J4.13 THE ATMOSPHERIC MOISTURE BUDGET IN THE ARCTIC —- INTRODUCING AND APPLYING A CONSISTENT METHOD TO USE RADIOSONDE DATA

Reinhard M. Hagenbrock*, Martin Göber†, Felix Ament*, Andreas Hense*
* Met. Institute, University of Bonn, Bonn, Germany † Met Office, Bracknell, United Kingdom

1. INTRODUCTION

1.1 Motivation

The arctic moisture budget plays a key role in the global climate system through its influence on the thermohaline circulation. High quality data of the net water transfer into the ocean is a basic input for ocean modelling.
Determination of the moisture budget components in high latitudes is very difficult, as measurements from satellite are problematic above ice and direct measurements, e. g. of precipitation, are very sparse or of limited reliability. Reanalyses — as the state-of-the-art depiction of atmospheric conditions — show inaccuracies in the parametrization of moisture and the *spin-up-problem* is still unsolved. The effect of these inaccuracies on large-scale patterns and temporal variability of the atmospheric water budget components is difficult to estimate, therefore an independent evaluation is necessary for validation. The authors of this paper are confident that radiosonde data can be used for such a purpose. This is possible due to the connection of moisture transport and storage to net water input into the lower boundary via the (approximate) moisture budget equation:

$$\underbrace{\frac{\partial}{\partial t}\int_V q dV}_{\text{storage term}} + \underbrace{\int_V \vec{\nabla}\left(q\vec{v}\right) dV}_{\text{moisture outflow}} + \underbrace{\left[P-E\right]_A}_{\text{net water input into surface}} = 0 \quad (1)$$

Here, q denotes specific humidity, $\vec{v}$ is the wind speed vector, P and E are precipitation and evaporation respectively, and $[\cdot]_A$ denotes the average over the area under volume V.

2.2 Existing Investigations

There exist a number of papers which investigate the moisture flux divergence based both on reanalysis and radiosonde data (cf. e.g. Walsh *et al.* (1994), Serreze *et al.* (1995), Genthon (1998), Bromwich *et al.* (2000), Cullather *et al.* (2000)). A preferred number for comparison is the net water influx into the polar cap north of 70°N. The long-term annual average is estimated as 0.33 - 0.55 $mm\,day^{-1}$, with sizeable differences between estimations based on reanalyses and on radiosondes. This is also true for the depiction of the annual cycle: Compared to the reanalysis based investigations, the radiosonde based budgets show a much smaller maximum in summer (cf. fig. 1).

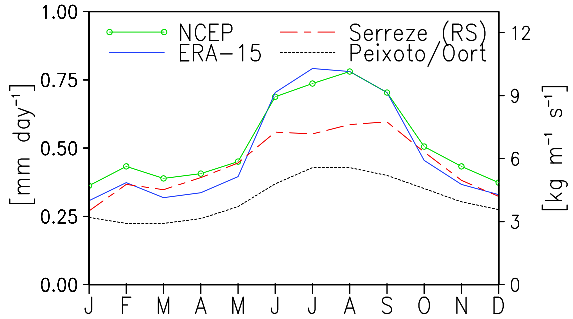

Fig. 1: Mean annual cycle of the net atmospheric moisture influx into the polar cap north of 70° N. Estimates are based on reanalyses (ERA-15, NCEP) and radiosondes (Serreze, Peixoto/Oort).

It has been assumed that the observed differences can be explained by the differences in spatial resolution of the data the investigations rely on. The present work provides a tool which enables us to compare budgets based on reanalysis and radiosonde data on *the same grid*, thus avoiding the problem of different resolutions.

2. METHOD

2.1 Problems and Solutions

Mass consistency

It is well known that for budget calculations it is necessary for the wind field to obey the continuity equation, cf. Ehrendorfer *et al* (1994). The standard solution, which was first included in a *mass consistent model* by Sherman (1978), is a variational approach: The wind field is slightly modified so that the continuity equation is fulfilled. The criterion that the energy of the wind field modification is minimal leads to a linear system of equations for the modifications.

Corresponding author address: Reinhard M. Hagenbrock, Meteorological Institute of the University of Bonn, Auf dem Hügel 20, 53 121 Bonn, Germany; e-mail: r.hagenbrock@uni-bonn.de

Irregular Grid

Radiosonde data are present on an irregular three-dimensional grid which changes over time. The standard way for calculating the desired flux divergences is first to interpolate data to a regular grid and then perform the differentiations. Doswell and Carazena (1988) show that this approach produces errors which are not negligible. The obvious solution is to do the differentiations exactly on the observational grid (cf. fig. 2).

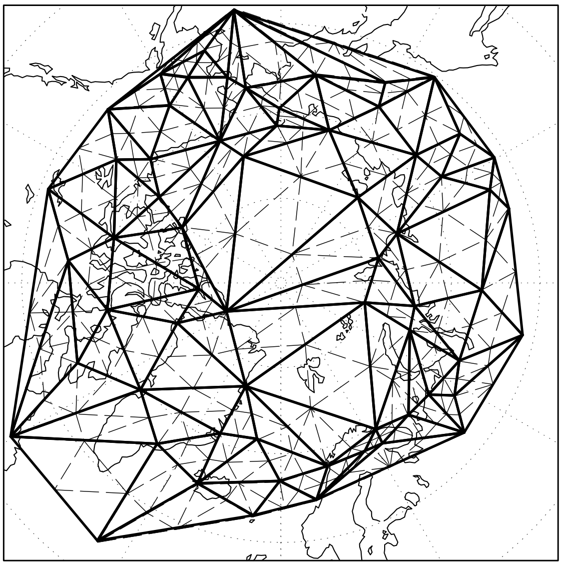

Fig. 2: Triangulation of the 850mb radiosonde station data used on Jan. 01, 1979 with original radiosonde distribution (bold solid lines) and with doubled resolution data by introduction of extra 'data' points in the middle of two adjacent radiosonde stations (thin dashed lines)

2.2 The Model Equations

The procedure consists in setting up a cost function and finding the field which minimizes it. The cost function sums up the quadratic wind field modification, complemented by hard constraints to achieve mass balance and an appropriate boundary condition:

$$I = \int \left[(\vec{v} - \vec{v}^o)^2 + \lambda \left(\vec{\nabla} \vec{v} \right) + \mu \,(\mathsf{BC}) \right] dV \stackrel{!}{=} 0 \qquad (2)$$

Here, λ and μ are Lagrangian multipliers, $\vec{v}$ is the three-dimensional wind speed, $\vec{v}^o$ is the observed wind speed, and the requirement $\vec{\nabla}\vec{v} = 0$ is the continuity equation in p coordinates. As a boundary condition (BC) we prevent all mass flux through the lower boundary. The wind field components as well as the Lagrangian multipliers are expanded after a set of linear basis functions, thus the cost function is descretized. The minimization leads to a set of linear equations that is solved with a pre-conditioned conjugate residual solver. This procedure is a familiar method from the finite element numerics, cf. Braess (2001).
An extensive sensitivity study was carried out in order to estimate the uncertainties of the method.

3. DATA

Radiosonde Data

The Historical Arctic Rawinsonde Archive (HARA) is a compilation of two times daily observations from more than 500 radiosonde stations north of $50°N$, covering the period 1973-1996. The data was quality controlled. To keep computational costs low, yet avoiding effects of the domain boundary, we chose an appropriate set of approx. 70 stations for each date. For comparison with reanalysis data we used only mandatory pressure levels.

Reanalysis Data

In order to overcome the problem of different resolutions, the data of the ERA-15 reanalysis (cf. Gibson *et al.* (1997)) was thinned out: Only those grid points were used where data from the radiosonde grid are available. Thus the calculation was performed on exactly the same grid.
In order to investigate the problem of different resolutions, an artificially generated radiosonde network was created by introducing additional sample points midway on each horizontal line connecting two radiosonde stations, increasing the number of data points by roughly a factor of 3.

4. RESULTS

4.1 Radiosonde Data on SPL and MPL

The HARA data are available on significant pressure levels (SPL), for comparison with reanalysis data we reduced them to 11 mandatory pressure levels (MPL) between 1000 and 150 hPa. Thus the number of vertical levels declined to about a third. The effect of this reduction of vertical resolution is to reduce the net water input into the Arctic atmosphere north of 70°N from 0.46 $mm\,day^{-1}$ by 0.01 $mm\,day^{-1}$ (average 1979-1993).

4.2 Radiosonde vs. Reanalysis Data

The net water input into the Arctic atmosphere north of 70°N obtained from reanalysis data on the radiosonde grid is 0.48 $mm\,day^{-1}$. Thus the large difference that had been found in the comparison between radiosonde and reanalysis based budgets is strongly reduced. The correlation of monthly averages is high ($r^2 = 0.83$). Budgets based on unmodified, not mass balanced data show smaller correlation of the monthly means. This indicates that noise is reduced by the mass balanced procedure. Long-term averages of the net water input based on unmodified wind fields differ by up to 0.05 $mm\,day^{-1}$, a value considered to be out of the range of uncertainty.

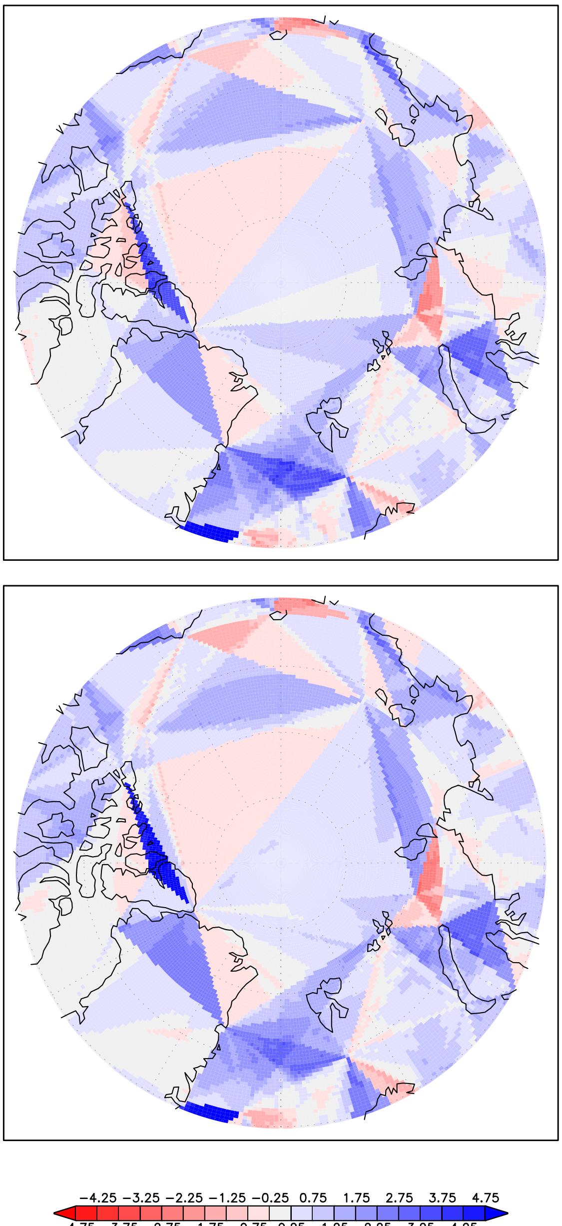

Fig. 3: Vertically integrated moisture flux convergence from mass balanced wind fields, calculated from radiosonde data (upper panel) and from reanalysis data thinned out to radiosonde grid (lower panel), average for summer (June-September) 1990, units are $mm\,day^{-1}$.

Horizontal patterns of moisture flux divergence integrated over columns also show large similarities (cf. fig. 3). For the case of unmodified wind fields, similarity between patterns based on radiosonde and reanalysis data is smaller than in the mass balanced case (not shown).

4.3 Effect of grid refinement

For the reanalysis depiction of Arctic atmospheric conditions, information additional to radiosonde observations is included, such as satellite observations or the model first guess. This and the higher grid resolution allow for dynamical processes smaller than the scale of radiosonde observations. The moisture flux convergence integrated over the polar cap north of 70°N, calculated from radiosonde grid data, is significantly smaller compared to the integrated flux over 70°N, calculated from full resolution data. In order to highlight the effect of different resolutions on the moisture budget calculations, resolution was doubled by introducing extra 'data' points. The resulting moisture flux convergence is very similar to the result obtained with full resolution data (cf. Fig. 4). This shows that indeed the resolution of the processes is one relevant parameter for estimating the moisture budget.

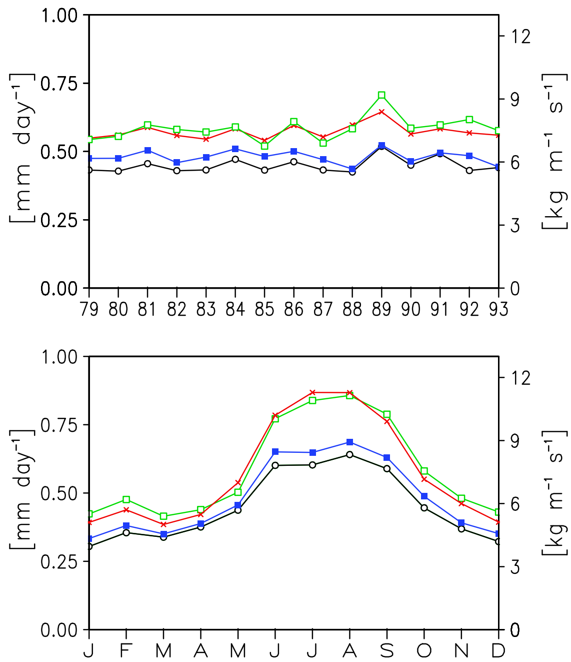

Fig. 4: Moisture flux convergence integrated over the polar cap north of 70° N, calculated from radiosonde data (green circles) and reanalysis data on the radiosonde grid (blue boxes) and on a refined radiosonde grid (cf. text) (black squares); moisture flux from full ERA-15 data integrated over 70° N (red crosses); upper panel shows annual means, lower panel mean annual cycle.

5. SUMMARY AND CONCLUSION

We present a method to use radiosonde data for the calculation of moisture flux divergence as a component of the atmospheric moisture budget. The procedure overcomes problems that make the results of existing investigations (at least, in detail) questionable. The method combines a variational approach with the Finite Element Method. Budgets can be calculated from radiosonde and reanalysis data without the problem of different grids. The results show very good agreement of spatial and temporal structures. Known features of the Arctic moisture flux convergence are reproduced. We estimate the net water gain of the Arctic atmosphere, averaged for the period 1979-93, as 0.46 ± 0.03 $mm\,day^{-1}$.

6. REFERENCES AND ACKNOWLEDGEMENTS

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Most aspects of the work described in this extended abstract are discussed in more detail in

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