UC Irvine
Faculty Publications

Title
Evaluation of land-surface interaction in ECMWF and NCEP/NCAR reanalysis models over grassland (FIFE) and boreal forest (BOREAS)

Permalink
https://escholarship.org/uc/item/0gd554ds

Journal
Journal of Geophysical Research, 103(D18)

ISSN
0148-0227

Authors
Betts, Alan K.
Viterbo, Pedro
Beljaars, Anton
et al.

Publication Date
1998-09-01

DOI
10.1029/98JD02023

Copyright Information

Peer reviewed

Evaluation of land-surface interaction in ECMWF and NCEP/NCAR reanalysis models over grassland (FIFE) and boreal forest (BOREAS)

Alan K. Betts,[1] Pedro Viterbo,[2] Anton Beljaars,[2] Hua-Lu Pan,[3] Song-You Hong.[3] Mike Goulden.[4] Steve Wofsy[5]

Abstract. The National Center for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) and European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis models are compared with First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment (FIFE) grassland data from Kansas in 1987 and Boreal Ecosystem-Atmosphere Study (BOREAS) data from an old black spruce site in 1996 near Thompson, Manitoba. Some aspects of the comparison are similar for the two ecosystems. Over grassland and after snowmelt in the boreal forest, both models represent the seasonal cycle of near-surface temperature well. The two models have quite different soil hydrology components. The ECMWF model includes soil water nudging based on low level humidity errors. While this works quite well for the FIFE grassland, it appears to give too high evaporation over the boreal forest. The NCEP/NCAR model constrains long-term drifts by nudging deep soil water toward climatology. Over the FIFE site, this seems to give too low evaporation in midsummer, while at the BOREAS site, evaporation in this model is high. Both models have some difficulty representing the surface diurnal cycle of humidity In the NCEP/NCAR reanalysis this leads to errors primarily in June, when the surface boundary layer stays saturated and too much precipitation occurs. In the ECMWF reanalysis there is a morning peak of mixing ratio, which an earlier work showed resulted from too shallow a boundary layer in the morning Over the northern boreal forest there are important physical processes, which are not represented in either reanalysis model. In particular very high model albedos in spring, when there is snow under the forest canopy, lead to a very low daytime net radiation. This in turn leads to a large underestimate of the daytime surface fluxes, particularly the sensible heat flux, and to daytime model surface temperatures that are as much as 15 K low. In addition, the models do not account for the reduction in evaporation associated with frozen soil, and they generally have too large evapotranspiration in June and July, probably because they do not model the tight stomatal control of the coniferous forest.

1. Introduction

The direct comparison between field experiment time-series data and model data from nearby gridpoints in data assimilation and forecast systems has proved very useful in identifying systematic errors in the model physical parameterizations [*Betts et al.*, 1993, 1996a, b, 1997, 1998a, b] and in developing improved model parameterizations [*Viterbo and Beljaars*, 1995; *Hong and Pan*, 1996, *Chen et al.*, 1996]. Primarily, these comparisons identify physical processes, which are represented poorly or not represented at all in the models. In this paper we evaluate the reanalysis models [*Kalnay et al.*, 1996, *Gibson et al.*, 1997] from

the National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) and European Centre for Medium-Range Forecasts (ECMWF) using data from two experimental sites. One grassland data set is from the First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment (FIFE) 15 X 15 km site in Kansas in 1987, centered at 38.68°N, 96.25°W [see *Betts et al.*, 1996a, 1998a]. The second data set for 1996 is from the Boreal Ecosystem-Atmosphere Study (BOREAS) old black spruce site at 55 879°N, 98.484°W near Thompson, Manitoba. Some aspects of the comparison are similar for the two ecosystems, but there are some additional physical aspects of the northern boreal forest which are not represented in the reanalysis models.

The NCEP/NCAR reanalysis (at a triangular spectral truncation of T-62) is available for both 1987 and 1996, but the ECMWF T-106 reanalysis is only available until February 1994, just before the first intensive phase of BOREAS. So for the BOREAS 1996 comparison we use hourly time-series data archived from the 1996 ECMWF T-213 operational model, which has the same landsurface model as that used in the ECMWF reanalysis. In this paper we first compare the surface fluxes and surface thermodynamic cycle of the two reanalyses over grassland before discussing the comparison over the more complex boreal forest ecosystem. The land-surface

[1]Atmospheric Research, Pittsford, Vermont
[2]European Centre for Medium-Range Weather Forecasts, Reading, England.
[3]NCEP/EMC, National Centers for Environmental Prediction, and Environmental Monitoring Center, Camp Springs, Maryland.
[4]University of California, Irvine.
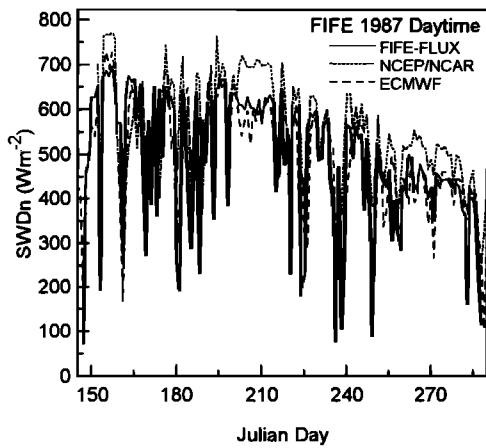[5]Harvard University, Cambridge, Massachusetts.

Figure 1. Daytime incoming solar radiation comparison between First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment (FIFE) 1987 and two reanalyses.

schemes in these models are described by *Viterbo and Beljaars* [1995], for the ECMWF model, and *Betts et al.* [1996a] for the NCEP/NCAR reanalysis. Both models have only a single vegetation type in their transpiration formulation. The NCEP/NCAR model has a globally fixed vegetation fraction of 0.7, while the ECMWF model has a global distribution of vegetation fraction.

Some care is needed in intercomparing forecast model data, representative of the 100-200 km scale for the global reanalyses, and field data representative of much smaller scales. Synoptic scale processes and advection are reasonably represented by the global reanalyses, which ingest sonde and satellite-derived data in their 6-hour analysis cycle, but the land-surface processes and subsurface state variables in the model are largely derived by the interactive model physical parameterizations for the soil, vegetation, surface and boundary layer, radiation and cloud fields. Consequently, comparing the model response on diurnal and seasonal scales and to intermediate timescale processes such as the dry-down of the soil after rain episodes, with field data gives insight into how well the observed physical processes are represented by the physical parameterizations in the model. This paper will show several examples.

2. Comparison Over FIFE Grassland

The FIFE data, discussed by *Betts and Ball* [1998], were an average of the surface automated meteorological stations (AMS), usually 10 in number, and the surface flux stations (variable in number from about 6 to as many as 20 during intensive field campaigns). *Betts et al.* [1996a, 1998a] contain the full details of the data and the individual separate comparisons, but neither paper compares the two reanalyses, which we shall do here. There are some differences in our reanalysis products as well as in resolution discussed above. For the NCEP/NCAR reanalysis we have the near surface thermodynamic fields at the four synoptic analysis times of 0000, 0600, 1200, and 1800 UTC as well as the accumulated fluxes for the 6-hour short-term forecasts between the analysis times. For the ECMWF reanalysis, where fields and fluxes were archived every 3 hours (to represent better the diurnal cycle), we have fluxes accumulated every 3 hours, and the 3-hour and 6-hour forecast fields, as well as the analyses themselves.

2.1 Radiation budget

Figure 1 compares daytime (a 1200-2400 UTC average) incoming solar radiation (*SWDn*) for the two reanalysis models, and an average of the FIFE "FLUX" station data (solid curve). We see that on sunny days (the upper envelope) the NCEP/NCAR reanalysis (dotted) has about 50 W m⁻² higher incoming solar radiation, while incoming solar radiation in the ECMWF reanalysis (dashed) shows little bias with respect to the data. In contrast, for the cloudy and rainy days (the lower envelope) the fall in *SWDn* is largest in the data and generally larger in the ECMWF reanalysis (at T-106), which has a prognostic cloud model, than in the NCEP/NCAR reanalysis, which has the lower resolution of T-62 and a diagnostic cloud scheme.

2.2 Surface Evaporative Fraction and Precipitation

Figure 2 compares in the FIFE "FLUX" data (top curves on left-hand scale) with the reanalysis models daytime (1200-2400 UTC) evaporative fraction (EF) defined as

$$EF = LH/ (LH +SH) \qquad (1)$$

where SH and LH are daytime averages of sensible and latent heat. The ECMWF reanalysis, which includes nudging of soil moisture based on 6-hour forecast errors in the low-level humidity [*Betts et al*, 1998a], follows the FIFE flux data more closely, although it has some significant high evaporative spikes when it rains in the model (see bottom curves). The ECMWF model tends to be low in EF in spring, and both models are high in fall, suggesting that a seasonal cycle of vegetation is needed. The NCEP/NCAR reanalysis has wider fluctuations and is generally low in midsummer [*Betts et al* , 1996a]. It has only two soil layers, and evaporation is high after rain, when the top 10-cm soil reservoir is replenished [see also *Betts et al.*, 1996a]. However, this upper layer has only a few days storage, and as the model has a fixed 70% vegetation fraction, direct soil evaporation from the 30% "bare soil" helps dry the upper layer fairly quickly. By midsummer the deep (10-200 cm) layer has dried down, and it is not replenished by rain events, and after a few days without rain, *EF* is systematically low. The FIFE data was one data set used in off-line tests to develop the four-layer ECMWF soil model [*Viterbo and Beljaars*, 1995], and the ECMWF reanalysis is able to approximately reproduce the seasonal cycle of soil moisture seen in the FIFE data in 1987 [*Betts*
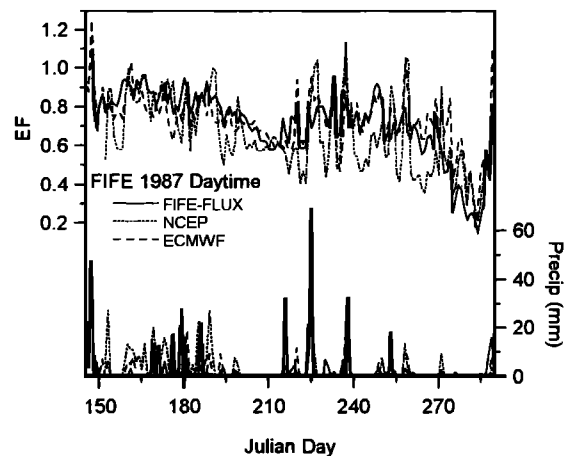

Figure 2. As Figure 1 for daytime evaporative fraction and 24-hour total precipitation.

et al., 1998a]. The continuous nudging of soil moisture prevents any downward interannual drift in this model. In the NCEP/NCAR reanalysis any long-term drift of the deep soil water is controlled by a nudging toward a climatological value (with a 2-month time constant), and this may be partly responsible for the dry deep soil water in midsummer.

The bottom curves, with the right-hand scale, show the 24-hour total precipitation for each day that observed at the FIFE site and that for each model analysis cycle (four 6-hour short term forecasts from each analysis). Some differences are to be expected, as FIFE is a 15 X 15 km site and the two reanalyses represent short-term forecasts at nearby grid points at T-62 and T-106 resolution, but after June, the forecast models generally pick up the wet days associated with synoptic events. However, it can be seen that there is rain on more days in the NCEP/NCAR model in June (around day 165) than observed. *Betts et al.*, [1996a] showed that this resulted from a spurious interaction among the land-surface, boundary layer (BL), radiation, and convection schemes, which we will summarize in section 2.4.

2.3 Seasonal Cycle of Temperature and Relative Humidity

Figure 3 shows the 24-hour average temperature (upper curves) and relative humidity (RH) for the FIFE automated meteorological station (AMS) data and the two reanalyses. Both reanalyses track the seasonal cycle of 24-hour mean temperature well. The most noticeable feature in the RH comparison is that while the models and data track quite well after the dry-down in late July (days 200-215), the NCEP/NCAR reanalysis has many days in June, when the model stays nearly saturated (100% RH) at the surface (see section 3, and *Betts et al.*, [1996a]). These correspond to the periods of excess rain in Figure 2. In the corresponding temperature comparison the NCEP/NCAR model is biased a little cold in June, during the periods when it is biased wet

2.4 Diurnal Cycle of Mixing Ratio and Temperature

Figure 4 shows the June mean diurnal cycle of temperature and mixing ratio *q*. The ECMWF model tends to be cold at sunrise, because the surface tends to cool and uncouple from the stable BL at night [*Viterbo et al.*, 1997, *Betts et al.*, 1998a] and warm in the daytime. The NCEP/NCAR reanalysis is systematically cold, because this model has too much precipitation in June, and often
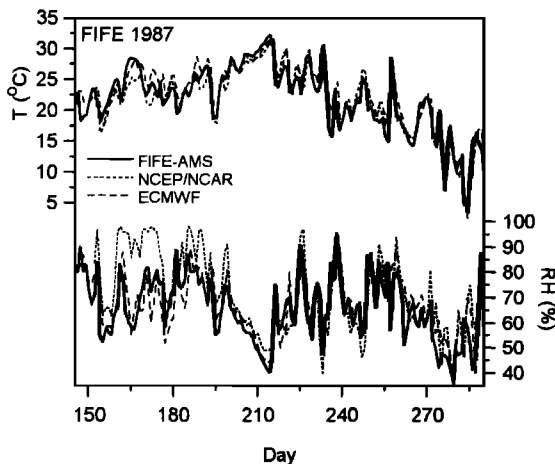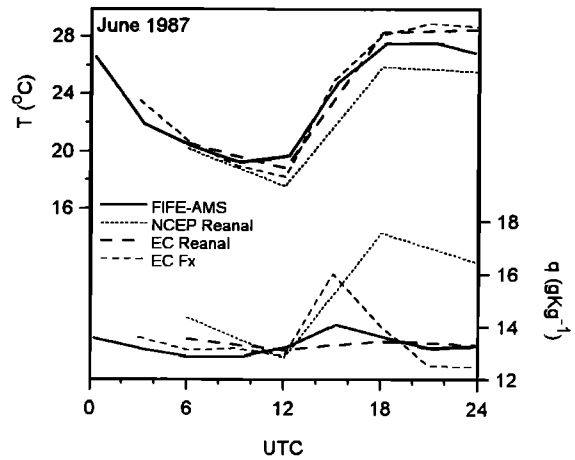

Figure 4. Comparison of June-average diurnal cycle of mixing ratio and temperature for FIFE 1987.

stays nearly saturated (Figures 2 and 3) The June average diurnal cycle of mixing ratio *q* shows that the models have different errors. The ECMWF model has a sharp midmorning peak in short-term (0-6 hour) forecasts and an evening trough relative to the FIFE data. This model's boundary layer (BL) uncouples at night, and the morning 2-m temperature is too cold. *Betts et al.* [1998a] concluded that the surface evaporation in the morning is trapped in a BL which is too shallow, resulting in this morning peak of *q*. Changes were made to the stable BL parameterization and the thermal coupling to the soil, and soil freezing was introduced in the ECMWF operational model on September 19,1996 [*Viterbo et al.*, 1997]. The NCEP/NCAR model is too wet in June in the daytime. *Betts et al.* [1996a] showed that an erroneous interaction in the model among the surface fluxes, precipitation, and the surface diurnal cycle was the cause. With a near-saturated surface, the convection scheme (which was not aware of low-level inversions) produces precipitation, which maintains a wet canopy Initially, very high potential evaporation occurs off this wet canopy under full sunlight, because the radiation scheme was only updated every 3 hours, so 3 hours pass before the model radiation scheme "sees" the precipitating clouds. Under these conditions the daytime BL stays shallow and saturated with precipitation turning on and off. The convection scheme has since been modified, and clouds in the model radiation scheme are now updated more frequently, but the key model change (fall 1996), which broke the evaporation-precipitation loop, was a change to the unstable BL scheme to include BL-top entrainment [*Hong and Pan*, 1996]. The deepening of the BL and the downward entrainment of dry air was the missing process which balanced surface evaporation and prevented saturation (see also *Betts and Ball* [1995]). By August the excess precipitation in the NCEP/NCAR model has disappeared (Figure 2), and *q* in the NCEP/NCAR reanalysis matches the FIFE observations a little closer than the ECMWF reanalysis (not shown).

3. Comparison Over Boreal Forest

In this section we will compare 1996 data from the BOREAS old black spruce site, 40 km west of Thompson, Manitoba (designated TF-3 for tower flux site 3 [*Goulden et al.*, 1997], with the NCEP/NCAR reanalysis and the 1996 ECMWF operational model Black spruce, a wetland conifer, is the dominant species of the boreal landscape in this area, covering about 50% of the area [*Barr et al.*, 1997]. Although there are other landscape "types"

Figure 3. As Figure 1 for 24-hour average temperature and relative humidity.

(deciduous aspen, dry conifers, including jack pine, mixed stands, as well as lakes and fens), we do not yet have a landscape surface flux average, so we will use this black spruce timeseries for illustration and as a reference. Evapotranspiration from both the black spruce and the other coniferous species is low in the boreal forest, considerably lower than the total evaporation in the global forecast models. In spring and early summer the lakes are cooler than the air, and evaporation from them is also small. The boreal landscape has frozen soil and is covered by snow about half the year. Neither the albedo with snow under the trees nor the effect of frozen soil is represented properly in the global reanalyses. Both models have consequently large errors in spring, when incoming solar radiation is high, but the ground is still frozen and there is snow under the canopy. The NCEP/NCAR data (from May to October, 1996) are from that reanalysis, but the ECMWF data are from the closest grid point in the 1996 T-213 operational model, which has the same land surface model as their reanalysis model (since the ECMWF reanalysis is not available for 1996). Not only is the spacial resolution higher, but we have for each day an hourly time series from a 24-hour short-term forecast from 1200 UTC, instead of 3 hourly values. However, as we shall compare chiefly daytime means, this higher temporal resolution is not significant here. We shall contrast in some figures some additional data from the March 1997 ECMWF model to show the impact of changes in the snow albedo introduced in late 1996 in the operational model.

3.1 Spring Over Boreal Forest

Figure 5 shows day-time (1200-2400 UTC) net radiation from March 1 to June 10, 1996, from the data and the ECMWF model and the NCEP/NCAR reanalysis from May 1. The data (solid line) show steadily rising R_{net} with maxima in April (days 92-121) in the range 300-400 W m^{-2}. In contrast, the ECMWF model R_{net} is <100 Wm^{-2} in April. The error here is caused by the use of a grassland snow albedo of 80% in the model, while in the boreal forest, the snow under the canopy is largely shaded, and the albedo is typically <20% [*Betts and Ball*, 1997]. The snow "melts" in the ECMWF model in the first week of May, and R_{net} climbs to values comparable to the observations. The NCEP/NCAR reanalysis has a similar error, as it generally has an albedo of 60% with snow. The snow in this model does not melt till late May (actual snowmelt near Thompson was middle to late May), so we see values of R_{net} <200 W m^{-2} during most of May (days 122-152).

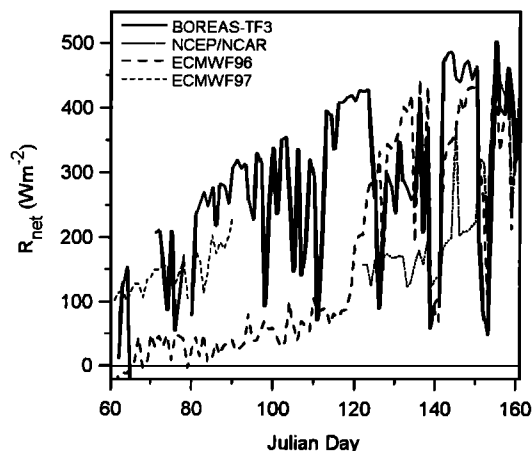The thin dashed curve is from the ECMWF model for the following year, March 1997, after the forest snow albedo was

Figure 5. R_{net} comparison with Boreal Ecosystem-Atmosphere Study (BOREAS) TF3 black spruce site in spring 1996.
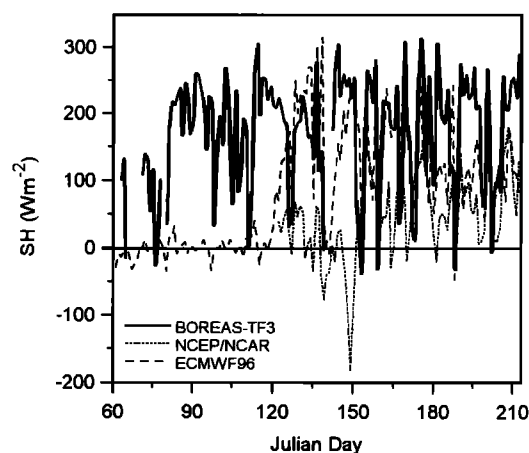

Figure 6. BOREAS daytime sensible heat flux comparison from March to July 1996.

corrected in the operational model in December 1996 to a more reasonable boreal forest landscape average of 20%. This has clearly improved the estimate of R_{net}: the model value is still below that observed, but this is consistent with the fact that the albedo of this spruce site is significantly lower than 20%. The boreal landscape contains lakes and fens, deciduous species, as well as spruce and pine forests. Both in summer and in winter, the spruce canopies have a lower albedo [*Betts and Ball*, 1997] than the other vegetated sites. The lakes have a low albedo in summer and a high albedo in winter, when frozen and snow covered.

This albedo error has a huge and very important impact on the SH flux in spring, as seen in Figure 6 (as well as on BL depth and lower tropospheric temperatures). By late March the observations show daytime (1200-2400 UTC) averaged SH fluxes above 200 W m^{-2} on sunny days, while the ECMWF model SH flux is near zero. After snow "melts" in the ECMWF model, the SH flux rapidly climbs (days 120-130). In the NCEP/NCAR reanalysis the SH also stays near zero till snowmelt and has some large excursions of downward SH flux (day 149) associated with the snowmelt itself. (The ECMWF model, in contrast, which has a separate snow analysis and does not have a self-consistent budget for the solid water phase, uses very little energy for the melt phase). The impact of these SH flux errors in the reanalyses is very large. Deep BLs are seen over the boreal forest in spring [*Betts et al.*, 1996b], driven by the large SH fluxes, as evaporation remains small before the ground melts. The models in contrast have low SH fluxes and cannot develop deep BLs in spring. This leads to large systematic errors in 5-day forecasts of lower tropospheric temperature (as large as -5 K at 850 mbar in March, April means over eastern Russia in the ECMWF analysis [see *Viterbo and Betts*, 1997]. Because the error involves a deep BL and extensive regions of forest, it has a global impact on the model high-latitude systematic errors. Figure 6 extends till the end of July. On sunny days the SH flux at this spruce site remains generally higher than in the ECMWF model and much higher than in the NCEP reanalysis.

Figure 7 shows the LH flux comparison. The observations show very low LH flux until May 20, and then as the soil and snow melt, average sunny day values in late May are around 100 W m^{-2}. The ECMWF model has low fluxes in early 1996 before snowmelt (for the wrong reason, as R_{net} is very small; see Figure 5), and then values climb and are generally above those observed. The dashed data from March 1997, after the snow albedo has been reduced to 20%, shows that although the model R_{net} is improved (Figure 5), the new 1997 operational model now gives too high LH fluxes in March (and consequently, its corresponding SH flux is still biased
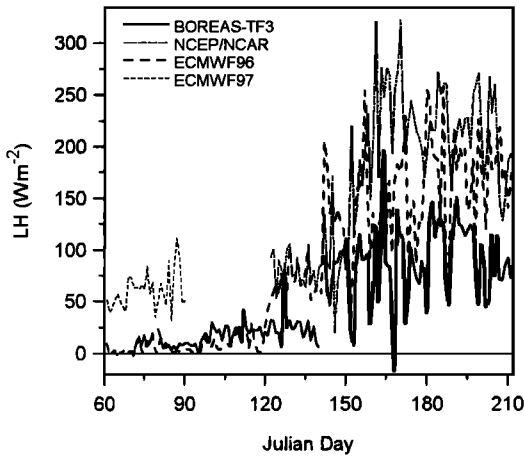
Figure 7 As Figure 6 for latent heat flux.

Figure 9. As Figure 8 for evaporative fraction.

low). This error results from the now high R_{net} driving evaporation of the snow under the canopy. The NCEP/NCAR reanalysis (dotted), even with the low values of R_{net} in May gives too high evaporation, and evaporation climbs steadily in late May after snowmelt, reaching values over 250 W m^{-2} in early June. Such large values were seen in BOREAS only over aspen forests.

Clearly, there is room for improvement in both models, both in the formulation of the snow albedo for forests and in the evaporation algorithms, which need to be aware that the snow is under the canopy (except after very recent snowfall) and that the ground is frozen at these high latitudes. The issue of the impact of high-latitude snow cover on winter climate has been of concern for some time [*Barnett et al.*, 1989; *Cohen and Rind*, 1991; *Thomas and Rowntree*, 1992; *Bonan et al.*, 1992, 1995], but insufficient attention has been paid to the proper representation of forest albedo with snow in global forecast models. Accurate global observational studies of forest albedo with snow under the canopy are needed. The reduction of the boreal forest snow albedo in the operational ECMWF model to 20%, in December 1996, while simple, is a clear improvement, but the evaporation in winter and spring now appears high.

3.2 Boreal Forest Fluxes in June and July

We will now look at the fluxes after snowmelt, and after the thaw of the upper layers of the soil (which occurs at different times
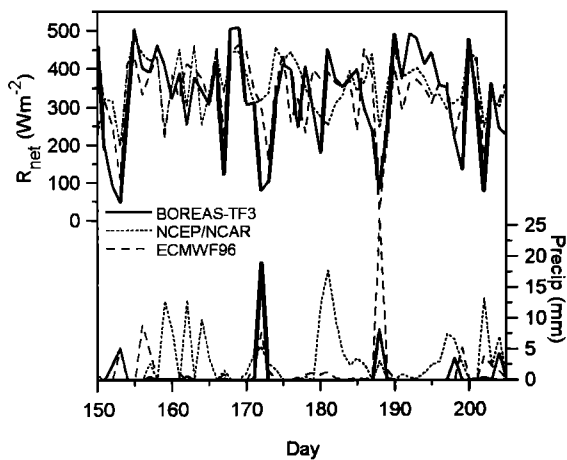

Figure 8. Comparison of daytime R_{net} and daytime precipitation for BOREAS after snowmelt.
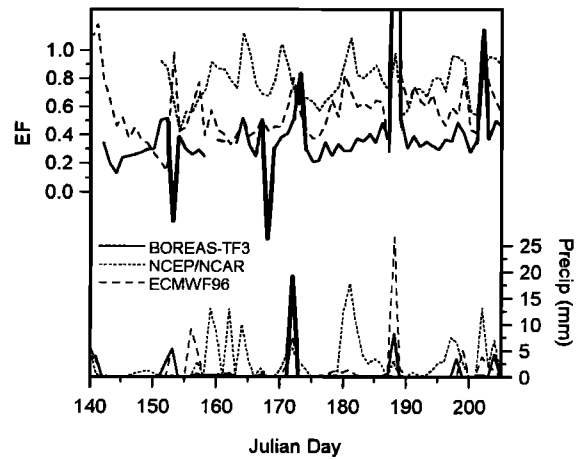
for different landscape types [*Betts et al.*, 1996b]). After snowmelt (late May in Thompson) the R_{net} comparison between models and data improves, as shown in Figure 8 from May 29 to July 31 (days 150-213). The upper curves are daytime R_{net} and the lower curves (right-hand scale) are 1200-2400 UTC precipitation for both models and the black spruce site. The black spruce data are of course, point data (summed for 12 hours), while the ECMWF data come from a T-213 model and the NCEP/NCAR reanalysis from a T-62 model, so some differences can be expected. We see that on rainy days, R_{net} falls more in the ECMWF model (to values similar to those observed), suggesting that their prognostic cloud scheme is handling the cloud field reasonably well. We also see that the NCEP/NCAR reanalysis has some spurious rainfall peaks, as over the FIFE site. The reason appears to be the same: namely, the model BL stays nearly saturated all day (see Figure 10 later) with a high θ_E, and rain persists. One consequence is that the SH flux stays low during these rainfall events in the NCEP/NCAR reanalysis, and evaporation stays high.

In June and July both models generally have a larger LH flux and a smaller SH flux than the spruce site (Figures 6 and 7). Figure 9 compares daytime (1200-2400 UTC) EF (upper curves) and precipitation (lower curves) for the period after snowmelt to the end of July. Observed daytime average EF remains quite low at the black spruce site all summer. (The spikes generally correspond to days of low fluxes). Typically, the ECMWF model has a higher EF and the NCEP/NCAR reanalysis is higher still, particularly in June when the surface stays near saturation. For the BOREAS northern study area, deciduous species and fens, which have a much higher EF than the black spruce, cover less than 20% of the area. Thus even without a proper landscape average for comparison, it seems likely that evaporation in the global models is too high in early summer. The tight stomatal control over evaporation by the forest is not well represented in the models. Note that the agreement between the ECMWF model and the data over the boreal forest is not nearly so good as over the FIFE grassland (Figure 2). In Figure 9, from days 142 to 151, we see the steady fall of EF in the ECMWF model, as the soil moisture falls in the absence of rain; much like the behavior at the FIFE site in late July. However, the boreal spruce forest (where EF is primarily biophysically controlled) does not behave in this way at all. The data (solid line) show a small fall after the rain, probably as the moss layer dries out [*Betts et al.*, 1998c], but EF then recovers and increases slowly, as the soil has just melted, and water is presumably more available to the trees. Clearly, further developments are needed to represent well the physiological controls of the boreal forest on evaporation over the season.
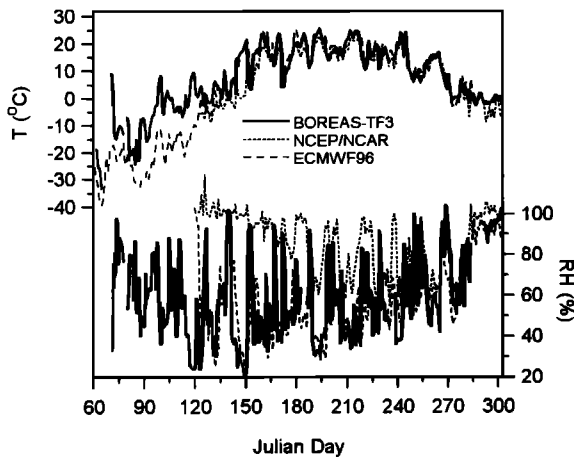
Figure 10. Daytime temperature and relative humidity comparison with BOREAS during 1996.

By August and September the difference in evaporation between the two models has become smaller, but both remain somewhat higher than the black spruce site (not shown). However, in addition to the fens, deciduous species, and recently burned areas, about 10% of the landscape of the northern study area (NSA) [*Barr et al.*, 1997] is open water. These lakes have higher evaporation in late summer after they have warmed, so that the landscape-average evaporation may be correspondingly larger than that at the black spruce site, and the model bias may be therefore less. We cannot draw conclusions about the late summer until we have landscape average fluxes.

3.3 Seasonal Cycle of Temperature and Humidity

Figure 10 (upper curves on left-hand scale) compares the daytime (1200-2400 UTC average) air temperature for black spruce site and models. In March and April the ECMWF model (at 30 m, the lowest model level) is some 10-15 K cooler than the data, because of the snow-albedo error. This leads to a large systematic error in the ECMWF model in the 850 mbar temperatures as mentioned earlier. This error disappears after snowmelt in early May. The NCEP/NCAR reanalysis is cooler than the data in May for the same reason, until its snow melts around day 150. From then on, the models track the black spruce site quite well for the rest of the summer, with the ECMWF model typically a little warmer than the data and the NCEP model often a little cooler. Note that the NCEP daytime average is of just 3 values at 1200, 1800 and 2400 UTC and is therefore less representative.

The lower curves on the right-hand scale of Figure 10 compare RH . We only show the ECMWF model data from May 1, because its temperature error is so large before then. After snowmelt the ECMWF model follows the observed RH quite well, despite the biases in EF seen in Figure 9. In the NCEP/NCAR reanalysis the high RH values near 100% in May are before the snowmelt. However, RH remains high in this model in June (days 153-182) after the snowmelt, as seen over the FIFE site in June (discussed earlier in section 2.3). Again, there is excess rain (seen in Figures 8 and 9) and it is likely that the cause is the same: that the BL does not deepen sufficiently during the day and stays saturated with a high θ_E and persistent rain [*Betts et al.*, 1996a; *Hong and Pan*, 1996]. Later in the summer both models and the spruce site track much better. When the RH is biased high in the NCEP/NCAR reanalysis, not unexpectedly, temperature tends to be low.

3.4 Diurnal Cycle of Precipitation

Figure 11 compares the mean diurnal cycle of precipitation for the months May-September 1996. The data show an afternoon peak at 1930 (an 1800-2100 UTC average), while the ECMWF model peak is broader and has significant rain in the 1500-1800 UTC morning period, when the observations show a minimum. Although we could not conclude this from the single site comparison, this is in fact a characteristic error of the ECMWF reanalysis model [*Betts et al.*, 1998b]; the model precipitation maximum is close to local noon. The NCEP/NCAR reanalysis has only a 6-hour time resolution. It has an 1800-2400 UTC maximum, but the values are too high, because of the many extra days when there is rain in this model (see Figures 8 and 9).

4. Conclusions

We have compared the surface fluxes and surface temperature and humidity for the NCEP/NCAR and ECMWF reanalysis models over the FIFE grassland site, and one of the BOREAS study areas, using a black spruce data set for illustration. The separate FIFE comparisons are shown in more detail, but not compared, by *Betts et al.* [1996a, 1998a]. We have found some similarities in the model land-surface interaction over the two sites as well as some additional differences in the northern boreal region. Over the FIFE grassland both reanalyses track daytime temperature quite well, although the ECMWF model is too cold at sunrise. The models have quite different soil hydrology components. The ECMWF model, which has a four-layer soil model and includes nudging of soil moisture in the analysis cycle based on near-surface humidity errors, tracks daytime evaporative fraction over the season well for the FIFE grassland site, although it has high evaporation on rainy days, and needs an improved seasonal cycle. The NCEP model with a two-layer soil model has a wet bias in June at the FIFE site, with excessive rainfall from BL errors interacting with the radiation and convection schemes, and a dry bias in midsummer, after its deep soil reservoir has dried. Both models have errors in the diurnal cycle of humidity, again associated with errors in the diurnal cycle of the BL growth.

Over the boreal forest we do not have landscape average fluxes, so our conclusions are more tentative and confined to the spring and early summer seasons when the model errors are large. The reanalysis models generally do not handle the boreal forest as well as the FIFE grassland. The biggest error in both models is in the spring, when too high forest albedos with snow under the canopy
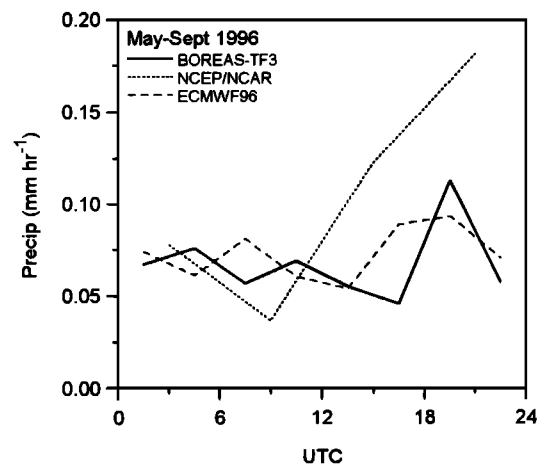

Figure 11. Diurnal cycle of precipitation; May-September 1996.

lead to large errors in surface radiation, SH and LH fluxes, and temperature. These are systematic errors of global scale at northern high latitudes. Both models do not account for the snow being under the canopy and the soil being frozen, which limit evaporation. While the ECMWF soil hydrology/vegetation model with soil moisture nudging works quite well for the FIFE grassland, it appears to give evaporation that is biased high over the boreal forest. The NCEP/NCAR model constrains long-term drifts by nudging deep soil water toward a climatology with a 60-day timescale. Over the FIFE site, this seems to give too low evaporation in midsummer, while at the BOREAS site, evaporation in this model is much too high. As a result, in June and July both models have much more evaporation than the black spruce site (the dominant landscape vegetation). One physical interpretation of this is that the models do not account for the tight stomatal control of the conifers, which limits evapotranspiration over the boreal forest. As more detailed studies of the surface energy balance in BOREAS are completed and, in particular, landscape averages are derived, we will be able to refine our conclusions further and extend them into the fall. However, we believe our conclusions are qualitatively correct as the fraction of deciduous forest (which has a higher EF) is relatively small near this site. We also show the diurnal cycle of precipitation for this site. The ECMWF model has a near-noon precipitation maximum, which has been seen in other studies, and is probably linked to the late morning peak in mixing ratio. The NCEP/NCAR summer precipitation is higher than observed.

This research is part of an ongoing effort to evaluate and improve the land-surface parameterizations in operational forecast models at NCEP and ECMWF. As mentioned in the text, some of the errors identified have already been corrected in the operational forecast models, while others will be dealt with in future model versions.

References

Barnett, T. P., L. Dumenil, U. Schlese, E. Roeckner, and M. Latif, The effect of Eurasian snow cover on regional and global climate variations, *J. Atmos. Sci.*, *46*, 661-685,1989.

Barr, A. G., A. K. Betts, R. Desjardins, and J. I. MacPherson, Comparison of regional surface fluxes from boundary-layer budgets and aircraft measurements above boreal forest, *J. Geophys. Res.*, *102*, 29,213-29,218, 1997.

Betts, A. K., and J.H. Ball, The FIFE surface diurnal cycle climate, *J. Geophys. Res.*, *100*, 25,679-25,693, 1995.

Betts A. K., and J. H. Ball, Albedo over the boreal forest, *J. Geophys. Res.*, *102*, 28,901-28,909, 1997.

Betts A. K., and J. H Ball, FIFE surface climate and site-average data set: 1987-1989, *J. Atmos Sci.*, *55*, 1091-1108, 1998.

Betts, A.K., J.H. Ball, and A.C.M. Beljaars, Comparison between the land surface response of the European Centre model and the FIFE-1987 data, *Q. J R. Meteorol. Soc.*, *119*, 975-1001, 1993.

Betts, A. K., S-Y. Hong and H-L. Pan, Comparison of NCEP/NCAR

Reanalysis with 1987 FIFE data, *Mon. Weather Rev.*, *124*, 1480-1498, 1996a.

Betts, A. K., J. H. Ball, Beljaars, A.C.M., M.J. Miller, and P. Viterbo, The land-surface-atmosphere interaction: a review based on observational and global modeling perspectives, *J. Geophys. Res.*, *101*, 7209-7225, 1996b.

Betts, A. K., F. Chen, K. Mitchell, and Z. Janjić, Assessment of land-surface and boundary layer models in 2 operational versions of the Eta Model using FIFE data, *Mon. Weather Rev.*, *125*, 2896-2915, 1997.

Betts, A. K., P. Viterbo, and A. C. M. Beljaars, Comparison of the ECMWF reanalysis with the 1987 FIFE data, *Mon. Weather Rev.*, *126*, 186-198, 1998a.

Betts, A. K., P. Viterbo, and E. Wood, Surface energy and water balance for the Arkansas-Red River basin from the ECMWF reanalysis, *J.Clim.*, *11*, in press, 1998b.

Betts, A. K., M. L. Goulden, and S. C. Wofsy, Controls on evaporation in a boreal spruce forest, . *J. Clim.*, in press, 1998c.

Bonan, G.B., D. Pollard, and S.L. Thompson, Effects of boreal forest vegetation on global climate, *Nature*, *359*, 716-718, 1992.

Bonan, G.B., F.S. Chapin III, and S.L. Thompson, Boreal forest and tundra ecosystems as components of the climate system, *Clim. Change*, *29*, 145-167, 1995.

Chen, F., K. Mitchell. J. Schaake, Y. Xue, H-L. Pan, V. Koren, Q. Duan, and A. Betts, Modeling of land-surface evaporation by four schemes and comparison with FIFE observations, *J. Geophys. Res.*, *101*, 7251-7268, 1996.

Cohen, J., and D. Rind, The effect of snow cover on climate, *J. Clim.*, *7*, 698-706, 1991.

Gibson, J. K., P. Kallberg, S. Uppala, A. Nomura, and E. Serrano, ERA description, *ECMWF Reanal. Proj. Rep. Ser.*, *1*, 72 pp., Eur. Cent. for Medium-Range Weather Forecasts, Reading , England, 1997.

Goulden, M.L., B.C. Daube, S.-M. Fan, D.J. Sutton, A. Bazzaz, J.W. Munger, and S.C. Wofsy, Physiological Responses of a Black Spruce Forest to Weather, *J. Geophys. Res.*, *102*, 28,987-28,996, 1997.

Hong, S-Y., and H-L. Pan, Implementing a nonlocal boundary layer vertical diffusion scheme for the NCEP medium-range forecast model. *Mon. Weather Rev.*, *124*, 2322-2339, 1996.

Kalnay, E. et al., The NCEP/NCAR 40-year Reanalysis Project, *Bull. Amer. Meteorol. Soc.*, *77*, 437-471, 1996.

Thomas, G., and P.R. Rowntree, The boreal forests and climate, *Q. J. R. Meteorol. Soc.*, *118* 469-497, 1992.

Viterbo, P., and A. C. M. Beljaars, An improved land-surface parameterization in the ECMWF model and its validation, *J. Clim.*, *8*, 2716-2748,1995.

Viterbo, P., and A.K. Betts, The forecast impact of changes to the snow albedo of the boreal forests, in *Research Activities in Atmospheric and Oceanic Modeling*, CAS/JSC Work. Group on Numer. Exp., Rep. 25, World Meteorol. Organ., Geneva, 1997.

Viterbo, P., A.C.M. Beljaars, J.-F Mahfouf, and J. Teixeira, The role of soil water freezing and its interaction with the stable boundary layer, in *Research Activities in Atmospheric and Oceanic Modeling*, CAS/JSC Work. Group on Numer. Exp., Rep. 25, WMO/TD-792, 4.44-4.45 World Meteorol. Organ., Geneva., 1997.

A. Beljaars and P. Viterbo, ECMWF, Reading, UK.

A. K. Betts, 58 Hendee Lane, Pittsford, VT 05763. (E-mail: akbetts@aol.com)

M. Goulden, Earth System Science, University of California, Irvine, CA 92717.

S.Y. Hong and H.-L Pan, NCEP/EMC, Camp Springs, MD 20746

S. Wofsy, Deptartment of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138.