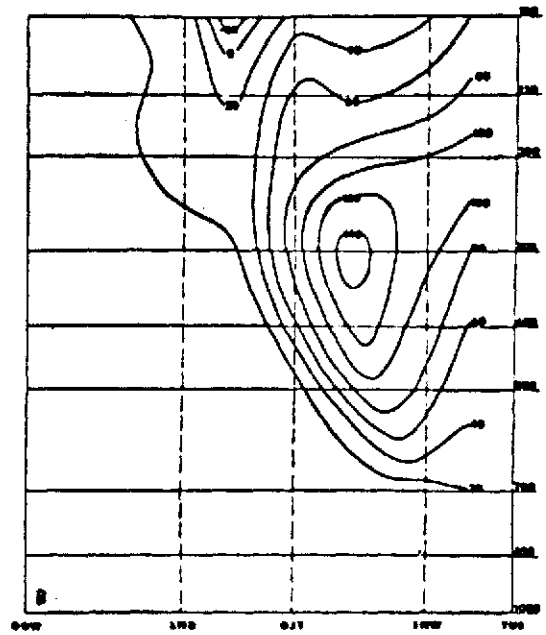
A second possible means for improving vertical resolution in profiles derived from remote radiance measurements is to use different absorption bands with sharper weighting functions. The 4.3μ CO_2 absorption band appears most promising in this regard. Theoretical work (Chahine, 1970) indicates that, in the 4.3μ region, a temperature accuracy of 1°K (average absolute error) can be expected with a 2% RMS random error in observations. In addition, as indicated in Figure 31, extremely high vertical resolution is possible. For an instrumental slit function of 40 cm^{-1} the vertical resolution is high enough to permit surface elevations to be determined within 25 to 50 mb, corresponding to an altitude resolution of better than 0.5 km. Experimental observations in this region using a balloon borne grating spectrometer (Shaw et al., 1970) are consistent with theoretical results of Chahine. With measurement errors of the order of 3% (mostly due to calibration errors) profiles were retreived with temperature accuracies of the order of 2°K compared to radiosonde and rocketsonde measurements. An example of the profiles obtained is shown in Figure 32.

Recently Smith has proposed using both 15μ and 4.3μ regions together in a sounder to be flown on Nimbus 6. Spectral channels and corresponding weighting functions are shown in Figure 33 (Smith, 1972). An example of the vertical resolution improvement made by including the 4.3μ channels is shown in Figure 34. In this figure the results of 15μ measurements only display the usual insensitivity to sharp changes in lapse rate (i.e. the inversion at 700 mb), while the addition of 4.3μ measurements permits this feature to be detected and described quite accurately.

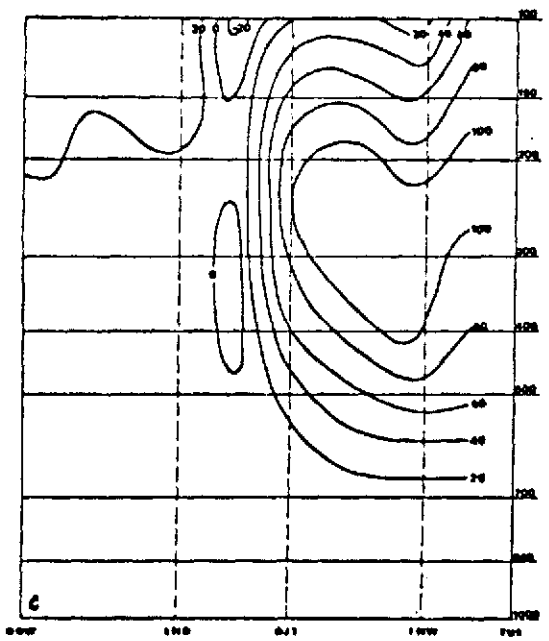
The major difficulty in using the 4.3μ band, and the main reason it has not seen much use so far, is the severe radiometric requirement it im-



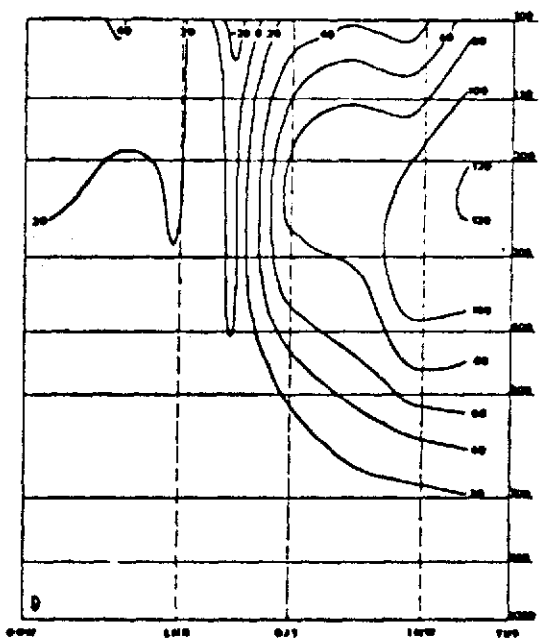
Derived, 0.05 mW/($m^2 cm^{-1}$ster) error



Actual Isotachs



Derived, 0.10 mW/($m^2 cm^{-1}$ster) error



Derived, 0.25 mW/($m^2 cm^{-1}$ster) error

Figure 30. Isotachs of the geostrophic wind compoents obtained using retrieved soundings. Results are based on a grid spacing of 222 km and assumed satellite observational errors of: A) 0.05 ergs, C) 0.10 ergs and D) 0.25 ergs. (Togstad, 1972)

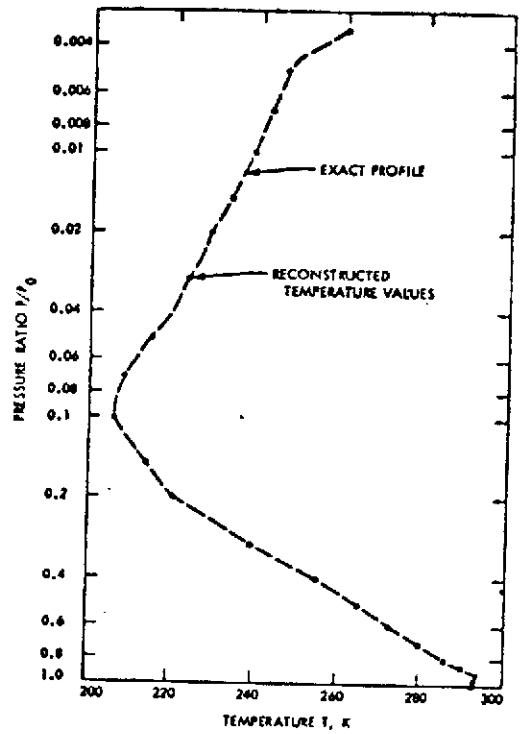


Figure 31. Comparison between the exact temperature profile and the reconstructed temperature values obtained from 22 sounding frequencies with an instrumental slit function having a base width of 40 cm^{-1} in the 4.3μ region (Chahine, 1970).

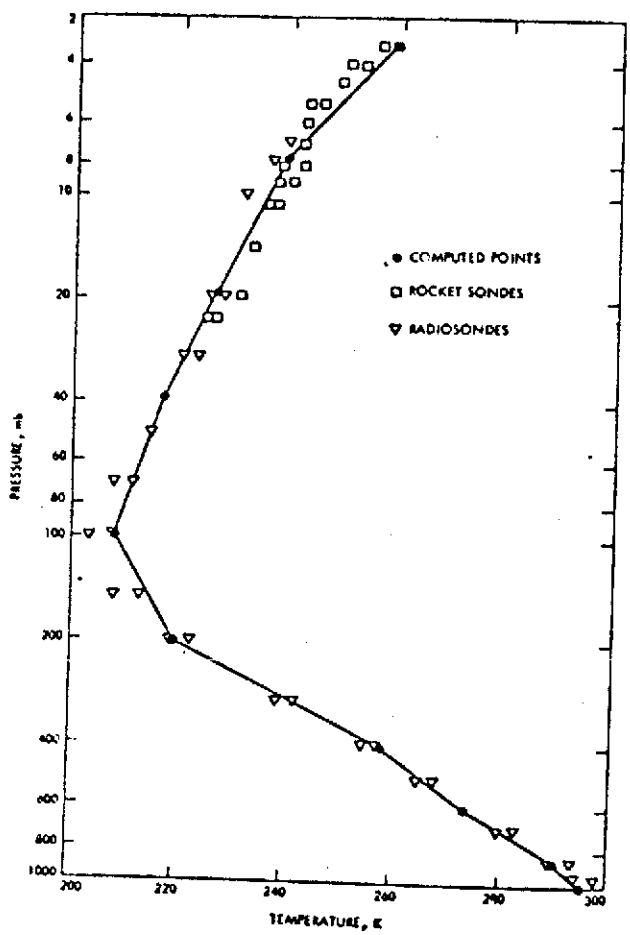


Figure 32. An example profile retreived by a balloon borne 4.3μ spectrometer (Shaw, 1970).

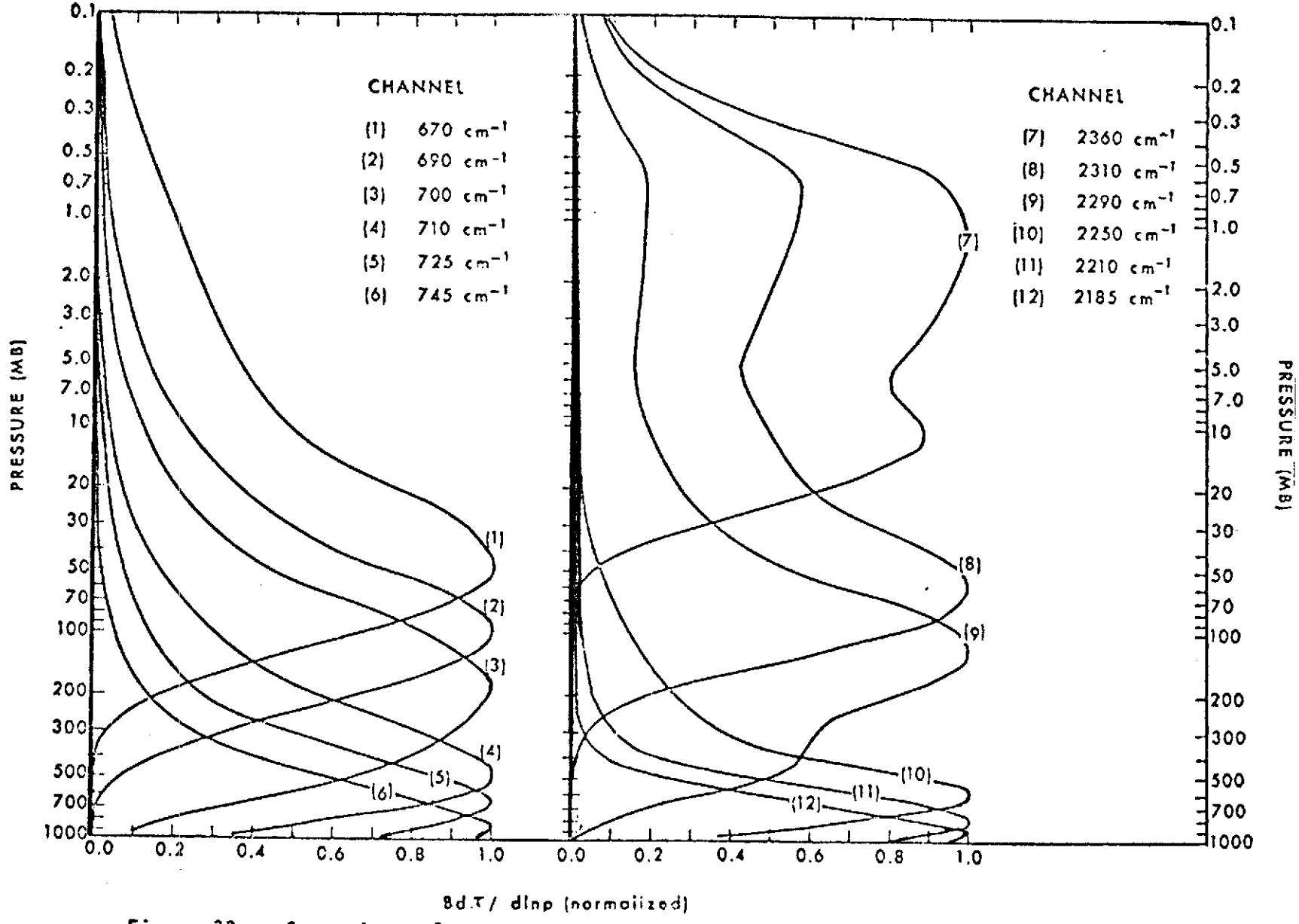


Figure 33. Comparison of vertical resolution of 4.3 micron and 15 micron CO_2 band weighting functions (Smith, 1972).

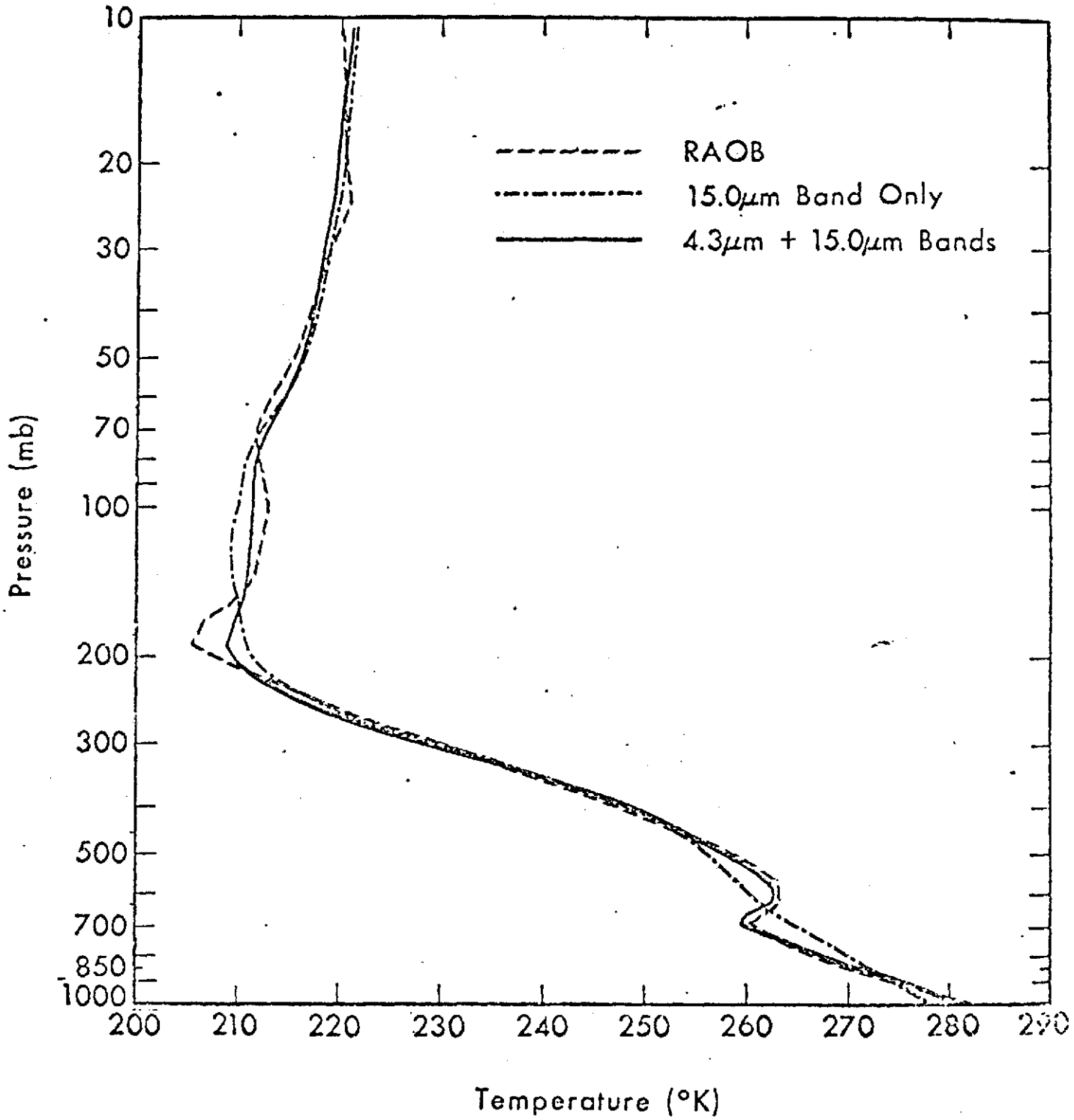


Figure 34. An example of vertical resolution possible with 4.3μ sounding data (Smith, 1972).

poses. Atmospheric emission is strongest near 10μ, decreasing with increasing wavelength and decreasing very rapidly with decreasing wavelength. At 4.3μ a change of 1°K near 300°K results in a change in emitted radiation of .08 $mW/(m^2\ cm^{-1}$ ster.), while at 15μ the same temperature change results in a radiance change of 1.67 $mW/(m^2 cm^{-1}$ ster.). At 200°K the difference is even greater, 0.0007 $mW/(m^2\ cm^{-1}$ ster.) for a 1° change at 4.3μ compared to 0.71 $mW/(m^2 cm^{-1}$ ster.) for a 1° change at 15μ. Thus the improved vertical resolution must be paid for by greatly increased observation time to bring down the effective detector noise.

4. Proposed Sounder for SEOS

Based on the requirements for mesoscale observation, the capabilities of previous satellite sounders, and the possibilities for improvement discussed in the previous section, a tentative selection of spectral channels and corresponding radiometric accuracy requirements was made. The selection of IR channels is described in Table XVII, although it should be stated that the choice of wavelengths, spectral bandpasses, and other characteristics are by no means optimized. They represent merely starting points for detailed simulation studies which could eventually result in the most efficient configuration.

Basic considerations employed in formulating this set are listed below.

1. Two window channels, one at 11.5μ and one at 3.7μ are required to correct for partial cloud cover in the instrument field of view, a technique successfully demonstrated by the ITPR experiment.

2. Eight 15μ band CO_2 channels with narrow spectral bandpass and greatly reduced noise levels are chosen to capitalize on possible improvements discussed previously.

3. Seven 4.3μ band CO_2 channels are chosen to improve vertical resolution in the middle and lower troposphere.

4. Four H_2O channels with very high radiometric accuracy are included to provide estimates of water vapor profiles.

In order to gauge the feasibility of meeting these tentative requirements with SEOS, radiometric performance estimates were made based on simple and rather general assumptions concerning instrument characteristics. The equation relating these characteristics, for a chopped detection system, to the Noise Equivalent Radiance (NER) is

$$NER = \frac{\gamma}{D^* C \Delta\nu A \Omega T} \left(\frac{Ad}{2t}\right)^{\frac{1}{2}} , \qquad (1)$$

where

Ad = detector area (cm^2)

Table XVII. Proposed sounding channels for SEOS

	Channel	$\nu(cm^{-1})$	$\Delta\nu(cm^{-1})$	α(mr)	NER[1] $mW/(m^2 cm^{-1} ster.)$	P(mb)[2]
15μ CO_2	(1)	669	5	1.0	0.05	30
	(2)	680	5	1.0	0.05	65
	(3)	690	5	1.0	0.05	100
	(4)	700	5	1.0	0.05	200
	(5)	705	5	1.0	0.05	350
	(6)	715	5	1.0	0.05	500
	(7)	740	5	1.0	0.05	700
	(8)	750	5	1.0	0.05	900
4.3μ CO_2	(9)	2360	40	1.0	0.002	1
	(10)	2310	40	1.0	0.0004	60
	(11)	2290	40	1.0	0.0004	130
	(12)	2250	20	1.0	0.002	600
	(13)	2230	20	1.0	0.002	700
	(14)	2210	20	1.0	0.002	800
	(15)	2185	20	1.0	0.002	900
11.5μ window	(16)	900	32	1.0	0.05	1000
3.7μ window	(17)	2700	200	1.0	0.0002	1000
H_2O	(18)	1490	60	1.0	0.02	~300
	(19)	430	40	1.0	0.1	~600
	(20)	507	80	1.0	0.1	~750
	(21)	1225	60	1.0	0.02	~1000

(1) Proposed RMS maximum

(2) Location in pressure of weighting function maximum

γ = preamplifier noise factor (1.4)

D^* = specific detectivity $cmH^{1/2}/W$

C = chopper efficiency due to loss of signal by obscuration (0.4)

$\Delta\nu$ = spectral bandpass (cm^{-1})

A = entrance aperture area

Ω = solid angle of acceptance

T = transmission of the optics (including effects of central obscuration)

t = integration time (sec)

For a square FOV α radians on a side the solid angle of acceptance is given by $\Omega = \alpha^2$. The minimum practical detector area is obtained for a convergence $\frac{1}{2}$ angle of $\frac{\pi}{4}$, yielding an optimum detector area of $Ad = \frac{\pi}{16}\alpha^2 D^2$, where D is the diameter of the primary (2m for SEOS). Defining $T = \tau T_o$ where $T_o = 1-(.35)$ is the obscuration factor, the remaining transmission factor τ is the product of the filter transmission, lens transmissions, and mirror reflectivities. The value $\tau = .3$ is assumed for all channels except those with 5 cm^{-1} bandpass for which $\tau = 0.15$ is assumed, although exact values will vary according to the details of the optical configuration chosen. For C = .4, $\gamma = 1.4$, and D = 2m, the integration time required for each channel can be calculated from the equation

$$t = (\alpha\Delta\nu x(NEW) \times D^* \tau \times 1.1139m)^{-2}. \qquad (2)$$

Required integration times per channel have been calculated for each channel for a single detector, although D* values were chosen to be maximized for each channel individually. Results are presented in Table XVIII. Note the unusually long times required for channels (10) and (11) in the 4.3μ band. These channels have peak sensitivity in a very cold region of the atmosphere where 4.3μ emission is very weak; in order to make meaningful observations in these channels it is necessary to reach very small NER values, requiring long integration times. These channels place a significant demand on the total observing time and their utility to mesoscale prediction must be carefully weighed before including them in any final selection.

The sum of all the integration times for all channels is 0.67 sec. If these channels were viewed in sequence with 10 msec allowed for stepping between filters the total time required would be 0.90 sec. The total radiometer observation time required to cover an area of 400 km x 400 km at this resolution (35.8 km) would be 125 (the total number of FOV's) times the time per sounding, or 112.5 sec (1.88 minutes). Allowing 20 millisec for an image plane scanner to step from one IFOV to the next would increase the total time to cover the 400 km x 400 km by only a few seconds.

The instrument FOV chosen for these calculations was 1.0 mr (35.8 km at the subsatellite point). If it is found necessary to reduce this by a factor of 2 to 0.5 mr (17.9 km at the subsatellite point) the indicated sounding times would increase approximately by a factor of four per FOV and by an additional factor of four per unit surface area covered. However, this assumes sequential measurement and single detectors. By using dichroic beamsplitters and multiple detectors for each channel the times could be considerably reduced, the exact degree depending on the capabilities of the SEOS radiative cooler to handle large numbers of detectors (the HgCdTe and InSb detectors assumed here require cooling to about 100°K). The pyroelectric detectors used for the 20μ H_2O band do not require such cooling.

We also recommend inclusion of a microwave sounding capability on SEOS to provide temperature and moisture profiles even under complete cloud cover (although at much lower spatial resolution than provided by the IR sounder) and also to provide estimates of liquid water content of clouds which will be valuable in estimating rainfall. An instrument measuring in the same channels and same radiometric accuracy as NEMS would require, in geosynchronous orbit, a fairly large antenna which probably is within reach of the SEOS satellite. The required size depends on wavelength and ground resolution as indicated in Table XIX. In this table results apply for a 2 second integration time per channel. The highest resolution is most desireable, although most demanding on antenna size.

The accuracy of the profiles retrieved from the SEOS sounder cannot be spelled out without extensive simulation studies. There is little doubt however that they can be better than anything so far available. Inclusion of a sounder on SEOS has the potential of providing unprecedented vertical resolution and accuracy which should greatly improve the chances of reliably predicting mesoscale phenomena which have such significant economic and social impact.

TABLE XVIII

Integration times required for SEOS sounding channels

	Channel(s)	$\Delta\nu(cm^{-1})$	τ	$D^*(cmHz^{\frac{1}{2}}/W)$	NER	t (millisec)
$15\mu CO_2$	(1) - (8)	5	.15	1×10^{10}	.05	57.3
4.3μ CO_2	(9)	40	.3	1×10^{11}	.002	1.4
	(10), (11)	40	.3	1×10^{11}	.0004	35.0
	(12) - (15)	20	.3	1×10^{11}	.002	5.6
11.5μ window	(16)	32	.3	1×10^{11}	.05	0.34
3.7μ window	(17)	200	.3	1×10^{11}	.0002	5.6
6.7μ H_2O	(18), (21)	60	.3	1×10^{10}	.02	0.62
20μ H_2O	(19)	40	.3	2.5×10^{8}	.10	90.0
	(20)	80	.3	2.5×10^{8}	.10	22.0

Notes: the required integration times are per channel and apply for a single detector only, NER units are $mW/(m^2cm^{-1}$ ster.).

TABLE XIX

Antenna size required for a NEMS capability on SEOS

FOV	Antenna Size (5mm O_2 band)	Antenna Size (1.35 cm H_2O band)
50 km	3.6 m	9.5 m
100 km	1.8 m	4.8 m
200 km	0.9 m	2.4 m

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E. Wind Measurement in the Atmosphere

1. Introduction

On a frequency of use basis the most important knowledge requirement for the observation and prediction of mesoscale weather disturbances is the motion field. Because it is so pervasive, and because knowledge of the wind field has so many potential uses it is not possible to specify accuracy and resolution requirements exactly. For example, in severe thunderstorm forecasting it is necessary to know the location of the upper level jet stream. This is determined reasonably well by the present radiosonde network with a station spacing of about 500 km. Studies of the divergence of flow near the tops of individual cumulonimbi which could be related to storm intensity require resolutions of about 20 - 40 km. Thus measurements on both the synoptic and the mesoscales are essential for the prediction of mesoscale weather systems.

Possible techniques for determining the wind field from SEOS observations include the following:

a) pattern recognition and semi-quantitative methods;
b) measurement of cloud tracer displacement between successive images in the visible and IR;
c) measurement of moisture pattern motion between successive images;
d) use of the thermal wind equation with vertical temperature soundings.

The problems and potential of each of these techniques are discussed in the following section.

2. Techniques for Determining the Wind Field

a) Semi-quantitative Methods

The association of the jet stream with such recognizable features as edges of cirrostratus sheets, banded cirrus clouds, boundaries between open and closed cellular convective patterns, and long bands of cirrus in the subtropics is discussed in detail in Anderson et. al, (1969). The jet stream may be positioned with good accuracy on the synoptic scale, but there is no quantitative information as to wind speeds, and directions can be only approximated. Similar information is available for lower levels when lines of small cumuli are visible. Somewhat more quantitative information on the vector velocity field may be obtained by noting the direction and extent of cirriform anvils on cumulonimbi. One can observe direction of cloud motion on time lapse displays such as movie loops and TV. Often the phenomenon scale size yields quantitative information, as from mountain wave and billow clouds. The McIDAS system (Man-computer Interactive Data Access System) at SSEC (1972) can align and measure digital satellite images very precisely (to better than a pixel) and display cloud motions in digitally enhanced false color time sequences. Multiple channel cloud tracking and access to the time domain are thus available in both a qualitative and quantitative sense.

b) Cloud Tracking

A considerable body of experience in the use of cloud tracking to derive wind fields from ATS III data has been developed at the University

of Wisconsin, NOAA, and elsewhere. Although ATS III is a spinning satellite, the basic elements of the wind determination process developed for it ar relevant to SEOS as well. These basic steps are:

1) select cloud tracers which persist on successive images.
2) use cross correlation (or other image matching procedures) to automatically measure (via a computer) the tracer displacement between images,
3) derive a time dependent transformation between satellite coordinates (line and element in the case of ATS III) and earth coordinates of latitude and longitude (this is called image navigation), and
4) use the derived transformation to convert raw displacements into velocity vectors relative to the earth.

The third step (image navigation) which must account for data frame geometry, satellite attitude, and satellite orbit, is perhaps the most difficult. The University of Wisconsin approach in deriving this transform for ATS III data requires landmark position measurements and orbit parameters as input information. Two distinct accuracy requirements must be considered in application of a navigation transform, i.e.,

1) relative navigation accuracy (this effects the accuracy of derived winds, since image to image location errors result in uncorrected apparent cloud motions), and
2) absolute navigation accuracy (this effects the assigned location of a derived wind vector but has only negligible effects on wind vector accuracy).

The effects of relative navigation errors on wind accuracy depends on satellite zenith angle at the position of the target and on the time between images see (Table XX.)

Table XX. Wind Errors at the Subsatellite Point

Relative Location Errors	Derived Wind Error			
	ΔT=10 min	ΔT=15 min	ΔT=20 min	ΔT=30 min
10μr	0.6m/s	0.4m/s	0.3m/s	0.2m/s
20μr	1.2m/s	0.8m/s	0.6m/s	0.4m/s
30μr	1.8m/s	1.2m/s	0.9m/s	0.6m/s
50μr	3.0m/s	2.0m/s	1.5m/s	1.0m/s
75μr	4.5m/s	3.0m/s	2.2m/s	1.5m/s
100μr	6.0m/s	4.0m/s	3.0m/s	2.0m/s

Away from the subsatellite point wind errors generally increase as a function of satellite zenith angle but depend on direction as well. At 60° zenith angle, for example, wind errors tangent to a circle of constant zenith angle are only slightly greater than those indicated in the table. Using an average degradation factor of 1.4 and the results of Table I, we see that for a time interval of 15 minutes between images relative location errors between images should be less than 20μr in the satellite coordinate system, which translates to a distance of .7 km at the subsatellite point. It is desirable that this location accuracy be obtained independent from the image itself. While the use of landmarks on ATS or SMS images is quite feasible for navigation, the limited area coverage of SEOS will reduce the likelihood of finding suitable landmarks within each image. It is also necessary for navigation (or location) parameters to be available in real time to insure that winds can be determined rapidly enough to have predictive utility.

In order for tracer selection and image matching processes (steps 1 and 2) to produce useful results the spatial resolution and radiometric accuracy must be adequate to reveal small clouds and structural details of larger clouds. Spatial resolution in the IR should be of the order of 0.5 km to 1.0 km for this application. A $\pm$ 1 m/s velocity may just barely be detectable over 10 - 15 minutes with this resolution. Radiometric accuracy required depends on the wavelength of observation and will be discussed in that context next.

In order to obtain winds at night and to assign altitudes to the derived winds, there is no question that infrared images should be of primary use for cloud tracking. A single window channel with a spectral passband from 10.5μ to 12.6μ would be useful in cloud tracking during the entire day and for thick clouds (i.e., clouds with near unit emissivities) it would be used to infer the cloud top pressure from its brightness temperature in the window channel. In a tropical atmosphere a noise equivalent temperature difference as large as 1°K would permit cloud top altitude resolution of better than 500 m from the surface to the tropopause (provided the temperature profile is known well enough).

However, for clouds partially transparent in the infrared (clouds with non-unity emissivity), such determinations are not possible with a single channel. In this case emissivity variations look exactly like altitude variations. Additional information is required to resolve this ambiguity. This information could be made available imaging simultaneously in two IR channels. Two possibilities are available:

1) two window channels, one at 11.5μ and one at 3.7μ. The temperature dependence of the emitted radiation in the 11.5μ window is much weaker than the temperature dependence in the 3.7μ window. As a result the apparent temperature of a scene with mixed radiation temperatures (partially transparent clouds over a warm surface) is different for the two channels. The difference in apparent temperatures can be used to infer cloud top temperature provided only a single cloud layer is present and provided that cloud emissivity is the same at 11.5μ and 3.7μ. Under equivalent assumptions a simulation study (Smith, William L., "The Improvement of Clear Column Radiances with a Supplementary 3.8μ Window

Channel," Technical Memorandum NESCTM 16, National Environmental Satellite Center, U.S. Department of Commerce, July 1969), indicated cloud top altitude resolution of 1 km was possible for noise equivalent radiances of 0.20 mW/(m^2-cm^{-1}-ster) at 11.5μ and 0.005 mW/(m^2-cm^{-1}-ster) at 3.8μ. Limitations of this technique are: (1) possible emissivity variations from 11.5μ to 3.7μ, (2) severe radiometric accuracy requirement at 3.7μ (probably should be .002 mW/(m^2-cm^{-1}-ster)), and (3) contamination of the 3.7μ emitted radiation by reflected solar radiation during the day.

2) one window channel at 11.5μ and one channel in the nearby CO_2 absorption band (a possible choice for the second channel is at 13.8μ corresponding to a wavenumber ν=725 cm^{-1}). The technique used in this case (William L. Smith, private communication) takes advantage of the fact that the two channels are sensitive to different atmospheric regions, the window channel being influenced only by surface or cloud emission, and the 13.8μ channel being influenced strongly by atmospheric emission as well. This difference provides sufficient information to solve for the cloud height
Altitude resolution of 500 m would be possible with an NER (Noise Equivalent Radiance) of about 0.1 mW/(m^2ster cm^{-1}) for each of the two channels. Since the bandpass of the 13.8μ channel could be as large as 100 cm^{-1} this should not be too difficult to achieve from SEOS.

Some consideration must also be given to the use of visible channel images for cloud tracking. Clouds are sufficiently transparent in the visible spectrum to produce measurable variations of scattered radiation as a function of cloud depth (Griffith and Woodley, 1973). As a result, it is possible to observe and track the bright cores of convective systems and thus measure the motion of the regions of deepest convection which are perhaps most indicative of severe weather situations (Martin and Suomi, 1972). In this application a spectral channel covering the range from .55μ to .75μ with a signal to noise ratio of 100 to 1 at 100% albedo should be sufficient. Tracking very small cumuli to measure 850 mb winds near the top of the boundary layer requires better resolution than the IR channels, probably of the order of 100 meters in the visible.

TABLE XXI

Proposed Imaging Requirements for Wind Determinations from SEOS

	λ	ν(cm^{-1})	$\Delta\nu$(cm^{-1})	NER
IR:	11.5 μm	870	160	0.1 mW/(m^2-cm^{-1}-ster)
	13.8 μm	725	100	0.1 "
	6.7 μm	1490	150	0.05 "
Visible:	.55 - .75μm		100:1 SNR @ 100% albedo	

C) Moisture pattern tracking

Synoptic scale moisture patterns observed by the 6.7 μ temperature-humidity infrared radiometer (THIR) on Nimbus 4 have been related to flow patterns on upper tropospheric pressure surfaces by Allison et. al., (1972) and Steranka et. al., (1973). The moisture is advected by the wind field so that streamlines may be inferred from the orientation of the moisture patterns (c.f. similar results on isentropic surfaces e.g., Petterssen, 1940). Following such moisture patterns with a geostationary device

could provide motion vectors. Vertical resolution would be small and the effects of turbulent diffusion of water vapor as well as vertical transports by convection might provide major obstacles. It seems unlikely, therefore, that useful mesoscale data could be obtained with soundings of any reasonable resolution or accuracy, but some important synoptic scale information might be forthcoming.

D) The Thermal Wind

If accelerations are at least constant with height then the so called "thermal wind" relationship is valid. It states that the change in the wind in the vertical (the wind shear) is proportional to the horizontal temperature gradient or

$$\frac{\partial \vec{V}}{\partial Z} = \frac{-g}{fT^*} \vec{\nabla}_p T^* \times \vec{k} \qquad (1)$$

where $\vec{V}$ the wind velocity, g is the acceleration of gravity, f is the coriolis parameter, T* is the virtual temperature, $\nabla_p(\ )$ is the gradient operation on a pressure surface, and $\vec{k}$ is the unit vector in the vertical. An integrated form of (1) may be used to determine the wind at a given level if the horizontal temperature distribution is known and the wind at some other level is known.

Togstad (1972) has shown that satellite soundings spaced at 1 degree latitude (111 km) with r.m.s. errors of no more than .10 and preferably .05 $erg(cm^2 \cdot sec \cdot sr \cdot cm^{-1})^{-1}$ are necessary if such important upper level features as the jet stream core are to be properly analyzed. He indicates that the thermal wind relationship or simple modifications of it can be used to determine the upper level winds in the vicinity of the jet stream provided winds are available from the low troposphere.

It must be acknowledged that the thermal wind relationship would be much less useful in determining shears through shallow layers such as in regions of clear air turbulence. Moreover, if the derived winds are to be used for direct determination of divergence, the thermal wind relationship cannot be used. Indirect techniques for inference of the divergence through the use of the vorticity equation or numerical prediction models could make use of winds determined by (1), but only on a large scale and with much lower reliability.

3. Summary

Table XXII is a summary of requirements and most applicable techniques as a function of the purpose for which wind observations would be used. It should be emphasized that the purposes involving synoptic scale features are as important in the predictions of mesoscale events as are mesoscale observations. Some of the larger scale data requirements might be met by combining data from other satellites and conventional data with SEOS observations. The most viable techniques for SEOS will be the use of cloud motions determined as a function of altitude and the thermal wind relationship combined with the surface pressure pattern from hourly surface observations.

Table XXII

Purpose	Accuracy (m/sec)	Horizontal Resolution (km)	Vert. Res. (km)	Period (min)	Spatial Coverage (km^2)	Techniques
Jet Detection	5	$(2-4)x10^2$	2	60	10^6	1,2,3,4
Vorticity Advection	5	$(3-5)x10^2$	2	60	10^6	1,2,3,4
Frontal Analysis	3	2.5×10^2	1.5	60	$.5 \times 10^6$	2,4
Synoptic scale Divergence	3	2.5×10^2	1.5	60	$.5 \times 10^6$	2,4 indirectly
High Level Turbulence	1	10^2	1	60	$.25x10^6$	2,4 possibly
Boundary Layer Turbulence	1	$.5 \times 10^2$	.2	60	$.10x10^6$	2,4 with surf. obs
Mesoscale Divergence	1	$.2 \times 10^2$	1	10	$.05 x10^6$	2

Techniques: 1 - pattern recognition; 2 - cloud motions; 3 - moisture pattern motion; 4 - thermal wind

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F. Hydrometeors and Fog

The most important condensation processes in the free atmosphere are associated with adiabatic cooling of ascending air and with redistribution of heat and moisture as a result of turbulent transfer. Cloud forms in the SEOS images will, therefore, reveal to the forecaster the broad aspects of the processes in operation. While condensation processes are capable of producing cloud droplets (or ice particles) of the order of 40 μ in diameter, an ordinary raindrop falls within the range from 1 to 6 mm in diameter. Thus, the mass of a common raindrop is about 10^5 times larger than that of an ordinary cloud droplet. This brings to the fore the difference between the condensation and precipitation processes. The purpose of this chapter is to describe the various forms of clouds (especially fogs) and precipitations and to give a brief account of the condensation processes, the release of precipitation, and the parameters desirable for remote satellite sensing.

1. Cloud Types

As seen from above the earth, the clouds may be divided into three main categories: (1) cirrus, or feathery clouds; (2) stratus, or layer clouds: (3) cumulus, or heap clouds. These basic forms may appear in various combinations, such as layers of cumulus, layers of cirrus, etc. Depending upon such combinations and the height above the ground, the clouds may be divided into 10 principal types. Their classification and structure is quite indicative of the meteorological conditions under which they are formed or maintained.

Cirrus (Ci) is the highest cloud. It has a typical fibrous (threadlike) structure and a white delicate and silky appearance. Cirrus clouds are sometimes arranged irregularly in the sky as detached clouds without connection with cirrostratus or altostratus. They are then called fair-weather cirrus. If the cirrus clouds are arranged in bands or connected with cirrostratus or altostratus or otherwise systematically arranged, they are usually harbingers of bad weather. In thundery or squally weather, a special kind of cirrus (cirrus densus) is frequently observed which originates from the anvils of cumulonimbus. These clouds are often called false cirrus, because they are denser and usually lower than the ordinary cirrus.

Cirrostratus (Cs) is a thin, whitish sheet of cloud, sometimes like a veil covering the whole sky, at other times showing signs of a fibrous structure like a tangled web. Cirrostratus often produces a halo around the sun or moon. It is often a sign of approaching bad weather.

Cirrocumulus (Cc) consists usually of small, white flakes of clouds without shadow, arranged in a regular pattern. Cirrocumulus develops from cirrostratus. The pattern is due to a single or a double undulation of the cloud sheet.

Altostratus (As) is a dense sheet of gray or bluish color, often showing a fibrous structure. It often merges gradually into cirrostratus. Increasing altostratus is usually followed by precipitation of a continuous and lasting type.

Altocumulus (Ac) differs from cirrocumulus in consisting of larger globules, often with shadows, whereas cirrocumulus clouds show only indications of shadows or none at all. Altocumulus often develops from dissolving altostratus. An important variety of altocumulus is called altocumulus castellatus. In appearance it resembles ordinary Ac; but in places turreted tops develop that look like miniature cumulus. Altocumulus castellatus usually indicates a change to a chaotic, thundery sky.

Stratocumulus (Sc) is a cloud layer consisting of large, lumpy masses or rolls of dull gray color with brighter interstices. The masses are often arranged in a regular way and resemble altocumulus.

Nimbostratus (Ns) is a dense, shapeless, and ragged layer of low clouds from which steady precipitation usually falls, It is usually connected with altostratus which is present above the nimbus. Fragments of cloud that drift under the rain clouds are called fractostratus.

Cumulus (Cu) is a thick cloud whose upper surface is dome-shaped, often of a cauliflower structure, the base being usually horizontal. Cumulus clouds may be divided into two classes. Flat cumulus clouds without towers or protuberances are called cumulus humilis or fair-weather cumulus. Towering cumulus clouds with typical cauliflower structure showing internal motion and turbulence are called cumulus congestus. They may develop into cumulonimbus.

Cumulonimbus (Cb) thunderclouds or shower clouds are great masses of cloud rising like mountains, towers, or anvils and having a base that looks like a r gged mass of nimbostratus. The tops are often anvil-shaped or surrounded by false cirrus. The cumulonimbus clouds are accompanied by showers, squalls, or thunderstorms and sometimes hail. The line squall cloud is a v riety of cumulonimbus that extends like a long line or arch across the sky.

Stratus (St) is a uniform layer of low cloudlike fog, but not lying on the ground.

The heights of the various types of cloud vary within wide limits. The "high" clouds are usually above 20,000 ft. (6000 m) and below 40,000 ft (13,000 m). The "medium" clouds are most frequently between 8000 and 20,000 ft (2500 and 6000 m), and the "low" clouds below 8000 ft (2500 m).

From a genetical point of view the clouds may be divided into four categories: (1) clouds that form in unstable air masses, (2) clouds that form in stable air masses, (3) clouds that form in connection with quasi-horizontal inversions, and (4) frontal clouds.

Categories (1) and (2) are typical internal clouds that reveal the stability conditions of the air masses to which they belong. The clouds belonging to (3) are most frequently related to group (2), but sometimes they are in certain features related to (1). The clouds of group (4) are formed because of upglide motion associated with frontal zones. These clouds, too, are strongly influenced by the stability conditions of the air.

The clouds typical of category (1) are cumulus and cumulonimbus. Other signs of instability are certain detached high clouds such as cirrus nothus and cirrus densus, which originate from the anvils of cumulonimbus.

The most typical cloud forms belonging to category (2) are fog and stratus, which are unmistabable signs of stable stratification. We shall treat fog separately because of its complexity.

Belonging to category (3) but related to (2) are stratocumulus and certain types of altocumulus. A great variety of clouds belong to category (3) but show signs of instability and are therefore related to category (1). Noteworthy are: stratocumulus vesperalis, stratocumulus castellatus, stratocumulus cumulogenitus, cumulus undulatus, and certain types of altocumulus castellatus.

The clouds belonging to category (4) are of a stratiform type when the air that takes part in the upglide motion is stable (e.g., altostratus); and when the air is unstable, the frontal cloud system may be of the cumulus type. When the air that takes part in the upglide motion becomes unstable while it ascends, the lower part of the cloud system may be stratified, while cumulus or cumulonimbus towers project from the upper part of the frontal cloud layer.

The greatest variations in shape and vertical extent are exhibited by the clouds of the cumulus family. While the individual cumuli are short-lived and undergo rapid changes, the cumulus sky, as a whole, is easily recognized. Once the state of the sky has been identified as a cumulus type, it is important to identify the subtypes, and in doing so, the vertical dimensions and the internal motions of the clouds are important. The principal types of cumulus clouds are shown schematically in Figure 35.

Cumulus humilis are typical fair-weather clouds and show no tendency to vertical growth. They usually develop in a shallow, unstable layer near the ground, surmounted by a stable layer or an inversion; they have a pronounced diurnal variation (over land), and dissolve readily in the late afternoon or evening. Towering cumulus often develop into cumulus humilis when a warm front, with altostratus and cirrostratus, approaches. On the whole, the presence of cumulus humilis is indicative of a stable stratification overthe surface layer.

Cumulus congestus (Diagram b) is easily recognized by the presence of towers and protuberances which grow and show signs of internal motion. One obtains the impression that large bubbles of air rise through the cloud and become visible as towers protruding from the main body of the cloud. Although the life of each protuberance is quite short, the cloud usually continues to develop, and when the cloud has attained sufficient depth, precipitation is released, and the cloud becomes a cumulonimbus. The cumulus pileus (Diagram c) resembles cumulus congestus, except that the towers are surrounded by a thin veil (pileus). This veil (or "scarf") indicates that the cloud is "working against" a stable layer within which condensation occurs.

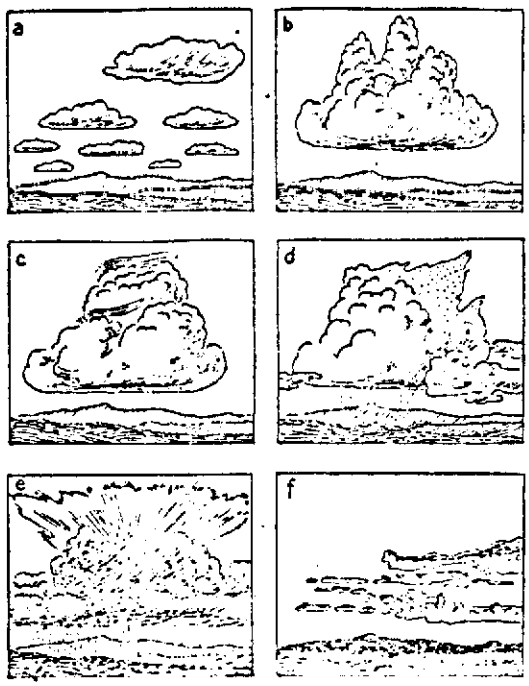

Figure 35. Types of convective clouds: a, cumulus humilis; b, cumulus congestus; c, cumulus pileus; d, cumulonimbus calvus; e, cumulonimbus incus; f, stratocumulus vesperalis.

Cumulonimbus clouds (Diagrams d and e) are characterized by precipitation falling out of their bases. While any cumulus cloud that is sufficiently deep may release precipitation, such release, in middle and high latitudes, is most frequently associated with the presence, in the upper part of the cloud, of ice crystals and supercooled water droplets. At the time when precipitation commences, the upper part of the cloud is often seen to develop as shown in Diagram d, and as the process continues, large masses of ice clouds develop (Diagram e), resembling an anvil consisting of a more or less uniform texture without visible convective bubbles.

When clouds of the cumulus type dissolve, the lower (water) portion usually develops into a layer of irregular heap-shaped masses resembling stratocumulus (Diagram f). The upper portion (the anvil) often becomes detached, flattens, and assumes the appearance of dense cirrus of irregular shape.

2. Hydrometeors and the Meteorological Conditions

Bodies of solid or liquid water falling through the air are called hydrometeors. From a genetical point of view hydrometeors may be divided into three main groups.

a. Hydrometeors of Frontal Cloud Systems. These hydrometeors are formed when huge bodies of air rise slowly because of the upglide movement due to a general convergence in the horizontal air flow along frontal surfaces; they originate from clouds of the altostratus-nimbostratus type and

comprise rain, snow or sleet. None of these hydrometeors is by definition indicative of frontal phenomena. What is characteristic of frontal precipitation is the even falling of rain, snow or sleet from a stratiform and extensive cloud system. The precipitation may be intermittent or of variable intensity, but its variations are never so pronounced as when it falls as showers or squalls.

b. Hydrometeors of Unstable Air Masses. These hydrometeors, which are formed when small bodies of air rise rapidly through the atmosphere, comprise all kinds of showery or squally precipitations. The showers or squalls may consist of rain, snow, sleet, or any kind of hail.

Showery or squally precipitation is characterized by the suddenness with which it starts and stops and by its rapid changes in intensity; also, by the aspect of the sky, which exhibits rapid variations in space and time from dark and threatening clouds (cumulonimbus) to clearings of short duration, often with an unusual blueness of the sky. Sometimes no definite clearing occurs between the showers, and the precipitation may not stop entirely between them; but, in such cases, the showery character is revealed by the sudden changes in intensity of precipitation and rapid alterations between lighter and darker clouds.

c. Hydrometeors of Stably Stratified Air Masses. These hydrometeors, which are characterized by the smallness of their dimensions and the slowness of their fall, originate from clouds of the stratus or the fog type. The principal types are drizzle, granular snow, and ice needles. Grains of ice are not necessarily typical of the stably stratified air masses, because they form as raindrops in warm air aloft and solidify in the cold and stable ground layer of air.

Figure 36 shows a typical example of the variations in intensity of warm-front rain, warm-sector drizzle, cold-front rain, and showers in the rear of a depression that passed the southern part of Norway on May 9, 1938. The left-hand portion of the diagram shows the even increase in the rain intensity as the warm front approaches, the sudden but not discontinuous change to warm-sector drizzle at the passage of the warm front, and the similar change to cold-front rain, which in this case was of moderate intensity. The right-hand portion of the diagram shows the simultaneous rain intensities in the unstable northerly current of polar air in the rear of the passing depression.

In spite of much progress in cloud physics research, the forecaster remains at a disadvantage, for the observations routinely available contain but little information related to the condensation and precipitation processes. In forecasting clouds and precipitation, forecasters are guided by the large-scale features of the synoptic systems. Although our knowledge of the precipitation processes is meager, some weight must be placed on forecasting experience which indicates the deep clouds, and particularly clouds that reach up to subfreezing temperatures, readily yield precipitation.

Any attempt at developing a quantitative method of forecasting precipitation must logically be based on considerations of the physical processes

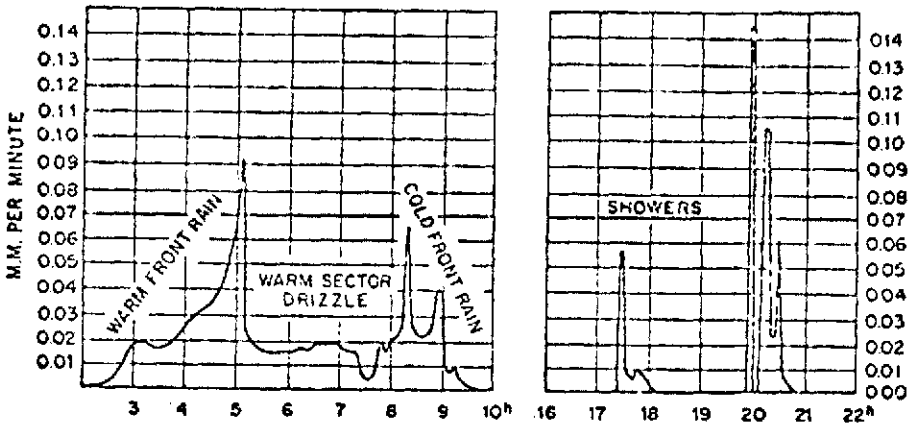

Figure 36. Rain intensities during the passage of a depression.

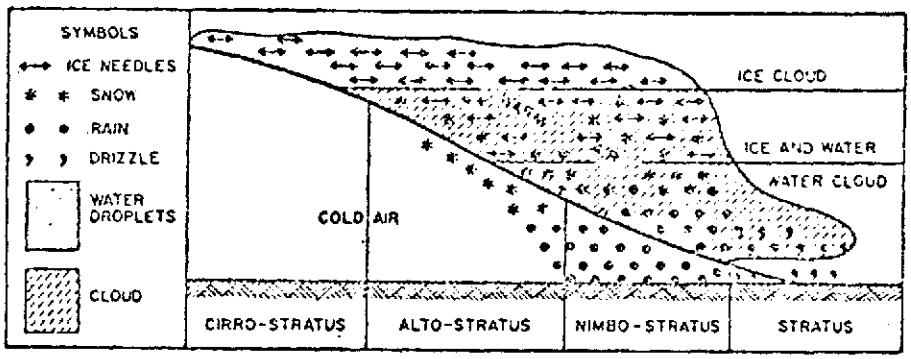

Figure 37. shows the idealized structure of a precipitating frontal cloud.

of the atmosphere. However, because of the complexities of these processes and the inadequacies of the observations routinely available, we are able, from a practical standpoint, to take account of only those factors which are of paramount importance. From its initial formation as a minute cloud particle to its final release from the cloud in the form of liquid or solid precipitation, the growing drop is influenced by, or associated with, most of the large- and small-scale dynamic and thermodynamic processes in the atmosphere. We find, therefore, that our ability to predict the occurrence and the amount of precipitation is closely related to our skill in forecasting the behavior of the weather in general.

In order to develop techniques for predicting the occurrence and the amounts of precipitation, it is necessary to construct simplified models which will approximate, as closely as possible, the true state of the atmosphere in so far as it is related to the problem of predicting precipitation. These models may be varied according to the data available and the particular avenue of approach. Thus we find that certain simplifications are made in the development of conventional forecasting procedures, while others no less restrictive are applied to formulate the problem for solution by computer. Certain simplifications are common to all models currently used, however, and these may be summarized briefly as follows.

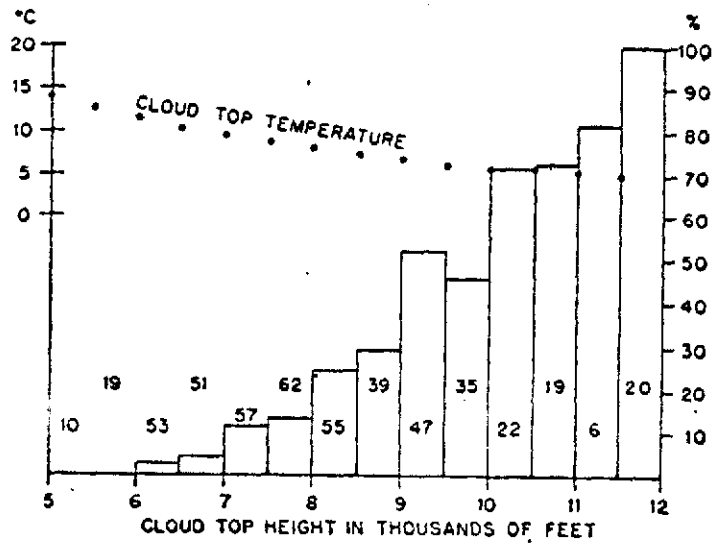

Figure 38. Percentage of over-water clouds with radar echoes as a function of cloud-top height and temperature.

1. Condensation Nuclei. While condensation nuclei may vary considerably in size and number, they are normally sufficiently plentiful to cause condensation to begin and clouds to form when the air is cooled to its saturation temperature.

2. Nonadiabatic Effects. Except in the layer of air near the earth's surface, it is found justifiable to assume that the temperature changes other than those due to adiabatic expansions are small. The effect of radiational cooling has been found to be of the order of about 1 to 2°C a day for middle clouds at altitudes below about 25,000 ft (8 km), while computations of solar heating within such clouds indicate the net temperature change to be even smaller. The rate of cooling due to m derate pseudo-adiabatic lifting, on the other hand, is of the order of 1°C hr^{-1}, and may be several times larger in strong vertical motion.

3. Storage of Water. Measurements made of the liquid-water content in various clouds indicate that values of the order of 2 g m^{-3} may be expected in heavy cumulus during the winter months. During the summer the water content would be expected to be even higher. For clouds of this type approximately 20,000 ft in thickness, say, the amount of precipitable water held in storage in the cloud as liquid-water droplets is equivalent to as much as 0.5 in (12.7 mm) of rainfall. In the absence of routine observations on drop size distribution, etc., there appears to be no adequate procedure for taking this factor into account, and it is usually considered necessary to neglect the effect of water storage within the cloud.

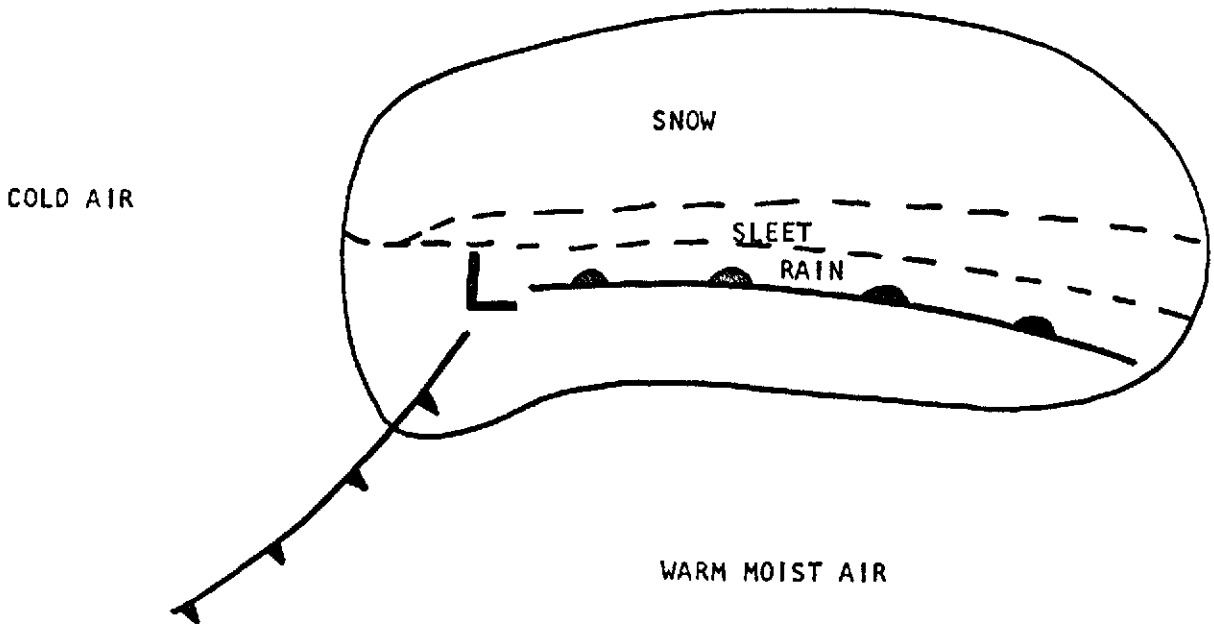

Figure 39. Narrow Demarcation between snow, sleet, and rain.

4. Evaporation from Precipitation. As a rule, the air below the cloud base is, to some degree, unsaturated, and the rain or snow reaching the ground will be decreased by a certain amount of evaporation. In ordinary rainfall situations, the evaporation loss is normally less than 10 per cent, and it is usually considered sufficiently accurate to neglect the evaporation loss in such cases.

All these factors are commonly neglected in current forecasting procedures, although in some empirical forecasting methods their total effect may be allowed for. If our knowledge and technological aids improve with proper observations from a SEOS type of satellite, it will be possible gradually to take them into account explicitly in routine forecasts and in this way increase the accuracy of our predictions.

The great need to identify lines of demarcation between snow, sleet and rain in a storm is evidenced by the occasional situations where forecasts of 10 inch snowfalls have been followed by flooding or where forecasts for rain have been embarrassingly followed by paralyzing snowfalls. Often, the difference is one of 1 or 2 degrees, or of 15 miles (see Figures 37 and 39).

The most important use of a SEOS instrumental satellite toward forecasting rain, sleet, and snow would be to observe by means of imaging near 100 meter resolution the development of the characteristic types of clouds as described in the first part of this section. IR sounding would define the physical conditions around clouds, while in the case of large frontal bands, microwave soundings would be needed. The advantage of SEOS observations over those of other satellites would be that SEOS could monitor the intensity of growth of regional cloud systems. The necessary parameters of temperature and water vapor vertical profiles must be determined under the following coverage.

A. Time: from the SEOS satellite, it must be possible to make soundings as often as required by changing atmospheric conditions.

B. Spatial resolution: due to many types of clouds that can occur, many soundings are required to be made every 20 km to 30 km over limited areas. In order to make measurements within broken cloud cover, the instrumental IFOV should be on the order of 10 km to 20 km.

C. Vertical resolution: in order to locate temperature and moisture layers in the lower troposphere, the vertical resolution should approach 1000 meters. This will be a necessary aid in distinguishing rain forecasts from snow forecasts.

D. Accuracy: the sounding error averaged over the vertical resolution length should be 0.5°K in temperature and $\leq$ 10% in relative humidity for the lower troposphere.

E. Spatial coverage: due to the development of snow and sleet at a number of geographic locations at the same time of year, it should be possible to make soundings over an area 200 km x 600 km within a period of 20 to 30 minutes.

4. Fog

It is difficult to attempt to exactly define a fog because of its many varieties and causes. It is basically a stratus-cloud cover that forms at the ground or so close to it as to affect seriously the surface visibility. On mountain tops, however, almost any cloud may exist at the surface and therefore be seen as fog. In urban regions it is difficult to distinguish between fog and smoke, and indeed it is universally impossible to determine a sharp demarcation between heavy haze and fog. Local differences in designation are not uncommon, e.g., the stratus-cloud cover prevalent on the California coast is called <u>high fog</u> because the hilly nature of the region presents stratus fog on the higher ground and stratus cloud over the valleys and lowlands. For aviation, the prinicpal concern is with critical values of "ceiling," visibility, and slant visibility as they affect approach and landing systems rather than with what is generally regarded as fog. As the systems change, so do the practical critical values of the meteorological elements.

Stratus clouds are characteristic of the lower part of the atmosphere when a well-developed temperature inversion or nearly-isothermal layer exists there. If the air below is sufficiently moist, a stratus layer will form, its top at the base of the inversion. For the formation to take place as fog, the base of the inversion must, then, be at the ground or very close to it. Of course, a temperature inversion at or near the ground is merely an expression of cooling from below and is therefore characteristic of air masses that were originally warmer than the surface over which they are passing or resting. The problem of investigating the forecasting of fog formation then reduced itself to the determination of the circumstances un-

der which cooling of air masses at the surface, in the presence of high moisture content, can take place. An exception is found in certain fogs that form on cold days over warm water, especially in the arctic; these are nothing but actual steam. Also many fogs owe their immediate origin to the increase of the water-vapor content without appreciable cooling, such as in a warm-front rain. However, the air must first be rendered stable by cooling. Over continents in winter this stability due to cooling is nearly always present, and the formation of stratus or fog simply awaits the addition of sufficient moisture by rain from an overrunning warm air mass.

To simplify the discussion of fogs and to clarify our understanding of the causes of their formation it is useful to have a fog classification. Such a classification, based on synoptic as well as physical considerations, was introduced by Willett and will be used here, with modifications. From the physical viewpoint, it recognizes that fog may form either by cooling to the dew-point temperature or by addition of water vapor until the dew-point temperature equals the actual temperature. The classification places the fogs in two main groups, depending on which of these two effects is predominant in bringing the temperature and the dew-point together. These two groups are (I) air-mass fogs which form by lowering of the temperature (except for steam) and (II) frontal fogs which form in the presence of precipitation, the increase of dew-point temperature being the more important factor.

A classification of fogs, modified from Willett, follows:

A. Air-mass fogs

1. Advection types

a. Types due to the transport of warm air over a cold surface.

1. Land and sea-breeze fog
2. Sea fog
3. Tropical-air fog

b. Types due to the transport of cold air over a warm surface.

1. Steam fogs (arctic "sea smoke")

2. Radiation types

a. Ground fog

b. High-inversion fog

3. Advection-radiation fog (radiation over land in damp sea air)

4. Upslope fog (adiabatic-expansion fog)

B. Frontal fogs

1. Prefrontal (warm-front) fog

2. Postfrontal (cold-front) fog

3. Front-passage fog

A. Land- and sea-breeze fog.

Advection-type fogs depend on the transport of air between regions of contrasting surface temperatures. Sea-coasts fulfill these conditions at nearly all seasons. In summer, in localities where conditions are favorable for the transport of warm moist air from the land out over the water, an ideal type of advection fog forms--land- and sea-breeze fog. In most cases of land- and sea-breeze fog, fluctuations in the wind direction, usually of a diurnal nature, are part of the mechanism. The air from the summer-heated land is cooled as it passes over the cooler surface afforded by the ocean. If the winds are of moderate to strong velocity, turbulence may preserve a steep lapse rate in the lowest layers, and stratus clouds will form unde a turbulence inversion. If, however, the winds are light, a dense surface fog may develop over the sea. This fog may be brought over the land by a sea breeze that comes up in the middle of the afternoon, receding again at night as the land breeze again becomes dominant.

B. Sea Fog

Fundamentally there is little difference between land- and sea-breeze fog and sea fog. While the former is developed by the cooling of land air over the ocean, the latter arises from the cooling of sea air over a cold ocean current. Sea fog, then, is not a purely coastal type but can occur anywhere over the ocean where contrasting water temperatures are found. However, many of the cold ocean waters are found in coastal currents, and sea fog often has its best development near land, e.g., on the California coast, where sea air passing over the cold California current produces persistent summer fogs.

In most cases where a sounding is made through the fog, intense surface cooling is shown by the existence of a pronounced temperature inversion. When the wind velocities are high, mechanical turbulence carries heat downward from above and tends to diminish the inversion or perhaps actually to cause the temperature to decrease with altitude. In such cases, the formation would be a stratus cloud instead of fog at the surface. Air that is undergoing very sudden cooling from below, however, could support fog in higher winds than air that was nearer equilibrium with respect to the surface. Those fogs that are able to persist in spite of strong winds and turbulence are found, in general, only when the difference between the air temperature and water temperature is large.

C. Tropical-air Fog

This type differs from sea fog in that it depends not on the cooling by passage over a cold current but simply on the gradual cooling of the air as it moves from low latitudes poleward over the ocean. Also, it can occur

in winter over the land in advancing tropical air. It is perhaps the most common type of fog over the open sea, and in the United States forms some of the most widespread fogs that are observed on land. Over continents in winter, the latitudinal temperature gradient is much greater than over the oceans; hence the poleward-moving tropical air is cooled more rapidly and forms fog more readily.

D. Steam Fogs

Steam fog forms when cold air having a low vapor pressure passes over water. If the water is very warm, the air does not have to be very cold for the steaming to occur. It is a simple problem in vapor-pressure differences. For example, if the water has a temperature of 4°C, its vapor tension is 8.13 mb; and, if the air above has a temperature of -10°C, the pressure of its water vapor will be 2.86 mb, even if at saturation. Thus there is a large vapor-pressure gradient directed out of the water, and, as one might expect, steaming of the water into the cold air takes place.

In general, steam fog is quite shallow, extending into the air 50 to 100 feet or less, but deep enough to interfere with safe shipping and over-water flying. It occurs over rivers, often when the air has been cooled by radiation, and tends to form radiation fog near the river as well as steam on the river. Such occurrences are especially common in autumn when the water is still warm but when the air is getting cold. Over the Great Lakes the principal occurrence of steam fog is in midwinter when the cold continental air passes over the lake waters, which have a temperature slightly above freezing. Over localities where both ice and open water are present, the steam fogs are quite common and have been given the name "arctic sea smoke."

E. Ground Fog

Nearly all fogs occurring over the land are caused wholly or in part by radiation cooling of the lower moist air. The simplest example of a radiation type is afforded by ground fog. Ground fog is considered as that forming from a temperature inversion at the ground caused by the radiation cooling occurring during a single night, the inversion disappearing during the day. This process, if sufficiently intense, may produce fogs deep enough to blot out the vertical visibility, but according to our genetical definition they would still be called ground fogs.

The greater the wind movement, the less will be the chance for a sharp reduction in temperature in the lowest layers, because turbulence accompanying the wind will carry heat downward and will prevent the development of a surface-temperature inversion. Another important factor is the presence or lack of cloud cover. If clouds prevail, they will absorb part of the radiation emitted by the earth and radiate it back downward where it will be absorbed again, thus making the net loss at the surface relatively slight. Clear skies, especially if only small quantities of water vapor are present aloft, allow practically all the radiation emitted from the surface to escape to space.

F. High-inversion Fog

This type of fog is essentially a winter phenomenon and, like all radiation fogs, occurs only over the land. It is formed not as the result of a single night of radiation cooling, as in the case of ground fog, but from the long-continued net loss of heat by radiation which is characteristic of the continents outside the tropics in winter.

The term "high inversion" as applied to these fogs not only means that the inversion extends through a deeper layer than that of ground fogs, but also includes types in which the vertical temperature curve may be isothermal, or the temperature may even decrease slightly with height, with a real temperature inversion at an altitude of 100 to 600 m above the ground. The latter type may become "high fog" or low stratus cloud during the day, changing to a dense surface fog again at night.

G. Advection-radiation Fog

This name is given to fog that forms by nighttime radiational cooling in air that has come inland from the sea during the day. In general, it is like other types of radiation fog except that it is derived from special circumstances. Air of high humidity coming from a warm-water surface is cooled by radiation during the night. For example, air from the Gulf of Mexico having a temperature of 76°F and a dew-point temperature of 66°F will come inland to a station where the nighttime temperature will go down, let us say, to 62°F owing to radiation. The advection of the sea air with its high dew-point temperature makes it possible for fog to form with the normal nocturnal cooling. Beyond the easy reach of this air, fog-free conditions may prevail even though the temperature has gone lower.

This fog occurs mainly in the late summer and autumn when the water is rather warm and is therefore capable of producing a high dew-point temperature in the overlying air and when the nights are long enough for considerable cooling.

H. Upslope Fog

In regions where the land slopes gradually upward, such as on the Great Plains of the United States and Canada, fogs sometimes form as a result of the cooling of the air by adiabatic expansion as it moves to the higher elevations.

This is one of the few kinds of fog that can be maintained in relatively high wind velocities. The reason for this fact is that the more rapidly the air moves up the slope the faster will be the cooling process, and the downward transport of heat by turbulence will be counteracted to some extent. As a general rule, however, stratus clouds form in winds of really strong force. The fogs are often formed by the combined effects of ascent and radiation and in some instances by moisture increases due to falling rain.

I. Prefrontal (Warm-front) Fog

Rain falling into stable air can raise the dew-point temperature until

fog is formed even without cooling of the lower air. These conditions are best fulfilled in the cold air ahead of warm fronts. If the air in the cold wedge does not have the required stable lapse rate, the added moisture is carried upward by turbulence or convection and condensed into stratus, stratocumulus or, in some cases, cumulus clouds. Continental-polar air of winter is the type that is most often stable; and when it is overrun by precipitating warmer air masses, fogs or very low stratus commonly form. True maritime-polar air that has not undergone an appreciable amount of cooling is usually not stable enough for this type of fog to form.

J. Postfrontal (Cold-front) Fog

Genetically there is little difference between warm- and cold-front fog, as each is formed from the moisture of falling precipitation. However, since the precipitation band associated with a cold front is much more restricted in area than that of a warm front, the post-cold-front fogs are less widespread. In fact, it is only a cold front that has become quasi-stationary, usually lying in an east-to-west direction and therefore closely resembling warm-front conditions, that has associated with it an extensive fog area. As in the case of the warm-front fog, these circumstances cause fog only if the cold air is stable. Unstable cold air masses, such as maritime-polar, have cumuliform clouds associated with them.

K. Ice Fog

We include ice fog for completeness even though it is not common in the contiguous United States and unlikely to be observed by SEOS. It does occur commonly in Alaska, and in other parts of the world where the temperature drops below -40°F. Fog condensation over snow is difficult since the saturation vapor pressure of snow is very low. The tendency is for moisture to condense on the snow not above it. At very cold temperatures, condensation can occur in the air in the form of ice crystals, which because of their low vapor pressure will persist in equilibrium with the snow.

5. Fog Observation with SEOS

Probably there is no type of fog that is not well represented in some region of the United States or its adjacent waters. It is well to devote some attention to the various fog regimes of the U.S. not only for practical reasons but also to furnish illustrations of the various types that we have classified. In doing so, each of the principal regions where fogs are observed will be discussed in the order of most frequent fog occurrence. This will in icate the sensoring rates and monitoring frequencies which may be expected from SEOS if fog is to be an observational objective.

We have, then, the following regions: (1) California coast, (2) New England outer coast, (3) northern Pacific Coast line, (4) Appalachian valleys, (5) Pacific Coast valleys, (6) middle Atlantic Coast, (7) Great Lakes, (8) southern Atlantic and Gulf coastal waters, (9) Gulf and Atlantic coastal plain and piedmont, (10) Great Plains, (11) Ohio, Missouri, and Upper Mississippi valleys. The delineation of the various regions is based

to a large extent on the data presented by Stone[1] which considers the former Weather Bureau definition of fog as including only those cases where the visibility is less than 1000 ft. Sections of the country not included in the list have, in general, less than 5 days a year with visibility of less than 1000 ft due to fog.

The map in Figure 40 shows in a rough way the various regions. Also, where possible, the predominating fog type is indicated by index letters, and, where well defined, the months of fog maxima are shown.

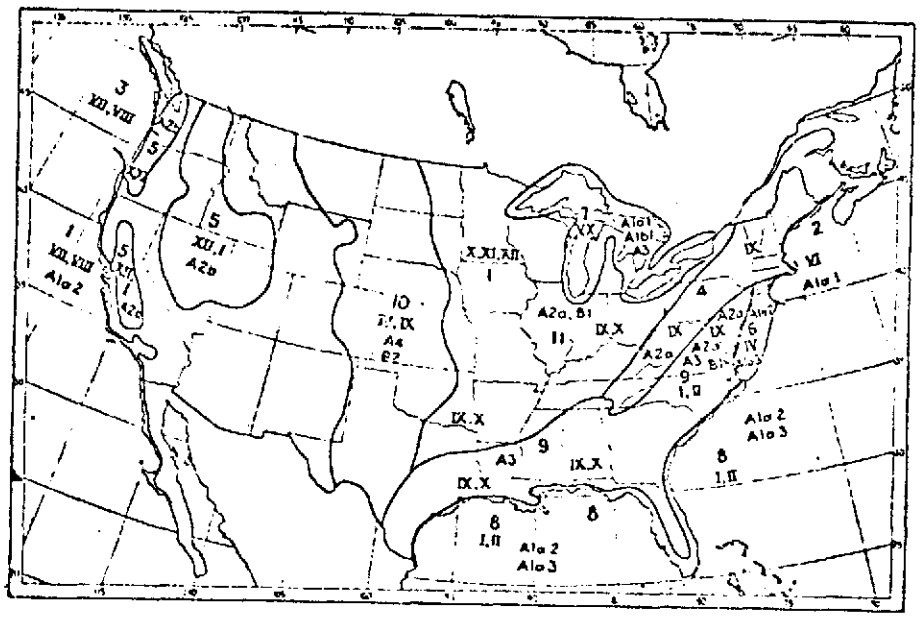

Figure 40. The fog regions of the contiguous United States. Large Arabic numbers correspond to the numbering of the regions as given in this section (e.g., 10 represents Great Plains). The letters and numbers such as Ala2 correspond to the lettering and numbering of the different kinds of fog in the classificaioin at the beginning. The Roman numerals give the month of maximum fog occurrence (I for Jan., II for Feb. etc.)

A. California Coast

The fogs of the outer California coast are sea fogs associated with a cold ocean current. The coldness of the water is caused by the action of the wind. In summer, the prevailing northwest wind exerts a stress on the water directed toward the southeast. The reason for the prevalence of the fog at some height above the surface is to be found in the high wind velocities along the coast.

The vertical distribution of temperature is shown in the typical curves of Figure 41, which represent airplane ascents at Sunnyvale, near San Francisco Bay, and at North Island, San Diego Bay. The ascents are selected in each case for a day on which low stratus clouds were observed. The San

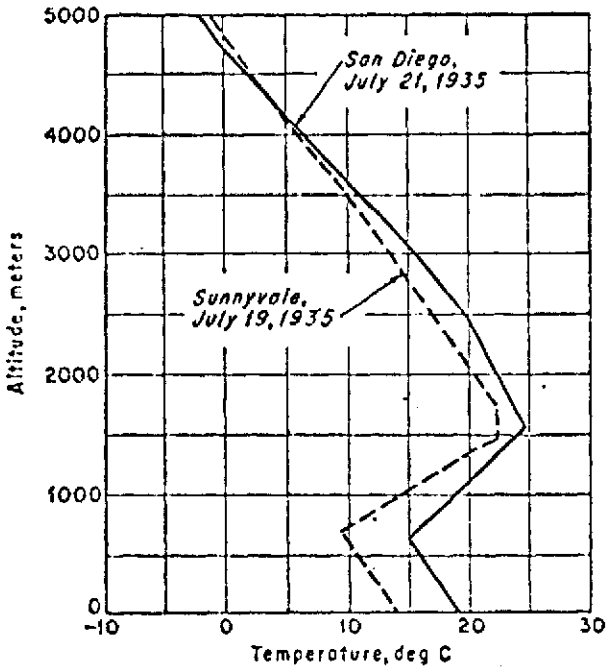

Figure 41. Vertical distribution of temperature during occurrence of stratus cloud on the California coast.

Diego data probably give a true representation of the conditions existing over the ocean off Southern California.

The role of surface heating is especially prominent as the air moves over the land during the day. This results in steepening the lapse rate and produces convection currents that in some cases change the clouds from stratus to stratocumulus. Ordinarily, however, the inversion is so low and the air above so dry that convection, in breaking down the inversion, simply introduces warm clear air. The dry clear weather characteristic of the valleys in summer is caused by the breakdown of the inversion due to intense surface heating. The maritime air, owing to its original low temperature, does not contain enough moisture for clouds at the higher temperature and the downward mixing of the upper air accentuates the dryness.

B. New England Outer Coast

During the summer months there are long periods when the temperature and humidity of the air over the eastern part of the United States are equivalent to those of real tropical regions. Air of this type, which usually comes with winds from a direction between south and west, is transported over the cool ocean waters that lie between the Gulf Stream and the shore northward from Cape Hatteras, and the moisture condenses into fog.

C. Northern Pacific Coast Line

The fogs of the coast of northern Oregon and Washington represent another summer-maximum type. Although it is difficult to separate the southern part of this area from the prevalent California coast regime, it seems evident that a different set of circumstances is operating. No ex-

ceptionally cold ocean current is involved such as is found farther south; the summer sea-surface temperatures off northern Washington are higher than along the northern California coast. A combination of tropical-air fog and sea fog seems to be characteristic of this region.

D. Appalachian Valleys

In this region are included all the mountainous or hilly regions of the Eastern United States, not counting stations located on or near summit of peaks and ridges. It is a region in which fog forms by radiation cooling and air drainage in valleys, swamps, and lowlands that are surrounded by hills and thus protected from strong winds.

Radiation fogs naturally have their maximum occurrence at the time of year when there is a considerable amount of water vapor and cooling by nocturnal radiation. In the eastern part of the United States, the water-vapor content is highest during July, August, and early September with June also fairly moist. The shortest nights of the year are in the latter half of June and early part of July, but in August and September the nights are becoming noticeably longer; and since the high specific humidities of summer prevail at that time, then comes the most favorable combination for fog formation.

E. Pacific Coast Valleys

The high-inversion type of radiation fog is represented in the United States by the winter fogs of the Pacific Coast valleys. Although confined almost entirely to the cold season, these fogs are the most persistent and tenacious to be found anywhere over the land. While many of the radiation fogs of other parts of the country are of the ground-fog type and therefore tend to disappear shortly after sunrise, those of the Pacific Coast valleys are of the type that can continue without interruption for several days at a time.

F. Middle Atlantic Coast

The waters of the continental shelf from Cape Cod to Cape Hatteras are coldest during the latter part of the winter. This is generally true of sea surfaces elsewhere in these latitudes but in this region, the February and March minimum is emphasized not only by the loss of heat to the cold continental atmosphere but also by the fact that several large rivers, such as the Connecticut, Hudson, Delaware, Susquehanna, and Potomac, discharge water that at this season is near freezing, thereby giving to the surface an almost arctic chill. The contrast in temperature between this and the Gulf Stream water provides an ideal situation for the formation of advection-type fogs. It is a condition typical of coastal locations where cold inshore waters are associated with high surface temperatures farther at sea.

G. Great Lakes

The seasonal lag in temperature of large bodies of water in relation

to the surrounding atmosphere is aptly demonstrated by the Great Lakes. In the spring and early summer when the atmosphere is rapidly becoming warmer the lake waters retain much of their winter chill; and in the fall when the first cold-air outbreaks come down from the North, the lakes still have the warmth of summer.

The spring and early summer conditions are conducive to the formation of land- and sea- (lake) breeze fogs; and in the fall, advection-radiation fogs on the nearby land are the rule. Practically all Great Lakes stations show the effects of these two separate fog-frequency maxima. In addition, during autumn and winter, steam fogs are observed over the lakes themselves.

H. Southern Atlantic and Gulf Coastal Waters

In many respects, the southern Atlantic Gulf coasts of the United States have conditions similar to those prevailing along the middle Atlantic Coast. In the late winter and spring, the river discharge produces cold inshore waters that affect the air from the warm Gulf Stream or the Gulf of Mexico itself sufficiently enough to produce fog. The contrasts in temperature of the surface are not so great as along the middle Atlantic Coast, and therefore the frequency of fogs is less in the southern region. On the Florida peninsula, where the river discharge is negligible and the real oceanic water lies close to shore, fogs are rare.

I. Gulf and Atlantic Coastal Plain and Piedmont

Fogs due to various causes occur in this region, but they are predominantly radiation type--either direct-radiation ground fogs or advection-radiation fogs. Prefrontal warm-front fogs also are important.

J. Great Plains

The fogs of the western Great Plains represent one of the few ideal cases of upslope fog. The gradual ascent of the prairies from near sea level to some 5000 to 6000 ft presents an almost perfect upglide surface for air from an easterly direction. A wind of this type usually occurs behind a quasi-stationary cold front over the Middle West, the air has usually had moisture added to it by precipitation along the front, and some of the fogs may be classed as post-frontal cold-front types. Moisture evaporated from the Great Lakes and from the Gulf of Mexico sometimes enters into the fog process. Air from this direction in the central states is in most cases of continental-polar origin, forming an air mass with a stable temperature lapse rate. Adiabatic cooling of the ascending air, combined with a certain amount of radiation cooling, is the main cause of the fog.

K. Ohio, Missouri, and Upper Mississippi Valleys

This region is one of spectacular differences in fog distribution depending on the effects of air drainage, proximity of rivers and other water bodies, city smoke, etc. The contrast between the amount of fogginess in bottom lands of the rivers and the higher surroundings is especially striking.

These highly localized fogs are of course radiation ground fogs that normally disappear during the day. Fogs of longer duration in this locality are usually frontal types. It is in this area that the only really significant postfrontal cold-front types occur. After nearly every cold-front passage that has been accompanied by general rains, low stratus clouds spread over the central states, and in many instances they reach to the surface and therefore can be classed as fogs. Prefrontal warm-front fogs and stratus are of great importance.

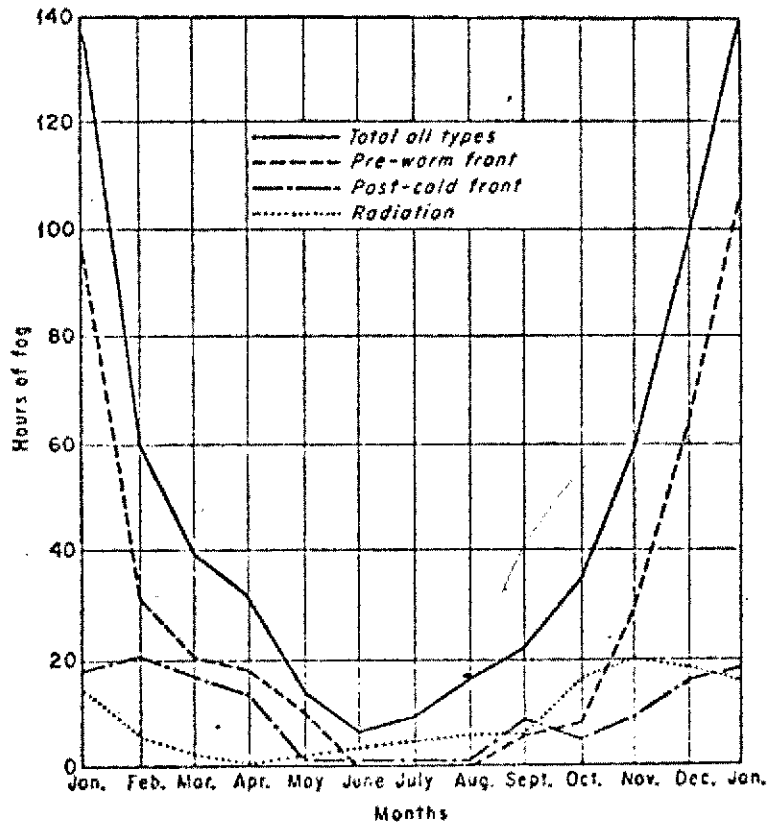

Figure 42. Hours of fog (ceiling 600 ft., visibility 1 mile) in each month at Louisville, Kentucky.

5. SEOS Forecasting

Aids to forecasting include past and future trajectories to determine the likelihood of the air passing over water surfaces of different temperatures or through rain areas and under cloud covers, whether upslope or downslope. Also, the delineation of areas of convergence and divergence may be pertinent to the problem.

Critical parameters influencing fog formation are the low level inds, especially under inversion layers, the vertical temperature distrition and moisture distribution near the ground and aloft, convective ability, surface temperatures (ground and water), dew point, and the sence of divergent or convergent areas where subsidence can dissipate

fog or rising air lift it.

The number of hours of sunshine during the day determines the beginning point of nighttime cooling in terms of temperature and obscure heat-exchange factors. Wind speed may enter into forecasting or, especially in the case of coastal stations, the wind direction may be important. The rate at which the dew point may be increasing or decreasing is taken into consideration.

The moisture content of the soil is an important parameter that should be included when forecasting the onset and duration of fogs over land surfaces. This quantity can be reasonably estimated from National Weather Service ground stations. However, in rural areas where there are few ground stations, this quantity may have to be roughly estimated from the atmospheric moisture soundings, variations in IR ground emissivity, or other indirect means.

In some cases a series of dependent graphs form a sort of check list to determine whether fog is likely to develop or not. Graphical methods have also been worked out for reedicting the dissipation of fog or stratus from daytime heating.

A. Time: from SEOS, it must be possible to make soundings as required by changing atmospheric conditions.

B. Spatial resolution: due to the many small regions in which fogs can occur, many soundings may be required to be made every 20 km to 30 km over limited areas. In order to make measurements within broken cloud cover, the instrumental IFOV should be on the order of 10 km to 20 km.

C. Vertical resolution: in order to locate temperature inversions and moisture layers in the lower troposphere, the vertical resolution should approach 500 m in the boundary layer.

D. Accuracy: the sounding error averaged over the vertical resolution length should be 0.5°K in temperature and $\leq$10% in relative humidity for the lower troposphere.

E. Spatial coverage: due to the development of fog at a number of closely related geographic locations at the same time of year, it should be possible to make soundings over an area 200 km x 600 km within a period of 20 to 30 minutes.

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V. System Possibilities, Operational Requirements, and Data Dissemination

1. Introduction

It has been shown (TableXI) that SEOS becomes considerably less efficient for monitoring stable situations and should concentrate its activities on those regions of earth which are potentially active. It is in such active or potentially active regions where SEOS can significantly contribute to mesoscale forecasts with data of more detail and higher accuracy. Consequently, other existing systems must provide the synoptic view. SEOS cannot waste its time making surveys or even spend much time moving from point to point. There is simply not enough time available.

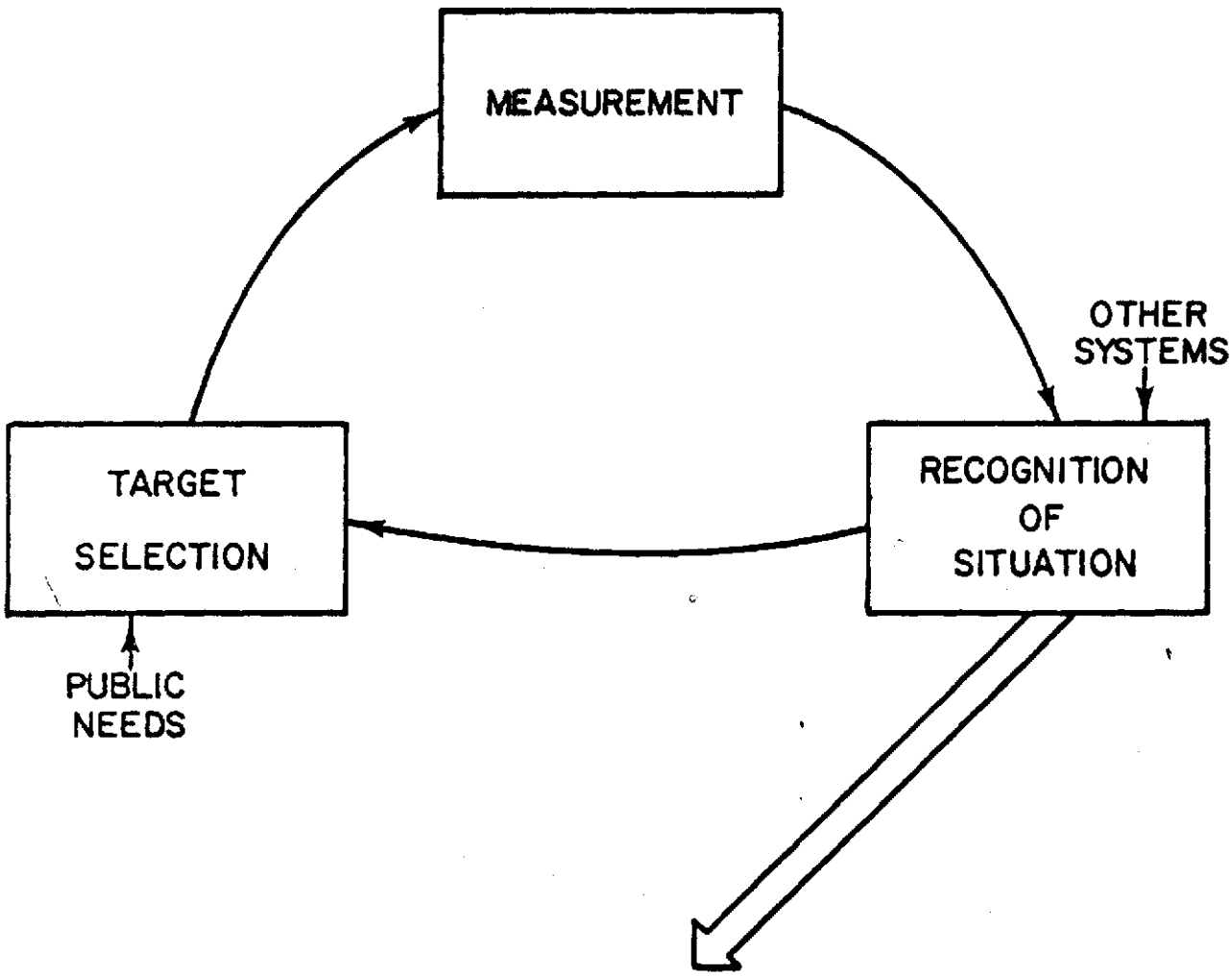
Thus, for instance, SMS or GOES should provide all large scale searches for cloud cover and active areas. The 30 minute time resolution and 1 km space resolution are quite compatible for observation of most weather patterns. The SMS geometry will be good enough to provide cloud motion measurements to 2 m/s from images 30 minutes apart. SEOS should be designed to give measurements of smaller clouds to 1 m/s from images 10 minutes apart or it presents no improvement for the mesoscale.

Likewise, SMS/GOES will provide synoptic scale soundings, while SEOS must concentrate on improving the vertical resolution (with high sensitivity) and the sample interval (with soundings as close together as 10 minutes). The vertical resolution SEOS provides is even more important to the mesoscale than improved x-y resolution, because it is the vertical resolution that attacks the convective stability question for the mesoscale.

Most of the synoptic situation should be available in the form of digital upper air and surface charts from which those segments of the large scale weather data needed for mesoscale monitoring can be selected. Such data may be made available largely through the National Weather Service AFOS (Automatic Field Operations and Services) system. The SMS/GOES imaging data in the visible and IR would come from the National Environmental Satellite Service SFSS (Satellite Field Service Station). Satellite sounder data may come either from NESS or NWS depending on the form SEOS will use in setting up its own mesoscale situation monitor.

Figure 43 illustrates the key functions the SEOS ground support system must fulfill. The meteorologist is, of course, interested in planning of the data acquisition scheme we have laid out as a datum for forecasting. This use emphasizes the feedback loop and its input channels, but leaves the output channel undefined, or at best similar to what now exists. Mesoscale phenomena grow up and die in an hour. If we cannot design the system to output accurate information to the public within 30 minutes, there may be no time left to react to the message. Today, the local weather service office sits at the end of a teletype line highly subject to disruption by severe weather or flood, and must often relay its crucial warning sequentially by phone (also highly disruptable) to radio stations and offices of emergency government. Tornado warnings are often made by means of sirens, which tend to alarm without communicating, generally fail by giving false warnings, and are tested often enough to generate apathy and distrust.

SEOS SYSTEM KEY FUNCTIONS



INFORM THE PUBLIC!

(SO IT CAN TAKE APPROPRIATE ACTION)

Figure 43

Figure 44 shows the relation of the proposed system functions in more detail. The four problem areas are indicated:

1. SEOS must be able to access data from a wide range of sources, implying both a means of access and criteria for selection.

2. SEOS must maintain monitoring of the mesoscale situation in the form of diagnostic models which both detect and predict trends. We have to know what data is needed and how to use it.

3. Recognition of danger, to be useful, requires a short response time. We need to achieve this with reasonably simple criteria.

4. Getting the message to the public requires a more effective communication system than now exists.

It turns out that AFOS can serve as the output of SEOS as well as a source of detailed synoptic data. To consider this, we need first to look at the existing structure of the National Weather Service.

2. Present NWS Field Operations Structure

The National Weather Service (NWS) presently receives data from an extensive network of observing facilities located throughout the United States and other parts of the world. While the vast majority of the domestic facilities are operated and maintained by the NWS, there are those which are operated by other government agencies, commercial organizations and private individuals.

National Meteorological Center (NMC).

Collection and distribution of the observational data is accomplished primarily via low speed local, regional and national teletypewriter circuits which deliver the information to a variety of real-time, near-real-time and non-real-time user groups within the meteorological community. Virtually all of the acquired data, however, ultimately arrive at the National Meteorological Center (NMC) in Suitland, Maryland, where they are correlated, analyzed and scientifically processed into a variety of products, most of which are in graphic form. Domestic distribution of the NMC graphic products is accomplished via independent facsimile circuits.

Weather Service Forecast Offices (WSFO).

The existing NWS field structure consists of 46 (ultimately 52) Weather Service Forecast Offices (WSFO), each of which is responsible for generation and issuance of weather forecasts and other relevant products within a specified geographic area. Although there are some exceptions, forecast area boundaries generally coincide with state boundaries. The average WSFO receives between 150 and 200 NMC-generated graphic products per day. The WSFO storage medium for this data is, of course, paper. In addition to

SEOS GROUND SUPPORT CONCEPT

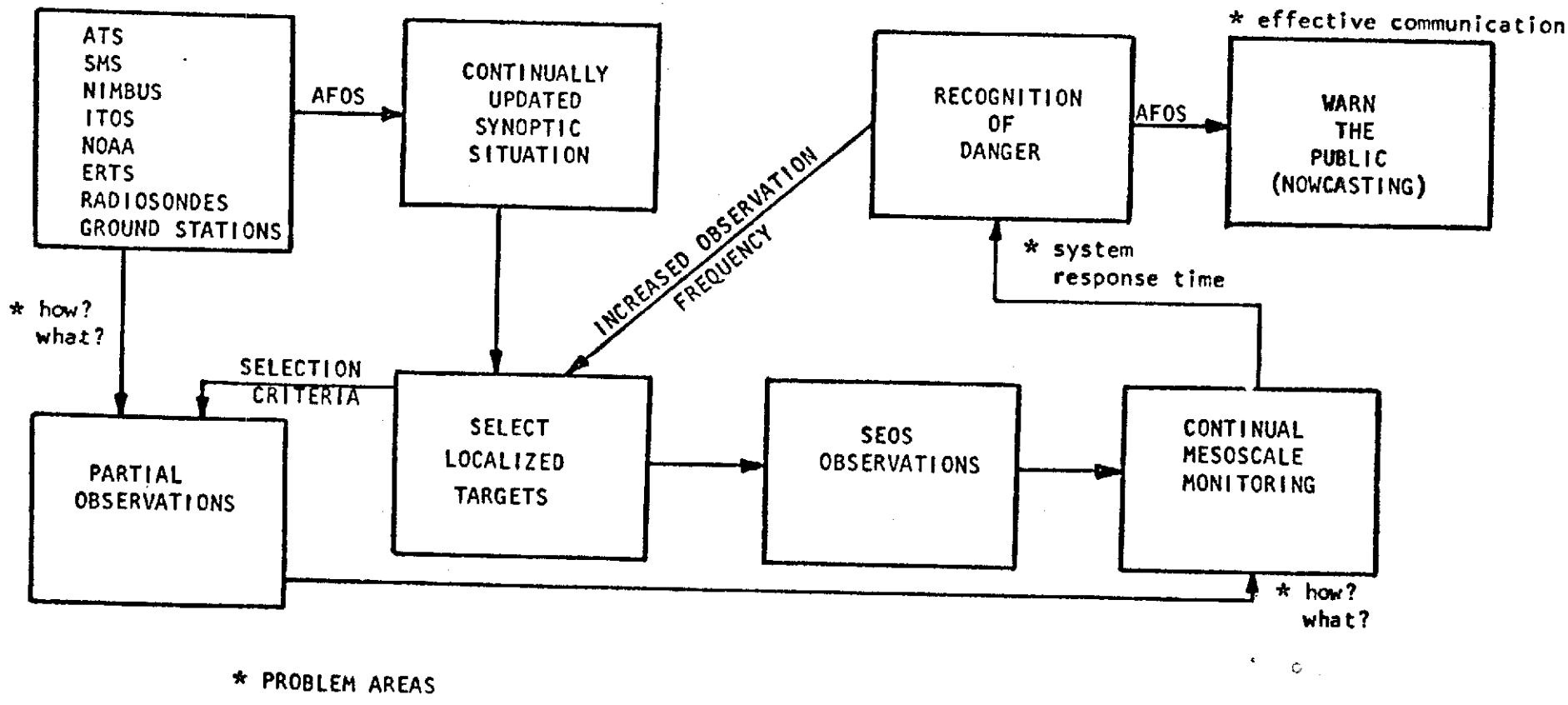


Figure 44

teletypewriter and NMC facsimile circuit data, all WSFO's have voice communications with both NWS and non-NWS area observers and many have a collocated NWS data acquisition function, i.e., surface, radar, upper air or any combination thereof, Some WSFO's also have a Weather Service radar remote receiver which provides a near-real-time facsimile image of the video data from a remotely located NWS radar.

Weather Service Offices (WSO).

Below the WSFO's in the field structure are the nearly 300 Weather Service Offices (WSO). The WSO's receive local and regional teletypewriter data and, in most cases, a limited number of NMC-generated facsimile charts. Although the basic forecast responsibilities of the WSO's are quite limited, they are responsible for preparation of local warnings and refinement and/or revision of the WSFO products to render them more meaningful to the local populace. The WSO's acquire data and disseminate forecasts, warnings, etc., but their service areas are much smaller.

Weather Service Meteorological Observatories (WSMO).

The lowest level field station is the Weather Service Meteorological observatory (WSMO) which generally has data acquisition responsibilities only.

River Forecast Centers (RFC).

Within the U.S. there are 12 River Forecast Centers (RFC) which collect and process hydrological and meteorological data and prepare river forecasts and warnings for primary points along river systems. Like the WSFO's, the RFC's receive area and regional teletypewriter data and selected NMC graphics. Weather radar data is used extensively at RFC's along with data acquired from high density rain gauge fields, snow depth measuring devices, etc., which are established and operated primarily for hydrologic applications.

River District Offices (RDO).

Below the RFC's in the field hydrological services structure are the 80 River District Offices (RDO) which relate to the RFC's in much the same way as the WSO's relate to the WSFO's. RDO's collect data and forward it to the area RFC, receive RFC products (forecasts, warnings, alerts, etc.), tailor them for local application, and disseminate them within their assigned service area.

Regional Weather Centers (RWC).

The Regional Weather Center (RWC) concept is still relatively new in the NWS and not all of the six planned RWC's (one per NWS region) have yet been established. The primary function of the RWC is to coordinate between the National Centers, other RWC's and lower level stations within the regional boundaries.

Other National Centers

The remaining major facilities in the field operations structure are the National Hurricane Center (NHC) collocated with the Miami WSFO in Coral Gables, Florida, and the National Severe Storms Forecast Center (NSSFC) in Kansas City, Missouri. These two national centers function very much like WSFO's except that their areas of responsibility are defined in terms of meteorological phenomena rather than by geography. The NHC is responsible for all technical matters pertaining to Atlantic hurricane predictions and warnings, while the NSSFC has nationwide responsibility for preparation and issuance of local severe storm (including tornado) forecasts. Hurricane forecasts and warnings in the Eastern Pacific are the responsibility of the San Francisco Hurricane Warning Office, collocated with the San Francisco WSFO in Redwood City, California. The Honolulu Hurricane Warning Office, collocated with the Honolulu, Hawaii, WSFO, is responsible for hurricane predictions and warnings in the Western Pacific.

3. Development of the AFOS system

The results of an extensive series of analyses, experiments and actual system developments conducted by the NWS over the last few years indicate quite clearly that a large scale effort toward nationwide Automation of Field Operations and Services (AFOS) is required. Through automation, products can be moved through the system to the end users in a fraction of the time that it presently takes, professional level field personnel can be relieved of time-consuming, subprofessional tasks which are necessitated by the present system, and overall system response to emergency situations can be significantly enhanced.

The key elements of the AFOS system are the WSFO's, all of which will have on-site minicomputers. The WSFO's will be serially interconnected with the National Meteorological Center, National Severe Storms Forecast Center, the National Hurricane Center, the National Climatic Center, and each other via a full duplex, voice grade, National Digital Circuit (NDC). This circuit, as depicted in Figures 45 and 46, will carry all inter-WSFO communications traffic, all field data destined for the National Centers, and all National Center products destined for field offices, both alphanumeric and graphic. Under this scheme, all data, regardless of its source or content, will be available to every "node" on the NDC. NDC protocol calls for each node to perform an error check on each data item arriving from either direction prior to forwarding it on to the next node.

As the NDC data passes each of the WSFO nodes, the on-site minicomputer will pick off the data required for application within that particular forecast area and add it to its electronically stored data base. The contents of this data base are then available on a high-speed request/reply basis to any operating position within the WSFO. The data will be displayed on TV-type monitors with hard copy available upon request.

The WSFO minicomputer will also perform the intra-forecast area data distribution and dissemination communications functions. All automated NWS facilities within a forecast area, e.g., major WSO's, RFC's, and WSMO's

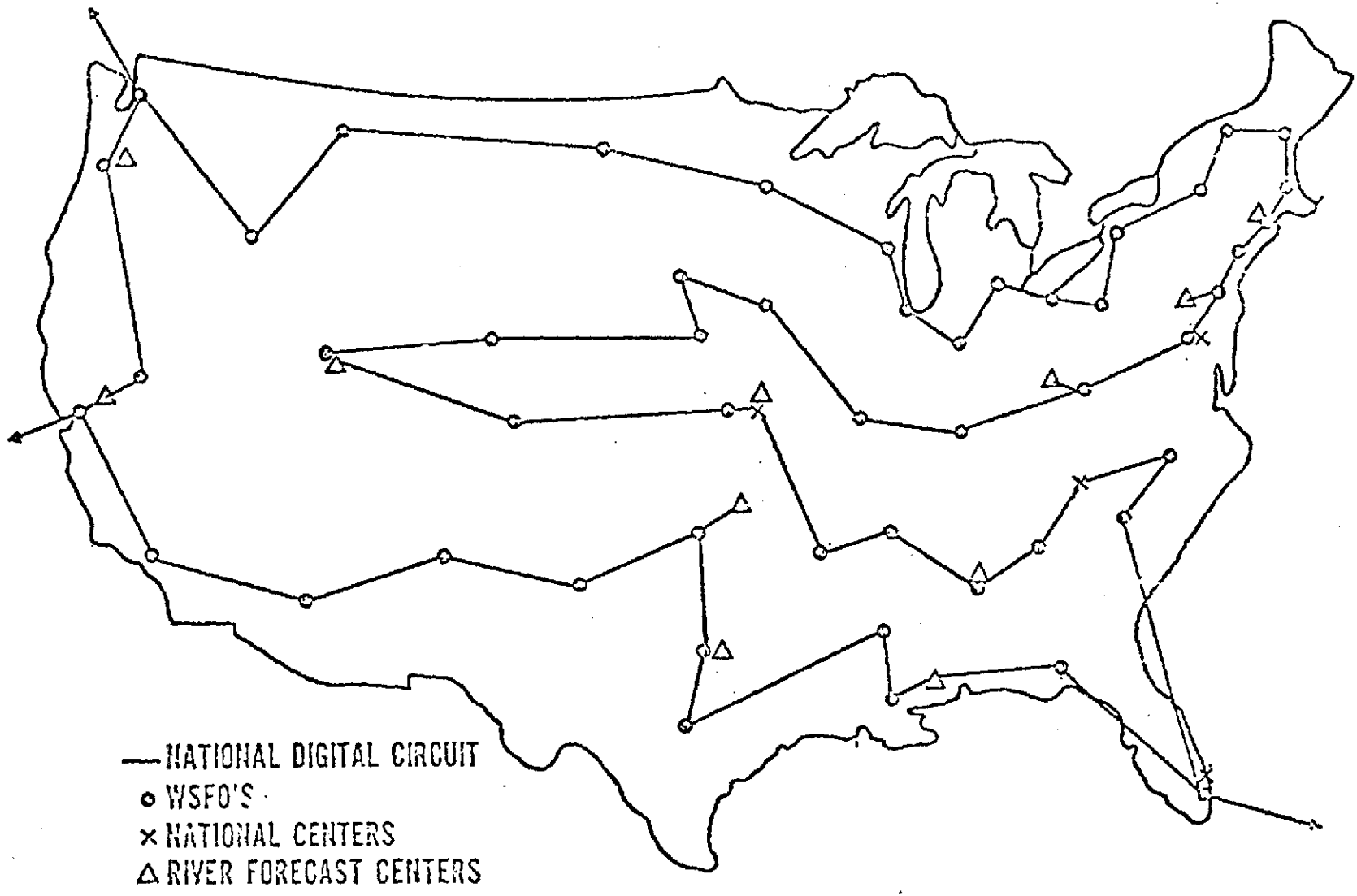


FIGURE 45 . NETWORK OF WSFO's, NATIONAL CENTERS AND RIVER FORECAST CENTERS

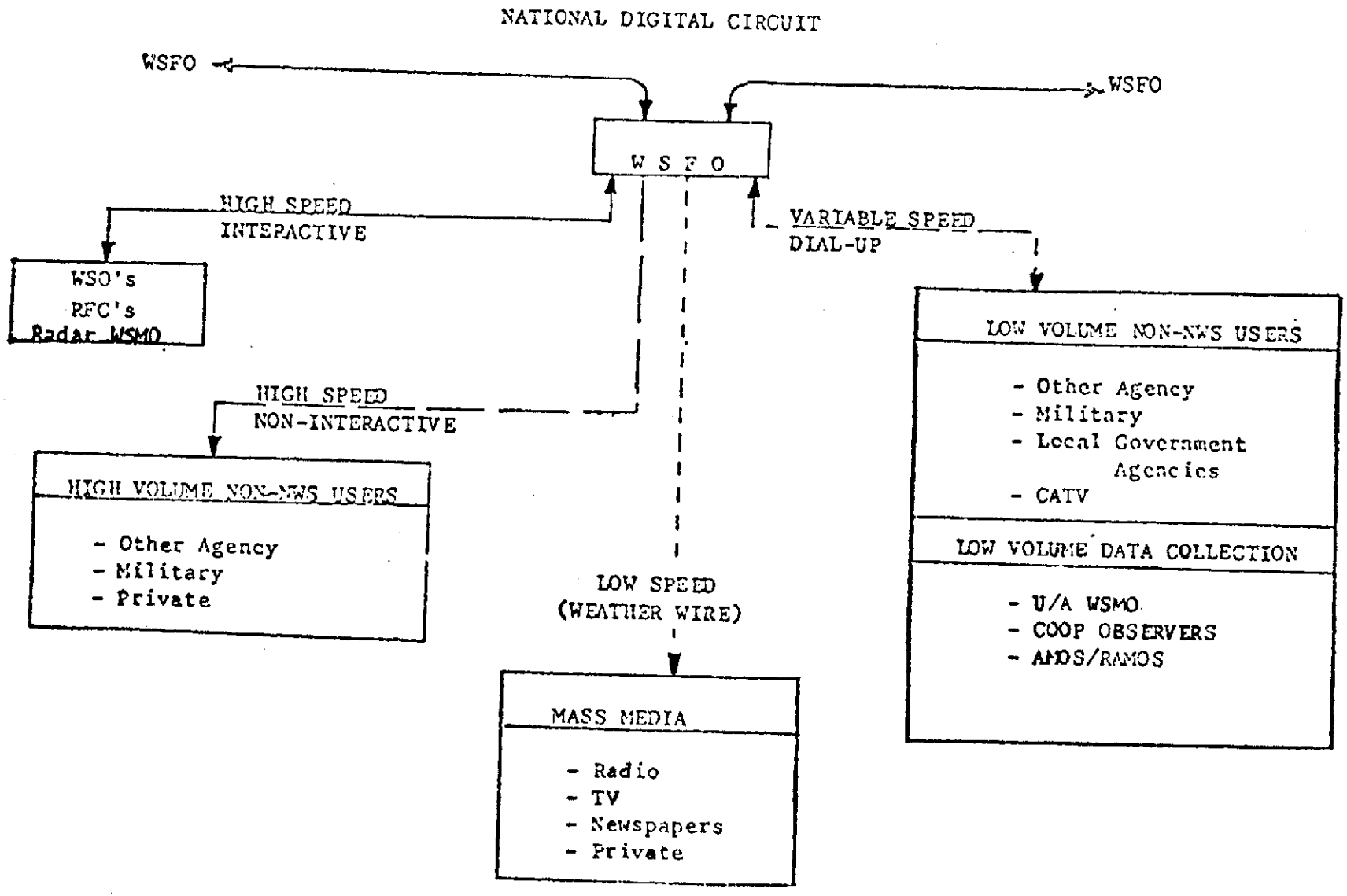


FIGURE 46 AFOS WSFO COMMUNICATIONS

with radar and/or upper air data acquisition functions, will have direct access to the WSFO minicomputer, including the data bsse. Data acquired at these various stations, plus that from the surface observation stations in the area, will all be funneled into the WSFO via these communications links for local storage and/or distribution over the NDC, and data arriving via the NDC or generated at the NSFO will be distributed via these same links. Data dissemination to user elements may be carried out by any of the automated stations within the forecast area since each has a direct tie-in with the WSFO data base.

Within each forecast area there are the WSO's, WSMO's, RDO's, private and commercial users, other Government users, and, in some cases, an RFC. The intra-forecast area structure has yet to be designed in final detail, but a general design with the following characteristics has been formulated.

1. Every upper air and radar site will have an on-site minicomputer.

2. Every RFC will have an on-site automatic data processing capability.

3. Every major WSO will have an on-site minicomputer with mass storage and CRT display capability.

4. Commercial and private users will be provided with at least the present level of service at no increase in cost to them.

5. Other Government users will be provided with a level of service equal to or superior to that presently being provided depending on their willingness and/or ability to upgrade their facilities.

6. The use of CATV for weather data dissemination will expand rapidly in the coming years.

7. High resolution satellite images will be provided to each WSFO at frequent intervals from the nearest Satellite Field Service Station (SFSS). These images will not be distributed over the NDC but will, instead, be received via high quality conditioned communications lines running directly from the SFSS to the WSFO. Satellite images selected for distribution and/or dissemination from the WSFO to other facilities within the forecast area will be of at least standard commercial TV quality.

8. The communications structure within a given forecast area will be dictated not only by operational considerations, but also by the geographic arrangement of the various stations and service facilities within the area, and by the local and area communications tariff structures.

A NWS/National Environmental Satellite Service (NESS) coordinated plan calls for delivery of high resolution satellite images, on a relatively frequent basis, to each WSFO and NWS National Center via conditioned, dedicated lines. This plan is completely compatible with the AFOS concept since it gets the high resolution data to the forecaster without impacting the

basic design philosophy of the NDC. The NDC would be incapable of handling the volumes of satellite imagery data required by each WSFO. Precisely how and where the satellite images will be stored at each WSFO, how they will be displayed, and how they will be disseminated within the forecast area have not yet been determined, but there appear to be a number of viable alternatives. These alternatives are presently being analyzed in detail by an NWS/NESS task team working in conjunction with the group responsible for the AFOS intra-forecast area detailed design.

C. Data Dissemination to the Public

We have briefly touched on the need to effectively inform the public about the weather if SEOS is to serve a predictive function for the mesoscale. The influence of the public's needs extends beyond SEOS ground data handling, however. There is also a hidden but highly significant influence of public desires on the SEOS satellite and sensor hardware design. Indeed, it is possible that in less than 10 years the capacity of the tail end of the SEOS data chain to suck out information could exceed the capacity of the front end imaging system to supply it. This problem is not very apparent because it is the opposite of the experience encountered by such high data volume systems such as ERTS. Consequently, it is essential to consider anticipated public needs of the 1980's. Designing to weather communication needs of the present is bound to make SEOS obsolete before it is operational.

Meteorology is in the midst of its third "revolution," brought about by the coincidence of three technologies: the geosynchronous weather satellite, the computer, and cable TV. From work done in the Multidisciplinary Studies Group at SSEC (1972, 1973) the logic of future development appears almost inescapable. The technology of cable TV is the final element which will become in the next few years perhaps the most important driving force behind weather satellite development, which up to now has satisfied only the scientist's desires.

The first revolution in meteorology was in the time period 1870-1900. It was marked by the scientific development of frontal analysis by Bjerknes and the new technology of the telegraph. Weather became 2-dimensional and could be followed by telegraph reports from distant stations.

In 1920-1940, the second revolution in meteorology occurred with the development of the radiosonde and the institution of nationwide soundings on 6 hour centers. Corresponding to the new technology was the development of synoptic analysis in meteorology, because the time and space scales of the measurements were compatible with the theory. Weather became 3-dimensional, and on a synoptic scale took on the added fourth dimension of time.

We are now in the middle of the third revolution in meteorology, which began about 1960 with the early weather satellites and the use of the computer to develop diagnostic models. It wasn't until ATS-1 was launched in 1966, however, that we recognized the organization of global weather patterns and their influence on developing weather such as cloud clusters. The reason for the revolutionary success of ATS was that it allowed the meteorologist to see developing weather-in-motion, with global images every 20-30 minutes. Accessing the data in a truly quantitative fashion required a bit more time, but it now seems generally agreed that one can make the best measurements in the digital domain. Thus the computer enters again as the technological tool for analysis of data from second and third generation meteorology satellites.

Where does TV fit in? In the multidisciplinary studies at SSEC, we identified a great unfulfilled need for "nowcasting," which for the purposes of this study we define as mesoscale weather information and prediction. People plan using weather forecasts, but they decide using nowcasting. It is in the decisions where the dollar value to our economy and the comfort and convenience of our lives lie. People can develop all sorts of contingency plans based on the probability of tomorrow's weather being hot or cold, sunny or wet. Once the decision has been made, people are committed. The farmer sprays his orchard and hopes it won't rain for a few hours. If rain washes off the spray, he must do it again, with the cost of extra spray and manpower coming out of his profit margin. The family which cancelled a picnic because of forecast rain which didn't occur is inconvenienced and angry. The fact that it rained 15 miles away may make the weather bureau happy with its forecast, but not mother and the kids. Right now, a lot of people feel that the weather bureau's 85% accuracy claim is a lie. They look out the window first before making their decisions.

Another interesting fact emerging from the SSEC study was that people prefer continuity in weather prediction. Figure 47 shows the region of interest. For nowcasting, people are interested in local, county sized information. It should, however, be placed in the context of transition in time. Also, it was found that the further forward

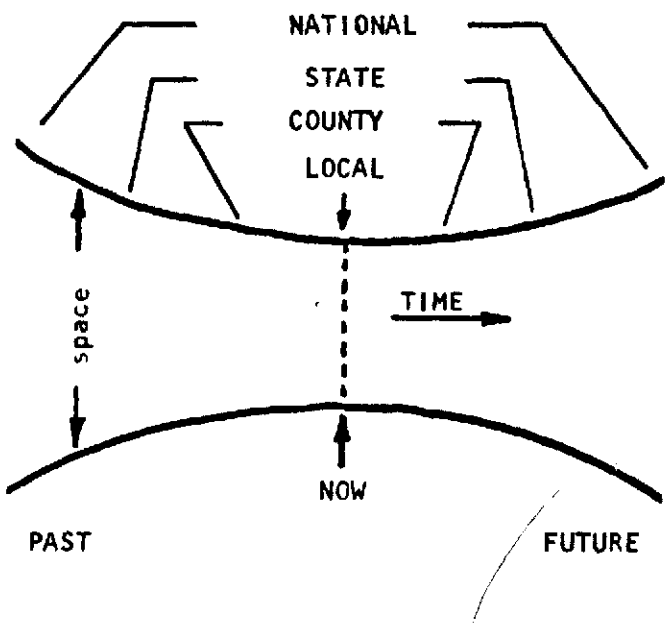


Figure 47. People prefer their weather information in a variable time and space domain. The further away in time the data is, the larger the geographical area of interest. Further, the weather information should always be presented chronologically to avoid disorienting.

or backward in time the information was, the larger the geographic area should be. Thus, people wanted to know what things were like in the entire country this morning, what happened in the state a couple hours ago, what is happening in the county now, what will be likely to happen in the state in a few hours, what will the U.S. weather picture be like tonight and tomorrow. The predictions need not even be right 100% of thetime, but if people feel that they are getting all the relevant information in which to base their imminent decision, they will have confidence in the nowcasting service. This sort of individualized attention is what a national weather service geared to regional forecasting cannot provide.

The preference for continuity has other interesting aspects. The synchronous orbit satellite pictures, preferably in a time lapse sequence, convey more information, better,easier to the user than any other single format. People identify much more readily with a picture than a diagram, and with the ATS pictures even place themselves in the image geographically. The weather image has meaning because a person can see himself in it. If one now adds the diagram to bring in the quantitative information, information transfer is further improved. The key factor though is "weather-in-motion," and the geosynchronous satellite images have the right coverage, the right resolution, and the right time repetition rate for the mesoscale. Such a means of information transfer is not unknown to the scientist working with ATS data. The use of TV as a communication medium between computer and man is well established, and the principle formed the foundation for the McIDAS system used at SSEC to measure cloud motions and analyze ERTS images. Thus, the fact that the general public also prefers to receive communication in visual terms with motion should be no great surprise.

A further important factor is that the communication must be voluntary. It should be enticing and informative for people, but they should be able to choose not to pay attention. Sirens and alarms attract attention but don't communicate. Putting such automatic devices into people's homes to "alert"(read "compel") them to listen to their radio for an important (who says so?) announcement has proven of little value. Such devices time and again ended up disabled or broken in various tests.

Nowcasting and natural disaster warnings are thus virtually identical in function. If the presentation is accessible, reliable, and comprehensive, and uses the simple rules just described, people will pay attention. In fact, most people stated they'd pay up to $5 per month for this service. Of course, to be accessible the service must be available 24 hours a day, and it must be updated every 30 minutes to adequately describe developing weather. It must be available on a countywide basis with local information. The presentation should be basically visual and kinetic but with audio commentary in order to fully communicate to a person through all input channels in the shortest time with a minimum of distraction. The service must be reliable, drawing from complete up-to-the-minute data sources (such as AFOS). Finally,

the service must be comprehensive enough to give all relevant data (probably no less than 8 minutes for a single general update followed by special program segments for aviators, cranberry farmers, boaters, skiers, construction, transportation, etc.

The attributes of the communication medium described are those of TV, but not commercial broadcast channels. They couldn't provide both entertainment and a 24 hour a day weather service and still stay in business. Such a single service TV channel is only available locally from cable TV companies, who should be eager to fill the nowcasting need if people are indeed willing to pay up to $5 per month for the service.

The remaining point to consider is growth demand for cable TV. Weather service is only one of the many information needs in our society. The competition in the cable TV industry is absolutely fantastic, and the fact that one very large firm has assets amounting to 2% of its indebtedness should indicate what bankers and investors feel about its future. A whole new industry has already arisen to supply equipment in this area. We feel that such a strong need will develop for information of all kinds on a national level that cable TV may by 1980 receive the same sort of mandate from the U.S. Government that rural electrification received in the 1930's. That being the case, every county in the country will be demanding images of the type SEOS can produce whenever threatening weather occurs.

On an average day in the U.S. we might have some 6-8 large scale weather features, each with 20 - 30 possible danger areas deserving of attention. Assuming we wish to look in 200 places with SEOS at 15 minute intervals in the average, that means that 13 times per minute--once every 4-5 seconds--SEOS must move to a new pointing position, stabilize, and collect data. SEOS has the information bandwidth (at 500 meter resolution covering a 100 - 200 km square area for each mesoscale feature) and the necessary sensitivity to function as an imager and sounder under these constraints. The currently predicted mechanical operation of the telescope movement and sensor scanning is nowhere near such performance. Moreover, the figures above do not take into account the fact that SEOS will be used for other purposes besides meteorology and will not be available 100% of the time.

Figure 5 showed the time and space coverage required by nowcasting with the information sources added. As the weather data arrives at each link in the AFOS chain, new information is added in a block. Image data is acquired over image grade circuits from SFSS in a continuing sequence, so that the latest pictures are available. The local TV station adds the final countywide data and organizes the updated presentation. No link in the data chain is required to produce special products aside from its normal functions. All stations in the country will carry the same NMC summary. State by state, the WSFO, forecasts will vary. The individualized data is very small in quantity and easily updated. This is where the SEOS images of one or two counties will be especially valuable, since they show how a storm is approaching, how big it is, how far from a person's home the storm is.

Table XXIIIdetails the data required by nowcasting. The difference between visual display imagery and that required for quantitative forecasting is not great. Long wave visible or near IR gives the best contrast of land and clouds, but thermal IR imagery could be used, although harder to interpret by the layman. For the 30 minute updates 500 meter resolution is adequate to display motion. Image alignment should be accurate to 1 pixel or better to avoid jitter in the time lapse display. The image geometry must, of course, be uniform from image to image. The dynamic range should be adequate to perform enhancement of cloud features. At least 128 levels are needed from 0.5% to 100% albedo. All data should be digital and the data system designed for easy video extraction.

TABLE XXIII

Nowcasting Requirements for SEOS

Imaging:	visible or near IR (day and night)	$0.6\ m < \lambda < 1.2\ m$
	ground resolution	500 meters
	dynamic range	> 128 levels
	field or frame coverage	> 100 km square ($10^4 km^2$)
	pointing accuracy knowledge	< 1 pixel
	distortion	uniform (picture to picture)
	data type	digital
	image rate	4 seconds/frame

VI. Conclusions and Recommendations

A. Technical Requirements and Sensor Parameters

Summarizing the sensor requirements is easy because all of the mesoscale phenomena involve similar physical processes of similar scale. Consequently, the observations needed to define the physical situation for widely different phenomena all cluster near the same parameters. The 500 meter vertical resolution for structure near the ground appears again and again. Further aloft a 1 - 1.5 km vertical resolution appears adequate. Thus the IR imaging and sounding channel parameters are relatively easy to define. The 500 meter ground resolution is also very common for both IR and visible imaging. The finer 100 meter resolution is restricted to use where high time resolution (5 - 10 minutes) is needed or one is looking for a means to precisely measure cloud growth rates or identify inversion layers and other physical processes from the cloud structure or type. In any case, the higher resolution measurements are always made in compensatingly smaller areas, so the system bandwidth does not increase. A 3 Mbps data rate seems tolerable for the combination of imaging area, resolution, and radiometric accuracy desired.

Several points should be emphasized here. The vertical resolution achieved by the sounder and IR imaging is the key to the prediction of the mesoscale. Imaging is the high bandwidth channel. It tells what is happening now and can be used to communicate that information to the public. On the other hand, the predictive capability of imaging is inadequate by itself because there are the other physical conditions of wind, moisture, and temperature at various levels in the atmosphere whose rapid changes anticipate cloud formation by up to several hours. These can only be observed by high accuracy soundings, frequent surface observations, and quantitative cloud motion measurements. As a result, sounding should have equal priority with visible and IR imaging and in-situ sensors. Removing any source of information is detrimental, as we have tried to show in the preceding pages. The value of making a certain design tradeoff is intimately related to the ultimate priority of uses to which SEOS is put. Table XXV identifies a compromise system which yields considerably better than what we now have in the way of time and space resolution.

Sensitivity, radiometric accuracy and dynamic range requirements are perhaps more easily understood because designers of imaging systems understand brightness enhancement, contouring, noise spikes, image saturation and underexposure, and the like. Moreover, the processing of SEOS images and soundings will not be unlike that for ATS and SMS. We should emphasize here that we need to have excellent relative radiometry and a linear system. A logarithmic response makes pretty pictures by sacrificing radiometric resolution to dynamic range. Both precise radiometry and good dynamic range are needed.

The SEOS imaging coverage of interesting areas, to be optimal, should be point coverage. Most phenomena in the mesoscale are 100-400 km in width and 100-1500 km in length, and can be adequately imaged for survey purposes every 30 minutes by SMS/GOES. If image geometry and navigation

(pointing knowledge) are adequate, coverage of localized phenomena within SMS images can be extracted in digital processing. It will be necessary, however, to look at isolated storms within a frontal system at greater frequency than the entire front. Thus the squall line may be SMS imaged at 30 minute intervals, but each local storm within the line imaged at 10 minute intervals by SEOS.

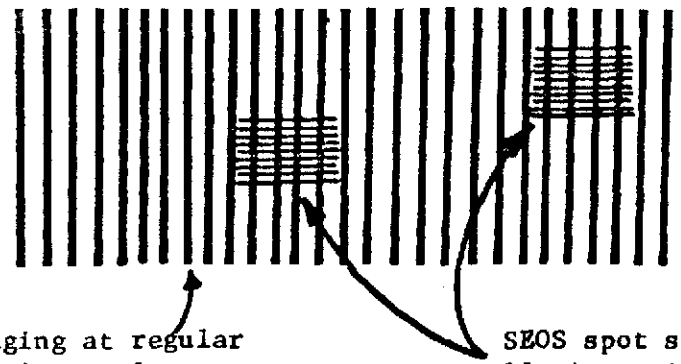


Figure 48

It is not inconceivable for SEOS to have 100-200 such spot samples to image at any given time. Since the measurements will take about 3 seconds, less than 35% of that time can be added for moving and stabilizing the telescope, or SEOS cannot sample each of 200 spots at 10 minute intervals. On really active days, with more than 200 storm targets, the situation gets even worse.

We have looked at the microwave sounding potential for a reasonably sized antenna on SEOS and find it possible in principle as well as desirable. The antenna diameter is given approximately by:

$$D = \frac{16550}{f_{MHz} \arctan \frac{l}{h}}$$

where l = the resolution element

h = synchronous altitude

f = microwave frequency

The table below is for 50 and 200 km resolution, and for the two extreme frequencies used on NIMBUS E:

D in meters

f \ l	50 km	200 km
22000 MHz	9.5 m	2.4 m
58000 MHz	3.6 m	0.9 m

Since the resolution of 50-200 km calculated for the SEOS is compatible with the resolution of the microwave experiment on NIMBUS E (100 nautical miles) it also implies that the same signal-to-noise level is expected, hence the same averaging time will be required (2 sec). The reasoning behind this statement becomes obvious if one looks at the reciprocal problem. Assume that there are two identical transmitters on board NIMBUS E and SEOS, and the antenna on SEOS is that much larger to yield the same (3 dB) coverage on earth as does NIMBUS. Then the powers per unit area, received on the ground from the two satellites, are identical.

Table XXV

SEOS Sensor Requirements

A. Visible Imaging:

Ground resolution (two imaging modes not necessarily simultaneous)	100 m 500 m
Spectral Bands	0.6-1.0μm ~0.4μm (optional)
Dynamic range	$>10^7$ (for nighttime imagery)
Signal to Noise Ratio	>150:1 @ 100% albedo
Gray scale digitizing	≥128 levels (linear)
Raster geometry	uniform, picture to picture determinable to <1/2 pixel
Raster shape	frame and/or strip (TV format compatible)
Raster size	variable line length and number >100 km square >600 lines
Area coverage (varies with scale of phenomenon)	10^4 - 10^6 km^2
Picture interval (per target)	10 min - 4 hours (4-5 sec/target)
Frame time	<4 sec/600 lines
Information bandwidth (constant)	~3 Megabits/sec.
Data type	digital
Pointing knowledge	20μr

B. IR Imaging:

Ground resolution	500 m desired (1-1.5 km acceptable)
Spectral Bands	6.7μm ($\Delta\nu$=150 cm^{-1}) 11.5μm ($\Delta\nu$=160 cm^{-1}) 13.8μm ($\Delta\nu$=100 cm^{-1})
NEΔT	0.5°C @ 225°K
NER	0.1 mW/($m^2 cm^{-1}$ ster.) 0.05 mW/(m^2 cm^{-1} ster.) [at 6.7μm]
Raster geometry	uniform picture to picture or determinable to 1/2 pixel
Raster shape	frame and/or strip
Raster size	variable line length and number >200 km square >600 lines
Area coverage (varies with scale of phenomenon)	10^4 - 10^6 km^2
Picture Interval (per target)	10 min - 4 hours (4-5 sec/target)
Frame time	<4 sec/600 lines
Information bandwidth	~500 kbps
Data type	digital
Pointing knowledge	20-30μr

C. IR Sounding

Ground Resolution 35 km

	Channel	$\nu(cm^{-1})$	$\Delta\nu(cm^{-1})$	α(mr)	NER[1] $mW/(m^2 cm^{-1} ster.)$	P(mb)[2]
15μ CO_2	(1)	669	5	1.0	0.05	30
	(2)	680	5	1.0	0.05	65
	(3)	690	5	1.0	0.05	100
	(4)	700	5	1.0	0.05	200
	(5)	705	5	1.0	0.05	350
	(6)	715	5	1.0	0.05	500
	(7)	740	5	1.0	0.05	700
	(8)	750	5	1.0	0.05	900
4.3μ CO_2	(9)	2360	40	1.0	0.002	1
	(10)	2310	40	1.0	0.0004	60
	(11)	2290	40	1.0	0.0004	130
	(12)	2250	20	1.0	0.002	600
	(13)	2230	20	1.0	0.002	700
	(14)	2210	20	1.0	0.002	800
	(15)	2185	20	1.0	0.002	900
11.5μ window	(16)	900	32	1.0	0.05	1000
3.7μ window	(17)	2700	200	1.0	0.0002	1000
H_2O	(18)	1490	60	1.0	0.02	~300
	(19)	430	40	1.0	0.1	~600
	(20)	507	80	1.0	0.1	~750
	(21)	1225	60	1.0	0.02	~1000

(1) Proposed RMS maximum

(2) Location in pressure of weighting function maximum

D. Microwave Sounding (ref. Nimbus E Microwave Spectrometer)

Antenna size		2-3 meters
Frequencies	H_2O	22.235 GHz 31.40
	O_2	53.65 54.90 58.80
Bandwidth		250 MHz
Sensitivity		same as on Nimbus E
Ground resolution		<200 km

E. Ground Sensors and In-Situ Measurements

Surface temperature	±0.5°K
Surface pressure	±0.1 mb
Mixing ratio	±0.5g/kg
Surface wind	±1 m/s, ±10°
Frequency of observation	$(10\ \text{min})^{-1}$ to $(3\ \text{hr.})^{-1}$
Precipitation type, intensity, duration, snow cover	--
River and lake levels	--
Watershed soil conditions	--

B. Areas of Further Study

There are a number of areas where SSEC can continue to develop and expand the concept of SEOS we have presented here. We state seven of them:

1. Study the impact of additional weather phenomena on SEOS requirements. In setting up the "sieve" concept early in this study, a list of possible social, economic, and scientific uses of SEOS was generated. We make no claim for completeness. Rather, since the list was generated in a very short time, it seems reasonable that other, undiscovered uses of SEOS can be found. Some of the seminar subjects (especially hurricanes) also appear potentially fruitful for more detailed study.

2. Study mesoscale cloud systems using SMS. In particular we would be interested in looking at the possibilities of using small, low cumulus as tracers of ageostrophic wind components and studying the feasibility of cloud size and area coverage as indicators of convergence and stability. Of significant help here would be the GATE data and later SMS images of the U.S. For this sort of study, ground truth is essential, and only a few places on earth have adequate surface data for mesoscale observations.

3. Definition of System Algorithms for mesoscale forecasting and recognition of potential and actual threats. This involves two components. The first is to work the data collection problem more throughly in the light of existing and future knowledge to determine more precisely the most useful observations (direct and indirect) from a forecasting viewpoint. The second component is to use McIDAS, the SSEC Man-computer Interactive Data Access System, to simulate an operational environment for SEOS (using real time SMS data from our DUS).

4. Refine SEOS technical requirements with the results of GATE. We will soon have, as a result of GATE, new observational data of high quality and a resultant improved understanding of the mesoscale. Much of this B and C scale data will be archived at SSEC and used by the University of Wisconsin Meteorology Department. Most of the SEOS requirements won't change much because they are based on physical processes in the atmosphere occurring on well known time and space scales. What can be expected to change is the relative importance of a certain kind of measurement. That sort of information is crucial to successful design tradeoffs.

5. Develop improved operational requirements. This means knowing how to achieve optimum observing times and frequencies for SEOS and learning how to acquire and select synoptic data. We may be able to attach McIDAS to the AFOS system and start work on control system simulation as well as recognition algorithms.

6. Study ways of more effective and timely communication of weather to the public. We expect in the next year to operate at SSEC a test service to the public such as was described in chapter V. It would use

SMS data, our McIDAS data processor, and a hookup to the local CATV utility in Madison. We hope to be able to pin down more accurately the impact of such a dissemination system on SEOS, based on public response to the test.

7. Continue work at SSEC in the area of IR sounding, especially the SMS sounder. Much of the workload of SEOS can be eased by utilizing SMS sounding data to full advantage. This requires continued study of VISSR sounder retrofit design and SMS ground data handling along the lines which SSEC is now proceeding. Especially important is the need to study the operational aspects of a SEOS sounder. It is by no means clear that 1-2 km vertical resolution can be achieved. We may have to settle for 3-4 km. The effects of ozone, water vapor, CO_2 transmission coefficient accuracy, sounder calibration, filter ageing characteristics, and cirrus contamination of the field of view are not well enough known to predict the exact extent of improvement possible from a SEOS sounder.

TABLE XXVI

Short List of SEOS Applications

Applications:

- Severe Thunderstorms, Hail, Tornadoes
- Hurricanes
- Flash Floods
- Frost Hazards
- Clear Air Turbulence
- Snow Pack, Spring Floods
- Sandstorms
- Rainfall Detection
- Atmospheric Resources Management
- Fog Prediction
- Terminal Forecasting
- Atmospheric Waste Disposal and Reclamation
- Snow, Sleet, Rain Delineation
- Lake and Sea Breezes

Research:

- Boundary Layer Dynamics
- Atmospheric Radiation Field
- Storm Development
- Forecast Verification
- Localized Climate Changes
- Baroclinic Structure
- Weather Modification
- Effect of Man on the Atmosphere