INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

SMR/534-1

ICTP/WMO WORKSHOP ON EXTRA-TROPICAL AND TROPICAL LIMITED AREA MODELLING
22 October - 3 November 1990

"Meteorological data: Kind, distribution, accuracy and representativeness"

by K. Arpe

Presented by:
Prof. S. TIBALDI
Institute of Physics
Univ. of Bologna
Bologna, Italy

Please note: These are preliminary notes intended for internal distribution only.

European Centre
for Medium Range Weather Forecasts

LECTURE NOTE

METEOROLOGICAL TRAINING COURSE

Lecture Note No. 2.1

METEOROLOGICAL DATA: KIND,DISTRIBUTION, ACCURACY AND REPRESENTATIVENESS

by

K. Arpe

Acknowledgement

This note makes use of a lecture note by L. Bengtsson (1976) and of other papers which are referenced in the text.

February 1985

METEOROLOGICAL TRAINING COURSE

Lecture Note No. 2.1

METEOROLOGICAL DATA: KIND, DISTRIBUTION,
ACCURACY AND REPRESENTATIVENESS

by

K. Arpe

Acknowledgement

This note makes use of a lecture note by Bengtsson(1976) and other papers which are referenced in the text.

CONTENTS

PAGE

1. INTRODUCTION

To make weather forecasts one first has to define the initial state of the atmosphere. After that, the further development of the atmospheric circulation can be simulated by a numerical model. The analysis methods and the forecasting model are described elsewhere in the lecture notes. Problems for analysing the atmospheric state arise from limitations in the availability, accuracy and representativeness of observational data. This lecture note will describe the observational data, their density, geographical distribution, representativeness and the reliability of their reception. In this it will closely follow the article by Bengtsson (1976). A more detailed and updated overview of satellite data is given by Johnson (1985).

In Section 2 we will investigate the requirement of observational data for analysing meteorological fields for numerical weather forecasts. How far these requirements are met by conventional data, i.e. TEMPS, SHIPS, etc., will be shown in Section 3. The possibility of replacing or supplementing these data by satellite data is discussed in Section 4, and in Section 5 some consideration will be given to future developments. For operational use one needs also to discuss the time allowed for collecting the data and the area to be used for the forecasts, which is dealt with in Section 6. Finally, in Section 7 we shall investigate in more detail how the observations can represent small scale meteorological features and how they are resolved in the analyses.

2. REQUIREMENTS FOR ANALYSING METEOROLOGICAL FIELDS

The observational meteorological network, which is now called the World Weather Watch (WWW), has been built up gradually during the last 200 years. However, the aerological observing network was developed mainly during and just after World War II. This network is very incoherent with widely varying density and quality. The reason is that the network has been constructed for such different purposes as local and regional weather watch, short-range forecasting, severe weather warning, aeronautical supervision, hydrological surveillance, as well as forecasting by use of dynamical models.

This network is now supplemented by an overwhelming variety of data from satellites, both in pictorial form as well as quantitative information. Also more recently, observational data from commercial aircrafts and automatic buoys have become important sources of information.

As these observing systems are quite expensive, we need to deal both with the question on what data are available and what data are really needed for numerical weather prediction. Answering this question was one of the main objectives of FGGE and research is still going on. Some results will be discussed in Section 5.

Here we want to try to answer the following questions:-

a) What are the most relevant variables to be observed?

b) What are the characteristic space and time scales of these variables?

c) How accurately do we need to measure and transmit then?

Unfortunately, these questions are not independent of each other, e.g. for analysing surface pressure meteorologists use a wider range of parameters (e.g. cloudiness and visibility) in data sparse areas than in data rich areas to achieve a wider horizontal and vertical extrapolation. Numerical data assimilation systems are restricted to the basic measurements such as temperature, wind, humidity and surface pressure. Even then the questions are not independent from each other because a highly accurate measurement, which is only valid for a scale that cannot be analysed by the analysis system, may be of little use.

2.1 Minimum scales

To get an idea of the minimum scales which should be resolved by the observational data, one has to take a look at a few weather maps. The following conclusions can be drawn:

a) The spatial scale of the main weather systems in the middle troposphere is rarely shorter than 1000 km.

b) Such systems develop in the order of 2 days and last mostly less than a week.

We may conclude from this very brief overall picture that a sampling density of 500 km in the horizontal domain and 12 hours in time is needed to be able to characterise the significant pattern of synoptic systems in the pressure, wind and temperature fields.

On weather maps we will find also smaller scale significant disturbances like fronts, cloud clusters and hurricanes, which would need a much higher sampling density. Most forecasting models, however, have horizontal resolutions of the order of 200 km or larger and are not able to retain and develop such features in the same way as the atmosphere, and it might be even detrimental to represent such features in the analyses. Some aspects of the problems concerning these smaller scales will be covered in Section 6.

To get a feeling for the required resolution in the vertical, we may consider a typical baroclinic wave. Fig. 1 shows the relative positions of troughs and ridges in the height and temperature fields at four levels. The temperature field is tilted slightly to the east with height and the height field is tilted westward. The degree of tilting is decisive for the future development of the baroclinic wave. To resolve this vertical structure, data with at least a 200 mb spacing are needed.

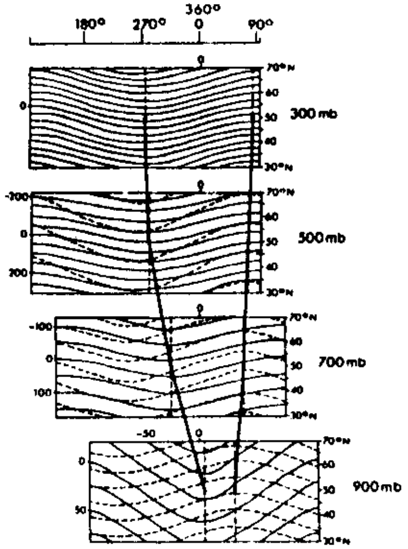


Fig. 1: Structure of a baroclinic wave at 4 pressure levels (from Defant, 1974). Dashed lines: temperature field. Solid lines: geopotential height field.

To resolve the boundary layer and the tropopause an even higher resolution is needed; however, at ECMWF these features are mainly governed by the first guess, which is generated by a forecast model.

Ideal measurements would be those which are representative for the time and space scale to be resolved in the analysis.

2.2 Relevant variables

The most relevant variables to be observed are those described by the equations used in the forecast model, i.e. temperature or height, horizontal wind components, humidity and surface pressure.

The horizontal wind components can be divided into divergent and rotational components, where the divergent component is diagnostically connected with the vertical wind component. To avoid or reduce spin-up effects in the forecasts it is important to have the right divergent wind in the initial data, especially in the tropics, but at present this is difficult to extract from observational data and in many analysis systems the divergent wind is generated by the model through the first guess. Attempts are underway to achieve true analyses of this component.

For a short period model generated humidity data was used at ECMWF by mistake. The reintroduction of analysed humidity did not give a significant change in the forecast quality. This could be due to several reasons, one could be that the present models are not sensitive to initial humidity data. It could also be that the present first guess in analysis system is either of good quality or that the observations are bad (which might be a problem of representativeness of humidity observations as discussed below), or that they are too sparse. We can draw the conclusion that for existing analysis-forecast schemes the humidity observations are not the most relevant observed data. When analysis-forecasting systems become more reliable, the humidity analysis might become more important, especially in connection with the analysis of divergent wind components as demonstrated by Krishnamurti et al. (1983).

The ECMWF forecasting system also uses analysed sea surface temperature, snow depth and soil moisture, which have an effect on simulations of the atmospheric circulation, but their immediate impact on medium range forecasts is difficult to prove.

2.3 Required accuracy

The ECMWF data assimilation system can cope with any accuracy of observational data as long as their accuracy is known and as long as the data have no systematic bias. In principle a large number of randomly inaccurate data can be used to gain analyses with a higher accuracy. Sample averages of observed data must, however, be more accurate than the first guesses. Observational data, which have a systematic bias have the most detrimental affect on the quality of analyses. Also isolated inaccurate observed data are difficult to use (see e.g. Hollingsworth et al., 1985).

The present operational observational network is very expensive to maintain and it would become even more expensive to increase the accuracies of the measurements. Attempts have been made to estimate the effect of the accuracy of initial data on forecast quality. The observational data errors are not the same as analysis errors, but the analysis errors will be highly influenced by the accuracy of observed data and therefore we can use such investigations to see if there is a limit of accuracy beyond which it would not be worth going. Such a study was carried out by Lorenz (1969) who investigated the error growth of a barotropic model.

This model has an energy spectrum as indicated by the heavy curve in Fig. 2. After disturbing the initial values in the smallest scales the rerun forecasts take a while before the larger scales are influenced by these disturbances due to non-linear interactions. The thin curves in Fig. 2 indicate how much of the spectrum is affected by the initial disturbances after 15 minutes, 1 hour, 5 hours, 1 day and 5 days. The error energy is seen to double very quickly while it is confined to the smallest scales.

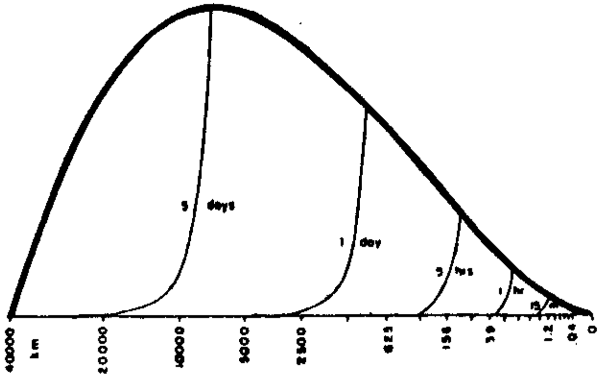


Fig. 2: Basic energy spectrum (heavy curve), and error-energy spectra (thin curves) at 15 minutes, 1 hour, 5 hours, 1 day, and 5 days, as derived from a numerical experiment. Thin curves coincide with heavy curve to the right of their intersections with heavy curve. The horizontal coordinate is the fourth root of the wavelength, labelled according to wavelength. Resolution intervals are separated by vertical marks at base of diagram. Vertical coordinate is energy per unit logarithm of wavelength, divided by the fourth root of wavelength. Areas are proportional to energy (from Lorenz, 1969)

The same model was run with different initial perturbances to estimate the gain of predictive skill in the forecasts by halving the initial error. Table 1 gives the range of predictability as a function of wavelength and initial error. Even with very large initial errors of 9 m/s, the synoptic scale circulation retains some predictive skill for one day, while some planetary scales retain some predictability for a week. If the initial error is halved, the range of predictability is nearly doubled for a large range of wavelengths. This is also nearly true when halving the initial error another time, but it is obvious that further reduction of initial errors give less and less gain in predictive skill. For the synoptic scale of motion (L > 1250 km) a reduction of the error below 1 m/s seems unnecessary.

Table 1: Predictability as a function of wavelength and initial error (d = days, h = hours) (after Lorenz, 1969).

wave length (km)	Initial Error (m/sec) 9	4.5	2.2	1.1	0.6	0.3
20000	5.7d	8.0d	9.2d	9.8d	10.0d	10.1d
10000	2.5	4.0	4.8	5.3	5.5	5.6
5000	1.1	2.0	2.6	2.9	3.1	3.1
2800	12.8h	23.8h	1.4	1.6	1.8	1.9
1250	6.1	11.9	17.8h	22.3h	1.0	1.1
625	3.0	6.0	9.6	12.7	14.4h	15.2h
312	1.5	3.1	5.2	7.2	8.5	9.1
156	0.7	1.5	2.8	4.1	5.0	5.5

If these results can be applied to the real atmosphere, there is no need to observe (or to have initial analyses) with higher accuracy than 1 m/s as far as the prediction of synoptic or planetary scales is concerned. Using the geostrophic approximation we can estimate from this an optimal accuracy for the height field. More realistic experiments are, however, needed to confirm these results. Uncertainties in the analyses are not restricted to small scales as in the experiments discussed above and therefore in realistic experiments one would also find error growth in the long waves due to analyses errors from the beginning of the forecasts.

3. HOW DO CONVENTIONAL DATA MEET THESE REQUIREMENTS

When discussing conventional data we will concentrate mainly on upper air soundings because of the requirement to describe the vertical structure of the atmosphere.

3.1 Distribution of observational data

Fig. 3 shows schematically the density of observational data in a zonal mean required to have 500 km between stations, together with the available radiosondes through GTS at ECMWF for the same latitudinal belts during April 1984. It is obvious that south of 30°N the density of radiosonde stations is far too low. Fig. 4 exhibits the geographical distribution of radiosonde data; clearly there appears to be a deficiency also in northern hemisphere mid-latitudes over the oceans. There are four quasi-stationary weather ships in the Atlantic and a few ships of opportunity in both oceans, which report fairly regularly but at different positions. These ships are definitely too few to fulfil our requirement of a 500 km spacing. This picture has not changed much in recent times. The number of radiosonde stations has slightly increased, but a few of the quasi-stationary weather ships were withdrawn.

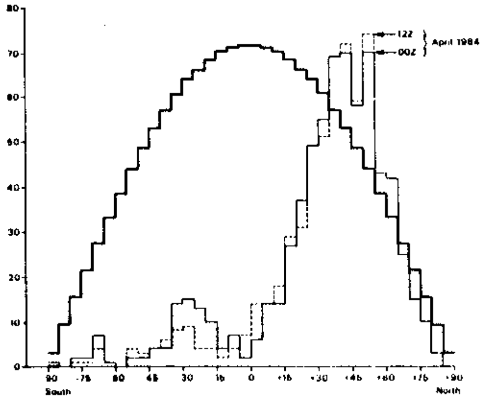


Fig. 3: Number of radiosondes in zonal belts of 5°. Thick solid line: requirement to meet 500 km distance between stations. Thin solid line: average number of radiosondes received during April 1984 at ECMWF for 00 GMT. Dashed line: same as above for 12 GMT.

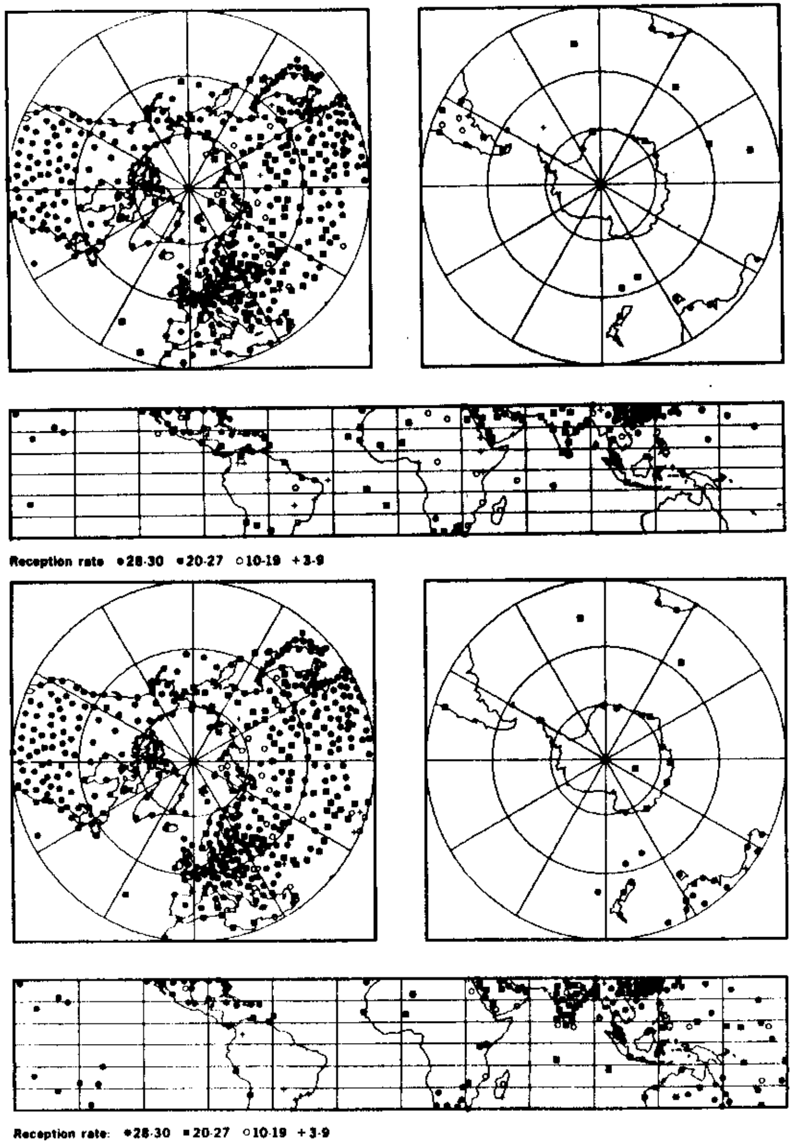


Fig. 4: Distribution and reception rate of radiosonde ascents from land stations at ECMWF during April 1984. Upper panels 12 GMT; lower panel 00 GMT.

More quasi-stationary weather ships will be withdrawn in the near future. The Automated Shipboard Aerological Programme (ASAP) will operate during 1987-88 to investigate if radiosondes launched from moving merchant ships can provide an adequate replacement.

In addition to the radiosonde soundings there are a fair amount of wind soundings (PILOT), especially in Africa and Australia. Fig. 5 gives an overview over a typical data coverage at 00 GMT for all observational data. In the Pacific area more radiosonde and pilot data are available at 00 GMT than at 12 GMT and more over South America at 12 GMT, as shown in Fig. 4.

The number of upper air soundings in the southern hemisphere is so sparse that this data source can be neglected compared to other data, as will be discussed below when we consider Observing System Experiments (Bengtsson, 1983). An extra handicap is that the reception of data at ECMWF is least regular for stations in data sparse areas as indicated in Fig. 4 by different markers. This could be due to irregular measurements or to problems with the transmission. For Africa and South America one finds the lowest reception rates. A similar survey by WMO during November 1975 (see Bengtsson, 1976) provided similar results; the present figures are, however, slightly more favourable.

From Fig. 5 we see further that observations at the surface, i.e. SYNOPs and SHIPs are much denser than upper air soundings but even they contain big gaps over southern hemisphere oceans. They are partly complemented by

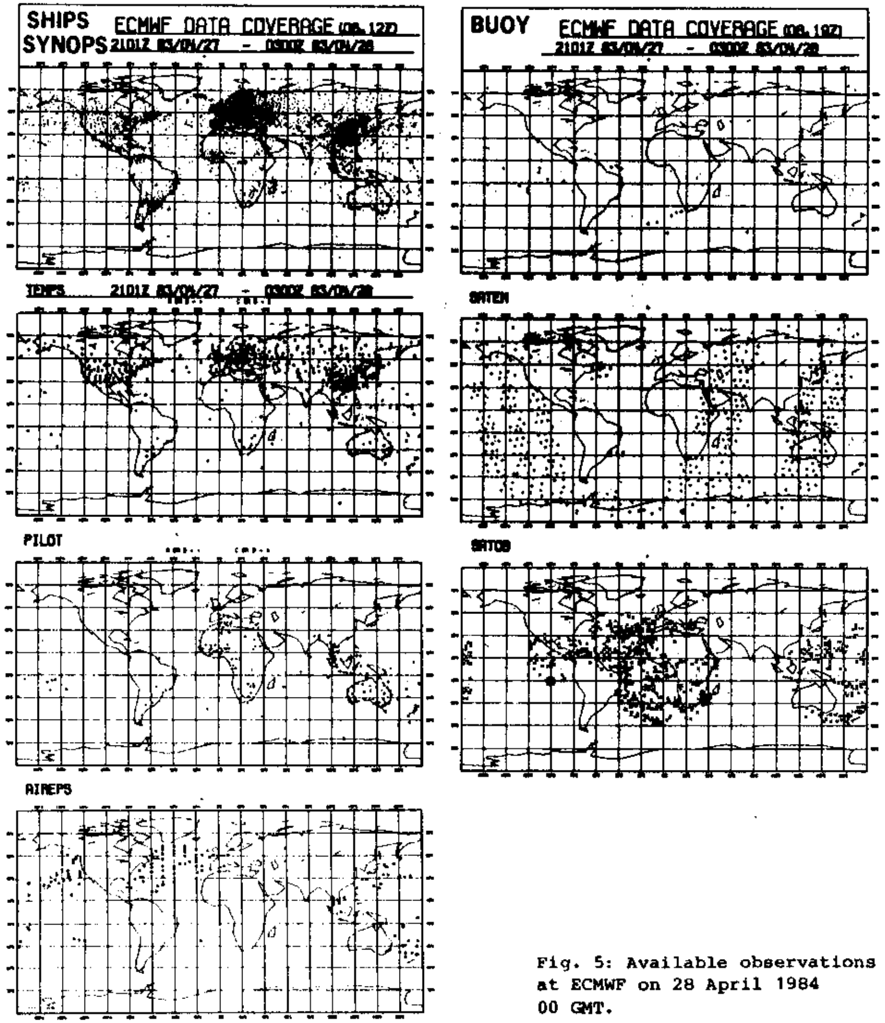


Fig. 5: Available observations at ECMWF on 28 April 1984 00 GMT.

observations from automatic buoys. During a test period in 1983, on the average 765 ship observations for 12 GMT were received at ECMWF which were supported by 100-200 observations from drifting buoys. The reception of data from buoys turned out to be very irregular. Such an amount of data would mean a good coverage over the oceans if they had been distributed evenly. If one counts only ship observations south of 10°N, only 178 messages were received. An average density of these data during FGGE is presented in Fig. 6. Although the FGGE period was very favourable because of the special efforts to collect all data, we still find large areas with less than 15 observations in boxes of 1000 km length per day or less than 4 for each analysis time.

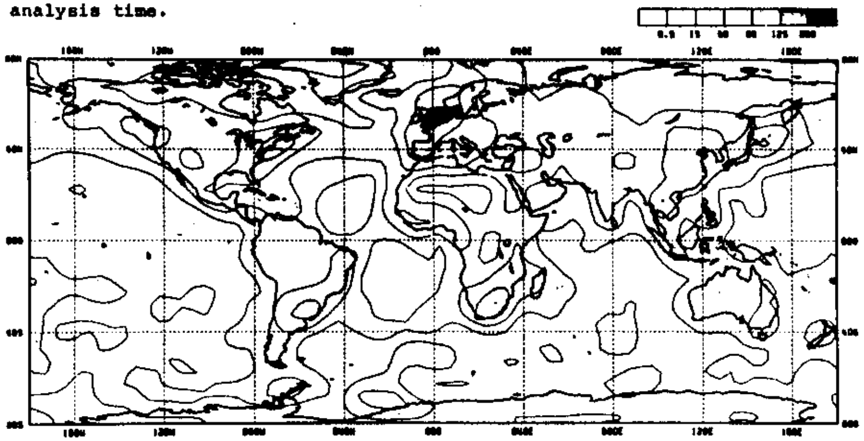


Fig. 6: Average number of surface observations (SYNOP, SHIP, BUOY) per day in boxes of 1000 km length over the period 15-24 June 1979 (from JPS,1981-82).

Another important source of data are measurements from commercial aircrafts (AIREPs and ASDARs) of which 1780 per day were received at ECMWF during March 1983 with a fairly homogeneous distribution during the day. From Fig. 5 we see that they are concentrated on the main flight routes and they do not help to fill the gaps over the tropical oceans. During a survey at NMC in 1976 only half as many aircraft reports were received, which means for the present system quite an improvement.

The most striking characteristic of the World Weather Watch ground based observations is their inhomogeneous coverage. In most areas the requirements of data density are not fulfilled.

3.2 Accuracy and representativeness of data

When considering the accuracy of meteorological data one has also to investigate their representativeness. As mentioned above the ideal observation should represent the space and time scales of synoptic disturbances, which should be gained by a sampling procedure providing averages of one hour in time, 100 km in the horizontal and 1 km in the vertical. These requirements are not met by any observing system; each system has its own sampling procedure and this can create great problems for comparing observations and for estimating their uncertainty.

When discussing the accuracy of some basic parameters in the following we will give some information about problems in the representativeness too.

(a) Surface pressure

Since the invention of the barometer in the middle of the 17th century by Torricelli, the surface pressure can now be measured very accurately, within ±0.1 mb. This is a very high accuracy since the variability of surface pressure is in the order of 100 mb.

This statement must however be qualified for several reasons. Air flowing around an obstacle can give rise to local pressure changes which can be in the order of 1 mb. Such dynamical effects are particularly important on ships. Different practices for compensating for dynamical pressure effects led to a 0.3 mb discrepancy between the measurements taken on USSR and US research vessels during GATE.

A further difficulty occurs mainly in the equatorial zone, where a significant semi-diurnal pressure oscillation associated with the atmospheric tide is present. This pressure wave (2 mb amplitude over the Indian Ocean) is an effect of solar heating and, therefore, locked on local time. Yet, pressure reports and analysis are synoptic and represent therefore an instantaneous picture of the pressure wave which may overshadow weak synoptic pressure disturbances. This may have a disastrous effect if the first guess by a forecast model does not capture this pressure wave and if the data coverage is poor. A proper sampling theory might help to overcome this problem.

A third problem arises over mountainous areas. As surface pressures are transmitted as mean sea level pressures, the surface pressure has to be extrapolated to this level. The assumption about the temperature below ground will strongly influence the extrapolated pressure. Such an extrapolation is done for stations up to 800 m above mean sea level. For such a height, a difference of 1 K in the assumed temperature below ground makes a difference of 1.5 mb. To reduce this problem the WMO code for transmission of observational data provides also the possibility to report surface pressure at station height.

(b) Temperature

Temperature measurements at screen height can be made very accurately, perhaps within ±0.1 K, because one can afford to protect the thermometer from radiation influences but such values might nevertheless be highly influenced by local effects, e.g. if the measurement is taken near a lake, on top of a hill or in a valley.

More important for numerical weather forecasts are temperature measurements by radiosondes in the free atmosphere. The main problem is to make sure that the thermistor or resistor measures the temperature of the air and not something else. Efforts have to be made to ensure a good protection against solar radiation and to provide reasonable ventilation.

In the troposphere radiosondes measure the temperature within ±1 K. Vaisala claims an accuracy of ±0.2 K (standard deviation) for their most advanced radiosondes. In the stratosphere the uncertainties become progressively larger. This is also reflected by the instructions by WMO for coding the data for transmission.

The problem of inadequate protection against solar radiation is exhibited by large diurnal fluctuations, especially in the stratosphere. Intercomparisons of radiosondes from different manufacturers show discrepancies as large as 3 K in the upper stratosphere (and worse for rocket soundings).

In Fig. 7 temperature measurements from several radiosonde types are compared with each other. The soundings with the FIN (Vaisala) and UK sondes have been corrected for radiative influences in the same way as it is done

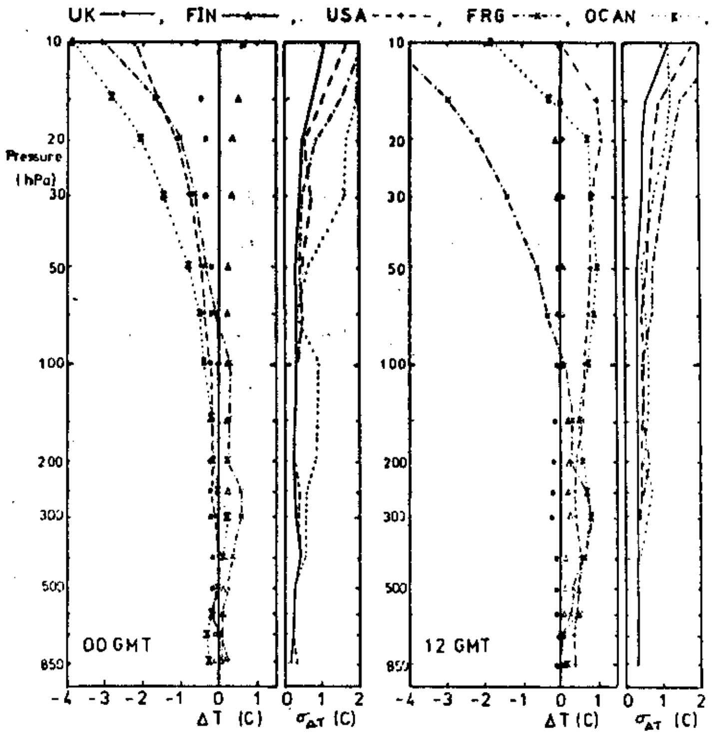


Fig. 7: Temperature differences between different sondes at standard pressure levels obtained during the WMO International Radiosonde Comparison, Phase I, Beaufort Park 1984 (from Nash et al. 1984). ΔT are the differences relative to the average of UK and FIN measurements; $\sigma_{\Delta t}$ is the standard deviations between the UK and the other measurements. Averages are calculated from varying sample sizes consisting of 20 to 25 flights.

operationally. The USA (VIZ) sonde data were not corrected and show large biases with opposite signs at 00 and 12 GMT in the stratosphere and upper troposphere. These differences can partly be corrected but intercomparisons between different radiosondes (e.g. UK and FIN sondes) show mean differences of up to 1 K after applying correction methods, which indicates the accuracy of temperature measurements by radiosondes. The random errors of radiosonde temperature measurements are indicated in Fig. 7 by standard deviations between the UK and the other sondes, which is mostly in the order of 0.2 K.

The assumed observational error of temperature in the ECMWF analysis scheme varies from 0.7 K in the middle troposphere to 1.5 K for the 20-10 mb layer (see Table 2 on page 27). This is larger than the observational errors shown in Fig. 7 but the error in the analysis scheme must also account for the fact that radiosonde data are not representative for the scales needed for analyses for numerical weather forecasts which have been discussed in Section 2.1.

(c) Wind

Turbulent motions in the atmosphere cause rapid fluctuations in wind speed and direction with time scales much shorter than the synoptic time scale in which we are interested. Therefore there is a higher requirement for longer sampling times for wind measurements than for pressure and temperature measurements, which are mostly not available. Experiments have shown that for upper air soundings small-scale atmospheric turbulence can create 2-3 m/s uncertainty on any instantaneous wind measurement.

Using the track of a rising balloon to measure the wind can create a further uncertainty as large as 5 m/s for a 500 m layer when the balloon is moving

through layers of persistent vertical wind shear. This can be especially strong in the stratosphere.

Wind measurements in the planetary boundary layer over land are of little use for synoptic scale analyses because these measurements are often subject to large diurnal variation which are only important for local weather. Also obstacles and surface irregularities strongly affect the windfield in the boundary layer.

The accuracy of upper air wind observations depends essentially on the specific sounding equipment. Optical or radiotheodolite tracking leads to severe loss of accuracy at very low elevation angles; measurements of especially strong winds can even be inhibited because of this. Strong upper air winds are generally less accurate due to resulting long distances between balloon and ground station. Omega (or Loran-C) wind-finding systems do not have this limitation and so they have more uniform errors; they are, however, not everywhere equally good and usable (WMO, 1983).

Fig. 8 shows a comparison between a radar wind profile and corresponding Omega sonde data. Note the scalloped appearance of both profiles, which is characteristic of a distinct layering of the atmospheric flow but also of significant measurement errors of the order of 1-2 m/s. A more recent comparison between radar, Omega and Loran-C wind findings (Karhunen, 1983) show similar discrepancies between radar and Omega systems, and larger discrepancies between Omega and Loran-C measurements. This will, however, depend strongly on the geographical region where the measurements are carried out. The assumed observational error in the ECMWF analysis scheme (see

Table 2) ranges from 2.2 to 3.8 m/s for each component in accordance with recent estimates by Morgan (1985), who gives values of 3.0 to 3.5 m/s for vector errors (2.1 to 2.5 m/s for components). The ECMWF analysis scheme does not distinguish between different methods of balloon tracking.

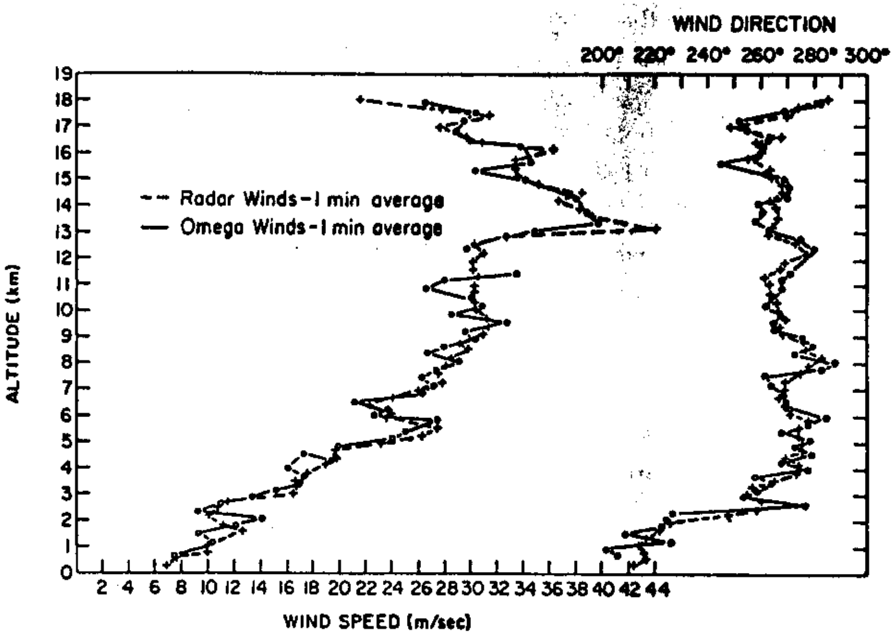


Fig. 8: Comparison of radar tracking and navigation by Omega V.L.F. signals for one typical radiosonde ascent (from Lally, 1973).

(d) Humidity

Measurements of humidity are less accurate than measurements of other atmospheric parameters. The relative humidity can be measured within ±10% by conventional observing systems. Advanced sondes from Vaisala are said to

have an accuracy of ±2%. This number represents the reproducability with sondes by the same factory while sondes of different make may deviate much more. A more serious problem is that these data are less representative for scales in which we are interested, because the humidity field is much more affected by small scale features such as cumulus convection, fronts, etc. than pressure or temperature fields. Both problems lead to much lower correlations between neighbouring radiosonde data. Fig. 9 compares correlation coefficients between measurements at neighbouring radiosonde stations in relation to distances between the stations. Dots represent correlations of 850 mb humidity data (van Maanen, 1982) and the solid line represents correlations of 500 mb heights fitted by an exponential curve (Schlatter, 1975). The difference in the correlations is obvious. Stations with 500 km distance have correlation coefficients of 0.87 for the 500 mb heights and only 0.5 for the humidity.

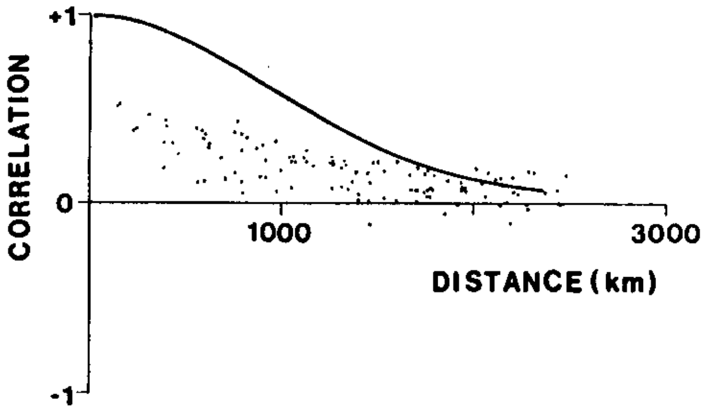


Fig. 9: Correlation between observations at neighbouring radiosonde stations in relation to the distance between the stations during winter. Solid line: 500 mb height (from Schlatter, 1975); dots: 850 mb humidity (from van Maanen, 1982).

Fig. 9 is representative for the winter season - a corresponding figure for summer exhibits even larger differences. Van Maanen (1982) suggests that the low correlations in the humidity field are mainly due to the high variability of the field and to a lesser amount due to the inaccurate measurements. To improve the analysis one should therefore concentrate more on a higher density of observations than on higher accuracy of measurements.

Krishnamurti et al. (1983) developed an analysis scheme for humidity which incorporates measurements like precipitation and cloudiness. He showed such analyses to be superior for forecasting in the tropics to an analysis scheme neglecting these observational data. Such an approach is, however, still in the development state.

(e) Geopotential height

Temperature and pressure measurements are used to calculate the heights of standard pressure levels on the basis of the hydrostatic assumption. If the temperature measurements are systematically wrong at a station, the height calculations will be seriously affected. Fig. 10 shows the mean differences between the radiosonde heights for the 200 mb level and the corresponding first guess from a forecasting model during February 1979. A dominant feature is the variability of these biases between neighbouring stations, especially when radiosondes by different manufacturers are involved. A good example can be found over Ireland where there is a bias of -71 m at a station in the north of Ireland and +20 m at a station in the south, which are only 400 km apart. If we assume that this difference is only due to errors in the

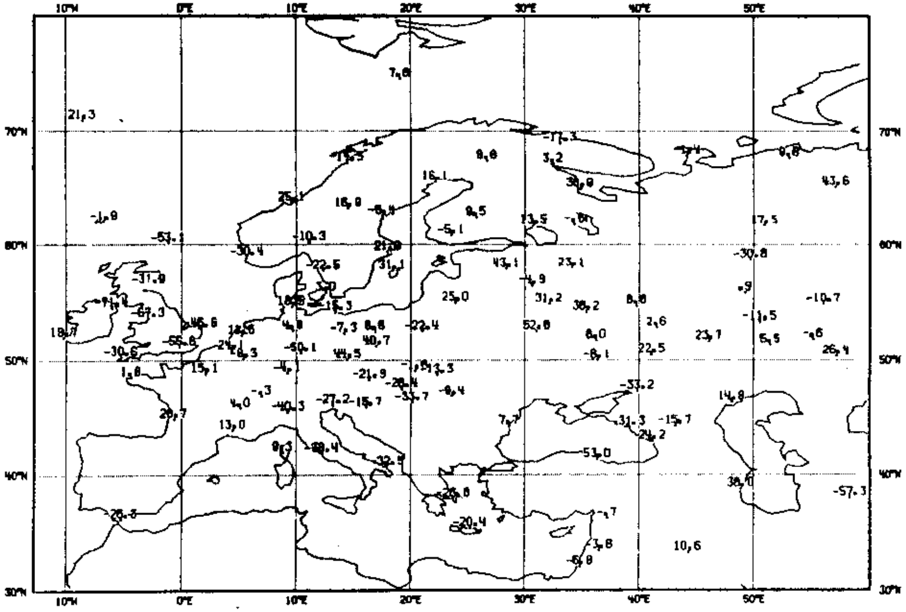


Fig. 10: Mean differences between the radiosonde 200 mb height and the first guess 200 mb height during 6-19 February 1979 (from Hollingsworth and Arpe, 1982).

temperature measurement, it means that the measurements at both stations differ systematically by 2 K. A more recent recalculation of such biases shows some improvement. Many meteorological centres use statistical correction methods of observed data to compensate for such problems (Lange, 1985).

Uncertainties in the height field of that amount are quite serious for analysing purposes because important atmospheric disturbances are of the same order of magnitude. It is therefore necessary to use other measured information, namely wind data, which are connected to the height field gradients via the geostrophic relation. We have seen above that the wind measurements are not very accurate and the question then arises as to which of the two measurements one should have more confidence. The wind in the planetary boundary layer is strongly influenced by the local environment which make them less useful than the height field measurements themselves. With increasing height more and more confidence can be given to wind measurements. This is also reflected by Table 2 which shows the assumed observational errors used operationally in the ECMWF analysis scheme (1984). The observational errors of heights by radiosondes increases by a factor of 10 from 850 to 10 mb, while the wind error is nearly constant with height. A random error of 3 m/s in the wind field measurement results in an error of 30 m/1000 km in the horizontal gradient in the height field at 42°N.

3.3 Overview of conventional data

We have seen that over the globe the coverage of conventional data is inadequate, especially over the tropical and southern hemispheric oceans. We also found that many of the observational data have problems with the

TABLE 2: RMS observation errors used in the ECMWF operational analysis scheme in summer 1984 (after Shaw et al., 1984).

height errors (m)

	850	700	500	400	300	250	200	150	100	70	50	30	20	10
SONDE	5.4	6.0	9.4	11	13	14	15	18	21	25	29	31	38	50

height thickness errors (m)

	1000	850	700	500	400	300	250	200	150	100	70	50	30	20	10
SONDE	4.2	4.8	6.7	6.3	7.4	6.7	7.2	7.6	9.5	9.4	7.9	11.2	15.2	30.4	
SATEMs															
clear	12.0	10.6	15.8	11.8	16.9	9.1	11.1	14.3	20.2	17.8	17.7	28.4	23.8	40.6	
part cl	12.0	11.7	15.8	12.4	17.7	10.1	12.4	14.3	20.2	17.8	17.7	28.4	23.8	40.6	
micro	12.0	12.3	15.8	13.7	19.4	10.1	12.4	14.3	20.2	17.8	17.7	28.4	23.8	40.6	

vertical mean temperature error assumed for height thickness (K)

	1000	850	700	500	400	300	250	200	150	100	70	50	30	20	10
SONDE	0.9	0.9	0.7	1.0	0.9	1.3	1.1	0.9	0.8	0.9	0.8	0.8	1.3	1.5	
SATEMS															
clear	1.8	1.9	1.6	1.8	2.0	1.7	1.7	1.7	1.7	1.7	1.8	1.9	2.0	2.0	
part.cl.	1.8	2.1	1.6	1.9	2.1	1.9	1.9	1.7	1.7	1.7	1.8	1.9	2.0	2.0	
micro	1.8	2.2	1.6	2.1	2.3	1.9	1.9	1.7	1.7	1.7	1.8	1.9	2.0	2.0	

wind component errors (m/s)

	1000	850	700	500	400	300	250	200	150	100	70	50	30	20	10
SONDE PILOT	2.2	2.5	2.6	3.1	3.7	3.8	3.3	3.0	2.8	2.4	2.4	2.4	2.5	3.1	3.5
SATOB	2.5	2.5	2.5	2.5	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
AIDS ASDAR AIREP	3.5	3.5	3.5	3.5	3.5	4.0	4.5	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0

surface observations

PAOBS	(1000 mb height)	32.0 m	(4 mb)
SYNOP/SHIP	(1000 mb height)	7.0 m	(0.9 mb)
DRIBU	(1000 mb height)	14.0 m	(1.8 mb)
SHIP (wind component)		3.6 m/s	

accuracy or representativeness to be of optimal usefulness to analyse the initial field for numerical weather forecasts. Table 2 gives an overview of the assumed observational errors in the operational ECMWF analysis scheme (1984).

Accuracies given in this section refer to observational data which have been handled and transmitted correctly. In an operational environment, however, error happen and Hollingsworth et al (1985) have shown the large impact of strongly erroneous data in the analysis-forecast scheme. Avoiding such, often human, errors would lead to large gains with little extra cost.

In the next section we will see how far satellite data can complement or replace the conventional data and in Section 5 both data sources are compared with each other.

4. USE OF SATELLITE DATA IN NUMERICAL ANALYSIS

In April 1960 the first meteorological satellite, TIROS 1, produced the first television pictures of the earth's surface and its weather systems. These pictures immediately proved to be very useful for meteorologists to improve weather maps and cloud analyses qualitatively, and they have become a standard tool for operational forecasting - especially for short range forecast and the warning and tracking of tropical storms.

This qualitative usage of satellite information will not be further investigated here, though it should be noted that cloud formations can be transformed to quantitative data by empirical rules (cf. Section 4.4). Instead we will concentrate on the usage of temperatures calculated from satellite measurements of radiances in small spectral bands and the usage of winds calculated from drifting of cloud formations. A more comprehensive overview of satellite data is given by Johnson (1985).

From Fig. 5 (SATEM and SATOB) it can be seen that such data have a much more uniform distribution over the globe and may be very useful for filling the gaps which are left by conventional data. One disadvantage of data from satellites, as from aircrafts, is that their measurements are not carried out synoptically which leads to errors in most present analysis schmes - however new techniques might overcome this problem. In Section 5 we will also consider if they can even replace conventional data.

4.1 Satellite temperature measurements

The possibility of inferring the vertical temperature structure of the atmosphere from satellite measurements of spectral radiances in the 15μm absorption band of carbon dioxide was first suggested by Kaplan (1959). On the basis of this suggestion, two instruments were developed and flown on Nimbus 3. These were the Satellite Infrared Spectrometer (SIRS) and Infrared Interferometer Spectrometer (IRIS). These pioneering experiments confirmed the feasibility of retrieving useful temperature information from purely spectrophotometric measurements in outer space, but they also indicated many problems. Hayden (1979) gives a more recent summary over the principles of remote soundings. The retrieval of temperature soundings in cloudy conditions still remain unsatisfactory. The detrimental effect of a correlation between the inaccuracy of data and active weather regions (that is where one finds clouds) has been demonstrated by Baumhefner and Julian (1975). Comparisons between temperature soundings by satellites and by radiosondes showed RMS-differences of 2-3 K (cf. Johnson, 1985). Satellite data have the advantage that they represent the horizontal and vertical scales in which we are interested, and a part of the differences between radiosonde and satellite soundings may be due to the fact that radiosonde data contain unrepresentative small scale features.

An uncertainty of 2-3 K make the data less useful for tropical regions because it is larger than variations within tropical disturbances, but the data are widely used in the southern hemisphere mid-latitudes. Satellite temperature soundings are sometimes affected by systematic biases which then effect large areas, e.g. over cloudy areas as already mentioned above. For the analysis schemes it is very difficult to detect such biases or to compensate for them. The impact of biases can be very detrimental. It has therefore been suggested that satellite horizontal gradients of temperatures should be used instead of temperatures themselves.

4.2 Satellite wind measurements

Clouds which are not very active drift with the mean atmospheric flow and it might be possible by tracing their positions to estimate their velocity and thereby the velocity of the atmosphere. In spite of the very high resolution of satellite images, it is usually not possible to resolve individual clouds. Also the life cycle of individual clouds is of the same order as the time interval between successive images. To use satellite images for tracing clouds one has to restrict the method to moderately weak but persistent meso-scale perturbations of the mean flow and the cloudiness associated with such perturbations which can be recognised for more than one hour. On the other hand one has to exclude cloud systems which do not move with the airflow, e.g. stationary lenticular clouds or frontal clouds. Typical cloud formations used for such tracing are cumulus clouds or cloud systems in the trade winds and blow off cirrus from convective cloud clusters. However there is a problem in estimating the correct elevation of the clouds. In earlier times it was assumed that the clouds were associated with the 900 mb and 200 mb level respectively. Nowadays radiometric measurements of the temperature at the top of the clouds are used to determine the cloud height by comparing them with profiles of temperature against height at that position, perhaps using the first guess from an analysis scheme. A summary of the wind derivation is given by Hubert (1979).

It is difficult to estimate the error of the cloud tracking winds. Suchman and Martin (1976) found differences between radiosonde data and cloud winds of less than 3 m/s. Cloud winds may even be better than radiosonde winds because they represent the scale of motion which are important for numerical weather forecasts. On the other hand they are more affected by biases, e.g. they are more likely to underestimate high wind speeds, hardly reporting values of more than 100 m/s.

In the ECMWF analysis scheme the assumed observational error for wind components from satellite is 3.5 to 5.0 m/s (Table 2) which is clearly larger than those for radiosondes; this is in agreement with investigations by Morgan (1985).

The importance of cloud drift winds for the ECMWF analysis scheme is demonstrated by Fig. 11 where mean differences of the 850 mb wind between analyses using cloud winds and analyses not using cloud winds are shown. The impact over tropical oceans is obvious. Differences of more than 2 m/s are widely spread. Comparing the difference field with the mean wind field (not shown) reveals that the use of cloud winds enhances the wind speed of the trade winds. Forecast comparisons from the different analyses indicate a clear advantage of using the cloud tracking winds (Kållberg, et al. 1982).

4.3 Humidity data

Radiance measurements in the microwave bands make it possible to estimate soundings of humidity from satellite. These estimates are still very crude and not much is known about their characteristics. Atmospheric humidity has often strong vertical gradients in the lower troposphere which cannot be resolved by present retrieval methods. In addition moisture retrievals are strongly contaminated by clouds. Cadet (1984) demonstrated, nevertheless, their usefulness but further work is needed.

Fig. 11: Differences between averaged 850 mb windfield analyses with and without the use of cloudtrack winds (from Kållberg et al., 1982).

4.4 Bogus data

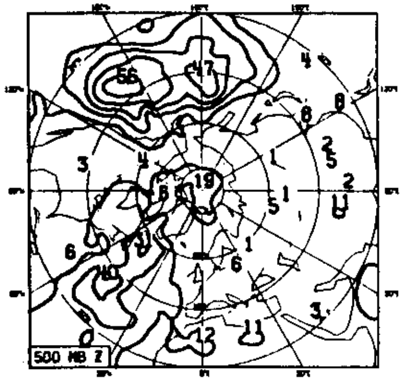
From the very beginning, experienced meteorologists have been able to recognise significant cloud patterns and associate them with the development of weather systems such as fronts, tropical disturbances, and, in particular, hurricanes. Through subsequent years the subjective analysis of these qualitative cloud images from space has been perfected to such a high degree of accuracy and reliability that "bogus" surface pressure and 300 mb geopotential height data over oceanic areas are produced routinely by experienced human analysts and fed into the computer with remarkably good results. In many cases these data have been so accurate that the replacement of the "bogus data" by the first objective determination of temperature profiles obtained by remote sensing (VTPR data) showed very little improvement, if any. The bogus data are still produced operationally in Australia and distributed world wide. The problem with these data is the variability of their quality. At ECMWF only surface pressure estimates are used assuming quite a large observational error (see PAOBS in Table 2).

5. OUTLOOK FOR FUTURE DEVELOPMENTS FOR OBSERVATIONAL DATA

It has already been mentioned above that generating, processing and transmitting of observational data is very expensive. As some variables are provided by two or more systems, it would be of considerable economical value if one could perform forecasts of the same quality on the basis of a reduced observing system.

Because of the unique coverage with data during FGGE, these data have been used to perform analyses and subsequent forecasts using subsets of observational data, in which the one or the other observational data source has been excluded. Fig. 11 has already demonstrated the impact of cloud winds on analyses. In Fig. 12 we find another example showing RMS 500 mb height differences between analyses with and without the use of data from satellites and commercial aircrafts. The differences in the northern hemisphere are considerable and are even larger in the southern hemisphere. To find out if the differences between analyses from different subsets of observational data are important, forecasts were carried out and their skill scores were used as a measure of the quality of the analyses.

Fig. 12: RMS differences of 500 mb height fields between analyses using all data and analyses neglecting satellite and aircraft data during 9-18 November 1979 (from Uppala, personal communication). Contour interval 10m.



The impact of different sources of observational data on medium range weather forecasts is demonstrated by Table 3.

TABLE 3: Length of forecasts with useful information.
The time until a drop of the anomaly correlation coefficient below 60% is given.
Units: days (Bengtsson, 1983).

Use of data for the analyses	Northern Hemisphere	Southern Hemisphere
All FGGE	7.0	5.5
All FGGE except satellite	7.0	3.5
All FGGE except satellite and aircraft	5.5	3.5
All FGGE except radiosonde	5.7	4.7

There are some indications of redundancies between aircraft and satellite data but on the whole one cannot find a single data source which can be replaced by others without loss of forecast quality. The impact of radiosonde data in the southern hemisphere is small because there are only few radiosondes available and the impact of satellite data in the northern hemisphere is small because of the relatively good coverage, and higher quality of conventional data. In future we cannot expect the amount of radiosonde stations to increase, it is more likely that even more weather ships will be withdrawn and therefore satellite data will hardly become redundant. The only hope of saving observing system costs lies in improvements of satellite data quality and/or in improvements of processing the data.

An improvement in the processing observational data may be achieved by better analysis systems. By using better forecasting models in the analysis cycle, it should be easier to detect erroneous observational data and the extrapolation of information from data rich regions into data sparse regions could be improved. Then the existence of gaps in the data coverage may be of less importance.

In Fig. 13 the RMS differences between analyses using different systems during a period of 5 days are displayed. The input for both analysis systems was identical, namely the main FGGE level II-b data set. Differences between the analysis arise only from the analysis systems for a number of reasons. Details can be found in Hollingsworth et al. (1985). An important reason for differences comes from the criteria used to decide if an observational datum should be accepted as correct or if it should be rejected. Differences in such decisions can lead to very large analysis differences when observational data conflict with each other. The differences between the analyses in Fig. 13 are larger than one would expect from the available density of observational data and their assumed accuracy. Large differences often exhibit impacts of few observations with larger errors which were accepted by one or the other analysis schemes. Detecting such erroneous observation with improved analysis schemes may yield better analyses even without changes in the quality and density of observational data.

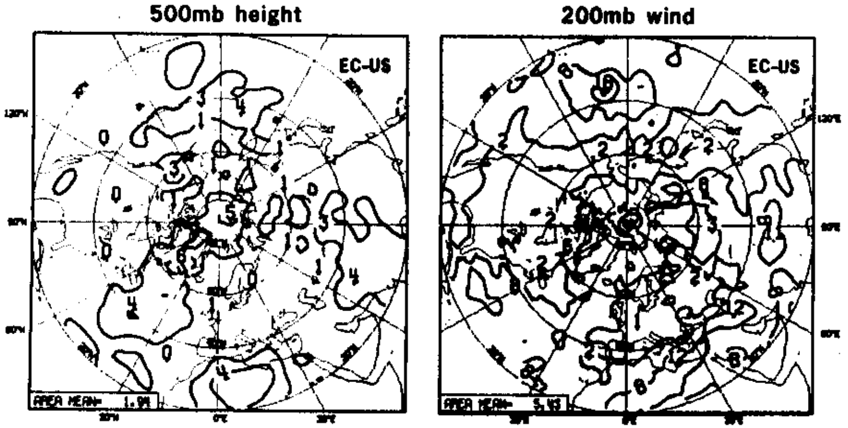


Fig. 13: RMS differences beween analyses made with the ECMWF and with the NMC analysis scheme using the same observational data during the period 15-19 February 1979. Area mean RMS differences north of 20°N are given in the lower boxes (from Hollingsworth et al., 1985).
Left panel: 500 mb height; contours 2 dam.
Right panel: 200 mb wind; contours 4 m/s.

6. DATA COLLECTION

We will now cover some operational aspects in which the conflicting aims of doing forecasts as quickly as possible and doing them as well as possible will be investigated. Here we will cover only the aspects concerning data collection.

To find out the required horizontal extent of data coverage for (numerical) weather prediction, we have to do some simple calculations: atmospheric impulses generally propagate with the group velocity G which is given by the expression:

$$G = c - L \frac{dc}{dL}$$

where c is the phase velocity and L the wavelength. The group velocity of pure gravity waves is the same as the phase speed because the phase velocity does not change with wavelength - they are non-dispersive. The phase velocity of Rossby waves is wavelength dependent, in the simplest case the phase velocity can be calculated by

$$c = U - \frac{L^2\beta}{4\pi^2}$$

where U is the mean undisturbed zonal wind speed and β the derivative of the Coriolis parameter with latitude. Using this relation to calculate the group velocity yields:

$$G = U + \frac{L^2\beta}{4\pi^2}$$

The group velocity is always larger than the mean zonal flow and larger than the phase velocity of the waves. In Fig. 14 this is demonstrated by means of a trough-ridge diagram. It shows the differences of the 500 mb height fields between forecasts based on two analyses which deviated only in a small area over the north eastern Pacific. The wave front propagates with a speed of 24 m/s to the east while one finds only much slower phase velocities of single waves of about 10 m/s. With an average mean flow (U) of 16 to 18 m/s these velocities agree favourably with the above equations. Fig. 14 shows also that interactions between the propagating disturbance and the undisturbed flow leads to amplifications of differences after a few days into the forecasts.

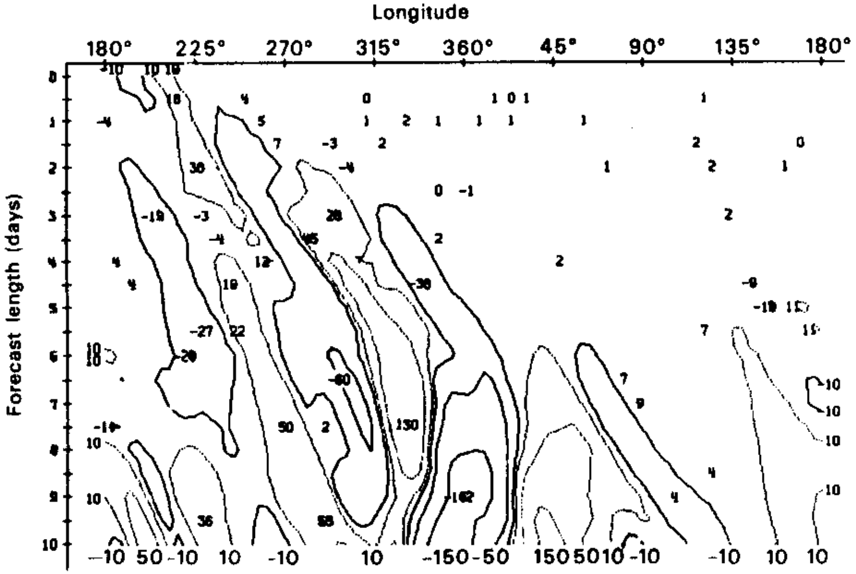


Fig. 14: Difference between 500 mb height fields of two forecasts of which the initial fields differ only over a small area over the north-eastern Pacific. Data are averaged between 35° and 55°N (after Hollingsworth et al., 1985). Contours at ±10, 50, and 150 m.

In Fig. 14 it is shown that information of initial disturbance travels three quarters around the world within 10 days. The equation for the group velocity shows a quadratic dependence of the velocity from the wavelength. Disturbances with double the wavelength of those shown in Fig. 14 will propagate with four times the speed, which means that information in the initial analysis can move around a latitude circle within 3 days. We have therefore to conclude that one needs initial information from a hemispheric domain for forecasts up to 5 days and global information for longer forecasts. This general result is supported by the work of Baumhefner (1971, 1972) and Miyakoda and Umscheid (1973), in which the effect of a tropical wall on the flow in middle and high latitudes was investigated. After we have seen that we need to collect meteorological information from the hemisphere for forecasts up to 5 days and from the globe for forecasts beyond that, we have to estimate the available time to collect the data and to process them so that the forecasts will be available to the customer within an acceptable time after observation.

If we assume the time between observation and availability of the forecast (total processing time) is one order of magnitude less than the length of forecast time, we come to the values given in Table 4.

This time includes the time for doing the observations, for the data transmission, for performing the analysis and forecast and for dissemination of the forecast to the customer. There are some extra operational constraints, e.g. the interest of most customers to receive the forecasts in early working hours.

TABLE 4: Maximum allowed total processing time for forecasts of different lengths.

Forecast length	Total processing time
12 hours	1-2 hours
1 day	2-4 hours
3 days	6-8 hours
10 days	1 day

A compromise between the aims of collecting as many as possible observational data and an early as possible start of the processing of the data (cut-off time) has to be found. To provide a guide, the average arrival time of radiosonde and ship data during a trial period, 1-10 March 1983, is given in Fig. 15 and 16. The reception of data from the whole globe and from south of 10°N is treated separately because of the sparse coverage south of 10°N. Note the different scales in the ordinates. 95% of all received radiosonde data from the whole globe is normally collected within 6 hours after observation time and 95% of the radiosondes south of 10°N arrive within 8 1/2 hours. For ship observations the time to collect 95% of all received data takes longer namely 8 1/2 hours globally and more than 11 hours for data south of 10°N.

At ECMWF the cut-off time for 12 GMT observational data is 8 1/2 hours and considerably longer for other observational times, which provides a good data coverage also for the southern hemisphere. Such a schedule allows another 10 hours for performing the analysis and forecast, and for dissemination to make the forecasts available to customers in the early morning for most member countries.

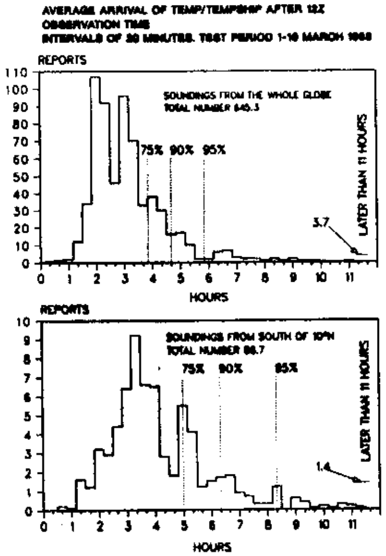


Fig. 15: Average arrival time of upper air soundings (TEMP and TEMP SHIP) after 12 GMT observation time in intervals of 20 minutes at ECMWF. Test period 1-10 March 1983 (from Akyildiz, personal communication).

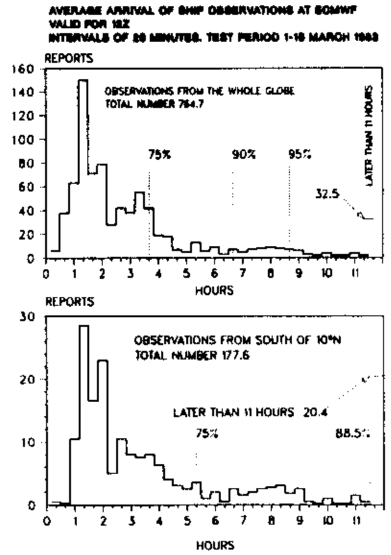


Fig. 16: Average arrival time of surface ship observations after 12 GMT observation time in intervals of 20 minutes at ECMWF. Test period 1-10 March 1983 (from Akyildiz, personal communication).

7. REPRESENTATION OF SMALLER SCALE FEATURES IN OBSERVED DATA

Above we have dealt with the problem of how observational data fulfil the requirements for analysing initial fields for numerical forecasts. It was stressed that horizontal scales of 1000 km or larger should be represented by the data. Very important features in meteorology are the frontal zones which are connected with the most important weather phenomena in daily life and which are of much smaller scale. A main task for short range forecasting of the meteorologist has been to identify the position of fronts on weather maps and to estimate their further development. The Norwegian (Bergen) School developed in the years following World War I a model of the typical cyclone structure which helped considerably to understand and predict the weather.

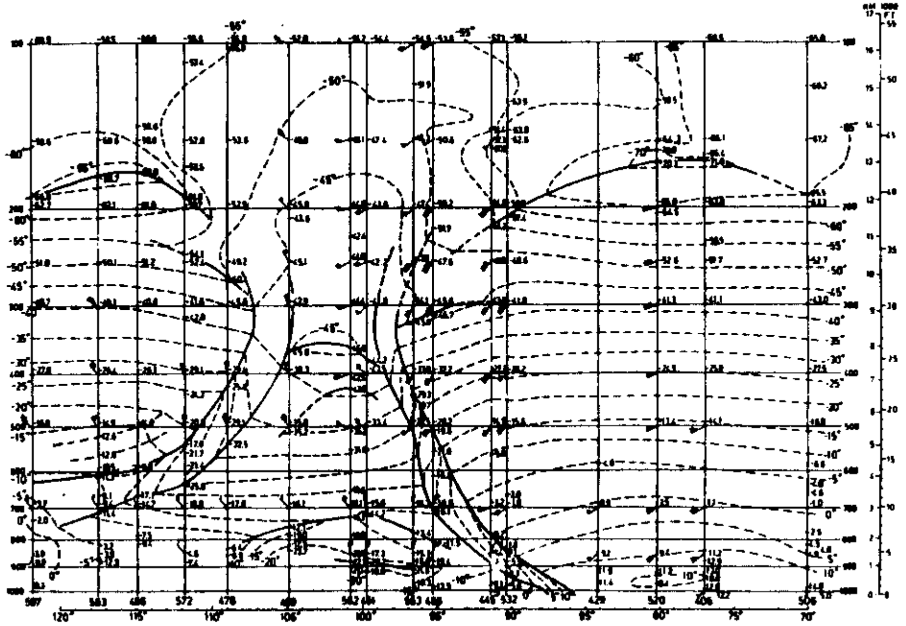


Fig. 17: Vertical section across the USA at 21 January 1959 12 GMT (from Palmén and Newton, 1969).

Knowledge of the typical cyclone and front structures helps to analyse weather maps also in data voids in a consistent way; cloud structures can provide information about the free atmosphere from surface stations. In Fig. 17 we see a cross-section through a trough over the USA on 21 January 1959. Dominant features are the very sharp changes of temperatures along the frontal zones and different heights of the tropopause above different air masses. The analysed temperature fields show mostly very homogeneous distributions with large changes only at the frontal zones. For this analysis an idealized cyclone and front model was used to fill the few gaps without measurements but most areas are well covered with data which fit the model very well.

This analysis was made under very favourable conditions concerning the density of measured data and a simple interpolation procedure for analysing the temperature field would have given a solution which would differ only in small details. Normally the data coverage is much worse and the quality of the analysis depends much on the skill of the analyst or the analysis scheme. As an example of the use of the front and cyclone model we see in Fig. 18 a manual analysis of the 500 mb temperature. One finds there nearly homogeneous air masses: polar air ranging from -32° to -40°C, air of the mid-latitudes from -20° to -27°C and tropical air from -13° to -20°C. The air masses are clearly separated by strong baroclinic zones. From the available observations at this level (given as numbers in Fig. 18) it is not immediately obvious that such strong frontal zones exist over the northern Atlantic. The analyst got his knowledge of the position and strength of the front from time series at each station and from the vertical structure of each sounding.

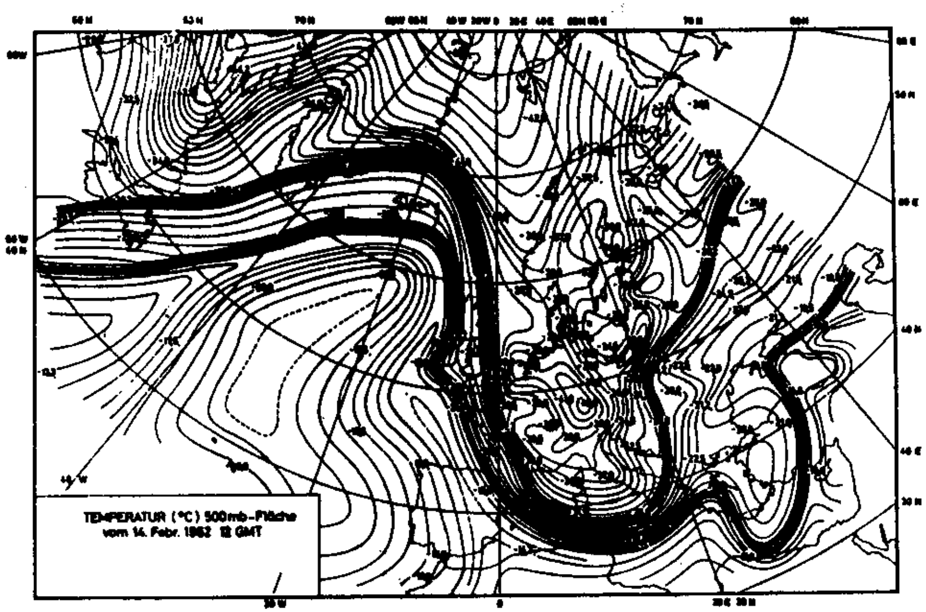


Fig. 18: Manual 500 mb temperature analysis (from Defant et al., 1972)

Using Fig. 19 we want to investigate how far the ECMWF analysis scheme can represent these meteorologically important features. For the 700 mb level the operational temperature analysis is compared with a manual analysis, which accepted all observed data as being correct and no reasons were given to reject any of the data. The hand analysis shows a strong concentration of isotherms between -10° and -16°C and perhaps a second somewhat weaker concentration between -4° and -6°C isotherms. The ECMWF operational analysis shows a more regular distribution of isotherms. For a more detailed

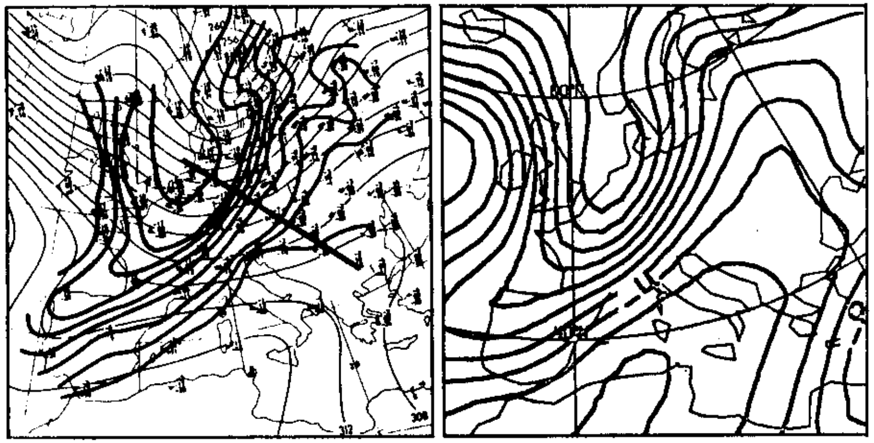


Fig. 19: 700 mb temperature analyses at 15 January 1983 00 GMT.
Left: Manual analysis accepting all observed data.
Right: Operational ECMWF analysis.
Contour interval 2°C.

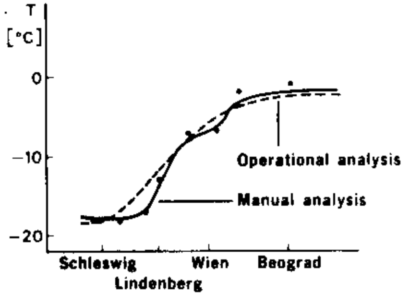


Fig. 21: Temperature sounding at Schleswig 10035 (solid line), Lindenberg 09393 (dotted), and Wien 11035 (dashed) at January 1983 00 GMT.

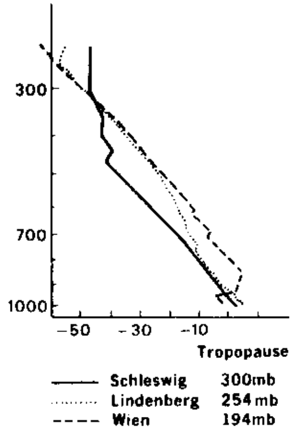


Fig. 20: 700 mb temperature along a line from the North Sea to Thessaloniki at 15 January 1983 00 GMT.
Dots: observed data;
solid line: manual analysis;
dashed line: operational analysis.

comparison, Fig. 20 shows the observed values together with the analysed ones along a line from the North Sea via Wien to Thessaloniki (indicated in Fig. 19 by a bold line). The operational ECMWF analysis, as displayed here, may be smoother than the original analysis because of interpolations from the original grid via spherical harmonics to the plotting grid and it should also be mentioned that the scheme analyses thicknesses between standard levels instead of the temperature at a level. Nevertheless, we see that the analysis scheme has done what it was told to do: it fitted a smooth curve which deviates from the observations according to the specified observational error. The stronger gradient in the manual analysis near Lindenberg is in accordance with our knowledge of the structure of a front but this in not incorporated into the analysis scheme.

In the manual analysis supported by the observations a double structure in the gradient can be found with a reduced gradient between Praha and Wien. This may indicate the existence of a subtropical front south east of Wien or at higher levels above Wien. Radiosonde soundings shown in Fig. 21 support this suggestion: Schleswig represents clearly an ascent within polar air masses. The tropopause is low, the tropospheric temperatures are low and the stratosphere is warm. The sounding at Lindenberg is cold in the lower tropopause like polar air; above 500 mb it has the structure of air masses of the mid-latitudes with a tropopause at 254 mb. The 700 mb level lies in the transition between both air masses which is the polar front. The sounding at Wien shows warm air throughout except a very shallow layer at the surface. Its high tropopause of 194 mb indicates that the upper part of the sounding lies within tropical air masses and some inversions around 700 mb may represent the subtropical front which separates tropical air masses from the those of mid-latitudes. The subtropical front is often not as clearly marked as the polar front in the temperature field and was also not analysed in the cross-section by Palmen and Newton (1969) in Fig. 17, although a few indications for its existence in that cross-section are given. We do not want to carry this discussion further but the existence of a subtropical front would explain the double structure in Fig. 20 and it would suggest that the manual analysis should enhance the temperature gradient south west of Wien even further.

These examples indicate that there are smaller scale structures resolved in the observational data which can be interpreted and incorporated in the analyses by using our knowledge of the atmospheric behaviour, even if the density of observational data is not sufficient to analyse these scales with straightforward methods. Defant and Taba (1957), and Baese and Arpe (1974) tried to quantify the knowledge of air masses and frontal structures to provide help for analysing them.

For present forecasting models which have coarse resolutions compared to these structures, this information is not needed or may even be detrimental. Future models with higher resolutions will probably need frontal structures in the initial data because they are the areas where the most important processes take place. It will require observational data with higher resolution also over the oceans.

REFERENCES

Baese, K. and K. Arpe, 1974: Der Jahresgang der characteristslischen Temperaturen der Polarfront in verschiedenen Standardniveaus. Meteorologische Rundschau, 27, 110-109.

Baumhefner, D.P. 1971: On the effects of an imposed southern boundary on numerical weather prediction in the northern hemisphere. J.Atmos.Sci., 28, 42-54.

Baumhefner, D.P. 1972: Further experimentation with an imposed southern boundary for large-scale numerical weather prediction. J.Atmos.Sci., 29, 768-772.

Baumhefner, D.P.,and P.R. Julian, 1975: The initial structure and resulting error growth in the NCAR GCM produced by simulated, remotely sensed temperature profiles. Mon.Wea.Rev., 103, 273-284.

Bengtsson, L., 1976: Initial data and some practical aspects of Weather Forecasting. In: Weather Forecasting and Weather Forecasts: Models, Systems and Users - Vol.1. NCAR/CQ-5 1976 - ASP.

Bengtsson, L., 1983: Operational requirements of long-range forecasting. The WMO/CAS JSC Expert Study Meeting on long-range forecasting, Princeton, 1-4 December 1982. WMO Programme on short, medium and long range weather prediction research.,11pp.

Cadet, D.L. 1983: Mean fields of precipitable water over the Indian Ocean during the 1979 summer monsoon from TIROS-N soundings and FGGE data. Tellus, 35B, 329-345.

Defant, Fr., 1974: Das Anfangsstadium der Entwicklung einer baroklinen Wellenstörung in einem baroklinen Grundstrom. Berichte aus dem Inst. f. Meereskunde, Kiel, Nr.4, 106 pp.

Defant, Fr., H. Fechner, and P. Speth, 1972: Synoptic und Energetik der Hamburger Sturmflutwetterlage vom Februar 1962. Berichte des Deutschen Wetterdienstes, Nr.127 (Band 17), 85 pp.

Defant, Fr., and Taba, 1957: The three-fold structure of the atmosphere and the characteristics of the tropopause. Tellus, 9, 259-274.

Hollingsworth, A., and K. Arpe, 1982: Biases in the ECMWF assimilation system. ECMWF Tech.Memo.No.46.

Hollingsworth, A., A. Lorenc, M.S. Tracton, K. Arpe, G. Cats, S. Uppala, and P. Kållberg, 1985: The response of numerical weather prediction systems to FGGE Level III-b data, Part I: Analyses. Quart.Jour.Roy.Met.Soc., 111, 1-66.

Hooper, A.H., 1975: Upper-air sounding studies, Vol. I: Studies on Radiosonde performance. WMO Tech.Note 140.

Hubert, L.F., 1979: Wind derivation from geostationary satellites. In: Quantitative meteorological data from satellites (J.S. Winston, ed.). WMO Technical Note No. 166, WMO-No. 531, 33-59.

JPS 1981-1982 FGGE Operations Report. Vol.1-12. ICSU/WMO, Geneva.

Johnson, D.S., 1985: Meteorological parameters derived from space-based observing systems - FGGE and after. ECMWF Seminar on Data Assimilation Systems and Observing System Experiments with Particular Emphasis on FGGE, 3 - 7 September 1984, Reading, U.K., 47-108.

Kållberg, P., S. Uppala, N. Gustafsson and J. Pailleux, 1982: The impact of cloud track wind data on global analyses and medium range forecasts. ECMWF Tech.Rep.No.34, 54 pp.

Kaplan, L.D., 1959 Interference of atmospheric structure from remote radiation measurements. J.Ops.Soc. of Am., 49, 1004-1007.

Karhunen, P., 1983: Automated windfinding developments. Vaisala News 98, 10-13.

Lange, A., 1985: Quality of TEMP data. ECMWF Workshop on Use and Quality Control of Meteorological Observations, 6-9 November 1984, Reading, U.K.

Lally, W.E., 1973: The Carrier-Balloon-Omega Dropsonde sub-system for the global experiment. GARP Publications Series No. 11, The First GARP Global Experiment, Objectives, and Plans, 80-82.

Lorenz, E.N., 1969: The predictability of a flow which possesses many scales of motion. Tellus, 21, 289-307.

Miyakoda, K., and, L. Umscheid, 1973: Effects of an equatorial "wall" on an atmospheric model. Mon.Wea.Rev., 101, 603-616.

Morgan, J., 1985: The accuracy of SATOB cloud motion vectors. ECMWF Workshop on Use and Quality Control of Meteorological Observations, 6-9 November 1984, Reading, U.K.

Nash, J., J.F. Ponting, M. Kitchen, and P.H. Jeffries, 1984: Intercomparison statistics from Phase I of the WMO International Radiosonde Comparison (CIMORSEX), June-July 1984. Volume I: Temperature [at standard pressure levels]. O.S.M. No.29, available from U.K. Met. Office Bracknell.

Palmén, E., and C.W. Newton, 1969, Atmospheric circulation systems. Their Structure and Physical Interpretation. Academic Press, New York and London, 603 pp.

Shaw, D., P. Lönnberg, and A. Hollingsworth, 1984: The 1984 revision of the ECMWF analysis system. ECMWF Tech.Rep.No.92, 69pp.

Suchman, D., and D.W. Martin, 1976: Wind sets from SMS images: an assessment of quality for GATE. J.Appl.Met., 15, 1265-1278.

van Maanen, J., 1981, Objective analysis of humidity by the optimum interpolation method. Tellus, 33, 113-122.

Whitney, L.F.,Jr., 1983: International comparison of satellite winds - an update. Adv. in Space Res., 2(6), 73-77.

W M O 1983 Guide to Meteorological Instruments and Methods of Observation, Fifth edition. WMO - No. 8, Secretariat of the World Meteorological Organization, Geneva, Switzerland.