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# The energy budget of the earth–atmosphere system in Europe

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ABSTRACT

Vertically integrated divergences of time mean atmospheric energy fluxes are computed for various subareas of Europe using radiosonde data from 1974–1976, and are used, together with relevant information in the literature, to discuss the energy budget of the earth–atmosphere system for these areas. It is found that a reasonable budget can be obtained when the size of the area is not smaller than $6\text{–}7 \cdot 10^6$ km$^2$.

Considering the mainland of Europe, the convergence of the atmospheric total energy flux amounts to $55 \pm 15$ W/m$^2$ annually, which is comparable to satellite-based estimates of the net radiation flux, $-35$ to $-70$ W/m$^2$, for the same region. This convergence is about twice as large as the corresponding zonally averaged convergence in the corresponding latitude belt.

In the atmosphere, the combined mean-flow flux of sensible heat and potential energy is found to be the most important factor in the energy budget. However, the role of the transient eddies is also important, particularly in the convergence of latent heat and kinetic energy. The transient eddy flux divergences of total energy in winter act so as to dissipate the longitudinal anomalies of total energy.

## 1. Introduction

The energy budget of the earth–atmosphere system has been studied in the past mainly for zonally averaged conditions (examples of the recent observational studies are Newell et al. (1974) and Oort and Vonder Haar (1976)). However, only very few studies of the budget of total energy for limited areas have been published, e.g. Hastenrath (1966) for the Caribbean Sea and the Gulf of Mexico, Gruber (1970) for the Florida peninsula, and Behr and Speth (1977) for northwestern Europe.

In this study the budget of the vertically integrated atmospheric total energy, defined as the sum of sensible heat, latent heat, and kinetic energy between the surface and the 150 mb level, is studied in different areas of Europe using aerological data from the 3 years 1974–1976. The computed vertically integrated divergences of energy fluxes are compared with the net radiative fluxes at the top of the atmosphere and the surface energy blance components found in the literature. Thus, information is gained about the present compatibility of the energy balance components measured in different ways. Through the use of areas of different size an estimate is obtained for the minimum size area for which a reliable energy budget can be evaluated. By dividing the fluxes into their mean-flow and transient eddy parts, the importance of different mechanisms in the atmospheric transport is examined.

The data used in this study for divergence computations are the same as in Alestalo and Holopainen (1980), in which the energy fluxes over Europe for the period 1974–1976 were presented.

## 2. Method of computation

### 2.1 *Energy budget equation*

The equation for total energy in an atmosphere–ocean–soil–cryosphere column is (e.g. Oort and Vonder Haar, 1976).

$$S_A + S_O = -\nabla \cdot (\mathbb{F}_A + \mathbb{F}_O) + R_{ea} \tag{1}$$



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In this equation

$$S_A = \frac{\partial}{\partial t} \int_0^{p_s} (c_p T + Lq + k) \frac{dp}{g} \tag{2}$$

is the local time rate of change of the sum of sensible heat ($c_p T$), latent heat ($Lq$) and kinetic energy ($k$) integrated over the mass of an atmospheric column. $p_s$ denotes the surface pressure and $g$ the acceleration due to gravity. The corresponding term for an ocean–soil–cryosphere column, $S_O$, is the local time rate of change of the energy content of that column when integrated from the surface of the earth down to the depth where there is no net vertical fluxes of energy through the lower boundary.

Further,

$$\begin{aligned} \mathbb{F}_A &= \int_0^{p_s} (c_p T + Lq + \Phi + k) \mathbb{V} \frac{dp}{g} \\ &= \mathbb{F}_S + \mathbb{F}_L + \mathbb{F}_P + \mathbb{F}_K \end{aligned} \tag{3}$$

is the vertically integrated horizontal flux of total atmospheric energy, split up to contributions due to the fluxes of sensible heat ($c_p T \mathbb{V}$), latent heat ($Lq\mathbb{V}$), potential energy ($\Phi\mathbb{V}$), and kinetic energy ($k\mathbb{V}$). $\mathbb{V}$ is the horizontal wind vector. The subindexes refer to sensible heat flux (S), latent heat flux (L), potential energy flux (P), and kinetic energy flux (K). $\mathbb{F}_O$ denotes the horizontal energy flux in the ocean–soil–cryosphere column. $R_{ea}$ is the net radiation at the top of the atmosphere (positive when downwards).

Equation (1) constitutes the basic equation for the energy balance computations. It states that the energy content of an atmosphere–ocean–soil–cryosphere column can change only due to the net flux of energy through its upper horizontal boundary ($R_{ea}$) or its vertical boundaries ($\nabla \cdot (\mathbb{F}_A + \mathbb{F}_O)$). Equation (1) is rather general. Only lateral turbulent and viscous fluxes of sensible and latent heat and horizontal transport of atmospheric water in the liquid or solid phase are neglected. Additional minor effects ignored are the net energy consumed in the photosynthesis and decay process and the flux of geothermal energy. Contributions other than oceanic ones in $S_O$ and $\mathbb{F}_O$ are also practically insignificant.

The atmospheric time mean flux ($\overline{s\mathbb{V}}$) of an arbitrary property $s$ can be split into contributions of the time mean flow ($\bar{s}\bar{\mathbb{V}}$) and transient eddies ($\overline{s'\mathbb{V}'}$). Here, as usual, an overbar denotes a time mean value and a prime a deviation from it. Thus we can write for the time mean vertically integrated total flux

$$\bar{\mathbb{F}} = \bar{\mathbb{F}}^M + \bar{\mathbb{F}}^T, \tag{4}$$

where $\bar{\mathbb{F}}^M$ is the flux associated with the mean motion and $\bar{\mathbb{F}}^T$ that associated with the transient eddies.

In the long-term steady state conditions, the storage terms disappear (the condition $\bar{S}_A = 0$ is also approximately true for the extreme seasons). Therefore, the equation of the time mean energy balance applied in this study is

$$\nabla \cdot \bar{\mathbb{F}}_A^M + \nabla \cdot \bar{\mathbb{F}}_A^T + \nabla \cdot \bar{\mathbb{F}}_O = \bar{R}_{ea}. \tag{5}$$

### 2.2 *Computation method*

The horizontal flux divergences were calculated for each polygon shown in Fig. 1. The fluxes were assumed to vary linearly between the aerological stations forming the polygons. Vertical integrals were obtained by using the trapezoidal rule. The 150 mb level is used as the upper boundary. The temperature dependence of $L$, latent heat of vaporization, was neglected and the value 2.5 MJ/kg was used.

### 2.3. *Correction for the mass balance*

A major problem in calculating the total energy budget is that the wind data do not normally fulfil the requirement of the conservation of atmospheric mass, as indicated by many studies (Gruber, 1970; Oort and Rasmusson, 1970; Behr and Speth, 1977). The investigations of the budget of latent heat (water vapour) alone, on the other hand, are not so sensitive to mass conservation requirements (e.g. Hutchings, 1957; Rasmusson, 1966).

The divergence of the time mean flux of $s$ may be written as

$$\nabla \cdot \overline{s\mathbb{V}} = \bar{s}\nabla \cdot \bar{\mathbb{V}} + \bar{\mathbb{V}} \cdot \nabla \bar{s} + \nabla \cdot \overline{s'\mathbb{V}'}. \tag{6}$$

Integrating vertically through the atmospheric column we get

$$\begin{aligned} \int_{150}^{p_s} \nabla \cdot \overline{s\mathbb{V}} \frac{dp}{g} &= \widehat{\nabla \cdot \bar{\mathbb{V}}} \int_{150}^{p_s} \bar{s} \frac{dp}{g} + \int_{150}^{p_s} \bar{s}\nabla \cdot \bar{\mathbb{V}}^{+} \frac{dp}{g} \\ &+ \int_{150}^{p_s} \bar{\mathbb{V}} \cdot \nabla \bar{s} \frac{dp}{g} + \int_{150}^{p_s} \nabla \cdot \overline{s'\mathbb{V}'} \frac{dp}{g}, \end{aligned} \tag{7}$$

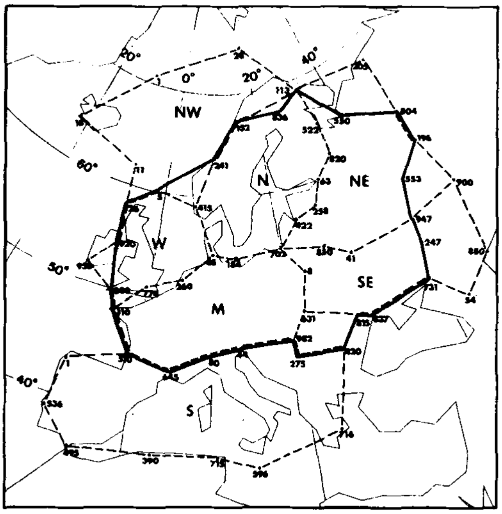


*Fig. 1.* The regions for which the energy budget is evaluated. The largest region, called A in the text, is shown with a solid line, and the seven smaller regions with dashed lines. Stations at the boundaries are identified by the WMO index numbers (omitting the block number).

where $(\widehat{\ })$ denotes a vertical average and $(\ )^+$ a deviation from it. We assume that the time mean vertical velocity disappears at the upper and lower boundaries. This implies vanishing of $\widehat{\nabla \cdot \bar{\mathbb{V}}}$ (mass balance requirement) and of the first r.h.s. term in (7). With real observations this is not the case and this largely spurious term must be subtracted. Strictly speaking, the mass balance need not be achieved in a column not extending to the "top" of the atmosphere. Computationally, however, this is necessary because even small imbalances adversely affect the budget evalutions.

Essentially, this correction method adjusts the time mean mass divergence values by the same amount at every level and could thus be called a "constant error method". It is naturally possible to assume vertical error distributions of a different kind. For instance, the method where the imbalance of the mass divergence is distributed linearly with pressure (O'Brien, 1970) was also used. However, it did not generally yield more realistic results than the constant error method.

It should be noted that, through the correction technique applied, only the condition of the mean mass balance in the atmospheric column (surface $-150$ mb) is fulfilled. The shape of the vertical distribution of $\nabla \cdot \overline{s\mathbb{V}}$ will be preserved almost totally. At individual levels the divergence estimates may still be erroneous and thus the corrected values of $\nabla \cdot \bar{\mathbb{F}}_A$ may still contain errors.

As a consequence of the correction method the seasonal or monthly mean estimates of corrected values of $\nabla \cdot \bar{\mathbb{F}}_A$, when averaged, do not exactly give the same value as obtained by applying the correction technique to the mean flux divergences for the entire period considered. This follows from the temporal (computational) correlation between $\widehat{\nabla \cdot \bar{\mathbb{V}}}$ and $\int \bar{s}(dp/g)$.

For reasons analogous to that given above, the corrected $\nabla \cdot \bar{\mathbb{F}}_A$ values for any polygon depend on whether the mass balance correction is applied to the polygon as an entity or to all the triangles (constructed by the stations and forming the polygon) separately. Now the different values are due to the spatial correlation between $\widehat{\nabla \cdot \bar{\mathbb{V}}}$ and $\int \bar{s}(dp/g)$. The values given later are based on computations when about 60 stations within the region A (Fig. 1) were used. The differences between the results for various triangle compositions were smaller than the error estimates given in Section 6.

## 3. Regions for energy balance calculations

The various regions for the energy budget computations are shown in Fig. 1. The selected regions can be roughly divided on the basis of size into two groups:

(1) The region A roughly corresponding continental Europe north of 45° N and west of 45° E with an area of $6.6 \cdot 10^6$ km$^2$
(2) The regions labelled with letters NW, N, NE, W, M, SE and S with areas varying between $0.9$–$2.6 \cdot 10^6$ km$^2$.

Quantitative results will be given in the following only for the region A. Originally calculations were also made for areas smaller than $1 \cdot 10^6$ km$^2$. However, in this case the results were badly affected by noise and will not be discussed here. In the construction of the regions (polygons) the main criterion was the number of available observations. The availability of wind observations determined the sample size for flux computations. In Alestalo and Holopainen (1980; Fig. 1) the percentage of wind observations available at 300 mb was reported.

Due to the lack of significant level data at some stations the data sample below 850 mb was less representative than at the standard levels, and as a worst case samples with about 50% of the total possible (2196) were accepted at or near the surface. Stations with only one observation per day were not used at all.

## 4. The energy balance

In this chapter the atmospheric energy flux divergences are presented on an annual and seasonal basis, and compared with estimates of the other quantities entering the energy balance eq. (5).

### 4.1. *Annual conditions*

The results for the annual mean atmospheric energy flux divergences, as calculated in the present study, are given in Table 1 together with other relevant figures, worked out from some recent publications on the energy balance.

No earlier estimates of $\nabla \cdot \bar{\mathbb{F}}_A$ are available for the region A (or Europe). An area-averaged annual mean $\bar{R}_{ea}$ for the region A was extracted from Budyko (1963), whose computations are based on climatological data, and from Vonder Haar and Suomi (1971), Raschke et al. (1973), Winston et al. (1979), and Stephens et al. (1981), who report values of $\bar{R}_{ea}$ based on satellite measurements. Corresponding estimates for $\nabla \cdot \bar{\mathbb{F}}_O$ were obtained from Bunker and Worthington (1976). Naturally, it is also of interest to compare the conditions over Europe with the average conditions prevailing in the same latitude belt; here Newell et al. (1974) and Oort and Vonder Haar (1976) have made the most recent contributions (zonal averages are denoted by brackets in the following).

According to our computations the atmosphere over Europe acts as an energy sink: the annual mean estimate of $\nabla \cdot \bar{\mathbb{F}}_A$ for the region A is $-55$ W/m$^2$. In Section 6 it is shown that this value has an uncertainty of about 15 W/m$^2$, which is about of the same magnitude as the error in the areal average of $\bar{R}_{ea}$ obtained by Raschke et al. (1973) for the region A (Raschke, personal communication). $\nabla \cdot \bar{\mathbb{F}}_O$ is practically insignificant in the region A.

The five annual mean estimates of $\bar{R}_{ea}$ for the region A are $-42$, $-35$, $-69$, $-70$ and $-52$ W/m$^2$. The scatter among these estimates is quite large and reflects the large uncertainty in them. In their computations, Raschke et al. (1973) used Nimbus III data for only four 15-day observation periods in different seasons during 1969–1970, whereas in Vonder Haar and Suomi (1971), Winston et al. (1979), and Stephens et al. (1981) long-term composite data sets were used. The large difference between $\bar{R}_{ea}$ given by Vonder Haar and Suomi (1971) and by other satellite based evaluations is probably understandable since the early measuring techniques and computing methods were not as advanced as in later studies. It is, however, strange that the two latest evaluations (Winston et al. and Stephens et al.) give results which deviate systematically about 20 W/m$^2$ from each other in all seasons in the region A.

Within the limits of uncertainties involved, our estimate of $\nabla \cdot \bar{\mathbb{F}}_A$ over Europe ($-55$ W/m$^2$) is compatible with the net radiation estimates. The results for the 3 separate years 1974, 1975, and 1976 ($-61$, $-47$, $-59$ W/m$^2$, respectively) also lie near the net radiation estimates. This shows that, in the region of a dense network of stations, the use of aerological data can be used for energy budget computations at least with horizontal scales down to about $7 \cdot 10^6$ km$^2$.

The comparison between the annual means $\nabla \cdot \bar{\mathbb{F}}_A$ and $\nabla \cdot [\bar{\mathbb{F}}_A]$ (Oort and Vonder Haar, 1976) shows that about twice as much energy is converging over Europe as in the corresponding latitude belt. On the other hand, our estimate of $\nabla \cdot \bar{\mathbb{F}}_A$ is close to the zonally averaged convergence of the total atmospheric and oceanic energy flux $\bar{\mathbb{F}}_A + \bar{\mathbb{F}}_O$ in the same latitude belt (Newell et al., 1974; Oort and Vonder Haar, 1976). In order to understand this we should first note that for annual mean conditions $\bar{S}_O = \bar{S}_A = 0$ in (1) and thus, at each longitude, $\bar{R}_{ea} = \nabla \cdot \bar{\mathbb{F}}_A + \nabla \cdot \bar{\mathbb{F}}_O$. The distribution of $\bar{R}_{ea}$ (e.g. Stephens et al., 1981) in the middle latitudes is practically axisymmetric and shows surprisingly little longitudinal variation. Because $\nabla \cdot \bar{\mathbb{F}}_O$ is non-zero only in oceanic areas and zero in land areas, the energy convergence in the atmosphere over land is expected to be larger than over oceans and close to the zonal mean of $\nabla \cdot (\bar{\mathbb{F}}_A + \bar{\mathbb{F}}_O)$.

### 4.2. *Seasonal variation*

The seasonal variation of $\nabla \cdot \bar{\mathbb{F}}_A$ as computed in this study can be compared with the corresponding zonal averages given by Oort and Vonder Haar (1976) (Table 1).

Table 1. *Annual and seasonal estimates of the atmospheric* ($\nabla\cdot\bar{F}_A$) *and oceanic* ($\nabla\cdot\bar{F}_O$) *divergences of energy fluxes, the net radiation of the earth–atmosphere system* $\bar{R}_{ea}$, *and the atmospheric* ($\bar{S}_A$) *and oceanic* ($\bar{S}_O$) *rates of change in the energy storage. Zonal averages for the latitude belt 45–70°N are denoted by brackets, otherwise the figures refer to the region A shown in Fig. 1. Unit W/m²*

| | | Winter | Spring | Summer | Autumn | Year |
|---|---|---|---|---|---|---|
| $\nabla\cdot\bar{F}_A$ | this study | −92 | −15 | +15 | −109 | −55* |
| $\bar{R}_{ea}$ | Budyko | | | | | −42 |
| | VH & S | | | | | −35 |
| | Raschke | | | | | −69 |
| | Winston | −160 | −30 | 35 | −125 | −70 |
| | Stephens | −141 | −6 | 53 | −99 | −52 |
| $\nabla\cdot\bar{F}_O$ | B & W | | | | | −2 |
| $\nabla\cdot[\bar{F}_A]$ | O & VH | −34 | −31 | −9 | −23 | −24 |
| $\nabla\cdot[\bar{F}_O]$† | O & VH | −51 | −22 | −2 | −30 | −26 |
| $\nabla\cdot[\bar{F}_A+\bar{F}_O]$ | Newell | −91 | −43 | −17 | −46 | −49 |
| | O & VH | −85 | −53 | −11 | −53 | −50 |
| $[\bar{R}_{ea}]$ | O & VH | −132 | −20 | 39 | −90 | −51 |
| | Newell | −134 | −3 | 38 | −97 | −49 |
| $[\bar{S}_A]$ | O & VH | −2 | 16 | 4 | −18 | 0 |
| $[\bar{S}_O]$† | O & VH | −45 | 17 | 46 | −18 | 0 |

References: B & W (Bunker and Worthington, 1976); Budyko (Budyko, 1963); O & VH (Oort and Vonder Haar, 1976); Newell (Newell et al., 1974); Raschke (Raschke et al., 1973); Stephens (Stephens et al., 1981); VH & S (Vonder Haar and Suomi, 1971), Winston (Winston et al., 1979).

* The four seasonal estimates of $\nabla\cdot\bar{F}_A$ do not exactly give the annual value when averaged. For explanation, see 2.3.

† To obtain approximate values referring to oceanic part only, divide by 0.4, the fraction of area covered by oceans in the latitude belt 45–70° N.

The seasonal course of $\nabla\cdot\bar{F}_A$ over Europe is characterized by a strong convergence in autumn and winter, a small convergence in spring, and a divergence in summer. It is interesting to note that the seasonal course of $\nabla\cdot\bar{F}_A$ for the region A shows much larger amplitude than that of the zonal average $\nabla\cdot[\bar{F}_A]$: in autumn and winter about four times more energy converges in the atmosphere above Europe than in the respective latitude belt. In spring and summer the convergence is smaller by about 20 W/m². This latter difference is not, however, fully reliable because the error estimates for the seasonal values of $\nabla\cdot\bar{F}_A$ are obviously larger than those for the annual values (15 W/m²). This may also be the reason for the fact that the maximum convergence in the region A is found in autumn instead of winter.

The large wintertime difference between $\nabla\cdot\bar{F}_A$ and $\nabla\cdot[\bar{F}_A]$ is understandable due to the role of the oceans. These do free large amounts of energy in winter (Table 1): $[\bar{S}_O]$ (−45 W/m²) is about half of the total atmospheric and oceanic divergence of $[\bar{F}_A+\bar{F}_O]$ (−85 W/m², Oort and Vonder Haar, 1976). The rate at which energy is lost by the pure oceanic area in the latitude belt considered is, however, about 115 W/m². The corresponding convergence of $[\bar{F}_O]$ is seen from Table 1 to be about the same size. Because the distribution of $\bar{R}_{ea}$ in winter in the middle latitudes (Stephens et al., 1981) is very axisymmetric, the energy losses to space over oceans are not greater than over land areas. Thus, in order to obtain an energy balance for the atmosphere–ocean system in the latitudes considered, there must be an upward energy flux through the surface of the ocean and a net transport of energy in the atmosphere from oceanic sectors to land sectors of the Northern Hemisphere. This obviously leads to zonal asymmetries in $\nabla\cdot\bar{F}_A$ with larger convergence over land areas and smaller convergence (possibly also divergence) over oceans. Because the effect of change in the atmospheric storage of energy is rather small and similar over Europe (not shown) as in the latitude belt in general, $S_A$ does not alter the above picture. Due to the small fraction of sea (the North Sea) in the region A, $S_O$ plays no significant role in the energy budget for this area.

### 4.3. *Mass balance considerations*

One of the factors involved in the computation of the vertically integrated divergences is the mass balance correction (section 2.3). The vertical integral of $\nabla \cdot \bar{V}$ (Fig. 2) is $1.8 \cdot 10^{-3}$ kg m$^{-2}$ s$^{-1}$ or, equivalently, about seven "atmospheres" per year. This clearly demonstrates the necessity of mass balance corrections.

The imbalance for the region A mainly results from the unexpected divergence below 850 mb. According to the wind profiles in this layer at some coastal stations, mean winds were observed which deviated from the general flow pattern in the corresponding areas. For the region A this leads to divergence which is not representative from the point of view of large-scale flow. In Section 6 the effect of this obviously erroneous divergence pattern is examined and found not to be fatal for the budget computations.

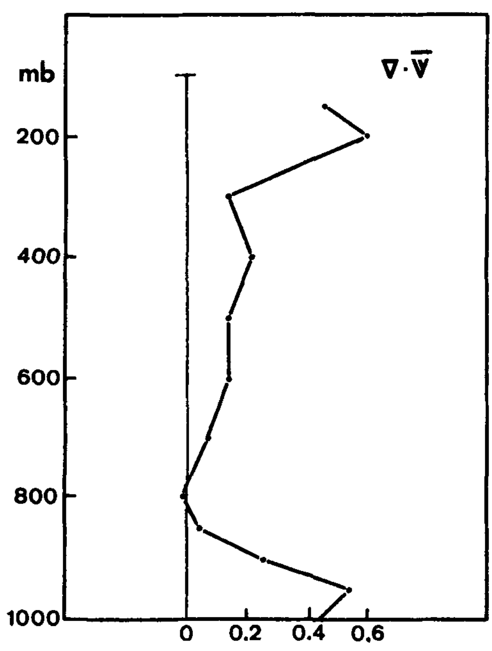


*Fig. 2.* The annual mean vertical profile of $\nabla \cdot \bar{V}$ for the region A shown in Fig. 1. Unit: $10^{-6}$ s$^{-1}$.

## 5. The mean-flow and transient eddy flux divergence of the energy components

In this section the relative importance of the mean-flow and transient eddy contributions to the different energy flux divergences are examined. The vertically integrated divergences of sensible and latent heat, and potential and kinetic energy fluxes associated with the two types of motion are given for annual and seasonal conditions in Table 2.

The question of what main mechanisms are responsible for the "required" transports of energy in the maintenance of the global balance of this quantity has been one of the main objects of diagnostic studies. Considering total energy in the zonally averaged conditions for the middle latitudes, the eddies have been found to be the most important factor. In winter the transient and standing eddies are of equal importance whereas in other seasons and annually the transient eddies dominate (Holopainen, 1965; Oort and Rasmusson, 1971). It has recently been shown (Lau, 1979) that for wintertime circulation, in the maintenance of the local mean heat budget, the time mean flow is in fact slightly dominant over the transient eddies in the lower troposphere. According to our study (Table 2), $\nabla \cdot \bar{F}_S^M$ and $\nabla \cdot \bar{F}_P^M$ dominate over corresponding transient eddy quantities in Europe. However, because of the balancing between $\nabla \cdot \bar{F}_S^M$ and $\nabla \cdot \bar{F}_P^M$, the difference between $\nabla \cdot \bar{F}_A^M$ and $\nabla \cdot \bar{F}_A^T$ is in general smaller than in the case of sensible heat or potential energy. In the case of $\nabla \cdot \bar{F}_L$ and $\nabla \cdot \bar{F}_K$ the transient eddy and mean-flow contributions are about equal.

### 5.1. *Mean-flow flux divergences*

The most important energy components forming $\nabla \cdot \bar{F}_A^M$ are sensible heat and potential energy. These tend to balance each other through mean vertical motions: in upward movements air is cooled adiabatically and its internal (potential) energy tends to decrease (increase) locally whereas the opposite takes place in downward movements. It is therefore natural to consider the combined effect of these two.

The vertical distribution of $\nabla \cdot \bar{V}$ is an important factor in determining the structure of the energy flux divergence connected with the mean motion (see (7)). Because $c_p T + \Phi$ increases monotonically upwards in a stable, stratified atmosphere, the conditions with the mean low-level convergence

Table 2. *The divergence of the different vertically integrated energy fluxes over Europe (region A in Fig 1) during 1974–1976. Unit W/m²*

| | $\nabla\cdot\mathbb{F}_S$ | $\nabla\cdot\mathbb{F}_L$ | $\nabla\cdot\mathbb{F}_P$ | $\nabla\cdot\mathbb{F}_K$ | $\nabla\cdot\mathbb{F}_A$ |
|---|---|---|---|---|---|
| | | | Year | | |
| Mean-flow | −51* | −4 | 22 | −2 | −34 |
| Transient eddy | −4 | −15 | 1 | −4 | −21 |
| Total | −55 | −19 | 24 | −5 | −55 |
| | | | Winter | | |
| Mean-flow | −108 | −18 | 36 | −5 | −95 |
| Transient eddy | 20 | −15 | 3 | −5 | 3 |
| Total | −88 | −33 | 39 | −10 | −92 |
| | | | Spring | | |
| Mean-flow | −23 | −1 | 26 | 0 | 2 |
| Transient eddy | −6 | −11 | 3 | −3 | −17 |
| Total | −28 | −12 | 29 | −3 | −15 |
| | | | Summer | | |
| Mean-flow | 15 | 14 | −3 | −1 | 25 |
| Transient eddy | −1 | −8 | 1 | −2 | −10 |
| Total | 14 | 6 | −2 | −3 | 15 |
| | | | Autumn | | |
| Mean-flow | −102 | −16 | 18 | −1 | −102 |
| Transient eddy | 8 | −12 | 0 | −4 | −7 |
| Total | −94 | −28 | 18 | −5 | −109 |

* In order to roughly convert the figures to °C/d divide by 100.

and upper-level divergence lead as a net effect to a divergence of the flux $(c_p\bar{T} + \bar{\Phi})\bar{\mathbb{V}}$. Although the above condition is valid in the region A, it proves, however, not to be the dominating mechanism. According to Table 2 the wintertime contributions of $\nabla\cdot\bar{\mathbb{F}}_S^M$ and $\nabla\cdot\bar{\mathbb{F}}_P^M$ are of different sign, as expected, but the sensible heat flux determines the total effect. This is due to the strong advection of sensible heat into the region. Of the wintertime divergence $\nabla\cdot\bar{\mathbb{F}}_S^M$ (−108 W/m²) for the region A, the portion due to the advection term $(\bar{\mathbb{V}}\cdot\nabla c_p\bar{T})$ amounts to −96 W/m² and that due to the divergence term $(c_p\bar{T}\nabla\cdot\bar{\mathbb{V}})$ to −14 W/m². Thus over Europe the advection of sensible heat (temperature) by the stationary component of the atmospheric flow mainly compensates the energy losses due to the radiation. The corresponding advection of potential energy (accomplished by mean ageostrophic motions) causes a little cooling of the atmosphere at a rate of 4 W/m².

During summer the heating contrast between latitudes is not so pronounced as in winter and the general circulation is less intense. Consequently, $|\nabla\cdot\mathbb{F}_A^M|$ is smaller than in winter. As in winter, the advection of sensible heat (not shown) is dominant, now cooling the atmosphere. The tendency of $\nabla\cdot\bar{\mathbb{F}}_S^M$ and $\nabla\cdot\bar{\mathbb{F}}_P^M$ to be of opposite sign comes clearly out from their seasonal values in Table 2.

The convergence of $\bar{\mathbb{F}}_L^M$ is generally smaller than the convergence of $\bar{\mathbb{F}}_S^M + \bar{\mathbb{F}}_P^M$. Only in summer does it make a considerable contribution to $\nabla\cdot\bar{\mathbb{F}}_A$. The seasonal variation of $\nabla\cdot\bar{\mathbb{F}}_L^M$ is quite clear: in winter and autumn convergence dominates (i.e. precipitation exceeds evaporation) whereas in summer divergence is found.

The role played by $\nabla\cdot\bar{\mathbb{F}}_K^M$ is not important from the point of view of total energy, even if it is important for the local budget of kinetic energy itself. Throughout the year it shows convergence of kinetic energy flux at a rate of a few W/m².

### 5.2. *Transient eddy flux divergences*

Considering now the transient eddy flux divergences in Table 2, the most important ones are those associated with the sensible and latent heat. The values of $\nabla\cdot\bar{\mathbb{F}}_S^T$ indicate a net outflux of sensible heat in autumn and winter and a small net influx during summer. $\nabla \cdot \bar{F}_L^T$ is negative all the year implying that the atmosphere in this region is warmed by the liberation of latent heat. The largest convergence of $\bar{F}_L^T$ is observed in winter but the seasonal differences are not large.

Even if there is convergence of $\bar{F}_L^T$ in the region A, large differences occur in the results (not shown) for the various subareas seen in Fig. 1. For example, during winter $\nabla \cdot \bar{F}_L^T$ was positive (divergence) in the oceanic areas near the Atlantic coast while it was negative (convergence) in the continental subareas. In the oceanic as well as continental areas the total divergence of latent heat ($\nabla \cdot \bar{F}_L$) was, however, negative indicating that, as a total effect, precipitation exceeds evaporation.

Also $\nabla \cdot \bar{F}_S^T$ showed large areal differences. During winter divergence was found in the oceanic areas and in central and northwestern Europe. Noticeable convergence was obtained only for northeastern Europe. This areal distribution coincides with the corresponding divergence pattern ($\nabla \cdot \overline{T'V'}$) for winter at 1000 and 700 mb reported by Lau (1979).

Fig. 3 shows the wintertime vertical profiles of $\nabla \cdot c_p \overline{T'V'}$ and $\nabla \cdot L\overline{q'V'}$ in the region A in comparison with the corresponding zonally averaged values derived from literature. It is seen that over Europe there is a convergence of latent heat flux and divergence of sensible heat flux at all levels. $\nabla \cdot L\overline{q'V'}$ over Europe is of the same sign (negative) but roughly twice as large by magnitude as the corresponding zonal average while $\nabla \cdot c_p \overline{T'V'}$ over Europe differs even by sign from the respective zonally averaged value.

The values of potential and kinetic energy flux divergences (Table 2) are rather small but systematic: the former cools and the latter warms the atmosphere in all seasons. This tendency to counterbalance has been previously shown to be valid for standing zonal eddies (Holopainen, 1969; Mak, 1969).

### 5.3. *The geographical variation of the divergence of the vertically integrated transient eddy flux of total energy*

The geographical distribution of $\nabla \cdot \bar{F}_A^T$ was computed by manually analysing the zonal and meridional components of the flux $\bar{F}_A^T$ and computing the divergence with standard finite difference methods in a spherical coordinate system with a $(\Delta\lambda,\ \Delta\varphi) = (5,\ 2.5)$ degree grid. The analysis method involves subjectivity but it may be assumed that in an area with a rather dense station network

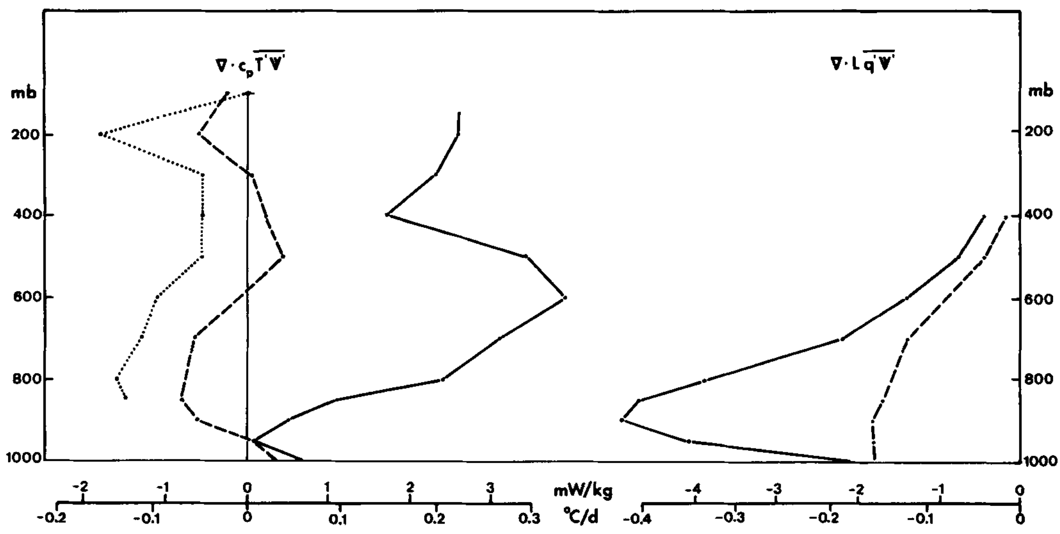


*Fig. 3.* The vertical profiles of $\nabla \cdot c_p \overline{T'V'}$ (left) and $\nabla \cdot L\overline{q'V'}$ (right) in winter. Solid lines refer to the region A (Fig. 1), dashed lines to the zonal averages between 45° and 70° N according to Oort and Rasmusson (1971), and dotted line to the corresponding zonal average according to Lau (1979).

this effect will be of minor importance. The analysed fields of $\nabla \cdot \bar{\mathbb{F}}_{A}^{T}$ are presented in Fig. 4 for winter and summer conditions.

The main feature seen in Fig. 4 is the high variability of the divergence field: during winter (Fig. 4a) the range of divergence values amounts to about 350 W/m$^2$. It is thus evident that the longitudinal averages filter out substantial variations and leave a relatively small net effect as zonal mean. The characteristic features of wintertime $\nabla \cdot \bar{\mathbb{F}}_{A}^{T}$ are the strong convergence just east of Greenland and in the main continental area of Europe, and divergence in the Norwegian Sea, in northwestern Europe and in the Mediterranean region.

In the North Atlantic the convergence of $\bar{\mathbb{F}}_{A}^{T}$ takes place over the cold northerly ocean current associated with a minimum of energy output from the sea (Bunker and Worthington, 1976), which may possibly be even negative during winter due to the increased amount of ice drifting near Greenland. The largest energy flux divergence in the Norwegian Sea, on the other hand, is associated with the area of a local maximum of energy output from the sea (Bunker and Worthington).

According to Lau (1979) the divergence pattern of the transient eddy flux of sensible heat at 700 mb for winter is correlated with the zonal anomaly pattern of the stationary temperature field so as to cause destruction of zonal anomalies. This same effect is found in our study for total energy, because, especially in winter, the convergence in middle Europe is associated with negative total energy anomaly whereas the divergence in the Norwegian Sea is associated with a positive anomaly.

In summer (Fig. 4b) the main features show similarity with the winter conditions, but the magnitude of the divergence values is considerably lower. Main differences are the extended area of convergence in the North Atlantic and in northwestern Europe, which is in accordance with the change of mean total energy distribution: the positive anomaly over the Norwegian Sea is replaced by a near zonal pattern. It is interesting to note that the divergence near the northwestern coast of Norway also remains in summer. Furthermore, the eastern part of Europe is characterized by divergence. Synoptically this would mean the effect of the frequent warmer continental air invasions towards the cooler regions in the west and north.

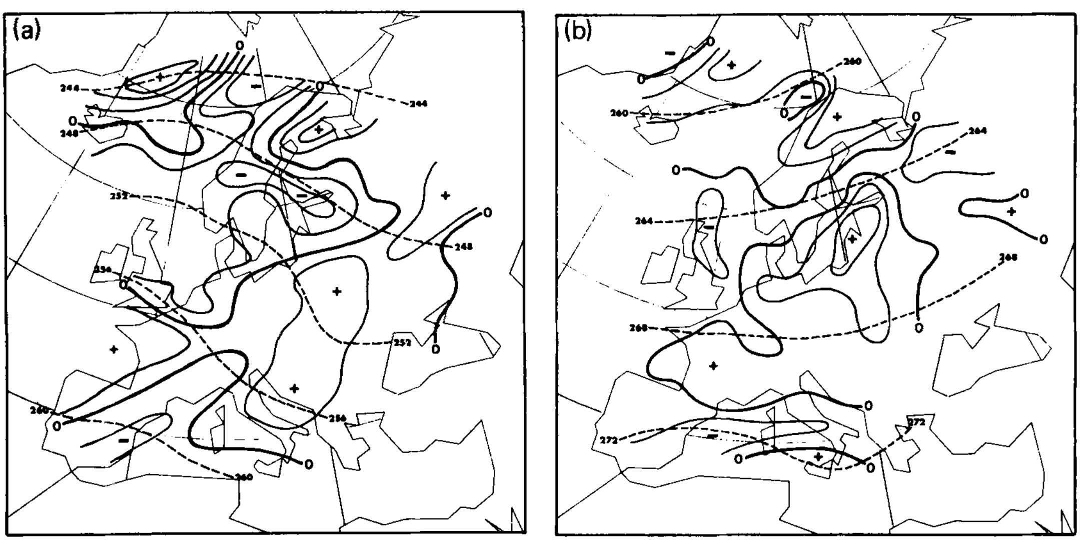


*Fig. 4a.* The distribution of $-\nabla \cdot \mathbb{F}_{A}^{T}$ in winter in the atmosphere between the surface and 150 mb (solid lines). The mean vertically averaged total energy ($c_p T + Lq + k$) is shown by dashed lines. Positive (negative) areas indicate warming (cooling) of the atmosphere by flux divergence. Isolines shown for $-\nabla \cdot \mathbb{F}_{A}^{T}$ are 0, $\pm 50$, $\pm 100$, and $+200$ W/m$^2$. Unit of total energy is $10^3$ J/kg.
*Fig. 4b.* As in Fig. 4a but for summer.

## 6. Error analysis

In this chapter a measure of the uncertainty involved with the 3-year mean $\nabla \cdot \bar{F}_A$ for the region A ($-55$ W/m$^2$) will be considered. The number given refers to the conditions when the constraint of a time mean atmospheric mass balance is fulfilled and thus the effect of the most important systematic error source, nonbalanced wind observations, is largely removed.

Assuming that random errors of the quantity $s$ and wind components ($u$ and $v$), $\delta s$ and $\delta v$, respectively, are uncorrelated in the vertical and horizontal and represent typical tropospheric values and that observations 24 h apart are independent, the random error of $\nabla \cdot \bar{F}_A$, $\delta(\nabla \cdot \bar{F}_A)$, can generally be expanded (with no mass balance corrections) as follows

$$\delta\left(\nabla \cdot \int_{150}^{p_s} \overline{s\boldsymbol{V}} \frac{dp}{g}\right) = \left(\frac{N}{2}\right)^{-1/2} \frac{1}{g} \times \delta\left[\sum_p w_p \sum_j (c_{\lambda j}(su)_{pj} + c_{\varphi j}(sv)_{pj})\right] = \left(\frac{N}{2}\right)^{-1/2} \frac{1}{g}\left[\sum_p \sum_j w_p^2 (c_{\lambda j}^2 + c_{\varphi j}^2)\right]^{1/2} \cdot (s\delta v + v\delta s). \qquad (8)$$

$N$ is the number of observations and $w_p$ are the weights in the vertical integration over pressure levels $p$. The coefficients $c_{\lambda j}$ and $c_{\varphi j}$ are used in the computation of horizontal divergence and are functions of geographical coordinates of the stations. According to Gauss' theorem, only boundary fluxes contribute and thus the summation is over boundary stations $j$. Similar procedures are to be found in Holopainen (1973) and Rasmusson (1977).

Typical values of $\bar{E}$ and $E'$ ($E = c_pT + Lq + \Phi + k$) are 310,000 J/kg and 15,000 J/kg, respectively, and 2 m/s is used as an estimate for $\delta v$ and $\delta v'$ (Schlatter et al., 1976). The second term in (8) is small and is ignored. From (8) one obtains for the error estimates of $\nabla \cdot \bar{F}_A$ and $\nabla \cdot \bar{F}_A^T$, $\pm 15$ W/m$^2$ and $\pm 2$ W/m$^2$. Thus the transient eddy flux divergences are determined with a considerably better accuracy than the mean flow flux divergences, and the estimate of the error in $\nabla \cdot \bar{F}_A$ (due to random errors in the basic parameters) is about $\pm 15$ W/m$^2$.

The random error of $\nabla \cdot \bar{F}_A$ is nearly totally due to the term involving $\delta v$ in (8) or, essentially, the random error of the vertically averaged mass divergence. However, applying time mean mass balance correction, the error effect on budget computations of all reasons leading to any mass imbalance is eliminated, i.e. also that of random errors of wind observations. Thus the remaining random error of $\nabla \cdot \bar{F}_A$ will be smaller than $\pm 15$ W/m$^2$.

On the other hand, there remain the possibly systematic instrumental, methodological (linear horizontal and temporal variation of quantities), and observational (lack of data) errors, and systematic local mesoscale effects in observations.

Because the mass balance requirement is essential for getting meaningful results for $\nabla \cdot \bar{F}_A$, an experiment was carried out to investigate the sensitivity of the results to the thickness of the layer over which the vertical integrals were computed. For this purpose, the computations were performed for the layers $p_s$–200 mb and $p_s$–300 mb (in each case requiring the mass balance in respective layers; $p_s$ denotes the surface pressure). The resulting values of $\nabla \cdot \bar{F}_A$ were $-58$ W/m$^2$ and $-57$ W/m$^2$, which are very close to the original computations for the $p_s$–150 mb layer ($-55$ W/m$^2$).

Another experiment was made with different treatments of the mass divergence in the layer below 850 mb. From Fig. 2 it is evident that $\nabla \cdot \bar{\boldsymbol{V}}$ in this layer in the region A is not very realistic because divergence was obtained (see also 4.3). Recalling (6), the mass balance correction is applied only to the divergence term $s\ \nabla \cdot \bar{\boldsymbol{V}}$ while the other terms (advection and transient eddy flux divergence) are left unchanged. Thus three different tests were made to study the effect of $\nabla \cdot \bar{\boldsymbol{V}}$ below 850 mb; (1) the layer $p_s$–850 mb was omitted and the mass balance was required in the remaining layer 850–150 mb, (2) a zero mass divergence was assumed in the layer $p_s$–850 mb while the mass balance was required in the whole atmospheric column, and (3) a constant convergence was used in the layer $p_s$–850 mb which would exactly balance the divergence in the upper layer 850–150 mb (here $\nabla \cdot \bar{\boldsymbol{V}}$ is implicitly assumed to be fully correct in the upper layer). The respective estimates for $\nabla \cdot \bar{\mathbb{F}}_A$ in these cases were $-52$, $-50$ and $-39$ W/m$^2$.

The above considerations indicate that the estimate of $\nabla \cdot \bar{\mathbb{F}}_A$ is not too sensitive to the method of mass balance correction. Basically this is due to the fact that the (corrected) contribution of the mass divergence related part $[\int \bar{s} \nabla \cdot \bar{\mathbb{V}}(dp/g)]$ is rather small in $\nabla \cdot \bar{\mathbb{F}}_A$: ignoring this term would yield a result of $-67$ W/m$^2$ for $\nabla \cdot \bar{\mathbb{F}}_A$.

As a summary, it is inferred that the error of the 3-year mean estimate of $\nabla \cdot \bar{\mathbb{F}}_A$ for the region A is probably less than $\pm 15$ W/m$^2$.

## 7. Summary

Vertically integrated divergences of the time mean atmospheric energy fluxes ($c_p T\mathbb{V}$, $Lq\mathbb{V}$, $\Phi\mathbb{V}$, $k\mathbb{V}$) for the various subareas of Europe have been computed for the period 1974–1976. The main results can be summarized as follows:

(1) The computed annual mean atmospheric energy flux divergence, $-55$ W/m$^2$, for the largest European area is in agreement with the corresponding recent net radiation estimates for the earth–atmosphere system, which vary between $-35$ and $-70$ W/m$^2$.

(2) The seasonal course of $\nabla \cdot \bar{\mathbb{F}}_A$ over Europe has a larger amplitude than the corresponding zonally averaged quantity in the latitude belt 45–70° N. Particularly in autumn and winter, about four times more energy converges over Europe than in the respective latitude belt in general.

(3) The effect of mean-flow fluxes dominate over the transient eddy fluxes, the former yielding $-34$ W/m$^2$ and the latter $-21$ W/m$^2$ to the total energy flux divergence ($-55$ W/m$^2$) on annual basis.

(4) The role of the transient eddies is important in the balance of latent heat and kinetic energy.

(5) To obtain a reasonable quantitive estimate of $\nabla \cdot \bar{\mathbb{F}}_A$, annually or seasonally, for a given area with a good network of aerological stations, the size of the area should not be smaller than $6\text{–}7 \cdot 10^6$ km$^2$.

(6) The spatial distribution of the vertically integrated transient eddy flux divergence of total energy shows a considerable longitudinal variation. The role of these eddies in winter is to remove energy from the relatively warm sea area. The transient eddies thus tend to smooth out the regional anomalies of energy.

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## БЮДЖЕТ ЭНЕРГИИ СИСТЕМЫ ЗЕМЛЯ-АТМОСФЕРА ДЛЯ ЕВРОПЫ

С использованием данных радиозондирования 1974–1976гг. для различных областей Европы вычисляются проинтегрированные по вертикали дивергенции средних по времени потоков энергии в атмосфере, которые используются совместно с относящейся сюда информацией в литературе для обсуждения бюджета энергии системы земля-атмосфера для этих областей. Найдено, что разумный бюджет может быть получен, когда размер площади не менее 6–7·$10^6$ км$^2$.

Для континентальной Европы конвергенция полного потока энергии в атмосфере достигает в среднем за год $55 \pm 15$ Вт/м$^2$, что сравнимо со спутниковой оценкой эффективного потока радиации от–35 до–70 Вт/м$^2$ для этой же области. Это значение конвергенции примерно вдвое больше значения зонально осредненной конвергенции для соответствующего широтного пояса.

Для атмосферы найдено, что наиболее важным фактором в бюджете энергии является комбинированный поток явного тепла и потенциальной энергии, переносимый средним ветром. Однако роль распространяющихся вихрей также важна, особенно, в конвергенции скрытого тепла и кинетической энергии. Дивергенция потока полной энергии, связанная с этими вихрями, приводит зимой к диссипации долготных аномалий полной энергии.