Forecasting Research Division

Technical Report No. 47

VERIFICATION OF NWP MODEL WIND AND TEMPERATURE FORECASTS USING ASDAR REPORTS

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1. INTRODUCTION

ASDAR reports have been used to verify forecasts out to T+12 of wind and temperature from the regional model. Verification statistics have been generated for winds and temperatures in the climb, cruise and descent phases of flight, and for route-mean equivalent headwinds, crosswinds and temperatures in the cruise phase of flight.

2. ARCHIVE DETAILS

Starting in December 1991, arrangements were made to archive ASDAR reports within the regional area which covers Europe, North Atlantic, and part of North America (see Fig 1). Together with each ASDAR report, the regional area NWP model wind and temperature forecasts were also archived, the forecast fields being interpolated spatially and temporally to the position, flight level and time of the aircraft report. The forecast fields used were the appropriate pair in the range T+0, T+3, T+6, T+9, T+12 which straddled the reporting time. Reports made between T+0 and T+02.35 were omitted from the archive for two reasons: firstly, the regional model forecast is not available until T+02.35 so shorter period forecasts are of no use in practice; secondly, observations received up to T+01.30 would have been used in the assimilation at this time and should not therefore be used for verification purposes.

Initially the archiving job was run twice a day at 0105 Z (extracting reports from the SDB for the previous afternoon) and 1305 Z (extracting reports for that morning), but due to the computer cost the daytime job was dropped after 17 February 1993. This produces a bias in favour of westbound Atlantic flights which tend to avoid the strong headwinds rather than eastbound flights which tend to fly with the strong tailwinds. This consequently results in a predominance of climbs rather than descents in Europe, but otherwise should not significantly affect the results over Europe.

The parameters archived comprise:
date, time, latitide, longitude, pressure,
reported and forecast temperature, wind direction, wind speed,
ASDAR unit identifier, phase of flight.

The ASDAR unit identifier is fixed for a particular aircraft, unlike the call sign which varies from flight to flight. During the archiving period a total of 8 ASDAR identifiers have been reported viz:

BA000N BA001L BA008D BA009B BA010P
CO0062 CO0076
PH012U

Asdar reports are generally made at 7 minute intervals in cruise, and at 50 hPa intervals in climb and descent (except near the ground where the interval is 10 hPa).

In addition, data has been archived from certain Qantas aircraft equipped with ACARS viz:

QF0000 QF0001 QF0002 QF0006 QF0009 QF0010 QF0016 QF0XXX

ACARS reports are generally made only in cruise at intervals of about 20 minutes.

The phase of flight indicator is LR for level flight, AC for climbing, DS for descending, but is sometimes missing. A small percentage of the aircraft reports contained one or more missing elements (such as longitude, temperature, wind direction or wind speed) and these were omitted from the analysis.

3. ANALYSIS

Various statistics of the wind and temperature differences (forecast minus observed) have been calculated for climb, cruise and descent separately. Results were obtained for each ASDAR equipped aircraft separately and for all aircraft combined; for each month separately, for months combined into seasons, and for all months combined; and for three geographical areas:

Inner Europe	54°N - 48°N	3°W - 12°E	(Manchester to Munich)
Europe	70°N - 35°N	10°W - 35°E	
Regional area	Europe, N Atlantic, N America		See Figure 1

Firstly, means and root mean squares (RMSs) are presented for temperature, wind speed, wind direction, westerly and southerly wind components and for the vector wind. Calculations for temperature, wind speed, and wind components are straightforward. For the wind direction the difference (forecast minus observed) must lie in the range -180° to +180° and the sign is positive if a rotation from the observed direction to the forecast direction is clockwise. (This is achieved by subtracting 360° if the difference is greater than +180° and by adding 360° if the difference is less than -180°.) For the vector wind the mean and RMS of the magnitude of the vector differences are calculated.

Secondly, for cruise only, means and RMSs of route-mean headwinds, crosswinds, equivalent headwinds, and temperatures are presented as a function of route length.

After sorting the data for each aircraft into chronological order, flight level and changes in flight level between successive observations were used to segregate flights into climb, cruise, and descent sections.

For each consecutive pair of observations during a cruise, the track direction, track length, and average values of temperature (T), headwind (HW), and crosswind (CW) were calculated for this section of track. The equivalent headwind (EHW) was then obtained using the approximate formula (Forrester, 1987):

$$EHW = HW + CW^2/2xTAS$$

The contribution from the crosswind term is generally small (except when the track crosses a strong jet) and it is fairly insensitive to the actual value of true airspeed (TAS) so a constant value of 450 knots (225 m/s) has been assumed in this study.

Route-mean values of temperature, headwind, crosswind, and equivalent headwind, weighted according to the length of the individual track sections, were then computed for each cruise. Changes of flight level during cruise were taken into account when extracting the forecast values, and route-mean values were computed for complete cruises.

Although ASDAR nominally reports every 7 minutes in cruise, extra reports can be made during a step climb or step descent, or when a strong jet is encountered. Conversely, not all reports were available in the archive, and gaps occur in some flights. If a gap of more than an hour was experienced during a cruise, then that cruise was deemed to have terminated and a new cruise begun with the next observation.

Statistics were accumulated for all possible sections of cruises, from the shortest, based on pairs of reports, up to the longest. Clearly the sample size for the shorter route sections is much larger than for the longer route sections.

4. RESULTS

The results are based on about 15 months of data, but are biased towards winter because two winters are included and data was scarce in the summer due to a problem with the ASDAR system.

Examination of the results for individual months and individual aircraft shows general consistency, except for two particular cases. Firstly, during May 1992 CO0062 produced mean and RMS temperature differences which were extraordinarily large, and wind differences somewhat larger than normal. As this is almost certainly due to corruption of the aircraft reports for some unknown reason, it was decided to omit this (relatively small) group of data from the analysis. Secondly, PH012U produced larger than usual monthly temperature biases in cruise of about -2°C (forecast colder than observations), but little bias in climb and descent, suggesting a possible problem with the conversion from total air temperature (TAT) to static air temperature (SAT) at high Mach numbers.

Table 1 summarises the results for the whole archive, after removing the above mentioned group of spurious data. Tables 2 and 3 give the corresponding results for Europe and Inner Europe respectively. Note that the results for climb and descent are very similar in all three tables, ruling out any significant bias in the aircraft observations which might have resulted from the climb versus descent profiles. Tables 4, 5 and 6 give the seasonal results for the cruise phase, and show that generally the errors are a little larger in winter and spring and a little smaller in summer and autumn.

The temperature has a negative bias of about 0.5°C indicating that the forecast is colder than the observations on average. Comparison with verification statistics of forecasts against radiosondes over Europe (see Annex 3A of Forrester and Dharssi, 1992) shows reasonably good agreement, but suggests the possibility of a small warm bias (of perhaps 0.25°C) in the aircraft temperature reports relative to the radiosonde measurements. Excluding the PH012U cruise reports, which display a warm bias, reduces the overall bias from -0.5°C to -0.4°C in cruise.

The RMS forecast minus aircraft temperature difference is about 1.5°C over Europe rising to 2.0°C elsewhere. This agrees well with the RMS forecast minus radiosonde temperature difference over Europe which lies between 1.0 and 2.0°C, and suggests (see Appendix 1) that the RMS error in the aircraft temperature observations is probably better than 1.0°C. The RMS forecast temperature error over the regional area is about 0.5°C larger than over Europe. Note that if the spurious data had been included, the RMS forecast minus aircraft temperature difference rises to about 2.5°C, indicating an RMS error in the aircraft temperature up to about 1.5°C.

The forecast wind speed has a negative bias of 1 m/s over Europe and 2 m/s over the regional area at cruise level, indicating that the forecast is an underestimate particularly at the higher levels (in cruise) where the winds are stronger. It is a well known problem that NWP models have a tendency to underforecast the strengths of the jet streams, and interpolation of NWP output tends to exacerbate this problem. However, comparison with verification statistics of forecasts against radiosondes over Europe suggests that the model forecast error may not explain all of this bias, and that part of the problem may be an overestimate (of perhaps 0.5 m/s) in the aircraft wind speed report relative to the radiosonde balloon measurement. Part of this bias may be explained by the fact that radiosondes average winds in the vertical, where shears can be large, whereas aircraft average winds in the horizontal, where shears are relatively small. The remainder of the bias may be a genuine overestimate of wind speed measured by aircraft. It can be shown that random, uncorrelated and unbiassed errors in airspeed, ground speed, heading and track angle will give rise to a small positive bias in aircraft wind speeds.

The RMS wind speed differences are about 3 to 4 m/s in climb and descent, 4.5 m/s in cruise over Europe, and about 6 m/s in cruise over the regional area.

The wind direction difference has almost zero mean, but large RMS, the value being larger (almost 30°) for climb and descent where there are more light (and variable) winds than for cruise where the value is almost half (17°).

The wind components show a negative bias of about 1 m/s in the westerly component over the regional area, and this is consistent with an underforecast wind speed.

The RMS vector wind difference is about 5 m/s in climb and descent (slightly smaller over Europe than over the regional area), and about 6 m/s in cruise over Europe and 7.5 m/s in cruise over the regional area. Comparison with the RMS forecast minus radiosonde vector wind difference over Europe of 4 to 6 m/s at cruise levels and 3 to 4 m/s at lower levels suggests that the RMS error in the aircraft vector wind observations is probably better than 3 m/s. This in turn implies an RMS forecast vector wind error of about 7 m/s at cruise levels over the regional area.

Consider now the forecast minus observation differences of route-mean headwinds, crosswinds, equivalent headwinds and temperatures.

Figure 2 shows a plot of the variation of the SDs as a function of route length. From theoretical considerations it can be shown (Purser, 1992) that the SD of the equivalent headwind error should be proportional to $L^{-1/2}$ for large scales L and this is indeed found to be the case. On the other hand, for small scales the SD should become constant. Whilst it is found that the SD does not increase as rapidly as $L^{-1/2}$ for small L, it is not possible to be certain of the asymptotic value due to the lack of resolution in the data sample, the distance between ASDAR reports being about 50 nm. However, it is significant that the SD of equivalent headwind errors is larger for the regional area than for Europe. In particular for $L = 50$ nm the value for the regional area is 5.5 m/s whereas the value for Europe is 3.4 m/s.

The erratic nature of the curves towards larger L is due to the small sample size in this domain.

The mean of the equivalent headwind differences is negative in the case of the regional area. Bearing in mind the bias in the data in favour of westbound Atlantic flights, this result is consistent with the underforecasting of the windspeed mentioned previously. The fact the the mean difference drops towards zero for large L shows that cancellation of errors in the forecast occurs in the case of longer routes and that this can have a beneficial effect on predicting the arrival times of aircraft on long haul routes.

The mean crosswind difference is almost constant (just under 1 m/s) independent of the route length L in the case of the regional area.

The mean temperature difference is consistently negative being about -0.5°C for small L decreasing in value to about -0.2°C for large L. The corresponding SD for small L is 2.2°C in the regional area and 1.5°C over Europe in agreement with results found earlier.

It is interesting to compare the current results based on the Cray 20/19 level regional model (resolution about 45 km) with previous results (Forrester, 1987) based on the Cyber 15 level global model (resolution about 150 km). The old study derived statistics of forecast minus analysis equivalent headwinds for a number of routes worldwide. Because that verification was based on analysis fields rather than actual observations (which were not readily available at that time) it was believed (by some) that the results might be overly optimistic particularly over the Atlantic where the analysis relies heavily on the background field in the absence of observations. Over Europe and the North Atlantic the RMS equivalent headwind differences were found to depend on route length roughly as follows:

	Route length	(T+12)-(T+0)	(T+24)-(T+0)
Europe	200 nm	4.5 m/s	5.0 m/s
	500	3.0	4.0
N Atlantic	3000	2.0	2.5

These results are plotted in Figure 2.

Comparison of the old and new results indicates that there has been a significant improvement in the accuracy of forecasting equivalent headwinds over Europe and a small improvement over the North Atlantic. Equivalent headwinds can now be forecast over Europe with an accuracy (SD) of about 3.5 m/s for a 100 nm route, about 3 m/s for a 250 nm route, and better than 2.5 m/s for a 500 nm route. Over the North Atlantic the accuracy is now about 2.5 m/s for a 1500 nm route, and better than 2 m/s for a 3000 nm route.

5. CONCLUSIONS

It has been shown that there has been an improvement over the last few years in the accuracy of forecasting equivalent headwinds over Europe and the North Atlantic.

Comparison of ASDAR and radiosonde verification statistics suggests that the accuracies of aircraft observations of temperature and wind vector have RMSs of 1°C and 3 m/s or better.

6. REFERENCES

Forrester, D A (1987) "Monitoring of equivalent headwind and temperature forecasts from the 15-level coarse mesh model" Met Office, SITN No 49, 1987

Forrester, D A and Dharssi, I (1992) "The Improvement of Meteorological Data for Air Traffic Management Purposes" Report for CAA on Stage 1 of Contract No 7D/S/988/1.

Purser, R J (1992) Personal communication

APPENDIX 1

Let F, O, and A be the forecast, the observed, and the (unknown) actual values of any parameter. Then

$$F - O = (F - A) - (O - A)$$

The mean (M) of a sample of size N is given by:

$$\begin{aligned} N \times M(F - O) &= \text{sum } (F - O) \\ &= \text{sum } [(F - A) - (O - A)] \\ &= \text{sum } (F - A) - \text{sum } (O - A) \end{aligned}$$

Hence $$M(F - O) = M(F - A) - M(O - A)$$

The mean square (MS) of a sample of size N is given by

$$\begin{aligned} N \times MS(F - O) &= \text{sum } (F - O)^2 \\ &= \text{sum } [(F - A) - (O - A)]^2 \\ &= \text{sum } (F - A)^2 + \text{sum } (O - A)^2 - 2 \times \text{sum } (F - A) \times (O - A) \end{aligned}$$

Now, if it can be assumed that the forecast errors and the observation errors are uncorrelated, then the last term on the right hand side vanishes, and one finds that:

$$MS(F - O) = MS(F - A) + MS(O - A)$$

Furthermore, it can be shown that the variances (VAR) are related by:

$$VAR(F - O) = VAR(F - A) + VAR(O - A) + 2 \times M(F - A) \times M(O - A)$$

	Climb		Descent		Cruise	
	Mean	RMS	Mean	RMS	Mean	RMS
Temperature (°C)	−0.5	1.8	−0.6	1.9	−0.5	1.9
Wind speed (m/s)	−1.0	3.7	−1.4	4.0	−2.1	6.1
Wind direction (°)	+0.5	29.4	+0.8	26.7	+0.0	17.3
Westerly wind (m/s)	−0.2	3.6	−0.7	3.8	−1.1	5.5
Southerly wind (m/s)	+0.3	3.8	+0.2	3.9	+0.2	5.3
Vector wind (m/s)	4.3	5.2	4.4	5.4	5.8	7.6
Number of observations	9150		8833		58289	

Table 1. Statistics of forecast minus observed differences for climb, descent and cruise phases of flight for the regional area.

	Climb		Descent		Cruise	
	Mean	RMS	Mean	RMS	Mean	RMS
Temperature (°C)	−0.6	1.5	−0.8	1.6	−0.2	1.5
Wind speed (m/s)	−0.7	3.3	−1.0	3.5	−1.2	4.5
Wind direction (°)	−1.0	30.4	−1.9	27.2	+0.1	21.0
Westerly wind (m/s)	+0.2	3.2	−0.3	3.6	−0.3	4.1
Southerly wind (m/s)	+0.4	3.3	+0.3	3.4	+0.2	4.2
Vector wind (m/s)	3.8	4.6	4.0	4.9	4.9	5.9
Number of observations	2457		1204		3748	

Table 2. Statistics of forecast minus observed differences for climb, descent and cruise phases of flight for Europe.

	Climb		Descent		Cruise	
	Mean	RMS	Mean	RMS	Mean	RMS
Temperature (°C)	−0.6	1.5	−0.8	1.6	−0.5	1.5
Wind speed (m/s)	−0.7	3.2	−1.1	3.6	−1.0	4.4
Wind direction (°)	−0.9	29.9	−1.8	25.9	−0.5	17.4
Westerly wind (m/s)	+0.2	3.2	−0.3	3.7	−0.5	4.4
Southerly wind (m/s)	+0.3	3.2	+0.3	3.4	−0.1	4.3
Vector wind (m/s)	3.8	4.5	4.1	5.0	5.0	6.1
Number of observations	2214		1108		617	

Table 3. Statistics of forecast minus observed differences for climb, descent and cruise phases of flight for Inner Europe.

	Winter		Spring		Summer		Autumn	
	Mean	RMS	Mean	RMS	Mean	RMS	Mean	RMS
Temperature (°C)	−0.5	1.9	−0.5	2.1	−0.2	1.7	−0.4	1.7
Wind speed (m/s)	−2.1	6.1	−2.1	5.8	−1.8	5.2	−1.9	5.4
Wind direction (°)	−0.0	14.9	−0.0	19.0	−0.4	22.7	−0.3	19.5
Westerly wind (m/s)	−1.3	5.6	−0.9	5.2	−0.4	4.8	−0.6	5.0
Southerly wind (m/s)	−0.0	5.3	+0.4	5.6	+0.2	4.8	+0.4	4.9
Vector wind (m/s)	6.0	7.7	6.0	7.6	5.4	6.7	5.6	7.0
Number of observations	28700		12482		3759		9344	

Table 4. Seasonal statistics of forecast minus observed differences for the cruise phase of flight for the regional area.

	Winter		Spring		Summer		Autumn	
	Mean	RMS	Mean	RMS	Mean	RMS	Mean	RMS
Temperature (°C)	−0.2	1.6	−0.2	1.5	−0.1	1.1	−0.1	1.3
Wind speed (m/s)	−1.3	4.6	−1.2	4.3	−0.6	3.5	−1.2	4.3
Wind direction (°)	−0.1	19.0	+0.8	22.3	−0.1	22.1	−0.2	21.4
Westerly wind (m/s)	−0.7	4.1	−0.1	3.9	+0.9	3.5	−0.9	4.3
Southerly wind (m/s)	+0.1	4.2	+0.2	4.2	+0.8	3.3	−0.4	4.2
Vector wind (m/s)	4.9	5.9	4.6	5.8	3.6	4.8	5.0	6.0
Number of observations	2108		1007		473		284	

Table 5. Seasonal statistics of forecast minus observed differences for the cruise phase of flight for Europe.

	Winter		Spring		Summer		Autumn	
	Mean	RMS	Mean	RMS	Mean	RMS	Mean	RMS
Temperature (°C)	−0.4	1.5	−0.2	1.1	−0.1	0.5	−0.3	0.8
Wind speed (m/s)	−1.1	4.5	−0.7	3.7	−0.1	1.7	−0.7	3.2
Wind direction (°)	−0.9	14.9	−1.6	15.2	−0.1	6.9	+4.1	24.5
Westerly wind (m/s)	−0.6	4.3	+0.1	3.2	+0.2	2.1	−0.8	3.8
Southerly wind (m/s)	+0.2	4.4	−0.4	3.4	−0.1	1.5	−1.0	3.3
Vector wind (m/s)	5.1	6.2	3.2	4.7	0.9	2.6	3.5	5.1
Number of observations	414		135		203		87	

Table 6. Seasonal statistics of forecast minus observed differences for the cruise phase of flight for Inner Europe.

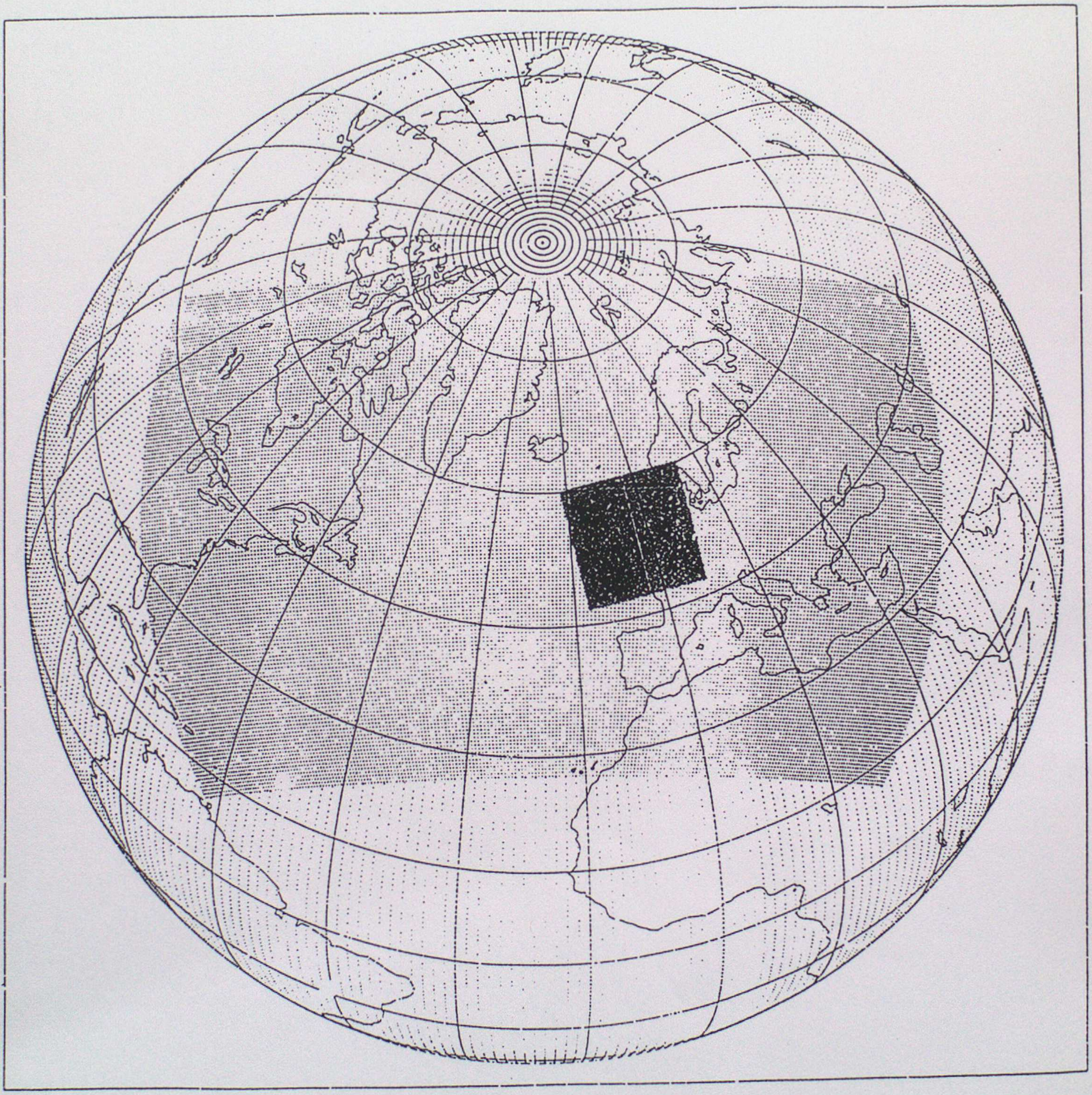

Figure 1. Chart showing the grid of the global, regional and mesoscale models.

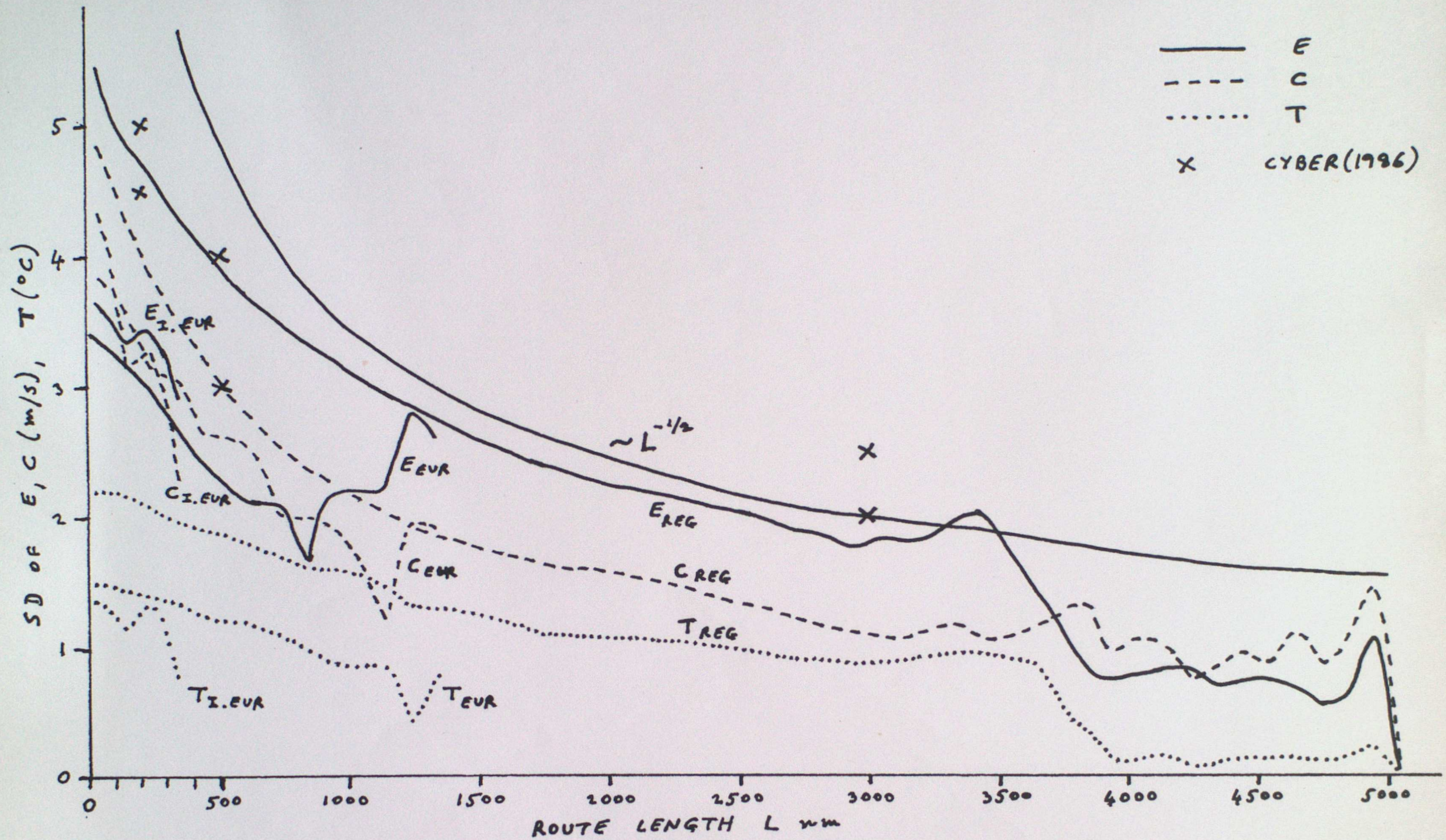

Figure 2. SD of forecast minus observed differences of route-mean equivalent headwinds (E), crosswinds (C), and temperatures (T) plotted as a function of route length (L) for the regional area, for Europe, and for Inner Europe.

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