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1. Introduction

The most basic systems and tools for weather forecasting are the worldwide networks of conventional surface and upper-air (radiosonde) observations and the numerical weather prediction (NWP) models that are used to generate forecast guidance. This paper, despite its title, is about none of these. NWP models are so important a tool that another whole review paper in this issue is dedicated to them (---------- 1994). Also, conventional observations have long been the mainstay of forecasting and, although there is a need for more of them (and better availability) from areas such as Africa, the major opportunity for future progress lies in the development of other, newer, kinds of observational systems. This paper describes a selection of such systems, most of them exploiting some form of remote sensing principle. It gives examples of their use in forecasting, both in conjunction with NWP models and in nowcasting, defined as a detailed analysis of the current situation together with some extrapolation. Included in the paper are satellite systems (Sec. 2), ground-based radars (Sec. 3), wind and temperature profilers (Sec. 4), and sferics detection networks (Sec. 5). The only reference to in situ measurements is in Sec. 6 where there is a brief mention of some important developments in operational observing systems involving aircraft, ships and buoys. Tools for generating and displaying combined products from these new systems are outlined in Sec. 7, with a consideration of the role of the human forecaster in the overall, largely automated, system in Sec. 8. The paper builds on developments worldwide but sets them within a European perspective.

2. The Space-borne observing system

2.1 Polar orbiting satellites

2.1.1 Current and planned systems and products

The space subsystem of the World Meteorological Organization's World Weather Watch (WWW) is nominally as in Fig 2.1. It consists of complementary series of geostationary satellites (Sec 2.2) and polar orbiting satellites. The National Oceanic and Atmospheric Administration (NOAA) currently provide a series of two polar orbiting meteorological spacecraft; one is operationally maintained in a morning orbit and the other in an afternoon orbit. They provide imagery from an instrument called the Advanced Very High Resolution Radiometer (AVHRR), vertical soundings of temperature and humidity from a suite of infra red and microwave radiometers called the Tiros Operational Vertical Sounder (TOVS) and relay of data from automated observing platforms via the so-called ARGOS system. Access to the data is via two direct broadcast services (High Resolution Picture Transmission (HRPT) and Automatic Picture Transmission (APT)) and also via a global data service of reduced resolution satellite observations (SATOBs) on the meteorological Global Telecommunications System (GTS). This service has been provided unchanged since 1978.

With the launch of the satellite NOAA K, planned for mid-1996, the TOVS microwave radiometers will be upgraded to provide humidity soundings and improved temperature soundings in cloudy areas. These are based on the Advanced Microwave Sounding Units (AMSU)-A and -B, and will be referred to as Advanced TOVS (ATOVS). Following the launch of NOAA L into the morning orbit in March 1997, the EUropean organization for the exploitation of METeorological SATellites, EUMETSAT, will take over the responsibility for providing the morning series of spacecraft with the launch of the meteorological operational satellite 'Metop 1' in 2000. At this time further improvements will be phased in. These will include:

- improved vertical resolution in temperature profiles using the Infrared Atmospheric Sounding Interferometer (IASI),
- additional channels in the imager and improved calibration,
- expansion of HRPT and conversion of APT to a digital service,
- network distribution of full resolution global data to the European operational meteorological community.

A recent study (SMSRC 1993) has looked in detail at the potential meteorological products available from ATOVS and the improvements attainable by adding IASI data. The results are summarised in Table 2.1.

Concerning meteorological satellite activity in Russia, the Meteor-3 series consists of three satellites in near-circular orbits with inclinations 81 to 83° and altitudes of 1200 to 1250 km. This is lower than the average altitude of the Meteor-2 series and it provides extended swathwidth for on-board television systems and global coverage of the Earth's surface. The primary imaging spacecraft, Meteor 3-3, is in regular service on a frequency of 137.850 mHz. Meteor 3-4 is in service on 137.300 mHz. Meteor3-5 is currently not operational.

Another series of satellites of use for weather forecasting is the Earth Resources Satellite (ERS) series. The first of these (ESR-1) was launched in 1991. Especially useful for forecasting are the high-resolution (25km) surface wind observations derived once-a-day over parts of the ocean from the microwave scatterometer and the measurements of sea surface temperature, obtained to an accuracy of about 0.5°C even in the presence of 80% cloud cover, from the Along Track Scanning Radiometer (ATSR). Another ERS satellite is planned to be launched in 1994 to provide continuity with ERS-1. Scatterometer data are also available from other satellites.

The US Air Force also maintains a series of observing satellites (called Defence Military Satellite Program (DMSP)). This series is primarily for military purposes and access to data is restricted. One of the instruments, the Special Sensor Microwave Imager (SSM/I), provides images of vertically integrated water vapour, cloud liquid water content and frozen precipitation aloft - a foretaste of things to come from ATOVS. First flown in June 1987, the SSM/I data are becoming more readily available to the civilian meteorological community, but not yet in real time for forecasting applications.

2.1.2 Use of polar orbiting satellite data in forecasting

The greatest value of polar orbiting satellites is in the production of soundings for the initialization of global and regional NWP models. Currently global data from the sounding instruments are converted into pseudo radio-sonde profiles (of temperature and humidity). The derived temperatures are referred to as SATEMs. Partly because of the intrinsically poor height resolution of these soundings, their late delivery, and the 6-hourly interval between overpasses, such sounding data, when assimilated into global numerical models, have been found to have a significant impact only over the data-sparse ocean areas of the Southern Hemisphere (Andersson et al 1991).

One way to improve the utility of TOVS data is to use full-resolution imagery with the sounding data as a means of identifying errors due to cloud contamination. Another way to improve the utilization of TOVS data is to use variational data assimilation techniques, allowing assimilation of data at observation times rather than synoptic times. Yet another way is to assimilate directly the basic (cloud free) radiance measurements rather than derived products into the data analysis step of the NWP model. Eyre et al (1993) show that these techniques together lead to a positive impact even in the Northern Hemisphere (Fig 2.2). The impact is still quite small, and substantially greater impact can be expected only when temperature profiles with improved height resolution become available from sounding systems such as IASI or its USA counterpart, AIRS.

Until recently many meteorologists had been pessimistic about the utility for NWP of surface winds inferred from scatterometer data. The optimum interpolation (OI) scheme traditionally used at most operational weather centres was found to be poor at spreading the influence of surface wind observations throughout the full depth of the model's atmosphere. However, according to Thépaut et al (1992), a variational approach to assimilation is able to exploit complex linkages between observations and the model state. They show that in its four-dimensional version, this method enables the effect of the scatterometer winds to propagate throughout the troposphere and to have a significant and lasting impact on the short range forecasts.

Improvements in the performance of regional NWP models can be expected to arise from the use of the improved humidity fields that will become available from ATOVS after 1996. Further improvements in short range forecasts will come from the ability to assimilate cloud imagery from AVHRR and from microwave imagery. An example of the kind of microwave imagery that will be useful is shown in Fig 2.3 which shows the distribution of vertically integrated water vapour associated with a mid-latitude frontal system.

The multispectral imagery from AVHRR helps not only to distinguish cloud from features of the underlying surface but also to differentiate between different cloud types. An example of a well developed operational system for multispectral cloud classification is the PROSAT system developed in Sweden (Karlsson and Liljas 1990). The infrequency with which the cloud imagery is obtained at any given location from polar orbiting satellites makes it generally less useful than comparable imagery from geostationary satellites, especially for nowcasting applications. The exception is at high latitudes: there the geostationary satellites give poor coverage whereas successive passes of a polar-orbiting satellite overlap and can provide useful image sequences. While it is sometimes difficult to detect cloud above snow covered surfaces, it is often possible to observe important systems such as polar lows. In the future AVHRR will carry a channel at 1.6μm with the main purpose of discriminating between clouds and snow, and between water clouds and ice clouds (Valovcin 1978).

2.2 Geostationary satellites

2.2.1 The current global system

The space subsystem of the World Weather Watch (Fig 2.1) contains five geostationary satellites. Their nominal locations were agreed by the satellite operators meeting within the Coordinating Group for Meteorological Satellites (GCMS). The locations were intended to ensure global coverage of the tropical and near tropical areas as well as middle latitudes, excluding only the polar regions which are covered by the polar orbiters. The common mission objectives are:

- imaging of the Earth's surface and its cloud cover, using the visible and thermal infra-red spectra, and extraction of meteorological information such as cloud motion vectors as a measure of winds. In addition to infra red and visible imagery, the water vapour channel provides images of the humidity field in the mid-to-upper troposphere,
- dissemination of cloud cover images and other meteorological information to user stations around the world, and
- collection and relay of environmental data from fixed or mobile Data Collection Platforms (DCP).

All current satellites, except INSAT, are spin-stabilised and resemble one another in their imaging capabilities. They rely on broad-band channels in the visible, the atmospheric window infra-red and water vapour parts of the spectrum. The GOES satellite is alone in complementing this with an infra-red sounding capability, known as the VAS. VAS stands for VISSR Atmospheric Sounder, VISSR being the acronym for the GOES imaging radiometer (VISible Spin Scan Radiometer). Information provided includes precipitable water vapour and a thermodynamic stability index at 7 km resolution, and 850 and 500 mb temperature fields at 80 km resolution (Smith et al 1985).

2.2.2 Current and planned systems for Europe

The METEOSAT series of spacecraft have been carrying out the common mission objectives described in Sec 2.2.1 almost continuously since 1977. Images are obtained every 30 minutes with an effective spatial resolution of 2.5 km at nadir in the visible channel and 5 km in the infra red and water vapour channels. The image data are calibrated and navigated centrally before being distributed to users. In addition to cloud motion vectors (so-called SATOBs), the following products are also generated centrally: sea surface temperature, cloud analyses, cloud top height, upper tropospheric humidity, as well as climate data sets. The satellite is also used to relay image data from other meteorological satellites. Recently it has started to be used to relay other meteorological data and products, in addition to its own imagery and derived products, in an encrypted form via a system known as MDD (Meteorological Data Distribution) (Bridge 1992).

The current series of METEOSATs will continue unchanged until year 2000 when the first of a new series called METEOSAT Second Generation (MSG) will be launched. The MSG will have the following attributes:

- the satellites will be spin-stabilised (three-axis stabilization as planned for the next GOES satellites is considered to entail a high risk),
- the core payload will contain a multispectral radiometer called SEVIRI (Spinning Enhanced Visible and InfraRed Images) providing imagery plus capabilities for monitoring atmospheric instability and giving more accurate Cloud Motion Vectors.

Existing technology does not allow the possibility of a sounding instrument operating from geostationary orbit that could have sufficient spectral or spatial resolution to provide significant information on temperature or humidity profiles in addition to that available from polar satellites and earth-based techniques. Thus, in broad terms, the functional split between different satellites is: imagery from geostationary satellites and soundings from polar orbiters.

2.2.3 Products from METEOSAT Second Generation

The final list of derived products from MSG remains to be defined because processing algorithms exploiting the full range of the MSG imager performance still need to be developed. A preliminary indication of potential products is given by Table 2.2. The products to be extracted in real time from the multispectral imager can be ordered into three main groups.

(a) Cloud, fog, snow and radiation products. They rely mainly on multispectral scene identification techniques. They are primarily for nowcasting but are also needed in the generation of other categories of products.

(b) Air mass and temperature products. They relate to the mean temperature and humidity structure of the atmosphere, the temperature of the land and sea surfaces, and fields of instability indices similar to those derived using GOES VAS. Their extraction will require products from the previous group (a) together with background fields from other sources.

(c) Wind products. They will be obtained with higher accuracy than at present by using frequent (¼ hourly) images in the water vapour and ozone bands in addition to the carbon dioxide band, to track inhomogeneities in water vapour and ozone as well as cloud features. The extraction of winds will require the availability of products in categories (a) and (b) above.

2.2.4 Use of geostationary satellite data in forecasting

(a) Nowcasting

Imagery from geostationary satellites along with that from ground based radars is the primary tool in nowcasting. It portrays the time evolution of cloud systems in sufficient detail not only to enable significant weather events to be identified and tracked but also to enable a forecaster to gain a dynamical understanding of what is happening on the mesoscale. Severe weather in particular often exhibits characteristic small scale structures whose rapid development can be identified from the frequent imagery especially when sequences of images are replayed repeatedly (looped) in quick succession. Considerable effort has been put into developing algorithms for interpreting infra-red and visible imagery, separately or together, in terms of surface rainfall (Lee et al 1991). Unfortunately the relationships are very situation-dependent and, whereas rainfall estimates over tropical regions are possible from satellite alone on a climatological basis (Arkin 1979), it is necessary to combine satellite information with other data in order to provide the accuracy required for many weather forecasting purposes (see Sec 7).

The phenomena that are amongst the most important to be monitored by means of geostationary satellite imagery are mid-latitude cyclones and frontal disturbances, tropical cyclones, convective storms and related convergence lines, and fog and cloud in the boundary layer. The existing METEOSAT series is useful for all these phenomena. The higher spectral, spatial and temporal resolution planned for MSG will provide even better support for nowcasting by improving the discrimination of cloud, winds and air mass stability. Fog, for instance, is not easy to distinguish using METEOSAT infrared imagery when the fog top temperature differs little from that of the underlying surface. However, with MSG it will be possible to use multispectral information to identify fog even at night, in much the same way as can be done at present using imagery from polar orbiters (Allam 1987) but with the major advantage of being able to monitor its movement, development and dissipation. MSG will also enable the clearer discrimination of features of the underlying surface (gradients in sea and land surface temperatures, snow cover, soil moisture and vegetation) which can be important in driving thermally-forced mesoscale circulations in the boundary layer (Pielke et al 1992). Improvements in the spatial and temporal resolution of the imagery will enable these (and other) circulations to be monitored as they develop, although the paucity of good tracers will cause this to be a challenging task that may benefit from human judgement. The availability of satellite-derived instability indices will provide an indication of where such circulations are liable to trigger the development of convective storms.

(b) Use with numerical models

The simplest application of imagery together with NWP models is for identifying errors in model predictions. Thus, for example, Fig 2.4(a) shows an area of enhanced cloudiness (I) on the northern flank of a frontal cloud band (FFF). The 18 h model forecast for the same time (Fig 2.4(b)) shows no corresponding enhancement in positive vorticity advection but there is one about 10 deg farther west. Hence the forecast fields of PVA can be recognized as erroneous and the model run in this case cannot be used to provide a reliable short-range forecast of frontal development. Similarly, comparisons between water vapour imagery and model-derived potential vorticity, may also be useful because of the close relationship between them in situations of rapidly deepening cyclones (Young et al 1987). Model validations such as this can be performed using polar orbiting imagery but geostationary imagery is more useful because its frequent availability provides more opportunities for comparisons.

Input of data from geostationary satellites directly into operational NWP models is limited mainly to cloud motion vectors (SATOBs)at present. The quality of operational SATOBs varies significantly for different height levels, areas and satellites. The quality of low-level SATOBs is generally satisfactory (except for INSAT). For high-level winds, especially for high wind speeds in mid-latitude jet streams, there is a tendency towards a negative bias, although recent studies indicate some improvement. In particular, comparisons of upper-level cloud motion vectors with rawinsondes by Miller and Menzel (1992) give a vector rms difference of about 7.5 m s^{-1} but a speed bias of only -1.3 m s^{-1}. One of the main sources of error arises in assigning heights to the cloud motion vectors. Different methods used by NESDIS (National Environmental Satellite and Data Information Service) and ESOC (European Satellite Operations Centre) are found to give rather similar results. The impact of SATOBs on NWP models depends on the region and on the nature of the quality control (Thoss 1991). In the tropics SATOBs are indispensable for realistic analysis. In the mid-latitude regions of the Northern Hemisphere the impact is less and stringent quality control is needed to ensure positive impact. To make the best possible use of SATOBs it will be necessary to develop suitable data quality indicators.

There is also considerable work being devoted to developing ways of using the satellite imagery as input to a NWP model (eg Wright and Golding 1990). The imagery can be used to classify features such as an area of showers or a region of fog. Conceptual models can then be used to define the feature in the model fields. For example, an area of fog detected in the imagery might be defined in terms of its depth and top temperature, by assuming a saturated adiabatic lapse rate throughout its depth and an adiabatic cloud water profile. Indeed the imagery can be used to define the model humidity and cloud water fields for cloud systems in general. These fields can provide useful information about the vertical circulations in the model. Where large scale uplift is present, the vertical motion is primarily forced by latent heat release. Thus, if the heating profiles are inferred via the model precipitation physics from a knowledge of the cloud (and precipitation) distribution (Golding 1987), then the model can be initialized with the correct forcing either (a) by applying the latent heating contribution to the diabatic heating term in the thermodynamic equation over a period of time at the start of the forecast or in the preforecast period (Wang and Warner 1988), or (b) by using the heating profiles to initialize the divergence profiles directly.

3. Ground-based weather radar systems

3.1 Networks of operational weather radars

In Western Europe the number of operational digital weather radars, stimulated by projects COST-72 and COST-73**, has grown rapidly especially during the last decade (Fig 3.1). Almost half these radars are Doppler radars, capable of measuring line-of-sight velocity components as well as precipitation intensity, but most are of modest sensitivity and hence suitable only for measurements of and within precipitation. In the United States a more ambitious programme, known as NEXRAD (NEXt generation weather RADar) will lead to coverage of most of the conterminous states with highly sensitive Doppler radars (Golden 1990). NEXRAD radars have sufficient sensitivity also to measure winds in the clear air boundary layer and to detect low-reflectivity features such as convergence lines. The more modest systems in Europe (and elsewhere), although not so useful outside areas of precipitation, are capable of providing many valuable products as described below.

3.2 Radar products

(a) Rain measurements

The main use to which weather radars are put is to measure the intensity and distribution of surface rainfall, frequently, with great detail and, with the aid of networks of radars, over large areas. Non-Doppler radars can accomplish this satisfactorily, although Doppler radars are better able to discriminate between rain and anomalous ground returns. Despite the failure of rainfall radars to deliver the high accuracies sought by some operational users, their widespread and increasing use by meteorologists and hydrologists testifies to the operational utility of the rain (and snow) patterns they provide.

What limits the accuracy of radar rainfall measurements most severely (Browning 1978) is that, even when scanning at low elevation angles, radar makes its measurements some way above the ground, especially at long ranges. There are many reasons why the rainfall intensity inferred from radar reflectivity measured aloft will differ from the actual rainfall intensity at the surface. One of the troublesome problems in regions of widespread frontal rain is the overestimation of surface rainfall due to detection of melting snow (the bright band). No entirely satisfactory operational method of correcting for this has yet been devised but in the longer term it may be possible to apply corrections based on melting level heights derived from radar polarisation information (Illingworth and Caylor 1991) or from NWP models. A particular difficulty in using radar to measure precipitation over land is the variation in reflectivity with height, especially in the lowest kilometre, due to orographic growth upwind (evaporation downwind) of hills. Radar cannot observe these levels except at close range and

** COST Projects are projects of the Commission of the European Communities concerned with COoperation in Science and Technology this sets a limit to the accuracy of precipitation measurements that can be improved upon only by combining radar methods with other information, eg NWP models and/or climatology.

There are several technical ways of reducing errors in rainfall measurements (Table 3.1). Some of these are 'high-tech', costly, and arguably not cost-effective (Joss and Waldvogel 1990), but there may be special circumstances where, for a particular radar site, the additional cost and complexity can be justified. These techniques will be investigated as part of a new COST project (COST-75). One of the simpler and most widely applied methods in Table 3.1 is the use of telemetering raingauges to adjust for drop size variability and radar calibration errors (Collier 1986 a,b). This method requires careful optimisation and Joss and Waldvogel recommend it should be applied only to data already corrected for vertical profile effects.

(b) Hail detection

A radar echo aloft with a reflectivity exceeding a certain threshold or a high value of vertically integrated reflectivity are often used as an indicator of hail. However, it is not always possible to distinguish between high reflectivity due to hail and high reflectivity due to very heavy rain. A complementary method of inferring the presence of hail is to use Doppler radar. Large hail grows within strong updraughts accompanied by strongly divergent outflow near the storm tops. These outflows can be measured by a Doppler radar provided it is 50 km or more away and able to scan the storm at a low elevation (to avoid confusing the horizontal and vertical components of motion). Polarization methods (Illingworth et al 1986) also offer ways of improving the accuracy of hail detection but more research is needed to evaluate their performance and cost-effectiveness.

(c) Tornado detection

In areas not prone to severe convective storms cost-benefit considerations sometimes go against the operational implementation of Doppler radar. In areas prone to severe weather, especially tornadoes and microbursts (see below) the case for Doppler is strong. Admittedly, tornadoes often accompany supercell thunderstorms, for which it is possible to use non-Doppler radar to infer the existence of the parent supercell on the basis of the characteristic 3-D structure of the precipitation echo (Browning 1964). However, such structural information is easy to resolve only at close range. A more reliable approach is to use Doppler radar to detect and quantify the characteristic velocity pattern associated with tornadoes. A single radar senses only the line-of-sight velocity component but this is generally sufficient to detect a well defined vortex. Fig 3.2, for example, shows the Doppler pattern corresponding to a small scale tornado vortex (velocity components 44 m s^{-1} away, 70 m s^{-1} towards) embedded within a larger scale mesocyclone circulation (velocity components 20 m s^{-1} away, 30 m s^{-1} towards). According to Burgess (1976) the mesocyclone circulation is often detectable up to 30 minutes before the tornado touches down and so there is an opportunity to provide a useful warning assuming that an appropriate dissemination system is available. A recent study by Donaldson and Desrochers (1990) suggests that tornado warnings produced in this way with 20 minute lead-time have error rates (false alarms) ranging from 0 to 40% for violent and weak tornadoes, respectively.

A research technique used to observe tornadic storms and other convective phenomena in great detail is to combine the data from two (or more) Doppler radars viewing the system from different directions. Although networks of Doppler radars are becoming operational, their spacing is usually too great to enable such 'dual Doppler' techniques to be used operationally.

(d) Microburst detection

A microburst is defined (Fujita 1981) as a downdraught that induces a sudden outflow of damaging horizontal winds at the surface with a horizontal extent of between 0.4 and 4 km. In some parts of the world, eg where convective clouds develop in the presence of very dry unstable layers, microbursts are sufficiently common to pose a serious hazard to aircraft especially at take-off and landing. Doppler radar is well suited to detecting microbursts because of the strong signature of horizontal divergence observable at low levels. Wilson et al (1984) have modified the definition of a microburst to refer to radar-observed divergent outflows due to convective storms in which the radial Doppler velocity difference across the divergence centre exceeds 10 m s^{-1}. Up to 10 minutes warning of a microburst can also be achieved by detecting the horizontal convergence aloft associated with the formation of the downdraught and then the lowering of the reflectivity core due to descent of the accompanying precipitation (Roberts and Wilson 1989). Because of the importance of along-track changes in the flight-parallel component of the wind it is desirable to site the radar along the axis of the runway, which leads to difficulties if there are multiple runways.

3.3 Use of radar in forecasting

Radar contributes to forecasting over periods ahead ranging from minutes (tornadoes and microbursts) to hours (mesoscale rainbands). The radar data may be used in three ways: (a) as an aid in analysis, (b) by extrapolation, and (c) by assimilation within a NWP model.

(a) Analysis. Because it provides frequent, detailed, spatial fields, radar is - along with geostationary satellite imagery - the most powerful tool for identifying significant mesoscale phenomena. Not only can it identify the occurrence of such events, but it can also enable unmeasured attributes to be inferred on the basis of conceptual models (Browning 1985). For example, a sharp wind shift can be inferred from the detection of a line convection echo or it can be explicitly detected using Doppler information. For larger scale events it is useful to use a composite radar display from a network of weather radars. Composite displays, first used widely in the UK (Browning and Collier 1982), are now produced in many countries.

(b) Extrapolation. Having identified individual phenomena or the overall pattern of precipitation, and having also determined the motion of the various parts from sequences of 2 or 3 radar images, very-short-range forecasts can then be achieved by one of several available linear extrapolation methods (see Collier 1989). The period of valid extrapolation depends on circumstances but can be quite short (<1h) in the case of deep convective raincells. This is partly because of errors in identifying the nature and movement of the phenomena at the initial time but mainly it is because of non-linear changes thereafter. Limited but useful success can be achieved by linear extrapolation alone but to address the important non-linear changes it is necessary to employ additional information on storm cell motion and development, as predicted by NWP models.

(c) Assimilation. The use of NWP model output, as described above, to adjust a nowcast is a simple and sometimes worthwhile approach but it is not the only approach. In the long run, a more powerful approach will be to assimilate the radar-derived precipitation and radial velocity data, along with other sources of data within the assimilation scheme of a high-resolution NWP model. This is probably best achieved using 4-D Variational Analysis (Adjoint) methods but the necessary research has only just begun (Lilly 1990; Pielke et al 1992). The advantage of these methods over the currently more widely used Newtonian relaxation, or "nudging" method, is the dynamical consistency of the initial conditions and the scheme's ability to retrieve unmeasured variables or to utilize observations such as radar reflectivity that are integral properties of model variables.

3.4 Multiple use of radar

Weather radar data are required for a variety of applications. Some applications, such as aviation forecasting in some regions and severe weather detection in general, require rapid 3-D volume scans. Other applications, such as hydrology, require mainly near-surface data with sufficient dwell times to enable quantitative measurement of precipitation, supplemented by scans at higher level to give some vertical profiles. It is difficult to reconcile these conflicting requirements with present-day operational radars. A possible future solution would be to use a frequency-stepped transmitter with an antenna rotating slowly in azimuth together with rapid electronic scanning in the vertical (Joss and Collier 1991). The size of the weather radar market in Europe alone (Fig 3.1) would probably justify the development costs which, though small in relation to costs of satellites for example, are large by the standards of the weather radar community.

4. Ground-based radar profilers for wind and temperature soundings

4.1 Towards operational profiler systems

Little (1982) foresaw the development of a wide range of ground-based remote sensing systems for operational measurement of wind, temperature and humidity profiles. Such profilers, as he called them, have many advantages over equivalent arrays of in situ sensors including the fact that conceptually the data are available

- in one, two or three spatial dimension,
- without the use of towers, balloons or aircraft,
- without the use of expensive telemetry networks,
- with excellent continuity in space and time,
- with excellent resolution in space and time,
- as spatial averages,
- and using systems that may be readily automated and operated unattended.

In the ten years since Little's article the greatest advances have been with wind profilers, using UHF and VHF Doppler radars, and, more recently, with temperature profilers using another active sounding technique known as RASS (Radio Acoustic Sounding System) (May et al 1990). These systems may be regarded as complementary to space-based systems. Whereas present-day satellites provide good horizontal coverage (especially of temperature) but poor vertical resolution and accuracy, the ground-based systems can provide good vertical resolution and accuracy especially at low levels.

(a) Wind profilers (VHF/UHF radars)

An international survey of wind profilers conducted at the end of 1991 (James 1992) lists over 170 wind profiler radars world-wide. Most are used for research. The strongest thrust towards operational profilers has been within the US National Oceanic and Atmospheric Administration (NOAA) Environmental Research Laboratories, in Boulder. Initial prototypes of an operational wind profiler (Strauch et al 1984) are being followed up by a demonstrator network of 30 wind profilers in the central United States (Beran 1991). In Europe, research and development towards operational wind profilers is brought to a focus within the COST-74 programme. Amongst the participants of COST-74 a French group is actively developing a network of operational profilers (Pilon 1992).

Wind profilers operate at VHF (eg 50 MHz) and UHF (eg 404 and 915 MHz) frequencies. They detect the very weak backscatter from refractive index inhomogeneities in the clear or cloudy air as well as from precipitation particles. The measurement technique adopted in operational prototypes is to determine the line-of-sight Doppler shift within beams directed vertically and at small angles to the vertical in order to detect all three components of the wind. Much development work has been directed at producing a profiler system that can obtain soundings cost-effectively over a sufficient height range and in almost all weather conditions. Careful choice of engineering trade-offs are needed to achieve a system that meets the requirements at an affordable cost. A recent evaluation of five wind profilers is shown in Fig 4.1. Two of them (Unisys 404 MHz and WPL 50 MHz) gave usable wind data 75% of the time to above 15 km. The 404 MHz profiler was able to obtain data down to within ½ km of the ground. Ground clutter prevented the 50 MHz profiler from operating below about 2 km; however, measurements in the boundary layer can be obtained by supplementary use of a low-cost 915 MHz system.

Many studies (eg Strauch et al 1987) have demonstrated that good accuracy can be achieved. There are, however, a number of potential sources of error due to a combination of instrumental and atmospheric effects (Röttger and Larsen 1990); these errors do not undermine the viability of the technique but they do call for careful system design. One key source of error is the presence of highly variable winds, due to gravity waves for example; this problem can be minimized by averaging, except in the presence of stationary mountain waves. Another source of error when precipitation is present is the detection especially at UHF of a Doppler shift due to a component of the precipitation fallspeed (Wuertz et al 1988). This causes difficulties when the precipitation is highly variable, ie convective, but not when it is stratiform. A further source of error for VHF radar arises from enhanced returns from specular reflection at near vertical incidence. This can cause the most intense radar return to be received at an angle significantly above that of the beam axis, leading to an underestimate in the winds especially in the upper level jet.

The dominant constraint is availability of frequency allocation. From its inception COST 74 has recognized the importance of obtaining appropriate frequency allocation for operational wind profilers. In Europe each country has its own frequency licensing authority and this has resulted in variations in availability of parts of the radio spectrum. If unique allocations can be obtained on an international basis then the wind profilers could be constructed more economically to common standards. The World Administrative Radio Conference in 1992 approved a recommendation that might lead to the allocation of frequency bands around 50, 400 and 1000 MHz to wind profiler radars; however, it warned that the allocation will have to be shared with ground based channels and that a frequency band near 400 MHz used for satellite communications for safety of ships at sea will have to be avoided altogether.

The key tasks now are to develop objective methods for assessing data quality, to sharpen up the user requirements so as to enable optimal selection of profiler frequency bands, and then to identify specific sites and to negotiate detailed frequency clearances on a site-by-site basis.

(b) Temperature profilers (RASS).

The form of profiler originally envisaged by Little (1982) as a companion for the wind profiler was a multi-channel microwave radiometer. Some of the channels could be used to derive temperature profiles; the others provide water vapour and liquid water information and can be used to apply corrections to the temperature channels. The best results are obtained when ground-based and space-based microwave radiometric measurements are analyzed together (Westwater et al 1985). Although a radiometric approach provides information throughout the troposphere and above, its vertical resolution is considerably worse than that of radiosondes, notably for the humidity but also for the temperature (~200 mb resolution). More recently attention has turned to another technique, RASS, which exploits the wind profiler radar as one of its main components and is able to achieve a vertical resolution that meets many operational requirements. It does not have the height capability of the radiosonde but it is effective for lower tropospheric sounding.

The RASS combines an acoustic source with a wind profiler radar to obtain measurements of the profile of temperature, strictly the virtual temperature. The profiler's Doppler radar measures the speed of refractive index perturbations induced in the atmosphere by the acoustic waves as they ascend at the local speed of sound, which is directly related to the virtual temperature at each height. The main source of error is contamination by the natural vertical motions associated with gravity waves (May et al 1989) and with convective precipitation. Comparisons with radiosondes indicate that, in the absence of significant vertical air motions, RMS differences are 1°C or less for systems operating at 50, 404 and 915 MHz, which is comparable with the RMS difference between radiosondes themselves. Sharp inversions on a scale of hundreds of metres cannot be resolved properly by systems operating at 50 and 404 MHz. Such inversions are well resolved by 915 MHz systems with 150 m height resolution, but these measurements are limited to the lowest 1 km. Fig 4.2 summarizes the height coverage statistics of temperature measurements obtained using five different RASS systems.

4.2 Use of profilers in forecasting

Profiler data can be employed in nowcasting or as input to a numerical model. Either way it is important to capitalize on the continuous-sounding capability which makes profilers well suited for resolving mesoscale features. The continuous-sounding capability also makes profilers attractive for simple monitoring purposes. For example, some European countries plan to use profilers for monitoring winds near airports, power stations and industrial plants.

(a) Nowcasting

Fig 4.3 gives an example of how the detailed time-height wind sequence from even a single profiler can be used to identify dynamical features missed by a sparse rawinsonde network. This sequence was used operationally by Beckman (1990), along with satellite imagery, to evaluate the short-term guidance from three different numerical model predictions. The key feature in Fig 4.3 was the increase in depth of the northerly winds with time. The resulting improvement in the analysis of a midtropospheric closed low led to a better forecast of the track of a heavy snowstorm. In similar vein, Forbes et al (1989) found that wind profiler time-height records clearly reveal when upper air troughs have passed - sometimes when NWP model guidance suggests otherwise. Such nowcast information is valuable to a forecaster since , for example, it may signify that the threat of precipitation has passed. Neiman and Shapiro (1989) have shown that the data from a single wind profiler can be used to retrieve realistic thermal gradients and advections, at least in quasi-balanced flow regimes. Operationally this can be useful for monitoring baroclinic features and associated temperature advections on an hourly basis.

(b) Input to numerical models

Data from profilers may be assimilated into NWP models in much the same way as rawinsonde data are now. Input to a COST 74 Working Group provided by ECMWF (James et al 1991) indicates that the impact of profiler data on global NWP models is likely to be small over Europe but significant over data sparse areas such as the oceans. A major problem for operational NWP is the quality control of observations. According to Dharssi et al (1992) the proportion of gross errors is typically between 1% and 5% for conventional meteorological observations but is often worse than this for profiler data when a low signal-to-noise ration causes Doppler signal processing to identify a wrong peak in the spectrum. To avoid a negative impact in NWP it will be necessary to reduce the probability of gross error to 5% or less by preprocessing and still further by quality control using methods similar to those described by Dharssi et al.

The COST-74 Working Groups recognized that high resolution numerical models would be able to benefit much more than global models from the continuous sounding capability of profilers. Table 4.1 summarizes the requirements of three types of model for wind profiler data. Although mobile weather systems are well represented by individual time records, quasi-stationary systems forced by non-uniform surface heating are not. According to Pielke and Segal (1986), situations characterised by non-uniform surface heating are ubiquitous: they include circulations driven by land-sea contrasts, soil wetness contrasts, cloudy-clear contrasts, and snow-bare soil contrasts. For such situations a network with very closely spaced profilers is required (Pielke et al 1989). Fortunately, the resulting quasi-stationary mesoscale circulations are shallow and require only relatively inexpensive lower tropospheric profilers to observe them. The use of data assimilation within a mesoscale model, to integrate the measurements into a cohesive and dynamically consistent 4-D data set, will require more development before the full operational potential of profilers can be realized.

5. Sferics observing networks

There are two main categories of system designed to detect lightning strokes over a large area.

- Systems using direction finders. Individual direction finders use two orthogonal loop aerials to resolve the direction of arrival of the sferics. Usually a regional network of three or more of these is used to locate lightning flashes by finding the intersection points of the directions. The only technically mature and commercially available system is the LLP direction finder (Maier et al 1984). The nominal range of 400 km dictates a spacing of 150 to 250 km between each site in a network. The present LLP model, called ALDF, is able to reject signals other than those originating from the cloud-to-ground flashes that are the primary concern to many end users.

- Systems using time-of-arrival receivers. Individual receivers measure the time of arrival of sferics signals. Because the time of occurrence of the lightning is not known, the time measurement is only relative and locating the source requires the determination of differences in arrival time at several sites. Two types of arrival-time systems are in operational use: the LPATS (Lightning Position and Tracking System) and the ATD (Arrival Time Difference) system. LPATS is a technically mature, commercial system (Bent and Lyons 1984) for use as a regional network with receivers separated by distances of 150 to 250 km. The ATD system, used operationally by the UK Meteorological Office for the last 3 years, employs 7 detectors separated by distances from 300 to over 3000 km to provide wide-area lightning location over Europe and the eastern Atlantic (Lee 1989).

Comparisons of the regional LLP and LPATS networks suggest that they offer broadly similar performance and are both technically straightforward to maintain (WMO 1993). Positional errors vary between 1 and 10 km. Detection efficiency is up to 80% or more according to circumstances. Positional errors for the long-range ATD system are similar, varying from 1-2 km over the UK and 2-5 km in Europe to 5-10 km over the eastern Atlantic; however, the detection efficiency of the present UK system is rather low. Higher detection efficiency over UK and continental Europe can be achieved by upgrading the ATD system or by complementing it with one of the regional systems described above. A VHF system in France, known as SAFIR, already combines direction finding and time-of-arrival techniques to achieve both high positional accuracy and high detection efficiency but the range over which the high performance is achieved is limited to 150 km (WMO 1993).

Sferics observations are of value in their own right to end users concerned about possible lightning strikes to forests, aircraft, power cables, etc (Holle et al 1990). They are also a valuable nowcasting tool for forecasters for pinpointing areas of thundery activity, especially over data-sparse regions such as oceans where they can provide important clues as to the instability of air masses and the location and movement of convectively active fronts, squall lines, etc. Fig 5.1 shows an example of sferics observations pinpointing the centre of a rapidly developing cyclone in the north Atlantic.

6. Developments in some in situ observing systems

Although the greatest opportunities for improved observing systems will arise from the application of remote sensing techniques, important limitations to what can be achieved by these means will remain well into the next century. In the weather forecasting context there will continue to be serious inadequacies in the measurement of winds and humidity. Possible remedies, in the form of space-borne lidars (and radars) for global wind sounding in clear (and cloudy) air, and differential absorption lidars (DIAL) for high-resolution humidity soundings, are still a long way off. Neither is there any immediate prospect of accurate space-borne measurements of surface pressure over remote ocean areas. There will in any case be a continuing long-term requirement for some in situ upper air soundings to serve as a standard. There will, therefore, continue to be a need for developments under the auspices of WMO of several kinds of in situ observing systems (Rannaleet 1991). Three of these are as follows:

Observations from aircraft. Manually prepared aircraft reports (AIREPs) have long constituted a limited but cost-effective source of observations at jet stream level. The winds are an especially valuable input to NWP models. Major improvements in the coverage will be brought about via the AMDAR (Aircraft Meteorological Data Reporting) system. AMDAR will include systems on wide bodied commercial aircraft that relay data either via satellite (ASDAR) or directly to ground over land areas (ACARS). The future AMDAR system is expected to include automated meteorological data reporting via commercial satellites (SATCOMs). The bulk of the data will be single-level data but, in data-sparse land areas such as Africa and South America, observations obtained during ascent/descent could be of great value.

Automated Shipboard Aerological Programme (ASAP). This programme has developed balloon-borne sounding systems for use on commercial ships. ASAP units are in use in the North Atlantic where they constitute an upper-air sounding system of a quality comparable to other operational systems.

They are a cost-effective alternative to the dwindling number of Ocean Weather Ships, although there are difficulties in achieving an optimal geographical distribution.

Drifting buoys. A new generation of low-cost drifting buoys shortly to come into operation will provide improved coverage of sea-level air pressure observations in data-sparse areas of the North Atlantic. These are required to compensate for the decrease in the number of Voluntary Observing Ship (VOS) observations which in any case are often of poor quality and timeliness.

7. Combining data from different sources

Huge amounts of data are generated by the observing systems described above. The assimilation systems associated with operational NWP models provide the means for integrating them in the context of numerical prediction. Procedures are well established for the assimilation of primary variables such as temperature and wind and, as noted earlier, improved procedures are becoming available for assimilating directly the more complex parameters actually measured by new observing systems, such as cloud, precipitation, radial velocity, radiance etc. However, there remains the task of combining and displaying data from these multiple data sets for the bench forecaster to use in deriving a variety of nowcast products. Although there is still a tendency to display single sensor observations in some forecast offices, a wide range of systems are under development in which data from different combinations of sensors are blended to suit particular requirements. Some examples are:

Radar and satellite imagery Two long-established systems for combining radar and satellite imagery in the nowcasting of rainfall patterns are FRONTIERS (Browning 1979, Conway and Browning 1988) in the UK and RAINSAT (Austin and Bellon 1982, King et al 1989) in Canada. A system based on RAINSAT, called SIRAM, has also been implemented in Spain (Nevado 1990). These systems combine visible and infrared imagery from geostationary satellite with data from networks of radars and produce very-short-range forecasts by extrapolation. A system for producing a composite display from geostationary satellite imagery and radars from many countries has been developed in Europe under the aegis of COST-73 (Fig 7.1).

Sferics and Radar or Satellite Imagery Techniques have been developed for merging radar imagery (Goodman 1991) or satellite imagery (Goodman et al 1988) with sferics data to produce a convective tendency image for the very-short-range forecasting of thunderstorm development. Although it is useful to highlight areas of rising storm tops in the satellite imagery (De Leonibus and Pagano 1992), not all developing storms are detectable above cirrus debris and so the addition of sferics is worthwhile.

Multiple data sources The Swedish Meteorological and Hydrological Institute has developed a pilot workstation for very-short-range forecasting called PROMIS 600 (Nilsson and Brunsberg 1990). This is an interactive system that processes, combines and displays data from satellites, radars, sferics and automatic weather stations. The system employs several forecasting techniques including specialized numerical models although it does not use a full 3-D NWP model. The US National Weather Service has developed the Advanced Weather Interactive Processing System (AWIPS) to handle the multiplicity of new data sources required for improved very-short-range forecasting. AWIPS, regarded as the linchpin of the NWS's 10-year modernization programme, will handle all of the data sources described in this review plus gridded data and contour data generated from operational NWP models. An important aspect of the design of both AWIPS and PROMIS is in the way they interface with the human forecasters.

8. The human forecaster within the total forecast system

The observing and forecasting systems described above form part of the total system depicted in Fig 8.1. Most parts of this system are already automated. Eventually all stages will be automated except for a few of the most critical interpretive and judgemental tasks. The reasons for automation are compelling (Conway 1992):

- cost — Capital costs of automated systems may be high but their running costs are small compared with manned systems.
- speed — Only if there is substantial automation can the forecaster keep pace (a) with the growing torrent of information from the new systems described above and (b) with the need to provide timely predictions of short-lived weather phenomena.
- production of tailored local forecasts. There is increasing demand for forecast products tailored to the needs of individual users. The needs of large numbers of different users can be met only by means of products automatically tailored to predefined requirements.
- repeatability. Objective (automated) forecasts are repeatable and provide the ability to run through series of archived cases to produce improved algorithms.

Automation is, however, not a panacea; there is still a role for the human forecaster even in tomorrow's forecasting system. As real weather events develop, particularly severe weather such as thunderstorms, their timing and location is governed by processes on increasingly small scales about which meteorological knowledge (and the data to which the knowledge can be applied) tends to be sparse. In this sense, it becomes more difficult to forecast imminent weather events than to delineate broad regions within which the small-scale events may eventually occur (Doswell 1986). Automated forecasts, especially those based on NWP, cope well with the broad delineation of areas of threat; however, it is difficult to be as sanguine about the capability of automated methods to cope satisfactorily with specific local events. This is where the qualitative judgement of the forecaster is required, to select between different guidance products and to quality control and amend analyses and very-short-range forecasts in the light of up-to-date observations and an understanding of what is going on meteorologically. Some of the interpretive and decision-making functions will eventually be taken over by Artificial Intelligence (eg Expert Systems) - see Conway (1992) for a brief review - but many can continue to benefit from the application of human judgement, at least in principle.

The extent to which the human forecaster can in practice continue to 'add value' as NWP products continue to improve is an open question. There are both threats and opportunities regarding the future role of the forecaster. The threat is that the forecaster will rely increasingly on the automated technology, will stop doing his own analyses and will therefore lose his meteorological skills, thereby making him less able to add value to forecasts and strengthening the case for more automation (Snellman 1977). The opportunity is that observational and forecasting systems of the kinds described in this paper will become good enough to enable the forecaster to understand what is going on on the mesoscale even though the forecast guidance will still be far from perfect particularly in severe storm situations. The ability of the forecaster to gain sufficient understanding of the evolving weather situation and to use it to improve upon the automated guidance depends on the availability of a new generation of very advanced interactive computer systems.

The interactive computer system required by the forecaster, according to Bullock and Heckman (1986), Bosart (1989) and Doswell (1992), should, amongst other things, be able to:

- display plotted observational data (including space-to-time conversion of continuously recorded data) and diagnostic fields (eg potential vorticity or moisture flux divergence) superimposed on conventional NWP analyses/forecasts and imagery products,
- store conceptual models which the forecaster can call up and compare with the current situation,
- allow the forecaster to accept or discard the automated products and to modify them quickly in the case of unforseen meteorological developments.

In system terms the key features of the interactive computer system, as described by Bullock and Walts (1991) are

- performance (speed is critical in severe weather conditions),
- the user-interface (this must be flexible, user-friendly and maintainable in the face of change in the products to be displayed),
- reliability (99.99% reliability is required for the generation of severe weather warnings).

Further detailed recommendations regarding ergonomic design are given by Hoffman (1991). Given such a system, fed with information from the new observing and forecasting systems described in this paper, the forecaster of the future should be able to function more effectively than at present. He should devote more of his time to meteorology and shift his emphasis from meeting product deadlines to maintaining an accurate depiction of current and forecast weather. Once the necessary meteorological fields have been determined by the forecaster, the system itself should be able automatically to generate and distribute a multitude of pre-determined products to customers.

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Table legends

Table 2.1	Potential products from the European operational meteorological satellite, 'Metop 1' to be launched in 2000.
Table 2.2	Potential products from the multispectral image data on MSG (METEOSAT Second Generation), to be launched in 2000.
Table 3.1	Estimate of the percentage reduction in error and directly related cost for seven different techniques for improving the accuracy of radar for hydrological applications (ie direct costs exclude cost of the satellite when combining satellite measurements with radar). The improvements are estimated as a reduction in the variance of daily amounts of Log (radar/gauge) assuming that today's non-Doppler (without adjustments) has a variance of 100%. The estimates refer to average improvement over the whole year and area, assuming flat country. (After Joss and Waldvogel 1990).
Table 4.1	Requirements of three types of high resolution models for wind data from profilers (From James et al 1991).

Figure legends

Fig 2.1	Worldwide system of geostationary meteorological satellites. The data from INSAT are not readily available: this satellite is located in place of GOMS, a satellite that was planned by the former USSR but has not yet been launched.
Fig 2.2	Results of pre-operational trials at the European Centre for Medium-range Weather Forecasting of a new scheme using variational assimilation of TOVS radiance data. The ordinate is a measure of forecast quality. The curves show the decay in forecast quality with time in the Northern Hemisphere with (solid curve) and without (dashed curve) the new scheme. (From Eyre et al 1993).
Fig 2.3	Distribution of vertically integrated water vapour (IWV) (kg m^{-2}) associated with a southern hemisphere frontal system, as obtained from the Scanning Multichannel Microwave Radiometer on Nimbus-7. The narrow strip of high IWV along the cold front is associated with a warm conveyor belt. (From Katsaros et al 1989).
Fig 2.4	(a) METEOSAT infra red image and (b) ECMWF 18-hour forecast 300 mb pattern of positive vorticity advection (in units of 10^{-9} s^{-2}) for the same time. (From Zwatz-Meise and Mahringer 1990).
Fig 3.1	Growth with time of the cumulative totals of operational digital weather radars in Western Europe. (From Newsome 1992).

Table 2.1: Possible products derived from planned EUMETSAT Polar Systems

Product	Area	Accuracy				Resolution (km)				Application
						Horizontal		Vertical (at different heights)		
		Target	Reported	Likely w/IASI	Likely w/o IASI	Target	Likely	Target	Likely	
Temperature Profiles and thickness charts	Regional	Troposph. 0.5-1 °C	1.7 °C	< 1 °C	1.5 °C	25	25	0-8 km:1 8-15 km:2 15-30 km:3	0-8 km:1 8-15 km:2 15-30 km:3	NWP (w/forecast initial guess)
	Global	Stratosph. 1-2 °C	2 °C	1-1.5 °C	2 °C	50-100				
	Regional	Troposph. 0.5-1 °C	1.7 °C	1-1.5 °C	1.7 °C	25	25	0-8 km:1 8-15 km:2 15-30 km:3	0-8 km:1 8-15 km:2 15-30 km:3	Regional and Nowcasting (w/o forecast initial guess)
		Stratosph. 1-2 °C	2 °C	< 2 °C	2 °C					
Wind vectors from - cloud imagery - water vap. imagery - ozone imagery	Polar Caps	5 ms^{-1}	6 ms^{-1}	-	-	100	50	-	-	NWP
Cloud Cover	Global	10% & ± 2°C tops	10%	-	-	100	50	-	-	NWP,Aviation, and Climatology
Relative Humidity Profiles	Regional	10%	5-10%	5-10%	5-10%	25	15	0-8 km:1 8-15 km:2 15-30 km:3	0-8 km:1 8-15 km:2 15-30 km:3	NWP (w/forecast initial guess)
	Global	10%	10%	< 10%	10%	50-100	50-100	0-8 km:1 8-15 km:2 15-30 km:3		NWP (w/o forecast initial guess)
	Regional	10%	10%	< 10%	10%	25	25			Regional and Nowcasting (w/o forecast initial guess)
Sea Surface Temperature	Global	0.5 °C	0.4-0.7 °C	0.3-0.5 °C	0.3-0.7 °C	25	-	-	-	NWP
	Global	0.3 °C	0.4-0.7 °C	0.3-0.5 °C	0.4-0.7 °C	100	-	-	-	Climatology
Water Content Products - Total precipitable water - Layer precip.water - Cloud Water Content - Cloud Ice Content	Global	0.01-0.02 mm	3 mm	?	3 mm	25-100	25-100	-	-	Climatology
	Global	0.01-0.02 mm	0.04 mm	-	0.04 mm	100	25-100	-	-	Climatology
Land Surface Temperature	Regional	1-2 °C	4 °C	-	2 °C	10	1.1	-	-	Agriculture, Nowcasting
	Global	1-2 °C	4 °C	1-2 °C	2 °C	50	25	-	-	NWP
		0.5 °C	4 °C	0.5 °C	2 °C	100	100	-	-	Climatology
Vegetation (land surface properties)	Regional	-	-	-	-	1	1.1	-	-	Agriculture
		-	-	-	-	10	1.1	-	-	Nowcasting
	Global	-	-	-	-	50	1.1	-	-	NWP
		-	-	-	-	100	1.1	-	-	Climatology
Precipitation	Regional	15-25%	10-20%	-	10-20%	10	50	-	-	Nowcasting Hydrology
	Global	15-25%	10-20%	-	10-20%	50	50	-	-	Agriculture
		10%	10%	-	10%	100	100	-	-	NWP & Climatology
Ozone Total	Global	2-3%	2-4%	2-3%	2-4%	25	25	3	3	Climatology
Ozone Profile	Global	10%	2-3%	2-3%	-	25	25	3	3	Climatology

PRODUCTS	Accuracy	Horizontal resolution (km)	Application	Product group
Cloud Type		1	Nowcasting	Cloud, fog, snow and radiation products
Cloud Cover	10%	1 100 100	Nowcasting NWP Climatology	
Cloud top height	500 m	0.5 to 1	Nowcasting	
Cloud top temperature	1°C 2°C	0.5 to 1 100	Nowcasting NWP	
Fog cover	20 m & 1°C	0.5 to 1	Nowcasting	
Snow cover	≤ 3%	10 50 100	Nowcasting NWP Climatology	
Albedo	≤ 3%	10 50 250	Agriculture NWP Climatology	
Radiation data (budget components, fluxes)	5 W m^{-2}	250	NWP Climatology	
Sea Surface temperature	0.8°C 0.5°C	1 to 10 25 100	Nowcasting NWP Climatology	Air mass and temperature products
Land Surface temperature	≤ 2°C	10 50 100	Nowcasting NWP Climatology	
Aerosols	≤ 3%	50 250	NWP Climatology	
Upper tropospheric humidity	10%	25 100	NWP Climatology	
Precipitable water	≤ 0.02 mm	25 to 100 100	NWP Climatology	
Layer mean temperature	0.5 to 1°C	25 50 to 100	Nowcasting NWP	
Stability index		1 to 10	Nowcasting	
Total ozone	2 to 3%	25 250	NWP Climatology	
Tropopause height	1 km	10 50	Nowcasting NWP	
Wind vectors from: - cloud imagery - water vap.imagery - ozone imagery	5 ms^{-1}	100	NWP	Wind products

Table 2.2: Potential products for extraction from the multispectral data from METEOSAT Second Generation

Means	Percentage of Reduction		Percentage of Cost
	Close (<30 km)	Far (<200 km)	
1. Raingauge adjustment	30	20	5
2. Vertical profile	20	50	5
3. Doppler radar	10	20	30
4. Measurement from space	5	20	3
5. Drop-size distribution	25	10	3
6. Polarization diversity	15	5	30
7. Multiwavelength radar	10	2	50
8. Combination (lines 1, 2, 3, 4 above)	50	70	43

Table 3.1

Table 4.1

Model type	Height range	Horizontal resolution	Vertical resolution	Temporal averaging	Temporal sampling
Fine mesh	surface-tropopause	100 km	150 m	10 min	3 h
Air pollution	surface-5km	10 km	50 m	30 min	30 min
Boundary layer	surface-2km	local	10 m	10 sec	continuous

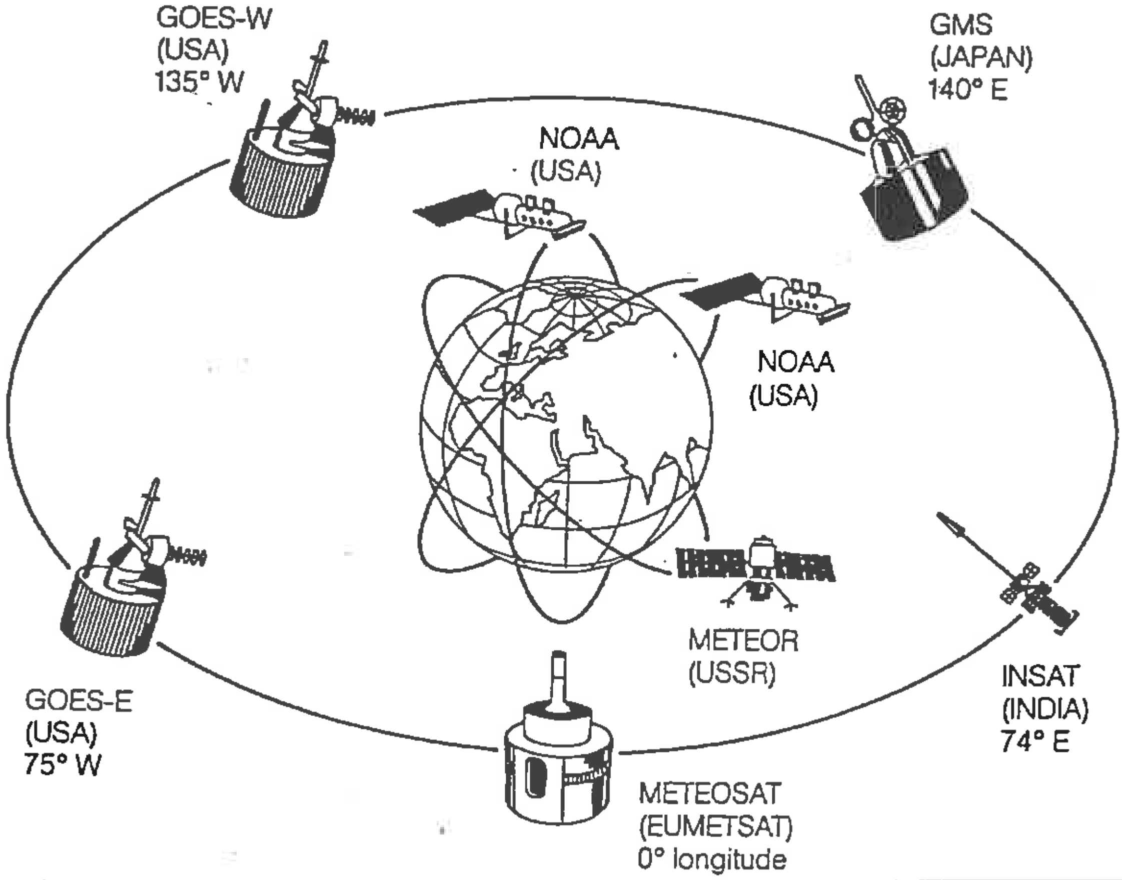

GOES-W
(USA)
135° W
GMS
(JAPAN)
140° E
NOAA
(USA)
NOAA
(USA)
METEOR
(USSR)
INSAT
(INDIA)
74° E
GOES-E
(USA)
75° W
METEOSAT
(EUMETSAT)
0° longitude

Fig. 2.1

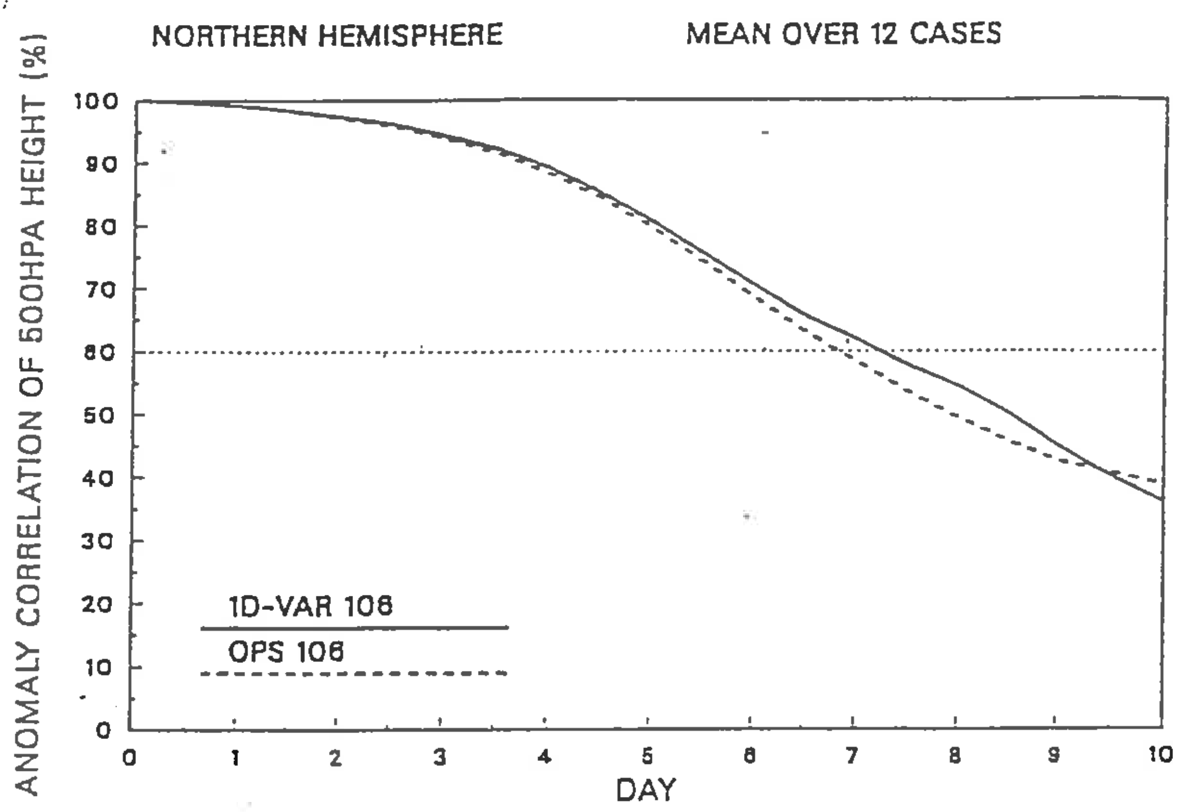

NORTHERN HEMISPHERE
MEAN OVER 12 CASES
ANOMALY CORRELATION OF 500HPA HEIGHT (%)
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
DAY
1D-VAR 106
OPS 106

Fig 2.2

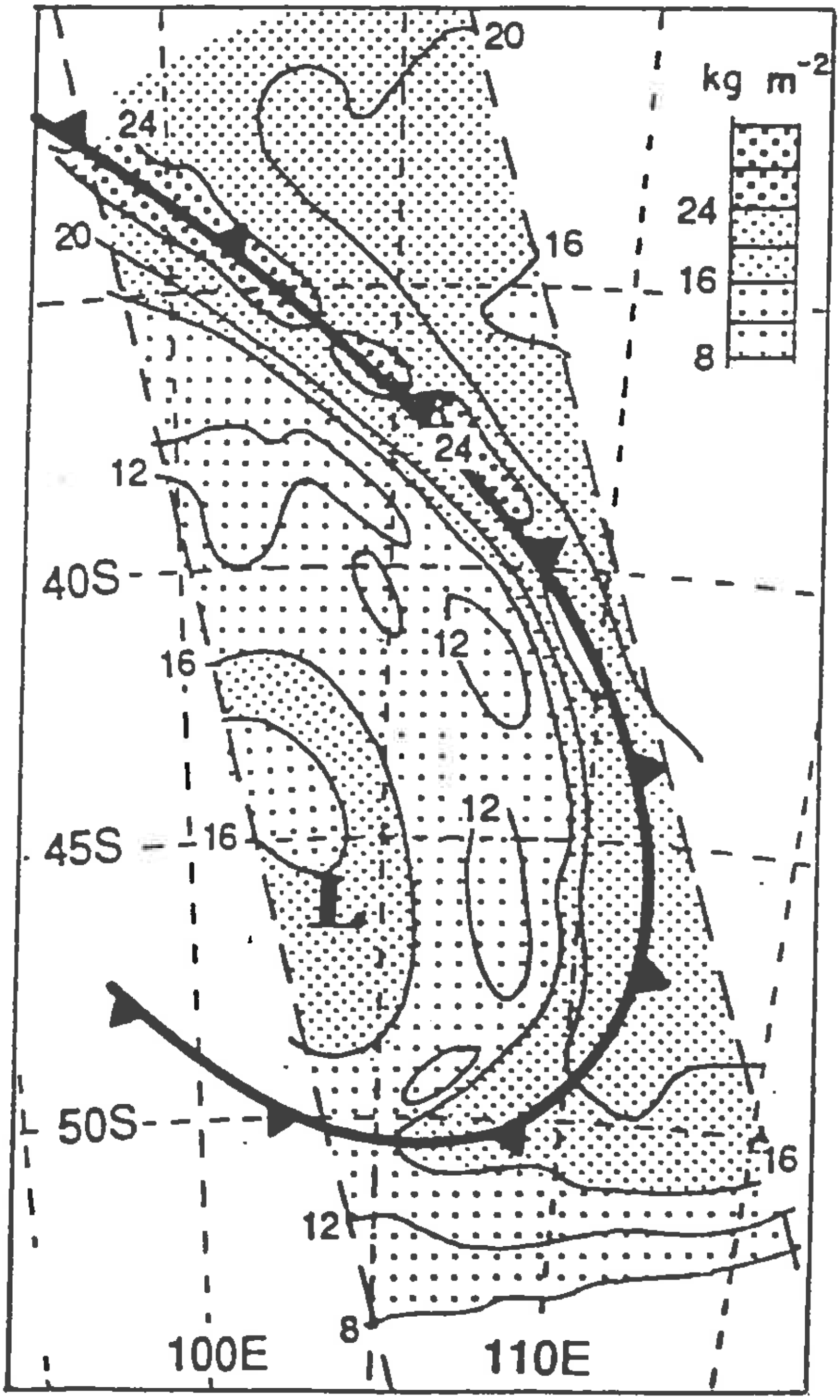
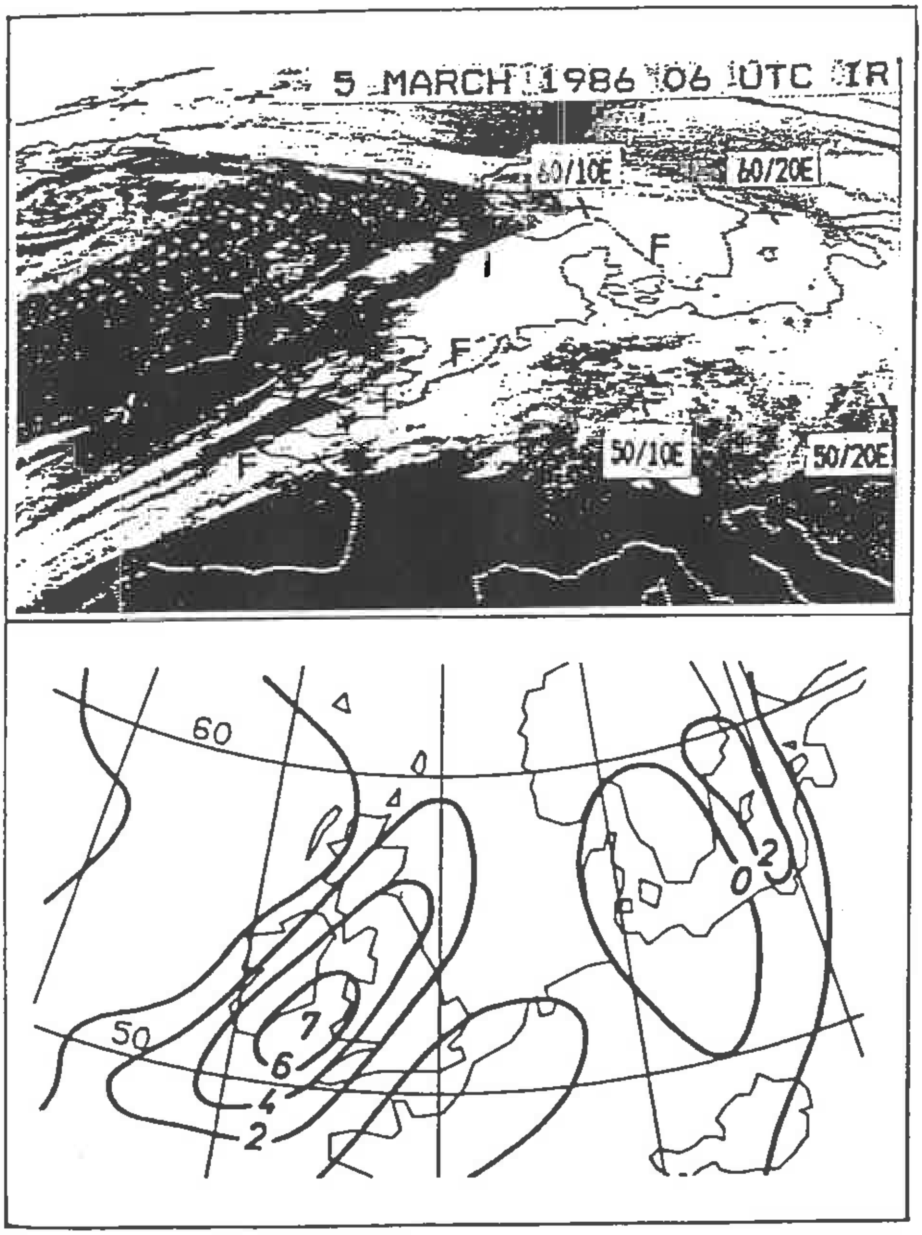
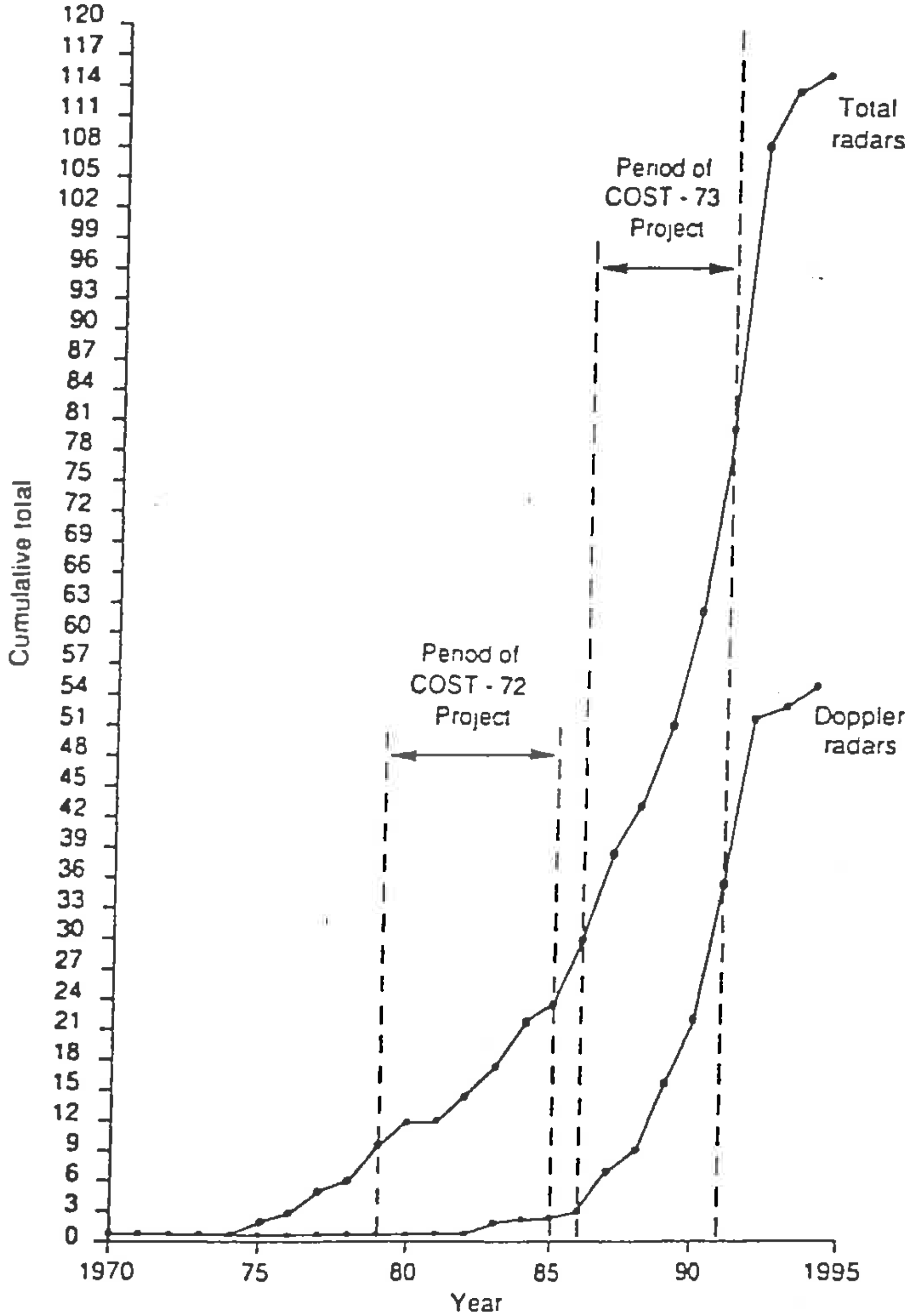

20
kg m^{-2}
24
16
8
24
20
16
24
12
40S
12
16
12
45S
16
L
50S
16
12
8
100E
110E

Fig. 2.3



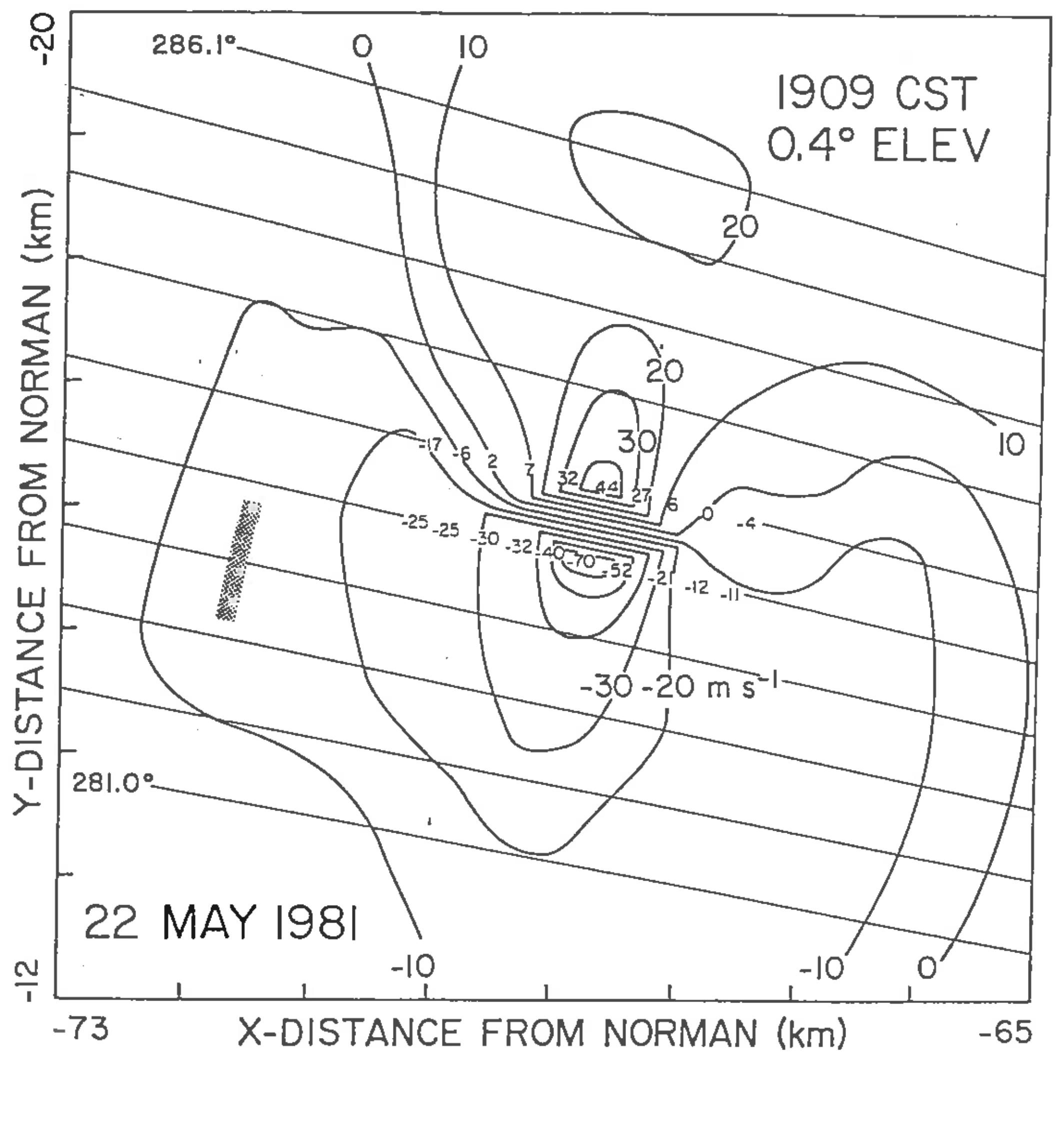
5 MARCH 1986 06 UTC IR
60/10E
60/20E
50/10E
50/20E
F
F
F
60
50
7
6
4
2
0
2

Fig 2.4



Cumulative total
120
117
114
111
108
105
102
99
96
93
90
87
84
81
78
75
72
69
66
63
60
57
54
51
48
45
42
39
36
33
30
27
24
21
18
15
12
9
6
3
0
1970
75
80
85
90
1995
Year
Period of COST - 72 Project
Period of COST - 73 Project
Total radars
Doppler radars

Fig 3.1



286.1°
0
10
1909 CST
0.4° ELEV
20
20
30
10
-17
-6
2
7
32
44
27
6
0
-4
-25
-25
-30
-32
-40
-70
-52
-21
-12
-11
-30 -20 m s-1
281.0°
22 MAY 1981
-10
-10
0
-20
-12
Y-DISTANCE FROM NORMAN (km)
-73
X-DISTANCE FROM NORMAN (km)
-65

Fig 3.2

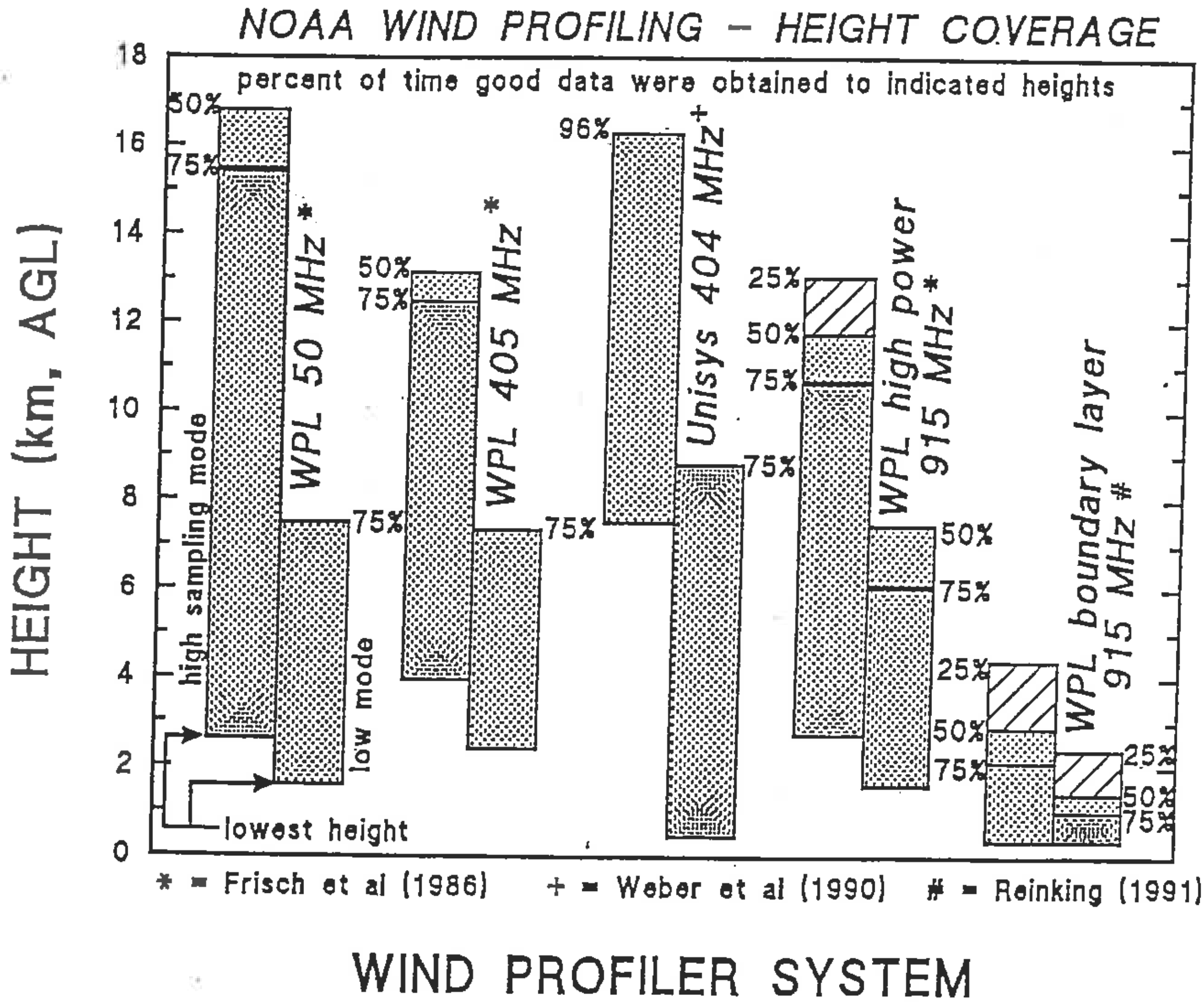

NOAA WIND PROFILING – HEIGHT COVERAGE
percent of time good data were obtained to indicated heights
HEIGHT (km, AGL)
0
2
4
6
8
10
12
14
16
18
50%
75%
high sampling mode
low mode
lowest height
WPL 50 MHz *
75%
50%
75%
WPL 405 MHz *
75%
96%
Unisys 404 MHz +
75%
25%
50%
75%
WPL high power 915 MHz *
50%
75%
25%
50%
75%
WPL boundary layer 915 MHz #
25%
50%
75%
* = Frisch et al (1986)
+ = Weber et al (1990)
# = Reinking (1991)
WIND PROFILER SYSTEM

Fig. 4.1

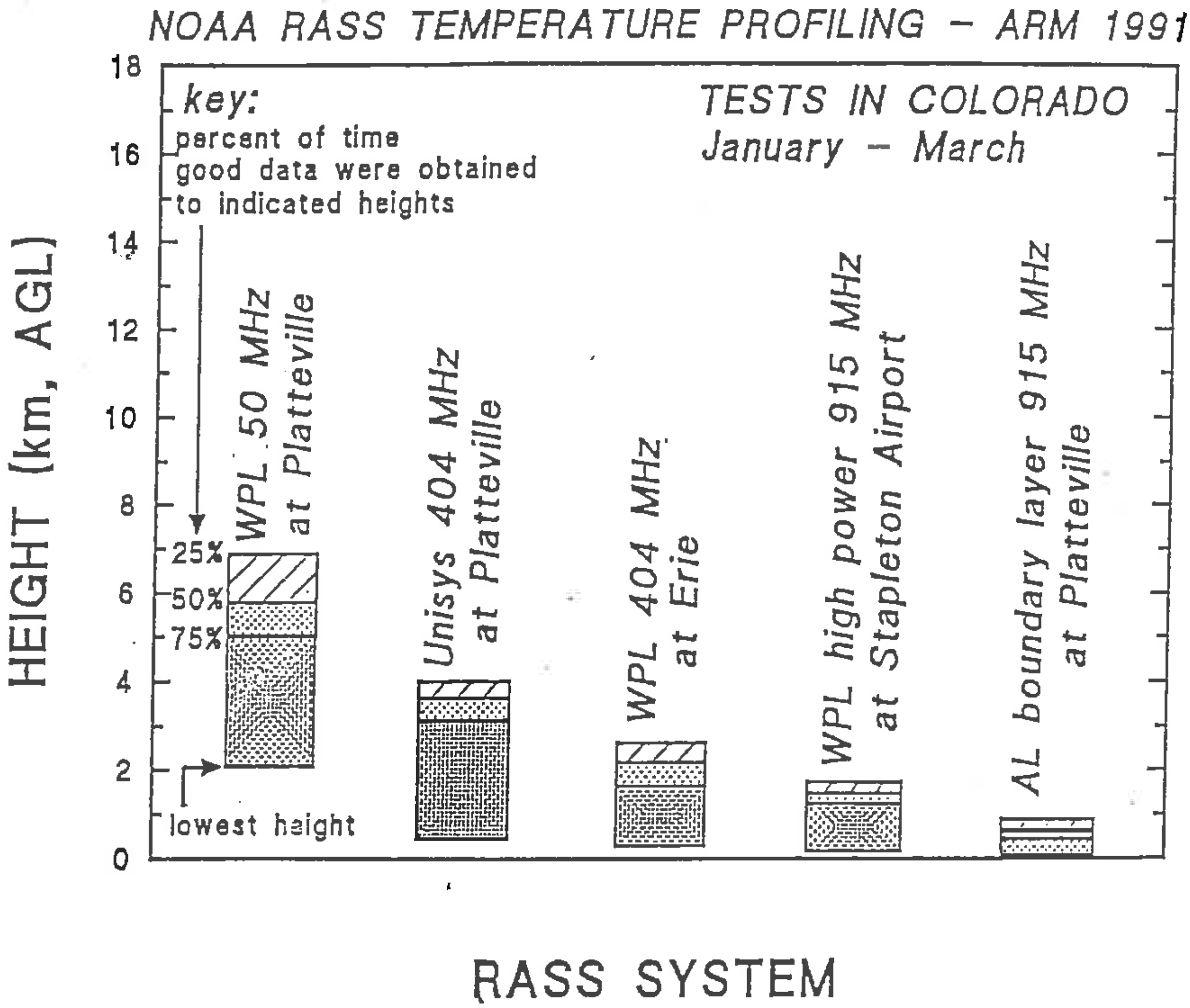

NOAA RASS TEMPERATURE PROFILING - ARM 1991
key:
percent of time good data were obtained to indicated heights
TESTS IN COLORADO
January - March
HEIGHT (km, AGL)
18
16
14
12
10
8
6
4
2
0
25%
50%
75%
lowest height
WPL 50 MHz at Platteville
Unisys 404 MHz at Platteville
WPL 404 MHz at Erie
WPL high power 915 MHz at Stapleton Airport
AL boundary layer 915 MHz at Platteville
RASS SYSTEM

Fig. 4.2

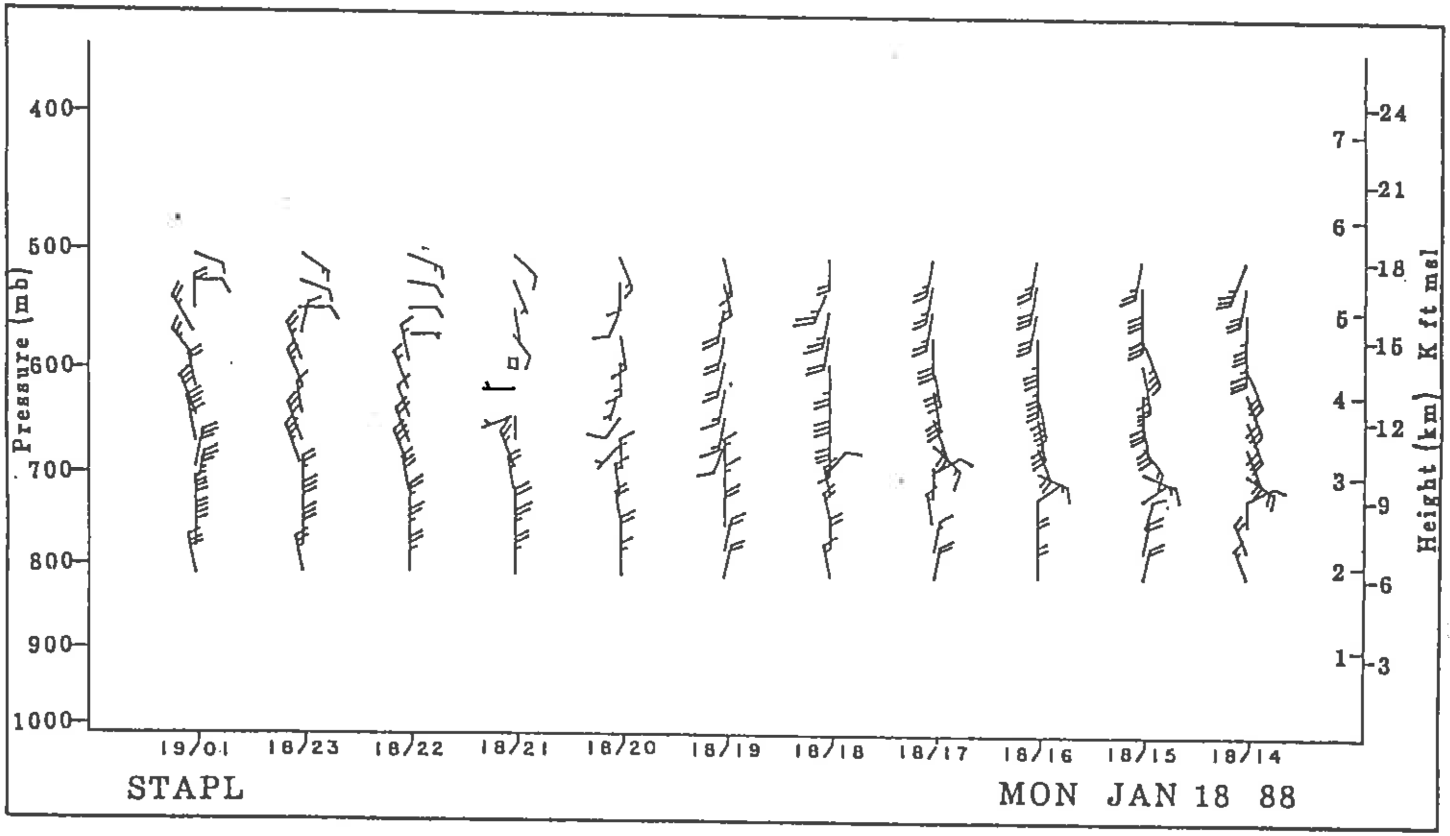

Pressure (mb)
400
500
600
700
800
900
1000
Height (km) K ft msl
7
6
5
4
3
2
1
24
21
18
15
12
9
6
3
19/01
18/23
18/22
18/21
18/20
18/19
18/18
18/17
18/16
18/15
18/14
STAPL
MON JAN 18 88

Fig 4.3

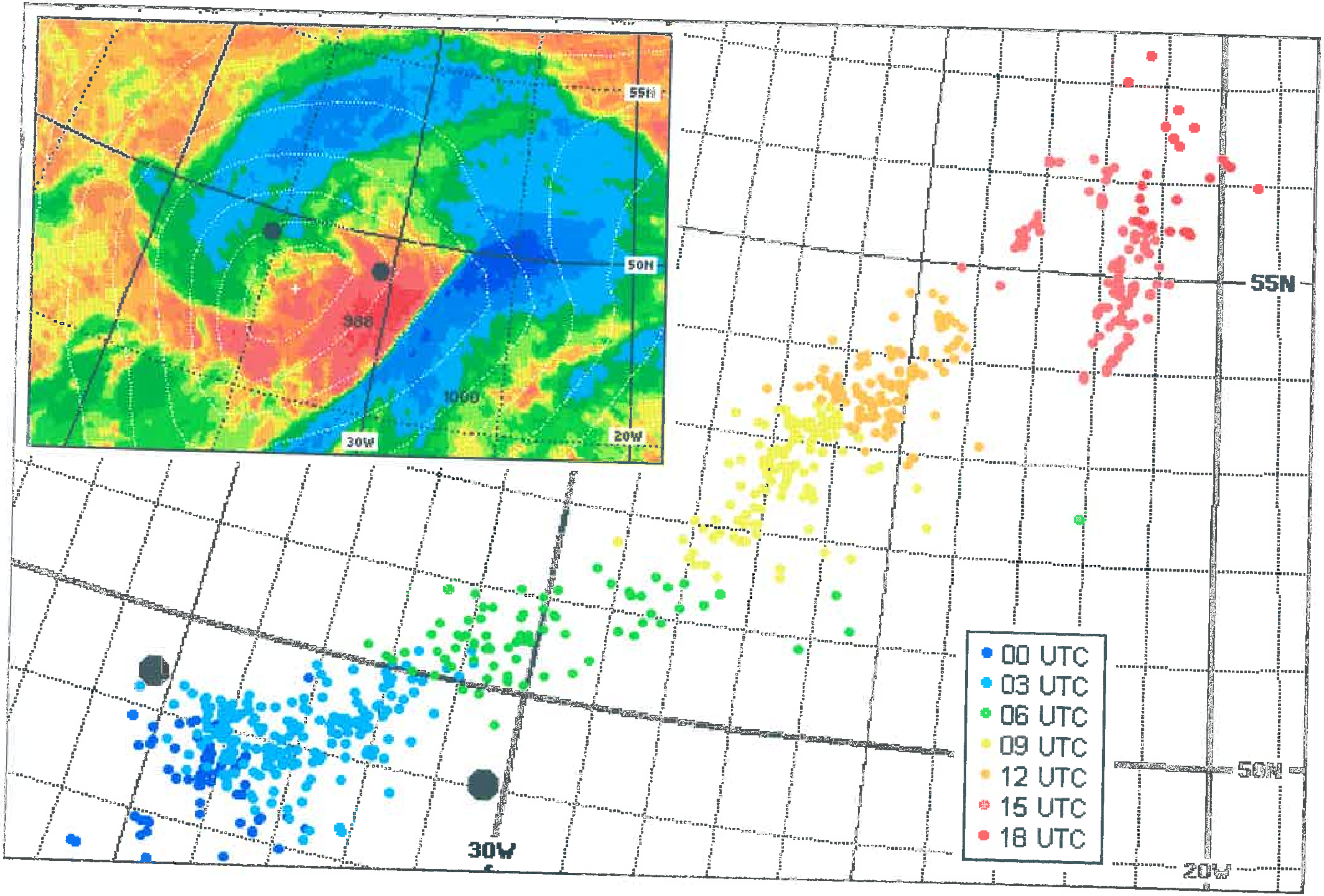

55N
50N
30W
20W
988
1000
55N
50N
30W
20W
00 UTC
03 UTC
06 UTC
09 UTC
12 UTC
15 UTC
18 UTC

Fig 5.1

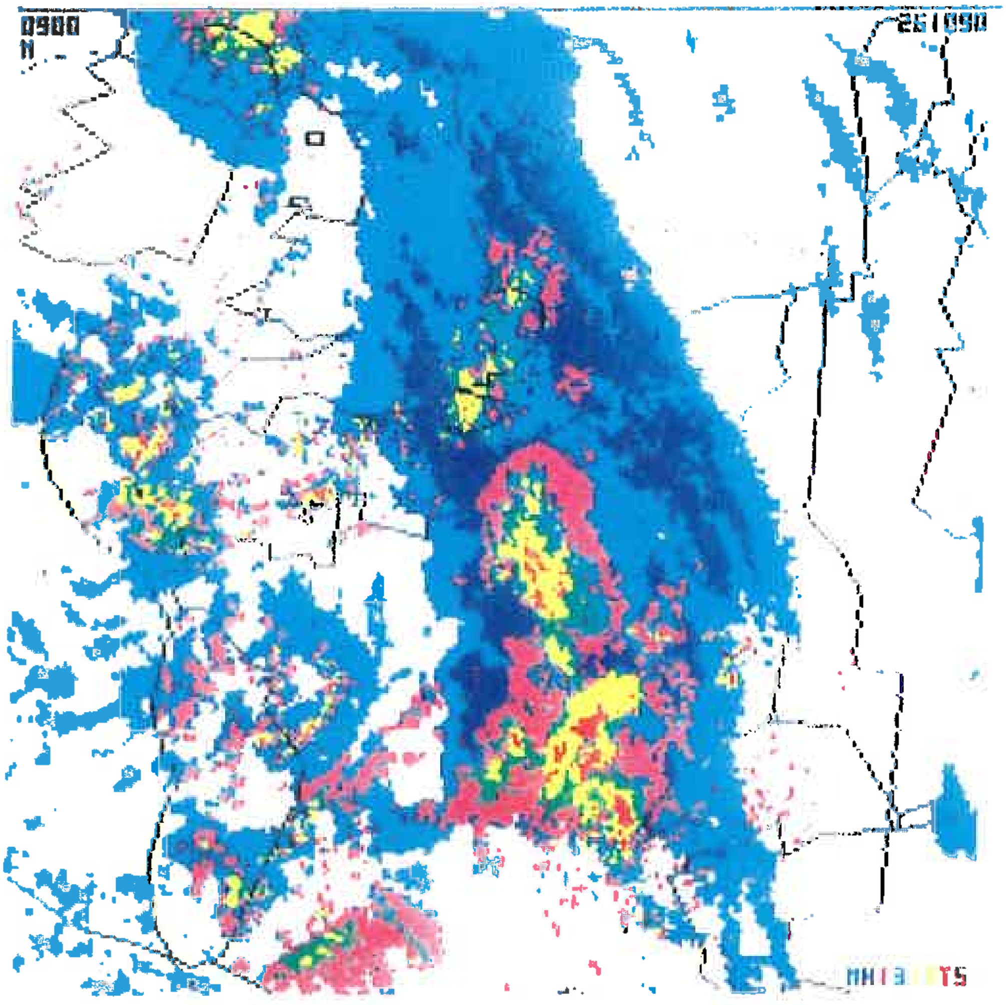
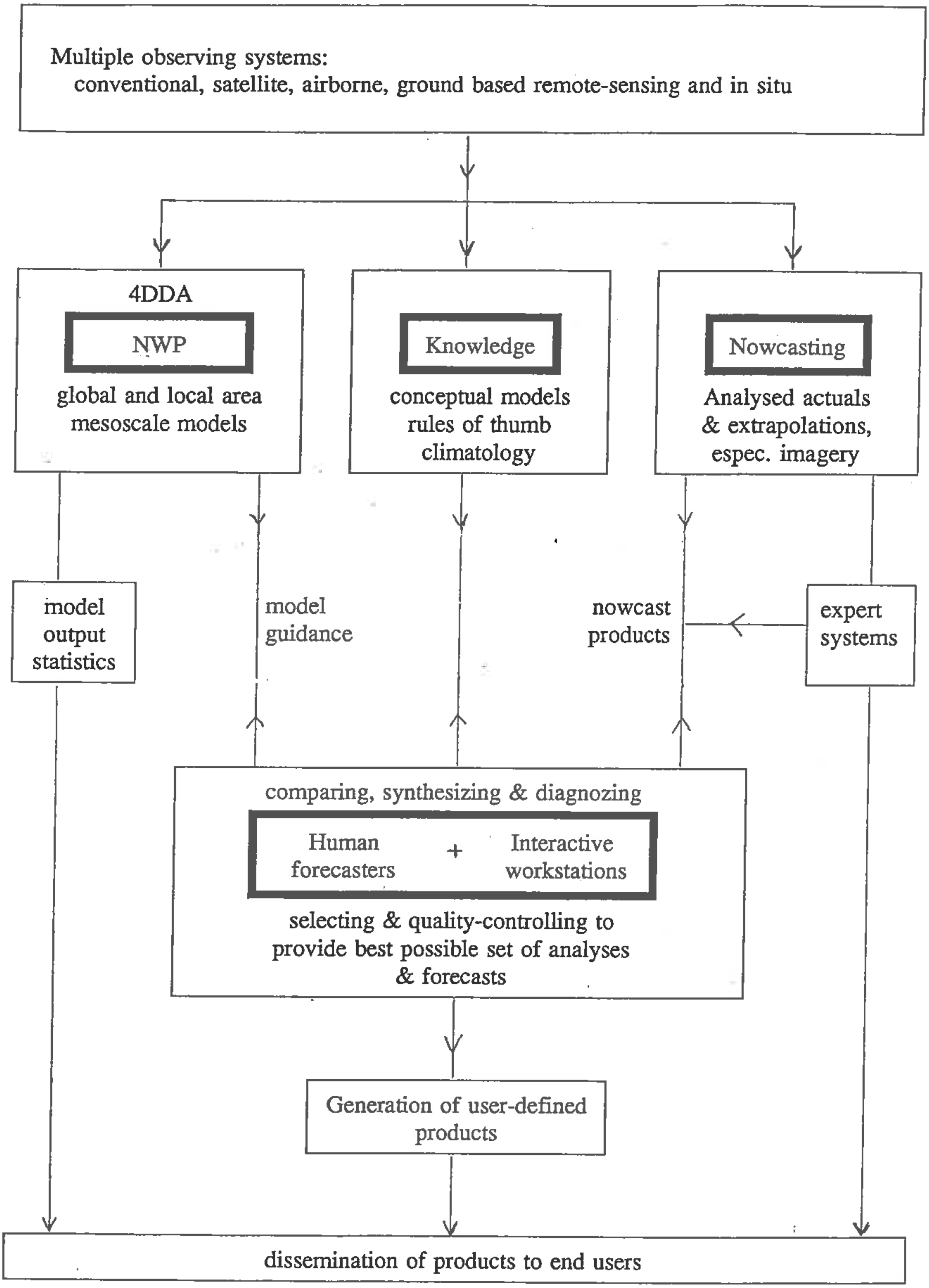


Fig 7.1

Fig 8.1 Total system for observing and forecasting



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