On the accuracy of general circulation statistics calculated from FGGE data—a comparison of results from two sets of analyses

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SUMMARY

By comparing statistics from two independent sets of analyses, and relating the differences seen to known characteristics of the analysis system, an indication is given of the likely accuracy of typical general circulation statistics calculated from FGGE data. The analyses compared are those made by the European Centre for Medium Range Weather Forecasts using the main delayed mode observations, and those made in near real time by the Meteorological Office FGGE analysis system. Examples are given of the accuracy of both zonal means and geographical distributions, for basic time mean fields, for derived fields such as divergence, variances and fluxes, and for budget calculations.

It was found that qualitative agreement between the two sets of statistics was very good, even in the tropics and southern hemisphere. Quantitative agreement was also in general good; most of the systematic differences could be traced to known characteristics of the analysis systems.

1. INTRODUCTION

The first objective of the First GARP Global Experiment (FGGE) was to obtain a better understanding of atmospheric motion through general circulation studies; many studies are now under way using FGGE data. In this paper we examine the accuracy of a range of general circulation statistics typical of such studies by comparing results calculated in identical fashion from two independent sets of analyses, and relating the differences to characteristics of the analysis systems. The analyses used are those made by the European Centre for Medium Range Weather Forecasts using delayed mode data (EC3B), and those made at the Meteorological Office in near real time (MO3A). Descriptions and references are given in section 2.

Historically two methods have been used for the calculation of general circulation statistics. In the first regular observations from a set of fixed stations are used to calculate the desired time averaged quantities at each station. These are then interpolated (analysed) to a regular grid. In the second synoptic analyses of basic parameters are made, and used to calculate on the regular grid the desired time averaged statistics. Results from the two methods have been compared by Rosen and Salstein (1980) and Lau and Oort (1981, 1982). The first method may be more faithful to observations in regions with a good network of conventional observations, but elsewhere the second method should be better because it can use irregular observations and because the analysis methods used to extrapolate into data voids can be based on knowledge of atmospheric dynamics and can include extrapolation in time (i.e. forecasts). During FGGE, observations from mobile observing systems (satellites, aircraft, drifting buoys) were a vital part of the global dataset, hence the second method is more appropriate and is the subject of this paper.

Comparisons of general circulation statistics calculated using this second method have been presented by Arpe (1980), Parker (1980), Trenberth and Paolino (1980), Van Loon (1980) and Jarvenoja (1982). However, these studies are very limited in the types of statistic compared, and they do not relate the differences seen to the particular analysis techniques. Other analysis intercomparisons have concentrated more on synoptic differences. Hollingsworth et al. (1984) is of particular relevance since it compares the EC3B analyses for a five-day period with analyses made using delayed mode observations and a modified version of the system used to produce MO3A.
Both analysis systems compared in this paper relied heavily on numerical forecast models to provide dynamically consistent first guesses which had significant impact on the analyses in data-sparse areas. Neither made significant use of climatological norms or human intervention; although these may well improve analyses in terms of mean square accuracy and subjectively judged consistency of basic fields in data-sparse areas, it seems unlikely that they will benefit more complex derived quantities. Thus the general circulation statistics compared in this paper were derived in identical ways from two sets of synoptic analyses made using similar four-dimensional data assimilation methodologies. Despite this we believe that there were sufficient differences between the two systems for the agreement or otherwise of the derived statistics to be a reasonable indication of their accuracy, particularly when interpreted in terms of known characteristics of the analysis systems. These differences, which are in the observations used, forecast models, analysis methods, and initialization methods, are discussed further in section 2.

Clearly a sample of two independent analysis systems is barely adequate to derive meaningful error estimates. We have therefore compared some results from these two systems with those from others, including MONEX (Krishnamurti et al. 1980), Australia (Guymer and Le Marshall 1981; Physick 1981), the Goddard Laboratory for Atmospheric Science (Baker 1983; Salstein and Rosen 1982) and the Geophysical Fluid Dynamics Laboratory (Lau, N-C, personal communication). These comparisons all indicate that the differences shown in this paper between MO3A and EC3B are typical.

It is not our purpose in this paper to study in detail any feature of the general circulation. Such studies using the EC3B data have been published for example by Bengtsson et al. (1982b), and using the MO3A data by Lyne et al. (1982). Nor can we attempt a comprehensive presentation of statistics in the space available. A fuller set from which many of the figures in this paper are drawn is available in a technical note (Swinbank 1983). A comparison of selected typical basic time mean fields is presented in section 3, and of some interesting derived fields in section 4. In section 5 we discuss the accuracy of budget studies, and in section 6 we summarize.

2. ANALYSIS DATASETS USED

(a) Meteorological Office (MO3A)

The Meteorological Office FGGE data assimilation scheme has been described by Lyne et al. (1982). The predictive variables (wind, temperature, humidity and surface pressure) of a global general circulation model were corrected each timestep towards values interpolated from nearby observations. Observations available at Bracknell within a cut-off time of between 8 and 18 hours were used (level IIa data in FGGE terminology). There was limited human quality control of data and creation of bogus data, guided by the Meteorological Office operational intervention in the northern hemisphere and the Australian PAOB reports in the southern hemisphere (PAOB reports are bogus data largely based on cloud picture interpretation). Analyses were produced for the Special Observing Periods (SOPs) of FGGE: SOP1 ran from 5 January to 5 March, SOP2 ran from 1 May to 30 June 1979. The assimilations were started five days earlier in each case to allow for initial adjustment, and the SOP2 assimilation was continued to 14 August to allow study of the SW monsoon. The Meteorological Office 11-layer global general circulation model on a quasi-homogeneous 200 km grid was used.

(b) ECMWF (EC3B)

The ECMWF data assimilation scheme has been described by Lorenc (1981a), and Bengtsson et al. (1982a). A 6-hour forecast was interpolated from sigma coordinates to
standard pressure levels, and used as first guess for a multivariate statistical height and wind analysis (Lorenc 1981c) and a univariate humidity analysis. These were then interpolated back to sigma coordinates and initialized using a nonlinear normal mode initialization procedure (Machenhauer 1977; Temperton and Williamson 1981; Williamson and Temperton 1981). The cycle was restarted with another 6-hour forecast. The analysis fields before initialization were the basis for the general circulation statistics, except for temperature and vertical motion, which were derived from the initialized fields. Observations collected within a 6-month cut-off (the main IIb data) were used, with no human intervention and no use of PAOBs. Analyses were made for the entire FGGE year, December 1978 to November 1979, on a regular 1.875° grid with 15 levels.

(c) Significant differences between analysis systems

These analysis systems have been described in more detail and compared, with particular regard to synoptic forecasting aspects, by Hollingsworth et al. (1984). Differences expected to affect general circulation statistics are discussed below.

(i) Model biases. Both numerical models have systematic errors in their simulated climates which might affect analyses and derived statistics, particularly in data-sparse regions. We believe that such errors are generally smaller than those in a purely statistical extrapolation of statistics into such regions; however, they can be significant especially when using the statistics to verify the simulations of climate models. An example of such a bias is the tendency of the MO3A model to cool by up to 1 K/day in some places; this is reflected in mean temperature and geopotential analyses. Arpe (1983) showed that eddy momentum fluxes in the subtropics increased with time in the ECMWF forecast model. This tendency might cause the EC3B analyses to overestimate such fluxes in data-sparse areas.

The models were both primitive equation sigma coordinate grid-point models with similar resolutions. However, the design and implementation of their finite difference schemes and physical parametrization schemes were independent, hence their biases are likely to be different.

Model biases are likely to be particularly important for humidity fields, since these are rather strongly determined by physical parametrizations and vertical motions in the models, and only slightly affected by the relatively inaccurate and sparse humidity data if they are given statistically correct weights. In fact MO3A and EC3B systems each had for some period errors such that humidity data were given even smaller weights than statistically optimal. For climate studies the analyses are useful, since model-generated humidity fields can look very reasonable (Lorenc and Tibaldi 1980) and associated rainfall patterns in the MO3A assimilation were close to climatological norms (Swinbank 1980). However, the humidity fields, being largely model generated, are of little value for verifying simulations by other models.

(ii) Initialization. The nonlinear normal mode technique used in the EC3B scheme was adiabatic, and effectively removed divergent motions driven by atmospheric heating, such as the Hadley circulation. Since the vertical motion analyses were derived from the initialized fields they reflect this. A 6-hour forecast is insufficient for such motions to be fully regenerated, so the first-guess fields too were affected. The multivariate analysis constrained the small scale (<700 km) corrections to the first guess to be non-divergent and, outside of the tropics, geostrophic. However, for larger scales there was no such constraint, and the horizontal wind analyses can show large-scale divergent circulations if the observations resolved them.

The MO3A assimilation scheme had no explicit balancing or initialization other than
the repeated insertion of data and a damping of high frequency variations, relying on
the general circulation model to achieve realistic flows. Thus we do not expect divergent
motions to be unrealistic unless they are affected by biases in the model. However, this
approach naturally leads to excessive gravity wave noise in the model’s fields, and
although these waves interact only weakly with meteorological motions some statistics
(e.g. the variance of transient modes) are affected.

(iii) Analysis method. The EC3B system uses observations over a rather large
three-dimensional volume, about 600 km in horizontal extent and a third of the atmos-
phere deep. This had a smoothing effect, particularly in the vertical, which was augmented
by those of the initialization and the interpolations each cycle between sigma and pressure
coordinates. Hence detailed vertical structures, for instance in the boundary layer or
near the tropopause, may not have been properly resolved. The MO3A system on the
other hand had little vertical coupling, leaving many layers with few effective data and
hence more susceptible to model bias. The MO3A scheme assimilated temperature data
into the model; height analyses were obtained by integrating the hydrostatic equation.
The EC3B scheme analysed height data; temperature analyses were derived. Thus the
MO3A heights might be biased at upper levels due to finite difference errors while the
EC3B temperatures, and, even more, the vertical stabilities, will have poor vertical
resolution.

The assimilation of mass field data without modifying winds is an inefficient way of
analysing synoptic-scale systems (Daley 1980), and in the southern hemisphere where
pressure and temperature data predominate the MO3A analyses did not fit the buoy
data as closely as did the EC3B analyses, which coupled the winds geostrophically (e.g.
in one case r.m.s. differences were 3.4 and 2.8 mb respectively: Lorenc 1981b). This,
along with poorer data coverage and possibly model bias, caused the MO3A analyses
to underestimate the intensity of southern hemisphere eddies.

(iv) Data used. Since the level IIa data used by the MO3A system contained only
data available in near real time over the Global Telecommunications System, such
observations as cloud motion winds for the Indian Ocean, some ship and aircraft data,
and many satellite temperature soundings, were not used. This may have affected results
in regions where these data were important, such as the southern hemisphere (as noted
above) and the Indian Ocean. Typical observation distributions for the two systems are
shown by Lyne et al. (1982) and Bjarheim et al. (1981a, b). Because of their global
coverage the satellite temperatures are likely to be particularly important; their use can
alter global mean statistics such as available potential energy (Miller and Hayden 1978),
although such an impact is likely to be system dependent. The EC3B system used
approximately 250 km resolution soundings from the TIROS-N satellite throughout
FGGE. The MO3A system used lower resolution soundings from the older NOAA-5
VTPR instrument (whose calibration was different) during SOP1, and only a 500 km
resolution of TIROS-N soundings during SOP2. (Unfortunately a processing error caused
many of these to be ignored during part of June.)

(v) Diurnal cycle. The forecast model used in the MO3A system simulated the
diurnal cycle in solar radiation; the EC3B model did not. Some diurnal effects such as
a tidal effect in the heights are visible in the MO3A analyses; these tend to be masked
in the EC3B analyses by a larger mainly semi-diurnal variation in observation density.
For instance the polar-orbiting satellites provide temperature soundings for any area
with approximately a 12-hour frequency, and effort for deriving cloud motion winds was
concentrated on 00 and 12 GMT. Indeed at 06 and 18 GMT there were often insufficient
winds to determine the large-scale divergences in the EC3B analyses (see (ii) above).
We have used only 00 and 12 GMT analyses for this comparison.
(d) Method of data processing

All the results presented here were calculated from fields of wind components and temperatures on standard pressure levels. The EC3B analyses were received in this form, but the MO3A analyses had to be interpolated vertically. The method used for this paper was cubic spline in \( \log p \); below the model topography the lowest \( \sigma \) level value was used (except for temperature, when this value was adjusted with a 5 K/km lapse rate). This method was chosen to give fairest comparison with the ECMWF \( \sigma \rightarrow p \) interpolation method used to interpolate the first guess. It is not the same as used for the results presented in Lyne et al. (1982) for which linear variation with \( \log p \) was assumed; this means that the extreme values plotted in the diagrams in this paper are generally slightly larger than the equivalent values in the previous paper.

All the calculation of statistics was carried out without any horizontal interpolation, and the results have been used directly to draw the cross-sections. For drawing maps the fields were interpolated (linearly) onto a polar stereographic or regular latitude–longitude grid, as appropriate, immediately before plotting.

The statistics have been calculated from 12-hourly analyses. In the case of monthly means the period used is from 00 GMT on the first day of the month to 12 GMT on the last day, except for January; in this instance the first analysis used was 00 GMT on the 5th, because this was the start of SOP1 and the Meteorological Office data assimilation experiment had not got properly under way until this time.

3. Basic mean fields

(a) Zonal means

Figure 1 shows cross-sections of the zonal mean wind and temperature fields from MO3A and EC3B for July. There is good agreement in the zonal \( u \) wind component, even in the tropics and southern hemisphere. Of particular interest is the agreement about the strength of the southern hemisphere polar night jet, previously believed to be weaker (Bengtsson et al. 1982b). In this and other months MO3A values are between about 2 and 4 m s\(^{-1}\) stronger near 70 mb above the subtropical jets and near 400 mb at the equator, and weaker by a similar amount in the southern hemisphere polar jet.

Above topography the pressure coordinate zonal mean \( v \) component of any horizontally non-divergent wind field must be zero, so those actually observed in Figs. 1(c) and (d) must be residues due to ageostrophic divergent flows. Thus they are smaller than the zonal mean \( u \) fields, and relatively less accurate, although the absolute accuracy is better. The tropical Hadley circulation is weaker in EC3B because of the bias introduced by its initialization, as discussed in 2(c)(ii). Only five vertical modes are initialized in the EC3B system, and the effect of this can be seen in the alternating vertical pattern (corresponding to higher modes) in the tropics. Momentum balance considerations lead to the conclusion that the MO3A Ferrel circulation maximum (of 0.8 m s\(^{-1}\)) near the southern hemisphere tropopause is too large (Swinbank 1981). The surface branch of this circulation is larger in EC3B, because of greater frictional inflow into its stronger southern hemisphere depressions. It is of interest that the differences between MO3A and EC3B in the zonal mean \( v \) fields for each month tend to be larger than the month-to-month differences. This is not the case for the zonal mean \( u \) fields.

From the various sources listed in the introduction we have available other plotted diagrams of general circulation statistics for the FGGE year. To show that the differences between MO3A and EC3B are typical, and a reasonable measure of accuracy of such statistics in general, we have constructed Table 1 from the available zonal mean cross-
Figure 1. July 1979 zonal mean cross-sections of $u$ (a, b) and $v$ (c, d) wind components for MO3A (a, c) and EC3B (b, d). The $u$ cross-sections also show the zonal mean temperatures (dashed contours).

section diagrams for January 1979. Note that the averaging period used for the different versions is not the same, for instance the GFDL figures include the first five days in January, nor are the methods of processing and plotting the same. The effect of these differences can be seen by comparing the EC3B figures with those produced from the ECMWF IIIB analyses at GFDL. Definite extrema of the plotted cross-sections near the
given positions are tabulated; where none existed the value at the given position is shown in brackets. The station data (from Salstein and Rosen 1982) were for the northern hemisphere only. The last two columns show the mean and estimated population standard deviation, the latter being an underestimate since two pairs of estimates, using the ECMWF analyses and using the GLAS analysis system, were not independent. The standard deviations given also exclude differences due to the extrema being in different locations. The first five rows of Table 1 refer to the zonal mean wind field; they support some of the statements made in the previous paragraph. Other rows are discussed in section 4(c).
### TABLE 1  PLOTTED EXTREMA OF ZONAL MEAN CROSS-SECTIONS FOR JANUARY 1979

<table>
<thead>
<tr>
<th>Row</th>
<th>Zonal mean of</th>
<th>Approximate latitude (mb)</th>
<th>MO3A</th>
<th>EC3B</th>
<th>ECMWF processed at GFDL</th>
<th>GFDL</th>
<th>GLAS without satellites</th>
<th>Station data</th>
<th>Mean</th>
<th>Standard deviation</th>
<th>Units</th>
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<tbody>
<tr>
<td>1</td>
<td>$\bar{u}$</td>
<td>200, 30°N</td>
<td>40.1</td>
<td>41.3</td>
<td>41.2</td>
<td>39.5</td>
<td>39.8</td>
<td>42.1</td>
<td>38.2</td>
<td>40.3</td>
<td>1.3  ms$^{-1}$</td>
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<tr>
<td>2</td>
<td>$\bar{u}$</td>
<td>250, 50°S</td>
<td>32.1</td>
<td>34.0</td>
<td>32.9</td>
<td>32.5</td>
<td>32.4</td>
<td>31.4</td>
<td>32.6</td>
<td>32.6</td>
<td>0.9  ms$^{-1}$</td>
</tr>
<tr>
<td>3</td>
<td>$\bar{v}$</td>
<td>250, 50°N</td>
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<td>-0.59</td>
<td>-0.6</td>
<td>-0.5</td>
<td>-0.55</td>
<td>-0.76</td>
<td>-0.32</td>
<td>-0.56</td>
<td>0.13 ms$^{-1}$</td>
</tr>
<tr>
<td>4</td>
<td>$\bar{v}$</td>
<td>200, 50°N</td>
<td>3.91</td>
<td>2.44</td>
<td>2.3</td>
<td>3.0</td>
<td>3.06</td>
<td>3.38</td>
<td>2.74</td>
<td>3.0</td>
<td>0.6  ms$^{-1}$</td>
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<td>5</td>
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<td>-0.7</td>
<td>-1.6</td>
<td>-0.92</td>
<td>-0.71</td>
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<td>-0.88</td>
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<td>27.3</td>
<td>26.7</td>
<td>(25)</td>
<td>(25)</td>
<td>19.9</td>
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<td>3.0  m$^2$s$^{-2}$</td>
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<td>$\bar{u}'v'$</td>
<td>300, 32°N</td>
<td>36.9</td>
<td>34.7</td>
<td>36.9</td>
<td>30.2</td>
<td>44.9</td>
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<td>(-1)</td>
<td>-18.8</td>
<td>-8.5</td>
<td>-19.1</td>
<td>-9.8</td>
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<tr>
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<td>$\bar{u}'v'$</td>
<td>250, 45°N</td>
<td>-42.1</td>
<td>-52.5</td>
<td>-49.3</td>
<td>-40.7</td>
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<td>-45.8</td>
<td>-42.2</td>
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<td>-50.8</td>
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<td>32.1</td>
<td>45.1</td>
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<td>150, 5°N</td>
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<td>-12.5</td>
<td>-13.2</td>
<td>-21.6</td>
<td>-48.9</td>
<td>-25.2</td>
<td>-28.4</td>
<td>-24.1</td>
<td>12.4 m$^2$s$^{-2}$</td>
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<td>$\bar{u}'\tilde{v}'$</td>
<td>150, 18°S</td>
<td>4.9</td>
<td>5.9</td>
<td>5.6</td>
<td>12.6</td>
<td>7.8</td>
<td>6.7</td>
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<td>2.8</td>
<td>2.8  m$^2$s$^{-2}$</td>
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<tr>
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<td>200, 30°S</td>
<td>-13.3</td>
<td>-16.5</td>
<td>-14.4</td>
<td>-17.9</td>
<td>-21.6</td>
<td>-14.6</td>
<td>-16.4</td>
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<td>3.0  m$^2$s$^{-2}$</td>
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<tr>
<td>15</td>
<td>$\bar{v}'T'$</td>
<td>850, 40°N</td>
<td>40.1</td>
<td>15.5</td>
<td>16</td>
<td>16.8</td>
<td>17.1</td>
<td>18.2</td>
<td>15.6</td>
<td>16.7</td>
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<td>16</td>
<td>$\bar{v}'T'$</td>
<td>850, 48°S</td>
<td>-8.3</td>
<td>-13.6</td>
<td>-13.1</td>
<td>-10.3</td>
<td>-8.4</td>
<td>-14.9</td>
<td>-11.4</td>
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<td>Kms$^{-1}$</td>
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<td>17</td>
<td>$\bar{v}'T'$</td>
<td>850, 47°S</td>
<td>-15.3</td>
<td>-13.5</td>
<td>-12</td>
<td>-12</td>
<td>-10.4</td>
<td>-13.3</td>
<td>-12.2</td>
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<td>18</td>
<td>$\bar{v}'T'$</td>
<td>850, 53°N</td>
<td>22.6</td>
<td>17.8</td>
<td>17</td>
<td>18.4</td>
<td>18.2</td>
<td>18.7</td>
<td>18.9</td>
<td>18.8</td>
<td>1.8  Kms$^{-1}$</td>
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(Brackets indicate no clear extremum: field value is given)
Differences between the temperature fields are more systematic than between the wind fields, as can be seen in Fig. 2. At 1000 mb MO3A is warmer in zones with mountains because of its assumption of a constant lapse rate when extrapolating under topography. Near the surface the MO3A values should be more accurate, because the EC3B values were calculated from a spline fit to height analyses at 1000, 850 and 700 mb, a rather low resolution. Moreover the EC3B system took no account of the diurnal cycle. At 850 mb the MO3A values are too low because of a known bias in the model used. Model biases and lack of resolution cause the other large differences seen higher in the atmosphere. In January the upper-level differences were much larger, having maxima of -7.6 K and +7.7 K at 55°S, 130 mb and 200 mb respectively. This vertical pattern was strongest in the southern hemisphere, but visible globally. It was caused by an error in using 200-300 mb thickness reports in the EC3B system during January, exaggerated by vertical interpolation using splines. The EC3B temperatures used for this comparison were those supplied on the standard data tapes; BJORHEIM et al. (1981b) recommend recalculating temperatures hydrostatically from the geopotential heights in order to obtain values unaffected by initialization. This made very little difference to the zonal mean temperature cross-sections, except near the tropopause, where the differences of up to 3 K were largely due to the cubic spline vertical interpolation.

It is clear from the vertical structure of Fig. 2 that there will also be systematic differences in derived fields such as static stability.

(b) Spatial distribution

An important scientific result of FGGE was the recognition of the intensity of the southern hemisphere depression belt around Antarctica. Figure 3 shows the June mean sea level pressure fields. It can be seen that EC3B centres are deeper than MO3A by several millibars; it was suggested in 2(c)(iii) that this is due to deficiencies in the MO3A analyses. This is confirmed by a comparison of Fig. 3 with Australian NMAC results.

![Figure 2. Differences between July zonal mean temperatures, EC3B minus MO3A.](image-url)
Figure 3. June 1979 mean sea level pressure for the southern hemisphere from MO3A (a) and EC3B (b) analyses. Contour intervals: 5 mb.
published by Guymer and Le Marshall (1981), which show low centres in close agreement with the EC3B values. These southern hemisphere MO3A – EC3B differences are of similar magnitude in other months; over northern oceans agreement is better. Over land agreement of sea level pressures, or of geopotential height fields at higher levels, is less good. This is mainly due to inconsistencies and biases in the MO3A system, for which height was a derived variable. The extrapolation of observations to the model’s surface, the tendency of the model to cool especially at low levels over land, and inaccuracies in the finite difference integration of the hydrostatic equation caused significant mean differences over land. For instance at 500 mb the MO3A geopotential is more than 2 dam lower for most northern hemisphere land areas during January. This is as large as the root mean square differences quoted for six different sets of analyses, including EC3B, by Jarvenoja (1982).

As an example of the wind fields we show the MO3A 200 mb mean for July in Fig. 4 and the vector wind difference between the EC3B and MO3A means in Fig. 5. In the northern hemisphere agreement is good, with jet intensities differing typically by only 1 m s\(^{-1}\). In the tropics and the southern hemisphere differences are somewhat larger, typically 2 m s\(^{-1}\). Results for January were similar, so the better agreement is due to data coverage, not season. Over the Indian Ocean area both sets of analyses give easterly or north-easterly winds in July. The MO3A winds are significantly stronger over Somalia and to the south of India, but both EC3B and MO3A show a jet maximum stronger than 20 m s\(^{-1}\) over the Arabian Sea. Neither analysis system used the Indian Ocean cloud wind data during July; these data were, however, used for the MONEX analyses of Krishnamurti et al. (1980). Their July mean flow was similar to MO3A and EC3B over India, but had a minimum of less than 15 m s\(^{-1}\) in the jet over the Arabian Sea. It seems likely that this is caused by a systematic underestimation of wind speed by the cloud track wind data. Such an effect has been noted elsewhere (Kallberg et al. 1982), and some of the observations plotted and drawn to closely in the Krishnamurti analyses have surprisingly low speeds. Overall, however, Kallberg et al. found that cloud wind data were beneficial to an analysis system similar to EC3B’s, alleviating the effect of the initialization on divergent circulations in areas which would otherwise be data voids and hence significantly changing the zonal mean Hadley circulation. In June the EC3B analyses did use Indian Ocean cloud track winds, and differences from the MO3A monthly means were greater.

4. Derived fields

(a) Divergence and vertical motion

Observations of vertical motion are entirely lacking from normal synoptic-scale networks, so vertical motion fields must be derived from other observations. The simplest method of doing this is directly, from the horizontal divergence fields, using the continuity equation. This can only be done if there is a sufficient homogeneous coverage of wind data to define the horizontal divergence, and if the analysis method is capable of using these data. We show below that this seems to be the case for large scales near 200 mb, where there are plentiful cloud wind and aircraft data. Otherwise more sophisticated diagnostic relationships must be used, relying in some way on the fact that atmospheric motions are ‘balanced’. The vertical motion fields which result from the EC3B initialization, as provided in the standard analysis data tapes, are an example of this. Adiabatic nonlinear normal model initialization is related to the quasi-geostrophic balance equation (Leith 1980), and the results obtained by the EC3B system are in realistic agreement with this theory for synoptic-scale extra-tropical motion (Lorenc 1981a; Hollingsworth
Figure 4. July mean wind at 200 mb from MOAA analyses.
Figure 5. Difference between July 200 mb mean winds, EC3B minus MO3A. Only differences greater than 2 m s$^{-1}$ are shown.
et al. 1984). However, diabatically driven motions, particularly important in the tropics, are not accurately represented. On the other hand the balance achieved, albeit incompletely, by the MO3A system, is based on the full forecast model including parametrization of diabatic processes, and the derived vertical motions reflect this. However, they are "noisy" due to the incomplete achievement of balance and are liable to reflect model biases.

Figure 6(a). Planetary-scale divergent modes for the period 6 May to 13 August 1979, calculated at spectral T12 resolution using MO3A analyses of 200 mb velocity potential. Time-mean, and the first three empirical orthogonal functions which explain most of the variance from the time-mean, scaled proportionally to the square root of the variance explained. Contour interval $1 \times 10^5$ m s$^{-1}$.

Figure 6(b). As 6(a) but for EC3B analyses.
The rather accurate determination of very-large-scale divergent flow is illustrated by Fig. 6, which shows the time mean and evolution of velocity potential at 200 mb over a 100-day period from May to August 1979. Study of divergent winds using velocity potential automatically emphasizes planetary-scale modes, and we have increased this effect by smoothing the fields by a spectral triangular truncation at wavenumber 12, and by applying a 1,2,1 filter to the 12-hourly fields to remove the diurnal cycle. Results using the MO3A analyses are shown in Fig. 6(a), those using EC3B in Fig. 6(b). (The time-varying coefficients are shown in Fig. 6(c)). The time mean fields show the large east-west (Walker cell) component of the summer monsoon circulation. The evolution is represented by calculating the empirical orthogonal functions (EOFs) which explain most of the variance from the time means. These data show the eastward propagating 30–50-day mode which interacted with the onset of the summer monsoon in 1979. Further description and interpretation is given by Lorenc (1984). The qualitative agreement between the two sets of analyses and this description is excellent. MO3A velocity potentials are somewhat more intense, probably because the EC3B analysis system underestimates divergent flows by giving some weight to its first guess, which for these modes is almost non-divergent. Because of the scale selectivity of velocity potential, changing the spectral truncation also has little qualitative effect on the time means or EOFs. At triangular 40 truncation the time mean divergent wind (i.e. the gradient of the velocity potential) across the Indian Ocean from 15°N 105°E to 15°S 45°E was 3-8
and 2.9 m s$^{-1}$ for MO3A and EC3B respectively, compared with 3.0 and 2.7 m s$^{-1}$ for the triangular 12 truncation shown in Fig. 6.

Figure 7. North-south vertical cross-sections from the Himalayas across the Bay of Bengal and the Indian Ocean, meaned for July and longitudes 80°E to 100°E. Top: MO3A; bottom: EC3B. Showing $u$ component (solid contours, negative shaded), $v$ and $w$ (arrows), potential temperature (pecked), and the model topography (heavy shading).
The shortcomings of the EC3B vertical motions derived from their adiabatic initialization are illustrated in Fig. 7. This shows a north–south vertical cross-section from the Himalayas, across the Bay of Bengal and the Indian Ocean. The cross-sections show the potential temperature, wind perpendicular to the cross-section, and wind in the plane of the cross-section. For this last the vertical (omega) component was obtained directly from the MO3A analyses in the top figure, and from the EC3B initialization in the bottom figure. For much of the area covered there is little east–west gradient in potential temperature, so for adiabatic flow the arrows should be parallel to the isentropes. This is clearly the case for much of the EC3B cross-section, showing the effect of their adiabatic nonlinear normal mode initialization. On the other hand the MO3A analyses show the effect of the diabatic heating over the Bay of Bengal during July.

(b) Variances

As well as mean fields it is important that the analyses accurately represent deviations from these. The time variability of the 500 mb height and mean sea level pressure fields on time scales of less than about 10 days has been used to indicate cyclone tracks. In the northern hemisphere the agreement between MO3A and EC3B for these statistics is good, usually within a few per cent. Both show somewhat similar distributions to those reported, for other years, by Blackmon (1976) and Lau et al. (1981), but for instance the January 1979 results from both sets of analyses show clearly the anomalous circulation pattern for this month, with a rather blocked flow. In the tropics the height variances are much smaller; here the MO3A variances are up to twice as large as the EC3B values. The MO3A values are probably too large because of gravity wave noise propagating from mid-latitudes, the EC3B values too small because of the lack of a diurnal cycle and the damping of tropical activity by the initialization. In the southern hemisphere the EC3B variances are larger, agreeing closely with those published by Guymer and Le Marshall (1981) and Physick (1981) using Australian analyses. The MO3A analyses show similar patterns, but some areas have less than half the variances during January. During July, when the MO3A system did use some TIROS-N temperature soundings, this difference was less but still significant.

Similar effects can be seen in the eddy kinetic energies. Figure 8 shows zonal mean cross-sections for July; the MO3A transient eddy kinetic energies are lower in the southern hemisphere than EC3B’s. As mentioned in section 2(c) the reasons for this are differences in data coverage and the less efficient assimilation of mass field data by the MO3A scheme. In January, when MO3A used NOAA-5 instead of TIROS-N temperature soundings, the differences in the transient eddy kinetic energies were even more marked.

The standing eddy kinetic energies agree much more closely, both showing a similar set of multiple centres at upper levels. This banded structure is much more noticeable than in longer period means given by Newell et al. (1974) and Oort and Rasmusson (1971). The major difference is at tropopause level, where the EC3B analyses lack strength in the monsoon return flow (see also Figs. 5 and 7).

(c) Fluxes and covariances

The momentum fluxes shown in Fig. 9 are the covariances between the $u$ and $v$ wind components for July. Figures 9(c) and (d) show the zonal mean of the transient eddy flux $\overline{u^'v'}$, (a) and (b) the zonal mean of the standing eddy flux $\overline{u^*v^*}$. Some extrema from the corresponding January cross-sections are shown in Table 1, rows 6–9 and 10–14. The differences in the monsoon flow near the tropical tropopause mentioned
Figure 8. Zonally averaged kinetic energies for July 1979. Standing eddy component (a, b) and transient eddy component (c, d) for MO3A (a, c) and EC3B (b, d).

above stand out in both months. Table 1 rows 8 and 12 confirm that the EC3B values are too low. In the southern hemisphere the effect of the weak eddies discussed in section 4(b) on the MO3A values is clear; in Table 1 rows 9, 13 and 14 they are consistently lower.

In the eddy temperature flux cross-sections this tendency is again the most significant difference. This can be seen in Table 1 row 16. However, the large flux near 200 mb (row 17) does not seem to be affected. In both seasons in the region 30–70°S 1000–
500 mb, which can be associated with the baroclinic development of surface depressions, the EC3B values are about 1.5 times the MO3A values. Elsewhere, for both transient and standing eddy fluxes, differences are smaller with no clear systematic errors.

The accuracy of southern hemisphere transient eddy temperature fluxes has been studied by Van Loon (1980), comparing Australian and US NMC analyses. At 850 mb in January 1979 he reports a maximum zonal mean flux near 45°S of $-10 \text{ K m s}^{-1}$ from the Australian analyses, agreeing well with Table 1 row 16 (note that Table 1 shows extrema near the quoted level). The Australian analyses, however, underestimate the upper extremum (row 17), giving a 200 mb value of only $-2 \text{ K m s}^{-1}$. Maps of 850 mb meridional fluxes from Australian and NMC analyses presented by Van Loon were
Figure 9. Zonally averaged momentum flux for July 1979. Standing eddy component (a, b) and transient eddy component (c, d) for MO3A (a, c) and EC3B (b, d).

markedly different. Maps of flux vectors at 700 mb for July from MO3A and EC3B are shown in Fig. 10. They agree rather better, but there are still large differences, with the MO3A fluxes being smaller in data-sparse regions. In adequately observed regions, such as Australia and most of the northern hemisphere, values differ by only 1 or 2 K m s⁻¹.
5. Budget calculations

(a) Effect of model biases

In budget studies observations of the rate of change of some conservative quantity are compared with observations of its sources and fluxes. They are useful both to gain understanding of the relative importance of different atmospheric processes, and to derive as residues components which are difficult to observe. Usually this involves subtracting terms of similar magnitude, amplifying the relative importance of errors. The effect of random errors can be reduced by averaging in space and time, but systematic errors remain important.
Budget studies using analyses like those in this study, which were made using data assimilation into a model, are particularly prone to biases. Separately both the atmosphere and the model (if it is well designed) satisfy the conservation laws, and balance the budget. However, if a slight bias exists in the model's mean value, then the assimilation of observations will act as an extra source term in the model, and if there are insufficient observations to determine flux terms to the same extent, spurious fluxes to balance this source will be generated by the model.

(b) Mean flow

In order to calculate budget terms due to the time mean flow it is necessary first to balance the mass budget, otherwise small errors in the analysed wind fields can have a critical effect on budget calculations (e.g. Alestalo 1981; Savijärvi 1982). Methods of correcting the wind fields are somewhat arbitrary; we have chosen to add constant corrections to the $v$ components at the northern and southern boundaries.

The effect of this adjustment on divergence and vertical motion is illustrated in Figs. 11 and 12 for the Bay of Bengal region (0-20°N, 80-100°E). The full lines in Fig. 11 show the divergences of the analysed winds. As expected the EC3B values are large only near 200 mb and the surface, where there were sufficient data, and are near zero at other levels. The 200 mb outflow is larger, leading to a vertically integrated mass loss that would empty the volume in 51 days. The corrected divergences are given by dashed
lines. (The recalculation is less necessary for MO3A, whose wind and vertical velocities were calculated from the same sigma coordinate analyses, but minor imbalances in these, and interpolation and finite difference errors mean that these pressure coordinate calculations show some differences.) Figure 12 shows the initialized (solid lines) and recomputed (dashed lines) vertical motion.

The arbitrary choice in the way the wind correction is distributed in the vertical can significantly affect budget calculations. Uncorrected, the EC3B winds in the example above gave a vertically integrated moisture convergence of 6 mg m$^{-2}$ s$^{-1}$; corrected as shown this became 18. It is likely that the boundary layer convergence is underestimated, while the 200 mb mass divergence as analysed is more correct; allowing for this would yield an even larger moisture convergence. The corresponding MO3A values are 42 and 38. Rasmusson (1967) showed that for humidity budgets for N. America the details of the flow between 1000 and 850 mb were important, and that these could be affected near coasts by diurnal effects. Our comparisons used standard pressure level data, and the EC3B analyses had little diurnal cycle. Repeating the MO3A calculation with levels every 50 mb changes the vertically integrated moisture convergence by about 10%.

Repeating the mass budget calculations for the same 0–20° N latitude band across the Pacific gave much worse agreement than in Figs. 11 and 12, with EC3B showing very little divergent flow. For other regions, particularly in mid-latitudes, agreement is better. However, it is clear that, although the qualitative picture presented by the analysed divergences may be correct, as may be the extratropical vertical motions from the EC3B system’s initialization, great care must be taken about their internal consistency and accuracy before they can be used quantitatively.
Figure 11. July area mean divergence for 0–20°N 80–110°E. Left: MO3A; right: EC3B. Solid curve: before mass balance correction; dashed: after.

Figure 12. As Fig. 11 but for vertical velocity $\omega$. 
(c) An energy budget example

Having discussed in sections 4(c), 5(a) and 5(b) the main sources of error in a budget calculation, here we present an example. Bretherton et al. (1982) have undertaken a feasibility study for CAGE, which is a possible experiment to study the oceanic energy budget of the North Atlantic. For this experiment the energy flux at the ocean surface is required. One way of calculating this is from the atmospheric energy budget and the net radiation. In order to assess the accuracy of these indirect calculations, Bretherton et al. compared energy flux divergences calculated from climatological data given by Oort (1983) with data calculated from EC3B FGGE analyses. A more satisfactory procedure is to compare analyses for the same period. We have compared energy flux divergences from EC3B and MO3A analyses for July 1979.

For this study, the energy fluxes have been divided into sensible heat, latent heat and geopotential components (kinetic energy has been omitted). Each of these is made up of a mean flow term, for which a mass budget correction has been made, and a transient eddy term. The energy flux divergences have been vertically integrated from the surface to 100 mb and averaged over four rectangular areas, each approximating to one of the northern hemisphere continents or oceans. The results and the exact areas used are detailed in Table 2.

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<td>20-60°N140°E-125°W</td>
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<td>Total</td>
<td>29.8</td>
<td>25.8</td>
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</table>

For the CAGE experiment Bretherton et al. suggest that an accuracy of 10 W m\(^{-2}\) would be required for the surface energy flux. Our results suggest that this criterion could just be met for the N. Atlantic region, where our totals differ by 4 W m\(^{-2}\). However, it should be pointed out that differences in the mean divergence and vertical motion cause differences in the geopotential and sensible heat fluxes which are larger than 10 W m\(^{-2}\), but which are largely compensating. For the other regions the differences between the MO3A and EC3B totals are similar in magnitude. It is somewhat surprising that the largest discrepancy is for the N. America region; in this case the differences in each of the three components are in the same sense.

It should be pointed out that these indirect calculations of surface fluxes are open to the model biases discussed in 5(a). For instance in areas with little detailed data, the evaporation will be determined by the model’s parametrization of boundary layer processes, together with prescribed sea surface temperatures. Again, lacking detailed observations, the horizontal fluxes will be influenced by the model to balance these surface fluxes.
6. SUMMARY AND CONCLUSIONS

A selection of general circulation statistics from two sets of analyses has been presented. Qualitative agreement was very good, even in the tropics and southern hemisphere. Quantitative agreement was also in general good: most of the systematic differences seen could be traced to known characteristics of the analysis systems.

The main systematic errors in the EC3B analyses were associated with the nonlinear normal mode initialization in that system, which damped diabatically driven circulations. There were sufficient data near 200 mb, and near the surface, for planetary-scale divergent modes to be accurately analysed despite the initialization's effect on the first guesses, but their intensity was slightly less than in MO3A analyses, and detailed structure was lacking. The smoothing effect of the vertical interpolations in the EC3B system, its lack of an adequate diurnal cycle, and the lack of adequate boundary layer resolution in the standard pressure levels on which the analyses were available, make these analyses inaccurate for the calculation of statistics such as moisture convergence.

The main systematic error in the MO3A analyses was an underestimation of the intensity of transient eddies in the southern hemisphere. This was due partly to model bias, and partly to inefficient use of mass data in the MO3A analysis system, probably exacerbated by the poorer data coverage in the IIa dataset. Biases in the MO3A system also adversely affected its mean temperature and height fields.

Comparison with statistics available from some other analysis systems confirms that differences between EC3B and MO3A statistics are generally typical, and hence provide a reasonable indication of their likely accuracy. However, in some cases study of the analysis systems and their likely biases can indicate that one set is more likely to be in error.

As long as the above features are remembered, both sets of analyses provide a description of the circulation during 1979 which is nearly always qualitatively correct, and generally numerically accurate. Either set may be used to study any aspect of the general circulation, although the EC3B analyses are to be preferred in the southern hemisphere and the MO3A analysis in the tropics. However, humidity fields, and derived variables such as convective stability and budget residues, may be significantly affected by the models used in the analysis systems, and little more accurate than a good general circulation model simulation. Care should thus be exercised when using these analyses to verify such simulations.

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