Comparative Energetics of FGGE Re-Analyses Using the Normal Mode Expansion

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Abstract

In this study, spectral energetics characteristics of FGGE III-b original analyses and the re-analyses are compared in order to assess the achievement of the FGGE project. We compare both of the GFDL and ECMWF versions of the old and new FGGE analyses. It has been noted that the old version of the FGGE GFDL data is noisy, containing excessive small-scale disturbances. The GFDL dataset also appears to be inconsistent with respect to the wind and mass balance. These characteristics result largely from the technique of the continuous data injection as well as from GFDL's philosophy such that the observed data should avoid model bias as much as possible. In contrast, the old version of the FGGE ECMWF data appears to be too smooth, showing a significant damping of divergent wind, especially in the tropics. The data assimilation and initialization cycle at the ECMWF is based on a philosophy such that a successful analysis is one which leads to a successful weather prediction. With this concept, the ageostrophic component of the atmospheric motion is damped to less than 5 percent in magnitude. According to normal mode energetics diagnosis, which separates atmospheric motions into Rossby and gravity modes, it turns out that the gravity mode energy level ECMWF is only 58 percent of that in GFDL for the old analyses.

The FGGE original analyses have been revised by the FGGE re-analysis based on knowledge and criticism gained after the FGGE. The GFDL re-analysis is now smoother, and the ECMWF re-analysis contains much divergent wind. In this study we have conducted the same normal-mode energetics analysis for the FGGE re-analyses, and the results are compared with the FGGE original analyses. It is found, however, that the gravity-mode energy level in ECMWF is still only 42 percent of that in GFDL. The significant difference remains in the re-analyses as before. The possible causes of this discrepancy are discussed.

1. Introduction

One of the main purposes of the FGGE (First GARP Global Experiment) was to improve the medium-range weather forecasting. Improving the data assimilation system as well as the dynamical forecasting models was the main objective of the FGGE. The FGGE III-b datasets were produced by two central institutions: the European Center for Medium Range Weather Forecasting (ECMWF) and the Geophysical Fluid Dynamics Laboratory (GFDL). After the release of the FGGE III-b datasets, numerous diagnostic studies have

been conducted to evaluate and compare the data assimilation systems of different institutions (*e.g.*, Bengtsson *et al.*, 1982; Kung and Tanaka 1983; 1984; Lau 1984a,b; Hollingsworth *et al.*, 1985; Rosen *et al.*, 1985; Holopainen and Fortner 1986; Paegle *et al.*, 1986).

From those comparative studies, the characteristics of different FGGE datasets by different institutions became apparent. It was noted that the GFDL analysis of the FGGE data is noisy, containing excessive small-scale structures, and is unbalanced for the mass and momentum fields. The spurious excitation of the small-scale disturbances resulted mainly from the continuous data insertion, which is unique in the

GFDL analysis scheme. Arpe *et al.* (1985) noted that the ECMWF analysis was more faithful to the available data than the GFDL analysis in that the analyzed data by the ECMWF was a better fit to the observations. The poor fit in the GFDL is, to a large extent, attributed to the small-scale irregularities due to the continuous data insertion.

On the other hand, the ECMWF analysis is criticized as having major defects in tropical data. The vertical velocity is weaker in the ECMWF than in the GFDL (Kung and Tanaka 1983), and the divergent wind is damped by a factor of two due to the adiabatic version of the non-linear normal-mode initialization (NLNMI) (see Paegle *et al.*, 1986). The imposed 95 % constraint toward the geostrophic balance may be justified in mid-latitudes since the atmospheric states produced by the assimilation are expected to remain reasonably close to a slow manifold. Yet, the constraint was too restrictive in the tropics.

After the production of the original FGGE analysis, the ECMWF has undergone many improvements in the assimilation technique. The day-to-day operational experience has provided invaluable information on the performance of the system. There has been a continuous process of modifications and improvements, including a diabatic version of the NLNMI. With this accumulated knowledge of the defects in the former analysis methods, both of the ECMWF and GFDL conducted the FGGE III-b re-analyses based on the improved analysis techniques.

The main changes of the ECMWF re-analysis are summarized by Uppala (1986). The notable modifications and improvements include the applications of new optimum interpolation (OI) structure functions; improved vertical interpolation of the analysis increments; improved humidity analysis; new error statistics; new data selection algorithms; introduction of a blacklist; treatment of SATOB winds in the analysis; application of diabatic non-linear normal-mode initialization; use of analyzed sea surface temperature; improved spectral truncation from N48 to T63 for the forecast model; and improved physical parameterization. The included and modified physics are a diurnal cycle, revised shallow convection scheme, new radiation scheme, cloud coverage algorithm, and realistic steeper orography. The results from the new scheme show intensified divergent and convergent winds in low-latitudes and a better fit of the analysis field to the observed data (see Uppala 1986).

Although the FGGE re-analysis for the ECMWF was released for the public in the mid-'80s, the completion and the public release for the GFDL re-analysis was not achieved until the quite recent '90s. The revised assimilation system for the GFDL is described by Stern and Ploshay (1992). The major improvement is summarized by Ploshay *et al.* (1992),

comparing the original and re-analyses of FGGE III-b data in reference to those by the ECMWF. The new features in the GFDL re-analysis include: a reduction in the assimilation cycle from 12 to 6 hours; the use of a 6-hour first guess for the optimum interpolation (OI) analysis as opposed to the previous use of persistence as a first guess; an extension of the OI search range from 250 km to 500 km with an increase in the maximum number of observations used per analysis point from 8 to 12; the introduction of incremental linear normal-mode initialization (ILNMI) for the first 4 vertical modes with a 6-hour period truncation, eliminating the periodic NLNMI; and an increase in the horizontal resolution of the assimilating model from R30 to R42, rhomboidally truncated. It is noted by Stern and Ploshay (1992) and Ploshay *et al.* (1992) that the new assimilation system shows a significant reduction in the level of noise, improved consistency between the mass and momentum analyses; and a better fit of the analysis field to observations.

In order to assess the achievement of the FGGE project, especially for the improvement in the data assimilation system, it is important to conduct comprehensive comparative studies between the FGGE original analysis and the re-analysis produced by the two central institutions of the ECMWF and GFDL. One of the useful diagnostic tools for that purpose is the normal-mode energetics developed by Tanaka (1985) and Tanaka and Kung (1988). The normal-mode energetics is an extension of the standard spectral energetics by Saltzman (1957; 1970). In this diagnostic scheme, the one-dimensional spectral decomposition of energy is expanded to three-dimensional (3-D) spectral domain. Observed atmospheric data are expanded in the 3-D normal modes of a resting atmosphere constructed by a product of vertical structure functions and Hough harmonics. The eigenfrequency of a 3-D normal mode may be regarded as a 3-D scale index for each of the gravity (first kind) and Rossby (second kind) modes due to the intrinsic dispersion relations (see Bare 1972). The atmospheric energy spectrum is then plotted as a function of the 3-D scale index, and the non-linear energy interactions among the different scales of motion are examined. This diagnostic analysis is especially useful in comparing the amount of high-frequency gravity modes which are closely related to the divergent field and are most sensitive to the assimilation technique employed.

The purpose of this study is to compare the energetic characteristics of the FGGE re-analyses with those of the FGGE original analyses. The comparison is made of both the ECMWF and GFDL versions of the original and re-analyses using the normal-mode energetics scheme. Special attention is paid to the energy spectra of the Rossby and gravity modes over the 3-D scale index. The dif-

ference in the high-frequency gravity mode energy between the ECMWF and GFDL is presented. Finally, an assessment is made of how the difference in the original analyses is modified by the new assimilation systems.

2. Data and analysis scheme

The FGGE re-analyses by the ECMWF and GFDL for the Special Observing Period 1 (SOP-1) are obtained from the National Center for Atmospheric Research (NCAR). Twice daily (0000 and 1200 UT) meteorological variables of horizontal wind vector $V = (u, v)$, vertical p-velocity $\omega (= dp/dt)$, temperature T , geopotential height Z , and relative humidity R are defined on 1.875° by 1.875° horizontal grids at 12 mandatory vertical levels of 1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, and 50 hPa. For the GFDL dataset, the top two vertical levels are set at 50 and 30 hPa rather than aforementioned levels. These FGGE data are interpolated onto 5° longitudinal grids and 60 Gaussian latitudinal grids. The data format is the same as used by Tanaka and Kasahara (1992) for a study of geostrophic modes of the zonal wavenumber zero.

The analysis scheme of the normal mode energetics has been detailed in Tanaka (1985) and Tanaka and Kung (1988). A brief description of the scheme is summarized here. First, the vertical structure functions and Hough harmonics are computed, using a reference state of the global mean temperature. Applied to a sequence of vertical, Fourier, and Hough transforms, the primitive equatoin become a system of ordinary, dimensionless differential equations in terms of the spectral expansion coefficients in the 3-D spectral domain:

$$\frac{d}{dt}w_{nlm} + i\sigma_{nlm}w_{nlm} = b_{nlm} + c_{nlm} + d_{nlm}, \quad (1)$$

where the complex variables of w_{nlm} , b_{nlm} , c_{nlm} , and d_{nlm} represent, respectively, the expansion coefficients for a dependent variable vector (u, v, Z) , non-linear term vector for the momentum field, for the mass field, and for the diabatic processes including frictional force. The symbol i represents the imaginary unit, time t is normalized as $\tilde{t} = 2\Omega t$ using the angular speed of the earth's rotation Ω , and σ_{nlm} is a dimensionless eigenfrequency obtained as a solution of Laplace's tidal equation with a basic state at rest. The subscripts n, l, m are for the zonal wavenumber, meridional index, and vertical index, respectively. The vertical indices $m = 0$ and $m \neq 0$ represent barotropic (external) and baroclinic (internal) modes, respectively. We have used a total of 50 meridional modes, including 26 Rossby modes and 12 eastward and 12 westward gravity modes.

An element of a total energy norm is simply defined by an absolute value of the expansion coefficient:

$$E_{nlm} = \frac{1}{2}p_s h_m |w_{nlm}|^2, \quad (2)$$

where the dimensional factors p_s and h_m are, respectively, a constant pressure near the surface and an equivalent height of m -th vertical index. The corresponding energy balance equation is given by differentiating (2) with respect to time and substituting (1) in the time derivatives:

$$\frac{d}{dt}E_{nlm} = B_{nlm} + C_{nlm} + D_{nlm}. \quad (3)$$

According to Eq. (3), the time change of the element of the total energy, E_{nlm} , is caused by the three terms in the right hand side: i) non-linear mode-mode interaction of kinetic energy B_{nlm} , ii) that of available potential energy C_{nlm} , and iii) a net energy source and sink due to the diabatic process D_{nlm} , which includes both generation and dissipation of energy. The diabatic process is evaluated as the residual balance of Eq. (3).

Results of the energetics analysis presented in this study are of the global variables. The energy spectrum expressed as a function of σ_{nlm} represents the 3-D spectral energy distribution. By summing the energy terms with respect to all indices but n , the result describes the zonal energy spectrum, while the summations over n and l describe the vertical energy spectrum. It is unique in the normal mode energetics that the energy summation can be separately taken for the Rossby and gravity modes. Therefore, we can examine the energy levels and the interactions separated in Rossby and gravity modes.

3. Results of the analysis

Figure 1 illustrates the energy spectra of the ECMWF and GFDL re-analyses expanded in the 3-D NMFs. The energy elements of E_{nlm} in Eq. (2) are plotted as functions of the scale index $|\sigma_{nlm}|$ for 50 meridional indices l , zonal wavenumbers $n = 1-6$, and vertical indices $m = 0$ (Fig. 1a) and $m = 2$ (Fig. 1b). The 50 meridional indices include 26 Rossby modes in the low-frequency side and 24 gravity modes in the high-frequency side. These two kinds of distinct modes are connected by the mixed Rossby-gravity modes (*i.e.*, the largest-scale Rossby modes) which have the highest frequencies among the Rossby modes. The largest-scale gravity modes are referred to as Kelvin modes, which appear at the lowest-frequency gravity modes.

As is shown by Tanaka (1985), clear energy peaks appear at the intermediate meridional indices within the Rossby modes. Separated by these peaks associated with each zonal wavenumber, the energy levels decrease toward the Rossby mode régime at the low-frequency side indicating a -3 power law and toward the gravity mode régime at the high-frequency side. The energy spectra of the Rossby mode régime are found to line up along a universal

Fig. 1. Spectral distributions of atmospheric total energy (Jm^{-2}) in the frequency domain for ECMWF (left) and GFDL (right) re-analyses for (a) the barotropic component ($m = 0$) and (b) the baroclinic component ($m = 2$). The dimensionless eigenfrequencies $|\sigma_i|$ in Eq. (1) are used in the abscissa to represent the meridional scale of atmospheric motions. Rossby and gravity modes are plotted in the low- and high-frequency ranges, respectively, for zonal wavenumbers $n = 1$ to 6.

Fig. 2. Comparison of the energy spectra (Jm^{-2}) for the GFDL and ECMWF re-analyses in the frequency domain for (a) the barotropic component ($m = 0$) and (b) for the baroclinic component ($m = 2$). The dimensionless eigenfrequencies σ_i are used in the abscissa as in Fig. 1 to plot energy levels for zonal wavenumbers $n = 1$ to 6. The modal energy levels for the GFDL re-analysis are plotted with symbols, and the difference bars without symbols are drawn toward the energy levels for the ECMWF re-analysis.

Rossby mode energy spectrum when plotted against a phase speed $c_{nlm} = \sigma_{nlm}/n$ instead of σ_{nlm} (see Tanaka and Kasahara 1992).

The comparison of the external modes of $m = 0$ (Fig. 1a) for the ECMWF and GFDL re-analyses shows similar energy spectra for the Rossby modes. However, a marked discrepancy is found in the gravity-mode energy spectrum. The gravity mode spectrum for the GFDL exhibits a $-3/5$ power law with respect to the scale index σ_{nlm} . The larger the modal scale is, the higher is the energy level. The largest-scale gravity modes indicate energy levels higher than 200 Jm^{-2} .

In contrast, the gravity-mode energy levels for the ECMWF are lumped together near 10 Jm^{-2} , and a power law is not evident. The low-frequency (*i.e.*, large-scale) gravity modes are obviously damped for the ECMWF. The energy level is one order of magnitude lower than the results for the GFDL.

Figure 1b compared the same energy spectra, but

for an internal mode of $m = 2$. Again, the Rossby-mode energy spectra are similar for these two re-analyses. It is shown that planetary-scale Kelvin modes dominate the other gravity modes, and the energy levels reach up to 1000 Jm^{-2} for these two re-analyses. The high-frequency Rossby modes, especially the mixed Rossby-gravity modes, and the low-frequency gravity modes are mixed along the same energy spectral slope, connecting the Rossby and gravity mode régimes. A notable discrepancy is found in the high-frequency (*e.g.*, small-scale) gravity modes; the energy level of the GFDL is about one order of magnitude higher than that of the ECMWF for the smallest resolvable-scale modes.

The difference in the modal energy levels for the ECMWF and GFDL are visually presented by difference bars in Fig. 2. The modal energy levels for the GFDL re-analysis are plotted with symbols, and the difference bars are drawn toward the energy levels for the ECMWF re-analysis without symbols. As

(b)

 $m=2 \quad n=1 \text{ to } 6$

Fig. 2. (Continued)

discussed above, the difference is relatively minor for the Rossby modes. The largest deviation is evident in low-frequency (*i.e.*, large-scale) external gravity modes of $m = 0$ and in high-frequency (*i.e.*, small-scale) internal gravity modes of $m = 2$.

Figure 3 illustrates zonal energy spectra for $n = 1-15$ as obtained by summing all meridional and vertical indices for Rossby and gravity modes. The results are compared for reanalyses by the ECMWF (dashed lines) and GFDL (solid lines). Refer to the Fig. 2 of Tanaka and Kung (1988) for the original analysis.

In the original analyses (not shown), the Rossby mode energy level for the ECMWF is slightly higher than that for the GFDL, but the difference is relatively minor. The gravity-mode energy level is, however, substantially different between these two original analyses. The energy levels of the GFDL are consistently higher, especially for large n . The GFDL analysis is about 4 time larger than the ECMWF analysis at $n = 15$. For planetary waves of $n \leq 4$, the eastward gravity modes are greater than the westward gravity modes due to the dominant Kelvin waves.

The discrepancies in the gravity modes between

the ECMWF and GFDL original analyses still remains for the FGGE re-analyses as shown by Fig. 3. The gravity-mode energy is consistently higher in the GFDL than in the ECMWF. The difference has even grown, as shown later in Table 1.

Figures 4 and 5 illustrate vertical energy spectra for the ECMWF and GFDL re-analyses calculated for $n = 0, 2, 4, 6$, respectively, by summing all meridional indices for the Rossby and gravity modes. The vertical wavenumber is defined here as the inverse of the equivalent height, h_m^{-1} , for vertical modes $m = 0-10$. The Rossby-mode energy level dominates the gravity-mode one. The largest amount of energy is contained in the internal mode of $h_m = 150$ m for the geostrophic mode ($n = 0$), whereas the energy peaks are seen at the external Rossby mode for $n \neq 0$. The vertical energy spectra of these two re-analyses are virtually same for the Rossby modes.

The gravity-mode energy spectrum for $n=0$ in the ECMWF is almost flat for low-order internal modes, except for the damped external mode. A minor energy peak at $h_m = 150$ m appears only in the GFDL. A clear peak is seen for $n = 6$ at $h_m = 150$ m, especially in the ECMWF. The peak energy levels are

Zonal Energy Spectra

Fig. 3. Zonal energy spectra (Jm^{-2}) over $n = 1-15$ for ECMWF (dashed) and GFDL (solid) re-analyses. Dots, squares, and circles denote Rossby modes and westward and eastward gravity modes, respectively.

reasonably close for these two re-analyses, but a discrepancy emerges at $m = 1, 2$, and higher vertical modes.

The non-linear energy transformations of kinetic energy B_{nlm} and available potential energy C_{nlm} are compared (not shown) for the ECMWF and GFDL re-analyses. The result shows that the largest transformation of available potential energy occurs from the zonal baroclinic mode at $m = 4$ toward the same baroclinic mode but with eddies centered at $n = 6$. The eddy available potential energy is converted to eddy kinetic energy by means of baroclinic conversions, which appear to excite the internal modes of synoptic-scale motions centered at $m = 4, n = 6$. The kinetic energy generated in the internal synoptic motions is redistributed by the non-linear energy interactions to external motions ($m = 0$) of planetary waves and zonal flow. There should be a net

upscale energy cascade from internal synoptic disturbances to external planetary-scale flows. In the total ($n = 0-15$), it is found that the kinetic energy generated at $h = 150$ m is transferred to the external mode ($h_m = 9700$ m) which has a larger vertical scale than the kinetic energy source range. We can conclude from the result that the kinetic energy transfer in the vertical spectral domain is fundamentally upscale. The downscale energy transfer from the source range, to smaller-scale motions is not obvious in present study.

The comparison for the results of the ECMWF and GFDL re-analyses shows reasonable agreement in energy transformations. The basic characteristics of the energy transformation are determined by the Rossby modes, and the contributions from the gravity modes are relatively small.

Table 1. Comparison of energy levels for the FGGE original and re-analyses by the ECMWF and GFDL. The energy levels are partitioned in zonal ($n = 0$) and eddy ($n = 1-15$) and in barotropic ($m = 0$) and baroclinic ($m = 1-10$) components for Rossby modes, westward and eastward gravity modes, and the sum of the gravity modes, respectively. Units are 10^3 Jm^{-2} .

GFDL original analysis					
n	m	Rossby	W. Gravity	E. Gravity	W+G Gravity
0	0	837.2	0.7	0.7	1.3
0	1-10	4826.5	3.9	3.9	7.9
1-15	0	381.1	1.3	1.3	2.6
1-15	1-10	696.7	30.7	36.1	66.8

GFDL re-analysis					
n	m	Rossby	W. Gravity	E. Gravity	W+G Gravity
0	0	849.5	0.6	0.6	1.2
0	1-10	4866.0	4.1	4.1	8.1
1-15	0	426.0	2.4	2.0	4.4
1-15	1-10	754.8	35.3	41.2	76.5

ECMWF original analysis					
n	m	Rossby	W. Gravity	E. Gravity	W+G Gravity
0	0	912.7	0.1	0.1	0.2
0	1-10	4899.0	1.7	1.7	3.4
1-15	0	476.6	1.5	1.9	3.4
1-15	1-10	757.4	14.6	23.8	38.4

ECMWF re-analysis					
n	m	Rossby	W. Gravity	E. Gravity	W+G Gravity
0	0	865.5	0.1	0.1	0.3
0	1-10	5093.2	3.3	3.3	6.7
1-15	0	479.7	1.0	1.0	2.1
1-15	1-10	793.6	13.1	19.5	32.6

4. Discussion

Finally, the results of the normal mode energetics is summarized in Table 1 for the four FGGE datasets of the ECMWF and GFDL original analyses and the re-analyses during the SOP-1. The total energy levels in the atmosphere are decomposed into zonal barotropic ($n = 0, m = 0$), zonal baroclinic ($n = 0, m \neq 0$), eddy barotropic ($n \neq 0, m = 0$), and eddy baroclinic components ($n \neq 0, m \neq 0$), for the Rossby modes, westward gravity modes, and eastward gravity modes. Zonal gravity-mode energy associated with negative and positive eigenfrequency is listed in the column of westward and eastward gravity modes, for convenience.

With this partitioning, the largest amount of energy is contained in the zonal baroclinic component ($n = 0, m \neq 0$) of the Rossby modes, due to the dominant available potential energy. The mean energy level for these four analyses is $4921 \times 10^3 \text{ Jm}^{-2}$. The discrepancy among these four datasets is within 3 %; the results are reasonably consistent with each

other. For the Rossby modes, the other mean energy levels are 866, 440, and 751 (10^3 Jm^{-2}) for ($n = 0, m = 0$), ($n = 1-15, m = 0$), and ($n = 1-15, m = 1-10$), and the discrepancies are 4 %, 11 %, and 6 %, respectively. The results are regarded as reasonably consistent with each other.

Contrary to this fact, the gravity-mode energy levels indicate significant discrepancies between the ECMWF and GFDL analyses. The total energy levels partitioned as gravity modes are 79, 90, 45, and 41 (10^3 Jm^{-2}) for the GFDL original and re-analyses and ECMWF original and re-analyses, respectively. Although the energy itself is small, the gravity modes of the GFDL re-analysis contain about a twice larger amount of gravity-mode energy than does the ECMWF re-analysis. It is worth noting that the gravity-mode energy has increased by 15 % from 66.8 to 76.5 (10^3 Jm^{-2}) for the GFDL re-analysis compared with its original analysis, whereas it has decreased by 10 % from 38.4 to 32.6 (10^3 Jm^{-2}) for the ECMWF re-analysis. Hence, the discrepancy between the ECMWF and

Fig. 4. Vertical energy spectra (Jm^{-2}) for the ECMWF re-analyses calculated for $n = 0, 2, 4, 6$. The vertical wavenumber is defined as the inverse of the equivalent height, h_m^{-1} , for vertical modes $m = 0-10$.

Fig. 5. As in Fig. 4 but for the GFDL re-analysis calculated for $n = 0, 2, 4, 6$.

GFDL has grown rather than been reduced by the re-analyses. This result is not anticipated from the fact of smoother fields in the GFDL re-analysis (Ploshay *et al.*, 1992) and intensified Hadley circulation in the ECMWF re-analysis (Uppala 1986).

The increased gravity-mode energy in the GFDL is attributed to the eddy internal components. Since the ILNMI is applied only for the first four vertical

modes, the excitation of the gravity modes in the higher vertical modes has not been removed by the re-analysis. The result of this study implies that the mass and momentum fields of the GFDL re-analysis are smoother, yet the flow is more ageostrophic than before. This finding can be related to the poor fit of the analyzed geopotential against the observed data, as discussed by Ploshay *et al.* (1992). The dynami-

cal inconsistency between the mass and wind fields related to the poor fit in geopotential may excite the gravity waves to raise the gravity-mode energy level.

In the ECMWF, the Hadley circulation is intensified as can be seen by the increased gravity-mode energy of ($n = 0$, $m = 1-10$) from 3.4 to 6.7 (10^3 Jm^{-2}). However, the overwhelming reduction in the eddy baroclinic component ($n = 1-15$, $m = 1-10$) results in the decreased gravity-mode energy in the ECMWF as shown before.

5. Concluding remarks

FGGE III-b original analyses were produced by two main institutions of the ECMWF and GFDL in the early 1980s. Numerous diagnostic analyses have revealed that the GFDL original analysis is too noisy with abundant small-scale disturbances excited by the continuous data injection to the analysis-forecast system. The ECMWF analysis indicates a defect in the tropics with damped Hadley circulation resulting from the adiabatic version of the non-linear normal-mode initialization. Based on those criticism and the accumulated knowledge about the characteristic biases of the original analyses, new analysis techniques have been developed and implemented to the FGGE re-analysis scheme. Recently, both of the institutions have completed the FGGE re-analyses. It may be important to analyze the new features of the re-analyses compared with the original analyses so as to assess the success of the FGGE project.

This study conducted the comparative diagnosis of the FGGE III-b re-analyses produced by the ECMWF and GFDL. In particular, the energy levels of the atmospheric gravity modes are examined by means of the recently developed normal-mode energetics scheme. In this diagnosis scheme, analyzed meteorological data are expanded into vertical normal modes and Hough harmonics, and the evaluated energy levels for Rossby and gravity modes are compared for the original and re-analyses by the ECMWF and GFDL.

As a result, we confirmed that the Rossby mode energy levels are virtually the same for these FGGE datasets. The Rossby modes appear to be less sensitive to the analysis technique. However, a notable discrepancy is found in the gravity-mode energy spectrum between the ECMWF and GFDL analyses. For the external modes, the GFDL analyses exhibit a $-3/5$ power law in the gravity mode energy spectrum with respect to the 3-D scale index σ_{nlm} . The gravity mode energy levels for the ECMWF are, however, lumped together at a very low level, and a power law is not evident. The low-frequency (*i.e.*, largest-scale) eddy gravity modes are significantly damped for the ECMWF, and the energy level is one order of magnitude lower than that of the GFDL re-analysis. The internal gravity modes are also damped in the ECMWF by an order of mag-

nitude for the high-frequency (*i.e.*, small-scale) components, compared with the GFDL re-analysis. We find that the gravity-mode energy in the ECMWF re-analysis has increased only in the zonal motion associated with the enhances Hadley circulation. However, the overwhelming reduction in the eddy baroclinic component results in the decreased gravity-mode energy in the ECMWF re-analysis. It is worth noting that the gravity-mode energy has increased by 15 % for the GFDL re-analysis compared with its original analysis, whereas it has decreased by 10 % for the ECMWF re-analysis. Hence, the discrepancy in the gravity mode energy between the ECMWF and GFDL has been grown rather than been reduced by the re-analyses. This result is not anticipated from the fact of smoother fields in the GFDL re-analysis (Ploshay *et al.*, 1992) and intensified Hadley circulation in the ECMWF re-analysis (Uppala 1986).

Ploshay *et al.* (1992) compared the GFDL original and re-analyses and discussed the poor fit of the analyzed geopotential field to the observed field in the re-analysis. It is inferred by this study that the GFDL re-analysis contains larger amount of ageostrophic wind related to the poor fit of the geopotential field, although the analyzed mass and momentum fields are smoother than before.

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ノーマルモード関数展開を用いた FGGE 再解析データのエネルギー比較解析

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本研究では、FGGE プロジェクトの評価を目的として FGGE III-b 解析データとその再解析データのスペクトルエネルギー解析を行ない両者を比較した。解析に用いたデータは GFDL および ECMWF の新旧 FGGE III-b 解析の 4 種類である。これまでの解析結果によると、GFDL の旧 FGGE 解析はノイズとしての小スケール擾乱を大量に含み、しかも風の場合と質量場のバランスがわるいことが指摘されていた。このような特徴は GFDL 特有の連続データ同化技術の適用によると考えられるが、解析値をより観測値に近付けモデルによるバイアスを極力おさえようとする GFDL の主義が反映されている。それに対し ECMWF の旧 FGGE 解析データは過度に平滑化されており、赤道付近の発散風が弱められているという指摘があった。より優れた解析値とはより良い長期予報を与える初期値のことであるとする ECMWF の主義がこのデータの特徴に反映されている。そのため、大気の非地衡風成分は一律 5 % 以下に押さえるという操作が施された。したがって、大気の運動をノーマルモード展開により Rossby 波と重力波に分離してエネルギーレベルを比較すると、ECMWF の重力波成分は GFDL の 58 % しかないという結果が旧 FGGE データに関して得られている。

FGGE プロジェクトにより得られた客観解析手法に対するこのような評価に基づいて、FGGE データの再解析が行なわれた。再解析の結果、GFDL データは旧解析よりも平滑化され、ECMWF データは発散風を豊富に含むようになった。しかし、FGGE 再解析データを同じノーマルモードエネルギー展開法により解析し、旧 FGGE 解析の結果と比較した本研究結果によると、ECMWF の再解析に含まれる重力波成分は GFDL の 42 % しかなく、両者の差異は改善されていない事が明らかになった。本研究では、このような、両者の差異が生じた原因についても考察した。