Forecasting Research

Forecasting Research Division
Technical Report No. 158

OBSERVATIONS IN THE UK UNIFIED MODEL AND RECENT IMPACT STUDIES

by

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CONTENTS

1. INTRODUCTION

1.1 AIMS

The aims of this Technical Report are to outline the latest use of observations in the UK Met Office's Unified Model (UM) and to review the results of the latest impact studies at the UK Met Office and other organisations. The need to write this review was agreed at the Steering Group on Observations for NWP (SGON). The contents will be updated to take into account new observations, new assimilation techniques and results of new impact studies.

The starting-off point for this Report was the Met Office College's '*Numerical Weather Prediction Notes*' (1993). Some of the material in these notes has been reproduced while other parts have been updated or expanded. The contents of the processes within the UK Met Office's NWP system have been extracted mainly from the non-technical sections of unpublished internal reports. Other information has been obtained from personal communication within the Central Forecasting and Forecasting Research Divisions.

1.2 SUMMARY OF OBSERVING SYSTEMS

Table 1.1 shows the typical numbers of observations used in Global NWP.

	00 GMT		12 GMT	
Surface land	4440	(97)	4822	(99)
Ships and fixed buoys	681	(91)	695	(94)
Drifting buoys	425	(70)	544	(68)
Radiosondes	783	(95)	777	(96)
Aircraft	5577	(94)	3368	(95)
Satellite cloud motion winds	2765	(95)	2997	(97)
Satellite soundings (500 km)	772	(81)	717	(74)
Local area satellite soundings	13	(100)	1102	(100)
Satellite soundings (120 km)	13729	(76)	12428	(67)
Satellite scatterometer winds	36787	(61)	37649	(64)

Table 1.1 *Average numbers of observations received in time for use in the Global Model forecast run, cut-off t+3.20, in December 1994. The figures in brackets are the ratios (expressed as percentages) of the numbers of observations available by t+3.20 to the numbers received in time for the update run, cut-off t+11.20. Note that local area satellite soundings are extracted and processed, but not currently (in Feb 95) used in the model. (Courtesy: Bruce Little).*

A fuller description of these observing systems is given in Section 2.2.

1.3 DATA ANALYSIS AND ASSIMILATION - AN OVERVIEW

Before the forecast model is run, it is vital that as good a representation as possible of the initial state of the atmosphere is achieved within the model. There are large areas of the globe with few meteorological observations of any kind and an initial analysis cannot be created by the use of a single set of observations valid at a given time. Also some of the observations may be misleading.

A means of filling these gaps in space and time is achieved by supplementing observations with a short period forecast from an earlier model run, known as a *background field*. The process of data assimilation consists of blending received observations of the real atmosphere with the background field in such a way that an objective best initial analysis may be derived.

This process effectively enables information contained in past observations to be carried forward in time and space to provide data for a model analysis after their valid time. For example, the analyses fields over the Atlantic are derived not only from observations in the local area, but also from information in past observations over North America spread eastward by the model as it is integrated forwards over several hours or even days.

As well as carrying information from past observations, the background field also provides a strong dynamical constraint on the analysis.

The UK Met Office employs a technique known as *repeated insertion*. This consists of repeatedly inserting an observation into an evolving model atmosphere over a period around its time of validity. An analysis is performed at each time-step, with observations being given changing weights according to the proximity to their data time. In this way, the evolving model is continually gently "nudged" towards the observed state of the atmosphere. Fields are thus given time to balance themselves without the need of a separate initialisation.

As well as avoiding the need for initialisation (which can have detrimental effects on the short period rainfall forecast), the scheme's principal advantages are (a) asynoptic data insertion (where the data may be inserted at their correct time rather than merely being inserted at the synoptic analysis time with reduced weight) and (b) the possibility of tailoring the assimilation to each observing system according to its characteristics. The process is described further in Section 3.

1.4 VERSIONS OF THE UNIFIED MODEL

Use of observations in three configurations of the UM - the global model (GM), the limited area model (LAM) and the mesoscale model (MES) - will be described. The three configurations share the same physical parametrizations. Fig 1.1 shows the domains of the GM, LAM and MES and how they relate to each other.

There is also an optionally relocatable LAM version (which to date has been specified at mesoscale resolution) to cover customer interests remote from the UK where a higher than global resolution is required.

Table 1.2 summarizes the differences in resolution and time-step of the three versions of the UM. (Note that the UM has three time-steps - for adjustment, advection and physics. It has been conventional just to quote the advection time-step, which has been the same as the physics time-step. For technical reasons, the assimilation time-step - quoted in Table 1.2 - is now tied to the physics time-step and is longer than the advection time-step.)

	Resolution (km)	Levels	Physics/ assimila-tion time-step (minutes)
Global model (GM)	~90	19	20
Limited area model (LAM)	~50	19	15
Mesoscale model (MES)	16.8	31	5

Table 1.2 *Characteristics of the global, limited area and mesoscale configurations of the unified model (January, 1995).*

Table 1.3 shows approximate heights of the model levels. These are important because, for example, some of the observations are pre-processed on to model levels prior to assimilation and some surface observations have their direct influence restricted to the boundary layer levels.

MES height (m)	MES level	LAM and GM height (m)	LAM and GM level
13700	26	13700	14
11750	25	11750	13
10260	24	10260	12
9040	23	9040	11
7900	22	7900	10
		6840	9
6800	21		
5870	20		
		5510	8
5050	19		
4300	18		
		4180	7
3640	17		
3080	16		
		2950	6
2600	15		
2200	14		
		1940	5
1870	13		
1600	12		
1365	11		
1155	10	1155	4
955	9		
770	8		
595	7	595	3
435	6		
300	5		
		215	2
190	4		
100	3		
40	2		
		25	1
10	1		

Table 1.3 *Approximate heights (metres) above the surface of GM, LAM and MES model levels up to 13.7 km.*

Above about 8 km, the levels in the MES are the same as in the LAM and GM, with an uppermost level at about 40 km.

From an 'observations' viewpoint, the height difference between model levels is important because the pre-processing gets more out of a radiosonde report in the MES, with a higher vertical resolution, than in the LAM or GM.

Boundary conditions and initial analysis for the LAM are provided by GM forecast values from an earlier run interpolated on to the LAM coordinates. The LAM provides boundary values for the MES.

2. <u>OBSERVATION PROCESSING FOR THE UM ANALYSIS CORRECTION SCHEME</u>

2.1 FILE HANDLING WITHIN THE OBSERVATION PROCESSING SYSTEM

The Observational Processing System (OPS) takes pre-processed observational data from a data base and processes them to a standard file which is used by the assimilation scheme. This scheme forms the front end to the various configurations of the UM. The OPS also provides some monitoring data to be returned to the data bases.

There are three main processes within the OPS (Fig. 2.1): processing and quality controlling any observation type, obtaining data for monitoring and converting data to assimilation format.

2.1.1 <u>Step (a):</u> <u>Processing and quality controlling any observation type</u>

This is the main processing performed on the observations. The steps prior to quality control are as follows (Dumelow (1993)).

(i) To extract data from the Synoptic Data Bank (SDB) or Meteorological Data Base (MetDB);

(ii) to carry out conversions of observed quantities into those required by the quality control and assimilation scheme e.g., wind speed and direction to u and v components;

(iii) to apply corrections to the observational data;

(iv) to accumulate information for archiving in the Observation Processing Database (OPD);

(v) to set:

- 'data use flags', determined from station list information, showing whether or not a variable from a given observation should be used,
- initial probability of error,
- observation error values;

(vi) to calculate differences between observed values and background values obtained from a short model forecast;

(vii) to obtain estimates of background error at observation positions, using algorithms which relate that error to components of the synoptic situation (e.g., pressure tendency, pressure gradient, wind speed); these algorithms are 'trained' using the monitoring data accumulated in Step (b).

The observations are described in Sections 2.2 and 2.3. The quality control is described in Section 2.4.

2.1.2 Step (b): Obtaining data for monitoring

For each observation catered for in Step (a), the set of model background values used in the quality control is obtained. These values are combined with the original data element and returned to the data base together with the quality control information. Data from the model analysis fields are also combined into the data base.

The monitoring data have several uses. Departures of an observation from model background and analyses, if considered carefully, yield information on, for example, observation rms error, background rms error, observation bias, the need to blacklist observations and bias corrections. The departures also provide feedback to the quality control scheme and error input to assimilation.

More details are given in Radford (1994a).

2.1.3 Step (c): Converting data to assimilation format

This step takes the final processed and quality controlled data and puts them into the format required by the assimilation part of the UM. This is the AC observation (ACOBS) file format. This file contains all the required information about those observations which have passed (or partially passed) the quality control stages.

The observations may be in a form similar to that observed (e.g. AIREP reports), or may have undergone substantial processing (e.g., radiosonde reports which are vertically averaged on to model layers). In all cases, the variables are transformed into those which are assimilated. For example, surface pressure is assimilated as p* (pressure at the model surface), moisture information as relative humidity and temperature as potential temperature.

The assimilation is described in Section 3.

2.2 OBSERVATION INPUT TO THE GM, LAM AND MES

In this section, a brief description is given of each observing system whose data are input to the UM observation processing. The contents of Sections 2.2.1 - 2.2.3 and 2.2.8 are based on Dumelow (1993).

Variables which are used from different data types in the GM, LAM and MES are shown in Table 2.1.

Observation type	MSLP	Temp	Geopot-ential	Wind	R.H.	SST	Cloud	Rain rate
Surface land	✓	*		*	*		*	*
Ships	✓	x		✓	x	✓	*	*
Fixed Buoys	✓	x		✓	x	✓		
Drifting Buoys	✓	x		x		✓		
TEMPS (from Sondes)		✓	x	✓	✓			
PILOTS (from Sondes)				✓				
Aircraft reports		✓		✓				
Winds from ERS-1 Scat-terometer				✓ GM only				
Cloud motion winds (SATOBS)				✓				
Satellite soundings 500 km		✓ Layer means			x			
Satellite soundings 120 km		✓ Layer means			x			
Radar imagery								*
METEOSAT imagery							*	

Table 2.1 *Observations available for the GM, LAM and MES over a 24-hour period.*

✓ *denotes an element that is measured and used by the model.*
x denotes an element that is measured but not used.
* *denotes observation types only used in the MES.*

Most meteorological measurements contain a contribution from motion (or from thermal and humidity structures) on spatial and temporal scales too small to be resolved by NWP models. A radiosonde wind observation, for example, comprises a contribution from the synoptic-scale flow which can be resolved and a contribution from local gustiness (scale of order 100 m) which cannot be resolved. Theoretically, the smallest scale which can be resolved on a model grid is given by twice the grid length (e.g. ~200 km for the GM; ~100 km for the LAM; and ~34 km for the MES). The small scale "roughness" which is sampled by the observations, but which the model is incapable of representing, is referred to as the *representativeness error*.

Such errors also apply to the vertical which may be more important than the horizontal when discussing multi-level observations (sondes and soundings). The issue of representativeness error can also arise from not being able to represent small temporal scales.

For most observations, the assimilation deals with the representativeness error (which can be estimated) by incorporating it into the overall observation error (i.e. observation error = instrument error + representativeness error) and weighting the impact of the observation in proportion to the inverse of the observation error. However, in some cases the representativeness error is considered so large that it is impracticable to use the observation. Examples are surface temperature observations which, overland, are subject to local (small-scale) heating effects and surface winds over land which are subject to local unresolved orographic effects. These observations are not used in the GM or LAM. In the MES, however, other observations which are included (Table 2.1) resolve the effects of the orography much better.

2.2.1 Surface Observations

Surface data consist of reports from land stations, ships, rigs, platforms, fixed and drifting buoys. Figs. 2.2(a) and 2.2(b) show examples of data coverage.

(a) Land

(i) GM and LAM

Land stations are widely and in some places (e.g. over north-west Europe) quite densely distributed over the world's land masses. They report pressure, temperature, wind speed and direction and dew point as well as many other quantities such as visibility and cloud amount which are not directly used to influence the model forecast (except for the MES).

The GM and LAM only use pressure which is reported in the form of either station level pressure, mean sea level pressure (MSLP) or the height of a standard pressure level at, for example, 850 hPa. This is converted to pressure at the height of the model surface.

Only one observation from any station is presented to each data assimilation cycle. For the GM, with a 6-hourly cycle, only the 00, 06, 12 and 18 UTC observations are used. Three-hourly reports are used in the LAM.

(ii) MES

One-hourly reports are used in the MES. The MES makes use of more information in the report (e.g. wind, temperature, cloud and visibility, dewpoint) as described in Section 2.2.7.

Hourly screen level temperature and humidity (SYNOP, not SHIP), 10 m wind over land and surface pressure data are assimilated by the MES. Bogus observations from the Central Forecasting Office (CFO) are also used (Section 2.2.8). Screen temperature data input into the MES are corrected before assimilation by a standard lapse rate to allow for differences between station and model orographic heights. Temperature increments are applied to the surface temperature T_*, and with decreasing weight up to a height of about 435 m (level 6). (An 'increment' in this context is the difference between the observation and model background field at the location of the observation.) No change is applied to sea surface temperatures.

SYNOP wind data increments are computed by comparing observations with a model background field of derived 10 m winds.

There is a station blacklist for excluding SYNOP 10 m wind observations from certain high level or valley stations where they are unrepresentative of the mesoscale grid box.

Aerosol and visibility observations are about to be introduced (February 1995).

(b) Marine

This type of data includes reports from ships, platforms and rigs and automatic buoys.

Reports from oil and gas-drilling platforms and rigs may be made manually or automatically and, together with ship reports, generally rely on manual transmission methods. Because of this, reports may be received several hours after the observation time and may miss the cut-off time for data used in NWP. These data are not as reliable as surface land reports and observations from certain ships particularly prone to error may not be used. A common type of error is bias in the reported pressure.

Automatic buoys fall into two categories, fixed and drifting. Fixed buoys may be interrogated for observations manually or by geostationary satellite.

Drifting buoys are regularly released in data-sparse ocean areas to drift with currents, though a few are moored. They have been deployed in greatest numbers in the southern hemisphere. Data are received via polar-orbiting satellite, being available during each NOAA overpass. Drifting buoys report MSLP, and some report sea surface temperature, dew point and wind speed and direction.

Ships, platforms, rigs and fixed buoys all report the same basic quantities as land stations, but always report MSLP. Most ships reporting are commercial vessels, but there are a few Ocean Weather Ships (OWS) devoted to making meteorological observations only.

Wind speed values are obtained either by visual estimate of the state of the sea surface, or by anemometer measurement. Visual estimates are considered to be a more accurate measurement of the surface wind, since instrument-measured values are influenced by the height of the instrument and the fact that the flow is disturbed by the structure of the ship itself. Additionally, instrument-measured winds have to be corrected to take account of the velocity of the ship. This process is a common source of error.

In the MES, ship wind observations are assumed to have a nominal height of 20 m, and are directly compared with model 'level 1' winds, at approximately 10 m. This procedure is the same as in the GM and LAM. As with screen temperatures, increments are spread with decreasing weight up to level 6 (435 m).

(c) Data Use and Conversions

MSLP is the quantity used by the quality control scheme from all reports, although pressure at the model surface is used in the assimilation scheme. Temperature, wind and dew point values from land stations are not used because of the representativeness error problem already discussed. (They may often contain information about small scale features of the atmosphere (such as those influenced by orography) which cannot be represented by the forecast model. Similarly, wind observations from drifting buoy reports are not used as they are considered to be unduly influenced by the motion of waves acting on the buoy.) However, ship winds are used because their anemometers are sufficiently high to be free of small-scale turbulent fluctuations. In the GM and LAM, surface temperature and dew point from ships and buoys are not assimilated.

Reports from certain ships, drifting buoys and land stations are permanently rejected as they are considered to be unreliable. Corrections are also made automatically to ships' pressures that are consistently too high or too low.

Station level pressure and the height of a standard pressure level from land reports must be converted into MSLP for use in the quality control scheme and model surface pressure for the assimilation. (Note that station level pressure is not available for UK stations.) These conversions are made using the hydrostatic equation, assuming a linear variation of temperature with height. Surface temperature from such reports is also used in the MES. These must be extrapolated by a standard lapse rate correction to the model surface before use.

2.2.2 Upper air data from Radiosondes

(a) The Data

Radiosonde reports give either temperature, dew point and wind speed and direction (called TEMP reports) or just wind speed and direction (called PILOT reports). TEMP reports and some PILOT reports also contain geopotential height. Measurements are taken at standard and non-standard pressure levels up to around 10 hPa.

(An upper air report for a particular location is received in up to four different parts called Part A, Part B, Part C and Part D. Part A consists of values taken at standard levels up to 100 hPa, Part B values at non-standard levels up to 100 hPa, Part C values at standard levels above 100 hPa and Part D values from non-standard levels above 100 hPa. The standard pressure levels are 1000, 925, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, 10 hPa. These parts are combined, and some quality control is performed on the values.)

Radiosondes are considered to produce very valuable data. All of the data from most reports are used by the quality control and assimilation schemes. Certain reports (e.g. Indian sondes), however, are considered to produce unreliable data which are permanently rejected.

Radiosonde observations from ships are called TEMPSHIPS. They are taken from ocean weather ships (OWS) and from merchant ships equipped with ASAP (Automated Shipboard Aerological Program) systems.

Figs 2.3a and 2.3b show the typical global distribution of TEMP and PILOT reports (from both land and ship). (Fig. 2.3b includes the special network of wind profilers in the USA since winds from profilers report in PILOT code.)

(b) Conversions

(i) Wind speed and direction to wind components

Wind speed from radiosonde reports is measured in knots (or ms^{-1}) and direction in degrees from north. These need to be converted into wind components (u, v) for use in the quality control and assimilation schemes.

(ii) Dew point to relative humidity

Dew point temperatures need to be converted to relative humidity since this is the quantity used by the quality control scheme.

Dew point observations are measured as a saturation temperature <u>with respect to water</u>, whereas the UM requires relative humidity <u>with respect to ice</u> when appropriate.

(iii) Heights to pressure

Certain radiosonde reports, particularly PILOT reports, contain geopotential height rather than pressure as a vertical coordinate. In these cases, the height must be converted to pressure so that the data can be used by the quality control and assimilation scheme. The conversion is carried out in one of two different ways depending upon the type of report. For TEMP reports with missing pressure levels, the conversion takes place assuming the UM standard atmosphere which is based upon the ICAO standard atmosphere.

PILOT observations sometimes have pressure sensors on board in which case no conversion is required. Most, however, measure their vertical position as a height. The heights at which observations of wind are made are specified by WMO and vary according to WMO region. Heights are converted to pressure using the model background field.

(iv) Bias correction to radiosonde relative humidity

A bias correction is added to radiosonde relative humidity values on model levels before presentation of the data to the assimilation. This correction can be seen mainly as an attempt to correct for a systematic dry observational bias in cloud, but in a manner consistent with the model cloud scheme and the residual effects of inadequate model resolution in the vertical. The correction is applied for relative humidity > 80%. It has a maximum value of 3% for the MES and 4.6% for the LAM/GM profiles.

2.2.3 Aircraft Observations

(a) The data

Wind speed, wind direction, and temperature are reported from aircraft. Apart from coding errors, the reports are generally of high quality. Vertical positions (flight levels) are reported in terms of geopotential height in feet. There are three systems by which aircraft observations are made: one manual and two automatic.

The manual observations - AIREPS - are usually taken at cruising levels (typically 10-13 km) as the aircraft crosses 10^0 longitude lines as indicated by radio beacons. They are transmitted to air traffic control when the pilot reports his position. Reports taken at certain beacon positions or from certain aircraft are considered unreliable and are permanently rejected.

Some AIREP reports, particularly those from the North Atlantic, do not report at beacon positions. Some values are taken during the ascent and descent phase of each flight. Fig 2.4(a) shows a typical data coverage for AIREPS.

The automatic reports are taken by instrumentation on board the aircraft and transmitted via satellite (called ASDAR data) or directly (by VHF signal) to ground stations (called ACAR reports). (Some ACAR reports, mainly from North America and Australia, report in a code form known as AMDAR.) Fig. 2.4(b) shows a typical global network of AMDARS and ASDARS.

(b) Conversions and corrections

(i) Wind speed and direction to u, v

Conversion to u and v components is performed as described for radiosonde data.

(ii) Flight level to pressure

The ICAO standard atmosphere is used to convert flight level to pressure.

No corrections are currently applied to aircraft observations.

2.2.4 Scatterometer data

The scatterometer on ERS-1 provides wind measurements over the oceans by measuring the microwave back-scatter from ocean capillary waves at three look directions. (For details, see Bell, 1994.) The triplet of back-scatter measurements can be related to a wind speed and direction using an empirical transfer function. Ambiguities in direction are removed with the assistance of NWP model background winds.

The final product of the data pre-processing is a 500 km wide swath of wind vectors with 19 overlapping 50 km cells across the swath at a separation of 25 km. With this swath width, one-third of the earth's ocean area is observed in one day. (In reality, the coverage is rather less because the scatterometer competes for operation with another instrument on ERS-1. Coverage over the North Atlantic is particularly poor.)

Fig 2.5 shows the coverage for a period of 24 hours during a trial in March 1993. There is an occasional missing orbit. There are gaps in the orbits where the instrument has been temporarily disabled (e.g. the three orbits in the North Atlantic between 0° and 40° west).

The scatterometer data have substantially higher quality than ship data in all areas. The scatterometer provides 15 times more data in the northern hemisphere than ships and 100 times in the southern hemisphere.

The data assimilation takes account of the characteristics of the scatterometer data which differ significantly from conventional sources of marine surface wind data. The main differences are the geographical distribution and the nominal height of the report. Another difference is that the scatterometer is unable to provide reliable directional information in light winds. Below 4 m/s, the assimilation uses only speed information.

2.2.5 Cloud-motion winds

Processing of successive pictures (typically every 30 minutes) from geostationary satellites can be used to measure cloud motions, and then to derive a wind measurement by assuming that the cloud motion is a good wind tracer. For each such measurement, a pressure level is assigned. These measurements are called cloud motion winds (SATOBS). In this section, winds from the IR channel are discussed. (It is also possible to derive winds from WV and VIS channels but these are not used).

There are several problems associated with deriving wind data from cloud motion, including the assignment of cloud height and the identification of cloud development and orographic effects. Height is usually related to IR cloud brightness temperature and may not be representative of the level at which the main bulk of the cloud is moving.

Winds are derived using data from five satellites (METEOSAT (operated by Europe and located at 0°E), GOES E (USA - 70°W), GOES W (USA - 140°W), GMS (Japan - 140°E) and INSAT (India - 74°E)) four times a day covering an area within approximately 50 degrees latitude and longitude of the sub-satellite position. Fig 2.6 shows a typical global coverage. At present, no INSAT winds are used; also, no low-level METEOSAT, GOES or GMS winds are used over land outside the tropics (20°N-20°S).

Most SATOBs are derived for the jet stream level or the boundary layer. In jets there tends to be a strong negative bias in wind speed (rarely reporting speeds over 100 m/s), although the directions are reliable. SATOBs are of great importance in the tropics, where the tracking of trade-wind cumulus is the principal data source.

2.2.6 Satellite temperatures (SATEMS)

(a) Overview

Radiometers on board polar-orbiting satellites measure upward radiative fluxes at a number of wavelengths in the infra-red and microwave spectrum. Two NOAA satellites provide a full global data coverage every six hours. The TOVS instrument package consists of three radiance measuring instruments:

- **(i)** High resolution Infrared Radiation Sounder (HIRS) sampling at 19 infra-red channels and one visible channel.
- **(ii)** Microwave Sounder Unit (MSU) sampling at 4 microwave frequencies.
- **(iii)** Stratospheric Sounder Unit (SSU) sampling at three additional infra-red channels.

The vertical resolution provided by each sounding is much lower than from radiosondes but horizontal detail may be good. Data are of much lower quality than that received from radiosondes, and temperatures over land are not used below 100 hPa.

In the mid-latitudes of the southern hemisphere, they constitute a valuable data source. Here, impact studies have shown a much reduced forecast quality in their absence.

Procedures for producing background values of temperature from radiances are complex. There are two basic methods. The first is based on matching the observed radiances with a library of profiles and is used by NESDIS. It is often called the "NESDIS" scheme.

An alternative method is to use temperatures from the model background field. A profile of temperatures and humidities from the background field is put through a Radiative Transfer Model to calculate brightness temperatures. The background profile is then modified until brightness temperatures calculated from it are in good agreement with the measured brightness temperatures. The final profile is the retrieval as passed to the assimilation scheme. This method has demonstrated better impact on NWP forecasts. In the presence of cloud, the quality of the retrievals is reduced. If cloud is detected, only channels not affected by the presence of cloud are used.

Four categories of satellite sounding data are available to the unified model assimilation. These all originate from the same radiance data from TOVS but are processed in different ways. The two types of "SATEM" reports described below are generated by the NESDIS scheme. The "LASS" and "GLOSS" reports are obtained in the UK using model background fields.

A full history of the assimilation of TOVS data together with details of current and future systems are presented in Gadd et al (1995).

(b) High resolution SATEM reports (SAT120)

The mean spacing between observations is 120 km. These reports give mean virtual temperatures for fifteen layers. However, only the temperatures for twelve layers, between standard levels 1000 hPa and 10 hPa, are used operationally in the GM, LAM and MES assimilation.

Fig 2.7 shows an example of the coverage from SAT120 soundings for a period of 6 hours.

(c) Low resolution SATEM reports (SAT500)

The mean spacing between observations is 500 km. The SAT500 is a thinning and re-formatting in terms of vertical representation compared with SAT120. The processing is identical to that for the SAT120. These reports give thicknesses between a reference level (1000 hPa) and standard levels, plus precipitable water content (PWC) for layers up to 300 hPa for soundings made in cloud-free conditions.

(d) Local Area Sounding System (LASS)

LASS reports are produced in Bracknell from radiances obtained as the satellite passes near the receiving station at Lasham. The soundings cover an area within about 1500 km of the UK (Fig 2.8) and are for insertion into the LAM. They are produced at a resolution of about 120 km by inversion of TOVS data (HIRS and MSU). Temperatures and dewpoints are produced at standard pressure levels. For further details on LASS, see Renshaw (1991).

(e) Global Sounding System (GLOSS)

GLOSS data, intended for the GM, are available at 120 km resolution and are obtained by inversion of TOVS radiance data (HIRS, MSU and SSU) which are in the form of cloud-cleared radiances from NESDIS and are part of SAT120. Humidities (up to 300 hPa only) and temperatures are produced on 18 standard pressure levels from 1000 hPa to 10 hPa.

The data are flagged and no retrieval is performed if the value of the observation differs from the background by 20 degrees or more in any one channel. The retrieval is flagged if the iteration procedure fails to converge sufficiently or if the retrieved profile differs too much from the observations. The method is described in Eyre (1989).

(f) Operational use

LASS is not assimilated at present because of problems about interaction with NWP background biases and the testing of a new retrieval scheme. LASS requires a thorough impact study before being re-introduced.

GLOSS awaits further testing before operational use.

NESDIS 120 km retrievals and NESDIS 500 km retrievals are currently used operationally in the GM, LAM and MES assimilation.

Within each 3° x 3° latitude-longitude box, at most one category of sounding data is selected for presentation to the assimilation in the order LASS (when operational), GLOSS (when operational), NESDIS 120 km, NESDIS 500 km. Humidity data in TOVS are not assimilated at present. Over land, soundings are not used below 100 hPa. Over the sea, the full profile is assimilated. (Note that GLOSS will include humidity).

Even at and above 100 hPa over the land, it is mainly the NESDIS 500 km soundings that are used while NESDIS 120 km soundings are not used except over Antarctica (ie south of 60°S). North of 30°S, NESDIS soundings are not used below 850 hPa.

2.2.7 Moisture Observation Pre-Processing System (MOPS)

This sub-section has been written by Bruce Macpherson.

It is important that as good a representation of the moisture field as possible exists in the model, not only because forecast details such as cloudiness and precipitation are directly dependent on humidity, but also because latent heating and cooling are important in driving mesoscale processes. To maximise the use of humidity data, including satellite and radar, a scheme known as the Moisture Observation Pre-processing System (MOPS) has been devised. Fig. 2.9 summarizes the observations in MOPS together with the other observations used in the MES assimilation.

A distribution of cloud cover is inferred using satellite data, radar data and surface observations. METEOSAT cloud top temperatures are used to diagnose cloudy areas by assuming that cloud is present wherever a brightness temperature is 5°C or more colder than the first-guess surface temperature. A cloud top height field is then derived by a combination of two methods.

For low cloud with cloud top temperature warmer than -20°C, a conceptual model of the temperature and moisture structure in a stratocumulus layer is used to assign a height to the satellite temperature.

For higher cloud, first-guess temperature profiles are used to assign heights to the cloud top temperatures. This method fails in the case of low cloud when the model has a poor representation of the associated inversion, hence the need for the conceptual model algorithm. The first-guess cloud base is adjusted if necessary to ensure that it is at least 200 metres below the cloud top.

Surface observations are used to analyze cloud bases. If an observation conflicts with the satellite-derived cloud data, it is assumed to be more accurate if the base is below 8000 ft, otherwise the satellite data are used in preference. The cloud analysis is also updated to be consistent with present weather precipitation reports, hourly rainfall accumulations (SREW) and FRONTIERS radar rainfall data.

Where no appreciable precipitation is analyzed, cloud-free layers are inserted around the -15C level to ensure the lower cloud does not glaciate. Where moderate or heavy precipitation has been analyzed, full cloud cover is set between 0C and -15C, allowing glaciation down to 0C.

From the MOPS cloud cover analysis, a three-dimensional relative humidity field is derived and is assimilated into the model in the same way as radiosonde data. Where the MOPS cloud fraction is zero, a special data value is set to constrain the model humidity to lie below the threshold for cloud formation.

The precipitation analysis from MOPS has been used in the MES model verification.

Since April 1995, the mesoscale model soil moisture field has been allowed to evolve freely during data assimilation, without periodic resetting to climatology. The MOPS precipitation rate analysis provides input to a surface hydrology correction scheme. By means of a linearised version of the model's hydrology scheme, increments to canopy water content, soil moisture content and snow depth are derived from precipitation rate increments. The scheme operates only within 100 km of radars whose calibration relative to raingauges is judged acceptable.

2.2.8 Bogus and Intervention data

The Central Forecasting Office (CFO) has facilities to generate artificial or BOGUS data. These data are usually generated when the model analysis is considered to be deficient in certain areas and the forecaster has information (e.g. satellite images) that cannot be directly used in the model. Any bogussing carried out on one configuration is automatically incorporated on to another configuration also covering the area of bogussing.

The types of bogus data allowed are:

- (i) MSLP and surface wind,
- (ii) Winds, temperature and relative humidity at any pressure level,
- (iii) 1000-500 hPa thickness,
- (iv) Re-position bogus.

Intervention is a means by which forecasters may use their knowledge and judgement to reject whole or part reports or correct elements within certain reports. Only radiosonde and aircraft reports may have their values corrected, but all types of report may be rejected. Particularly important observations can also be supported which effectively increases their weight. For further details of intervention facilities, see the technical documentation (Dumelow, 1994a).

Re-position bogus data are created by CFO as a means of correcting the positions of tropical or sub-tropical depressions in the model background fields.

2.3 OBSERVATION INPUT TO THE SEA-SURFACE TEMPERATURE SYSTEM

Material in this section is extracted from Jones (1991).

Each day, several thousand measurements are made of the sea surface temperature (SST) by a variety of observing platforms. These measurements are sent over the Global Telecommunications System (GTS) and received at Bracknell where they are stored in the SDB from which they can be extracted to be used in the analysis.

SST observations from the following observing platforms - SHIP, FIXED BUOY, DRIFTER, SATOB, BATHY, TRACKOB - are used in the analysis.

The names refer to the WMO code format in which they are sent over the GTS, except fixed buoys which are reported in the same format as ship observations. DRIFTER is the code for drifting buoy observations and BATHY is the code for bathythermograph observations. TRACKOBS are observations taken along a ship's track on the same date. In the observation processing system, each individual SST report within a TRACKOB report is treated as an isolated hourly ship observation. Thus, a single TRACKOB report may produce up to 24 hourly ship observations.

Observations reported from ships, fixed buoys, DRIFTER, BATHY and TRACKOB reporting types are referred to collectively as in-situ observations. Figs 2.10a and b show the distribution of data from the observing platforms. It can be seen from the maps that the majority of in situ data are for the northern hemisphere. However, in the southern hemisphere, most SST data are satellite reports (Fig. 2.10c).

The SATOB code is used for the transmission of satellite-derived SST products. (Note that in the rest of this Technical Report, the SATOB code refers to cloud motion winds.) These products come from two distinct sources. First, there are products derived from measurements from the Visible and Infra-red Spin Scan Radiometer (VISSR) which is flown on board METEOSAT. The second source of SATOB reports are products derived from measurements taken by the Advanced Very High Resolution Radiometer (AVHRR) which is an instrument carried on board the polar orbiting NOAA series of satellites. The AVHRR products give one observation per 2.5° lat/long box (Fig. 2.10c).

Of the satellite products, only AVHRR data are used operationally. (Although data from VISSR and the along-track scanning radiometer (ATSR) carried on ERS-1 are received, they are not used operationally.)

The job to extract the observations is executed at approximately 12Z each day. All observations made in the 24 hours up to the previous midnight that are received by the time the extraction job is run are extracted. This means that as many observations as possible are used in the analysis including those which are late arriving. The validity time of the subsequent analysis is the previous midnight.

Satellite data are very important in any SST analysis but require special treatment because of sources of error arising from diurnal effects, the "skin bulk" effect and atmospheric absorption. The aim is to obtain bulk SST within or below the diurnal thermocline where measurements from buoys or ships are made.

The SST quality control system is the same as that used in the atmospheric model (Section 2.4) but with some simplifications to allow for the fact that SST data are uni-variant and single levelled. No buddy checking is performed.

The analysis scheme is based upon the AC scheme described in Section 3.1 but also included is a satellite correction scheme to accommodate local biases in satellite-derived SST arising, for example, from volcanic aerosol. The scheme is described in Jones (1993).

2.4 AUTOMATIC QUALITY CONTROL

This section has been written by Bruce Ingleby.

2.4.1 Overview

The current automatic quality control system (operational since June 1991) is based on Bayesian probability theory, and a careful statistical analysis of observational and background errors.

Each observed element is given an initial "probability of gross error", PGE. For example, for SYNOP pressures we expect about 1.5% of the observations to be 'bad' and therefore assign them an initial PGE of 0.015. (The figures are 6%, 3% and 5% for ships, moored buoys and drifters respectively.) This PGE is increased if the element has failed one of the earlier SDB consistency checks.

Even 'good' observations have small errors. (For example, barometer accuracy is about 0.2 hPa; inaccuracies in knowledge of the station height can introduce larger errors). Account is also taken of the fact that observations include small scale detail, not resolved by the model (i.e. the representativeness error). Including this factor, the observation error for good observations of PMSL is estimated as 1.0 hPa.

Background error (BGE) fields are synoptically dependent, which means that larger errors are estimated in the vicinity of fast-moving vigorous depressions than in large anticyclones. There is also a climatological element to the BGE fields, such that latitudes having large numbers of observations will have generally lower BGE's (average about 1.3 hPa) than data sparse latitude zones (typical errors of 2-3 hPa). Large BGE estimates imply that the automatic quality control has less strict limits and also that the observations have more weight in the analysis.

2.4.2 Check against forecast background field

The most important single check is that against the forecast background (T+3 for the LAM and MES, T+6 for the GM), giving PGE2. It includes an estimate of the probability that the whole observation is wrong (e.g. position reported wrongly). The quality control of wind is based on vector differences from background rather than considering speed and direction separately.

Several observation-type specific checks are applied:

(a) Calm aircraft winds are rejected,

(b) An asymmetric check for SATOBs - tighter limits for winds weaker than the background,

(c) A tropospheric stability check for satellite soundings (rejects almost 20% of them),

(d) Multi-level checks for satellite soundings (i.e. if one or two levels appear wrong then reject all levels above/below 100 hPa as appropriate).

Radiosonde standard and significant levels are checked against the background, and then averaged over the model layers omitting levels with PGE > 0.999. The averaged data are then rechecked against the background and used in the buddy check.

2.4.3 Buddy check

The buddy check compares each observation against up to about 12 neighbouring observations, giving PGE3. If the value of PGE3 is greater than or equal to 0.5, a final flag is set and the observation is not used in the analysis.

The buddy checks performed are: surface-surface, radiosonde-radiosonde, aircraft-aircraft, SATOB-SATOB, radiosonde-aircraft. In general, observations with the same call sign are not allowed to buddy check each other, although this does not apply to SATOBs. The buddy check compares differences from background, rather than observed values themselves, e.g. two ships both 5 hPa lower than background will buddy check well, even if one is in the middle of a depression and the other has pressure 10 hPa higher 200 km away.

A fuller description of the quality control procedure is given in Ingleby and Parrett (1993a, b).

3. UNIFIED MODEL ANALYSIS CORRECTION

3.1 OVERVIEW

Once the data to be used by the model have been selected, they are combined with the model forecast fields in a way that provides the best possible estimate of the initial state of the atmosphere from which to start the forecasts. One definition might be the model state which gives the smallest short range forecast errors.

The aim is to find a model state which best fits the prior knowledge of the atmosphere and the observations, not to provide the best fit to the observations only. This prior knowledge consists of balance constraints (e.g., on the degree of geostrophy or non-divergence of analysis increments) plus information from observations made at earlier times. This information is best encapsulated in a model forecast from previous analyses. The best fit is found by minimising the departures from the background and from the observations.

(Theoretically, a 'penalty function', which is the sum of the background and observation penalty functions, is minimized. A penalty function is really a complicated multidimensional vector notation equivalent to a simple least squares fit. The analysis is optimal when its departure from both background and observations is minimised.)

Account has to be taken of the errors in the observations and background field. The errors are assumed to be Gaussian, any non-Gaussian errors having already been removed by the quality control (Section 2.4). The observation error includes a component called the representativity error which arises because observations representing a model grid box are needed.

The UM assimilation scheme is called the *analysis correction scheme* because an analysis made at each time-step corrects the model's forecast fields towards the observed state. The scheme is described in Lorenc et al (1991). The UM employs a repeated insertion technique whereby observations are repeatedly inserted into an evolving model around their validity time (Fig. 3.1).

During each time-step of the assimilation period, the fields of motion and mass are adjusted towards hydrostatic and geostrophic consistency. This, together with the fact that model fields are continuously 'nudged' towards the observed state in small amounts, ensures that the balance is approximately maintained within the model and a final initialisation step is not necessary. Repeated insertion also achieves simultaneous consistency between the observations and a slowly varying rate of the model, thereby reducing 'spin-up' problems.

Observations are allowed to influence the model even if they are valid after the nominal analysis hour. (For example, in the GM, there is a well-defined change from assimilation mode to forecast mode at 4 hours after the analysis hour.)

3.2 STAGES IN THE ANALYSIS CORRECTION SCHEME

An attempt will be made to outline the steps in the analysis correction scheme in a simple way. For more detailed information, the reader is referred to Bell et al (1993).

The sequence of steps is shown in Fig. 3.2. First, data are SPLIT into categories affecting each model variable - surface pressure, potential temperature, wind and relative humidity. The scheme may then be regarded as a multi-stage process - the vertical processing ('PREPARE' - Stage 1), the horizontal processing (' ANALYZE' - Stage 2) and the balancing of increments ('BALANCE' - Stage 3). Although each iteration is split into a vertical and horizontal time step, the analysis is essentially three-dimensional.

3.2.1 Stage 1: Vertical processing

The vertical profiles of observation increments and errors on model levels are generated. (An *'increment'* is the departure of an observation from the current model field. An *'error on a model level'* is an observation error normalised by background error and scaled by the vertical error correlation which reduces the influence of the observation at levels distant from it.) This process is carried out for data from single level observations, radiosondes and satellite soundings.

It is important to recognise that the influence of a single level observation is spread such that it may extend through many model levels. For example, although the influence of an AIREP decreases away from its nearest model level, its influence may still be felt down to quite low levels (Fig. 3.3).

For some observations, a cut-off in influence region is imposed. For surface wind data, the influence region extends only to the top of the boundary layer. Data from surface observations in MOPS also extend only to a certain height. Bogus humidity data are used only at the nearest model level.

3.2.2 Stage 2: Horizontal processing

(a) The analysis equation

The horizontal processing is best understood by appreciating the roles of the terms in a simplified form of the analysis equation for an increment of any model variable 'x' at grid point k at a model level (Fig. 3.4).

> The relaxation coefficient (α) determines the rate at which the model adjusts to the observation,
>
> The observation increment (C_i) is the difference between the observed value of the model variable and the model background value interpolated to the observation position at the current time step.

The other terms contribute to the weight applied to the observation at the grid point.

> The time factor ($R^2\delta t_i$) is a function of the difference between the time of the current model step and the observation time.
>
> The correlation function (μ_{ki}) decreases as the horizontal

separation between the grid-point and the observation increases.

As a result of combining the time factor and correlation function, an observation enters the assimilation with low weight affecting larger scales. As the model time approaches the observation time, the observation affects smaller scales with high weight.

The normalisation factor (Q_i) for each observation takes account of

- the density of observations in space and time; the term ($1+D_i$) allows more weight to be given to an isolated observation,

- the ratio of the observation error to the background error in the term epsilon.

(b) Insertion period and time weighting

Because the adjustment process cannot be achieved instantaneously without upsetting balances in the model and giving rise to spurious motions, the changes are applied in small amounts during an insertion period which depends on the model configuration (Bell et al, 1994b).

(i) GM and LAM

For the GM the insertion period is 5 hours: 4 hours before observation time and 1 hour after.

For the LAM the insertion period is 3 hours: 2.5 hours before the observation time and 0.5 hours after.

For the GM and LAM, the same insertion period applies to all observation types.

(ii) MES

For the MES, the insertion periods are as follows:

For hourly surface data (p*, screen temperature, screen relative humidity, SYNOP 10 m wind): 2 hours before observation time and 24 minutes after.

For upper air data: 2.5 hours before observation time and 0.5 hours after.

Hourly surface data up to T+1 can be used. (T+2 is beyond the data cut-off time of 1 h 55 min). Asynoptic data, e.g. AIREPS close to cut-off time, can be accommodated. MOPS data are generated and assimilated every 3 hours.

The time factor term in the analysis equation allows the full observed value to be inserted at the observation time (i.e. weight = 1); smaller weights are applied before and after the observation time. At the start and end of the insertion period, the value is 0.05 (Bell et al, 1994b). An example of the weighting during the insertion period for the GM is shown in Fig. 3.5.

Fig. 3.6 shows a schematic of the insertion periods in the GM and relative weights of observations made at different times. Fig. 3.7 shows a similar schematic for the MES.

(c) The correlation function

The correlation function determines the area of influence of an observation. A sketch is shown in Fig. 3.8. The function itself tends exponentially to zero as the distance from the observation increases. However, it is modified to have a value of zero at the edge of the influence area at radius r_{inf}. Owing to the shape of the correlation function, the influence of an observation decreases significantly well before r_{inf} is reached.

(i) Influence radius for GM and LAM

The character of the correlation function and the values set for r_{inf} (Bell et al. 1994b) give the values of the influence radius in Table 3.1 for the northern hemisphere in the LAM and GM.

INFLUENCE RADIUS FOR GM AND LAM		GM	LAM
Influence radius (km) for all variables except relative humidity.	At start of insertion period	1260	1050
	At observation time	700	630
	At end of insertion period	700	630
Influence radius (km) for relative humidity.	At start of insertion period	810	675
	At observation time	450	405
	At end of insertion period	450	405

Table 3.1 *Influence radius for the GM and LAM in the northern hemisphere.*

In the southern hemisphere, the values are 1½ times those in Table 3.1.

(ii) Influence radius for the MES

In the MES, the values set for r_{inf} multiplied by the correlation scales for each observation type give the radii of influence in Table 3.2.

OBSERVATION TYPE	INFLUENCE RADIUS (KM)	
	At start of insertion period	At observation time and at end of observing period
p*	525	315
Upper air temperature	420	350
Screen temperature	184	149
Upper air wind	420	350
10 m wind	166	131
Screen relative humidity	175	131
Upper air relative humidity	259	191

***Table 3.2** Influence radii for the MES.*

3.2.3 Stage 3: Interleaved balancing increments

The stage 'Balance' in Fig. 3.2 involves the interleaving of the balancing increments derived from hydrostatic and geostrophic relationships. It is described in Section 7 of Bell et al (1993). Adjustment of the mass field following updating of the wind field and vice-versa helps to keep the mass/wind balance, reduces noise and speeds the convergence of the model towards the observations.

The scheme then goes on to the next analysis iteration (ANALYZE) or next model time-step (Advance).

3.3 ASSIMILATION CYCLES

3.3.1 The Global Model (GM)

The GM operates on a 6-hour assimilation cycle, assimilating data in forecast mode whilst integrating the fields forward in time to provide the background for the next processing and quality control step.

3.3.2 The Limited Area Model (LAM)

The assimilation cycles for the LAM are the same as for the GM except for the following:

(i) The assimilation is not continuous; the starting analysis is interpolated from the GM every 12 hours.

(ii) There is a 3-hour cycle instead of a 6-hour cycle.

The input of observations during the operational cycle for the LAM is described in detail in Annex 1.

3.3.3 The Mesoscale Model (MES)

The assimilation is the same as for the LAM except for the following.

(i) The cycle is continuous (as of Sept 94).

(ii) Screen temperatures and humidities and 10 metre winds over land are assimilated. (In the GM and LAM, only wind from ships is used, not temperature or relative humidities).

(iii) The Moisture Observation Pre-processing System (MOPS) is used. For a description, see Section 2.2.7.

The MES obtains its boundary conditions from the LAM.

4. IMPACT STUDIES

4.1 ASSESSING THE BENEFIT OF DATA TO NWP FORECASTS

This sub-section was written by Richard Graham.

4.1.1 Overview

The observing process is the most expensive component of the forecasting system. Impact studies are a means of assessing the value of observing systems in terms of the benefit they deliver to model forecasts, and help identify profitable uses of the available resources.

More specifically, they are usually carried out for one of the following reasons:

(a) To assess the impact of current operational observation systems on the accuracy of NWP forecasts,

(b) To ensure that new observations and new methods of using observations have a positive impact (before including them in the operational assimilation; e.g. in recent times ERS-1 scatterometer winds and GLOSS),

(c) To evaluate the likely benefit of proposed future observing instruments and to assess the impact of different instrument design options.

There are two main methods for addressing the above tasks:

Observing System Experiments (OSEs) used for evaluating existing observations ((a) and (b) above).

Observing System Simulation Experiments (OSSEs) used to evaluate the likely impact of proposed future observing systems ((c) above).

4.1.2 Observing System Experiments (OSEs)

Fig. 4.1 shows the basic form of an OSE. After selecting a period for study, two model assimilation runs are performed, one "with" and one "without" use of the data type we wish to evaluate. Each assimilation run is normally followed by a forecast. The benefit of the data is then assessed by evaluating the greater accuracy (if any) of the "with" forecast compared to that of the "without" forecast.

As indicated on the diagram, verification may be performed either by comparing each forecast with observations, or with model analyses. Each method has advantages and disadvantages. Verification against observations is in some ways more rigorous, but has the disadvantage that results will contain little contribution from the performance in data scarce regions (e.g. over oceans). Verification against analyses overcomes the problem of data scarcity. However, because of the role of the model background in the analysis, the "with" forecasts will tend to verify better than the "without" forecasts when the "with" analyses are used as truth; and vice versa when evaluation is against the "without" analyses. This difficulty is most acute in the early part of the forecast and in data scarce regions.

Evaluation often takes the form of objective (statistical) assessments of performance for a number of forecasts over a specified geographical region. Statistical quantities such as mean error, root mean square error, and anomaly correlation are commonly used. The parallel suite is often used for this type of study. Alternatively, evaluation can take the form of case studies of impact on a particular meteorological feature. A combination of both approaches is often used. In case study assessments, a subjective evaluation of the forecasts is usually valuable and often helps in identifying the meteorological reasons which lie behind the results of the statistical assessments.

4.1.3 Observing System Simulation Experiments (OSSEs)

(a) Method

Clearly, the OSE approach cannot be used to evaluate a proposed observing system for which no observations have yet been made! For this purpose the OSSE approach, illustrated in Fig.4.2 is used. The method involves

- simulating the real atmosphere (with a model forecast - referred to as the "nature" run)
- simulating observations of the "nature" run
- performing forecasts with and without the simulated observations from the new system.

The process is explained in more detail below.

(i) Perform a long model forecast (typically 30 days). The output fields from this forecast (the "nature" run) become our surrogate for the real atmosphere. The nature run is used both as a starting point for simulating observations and as "truth" in verifying the forecast experiments. Note that in the surrogate atmosphere (unlike the real atmosphere) truth is known exactly at all model grid points.

(ii) Next, the distribution of the synthetic observations is determined. For simulation of the current observing system the distribution is usually based on the global distribution of real observations at the corresponding time. For the future observing system it is necessary to construct the distribution from the proposed deployment. For satellite systems, for example, the distribution will depend on the envisaged orbit height and inclination and also on the instrument viewing characteristics. A number of different characteristics may be simulated and their impact compared.

(iii) "Perfect" observations are generated by interpolating the nature run fields to the observation location.

(iv) The "perfect" observations are then perturbed with errors characteristic of the observation type. This part of the simulation often requires much background study to determine the likely characteristic error of the proposed observing system being evaluated.

Once the observations have been simulated, the procedure is similar to that for an OSE. At least two runs are performed:

- a run in which, for example, simulated data for all currently used observations are assimilated - the control run;

- a run in which simulated data from the proposed observing system are also assimilated.

Comparison of the two runs with the 'truth' of the nature run gives a measure of the likely impact of the proposed observing system.

Although verification of the forecasts is usually performed against the nature run "truth", verification may also be performed against the synthetic observations. The latter method is more comparable to the verification process for OSEs and is preferable, therefore, for purposes of OSSE validation (see below) in which OSE and OSSE results are compared.

(b) Validation/Calibration

It is useful to validate the OSSE system by ensuring that the impact of simulated data on the OSSE assimilation is similar to the impact of real data on operational forecasts. For example, the impact of simulated TOVS temperature soundings on the OSSE forecasts should be similar to the impact of genuine TOVS on operational forecasts.

Often, the benefit of the simulated data in the OSSE is greater than that of the real data on operational forecasts - indicating that the OSSE evaluation of the benefit will be over-optimistic. For example, pre-FGGE studies on the utility of satellite-derived temperature soundings gave over-optimistic results (Atlas et al, 1985).

(c) Identical twin and fraternal twin OSSEs

In early OSSE studies, the same model was used to assimilate the synthetic data (and to run forecasts) as was used to generate the "nature" run, or truth. In these so-called "identical twin" OSSEs the physical and dynamical processes in the assimilating model are identical with those in the surrogate atmosphere. Consequently, forecast errors arising from deficiencies in the model representation of the real atmosphere are not accounted for; only forecast errors due to errors in the initial conditions are represented. This limitation usually leads to over-optimistic results.

It is now more usual to perform the assimilation experiments with a model which is different to the model used to generate the nature run. This type of study, referred to as a "fraternal twin" OSSE, effects a crude simulation of the difference between the assimilating model and the real atmosphere.

4.2 SUMMARIES OF STUDIES

The tables that follow summarise recent impact studies. They were last updated in January, 1995. The intention is to add new information when it becomes available.

WINDS FROM ERS-1 SCATTEROMETER			
LOCATION OF STUDY AND REFERENCE	**MODEL**	**METHOD**	**RESULTS**
Bell, 1994 UK Met Office	Global model	OSE: real time parallel trial for 11 days, March 1993. Compared model runs up to T+120 with and without scatterometer winds. Verification: objective.	30°-90°S Substantial positive impact. Average change in rms score for all variables for all forecasts: 3.7%. Up to 10% reductions in rms errors for surface and low-level height at all forecast ranges. Improvements greatest at shortest forecast ranges but much of the improvement retained to medium range. **North of 30°S** Neutral impact.
Hoffman, 1993 ECMWF	ECMWF model	OSE: comparison of model runs with and without scatterometer data for 11 days between Dec 91 and Jan 92.	Overall, neutral impact in southern hemisphere. Better low-level wind analysis (especially correcting overestimation of wind speed in warm air advection).

SATELLITE CLOUD MOTION WINDS			
<u>LOCATION OF STUDY AND REFERENCE</u>	<u>MODEL</u>	<u>METHOD</u>	<u>RESULTS</u>
Radford, 1994b UK Met Office	Global model	OSE: real time parallel trial; 13 days, May 1994. Forecasts up to T+120. Configuration tested was as follows. Adding: **Extra-tropical high-level winds from GOES/METEOSAT over land,** **Extra-tropical high-level GMS winds over land and sea,** plus removing: **Extra-tropical low-level winds from GMS/GOES/ METEOSAT over land.** Objective and subjective verification.	Impact was compared with previous deployment. Greatest (mostly positive) impact between 30° and 90°S, especially from T+72 in the verification of height and temperature. Largest improvement in rms verification score was 2.7% in 850 hPa temperature at T+120. Marginal positive impact between 30° and 90°N. No signal in tropics (30°N - 30°S). Positive impact over area covering a large part of North America, the North Atlantic and most of western Europe, especially at T+120. Changes in rms verification scores up to 1%. This suggests that including high-level GMS data over the western Pacific is having a positive impact downstream in the medium range.

SATELLITE TEMPERATURES			
LOCATION OF STUDY AND REFERENCE	**MODEL**	**METHOD**	**RESULTS**
Gadd et al, 1995 UK Met Office	Global model	OSE: real time parallel trials; June, Nov 1993. Forecasts up to T+72. In the experimental runs, the NESDIS 120 km temperature retrievals were replaced globally with the GLOSS 120 km data. 120 km soundings were assimilated only over the sea (including sea-ice). Over land, NESDIS 500 km retrievals were assimilated, but only at levels above 100 hPa. TOVS humidity retrievals were not assimilated. Verification: objective and subjective.	Positive impact of GLOSS in extratropical areas (northern and southern hemisphere) at all levels. Increasing positive impact during the forecast period. Positive impacts, expressed as increases during forecast period for a given level of accuracy, are up to 11 hours for 500 hPa height and MSLP. Mixed results at low latitudes (30°N-30°S). More amplitude in and stronger flow around larger scale ridges and troughs at 250 hPa.

SONDES FROM SHIPS			
LOCATION OF STUDY AND REFERENCE	**MODEL**	**METHOD**	**RESULTS**
Heming and Radford, 1993 UK Met Office	Global and limited area models	OSE: real time parallel trial; 3 days, Mar 1992. GM forecasts out to 3 days; LAM out to 36 hours. Compared runs with and without TEMPSHIPS. Verification: objective and subjective.	Mixed or slightly negative impact overall. Subjective verification revealed a small negative impact. Small positive impact in the LAM for rainfall, especially over Europe. Positive impact on jet level wind forecasts in the GM. TEMPSHIP observations most effective filling in information in certain critical situations when NWP models have not picked up the rapid deepening or movement of a weather system. A good quality upper air ascent is vital for providing the model with the missing information it requires.

ALL TYPES OF CURRENT OBSERVATIONS			
LOCATION OF STUDY AND REFERENCE	**MODEL**	**METHOD**	**RESULTS**
Graham, 1994 and also personal communication UK Met Office	UK Global model	OSE: Case studies. Benefit ranking for observations in the northern hemisphere. Assessment of impact from all types of observation on 2-3 day forecasts.	Out of 9 cases of marked beneficial data impact over North America and Europe, a significant contribution to the beneficial impact could be attributed to: **Aircraft winds in 7 cases** **Radiosonde winds in 5 cases** **Cloud track winds in 3 cases** **Aircraft temps in 3 cases** **Surface data in 2 cases** **Satellite temps in 1 cases**

AIRCRAFT AND WIND PROFILER DATA			
LOCATION OF STUDY AND REFERENCE	**MODEL**	**METHOD**	**RESULTS** **(Preliminary)**
Smith and Benjamin, 1994 NOAA Forecast Systems Laboratory, Boulder, Colorado, USA.	USA Mesoscale Analysis and Prediction System (MAPS)	OSE: series of parallel runs, during 8 days in March 1992, to compare impact on MAPS of: - ACARS wind and temperature data - wind profiler data. 3, 6 and 12 hour forecasts. Experimental runs excluding (a) all ACARS data (b) all profiler data Objective verification.	**ACARS data** Most impact on wind forecasts at jet levels only. Significant improvement in temperature forecasts. **Profiler data** Improvement in wind forecasts at all levels plus a significant contribution at jet levels. Negligible impact on temperature forecasts. ------------------- Strong impact from **both types** of data in 3-h and 6-h forecasts but not detectable at 12-h. Better forecast using **both data sources** together than just one.

AUTOMATED AIRCRAFT DATA			
<u>**LOCATION OF STUDY AND REFERENCE**</u>	<u>**MODEL**</u>	<u>**METHOD**</u>	<u>**RESULTS**</u>
Bell, Ingleby and Parrett, 1994a UK Met Office	Global model	OSE: assess impact of US ACARS data. Four cases during three days in Dec 92. Forecasts out to T+48. Compared forecasts against observations.	<u>Objective assessment</u> Improvement in rms scores of up to 4% over Atlantic sector. Best improvement at T+48. <u>Subjective assessment</u> Positive impact in structure, phase and strength of upper flow as features moved out into the Atlantic sector.

BOGUSSED OBSERVATIONS			
LOCATION OF STUDY AND REFERENCE	**MODEL**	**METHOD**	**RESULTS**
Heming, 1993 UK Met Office	Global model	OSE: real time parallel trial; 17 days, Oct 1992. Forecasts out to T+120. Runs with and without intervention. Verification: Objective and subjective.	Intervention has small positive impact overall but with marked variations. Best impact: on fields and features that can be directly intervened on (e.g., MSLP, tropical cyclones). Negative impact on fields and features not intervened on directly but indirectly influenced by intervention on other fields or nearby features.
Grant and Bader, 1994 UK Met Office	Limited area model	Case study, April 1993. Forecast out to T+24. Bogussing by conceptual model of a depression using satellite imagery and supported by cloud motion winds.	Improved forecast of amount and timing of rainfall over part of UK.
Seaman et al, 1993 Bureau of Meteorology, Melbourne, Australia	Australian Global Assimilation and Prediction System	OSE: parallel trials over two 4-week periods in different seasons. Runs with and without PAOBS. Forecasts up to 5 days. Objective verification using anomaly correlation coefficients.	Small positive impact on forecasts of broad-scale southern hemisphere extra-tropical flow patterns up to 500 hPa.

TOTAL PRECIPITABLE WATER			
LOCATION OF STUDY AND REFERENCE	**MODEL**	**METHOD**	**RESULTS**
Wu and Derber, 1994 USA	NMC assimilation and forecast system	OSE: 5-day predictions during a 26-day period of assimilation, Jan-Feb 1994. Runs with and without precipitable water from SSM/I. Objective verification represented by 1-5 day mean anomaly correlations of 1000 and 500 hPa heights.	Small impact over northern hemisphere. Positive impact over southern hemisphere: increases with forecast time out to day 5.
Karyampudi et al, 1994 USA	Penn State/NCAR Mesoscale Model (40 km grid)	OSE: assimilation of satellite-derived precipitation rates based on SSM/I and GOES IR rainfall data. 12 hour simulations.	Significant positive impact on central pressure and location of Hurricane Florence. Further improvement in deepening needed.
Peng and Chang, 1994 USA	Naval Research Lab Limited Area Model	OSE: assimilation of SSM/I retrieved rainfall rates.	Improvement on 48 hour forecasts of intensity and track of Typhoon Flo. 5 hPa reduction in minimum surface level pressure.
Holt and Chang, 1994 USA	Naval Research Lab Mesoscale Model	OSE: assimilation of SSM/I precipitable water on forecasts of a rapidly deepening cyclone during ERICA.	Small changes in position and reduction in central sea level pressure (up to 3 hPa) for forecasts of up to 24 hours.

TOTAL PRECIPITABLE WATER (CONTINUED)			
Aune, 1994 USA	Co-operative Institute for Meteorological Satellite Studies. Regional Assimilation System.	OSE: assimilation of total precipitable water from VAS on GOES-7. 6 month period over USA. 36 hour forecasts.	Improvements to dewpoint verification statistics. Improvements to forecasts of 24 hour precipitation totals are case dependent.
Ledvina and Pfaendtner, 1994 USA	Goddard Earth Observing System Data Assimilation System.	OSE: assimilation of SSM/I total precipitable water. 3-day global forecast from July 1987.	Reduction of model dry bias and increased globally averaged precipitation. Reduction of mean bias by 50% and rms error by nearly 30%.

SCREEN HUMIDITY, TEMPERATURE AND ALSO CLOUD DATA			
LOCATION OF STUDY AND REFERENCE	**MODEL**	**METHOD**	**RESULTS**
Macpherson (personal communication) UK Met Office	UK mesoscale	Case showing impact of screen humidity data, April 1993. Average results from 5 cases showing impact of MOPS cloud data. Average results (r.m.s. error) showing impact of screen temperature data: 9 cases up to T+18 4 cases at T+24 and T+30.	Improvement of fog forecast over Central and Eastern England (6 hours ahead). Positive impact as measured by mean and r.m.s. errors. Reduction in error of screen temperature forecast, especially during the first 9 hours.

ACKNOWLEDGEMENTS

Special thanks to Stuart Bell, Richard Graham and Bruce Macpherson for providing a considerable amount of guidance and advice as well as individual contributions.

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ANNEX 1

ROLE OF OBSERVATIONS IN THE OPERATIONAL CYCLE

1. THE BASIC CYCLE FOR THE LAM

The aim of this section is to explain how observations are presented to the UM system. The schematic in Fig. A1 applies to the LAM but the procedure for the other configurations of the UM is based upon the same principle.

The 00Z LAM analysis (A1) is interpolated from the 00Z GM analysis.

Starting from this analysis, a forecast is run to generate a background field (B1) at 03Z.

This background field is used for quality controlling the observations made within 1.5 hours before and after 03Z. The values accepted undergo some processing (e.g. averaging of sonde data on to model levels) and are written to a file in the format required by the model. The file is the 03Z ACOBS file (ACOBS 1).

The forecast from 00Z, based on A1, is repeated but this time using the information in the ACOBS 1. This forecast is called QL03 in the operational schedule (Table A1) and is run to 09Z. Each observation is used at every time-step within a time window around the observation time. To continue the assimilation cycle, an analysis dump valid for 03Z and a background field (B2) valid for 06Z are produced.

The forecast based on the 03Z analysis, A2, utilizes both the 03Z and 06Z ACOBS files (ACOBS 1 and ACOBS 2). The forecast is run to 06Z, two days ahead. It is called QL06 in the operational schedule listed in Table A1. (Note that the start time in Column 2 of Table A1 is also the cut-off time for the observations to be included in the run).

Subsequent runs, QL09 and QL12, are identical in configuration to QL03 and QL06. The 12-hour cycle starts afresh at 12Z - generating runs QL15, 18, 21 and 00. Note that the analysis at 12Z is obtained from the GM and not from a continuous cycle of the LAM. Boundary files are also taken from the GM.

2. UPDATE RUNS

The runs QL06 and QL18 are repeated some hours later but are run only to T+6. They are called 'update' runs - QV06 and QV18. They are carried out so that data which became available after the operational cut-off for QL06 and QL18 may be incorporated into the model and thus influence the important runs - QL00 and QL12 - that are run to T+48.

RUN	START	END	DESCRIPTION
QL00	0155Z	0240Z	Limited-Area 00Z to T+48
QM00	0240Z	0310Z	UK Mesoscale 00Z to T+18
QG00	0320Z	0450Z	Global 00Z to T+144
QL03	0450Z	0505Z	Limited-Area 03Z to T+6
QS00	0505Z	0520Z	Stratospheric 00Z to T+6
QM03	0735Z	0750Z	UK Mesoscale 03Z to T+3
QL06	0755Z	0830Z	Limited-Area 06Z to T+48
QM06	0830Z	0910Z	UK Mesoscale 06Z to T+30
Changes/Systems time 0915Z to 1115Z			
QU00	1120Z	1200Z	Global 00Z Update to T+9
QG06	1200Z	1230Z	Global 06Z to T+9
QV06	1230Z	1245Z	Limited-Area 06Z Update to T+6
QL09	1245Z	1300Z	Limited-Area 09Z to T+6
QM09	1300Z	1315Z	UK Mesoscale 09Z to T+3
QS06	1315Z	1330Z	Stratospheric 06Z to T+6
QL12	1355Z	1440Z	Limited-Area 12Z to T+48
QM12	1440Z	1510Z	UK Mesoscale 12Z to T+24
QG12	1520Z	1650Z	Global 12Z to T+144
QA18	1650Z	1715Z	Gulf Mesoscale 18Z to T+30
PM/Systems time 1730Z to 2000Z			
QL15	2000Z	2015Z	Limited-Area 15Z to T+6
QL18	2020Z	2050Z	Limited-Area 18Z to T+48
QB18	2050Z	2110Z	Bosnia Mesoscale 18Z to T+24
QM15	2110Z	2125Z	UK Mesoscale 15Z to T+3
QM18	2125Z	2155Z	UK Mesoscale 18Z to T+18
QS12	2155Z	2210Z	Stratospheric 12Z to T+6
QU12	2320Z	0000Z	Global 12Z Update to T+9
QG18	0000Z	0030Z	Global 18Z to T+9
QV18	0030Z	0045Z	Limited-Area 18Z Update to T+6
QL21	0045Z	0100Z	Limited-Area 21Z to T+6
QM21	0100Z	0115Z	UK Mesoscale 21Z to T+3
QS18	0115Z	0130Z	Stratospheric 18Z to T+6

Table A1: *Operational Schedule on the CRAY valid from 8 Nov 1994 (Courtesy: Chris Hynes)*

3. CYCLES FOR OTHER MODEL CONFIGURATIONS

The cycles for the GM and MES cycles adopt the same basic scheme, but are continuous and do not rely on the analyses from other configurations. The operational schedule is in Table A1. There are 4 runs per day for the GM - labelled QG - and 8 for the MES - labelled QM.

ANNEX 2

ACRONYMS AND ABBREVIATIONS

AC	Analysis Correction
ACARS	ARINC Communications Addressing and Reporting System
ACOBS	Analysis Correction OBServation
AIREP	Code for AIRcraft REPort (Single-level observations performed on-board an aircraft at flight level).
ALADIN	Atmospheric Laser Doppler Instrument
AMDAR	Aircraft Meteorological DAta Relay
AMSU	Advanced Microwave Sounding Unit
ARINC	Aeronautical Radio INCorporated
ASAP	Automated Shipboard Aerological Programme
ASDAR	Aircraft to Satellite DAta Relay
ATSR	Along Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
AWS	Automatic Weather Station
BATHY	Code for BATHYthermograph observations
BGE	BackGround Error
BOGUS	BOGUSsed observation
CFO	Central Forecasting Office of the UK Met Office
CMW	Cloud Motion Winds
COSNA	Composite Observing System for the North Atlantic
DA	Data Assimilation
DMSP	Defence Meteorological Satellite Program
DRIFTER	Code for surface observations taken from a DRIFTing Buoy
DT	Data Time
ECMWF	European Centre for Medium-Range Weather Forecasts
ERS-1	European Remote Sensing Satellite - 1
ESA	European Space Agency
FRONTIERS	Forecasting Rainfall Optimized using New Technique of Interactively Enhanced Radar and Satellite data
GLOSS	GLObal Sounding System
GM	Global Model
GMS	Geosynchronous Meteorological Satellite
GOES	Geostationary Operational Environmental Satellite
GTS	Global Telecommunications System
HIRS	High resolution Infrared Radiation Sounder
ICAO	International Civil Aviation Organisation
INSAT	Name of Geostationary Satellite at 74^0 E
LAM	Limited Area Model
LASS	Local Area Sounding System
LAWS	Laser Atmospheric Wind Sounder
LIDAR	Doppler LIght Detection And Ranging
MAPS	Mesoscale Analysis and Prediction System (USA)
MDB,	Meteorological DataBase
MetDB	"
MES	MESoscale model
METEOSAT	European Geostationary METEOrological SATellite
MIMR	Multiband Imaging Microwave Radiometer
MOPS	Moisture Observation Pre-processing System
MSLP	Mean Sea Level Pressure
MSU	Microwave Sounder Unit
NESDIS	National Environmental Satellite and Data and Information Services (USA)
NOAA	National Oceanic and Atmospheric Administration (USA)
NWP	Numerical Weather Prediction

OPD	Observational data Processing Database (A database of observations with relevant model values added to enable comparisons and quality assessments to be made. Additional quality information is included.)
OPS	Observation Processing System
OSE	Observing System Experiment
OSSE	Observing System Simulation Experiment
OWS	Ocean Weather Ship
PAOB	PAid OBservations, i.e. code name for bogus MSLP values produced operationally in Australia
PGE	Probability of Gross Error
PILOT	Code for upper air report from a radiosonde (wind only)
PWC	Precipitable Water Content
RADAR	RAdio Detection And Ranging
RASS	Radio Acoustic Sounding System
RH	Relative Humidity
SAT120	SATellite retrievals at 120 km resolution
SAT500	SATellite retrievals at 500 km resolution
SATEM	SATellite TEMperatures
SATOB	Cloud Track Winds using consecutive images from geostationary satellite (SATellite OBServations)
SDB	Synoptic Data Bank (acts as a data source for the NWP model suite)
SHIP	Code for Surface SHIP report
SREW	Hourly rainfall accumulations
SSM/I	Special Sensor Microwave Imager
SST	Sea Surface Temperature
SSU	Stratospheric Sounder Unit
SYNOP	Code for Surface land report
TEMP	Code for upper-air report from a radiosonde (dry-bulb temperature, dewpoint, wind)
TEMPSHIP	Code for radiosonde observations from ships
TIROS	Television Infra-Red Observation Satellite
TOVS	TIROS Operational Vertical Sounder
UM	Unified Model of the UK Met Office
UTC	Universal Times Co-ordinates
VAS	VISSR Atmospheric Sounder
VISSR	Visible and Infra-red Spin Scan Radiometer
VT	Validity Time
WMO	World Meteorological Organisation

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AREAS OF GLOBAL, LIMITED AREA AND MESOSCALE MODELS

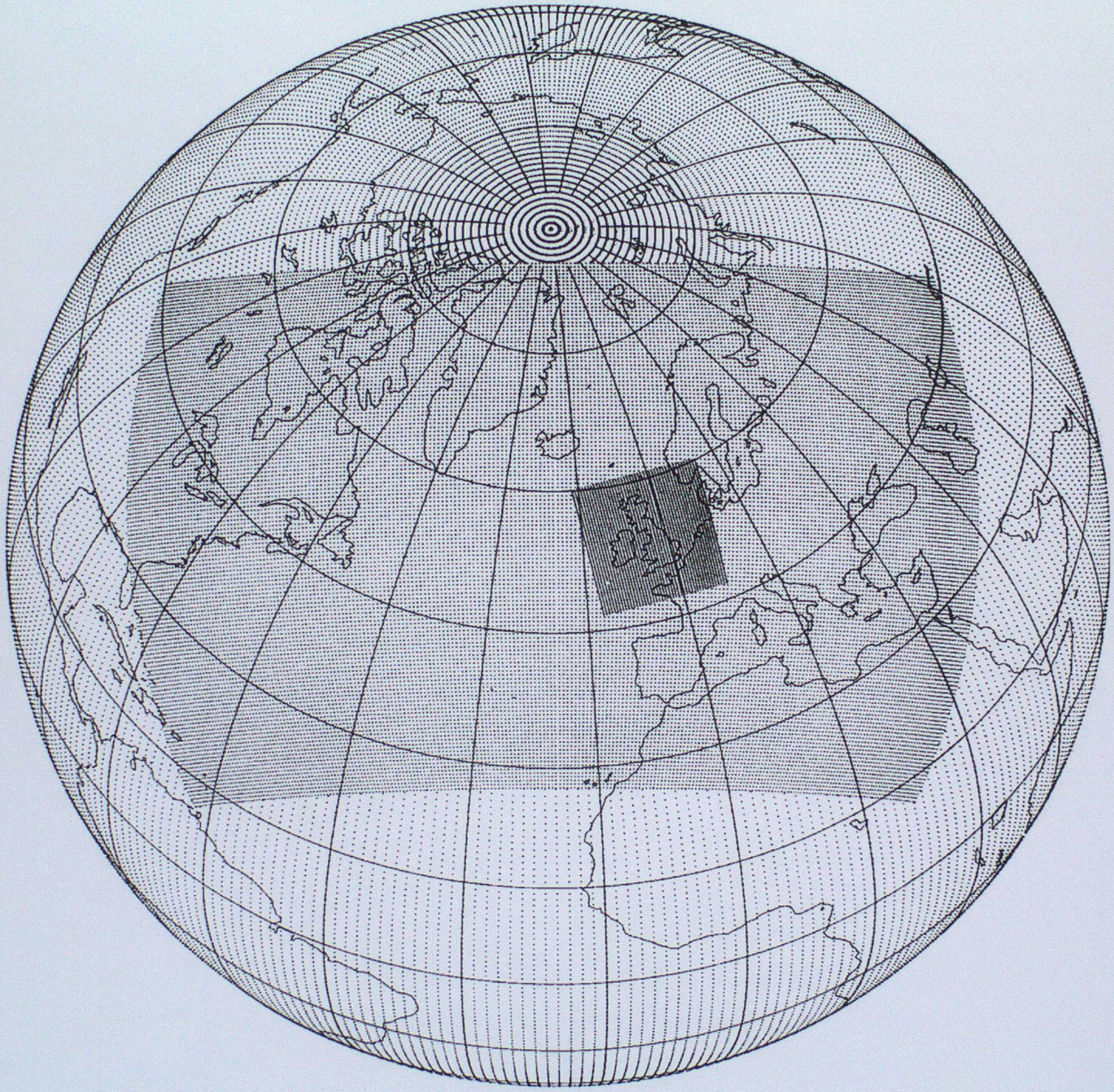


Fig. 1.1 The relationship between different configurations of the Unified Model.

Coarse grid:	Global model (GM)
Intermediate grid:	Limited area model (LAM)
Fine grid:	Mesoscale model (MES)

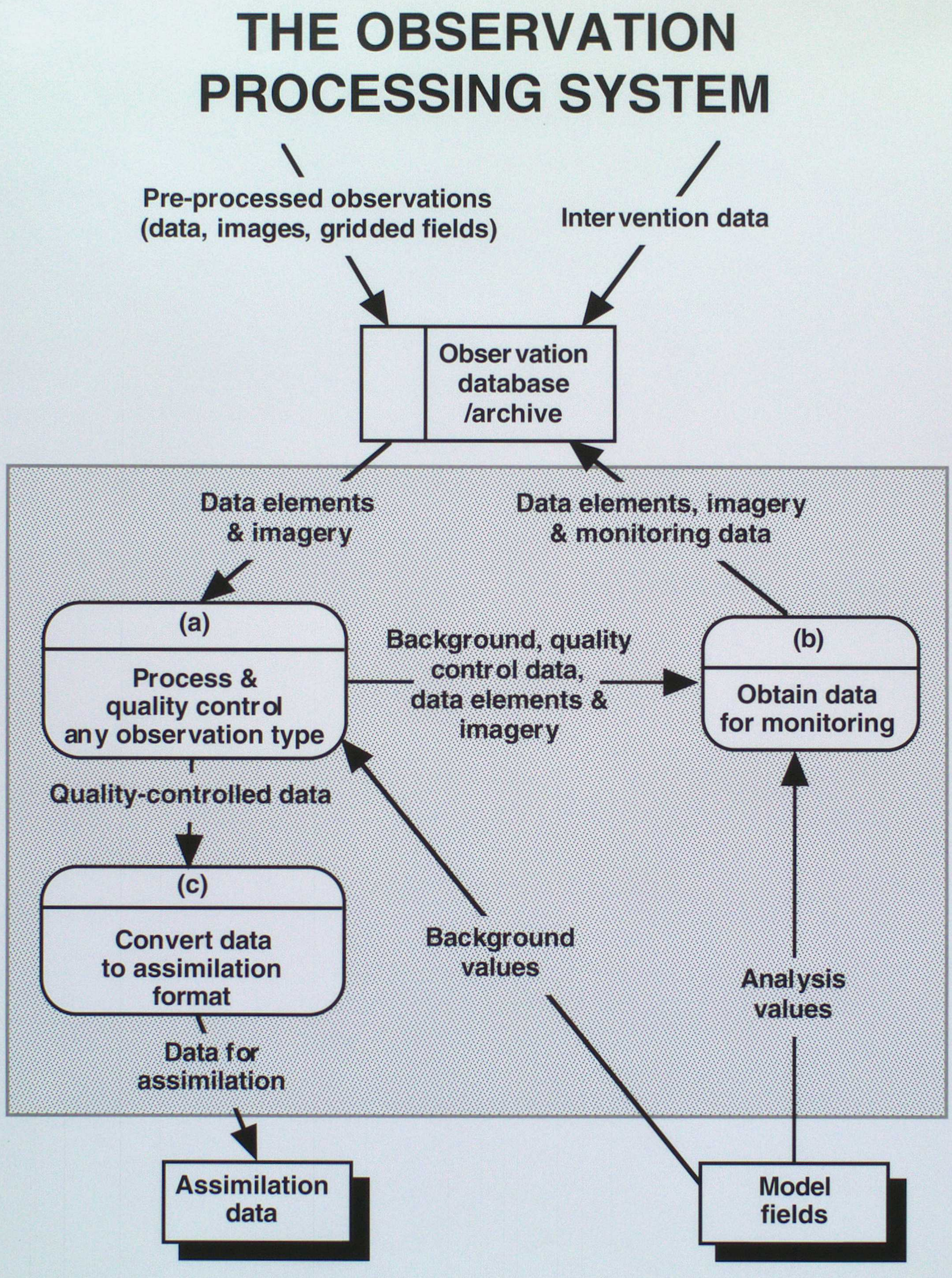


Fig. 2.1 Schematic showing steps in the Observational Processing System (OPS). (Adapted from Dumelow, 1994b). The OPS is within the large box.

SURFACE OBSERVATIONS: LAND AND SHIP

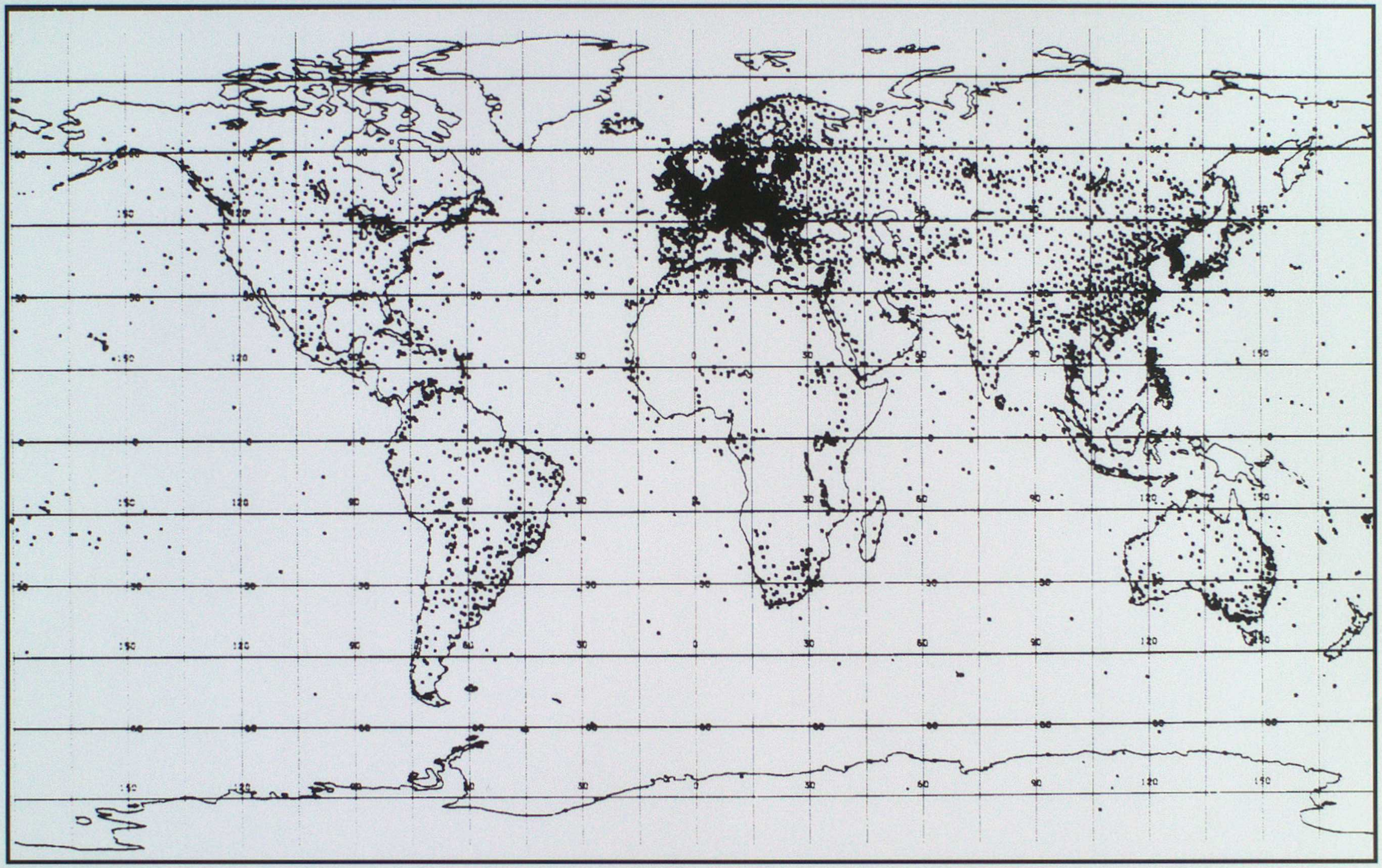


Fig. 2.2a Example of global data coverage of SYNOP/SHIPS reports for 12 UTC on 7th January 1995. (Courtesy: Alan Radford).

DRIFTING BUOYS

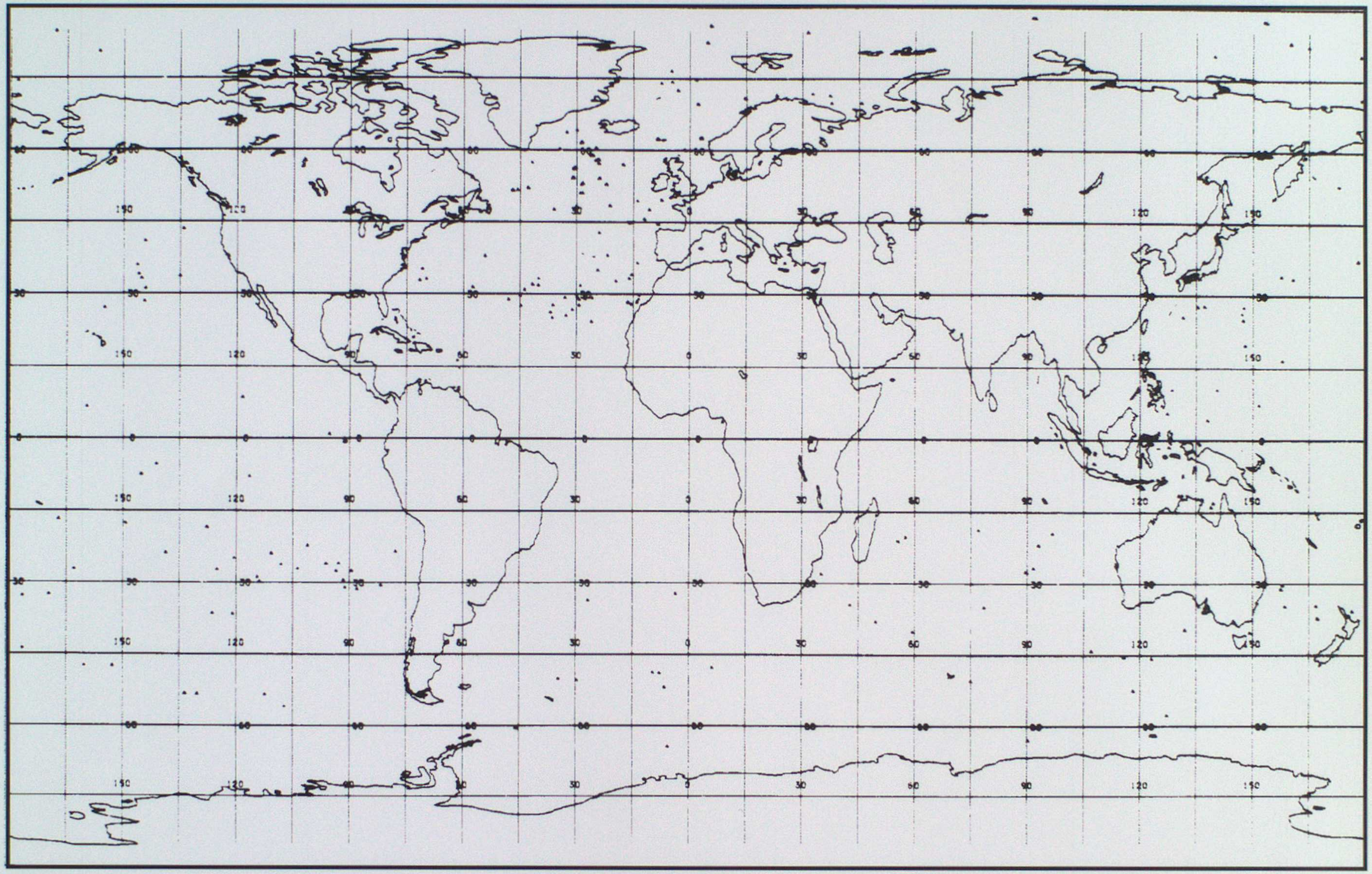


Fig. 2.2b Example of global data coverage of drifting buoy reports for 12 UTC on 7th January 1995. (Courtesy: Alan Radford).

UPPER-AIR OBSERVATIONS: LAND AND SHIP

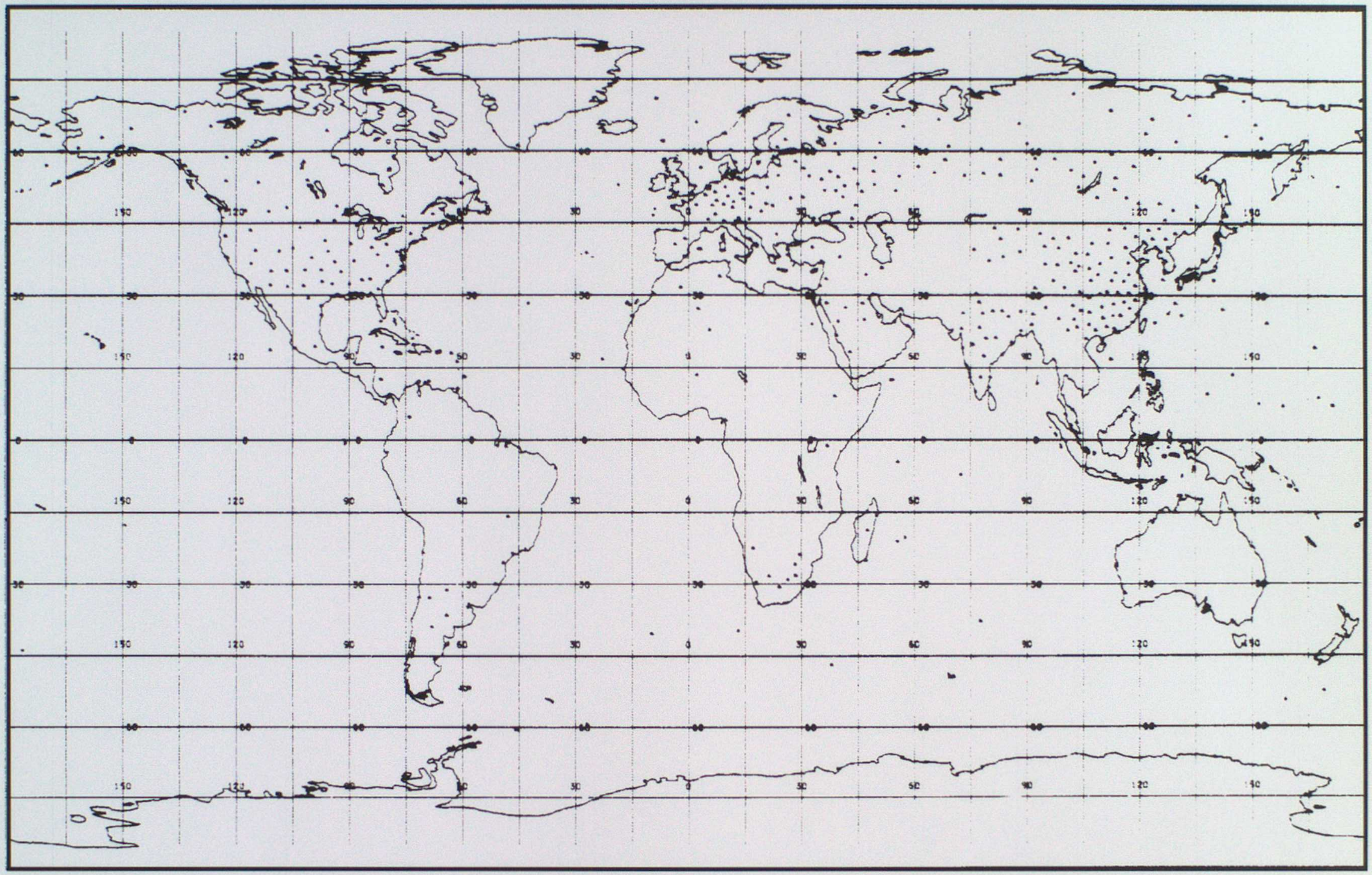


Fig. 2.3a Example of global data coverage of TEMP/TEMPSHIP reports for 12 UTC on 7th January 1995. (Courtesy: Alan Radford).

UPPER WINDS

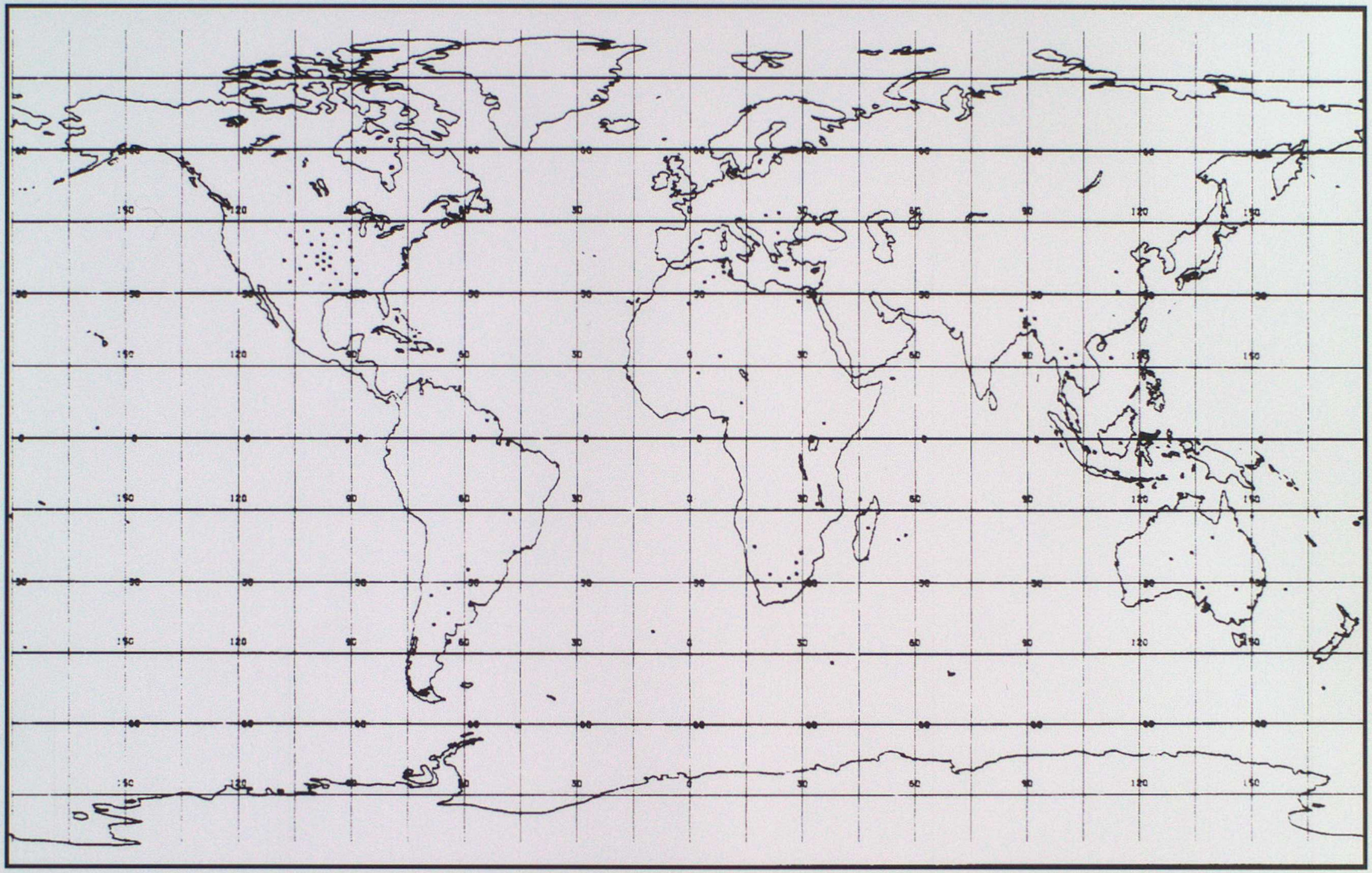


Fig. 2.3b Example of global data coverage of PILOT reports for 12 UTC on 7th January 1995. Note that data from the North American wind profilers, which are stored in the PILOT code, are also included. (Courtesy: Alan Radford).

AIRCRAFT REPORTS (MANUAL)

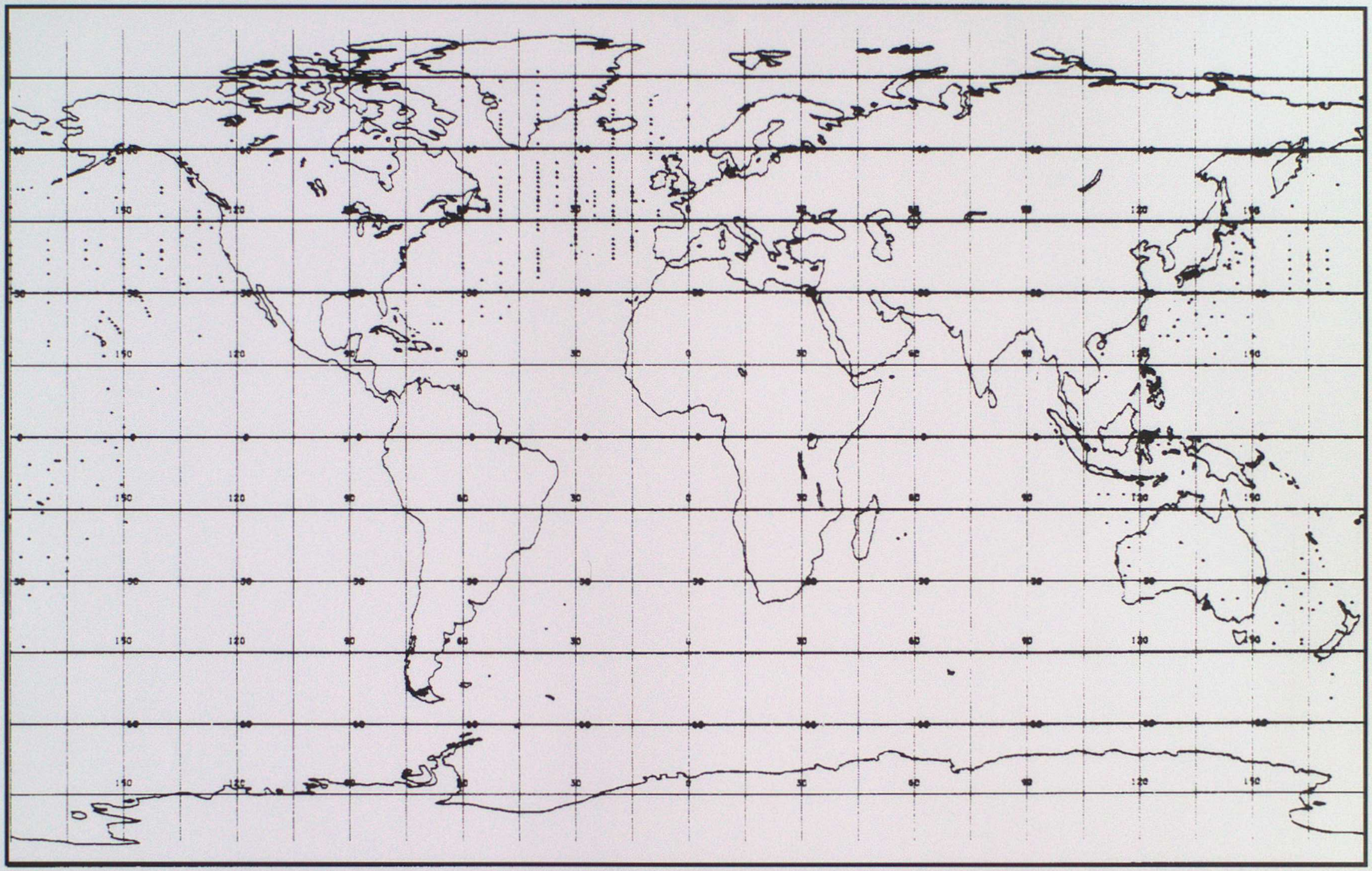


Fig. 2.4a Example of global data coverage of AIREPS for 12 UTC on 7th January 1995. (Courtesy: Alan Radford).

AIRCRAFT REPORTS (AUTOMATIC)

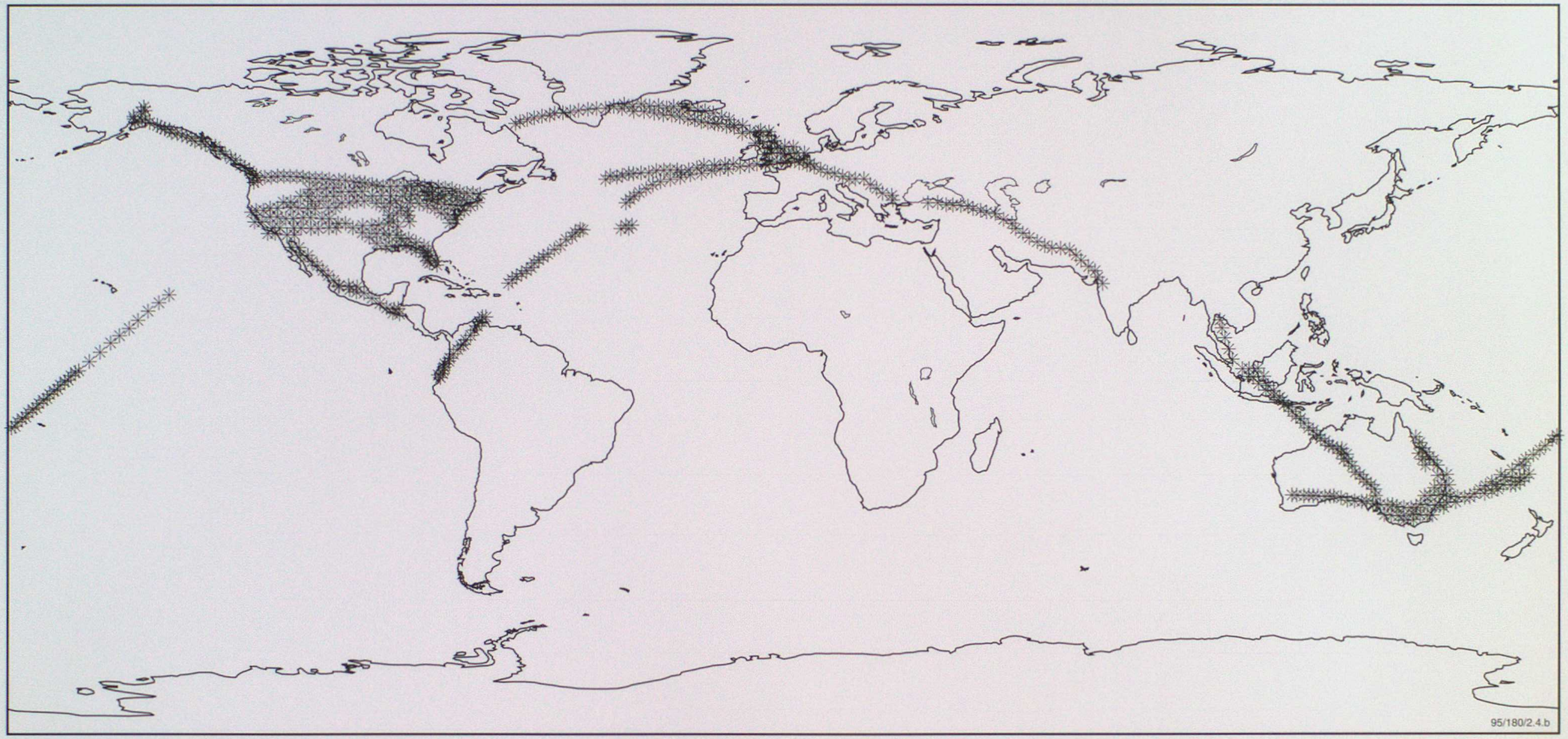


Fig. 2.4b Example of global data coverage of AMDARS and ASDARS for 12 UTC on 7th January 1995. (Courtesy: Alan Radford).

WINDS FROM ERS-1 SCATTEROMETER

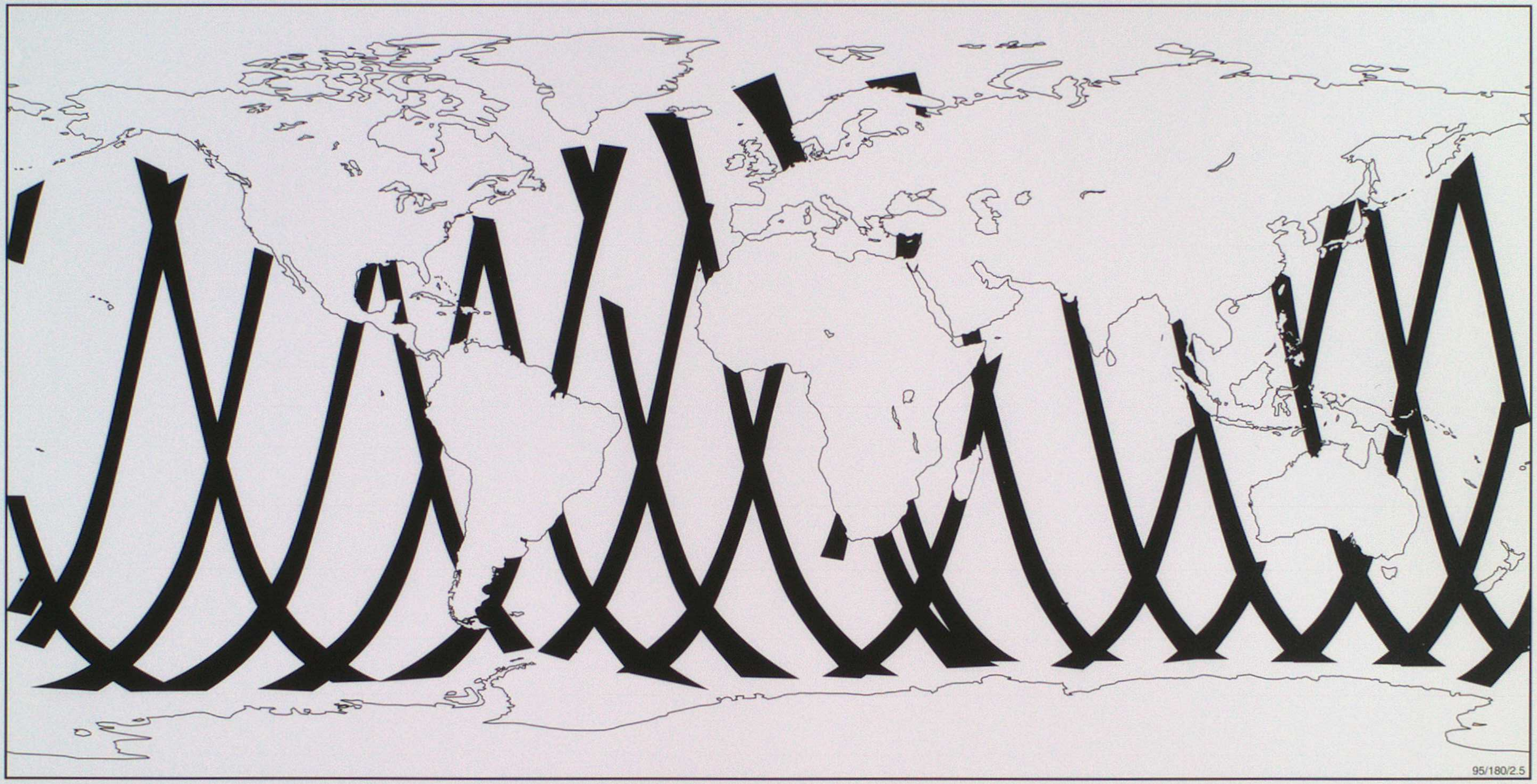


Fig. 2.5 Typical daily coverage of the ERS-1 swath of scatterometer winds, where the data were available during 21st March 1993. (From Bell, 1994).

CLOUD MOTION WINDS

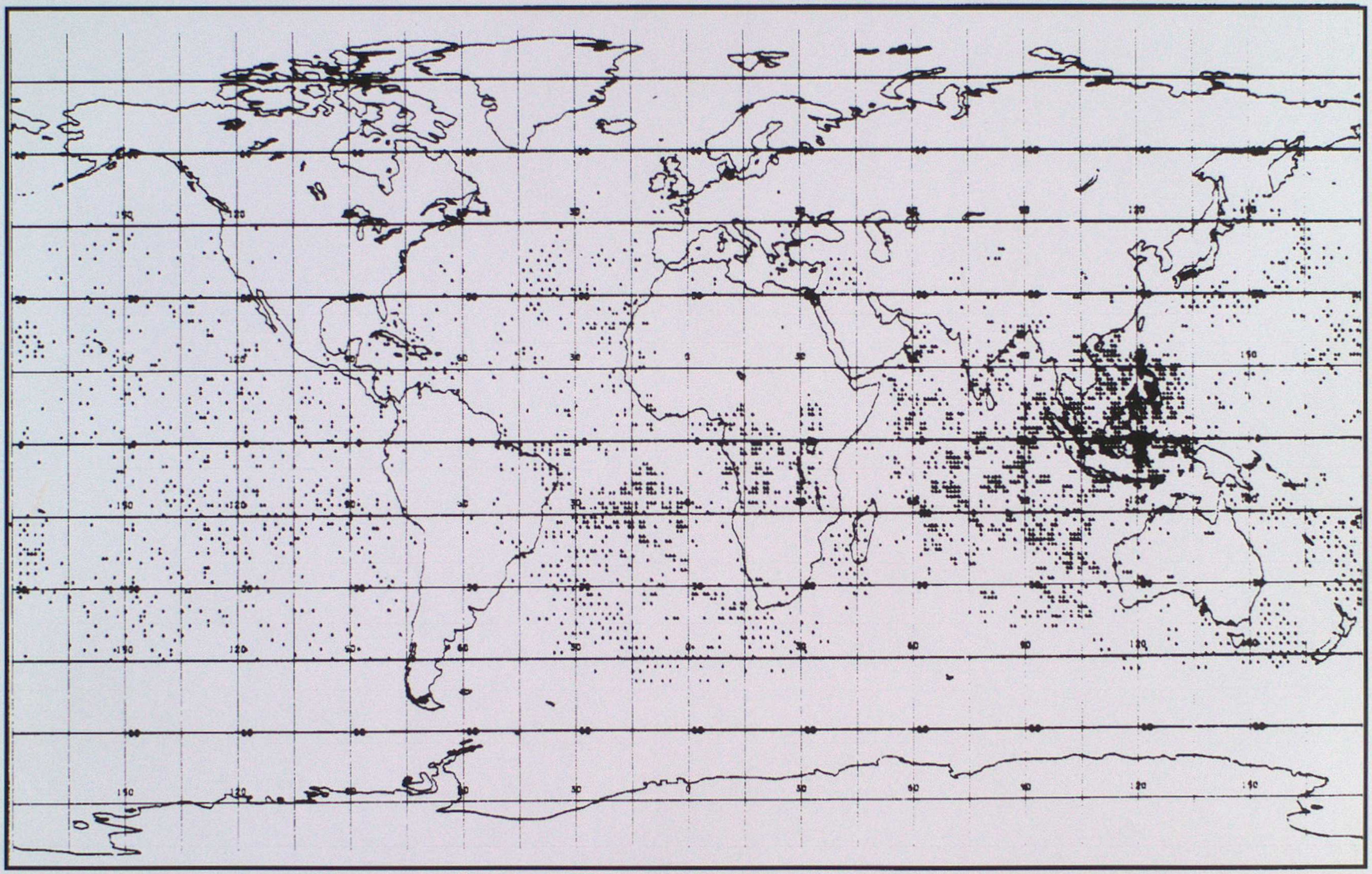


Fig. 2.6 Example of global data coverage of cloud motion winds for 12 UTC on 7th January 1995. (Courtesy: Alan Radford).

SATELLITE TEMPERATURES (120 km)

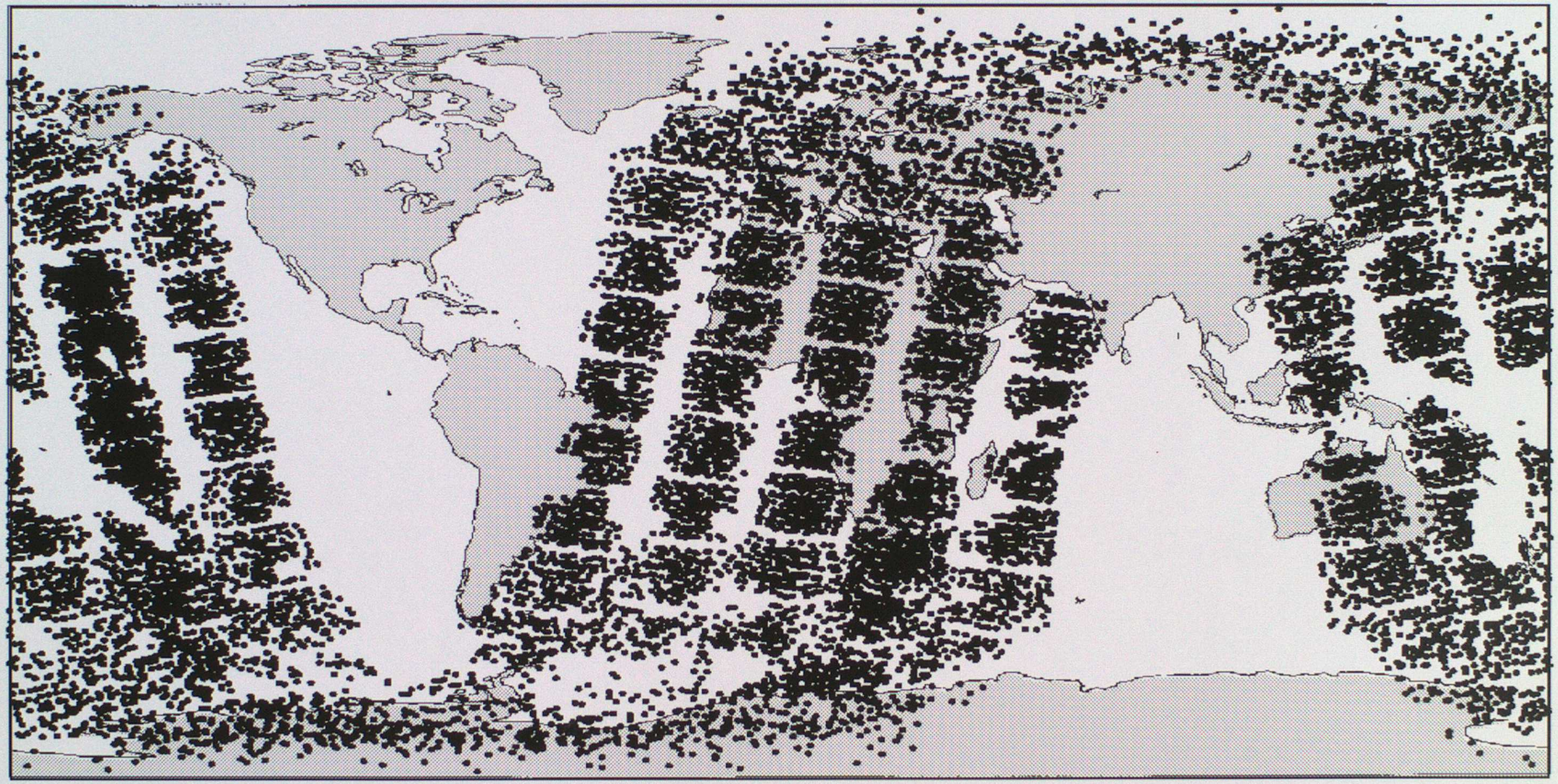


Fig. 2.7 Examples of global data coverage of 120 km SATEMS from NOAA-11 and NOAA-12 satellites between 03 and 09 UTC on 22nd of January 1995. (Courtesy: Alan Radford).

COVERAGE OF LIMITED AREA MODEL AND LOCAL AREA SOUNDING SYSTEM

Fig. 2.8 **Areas of coverage of the Local Area Sounding System (LASS) – within the circle – and the LAM. (Courtesy: Alan Radford).**

MESOSCALE DATA ASSIMILATION

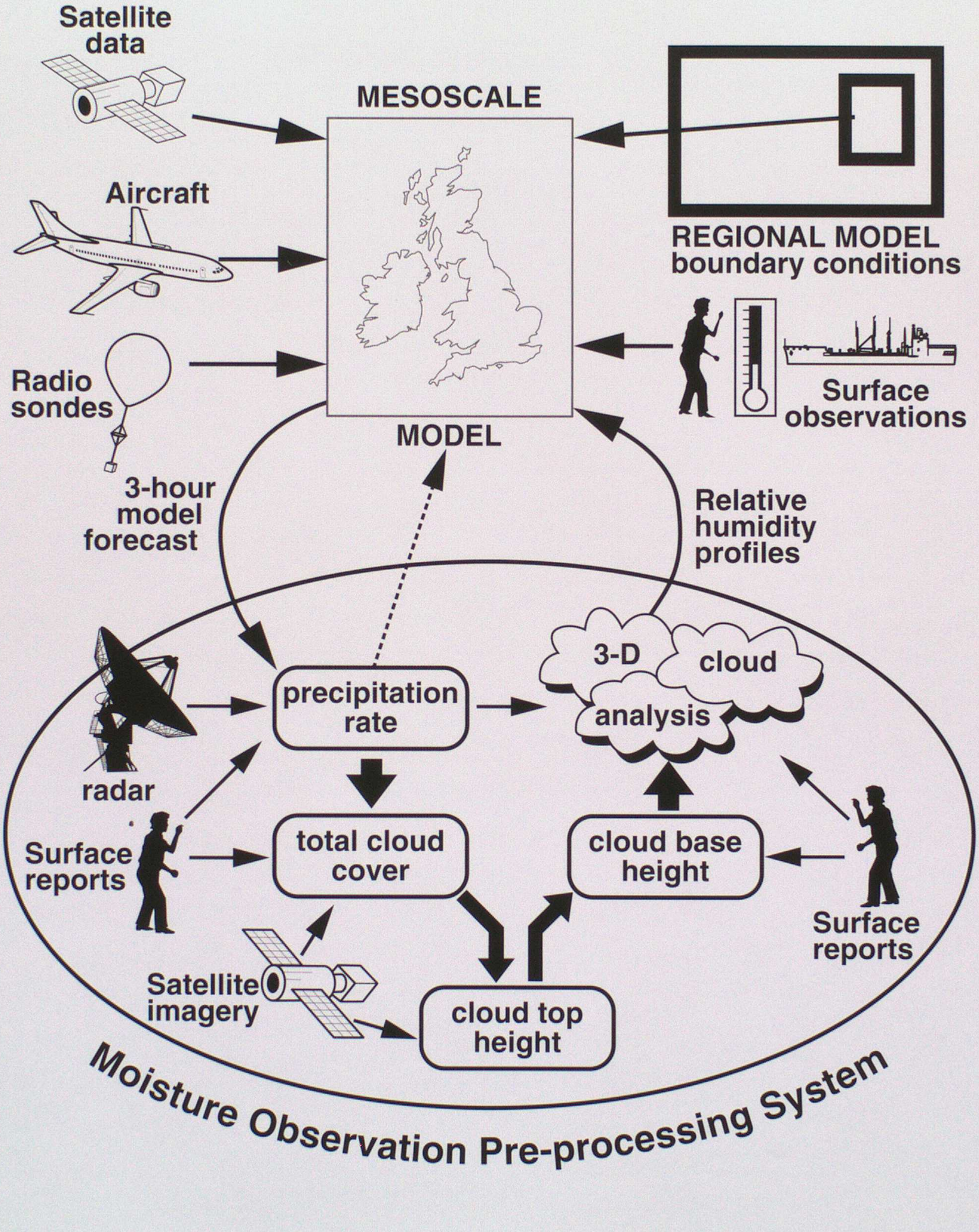


Fig. 2.9 Assimilation scheme for the MES, including the Moisture Observation Pre-processing System (MOPS). (Courtesy: Bruce Macpherson)

SEA SURFACE TEMPERATURES FROM SHIPS AND BATHYTHERMOGRAPHS

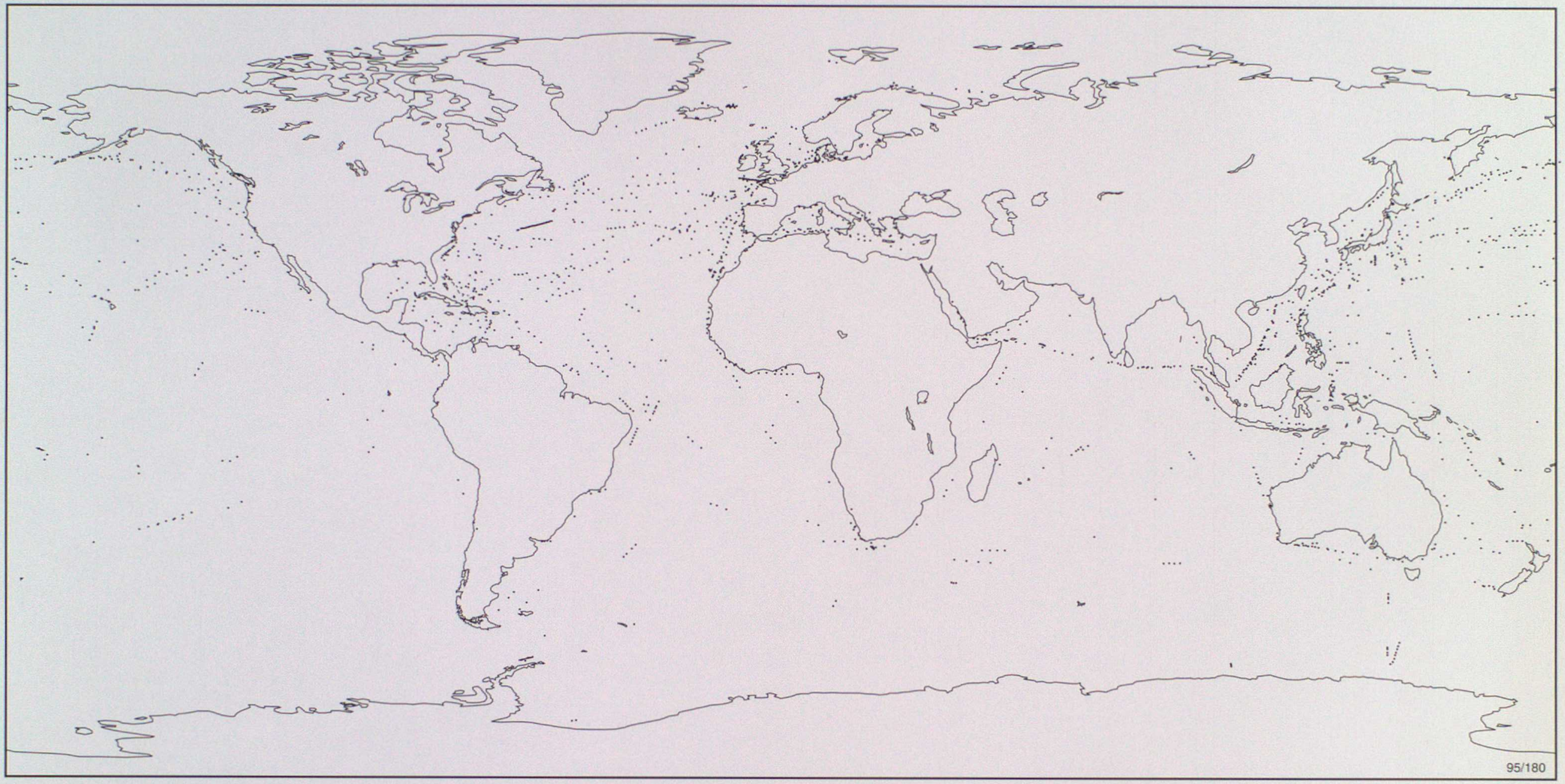


Fig. 2.10a Global data coverage for sea surface temperature valid at 00 UTC on 23rd January 1995. Ships (1707 observations), TRACKOBS (12) and BATHY (15). (Courtesy: Clive Jones).

SEA SURFACE TEMPERATURES FROM MOORED AND DRIFTING BUOYS

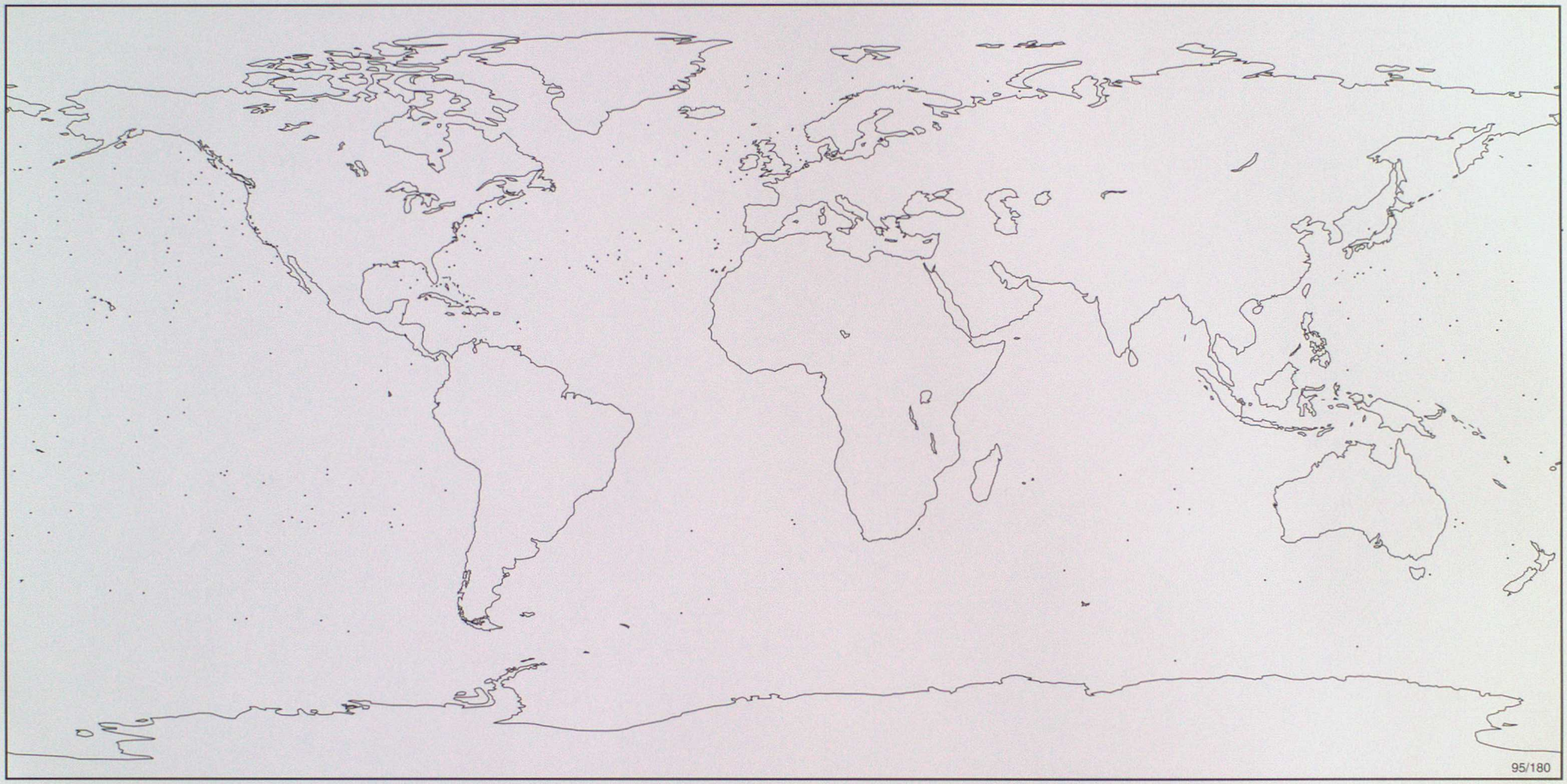


Fig. 2.10b Global data coverage for sea surface temperature valid at 00 UTC on 23rd January 1995. Moored buoys (85 observations) and DRIFTER (241). (Courtesy: Clive Jones).

SEA SURFACE TEMPERATURES FROM SATELLITE

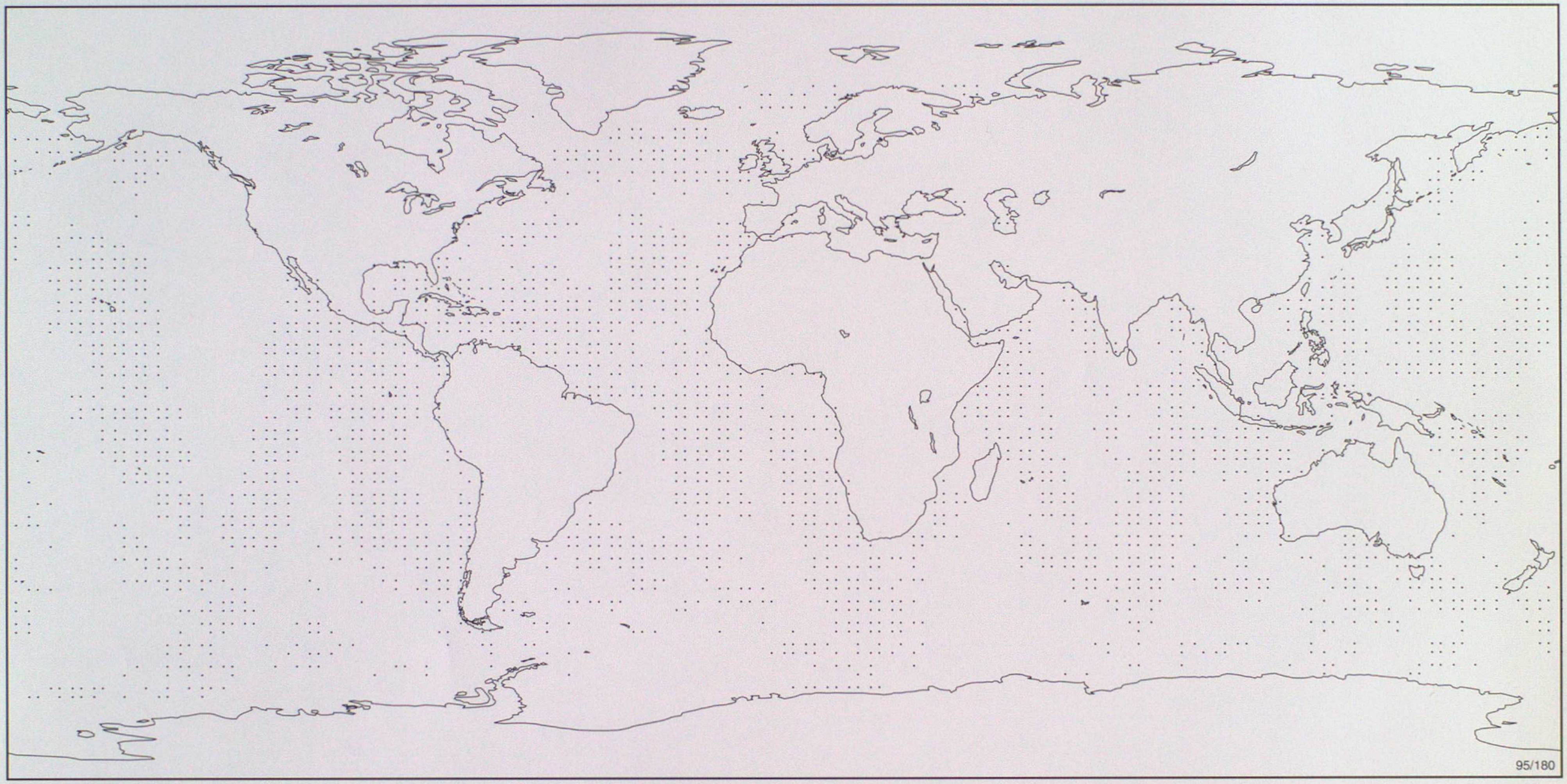


Fig. 2.10c Global AVHRR data coverage for sea surface temperature valid at 00 UTC on 23rd January 1995. There are 3114 observations. (Courtesy: Clive Jones).

EFFECTS OF REPEATED INSERTION

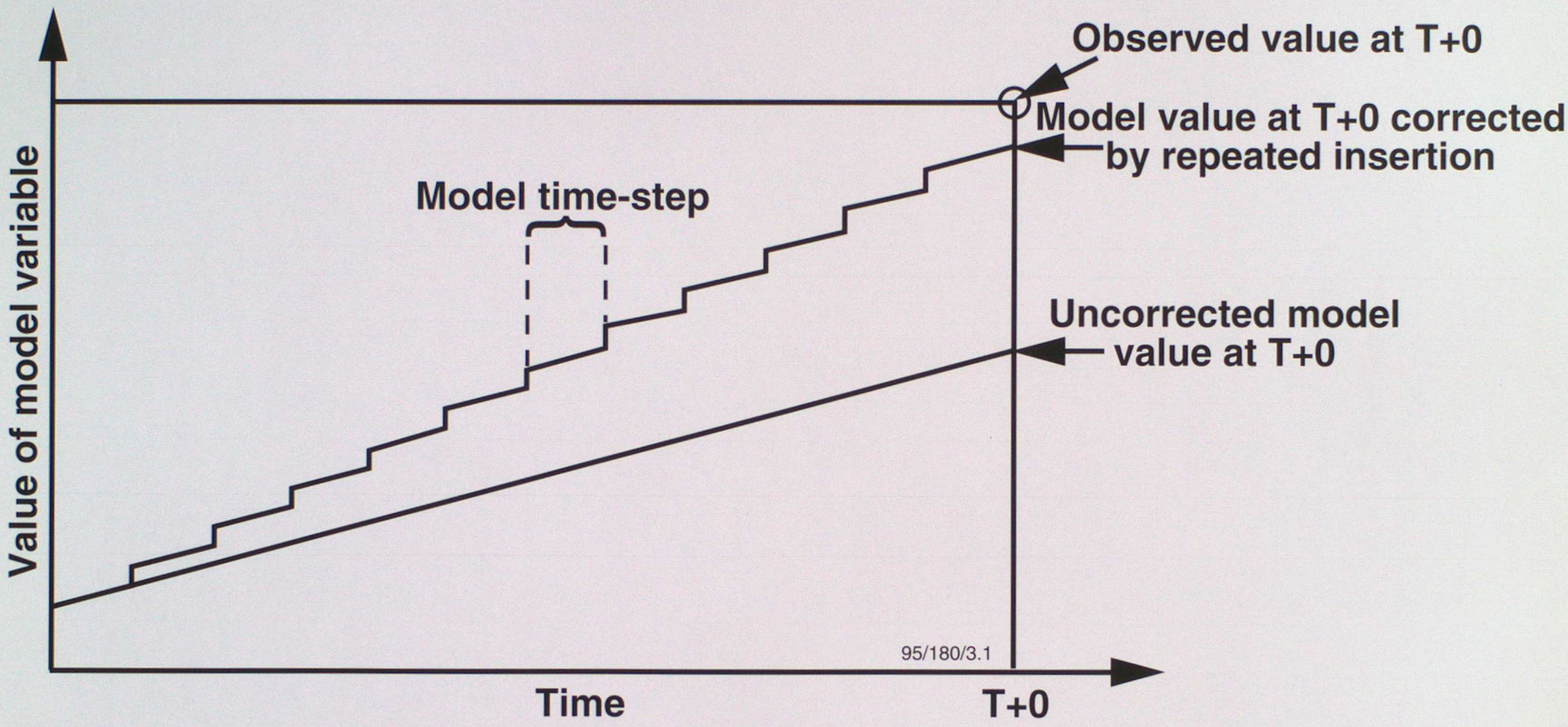


Fig. 3.1 The effects of repeated insertion of data on a model variable. (From Met. O College, 1993).

ANALYSIS CORRECTION SCHEME

SPLIT	Partition observations by model variable
PREPARE	Generate vertical profiles of observation increments and errors on model levels
ANALYSE	surface pressure (p)
Balance	Δp by hydrostatic temperature increments $\Delta\Theta_h$
Balance	Δp and $\Delta\Theta_h$ by geostrophic wind increments
ANALYSE	potential temperature (Θ)
Balance	$\Delta\Theta$ by geostrophic wind increments
ANALYSE	wind (V)
ANALYSE	relative humidity (RH)
Advance	Integrate forward one time-step with additional smoothness constraint (divergence damping)

Fig. 3.2 Stages in the Analysis Correction Scheme. (Courtesy: Stuart Bell).

WEIGHTING OF OBSERVATIONS IN VERTICAL

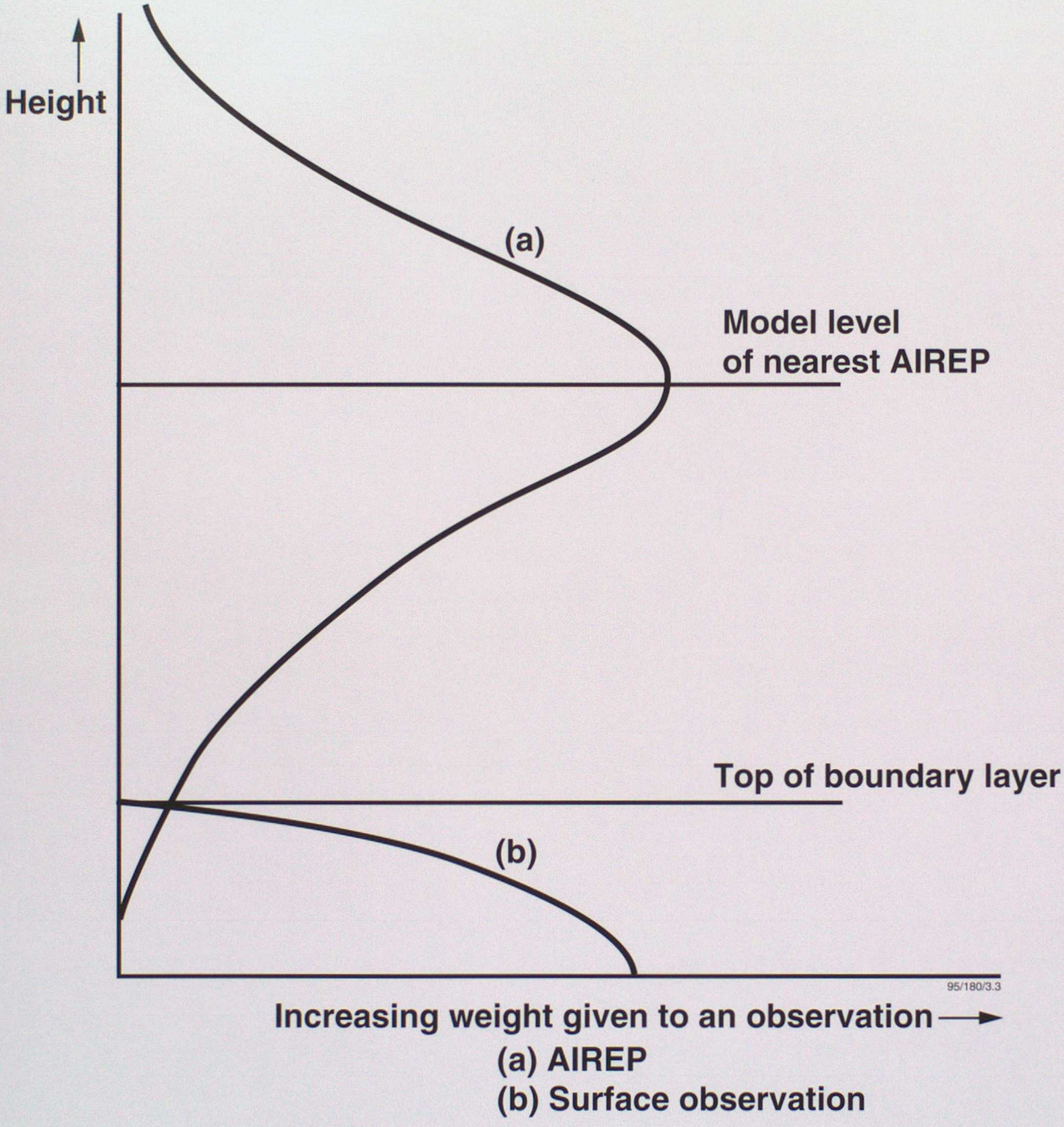


Fig. 3.3 Schematic showing weight as a function of height for

a. an AIREP

b. a surface observation

HORIZONTAL ANALYSIS EQUATION

$$\Delta X_k = \alpha \Sigma_i \mu_{ki} \, Q_i \, R^2(\delta t_i) C_i$$

α Relaxation coefficient

μ_{ki} Correlation function

$R^2(\delta t_i)$ Time factor (parabolic about ob. time)

C_i Observation increment

Q_i Normalization factor $= \{ \varepsilon_i^2(1+D_i)\}^{-1}$

where ε is obs/model error variance ratio and D is a data density function.

Fig. 3.4 Explanation of terms in the horizontal analysis equation. (Courtesy: Stuart Bell).

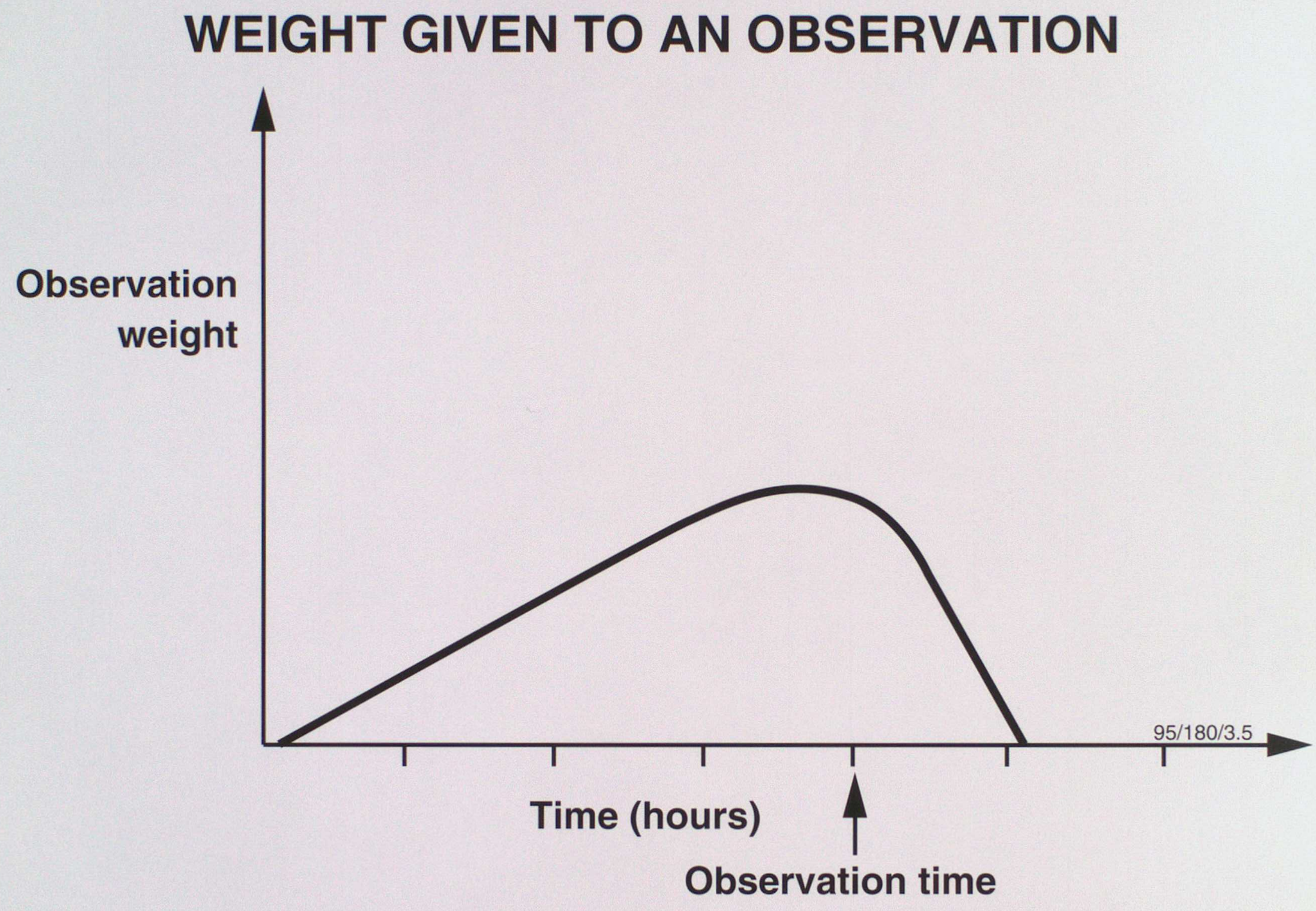


Fig. 3.5 Example of weight given to data. The shape of the weighting function is actually parabolic and applies also to Figs 3.6 and 3.7 (Adapted from Met. O College, 1993).

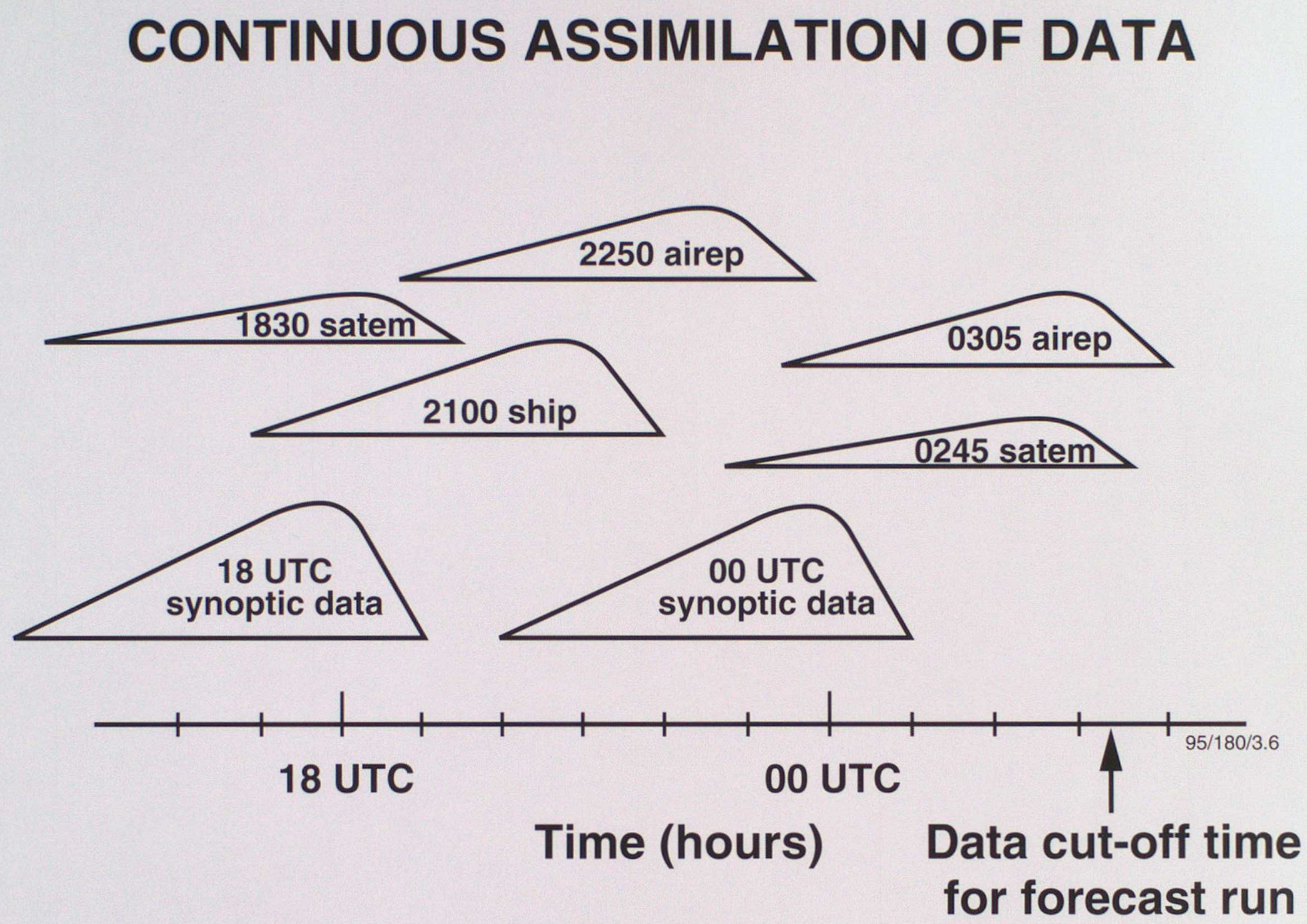


Fig. 3.6 Example of continuous assimilation of data in the Global Model. 'AIREP' is an aircraft report. 'SATEM' is a satellite temperature. (Adapted from Met. O College, 1993).

OBSERVATION WEIGHTING IN THE MESOSCALE MODEL

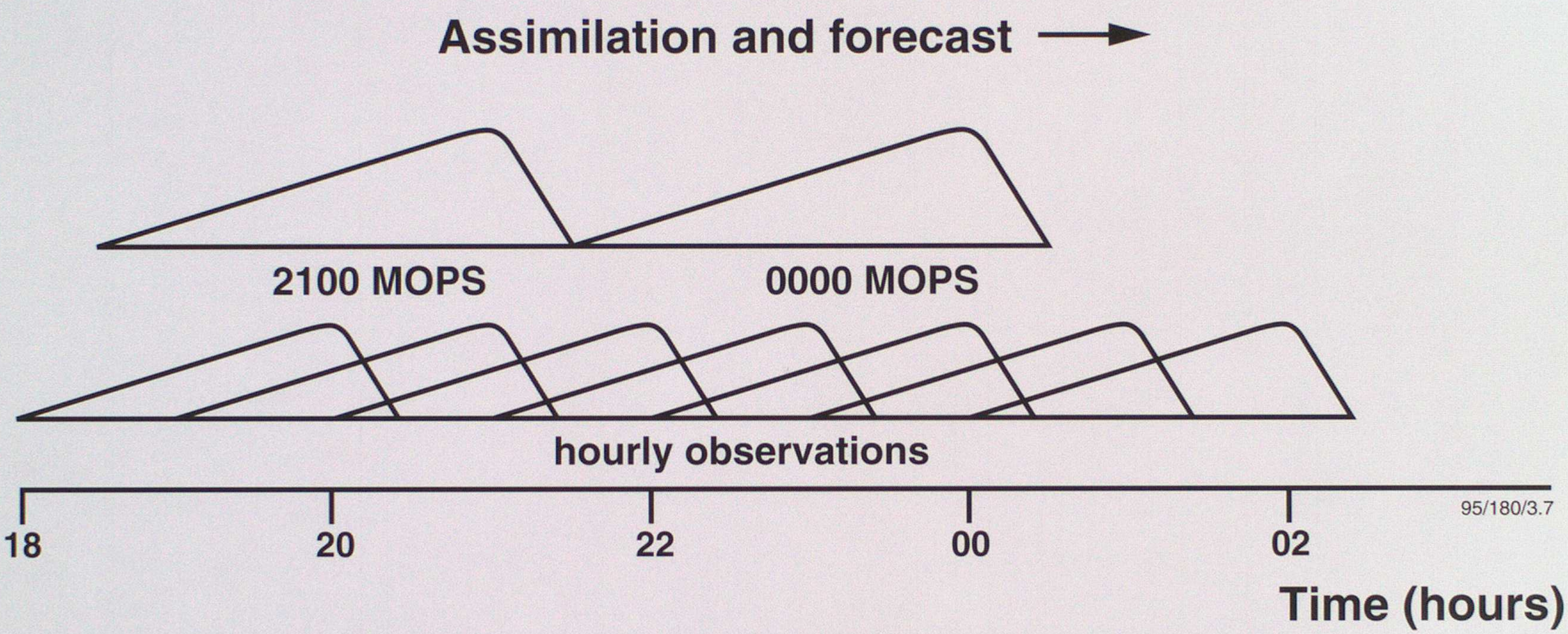


Fig. 3.7 Weighting for surface and moisture data in the MES analysis correction scheme (Adapted from Met. O College, 1993).

THE CORRELATION FUNCTION

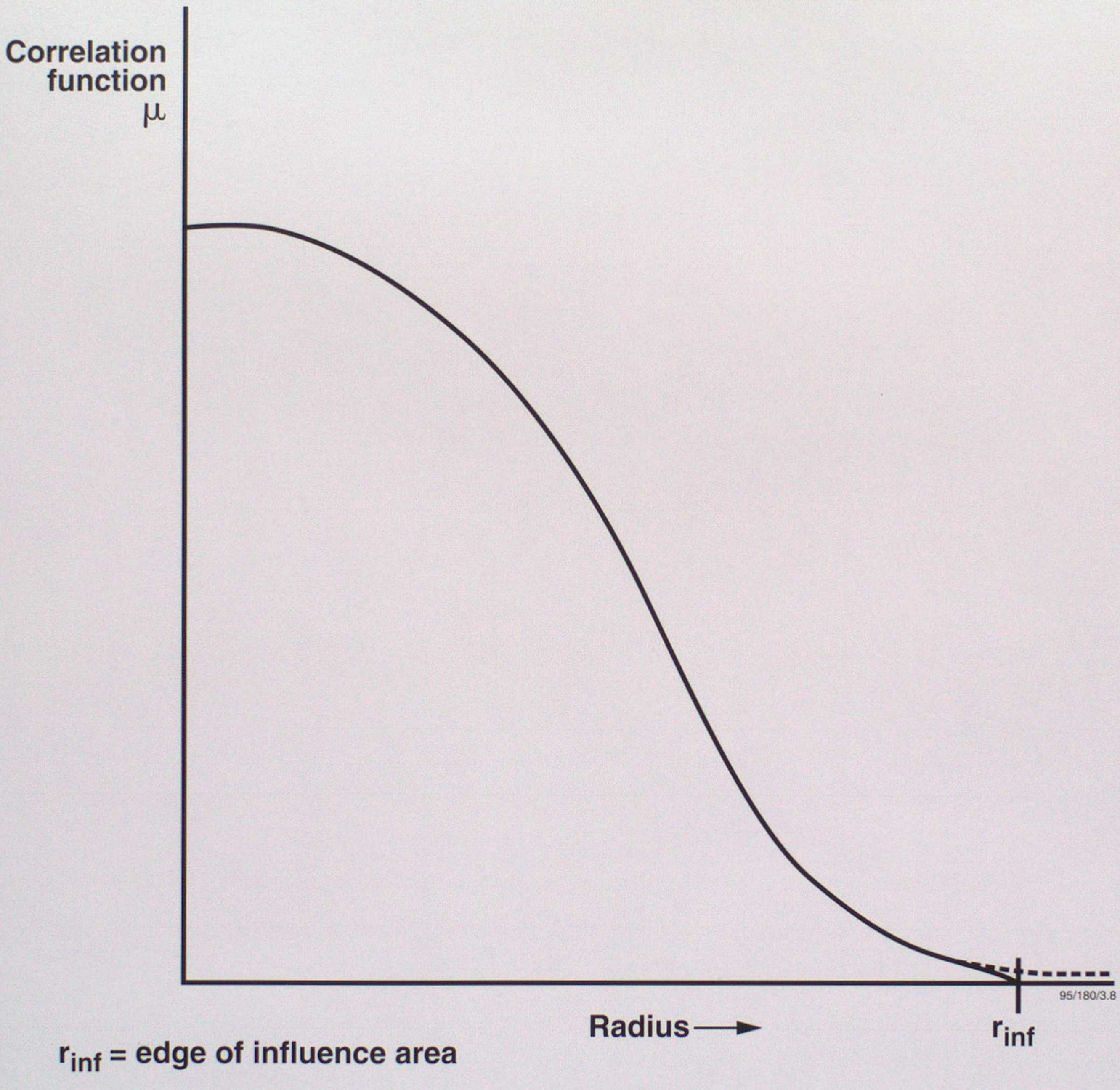
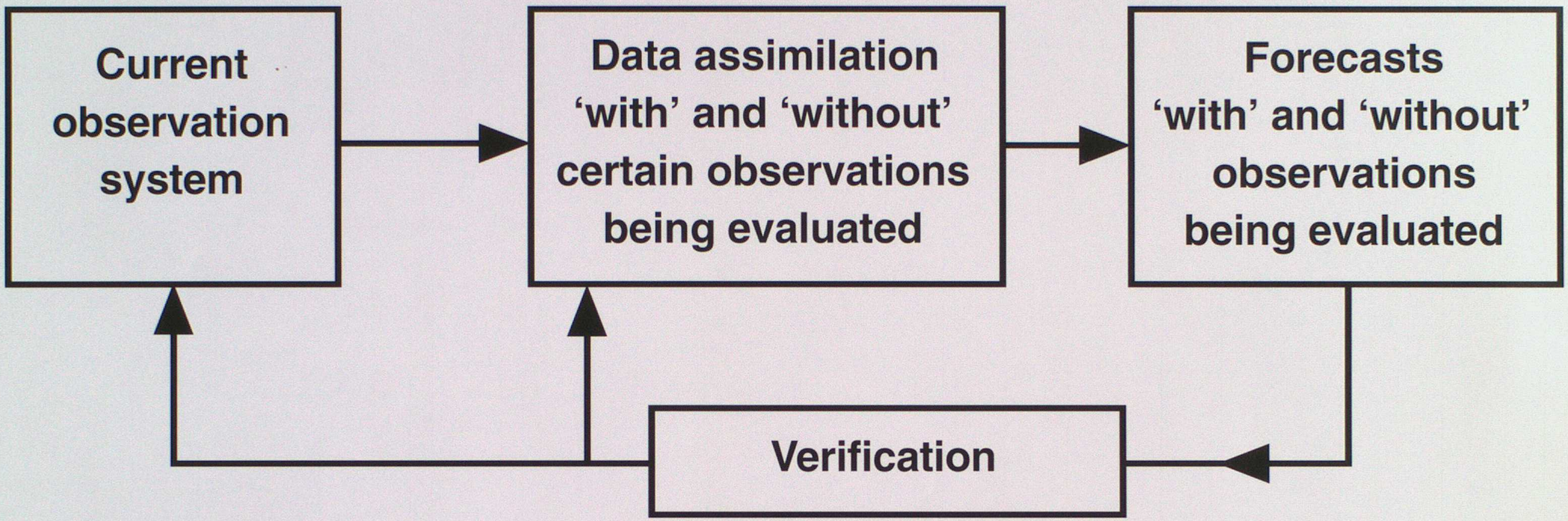


Fig. 3.8 Schematic showing variation of correlation function with radius. r_{inf} is the radius of influence of the observation.

OBSERVATION SYSTEM EXPERIMENTS (OSEs)



Evaluation in form of:

- **Statistics for a number of forecasts**
- **Case studies of individual systems**

Fig. 4.1 Schematic of an Observing System Experiment (OSE). (Courtesy: Richard Graham).

OBSERVING SYSTEM SIMULATION EXPERIMENTS (OSSEs)

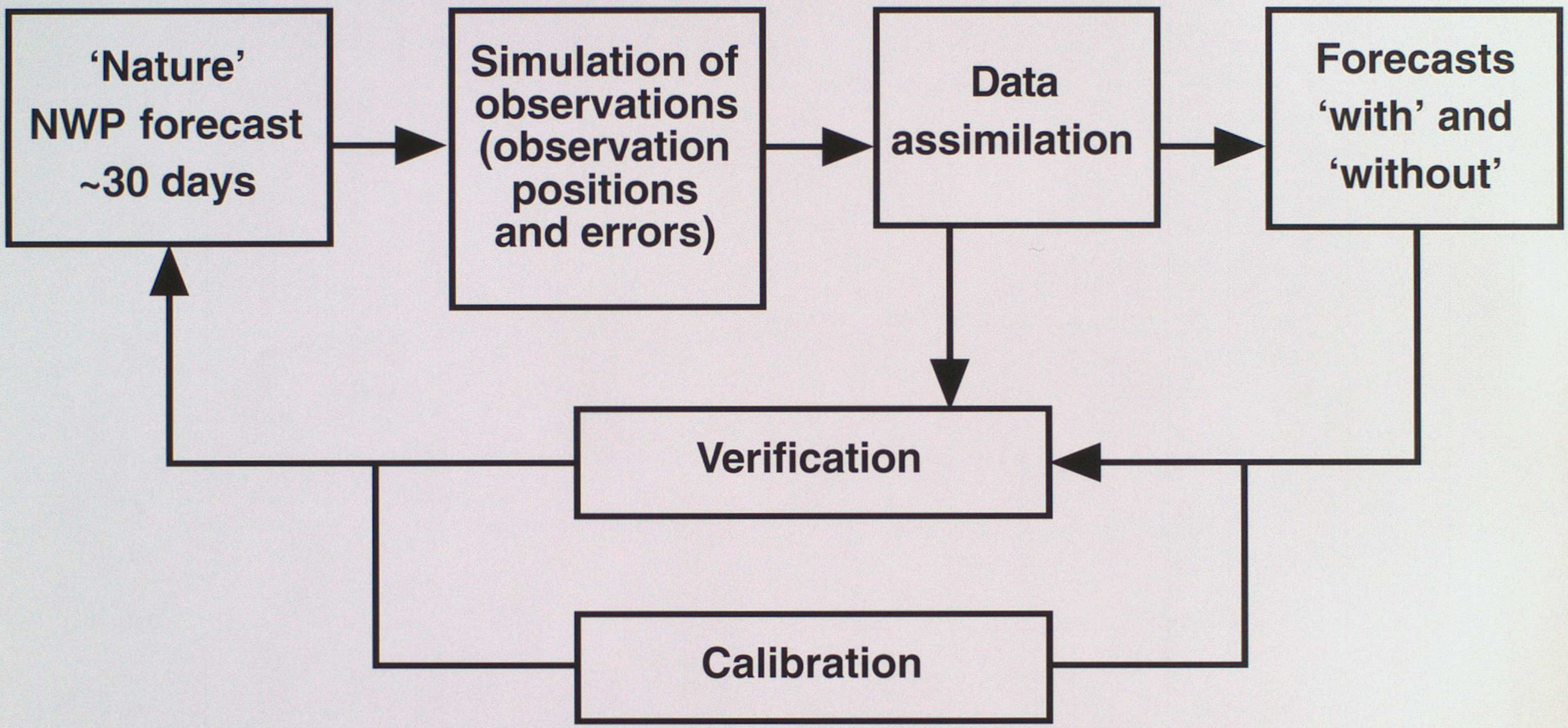


Fig. 4.2 Schematic of an Observing System Simulation Experiment (OSSE). (Courtesy: Richard Graham).

OPERATIONAL CYCLE FOR LIMITED AREA MODEL (LAM)

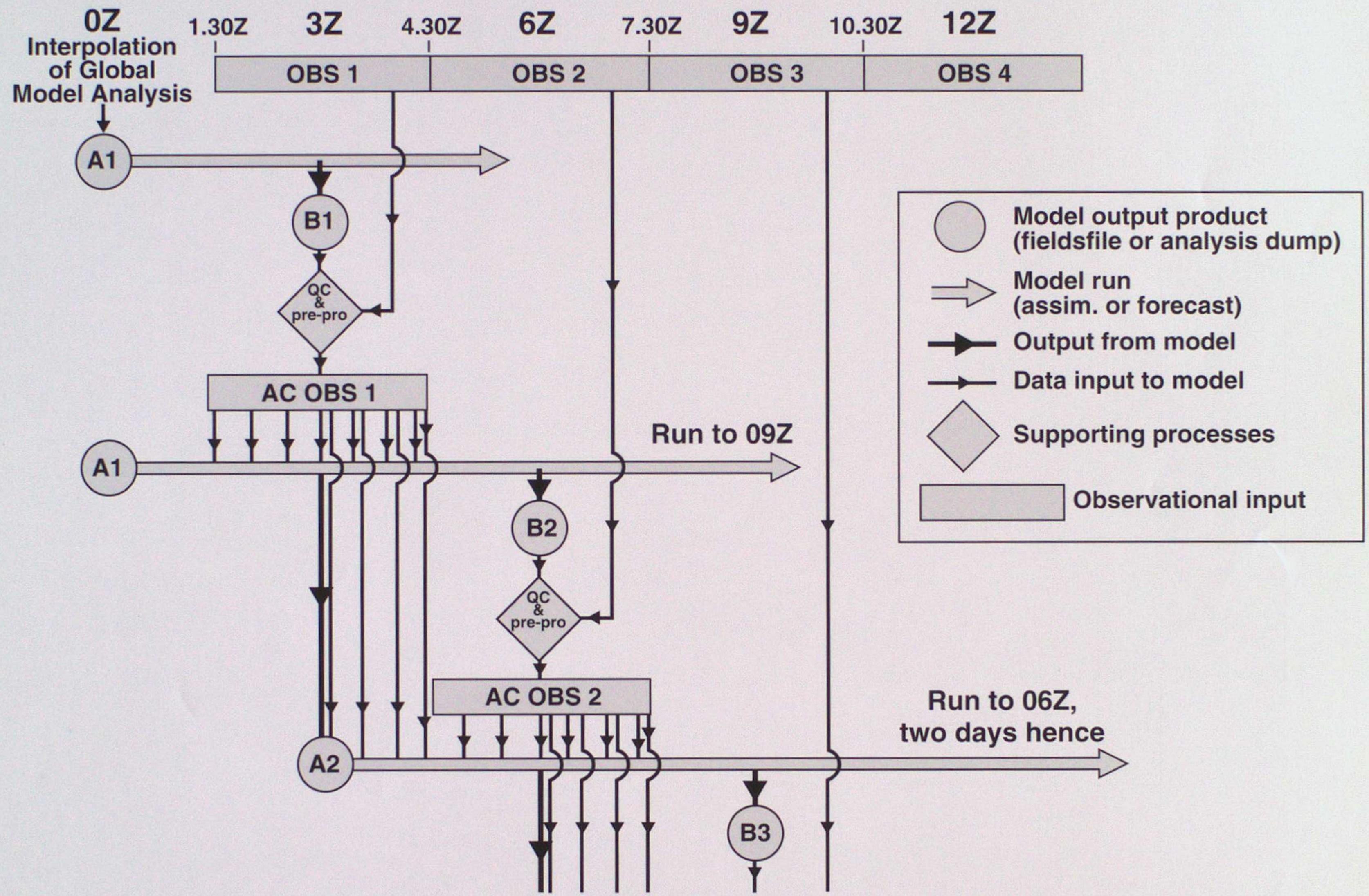


Fig. A.1 Schematic showing how the input of observations is related to the cycle of analysis and forecasts for the LAM. Labels are explained in the text. (Courtesy: Richard Graham).