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Facilities for research and weather observations on the 213 m tower at Cabauw and at remote locations

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1. Introduction

Since 1972 meteorological observations of high vertical resolution are carried out on the 213 m tower at Cabauw in The Netherlands by the Royal Netherlands Meteorological Institute (KNMI). The need for high quality data in boundary layer research was the motive for the construction of this tower (Driedonks et al., 1978). There is a continuous measuring program of the mean structure of the boundary layer. The turbulent structure can be observed with additional instruments under special atmospheric conditions. In the past years several experiments were carried out, often in co-operation with scientists from other institutes. Weather forecasters at KNMI also became interested in the use of the continuously measured boundary layer data for short-range weather prediction. Moreover the need for meso-scale experiments arose, and in 1981 a mobile field-work station was put into use.

Maintenance and replacements resulted in regular interruptions of the measuring program at Cabauw. Growing experience led to several improvements of instrumentation and data handling, and to a gradual extension of the observations. In the beginning of 1984 the data collection computer had to be replaced. It was then decided to start a new measuring program and to revise the data handling procedure, according to the recent ideas about the use of boundary layer measurements. At present the continuous measurements are not used for research only, but also provided as supplementary information to weather forecasters. To that end data transmission to the 22 km distant institute at De Bilt and a code form were arranged.

In this paper a description is given of the present facilities for boundary layer research and weather observations as in use at Cabauw since 1986. Moreover the mobile field-work station is described. Background information relevant to the use of measured data and to the planning of future experiments is provided. In the last chapter a broad survey is given of publications based on measurements with these facilities.

2. Site, topography and climate

The tower is located in the center of The Netherlands, near the village of Cabauw. The co-ordinates are 51°58'16"N and 04°55'36"E. The foot of the tower is at 0.5 m below mean sea level; the distance to the sea is about 45 km. Maps are given in figures 1 and 2.

This location was chosen because its topography is very suitable for boundary layer measurements. The surroundings are flat within a radius of at least 20 km. The country consists of meadows and ditches, with scattered villages, orchards and lines of trees. The river Lek (a main branch of the Rhine) runs at one kilometer south of the tower. The surface layer roughness length depends on direction and season, and varies from 0.05 to 0.35 m (Van Ulden et al., 1976). In the SW direction a zone of 2 km long and 1 km wide is almost free of obstacles. The soil consists of a 0.4 to 0.8 m thick bed of river-clay on top of a peat-layer. At a depth of 6 m pleistocene sand is found (Jager et al., 1976). The water table is usually at 1 m below the surface, but can be considerably higher during wet periods of time.

The meadows are used for cattle-breeding and as hay-fields. In the winter season liquid manure is used for fertilizing. In the immediate vicinity of the tower there are no cattle. Here the grass is kept at about 8 cm height by frequent mowing; the fresh-cut grass is not removed. The last fertilizing was carried out 2 years ago with a mixture of nitrogen, phosphate, potassium and lime. A new fertilizing scheme will be planned.

The tower is situated outside highly polluted areas. Most of the roads are used by local traffic only. The nearest well-used road is at 350 m S of the tower. It runs parallel to the river Lek. On an average there are passing by about 5200 vehicles a day (1984). An important regional source of air pollution is the industrial area of Rijnmond, which extends from Rotterdam at 30 km from the tower to the coast.

The weather in the area is characterized by a moderate maritime climate, with a prevailing westerly circulation. Some climatological data are given in table 1. For rain and thunderstorms data from the synoptic station De Bilt (06260) are chosen. The other data are from Rotterdam Airport (06344).

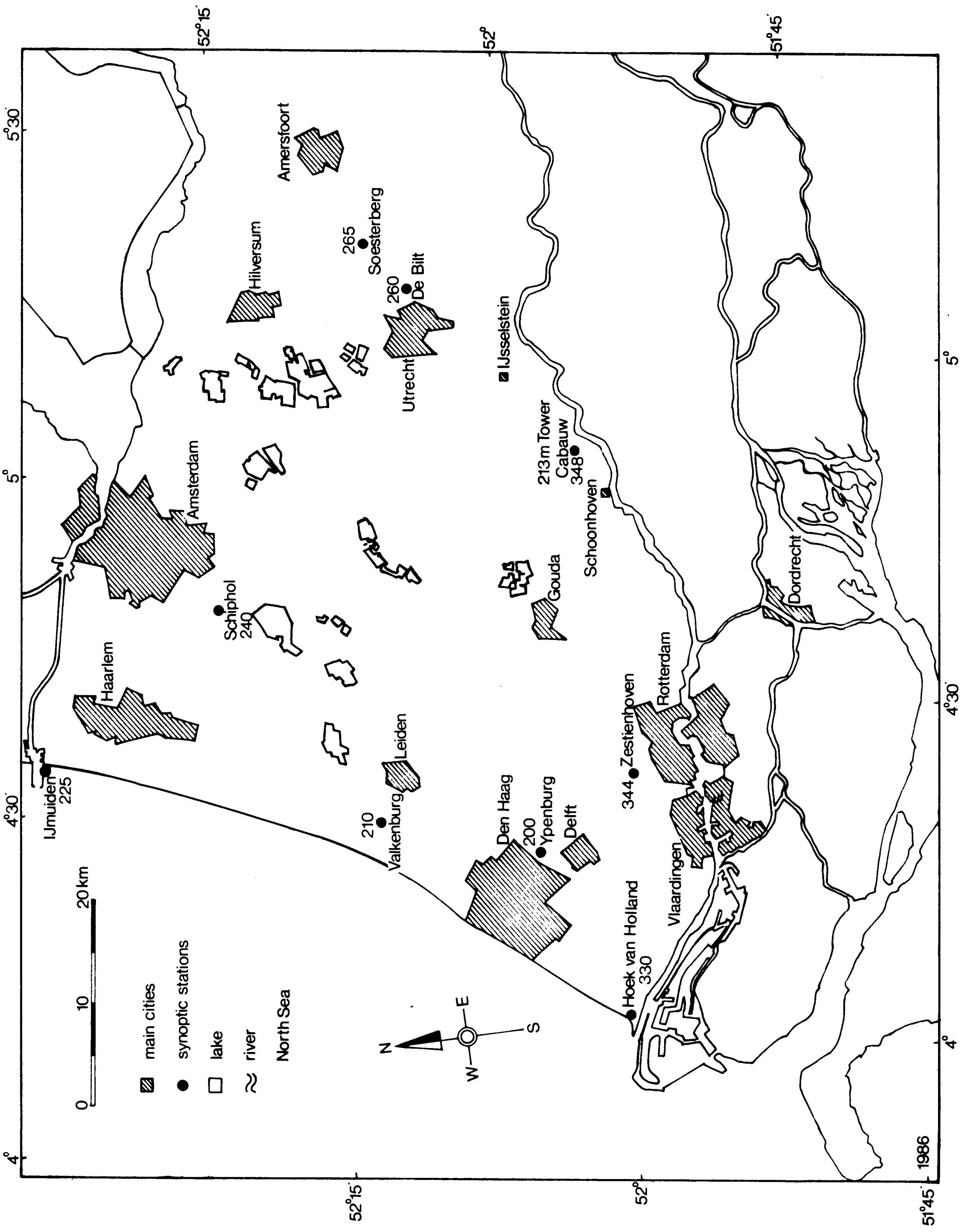

fig. 1. Location of the tower

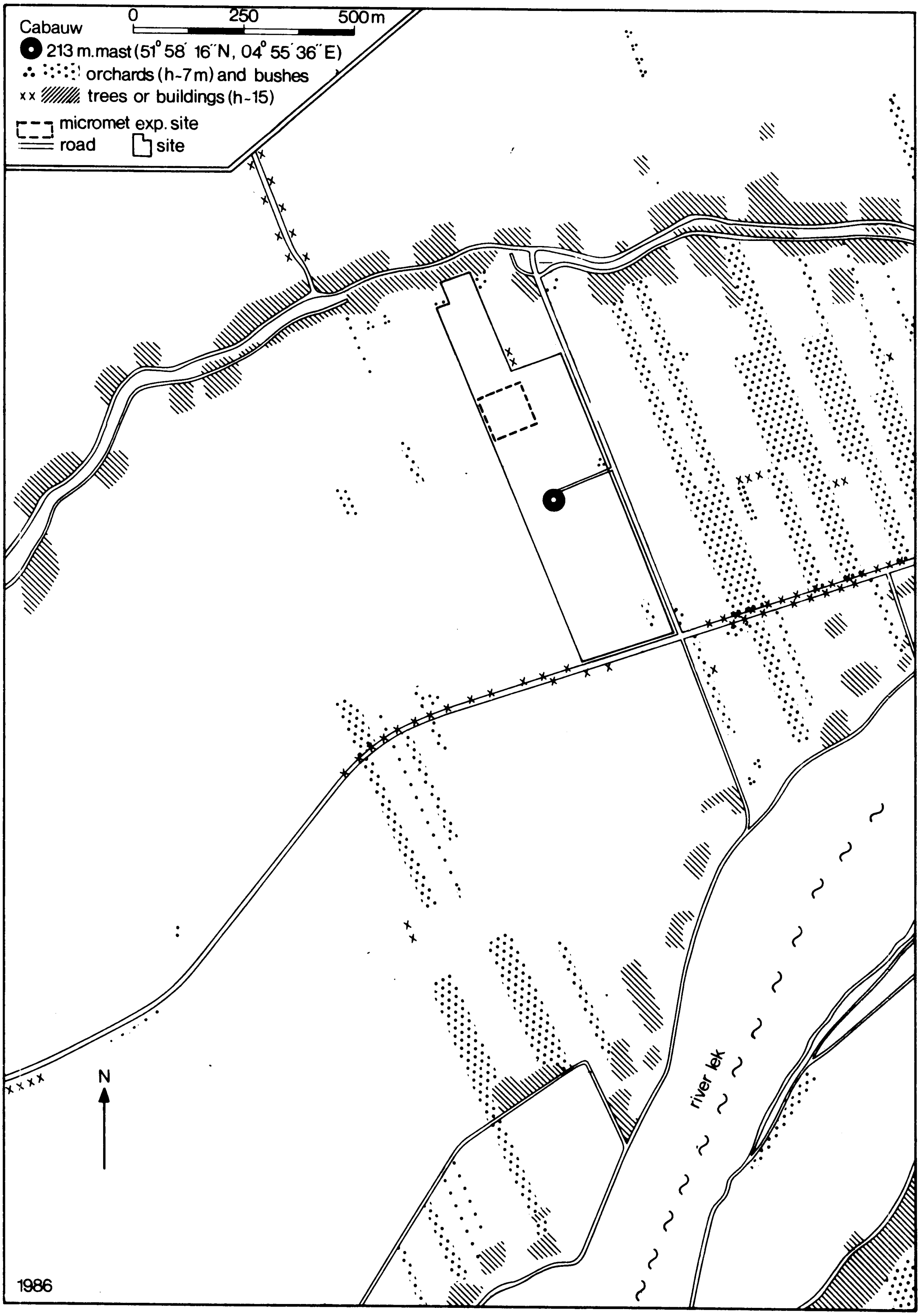

fig. 2. Surroundings of the tower

	winter	spring	summer	autumn
mean temperature (°C)	3.0	8.3	16.1	10.5
mean max. temp. (°C)	5.5	12.2	20.1	13.9
mean min. temp. (°C)	0.4	4.2	11.7	7.1
number of days with:				
T max. ≧ 25°C	-	1	10	1
T max. ≧ 20°C	-	7	44	11
T max. < 0°C	8	0	-	0
T min. < 0°C	36	13	-	6
T min. < -10°C	3	0	-	-
rel. humidity (%)	89	81	81	86
duration of sunshine (%)	20	38	41	30
numb. of days without sunshine	38	12	4	19
amount of precipitation (mm)	196	158	235	209
duration of precipitation (h)	186	137	122	155
number of days with:				
rain	59	55	58	58
prec. ≧ 0.3 mm	49	41	41	44
prec. ≧ 1.0 mm	36	31	34	34
prec. ≧ 10.0 mm	5	3	7	6
thunderstorms	2	7	15	5

wind frequency P (%) and mean wind speed S (m/s):

	winter		spring		summer		autumn	
class (degrees)	P	S	P	S	P	S	P	S
350 - 70	17	4.3	28	4.5	21	3.8	14	3.7
80 - 160	18	4.7	15	4.2	9	3.3	17	3.7
170 - 250	39	6.2	26	5.7	32	5.0	39	5.5
260 - 340	18	6.0	24	5.2	29	4.7	19	5.5
variabele	6		6		8		9	

Table 1. Climatological data

3. Installation

The 213 m high tower (fig. 3) is constructed as a closed cylinder of 2 m diameter, with an elevator running inside. The tower is guyed at 4 levels. From 20 m upwards, horizontal booms are installed at 20 m intervals (fig. 4). At each level there are three booms, extending 9.4 m beyond the cylinder surface, pointing into the directions 10°, 130° and 250°. The booms can be swivelled upwards hydraulically, so that the instruments can be serviced from a balcony. At the ends of the SW and N booms, two lateral extensions (1.5 m) carry 4 plugs on which instruments can be mounted. The SE boom-ends carry either one plug or a transmissometer light source. Around the foot of the mast stands a 3.8 m high octogonal building, with a diameter of 17.3 m and rounded-off corners. Investigations (unpublished) have shown that the disturbance of the airflow around it is moderate and negligible at the 20 m boom level. The building contains the recording instrumentation (fig. 5), a small workshop, a storage room and a small canteen. Sufficient space is available for experimental equipment.

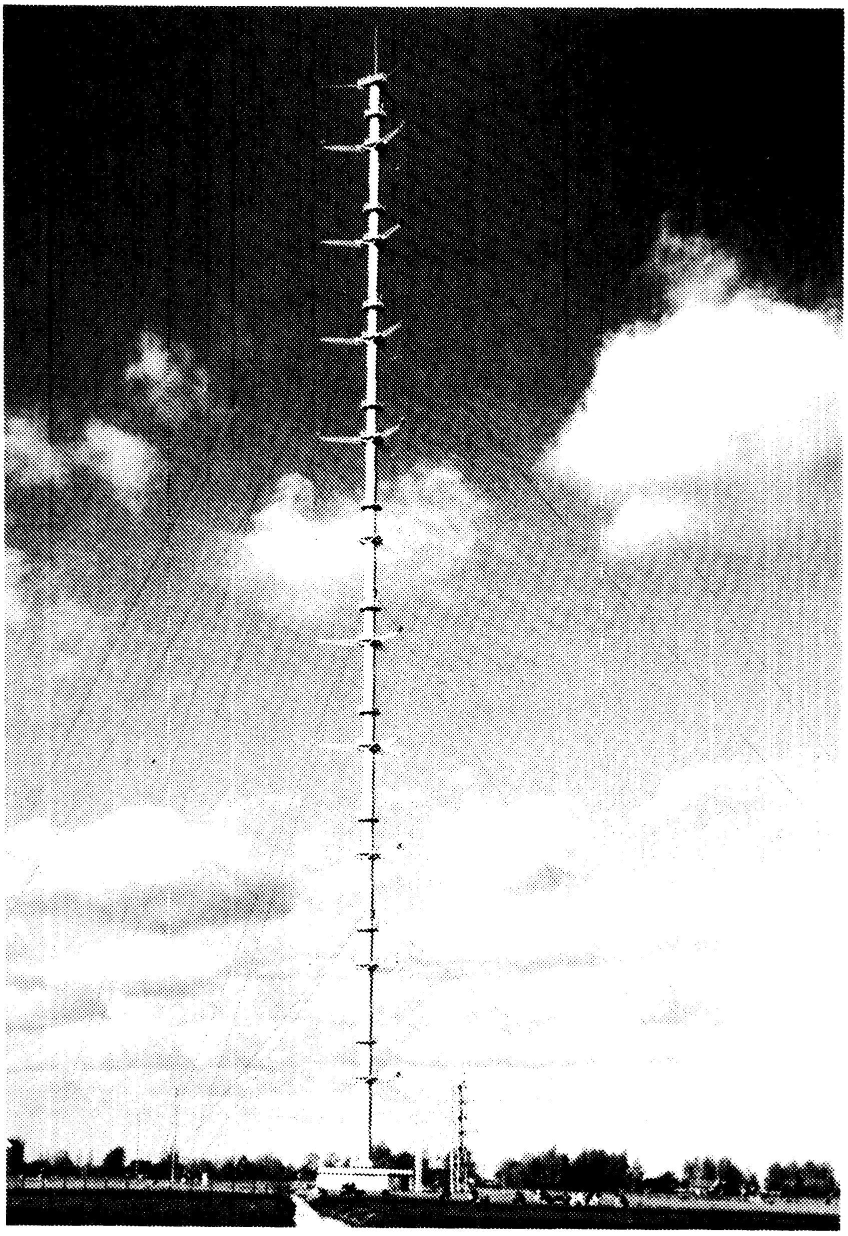

fig. 3. The 213 m tower

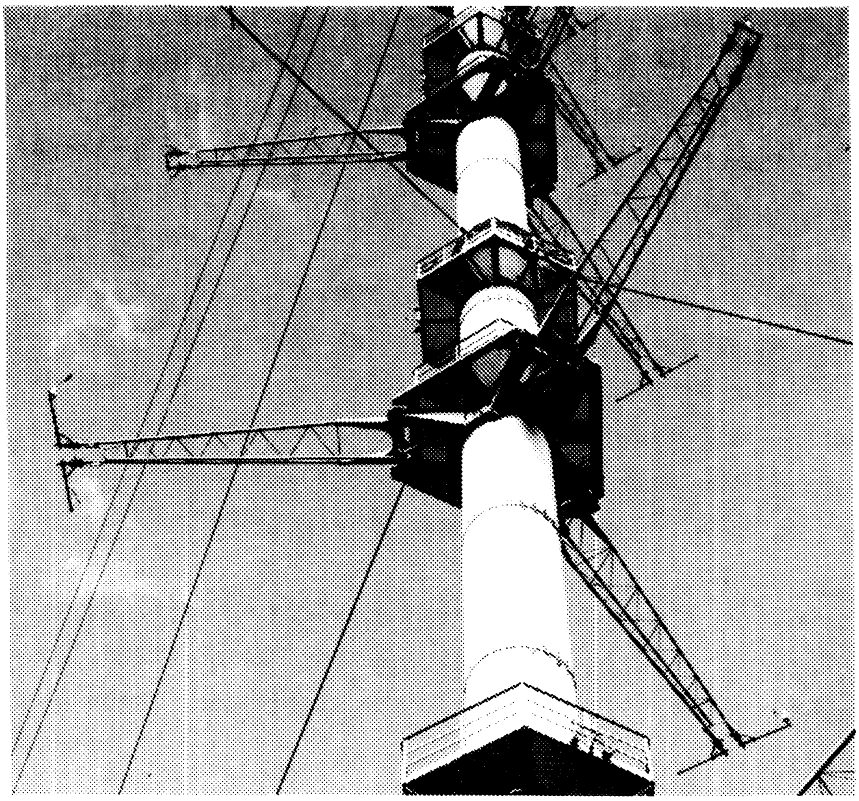

fig. 4. The booms

fig. 5. Control room

Due to the size of mast and building, accurate measurements below 20 m are impossible. To overcome this limitation, auxiliary masts were installed at a sufficient large distance of the main tower. The positions are shown in fig. 6. At 29 m SE stands a 19.7 m high mast of open construction, with 3 extension booms (fig. 7). At about 73 m NW of the main tower there are 2 slender masts of 10.1 and 20.0 m height (fig. 8).

At about 200 m N of the tower, a special site measuring 100 by 100 m is reserved for micrometeorological observations (fig. 9). There the soil has been carefully smoothed, and drained at a depth of 0.65 m, so the original soil profile, as described before, has been disturbed here, but the actual structure still resembles that of the surroundings and is horizontally homogeneous. More details are given by Jager et al. (1976).

All instrument plugs are wired to a rack in the building, from where each signal can be connected to any device available for registration. The installation is powered by 220 V, 50 Hz mains, partly stabilized. Three phase 380 V is also available.

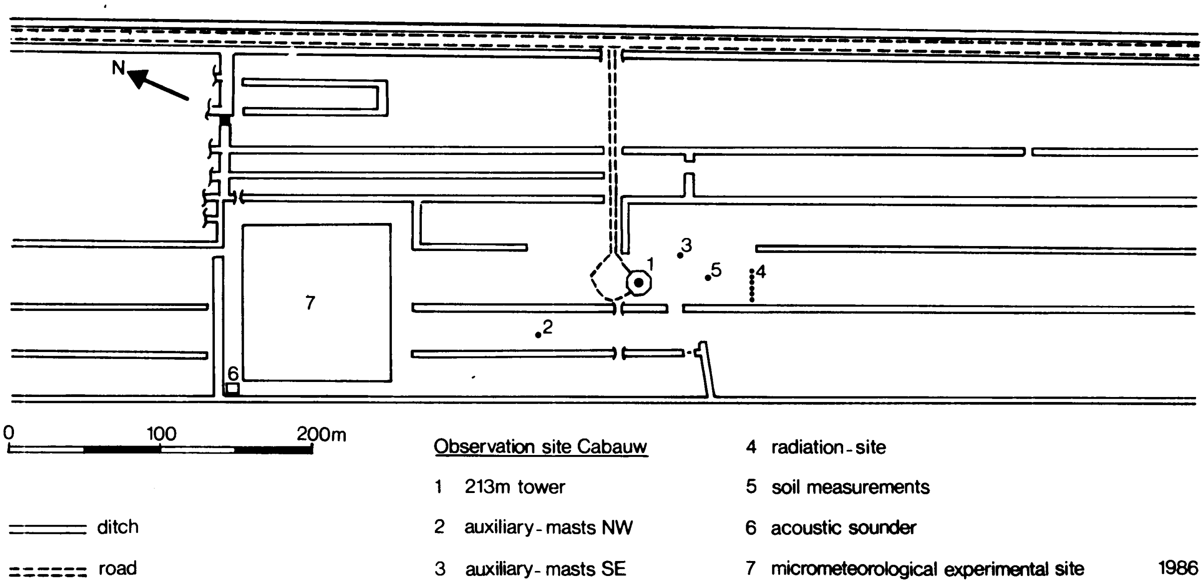

fig. 6. The site

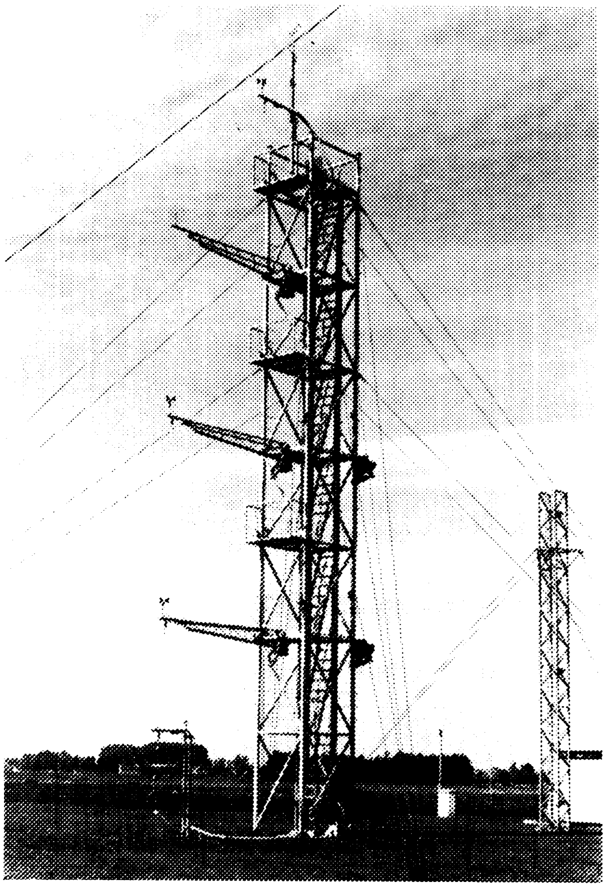

fig. 7. Auxiliary mast (SE)

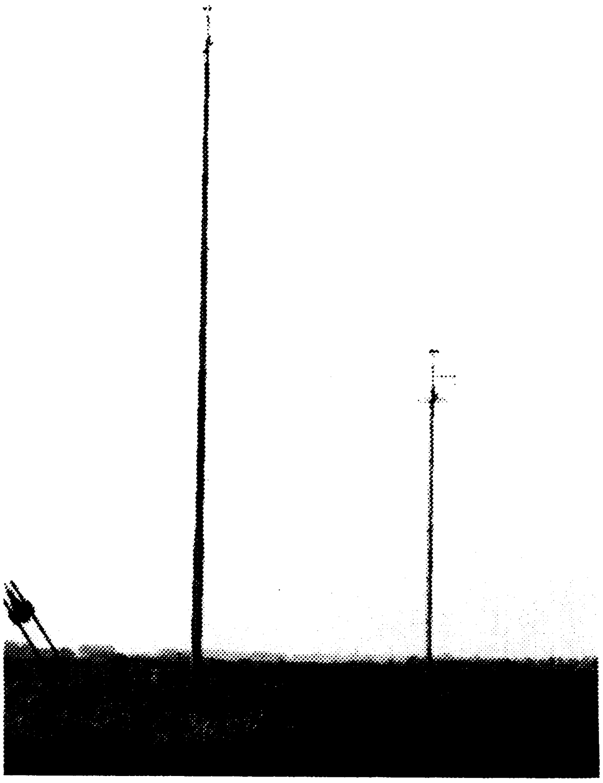

fig. 8. Auxiliary masts (NW)

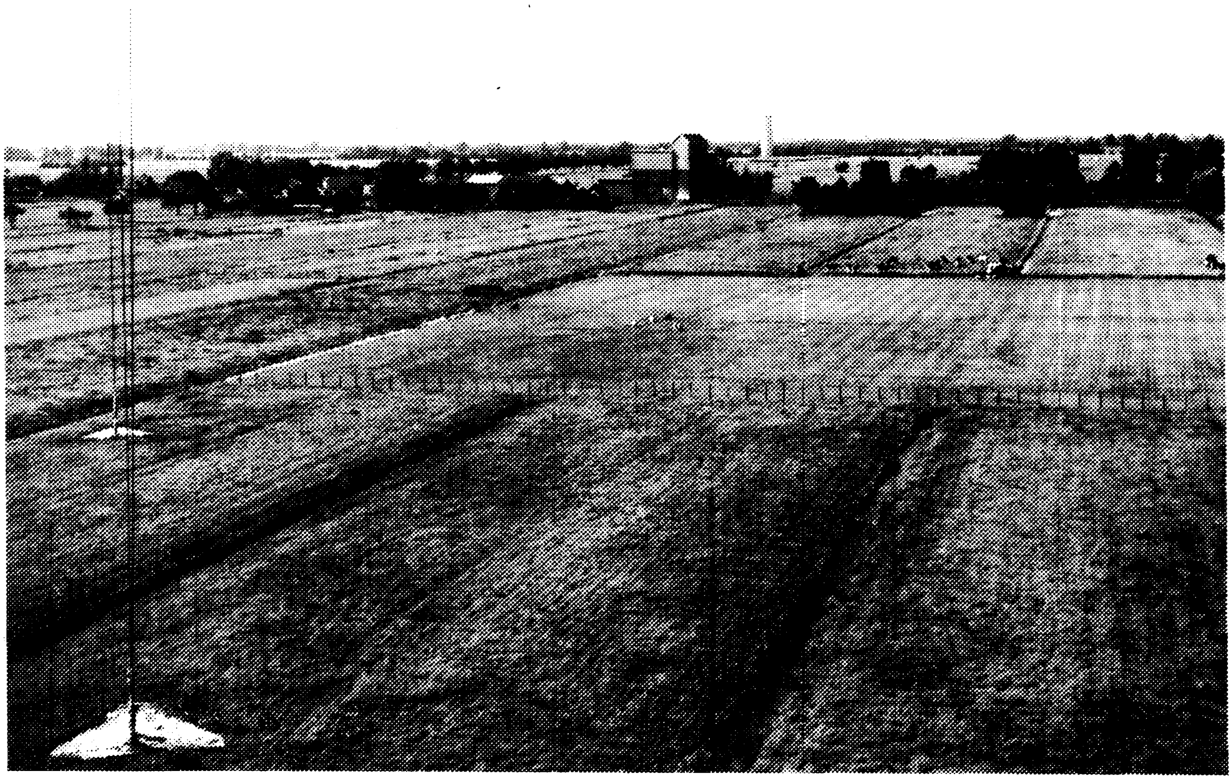

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fig. 9. Micrometeorological experimental site

4. Continuous measuring program; instrumentation

The continuous measuring program provides data on the mean vertical profiles up to 200 m of wind speed and direction, temperature, humidity and visibility. In addition various radiation components, soil heat-flux, soil temperature, precipitation and mixing height are measured. In co-operation with the National Institute for Public Health and Environmental Hygiene (RIVM) measurements of several air pollution components (SO_2, O_3, NO and NO_2) are made at the levels 3, 40 and 100 m.

The position of the various instruments on the tower and on the masts have been chosen so as to provide reliable measurements for all wind directions. To that end the construction with three booms per level was designed. A boom length was chosen that would limit interference of the mast on wind measurements to less than 1% according to the knowledge at that time (Gill et al., 1967). By the time the first measuring program was planned, it appeared that the data handling capacity would be insufficient for three instruments at each level. Moreover, it was necessary to leave open some positions for special instruments that would be used during experiments. The working solution to this problem is that wind speed is measured on the N and the SW booms only, and wind direction on all three booms. At most one vane is in the wake of the mast, and from the three available azimuths at any time two can be found to agree well. After the determination of azimuth, the least obstructed wind speed measuring position can be selected. With regard to temperature, it was shown experimentally that measurements at the three boom ends had an average difference of less than 0.05 K. Therefore temperature is measured at one boom only.

Not only the mast, but also the booms themselves cause disturbances in the wind flow field. From experimental and theoretical studies (Van der Vliet, 1981; Wessels, 1984a) appropriate corrections, up to 4% in wind speed and 2° in azimuth were determined for each wind measuring position as a function of azimuth.

In table 2 the instrumentation is summarized. The instruments are described below in more detail. See also Wessels (1984b).

Z (m)	T	T_w	W	V	Q_1	Q_2	G
214					x		
200	x	x	x				
180				x			
140	x	x	x	x			
80	x	x	x				
60				x			
40	x	x	x				
20	x	x	x	x			
10	x	x	x	x			
2	x	x		x	x	x	
0.6	x	x					
0.0	x						
-0.02	x						
-0.05							x
-0.10							x

Z = instrument level

T = dry-bulb temperature

T_w = wet-bulb temperature

W = wind speed and direction

V = horizontal visibility

Q_1 = short wave radiation

Q_2 = short wave shadowband, net, longwave ↓ and longwave ↑ radiation

G = soil heat flux

Not shown here are the measurements of rain and pressure, and the acoustic sounder.

Table 2. Continuous measuring program

Wind speed and direction

For wind measurements Gill propeller vanes type 8002DX are used (Gill, 1975). This instrument was slightly modified by KNMI to improve its resistance against the Dutch humid climate. The dynamic properties of the instrument are: propeller response length 2.2 m, damping ratio 0.40 and damped wavelength 3.8 m (Monna and Driedonks, 1979). Careful calibration procedures and application of corrections assures an accuracy of 1% in wind speed and 0.5° in azimuth.

Temperature

The temperature profile is determined by measuring the temperature differences by means of thermocouples between nearby levels. At both ends of the thermocouple chain reference is made to a zero degree Celsius ice-water bath. The sensors are ventilated and double shielded (Slob, 1978). A ventilation speed has been chosen that keeps the air speed within the shield independent of the wind speed. The best value was found to be 6 m/s. The accuracy of the measured temperature differences between the levels is 0.05 K.

Humidity

For humidity measurements wet bulb sensors are positioned close to the dry bulb sensors, mentioned above. The design is essentially the same as that of the temperature sensor. For the water supply peristaltic pumps are used. In this way a wet bulb temperature profile is measured. There is no alternative for the humidity measurements when the wet bulb is frozen.

Visibility

Transmissometers are used to measure visibility (Wessels, 1984b). The path length is 10.5 m. Fog with a visibility of less than 500 m can be detected.

Radiation

About 60 m SE of the tower several radiometers are installed at 2 m height to measure the various radiation components.

- Global radiation (0.3 - 3 μm) is measured with a Kipp CM 11 pyranometer, ventilated to prevent condensation on the dome. At 215 m height on the tower a similar instrument is installed.
- Diffuse radiation is measured with a Kipp CM 11 pyranometer, equipped with a shadow band.

- Longwave radiation (3 - 50 µm, upward and downward) is measured with two Eppley radiometers with silicon domes. One instrument is mounted on top of the other; both are ventilated. The temperature of the housing is measured separately.
- Net radiation (0.3 - 50 µm) is measured with a Funk net radiometer. This instrument is ventilated as well.

Soil heat flux

The soil heat flux is measured at 5 and 10 cm below the surface. To determine an average value 3 heat flux plates are used per level, positioned 3 m apart, forming a triangle. The plates are manufactured by TNO Institute of Applied Physics (TPD).

Soil temperature

The soil temperature is measured at surface level and at 2 cm depth. Wire-wound nickel resistors (length 35 cm, diameter 0.3 cm), designed by KNMI are used.

Precipitation

Precipitation is monitored continuously. A KNMI designed rain gauge (0.04 m^2) with a float recorder is used. An additional sensor is installed to monitor the occurrence of precipitation at any time, even in quantities not detectable by the standard gauge.

Mixing height

A monostatic acoustic sounder from Aerovironment Inc (option 300) has been installed for continuous monitoring of the lowest kilometer of the atmosphere. The antenna is placed on the ground at about 300 m NW of the tower. At present the echoes are displayed on a recorder. In the future automatically analyzed inversion heights will be inserted in the computer registration.

Cloud-base height

The installation of a ceilometer is planned. A laser beam device will be installed in 1987.

Pressure

Pressure is measured with a Negretti and Zambra barometer Mk 2, type M2236. Automatic reading is realized by an additional device constructed by KNMI.

5. Continuous measuring program; data handling

For data handling a PDP11/23-plus computer has been installed. Another identical computer is used as back-up, for the development of programs and for data handling during experiments. Every 3 seconds 68 data channels and 80 status lines are sampled. These signals can be monitored on a video terminal. Every 10 minutes a data processing cycle is executed. This procedure includes:

- check on the data quality;
- selection of the best boom for the actual wind measurement;
- computation of average values;
- computation of absolute temperatures and additional humidity parameters;
- computation of standard deviations for wind speed and wind direction;
- determination of wind extremes (3 s gusts).

For most parameters 10 min. average values are computed.
Exceptions are:

- visibility: for 5 visibility classes a frequency distribution for 20 half minute periods is given;
- precipitation: for each 5 minute period the total amount of precipitation since reset is given;
- rain indication: given for 20 half minute periods;
- pressure: an average value for the last minute of a 10 minute period is given.

Finally these data are transmitted to De Bilt by telephone line. A printout at Cabauw can be used to check the data.

In the computer at KNMI a database is maintained. A selection of measurements is transmitted to the weather office as additional information for weather forecasting. The database is examined by means of automatic routines and by manual checking. When all the erroneous data has been removed from the 10 min. database, 30 min. averages are derived and stored in files that are easily accessible by users. At this stage also surface fluxes of momentum, sensible heat and latent heat are computed (Nieuwstadt, 1978; Beljaars, 1982) and added to the 30 min. files. The 30 min. database is considered to be a high quality data set for boundary-layer research.

6. Facilities for research; instrumentation

Observations of the turbulent structure of the boundary layer can be carried out simultaneously with the continuous measuring program. To that end special instruments can be installed. Some of these fit on standard instrument plugs. Others must be mounted directly on a boom or on the ground. In principle the positions can be chosen freely, provided that no interference is produced on the continuous measurements. Some instruments available at KNMI are described below. Other instruments could be used as well.

Propeller bivane

For wind measurements a propeller bivane is used, which was developed at KNMI (WMO, 1976). The dynamic properties of this instrument are: propeller response length 0.5 m, damping ratio 0.56 and damped wavelength 4.0 m (Wieringa, 1967; Monna and Driedonks, 1979). It is possible to measure turbulence reliably with this instrument during rain if windspeeds exceed 5 m/s (Wieringa, 1972). It is, however, not sufficiently rugged to be used in extreme harsh weather conditions. In combination with the fast response psychrometer, which is described hereafter, this "trivane" is used to measure turbulent fluxes of sensible and latent heat.

Fast response psychrometer

This psychrometer was developed at KNMI (Kohsiek and Monna, 1980). The thermocouple sensors are made of 50 µm wire. A peristaltic pump is used for the wetting. The junctions are exposed freely in the air. The response times are 0.05 s for the dry bulb and 0.3 s for the wet bulb at a free air speed of 4 m s^{-1}. For flux measurements two psychrometers are used, placed about 1 m apart, with a propeller bivane in between. The response of such an array of thermocouples is primarily determined by the distance between the sensors and is considered to be equivalent to a first-order response length of about 0.5 m (Wieringa and Van Lindert, 1971).

Sonic anemomter, fast response thermometer

A sonic anemometer type DAT-300 with probe TR-61A, made by Kaijo Denki can be used for turbulence measurements (Hanafusa et al., 1980). An electronic levelling instrument, type Kaijo Denki IC-05D, and a rotator (designed by KNMI) with electronic read out of azimuth, are used to determine the orientation of the sonic. The rotator is operated by hand. Since the sonic does not have a true cosine azimuth response, the instrument is calibrated in a wind-tunnel (Schotanus et al., 1983). The mounting of the sonic - and additional instruments - is constructed as slenderly as possible, in order to avoid mast induced errors (Wyngaard, 1981). The instrument can be placed on a boom or on a special mast. It is primarily meant to be used below 20 m, where the response of the propeller bivane is not sufficiently fast.

To determine the sensible heat flux with a sonic, the temperature fluctuations as measured by the sonic can be used (Schotanus et al., 1983). When it is preferred to measure the temperature fluctuations independently, a Pt-wire sensor (2.5 μm, 50 Ω) can be mounted on the sonic probe. The fast response psychrometer described before cannot be used in combination with the sonic.

Lyman-alpha hygrometer

To determine the latent heat flux a Lyman-alpha hygrometer is mounted on the sonic probe. Two types are available:

- a sensor built by the Electromagnetic Research Corporation, model BLR;
- a KNMI design, described by Kohsiek (1987).

Infrared thermometer

A Heimann KT24 infrared thermometer is available to measure surface radiation temperatures.

Doppler Sodar

A windprofile up to several hunderds of meters can be measured with a Doppler Sodar, manufactured by Remtech. It is a three dimensional monostatic system. The three antennas each have a parabolic reflector of 1.2 m diameter and are mounted on a trailer. The frequency of the emitted sound pulse is 1600 Hz, modulated with 30 Hz. A microcomputer, which is usually placed in an air-conditioned office trailer, provides for the complete data handling. Fourier transformation is used to calculate the spectral distribution of the received signal. The data are stored on cassette, and printed. The averaging period is usually chosen between 15 and 30 min. The instrument should run on 220 V mains, preferably not on a generator because of acoustical noise. The accuracy of the measured horizontal wind components is about 1 m/s; see Beljaars (1985) for a detailed evaluation.

Upper air observations

So far local upper air observations have been carried out during experimental campaigns with Vaisala equipment, that is RS21-12C sonde, UHF receiver UR12 and PTU digitizer COD11. To determine the wind profile a Self Reading Theodolite is used (Warren Knight, Philadelphia U.S.A., model 87 AG). The radiosonde data are stored on papertape and then processed on the KNMI mainframe computer at De Bilt (Monna and Den Braber, 1985). At present a new radiosonde system is offered by Vaisala, i.e. sonde RS80 and Digicora ground equipment. This system includes Omega windfinding. When the stock on hand of RS21-12C sondes will be used up, it is intended to hire a Digicora system for experiments. Upper air observations are not restricted to the Cabauw site. Both systems can be used elsewhere, provided that 220 V mains is available.

The synoptical radiosonde station De Bilt (06260), 22 km NE of Cabauw, launches radiosondes at the standard synoptical hours.

7. Facilities for research; data handling

The maximum registration capacity is 40 analog channels, with a sampling frequency of 10 Hz. A PDP11/23-plus computer, which normally serves as a back-up for the continuous registration, is used for research data handling. Any instrument on or near the tower can be wired to this computer. The basic samples of the various channels are stored on magnetic tape without any processing. Information on the calibration and status of the instruments in use is also stored on this tape. At 10 Hz the capacity of one tape is three hours of registration. For control purposes 10 min. average values and standard deviations of the measured parameters (in SI-units) are computed and printed at Cabauw. Since these calculations are sometimes approximations, these printed data must not be used for research. Further processing is carried out on the KNMI mainframe computer. To that end a set of computer programs is available (Driedonks et al., 1980). The main functions are technical inspection, transformation to SI-units and calculation of average values, variances and covariances. Auxiliary routines are available for the computation of power spectra.

8. Mobile field-work station

In 1980 a mobile meteorological station was put into use for boundary layer research at remote locations. In the meantime it has been used for several field experiments. The layout of the station is rather flexible, and depends on the measurements that have to be carried out, so only a broad survey is given here.

Heart of the station is a DEC minicomputer, type MINC-11. Analogue data from 28 channels can be sampled with a frequency of about 1 Hz. The resolution is 12 bits. After processing and transformation to SI units, mean values (e.g. at 10 min. intervals) are stored on cassette and on floppy disk. A direct print-out is available. Moreover the signals can be monitored on recorders. The hardware is mounted in an office trailer of 2 by 4 m. A 220 V generator or 220 V mains is necessary to power the station.

In principle all meteorological instruments as described above can be connected. The actual choice will depend on the experiment. Several masts up to 10 m height including one with psychrometers at two levels are available. The usual configuration is a more or less complete synoptical station, extended with some special instruments. The station has been used in combination with Doppler sodar and radiosoundings (fig. 10).

fig. 10. Radiosounding during field-work (COAST 83)

9. Survey of publications

The data from the 213 m tower have been used for research by numerous scientists. The mobile field-work station has been used in several, often international, meso-scale experiments. A broad survey of the resulting publications is given below. The division in subjects is only very rough.

A. Surface fluxes	
- energy balance	De Bruin, 1982
- estimation from routine weather data	Nieuwstadt, 1978
	De Bruin and Holtslag, 1982
	Berkowicz and Prahm, 1982
	Holtslag, 1984
	Van Ulden and Holtslag, 1985
- over non-homogeneous terrain	Beljaars, 1982
	Beljaars et al., 1983
B. Atmospheric boundary layer modeling	
- daytime	Driedonks, 1981
	Driedonks, 1982
	Driedonks and Tennekes, 1984
- nocturnal	Nieuwstadt and Driedonks, 1979
	Nieuwstadt and Tennekes, 1981
	Arya, 1981
	Nieuwstadt, 1981
	Garrett, 1982
	Nieuwstadt, 1984a
	Nieuwstadt, 1984b
	De Baas and Driedonks, 1985
	Lacser and Arya, 1986
- wind measurements and terrain roughness	Wieringa, 1980
	Wieringa, 1981
C. Air pollution	
- experiment with tracer	Van Duuren and Nieuwstadt, 1980
	Agterberg et al., 1983
- measurement of components	Van Dop et al., 1977
	Van Dop et al., 1980

D. Special topics	
- mist	Grandin, 1983
- propagation of sound	Wessels and Velds, 1983
E. New techniques	Kohsiek, 1985
	Beljaars, 1985
	Schotanus et al., 1983
F. Meso-scale experiments	Kraus, 1982
	Driedonks, 1983
	Beljaars et al., 1985
	Hotzler, 1984
	Laude et al., 1984
	Driedonks et al., 1985
	Dubosclard et al., 1985
	Weill et al., 1985
	Desbraux and Weill, 1986
	Van Wijk et al., 1986
	Gera and Weill, 1987
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G. Dry deposition	Duyzer and Bosveld, 1986

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