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ATMOSPHERIC ENERGY BUDGETS FROM FGGE AND STATION DATA

by

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Abstract

The atmospheric kinetic energy, sensible and latent heat, and total energy budgets are presented for the FGGE year over North America and the North Atlantic areas. They are based on ECMWF FGGE IIIb analyses on sigma levels after initialization. Similar budgets are also calculated for the adjacent areas of Mexico and the Gulf of Mexico from the 10-year monthly mean and covariance analyses based on the radiosonde station network (OORT, 1983). The results in the two sets of analyses agree fairly well in their basic features, indicating increased tropospheric dissipation over the mountainous area, decreased stratospheric dissipation and even acceleration in the mountainous area, acceleration of the 700 mb flow over the ocean area, and strong, deep low-level heating over the sea surfaces.

Compared with the budgets from ECMWF operational data (for 1980), the atmospheric total energy flux divergence from the FGGE analyses is improved in that the differences with satellite-derived net radiation estimates over North America are reduced from 19 to 7.5 W/m^2. The difference is much larger (70 W/m^2) in the station data.

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1. *Introduction*

The Global Atmospheric Research Program (GARP) First Global Experiment (FGGE) was aimed to produce a high quality data set for one year, which could be used to improve our knowledge of the climate system in providing more accurate initial (and verification) conditions for numerical models of all kinds, and providing a more accurate data base for diagnostic calculations. Many facets of the climate during the FGGE year have already been discussed (*e.g.* WMO, 1985), and more will become available. The study of local energy budgets in the FGGE ECMWF-produced IIIb grid point daily analyses is the subject of the present article. The energy budgets for air columns are calculated here over a continental land surface with a dense observational network as well as over an ocean area with fewer traditional observations. The results are compared with similar calculations for another year (SAVIJÄRVI, 1983, referred to as S83 in what follows) when the extra observational FGGE platforms were not available. Thus the value of these extra efforts may be assessed assuming that year-to-year variations are small. In S83, also ECMWF model forecast budgets were calculated, allowing direct comparison to model physics.

The FGGE IIIb analyses, produced by several different centers, are all based on a quasi-operational assimilation cycle developed for the purpose of numerical weather prediction (NWP) where a short-term forecast is used as the background (»first guess») to the objective analysis. Several sources of information (radiosoundings, satellite data, and airplane data) are used in making the analysis, which is finally initialized by removing the tendencies of fast gravity wave modes of the forecast model. While this method, as used for instance, by the ECMWF (for a detailed description, see LORENC (1981)), produces fine analyses specially suitable for making short and medium range weather forecasts, it does introduce some model dependency in the analyses. To make a more interesting and more reliable energy budget study we have also used another independent data set produced at GFDL (OORT, 1983), not based on a forecast model. In this last set the radiosonde data (without any other information) are time-averaged for a month at each station and the station statistics (means and covariances) are then analyzed onto a 2.5 x 5° latitude-longitude grid covering a 10 year period (1963–1973).

The station and the NWP/FGGE analyses tend to produce slightly different climatologies as shown for some climatological parameters by *e.g.* LAU and OORT (1981) and ROSEN *et al.* (1985). The present study extends the previous comparisons to area mean energy budget calculations, which are notoriously sensitive to the various types of errors in the processing chain. In an attempt to retrieve information from such calculations with a low signal-to-noise ratio, even the selection of the areas becomes important. The station analyses do not include any initialization steps. Mainly for this reason the wind divergences based on midlatitude mean winds are very noisy. An attempt was made to compare the station budgets with the FGGE budgets for the same midlatitude areas (North America and North Atlantic), but the raw station wind analyses did not produce reliable results, even when a mass balance correction was applied (*c.f.* OORT, 1983). Therefore, in the case of the station data, we use instead the subtropical areas over Mexico and the Gulf of Mexico. It appears that in the tropics and subtropics, which are dominated by the Hadley circulation, the divergent wind is a relatively large part of the observed wind and that its main features are reasonably well captured by the station analyses. The Mexico/Gulf of Mexico areas, although smaller than the FGGE analysis North America/North Atlantic areas (Fig. 1), are presumably typical enough to allow for a qualitative land/sea intercomparison. Moreover, these regions are interesting by themselves because of the sharp contrast in the surface properties between the high and narrow mountain chain in Mexico and the adjacent Gulf of Mexico. Both regions are covered by a relatively dense network of rawinsonde stations making the station analyses reliable even over the sea. On the other hand, the ECMWF initialization was known to reduce the Hadley circulation so subtropical (Mexico) areas were not representative in the first set of ECMWF FGGE analyses. We thus make the comparison here favourable for both analysis methods by choosing those areas where they are supposed to work well.

The station analyses can be improved in extratropics by replacing the »observed» (noisy) divergence field by indirectly derived (dynamically constrained) divergence

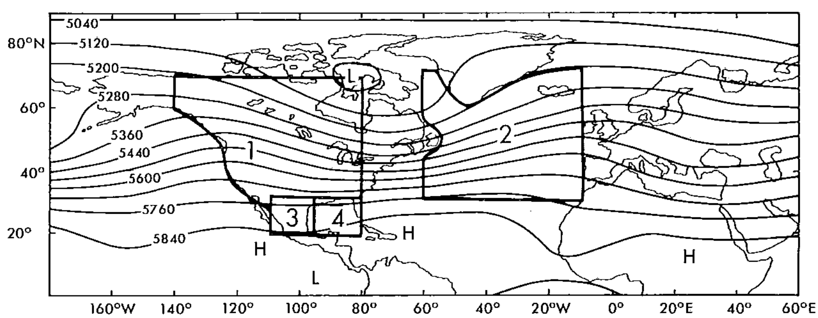

Fig. 1. Normal January 500 mb height contours and the areas used in energy budget calculations.

1 = North America (28°N, 70°N, 80°W, 140°W, land only)
2 = North Atlantic (30°N, 70°N, 10°W, 60°W, sea only)
3 = Mexico (20°N, 30°N, 95°W, 110°W)
4 = Gulf of Mexico (20°N, 30°N, 80°W, 95°W)

values. Because this procedure is best applied in a global domain, the results will be reported in a later article.

The individual energy budgets provide information on the diabatic effects in the form of residuals needed to balance the time mean budget equations. Thus, they offer information on frictional effects in the surface boundary layer, at jet stream levels and in the stratosphere, that are possibly different over flat land, mountains and ocean areas. They can also provide an estimate of the net diabatic heating profiles, and the water budgets over the land/ocean areas. Finally, the total energy flux divergence in the atmosphere may be compared with the satellite net radiation data to give an estimate of the poorly known heat transport in the ocean areas. Over the land areas the difference between the atmospheric energy divergence and the net radiation (which should be zero) provides an independent estimate of the error in the total energy budget. This »Oort-Vonder Haar» (1976) method to derive the ocean heat transport has been widely discussed in the literature (*e.g.* BRETHERTON *et al.*, 1982, LORENC and SWINBANK, 1984, BOER, 1986, HOLOPAINEN and FORTELIUS, 1986) but the error estimates show a large range. We will discuss this error using both data sets.

The reliability of the results, and especially that of the small residuals, is an important issue in energy budget studies. The use of two very different data sets and calculation algorithms may enhance the credibility of the present results: if the same but perhaps weak and counter-intuitive feature, *e.g.* negative viscosity, will appear in both of the two »observed» data sets, its chances to be a real signal above noise level are improved. The ECMWF-analysed budgets for another year, and the ECMWF model budgets, reported in S83, provide further comparison.

2. *The FGGE results for North America – North Atlantic*

The present calculations used the first FGGE IIIb data set produced at ECMWF during 1980–1981 with the assimilation scheme described in LORENC (1981). They were made during the assimilation cycle on the sigma levels, immediately after the normal model initialization. It was thought that interpolation from sigma to pressure levels might smooth out important details; also, vertical averaging and the boundary layer representation benefit from the exact boundary conditions ($\dot{\sigma} = 0$ at $\sigma = p/p_s = 1$ and $\sigma = 0$) in the σ-system. The 15 σ-levels, the 1.875° grid and the finite differencing schemes used in the present calculations were the same as those of the ECMWF grid point N48 model used in the assimilation scheme.

In pressure coordinates, the kinetic energy ($k = 1/2\, V^2$), sensible heat ($c_p T$) and latent heat (Lq) energy budget equations may be given in the following standard flux form:

$$R_k = \frac{\partial}{\partial t} k + \left(\nabla \cdot kV + \frac{\partial}{\partial p} k\omega \right) + V \cdot \nabla \phi \tag{1}$$

$$R_T = \frac{\partial}{\partial t} c_p T + \left(\nabla \cdot c_p T V + \frac{\partial}{\partial p} c_p T\omega \right) - \alpha\omega \tag{2}$$

$$R_q = \frac{\partial}{\partial t} Lq + \left(\nabla \cdot LqV + \frac{\partial}{\partial p} Lq\omega \right) \tag{3}$$

Furthermore,

$$0 = \left(\nabla \cdot \phi V + \frac{\partial}{\partial p} \phi\omega \right) + \alpha\omega - V \cdot \nabla\phi \tag{4}$$

Here R_k, R_T, R_q represent the frictional dissipation $V \cdot F$, the net diabatic heat sources and sinks Q, and the net latent heat sources and sinks (condensation-evaporation, and turbulent mixing), respectively. The actual σ-coordinate forms of (1)–(4) and details of the calculation of the right-hand side terms (in W/m^2) can be found in S83. Care was taken to get an exact budget, *i.e.* R's as residuals from the ECMWF model data were the same as the actual net effect of the model parameterization schemes.

In S83, the terms in (1)–(4) were presented for the year 1980, (December 1979–November 1980), the first fully operational year of ECMWF, both for the analyses and for a set of forecasts. In the present article, the same computational schemes and two areas (North America, North Atlantic, see Fig. 1) are used for the FGGE year (December 1978–November 1979), averaging four analyses per day over the whole year. The budgets were also computed using the 6 hour »first guess» forecasts. The 6-hour forecast budgets will be discussed later. They were close to those from the initialized analyses shown here. On the other hand, when the budgets were computed before initialization the wind divergence fields were very noisy, which made the budget calculations, especially Eq. (2) and (4), unreliable. The mass balance correction in the σ-coordinate system means subtracting the vertical integral of the time mean mass flux divergence $\int_0^1 \nabla_\sigma \cdot \overline{p_s V}\, d\sigma/g$ (which should be zero) from the divergence fields. It was small (typically $\sim 10^{-4}$ Pa/s) in the initialized analyses, but about 100 times larger in the analyses before the normal mode initialization.

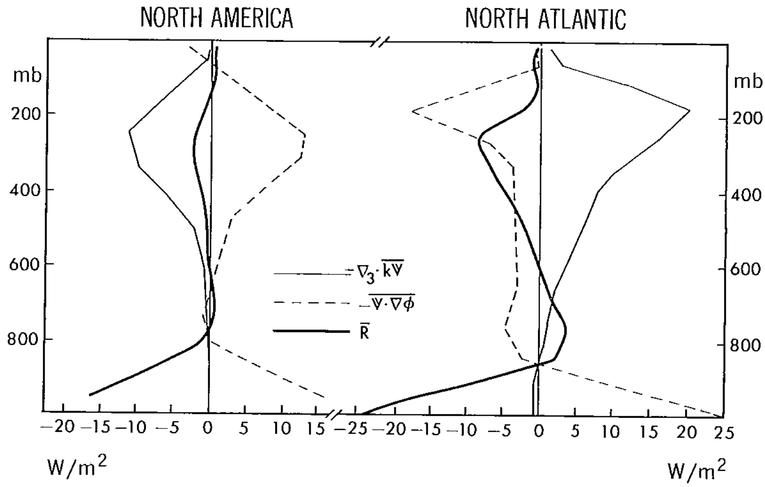

Fig. 2. The annual kinetic energy budget (W/m^2) over North America and the North Atlantic from FGGE IIIb ECMWF analyses.

Fig. 2 shows the annually averaged kinetic energy 3-D flux convergence $-(\nabla \cdot kV + \partial/\partial p k\omega)$ profiles, the generation term $-V \cdot \nabla\phi$ profiles and the (residual) dissipation profiles for the two areas in W/m^2 for the FGGE year. The well-known features of kinetic energy flux convergence and destruction in the upper troposphere over the diffluent North Atlantic flow and divergence and generation over North America (where a confluent flow pattern is typical) are obvious in Fig. 2. The frictional dissipation $V \cdot F$ is largest in the planetary boundary layer. Its (absolute) values are somewhat larger over the ocean surface indicating that the stronger winds over the ocean make the product $V \cdot F$ large even if the surface drag F itself is smaller over the smooth ocean area. However, this is a feature, which may be dependent on the first guess (given by the forecast model), and should be checked from other sources.

At the jetstream levels around 300 mb there is another dissipation maximum. It is stronger over the ocean area, where the winds are also stronger. The residual values are positive around 700 mb, especially over sea, and weakly positive in the stratosphere over the land area. If real, this would indicate energy input from the subgrid to large scale motions, *i.e.* negative viscosity. While there are suggestions that cumulus convection and frontal circulations might act in this way, it will be interesting to see if the station data includes similar features.

All features in Fig. 2 are both qualitatively and quantitatively very close to

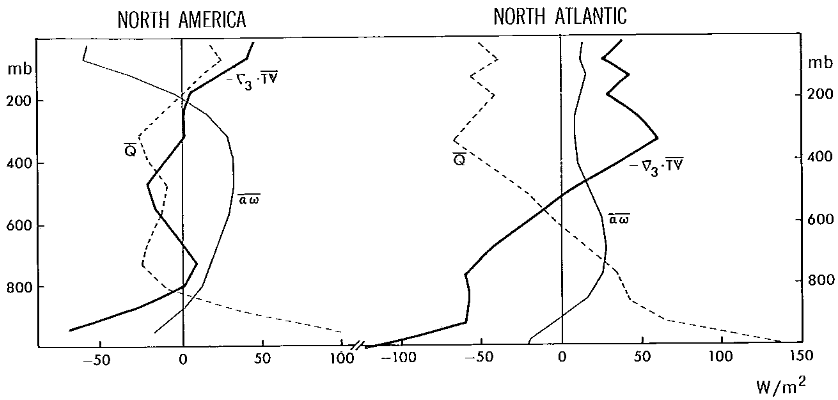

Fig. 3. The annual sensible heat budget (W/m^2) over North America and the North Atlantic from FGGE IIIb ECMWF analyses.

those in the post-FGGE year ECMWF analyses. The negative viscosity features were not present in the forecast model data residuals in S83 as the parametrizations cannot produce them.

Fig. 3 shows the annually averaged sensible heat flux convergence $-(\nabla \cdot c_p TV + \partial/\partial p \cdot c_p T\omega)$ profiles, the adiabatic heating $\alpha\omega$ profiles and the (residual) net diabatic heating profiles for the North American and North Atlantic areas during the FGGE year. The basic features are much the same as in the operational post-FGGE data in S83 over North America. They are more different over the North Atlantic where the $\alpha\omega$-term is mainly positive in the FGGE data and negative in S83. Near the surface there is heat flux divergence (mainly due to upward transport) and negative $\alpha\omega$ (due to frictional turning of surface winds toward lower pressures), compensated by strong diabatic heating especially over the ocean area, where the heating extends up to 600 mb.

In Fig. 4, the three-dimensional flux divergences of k, c_pT, Lq and ϕ are shown for the two areas during the FGGE year. The large positive values of $\nabla_3 \cdot LqV$ near the surface indicate strong evaporation excess over condensation, especially over the ocean surface. The condensation surplus over evaporation (negative values of $\nabla_3 \cdot LqV$) in the midtroposphere is, however, similar over both areas. The vertical integral of $\nabla_3 \cdot LqV$ is equal to $L(E-P)$. For the North American continent its value is -16.4 W/m^2 or -19.7 cm/year from the FGGE data, which is larger than in S83 (-13.4 cm/year) but closer to earlier estimates (-16.0, -18.8 cm/year for two years from aerological data) of RASMUSSON (1968).

If the atmospheric energy equations (1)–(4) are integrated vertically and if the respective energy equations for the ocean-soil-cryosphere column are integrated

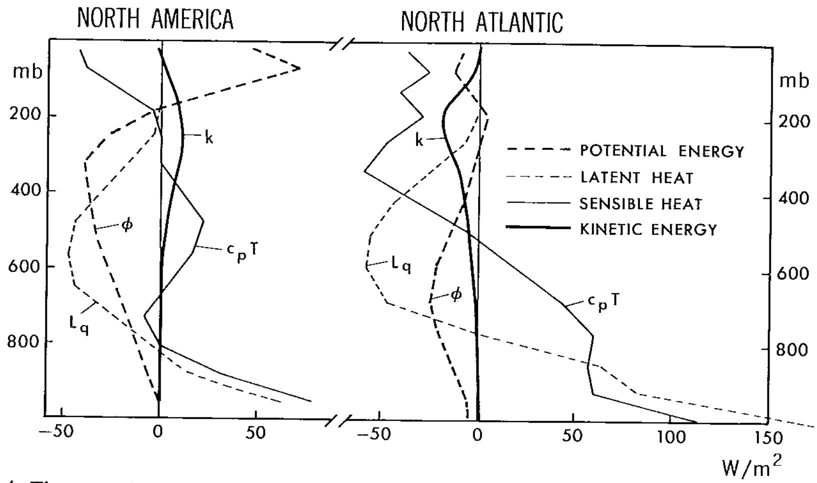

Fig. 4. The annual mean flux divergences of k, c_pT, Lq and ϕ (W/m^2) over North America and the North Atlantic from FGGE IIIb ECMWF analyses.

below the presentation level of annual temperature cycle, the sum becomes for long time average conditions

$$\nabla \cdot F_A + \nabla \cdot F_0 = R_{ea} \tag{5}$$

(OORT and VON DER HAAR, 1976). R_{ea} is the net radiation at the top of the atmosphere-earth column, obtained from satellite data, $F_A = {}^{ps}_{0}\int (c_pT + Lq + \phi + k)\, Vdp/g$, and F_0 are the energy transports in the atmosphere and oceans, respectively. Over land $\nabla \cdot F_0$ should be zero but it may be very large and difficult to measure in the ocean currents. Eq. (5) thus offers an indirect method to derive the oceanic heat transport when R_{ea} and $\nabla \cdot F_A$ are known. However, this »OORT and VON DER HAAR»-method is very sensitive to errors in the atmospheric data, and various estimates of its local accuracy differ widely. An accuracy of ±10 W/m^2 was set as an optimistic goal in the CAGE-report (BRETHERTON *et al.*, 1982) for the North Atlantic region. The sum of the vertical means of the four flux divergence curves in Fig. 4 represents the atmospheric part $\nabla \cdot F_A$ in (5). It is evident from Fig. 4 that there is much compensation between the four curves, and that the result may be sensitive to any small changes in the calculation chain of (5). Thus, if the extra observations available during FGGE had any effects in the IIIb analyses, these should become clear through use of (5). We therefore compare in Table 1 the total energy budget $\nabla \cdot F_A$ of FGGE and post-FGGE (from S83) years for the North American continental area, where $\nabla \cdot F_0 \cong 0$ and thus $\nabla \cdot F_A$ should

Table 1. Annually averaged vertically integrated total energy budget over North America (W/m^2).

Flux Divergence of:	c_pT	Lq	ϕ	k	sum = $\nabla\cdot F_A$	R_{ea}	error
1980 (S83) data	17.9	−11.0	−20.1	2.2	−11.0	−30	−19
1979 (FGGE) data	4.0	−16.4	−12.2	2.1	−22.5	−30	−7.5

equal the annual mean of R_{ea}, which is about -30 ± 10 W/m^2 for the North American and North Atlantic areas (OORT and PEIXOTO, 1983).

The indications from Table 1 are that the level of uncertainty in $\nabla\cdot F_A$ is reduced during the FGGE year, and that large area and time means are approaching the ±10 W/m^2 error level, provided that the (midlatitude) data are well initialized and analyzed and that the mass balance correction is properly applied.

Table 2. Annually averaged vertically integrated total energy budget over the North Atlantic (W/m^2).

Flux Divergence of:	c_pT	Lq	ϕ	k	sum = $\nabla\cdot F_A$	R_{ea}	$\nabla\cdot F_0 = R_{ea} - \nabla\cdot F_A$
1980 (S83) data	−21.6	−6.7	30.1	−5.3	−3.5	−30	−26.5
1979 (FGGE) data	12.6	−8.2	−10.1	−5.3	−11.0	−30	−19.0

Table 2 presents the total energy balance (5) for the North Atlantic area. The heat transport convergence in the ocean (presumably by the Gulf Stream) is, according to Table 2, of the order of 20 W/m^2 during the FGGE year. However, while the four atmospheric flux divergence curves of Fig. 4 were very similar in the 1980 and 1979 (FGGE) data over North America, the geopotential and sensible heat flux divergences over the North Atlantic area are nevertheless more variable in the 1980 and FGGE data (note the change of signs in the vertical averages in Table 2). Whether these changes are due to large year-to-year variations over the ocean area, or result from the extra FGGE observations is an open question. In any case they emphasize again the sensitivity of the total energy budget. Perhaps the quality of objective analyses could be monitored by their capability to match the net radiation data over continents as shown, for example, in Table 1.

3. *The GFDL data and results for Mexico – Gulf of Mexico*

The GFDL General Circulation Library data, collected in the spirit of V. Starr by OORT (1983), has formed the »observed» climatology against which many general circulation models have been validated in the past. The GFDL 10 year data set (1963–1973) consists of rawin station monthly mean statistics ($\bar{u}, \bar{v}, \bar{T}, \bar{q}, \bar{\phi}, \overline{u'v'}, \overline{u'T'}$...) based on data at 11 pressure levels and analyzed onto a 2.5 x 5° grid. The seasonal and yearly values are used here. The data below the surface ($p_s < 1000$ mb) has been extrapolated from above.

As discussed in the Introduction, the two equal areas chosen for the intercomparison were located above Mexico and the Gulf of Mexico in the GFDL data (Fig. 1). The mass balance correction, essential for reasonable results when working with radiosonde data, was done by removing the vertical average of $\nabla \cdot V$ from the wind divergences. All the vertical averages were computed from 0 to 1000 mb and thus use the extrapolated values »inside» the mountains of Mexico. While this introduces some error, it was thought to do less harm than trying to use approximate kinematic boundary conditions ($\bar{w}_s \sim \bar{V}_s \cdot \nabla \bar{p}_s$), and integrating from 0 to p_s.

Instead of the kinetic energy budget (1), the GFDL data offered an opportunity to study the area mean budgets of time mean u and v momentum:

$$0 = R_u \underbrace{- \nabla \cdot \bar{u}\bar{V} + \frac{\bar{u}\bar{v}}{a} \tan\phi - \nabla \cdot \overline{u'V'} + \frac{\overline{u'v'}}{a} \tan\phi}_{A_u} \underbrace{+ f\bar{v} - \frac{\partial \bar{\phi}}{a\cos\phi\partial\lambda}}_{B_u} \underbrace{- \bar{\omega}\frac{\partial \bar{u}}{\partial p}}_{C_u} \tag{6}$$

$$0 = R_v \underbrace{- \nabla \cdot \bar{v}\bar{V} - \frac{\bar{u}^2}{a} \tan\phi - \nabla \cdot \overline{v'V'} - \frac{\overline{u'^2}}{a} \tan\phi}_{A_v} \underbrace{- f\bar{u} - \frac{\partial \bar{\phi}}{a\partial\phi}}_{B_v} \underbrace{- \bar{\omega}\frac{\partial \bar{v}}{\partial p}}_{C_v} \tag{7}$$

$\bar{\omega}$ was estimated kinematically by integrating the mass balance corrected values of $\nabla \cdot \bar{V}$ downward from $p = 0$ at each grid point. R_u and R_v include here the components of the frictional force F from molecular to subsynoptic scale and the presumably small vertical eddy advection terms $\overline{\omega'\partial u'/\partial p}$, $\overline{\omega'\partial v'/\partial p}$. Since R_u and R_v are computed here as residuals, they will also contain the accumulated systematic errors in the estimates of the other terms in (6) and (7). For instance, in quasi-geostrophic balance the terms B_u and B_v are residuals of two larger terms.

Fig. 5 shows the u-momentum budget terms A_u, B_u, C_u and R_u for the Mexico and Gulf of Mexico areas together with the mean $\bar{u}$-profiles for the 10 year period. The vertical profiles of negative A_u (divergence of zonal momentum) and positive B_u (production through northward ageostrophic flow) in the free troposphere are in agreement with the North American kinetic energy budget for the FGGE year shown in Fig. 2. These distributions are also quite similar to the analogous terms

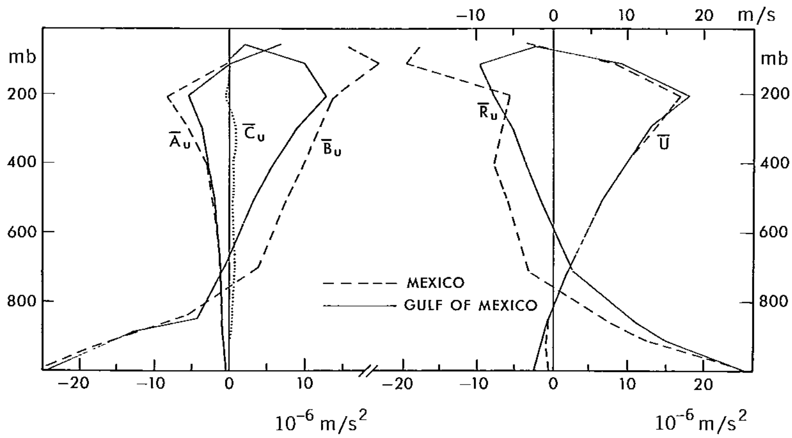

Fig. 5. The annual budget of zonal momentum (unit: 10^{-6} m/s^2) and the vertical profile of the mean zonal wind $\bar{u}$ over Mexico and the Gulf of Mexico from GFDL 10 year radiosonde analyses.

for North America from the GFDL data by HOLOPAINEN *et al.* (1980). These last authors further divided the area of North America into »mountains» and »plains» regions and found that the residual force R_u was more decelerating over the mountains than over the plains area.

The same tendency can be seen in Fig. 5, where over the mountaineous Mexico highland R_u is more negative than over the Gulf of Mexico area in mid troposphere where $\bar{u}$ is positive. Although the residual results should be taken with caution, this might indicate the presence of mountain gravity wave drag in mid troposphere over Mexico, where westerlies blow over the high (2–3 km) and narrow mountain chain. It is interesting to note also that the residual R_u remains strongly negative in the stratosphere over Mexico, but not over the sea. As the stratospheric mean zonal winds are easterlies above 100 mb this indicates an accelerating effect of the zonal easterly flow in the mountain area stratosphere. Note that in Fig. 2 for the ECMWF FGGE analyses the frictional dissipation was also weakly positive (an accelerating effect) over the North American area stratosphere, but not over the North Atlantic.

Near the surface the winds are easterlies in the two subtropical areas and the positive residuals (R_u) thus indicate strong deceleration, *i.e.* boundary layer friction. At the 700 mb level the winds are westerlies but R_u is positive over the sea area, and negative over the land area. Over the sea, the residual friction thus appears to be an accelerating force at the 700 mb level, as was also the case in Fig. 2 for the North Atlantic area in the FGGE data (and in S83, for 1980). In HOLOPAINEN-

et al. (1980), a large accelerating effect was also reported over the 700 mb plains region of North America, but not over the mountain region. The mechanism for this subgrid scale energy transfer to synoptic scales was suggested by them to be due to frontal circulations, but active mesoscale organized cumulus convection might be a more probable candidate over the subtropical ocean.

Interestingly, an Ekman-spiral with $\bar{u} = 15$ m/s, $\phi = 45°$, $K_z = 20$ m^2/s can quantitatively simulate the overshooting in R_u and $V \cdot F$. This suggests that a locally large vertical eddy mixing coefficient K_z could be applied near the top of the maritime boundary layer. The extra mixing so induced must be due to thermal reasons since purely mechanical mixing would require a strong wind shear. Such a local increase of K_z was recently added to the ECMWF model to simulate shallow convection in moist convective conditions.

In any case, there seems to be some evidence from several sources that over flat land or ocean in the subtropics and midlatitudes the subgrid scale »frictional» force may accelerate the zonal synoptic scale flow at 700–800 mb level due to reasons yet unclear. This is a challenging problem for numerical modellers. Whether this effect is present but overcompensated by mountain wave drag over hilly areas is not known.

The v-momentum budget terms A_v, B_v and R_v are shown in Fig. 6 (C_v is very small and is not plotted). The results for R_v are even less reliable than for R_u because the two terms in B_v are about one order of magnitude larger than in B_u.

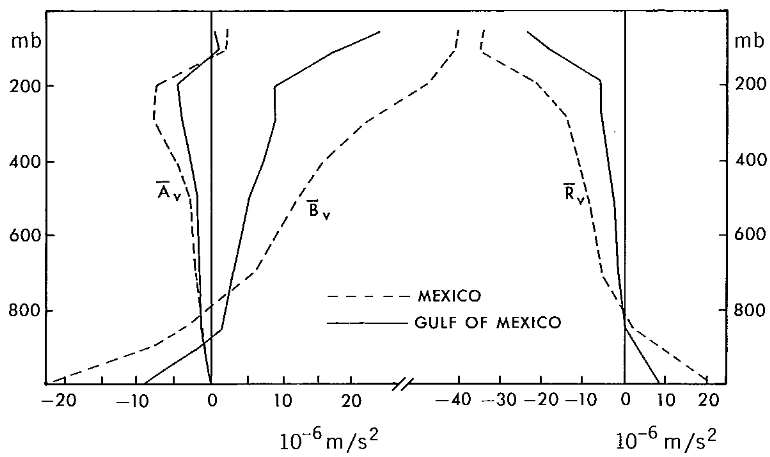

Fig. 6. The annual budget of meridional momentum (unit: 10^{-6} m/s^2) over Mexico and the Gulf of Mexico from GFDL 10 year radiosonde analyses.

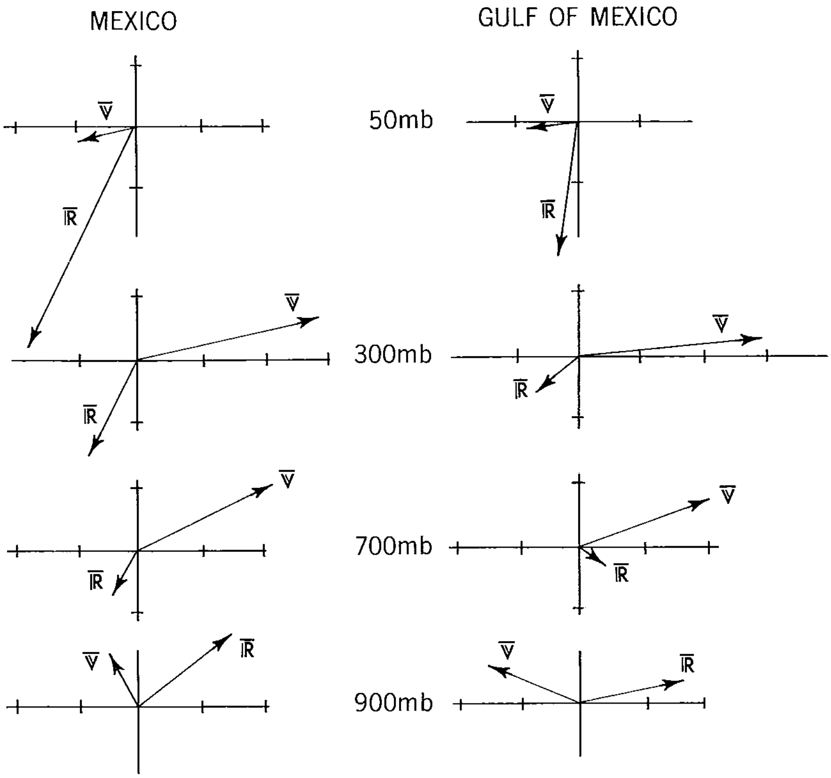

Fig. 7. Annual mean wind vector $\bar{V}$ (tick mark: 5 m/s) and the residual force vector $R = R_u\hat{i} + R_v\hat{j}$ (tick mark: 10^{-5} m/s^2) of the momentum budget at 50, 300, 700 and 900 mb levels over Mexico and the Gulf of Mexico.

The qualitative message from Fig. 6 seems to be that R_v is larger in magnitude over the mountain (Mexico) area than over sea.

Fig. 7 shows the residual force R $(R_u\hat{i} + R_v\hat{j})$ in vector form relative to the mean wind vector $\bar{V}$ for the two areas at some key pressure levels. In the strong westerly flow at 300 mb the retarding nature of R is evident. The obvious non-linearity $(R \neq -\lambda V)$ may be partly due to the larger uncertainty in the R_v-values. At the 50 mb level the acceleration effects in R can be seen over both the mountain and sea areas, and at 700 mb over the sea area only. Near the surface the distributions are as expected; less wind and stronger friction over the land than over sea.

The moisture budget in the GFDL data (not shown) is very dependent on both the mean and eddy vertical motions, so it is advisable to integrate the budget vertically to remove the vertical flux divergence terms. The vertical integral of $\nabla \cdot \bar{q}\bar{V} + \nabla \cdot \overline{q'V'}$ produces an estimate of $\bar{E}-\bar{P}$, which for the Gulf of Mexico (10 year average) is equivalent to 65 W/m^2. This is more than the annual zonal average for the latitude belt 20–30°N (60 W/m^2, from LORENZ, 1967) but less than BUDYKO's (1963) separate estimates for $\bar{E}$ and $\bar{P}$ would indicate (~80 W/m^2) in that area. In the Mexico area, $\bar{E}-\bar{P}$ is much smaller, 20 W/m^2, as can be expected on the basis of reduced evaporation from the dry land regions and increased rainfall over the windward mountain slopes.

The temperature budget in the GFDL data was estimated from the following modified form of (2)

$$\bar{Q} = \left\{ \bar{V} \cdot \nabla \bar{T} + \nabla \cdot \overline{T'V'} + (p/p_0)^{\kappa}\, \bar{\omega} \frac{\partial \bar{\theta}}{\partial p} + (p/p_0)^{\kappa} \frac{\partial}{\partial p} (\overline{\omega'\theta'}) \right\} C_p \tag{8}$$

where the last term will be included in the residual $\bar{Q}$ as the necessary information for its direct calculation was not available. The results for the Mexico and Gulf of Mexico areas are shown in Fig. 8 in units, which correspond to W/m^2. In both areas, the strong divergence of the eddy flux in the lower troposphere and the export of mean temperature in the upper troposphere lead to the typical diabatic heating distribution of heating near the surface and cooling above.

The most interesting aspect here is to compare the results with the FGGE data calculations in Section 2. Although the individual terms in Eq. (2) (shown in Fig. 3) are different from those in Eq. (8) the residuals in Figs. 3 and 8 should represent the same thing, namely the annual mean profile of the diabatic heating Q.

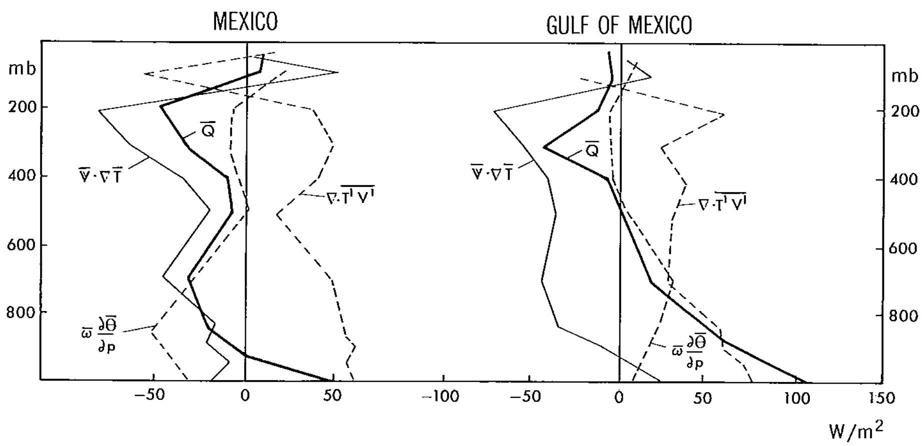

Fig. 8. The annual sensible heat budget (W/m^2) over Mexico and the Gulf of Mexico from GFDL 10 year radiosonde analyses.

The residuals in Fig. 3 and Fig. 8 are remarkably similar keeping in mind that they are for different data sets, for different calculation algorithms, and for different areas. Over the sea areas, both of them indicate strong surface heat flux (100... 150 W/m^2) in a deep layer up to 500–600 mb, a cooling peak at 300 mb (–40... –60 W/m^2) and less cooling above. Over the land areas, the surface heating layer is smaller and shallower, there is a relative minimum of cooling around 500 mb level (which might be partly due to orographic condensation) and there is a cooling peak at 200–300 mb. In Section 2 it was noted that even if the terms in Eq. (2) seemed to vary from the FGGE year to the next one the residuals R_T remained much the same. As similar heating profiles are reproduced also in the independent GFDL data set, they look reliable enough for model verification purposes.

In S83, the annual mean diabatic heating in the ECMWF model at forecast days 3 was compared to the residual R_T from ECMWF operational analyses with the notion that the model cooled the stratosphere too much and that it warmed and moistened the maritime boundary layer too much inside the layer and too little above it. The FGGE 6-hour »first guess» energetics in the ECMWF forecast (not shown) indicate similar defects, although weaker. This is no surprise because the assimilating grid point model was the same. These systematic errors have been largerly removed since that time by changes in the ECMWF model radiation scheme and by the addition of a shallow convection scheme to boost the heat and moisture vertical mixing.

Finally, our attempts to use the GFDL data for the total energy budget calculations (as described in Section 2) end up with error estimates of 70 W/m^2 for the land (Mexico) area. Thus the use of »raw» radiosonde data for quantitative total energy budget is not advisable even for large areas. The error source is probably in the divergent part of the mean winds $\bar{u}, \bar{v}$ where a tiny error of 10 cm/s may amplify to 100 W/m^2 when it is multiplied by the large numerical values of $C_p T$ and ϕ. Compared with this the ECMWF FGGE wind analyses are of a higher quality.

4. *Discussion and concluding remarks*

This work was intended to reduce the well-known inaccuracy of residual methods in deriving small, poorly known terms as the sum of large balancing terms in the budget equations. Furthermore, atmospheric analyses are nowadays based on a complex data assimilation system involving numerical models and many simplifying assumptions. To eliminate these drawbacks to some extent, two data sets were used in the present study. One study, of the FGGE period, was made with state-of-the art model-analyzed (ECMWF) data, and the other study with directly computed (GFDL) station statistics. The hope was that a common but perhaps weak signal would appear above the noise level in both data sets. A previous study of (ECMWF) analysis and model data budgets (S83) provided further comparison.

The results are encouraging. In the annual kinetic energy and momentum budgets the residual (interpreted as friction from molecular to subsynoptic scales) reproduce in both data sets not only the strong surface friction over land and the upper level jet stream dissipation (the last one being especially strong over sea) but also the weaker features of a slightly stronger deceleration over the land area mid troposphere, an acceleration over land area stratosphere, and an acceleration over the ocean area boundary layer. The profiles of the residuals in the heat budget (the diabatic heating) are also quite similar in the two data sets and indicate strong boundary layer heating in a deep layer over the ocean areas. These features support the idea of mountain-wave »drag» in mid troposphere, now being parametrized in some GCM's. They also indicate net extra heat transfer over both sea areas, which may be connected with shallow convection. All the features highlighted above appeared also in the operational (1980) ECMWF analyses.

The accuracy of the residual method applied to large-scale grids may not, however, be extendable much beyond FGGE IIIb analyses in the near future. To get a deeper insight into the organized mesoscale features and their parametrization in synoptic scale models one might perhaps proceed by using mesoscale models to produce these phenomena (mountain waves, convection, sea breeze, etc.) and by averaging spatially to get the net feedback effect into the synoptic scale slow (SAVIJÄRVI, 1985).

The comparison of FGGE and post-FGGE year areal energy budgets show stability in the kinetic energy budget, while the latent and sensible heat energy budget terms experienced more year to year variation over the North Atlantic Ocean. The residuals remained, however, very similar.

The sum of all atmospheric energy flux divergences, integrated vertically and over the whole year, should nearly equal the net radiation at the top of the atmosphere over land areas as obtained from satellites. The radiosonde (station) analyses were not sufficiently accurate to satisfy this »Oort-Vonder Haar» test. On the other hand, the FGGE ECMWF IIIb analyses showed improved accuracy over the post-FGGE year, approaching a 10 W/m^2 error level for the North American area mean. The larger year-to-year variations over the ocean (North Atlantic), and fewer observations there may increase the error level. However, the present results, those of LORENC and SWINBANK (1984) and the maps of BURRIDGE (1985) for ECMWF FGGE IIIb and SAVIJÄRVI (1984) for ECMWF operational σ-level analyses suggest that with plenty of new extra observations (SATEM, SATOB, AIREP...), with improved assimilation-initialization schemes, with proper mass balance correction and with correct boundary conditions (use of σ coordinates), the local oceanic heat flux convergences may be deduced in the not so far future with some better accuracy. Meanwhile, the quality of objective analyses might perhaps be monitored in their capacity to pass the »Oort-Vonder Haar» test.

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