ENERGY BUDGET CALCULATIONS AND DIABATIC EFFECTS FOR LIMITED AREAS COMPUTED FROM ECMWF ANALYSES AND FORECASTS

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ABSTRACT

The diabatic forcings in the kinetic energy, sensible and latent heat energy equations were calculated as residuals from a 90-day period of analyzed and forecast data. Compared to the analyzed data results from the longer forecasts (days 6-10) show good agreement in the net physical forcing but the short forecasts suffer from an initial spin-up of condensational processes leading to rapid cooling by radiation, except in the tropics and near the surface, where evaporation, net heating and friction processes are all stronger than in the analyzed data. The global kinetic energy dissipation rate increases from 1.85 W/m^2 in the initialized analyses to 3.4 W/m^2 in day 2-4 forecasts but decreases again in the longer forecasts.

1. INTRODUCTION

In diagnosing the irreversible diabatic processes in the atmosphere, which cannot be observed directly, there are two alternatives. First, individual processes such as radiative heating or latent heat release can be related to the observed variables using parameterization formulae, which provide a method for approximate quantitative evaluation of these processes. The second alternative is to use the energy budget equations and to calculate the diabatic terms from the data as residuals needed to balance the equations. The advantage in this method is that no approximations need to be done on the nature of the diabatic processes, but on the other hand the result is the net of all effects without the possibility of separating between them, and the residual is rather sensitive to inaccuracies in approximating the remaining terms in the budget equations. Clapp's (1961) comparison of the two methods revealed rather large differences in the large scale net diabatic heating fields for winter time in the Northern Hemisphere. The accuracy by which we know this driving force for the general circulation is still not much higher than in Clapp's calculations.

The diabatic effects become important in numerical forecasting in the time scale of a few days. For this reason the ECMWF model has an elaborate parameterization scheme of the diabatic effects (the model physics) described in Tiedtke et al (1979). For the verification of this model physics, and also for getting general information about the diabatic effects, the residual method is in this paper applied to the ECMWF analyses and forecasts over fixed limited areas. Results from a 3-month winter period in 1979-1980 using the operational analyses and forecasts are reported.

2. THE BUDGET EQUATIONS

In pressure coordinates the kinetic energy, total potential energy and latent heat energy budget equations can be written

$$R_K = \frac{\partial K}{\partial t} + \nabla . K\mathbb{V} + \frac{\partial}{\partial p} K\omega + \mathbb{V}.\nabla\phi \qquad = \mathbb{V}.\underset{\sim}{\mathbb{F}} \tag{1}$$

$$R_T = \frac{\partial}{\partial t} c_p T + \nabla . c_p T\,\mathbb{V} + \frac{\partial}{\partial p} c_p T\omega - \alpha\omega \qquad = Q_R + Q_L + Q_T - \mathbb{V}.\underset{\sim}{\mathbb{F}} \tag{2}$$

$$R_q = \frac{\partial}{\partial t} Lq + \nabla . Lq\,\mathbb{V} + \frac{\partial}{\partial p} Lq\omega \qquad = L(E-C) + S \tag{3}$$

where R_K, R_T, R_q are the net effects of all diabatic contributions. For kinetic energy R_K is physically the kinetic energy dissipation through surface and internal friction, for heat the net heating R_T consists mainly of radiative effects Q_R, latent heat release $Q_L = L(C-E)$ due to the net effect of condensation C and evaporation E and turbulent heating Q_T. In the humidity equation (3) the main contribution to R_q comes from evaporation, LE, condensation -LC, and the turbulent flux convergence S (which, when integrated vertically, is determined by the evapotranspiration at the surface). The kinetic energy and potential energy equations are coupled by the conversion formula for the adiabatic source terms.

$$-\mathbb{V}\cdot\nabla\phi = -\nabla\cdot\phi\mathbb{V} - \frac{\partial}{\partial p}\phi\omega - \alpha\omega$$

which links the kinetic energy generation $-\mathbb{V}\nabla\phi$ to conversion $\alpha\omega$ through pressure forces (net mass inflow) on the boundaries of the air volume considered.

In sigma coordinates the equations are slightly more complicated but the physical meaning of the terms remains the same:

$$\text{net diabatic source} = \text{local change} + \text{horizontal} + \text{vertical flux divergence} - \text{adiabatic source}$$

$$p_s\frac{R_K}{g} = \frac{\partial}{\partial t}(p_s\frac{K}{g}) + \nabla_\sigma\cdot(p_s\frac{K}{g}\mathbb{V}) + \frac{\partial}{\partial\sigma}(p_s\frac{K}{g}\dot{\sigma}) + p_s\frac{\mathbb{V}}{g}\cdot(\nabla_\sigma\phi + RT\,\nabla_\sigma\ln p_s) \tag{4}$$

$$p_s\frac{R_T}{g} = \frac{\partial}{\partial t}(p_s\frac{C_pT}{g}) + \nabla_\sigma\cdot(p_s\frac{C_pT}{g}\mathbb{V}) + \frac{\partial}{\partial\sigma}(p_s\frac{C_pT}{g}\dot{\sigma}) - p_s\frac{\alpha\omega}{g} \tag{5}$$

$$p_s\frac{R_q}{g} = \frac{\partial}{\partial t}(p_s\frac{Lq}{g}) + \nabla_\sigma\cdot(p_s\frac{Lq}{g}\mathbb{V}) + \frac{\partial}{\partial\sigma}(p_s\frac{Lq}{g}\dot{\sigma}) \tag{6}$$

The conversion in σ-coordinates is given by

$$-p_s\mathbb{V}\cdot(\nabla_\sigma\phi + RT\,\nabla_\sigma\ln p_s) = -\nabla_\sigma\cdot(p_s\phi\mathbb{V}) - \frac{\partial}{\partial\sigma}(p_s\phi\dot{\sigma} + \phi\sigma\frac{\partial p_s}{\partial t}) - p_s\,\alpha\omega \tag{7}$$

The factor 1/g was introduced in Eqs. (4) - (6) to produce the convenient unit of W/m^2 ($115\ W/m^2 \sim 1^oC$/day) for all the terms.

The analysed or forecast grid point wind, humidity and temperature data can be used to determine the right hand side terms in Eqns. (4) - (6) at any time. For the forecasts the residual should be the sum of what was introduced by the model physics, and for the analysis the residual represents the net effect of all diabatic contributions in the observed atmosphere. The results are averaged horizontally over large areas and over a long time span: this helps to smooth out random errors. The technique is basically similar to that used by e.g. Kung (1967), Holopainen (1963) and Palmen (1967) except that grid point σ-level data is used instead of observed (aerological) data on pressure levels. As long as the area chosen is not too mountainous, the σ-level and p-level grid point calculations give very similar results (Savijärvi and Capaldo, 1980) and the results can be interpreted as in the more common pressure level context.

The data consisted of the global initialized analyses (normal mode initialization, Temperton, 1979) and forecasts for the three month (90 days) winter period 8 Nov. 1979 - 6 Feb. 1980. The analysis and initialization schemes may have a smoothing effect on the results. The original ECMWF analyses are made on pressure levels and interpolated to 15 sigma levels before initialization. Unfortunately the vertical resolution of the original analyses is low near the ground (1000-850-700 mb). The horizontal resolution of the analyses and forecasts is 1.875° in latitude and longitude (N48).

The finite difference approximations of the right hand side terms in Eqns. (4) - (6) were derived from the ECMWF model momentum, thermodynamic and humidity equations in the staggered grid. The derivation of the model energy equations can be found in Burridge and Haseler (1977) and Burridge (1979). In adiabatic, frictionless flow the finite difference equations conserve mass and total energy globally.

During the 90 day period one major change was introduced in the model physics on 16 January 1980, whereby the drag coefficients were modified and new formulation chosen for the humidity parameters used in the radiation scheme. These changes improved the individual physical processes involved but the net effects remained much the same (ECMWF Forecast Report, Number 1 , 1980) because of the feed-back mechanisms built into the parameterization scheme. Thus the whole 90 day period is considered in the residual calculations, which only deal with the net effects.

The ten areas listed in Table 1 were used for all analyses (00, 06, 12, 18 GMT) and all available forecasts (not done during the weekends) for 6 and 12 hours and days 1, 2 ... 10. A selection of the results is shown in the form of vertical profiles of the terms in Eqns. (4) - (6).

Table 1. Areas used in the residual calculations

North pole cap 90-75° N
Northern hemisphere midlatitude belt 75-25° N
Tropics 25°N-25°S
Southern hemisphere midlatitude belt 25-75°S
South pole cap 75-90°S
All land areas (29.3% of the globe)
All ocean areas (70.7% of the globe)
Europe (10W, 70N, 40E, 35N)
North Atlantic (60W, 70N, 10W, 30N)
North America (70N, 30N, coastlines)

3. RESULTS

Fig. 1 shows the different terms on the right hand side of (4) - (6), and the resulting residuals (thick dashed lines) in the kinetic energy, temperature and humidity budgets averaged over the North American continental area limited by $30^{o}N$ and $70^{o}N$ latitudes and the coastlines, for the 90 day winter period, calculated from the daily operational 12 GMT initialized analyses. This area is almost exactly the same which Kung (1967) used for kinetic energy budget studies from radiosonde data; his 5-year means are reproduced in Fig. 1 for comparison, for the 6-month winter.

In the kinetic energy budget the agreement with Kung's results is good showing that the North American upper troposphere is on average generating kinetic energy which is exported horizontally out of the area. The residual shows the boundary layer dissipation maximum and another maximum in the free atmosphere, which is flatter than in Kung's calculations.

In the temperature budget (Eqn. (5)) the two flux divergence terms are not shown as they are very large, (and to a large extent counterbalance each other). The adiabatic conversion ($\alpha\omega$) term is positive, indicating sinking motion on the average, and the residual is negative. The physical mechanism causing this diabatic cooling of $-0.7^{o}C$/day may be expected to be mainly radiative long wave cooling in the winter continental area.

The humidity budget shows horizontal humidity net import into the North American continent at all levels, export of humidity from the lowest levels upwards, and a residual, which indicates a net moisture sink at all levels except near the surface. The local change of all the energy quantities is very small over the three month period.

Fig. 2 shows the same budgets for the same 90 day period from 12 GMT analyses averaged over the North Atlantic Ocean bounded by $60^{o}W$, $70^{o}N$, $10^{o}W$, $30^{o}N$. In the kinetic energy budget the 3-year means of Holopainen and Eerola (1979) are reproduced for comparison; although their area (the British Isles) is much smaller and not coinciding, it is synoptically in a similar region of diffluent jet exit flow in the upper troposphere and vigorous cyclone activity in the surface.

The Atlantic region is a strong sink of kinetic energy in the free atmosphere, largely compensated by import of kinetic energy through horizontal boundaries. The residual from the ECMWF analyses is negative except in a shallow layer between 700-800 mb, while the residual from radiosonde observations (Holopainen and Eerola) is positive in the free atmosphere, especially in the jet level. A mechanism aimed to produce this negative viscosity phenomenon in a diffluent jet

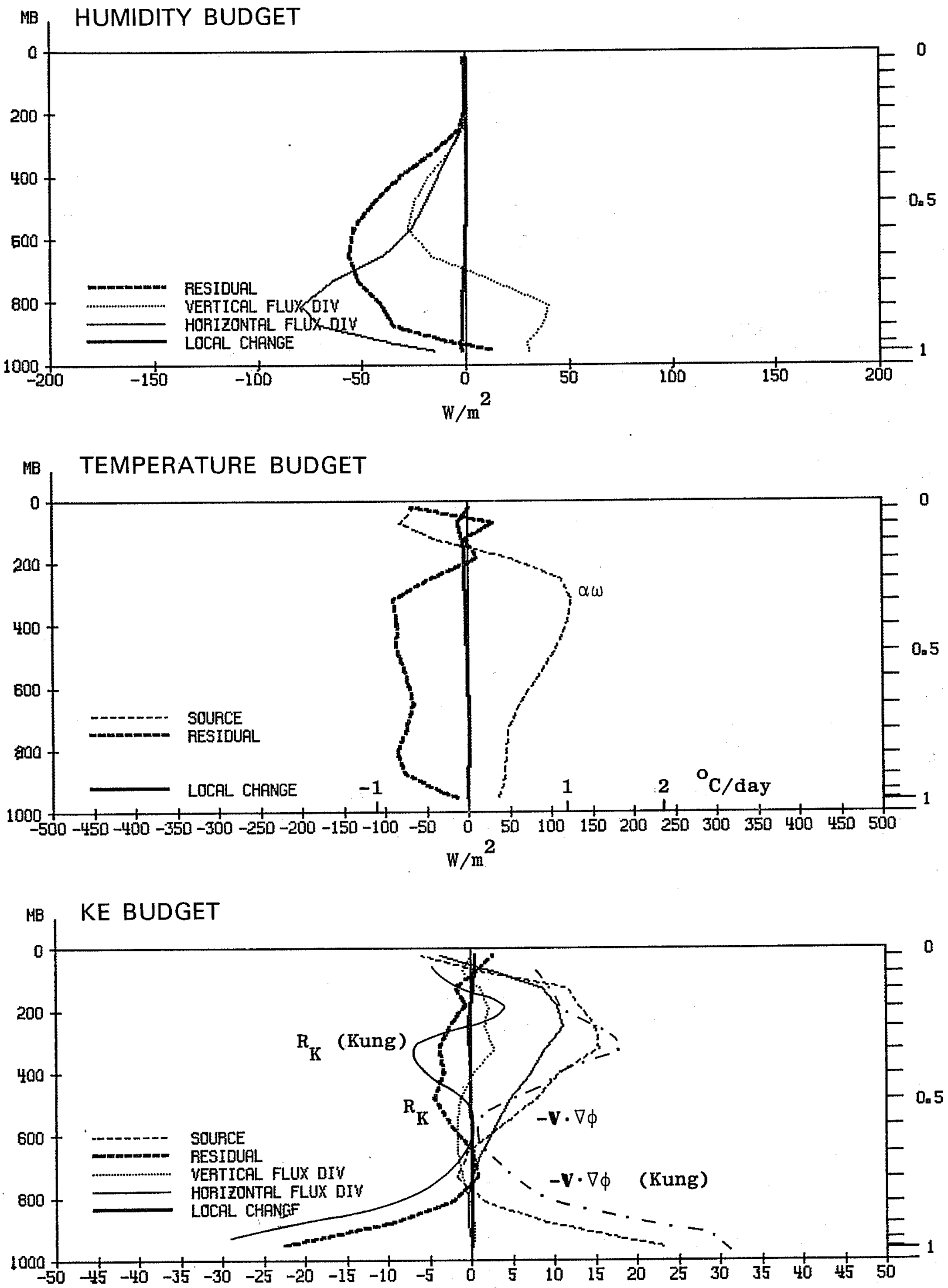


Fig. 1 Mean budgets of humidity, temperature and kinetic energy over North America between 30-70°N, calculated from 12 GMT initialized analyses for the 90-day period beginning from 2 November 1979. The 5-year mean winter values from Kung (1967) are shown for comparison.

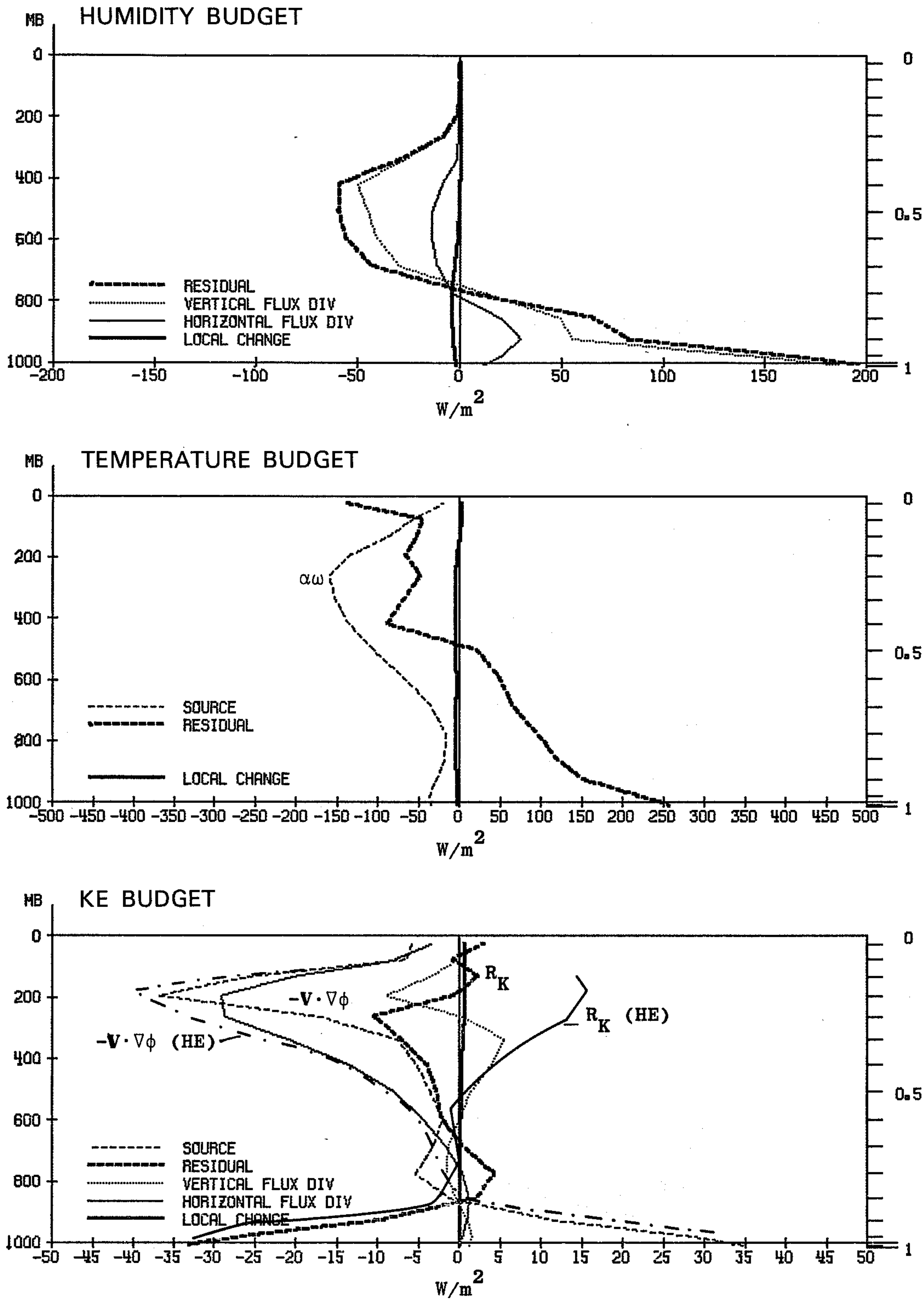


Fig. 2 Mean budgets of humidity, temperature and kinetic energy over North Atlantic (60°W, 70°N, 10°W, 30°N), calculated from 12 GMT initialized analyses for the 90-day period beginning from 8 November 1979. The 3-year mean values over the British Isles from Holopainen and Eerola (HE,1979) are shown for comparison.

was suggested in Holopainen and Eerola (1979); if it is generally valid the present approximations of friction in the numerical models may need reformulation.

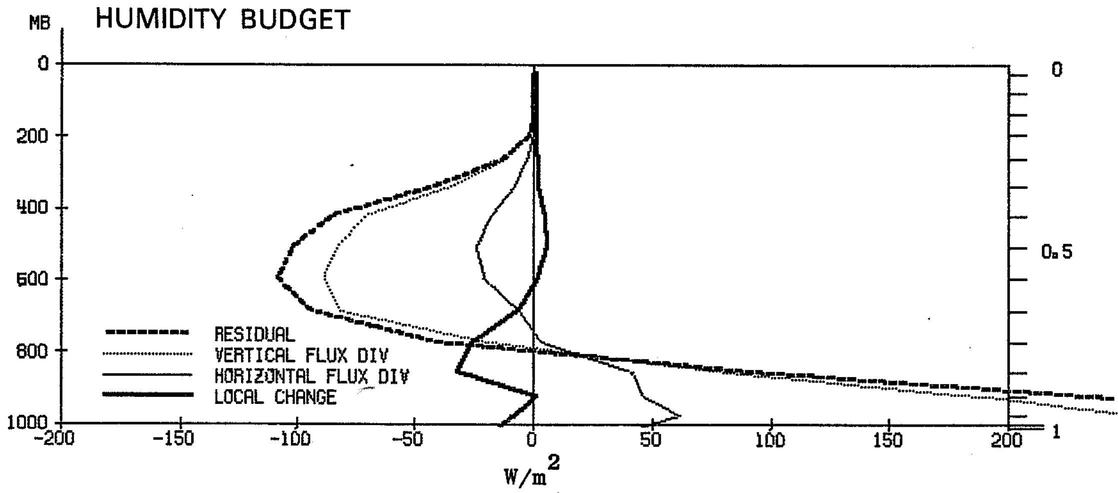
In the temperature budget the adiabatic cooling ($\alpha\omega$) indicates rising motion on the average over the North Atlantic area. The vertical profile of the residual (cooling above 500 mb and heating helow, especially near the surface), is reasonable taking into account the strong heat transfer from the relatively warm ocean surface, strong latent heating in the middle troposphere through condensation in the moving cyclones over the Atlantic area, and radiative cooling in the upper atmosphere. The humidity budget residual shows indeed strong condensation in the middle troposphere and large evaporation near the surface, mainly needed to balance the strong vertical transport of humidity in the ocean area.

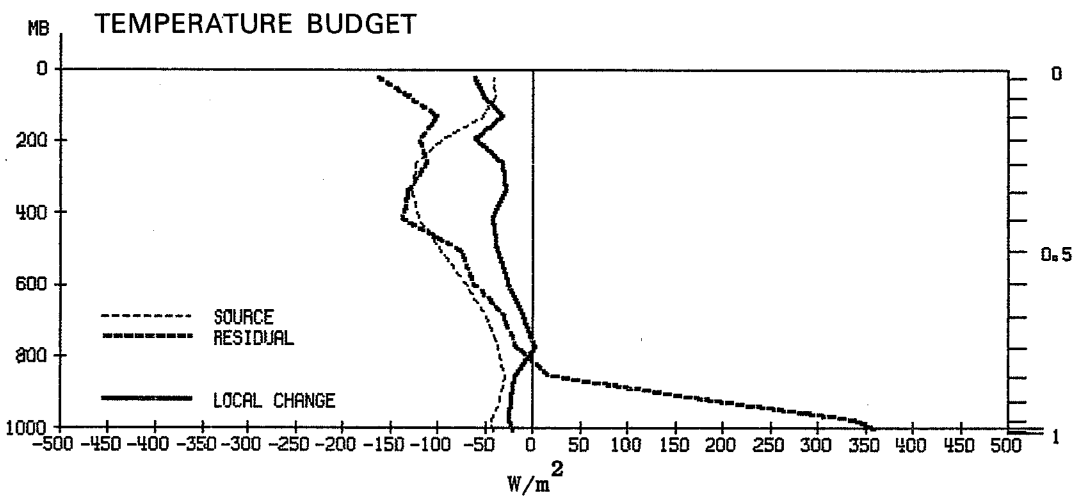
Fig. 3 shows the same budgets for the same area as in Fig. 2 but now averaged over all 3-day forecasts valid within the 90-day period. Because of the week-end gap in the production of forecasts there are only 63 cases available.

In the kinetic energy budget the individual terms look much the same in the 3-day forecasts as in the analyzed data. However, the absolute values of generation term and the residual friction term near the ground are in the forecasts larger than in the analyses (50 W/m^2 to 25 W/m^2 respectively in the lowest layer). The residual is almost constant in the free atmosphere having a very small secondary maximum at 350 mb.

The $\alpha\omega$-term is similar to that in the analyzed data, but the local temperature change is negative: the model atmosphere is systematically cooling at all levels with a rate of about $-0.4^{o}C$/day (40 W/m^2) at day 3. The residual term indicates higher diabatic cooling rates in the forecasts than in the analyzed data, except in the boundary layer. The model atmosphere is also drying; the local change of humidity is negative, which may be a consequence of the cooling with the cooler model atmosphere not being able to maintain the same amount of moisture. The humidity flux divergences have in the forecasts a larger magnitude than in the analyzed data. The same applies to the residual term.

In the forecast results the residual method should reproduce the net effect of all physics incorporated in the model; the difference would indicate the level of accuracy in the residual calculations. Fig. 4 summarizes the actual model physics given by the various parameterizations. The profiles are average over all land points ($^1/3$ of globe) and all forecasts from day 1 to day 10 for the two-week period 16 - 31 January 1980. The large-scale and convective (Kuo scheme) condensation and evaporation processes are included in the model separately but combined in Fig. 4.





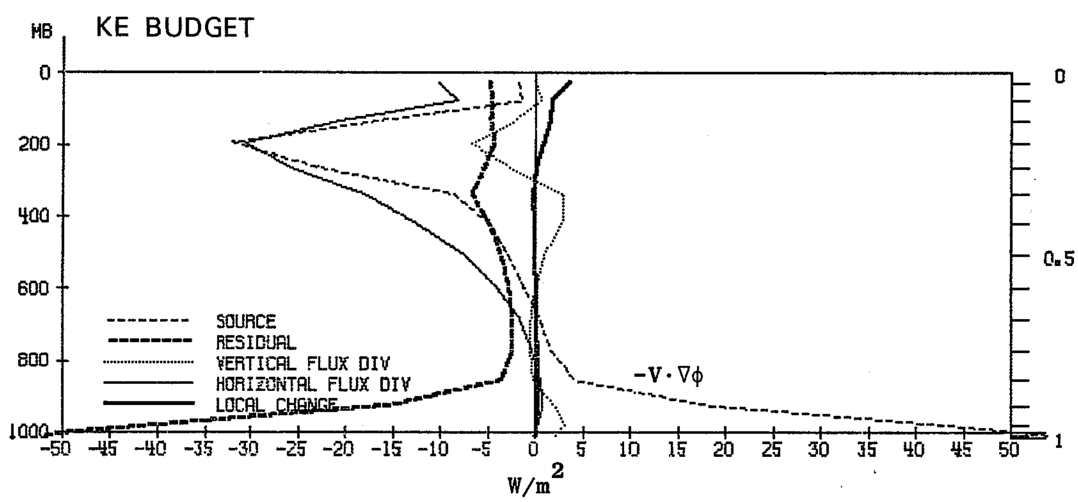


Fig. 3 As Fig. 2 but calculated from all 3 day forecasts

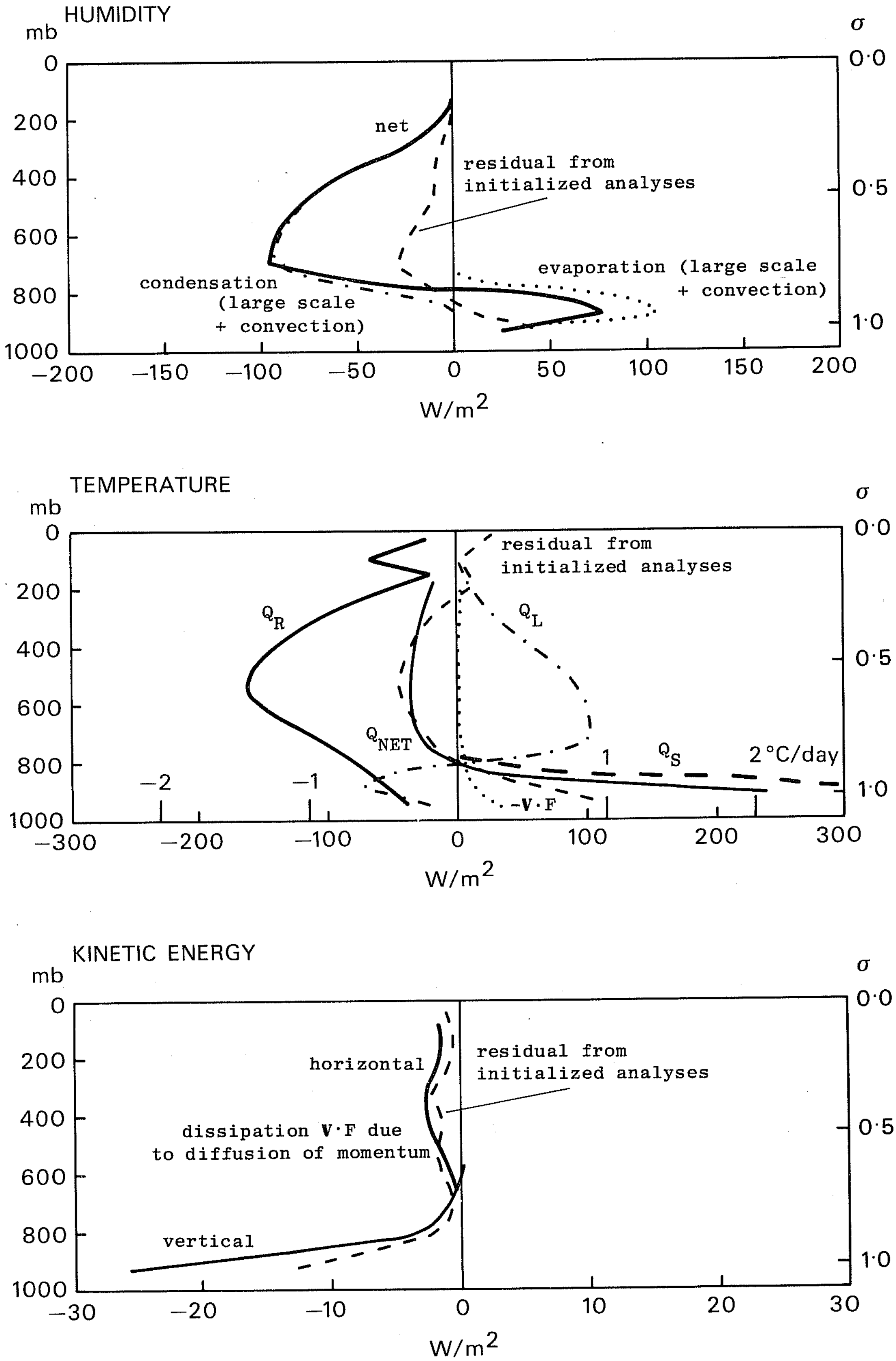


Fig. 4 The contributions from the various parameterizations in the ECMWF model averaged over all land points and all forecasts (1-10 days) for 16-31 January 1980.

Fig. 5 compares the net effect of the model physics (from Fig. 4) with that obtained as a residual for the same period.

The results agree rather well. The residuals from 12 GMT analyses for the same period are also included in Fig. 5 and it can be noted that the kinetic energy residuals in the forecasts and in the analyses are rather similar above the boundary layer although the analysis values are somewhat smaller. The temperature budget residual is nearly 0 in the stratosphere in the analyzed data while the model tends to cool the stratosphere due to radiation (cf. Fig. 4). In the middle troposphere the average heating over all 1-10 days forecasts is rather close to the observed. In the boundary layer the model data indicates enhanced heating.

The humidity budget residual is much smaller in absolute values in the analyses than in the forecasts, but this may just indicate problems in the humidity analysis and initialization scheme. The normal mode initialization which uses one time step of the adiabatic model removes small scale motions mainly associated with gravity waves, decoupling humidity (which is not initialized) and vertical motion fields every 6 hours in the analysis cycle; as a result the analyzed humidity field may remain unadjusted with the vertical motions leading to too small vertical humidity fluxes in the analysis and only weak evaporation-condensation processes needed to maintain the balance.

The 10 day bulk average does not tell how the model physics varied during the forecast period. This is seen in Fig. 6 where the residuals are shown separately for days 1, 3, 6 and 10 in the period 16 - 31 January 1980 for all land points. In the kinetic energy budget the PBL dissipation remains constant throughout the 10 day period while the dissipation in the free atmosphere is at maximum at day 3. In the humidity budget the residual shows the spin-up effect of the model condensation processes in the free atmosphere: starting from the (weak) analysis values the condensation processes slowly increase until they reach maximum at day 6 and decrease slightly thereafter. Near the surface the evaporation is very large during the first two days but then reaches a quasi-steady state.

The temperature budget residual is also affected by the spin-up; in the first days of the forecast the net latent heating is not strong enough to balance radiative cooling in the middle troposphere (Fig. 4). The net result is rapid cooling of the model atmosphere in the beginning of the forecast. A small part of the cooling is coming from the radiative peak in the stratosphere, which is strong in the beginning of the forecast but not present in the analyzed data.

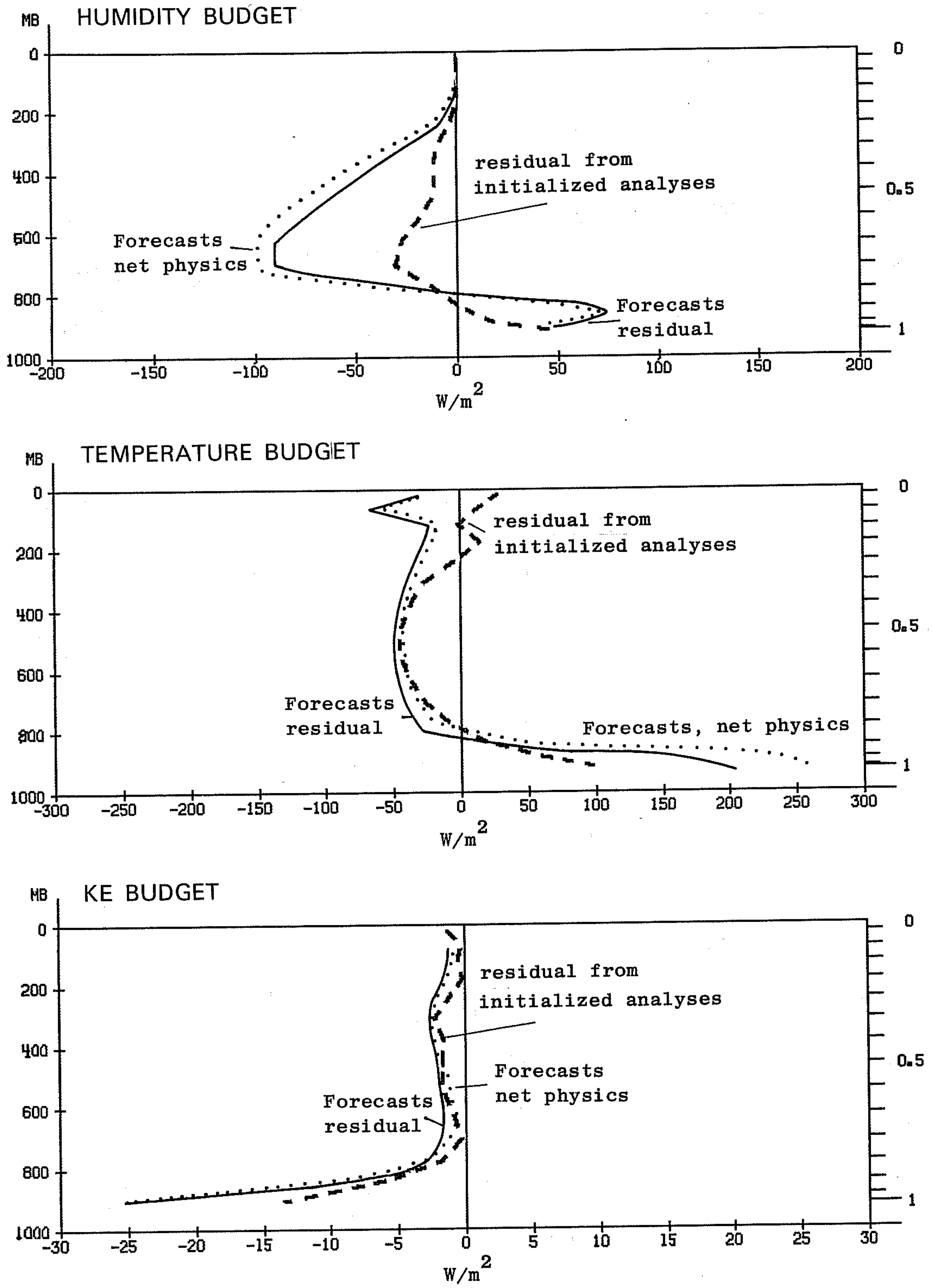


Fig. 5 The net effect of model physics (from Fig. 4) and residual from all forecasts (1-10 days) and analyses averaged over all land points for 16-31 January 1980.

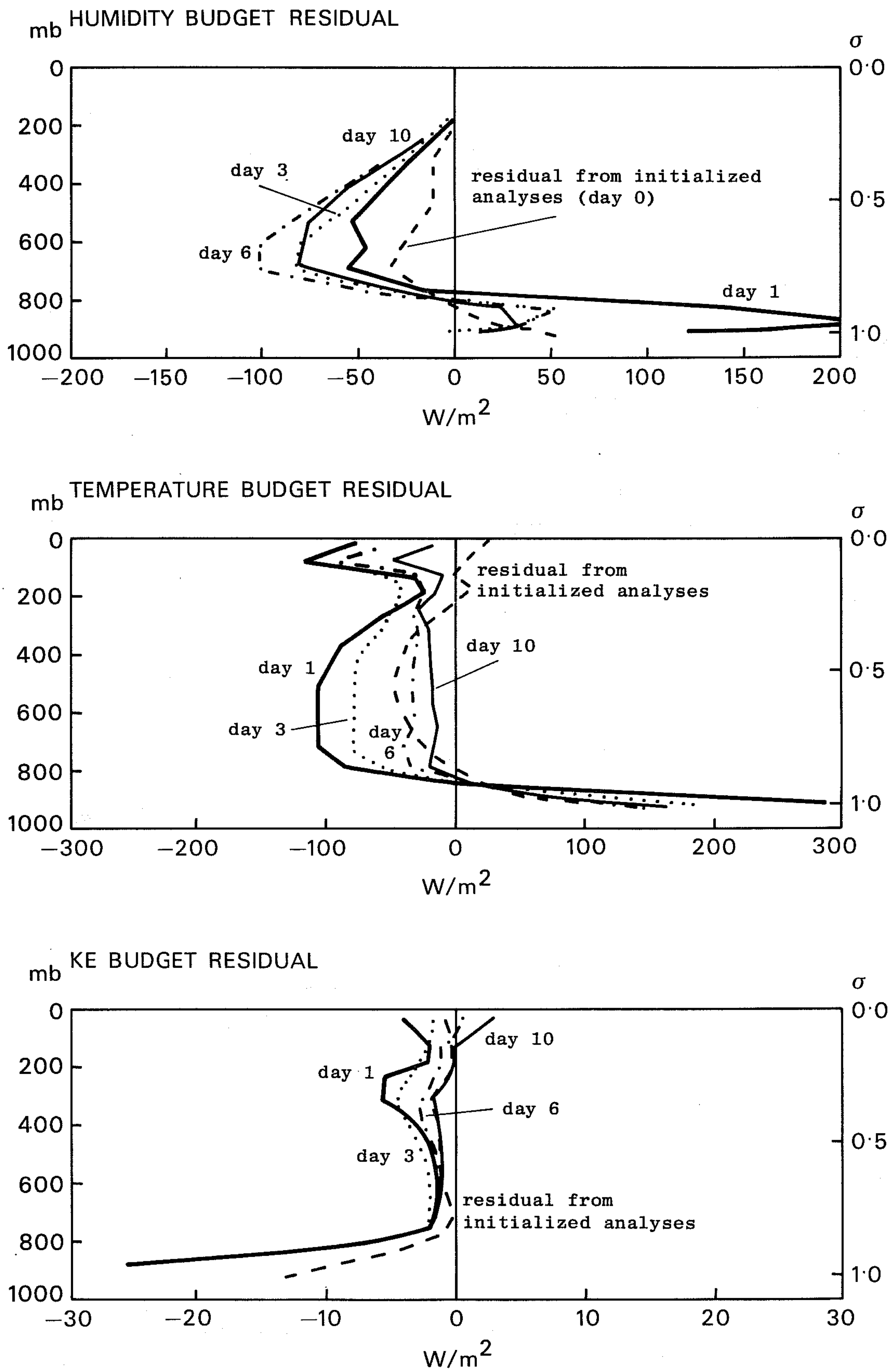


Fig. 6 Same as Fig. 5 but for residuals from forecasts for days 1,3,6,10 separately

In the lower troposphere the strong cooling by evaporation is opposed by strong sensible heat transfer from the surface in the first forecast days. A quasi-steady net surface heating level of about 170 W/m^2 is reached in two days.

Fig. 7 shows the residual heating rate integrated vertically as the function of forecast time for different areas, averaged over the 90-day winter period. The mid latitude areas exhibit a strong cooling in the beginning of forecasts while the tropics show net heating, reaching a maximum of ~1 ^{o}C/day at day 5 then decreasing to cooling in the longer forecasts for days 8-10.

The global generation of available potential energy, its conversion to kinetic energy and subsequent dissipation by friction is estimated in the literature to be between 2 and 5 W/m^2 (e.g. Oort, 1964). This value, compared to the effective energy input to the earth-atmosphere system, determines the effectiveness of the atmosphere as a heat engine. Fig. 8 shows the kinetic energy dissipation rates as a function of forecast time, averaged over the 90 day winter period and integrated vertically.

The global mean value of dissipation calculated from the analyses is 1.85 W/m^2. This may be an underestimate as it is based as a residual on initialized analyses, where the contribution from the generation of kinetic energy through high-frequency gravity wave modes may be suppressed.

The energetic activity of the model increases rapidly from this relatively low value to about 3.5 W/m^2 at days 2-4 after which it swings back to about 2 W/m^2 level. Most of the increase takes place in the northern mid latitude belt. A similar but weaker cycle is found in the southern hemisphere but not in the tropics. The spin-up time for the energy dissipation is much faster than for the condensation processes. The variation around the ensemble mean is small so that all individual forecasts exhibit the same cycle. In the longer integration experiments (not shown) the global dissipation levels off to an average value of 3 W/m^2 after 20 days. Also shown in Fig. 8 is the dissipation rate for the North American continent. While the result is not as smooth as for larger areas the energy cycle can be clearly seen. The values agree well with Kung's result (1967) from aerological data over the same area (3.74 W/m^2 for 12 GMT; 4.94 for 00 and 12 GMT).

The larger efficiency of the model (relative to the "observed" atmosphere) as a heat engine might be related to its tendency to generate too intense cyclones in the northern mid-latitudes, associated with the systematic error structure of too low geopotential heights in the main cyclone track areas over the eastern oceans.

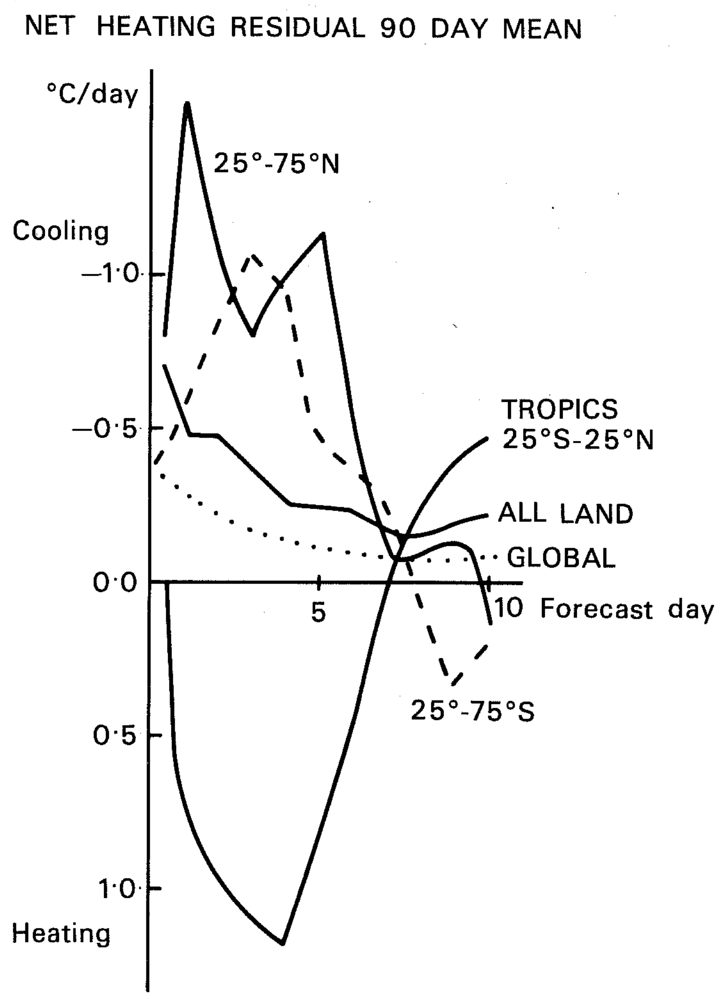


Fig. 7 The temperature budget residual as the function of forecast time averaged over the 90 day winter period. Unit °C/day.

RESIDUAL DISSIPATION 90 DAY MEAN .

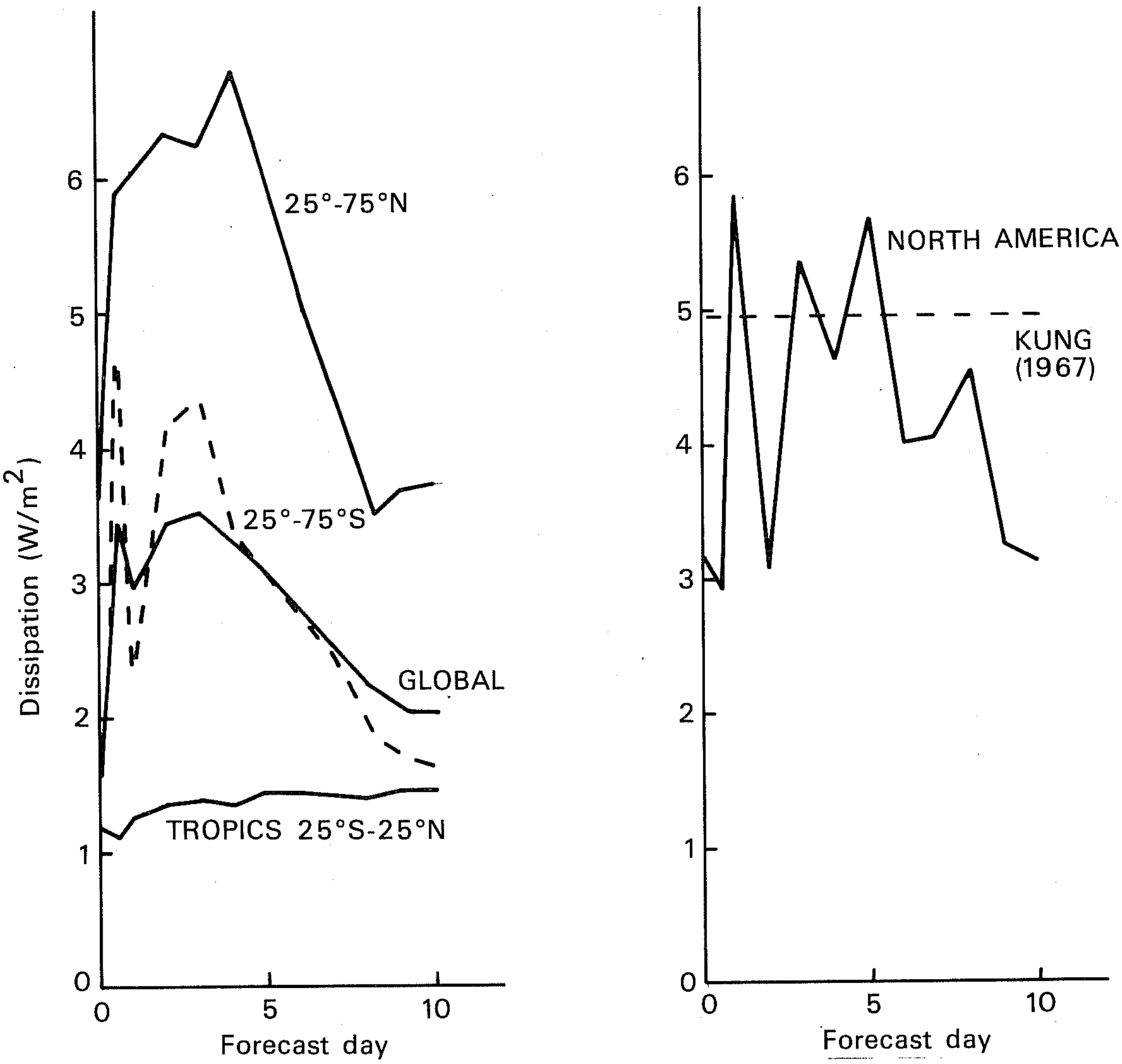


Fig. 8 The vertically integrated dissipation of kinetic energy as the function of forecast time averaged over the 90-day winter period. Unit W/m^2.

The strong diabatic cooling in the cold northern winter mid-latitudes and heating in the warm tropics during the first forecast days leads to generation of extra available potential energy which is then released to eddy kinetic energy in the mid-latitude cyclone families.

4. SUMMARY AND CONCLUDING REMARKS

The analyzed and forecast grid point data for 90 winter days were employed to calculate the diabatic effects on one hand from the ECMWF model parameterization scheme and on the other hand as residuals in the energy budget equations. Results were compared with earlier observational studies.

The results from the analyzed data for the two adjacent areas of North America (mean jet entrance) and North Atlantic (mean jet exit) demonstrate the large longitudinal differences in the kinetic energy maintenance with the jet entrance area being a source and the jet exit area a sink of kinetic energy, agreeing with the results of e.g. Kung (1967) and Lau (1980). The kinetic energy dissipation is positive in both areas in the present data. While this is what is normally expected, Holopainen and Eerola (1970) report systematic negative dissipation in the upper troposphere over the British Isles when aerological data is used. If this finding is true the present diffusive parameterizations of internal friction in numerical models may need reformulation as they cannot reproduce negative viscosity phenomena[1]. Because of the large influence of 6 hour forecast in the ECMWF analysis over the data-sparse ocean areas and the inherent smoothing in the analysis and initialization scheme such a cascade of unresolved scale energy to the resolved scale might be masked in the grid point data.

Averaged over the 10 day forecast period the diabatic processes parameterized in the model give a good fit to the net residual from the analyses over large areas. However, in the beginning of the forecast there is a spin-up effect in the condensational processes, which start from rather low values and reach a stationary level at day 3-4. The low values of humidity sources and sinks in the analyzed data may result from the uncoupling between humidity and wind field in the 6-hourly analysis-initialization-data assimilation scheme and from the general suppression of vertical motions in the tropics as a by-product of the normal mode initialization. The slow spin-up of condensational processes (mainly in the Kuo convection scheme) leads to net cooling through radiation in the first forecast days except in the tropics where net heating is experienced. Both the evaporation processes and vertical heat exchange near the ground are large in the first forecast days.

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1) cf.also Holopainen and Nurmi (1979,1980).

As a heat engine the model is more efficient than the analyzed atmosphere, judged from the global kinetic energy dissipation rate which is slightly less than 2 W/m^2 in the analyzed data, climbing up to 3.5 W/m^2 for days 3-4 in the forecasts and decreasing to about 2 W/m^2 towards day 10. The surface friction is consistently higher in the model than in the initialized data.

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