

A spectral view on the atmospheric intraseasonal variability in the extratropics: ECMWF re-analyses versus operational analyses

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ABSTRACT

Various aspects of the atmospheric intraseasonal variability in the extratropics as given by the ECMWF re-analyses are investigated. By comparing these results with those obtained from the original operational analyses by ECMWF, we assess the differences between these two data sets, considering both the long-term mean values and the temporal evolution of these differences. The atmospheric intraseasonal variability in the extratropics is larger in the re-analyses than in the operational analyses, to a small extent in the Northern and to a large extent in the Southern Hemisphere. These differences are mainly related to the contributions of the transient fluctuations to the intraseasonal variability. Their magnitude depends, however, on the spatial and temporal scales of the transient disturbances with the largest differences associated with the longest (zonal wavenumbers 1–3) and the smallest differences associated with the shortest planetary scale waves (zonal wavenumbers 6–9). Over the period of investigation the magnitude of the differences between the two data sets varies only slightly in the Northern but considerably in the Southern Hemisphere with small differences between the re-analyses and the operational analyses in the beginning of the re-analyses and after 1985 but large ones in the early 1980's. These temporal variations of the differences can be assigned to both changes in the data coverage and changes in the analysis-forecasting-system at ECMWF.

1. Introduction

A variety of phenomena on different spatial and temporal scales contribute to the atmospheric intraseasonal variability in the extratropics (Blackmon, 1976). Baroclinic disturbances such as travelling cyclones with a typical lifetime of a few days affect the day-to-day variability of the atmosphere, while large-scale flow anomalies such as blocking anticyclones or cutoff lows (Rex 1950a,b; Blackmon et al., 1986) may last for several weeks. These transient fluctuations on different scales are, however, influencing each other via non-linear interactions, affecting particularly each other's

temporal evolution and the spatial distribution (Mullen, 1987). Moreover, variations of the amplitude of the stationary planetary waves contribute to the intraseasonal variability.

A method to distinguish the contributions of the transient fluctuations on different spatial and temporal scales to the atmospheric intraseasonal variability is the wavenumber-frequency analysis (Hayashi, 1982). This technique provides also a partition of the variance due to transient fluctuations into an eastward and a westward propagating component, a standing component and the noise introduced by errors in the observations or in the analysis scheme (Deland, 1972).

About two decades ago there have been numerous studies of wavenumber-frequency spectra

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computed from observational data (Pratt and Wallace, 1976; Fraedrich and Böttger, 1978; Mechoso and Hartmann, 1982; Speth and Madden, 1983) and also some studies based on model data (Pratt, 1979; Hayashi and Golder, 1977, 1983). These models of the first generation of general circulation models (GCMs) have had numerous deficiencies, but in recent years the wavenumber-frequency analysis has also been applied to data originating from present-day state-of-the-art models, which are able to simulate the present-day climate quite realistically. Hayashi and Golder (1993) studied, for instance, the nature of the atmospheric intraseasonal variability in the tropics employing a state-of-the-art model, while Marcus et al. (1994, 1996), Doblas-Reyes et al. (1998) and May (1998, 1999) (the latter one referred to as M99 hereafter) computed wavenumber-frequency spectra of the atmospheric intraseasonal variations in the extratropics. Doblas-Reyes (1998) and May (1998) found that the wavenumber-frequency spectra obtained from their GCMs depend on the horizontal resolution of the respective model. In the case of the ECHAM4 model it became obvious that the resolution, at which the model had been tuned, generally gave the best results compared to observational data (May, 1998). Further, several studies have found observational evidence that the spectral distribution of the intraseasonal variability in the Northern Hemisphere extratropics (Hansen et al., 1989; Fraedrich and Müller, 1993, M99) as well as in the Southern Hemisphere midlatitudes (M99) is affected by the El Niño/Southern Oscillation (ENSO) phenomenon, indicating the sensitivity of the spectral distribution to forcing mechanisms external to the atmosphere. Obviously the wavenumber-frequency analysis is a method suitable to identify both internally and externally forced variations of the spectral distribution of the atmospheric intraseasonal variability.

In order to create homogeneous high-quality atmospheric data sets for numerous applications in earth sciences several of the major weather forecasting centres have performed so-called re-analyses, as originally proposed by Bengtsson and Shukla (1988). That are the European Centre for Medium-Range Weather Forecasts (ECMWF) (Gibson et al., 1997), the National Center for Environmental Prediction in collaboration with

the National Center for Atmospheric Research (Kalnay et al., 1996) and the Data Assimilation Office of NASA's Goddard Space Flight Center (Schubert et al., 1993). Each of these centres has undertaken a comprehensive analysis of global observations based on a four-dimensional data assimilation system with a realistic GCM to integrate space and in situ observations, aiming for internally consistent and homogeneous multivariate data sets describing the earth's climate system.

In this paper, we consider one of these data sets, namely the ECMWF re-analyses and compare them to the original operational analyses by ECMWF, which reveal numerous inconsistencies and deficiencies in the course of the years (Trenberth, 1992). We will concentrate on the aspects of the atmospheric intraseasonal variability in the extratropics, applying different kinds of analysis, namely an analysis of the overall variance, a wavenumber-frequency analysis as well as a spectral filtering technique. This includes both the comparison of the mean values derived from the operational and the re-analyses and the temporal evolution of the differences between the two data sets. By this, we are able to give a further contribution to the evaluation of the quality of the ECMWF re-analyses.

The paper is organized as follows: In Section 2, we describe the data used in our study. Subsequently the results from an analysis of the overall variance (Section 3) and from a wavenumber-frequency analysis (Section 4) are discussed. In Section 5, we investigate the geographical distribution of the intraseasonal variability. A summary and some concluding remarks follow in Section 6.

2. Data

2.1. ECMWF operational analyses

As for the operational analyses from ECMWF, we use the initialized analyses of the geopotential height in 500 hPa for the period September 1979 through December 1992 (Trenberth, 1992). In this study, we use the data once daily, that is at 00 UTC, whereas the main daily analysis at ECMWF is made at 12 UTC. The data have been truncated to T42 triangular spectral truncation for the purposes of this study.

Since the complex analysis-forecasting-system,

which has been employed to obtain global analyses on the basis of space and in situ observations of various meteorological variables, has experienced numerous changes in the course of the years, the operational analyses reveal a number of inhomogeneities. At ECMWF the analyses are produced using a four-dimensional data assimilation (Bengtsson et al., 1982). This is based on global multivariate analyses at 6-hour intervals, in which information from a first guess, provided by a 6-hour forecast from the numerical weather prediction (NWP) model, is combined with observations using optimum interpolation procedures (Shaw et al., 1987). This is followed by an initialization, which is designed to bring the large-scale fields into balance and to reduce the noise induced by gravity waves (Wergen, 1988). As a consequence, changes in the NWP model as well as changes in the data assimilation system and the availability of data can strongly affect the resulting analyses. In the course of the years more and more data derived from satellite measurements have been incorporated into the analyses. By this observations from regions with hardly any in situ measurements can be included to a certain extent. The changes in the analysis-forecasting-system have their strongest impact in those regions, where observations are hardly available, in particular for such meteorological variables that cannot be directly observed, but are retrieved from observed variables. Therefore, the divergent wind component as well as the vertical velocity, which is derived from the divergent wind component, are the most sensitive ones to the changes in the analysis-forecasting-system. But also such a meteorological field as the atmospheric humidity, which is very hard to observe, depends crucially on the features of the model. For a detailed discussion of the quality of the ECMWF operational analyses we refer to Trenberth (1992).

2.2. ECMWF re-analyses

As for the ECMWF re-analyses, on the other hand, we use the initialized analyses of the geopotential height in 500 hPa for the period January 1979 through December 1993 (Gibson et al., 1997). The data have been available twice daily (00 and 12 UTC) and have also been truncated to T42 triangular spectral truncation for the purposes of our study. In order to allow for a fair comparison

between the re- and the operational analyses, we also consider a subset of the re-analyses, which includes once daily (00 UTC) data only. In addition to the general description of the ECMWF re-analyses by Gibson et al. (1997), certain aspects of the ECMWF re-analyses have subsequently been investigated in a series of reports, such as the aspects of the re-analysed climate in Källberg (1997) and the evaluation of the hydrological cycle in the re-analyses by Stendel and Arpe (1997).

As the result of a number of tests with different configurations of the analyses-forecasting-system, the following ECMWF re-analyses data assimilation scheme has been selected and used for the 15 years of re-analyses.

- Spectral T106 resolution with 31 vertical hybrid levels.
- Intermittent statistical (optimum interpolation) analysis with 6 hour cycling and no FGAT (First Guess at Appropriate Time).
- One dimensional variational (1D-VAR) physical retrieval of TOVS cloud cleared radiance below 100 hPa and NESDIS operational retrievals above. No TOVS data were used above 100 hPa between 20°N and 20°S.
- Diabatic, non-linear normal mode initialization, 5 vertical modes.
- The Integrated Forecast System (IFS) version of the ECMWF forecast model with 3-dimensional semi-Lagrangian advection.
- Mean orography with a compatible parameterization of the effects of sub-grid orography.
- Prognostic soil temperature and soil moisture with nudging of the moisture from boundary layer atmospheric humidity analyses.
- Prognostic equations for cloud water and ice content and the cloud cover.
- ECMWF operational radiation parameterization with prescribed concentrations of aerosols, CO₂ and O₃ varying geographically and seasonally, the aerosols varying geographically and vertically and the CO₂ held constant.
- ECMWF operational planetary boundary layer parameterization.

For detailed descriptions of the various components of the ECMWF data assimilation and forecasting system we refer to Gibson et al. (1997) and references therein.

The externally prescribed forcing of the

re-analyses, in addition to the observations, comes from the sea surface temperatures and sea-ice cover (Gibson et al., 1997). Except for the horizontal resolution, the ERA assimilation system is identical with the ECMWF operational system used between April 1995 and January 1996.

3. Analysis of variance

3.1. Long-term means

The total variance of the geopotential height field associated with longitudinal and temporal variations can be separated into three different parts: the contributions of the transient cell and of the stationary and transient eddies. For details on the procedure how to obtain these contributions, we refer to Appendix A in M99.

Fig. 1 shows the longitudinal and temporal means of these three contributions to the intraseasonal variance of the geopotential height at 500 hPa for the ECMWF re-analyses (based on both twice and once daily data), as well as for operational analyses, that are mean values for the extratropical regions of both hemispheres over the zones between 40° and 70° northern and southern latitude, respectively. In order to compute the area averages over these zones the estimates at a given latitude have been weighted with the cosine of the latitude. The different data sets are often referred to as ERA and OPA, respectively, in the following text. We distinguish between different seasons, which are defined in the conventional way, that is boreal winter is defined as December, January and February (DJF), spring as March, April and May (MAM), summer as June, July and August (JJA) and fall as September, October and November (SON), respectively. The significance of the differences between (a) the re-analyses with different temporal resolutions and (b) the re-analyses (once daily data) and the operational analyses has been estimated via a two-sided t-test (Essenwanger, 1986), since the mean values of the estimates of the different contributions to the intraseasonal variability are compared.

In the Northern Hemisphere extratropics, we find only small, yet to some extent systematic differences between the ECMWF re-analyses and operational analyses for all the different contributions to the variance (Fig. 1a), but the differences between these two data sets do not exceed the

75%-level of significance in any season. The contributions of the transient eddies are, for instance, larger in ERA than in OPA in all seasons but JJA, while this is the case in DJF and JJA for the stationary waves. As for the transient cell, the contributions to the variance are larger in ERA in DJF and MAM. As a consequence, the total variance obtained from the re-analyses in the Northern Hemisphere extratropics exceeds the operational analyses in all seasons but JJA, when the intraseasonal variability is stronger in OPA. The estimates of the different contributions to the variability reveal a quite substantial amount of interannual variability, which to some extent can be attributed to the ENSO phenomenon (M99). In data-sparse regions the atmospheric response to the ENSO phenomenon may actually depend on the analysis scheme. Model simulations have shown that the impact of both warm and cold ENSO-events on the characteristics of the intraseasonal variability in the extratropics varies for different configurations of a GCM, in particular with regard to changes in the physical parameterizations (M99). The effect of the different temporal resolutions of the re-analyses is only minor, and none of the respective differences is statistically significant.

In the Southern Hemisphere extratropics, on the other hand, things are quite clear (Fig. 1b). Here, all the three contributions to the variance are stronger in ERA than in OPA. In particular the contributions of the transient disturbances are considerably larger in the re-analyses, reaching a significance level of 100%. For the stationary eddies, the differences between the re-analyses and the operational analyses exceed the 75%-level of significance in all seasons but SON. Different to the Northern Hemisphere, where numerous radiosonde data are available (Uppala, 1997), in the Southern Hemisphere extratropics the analyses of the geopotential height field depend to a large extent on the characteristics of the NWP model that is part of the analysis-forecasting scheme at ECMWF as well as on the usage and quality of satellite data. Hence, it is not surprising that the most pronounced differences between the two data sets occur in the Southern Hemisphere, considering the general improvement of the NWP model and of the assimilation scheme as well as the increasing quantity and quality of satellite data over a period of about 17 years. As for the

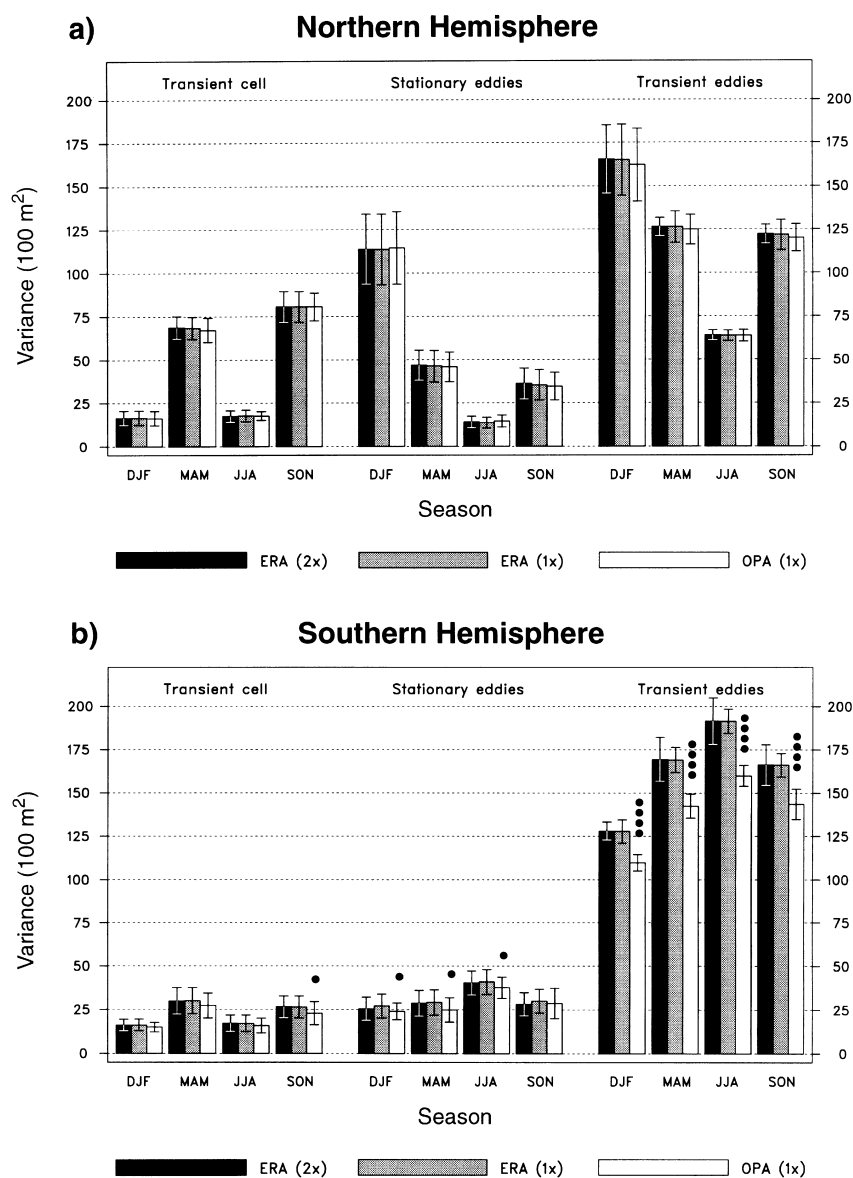


Fig. 1. Long-term means of the contributions of the transient cell, the stationary as well as the transient eddies to the variance of the geopotential height at 500 hPa distinguishing between ERA ($1 \times$ and $2 \times$ daily data, respectively) and OPA ($1 \times$ daily data) for different seasons. The values represent area averages over the zones between 40° and 70° northern (a) and southern latitude (b), respectively. The interannual variations of the various contributions ($\pm \sigma$) are indicated by the bars. The significance of the differences between ERA ($1 \times$) and OPA ($1 \times$) is indicated by the dots. Four dots denote a significance level of more than 99% and one a level of more than 75%.

intraseasonal variability in the extratropics, primarily the transient eddies (representing the combined temporal and longitudinal fluctuations of the geopotential height) are affected by the numer-

ous changes in the analysis-forecasting-system at ECMWF.

The marked differences between the re-analyses and the operational analyses are of practical relev-

ance for the development of GCMs. The ECHAM model is, for instance, characterized by a reduced activity of the transient disturbances in the extratropics, both in the Northern and in the Southern Hemisphere (Fig. 1 in M99), so that the ECHAM model is generally closer to OPA than to ERA. In the Southern Hemisphere the ECHAM model, in particular the latest version (ECHAM4) is actually in rather good agreement with OPA, whereas in the Northern Hemisphere the differences between the model and the two sets of analyses are considerably larger than the deviations between the re-analyses and the operational analyses themselves.

3.2. Temporal evolution

Since the ECMWF analysis-forecasting-system, which has been used to produce the operational analyses, has undergone numerous changes in the course of the years, it is interesting to investigate the temporal evolution of the differences between the re-analyses and the operational analyses. Figs. 2, 3 therefore show time series of the differences between these two data sets for individual seasons, distinguishing between the different contributions to the intraseasonal variability. Here, once daily data have been used for ERA. The estimates have been normalized by the long-term mean values for the respective season (Fig. 1) in order to eliminate the effects of the considerable annual cycle of the different terms (M99).

In the Northern Hemisphere extratropics, where a rather large number of in situ observations, in particular radiosonde data is available (Uppala, 1997), the differences between the ECMWF re-analyses and the operational analyses do not reveal any characteristic change from one year to the next (Fig. 2), and it is very difficult to infer such big changes in the analysis-forecasting-system as the introduction of the T63 spectral model in April 1983, the introduction of the T106 spectral model with substantial changes in the model physics in May 1985 or the introduction of the T213 spectral model in September 1991 (Trenberth, 1992) from the time series. It is interesting to note that for the contributions of the transient eddies the differences are positive (the estimates in ERA exceed those in OPA) almost all of the time (Fig. 2c), whereas negative differences for the stationary eddies are found over most of the time

(Fig. 2b). Especially during the boreal summer season the contributions of the stationary eddies are relatively strong in OPA, as the differences are negative in all the individual summer seasons. The largest differences between -4 and -8% occur during JJA in the periods 1981–85 and 1987–90, respectively. The contributions of the transient eddies, on the other hand, are relatively strong in OPA during summer in the period 1984–86 (Fig. 2c). Apparently during the boreal summer season the analysis of the stationary waves depends much more on the characteristics of the analysis-forecasting-system than for the other seasons, even though about the same number of observations should be available. One should, however, keep in mind that the contribution of the stationary eddies is relatively weak during summer (Fig. 1a), so that during this season deviations with relatively small magnitude have relatively large effects on the estimates on the variability as compared to the other seasons.

In the Southern Hemisphere extratropics, where significantly less radiosonde data are available and, hence, the characteristics of the analysis-forecasting-system are of greater importance than in the Northern Hemisphere, the time series of the differences between the ECMWF re-analyses and the operational analyses reveal an evolution in time (Fig. 3). In the beginning of the period of investigation, i.e., between September 1979 and May 1980, when considerably more radiosonde data were also available in the Southern Hemisphere during and in the aftermath of the First GARP Global Experiment (FGGE) (Uppala, 1997), the differences are generally rather small. Bengtsson et al. (1982) have concluded that the considerable improvement in the data coverage in the tropics and in the Southern Hemisphere during FGGE had made it possible to analyse in great detail weather systems that before had been hardly possible. For the stationary eddies the differences between the two data sets are actually close to zero during this period (Fig. 3b), while for the transient eddies they have about the same magnitude as in the early 1990's (Fig. 3c). It is also for these two contributions to the intraseasonal variability that the time series reveal a positive trend, that is an increase in the magnitude of the differences with the passage of time until 1983 and a negative trend later on. In particular for the stationary eddies the replacement of the old

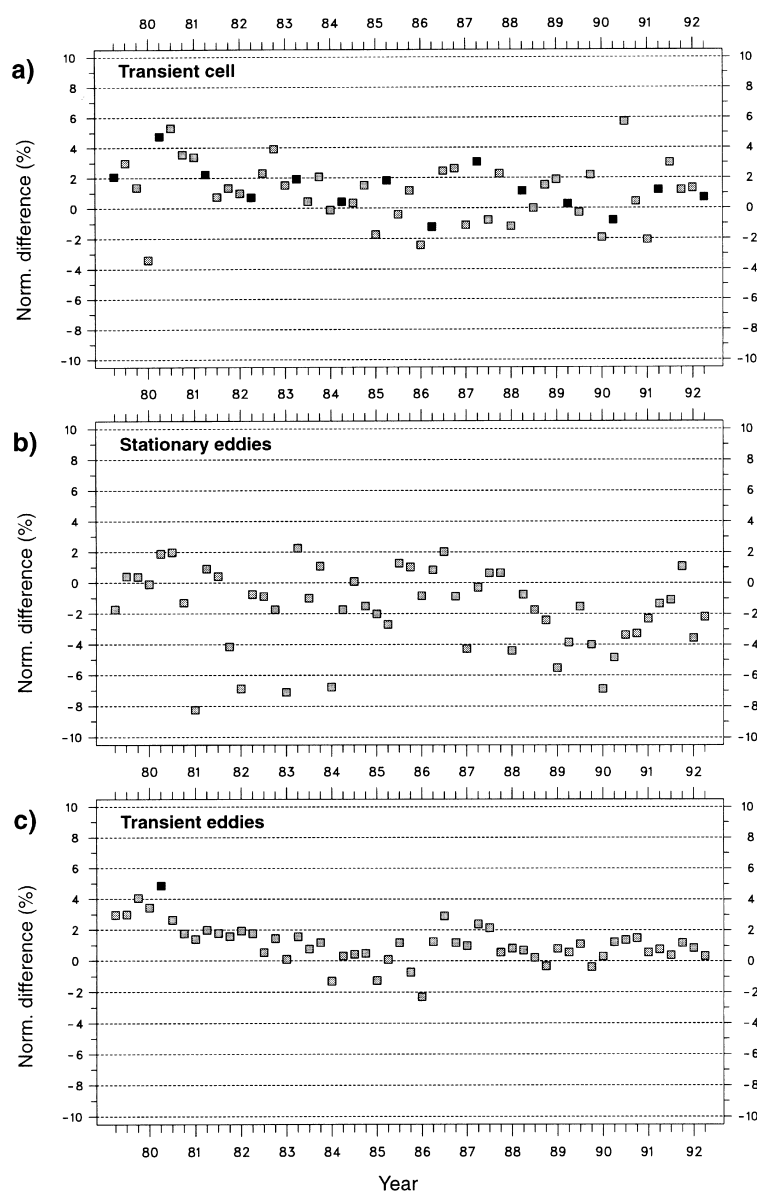


Fig. 2. Normalized differences of the contributions of the transient cell (a), the stationary (b) as well as the transient eddies (c) to the variance of the geopotential height at 500 hPa between the ERA (1 $\times$) and OPA (1 $\times$) for individual seasons. The values represent area averages over the zone between 40° and 70°N. Those values that exceed the 95%-level of significance for the respective season are marked in black. The years are centred at JJA.

ECMWF gridpoint model by the T63 spectral model in April 1983 (Girard and Jarraud, 1982) and the other improvements of the analysis-forecasting-system in the years to follow have lead to a better analysis in the Southern Hemisphere

extratropics (Fig. 3b). Part of this progress may be related to the increased use of satellite data during the mid-1980's, in particular in 1985, when data from the TIROS Operational Vertical Sounder (TOVS) and satellite derived temper-

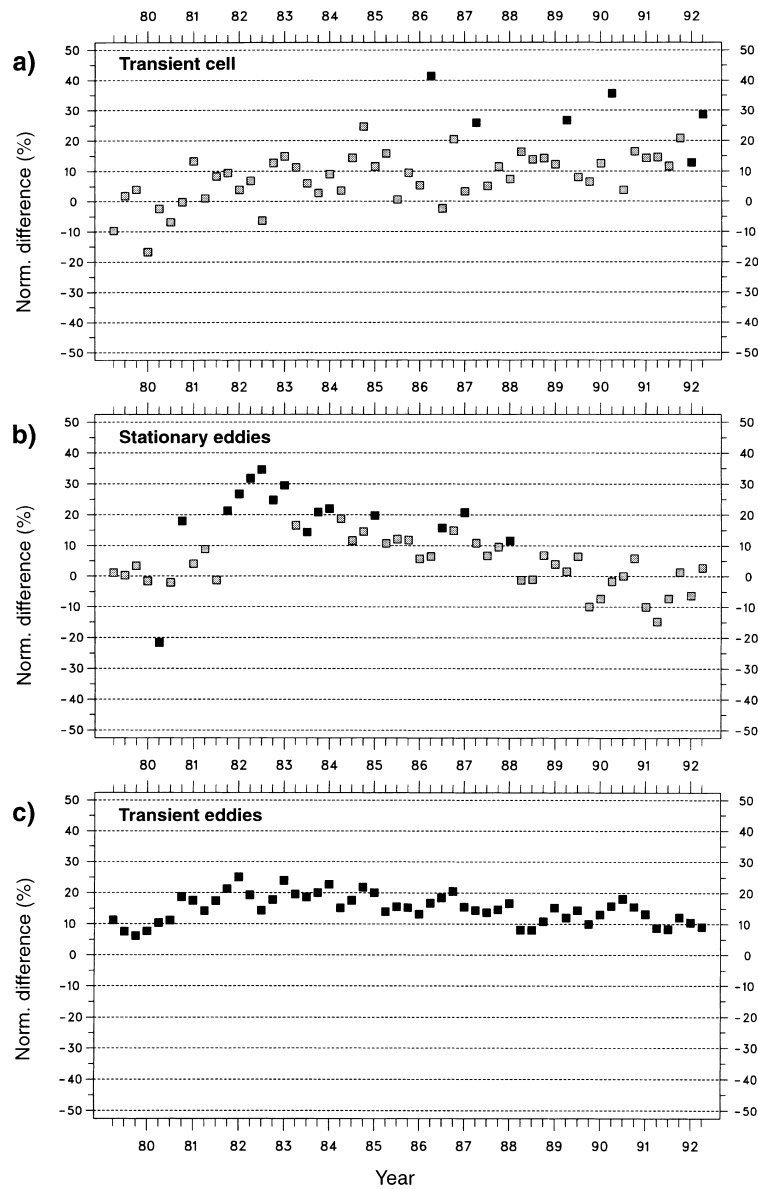


Fig. 3. As Fig. 2, but for the Southern Hemisphere (40°–70°S).

atures have been included in the operational analyses. This trend can, however, not be found for the transient cell (Fig. 3a). Here the time series shows a slight increase of the differences between the two data sets over the entire period of investi-

gation, indicating that the NWP model used in the re-analyses system is characterized by larger temporal variations of the zonal mean geopotential height than the T106 and T213 spectral models in use after 1985.

4. Wavenumber-frequency analysis

In order to characterize the contributions of the transient eddies to the atmospheric intraseasonal variability by their longitudinal and temporal scales, we perform a wavenumber-frequency analysis of the contributions of the transient eddies to the variance of the geopotential height at 500 hPa. The method, originally developed by Hayashi (1971) and later refined by Pratt (1976), is described in further detail in Appendix B in M99. We will concentrate on the local winter seasons, since the activity of the transient disturbances in the extratropics is strongest in these seasons (Fig. 1). Here one should, however, note that the characteristics of the wavenumber-frequency spectra vary by season, that is for both the spectral distribution onto certain regimes and the magnitude (May, 1994).

4.1. Northern Hemisphere

4.1.1. Long-term means. In the following, we show variance spectra derived from the ECMWF re-analyses (twice daily data) as well as from the operational analyses. The estimates represent the long-term means computed from the two data sets. In order to compute the area averages over the zone between 40° and 70° northern and southern latitude, respectively, the spectral estimates at a given latitude have been weighted with the cosine of the latitude. The comprehensive presentation for each data set is double-logarithmic with the period on the abscissa and the zonal wavenumber ranging from 1 to 10 on the ordinate. The spectral densities have been multiplied by the wavenumber and frequency in order to emphasize spectral peaks.

Fig. 4 shows the variance spectra in the Northern Hemisphere midlatitudes obtained from the two data sets in boreal winter. For each data set the total spectrum gives a fair amount of variability for all the wavenumbers and periods shown, indicating three prominent planetary wave regimes. On time scales longer than 10 days, which will be referred to as the low-frequency part of the spectrum, the ultra-long planetary waves at zonal wavenumbers 1, 2 and 3 give major contributions to the intraseasonal variability. On time scales shorter than 6 days, the high-frequency part of the spectrum, the variability is mainly caused by

the baroclinic waves at wavenumbers 6 and higher. On intermediate time scales between 6 and 10 days the long planetary waves at wavenumbers 4 and 5 give major contributions to the intraseasonal variability. While the variance on intermediate and short time scales is mainly due to propagating disturbances, in the low-frequency part of the spectrum the propagating and standing waves contribute to the same extent to the total variance. As for the spectral distribution, the variance spectra for the Northern Hemisphere are in good agreement with those of Fraedrich and Böttger (1978) and Hansen et al. (1989), whose spectra were based on different data. But with respect to the magnitude the standing and the propagating variance spectra obtained by Fraedrich and Böttger indicate more (standing) and less (propagating) variability on time scales longer than 10 days, whereas in Hansen et al. (1989) these spectra are also with regard to the magnitude in good agreement with the spectra shown here. The overestimation of the standing variance in Fraedrich and Böttger (1978) is related to the fact that their estimates of the standing variance also include the noise (Hansen et al., 1989).

The variance spectra obtained from the ECMWF re-analyses and the operational analyses are very similar, considering both the spectral distribution onto the three prominent regimes and the magnitude. The only difference is the relatively high energy at the smallest scales (periods of 2–4 days at zonal wavenumbers 7–10) to be seen in the standing variance spectrum obtained from the operational analyses. This difference reflects the aliasing effect in the frequency domain caused by the fact that the operational analyses have been available only once daily (Priestley, 1981). This effect is primarily visible in the standing variance spectrum, since in this case the error compared to the absolute value of the variance is much stronger than for the propagating variance spectrum.

In order to compare the results obtained from the different data sets directly, we present in Fig. 5 the variance spectra for all data sets, that are the ECMWF re-analyses (once and twice daily data) and the operational analyses. We distinguish between the 3 different wave regimes identified earlier, classifying ultra-long (zonal wavenumbers 1–3), long (wavenumbers 4–5) and short planetary wave (wavenumbers 6–9) regimes. In addition the contributions of all planetary scale waves (wave-

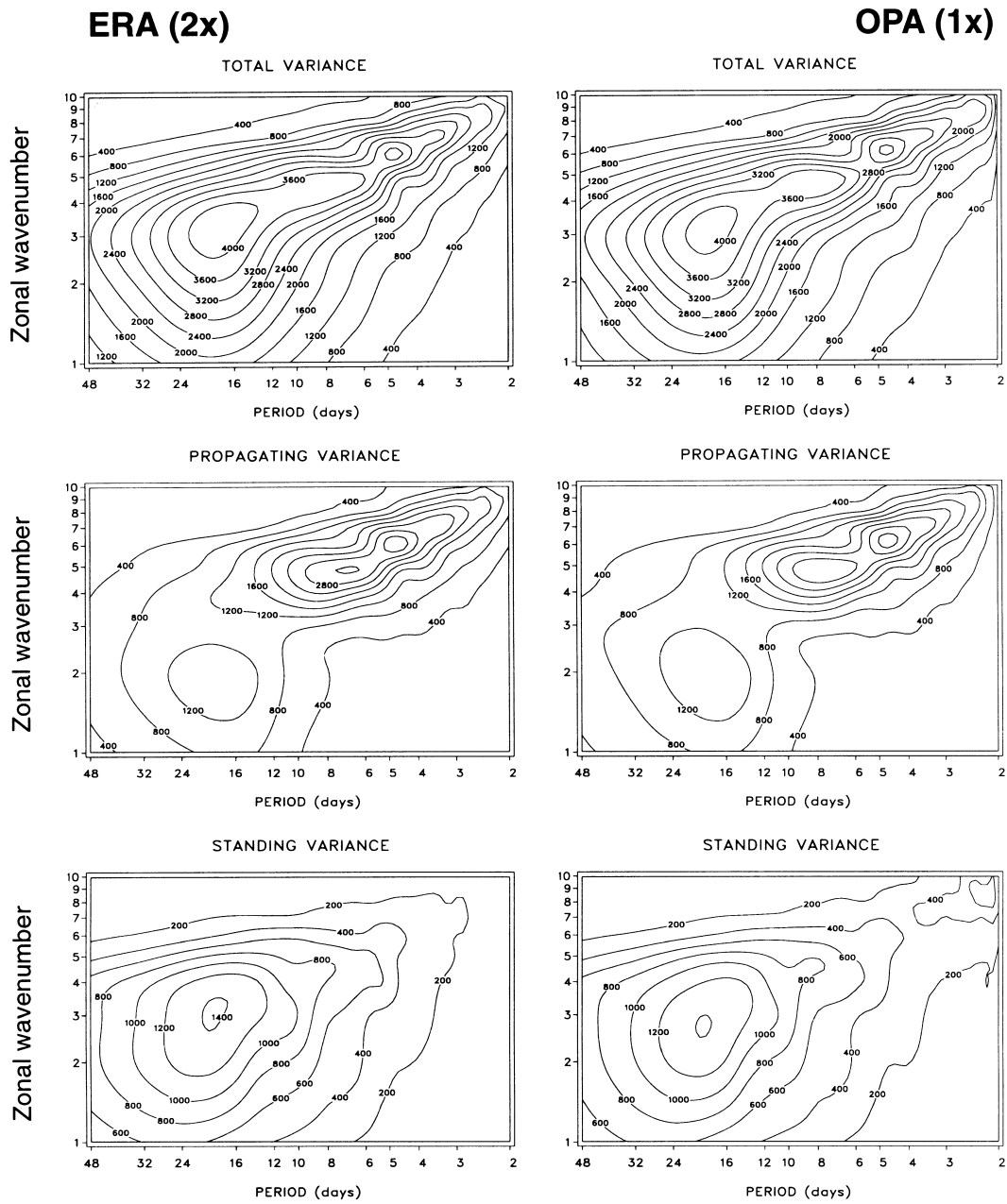


Fig. 4. Variance spectra of the geopotential height at 500 hPa during boreal winter (DJF) in 40°–70°N obtained from ERA (2×; left column) and OPA (1×; right column). The spectral estimates are multiplied by wavenumber and frequency. The contour interval is 400 m² for the total and propagating variance and 200 m² for the standing variance.

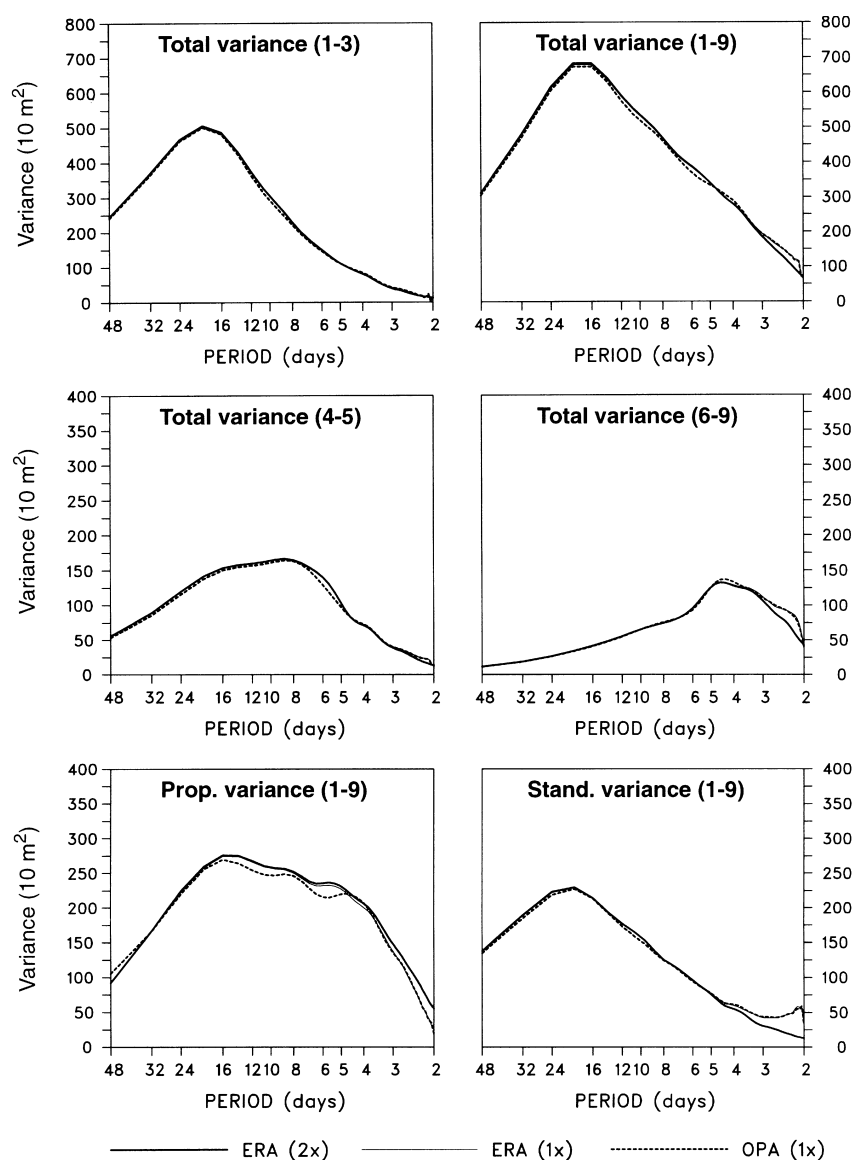


Fig. 5. Variance spectra of the geopotential height at 500 hPa during boreal winter (DJF) in 40°–70°N obtained from ERA (1× and 2×) and OPA (1×) for different planetary wave regimes: ultra-long (1–3), long (4–5), short (6–9) and all planetary scale waves (1–9). The spectral estimates are multiplied by frequency.

numbers 1–9) are given. In these representations the spectral densities have been multiplied by the frequency. By comparing the spectra based on the re-analyses at different temporal resolutions, we are able to assess the effect of aliasing on the variance spectra.

Apparently the somewhat smaller contribution

of the transient eddies to the intraseasonal variability in the Northern Hemisphere extratropics during the boreal winter season in OPA, which was already revealed by the analysis of variance (Fig. 1a), comes from the time scales longer than 6 days, which are associated with the ultra-long (1–3) and the long waves (4–5) (Fig. 5). On the

short time scales below 6 days associated with the short planetary scale waves (6–9), on the other hand, the re-analyses and the operational analyses give the same contributions. But it is this wave regime, where aliasing causes an artificial overestimation of the variance in particular on time scales shorter than 3 days. This is also the case for the standing variance spectrum, whereas for the propagating variance the aliasing effect leads to an underestimation of the variance at the high-frequency end of the spectrum. But since the effect is stronger for the temporal variation of the amplitudes of the standing waves than for the propagating waves, it results in an overall overestimation of the variance. The propagating variance spectra clearly reveal the underestimation of the variance in the operational analyses on the long time scales between 6 and 24 days associated with a weaker activity of the ultra-long as well as the long waves (not shown here), while for the standing variance a slight underestimation of the variance on all temporal scales longer than 6 days is found.

4.1.2. Temporal evolution. In order to investigate the temporal evolution of the differences between the two data sets, time series of the differences of the contributions of the transient eddies between the ECMWF re-analyses (once daily data) and the operational analyses during boreal winter are shown in Fig. 6. We distinguish between the estimates obtained from the analysis of variance (Section 3) and from the total variance spectra for various planetary wave regimes.

Apparently the two methods lead to similar estimates of the differences between the two data sets for most of the time, that is for all years but 1982, i.e., the winter 1982/83. In some years the analysis of variance gives a somewhat larger value and in some a somewhat smaller value than the wavenumber-frequency analysis. This means that in some years also the transient fluctuations on those relatively small spatial scales, which are not covered by the zonal wavenumber 9 and smaller, give rise to differences and in some years counteract the differences associated with the fluctuations on planetary scales. The boreal winter 1982/83 is also untypical from another point of view, since the spectral analysis gives a pronounced negative difference between the two data sets during this particular season. This discrepancy is mainly accounted for by peculiarities on the very large

spatial scales of the ultra-long waves (1–3). The long waves (4–5), on the other hand, reveal the opposite behaviour, while the short planetary scale waves (6–9) also show an overestimation of the variance in OPA for this particular winter. Since there have not been any changes in the analysis-forecasting-system at that time, this indicates that something strange must have happened during this period with presumably a number of erroneous observations leading to very large abrupt changes in the analyses in very large areas from one to day to the other. The inspection of the time series of the total values of the different contributions to the variance for the two data sets (not shown here) leads to the conclusion that the error has presumably occurred in OPA, since for this particular season the difference between the estimates obtained via the analysis of variance and via the spectral analysis is larger in OPA than in ERA. The differences do not show a tendency to decrease in the course of the years as the analysis-forecasting-system is improved and gets more advanced. The largest differences occur, however, in the first three years, when the old gridpoint model was in use, but rather large differences can also be found in 1986 and 1987 after the T106 spectral model with 19 vertical levels has been implemented.

Fig. 7 shows the differences of the total variance spectra obtained from the two data sets for individual boreal winter seasons for the various planetary wave regimes. Please note, that the values presented in Fig. 6 actually are the time-integrals of the curves shown in this figure. As for the contribution of all planetary scale waves, we find by and large positive differences for all years but 1982, when the curve exhibits a rather irregular behaviour shifting from considerable negative differences to smaller negative and even positive values at different periods (Fig. 7a). Noteworthy are also the relatively large (positive) differences in the low-frequency part of the spectrum in the winter 1979/80 and on time scales between 4 and 10 days in 1985/86. The discrepancy in 1979 is related to the ultra-long waves, while in 1985 it is accounted for by the so-called synoptic waves (combining the long (4–5) and the short planetary scale waves (6–9)) on the respective time scales (not shown here). Considering the individual wave regimes, the differences also illustrate, how untypical the estimates of the contributions of the

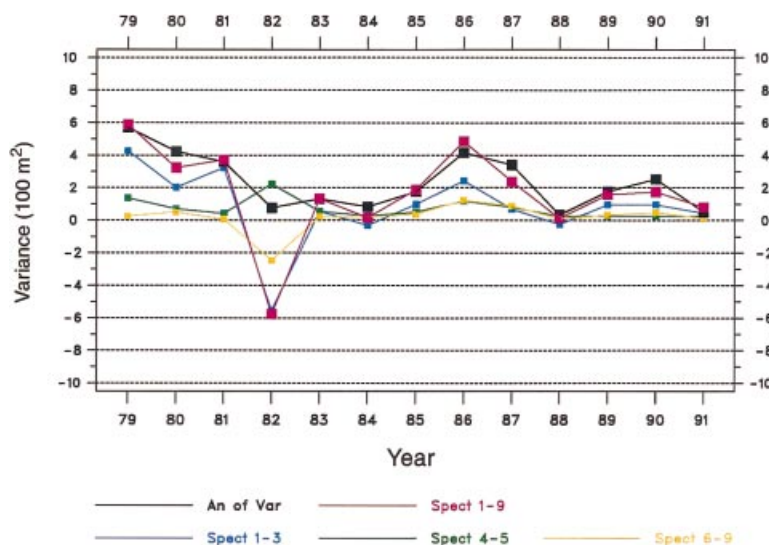


Fig. 6. Differences of the contributions of the transient eddies to the variance of the geopotential height at 500 hPa distinguishing between ERA ($1 \times$) and OPA ($1 \times$) for individual boreal winter seasons (DJF). The dates of the years "79", "80", etc. indicate the winters 1979/80, 1980/81, etc. The values represent area averages over the zone between 40° and 70°N . The estimates have been obtained via an analysis of variance and a wavenumber-frequency analyses distinguishing between different planetary wave regimes.

transient eddies to the intraseasonal variability in the winter 1982/83 really are: As for the ultra-long waves, the variance is overestimated in the operational analyses on all temporal scales (Fig. 7b). The differences and, hence, the variance in OPA are also rather large on time scales shorter than 10 days, where these waves actually should not give such a strong contribution to the intraseasonal variability (Fig. 5). The synoptic waves, on the other hand, give rather large differences at the low frequencies, indicating unusually large contributions to the variability on these time scales in OPA. The synoptic waves are also associated with the positive overall difference indicating an underestimation of the variance in OPA at a period of about 6 days (Fig. 7a).

4.2. Southern Hemisphere

4.2.1. Long-term means. In Fig. 8 the variance spectra in the Southern Hemisphere extratropics derived from the two data sets in austral winter are given. For each data set the total spectrum gives a fair amount of variability for all the wavenumbers and periods shown, but in contrast to the Northern Hemisphere only two prominent planetary wave regimes appear. On time scales

shorter than 6 days the variability is mainly caused by the planetary waves at zonal wavenumbers 5, 6 and higher, whereas on time scales between 6 and 16 days the long planetary waves at wavenumbers 3 and 4 give major contributions to the intraseasonal variability. The variance on these scales is more than twice that in the Northern Hemisphere in boreal winter. The ultra-long waves at wavenumbers 1 and 2 contribute about one third less to the intraseasonal variability than in the Northern Hemisphere. The propagating disturbances are mainly responsible for these inter-hemispheric differences. The propagating variance spectrum also exhibits the pronounced peaks on intermediate time scales at wavenumber 4 and on shorter temporal scales at wavenumber 5. The standing variance spectrum reveals enhanced variability at wavenumber 3, whereas the ultra-long waves at wavenumber 1 and 2 do not contribute as much to the standing variance as in the Northern Hemisphere. The variance spectra for the Southern Hemisphere are in general agreement with those shown in Fraedrich and Kietzig (1983) and with spectra of the sea-level pressure in Mechoso and Hartmann (1982). In Fraedrich and Kietzig (1983), the main peak in the propagating

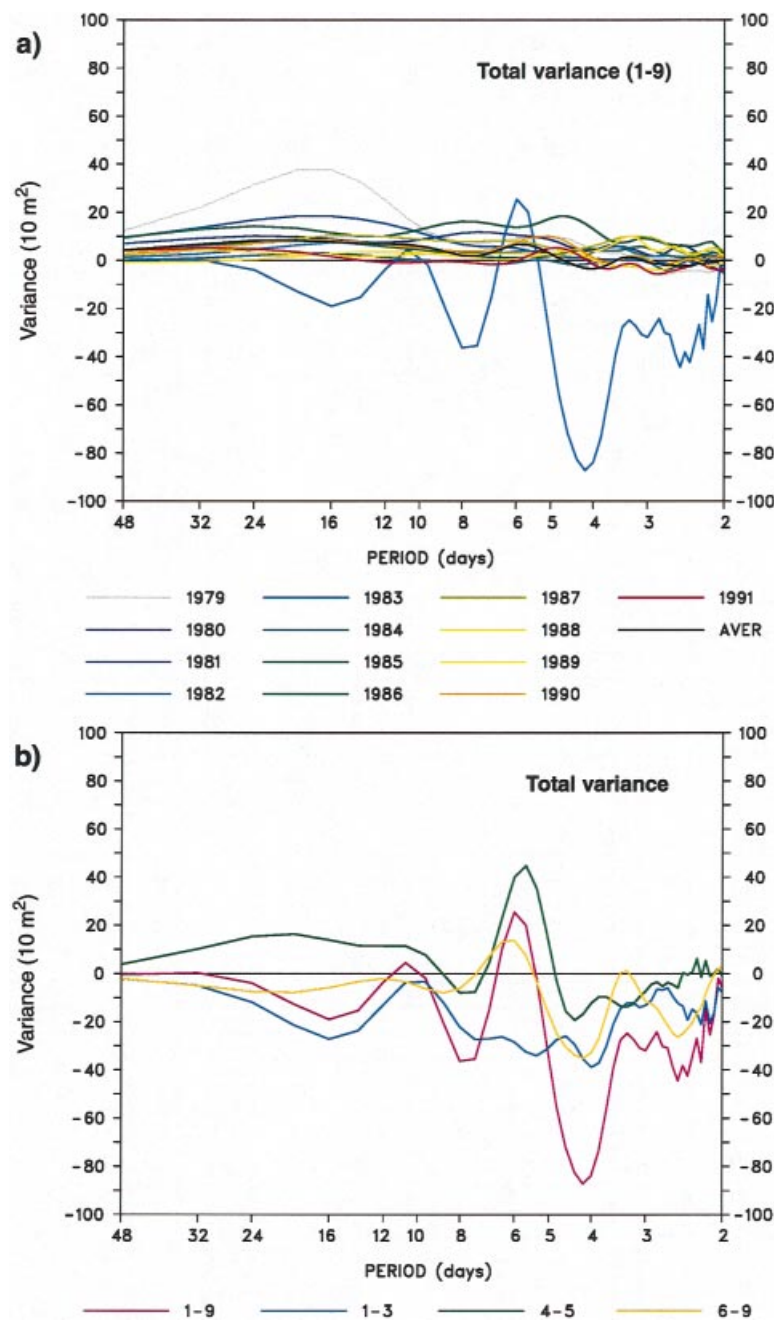


Fig. 7. Differences of the contributions of the total variance spectra of the geopotential height at 500 hPa between ERA ($1 \times$) and OPA ($1 \times$) for individual boreal winter seasons (DJF) (a) as well as the differences for the winter 1982/83 distinguishing between different planetary wave regimes (b). The values represent area averages over the zone between 40° and 70°N . The estimates have been obtained via a wavenumber-frequency analyses distinguishing between different planetary wave regimes. The spectral estimates are multiplied by frequency. The dates of the years "1979", "1980", etc. indicate the winters 1979/80, 1980/81, etc.

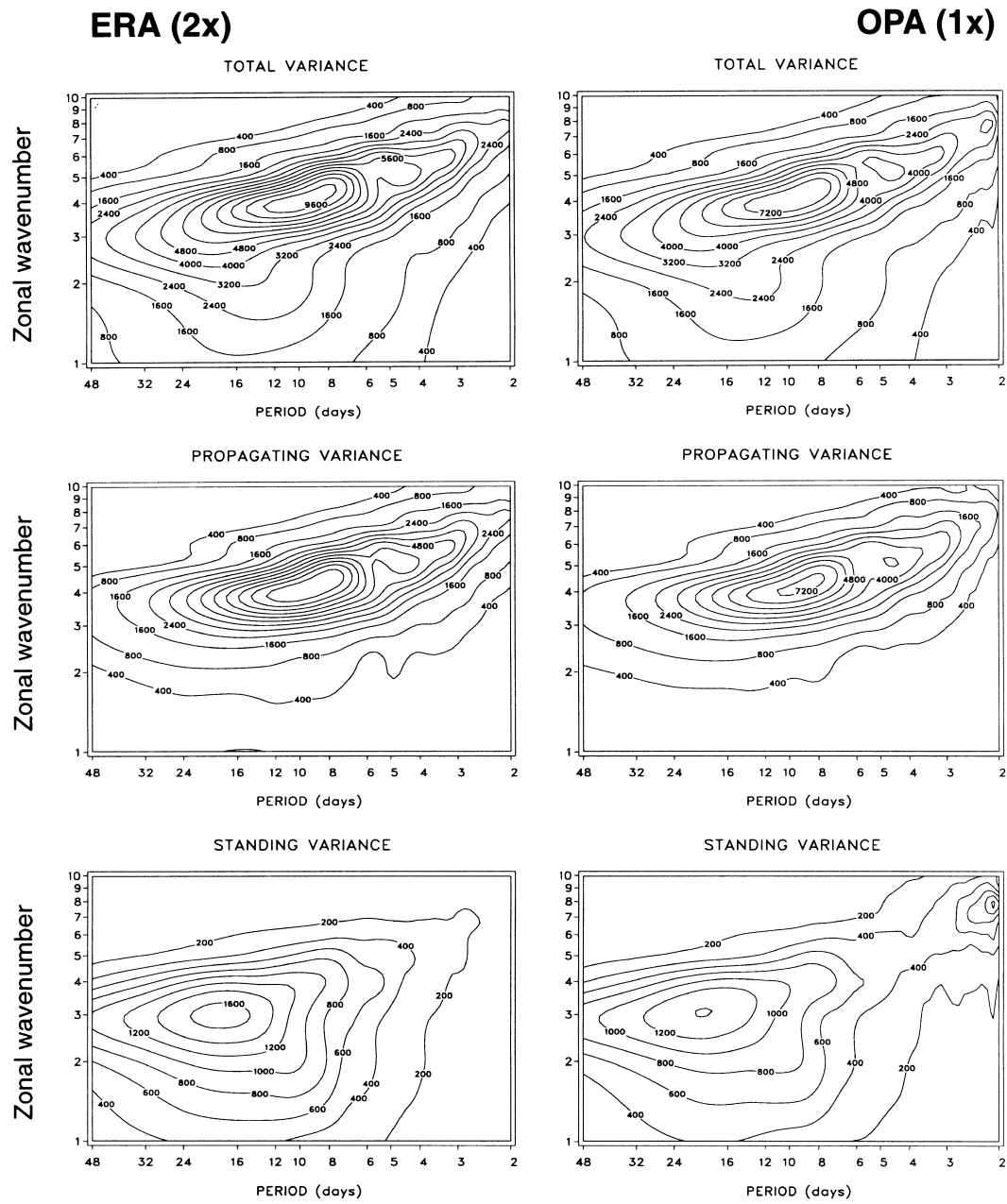


Fig. 8. As Fig. 4, but for the Southern Hemisphere (40° – 70° S) during austral winter (JJA). The contour interval is 800 m^2 for the total and propagating variance (the 400 m^2 contour line is indicated as well) and 200 m^2 for the standing variance.

variance spectra at zonal wavenumber 4 occurs at a somewhat longer period of about 12 days compared to 10 days in ERA (Fig. 8). This may be related to the fact that Fraedrich and Kietzig (1983) compute spectra at 50°S, while here averages over the zone between 40 and 70°S are presented. The spectral distributions vary, however, with latitude (Mechoso and Hartmann, 1982). Moreover, the spectral distributions may undergo low-frequency variations. In the period 1980 through 1983 also the wavenumber-frequency spectra based on OPA reveal, for instance, a peak at a period of about 12 days (Hansen et al. 1989). The differences between the Northern and the Southern Hemisphere can be attributed to the different topographic forcing in the two hemispheres, as was pointed out by Hayashi and Golder (1983).

The variance spectra obtained from the ECMWF re-analyses and the operational analyses are very similar with regard to the spectral distribution onto the two prominent regimes, but the magnitude is significantly larger in ERA. The total variance spectra give, for instance, maximum values of about 9600 m² in ERA and 7200 m² in OPA, respectively. Moreover, aliasing is a more severe problem in the Southern Hemisphere than in the Northern Hemisphere extratropics, since the artificial peak, which is in particular visible in the standing variance spectrum at the high-frequency end of the spectrum, is more pronounced.

According to Fig. 9, transient fluctuations on all temporal scales and, hence, all planetary scale waves contribute to the underestimation of the contributions of the transient eddies to the intraseasonal variability in the Southern Hemisphere extratropics during austral winter in OPA, which was already found in the analysis of variance (Fig. 1b). This is particularly the case for the propagating waves, while the standing variance spectra show a somewhat smaller underestimation of the variance due to an underestimation of the activity of the ultra-long waves. Fig. 9 also reveals that the aliasing effect is about twice as strong as in the Northern Hemisphere (Fig. 5) in association with a doubling of the variance on time scales shorter than 4 days in the Southern Hemisphere.

The differences between the re-analyses and the operational analyses are of relevance when investigating the quality of a GCM. The total variance spectra obtained from the ECHAM model (Fig. 6

in M99) are, for instance, in rather good agreement with ERA but not with OPA, where the activity of the transient eddies is considerably weaker. This is in particular the case on time scales longer than 10 days, where the ultra-long waves (1–3) give major contributions to the intraseasonal variability, while on the short time scales associated with the synoptic waves (4–9) the ECHAM model is in better agreement with OPA. The separation between the propagating and the standing variance spectra reveals that the new version of the ECHAM model (ECHAM4) is in better accordance with ERA for the propagating but with OPA for the standing variance spectrum, while the opposite is the case for the old version (ECHAM3).

4.2.2. Temporal evolution. The underestimation of the contribution of the transient fluctuations to the intraseasonal variability in the Southern Hemisphere extratropics during austral winter in OPA varies considerably in the course of the years, while the general tendency remains the same throughout the entire period (Fig. 10). The smallest differences actually occur in 1980 in the aftermath of FGGE, when a relatively high number of observations has been available also in the Southern Hemisphere (Uppala, 1997). But as soon as these observations are not available any more, the differences increase dramatically until 1983, decrease subsequently until 1986, when the T106 spectral model with 19 vertical layers was introduced, and then remain on about the same level until the end of the period of investigation, when the T213 spectral model was used. In the beginning of 1986 also the number of radiosondes in the Southern Hemisphere extratropics starts growing, and during 1989 and most of 1990 there were about as many radiosonde data available in that area as during the FGGE period. But unfortunately the number of radiosondes in the Southern Hemisphere dropped dramatically again by the end of 1990. Hence, some of the improvement of the operational analyses in the Southern Hemisphere extratropics is presumably related to the increase in the number of observations in that area. But some of the improvement has to be accounted for by the changes in the analysis-forecasting-system at ECMWF before 1986, since according to Bengtsson and Shukla (1988) analyses produced with the operational analysis-

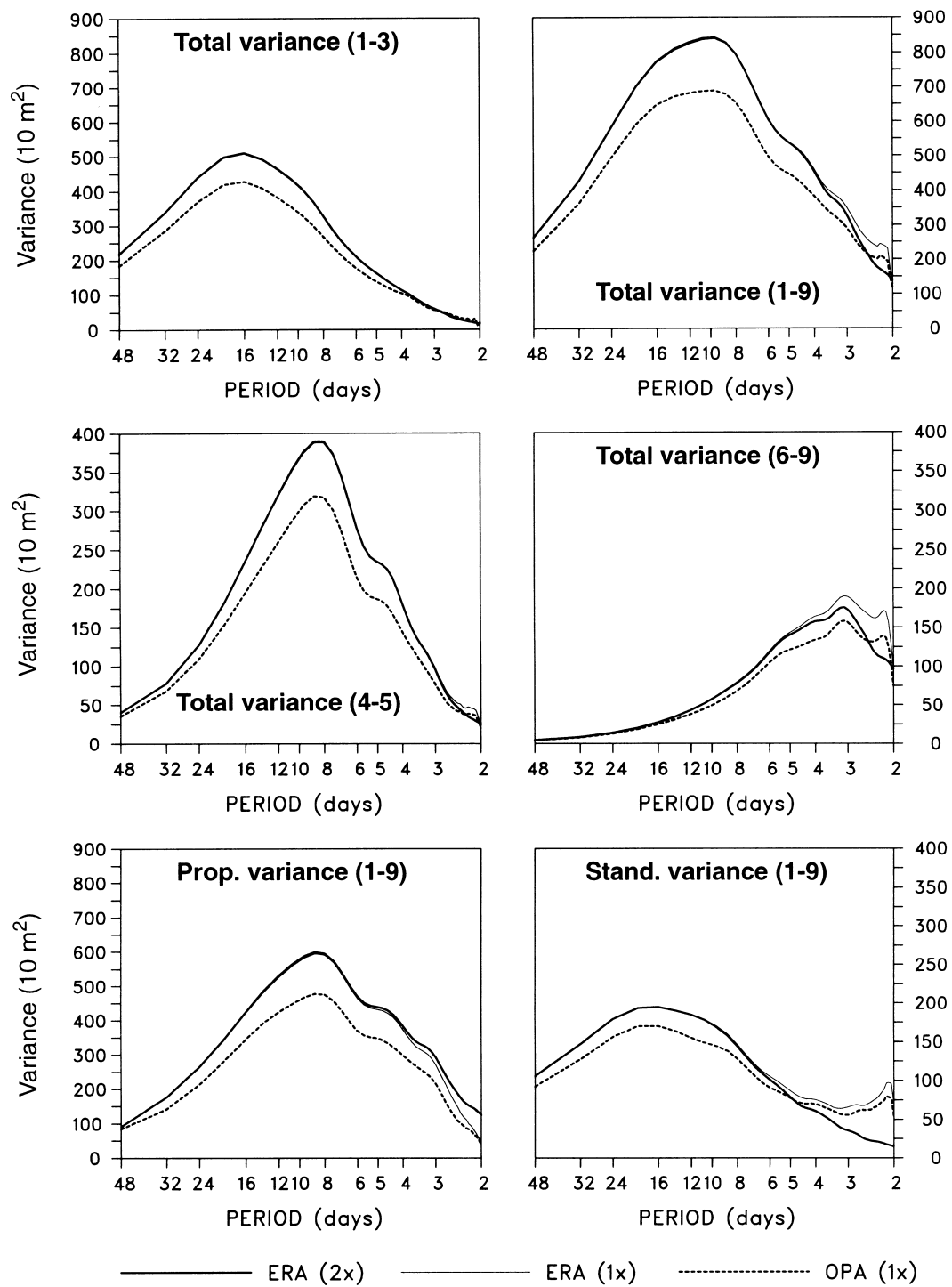


Fig. 9. As Fig. 5, but for the Southern Hemisphere (40°–70°S) during austral winter (JJA).

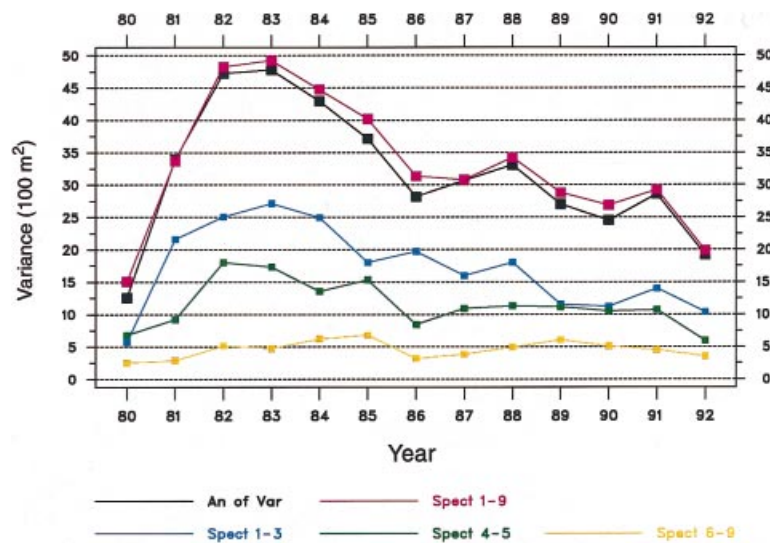


Fig. 10. As Fig. 6, but for the Southern Hemisphere (40° – 70° S) for individual austral winter seasons (JJA).

forecasting system at the end of 1986 were characterized by significantly stronger transient eddy activity than the analyses from the time, when the old ECMWF gridpoint model was in use. The estimates of the differences between ERA and OPA obtained via the analysis of variance are generally somewhat smaller than those originating from the wavenumber-frequency analysis, indicating that the disturbances with small spatial scales tend to counteract the differences associated with the planetary scale waves. The distinction between the different wave regimes illustrates that the temporal evolution of the differences between the two data sets varies for the different scales. The relatively large differences between 1981 and 1986 are pronounced for the ultra-long (zonal wavenumbers 1–3) as well as for the long planetary scale waves (4–5), but not for the baroclinic waves (6–9). This indicates that primarily the large-scale phenomena are affected by the lack of in situ observations in the Southern Hemisphere, while the characteristics of the short waves are more controlled by the NWP model. The relatively small differences between the two data sets in 1985 and the years to follow can be related to the increased as well as the improved use of satellite data in OPA in the mid-1980's. In February 1985, for instance, TOVS data and satellite derived temperature data have been included in the operational analyses.

The differences between the total variance spectra computed from the two data sets show consistently the underestimation of the contributions of the transient fluctuations to the intraseasonal variability on virtually all temporal scales for each year (Fig. 11). As to be expected, the smallest differences can be found in the austral winter 1980 at almost all periods, while relatively large differences especially at the low frequencies occur in the early 1980's (Fig. 11a). An interesting feature exhibit the waves at zonal wavenumbers 4 and 5, where for the austral winters 1983 to 1985 the differences have a maximum at exactly the same periods between 6 and 10 days (Fig. 11b). This indicates one of the systematic differences between the model at that time (the spectral model at T63 and at T106 with 16 vertical levels) and the model used in the re-analyses, since in this data-sparse region the NWP model as a component of the analysis-forecasting system is of major importance.

5. Transient fluctuations

In this Section, we investigate the geographical distribution of the intraseasonal variability in the extratropics associated with the transient fluctuations. On the basis of the previous wavenumber-frequency analyses (Figs. 4, 8) we distinguish between the high-frequency part (periods between

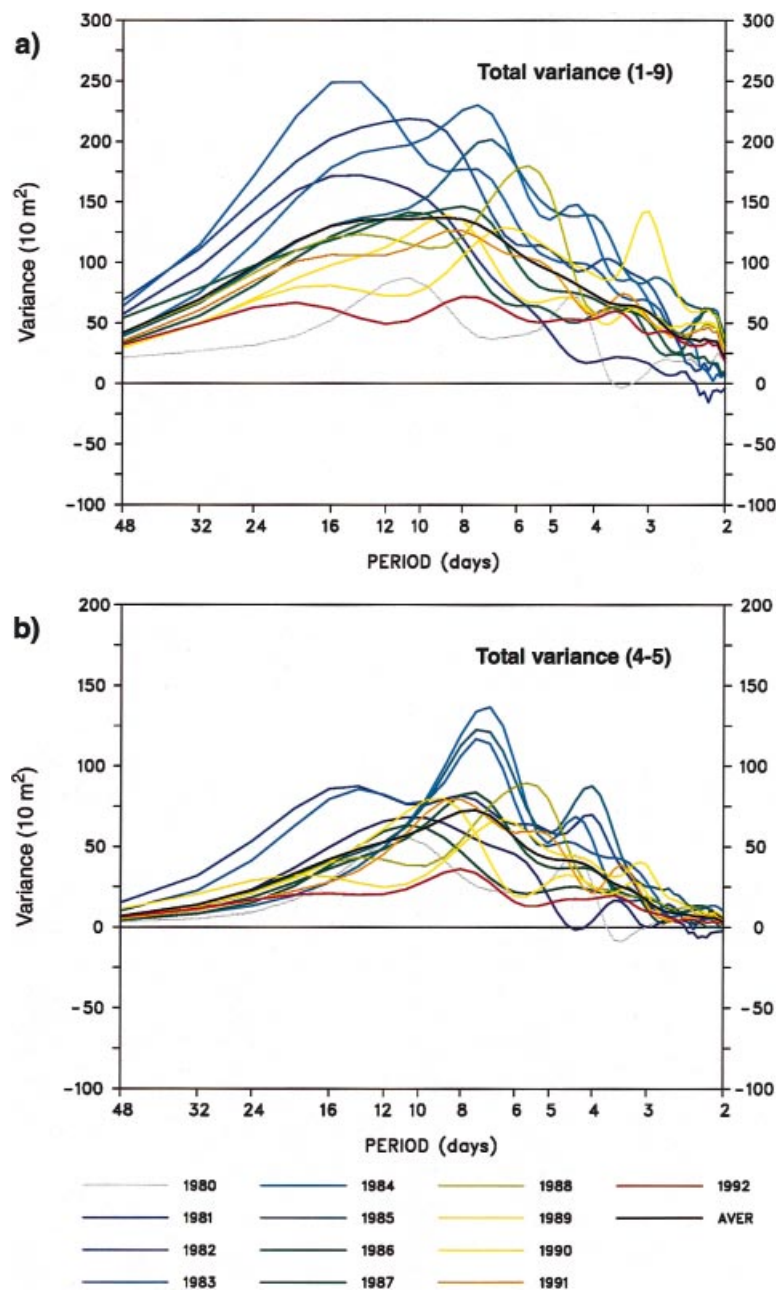


Fig. 11. As Fig. 7, but for the Southern Hemisphere (40° – 70° S) for individual austral winter seasons (JJA) distinguishing between two different planetary wave regimes.

2 and 10 days in the Northern and 2.5 and 6 days in the Southern Hemisphere, respectively), where the synoptic waves are active, and the low-frequency part (periods longer than 10 days in the Northern and longer than 6 days in the Southern Hemisphere, respectively). In the Northern Hemisphere the waves at zonal wavenumbers 1–3 give major contributions to the variability on these long time scales and in the Southern Hemisphere the waves at zonal wavenumbers 1–4. We have retained the transient fluctuations on the different temporal scales by applying spectral filters for the appropriate frequency range. For this purpose the (once daily) data have been multiplied with 21 filter coefficients in the way as described in Blackmon and Lau, 1980.

5.1. Northern Hemisphere

Fig. 12 shows the geographical distributions of the root-mean-square (RMS) deviations in the geopotential height field at 500 hPa associated with the transient fluctuations on the different time scales mentioned before. As for the high-frequency variability, the distributions reveal an enhancement of the intraseasonal variability over the northern Pacific in the ECMWF re-analyses, while the high-frequency variability is reduced over the northern Atlantic and western Europe (Figs. 12a, b). Hence, the Pacific storm track is intensified and extending further downstream in the ECMWF re-analyses than in the operational analyses, while the Atlantic storm track is weakened and not extending as far into western and central Europe as in OPA. Over the high northern Atlantic and northern Europe, on the other hand, the activity of the synoptic waves is stronger in ERA. At the low frequencies, we find an enhancement of the variability over the Pacific and the Atlantic as well as over northern and southeastern Europe (Figs. 12c, d). This includes the two centres of action near the Aleutians and south of Iceland, respectively. Hence, considering the transient fluctuations on all intraseasonal time scales the distributions reveal stronger variability in the re-analyses over the Pacific and over the northern Atlantic as well as over northern and southwestern Europe (Figs. 12e, f).

In Fig. 13 the temporal evolution of the differences between the ECMWF re-analyses and the operational analyses is described via (a) the RMS

deviations between the two data sets for individual boreal winter seasons and (b) the pattern correlations of the differences for individual seasons and the differences between the long-term means for the two data sets, which are shown in Figs. 12b, d, f. Different to the previous sections, where we have looked at the zone between 40 and 70°N, here we consider the extended zone between the 25 and 70°N in order to cover all regions with considerable differences between the two data sets.

As for the magnitude of the differences between the re-analyses and the operational analyses, some variations are visible over the period of investigation (Fig. 13a). Relatively small differences can be found in the boreal winters 1982/83, 1988/89 and 1991/92, when the differences are rather small for both the high-frequency and the low-frequency variability. The differences are typically smaller for the transient fluctuations on time scales between 2 and 10 days than on the long time scales beyond 10 days. The only exception is the boreal winter 1986/87, when very large positive differences of the high-frequency variability occur over the eastern Pacific and the eastern Atlantic (not shown).

Also the spatial structure of the differences varies in the course of the years (Fig. 13b). In the period 1986 through 1990, when the T106 spectral model with 19 vertical levels was used, the distributions of the differences are rather coherent for both the high-frequency and the low-frequency variability. Before 1986, however, the distributions of the differences are not only less coherent, but the coherence differs very much for the different time scales of the transient fluctuations. In the winter 1982/83, for instance, rather typical differences are found for the high-frequency variability, but untypical ones for the low frequencies. These are accounted for by negative differences between ERA and OPA in the two centres of action near the Aleutians and south of Iceland (not shown). It is interesting to note that also the wavenumber-frequency analysis reveals this peculiar behaviour: for the contributions of the ultra-long waves (1–3), which give major contributions on the long time scales, we find only during that particular season negative differences between the two data sets (Fig. 6).

One should, however, be aware of the fact that the temporal coherence of the differences may

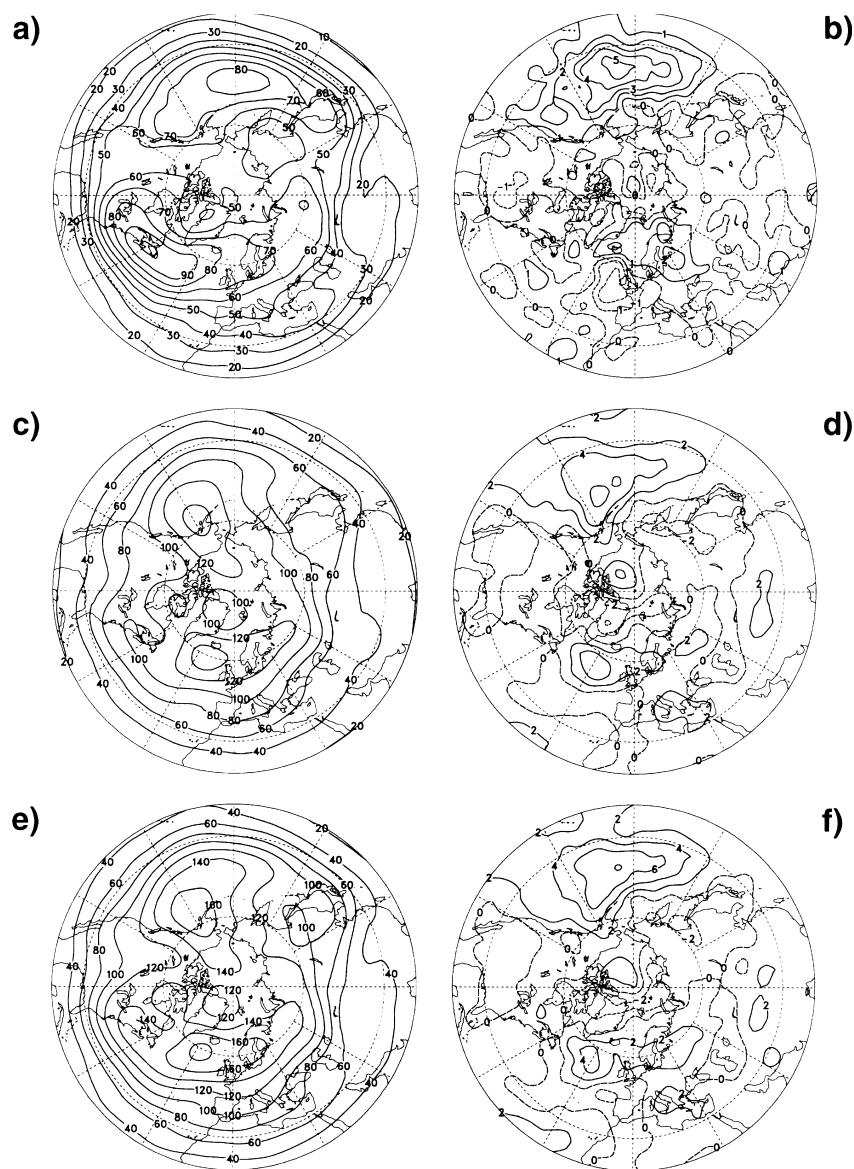


Fig. 12. RMS deviations of the geopotential height at 500 hPa obtained from ERA ($1 \times$; left column) as well as the differences between ERA ($1 \times$) and OPA ($1 \times$) (right column) for the boreal winter season (DJF). We distinguish between different temporal scales: 2–10 days (a, b), 10–90 days (c, d) and 1–90 days (e, f). Units are [m]. The contour interval is 10 (a), 20 m (c, e), 1 m (b) and 2 m (d, f), respectively.

vary by region. Over the central extratropical Pacific, i.e., between 150 and 180° western longitude, the high-frequency variability is stronger in the re-analyses during virtually all individual boreal winter seasons (not shown).

5.2. Southern Hemisphere

In the Southern Hemisphere the intraseasonal variability is considerably stronger in the re-analyses than in the operational analyses in almost the entire extratropics (Fig. 14). This is the case

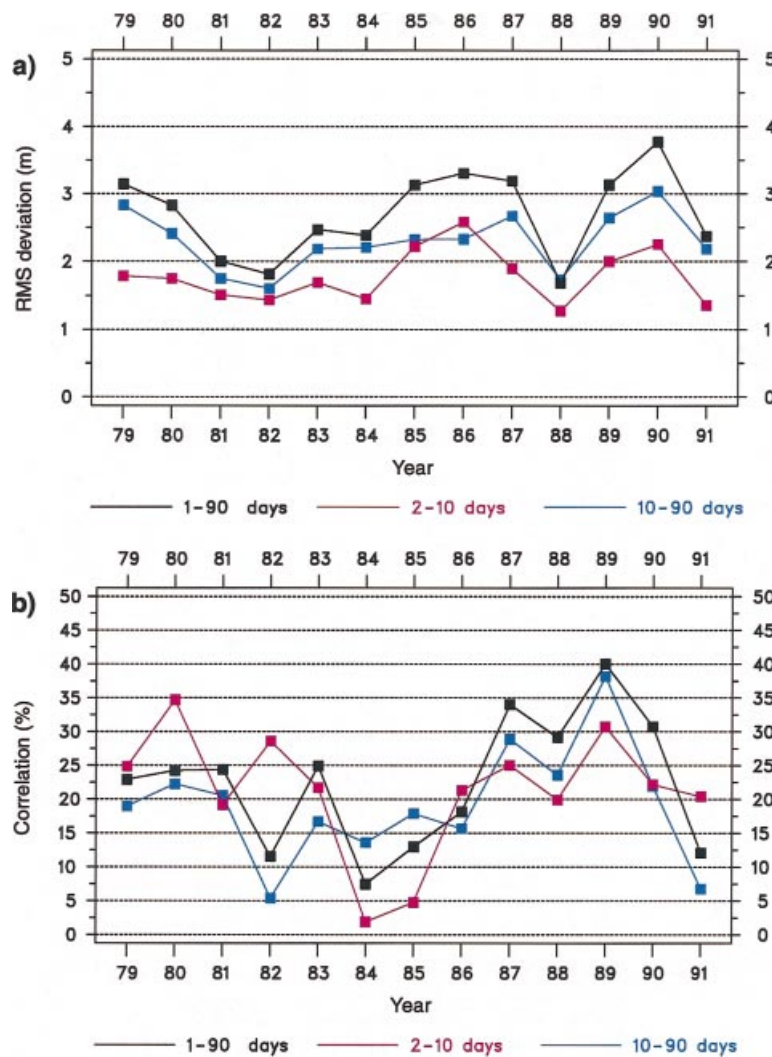


Fig. 13. RMS deviations (a) as well as pattern correlations with the difference of the long-term means (b) between ERA (1 ×) and OPA (1 ×) for the RMS deviations the geopotential height at 500 hPa distinguishing between different temporal scales for individual boreal winter seasons (DJF). The dates of the years “79”, “80”, etc. represent the winters 1979/80, 1980/81, etc. The values represent averages over the zone between 25° and 70°N.

for both the high (Fig. 14b) and the low frequencies (Fig. 14d). As for the high-frequency variability, maximum differences occur between 30°W and 60°E leading to a substantial intensification of the main storm track in the Southern Hemisphere extratropics (Figs. 14a, b). At the low frequencies, on the other hand, maximum differences can be found between 75 and 150°W at about 60° southern latitude, so that the centre of action is located

about 60° farther downstream in the re-analyses (Figs. 14c, d). The deviations between the two data sets also reveal the central role of in situ observations for the analyses. That is in those regions, where in situ observations including radiosonde data exist, i.e., New Zealand, the southern tip of South America and the Antarctic Peninsula or various small islands in the southern oceans, the differences between ERA and OPA are

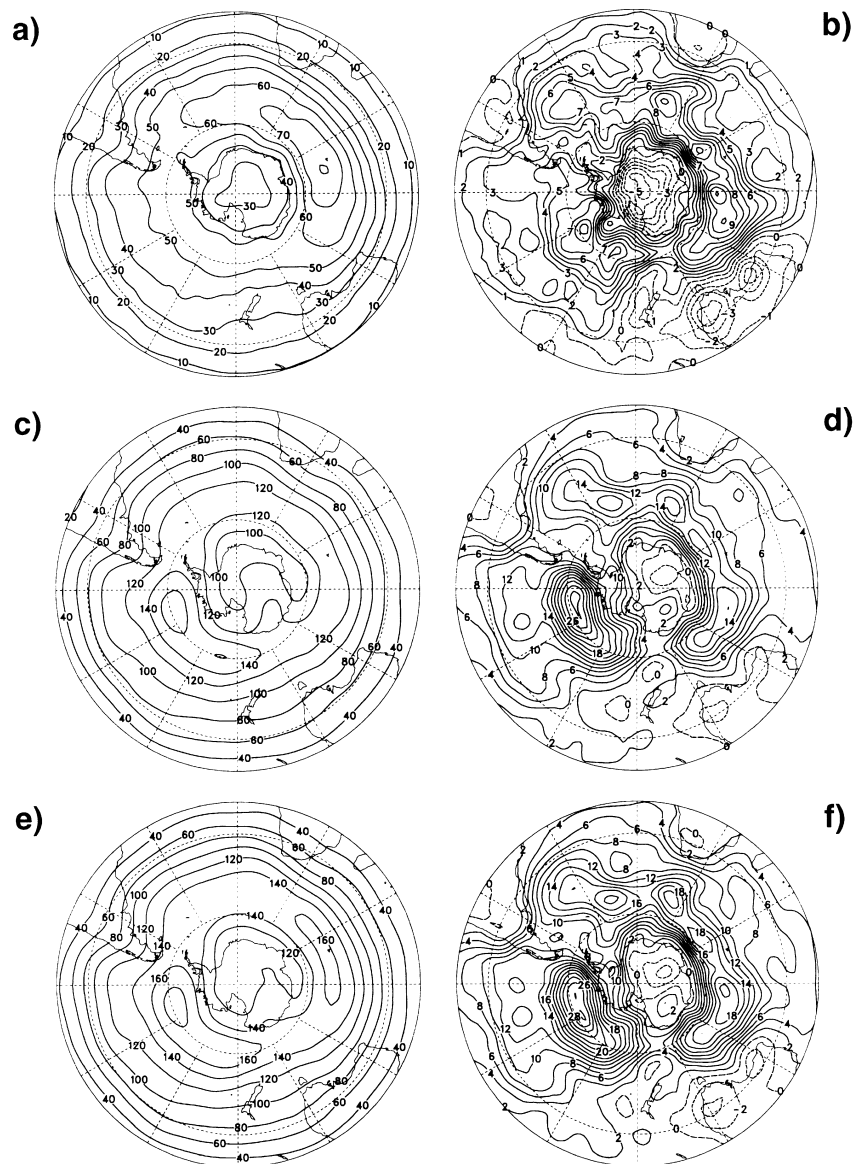


Fig. 14. As Fig. 12, but for the austral winter season (JJA). Here I distinguish between the following different temporal scales: 2.5–6 days (a, b), 6–90 days (c, d) and 1–90 days (e, f).

relatively small. But even with the help of these kind of “fixed points” it is very hard to objectively decide, which data set yields the better analyses in the Southern Hemisphere. Both data sets show, for instance, an estimate of about 140 m for the low-frequency variability in the area south of New Zealand (Figs. 14c, d), but it is not clear, whether

this estimate represents the maximum value and, hence, the centre of action in the Southern Hemisphere extratropics as in OPA or rather the upstream extension of the maximum including the centre of action located at about 60° farther downstream as in ERA.

As for the ECHAM3 model (May, 1994), the

strength of the storm track in the Southern Hemisphere is comparable to the estimates obtained from OPA and, hence, weaker than for ERA. Considering the location it combines, however, aspects of both the re-analyses and the operational analyses: in the entrance region it is in considerably better agreement with OPA and in the exit region with ERA. As for the low-frequency variability, ECHAM3 shows a similar spatial structure as ERA with the centre of action located at about 120°W but the variability is generally somewhat weaker.

As in the Northern Hemisphere, we have chosen an extended zone between 30 and 75°S for investigating the temporal evolution of the differences between the re-analyses and the operational analyses, which is illustrated in Fig. 15. As for the magnitude, we find a strong variation of the low-frequency variability with rather large differences in the early 1980's and relatively small values in 1980 and from 1986 onwards (Fig. 15a), when the T106 spectral model with 19 vertical layers was used and considerably more radiosonde data were available again. In the mid-1980's also the use of satellite data has been considerably improved. For the high frequencies, on the other hand, the magnitude of the differences varies over the entire period of investigation. For the low-frequency variability the differences are coherent with the mean difference between the two data sets in all years but 1980 (Fig. 15b), when the maximum differences located between 75 and 150°W are not pronounced (not shown). For the high-frequency variability, on the other hand, the coherence is rather small during the first 3 years, when the gridpoint model was used. Apparently this NWP model simulates the short baroclinic waves in the Southern Hemisphere extratropics in a quite different way than the different spectral models used after April 1983, which, however, simulate these disturbances in a similar way despite the accompanying changes in the analyses-forecasting system.

6. Summary and concluding remarks

In this paper, we have investigated various aspects of the atmospheric intraseasonal variability in the extratropics as given by the ECMWF

re-analyses and compared them with the original operational analyses by ECMWF, considering both the long-term mean values and the temporal evolution of the differences between the two data sets.

The comparison has revealed rather small differences in the magnitude of the intraseasonal variability in the Northern Hemisphere extratropics, where numerous in situ observations including radiosonde data have been available, and large differences between the two data sets in the Southern Hemisphere extratropics, where the number of in situ measurements is limited. The differences are particularly large for the contributions of the transient disturbances to the intraseasonal variability. Generally the intraseasonal variability is stronger in the re-analyses than in the operational analyses, to a large extent in the Southern and to a small extent in the Northern Hemisphere. In the Southern Hemisphere extratropics the differences show a typical temporal evolution with very small differences in 1979 and 1980, when considerably more radiosonde data have been available during and in the aftermath of FGGE, and very large differences in the early 1980's, when the old ECMWF gridpoint model was used and the number of radiosonde data in the Southern Hemisphere was limited. With the introduction of the spectral models (T63, T106 with 16 and 19 vertical layers, respectively, and finally T213) and with considerably more radiosonde data being available again as well as with the improved use of satellite data the differences between the two data sets decrease and reach in the early 1990's the same level as in the beginning of the period of the re-analyses.

As for the spectral distribution of the contributions of the transient fluctuations to the intraseasonal variability, the largest differences are found to be associated with the largest (zonal wavenumbers 1–3) and the smallest differences with the smallest planetary scale waves (wavenumbers 6–9). The different planetary wave regimes typically show the same tendencies, namely the enhanced activity of the transient disturbances in the re-analyses. The only exception is the boreal winter 1982/83 for the Northern Hemisphere extratropics. In this particular season both the ultra-long and the short planetary waves give stronger contributions to the intraseasonal variability in the operational analyses, while the opposite

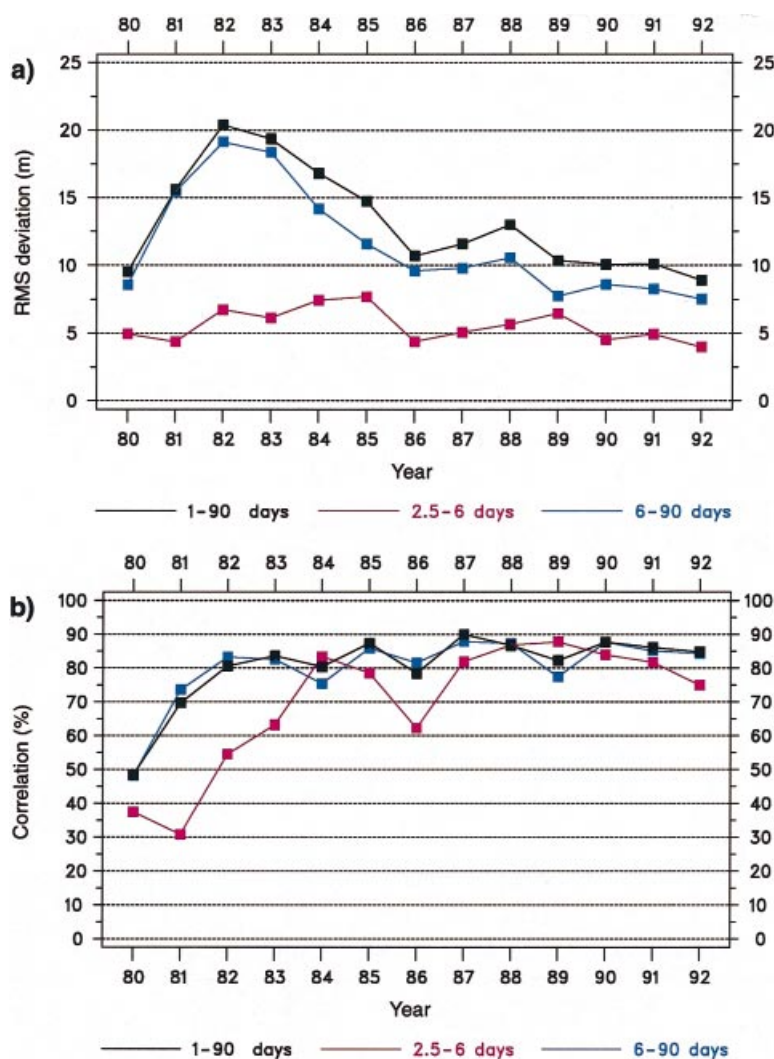


Fig. 15. As Fig. 13, but for the Southern Hemisphere (30° – 75° S) for individual austral winter seasons (JJA).

behaviour is found for the long waves. Moreover, the spectra show very untypical deviations with rather large differences on short temporal scales associated with the ultra-long and on long time scales associated with the short planetary scale waves. During this particular period erroneous observations may have lead to very large abrupt changes in the analyses in extensive areas from one day to the other.

During the boreal winter 1982/83 the differences between the re-analyses and the operational analyses are not spatially coherent with the overall

differences between the two data sets due to enhanced low-frequency variability in OPA in the centres of action near the Aleutians and south of Iceland. In the Southern Hemisphere extratropics, on the other hand, the differences for individual seasons are spatially coherent with the overall differences in all years except 1979 and 1980 for the low-frequency variability, whereas at the high frequencies the differences are spatially coherent after 1983, when the spectral model at different resolutions, though, has been used.

These results illustrate the main problem of

global analyses derived from in situ and space observations. In regions with numerous observations such as the Northern Hemisphere extratropics the analyses are only to a small extent affected by the characteristics of the analysis-forecasting-system in general and by the NWP model or the assimilation scheme that are parts of this system in particular. But in the Southern Hemisphere extratropics, where particularly the number of radiosonde data is limited, the NWP model plays a key role and, hence, the analyses strongly depend on the characteristics of this model. This is illustrated by the fact that in the case of the ECMWF re-analyses the differences with the operational analyses are not only relatively small in the beginning of the period of the analyses but also not spatially coherent with the differences between the two data sets in the following years. It is interesting to note that the characteristics or rather the quality of the NWP model (it should be allowed to assume that the old ECMWF gridpoint model is not as good as the more advanced spectral models (Girard and Jarraud, 1982)) becomes considerably less important as soon as a certain number of observations becomes available. In the case of the analyses by ECMWF one has, however, to distinguish between the barotropic and the baroclinic components of the flow. The gridpoint and the various spectral models have similar structures for the barotropic waves, while the storm tracks, which are associated with the activity of the baroclinic synoptic waves, show different characteristics in the gridpoint model than in the different spectral models, which are consistent with each other.

The motivation for performing the re-analyses at ECMWF and elsewhere has been to create homogeneous atmospheric data sets of high quality as originally proposed by Bengtsson and Shukla (1988). Even though the operational analyses, which have been produced at ECMWF and other institutions, provide a valuable resource for research, they are affected by the major changes in the NWP models, the analysis technique, the assimilation scheme and the usage of observations in the course of the years and, hence, have a number of limitations. As documented by the steady increase in the skill of ECMWF's forecasts (Bengtsson, 1999) many of the changes in the individual components of the analysis-forecasting-system have led to an improvement not only of

these components but also of the entire system with better short- and medium-range forecasts and better analyses. As for the assimilation system, the developments over the last 20 years have made it possible to combine conventional observations with space observations and therewith improved the analyses in those regions, where in situ observations are sparse. The increase of the resolution of the NWP models have led to a more realistic presentation of the local effects such as the orographic impact on local weather and climate as well as to an improvement of the dynamical aspects, since finer and finer scales can be resolved directly by these models. But also the advancements of the parameterizations of physical processes in the NWP models have led to a better quality of both forecasts and analyses.

In order to define the ECMWF re-analysis system a substantial programme of experimentation, closely coordinated with the Centre's Research and Operational activities has been completed. These experiments, which have addressed a number of issues such as the vertical resolution, timelines for the first guess, orography and the parameterizations of soil processes and clouds, are further described in Gibson et al. (1997). As a result of these experiments, the number of vertical levels was set to 31 instead of 19, and it was decided to use a mean instead of an envelope orography (Jarraud et al., 1988), since the usage of an envelope orography considerably reduces the number of observations used in mountainous areas. In another experiment the parameterization of the effects of sub-grid-scale orography, which also includes a revised formulation of the gravity wave drag was tested successfully in the re-analysis system (Lott and Miller, 1997).

In spite of the carefulness used when defining the ECMWF analysis-forecasting-system, a number of problems and deficiencies of the re-analyses have been uncovered. The most serious, which have been described and analysed in further detail in Kållberg (1997) are a.o. surface temperatures in extremely stable conditions, surface temperatures in boreal forests during spring, the "Amazon" problem or temperature and humidity biases in the tropics. Despite of these problems and others yet to be detected, the ECMWF re-analyses can be considered as of a very high quality, so that they constitute a unique base for studies of the general circulation of the atmo-

sphere. It is, however, important to be aware of limitations and deficiencies of this data set.

As indicated in this study the ECMWF re-analyses can differ quite substantially from the Centre's operational analyses in data-sparse regions such as the Southern Hemisphere extratropics, showing how much the analyses in these regions are affected by the characteristics of the analysis-forecasting-scheme. And even though the current or future re-analyses provided by the different institutions may give very similar analyses

also in such data-sparse regions, they cannot replace observations such as those available during the FGGE period.

7. Acknowledgements

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