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Diagnostic studies on atmospheric budgets of water and energy based on aerological data

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ABSTRACT

This note reviews recent diagnostic studies of the atmospheric heat and moisture sources using aerological data. It appears that the large-scale features of evaporation minus precipitation, as well as of the diabatic heating of air in general, can nowadays be deduced from three-dimensional fields of aerological variables relatively accurately. However, the usefulness of the aerological method for smaller scales, e.g., those associated with the BALTEX (Baltic Sea Experiment), remains to be established.

1. Introduction

The difference between evaporation (E) and precipitation (P) links the atmospheric branch of the water cycle to that of the land and oceans. The traditional hydrological/oceanographic methods infer this difference (E-P) from surface observations. By contrast, the "aerological method" derives E-P from the conservation equation for atmospheric water vapour using aerological data, as demonstrated for the global domain by Starr and White (1955) and for the Baltic Sea area by Palmén (1963).

The latent heat of water vapour is part of the atmospheric total energy. The budgets of water vapour and energy must therefore be considered together. In principle, aerological data can be used to infer not only the net moisture source E-P, but also the diabatic heating which is the "prime mover" of the atmospheric circulation and notoriously difficult to calculate accurately (Hoskins et al., 1989; Fortelius and Holopainen, 1990; Fortelius, 1994).

In this note, recent diagnostic studies of atmospheric moisture and energy sources using the aerological method are reviewed, having particularly in mind the potential applicability of the method for the Baltic Sea Experiment (BALTEX, 1995). Besides recent studies, some pioneer contributions in the field are mentioned so as to give a historical perspective to the subject. Section 2 discusses the basic principles of the method and gives some examples of its application on the global scale. The important issue of validating the results is briefly addressed in Section 3. In Section 4, some remarks are made on the application of the method within the framework of BALTEX.

2. Basic equations and approaches

2.1. *Equations*

For a vertical column (of unit horizontal area) including the atmosphere and the energetically active layer of the underlying medium (soil or water) the equation of total energy has the form (Palmén and Newton, 1969; Hartmann, 1994):

$$\frac{\partial(I_A+I_O)}{\partial t}+\nabla\cdot(\boldsymbol{F}_A+\boldsymbol{F}_O)=R_T, \qquad (1)$$

and the energy equations separately for the atmosphere and ocean/land part of the column are

$$\frac{\partial I_A}{\partial t} + \nabla \cdot \boldsymbol{F}_A = R_A + LE + H \quad (2)$$

$$\frac{\partial I_O}{\partial t} + \nabla \cdot \boldsymbol{F}_O = R_S - LE - H. \quad (3)$$

In these equations the subindex A refers to the atmosphere, O to ocean/land, T to the top of the atmosphere and S to the surface. I indicates the vertically-integrated amount of energy and $\boldsymbol{F}$ the corresponding horizontal energy flux associated with the flows in the atmosphere or in the ocean. As usual, E denotes the evapotranspiration, L the heat of vaporization (taken here to be constant, 2.5×10^6 J kg^{-1}), and H the turbulent flux of sensible heat from the underlying surface. R denotes the net radiative downward flux of energy with $R_A (= R_T - R_S)$ being the net radiational energy source of the air column. In eqs. (1)–(3), the small terms related to kinetic energy have been disregarded. The atmospheric part of (1) is illustrated schematically in Fig. 1a.

According to (1), R_T is a quantity of paramount importance for the energy balance of the atmosphere/land/ocean system. Traditionally, satellite-based estimates of this quantity have been used to infer from (1) the required total meridional heat transport in the atmosphere and oceans for long-term means, in which the first term on the left-hand side can be assumed to be negligible. Recent examples of such studies are those of Trenberth and Solomon (1994) and Keith (1995). For shorter periods the rate of heat storage in the ocean can be large and is very difficult to estimate accurately from the observations available at present. Over continents, however, $\nabla \cdot \boldsymbol{F}_O = 0$ and also the rate of heat storage can often be neglected. In this case (1) gives:

$$\nabla \cdot \boldsymbol{F}_A \approx R_T. \quad (4)$$

This equation is used in Section 3 in validating the energy budget.

The total energy of an atmospheric column can be written as the sum of the latent heat, associated with the atmospheric water vapour, and the "dry static energy": $I_A = I_{LAT} + I_{DRY}$. A corresponding partitioning can be made for the horizontal energy flux in the atmosphere: $\boldsymbol{F}_A = \boldsymbol{F}_{LAT} + \boldsymbol{F}_{DRY}$. The relevant budget equations are (Palmén and Newton 1967):

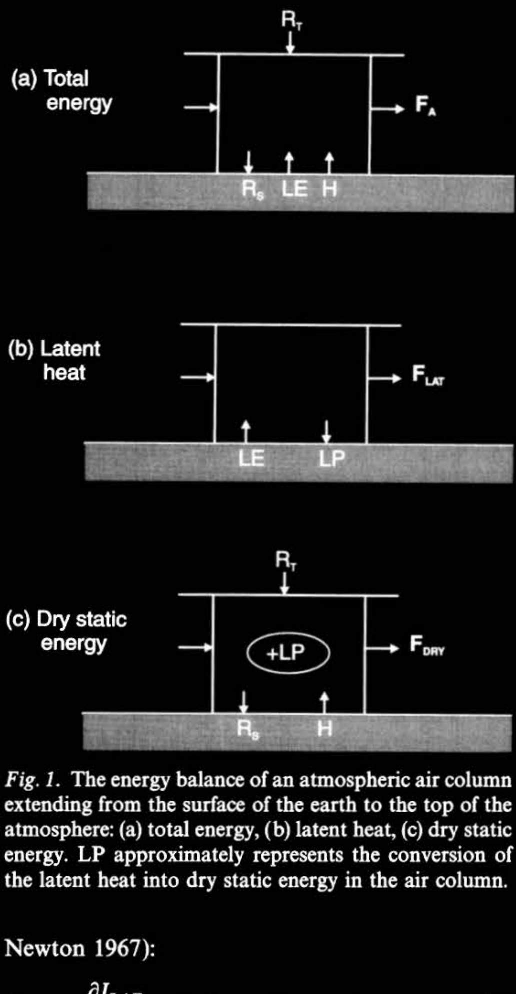

Fig. 1. The energy balance of an atmospheric air column extending from the surface of the earth to the top of the atmosphere: (a) total energy, (b) latent heat, (c) dry static energy. LP approximately represents the conversion of the latent heat into dry static energy in the air column.

$$Q_{LAT} \equiv \frac{\partial I_{LAT}}{\partial t} + \nabla \cdot \boldsymbol{F}_{LAT} = LE - LP, \quad (5)$$

$$Q_{DRY} \equiv \frac{\partial I_{DRY}}{\partial t} + \nabla \cdot \boldsymbol{F}_{DRY} = R_A + LP + H, \quad (6)$$

where LP is an approximate measure of the net release of latent heat in the air column (neglecting the latent heat of freezing). Note that (4) can be written in the form

$$Q \equiv Q_{LAT} + Q_{DRY} \approx R_T. \quad (7)$$

In (5), Q_{LAT} can in principle be estimated from aerological data, thus providing an indirect estimate of $L(E\text{-}P)$. Similarly, Q_{DRY} in (6) provides an indirect estimate for $(R_a + LP + H)$, the diabatic heating of the air column. Eqs. (5) and (6) are schematically illustrated in Figs. 1b and 1c. These equations refer to the vertically-integrated, two-dimensional (2D) case. The aerological method can also be applied in the full three-dimensional (3D) case (e.g. Fortelius, 1994).

In the past, two approaches have been used to determine Q_{LAT} and Q_{DRY} (and Q) from aerological data. They could be called the "station data approach" and the "data assimilation approach". In the first approach the aerological observations are used for calculating the vertically-integrated local fluxes $\boldsymbol{F}_{LAT}$ and $\boldsymbol{F}_{DRY}$ at each rawinsonde station, an analysis of the geographical distribution of the fluxes is performed and the flux divergence determined. For example, this method has been used by Starr and White (1955), Oort and Peixoto (1983) and Savijärvi (1988) on a global scale, and by Palmén and Söderman (1966), Alestalo (1981), Walsh et al. (1994) and Serreze et al. (1995) on regional scales.

The data assimilation approach uses 3D analyses of the circulation variables, produced normally in connection with operational weather prediction. Nyberg (1958) was the first to estimate Q_{LAT} from subjective isobaric analyses of humidity and geopotential height, and Wiin-Nielsen and Brown (1962) the first to estimate the distribution of Q_{DRY} from objective numerical analyses of aerological variables. While the numerical analyses at the beginning of the 1960's depended strongly on the radiosonde observations, the data assimilation systems today also use many other observations including those from satellites, aircrafts and ocean buoys. Recent global estimates of Q_{LAT} and Q_{DRY} using the data assimilation approach have been made by Klinker and Sardeshmukh (1987), Fortelius (1994), Schaack and Johnson (1994), Keith (1995), Trenberth and Solomon (1994), Trenberth and Guillemot (1995) and Rassmussen and Mo (1995). A regional application of this approach has been reported, e.g., by Calanca (1994) to study study the atmospheric water budget over Greenland, and by Bromwich et al. (1995) to study the atmospheric hydrologic cycle over the Southern Ocean and Antarctica.

The data assimilation approach alleviates the sampling problem associated with the station data approach. It involves the use of a forecasting model giving a first guess to the analysis and, hence, provides a physically-based temporal and spatial interpolation of data. On the other hand, the results are to some extent model-dependent.

3. The validation problem

Independent estimates are needed for validation of the results obtained for Q_{LAT}, Q_{DRY}, and Q. Ideally, one should have measurements/estimates of these quantities with as small errors as possible. In reality, however, one often has to be satisfied with an intercomparison of the various estimates of Q_{LAT} and Q_{DRY} or their components having unknown, but typically very large error bars.

A set of independent estimates of $Q_{LAT} = L(E-P)$ is obtained from ordinary measurements of precipitation, combined with hydrological/climatological estimates of evapotranspiration as derived from surface observations on the basis of semiempirical formulas. Fig. 2 shows 3 estimates of the latent heat source, averaged longitudinally over all oceans. The estimates of Q_{LAT} by Fortelius and Holopainen (1990) represent the data assimilation approach, and those by Bryan and Oort (1984) the station data approach. These two estimates obtained using the aerological method are rather different. In Fig. 2 they are compared with an independent estimate obtained by Oberhuber

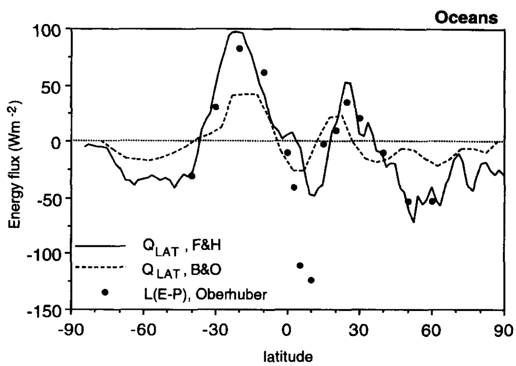

Fig. 2. Q_{LAT} over the oceans, as determined by the data assimilation approach for July 1979 by Fortelius and Holopainen (1990) (solid line), and by the station data approach from 10-year station data statistics for June-August by Bryan and Oort (1984) (dashed line). The large dots show the long-term mean values of $L(E-P)$ for June-August estimated by Oberhuber (1984) from surface observations. Values are longitudinal averages over all oceans. (Adapted from Fortelius and Holopainen 1990).

(1988) on the basis of surface observations. Large error bars must be associated with all the estimates. In addition, results from quite different periods are being compared. Nevertheless, the comparison suggests that the data assimilation approach is superior to the station data approach, at least over data-sparse oceanic areas. This is to be expected because of the better interpolation obtained by the use of the data assimilation approach. The recent study by Rassmusson and Mo (1995) appears to support this view. The results for Q_{LAT} obtained by the data assimilation approach still suffer from the spinup and spindown problem. This has been pointed out e.g. by Trenberth and Guillemot (1995), and by Ulbrich (1995) in his comments on the paper by Roads et al. (1994) dealing with the large-scale aspects of the hydrological cycle in the United States area; the same comment is undoubtedly also valid concerning the paper by Rassmusson and Mo (1995).

In the light of (1) and (4), a satellite-measured quantity of particular importance for validation of the estimates of $Q(=Q_{LAT}+Q_{DRY})$ obtained from the aerological data is R_T. Fig. 3 shows Q and R_T for July 1979, averaged longitudinally over all continents. In the extratropics of the northern hemisphere, where the aerological observational network is dense, the two totally independent estimates are seen to agree within about 20 W m^{-2}. The agreement is, however, poor south of about 25°N, where the density of the aerological stations is much smaller.

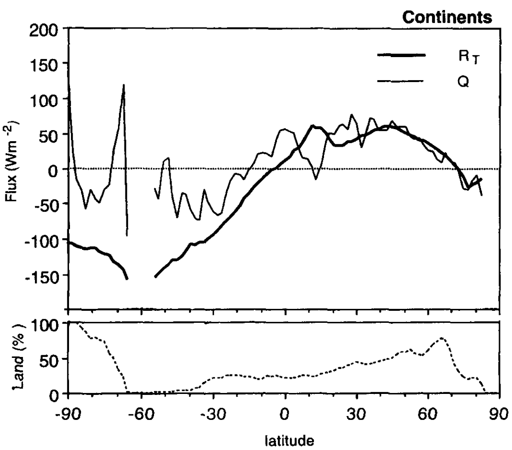

Fig. 3. The net downward radiation flux at the top of the atmosphere R_T (thick solid line) and the net atmospheric energy source $Q=Q_{LAT}+Q_{DRY}$ (thin solid line) in July 1979, averaged longitudinally over all continents. R_T is determined from the NIMBUS 7 radiation observations and Q from the 3D analyses using the aerological method. According to (4), these totally independent estimates should approximately equal each other. The dashed line in the lower part of the figure indicates the percentage of land at each latitude (adapted from Fortelius and Holopainen (1990)).

The data assimilation systems provide through their parametrization schemes estimates of vertical radiative and subgrid-scale heat fluxes. The parametrized fluxes of radiation can be compared with radiation measurements at the surface and at the top of the atmosphere, and thus provide a possible indirect validation method (Morcrette, 1990; Chen and Roeckner, 1995; Fortelius, 1994; Wild et al., 1995)). Surface measurements/estimates of R_S, E and H combined with the aerological method provide vertical profiles of subgrid-scale vertical fluxes of heat and moisture (Dorninger et al., 1992; Haimberger et al., 1995), which can be compared with the parametrized fluxes.

4. Application of the aerological method to study the water and energy cycle in the Baltic Sea region

Palmén (1963) and Palmén and Söderman (1966) applied the station data approach in their study of evaporation from the Baltic Sea area. For calculation of the horizontal moisture flux divergence they used the aerological stations at Jokioinen, Stockholm, Copenhagen, Greifswald, Kaliningrad and Riga. At present, the network of aerological stations is actually in a worse condition than in the 1960's (for example, the aerological station at Stockholm no longer exists). Hence, the usefulness of the station data approach in the BALTEX region today is by no means obvious.

Heise (1996) has made preliminary investigations of the energy and water budgets for the BALTEX area using data from the German limited-area model. He applied a "reversed aerological method" by taking the local tendencies as well as the terms LE, LP, R_A and H in (5) and (6) as given by the model, and obtaining the flux divergence terms as residuals. Although the results appear promising, their real validation was not possible.

Independent data, not yet utilized in the assimilation systems, are needed for validation. In addition to those mentioned in Section 3 such data are, for example, radar-based estimates of precipitation. Whatever the scale considered, observations of the net radiation at the top of the atmosphere should be useful in validation of the estimates of the budget of atmospheric total energy. In some reanalysis periods for BALTEX, the ERBE (Earth Radiation Budget Experiment) data on this quantity may be used.

5. Concluding remarks

From the brief review presented it can be concluded that developments in meteorological data assimilation methods have made the "aerological method" useful for estimating the large-scale distribution of *E-P* and, more generally, of the large-scale 3D distribution of the diabatic heating in the atmosphere. Today this method may indeed be useful for estimating the large-scale distribution of *E-P* in operational hydrology, and also for studying the fresh water budget in oceanography. However, the smallest scale to which the usefulness of this method extends is not known. Accordingly, we cannot yet say whether or not it is applicable in the framework of BALTEX.

One of the major points of this paper was to emphasize the use of satellite data of R_T as an independent validation tool. This may be especially interesting for BALTEX, because for the Baltic Sea region as a whole $\nabla \cdot \boldsymbol{F}_O \approx 0$ in (1).

Key issues in the future analysis of the atmospheric energy and water cycle include better global observations of wind (Baker et al. 1995), temperature and humidity, and good data assimilation systems to analyze various meteorological, hydrological and oceanographic observations (Bengtsson and Shukla 1988). Such systems may eventually provide the best estimates not only for circulation variables (such as pressure, temperature, humidity and wind) but also for the small-scale fluxes that play an important rôle in these cycles.

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