TECHNICAL MEMORANDUM

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The decrease of the systematic error and the increased predictability of the long waves in the ECMWF model

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Abstract

Model diagnostics and some estimates of predictive skill for the ECMWF model are discussed which were calculated from the so-called "Lorenz files". In 1981 E. Lorenz visited ECMWF to study predictive skill. For this he used daily 500 hPa height field data from the ECMWF archives. The data, forecasts and analyses, were ordered according to verifying analyses rather than initial analyses, which is very convenient for predictive skill and diagnostic studies. These Lorenz files have been updated and currently all 37 seasons of 500 hPa height field analyses and 10-day forecasts since 1981 are available. A description of how to access the files is given in an appendix.

In the first part of this memo an assessment is made of the contribution of the seasonal systematic error in the 500 hPa height of the ECMWF model to the forecast skill. The seasonal systematic error has decreased considerably in the last 9 years. The significance of this was different in the short range and in the late medium range. In the short range (day 1-2) the decrease of the non-systematic error in the Southern Hemisphere was large which caused an improvement in the global skill of the model. In the late medium range (day 6-10), a large contribution to the improvement in the global skill of the model has come from the reduction of the systematic error. Since the systematic error is a large scale feature, this has had consequences for the predictive skill of the long waves. In the early years of the model the predictive skill of the long waves and short waves was equal, but now the predictive skill of the long waves has become larger (by approximately one day) than that of the short waves.

In the second part the method of determining the limit of predictive skill as introduced by Lorenz (1982), is discussed. Lorenz (1982) made estimates of the error growth of a "perfect" model, which would serve as an indication of the upper limit of the skill of a weather forecasting model. It will be shown that the estimates of the skill of his "perfect" model underwent a great deal of annual and interannual variability, very much depending on the quality of the model.

1. INTRODUCTION

The success of a weather forecast model is limited by the predictive skill of the atmospheric flow, by errors in the initial data and the analysis method and by errors in the model. The error growth due to the first is fundamental, and the limit of predictive skill due to this error growth is estimated to be in the order of 14 days on average (Lorenz, 1963). Model and analysis errors limit the global skill of numerical weather prediction models at present to about 6-8 days, so there still is some potential for improvement. Several methods have been used to assess the room for improvement, such as diagnosing the errors of the model or like (in various sophisticated ways) separating the intrinsic errors from the model and analysis errors (Lorenz, 1982; Arpe et al., 1985; Dalcher and Kalnay, 1987). The latter method is not straightforward. A practical and commonly used distinction in error is between the systematic part of the error (defined as the error of the time mean day-n forecast, sometimes referred to as the drift, bias or mean error) and the non-systematic or random part. The systematic error in the ECMWF model has been documented very extensively (Arpe and Klinker, 1986; Arpe, 1988; Tibaldi, Brankovic and Cubasch, 1987). The systematic error is however only a small part of the total error. In this note the evolution of the seasonal mean systematic error in the 500 hPa height field in the ECMWF model in the past 9 years will be examined and compared with the evolution of non-systematic errors. The following problems will be addressed: 1) are changes in the total error related to changes in the systematic error? 2) how do changes in both the total error and the systematic error relate to various model changes? 3) by how much is the skill affected by (a reduction in) the systematic error 4) is the predictive skill of the long waves affected differently by a reduction in systematic error.

In order to separate the systematic error from non-systematic errors the approach of Dalcher and Kalnay (1987) and Savijarvi (1984) is followed. A distinction is made between the squares of the total error, of the systematic error and the non-systematic forecast error which is simply the difference between the first two. The definition of the systematic error is somewhat arbitrary, since a time averaging period has to be specified. Here we will limit ourselves to seasonal mean errors and concentrate on the trend in the seasonal systematic error in the 500hPa height field in all seasons since winter 1980/81.

Dalcher and Kalnay (1987) calculated the seasonal mean error growth as a function of forecast day for the summer of 1980 and the winter of 1980/81. They found that the square of the systematic error contributed in 1981 about 20% to the total forecast error at day 10, which meant a loss of global skill of about 1 day. A similar estimate was made by Hollingsworth et al. (1980), based on a small set of forecasts. The results of Dalcher and Kalnay also indicated that the systematic error was largest in the long waves and that the potential predictive skill in the medium range is larger for these scales (i.e. after a reduction of the systematic error). This is in line with earlier findings by Persson (1984 a,b) who recommended the use of spectrally filtered forecasts. To illustrate the scale dependence of the errors, the error growth will be calculated as a function of truncation. Calculations will be carried out for various regions: for the whole globe, for the N-Hemispheric and S-Hemispheric mid-latitudes and for the European-Atlantic region. The global calculations will be evaluated for 4 truncations in total wave number space (spherical harmonics) and the regional calculations for 3 truncations in fourier space.

The data base which will be used is the set of so-called Lorenz files (Lorenz, 1982). These files contain daily 500hPa height fields (forecasts and analyses) in a T40 truncation for spring, summer, autumn and winter 1981-1990, stratified by verifying date, rather than initial date. Examples how to access the data are given in Appendix B.

2. TECHNIQUE

As in Dalcher and Kalnay (1987), squared errors rather than RMS errors will be calculated, since they have convenient additive properties. The error can be split in 2 parts as follows. Consider an analysis Z_0, and the 10 forecasts for each forecast day i, verifying on this analysis :

$$Z_1, Z_2, \ldots..Z_i,\ldots,Z_{10},$$

in which the Z_i can be spectral coefficients or gridpoint values.

If the seasonal mean is represented by a bar: $\overline{Z}_0$, $\overline{Z}_i$ etc. and the 7 year climatological mean by a double bar, we can for each forecast day i (in each gridpoint or spectral component) define :

the actual forecast error : $E_i = Z_i - Z_0$,

the seasonal systematic error : $\overline{E}_i = \overline{Z}_i - \overline{Z}_0$,

the non-systematic error variance : $\overline{E_i^2} - \overline{E}_i^{\,2}$,

the seasonal variance : $\overline{(Z_i - \overline{Z}_i)^2}$,

the climatological variance : $\overline{\overline{(Z_i - \overline{\overline{Z}}_i)^2}}$

Note:

1. Each season consists of 100 days, starting from the first of December, first of March etc. (Lorenz, 1982).
2. The non-systematic error variance represents the error of a model without a systematic error.
3. The climatological variance is evaluated from the analyses in each season, averaged over 7 years. It has been calculated as an average over five 20-day periods in each season to remove the seasonal cycle.

As an example the horizontal distribution of the systematic errors at day 10 is shown in Fig. 1a for the Northern Hemispheric winter of 1989/90. The seasonal mean circulation of this winter is shown in Fig. 1b. The pattern of the systematic error is typical for other recent seasons. The non-systematic forecast error (see Fig. 1c) is more complex. It is not clear a priori what part of the non-systematic forecast errors as defined here is the result of model deficiencies and what part is purely random and unpredictable (Arpe et al., 1985). It is, however, clearly related to the variability of the flow. Maxima of more than 200m occur, where the seasonal variability in the height field is large. This is illustrated in Fig. 1d where the observed seasonal variability is shown (cf. Wallace and Woessner, 1981).

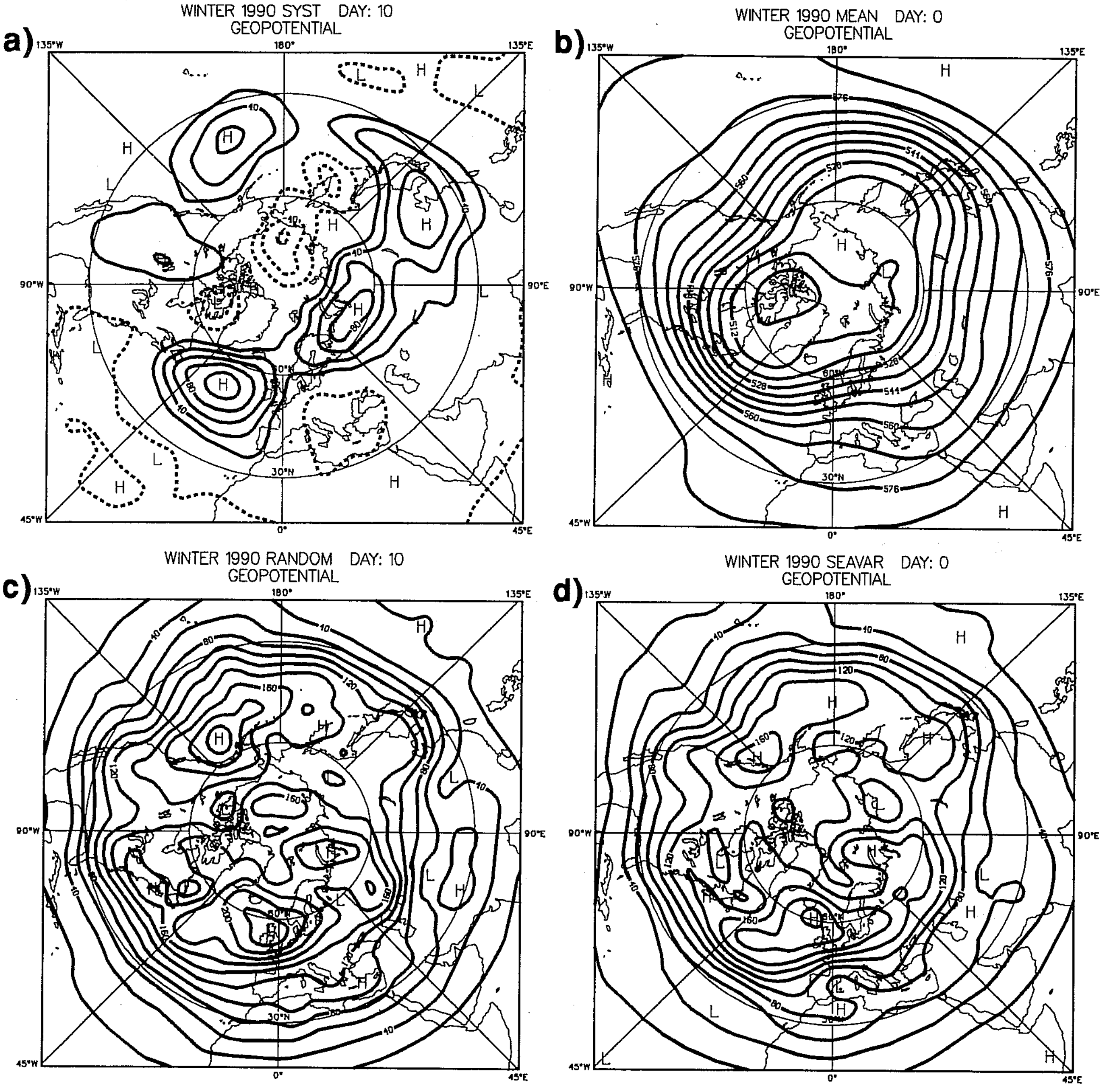


Fig. 1 Errors of the winter of 1989/90.
(a) The systematic error at day 10. Contours every 20 m.
(b) Seasonal mean 500 hPa flow. Contours every 8 dam.
(c) Non-systematic error at day 10. Contours every 20 m.
(d) Seasonal variability. Contours every 20 m.

3. RESULTS

3.1 Comparison between winter 1980/81 and 1989/90

For all seasons since the winter of 1980/1981 the seasonal mean growth of the error was calculated as a function of forecast day. In this section a comparison will be made between the error growth characteristics of the winter 1989/90 and the winter of 1980/81 which is the first winter in the series. It will be made for the entire globe and for the Northern Hemisphere (20°N-70°N). The comparison will merely serve to give a simple illustration of, in particular, the impact of the systematic error reduction on the predictive skill of the large global scales. In section 3.2 a detailed account will be given of the characteristics of the other seasons for the entire globe as well as for the Northern and Southern Hemispheric mid-latitudes.

3.1.1 Global Verification

In Fig. 2a,b the global error growth is shown for the winters of 1980/81 and 1989/90. (In the appendix A1, the error growth curves are shown for all seasons since 1981). The results are displayed for selected triangular truncations in spherical harmonics: T40, T10, T7, T5 to illustrate the scale dependence of the error growth. Each pair of curves in the figure represents one truncation. The upper curve (solid line) in each pair represents the growth of the total squared forecast error and the lower curve (dashed line) the random forecast error. The systematic error is indicated by the shaded area. In the same figure also the 80% level of the 7-year climatological variance for each truncation is indicated by the horizontal dotted line. The figure shows the well known feature that the forecast errors grow rapidly until day 7-8, after which the growth rate decreases. The errors level off in the extended range at about twice the climatological variance. Three points can be noted when comparing the two seasons:

a. the total squared global error at day 10 has decreased by about 20% from 12000 m^2 in the winter of 1980/81 to 9500 m^2 in the winter of 1989/90;

b. the contribution of the systematic error at day 10 to the total error of the model has decreased from 15% in 1981 to less than 5% in 1990 .

c. the contribution of the systematic error has been reduced most in the large scales (T5, T7 and T10).

The question to be answered is how much the forecast skill is affected by the existence of the systematic error and how much the skill has improved by the reduction of the systematic error. The skill of the model is here defined as the day at which an error growth curve reaches the level of 80% of its corresponding climatological variability (dotted

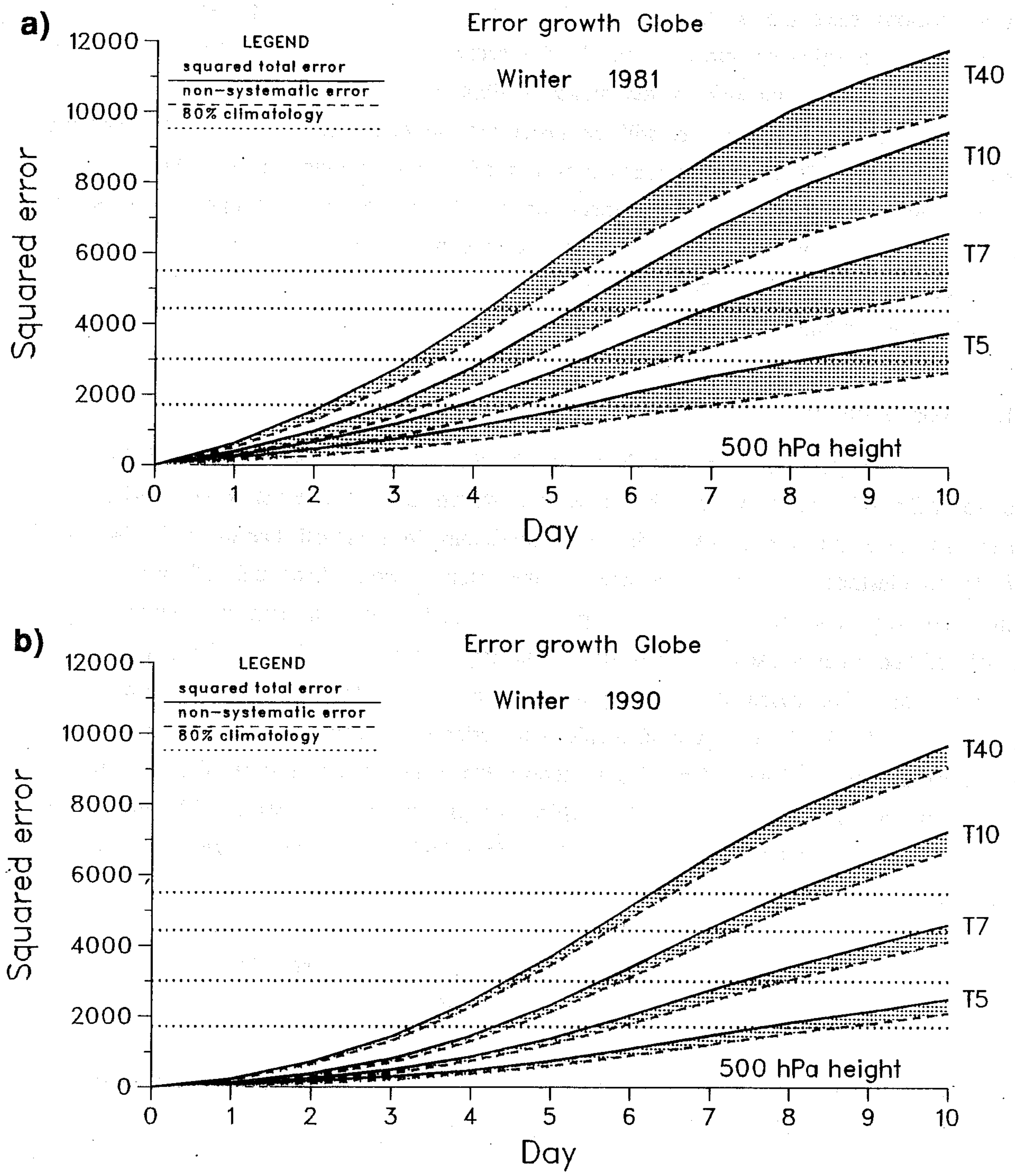


Fig. 2a,b Error growth in the winter of 1980/81 and 1989/90, for four different triangular truncations of spherical harmonics (T40, T10, T7, T5). The solid line represents the total squared error as a function of forecast day, the dashed line the non-systematic error. The shaded area represents the squared systematic error. The dotted line represents the 80% level of the 7 year mean climatological variance. Units: m^2.

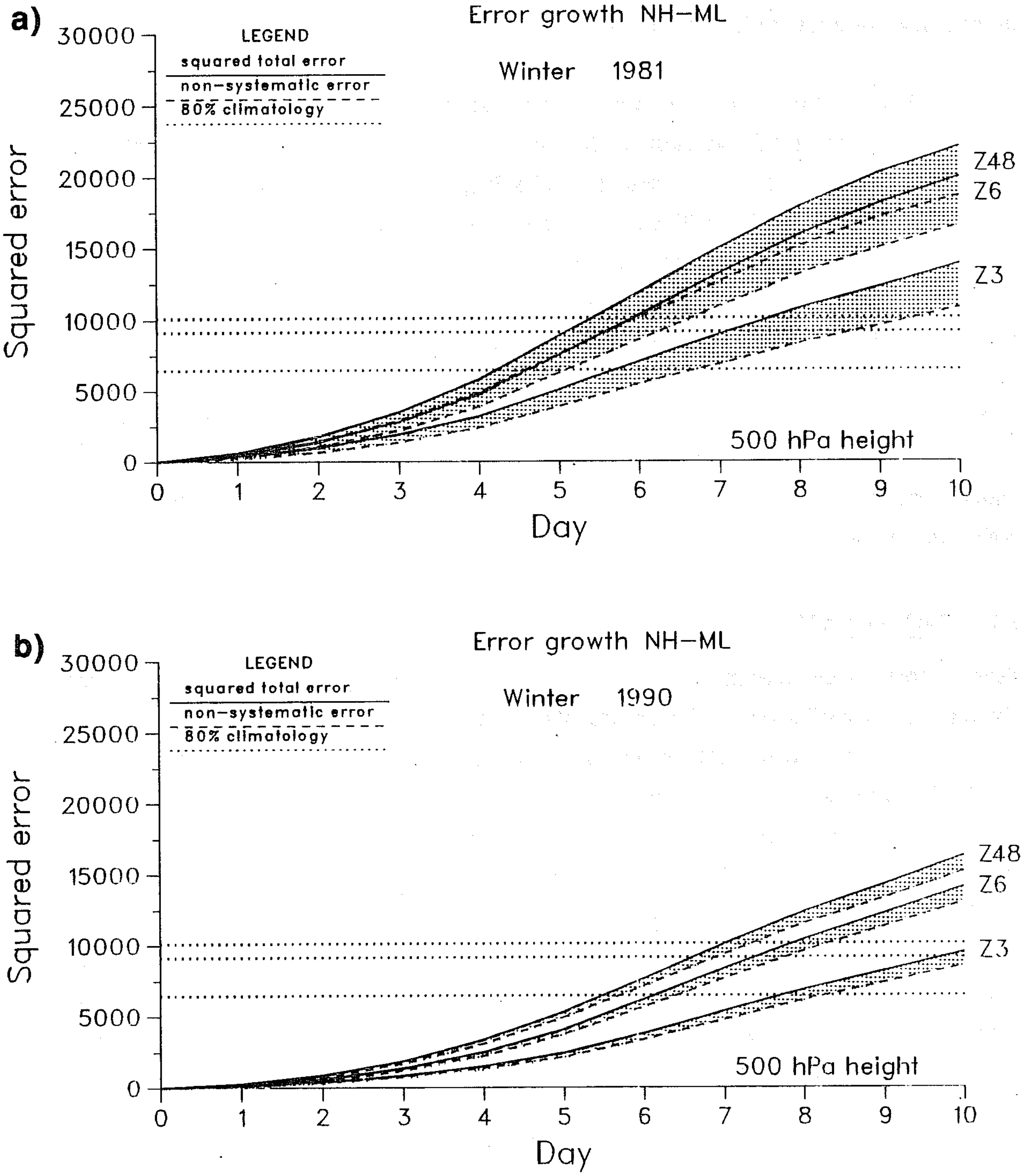


Fig. 3a,b Error growth in the winter of 1980/81 and 1989/90 in the Northern Hemisphere (20°N-70°N) for three different truncations in the zonal domain. The solid line represents the total error, the dashed line the random error, as in Fig. 2.

line). This corresponds to an anomaly correlation threshold of 0.6. According to this definition, the global skill of the model has increased by 1.5 days from 4.5 days in 1980/81 to 6 days in 1989/90, as can be inferred from Fig. 2a,b by comparing the curve labelled T40 with the uppermost dotted line. In 1981 about 1 day of skill was lost because of the systematic error, in 1990 one third of a day was lost.

The systematic error is a large scale feature, so its reduction in the medium range has mainly affected the predictive skill of the long waves. In 1981 the skill of the global scales was approximately 5 days. The skill of scales larger than T10 has improved by 2 days to 7 days. For T7 and T5 the skill went up from 5.5 days to 7.5 days. A T5 truncation does not have much practical meteorological use, but a T10 truncation, which has one day more skill than T40, is able to represent the main meteorological features, as was demonstrated by Persson (1984a,b), who recommended the use of spectrally filtered forecasts.

Note that the curves for the various truncations in Fig. 2 are cumulative. The contribution of the errors of the small scales can be found by comparing the curves of the various truncations. It is clear from Fig. 2 that there is hardly any systematic error in scales smaller than T7.

3.1.2 The Northern Hemisphere

Several areas were examined in a similar way as in the previous section. In order to eliminate the contribution of the tropics, the error was split in groups of zonal waves along an entire latitude circle. All fields were first transformed to a regular lat-lon grid after which the error statistics were calculated for the mid-latitudes. Since much of the error variance in mid-latitudes is found in the ultra-long waves (up to wavenumber three), just three truncations were considered, all including the zonal mean: all 48 wavenumbers (Z48), the first six zonal waves (Z6) and the first three zonal waves (Z3). In Fig. 3 the results are displayed for the Northern Hemisphere (20°N-70°N). (For all seasons see appendix A.2). Here as well we find a large reduction of the systematic error and an increase in predictive skill for the long waves: the skill of the model in the early years was about 5.5 days with a loss due to the systematic error of about 1 day. It has improved by about 1 day to 6.5 days with a relatively small systematic error in 1989/90.

3.1.3 Trends

The above characteristics are not only found in these two seasons. In Fig. 4 a time series of the (squared) global error is shown at day 1, 3, 5 and 10 for all seasons from the winter of 1980/81 until the winter of 1990. The seasons before 1985 (the introduction of a T106

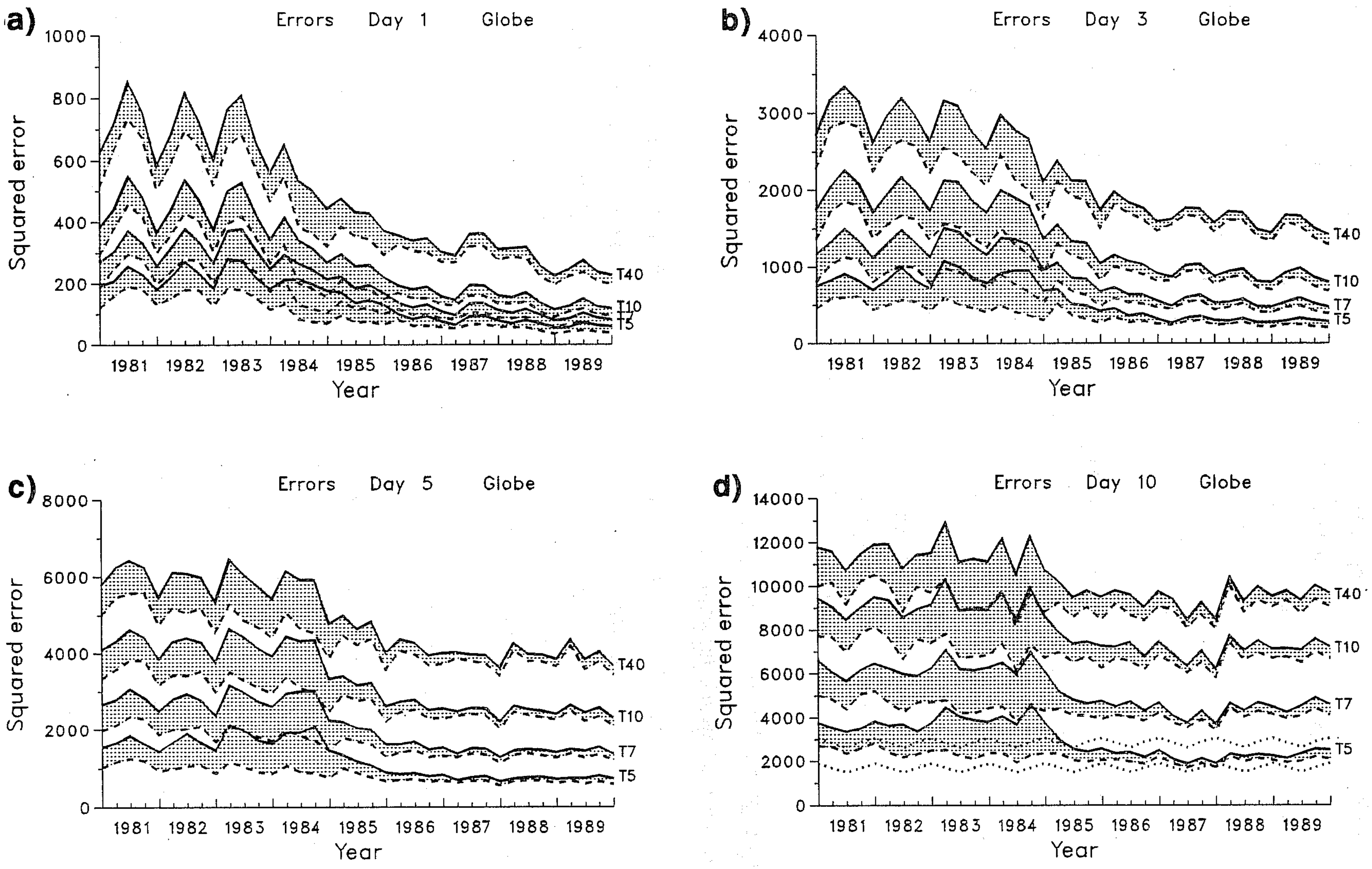


Fig. 4 Time series of the global errors (squared) at day 1, day 3, day 5 and day 10, for T40, T10, T7 and T5 truncation. Units: m^2.
The shading represents the contribution of the systematic error as in Fig. 2.
The dotted line represents the 80% level of the climatological variance of the T7 and T5 truncation.

model and new physical parametrizations) have similar characteristics as the winter of 1981: a contribution of the systematic error to the total error of about 15%. All seasons after 1985 have similar characteristics as the winter of 1989/90: a systematic error of about 5%. We can conclude therefore that the reduction in the seasonal mean systematic errors has contributed substantially to the improvement in skill of the ECMWF model. We can furthermore conclude that we can not expect a large gain in skill from further improvements in seasonal mean systematic error alone, assuming that the systematic error and the random error are independent.

There is more detail to be found in the variability of the error as shown in Fig. 4 which is related to various model changes over the years. An extensive list of model modifications can be found in Arpe (1988). Apart from the well documented decrease in errors since the beginning of numerical weather forecasting one can see in Fig. 4: a reduction in an initially very large annual cycle in the global forecast error in the short and early medium range, a rise in systematic error between 1983 and 1985 in the medium range, a relatively large reduction of systematic errors after the spring of 1985 and a rise in errors at day 10 in the spring of 1988. These points will be discussed briefly in the next section.

3.2 Effect of model changes on forecast errors

3.2.1 Global seasonal cycle in the short range

A striking feature in Fig. 4 is the global seasonal cycle in the forecast errors before 1984 in the short and early medium range. This is not a global feature, however. In Fig. 5 the errors are shown for the mid-latitudes in the Northern and Southern Hemisphere separately (note the different scale). It clearly shows that major improvements at day 1 have occurred in the Southern Hemisphere, which are most likely the result of changes in the analysis system in May 1984. Note that the day 1 errors in the Southern Hemisphere dominate the global errors, before and after 1984.

The short range errors in the Northern Hemisphere have followed a more linear trend. Here the error went gradually from about 500 m^2 to 250 m^2, with a relatively large contribution to the decrease from the systematic error.

After 1984 the global error has become a very sensitive and convenient measure of model skill since it no longer exhibits a large annual cycle. The seasonal cycles of both hemispheres compensate each other so that the global curve can show a secular trend. Note that although there was a distinct global annual cycle in the early medium range it did not penetrate into the later medium range. The errors have always been nearly constant throughout the year for the globe at day 10 (see Fig. 4), both before and after 1984.

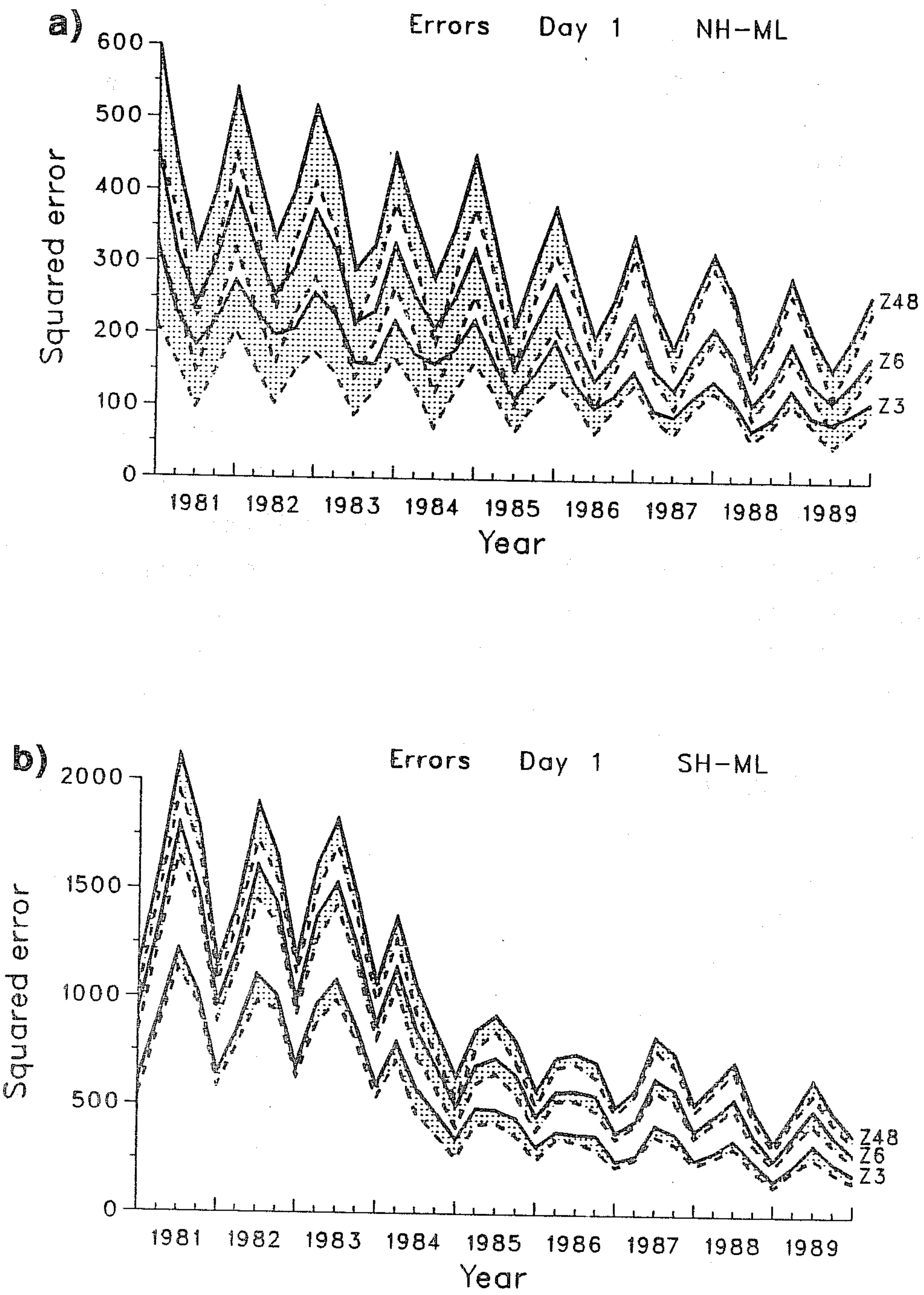


Fig. 5 Time series of the errors (squared) at day 1 since the winter 1980/81, for the Northern Hemispheric and Southern Hemispheric mid-latitudes (20°-70°). The shading represents the contribution of the systematic error as in Fig. 2.

3.2.2 Model changes and systematic error

There has not only been variability in the total forecast error, but also in the systematic error. A clear reduction occurred in 1985, but there was a rise in systematic error before that in 1983 at day 10 (see Fig. 4). Although we have to take the seasonal variability in skill into account, the length of the period with increased systematic error (spring 1983 until spring 1985) gives rise to the suspicion that it is related to model modifications, since in April 1983 the spectral T63 model as well as the envelope orography had been introduced, and in May 1985 the T106 model and the new parametrization schemes for the physics were introduced.

The major contribution to the error change comes from the tropics. In Fig. 6 the RMS values of the systematic error are plotted for the mid-latitudes in both hemispheres and for the tropics respectively. The abrupt changes in spring 1983 and spring 1985 are seen to be dominated by the changes in the tropics where the errors before 1985 were almost exclusively systematic errors. In mid-latitudes the trends in systematic error were more gradual. In the Northern Hemisphere, for instance, the error at day 1 went down gradually from about 10 metres to 5 metres. At day 10, a similar upward trend as in the tropics seems to occur in 1983, but it was statistically not significant. A t-test was carried out assuming that the RMS errors are Gaussian distributed. (This assumption is not strictly valid, see Branstator (1987)). Three periods were intercompared: the first 9 seasons up to spring 1983, the second 8 seasons between spring 1983 and winter 1984/85 and the last 20 seasons. Only in the tropics, both the changes in 1983 and 1985 were significant at the 1% level in all forecast ranges. In mid-latitudes, the increase in systematic error at day 10 in 1983 is not significant. The decrease after 1985 is significant at the 1% level in both hemispheres, but from Fig. 6 we learn that this mainly happened because of the reduction in the seasonal cycle after the summer of 1986. The latter might be associated with the extension from 16 to 19 levels and the introduction of gravity wave drag in the model in May and July 1986 respectively.

3.2.3 Error reduction in the late medium range

In the late medium range the global systematic error reduction has been relatively large. The total errors at day 10 went down from 12000 m^2 to 9000m^2 due to the relatively large reduction in systematic error from 2000m^2 to 500m^2. Because the systematic error is a large scale feature, the skill of the large scales has improved relatively more than that of the small scales. In Fig. 4 the climatological variance of the global scales T5 and T7 is indicated by the dotted line, which shows that the improvement has been very consistent from 1985 until 1988. We will return to this in section 3.2.4.

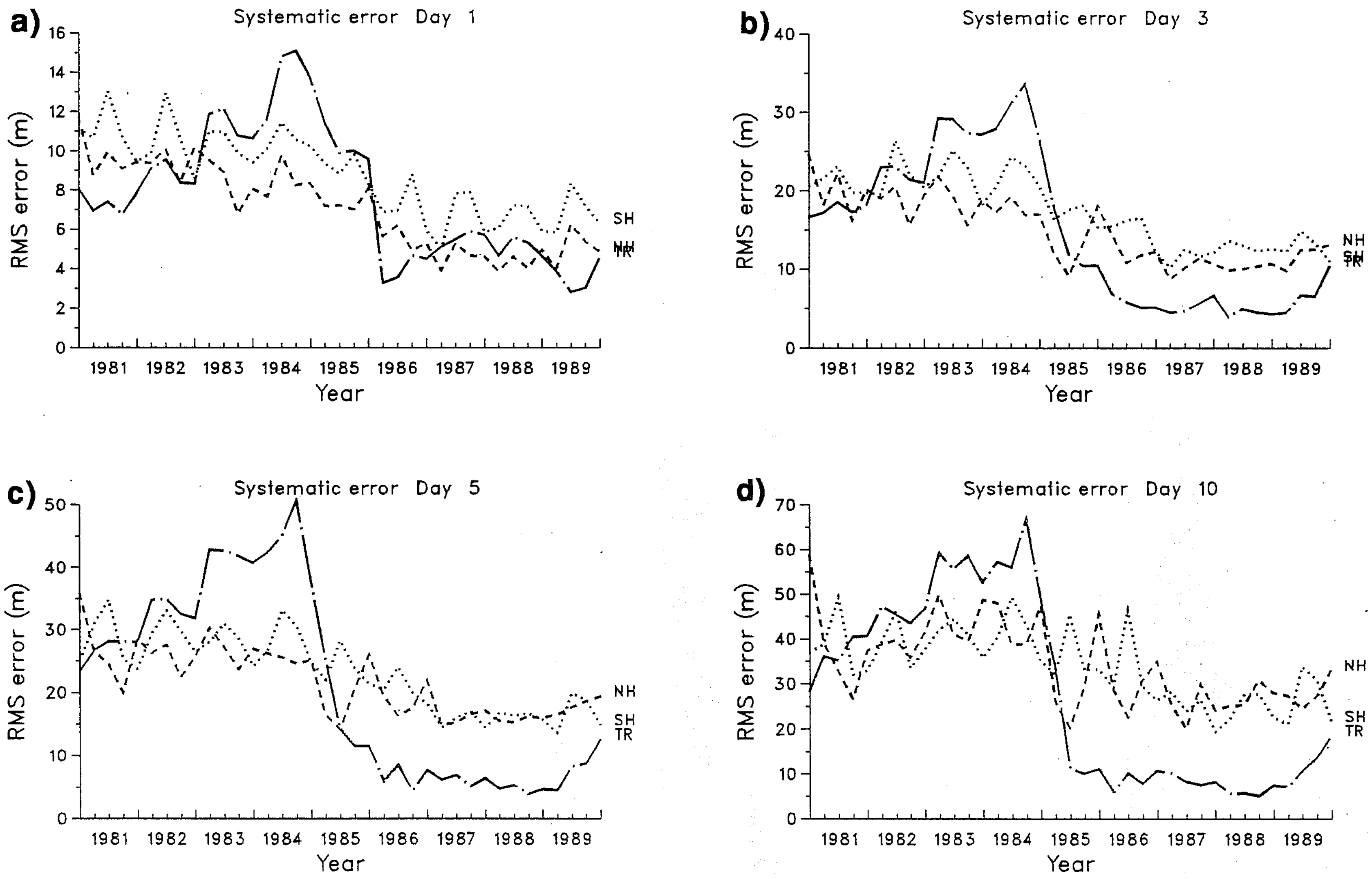


Fig. 6 Systematic error (RMS) of 500 hPa flow (m) for the Northern Hemisphere (dashed), Southern Hemisphere (dotted), and the Tropics (dash-dotted).

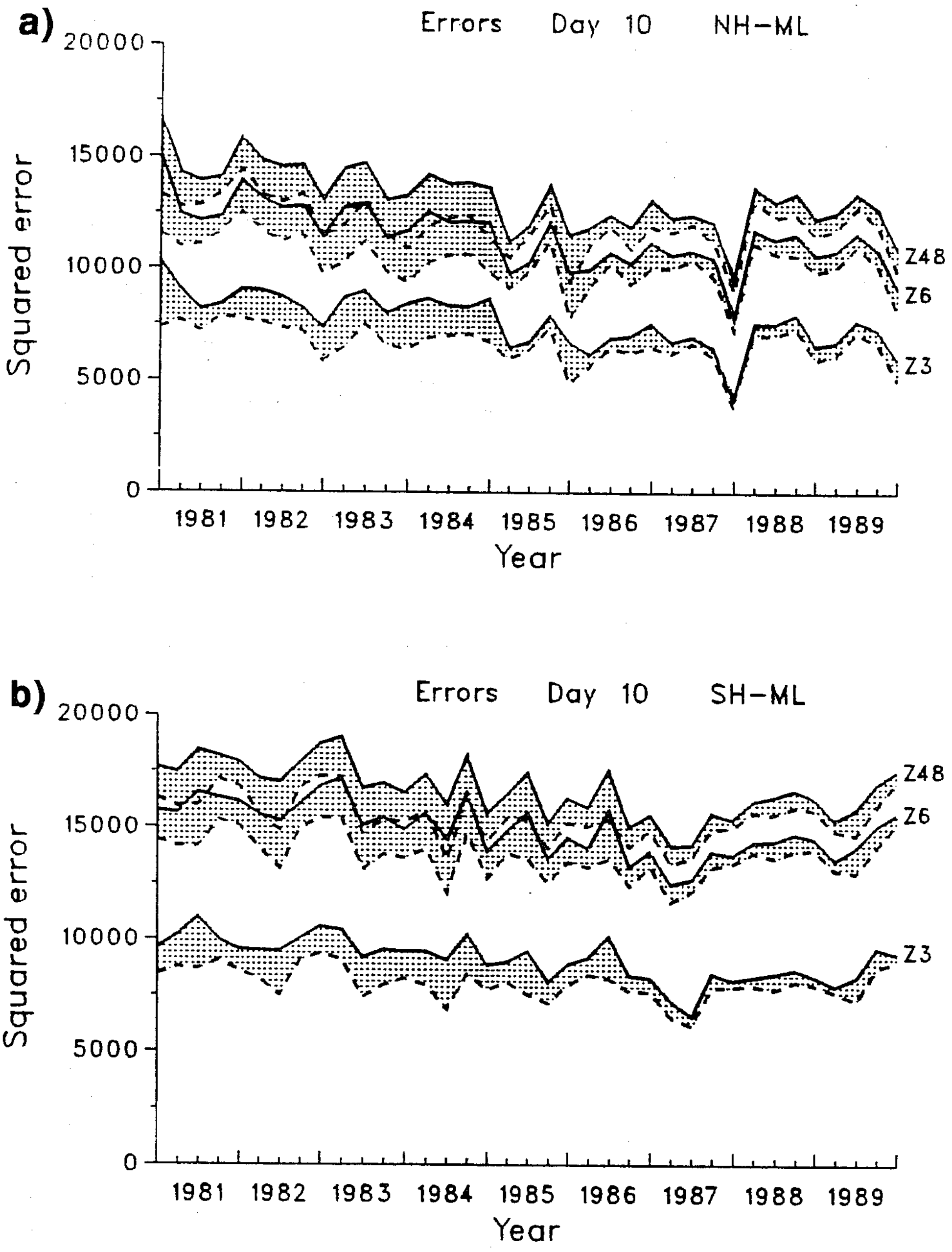


Fig. 7 Trends of the total errors (squared) at day 10, for the Northern Hemispheric mid-latitudes and the Southern Hemispheric mid-latitudes, (as in Fig. 4). the annual cycle has been removed by subtracting the 9 year mean amplitude of each season.

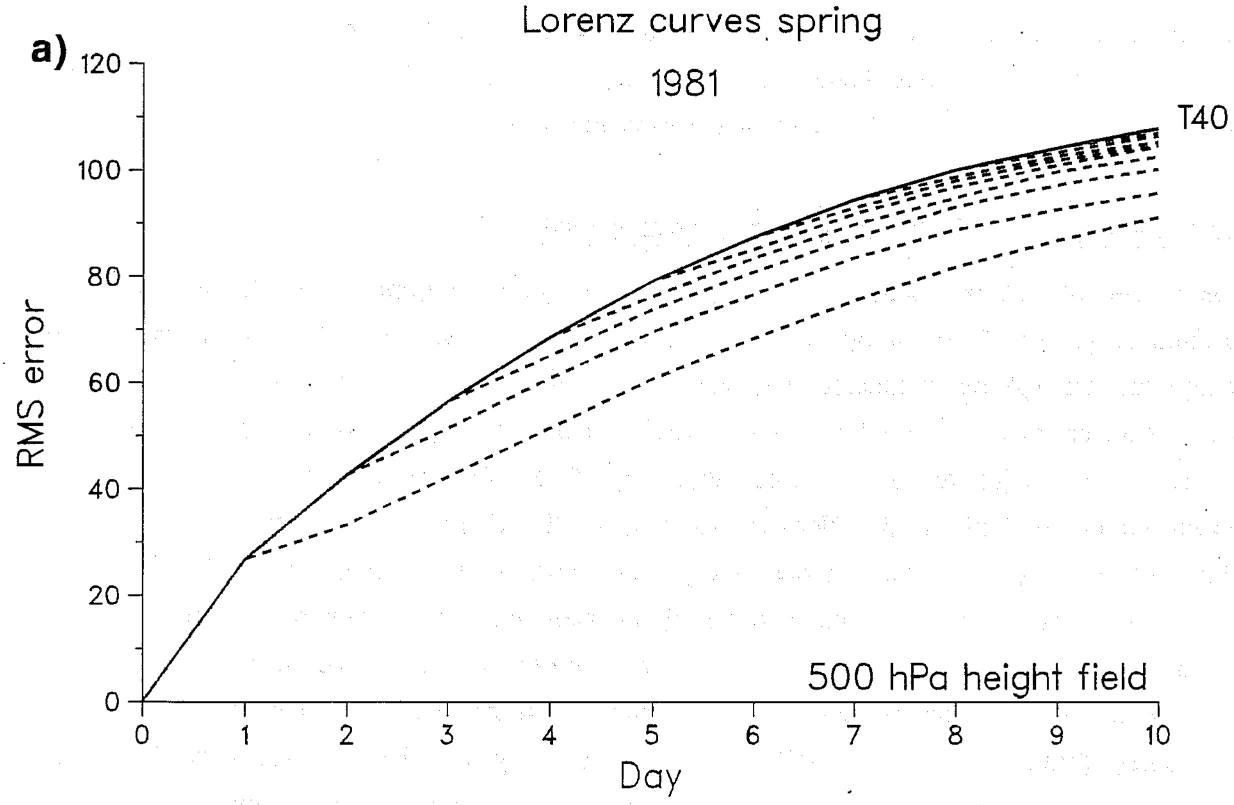
A large part of the global improvement is caused by the removal of the large bias in the tropics. The relative improvement in mid-latitudes is therefore somewhat smaller. This is illustrated in Fig. 7, which shows the errors at day 10 in mid-latitudes in both hemispheres after the annual cycle has been removed. In the Northern Hemisphere the errors went down with 15% mainly due to the reduction in systematic error.

3.2.4 The rise in errors in the late medium range after 1988

The winter of 1987/88 which showed a relatively good performance of the model in the medium range was followed by a spring with large RMS errors (see Fig. 4). In the former season the atmospheric circulation was close to the model climate which made the total error much smaller than in previous winter (Arpe, pers. comm.). In the spring of 1988, however, the model errors increased after day 5 at all scales (without affecting the systematic error), both in the Northern as well as the Southern Hemisphere. This is also illustrated in Fig. 7. All seasons except the most recent winter, since the winter of 1987/88 have larger errors in the Northern Hemisphere than in the previous 2 years. In the Southern Hemisphere the rise in the most recent winter is larger, resulting in a global error level similar to previous seasons. An explanation can not be given, but the reduction of the vertical diffusion in January 1988 seems to be a likely candidate. It has made the model more "active". The eddy kinetic energy reaches a higher, more realistic level, but generates at the same time more variability in the model in the medium range. Note that in the short range the errors actually went down very consistently (see Figs. 4 and 5).

3.3 Variability in estimated optimum skill

According to Lorenz (1982) an estimate of the growth rate of small initial errors in a perfect model can be made by taking the difference between forecasts verifying on the same day. The difference between today's day n-1 forecast and yesterday's day n forecast, verifying on day n, of small errors in the initial state. A day 2 forecast from 2 days ago can be considered as today's analysis with a somewhat larger error superimposed etc. This enabled Lorenz to estimate the growth rate of errors of different amplitudes. An example of such a calculation is shown in Fig. 8, where the lowest dashed curve indicates the error growth of the day n minus day n-1 forecast, the second curve the same but for the day n forecast minus day n-2 etc. The error in a perfect version of the model may then be estimated by taking the difference between the day n and day n-1 forecasts, since this represents the smallest type of error and may be representative for realistic errors in a perfect model. We will refer to this as the minimum day n error. The calculation by Lorenz have been repeated for all seasons. Results for the Globe and the Northern Hemisphere can be found in Appendix A3 and A4.



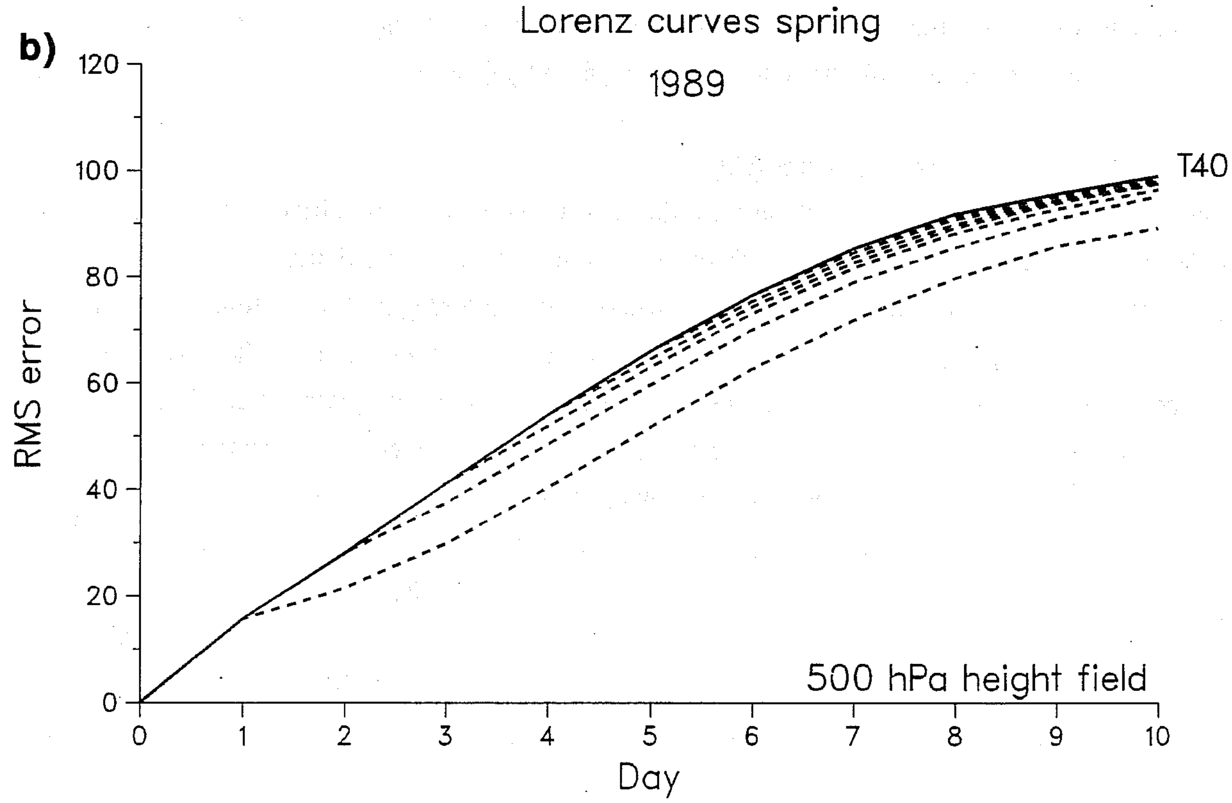


Fig. 8 Error growth in spring 1981 and spring 1989 in a T40 truncation (solid line). The dashed lines indicate the error growth curves calculated by taking the difference between the day n and day n-1 forecast (n=1,10).

Here we will discuss the results in a somewhat different format. For each season the skill, as defined in 3.1.1 ., was determined for both the model error as well as for the 1-day difference Lorenz curve (the lowest dashed curve in Fig. 8). The resulting time series of the skill of the globe and the Northern and Southern Hemispheric mid-latitudes are shown in Fig. 9, where the skill of the model is indicated by the solid lines (for different truncations), and the skill as derived from the Lorenz curve, the so called optimum skill, by the dotted lines (marked by the letter L and the corresponding truncation). It is clear from the figure that there is no such thing as a unique optimum skill. It shows a large annual as well as interannual variability. Initially, there was a general upward trend due to the reduction of the day 1 error, more or less following the trend in the total forecast errors (solid line). So, we see confirmed, as was anticipated by Lorenz, and found by Hollingsworth et al. (1987) who compared two winters, that estimates made in 1982 were, initially, too pessimistic, because of the low quality of the day 1 forecast at the time.

Lorenz (1982) also warned that his estimates might be too optimistic! By improving the model and enhancing the resolution smaller scales are introduced in the model which might amplify more rapidly than could be estimated with the model of 1982. There is an indication in Fig. 9 that this may have happened. In January 1988 vertical diffusion was removed in the free atmosphere which made the model more active. We saw in the previous section that forecast errors did rise, and we see in this figure that also the optimum skill went down in the spring of 1988. This decrease is global. It occurs in the tropics (not shown) as well as in the mid-latitudes of both the Northern as well as the Southern Hemisphere (Fig. 9b,c).

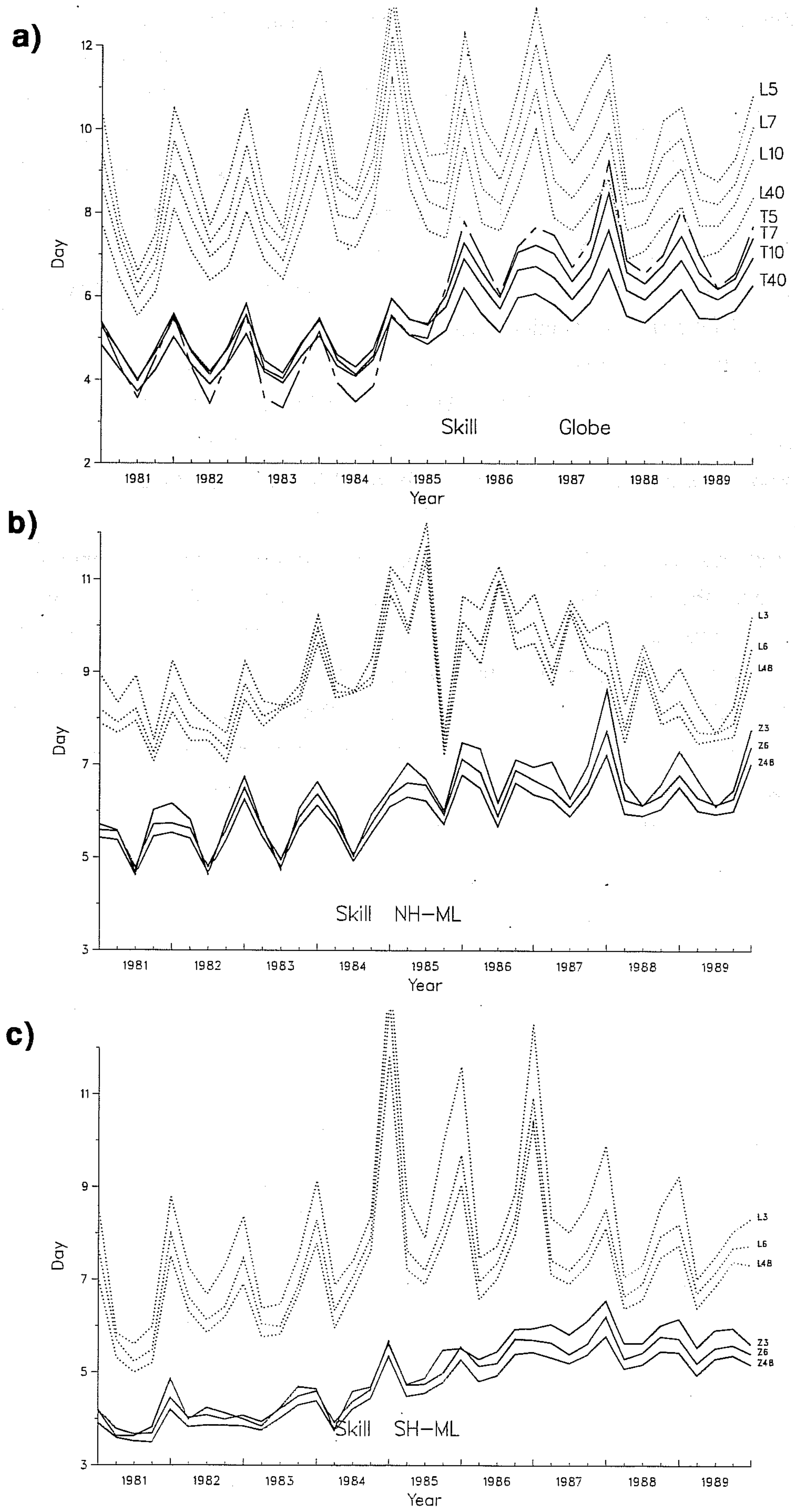


Fig. 9a,b,c Skill of the model for different truncation (solid lines). The dotted lines represent the optimum skill according to the Lorenz curves (see text).

4. DISCUSSION

The seasonal systematic error has decreased substantially in the past 9 years. The significance of the decrease was different for the medium and the short range. In the short range non-systematic errors gave the largest contribution to improved model performance, whereas in the late medium range systematic errors gave a large contribution as well. The predictive skill of the long waves has increased because of this and the use of filtered forecasts deserves perhaps renewed attention (Böttger, 1988). At present the seasonal systematic error affects the global forecast skill very little, and further reduction would lead to a gain in forecast skill of at most half a day. This does not mean that systematic errors have become negligible. Model errors manifest themselves on various timescales and are dependent on flow regime (Palmer, 1988; O'Lenic and Livezey, 1988; Epstein, 1988; Molteni and Tibaldi, 1990). Usually the systematic error is interpreted as a drift: a steady change more or less independent of flow regime. In Fig. 10 the ratio of the squared global systematic error and total error at day 1 and 10 has been plotted as a function of averaging time for the winter of 1987/88. Errors were determined for non-overlapping periods and then averaged over the season. The drift, which remains after averaging over a long period, has become very small: about 5% at day 10 and about 10% at day 1. For shorter averaging periods the systematic error increases. The monthly systematic error, for instance, is about twice as large as the seasonal error. The long term trend for the monthly error is however the same as for the seasonal error (not shown) with similar breaks in spring 1983, 1985 and 1988. The insignificance of the seasonal mean systematic error in the (late) medium range supports the suggestion that more attention should be given to the diagnosis of regime dependent errors, on a time scale of about 10-20 days.

The estimates of optimum skill have shown that there seems to be a higher potential skill for the large scales. It was also demonstrated, however, that it is difficult to make consistent quantitative estimates based on the calculation from only a few seasons, since these estimates seem to be clearly dependent on the quality of the model.

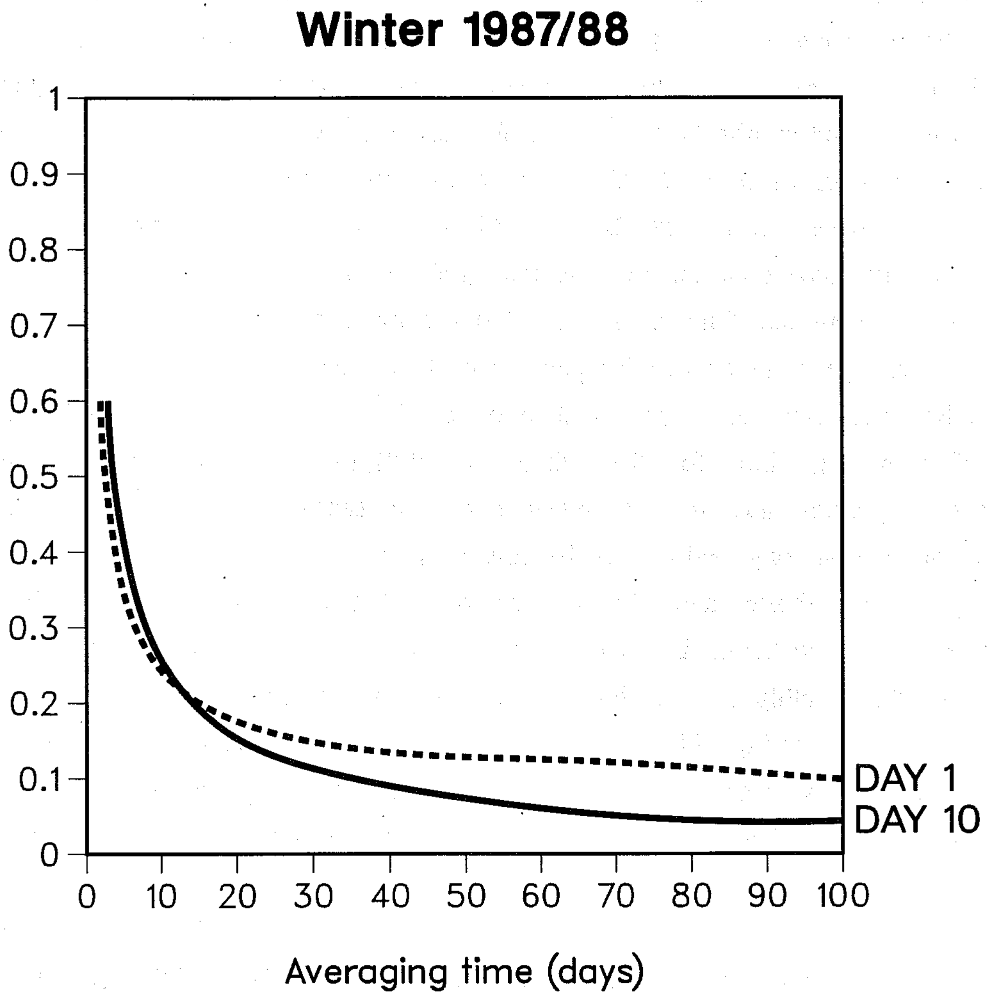


Fig. 10 Ratio of squares of systematic error and total error at day 1 and day 10 as a function of averaging time. Winter 1987/88.

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Appendix A

Fig. A.1 Same as in Fig. 2 for the entire globe for all seasons.

Fig. A.2 Same as in Fig. 2 for Northern Hemisphere mid-latitudes.

Fig. A.3 Lorenz curves for the globe (T40 representation).

Fig. A.4 Lorenz curves for the Northern Hemisphere mid-latitudes.

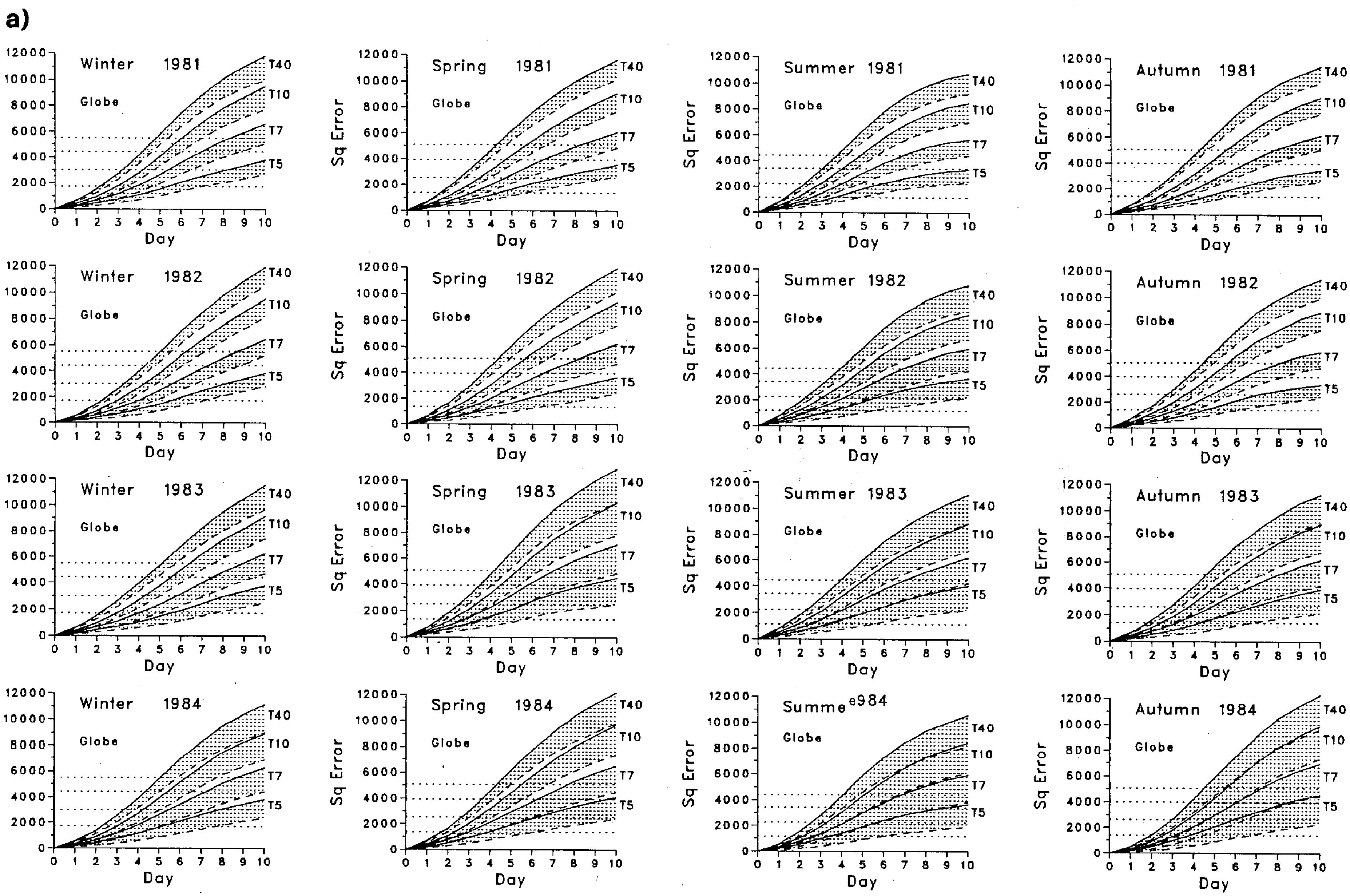

Fig. A.1 a,b,c Same as in Fig. 2 for the entire globe for all seasons.

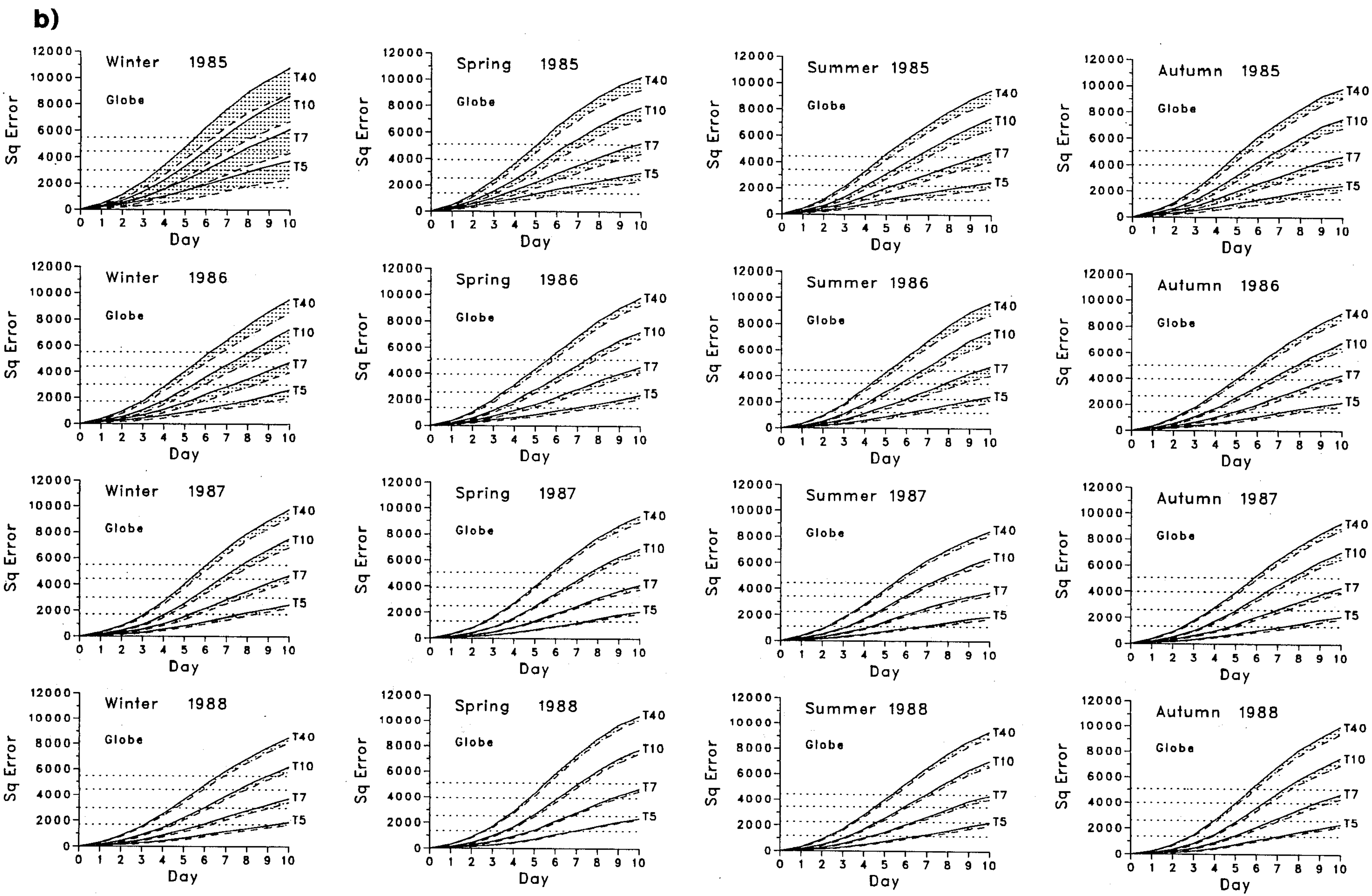
b)
Winter 1985
Spring 1985
Summer 1985
Autumn 1985
Winter 1986
Spring 1986
Summer 1986
Autumn 1986
Winter 1987
Spring 1987
Summer 1987
Autumn 1987
Winter 1988
Spring 1988
Summer 1988
Autumn 1988
Globe
Sq Error
Day
0
2000
4000
6000
8000
10000
12000
0 1 2 3 4 5 6 7 8 9 10
T40
T10
T7
T5

Fig.A.1 b

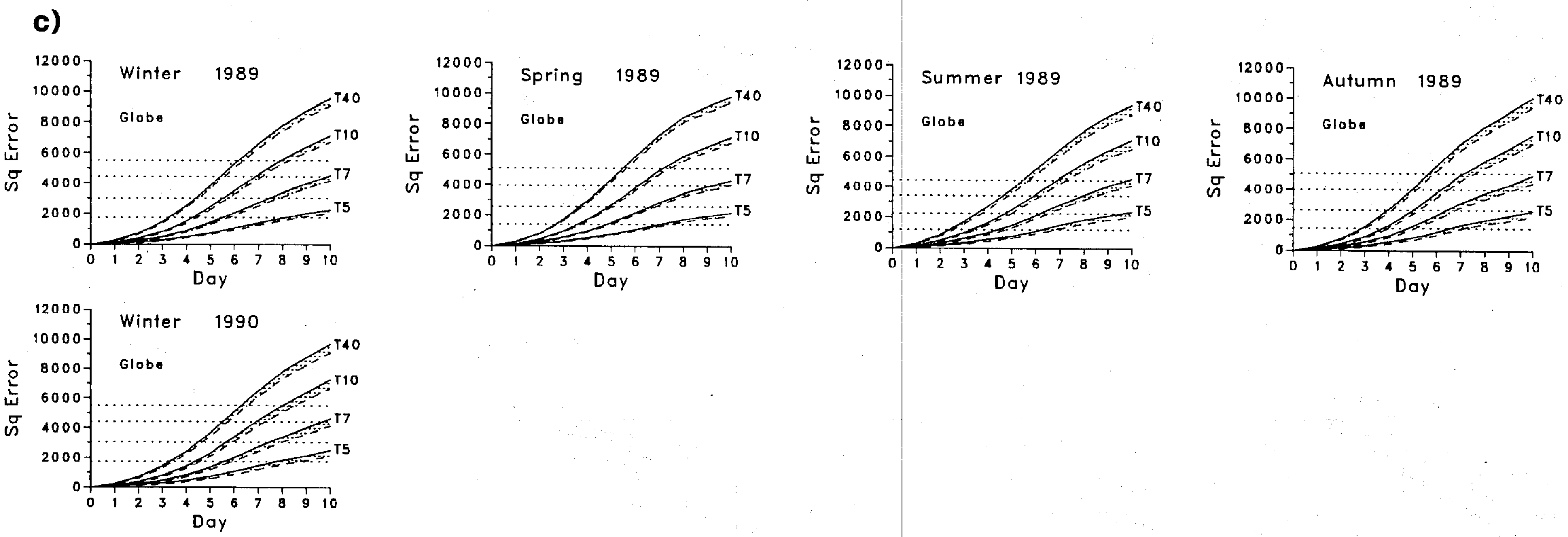
c)
Winter 1989
Globe
Spring 1989
Globe
Summer 1989
Globe
Autumn 1989
Globe
Winter 1990
Globe
Sq Error
0
2000
4000
6000
8000
10000
12000
Day
0 1 2 3 4 5 6 7 8 9 10
T40
T10
T7
T5

Fig.A.1 c

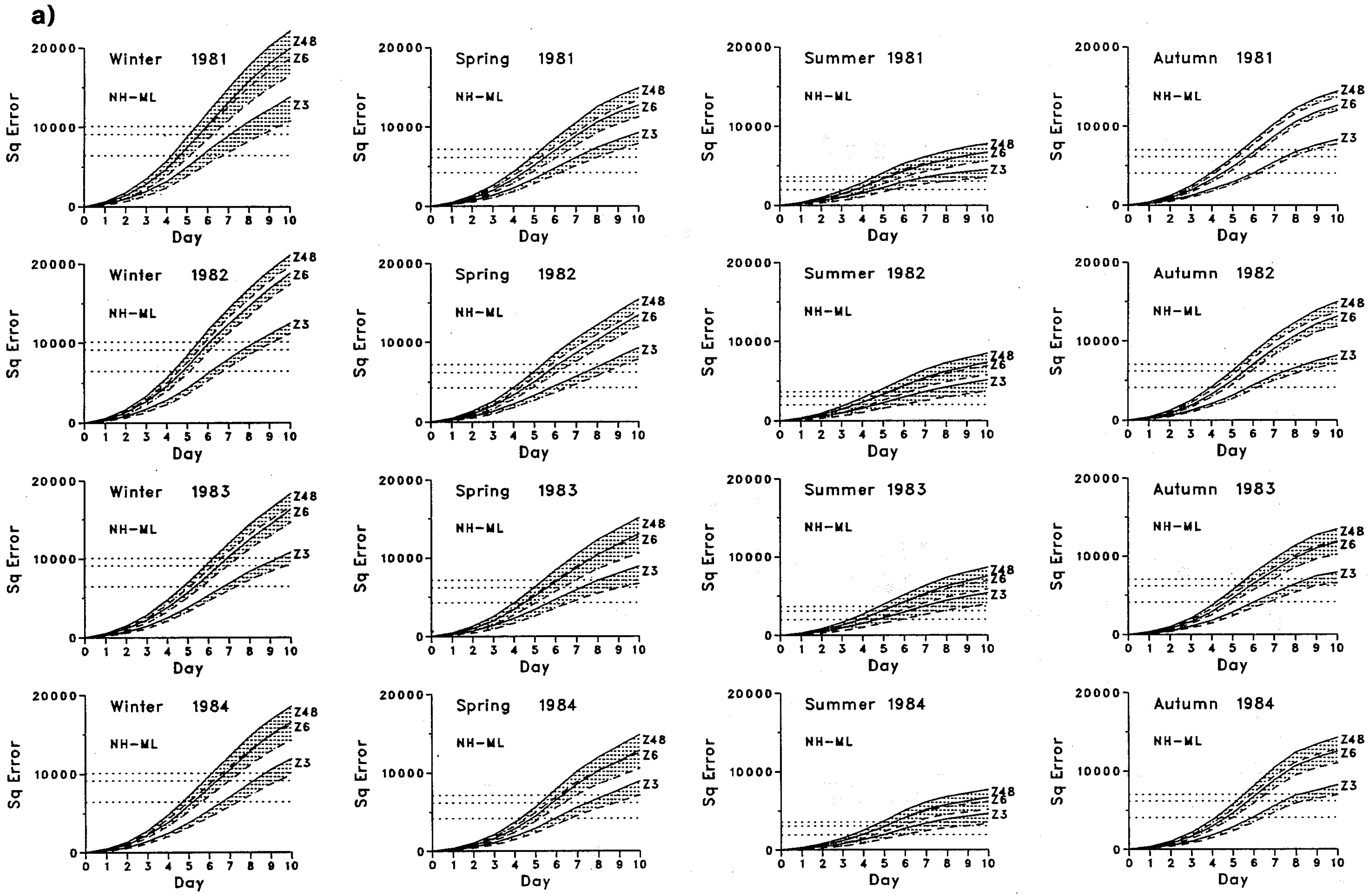

Fig. A.2 a,b,c Same as in Fig. 2 for Northern Hemisphere mid-latitudes.

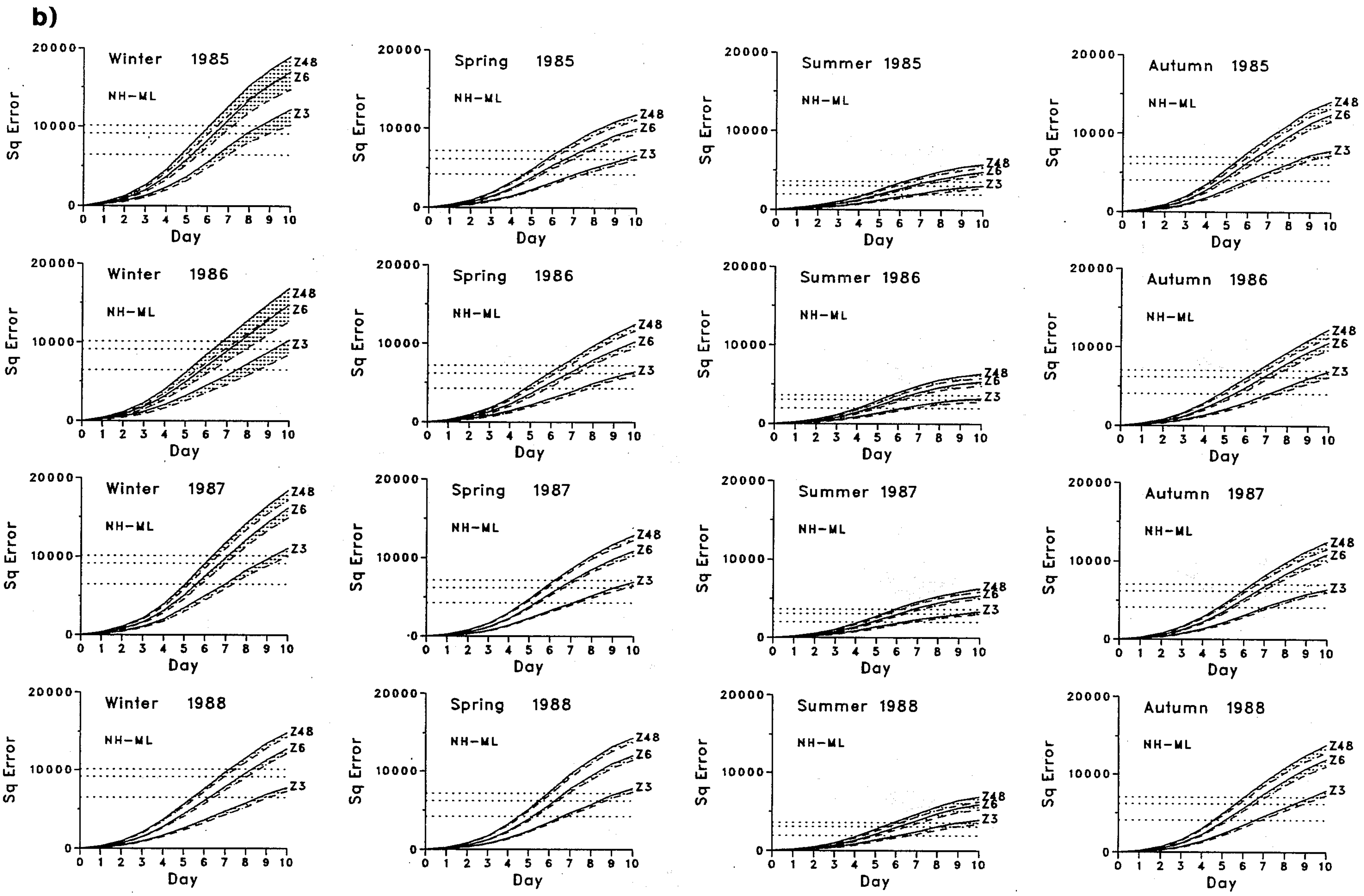b)
Winter 1985
Spring 1985
Summer 1985
Autumn 1985
Winter 1986
Spring 1986
Summer 1986
Autumn 1986
Winter 1987
Spring 1987
Summer 1987
Autumn 1987
Winter 1988
Spring 1988
Summer 1988
Autumn 1988
NH-ML
Sq Error
Day
Z48
Z6
Z3
0
10000
20000
0 1 2 3 4 5 6 7 8 9 10

Fig.A.2 b

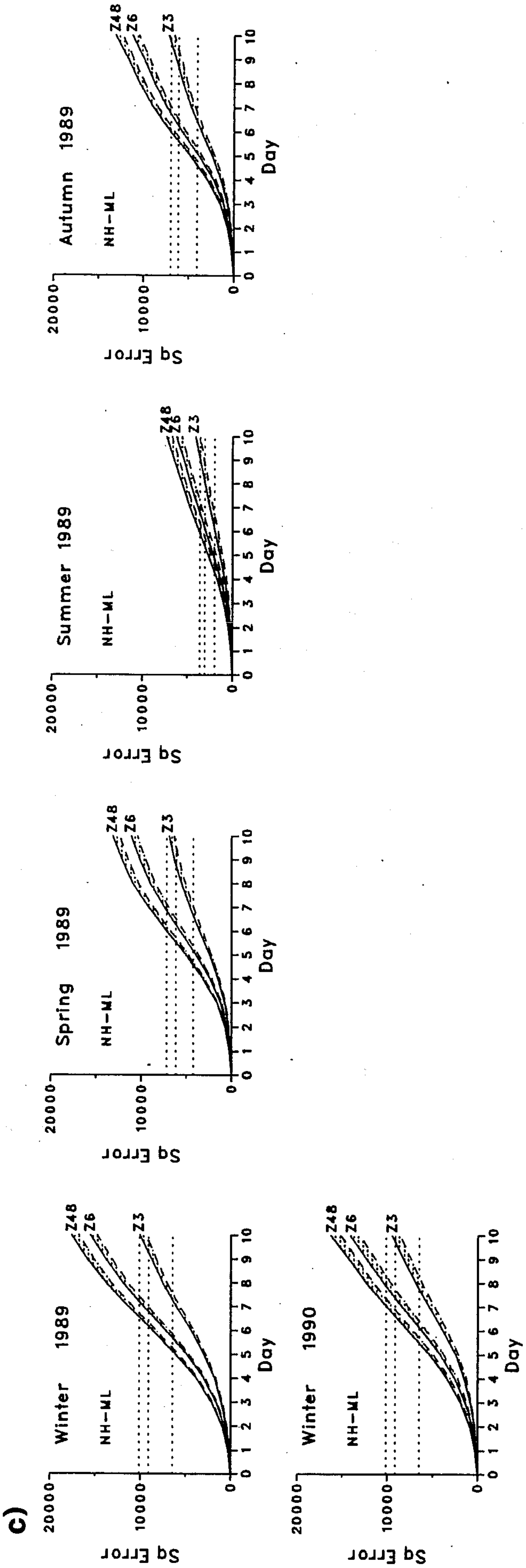
c)
Winter 1989
NH-ML
Winter 1990
NH-ML
Spring 1989
NH-ML
Summer 1989
NH-ML
Autumn 1989
NH-ML
Sq Error
20000
10000
0
Day
0 1 2 3 4 5 6 7 8 9 10
Z48
Z6
Z3

Fig.A.2 c

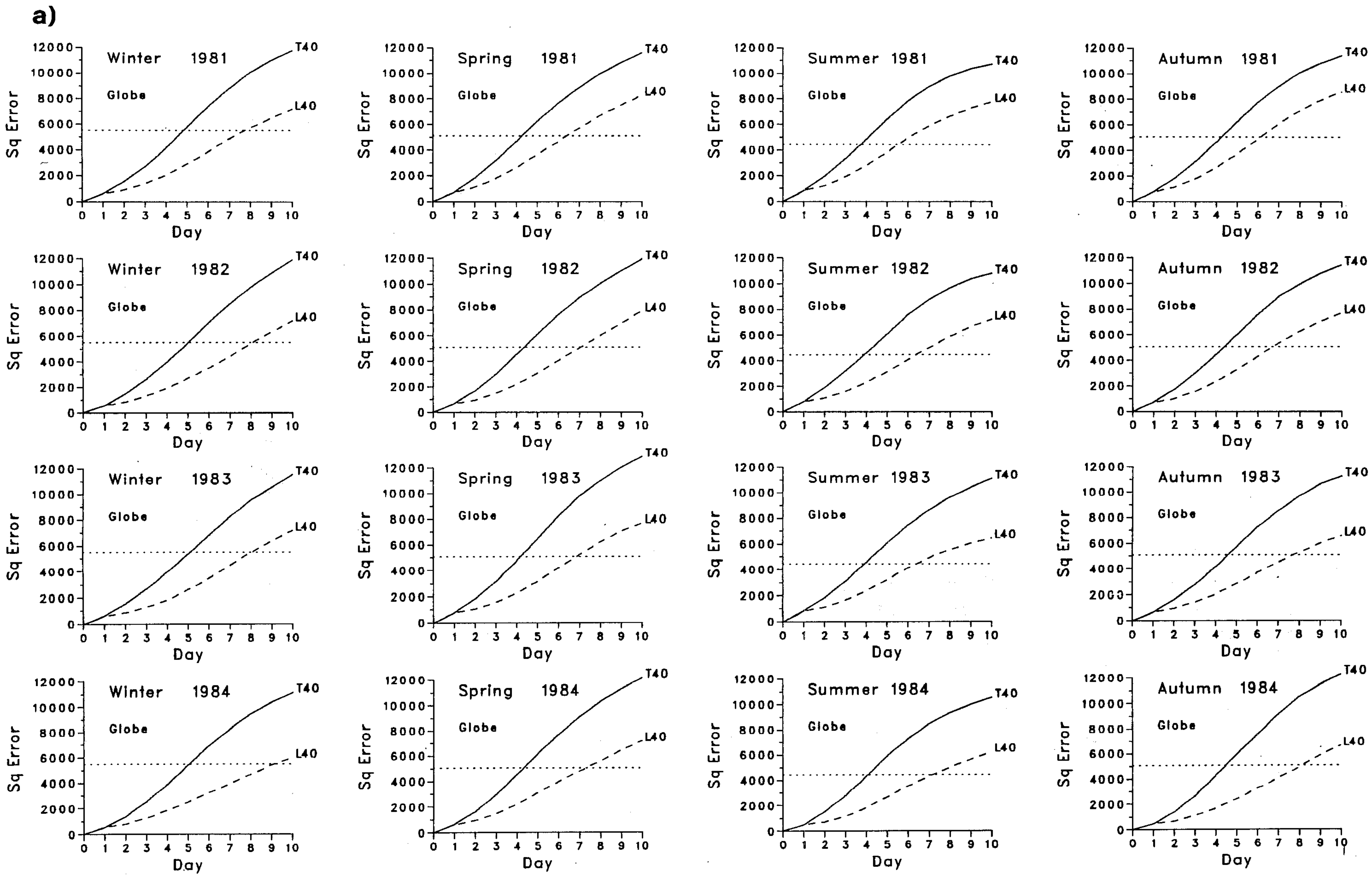

Fig. A.3 a,b,c Lorenz curves for the globe (T40 representation).

b)

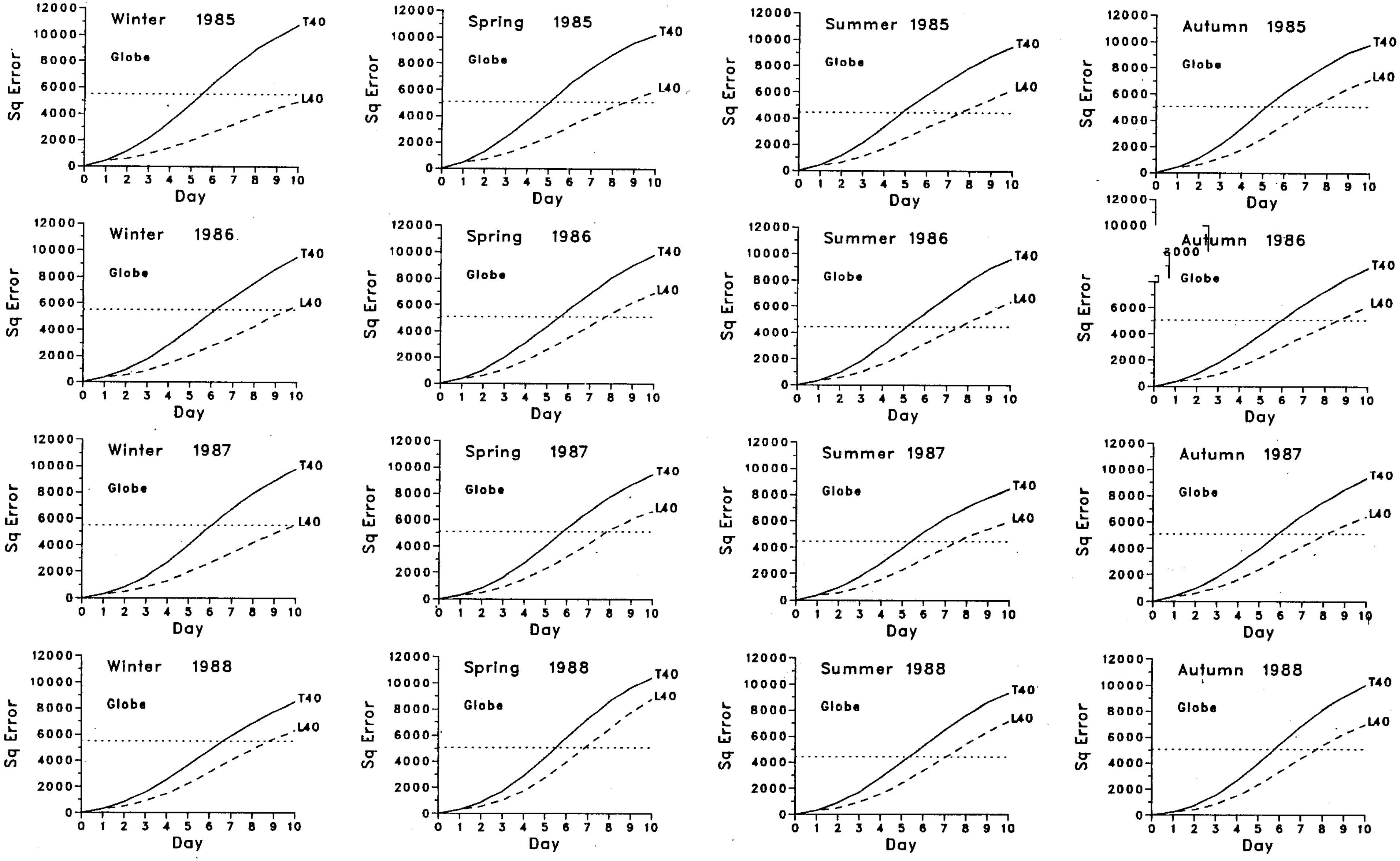
Winter 1985
Spring 1985
Summer 1985
Autumn 1985
Winter 1986
Spring 1986
Summer 1986
Autumn 1986
Winter 1987
Spring 1987
Summer 1987
Autumn 1987
Winter 1988
Spring 1988
Summer 1988
Autumn 1988
Globe
T40
L40
Sq Error
Day
0
2000
4000
6000
8000
10000
12000
0 1 2 3 4 5 6 7 8 9 10

Fig.A.3 b

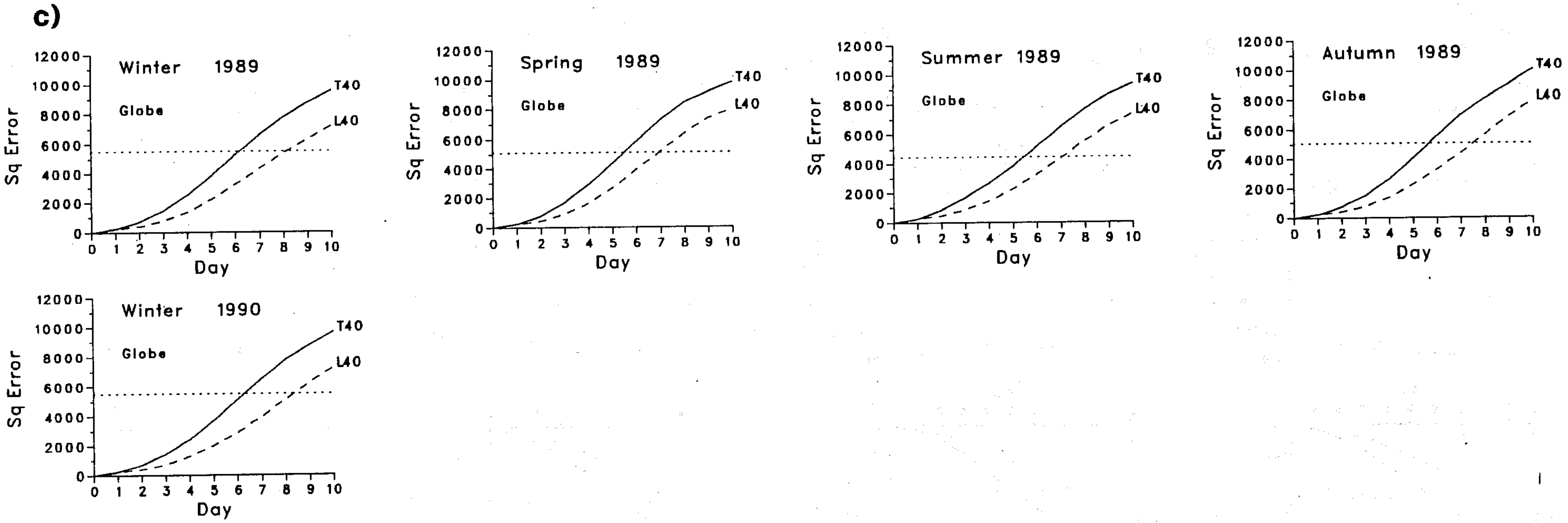
c)
Winter 1989
Globe
Spring 1989
Globe
Summer 1989
Globe
Autumn 1989
Globe
Winter 1990
Globe
Sq Error
12000
10000
8000
6000
4000
2000
0
Day
0 1 2 3 4 5 6 7 8 9 10
T40
L40

Fig.A.3 c

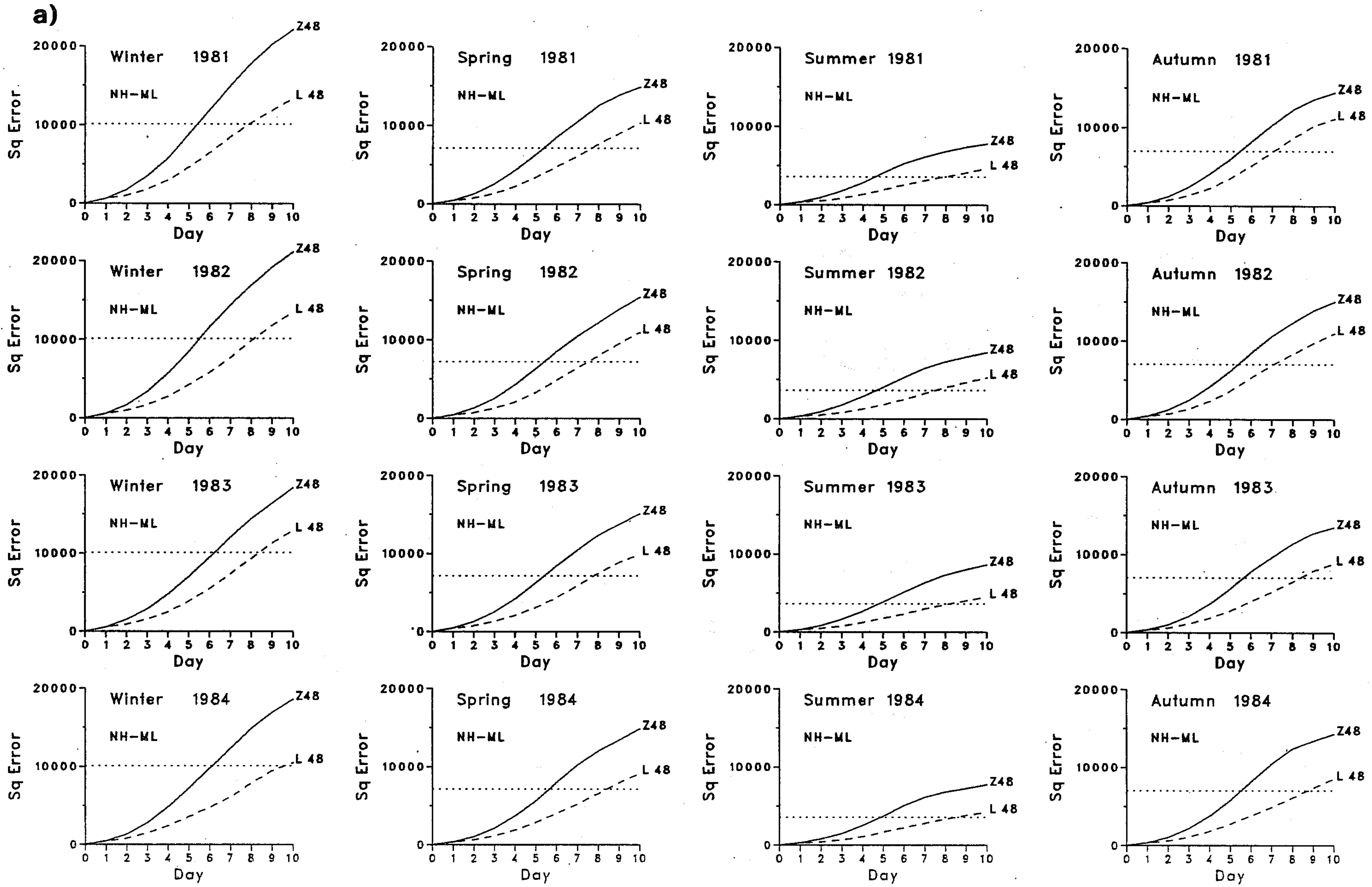

Fig. A.4 a,b,c Lorenz curves for the Northern Hemisphere mid-latitudes.

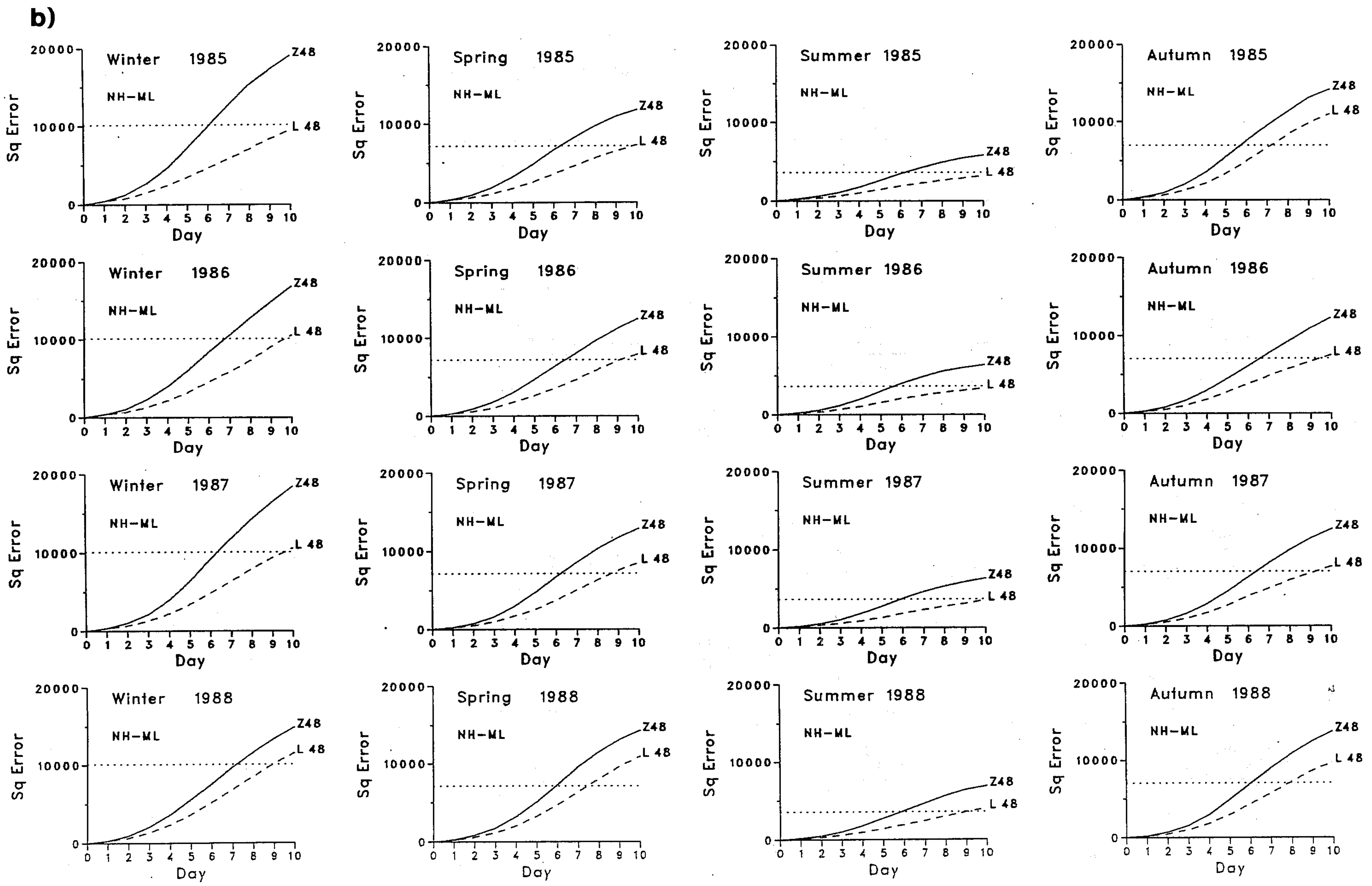
b)
Winter 1985
NH-ML
Spring 1985
NH-ML
Summer 1985
NH-ML
Autumn 1985
NH-ML
Winter 1986
NH-ML
Spring 1986
NH-ML
Summer 1986
NH-ML
Autumn 1986
NH-ML
Winter 1987
NH-ML
Spring 1987
NH-ML
Summer 1987
NH-ML
Autumn 1987
NH-ML
Winter 1988
NH-ML
Spring 1988
NH-ML
Summer 1988
NH-ML
Autumn 1988
NH-ML
Sq Error
20000
10000
0
Day
0 1 2 3 4 5 6 7 8 9 10
Z48
L 48

Fig.A.4 b

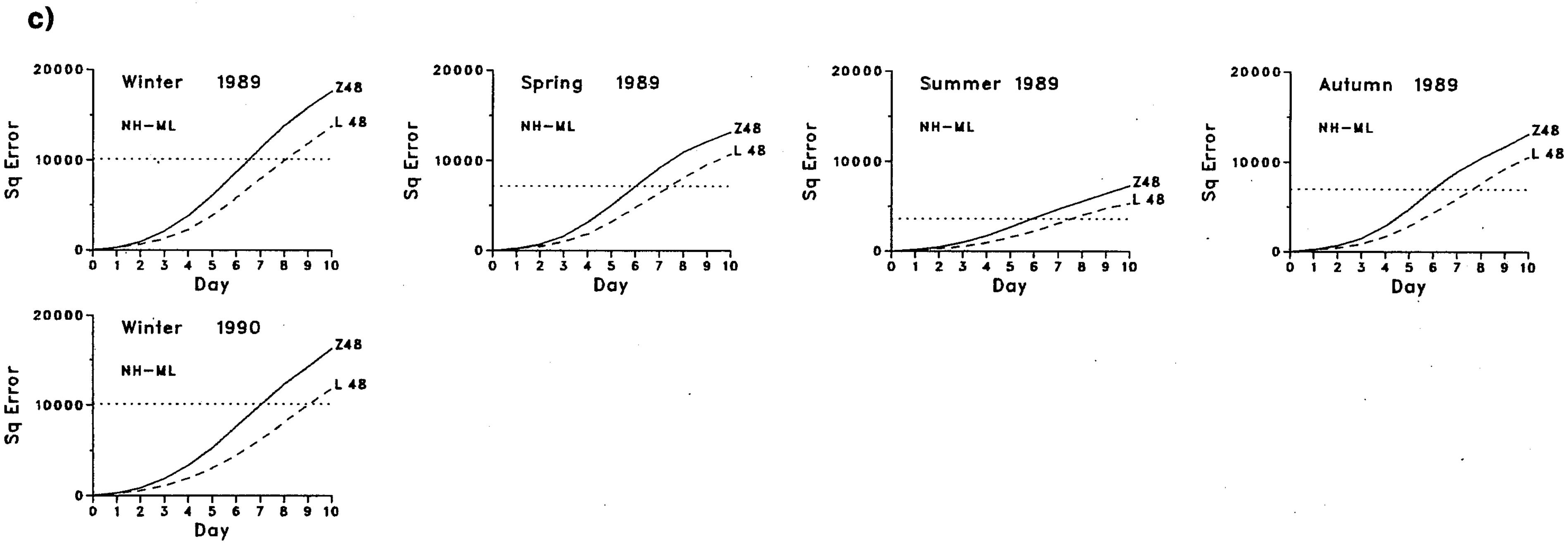
c)
Sq Error
20000
10000
0
Winter 1989
NH-ML
Z48
L 48
0 1 2 3 4 5 6 7 8 9 10
Day
Spring 1989
NH-ML
Z48
L 48
Summer 1989
NH-ML
Z48
L 48
Autumn 1989
NH-ML
Z48
L 48
Winter 1990
NH-ML
Z48
L 48

Fig.A.4 c

Appendix B: Lorenz files

1. ECFILE

All seasons with the 500 hPa height field are available from winter 1980/81 until winter 1989/90. All files are stored on CFS. The path names are straightforward, for instance:

spring 1983 : path =/nem/cos/lorenz/archives/z500hPa/spring 83
winter 1985/86 : path =/nem/cos/lorenz/archives/z500hPa/winter 86

2. File Description

Each file contains 1 season (=100 days),
each day consists of 11 fields:
first the analysis, then the 10 forecasts verifying on the same date.

Each field consists of 1724 words.

The first two words of each field contain the dates of the analysis and the forecast (integers).

The next 1722 words contain the T40 spectral coefficients
(1722 = (ntrunc+1)*(ntrunc+2) ; ntrunc = 40)

3. Example to read one season

```
nxx,stcra.
account,ecxxxx.
ecfile (fn=get,dn=ft10,path=/nem/cos/lorenz/archives/z500hPa/spring87)
cft.
ldr.
      program contrl
      real buf(1724)
      integer ibuf(1724)
      equivalence (buf(1),ibuf(1))
      do 150 iday=1,100
      do 150 ifor=1,11
        read(10) (buf(i),i=1,1724)
 150  continue
      stop
      end
```