Pergamon

Atmospheric Environment Vol. 32, No. 24, pp. 4151–4156, 1998

Printed in Great Britain
1352–2310/98 $19.00 + 0.00

PII: S1352–2310(98)00185–X

EVALUATION OF TRAJECTORIES CALCULATED FROM ECMWF DATA AGAINST CONSTANT VOLUME BALLOON FLIGHTS DURING ETEX

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Abstract—This paper validates trajectories calculated from ECMWF analyses against the tracks of constant volume balloons (CVBs) released during the European tracer experiment (ETEX). The altitudes of the calculated trajectories were adjusted to the altitudes of the respective balloons in short intervals to allow direct comparisons. The agreement between the calculated trajectories and the balloon tracks was very good for the first experiment (individual errors from 1 to 26%, average 15%), and excellent (errors from 2 to 11%, average 6%) for the second one. The agreement for the second experiment was probably partly better because the CVBs travelled above the planetary boundary layer, but the small errors also indicate that the ECMWF fields of the horizontal wind were of exceptionally good quality in the second experiment. This is in sharp contrast to the results of the dispersion models which all failed in the prediction of the perfluorocarbon tracer dispersion for the second experiment. A likely explanation for this is that vertical motions, possibly on small scales, were not correctly captured by the ECMWF analyses, but it is not possible to clarify this with the CVB data. © 1998 Elsevier Science Ltd. All rights reserved

Key word index: Trajectories, ETEX, tracer experiments, constant level balloons, constant volume balloons.

1. INTRODUCTION

During ETEX, the dispersion of an inert perfluorocarbon tracer released from a point source in western France was studied (Nodop *et al*., 1998). Two releases were made. For the first release (E1), many models predicted the dispersion of the tracer well, but for the second one (E2) they all failed, strongly overpredicting the tracer concentrations (Klug *et al*., 1997).

In addition to the tracer releases, CVBs were launched during both ETEX experiments (Koffi *et al*., 1998). CVBs are intended to remain on constant density surfaces and drift with the horizontal wind. Although excursions from the equilibrium level can be induced by updrafts or downdrafts in the convective boundary layer, CVBs do not follow the weaker synoptic-scale vertical motions since buoyancy forces them back to their equilibrium level. Therefore, they can trace only the horizontal motions (Stohl, 1998). Nevertheless, CVBs and other balloons have often been used to evaluate computed trajectories (Pack *et al*., 1978; Reisinger and Mueller, 1983; Clarke *et al*., 1983; Draxler, 1996; Baumann and Stohl, 1997; Stohl *et al*., 1997).

In this paper, trajectories computed from wind analyses of the European Centre for Medium-Range Weather Forecasts (ECMWF, 1995) model are compared to the CVB tracks to assess the quality of the ECMWF fields of the horizontal wind during ETEX independently from the perfluorocarbon tracer data. This is of interest, because in the more complex dispersion models, errors in the fields of the horizontal wind and other errors cannot be separated. Thus, the comparison helps to answer the question why all the dispersion models failed for E2.

2. DESCRIPTION OF THE DATA AND MODEL USED

Data of 16 CVB flights were available, 10 for E1 and 6 for E2. The CVBs were operated by two groups, one from the University Paul Sabatier (Toulouse, France), the other from the Swiss Meteorological Institute (Payerne, Switzerland). The French CVBs were cylindrical in shape, had a volume of approximately 2 m^3 and were made of transparent mylar and polyethylen films. The Swiss CVBs were tetrahedron shaped (socalled tetroons), had a volume of 1 m^3 and were made of polyester film. The balloon positions were determined with the radionavigation OMEGA system. The lengths of the CVB tracks were between 21 and 189 km; their average travel altitudes were

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Table 1. Summary statistics for the balloon tracks and the errors of the calculated trajectories. F denotes the French CVBs, CH the Swiss CVBs, Time gives the release times of the CVBs (release dates were 23 and 24 October for E1 and 14 November for E2). L(CVB) and L(EC) are the lengths of the CVB tracks and of the trajectories calculated from ECMWF data, RHTD(EC) and RHTD(HI) give the *RHTD* for trajectories based on data from the ECMWF model and from the HIRLAM model, respectively

Number	Time	Group	Average height (m)	L(CVB) (km)	L(EC) (km)	AHTD (EC) (km)	RHTD (EC) (%)	RHTD (HI) (%)
1	1319	CH	222	21	25	6	25.6	30.7
2	1330	F	470	101	104	10	10.1	14.6
3	1636	CH	730	122	116	7	5.7	15.9
4	1702	F	672	105	83	23	24.8	35.5
5	2000	CH	655	118	98	23	21.0	37.9
6	2010	F	600	108	91	18	18.1	34.6
7	2359	CH	331	52	42	10	20.4	20.2
8	0002	F	727	110	97	17	16.0	15.5
9	0354	F	748	45	46	1	1.3	14.4
10	0359	CH	337	47	43	4	8.1	26.6
E1 average			549	83	75	12	15.1	24.6
11	1302	F	3175	126	124	2	1.7	3.7
12	1303	CH	1922	62	61	2	2.8	5.4
13	1538	F	1684	156	145	17	11.3	8.8
14	1606	CH	1301	162	148	14	8.9	4.5
15	1906	CH	2133	189	195	15	7.8	13.7
16	1910	F	701	68	72	4	5.7	10.8
E2 average			1820	127	124	9	6.4	7.8
Total average			1026	99	93	11	11.8	18.3

between 200 and 3200 m (Table 1). The positions were reported every 10 s and had an accuracy of approximately 1–5 km for a travel distance of 50–200 km. For a more detailed description of the CVB data see Koffi *et al*. (1998).

The model FLEXTRA† (Stohl *et al*., 1995) was used for calculating the trajectories. FLEXTRA has been validated through comparison of model results to independent data using wind fields of varying spatial and temporal resolution (Stohl *et al*., 1995), the tracks of CVBs (Stohl *et al*., 1997), gas balloons (Baumann and Stohl, 1997) and hot-air balloons (Baumann *et al*., 1996), and using potential vorticity and specific humidity (Stohl and Seibert, 1998) as tracers. The input data to FLEXTRA were initialized analyses and 3 h forecasts on 31 levels (approximately 10 levels below 2800 m) of the T213 L31 ECMWF model with a resolution of 1°. The Lagrangian particle dispersion model FLEXPART used the same input data for simulating the perfluorocarbon tracer dispersion; hence the results presented in this paper can be directly compared to those of Stohl *et al*. (1998).

With FLEXTRA it is possible to compute several types of kinematic trajectories, such as three-dimensional, constant model level, isobaric, or isentropic trajectories. The trajectory equation is integrated using the iterative scheme after Petterssen (1940). Bicubic interpolation in the horizontal, quadratic interpolation in the vertical, and linear interpolation in time are used. Since CVBs drift with the horizontal flow, but sink because of downdrafts, radiative cooling, loosing helium or wetting of the balloon envelope and rise because of updrafts or solar warming, none of the usual trajectory types can represent their paths correctly. Therefore, we used a special model version that adjusted the height of the trajectory at each time step (here, 30 s) to the height of the CVB (see Stohl *et al*., 1997).

† The FLEXTRA model source code and a description are available via the Internet from http://www.forst.uni-muenchen.de/LST/METEOR/stohl/astohl.html.

3. RESULTS AND DISCUSSION

In addition to visual comparisons, two quantitative measures were used to evaluate the model performance: first, the absolute horizontal transport deviation (Rolph and Draxler, 1990)

$$\mathrm{AHTD}(t) = \sqrt{[X(t) - x(t)]^2 + [Y(t) - y(t)]^2} \quad (1)$$

where (X, Y) are the locations of the CVB trajectories and (x, y) are the locations of the calculated trajectories at travel time t; second, the relative horizontal transport deviation RHTD = AHTD/L (Stohl *et al*., 1995), where L is the average length of the calculated trajectory and the CVB track. RHTD are mainly used in the following discussion, since they are independent of trajectory length which varied by almost a factor of 10 (Table 1). Values are only reported for the end points of the CVB tracks, because at short travel times RHTD tend to fluctuate strongly with travel time.

3.1. *The first experiment, E1*

The first two CVBs launched during E1 drifted into eastnorth–easterly direction, indicating little directional shear with height. The calculated trajectories travelled into slightly more northerly direction than the CVBs. CVBs 3 and 4 were launched shortly after the start of the tracer release. They represent a transition state, travelling straight to the east (Fig. 1). CVBs 5 and 6 were started at 2000 UTC and drifted to the eastsouth-east, whereas the calculated trajectories had a smaller northern component. CVBs 7 and 8 drifted the farthest to the south (Fig. 2) before, towards the end of the tracer release, the wind direction shifted back to the west (Fig. 3).

Most calculated trajectories travelled too far to the north and were slightly shorter than the CVB tracks (Table 1). There was no clear dependence of the RHTD on the travel height, and there was also no obvious temporal trend of the model performance. The average RHTD was 15%, with individual values ranging from 1 to 26%. Compared to errors found in other studies using the same model and the same type of input data (Baumann and Stohl, 1997; Stohl *et al.*, 1997), these are relatively small values, suggesting that the wind fields were well analyzed by the ECMWF. These correct wind analyses were an important precondition for the good performance of the Lagrangian particle dispersion model FLEXPART (Stohl *et al.*, 1998) and other models based on ECMWF data.

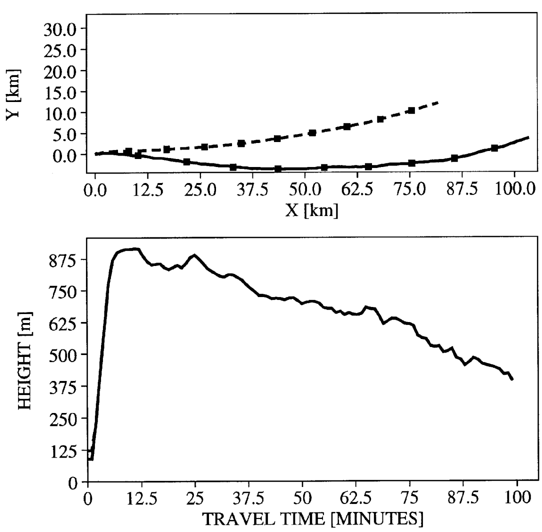

Fig. 1. Comparison of the computed trajectory (dashed line) with the track of CVB 4 (solid line) released on 23 October 1702 UTC. The upper part of the figure shows the horizontal projection of the path on a Cartesian coordinate system centered at the release location (X-axis positive to the east, Y-axis positive to the north). Solid squares mark the trajectory and CVB positions every 10 min. The lower part of the figure shows the time-height profile of the flight (bottom).

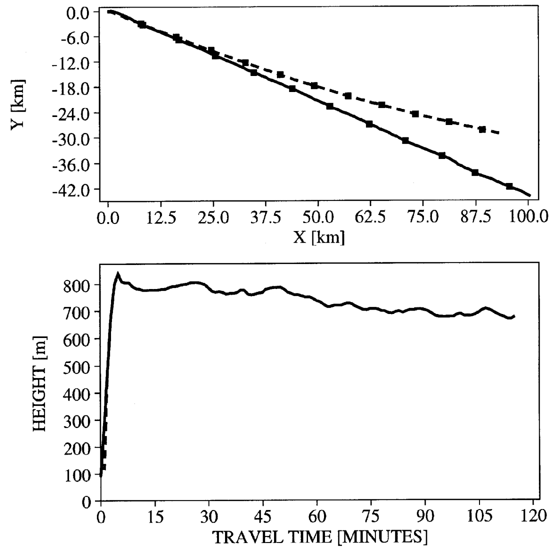

Fig. 2. Same as Fig. 1, but for CVB 8 released on 24 October 0002 UTC.

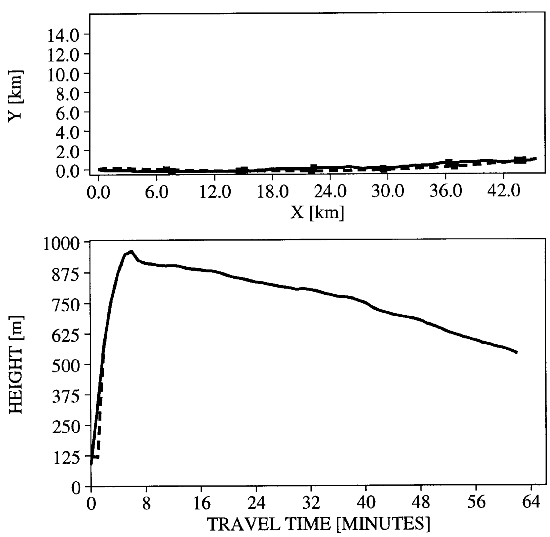

Fig. 3. Same as Fig. 1, but for CVB 9 released on 24 October 0354 UTC.

3.2. *The second experiment, E2*

CVBs were only launched during the first 4 h of the E2 tracer release. Later, a cold front approached the release location, and the rain and heavy winds made CVB launches impossible. In these first few hours, there was no trend of the travel direction of the CVBs. They drifted towards the eastnorth-east at greater altitudes (Fig. 4) and to the northeast at lower altitudes (Fig. 5).

All CVB tracks were extremely well reproduced by the trajectory model, with the largest error being 11% and the average error being only 6% (Table 1). These small values suggest that the quality of the horizontal wind fields was excellent. Nevertheless, all models

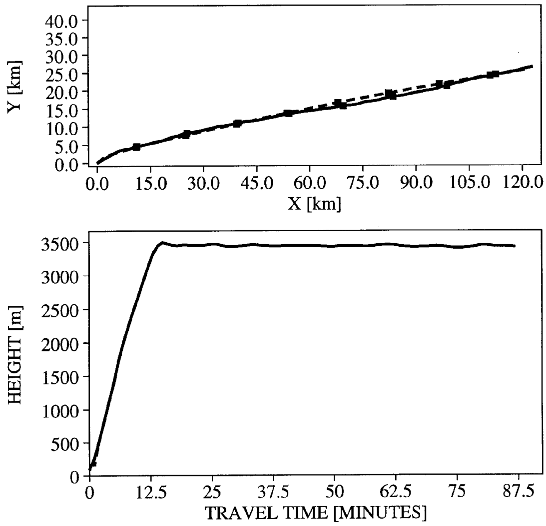

Fig. 4. Same as Fig. 1, but for CVB 11 released on 14 November 1302 UTC.

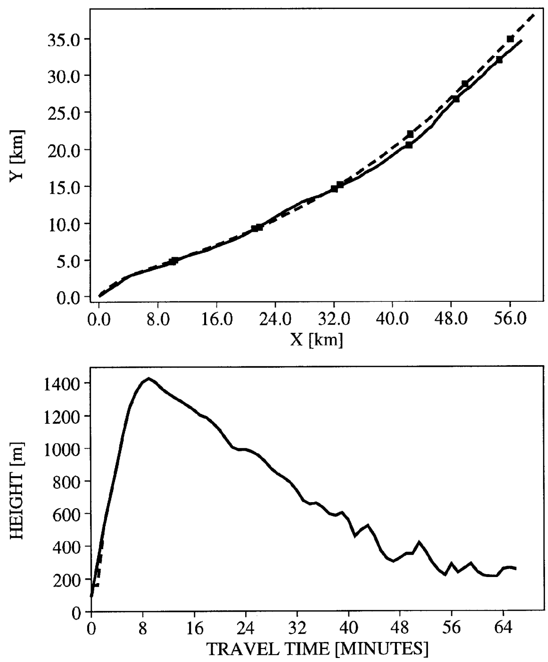

Fig. 5. Same as Fig. 1, but for CVB 16 released on 14 November 1910 UTC.

failed completely to predict the dispersion of the perfluorocarbon tracer (Klug *et al.*, 1997). The FLEXPART model produced—by far—the worst results of all the 40 cases studied with this model (Stohl *et al.*, 1998).

One possible explanation for this seemingly contradiction is that the CVBs travelled outside the boundary layer most of the time and were thus not representative for the flow in which the perfluorocarbon tracer travelled. However, this explanation is not sufficient, because there is equally good agreement between the calculated trajectories and the CVB tracks for those short parts of the flights that were within the boundary layer. Also, the RHTD for CVB 16 (Fig. 5) was slightly smaller than the average RHTD, although CVB 16 travelled by far at the lowest level (Table 1). The results of the dispersion model FLEXPART do also not suggest that the horizontal wind fields caused its poor performance, since the position of the plume was well reproduced during the first 24 h (Stohl *et al.*, 1998). Only the concentrations were overestimated by an order of magnitude.

A more likely explanation of this discrepancy is that the tracer was lifted into the free troposphere in the vicinity of a cold front located near the release position towards the end of the release (Berliner Wetterkarte). Since the perfluorocarbon plume travelled almost along this front, there was enough time for most of the tracer material to be lifted into the free troposphere by organized rising motion ahead of the front or by convective processes behind the front. These small scale flow features were not resolved by the ECMWF data.

Another interesting feature of the perfluorocarbon measurements is that there was still some tracer observed in Middle Europe up to 72 h after the release. Trajectory calculations at many different levels (not shown) revealed that—according to the ECMWF analyses—no return circulation could have caused this. Probably, some of the tracer was trapped below a shallow inversion somewhere, and was released after the break-up of this inversion. However, the strong winds did not favor the accumulation of tracer material below shallow inversions. Therefore, the late appearance of tracer material in central Europe remains unexplained from trajectory calculations.

3.3. *The effect of a reduced temporal resolution of the wind fields*

Many of the dispersion models used during ETEX had meteorological fields available at intervals of only 6 h. Therefore, we studied how strongly a reduction of the temporal resolution from 3 to 6 h affected the trajectory accuracy. For this, we disregarded the 3 h forecasts, and used only the analysis wind fields.

The negative impact on trajectory accuracy was relatively small. The average RHTD increased from 15.1 to 17.3% for E1, from 6.4 to 7.1% for E2, and from 11.8 to 13.5% totally. Nevertheless, since such small differences can strongly amplify in divergent wind fields, the highest possible resolution should be used for dispersion calculations. It would be beneficial if the ECMWF could store short-term forecast wind fields at even higher resolution than 3 h in the future.

3.4. *Comparison with HIRLAM trajectories*

Koffi *et al.* (1998) computed trajectories based on forecast wind fields of the high-resolution limited area model (HIRLAM) (Källen, 1996) that were also widely used among the ETEX participants. The method of trajectory calculation was the same as was used here, although another trajectory model was applied. The horizontal resolution of the HIRLAM wind fields (0.5°) was higher than that of the ECMWF wind fields, but the temporal resolution was lower (6 h). The forecasts were initialized with data from the coarse-resolution ECMWF model T63 L19 at 12 UTC at the day of the releases.

On average, the trajectories calculated from the HIRLAM data were clearly less accurate than those based on ECMWF data, especially during E1. The average RHTD at the trajectory end points were 24.6, 7.8 and 18.3% for E1, E2 and totally (Table 1). 75% of the trajectories were less accurate than the respective trajectories calculated from ECMWF wind fields. The comparison of forecast trajectories from HIRLAM against analyzed trajectories from ECMWF puts the HIRLAM trajectories at disadvantage. Nevertheless, it seems that the quality of the ECMWF wind fields was higher during ETEX, since only short-term forecasts of HIRLAM (maximum forecast period 17 h, but for most trajectories less than 12 h) were used. Trajectories started immediately after the initialization of the HIRLAM model were also less accurate than their ECMWF counterparts. This is not surprising, since HIRLAM was initialized with coarse resolution ECMWF data.

4. CONCLUSIONS

In this study, trajectories calculated from ECMWF wind fields were compared to the tracks of CVBs. The quality of the analyzed ECMWF fields of the horizontal wind was very good during E1 and excellent during E2. Average trajectory position errors were 15 and 6% of the distance travelled during E1 and E2, respectively. This can be compared to slightly less than 20% found on a larger scale in the free troposphere (Baumann and Stohl, 1997) and approximately 50% found on a smaller scale during convective conditions in the boundary layer (Stohl *et al*., 1997) using the same model and ECMWF input data. Also, compared to trajectory errors reported in many other papers (for an overview see Stohl, 1998), the errors found in this study are very small.

The CVBs travelled mostly above the boundary layer during E2 and may not be fully representative for the path of the perfluorocarbon tracer. However, the initial phase of the flights, when the CVBs ascended through the boundary layer, was equally well reproduced by the ECMWF model; and the lowest CVB flight was even slightly better reproduced by the calculations than the average.

Thus, the poor performance of the dispersion models during E2 is not likely to be due to errors in the horizontal winds. Since the horizontal winds are balanced by the vertical winds, this also gives an indication that the grid scale vertical winds were not too bad. It is more likely that unresolved small-scale vertical winds in the vicinity of the cold front have lifted the perfluorocarbon tracer into the free troposphere.

A reduction of the temporal resolution of the input wind fields from 3 to 6 h had a relatively small negative impact on trajectory accuracy. Trajectories calculated from forecasted HIRLAM wind fields were less accurate than trajectories calculated from analyzed ECMWF wind fields, as expected.

Acknowledgements—Many thanks are due to the Swiss (Meteorological Institute, Payerne) and French (University Paul Sabatier, Toulouse) teams who carried out the valuable CVB measurements. The calculations were performed on data from the European Centre for medium-range weather forecasts and the Norwegian Meteorological Institute. The comments of two anonymous reviewers were helpful.

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