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BALTEX water and energy budgets in the NCEP/DOE reanalysis II

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Water and energy budgets from the National Centers for Environmental Prediction/Dept. of Energy (NCEP/DOE) reanalysis II (NCEPRII) are described for the Baltic Sea catchment and sea (BALTEX). Annually, NCEPRII shows 0.7 mm d^{-1} of atmospheric moisture converged into the land region with a corresponding runoff of 0.7 mm d^{-1} to the Baltic Sea, consistent with observations. However, precipitation is too low; evaporation is too large; runoff does not have an appropriate winter minimum and spring maximum; the assimilation and surface nudging are too large. Important hydroclimatic characteristics can still be discerned. During summer, atmospheric water vapor, precipitation, evaporation, and surface and atmospheric radiative heating increase and the atmospheric radiative cooling, dry static energy convergence decrease. There are large contrasts between the sea and land; during winter sensible heat is transferred from the sea to the atmosphere and sea evaporation and precipitation are largest during the fall and winter; somewhat opposite behavior occurs over land.

Introduction

BALTEX (*see* Raschke *et al.* 1998, 2001) is investigating the entire Baltic Sea Drainage basin as a scientific collaboration among atmospheric, ocean, and land scientists in 14 countries. A number of previous studies (Heise 1996, Karstens *et al.* 1996, Hagedorn *et al.* 2000, Jacob 2001, Jacob *et al.* 2001) described the capabilities of regional models to simulate the BALTEX hydroclimate. A future BALTEX goal is to transfer the regional models developed for BALTEX to other global regions.

Can current global analyses describe regional characteristics of the BALTEX hydroclimate? A number of previous studies with the various National Center for Environmental Prediction (NCEP) global analyses (operational, first reanalysis, second reanalysis) and models (global and regional) focused on the Mississippi River Basin (Roads *et al.* 1994, 1997, 1998, 1999, Roads and Betts, 2000, Roads and Chen 2000, 2001, Maurer *et al.* 2001, Roads *et al.* 2002b, 2002c) suggested that at least qualitative features of the Mississippi River Basin hydroclimate and the global hydrologic cycle (Roads *et al.* 2002, Roads 2002a, 2002b) could be simulated. It therefore seemed useful to also examine the capability of NCEP global analyses to describe the BALTEX hydroclimate, since this might provide some indication as to how BALTEX regional modeling and observational advances could help develop the next generation of global reanalyses and predictions (Roads *et al.* 2001).

NCEPR and NCEPRII reanalyses

The first NCEP/NCAR (National Center for Atmospheric Research) global reanalysis (NCEPR) used the NCEP global spectral model (GSM), or medium range forecast (MRF) model, which is used for making the four times daily global data assimilation system (GDAS) analysis and for making the medium range forecast (MRF) predictions. The resolution of the NCEPR (Kalnay *et al.* 1996) was L28T62, corresponding to 28 vertical sigma levels and a Gaussian global grid of 192 × 94 grid points (about 2° lat. and long. resolution). The second NCEP/Dept. of Energy reanalysis (NCEPRII, *see* Kanamitsu *et al.* 2000) fixed a number of bugs in NCEPR and used an updated (1999 NCEP global model) version of the GSM (same resolution as NCEPR), which had a number of notable parameterization improvements. For example, NCEPRII used observed precipitation (Xie and Arkin 1997), instead of NCEPRII precipitation to force the land soil moisture. By contrast NCEPRI used the model precipitation but then damped the soil moisture to an assumed climatology. Although mainly NCEPRII variables are examined here, previous calculations for the heat and moisture convergence (*see* Roads *et al.* 2002 for the justification, as well as Roads 2002) from NCEPR (these were not available from NCEPRII) supplemented other NCEPRII processes.

In order to compare the NCEPRII precipitation to the Global Precipitation Climatology (hereafter denoted as GPCP) precipitation (Huffman *et al.* 1997), the 12-year period (1988–1999) was chosen. It should be noted that the GPCP dataset has some missing data at high latitude grid points and these were filled-in with precipitation "observations" from the similar Xie and Arkin (1997) dataset. A runoff climatology was also available from the Global Runoff Data Center (Fekete *et al.* 1999) for comparison to the climatological runoff from the reanalysis. Other climatological estimates (Speth and Skade 1977, Henning 1988, Heise 1996, Isemer and Rozwadowska 1999, Omstedt and Rutgersson 2000, Jacob 2001, Jacob *et al.* 2001) for basin means were also available from the literature. More widely available gridded data products from BALTEX are critically needed for more thorough model evaluations.

Water and energy cycle equations

Water and energy cycles are time varying three-dimensional quantities. Taking vertical averages in the atmosphere (pressure weighted) and subsurface, we focus here on two-dimensional horizontal variations. The equations below are applicable to both the BALTEX sea and the land regions.

Atmospheric water

$$\frac{\partial Q}{\partial t} = E + \mathrm{MC} - P + \mathrm{RSQ}'. \qquad (1)$$

Surface water

$$\frac{\partial W}{\partial t} = P - E - N + \mathrm{RSW}'. \qquad (2)$$

The two state variables for these water mass conservation equations are Q, the vertically (pressure weighted) integrated specific humidity or precipitable water and W, the vertically integrated (two meters below the surface to the surface in the NCEP model) soil moisture, M, plus snow liquid water, S. Hydroclimatic processes include evapotranspiration, E, precipitation, P, moisture convergence, MC, and runoff, N. There are additional residual forcings (Roads *et al.* 1998, 2002), RSQ′ and RSW′, that appear in four-dimensional data assimilation (4DDA) analysis water budgets because the analysis constantly corrects the tendency of the model to move toward its own intrinsic climatology; these are combined here with the negative of the tendency terms ($\mathrm{RSQ} = \mathrm{RSQ}' - \partial Q/\partial t$ and $\mathrm{RSW} = \mathrm{RSW}' - \partial W/\partial t$). Note that the natural surface water tendency, over both land and sea, may be quite large and comparable to the other terms; we thus have to be careful when discussing RSW as to whether this is a real phenomenon or whether this is part of the background analysis error. Roads (2002a, 2002b) discuss how errors in the various processes contribute to the overall analysis error, which represents one measure of how well we can close the water budget. In that regard, note that errors in both the atmospheric and surface can cancel, that errors in precipitation and evaporation can cancel and that the overall closure error may not adequately represent the much larger errors for individual processes.

The Baltic Sea is the sink for the Baltic catchment land surface runoff (Heise 1996). Conservation of mass requires

$$N_o A_o = NA, \tag{3}$$

where N is the runoff of the Baltic land region, A is the area of the Baltic land catchment (1.721×10^6 km^2), A_o is the area of the Baltic Sea (4.15×10^5 km^2), and N_o is the runoff into the Baltic Sea (NA is about 420 km^3 per year; *see* Heise 1996, Graham 1999, Fekete *et al.* 2000). N_o is hereafter assumed to be equal to $4.14N$ (the ratio of the land to sea area) and to be a negative value since unlike the outflow N in the land surface equation N_o is an inflow term. N_o is much larger than the Baltic Sea precipitation and evaporation difference, and is presumably balanced (at least on the average) by an almost equivalent freshwater outflow through the Danish Straits.

The surface energy equation is simply the surface temperature equation:

$$C_v \frac{\partial\{T_s\}}{\partial t} = [\mathrm{QRS} - \mathrm{LE} - \mathrm{SH} + G']. \tag{4}$$

The atmospheric energy equation to a first approximation (mainly neglecting kinetic energy) is the atmospheric dry static energy or temperature equation (Roads *et al.* 1997):

$$C_p \frac{\partial\{T_s\}}{\partial t} = [\mathrm{QR} + \mathrm{LP} + \mathrm{SH} + \mathrm{HC} + \mathrm{RST}']. \tag{5}$$

Energy variables include atmospheric temperature, T, and surface temperature, T_s. Processes include surface radiative heating from incoming solar and downwelling infrared radiation, moderated by reflected solar radiation and outgoing infrared radiation, QRS, the corresponding atmospheric radiative heating (actually net cooling), QR, latent cooling by evaporation, LE, latent heating by net precipitation, LP, sensible heating, SH, adiabatic and horizontal convergence of dry static energy, HC, and ground (or sea) heat flux, G'. Again, there are some additional terms (RST′, G') that appear in analysis energy budgets that are combined with the negative of the tendency terms. The land tendency terms are small ($\mathrm{RST} = \mathrm{RST}' - C_p\partial T/\partial t$ and $G = G' - C_v\partial T_s/\partial t$) whereas the sea tendency terms can be large, and here this residual forcing term also implicitly includes ocean fluxes. For presentation, both energy equations were divided by the heat capacity of the atmosphere $C_p p_s/g$, so that both atmospheric and surface quantities could be presented in units of K day^{-1} (The conversion between W m^{-2} and K day^{-1} is ~118 ps/1000, where ps is the surface pressure in millibars)

Annual means

Table 1 provides the annual mean values for the various water and energy processes averaged (cosine weighted) over the BALTEX land and sea separately. The land regions utilized the masked region described previously by Roads *et al.* (2002); corresponding Baltic Sea regions were also added here with the additional *proviso* that these sea grid points should correspond to the NCEPRII ocean mask. Complications arising from the upper Baltic Sea becoming ice covered during the winter are ignored here (but not in NCEPRII which can have snow accumulation over ice covered oceans) and these grid points are still treated as ocean points for this analysis. The mask (Fig. 1) has 70 land and 14 ocean grid points, with corresponding areas of 1.56×10^6 km^2 and 3.14×10^5 km^2; we will still use the Heise (1996) areal estimates for the runoff ratios described earlier.

NCEPRII BALTEX precipitable water has an annual average of 13.35 mm over the land and slightly larger values over the sea (13.42 mm), consistent with the higher skin temperatures (7.1 °C versus 4.6 °C). Surface water

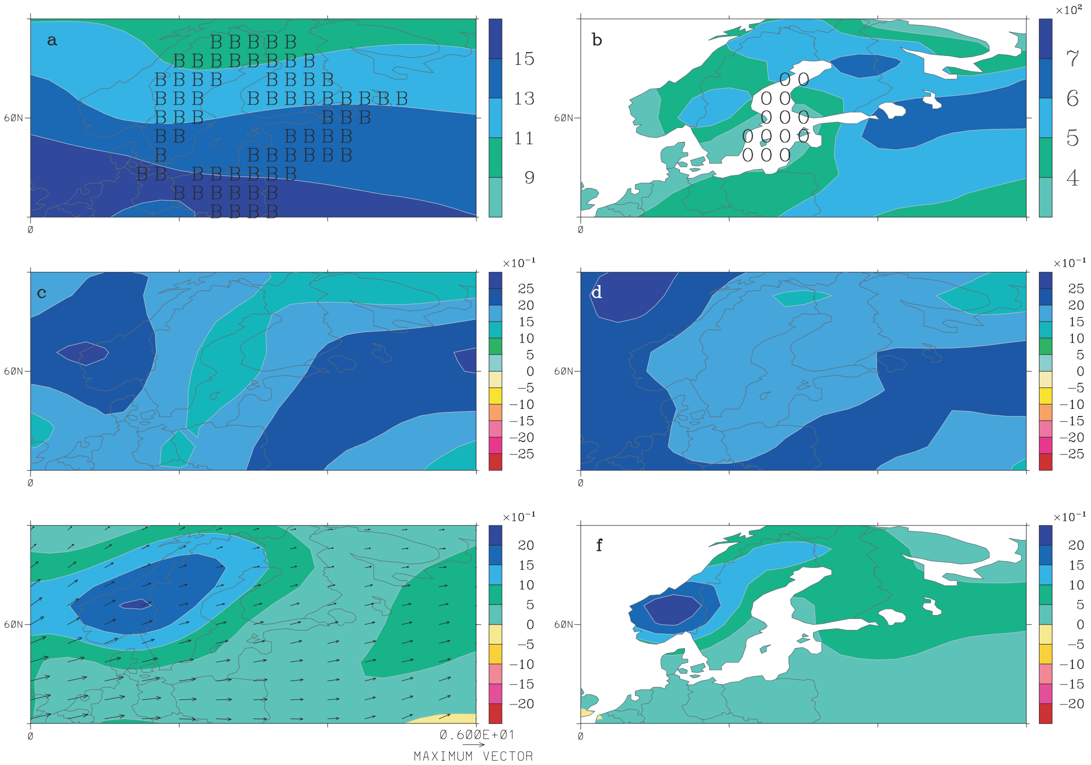

Fig. 1. Annual mean NCEPRII atmospheric water cycle: (**a**) *Q*, precipitable water, mm; (**b**) *W*, surface water, mm; (**c**) *P*, precipitation, mm day^{-1}; (**d**) *E*, evapotranspiration, mm day^{-1}; (**e**) MC, moisture convergence, mm day^{-1}, moisture flux vectors, kg m^{-1} s^{-1}; (**f**) *N*, runoff, mm day^{-1}. The mask for land points (B) and sea points (O) is also shown.

Table 1. Land and sea basin annual means.

Processes	Land	Sea
Q, precipitable water (mm)	13.35	13.42
P, precip. (mm day^{-1})	1.87	1.20
E, evap. (mm day^{-1})	1.90	1.82
MC moist. conv. (mm day^{-1})	0.70	0.60
RSQ resid. moist. forc. (mm day^{-1})	–0.73	–1.22
GPCP precip. (mm day^{-1})	2.09	2.31
W surf. water (cm)	56.70	
N runoff (mm day^{-1})	0.66	–2.73
RSW resid. surf. wat. forc. (mm day^{-1})	0.69	–2.11
GRDC runoff (mm day^{-1})	0.67	–2.77
QR atmos. rad. cooling (K day^{-1})	–0.90	–1.01
LP lat. heat of cond. (K day^{-1})	0.47	0.30
HC dry static energy conv. (K day^{-1})	0.13	0.30
SH sens. heating (K day^{-1})	–0.19	0.11
RST resid. temp. forc. (K day^{-1})	0.49	0.30
T_s skin temp. (°C)	4.63	7.08
QRS surf. rad. heating (K day^{-1})	0.40	0.52
LE lat. heating (K day^{-1})	0.47	0.45
G ground heat flux (K day^{-1})	–0.12	0.05

(upper two meters of soil moisture plus snow equivalent water) has an average value of 56.7 cm over land. Precipitation has an average land value of 1.87 mm d^{-1} over the land regions, with smaller values over the sea (1.2 mm d^{-1}), which is lower than the GPCP observations of 2.1 mm d^{-1} over land and 2.3 mm d^{-1} over the sea. NCEPRII evaporation has an average land value of 1.9 mm d^{-1}, which is large in comparison to a deduced land evaporation (GPCP – GRDC) of 1.4 mm d^{-1}. Smaller values occur over the sea (1.8 mm d^{-1}), which are still higher than the NCEPRII precipitation and inconsistent with the observations of freshwater fluxes (Omstedt and Rutgersson 2000). The imbalance in the NCEPRII atmospheric water budget is contributed by the analysis error (RSQ), –0.7 mm d^{-1} over land and –0.9 mm d^{-1} over the sea; these are related to errors in NCEPRII precipitation, as well as NCEPRII evaporation. The surface water balance over the land has runoff equivalent to a moisture convergence of 0.7, consistent with the climatologically observed runoff (Fekete *et al*. 1999; see also Graham and Jacob 2000) from the land (0.7 mm d^{-1}) and into the sea (–2.77 mm d^{-1}). Annual mean RSW is significant over the land because NCEPRII uses observed precipitation instead of NCEPRII precipitation to force the land soil moisture. The residual forcing, RSW, over the sea is also quite large (–2.11 mm d^{-1}), indicating substantial outflow through the Danish Straits, which is consistent but slightly low (320 km^3/year) with respect to various climatological observations (e.g. Heise 1996, Graham 1999, Omstedt and Rutgersson 2000, Lehmann *et al.* 2002) again because of the erroneously low precipitation in the NCEPRII.

Annual mean NCEPRII atmospheric cooling rates of –0.9 K day^{-1} (100 W m^{-2}) are slightly greater over the sea (–1 K day^{-1}) than over land (consistent with observations of Heise 1996 and others). These cooling rates are balanced by the latent heat released by precipitation (0.5 K day^{-1}), the heat converged into the area (0.1 K day^{-1} over land and 0.4 K day^{-1} over the sea) and the sensible heating (–0.2 K day^{-1} over land and +0.1 K day^{-1} over the sea), consistent with climatological estimates (Heise 1996). A residual forcing, RST, of 0.5 K day^{-1} is also needed over the land and 0.15 K day^{-1} is needed over the sea. At the surface, the latent cooling (0.5 K day^{-1} over the land and 0.4 K day^{-1} over the sea) is larger than the SH, which warms the land surface and cools the sea surface. G is small but negative over the land region, perhaps in part because the snowmelt is included in this diagnostic term, although the negative value seems large.

Geographic variations

Precipitable water (Fig. 1a), which is strongly temperature dependent, is largest in the southern part of the domain and decreases to the north, consistent with the zonal temperature variations (not shown). Surface water (Fig. 1b) is much greater in mid to high latitudes, especially in regions where snow provides a major contribution. Precipitation (Fig. 1c) has greater longitudinal variations, with a minimum over the inland area and a maximum along the Norwegian coast and Scandinavian mountains, which block low-level moisture convergence from the Atlantic. Evaporation (Fig. 1d) corresponds to precipitation except on the westernmost land regions where moisture convergence (Fig. 1e) plays an important role. The moisture flux for the BALTEX land and sea regions appears to originate in the North Atlantic. Moisture convergence is related to surface runoff (Fig. 1f) except over Finland where the runoff is larger than the moisture convergence. This excessive surface runoff is balanced annually certain extent by the RSW, which arises because of differences between model precipitation and observed precipitation being used to force the soil moisture. The potential errors in the precipitation, evaporation and runoff are also influenced by the simplifying soil moisture and snow assimilation procedures.

NCEPRII longwave radiative cooling dominates over the solar heating in the atmosphere and the net radiative cooling (Fig. 2a) is balanced by the latent heat resulting from precipitation (Fig. 2c) as well as the dry static energy convergence (Fig. 2e) in the western portion of the domain. In the easternmost portion of the domain the heat convergence is negative, balancing the excessive latent heat released during ascent over the Scandinavian mountains. Sensible heat transfer from the atmosphere to the surface (Fig. 2f) also contributes to the overall cooling. At the surface, solar radiation dominates the infrared cooling and the net surface radiation (Fig. 2b) heats the surface, which is also heated over the land by sensible heat transfers from the atmosphere (Fig. 2f) and cooled by the latent cooling (Fig. 2d) associated with surface evaporation. Over the western portion of the domain and the southern Baltic Sea, sensible heating is negative.

Annual mean RSQ and RST residual forcings (Fig. 3a and b) are related to the difference between the model precipitation and the observed (GPCP) precipitation (Fig. 3c and d). Also, the evaporation seems to be too high, as indicated by the difference (Fig. 3h) between the model evaporation and (GPCP – GRDC). Runoff differences (Fig. 3g) also contribute to RSW (Fig. 3e). Finally, surface heating by the ground fluxes (Fig. 3f) indicates that there is a systematic cooling in almost all regions, except for the regions next to the Arctic Ocean. The cooling is partially related to the energy lost to snowmelt

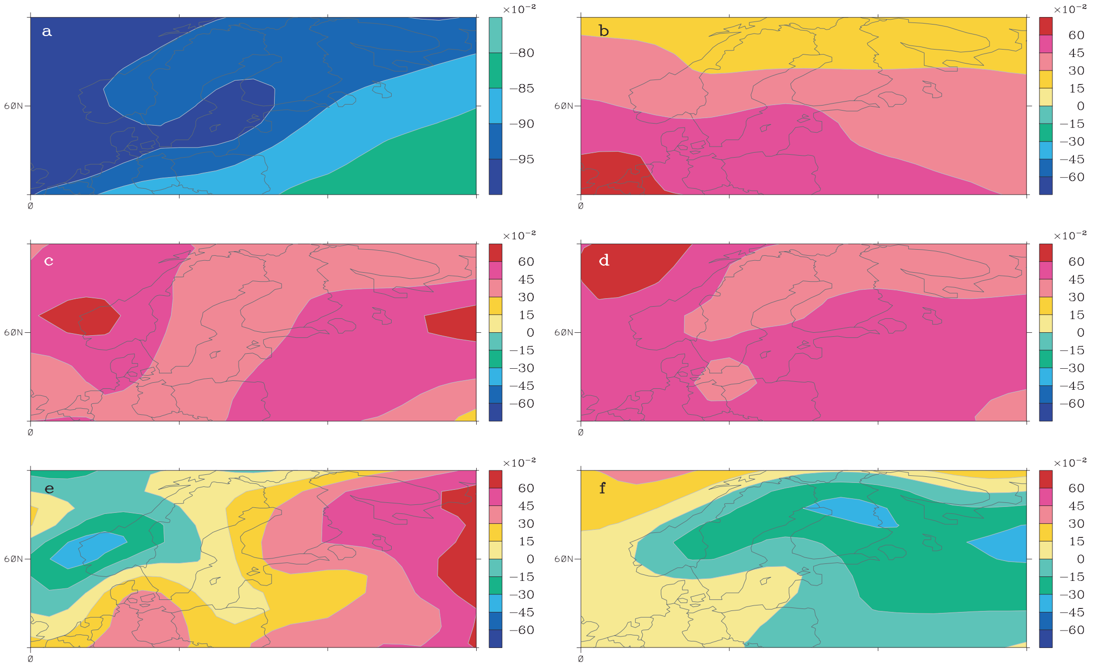

Fig. 2. Annual mean NCEPRII atmospheric energy cycle, K day^{-1}: (**a**) QR, atmospheric radiative cooling; (**b**) QRS, surface radiative heating; (**c**) LP, latent heat of condensation; (**d**) LE, latent heat of evaporation; (**e**) HC, dry static energy convergence; (**f**) SH, sensible heating; (**g**) *G*, subsurface heat flux.

(Roads *et al*. 2002), which is implicitly included in this term. Again, this cooling seems excessive, more would be required if the evaporation were reduced, indicating that besides the potential errors in the surface radiation and ground heat parameterization (which may be affected by positive temperature biases in the reanalysis), there may also be a contribution from the simplifying assumptions involved in soil moisture and snow assimilation.

Seasonal variations

Precipitable water (Fig. 4a) appears quite reasonable in comparison to available observations (Raschke *et al*. 2001), reaching maximum values during the summer over the land regions and then decreasing during the winter, with an overall seasonal difference of 14 mm. Surface water (Fig. 4b), which includes snow, reaches a maximum value during the winter and has an overall seasonal amplitude of 12 cm. Note that evaporation (Fig. 4d), which moistens the atmosphere, is positive year round and reaches its maximum during the summer over land and during the fall over the sea, and is excessive in comparison to observationally estimates (e.g. Bumke *et al*. 1998 and Rutgersson *et al*. 2002), which are more consistent with annual mean (GPCP – GRDC) values. Precipitation (Fig. 4c) reaches its maximum value during the summer over land and during the fall over the sea, which is somewhat consistent with observations although the summertime precipitation is too large and the wintertime precipitation is too small. The typical spring minimum in precipitation also does not show up in the NCEP analysis.

BALTEX has typical midlatitude moisture convergence seasonal variations (Roads *et al*. 2002); the largest moisture convergence (Fig. 4e) occurs during the winter and smaller and even divergence occurs during the summer. Convergence implies that NCEPRII evaporation is less than precipitation during the wintertime, which it would be except for the contribution by RSQ (Fig. 4g). Presumably this seasonal RSQ pattern represents spinup during the winter, especially over the sea and spindown over the land during the summer, which are known problems with

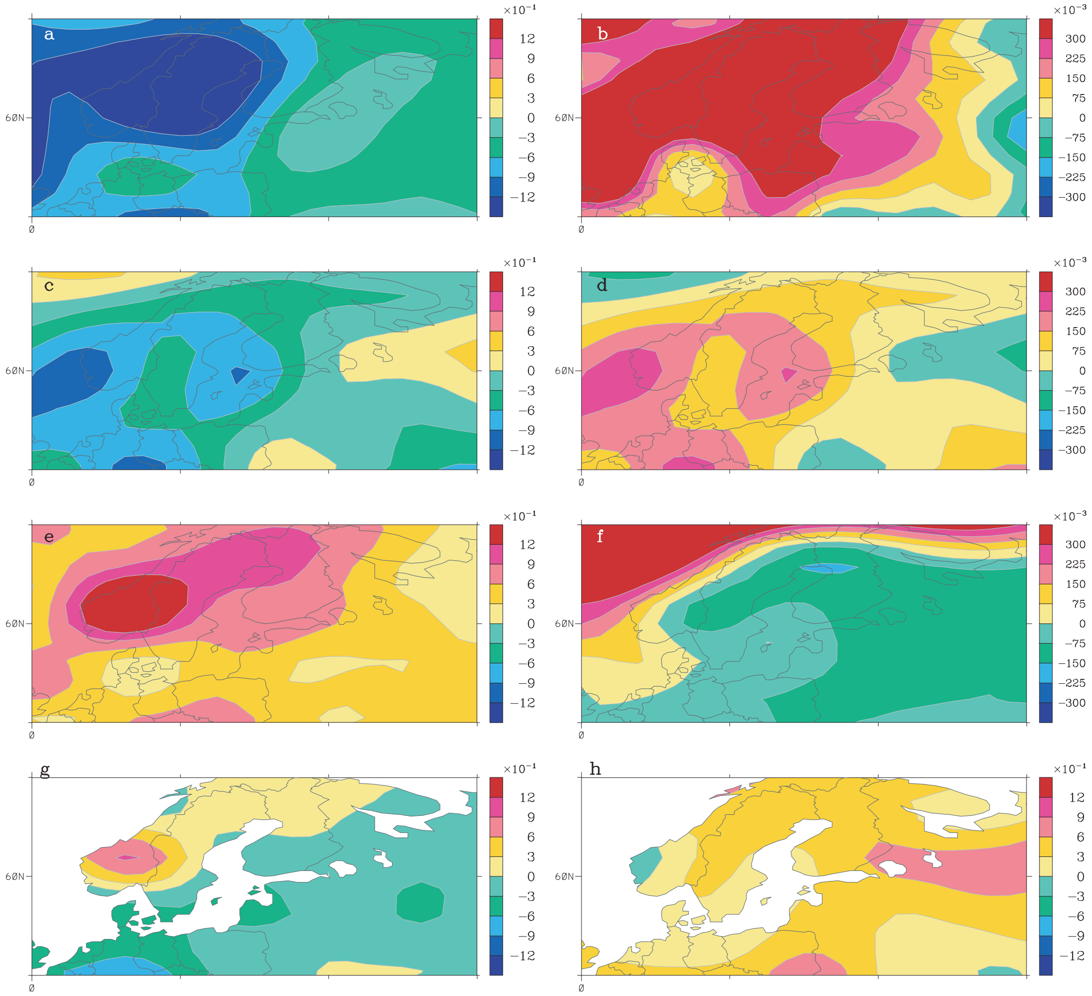

Fig. 3. Annul mean NCEPRII residual atmospheric moisture (RSQ), surface water (RSW), atmospheric temperature (RST), and surface temperature (G), forcings in comparison with differences between reanalysis precipitation (P) and GPCP, reanalysis runoff (N) and GRDC, and reanalysis evaporation (E) and an inferred evaporation (GPCP – GRDC): (**a**) RSQ, mm day^{-1}; (**b**) RST, K day^{-1}; (**c**) P – GPCP, mm day^{-1}; (**d**) $-L(P - \text{GPCP})/C_P$, K day^{-1}; (**e**) RSW, mm day^{-1}; (**f**) G, K day^{-1}; (**g**) N – GRDC, mm day^{-1}; (**h**) E – GPCP – GRDC, mm day^{-1}.

NCEPRII condensation schemes (Roads *et al.* 1997) for the Mississippi River Basin. That is, precipitation is too low in the first 6 hour forecast of the analysis. If longer term forecasts were used, the precipitation would become larger and the analysis error, RSQ, would then be less. However, NCEPRII evaporation may also be too high, and this error is also contributing to the overall analysis error (Roads *et al.* 2002, Roads 2002a, Roads 2002b)

Surface runoff (Fig. 4f) and moisture convergence (Fig. 4e) approximately balance and appear to be quite reasonable in comparison to BALTEX observations (Raschke *et al.* 2001). Still, the analysis error (Fig. 4h) becomes large and comparable to the runoff (Fig. 4f), especially during the winter when snow is accumulated and the soil is frozen and during spring when the snow melts. Again, it must be remembered that this residual forcing term, which is partially the natural surface water tendency, shows somewhat realistic behavior in that the positive values indicate that surface water is decreasing during the summer and the negative values indicate it is increasing during the winter; this would be especially obvious if the annual mean bias were

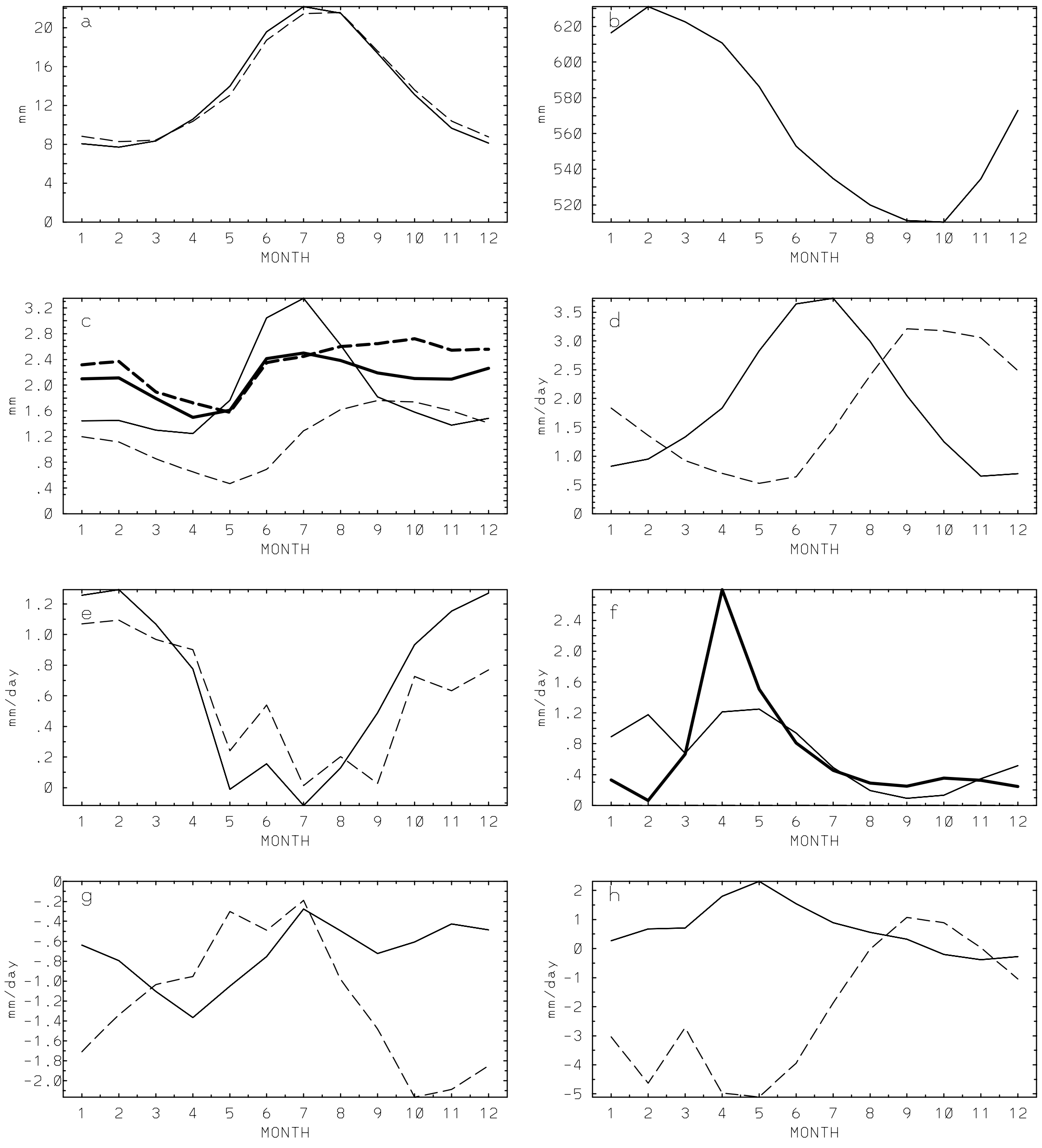

Fig. 4. Seasonal mean NCEPRII water cycle for the BALTEX land (solid thin lines) and sea (thin dashed lines); GPCP precipitation and GRDC runoff are provided by thick solid (land) and dashed lines (ocean): (**a**) *Q*, precipitable water, mm; (**b**) *W*, surface water, mm; (**c**) *P*, precipitation, mm day^{-1}; (**d**) *E*, evapotranspiration, mm day^{-1}; (**e**) MC, moisture convergence, mm day^{-1}; (**f**) *N*, runoff, mm day^{-1}; (**g**) RSQ, residual atmospheric moisture forcing, mm day^{-1}; (**h**) RSW, residual surface water forcing, mm day^{-1}.

removed. The negative forcing by the residual over the sea thus represents freshwater flux through the Danish Straits.

Atmospheric radiative cooling (Fig. 5a) decreases during the summer, especially over the land regions. The latent heat released by precipitation (Fig. 5c) also increases during the summer, and a balance is reached through the heat divergence (Fig. 5e), which is positive during the winter and a minimum during the summer. The residual RST is positive during the winter and becomes negative during the summer,

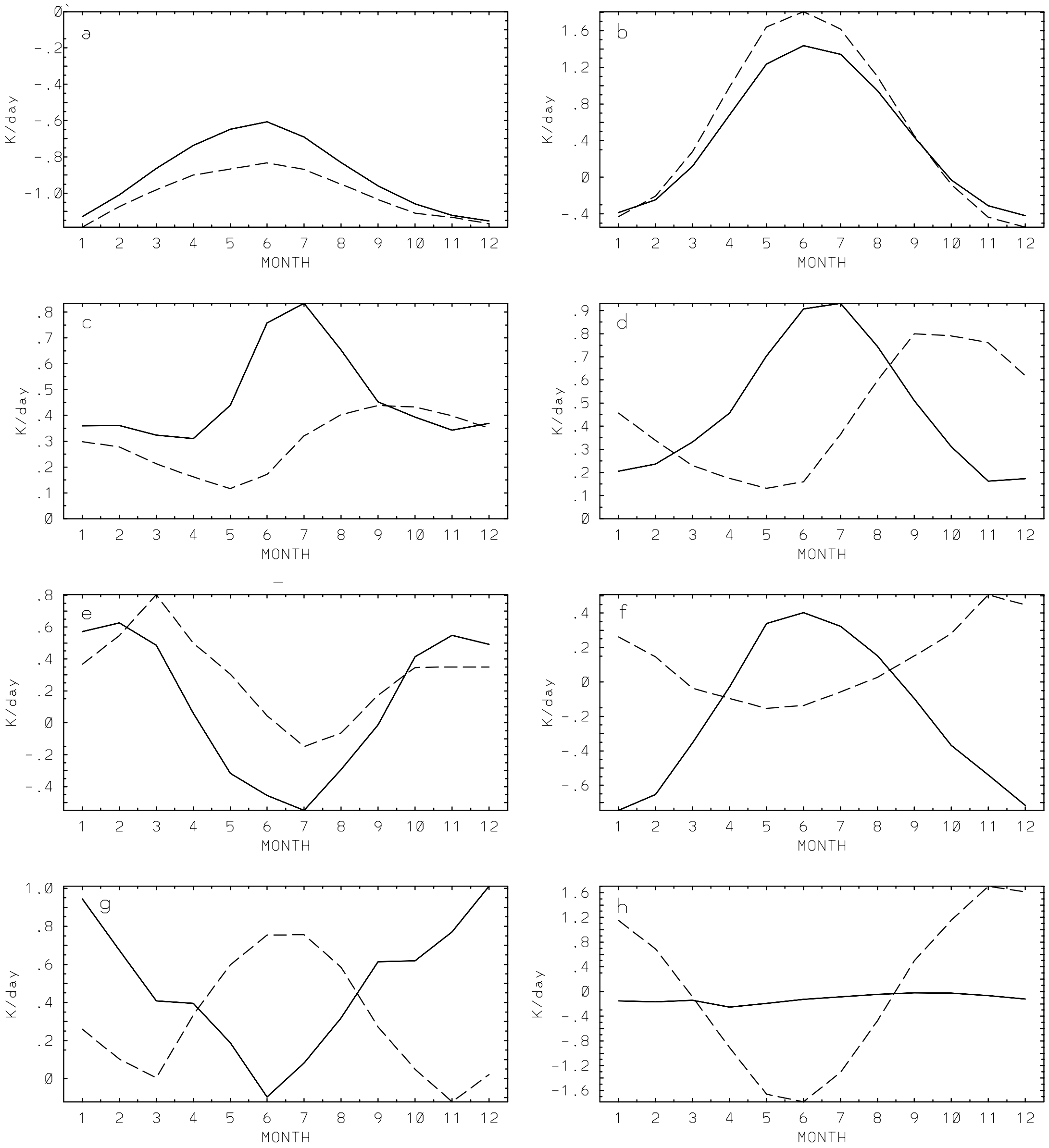

Fig. 5. Seasonal mean NCEPRII energy cycle for the BALTEX land (solid lines) and sea (dashed lines), K day^{-1}: (**a**) QR, atmospheric radiative cooling; (**b**) QRS, surface radiative heating; (**c**) LP, latent heat of condensation; (**d**) LE, latent heat of evaporation; (**e**) HC, dry static energy convergence; (**f**) SH, sensible heating; (**g**) *G*, subsurface heat flux.

which is similar to the impact (inverse) upon the moisture equation by the NCEPRII precipitation. These and other errors will become better known as additional processes, such as sensible heating (Fig. 5f), are measured throughout the region.

The surface is heated by the net surface radiation (Fig. 5b), which is dominated by downwelling solar radiation especially over the sea (Isemer and Rozwadowska 1999). The net solar heating is balanced by the evaporation (Fig. 5d), and the sensible heating (Fig. 5f) especially over the land regions. Over the sea, sensible heating cools the surface with the maximum sensible heat flux (surface to the atmosphere) occurring during the late fall and early winter and the minimum occurring during the summer, consistent with observations (Henning 1988, Omstedt and Rutgersson 2000) and model simulations (e.g. Heise 1996, Jacob 2001). Over the sea, the thermal heat capacity and perhaps dynamical transports (Fig. 5h) are major contributors, with the sea subsurface heat flux, *G*, being large and positive during the winter (when the sea temperature is decreasing) and negative during the summer (when the sea temperature is increasing).

Summary

NCEPRII values are broadly consistent with regional model products and available observations. On the average there is about 0.7 mm d^{-1} of moisture converged into the land region; a corresponding land runoff of 0.7 mm d^{-1} (and sea freshwater input of 2.73 mm d^{-1}), which, in concert with the deficit in precipitation with respect to evaporation over the Baltic sea, results in a sea residual of 2.11 mm d^{-1}, somewhat consistent (but quite low) with observations of freshwater outflow through the Danish Straits. The atmospheric radiative cooling of 0.9 K day^{-1} is partially balanced by the convergence of dry static energy into the region as well as the latent heat released by precipitation. The surface latent cooling and the sensible cooling over the sea and sensible heating over the land balance the surface radiative heating. The sea fresh water and sea surface temperature tendencies are important components of the seasonal cycle.

Over the Baltic sea catchment and sea, NCEPRII land precipitation is too low on average but too large during the summer; the evaporation may be too high, especially during the summer. As was shown, errors in these global model processes may be one reason the assimilation analysis errors are also important components of analysis budgets. Global reanalysis errors should be reduced as parameterization improvements are made in the BALTEX atmospheric and land surface models and regional analyses and then transferred to the global models and analyses. In that regard, more widely available gridded data products from BALTEX are critically needed to develop better BALTEX model evaluations in the future. Although a few process means were available from the literature of BALTEX, we really need better basin-wide estimates of evaporation, radiation, turbulent fluxes and so on.

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