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# SYSTEMS AND TECHNIQUES FOR IDENTIFYING AND AVOIDING ICE

**R. John Hansman**

Aeronautical Systems Laboratory
Department of Aeronautics & Astronautics
Massachusetts Institute of Technology
Cambridge, Massachusetts USA

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# Systems and Techniques for Identifying and Avoiding Ice

Prof. R. John Hansman
Dept. of Aeronautics & Astronautics
Massachusetts Institute of Technology

## Introduction

In-flight icing is one of the most difficult aviation weather hazards facing general aviation. Because most aircraft in the general aviation category are not certified for flight into known icing conditions, techniques for identifying and avoiding in-flight ice are important to maintain safety while increasing the utility and dispatch capability which is part of the AGATE vision.

This report summarizes a brief study effort which:

- Reviewed current ice identification, forecasting, and avoidance techniques.

- Assessed feasibility of improved forecasting and ice avoidance procedures.

- Identified key issues for the development of improved capability with regard to in-flight icing.

## Current Information Sources for Ice Identification

Current methods for identification of icing conditions can be separated into Pre-Departure methods and Enroute methods. Each of the information sources appropriate to these phases of flight are identified and discussed briefly below.

### Pre-Departure Information Sources

*Icing SIGMETs (Significant Meteorological Events)* - Are used for general guidance to potential icing hazards. Icing SIGMETs are generally somewhat vague (e.g. "chance of moderate rime ice in cloud and precipitation above the freezing level") and cover a wide geographical area. As a consequence, SIGMETs are not particularly useful for detailed assessment of icing potential.

*Freezing Level Forecasts* - Icing SIGMETs do typically contain a more detailed freezing level forecast than is normally available, which can be used to more carefully isolate regions of icing potential. It should however be noted that in situations where there are multiple freezing levels, the forecasts usually only identify one of the freezing levels which can result in significant misinterpretation of the icing hazard.

*PIREPs (Pilot Reports)* - The most reliable indication of icing conditions are PIREPs issued from pilots who actually experience icing. The reports are most useful for establishing the presence of icing in a specific region at a specific time. PIREPs are also useful for identifying cloud tops and cloud free layers which may not be observable by any other source.

There are, however, several problems with PIREPs. First, PIREPs are not uniformly issued so the lack of PIREPs does not imply ice-free conditions. This is a particular problem early in the morning or in remote areas where no prior aircraft may have flown. In addition, pilots are often too busy dealing with icing to issue a formal PIREP although controllers will sometimes initiate a PIREP on behalf of the pilot if he or she request a deviation due to icing. A second problem with PIREPs is variability in the intensity and ice type reports. Most pilots do not have a clear operational understanding of the difference between rime, mixed, and glaze ice, and the light, moderate, and severe intensity metrics are very loosely interpreted. This is made even more difficult when different aircraft types and velocities are considered. Differences in collection efficiency and Total Air Temperature can result in quite different ice accretion rates and types in the same air mass.

Finally, there is an inherent delay between the issuance of the PIREP and when it gets broadcast. This is mitigated somewhat for moderate and severe icing reports which normally result in an "Urgent PIREP" which is transmitted more quickly.

*Winds Aloft Forecasts* - Winds Aloft Forecasts are a secondary source of freezing level data. The data is very course both horizontally and vertically. Vertical resolution is only every 3000 ft and reporting points are spaced on the order of 100 nm apart.

*Satellite* - Satellite data (both visible and IR) is used to define the horizontal boundary of cloud mass. This is useful in identifying ice free zones. In principle, cloud tops can be inferred from IR satellite measured cloud top temperatures. However, the accuracy and reliability at lower altitudes is not sufficient for reliable GA use.

*Area Forecasts* - Area forecasts are used for a general understanding of the meteorological environment between airports but has limited utility for icing and is clearly secondary to SIGMETs for area prediction of icing conditions.

*Surface and Upper Air Charts* - Surface charts are normally used for monitoring the general synoptic situation. There is some utility in predicting regions of potential cloud cover, frontal or cyclonic action and for estimating the location of the freezing level.

## Enroute Ice Identification

*Temperature and Visible Moisture* - The basic technique for identification of potential icing conditions is the combination of temperature below freezing and visible moisture. For low speed general aviation, the Outside Air Temperature (OAT) is adequate while for jet aircraft Total Air Temperature (TAT) is normally monitored. Typically temperatures between 0°C and -10°C are the most hazardous for icing. As a consequence, the OAT probe is a very important sensor to determine proximity to the freezing level and temperature buffer. When operating in clouds near potential icing conditions, experienced pilots will typically monitor the OAT carefully to track temperature trends.

Visible moisture is also a prerequisite for icing. Clouds are the normal source of icing and pilots will normally be aware of where they are with respect to the cloud mass. Freezing rain is also a source of hazardous icing and is normally associated with warm

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fronts. The presence of snow is normally an indication of ice free regions. This is because the snow growth process collects the small water droplets resulting in very little liquid water for icing.

*Direct Ice Accretion* - The most reliable measurement of icing is direct observation of ice accretion on a visible part of the aircraft. Since ice is more effectively collected on probes and small protrusions, it is common to monitor protruding objects near the windshield like the OAT probe shield or the windshield wipers for early indication of ice accretion. It is also possible to monitor the wing but this has a slower response time. At night, it is important to have a flashlight or other means to observe the ice accretion. For unprotected aircraft, initial observation of ice accretion should initiate an escape or avoidance process.

*Identification of Clear Regions* - Since visible moisture is necessary for icing, one method that is commonly used to avoid icing is to avoid flight in cloud or in precipitation. Visual identification of clear regions and requesting cloud free altitudes minimizes time in cloud and the exposure to potential icing conditions.

*PIREPs* - In flight, PIREPs are also a valuable source of information to avoid icing. As discussed above, PIREPs are valuable for the identification of points in space and time where icing was encountered. They are also useful for identifying cloud tops and layers. In flight, Urgent PIREPs are usually passed on by the controller. Less formal PIREPs are also used or inferred. One mechanism is to infer a PIREP by requesting from the controller if any icing conditions have been encountered in the sector.

## Current Ice Avoidance Techniques

The basic method of ice avoidance for non-protected or minimally ice protected aircraft is to minimize time, in cloud, at temperatures below freezing.

If ice accretion is encountered, immediate response is required. The appropriate escape maneuver is dictated by the freezing level structure and the cloud structure and the viability of the escape is dictated by the pilots knowledge of the temperature structure. Several options include:

*Descent to a Warm Layer* - This maneuver requires the freezing level to be above the Minimum Enroute Altitude (MEA) or the Minimum Obstruction Clearance Altitude (MOCA) in order to be able to safely descend to a level where ice will melt.

*Climb to a Dry Layer* - In some cases when ice is encountered near cloud tops (e.g. Cumulus development), it is advisable to climb above the cloud to a dry layer where the accreted ice will sublimate. This requires that the dry layer be within the degraded climb capacity of the aircraft.

*Course Reversal* - One standard hazardous weather escape method is to reverse course. This method is often difficult to implement for icing conditions because it requires re-penetrating the known icing conditions which formed the basis for the need to escape. If ice is detected early, course reversal is a good alternative.

*Emergency Descent to an Alternate* - In some cases, it may be necessary to descend to an alternate airport if it is not possible to find an ice free altitude and the freezing level is at the surface. This emergency descent should be managed to minimize exposure to icing but to also find an acceptable alternate airport. Preferably, the alternate airport will have

VMC conditions or an ILS since the approach will be made with poor visibility due to ice on the windshield and questionable handling which normally requires higher airspeed. Moving map area navigation systems like GPS or LORAN can have significant utility in rapidly identifying and navigating to diversion airfields.

*Climb to Warm Layer* - In cases of temperature inversion it may be advisable to actually climb to a warm layer. One example would be in sub-freezing conditions in the cold sector under an advancing warm front where freezing rain is most often encountered.

## Current Icing Forecast Methods

The icing forecasts which are used to generate the SIGMETs and AIRMETs issued by the National Aviation Weather Advisory Unit (NAWAU) are based on 48 hour numerical weather models which predict temperature and relative humidity on a grid basis. Current models such as NGM and ETA (Appendix A) have an 80 km grid and are run twice per day. The ETA model has 38 vertical levels.

Aside from spatial resolution, the principle limitation of numerical models for icing forecasting is the lack of explicit liquid water prediction. This is because none of the existing numerical models incorporate the detailed cloud physics necessary to estimate liquid water. As a consequence, clouds are not explicitly predicted in the models but rather inferred from the relative humidity fields.

The current icing prediction is based on a relative humidity and temperature algorithm developed over time by the NAWAU. The NAWAU algorithm is:

Level 1    0°C to -19°C   > 60% Relative Humidity

Level 2    -1°C to -14°C  > 75% Relative Humidity

The algorithm is used for forecast guidance by the NAWAU forecasters when considering icing SIGMETs, it is combined with recent icing PIREPs and orographic corrections. It does not directly correlate to standard icing types or intensity.

A similar algorithm has also been developed by the Research Applications Program of the National Center for Atmospheric Research. The RAP algorithm is similar to the Level 1 NAWAU algorithm with the low temperature limit raised to -16°C and the Relative Humidity above 63%.

The predictive power of these algorithms is not particularly good. In a study which compared the algorithms with icing PIREPs, NCAR found that the best Probability of Detection (POD) was 70% for the NAWAU Level 1 algorithm. The NAWAU Level 2 algorithm had a POD of 52% and the RAP algorithm had a POD of 67%.

In addition, the existing algorithms significantly over-predict the actual icing regions due to the limited spatial resolution (both vertically and horizontally), the limited update cycle and the lack of explicit liquid water which requires a conservative algorithm to even get 70% POD.

Finally, the existing forecasting methods have no physical basis for prediction of the ice type (e.g. rime, glaze mixed) and only a limited physical basis for intensity. Because of the lack of reliable forecast models, forecasters rely heavily on PIREPs which can result in a significant lag between the first report of icing and the dissemination of the SIGMET.

## Experimental/Developmental Icing Forecast Methods

There are several efforts underway to improve icing forecast capability. The first is the development of improved numerical weather models to support the forecast efforts. The goal is for the models to carry Aviation Impact Variables (AIVs) such as icing and turbulence potential. However, the correlation of current model outputs and AIVs is still in early development. It is clear that both temporal and spatial resolution of the models will be improved. For example the Rapid Update Cycle (RUC) model described in Appendix A updates on a 3 hour cycle. It currently has a 60 km grid and is expected to go to a 30 km grid by 1998.

There is some effort to include explicit liquid water content and cloud physics in an ETA type model but these efforts are at a research level and there are no current projections for explicitly liquid water in the operational models.

In addition to improving the underlying forecast models (RUC and ETA) there are several efforts to improve the icing algorithms. NCAR and the NAWAU have been working on improved algorithms as discussed above and have investigated other approaches with limited success.

The NOAA Aviation Weather Center Experimental Forecast Facility has put an extremely experimental neural network icing product out on the World Wide Web. This system appears to use PIREPs as truth to train an neural net which uses RUC data as the base input data. The output consists of 6 levels ranging from 0 = no icing, 2 = light icing, 4 = moderate icing to 6 = severe icing. It is unclear why there are intermediate levels (i.e. 1,3,5). The approach is interesting in that PIREPs are well suited to training a neural net algorithm. However, the current skill of the system is not very high and it is unclear if the RUC can provide sufficient observability to improve the skill level. There is also concern that such an untested product has appeared in a place it has apparent face validity and pilots may be using it to make decisions.

Finally, there are several graphical weather products such as the NCAR icing depiction on the Aviation Weather Product Generator Display shown in Figure 1. While the 3 dimensional display features are appealing, the underlying icing prediction algorithms are limited by the issues discussed above. For the foreseeable future, it is unlikely that the grid resolution will be better than 20 km horizontal and 1000 ft vertical. For this reason, such products will be limited to flight planning and strategic decision making and will have limited utility for tactical decision making.
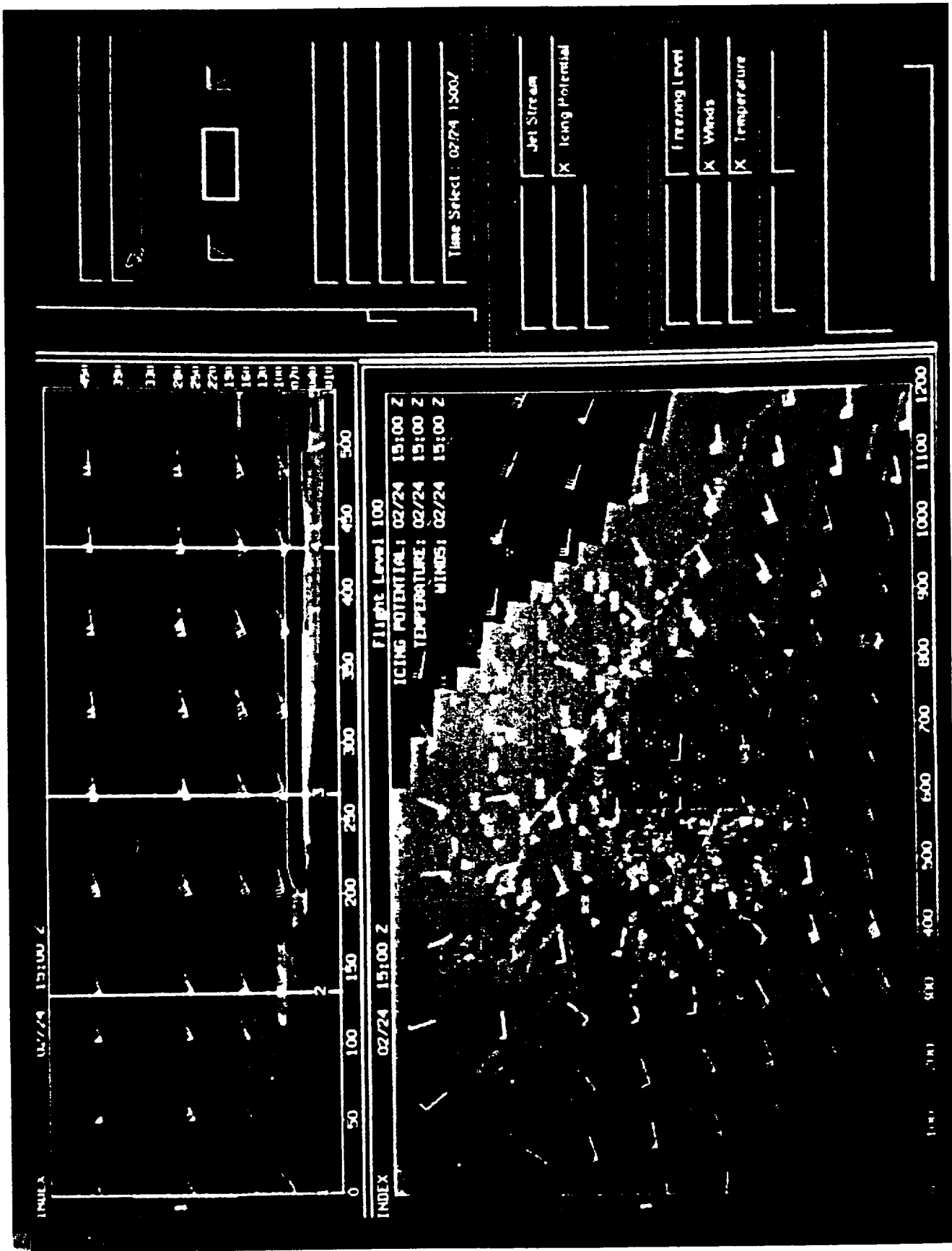
A depiction of icing potential, temperature and winds at 10,000 feet MSL presented on the Aviation Weather Product Generator display

**Figure 1: Example of NCAR Graphical Icing Depiction Display.**

## Ice Detectors

There are a variety of onboard "in-situ" ice detectors which are applicable to General Aviation. The primary role for ice detectors is for the management of ice protection systems and for alerting of icing on critical components such as tail plane icing for some aircraft. Ice detectors have limited utility for avoidance in that they require penetration of the icing condition so they do not give any advance warning and they have no substantial advantages over very low cost alternatives such as viewing ice accretion on a simple OAT probe.

There may be a role for ice detectors as part of an automated PIREP system but due to certification costs, even low cost ice detectors are not expected to be cost effective for AGATE class aircraft.

Remote ice detectors such as Millimeter Wave Radars could be used in flight or on the ground for the remote detection of cloud liquid water and icing potential. However, such radars are not currently at a sufficient stage of development for use in identifying icing regions. If developed, such systems would likely be cost prohibitive.

## Feasibility of Improved Forecasting and Ice Avoidance Procedures

Based on the current state of the art in icing forecasts and the expected developments in the foreseeable future, it is unrealistic to expect high resolution, high reliability forecasts of icing intensity and ice type to be available to the AGATE class aircraft. However, it is reasonable to expect some level of decision support for ice avoidance.

### Ice Free Zone Identification

With existing tools and improved ground-air communication, it should be possible to significantly improve the identification of ice free zones which can be used for strategic flight planning and tactical escape. For example, it would be possible to depict all regions where the freezing level is more than 1000 ft above the Minimum Enroute Altitude thereby assuring that there would be a safe escape layer below the freezing level. Similarly, cloud tops and cloud boundaries can be determined by satellite and very dry regions can be determined by the numerical forecast models.

### PIREP Dissemination

Because PIREPs are the most reliable and valuable source of icing information, mechanisms need to be put into place to improve the generation and dissemination of PIREPs. Automated wind and temperature PIREPs are already being issued by ACARS equipped air transport aircraft. In the future it would be desirable to automate reporting of icing and also to encourage pilot initiated datalinked PIREPs. In addition, consideration should be given to a mechanism to uplink and display PIREPs to AGATE class aircraft.

There are a variety of display issues with regard to icing PIREPs. For example: how long should a PIREP remain valid? Should different classes of aircraft be identified? Are PIREPs potentially misleading due to velocity effects (e.g. ram temperature rise) or collection efficiency effects? How can the quality of PIREPs be assessed? How do you identify regions where no aircraft have recently penetrated?

**Decision Support Services**

Based on the prognosis that there will continue to be uncertainty in the identification of icing regions, there needs to be some level of decision support for novice pilots of AGATE class aircraft. This is not unique to icing, there are other weather conditions which will be beyond the capabilities of the AGATE class aircraft. These include: thunderstorms, severe turbulence, high or gusty surface winds, very low visibility, and poor breaking.

It may be possible to automate some of the decision support elements, however the same factors which limit the accuracy and reliability of icing forecasts will also limit the accuracy and reliability of the decision support system. It is expected that some level of human involvement will be required to assist in decision support. For air carrier operations (Part 121) this role is taken by a dispatcher who consolidates weather, flight planning, weight and balance, and fuel information and supports the pilot in decision making. Much of this interaction is now done by datalink using the ACARS system. A similar system would have significant utility to AGATE class aircraft and could be implemented with existing technology. While there would be a significant market for GA dispatch services, issues of liability and insurance need to be resolved.

## Conclusions

Based on a review of the current ice identification, forecasting, and avoidance techniques and an assessment of the feasibility of improved technologies, forecasting and ice avoidance procedures, the following conclusions have been made.

- Icing will be a critical factor limiting AGATE class aircraft dispatch reliability and flight safety since it is unlikely that a majority of AGATE class aircraft will be equipped and certified for flight into known icing.

- Current ice avoidance techniques require significant pilot skill and judgment to operate safely during periods where icing potential exists.

- PIREPs and freezing level information are the most useful elements in identifying and avoiding icing conditions. Efforts should be undertaken to uplink this information as part of the weather uplink to AGATE aircraft.

- A key element of safe operation during periods of icing potential is to identify ice free regions and have viable escape options when inadvertent icing conditions are encountered.

- In-situ ice detectors will principally be used for management of ice protections systems and for monitoring of critical components. On AGATE class aircraft, it is unlikely that ice detectors will be cost effective compared with low cost visual inspection alternatives.

- Remote ice detectors such as Millimeter Wave Radars are not at a sufficient stage of development for use in identifying icing regions. If developed, such systems would likely be cost prohibitive.

- Current ice forecasting techniques based on numerical weather models are limited both in resolution and accuracy. Current resolution is on an 80 km grid with plans to reduce the grid spacing to 20 km. Numerical weather models do not explicitly predict liquid

water so icing potential must be inferred from relative humidity, thereby limiting the accuracy and validity of the forecasts.

- Work is underway to improve icing forecasts but only a limited improvement can be expected. Resolution will at best be on the order of tens of km and the reliability will be questionable. Icing forecasts and nowcasts will not be of sufficient quality to be used as a tactical decision tool for in-flight avoidance of icing conditions.

- Rather than attempting detailed icing intensity forecasts, forecasting efforts should consider attempting to forecast ice free zones with a high degree of confidence. This appears more technically feasible and will have the greatest impact on dispatch reliability and icing escape routes.

- Because neither full ice protection or high confidence ice forecasting are expected for near term AGATE class aircraft, some level of decision support will be required to support novice AGATE pilots who fly in regions of icing potential. Advanced communication technologies make this technically feasible.

*Appendix A:*

## Description of Meteorological Numerical Models

*from* : http://unidata.ucar.edu/data/models.html

### Regional Systems

### Nested Grid Model (NGM)

The NGM is a 16-layer model with 80 km resolution. It generates 48-hour forecasts twice a day and is used for model output statistics guidance. Development has been frozen on the NGM since 1990 and the model itself will be discontinued in 1998. This is after the Class VIII system and the model enhancements that it will support are in operational use. The NGM forecast hours are 00-48, running at 00Z and 12Z.

### Early ETA Forecast Model (ETA)

The early ETA run involves a 38-level model with 80 km resolution. Like the NGM it generates 48-hour forecasts twice per day. The ETA utilizes a first guess from the Global Data Assimilation System (GDAS) and an ETA Optimal Interpolation (OI). The need for the early ETA run will be obviated by the aviation (AVN) global model when it begins to run four times per day in 1996. Once the AVN demonstrates accuracy comparable to or better that the ETA for precipitation guidance in the 24-48 hour range, then the early ETA will be discontinued.

### Mesoscale ETA Data Assimilation System (EDAS)

This OI-based data assimilation system is used to initialize the mesoscale ETA model. It is performed on the model domain at 29 km resolution and for 50 levels. It will become operational in early 1995 and will initially run two 12-hour cycles per day, each with an intermittent (3-hour) assimilation of data. Later in 1995 the EDAS will begin to run four times per day. In 1998 the EDAS will evolve into a four-dimensional variational regional data assimilation scheme based on the adjoint of the ETA model. It will then run four times per day with continuous data assimilation over 6 hours for each of the four cycles.

### Mesoscale ETA Forecast Model (Meso-ETA)

This is a 50-layer model with 29 km resolution. Initial conditions come from the EDAS. The Meso-ETA will become operational in early 1995 and will produce 33-hour forecasts twice per day. The base times for these runs will be 03Z and 15Z in order to use updated boundary conditions from the AVN model. Later in 1995 the Meso-ETA will begin to run four times per day. Special ETA forecasts will be run over Alaska if computationally feasible. After the arrival of the Class VIII system, plans are to consider an increase in the horizontal resolution of the Meso-ETA to 15 km and to increase the number of levels to 70.

### Regional Spectral Model (RSM)

This model is presently under development. The RSM, now run experimentally within the global spectral model, is a 28-level model with 40 km resolution covering a North

American sub-domain of the NGM. It produces one 48-hour forecast per day for comparison with the ETA model. The RSM should become operational in 1995, perhaps with an increase to 42 levels. After the operational implementation of the Class VIII system in 1998 the RSM will run with 20 km resolution within the AVN model four times per day as an enhancement over North America. In the same time frame a non-hydrostatic version with 10 km resolution will come into use experimentally.

### Rapid Update Cycle (RUC)

The RUC is a hybrid sigma-isentropic analysis and forecast system. It utilizes a 3-hour, OI-based data assimilation cycle to produce 12-hour forecasts eight times per day. This is a 25-layer model with 60 km resolution. With the implementation of the Class VIII system in 1998 the will run hourly, 24 times per day. The resolution of the model will increase to 50 levels and 30 km in that same time frame.

## Regional Systems Outlook

The outlook for the 5 years after 1998 is that, the NCEP will run a national domain mesoscale model at 5-10 km resolution based on a non-hydrostatic version of the ETA model (possibly the RSM), together with ensembles of lower resolution. This system will be coupled with multiple storm-scale (1 km or less) models used for very short range forecasts (up to 6 hours). The storm-scale forecasts will be nested within the national domain in areas threatened by severe weather. Together with extensions of NCEP models, candidates for such storm-scale models could be those developed at universities or other research centers. Candidate models will be evaluated for potential operational use in the Model Test Facility to be established within the Environmental Modeling Center.

## Global Data Assimilation and Forecast Systems

### Aviation (AVN) Global Model

The AVN is a 28-level model with 100 km horizontal resolution which runs twice per day producing 72-hour forecasts. It will be refined to 40 levels and approximately 80 km resolution in late 1994. Another advancement will be the conversion from spectral to semi-Lagrangian methodology in 1995. The AVN will run four times per day beginning in early 1996. In 1998 the AVN will run with 60 km or finer resolution using 50 levels. The RSM will run within this model at 20 km resolution providing the main synoptic guidance over North America.

### Medium Range Forecast (MRF) Model

The MRF is the same numerical model as the AVN but it will run under a wider variety of conditions and for different purposes. By late 1994 it will run once per day at the resolution of the AVN to produce a 7-day forecast. A low-resolution version of the MRF (using a 2.5 degree grid) will run out to 16 days as a tool for ensemble forecasting. The low-resolution MRF will also run experimentally on the Class VII machine with an imbedded version of the RESM as referred to above.

In 1998 the MRF will probably be used in ensembles of a few runs with 70-100 km resolution out to 7 days; and ensembles of many low-resolution runs for days 7 to 30.

**Global Data Assimilation System (GDAS)**

The GDAS will continue to use the spectral statistical interpolation technique but will add refinements as they are developed. By 1998 it will apply four-dimensional variational methods with a 12-hour assimilation interval and continuous data utilization.

The GDAS will also use a number of new or expanded data sources. Satellite instrumentation in particular will provide new data that will be incorporated by the GDAS over the next several years. Data from profilers and from new aircraft sensors will be assimilated too. In addition, the GDAS will be refined to better utilize information from traditional sources such as pressure tendencies and cloud reports from surface observations.

**Global Systems Outlook**

The outlook for NCEP global models after 1998 is that they will have a horizontal resolution of about 20 to 40 km and will run through 72 hours in the case of the AVN and through 7 days for the MRF. Ensembles of somewhat lower resolution model forecasts will be run for one month or longer. With better data assimilation, skillful tropical forecasting based on these models and ensembles may become possible through 10 days. Ozone forecasts should be routinely available and forecasts of atmospheric contaminants may also prove useful.