Comparison and evaluation of gridded radiation products across northern Eurasia

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Abstract
Northern Eurasia is a region experiencing documented changes in temperature and large-scale streamflow, yet little attention has been focused on the large-scale energy budgets over the region. We compare station data and gridded radiation products from reanalysis and remote sensing to evaluate the radiative fluxes across northern Eurasia. On annual timescales, we find that the downward shortwave radiation products, with the exception of those of the NCEP/NCAR reanalysis, compare well with long-term station observations, but that this agreement breaks down with smaller timescales and for downward longwave and upward shortwave and longwave radiation. Of the six gridded products, the Surface Radiation Budget data set performs the best as compared to observations. Differences in radiative fluxes are on the order of 15–20 W m$^{-2}$ on seasonal timescales, averaged across the region, with larger variations spatially and at smaller timescales. The resulting uncertainty in net radiation has implications for climate and hydrologic analyses that seek to understand changes in northern Eurasia climate and its hydrologic cycle.

Keywords: radiation budgets, reanalysis, Eurasia

1. Introduction
The energy balance of the Earth’s surface is largely driven by net radiation. Incoming shortwave radiation from the sun travels through the Earth’s atmosphere, and clouds and aerosols influence how much shortwave radiation reaches the surface. Outgoing shortwave radiation is determined by the surface albedo and incoming radiation. Downward and upward longwave radiation is dependent on the temperature and emissivity of the atmosphere and land surface, respectively.

Radiative fluxes at the land surface impact many important physical processes. The net radiation is the primary energy input to the land surface, and it directly affects surface temperatures and surface heat fluxes. The imbalance between incoming and outgoing radiation serves as a primary control on evapotranspiration and therefore affects the hydrologic cycle (Wild et al 2008). In snow-dominated regions, incoming radiation partially determines snowmelt, and the timing and magnitude of snowmelt has a significant effect on streamflow. A number of gridded, global radiation products exist from remote sensing (Stackhouse et al 2004, Zhang et al 2004), reanalysis (Kalnay et al 1996, Uppala et al 2005), and a combination of sources (Sheffield et al 2006). Many papers have been written about the data products globally (Allan et al 2004, Betts et al 2006, Fasullo and Trenberth 2008, Lin et al 2008, Wild et al 1998), but few have focused on northern Eurasia (Abakumova et al 1996). This paper seeks to fill that gap in the literature for several reasons. Northern Eurasia (defined as north of 40°N, and east of 30°E) comprises approximately 20% of the global land mass (Groisman and Soja 2007) and contains a number of biomes. Additionally, it has been a region of significant documented climate change. Air temperatures have been rising at a rate faster than the global average (Trenberth et al 2007), and river discharge has increased 7% since 1936 (Peterson et al 2002). Consequently, recent studies have tried to understand the changes in the water cycle (Adam et al 2007, McClelland et al 2006), but little research has focused on the energy inputs to the system.
We compare six global, gridded data sets to understand the radiative flux estimates over northern Eurasia. We use long-term station observations of downward shortwave radiation to evaluate the global data sets. We then examine the mean and interannual variability of the downward and upward radiative fluxes, finding that significant uncertainty still exists in the estimates of the radiative budget at the land surface.

2. Data

Seven data sources were used in this study: long-term station observations, two remote sensing-based products, three reanalysis products, and a global meteorological forcing data set that is a blend of remote sensing-based observations and reanalysis. Table 1 summarizes the data sets’ characteristics.

2.1. World Radiation Data Centre archives (WRDC)

The World Radiation Data Centre, located in St Petersburg, Russia at the Main Geophysical Laboratory, contains archives of radiation measurements for approximately 1000 stations worldwide. For this study, we downloaded data for 32 stations located in the study domain from the WRDC mirror site maintained by the US Department of Energy’s National Renewable Energy Laboratory (http://wrdc-mgo.nrel.gov/, accessed 10 July 2008 and 21 October 2008). The station data contains daily downward shortwave radiation measurements for varying record lengths between 1964 and 1993. For a majority of the archived stations in the former USSR, the observations began in 1964. Of these 32 stations, 24 stations contain over 20 years of data and 19 stations contain over 25 years of data (figure 1). They therefore constitute a long-term data set of shortwave radiation that can be used for validation.

2.2. ERA-40

The European Centre for Medium Range Weather Forecasts (ECMWF) produced a 40 year global reanalysis (Uppala et al 2005) that has been evaluated and used in a variety of studies (Allan et al 2004, Slater et al 2007). The ERA-40 extends from September 1957 through August 2002 with a 6 h, 3D assimilation system and T159 horizontal resolution. (Betts et al 2006) demonstrated that the ERA-40 underestimates downward shortwave radiation compared to other global products over Eurasia, a result that we confirm over northern Eurasia with comparisons to station observations in section 3.1.

2.3. ERA-interim

The ERA-interim is a global reanalysis product produced by ECMWF (Simmons et al 2006) with data publicly available
from ECMWF for 1989–2005 at the time of writing. The ERA-interim uses a 12 h, 4D variational assimilation system at T255 horizontal resolution, with the same 60 vertical model layers as the ERA-40. Improvements from the ERA-40 include variational bias correction of satellite radiances and an improved hydrologic cycle (Simmons et al. 2006, Uppala et al. 2008).

2.4. NCEP/NCAR reanalysis (NCEP)

The NCEP/NCAR reanalysis (referred to as the NCEP reanalysis hereafter) is a global reanalysis from 1948 through near real-time at a horizontal resolution of T62 and temporal resolution of 6 h (Kalnay et al. 1996). Downward surface short- and longwave radiation are predicted by the NCEP reanalysis forecast model. Previous studies have found this model to overestimate surface downward shortwave radiation (Brotzge 2004, Sheffield et al. 2006), and this overestimation is confirmed in this study with comparisons to station observations.

2.5. Surface radiation budget (SRB)

The surface radiation budget data set (Stackhouse et al. 2004) is a 1°, 3-hourly global radiation data set, extending from July 1983 through June 2005 for longwave radiation and through June 2006 for shortwave radiation. Cloud data comes from the International Satellite Cloud Climatology Project (Rossow and Schiffer 1999), and meteorological inputs (temperature and humidity profiles) are taken from Goddard Earth Observing System reanalysis product. For downward shortwave, we use release 3.0; for upward and downward longwave and downward shortwave, we use release 2.5.

2.6. International Satellite Cloud Climatology Project (ISCCP)

The ISCCP FD radiation data set is a 2.5°, 3-hourly global data set of radiative fluxes at the surface, top of atmosphere, and at several levels of the atmosphere (Zhang et al. 2004). The data begins in January 1984 and ends in December 2006. The ISCCP FD uses the NASA Goddard Institute for Space Studies (GISS) radiative transfer model, the ISCCP cloud data set (Rossow and Schiffer 1999) and satellite data for temperature and humidity.

2.7. Princeton Global Forcings (PGF) data set

The Princeton Global Forcing (Sheffield et al. 2006) data set is a 1°, 3-hourly global data set of meteorological forcings. The data set is a blending of the NCEP reanalysis and observational data sets. They adjust for systematic biases in radiation using the SRB climatology and a historic cloud data set. The data set has been extended through 2006 and updated using the SRB v3.0 product (Sheffield 2009). For 1984–2006, monthly downward shortwave was scaled directly to SRB, without using the cloud data set to adjust for trends. Downward longwave after 1984 is scaled to match the SRB r3.0 QC product.

3. Results

3.1. Downward shortwave radiation: comparisons to station data

To compare the gridded products with the WRDC station data, the radiative fluxes for each gridded data set were extracted for the grid cell in which the station was located. Mean daily downward shortwave radiation (DSW) was calculated, and then temporal moving averages were calculated with windows of 1, 2, . . . , 29 and 30 days. Whenever station data was missing within an averaging window, the window was set to missing for all data sets. The root mean square error (RMSE) was then calculated between each of the five gridded products and the WRDC stations (the ERA-interim was excluded because of the small temporal overlap). Figure 2 shows the average RMSE across all 32 stations; for the left panel, the RMSE

![Figure 2. Root mean square error (RMSE) was calculated for each station and then averaged for all stations. The RMSE was calculated for the daily time series (averaging period of 1 day) and for averaging periods of 2, 3, . . . , 30 days, where the averaging period is the number of days used to calculate the moving average for each time series. The left panel uses all data when available (SRB and ISCCP begin in 1983 and 1984, respectively); the right panel uses the common overlap period of 1984–1993.](image-url)
was calculated for each product whenever concurrent data between the gridded product and the station existed. Therefore the SRB and ISCCP error statistics begin in 1983 and 1984, respectively, whereas the other three gridded data sets extend back to 1964. For the right panel, the RMSE was calculated for the same time period across data sets (1984–1993, when station data was available).

As the averaging window becomes longer, the RMSE declines and eventually stabilizes. This decline in RMSE resulting from temporal averaging can be partially attributed to scale. The station observations are for a point, and the gridded data sets have a spatial resolution of $1^\circ - 2.5^\circ$. The RMSE for the SRB, ISCCP, and ERA40 data sets are nearly identical, with the SRB performing slightly better for averaging periods less than 10 days. On a 30 day timescale, all but the NCEP reanalysis have RMS errors of less than 20 W m$^{-2}$. The SRB and ISCCP have errors of approximately 15 W m$^{-2}$, a number on the outer bound of the ISCCP data set’s estimated errors of 10–15 W m$^{-2}$ (Zhang et al. 2004, 2007). Some of the PGF’s daily variability is adjusted for observed rain days, and as such should match the monthly, not daily, observations. Because of the sampling, the RMS errors decrease substantially by the 30 day window that corresponds to the monthly scale. The notable difference between the two panels of figure 2 is the decrease in RMSE in the PGF data set when the shorter time period of 1984–1993 is used. This is because the PGF shortwave radiation is scaled to match SRB at the monthly scale from 1984 to 2006; prior to 1984 the shortwave radiation is scaled using a regression with historical cloud data (Sheffield et al. 2006).

The large RMS error of the NCEP reanalysis is due to its large bias compared to station observations (table 2). The ERA-40, SRB, ISCCP, and PGF data sets all have small, negligible biases (±2–3 W m$^{-2}$), compared to station observations across the region, although larger seasonal biases exist. The monthly anomaly time series (with the seasonal cycle removed) of the ERA-40 has smaller errors and stronger correlation with observations than the NCEP reanalysis and the PGF data set (table 2). The SRB has slightly smaller errors than the ISCCP data set, with a stronger correlation to observations. Again, the time periods for the SRB and ISCCP are shorter than the other three gridded data sets. Across the region, the ERA-40 had the least variability between stations for all of the errors statistics calculated in table 2.

The seasonal cumulative distribution function (CDF) of daily downward shortwave radiation provides another measure against which to compare the data (figure 3). The CDFs in figure 3 are calculated by first screening the data sets for days in which all data sets have values. Therefore, no data prior to 1 January 1984 is included because of the SRB and ISCCP data periods. Then, the CDF is calculated using data from all station locations. As in figure 2, the NCEP reanalysis has a high bias in DSW. During summer, the other four data sets exhibit a high bias for low radiation days and a low bias for high radiation.

![Figure 3](image-url)
Figure 4. Interannual variability in seasonal components of downward shortwave (DSW), downward longwave (DLW), upward shortwave (USW), upward longwave (ULW), and net radiation (Rnet) averaged over the region.

Table 2. Downward shortwave radiation error statistics for 32 stations (24 for ISCCP and SRB). Standard deviations are the standard deviation of the statistic among stations (not of the individual time series). All units where applicable are W m$^{-2}$.

| Product | Bias (%) | Bias St. Dev. | RMSE St. Dev. | Mean absolute error | Mean absolute error St. Dev. | RMSE St. Dev. | Corr. coeff |
|---------|----------|---------------|---------------|---------------------|-----------------------------|---------------|-------------|
| ERA-40  | $-3.2$ $(-2.6\%)$ | 6.9 | 35.1 | 4.5 | 6.8 | 0.9 | 9.9 | 1.2 | 0.71 |
| NCEP    | 42.7 $(26.0\%)$ | 7.4 | 63.1 | 6.5 | 8.1 | 1.2 | 12.0 | 1.5 | 0.55 |
| ISCCP   | 2.8 $(2.2\%)$ | 6.9 | 33.5 | 4.9 | 8.2 | 1.6 | 11.7 | 2.3 | 0.66 |
| SRB     | 2.1 $(1.7\%)$ | 7.4 | 29.9 | 6.9 | 7.7 | 1.9 | 10.8 | 2.7 | 0.73 |
| PGF     | 2.8 $(2.3\%)$ | 7.3 | 47.0 | 4.7 | 8.4 | 1.2 | 12.3 | 1.4 | 0.54 |

3.2. Comparison of all radiative flux components

In addition to downward shortwave radiation, the downward longwave and upward short- and longwave radiation are critical in understanding the energy balance of the land surface. Table 3 shows the mean seasonal fluxes for each data set, and figure 4 shows the seasonal mean time series, averaged across northern Eurasia (north of 40°N, east of 30°E). Differences between the data sets are apparent for many of the seasons and fluxes. For downward shortwave, the ERA40 is lower than the other estimates, which is consistent with its negative bias (table 2). The other four data sets do not show any pattern. Downward longwave radiation (DLW) shows...
differences between the products, with differences of up to 21 W m$^{-2}$ in mean winter DLW. For DLW, the ISCCP data set exhibits an increase after 2000. In 2001, the ISCCP data set had a change in the TOVS algorithm to include the AMSU system, thereby including microwave water vapor profiles (Zhang et al 2006).

Upward shortwave radiation displays more consistency among the products, with the exception of the spring. The upward shortwave radiation is dependent on the incoming shortwave radiation and the surface albedo. For the winter and spring, ISCCP’s shortwave albedo is 0.10 higher than the other products. Zhang et al (2007) found ISCCP’s albedo to be higher by roughly the same amount over global snow-covered areas, and a large portion of northern Eurasia is snow-covered during winter and spring months. During summer and fall, the ERA reanalyses and two remote sensing products have albedos within 5% of each other. Upward longwave radiation shows variations of up to 10–15 W m$^{-2}$. This is the range of uncertainty specified in Zhang et al (2007), who point out that differences of 2–4 K in skin temperature can lead to uncertainties of 10–15 W m$^{-2}$ in upwelling longwave fluxes.

These differences in the four radiative components result in notable differences in the net radiation at the land surface. Estimates of seasonal mean net radiation vary by up to 15–20 W m$^{-2}$ between the products. SRB has higher estimates of net radiation for fall, winter, and spring. This is because of its lower outgoing radiation as its downward short- and longwave radiation are not significantly lower than the other products. Overall, the net radiation estimates show a lack of consistency amongst the data sets, both in terms of mean and interannual variations.

### 4. Discussion

Many studies have compared and validated radiation data products, but these comparisons were typically global or zonal means. In this paper, we evaluate several global data sets over northern Eurasia, a region with documented changes in surface air temperature and hydrology. We compare five global data sets’ downward shortwave radiation to 32 stations archived at the World Radiation Data Centre between 1964 and 1993. In general, the errors in the gridded data sets decreased as the data were averaged through time, with the errors approaching their minimum after approximately 10 days. Annual biases were within approximately ±3 W m$^{-2}$ for all the gridded data sets except the NCEP reanalysis. Betts et al (1996) suggested that the NCEP reanalysis’ overestimation of downward shortwave radiation resulted from an atmosphere that is too transparent and an underestimation of cloudiness.

Averaged across the region, the data sets show seasonal differences for the downward shortwave radiation (figure 4). As shown in figure 4 and summarized in table 2, differences are also evident in the other components of the radiative budget. These differences result in discrepancies as large as 20 W m$^{-2}$ in the estimated net radiation. If the 20 W m$^{-2}$ of additional energy was converted equally into latent and sensible heat (assuming a Bowen ratio of 1.0 based on the results of Barr et al (1997) over a boreal forest), this would result in a difference of approximately 11 mm/month of evapotranspiration. This is a significant uncertainty as estimated evapotranspiration is approximately 60–100 mm/month over regions of the Eurasian Pan-Arctic during summer (Su et al 2006).

The six gridded products are all subject to errors from input data sets and from parameterizations in the radiative transfer models. Uncertainties in air temperature and humidity result in errors in downward longwave fluxes, and uncertainties in clouds and aerosols induce errors in downward shortwave fluxes. Walsh et al (2009) show that errors in cloud cover was the primary cause of errors in downward shortwave fluxes for reanalysis products at the ARM site at Barrow, Alaska. The ISCCP, SRB, and PGF products all use the ISCCP cloud product, and the difference in cloud cover from ISCCP and the ERA40 reanalysis may lead to the ERA40 consistently estimating lower downward shortwave fluxes. Errors in albedo, particularly over snow-covered regions, affect upward shortwave fluxes. Errors in upward longwave fluxes are caused by uncertainties in surface temperature and emissivity. For a further discussion of the potential errors caused by these uncertainties, see (Zhang et al 2007, 2006).

Regardless of the sources of errors, the five gridded products analyzed in figure 4 show similar interannual variability in the downward and upward longwave radiation. SRB, ISCCP, and PGF have similar estimates and variability for downward shortwave radiation. For the PGF data set, this is because it is scaled to match SRB. For SRB and ISCCP, there is overlap in the input data sets. The SRB data set has the smallest bias and RMSE compared to the station observations.

Regional analyses as in this paper highlight the uncertainties that exist in radiation products, and therefore they pose a challenge to the research community to continue efforts to improve radiation data sets not only globally but also regionally. The radiative balance couples the atmosphere and land, so better radiation estimates for the hydrologic and ecological communities to improve their estimates of hydrology, plant primary productive and other

### Table 3. Mean of seasonal radiative fluxes over northern Eurasia for 1984–2005 (ERA-40 1984-2002; ERA-interim 1989–2005).

|          | Winter (DJF) | Spring (MAM) | Summer (JJA) | Fall (SON) |
|----------|--------------|--------------|--------------|------------|
|          | DSW          | DLW          | USW          | ULW        | DSW          | DLW          | USW          | ULW        | DSW          | DLW          | USW          | ULW        |
| ERA40    | 40.9         | 201.3        | 13.4         | 246.1       | 183.5       | 255.5        | 45.7         | 319.7       | 214.1       | 338.3        | 35.7         | 402.0       | 80.4        | 262.1       | 16.6        | 315.1       |
| ERaint   | 44.2         | 202.0        | 15.8         | 248.7       | 284.1       | 295.1        | 64.6         | 323.1       | 228.2       | 331.2        | 37.8         | 399.7       | 71.2        | 260.0       | 17.7        | 312.5       |
| ISCCP    | 46.8         | 215.2        | 21.9         | 253.5       | 185.0       | 264.0        | 64.6         | 322.1       | 224.0       | 336.6        | 29.2         | 396.1       | 82.7        | 265.3       | 15.9        | 314.9       |
| SRB      | 47.0         | 205.4        | 13.6         | 232.7       | 181.1       | 258.9        | 46.0         | 310.2       | 226.2       | 337.7        | 34.8         | 407.3       | 87.2        | 261.0       | 15.1        | 308.1       |
| PGF      | 47.0         | 205.6        | —            | 180.9       | 262.3       | —            | —            | 222.7       | 342.5       | —            | 87.3         | 264.8       | —            | —           | —           | —           |
variables. Improved estimates of the terrestrial energy budget components are essential to furthering our knowledge about the linkages between the atmosphere, land, and biosphere. In a region with documented temperature and hydrologic changes, it is difficult to quantify changes in the energy budget when such uncertainty exists in our historic baseline.

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