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The use of a trajectory-model for studying interregional transport of air pollution.

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CONTENTS

SAMENVATTING

Dit rapport beschrijft de mogelijkheden om het K.N.M.I.-trajectoriënmodel te gebruiken in die luchtverontreinigingssituaties, waarbij transporten op interregionale schaal (schaal Nederland-Duitsland) van belang zijn.

Na een inleiding, die het eerste hoofdstuk beslaat, wordt in het tweede hoofdstuk een beschrijving gegeven van a) het huidige operationele trajectoriënmodel, met een tijdstap van 6 uur, gebaseerd op analyses van horizontale windvelden (en hieruit berekende verticale windvelden) op 300, 500 en 850 mbar en b) het medio 1979 operationele model, met een tijdstap van 3 uur, gebaseerd op windvelden van 300, 500, 850 en ook 1000 mbar.

In het derde hoofdstuk worden resultaten gegeven van onderzoeken bedoeld om de nauwkeurigheid van de trajectoriënberekeningen na te gaan. Hieruit blijkt, dat op 850 mbar een minimale tijdstap van 6 uur in de trajectoriënberekeningen vereist is, en dat bij de top van de grenslaag een tijdstap van minimaal 3 uur wenselijk is. Verder blijkt, dat het verwaarlozen van verticale bewegingen kan leiden tot fouten, die kunnen oplopen tot 25% van de afgelegde afstand. Een foutenschatting blijkt beter per trajectorieberekening apart te geven dan als een gemiddelde; voor het laatste lopen de geschatte fouten per trajectoriënberekening te ver uiteen.

In het vierde hoofdstuk worden twee perioden beschreven, waarin luchtverontreinigingstransporten op interregionale schaal belangrijk waren: Trajectoriën, eindigend op 850 mbar, berekend met het huidige trajectoriënmodel worden vergeleken met handgeconstrueerde trajectoriën, die het transport op 10 meter hoogte beschrijven, en trajectoriën die het transport in de laag 80-200 m beschrijven.

In het laatste hoofdstuk, dat de conclusies bevat, wordt geconcludeerd, dat het toekomstige trajectoriënmodel gebruik kan worden om routinematig trajectoriën te berekenen, die bij onderzoek naar het interregionale transport van luchtverontreiniging gebruikt kunnen worden.

Dit rapport is het resultaat van een studie die begonnen is, tijdens het Nederlands-Duitse samenwerkingsproject "Interregionale luchtverontreiniging".

SUMMARY

This report is the result of a study initiated during the official German-Netherlands project "Interregional transport of air pollution". It describes the possibility of using a trajectory-model, including vertical wind components, to calculate the path of air pollution travelling across the German-Netherlands border.

The second chapter of this report presents a description of the operational trajectory-model, which principally has been set up for weather forecasting and which uses windfields from the institute's three-layer vorticity-model. The properties of a near-future trajectory-model, based on a four-layer vorticity-model are also discussed.

The accuracy of the trajectory model is discussed in the 3rd chapter. A time-step of 6 hr will be sufficient for the 850 mbar level, but near the boundary layer a 3-hr time-step is preferable. Neglecting vertical wind components can lead to errors as large as 25 percent of the travelled distance.

The fourth chapter describes two periods of interregional transport. Trajectories calculated with the operational model arriving at the 850 mbar level are compared with hand-analysed trajectories at the 10 m level and with trajectories in the 80-200 m layer.

The conclusions are given in the last chapter. It is concluded that a trajectory-model including vertical wind, together with the institute's next four-layer model, gives promise of success for air pollution studies, as air paths can be calculated fairly easily on a routine basis.

THE USE OF A TRAJECTORY-MODEL FOR STUDYING INTERREGIONAL TRANSPORT OF AIR POLLUTION

J. Reiff,
C.A. Velds

1. INTRODUCTION

Already in 1969 indications have been found of air pollution transport over long distances and especially that crossing the German-Netherlands border (Zeedijk, 1969). A closer examination of this phenomenon showed that under certain meteorological conditions air pollution from the German Ruhr area could travel more than 100 km and doing so could influence the SO_2 concentration levels in Eindhoven (Zeedijk en Velds, 1973) and Enschede (Velds, 1973).

During 1969 the German Bundesgesundheitsamt and the Netherlands Ministry of Public Health and Environmental Hygiene decided for an official cooperation in the area of water- and air pollution. Two years later a working group (Arbeitsgruppe 3) has been set up under the auspices of this cooperation, to study the problem of interregional transport of air pollution. The working group with members of both countries decided to implement an experimental and theoretical project on the interregional transport of SO_2 with a running time of 5 years (1972-1977).

The following institutes took part in the project:
Hygiene-Institut des Ruhrgebietes, Gelsenkirchen (SO_2 measurements at ground level);
K.N.M.I., De Bilt (measurements of meteorological parameters);
Rheinisch-Westfälischer Technischer Überwachungsverein, Essen (emission inventory of the Ruhr area);
Rijks Instituut voor de Volksgezondheid (R.I.V.), Bilthoven (SO_2 measurements at ground level, remote-sensing of the total SO_2-burden, airplane flights of SO_2);
Technische Hochschule Sektion Meteorologie, Darmstadt (data-handling and modelling activities);

Universitätsinstitut für Meteorologie und Geophysik, Frankfurt/Main (airplane measurements of SO_2 and sulfate);
Wetteramt Essen des DWD, Essen (measurement of meteorological parameters and forecasting of episodes);
Zentralamt des DWD, Offenbach/Main (measurement of meteorological parameters and forecasting of episodes).

During the project it was decided that K.N.M.I. should also investigate the possibility of using trajectories to calculate the path of air pollution during interregional transport.

The use of trajectories for long range transport has been investigated earlier by Eliassen and Saltbones (1975) and Apsimon (1978). In a study of interregional transport during a frost-period in 1976, Den Tonkelaar (1978) used handmade trajectories. However, such a method is rather time consuming. Therefore we investigated whether a trajectory-model, principally developed for forecasting purposes, gives similar results.

As this study is applied to air pollution transport, we are especially interested in stable weather situations, without frontal disturbances. Attention has only been given to the trajectories in such situations; a "climatological study" in which for example 2 or 4 trajectories a day are calculated for the total duration of the German-Netherlands project, to investigate the relative importance of interregional pollution transport has not been carried out, because the input data for the model are only available since January 1976.

The result of this investigation also serves as a final report (Abschlussbericht) on the work done by the K.N.M.I. during the project.

Firstly the procedure is described how trajectories are calculated in a numerical model; secondly examples are given for two periods of interregional transport. Then preliminary results are presented, giving information about the various errors expected in such trajectory calculations; a proposal is made to calculate the expected error for each trajectory apart. Finally some conclusions are drawn about the usefulness of our institute's trajectory-model for studying air pollution transport.

2. TRAJECTORIES

2.1. The operational trajectory-model

A trajectory is formally defined as the path traced by a moving system. In this context it is the path traced by a polluted air parcel. Such a trajectory can in principle be computed from analysed or forecast maps of windfields. The computation can be forward in time, starting from a source area to calculate the region where the air pollution is going to, or backwards in time, starting from a region with a high pollution level to determine where the polluted air has come from.

At our Institute a trajectory-model has been set up, in principle for forecasting purposes, with the aim of estimating the properties of air masses which will arrive 24 hours later in The Netherlands (Reiff et al, 1979). This has been done along the same lines as Reap did at the National Meteorological Center of NOAA (Reap, 1972).

The trajectory-model uses winds (all three components) from our operational forecast-model, a vorticity model with levels at 300, 500 and 850 mbar and a grid distance of 375 km at 60° North Latitude.

With the aid of the + 24 hr analysis an estimation (for that time) is made of the wind direction and wind speed at a particular point for instance Groningen (NE-Netherlands). With this wind vector $\vec{v}$ the air parcel is advected backwards in time over a distance $\bar{v} \times 6$ to calculate a provisional + 18 hr position. At this position the wind vector is estimated, using the + 18 hr windfields. This wind vector is averaged with the wind vector for Groningen at + 24 hr. The mean vector is used to calculate a new back-trajectory from Groningen at + 24 hr. And so on, until the difference between successive mean winds is lower than a prescribed value. Then the trajectory between + 18 hr and + 12 hr is calculated in the same way.

For the German-Netherlands project "Interregional transport of air pollution" trajectories have been calculated from analysed geostrophic wind fields for specially chosen air pollution episodes in the past. Results are given for trajectories at 850 mbar.

2.2. The future trajectory-model

Early 1979 a four-layer vorticity-model with a horizontal grid distance of 180 km, will be introduced in our forecast department.

Six-hourly upper air analyses will be available. At the intermediate 3-hours in between data from synoptical observations (SYNOP's) will be used to make an analysis at 1000 mbar and to update the upper air forecasts.

For the 1000 mbar analysis use will be made of pressure measurements at land and wind measurements at sea, the latter corrected for shear caused by surface drag. In this way a geostrophical windfield will be obtained. So our next trajectory-model will use 3-hourly time-steps and will also be able to calculate trajectories at levels between 1000 and 850 mbar.

Gradually topography, surface stress and a better condensation process will be incorporated into the forecastmodel with the aim that more realistic vertical winds will become available.

3. THE ACCURACY OF THE TRAJECTORY-MODEL

The accuracy of the trajectories has been determined in a number of preliminary studies. In the following special attention will be given to errors being important in typical air pollution periods, which means "stable weather" situations.

3.1. The time-step

For 33 cases prognoses for 24 hour have been calculated with a time-step of 12 hour as well as with a 2 hour step. For these cases the mean distance from De Bilt of the 24-hour source area was 1050 km at the 850 mbar level. The difference in the position of the source areas, calculated with a 12-hour time-step and with a 2-hour time-step respectively, was about 10% of the covered distance, averaged over all 33 cases. This difference decreases fast with decreasing time-steps. In Table I 5 cases with a 6-hour time-step are compared with a 2-hour time-step trajectory. Calculations are given for the 850 mbar, as well as the 500 mbar level; vertical winds were included in the model.

The largest difference between the source areas is 8% of the travelled distance. Averaged over the 5 cases the mean difference is only 2 percent, negligable compared to other error sources. The cases given above were chosen at random. When the velocity fields do not change much in time, as is often the case in stable weather periods, the error will be equal or less. So, in stable weather situations, lasting a few days, with no strong horizontal wind gradients, errors due to a time-step of 6 hours may be negligible at 850 mbar.

Lower in the troposphere, near the boundary layer, larger errors may arise in trajectories with a 6-hour time-step, so there a time-step of 3 hours is preferable.

TABLE I DIFFERENCE IN SOURCE AREAS OF 24-HOUR TRAJECTORIES ENDING AT DE BILT WITH A 2-HOUR AND 6-HOUR TIME-STEP

Date	Difference pressure level P(t=0) → P(t=24) mbar (2 hr time-step)	Distance km (2 hr time-step)	Δ P mbar (between 2 hr and 6 hr time-step)	Difference	
				km	procent
23-11-78	541 → 500	1376	0	10	1
"	851 → 850	1174	1	13	1
24-11-78	602 → 500	1847	0	14	1
"	847 → 858 → 850	1083	2	24	2
25-11-78	486 → 500	1868	4	24	1
"	848 → 846 → 850	1394	2	8	1
01-12-78	445 → 500	386	2	8	2
"	816 → 850	334	1	14	3
06-12-78	457 → 500	363	7	30	8
"	825 → 850	728	0	7	1

3.2. The vertical wind

During two periods in 1978, July and November, 24-hour trajectories have been calculated at a regular basis. From this relatively small sample statistics are derived for the vertical displacements during 24 hours (Table II).

TABLE II NUMBER OF 24-HOUR TRAJECTORIES ENDING AT 500- AND 850 MBAR WITH A VERTICAL DISPLACEMENT WITHIN PRESCRIBED INTERVALS

pressure level	vertical displacement after 24 hour				total
mbar	< 20 mbar (± 320 m at 500 mbar ± 180 m at 850 mbar)	20-40 mbar	41-60 mbar	> 60 mbar	
500	12	13	4	6	35
850	28	6	1	0	35

Differences between source-areas for 24-hour trajectories ending at De Bilt, calculated with and without vertical winds, for five strong vertical wind situations, are given in Table III.

TABLE III DIFFERENCE IN SOURCE AREAS OF 24-HOUR TRAJECTORIES ENDING AT DE BILT, CALCULATED WITH AND WITHOUT VERTICAL WINDS FOR FIVE SITUATIONS WITH STRONG VERTICAL WIND

Date	Difference pressure level P(t=0) → P(t=24) mbar	Distance km (with vertical wind)	Difference	
			km	percent
27-01-76 12.00 Z	497 → 460 → 500	1535	148	10
" "	795 → 850	480	120	25
28-01-76 12.00 Z	438 → 500	1190	80	7
" "	806 → 850	782	115	15
20-11-77 12.00 Z	382 → 500	1157	202	17
" "	830 → 819 → 850	854	53	6
03-01-78 12.00 Z	568 → 589 → 500	2114	341	14
" "	843 → 884 → 850	1024	77	8
17-07-78 00.00 Z	556 → 500	1320	109	8
" "	873 → 850	616	18	3

It appears from Table III that errors in strong-wind situations may be as large as 25% of the travelled distance! It can also be seen that these errors are large in stable situations, when there is also a strong downward movement. These situations are often typical air pollution situations.

Danielsen (1961) has found the same qualitatively. However, in the few examples he has given, there is one extreme case, a stable weather situation, where the difference in source areas is more than 100 percent of the travelled distance. This discrepancy with our results may partly be due to an underestimation by a factor of two in our vertical winds during some extreme situations, as a consequence of the vorticity model we use (Opsteegh, 1978). However, Danielsen's results are exaggerated, for he compared a three-dimensional isentropic trajectory (following ψ-isopleths) with an isobaric trajectory, taking time-steps of 12 hours.

This is too long, as shown before, especially in such a situation with strong wind gradients.

Near the top of the boundary layer large wind-shears can exist. In Cabauw, at the 200 m high meteorological tower of the K.N.M.I., extreme wind-shears have been measured in southerly winds during neutral conditions as given in Table IV.

Using data of a special measuring period Kottmeier (1978) has found in Meppen (Germany) that large differences in trajectories occur due to the influence of the nocturnal jet just above the mixing layer.

TABLE IV EXTREME WIND-SHEARS AT CABAUW, THE NETHERLANDS (WIERINGA, 1978)

Layer	wind speed	wind direction	remarks
200 m - 10 m	$\frac{u_{200}}{u_{10}} = 2.66$	$dd_{200} - dd_{10} = 35^\circ$	$u_{10} > 5.5$ m/s
80 m - 10 m	$\frac{u_{80}}{u_{10}} = 1.83$	$dd_{80} - dd_{10} = 12^\circ$	$u_{10} > 5.5$ m/s
200 m - 80 m	$\frac{u_{200}}{u_{80}} = 1.52$	$dd_{200} - dd_{80} = 18^\circ$	$u_{10} > 5.5$ m/s

Data given are the averages of the 5 percent percentile with the most extreme windshears.

So in the inversion layer, on top of the mixing layer the right horizontal transport-wind (and the vertical wind which changes the transport from one level to the other) is very important. In general, in typical air pollution weather situations large scale vertical winds may not be neglected in trajectory calculations.

3.3. The accuracy of the analysed windfields

3.3.1. The horizontal windfields

The windfields used in the trajectory-model are derived using the geostrophic assumption from height-fields delivered by the K.N.M.I. forecast-model. These height-fields are products of the following analysis procedure:

A 12-hour height forecast valid for time 0.00 Z for the three pressure levels of the model is changed in such a way, that wind-measurements and height measurements obtained from the meteorological network at time 0.00 Z are incorporated as well as possible. The wind-measurements are changed to height differences in the analysis procedure by using the geostrophic relation.

The accuracy of the windfields derived from these height-fields is influenced by the following sources:

- The errors in the wind- and height measurements, which partly are reduced by the analysis program if many measurements are available (as is the case above Western Europe).
- The use of the geostrophic assumption, which is not as good as the use of the full balance equation, or the full divergence equation (including isallobaric effects). However, when another wind-height relation is used, it must be done as well in the analysis procedure, as in the derivation of winds from the height-fields obtained from the forecastmodel!
- The gridpointdistance of the forecastmodel. A gridpointdistance of 360 km at 60° North is not suited to describe the displacements of small synoptic systems very well. So the 12-hour height forecast, from which the analysis procedure starts, may sometimes have small errors. However, due to the many measurements above Western Europe the analysis does not weight very strong on the 12-hour forecast.

In general the total error in the analysed windfields can at 850 mbar be taken as $\approx$ 1 m/sec for each windcomponent.

3.3.2. The vertical windfields

The vertical winds derived from the horizontal winds by taking one timestep in the vorticity-model also do have errors. However, comparisons between negative vertical wind areas of our vorticity-model (air masses moving upward) and cloud systems on satellite pictures show good agreement (Opsteegh, 1978). So at 700 ∿ 500 mbar the vertical winds have the correct sign and magnitude. Lower in the troposphere, where surface drag plays an important role, the error in the "analysed" vertical winds probably will be larger.

In our new 4-layer vorticity-model the vertical winds will be better due to incorporation of surface drag and topography. The horizontal windfields will be better, due to incorporation of 6-hourly upper air wind-measurements, 3-hourly (geostrophic)surface winds and a distance of 180 km between gridpoints.

3.4. A quantitative error estimate of each trajectory apart

Error estimates of trajectories depend strongly on the wind pattern through which the trajectory passed. Large windgradients in space or time in the early stage of the trajectory lead to an early exponential growth of the expected error. This is illustrated in figure 7a and b.

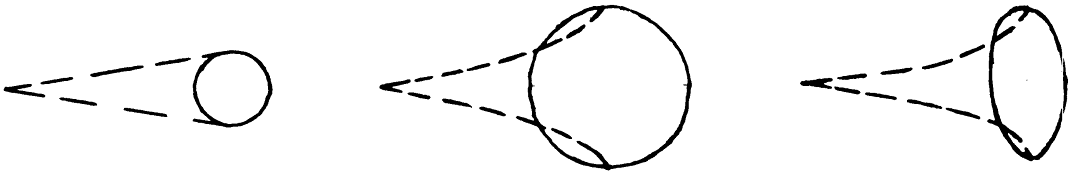
(a) (b) (c)

Figure 7 Illustration of the exponential growth of the error in a trajectory (see text).

A trajectory which starts with a velocity containing a certain random analysis error will have an uncertainty in space which grows linearly in time (the circle in figure 7a). After a few time-steps the air parcel has got a velocity error and an error in the calculated position. The velocity for the next time-step read at this position thus has an error due to the wrong position where it is read off as well as a random error. This makes that the error in the calculated position grows exponentially (Fig. 7b). The exponential growth of the error will dominate the linear growth when large space gradients in the velocity field do exist. The earlier large space gradients, like a centre of a low pressure system or a saddle area, are met, the faster the exponential growth will dominate and the larger the expected error in the position of the air parcel will be after 12 or 24 hours.

Sykes and Hatton (1976) have expressed this in the following formula:

$$\varepsilon_{i+1} = \varepsilon_i + v^1 \, \Delta t + \varepsilon_i \left(\frac{\partial \vec{v}}{\partial r}\right)_i \Delta t \qquad (1)$$

where ε_i is the expected position error after time i, v^1 is the random error in the analysed winds, Δt the time-step and $\left(\frac{\partial \vec{v}}{\partial r}\right)_i$ the velocity gradient in some direction at the position reached by the air parcel at time i.

This formula may be refined:

1. In general the velocity gradient will be different along the trajectory and perpendicular to the trajectory (see figure 7c). So two errors may be calculated accordingly:

$$\varepsilon_r\,(i+1) = \varepsilon_r\,(i) + v^1\,\Delta t + \varepsilon_r\,(i)\left(\frac{\partial v}{\partial r}\right)_i \Delta t \quad \text{(r along trajectory)} \qquad (2)$$

$$\varepsilon_n\,(i+1) = \varepsilon_n\,(i) + v^1\,\Delta t + \varepsilon_n\,(i)\left(\frac{\partial v}{\partial r}\right)_i \Delta t \quad \text{(n perpendicular to trajectory).}$$

2. Moreover the time-step introduces errors. Errors due to time-steps of 3-hours or less are negligible. Time-steps of 6 or 12 hours may give errors dependent on the situation.

In the last terms of the right hand side of formulae (2) a dimensionless factor containing the difference in speed $| \vec{v}_i - \vec{v}_{i-1} |$ has then to be incorporated. Because we intend to take 3 hour as a time-step we will not concentrate on this any more.

In the following some numerical examples of errors calculated with formulae (2) for a 24-hr trajectory with 3-hr time-steps will be given.

Suppose the error in the analysed windfield at 850 mbar above north-western Europe is 1 m/s in both horizontal components. The error in the vertical velocity is neglected here. Two cases for $\frac{\partial v}{\partial x}$ will be considered: One with a "normal" wind gradient of 1 m/s over 100 km and one with a very large wind gradient of 5 m/s over 100 km.

TABLE V ERRORS IN THE WINDFIELD AS A FUNCTION OF TIME FOR (1) $\frac{\partial v}{\partial x} = 10^{-5}$ s^{-1} AND FOR (2) $\frac{\partial v}{\partial x} = 5.10^{-5}$ s^{-1}.

TIME (HOURS)	3	6	9	12	15	18	21	24
ε_1 (km) (1)	10.8	22.6	36	50	65	81	100	143
ε_2 (km) (2)	10.8	27.4	52	88	143	225	348	532

The results are given in Table V.

Without the exponential growth factor in formulae (2) the total error in 24 hr would have been 85 km. So in the "normal" case (1) the error, due to the exponential growth, doubles roughly after 24 hr. But in situations with strong horizontal wind gradients the exponential factor works already strongly after 6 hr and an enormous error after 24 hr does exist.

Remarks

- The error calculated above is independent of the wind speed itself. This is probably not correct. In situations with strong winds the analysis error will be larger than 1 m/s.
- The random error in the analysed windfield is taken everytime as 1 m/s. Usually these random errors have a certain correlation in space and time.

  The "correlation distance" may be taken as 500 km in the stream direction and 250 km perpendicular on the stream direction. As every 6 hours new upper air data are used from a dense upper air station network, the correlation in time may be taken as 6 hr. So each 6 hr a new random error has to be taken in formulae (2). (The correlation in space is now not important any more, because an air parcel at 850 mbar will normally not have a speed greater than 500 km/6 hr.) The derivation of formulae (2) with a random error can be simulated better on a computer with different runs.
- Such calculations with random errors can be simulated best by taking computer runs which make use of a random error generator. Then several runs can be made and so can be checked how the arguments given above do influence the result of formulae (2). We intend to do these runs when our new four-layer vorticity-model is available.

4. AN APPLICATION OF THE MODEL TO TWO PERIODS OF INTERREGIONAL TRANSPORT

In the first part of this chapter the results are given of trajectory analyses for two periods with high SO_2 concentrations due to interregional transport. During the first period, 27-31 January 1976, high SO_2 concentrations have been measured at many sites in The Netherlands; during the second period, 23-24 March 1976, measuring flights have been performed at the German-Netherlands border.

The trajectories ending at 850 mbar, as described in 2.1. are compared with 3-hourly hand-made trajectories calculated from the observed surface wind (10 m above ground level). Owing to local disturbances this wind is, however, not considered representative for transport over large distances. Therefore both trajectories are compared with trajectories, calculated by Den Tonkelaar (1978) for the 80-200 m layer.

4.1. The 27-31 January 1976 period

The meteorological situation of this period has been described already by Den Tonkelaar (1978). He calculated 3-hourly trajectories by hand for the transport in the lowest 200 m of the atmosphere and compared his trajectories with SO_2 measurements made by R.I.V. during this period. As these comparisons were satisfactory, we consider those trajectories as representative for the SO_2 transport during this period.

We will compare, when possible, our surface wind trajectories (full-line) and 850 mbar trajectories (dashed line) with Den Tonkelaar's trajectories (dotdashed line).

A depression which passed The Netherlands from north-west to south-east induced snowfall at many places. During the 27th January it started to freeze due to the advection of cold air with the north-easterly wind behind the depression. This was the onset of a freezing period which lasted until the end of the month. It was generally clear weather with extensive fog banks at some places. The wind force was moderate at first, later on strong from easterly directions. In the evening of 27 January a strong ground inverseion developed with a top between 180 and 200 m.

Figure 1 gives an analysis of the 850 mbar level on 27 January 1976 at 12 GMT with isohypses *) at 4 dam intervals. Trajectories have been calculated for 27 January 12 GMT till 28 Januari 12 GMT. During this time the depression moved from the Ruhr area south-southeastwards to the Alps and a ridge of high pressure extended southwards from Scandinavia. The pressure in The Netherlands rose from 1001 till 1014 mbar.

The northernmost trajectories show a cyclonic curvature in the first 12 hours with the wind direction veering with height. In the last 12 hours the curvature has changed to anticyclonic, whereas the wind direction appears to back with height, but the wind speed was very low at that time. The downward movement of the air as a result of the increasing ridge of high pressure is strongest in the northern part of the region where the trajectory ending at the 850 mbar level over Den Helder started at the 796 mbar level. For the southernmost trajectories there is only a vertical shear in the wind speed.

Twenty four hours later the high pressure area over the Federal Republic of Germany and Scandinavia has intensified and the air arriving in The Netherlands has come from the east (Figure 2). During this period there was only a shallow mixing layer (100-200 m) capped by a strong inversion. All trajectories now show an anticyclonic curvature. The trajectories at the 850 mbar- and 10 m-level are compared with the trajectory analysed by Den Tonkelaar as being representative for the transport in the mixing layer. The veering of the wind with height is smaller than in the first example. The mixing layer trajectory takes an intermediate position between the 10 m-level and the 850 mbar trajectory. According to Den Tonkelaar this trajectory described the transport of air pollution from the Federal Republic to The Netherlands rather well, as the pollution was limited to the lowest 200 m due to the strong stability.

*) an isohypse or contour line connects points where a constant-pressure surface (here 850 mbar) has a constant elevation above mean sea level.

To describe the interregional transport in such a situation, our new four-layer vorticity-model, from which trajectories with a 3-hour time-step between 1000 mbar and 850 mbar can be calculated, is necessary. Both the 10 m trajectory and the 850 mbar trajectory are not satisfactory in this case.

The loss of detail by the 6-hour time-steps can be seen also in figure 3, where trajectories are shown arriving at 30 January 00 GMT. During the last hours of 29 January the wind direction in the boundary layer backed from south-east to east, which worked out in the 10 m trajectories as well as in the dotted-dashed 80 m- 200 m level trajectory, representing the flow in the boundary layer.

The increasing wind speed at all heights resulted in a transport of more than 300 km during 6 hours at the 850 mbar level, which is too large to study details of the transport of air pollution between the Federal Republic and The Netherlands.

Here again the mean trajectory for the boundary layer takes an intermediate position with a transport of 220 km during 6 hours, between a transport of 125 km at the 10 m level and 280 km at the 850 mbar level. The vertical shear in the wind direction is not very remarkable.

Figure 4 shows the trajectories for the period 29 January 12 GMT until 30 January 12 GMT. The 10 m level trajectories for Eelde and De Bilt differ completely from those arriving at 30 January 00 GMT. The air arriving at Eelde at 12 GMT was near Hamburg 12 hours earlier, but the air arriving at 00 GMT originated from Hannover (figure 3), a difference of 160 km. The difference in the source area's of the 850 mbar trajectories arriving at Eelde during this 12 hour period is only 100 km.

Furthermore the 10 m trajectories show a cyclonic curvature and the 850 mbar trajectories a weak anticyclonic curvature. This different behaviour of the trajectories is due to the factthat at the surface weather map a trough of low pressure is situated over France, while at the 850 mbar level the anticyclone over Scandinavia is prominent.

According to the direction of the SO_2 transport as measured by R.I.V. (Van Egmond and Tissing, 1976) it appeared that the 10 meter trajectory and the trajectory for the mixing layer as analysed by Den Tonkelaar better describe the interregional transport in this situation.

During the 30th January the wind speed increased at all heights, the mixing height increased around noon to 500 m, through the intrusion of a deep layer of cold air of continental origin (Den Tonkelaar, 1978). The trajectories arriving at 31 January 00 GMT are depicted in figure 5. For De Bilt also the trajectory for transport in the boundary layer, analysed by Den Tonkelaar, is available. It is clear from figure 5 that there is a difference between the transport in the boundary layer, reflected by the 10 m level trajectory and "the boundary layer" trajectory, and the transport above the boundary layer as given by the 850 mbar trajectory. Air pollution transported in the boundary layer originated from the northern part of the Federal Republic, while the 850 mbar trajectory started in south Bavaria, 12 hours earlier.

Our conclusion is, that during stable weather periods, like the one described above, a trajectory model with time-steps of 3 hours and a transport level just above 1000 mbar will describe the air pollution transport best. With the institute's new 4 level vorticity-model computer calculations of such trajectories will be possible.

4.2. The 23-24 March 1976 period

Trajectories for the period 22 March 1976 12 GMT till 23 March 1976 12 GMT are given in figure 6, together with the analysis of the 850 mbar level on 22 March at 12 GMT.

A ridge of high pressure was situated over Scandinavia and the North Sea (circulation type HFa) inducing an easterly to northeasterly flow over The Netherlands. As during this period air pollution transport from the German Ruhr area to The Netherlands could occur, extensive measurements of the total SO_2 gasburden were made with a van and an aeroplane equiped with a sulfurdioxyde remote-sensing correlation spectrometer, by the National Institute of Public Health (R.I.V.) of the Netherlands along the German-Netherlands border (Van Egmond et al, 1977).

The mixing height varied between 700 and 1000 m.

The SO_2-gas burden measurements with the van have been performed between 8.37 and 10.43 GMT. The highest gas burden has been measured at about 10.30 at point V (figure 6). From this point a 10 m level trajectory has been calculated backwards in time, which has passed the German Ruhr area between Düsseldorf and Essen at 05 till 06 GMT.

The airplane measurements at a flight altitude of 200 m have been done between 11.59 and 13.34. The highest gas burden has been measured at about 12.30 above point A (figure 6). A 10 m level trajectory from this point passed north of the Ruhr area.

When we consider the 850 mbar trajectories, however, we see that there is a large veering in wind direction compared with the 10 m trajectory. A 850 mbar trajectory from point A could originate from the Ruhr area.

According to Van Egmond et al (1977), it appeared from the airplane measurements that an important part of the air pollution has been transported at higher levels to 1200 m altitude, consequently above the mixing layer. So it can be concluded that the 850 mbar trajectory describes the transport above the mixing layer rather well.

5. CONCLUSIONS

- During air pollution periods, when the lower layers of the atmosphere have normally a stable vertical configuration, trajectory calculations with a 3-hour time-step, based on the K.N.M.I. four-layer vorticity-model seem worthwhile.
- In the mixing layer a 1000 mbar geostrophic wind trajectory from the four-layer model can be used; above the mixing layer an interpolation between the 850 mbar and 1000 mbar wind must be made.
- During stable weather situations a time-step of 3 hour at most in the trajectory calculations near the mixing layer is necessary. From the comparisons between the different trajectories, it has been shown that longer time-steps will often introduce unacceptable errors.
- Even this preliminary study reveals that trajectory calculations above the mixing layer in a stable weather situation have to include the large-scale vertical windfield, as our trajectory model does.
- Using formulae (2) during the trajectory calculations we are able to give an estimation of the error in source area for each trajectory apart. This is much better than giving a kind of mean error for all trajectories, as the error in source area depends heavily on the horizontal space gradient in wind speed along the trajectory.
- A good estimate of the mixing height and real wind information in the inversion layer is very worthwhile, if available over the whole area covered by the trajectories. Therefore wind measurements will be made in the near future at the top of five TV-towers in addition to the already existing meteorological tower with a height of 213 m at Cabauw near Utrecht *).

*) The TV-towers, ranging from about 150 m to 300 m high, are spread over the country: In the NE-part at Smilde, in the east at Markelo (where wind measurements are already in operation), in the SE at Roermond, in the SW at Goes and in the NW region at Wieringermeer (Figure 8). The data will be available in real time in a few years.

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Figure captions

Fig. 1 Analysis of the 850 mbar level for 27 Jan. 1976 1200 GMT. Isohypses in dam. 24 hr trajectories ending on 28 Jan. 1976 1200 GMT ——— at 10 m level.
---- at 850 mbar level. Numbers in rectangles give the pressure of the level where the 850 mbar trajectory started.

Fig. 2 Analysis of the 850 mbar level for 28 Jan. 1976 1200 GMT. Isohypses in dam. Trajectories ending on 29 Jan. 1976 1200 GMT: ——— at 10 m level, - - - at 80-200 m level ---- at 850 mbar level. Numbers in rectangles give the pressure of the level where the 850 mbar trajectory started.

Fig. 3 Analysis of the 850 mbar level for 29 Jan. 1976 0000 GMT. Isohypses in dam. Trajectories ending on 30 Jan. 1976 0000 GMT: ——— at 10 m level, - - - at 80-200 m level,
----- at 850 mbar level. Numbers in rectangles give the pressure of the starting level of the 850 mbar trajectory.

Fig. 4 Analysis of the 850 mbar level for 29 Jan. 1976 1200 GMT. Isohypses in dam. Trajectories ending on 30 Jan. 1976 1200 GMT: ——— at 10 m level, - - - at 80-200 m level,
----- at 850 mbar level. Numbers in rectangles give the pressure of the starting level of the 850 mbar trajectory.

Fig. 5 Analysis of the 850 mbar level for 30 Jan. 1976 0000 GMT. Isohypses in dam. Trajectories ending on 31 Jan. 1976 0000 GMT: ——— at 10 m level, - - - at 80-200 m level,
----- at 850 mbar level. Number in rectangle givesthe pressure of the starting level of the 850 mbar trajectory.

Fig. 6 Analysis of the 850 mbar level for 22 March 1976 1200 GMT. Isohypses in dam. Trajectories ending 23 March 1976 1200 GMT and the time that the highest SO_2 gas burdens have been measured (10.30 and 12.30): ——— at 10 m level, ---- at 850 mbar level. Numbers in rectangles give the pressure of the starting level of the 850 mbar trajectory.

Fig. 7 Illustration of the exponential growth of the error in a trajectory (see text).

Fig. 8 Positions of the meteorological tower at Cabauw and the five TV-towers in The Netherlands.

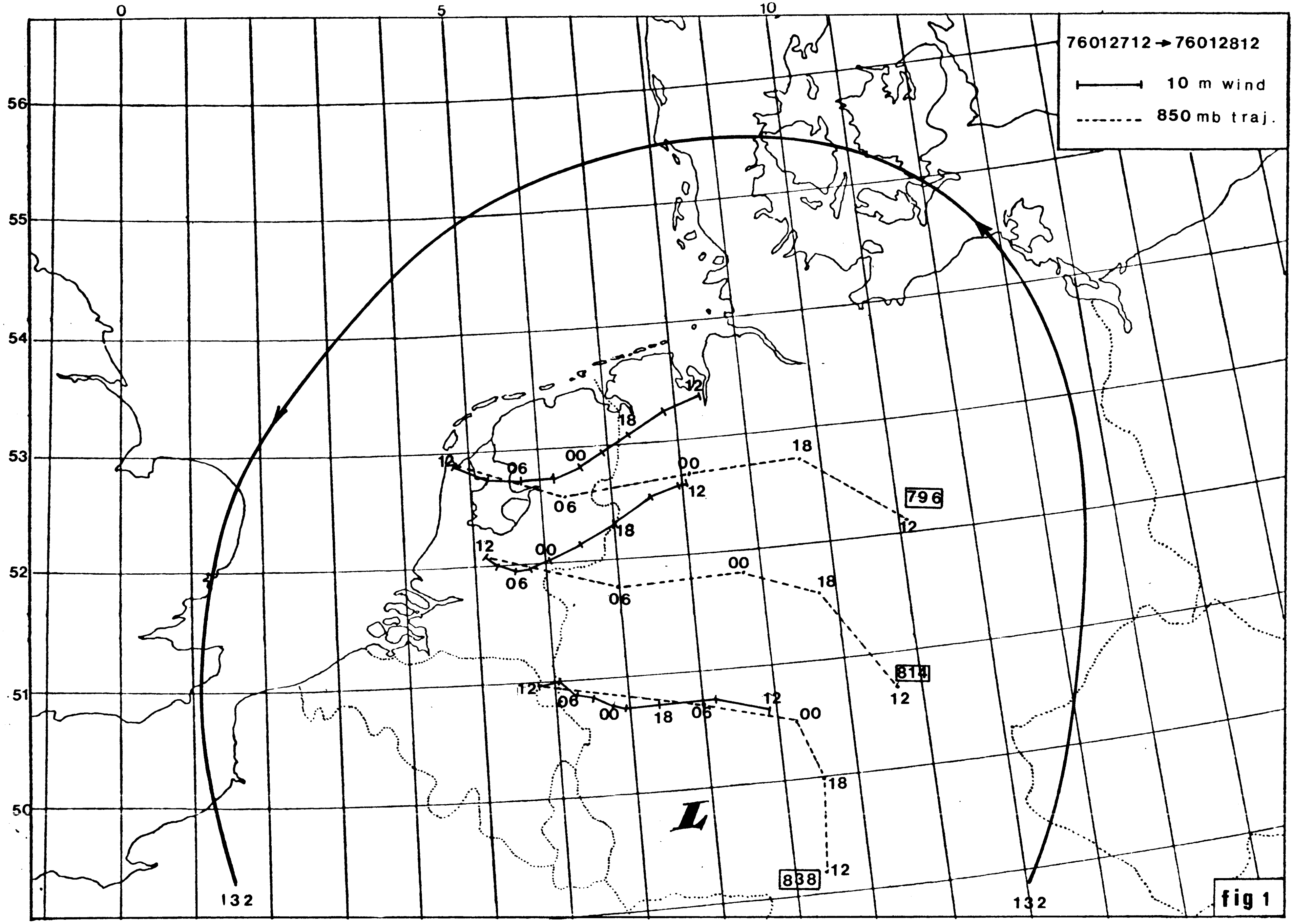

76012712 → 76012812
10 m wind
850 mb traj.
0
5
10
56
55
54
53
52
51
50
132
132
796
814
838
L
12
18
00
06

fig 1

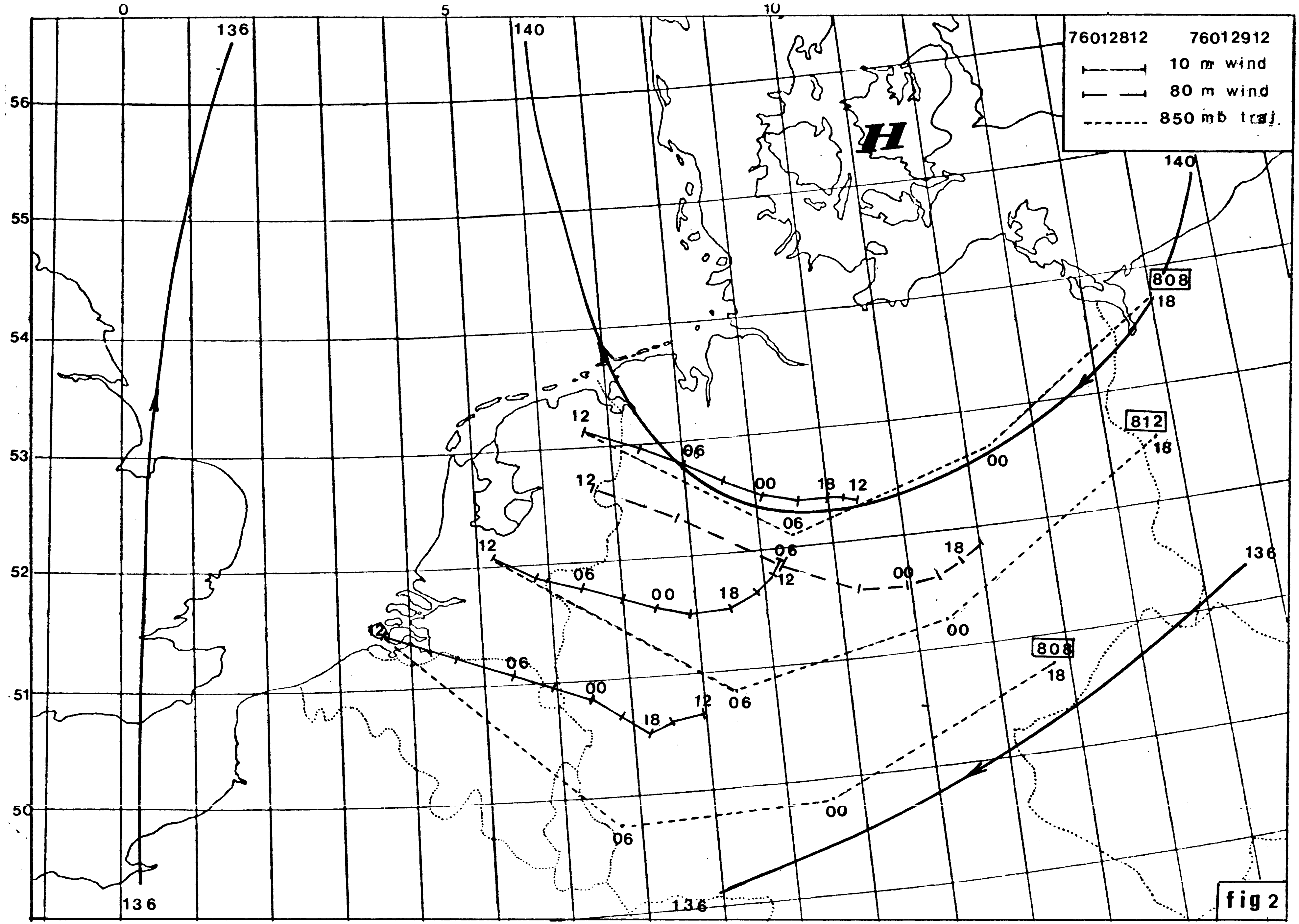
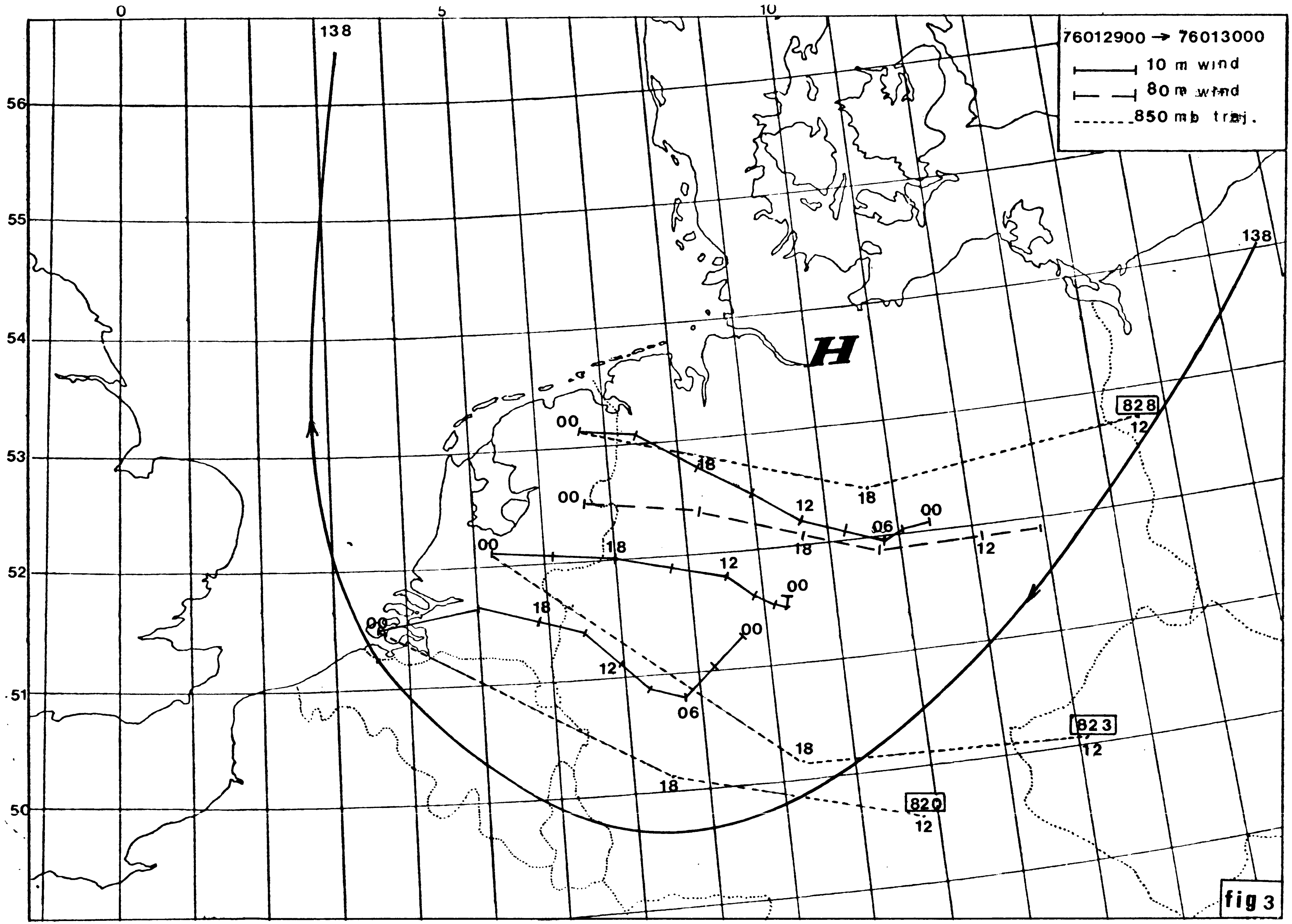

76012812
76012912
10 m wind
80 m wind
850 mb traj.
0
5
10
56
55
54
53
52
51
50
136
140
808
812
18
00
06
12
H

fig 2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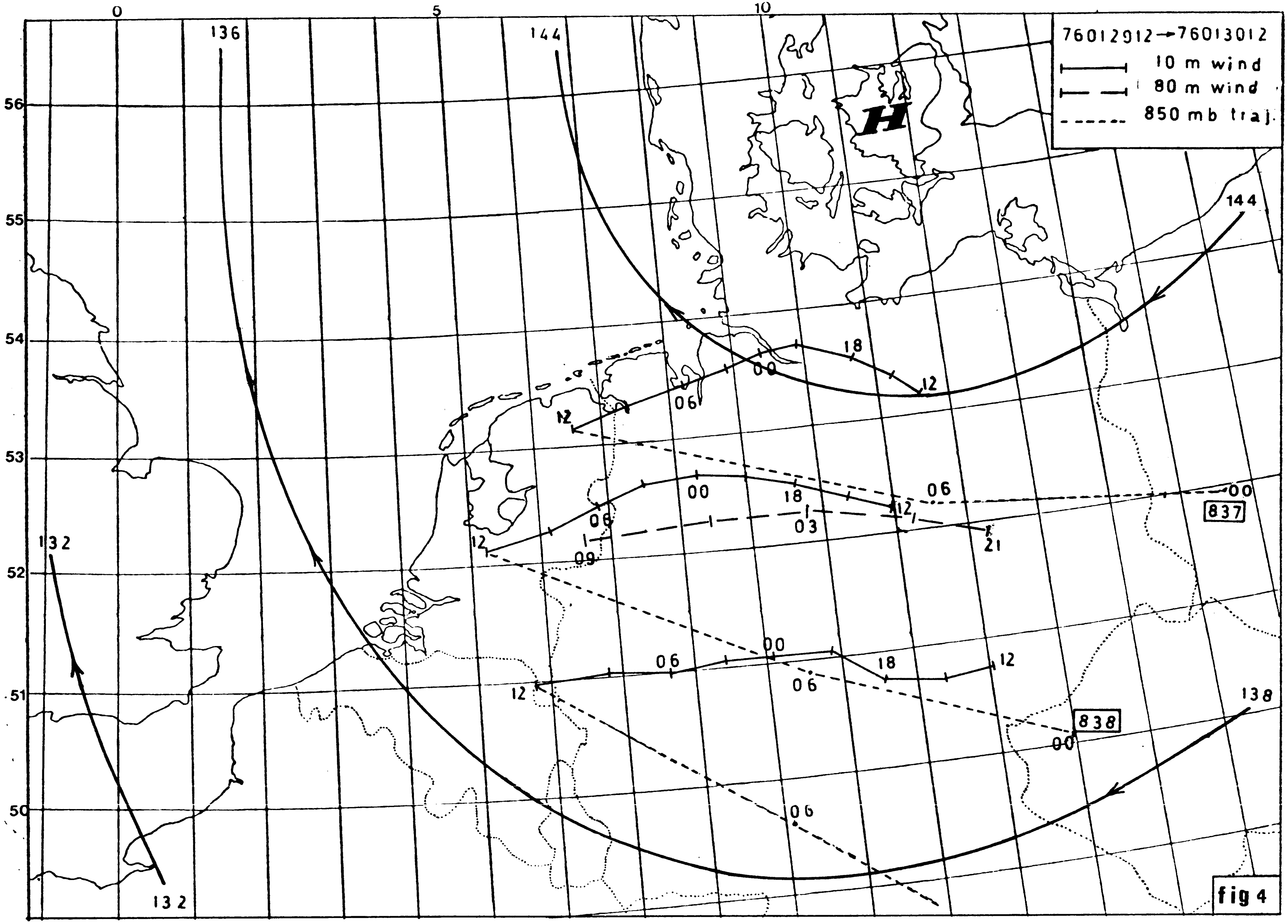
10 m wind
80 m wind
850 mb traj.
0
5
10
56
55
54
53
52
51
50
H
138
138
828
823
820
00
06
12
18

fig 3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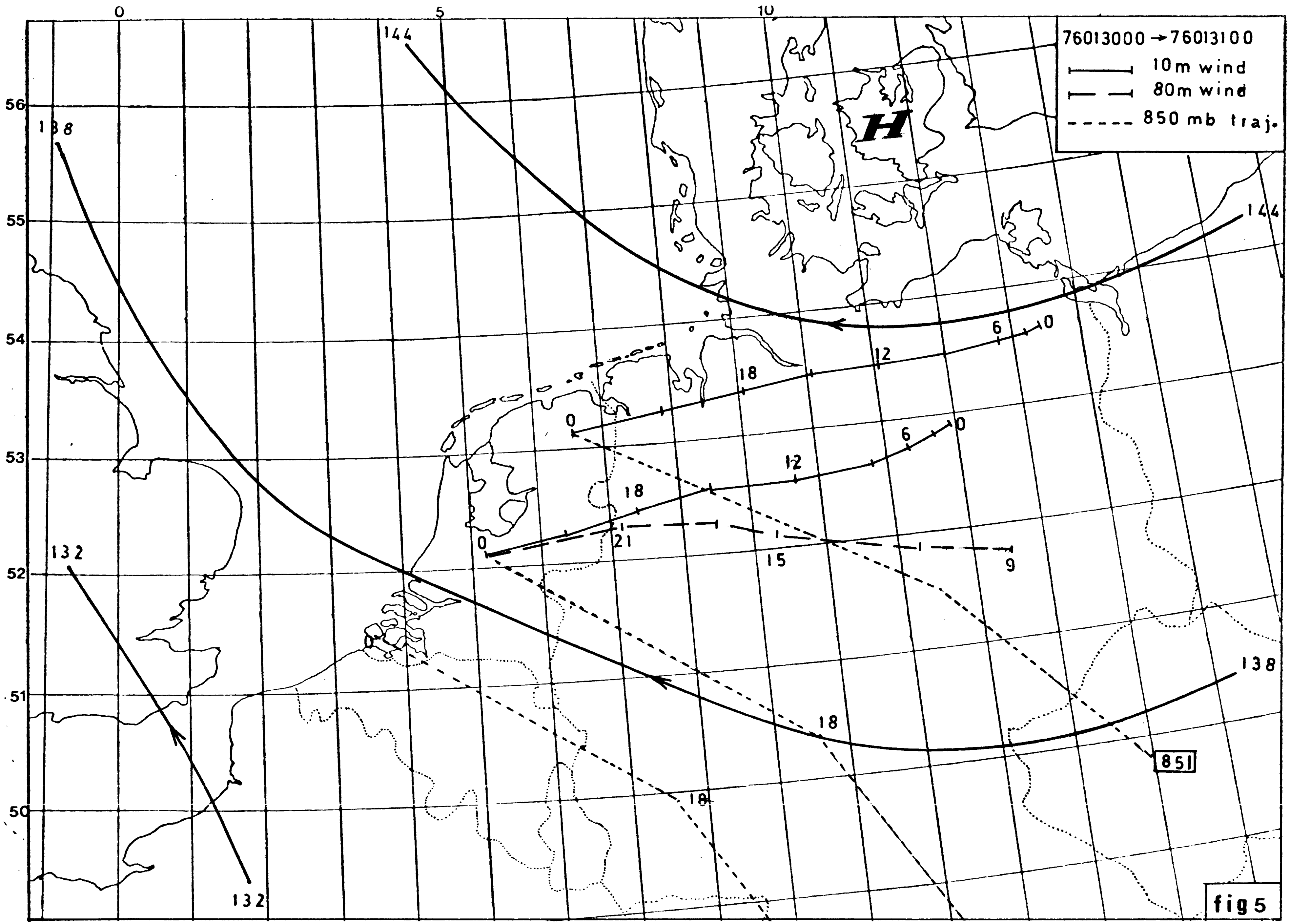
10 m wind
80 m wind
850 mb traj.
H
0
5
10
56
55
54
53
52
51
50
144
136
132
138
837
838
00
06
12
18
21
03
09

fig 4


76013000 → 76013100
10m wind
80m wind
850 mb traj.
H
144
144
138
138
132
132
851
0
6
12
18
0
6
12
18
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21
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9
18
18
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5
10
56
55
54
53
52
51
50

fig5

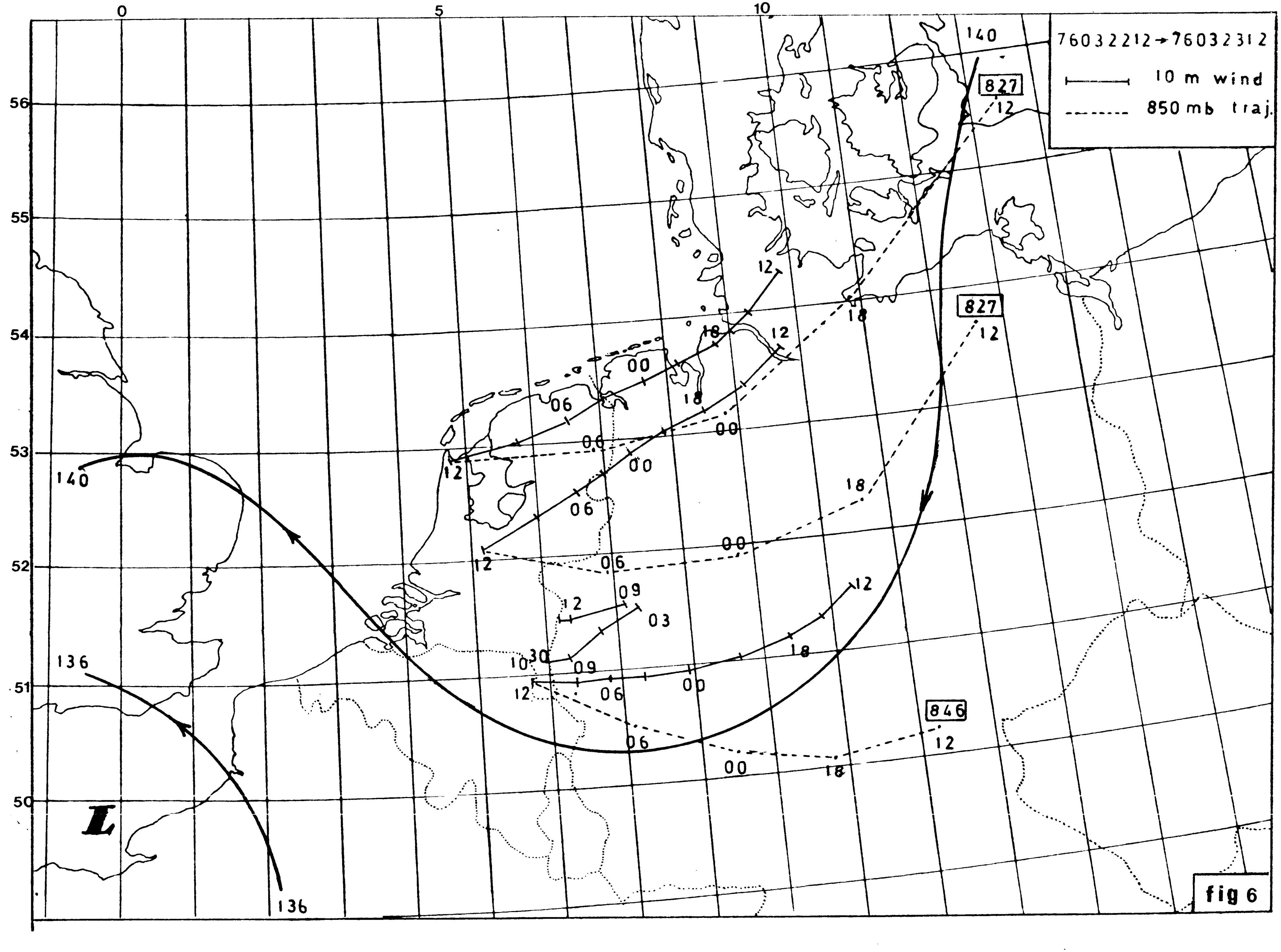
76032212→76032312
10 m wind
850 mb traj.
827
827
846
140
136
L
0
5
10
50
51
52
53
54
55
56
12
18
00
06
09
03
1030

fig 6

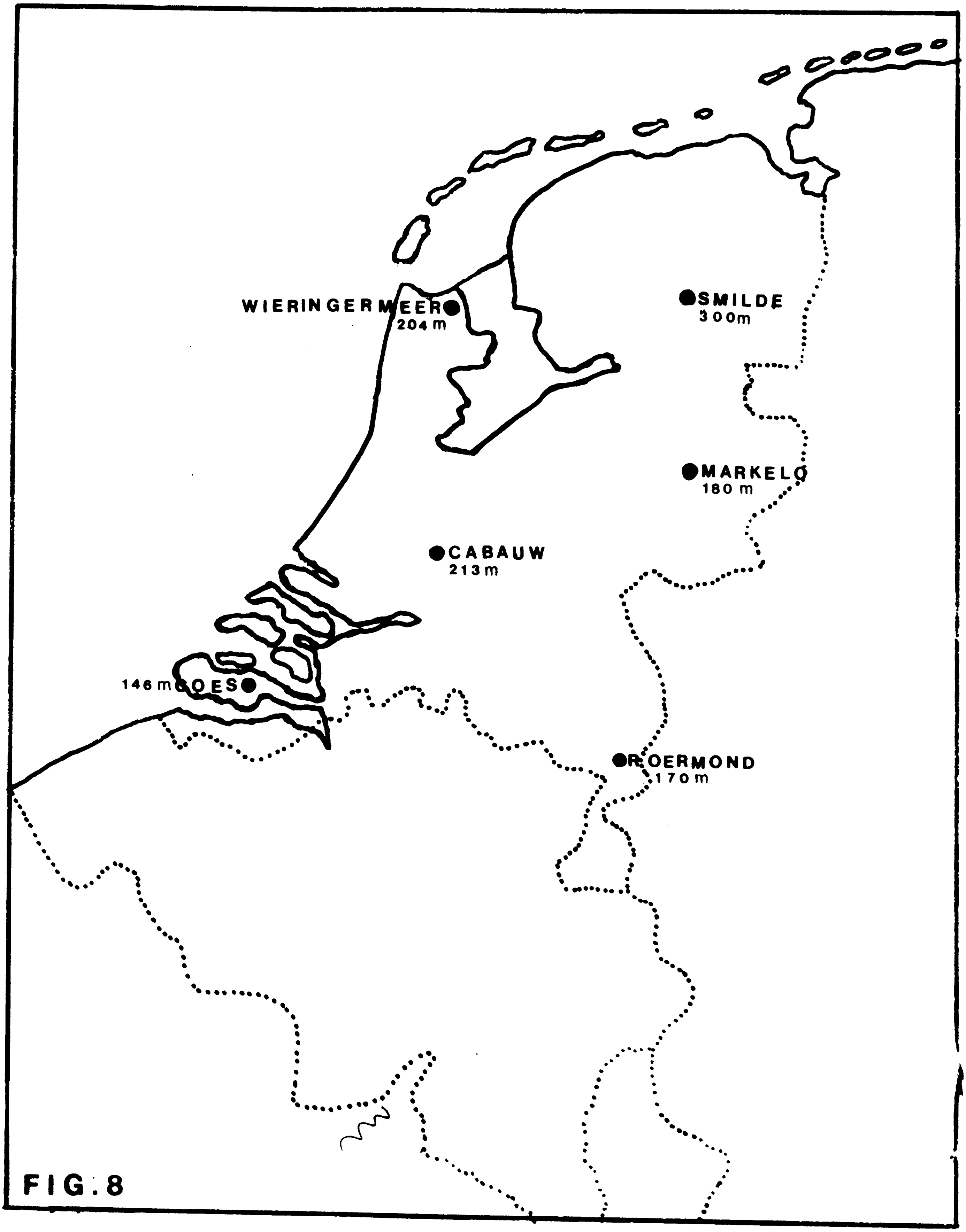
WIERINGERMEER
204 m
SMILDE
300m
MARKELO
180 m
CABAUW
213m
146m GOES
ROERMOND
170m

FIG. 8