The Energy Budget of the Polar Atmosphere in MERRA

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ABSTRACT

Components of the atmospheric energy budget from the Modern Era Retrospective-Analysis for Research and Applications (MERRA) are evaluated in polar regions for the period 1979-2005 and compared with previous estimates, in situ observations, and contemporary reanalyses. Closure of the energy budget is reflected by the analysis increments term, which results from virtual enthalpy and latent heating contributions and averages $-11 \text{ W m}^{-2}$ over the north polar cap and $-22 \text{ W m}^{-2}$ over the south polar cap. Total energy tendency and energy convergence terms from MERRA agree closely with previous study for northern high latitudes but convergence exceeds previous estimates for the south polar cap by 46 percent. Discrepancies with the Southern Hemisphere transport are largest in autumn and may be related to differences in topography with earlier reanalyses. For the Arctic, differences between MERRA and other sources in TOA and surface radiative fluxes maximize in May. These differences are concurrent with the largest discrepancies between MERRA parameterized and observed surface albedo. For May, in situ observations of the upwelling shortwave flux in the Arctic are $80 \text{ W m}^{-2}$ larger than MERRA, while the MERRA downwelling longwave flux is underestimated by $12 \text{ W m}^{-2}$ throughout the year. Over grounded ice sheets, the annual mean net surface energy flux in MERRA is erroneously non-zero. Contemporary reanalyses from the Climate Forecast Center (CFSR) and the Interim Re-Analyses of the European Centre for Medium Range Weather Forecasts (ERA-I) are found to have better surface parameterizations, however these collections are also found to have significant discrepancies with observed surface and TOA energy fluxes. Discrepancies among available reanalyses underscore the challenge of reproducing credible estimates of the atmospheric energy budget in polar regions.
1. Introduction

The objective of this study is to examine the performance of the Modern Era Retrospective-analysis for Research and Applications (MERRA) in representing the high latitude atmospheric energy budget. MERRA was recently released by NASA’s Global Modeling and Assimilation Office (GMAO). This effort, as well as a companion paper examining the atmospheric moisture budget (Cullather and Bosilovich, 2010), represent an initial examination of this reanalysis in the polar regions.

A quantitative knowledge of the flow, storage, and conversion of energy within the climate system has evolved with time as a result of contributions made by improvements in the observing system and by numerical atmospheric reanalyses (e.g., Fasullo and Trenberth, 2008). In the polar regions the energy budget and its variability are frequently used as a diagnostic for understanding rapidly changing conditions including glacial mass balance and perennial sea ice reduction (e.g., Porter et al., 2010). As noted in Cullather and Bosilovich (2010), numerical reanalyses are widely used in polar research for evaluating polar processes, as boundary conditions for limited area atmosphere and ocean–sea ice models, and as a first-order validation for climate models. However reanalyses inevitably contain inaccuracies resulting from limitations in the observing system, inconsistencies between differing observations, and incomplete knowledge of the physical processes that are represented in the assimilating weather forecast model. In particular, surface albedo characteristics over polar oceans and high latitude cloud properties are both associated with important but complex energy feedback mechanisms that have historically been poorly simulated (Randall et al., 1998). An initial evaluation of the high latitude energy budget in a reanalysis record is therefore a constructive activity.

Some questions of interest pertaining to this study are as follows.
• What are the spatial and temporal patterns of energy budget components in MERRA, and how do they compare with previous studies and contemporary reanalyses?

• How do MERRA surface fluxes compare with in situ field studies?

• What is the nature of adjustment terms in the energy budget?

Section 2 provides an overview of the MERRA data set and method. An evaluation of the atmospheric energy balance in polar regions is given in section 3. A discussion of these comparisons is then given in section 4.

2. MERRA description and method

Specification of the MERRA system is given in Cullather and Bosilovich (2010) and Rienecker et al. (2010). MERRA utilizes the incremental analysis update assimilation method (IAU; Bloom et al., 1996). In this method, a tendency is computed from the difference between an initial 6-hourly analysis field and the background forecast model state. The forecast model is then run a second time over the six-hour interval using this tendency as an additional forcing term. The resulting MERRA product is then composed of dynamically-consistent one-hourly fields that are incrementally corrected to observation every six hours. Thus atmospheric budgets—as they are constructed in the GEOS-5 AGCM—and their analysis increments are maintained within MERRA to the accuracy limited by round-off and data compression errors.

Following a form similar to Trenberth (1997), the MERRA total energy equation integrated over the atmospheric column may be written as

\[
\frac{\partial A_E}{\partial t} + \nabla \cdot \mathbf{F}_A = R_{top} + F_{sfc} + L_r \left. \frac{\partial W_r}{\partial t} \right|_{CHM} + \left[ L_r \frac{\partial W_r}{\partial t} - L_f \frac{\partial W_f}{\partial t} \right]_{FIL} + ANA_{(E)} - Q_{NUM},
\]

(1)
where $A_E$ is total energy in the atmospheric column, $\bar{F}_A$ is the horizontal transport of total atmospheric energy, $R_{top}$ is the downward net radiative flux at the top of the atmosphere (TOA), $F_{sfc}$ is the upwelling net surface flux, $L_v$ is the latent heat of vaporization, $L_f$ is the latent heat of fusion, $W_i$ is column-integrated water vapor (precipitable water), $W_i$ is column-integrated cloud ice condensate, $ANA(E)$ is the sum of analysis increments from the IAU method, and $Q_{NUM}$ is the sum of spurious numerical adjustments. The time rate of change in total atmospheric energy storage $A_E$ is expressed as

$$\frac{\partial A_E}{\partial t} = L_v \frac{\partial W_v}{\partial t} - L_f \frac{\partial W_i}{\partial t} + \frac{\partial}{\partial t} \left\{ \int_{p_{top}}^{p_{sfc}} (c_p T_v + \Phi_S + k) \frac{dp}{g} \right\},$$ \hspace{1cm} (2)

where $p_{sfc}$ is surface pressure, $p_{top}$ is the fixed pressure at the top model level which is 0.01 hPa, $c_p$ is the specific heat of the atmosphere at constant pressure, $T_v$ is virtual temperature, $\Phi_S$ is surface geopotential, $k = \frac{1}{2} \|
abla\|^2$ is kinetic energy, and $g$ is the gravity constant. The product $c_p T_v$ is referred to as virtual enthalpy. The divergence term may be expanded as follows:

$$\nabla \cdot \bar{F}_A = \nabla \cdot \int_{p_{top}}^{p_{sfc}} (L_v q_v - L_f q_t) \frac{\nabla dp}{g} + \nabla \cdot \int_{p_{top}}^{p_{sfc}} c_p T_v \frac{\nabla dp}{g} + \nabla \cdot \int_{p_{top}}^{p_{sfc}} \Phi \frac{\nabla dp}{g} + \nabla \cdot \int_{p_{top}}^{p_{sfc}} k \frac{\nabla dp}{g},$$ \hspace{1cm} (3)

where $\Phi$ is geopotential within the atmospheric column. The net upward surface flux is given as

$$F_{sfc} = Q_H + Q_E + L_f P_s - R_{sfc},$$ \hspace{1cm} (4)

where $Q_H$ and $Q_E$ are the upwelling surface turbulent sensible and latent heat fluxes, the product $L_f P_s$ is latent heating resulting from solid precipitation, and $R_{sfc}$ is the net downward radiative flux at the surface. The tendency imposed by the analysis increments $ANA(E)$ represents the summation of latent heat, virtual enthalpy, kinetic, and geopotential energy term contributions. Finally, $Q_{NUM}$ in (1) denotes the contribution of spurious residuals resulting from inertial terms,
the discretization of the thermodynamic equation, coordinate remapping during model
integration, and time-truncation errors. The relation between MERRA variables and equation
notation is given in the appendix.

The approach of this study is to evaluate MERRA values against prior studies for large-
scale areal averages of the terms in (1-4) over fixed polar regions as shown in Fig. 1, with a
particular focus on the polar caps. Studies for comparison include Nakamura and Oort (1988),
Genthon and Krinner (1998), Serreze et al. (2007), and Porter et al. (2010). Nakamura and Oort
(1988) produced budget estimates for both polar caps using the ocean flux values of Levitus
(1984), composite satellite data from the period 1966-1977, and atmospheric circulation statistics
from Oort (1983) which are largely based on the upper air station network. Nakamura and Oort
(1988) found the observational network insufficient for computing atmospheric energy transport
into the south polar cap and instead produced output from the NOAA Geophysical Fluid
Dynamics Laboratory GCM. Genthon and Krinner (1998) used the 15-year re-analysis of the
European Centre for Medium-Range Weather Forecasts (ECMWF) (ERA-15; Gibson et al.,
1997) for the period 1979-1993 to evaluate the south polar cap. Serreze et al. (2007) examined
the north polar cap and Arctic Ocean domains using the more recent 40-year re-analysis of
ECMWF (ERA-40; Uppala et al., 2005) and the National Centers for Environmental
Prediction/National Center for Atmospheric Research Reanalyses (NCEP/NCAR; Kalnay et al.,
1996) for the period 1979-2001. Serreze et al. (2007) also examined TOA radiative fluxes from
the Earth Radiation Budget Experiment for the study period February 1985 to April 1989
(ERBE; Barkstrom, 1984). Porter et al. (2010) similarly examined the north polar cap energy
budget for the period November 2000 to October 2005 using the 25-year Japanese Re-Analysis
(JRA-25; Onogi et al., 2007), and satellite data from the Clouds and the Earth's Radiant Energy
System (CERES; Wielicki et al., 1996) product. In support of budget comparisons with these
previous studies, the evaluation of near-surface state variables against in situ station observations
is also instructive.

Corresponding values for surface and TOA energy fluxes are also tabulated for two
contemporary reanalyses for comparison: the ECMWF Interim product (ERA-I; Simmons et al.,
2007) and the NCEP Climate Forecast System Reanalysis (CFSR; Saha et al., 2010). The ERA-I
was produced at T-255 spectral resolution, which is similar to the grid resolution of MERRA.
Energy flux fields are produced from 12-hour forecasts initialized by 4D-Var assimilation.
Monthly fields of the ERA-I were obtained for the years 1989-2005 at a reduced resolution of
1.5° × 1.5°. The CFSR utilize a coupled atmosphere-ocean model for the initial guess field and
an interactive sea ice model and was produced at T-382 spectral resolution. Model variables are
produced from 6-hour forecasts. Energy flux fields from the CFSR were obtained at full spatial
resolution.

Evidence of an evolving climate system in polar regions—particularly for the Arctic (e.g.,
Porter et al., 2010)—motivate an exclusion of the most recent years in the available MERRA time
series for an averaging period. The results presented here are for the years 1979-2005.

3. Atmospheric energy budget

a. Analysis increments

Terms of the atmospheric energy budget averaged over the period 1979-2005 from
MERRA are shown in Table 1 for the polar regions defined in Fig. 1. The far right column
indicates budget adjustment quantities. As noted earlier, artificial moisture filling and chemistry
parameterization terms of the energy budget from equation (1) have essentially zero magnitude.
Not shown, the spatial pattern of the spurious residual $Q_{NUM}$ is characterized by alternating positive and negative values in regions of steep topography. Averages taken over limited areas may produce aliasing of these oscillating values. For example, $Q_{NUM}$ averages 1.5 W m$^{-2}$ over the Greenland Ice Sheet. But in general, $ANA(E)$ is the largest adjustment quantity of interest in the atmospheric energy budget, and its spatial patterns are shown in Fig. 2. Here, positive values indicate an energy surplus in the balance equation while negatives indicate a deficit. The magnitude is a measure of closure obtainable by physical terms. The spatial patterns shown in Fig. 2 are complex, vary with time, and are typically dissimilar to the patterns of the analysis increments for the atmospheric moisture budget shown by Cullather and Bosilovich (2010).

As noted previously, analysis increments for the energy budget are the summation of contributions from latent heat, virtual enthalpy, kinetic, and geopotential energy terms. Of these four, the contribution to $ANA(E)$ from virtual enthalpy is large for monthly and annual averages in both polar cap regions, while analysis increments from latent heating are also significant for the north polar cap. For the Northern Hemisphere polar region, negative values for $ANA(E)$ are found over the Arctic Ocean, while positive values are present over surrounding lower latitudes. Mean annual amounts less than $-40$ W m$^{-2}$ are present in the vicinity of the North Pole with smaller magnitudes over Greenland and marginal seas. Seasonally, these magnitudes are larger in summer than in winter, however the values do not approach the local imbalances of greater than 100 W m$^{-2}$ that are shown for the ERA-40 in Serreze et al. (2007). For the average over the north polar cap, $ANA(E)$ ranges from $-4$ W m$^{-2}$ in February to $-17$ W m$^{-2}$ in June.

In Cullather and Bosilovich (2010), MERRA analysis increments for the atmospheric moisture budget were shown to be characterized by closed contours denoting upper air stations in coastal Greenland and Antarctica. Although signatures of upper air station locations are not as
evident in the $ANA(E)$ field as in the analysis increments field for the atmospheric moisture
budget, a dipole is apparent in Fig. 2a in the vicinity of Hudson Strait with centers near Kuujjuaq
(58°N, 68°W) and Cape Dorset (64°N, 77°W). Averaged over the north polar cap and the period
1979-2005, $ANA(E)$ is $-11$ W m$^{-2}$. The temporal variability of $ANA(E)$ in the Arctic also differs
markedly from the analysis increments field of the atmospheric moisture budget presented in
Cullather and Bosilovich (2010). Changes in the high latitude atmospheric moisture budget
analysis increments were largely found to be associated with the introduction of data from the
Advanced Microwave Sounding Unit (AMSU) in November 1998, which has a global impact on
MERRA (Bosilovich et al., 2010). In contrast, the $ANA(E)$ time series for the north polar cap
indicates changes which are not concurrent with satellite observing system changes. The
magnitude of energy budget analysis increments for the north polar cap averages less than
10 W m$^{-2}$ for the period 1979-1991, approximately 18 W m$^{-2}$ over the period 1992-1997, and
9 W m$^{-2}$ thereafter. These shifts may be due to changes in the surface observing system or in
atmospheric conditions.

In the Southern Hemisphere, the MERRA energy budget analysis increments term— as
shown in Fig. 2b— has a larger magnitude than for the north polar cap, with amounts of greater
than $(-)80$ W m$^{-2}$ over Victoria Land and regions of northern Queen Maud Land in East
Antarctica. Over the south polar cap, $ANA(E)$ ranges from $-27$ W m$^{-2}$ in February to $-20$ W m$^{-2}$
in August and September. The annual average of $ANA(E)$ is comparatively smaller over the lower
latitudes of the Southern Ocean as seen in Fig. 2b. There is a considerable annual cycle for the
Southern Ocean domain ranging from $-40$ W m$^{-2}$ in January and February to $-9$ W m$^{-2}$ in June.
The year to year time series for the south polar cap is highly variable and ranges from
$-37$ W m$^{-2}$ in 1983 to $-9$ W m$^{-2}$ in 1998. The analysis increments time series for the south polar
cap energy budget is uncorrelated with that of the north polar cap, and its relation to changes in
the observing system is also not readily apparent. But over the data-sparse Southern Ocean
domain there is a discontinuity in the $\text{ANA}(E)$ time series in 1998 that is likely associated with the
introduction of AMSU. Southern Ocean analysis increments average $-21.8 \text{ W m}^{-2}$ prior to 1998,
and $-26.7 \text{ W m}^{-2}$ thereafter.

b. Total atmospheric energy tendency

In both the north and south polar caps, the MERRA total energy tendency is near zero
for annual averages and is small for months of solstice, as shown in Table 1. But there is an
oscillatory annual cycle for the tendency terms as seen in Fig. 3. For the north polar cap, the
tendency term reaches a maximum of $26 \text{ W m}^{-2}$ in April and a minimum of $-26 \text{ W m}^{-2}$ in
September. This annual cycle agrees very closely with values from other reanalyses as reported
by Porter et al. (2010), Serreze et al. (2007), and from the observational study of Nakamura and
Oort (1988). The RMS difference of monthly means with MERRA is only $4 \text{ W m}^{-2}$ for both
NCER/NCAR and JRA-25 as reported by Porter et al. (2010), less than $1 \text{ W m}^{-2}$ for the ERA-40
as reported by Serreze et al. (2007), but $10 \text{ W m}^{-2}$ for Nakamura and Oort (1988). In general the
reanalyses are more similar to each other than to the earlier Nakamura and Oort time series.

For the south polar cap, the total energy tendency in MERRA ranges from a minimum of
$-16 \text{ W m}^{-2}$ in April to $30 \text{ W m}^{-2}$ in November. As seen in Fig. 3b, the annual cycle is less
sinusoidal than in the Northern Hemisphere, with the November peak offsetting an average
negative tendency that extends from January through July. The RMS difference with monthly
values reported by Nakamura and Oort (1988) as compared to MERRA is $13 \text{ W m}^{-2}$, although
each month is within the standard deviation of MERRA for the 1979-2005 period. As seen in
equation (4), the MERRA energy tendency incorporates the cloud ice latent heating and kinetic energy terms which are not considered in other studies. For monthly means over the regions examined, however, these terms are negligible.

c. Energy convergence and transport

As seen in equation (3), the divergence term is composed of contributions from latent heat, virtual enthalpy, kinetic, and geopotential energy terms. For the north polar cap, the annual cycle of energy convergence from MERRA consists of values greater than 100 W m⁻² during winter months September through March and a minimum of 72 W m⁻² in May, as seen in Fig. 3a. Porter et al. (2010) present annual cycles of energy convergence computed as a residual using several combinations of reanalyses and radiative flux data sets for the period 2000-2005, while Serreze et al. (2007) present ERA-40 and NCEP/NCAR reanalysis average monthly values for the period 1979-2001. While there is agreement in larger energy convergence in winter, there is considerable variability among the data sets on the months of the minimum and maximum value, with May providing a spread of 40 W m⁻² among the various methods. MERRA values concurrent with these previous studies are found within this large range.

Figure 4a indicates that the average poleward energy transport across 70°N is zonally asymmetric and is focused at preferred longitudes which are associated with the mean longwave circulation patterns in the middle troposphere (Serreze et al., 2007). In comparison to energy transports across 70°N from ERA-40 as reported by Serreze et al. (2007), MERRA transports shown in Fig. 4a are comparable but with some differences. First, the poleward (positive) flux centered near 315°E (45°W) has a smaller zonal extent than is shown in Serreze et al. (2007). This may be due to the higher spatial resolution of MERRA and the role of the Greenland Ice
Sheet topography in defining the mid-tropospheric trough pattern over eastern North America. Second, the wintertime poleward transport near 150°E is shown in MERRA to be greater than $20 \times 10^9$ W m$^{-1}$. This is stronger by one contour level ($5 \times 10^9$ W m$^{-1}$) than that shown by Serreze et al. for ERA-40. But in general the average meridional transport patterns of MERRA and ERA-40 are remarkably similar.

In the Southern Hemisphere, prior studies on atmospheric energy convergence are not as recent. However comparisons to MERRA may be made using Nakamura and Oort (1988) and Genthon and Krinner (1998). Using GCM output, Nakamura and Oort (1988) estimated a mean annual energy convergence across 70°S of 95 W m$^{-2}$, which is 23 W m$^{-2}$ less than shown for MERRA in Table 1. As seen in Fig. 3b, the annual cycle in MERRA contains a broad maximum over winter months and a short period of minimum of values less than 100 W m$^{-2}$ in December, January, and February. In contrast Nakamura and Oort (1988) indicate lower amounts in the autumn, and their annual cycle is generally more sinusoidal. Nakamura and Oort (1988) and MERRA monthly energy convergence values are comparable over the months June to October but MERRA is larger by 45 W m$^{-2}$ in January. More recently, Genthon and Krinner (1998) produced seasonal averages and zonal distributions of energy transport using ERA-15 for the period 1979-1993. The annual atmospheric energy convergence derived from ERA-15 of 81 W m$^{-2}$ is considerably smaller than corresponding values of either MERRA or Nakamura and Oort (1988). Seasonally, the largest differences between MERRA and Genthon and Krinner (1998) ERA-15 values are in autumn. Energy convergence for the south polar cap for March-April-May averages 134 W m$^{-2}$ in MERRA, while Genthon and Krinner (1998) reported 79 W m$^{-2}$. The spatial distribution of energy transports along the 70°S parallel is strongly dependent on the meandering coastline, such that spatial resolution and topography are
significant. Thus the differences between MERRA and ERA-15, though large, may partially result from differing model grids. Additionally, ERA-15 was known to employ a defective orography over the ice sheet (Uppala et al., 2005). A visual inspection of Genthon and Krinner (1998) results indicates that the ERA-15 mean annual poleward transport is less than MERRA near 30°E, an intersection point between the 70°S parallel and the East Antarctic coastal escarpment. For this location, Genthon and Krinner (1998) plot amounts of between 2 and $3 \times 10^8 \text{ W m}^{-1}$ while MERRA values are greater than $5 \times 10^9 \text{ W m}^{-1}$. Additionally Genthon and Krinner (1998) indicate an annual mean equatorward energy transport in the Ross Sea, while MERRA indicates an average poleward flux. MERRA and ERA-15 share some general characteristics of the meridional energy transport including a directional change with season in the South Pacific region between 180°E and 270°E from poleward during winter months to equatorward in summer, as shown in Fig. 4b. The figure also shows an opposing seasonal reversal between 270°E and 300°E in MERRA, and this is also reflected in Genthon and Krinner (1998).

\[d. \text{ TOA radiative fluxes}\]

For the north polar cap, MERRA TOA radiative fluxes are compared to ERBE (Serreze et al., 2007) and CERES (Porter et al., 2010). With the exception of midsummer months, the Arctic TOA radiative flux in MERRA is mainly directed upwards ($R_{top} < 0$), with an annual average shown in Table 1 of $-110 \text{ W m}^{-2}$. Annual estimates from ERBE and CERES are within the standard deviation of this value. On the monthly time scale, the largest differences are for the month of May, where the MERRA 1979-2005 value of $-23 \text{ W m}^{-2}$ compares with $-53 \text{ W m}^{-2}$ in ERBE (Serreze et al., 2007) and $-37 \text{ W m}^{-2}$ in CERES (Porter et al., 2010). Using MERRA
averages concurrent with these satellite records, MERRA is less than satellite estimates for May by 29 W m$^{-2}$ as compared to ERBE and by 12 W m$^{-2}$ as compared to CERES. In July, CERES indicates a net downwards TOA flux of 21 W m$^{-2}$ compared to a 1 W m$^{-2}$ upwards flux in MERRA, while ERBE and MERRA concurrent July values are equal. For other months, the differences are small.

Table 2 also presents $R_{top}$ values for MERRA in comparison to contemporary reanalyses of the ERA-I and CFSR for the period 1989-2005. As seen in Table 2 for the north polar cap, the MERRA annual net TOA radiative flux is greater than for the other two reanalyses by 4 W m$^{-2}$. Again, the largest differences are for the spring time period. For the month of May, $R_{top}$ for the ERA-I averages $-34$ W m$^{-2}$ while the CFSR value is $-36$ W m$^{-2}$, and MERRA again averages $-23$ W m$^{-2}$ for 1989-2005. Most of this difference is associated with the upwelling shortwave flux. For the month of May, the MERRA TOA upwelling shortwave flux is less than CFSR and ERA-I by 15 W m$^{-2}$ and 18 W m$^{-2}$, respectively. It is noted that CFSR incorporates an 11-year solar cycle while MERRA and ERA-I use climatological solar forcing, and that ERA-I uses a larger solar constant value than MERRA. For the north polar cap, differences in incoming solar radiation between MERRA and CFSR are as large as $\pm 3$ W m$^{-2}$ for a given month, but average less than 1 W m$^{-2}$. Differences between ERA-I and MERRA are as large as 9 W m$^{-2}$ for a given month, and average 3 W m$^{-2}$.

For the south polar cap, the TOA net radiative flux remains negative throughout the year. Comparisons to both ERBE data and the values from Nakamura and Oort (1988) indicate that the annual net TOA radiative flux magnitude in MERRA is too large, and that the discrepancy is largest during winter months. The 1979-2005 average net flux as shown in Table 1 for MERRA is $-101$ W m$^{-2}$. This compares with $-90$ W m$^{-2}$ from the historical satellite data used in
Nakamura and Oort (1988), and $-95 \text{ W m}^{-2}$ from ERBE for the period February 1985 to April 1989 (Briegleb and Bromwich, 1998). The 1979-2005 annual average for $R_{\text{top}}$ is by chance equal to the 1985-1989 time period for MERRA. In the annual cycle, the differences with satellite observations are associated with the winter season. For the months of June, July, and August, the average flux from Nakamura and Oort (1988) is $-131 \text{ W m}^{-2}$, and from ERBE, $-134 \text{ W m}^{-2}$. For MERRA, the corresponding value is $-142 \text{ W m}^{-2}$ for both 1979-2005 and 1985-1989 time periods. In these winter months, the difference between MERRA and satellite values is almost entirely composed of the outgoing longwave component.

Values for the south polar cap from ERA-I and CFSR reanalyses tend to agree more closely with MERRA than with values from satellite data sets. For the 1989-2005 period, the net TOA radiative flux shown in Table 2 averages $-101 \text{ W m}^{-2}$ for MERRA, $-109 \text{ W m}^{-2}$ for CFSR, and $-102 \text{ W m}^{-2}$ for ERA-I. In the annual cycle, the MERRA upwelling longwave flux is less than the other two reanalyses by 3 W m$^{-2}$ in spring and up to 7 W m$^{-2}$ in autumn. The CFSR upwelling shortwave flux is greater than the other two reanalyses by more than 10 W m$^{-2}$ in December and January, and the ERA-I solar constant difference with the other two reanalyses accounts for 3 W m$^{-2}$ on the annual average.

The time series of MERRA TOA radiative fluxes indicate potentially spurious trends in both polar regions. Over north and south polar caps, year to year variability in $R_{\text{top}}$ resembles that of the energy budget analysis increments. For the north polar cap, a maximum for $R_{\text{top}}$ is reached in 1993 with $-107 \text{ W m}^{-2}$, with values as low as $-112 \text{ W m}^{-2}$ occurring in 1981 and 2005. MERRA TOA fluxes for the south polar cap have an irregular time series with a range between minimum and maximum values of 4 W m$^{-2}$. Over the Southern Ocean domain, a sharp change is noted after 1998. This is likely due to the introduction of AMSU data to the observing system as
noted earlier. Annual average values prior to 1998 are consistent with an average of $-81 \text{ W m}^{-2}$.

For the period 1999-2005 the MERRA average for the Southern Ocean is $-86 \text{ W m}^{-2}$.

e. Surface fluxes

Figure 5 shows the annual average surface net heat flux from MERRA for both polar regions. In the Northern Hemisphere, small negative values of between 0 and $-5 \text{ W m}^{-2}$ are found in a uniform field over nonglaciated land surfaces, which is consistent with subsurface warming in recent years (Serreze et al., 2007). Over the central Arctic Ocean, MERRA net surface flux values are positive as expected but are exceptionally large. Values greater than $15 \text{ W m}^{-2}$ are found in the central Arctic, and greater than $20 \text{ W m}^{-2}$ in the approaches to the North Atlantic. These annual values are extraordinary and likely not realistic. A comparison of the averaged annual time series of monthly values with previous studies indicates largest discrepancies occurring in summer months. The July 1979-2005 net surface flux for MERRA is $-68 \text{ W m}^{-2}$ for the north polar cap as shown in Table 1. This compares with $-85 \text{ W m}^{-2}$ for ERA-40 (Serreze et al., 2007) and $-86 \text{ W m}^{-2}$ for JRA-25 (Porter et al., 2010). Similar differences are found between MERRA and contemporary reanalyses as shown in Table 2. For the concurrent 1989-2005 averaging period, the July net surface flux for the north polar cap is $-87 \text{ W m}^{-2}$ for the CFSR and $-78 \text{ W m}^{-2}$ for ERA-I.

Discrepancies in the surface flux fields are evaluated using observations from the Surface Heat Budget of the Arctic ice camp field study in the Beaufort Sea in October 1997 to October 1998 (SHEBA; Uttal et al., 2002). MERRA surface flux values are compared with a compilation of observed SHEBA radiative and turbulent flux measurements by Duynkerke and de Roode (2001). Comparisons are made using the nearest MERRA grid point to the reported hourly drift.
camp position. For this data source, SHEBA latent heat flux observations were limited and are not considered. Using the remaining energy budget components, a net flux comparison indicates a positive (upward) bias in MERRA of 18 W m\(^{-2}\) for the months October to April, -1 W m\(^{-2}\) for May, and small positive biases for the following summer months.

There are three fundamental results of the comparison. As shown in Fig. 6, substantial differences in the upwelling shortwave radiative flux result from an overly simplistic representation of sea ice properties. Sea ice albedo is set to a fixed value of 0.60 for MERRA. The surface observed using SHEBA tower measurements has a much higher albedo in springtime, with monthly averages of 0.83 in March, April, and May, and 0.74 in June. Apart from the tower flux measurements, a line of surface albedo observations made during SHEBA provide a range of values that are dependent on the surface ice conditions. The average of these surface observations is shown in Fig. 6 for June to September 1998. Albedos from tower measurements in May 1998 are consistent with area-averaged surface and aircraft observations.

For example, Curry et al. (2001) note that albedo for April and May at the SHEBA site averaged 0.84, that the melt season lasted from late May to mid August, and that winter-spring albedo values were again reached in late September. This difference with observed albedo contributes to an underestimate in the upwelling shortwave flux in MERRA of 55 W m\(^{-2}\) in April, 80 W m\(^{-2}\) in May, and 56 W m\(^{-2}\) in June. In late summer, the observed surface albedo is degraded by melting and becomes comparable to the MERRA value. In late autumn, freezing and the introduction of solid precipitation again produces surface albedo differences between MERRA and observation, however the incoming solar flux is reduced and the impact on the upwelling shortwave is less consequential. The difference with observation in the upwelling shortwave radiative flux for May is the largest of any monthly budget component.
The second result is a response in other MERRA surface energy budget terms in May to the albedo bias. Surface temperatures over ice in MERRA are determined via energy balance, and the underestimate of the surface albedo results in a perceived increased absorption of solar energy and a surface warming. This likely results in the springtime MERRA sensible heat flux bias, which is found to be 16 W m\(^{-2}\) in May. Other than the April, May, and June period, the MERRA sensible heat flux difference with SHEBA observations is only 2 W m\(^{-2}\). An intriguing finding is a springtime negative bias with SHEBA observations in the downwelling shortwave radiative flux. The MERRA downwelling shortwave is underestimated by 36 W m\(^{-2}\) in April, 37 W m\(^{-2}\) in May and 25 W m\(^{-2}\) in June. In other months this difference is about 1 W m\(^{-2}\). This bias is likely associated with general deficiencies in the representation of cloud properties. From the seasonal timing of the bias, however, it is speculated that a portion of the amount is due to a redistribution of cloudiness in the atmospheric column resulting from anomalous surface warming. The large May bias in upwelling shortwave radiation is then compensated for by biases in other fluxes to produce the surface net energy flux bias of \(-1\) W m\(^{-2}\).

Shown in Fig. 7 is the time series of hourly near-surface air temperature in comparison to the observed time series from SHEBA for the period 1 February to 30 June, 1998. A temperature bias in spring is readily apparent, with a difference of greater than 3.5°C in April and May before the freezing value is reached in early June. In particular, the period 19 April to 10 May shows an average bias of 6.1°C in MERRA. For daily averages, however, there is a good correlation between MERRA and observation for the period shown (\(r = 0.95\)). It may be seen in the time series of hourly values shown Fig. 7 that the diurnal cycle in MERRA temperature has an amplitude between 2 and 10°C, which begins abruptly on 28 March and continues unabated until the freezing point is reached in June. The observed SHEBA diurnal cycle has a similar
amplitude, however the cycle is not as regular as in MERRA and there are periods of considerable interruption, perhaps due to synoptic variability. These differences are suggestive of difficulties in MERRA boundary layer parameterizations. Springtime air temperature biases are found at Arctic station locations as well. For example, a comparison with Sachs Harbor (72°N, 125°W) over the period 1979-2005 indicates an average of 4.9°C difference for April but only 1.9°C for the months August through March. A comparison with Barrow (71°N, 157°W) similarly indicates an average bias in MERRA of 3.6°C for the spring months of March, April, and May and 0.9°C for other months. But as shown in Fig. 8, MERRA performs well in a comparison of monthly anomalies. The correlation between temperature anomalies at Barrow and Jan Mayan (71°N, 9°W) is 0.99 for both stations. The time series shown in Fig. 8 contain observations that cover the entire time period. Other stations in the Arctic with shorter and/or interrupted records compare similarly well.

The third result from the comparison with SHEBA is a negative bias in the downwelling longwave radiative flux throughout the year of 12 W m⁻². This quantity leads to the overall positive bias in the net surface flux for summer, autumn, and winter months. As with the springtime downwelling shortwave radiative flux bias, an inadequate representation of cloud properties is implied. To evaluate this further, comparisons were made between MERRA and SHEBA hourly microwave radiometer retrievals over the period 5 December 1997 to 9 September 1998. More than 5000 observations were made over the period. Retrievals of precipitable water compare remarkably well to MERRA values as seen in Fig. 9a, although differences are apparent for small quantities in winter. For monthly intervals, the correlation between MERRA and the hourly microwave radiometer precipitable water retrievals ranges from \( r = 0.87 \) in December 1997 to \( r = 0.96 \) in May 1998. A consistent bias of 0.6 mm in monthly
averages is found, which amounts to 31 percent of the observed average for January but only
3 percent for July. In contrast, the comparison to retrieved liquid water content shown in Fig. 9b
is less favorable. Cloud liquid water from the SHEBA microwave radiometer ranges from an
average of 0.017 mm in January 1997 to 0.106 mm in August 1998. Typical MERRA values are
about 45 percent of the microwave radiometer amounts. Although large discrepancies have been
noted between the SHEBA microwave radiometer values for liquid water path and simultaneous
aircraft measurements (Lin et al., 2001), the differences between MERRA and SHEBA values
exceed 50 percent. Additionally, the correlations of hourly liquid water path values with
MERRA over monthly time intervals are low and range from $r = 0.14$ in April 1998 to $r = 0.55$ in
January 1998. The presence or absence of cloud liquid water significantly alters the downwelling
longwave radiative flux. An underestimate of cloud liquid water in MERRA is qualitatively
consistent with differences in the surface net flux with observation.

Comparisons with MERRA for the Arctic are also conducted using the CFSR and ERA-I
reanalyses. Using monthly values co-located with the SHEBA ice drift camp, it is noted that
surface albedo varies seasonally and interannually in both CFSR and ERA-I. In agreement with
the SHEBA time series, both CFSR and ERA-I have albedos greater than 0.8 for April 1998, and
values decrease with the onset of the summer melt season. This decrease occurs more rapidly in
both CFSR and ERA-I than for tower observations, but is within the lower range given by
SHEBA line albedo measurements. The June 1998 albedo is 0.59 for MERRA, 0.65 for CFSR,
0.69 for ERA-I, 0.74 for the SHEBA tower observation, and 0.62 for the line observation. All
three reanalyses underestimate the downwelling longwave radiative flux over winter months in
comparison to SHEBA. For the period October 1997 to May 1998, this flux is underestimated by
5 W m$^{-2}$ in ERA-I and 18 W m$^{-2}$ in CFSR. Finally, the November 1997 to March 1998 average
sensible heat flux observed at SHEBA is less than 1 W m$^{-2}$. This compares with 3 W m$^{-2}$ in MERRA, −7 W m$^{-2}$ in ERA-I, and −21 W m$^{-2}$ in CFSR.

Turning to the Southern Hemisphere, the annual average net surface heat flux for the south polar cap is shown in Fig. 5b. Of immediate concern is the anomalous non-zero field over Antarctica, which is shared by the major ice sheets in both polar regions. Over grounded ice, the MERRA subsurface energy flux is determined in the GEOS-5 model by the prognostic temperature for a 7 cm (water-equivalent) surface ice layer and a “deep” layer temperature at 2 m depth that is fixed at 230°K. Thus, the location of the zero value contour in Fig. 5b exactly matches the annual-average 230°K surface temperature isotherm. Observations from automatic weather stations indicate that annual mean subsurface conductive heat fluxes are not significant (e.g., Reijmer and Oerlemans, 2002), and annual surface energy flux patterns in MERRA over Antarctica (as well as Greenland) are erroneous.

The pattern in the MERRA annual surface net energy flux in Antarctica is manifest as a complementary distribution of downward (negative) turbulent and upward (positive) radiative fluxes that are not balanced. MERRA annual mean latent heating exceeds 5 W m$^{-2}$ only along the East Antarctic coast in selected locations, and averages less than 1 W m$^{-2}$ for the total grounded ice sheet area. The annual averaged sensible heat flux over the ice sheet is uniformly negative and is approximately contour-parallel with topography, with magnitudes greater than (−)60 W m$^{-2}$ along the East Antarctic coastal escarpment decreasing to less than (−)10 W m$^{-2}$ over the central plateau. The annual mean net radiative flux field in MERRA is spatially more uniform with values ranging from (+)25 to 35 W m$^{-2}$ for East Antarctica, and smaller positive values over West Antarctica. This results in the imbalances in the net surface heat flux as shown. Over the interior plateau, net flux values are as large as +15 W m$^{-2}$ while the net amounts at
lower elevations are negative and are less than $-30 \text{ W m}^{-2}$ over the East Antarctic coastal escarpment. These errors in the net surface flux have relation to near-surface temperature biases. As shown in Fig. 10, there is a considerable wintertime warm bias of 5°C at Amundsen-Scott (90°S), while a summer cold bias of 5°C is found at Scott Base (78°S, 167°E). Visual comparison with satellite-derived surface air temperatures in Comiso (2000) indicates that a summer cold bias extends over the embayment regions.

Comparisons of surface energy budget components are made with Antarctic station values compiled by King and Turner (1997). Values compiled by King and Turner (1997) reflect studies of opportunity and do not account for interannual variability. For the sensible heat flux, MERRA averages at Mizuho (71°S, 44°E) of $-47 \text{ W m}^{-2}$ in July and $-19 \text{ W m}^{-2}$ in December compare with observational values of $-37$ and $-25 \text{ W m}^{-2}$ for July and December, respectively (Ohata et al., 1985). At South Pole, differences in seasonal values of the sensible heat flux are largest in spring and summer. The December-January-February sensible flux average from MERRA is $-3 \text{ W m}^{-2}$ and $-22 \text{ W m}^{-2}$ in observation (Carroll, 1982). This contributes to a difference of 9 W m$^{-2}$ in the annual average.

Differences between MERRA and available observations are also associated with the net radiative flux. At Halley (76°S, 26°W), the annual average net radiative flux for MERRA of 13 W m$^{-2}$ approximates the observational values of 9.8 W m$^{-2}$, however seasonal differences are as large as 10 W m$^{-2}$ in winter. At South Pole, the annual net radiative flux of 19 W m$^{-2}$ matches the observation of Carroll (1982), however seasonal differences are large. In winter, the net radiative surface cooling of 36 W m$^{-2}$ exceeds the observed value of 21 W m$^{-2}$. In summer, the MERRA radiative flux value of $-7 \text{ W m}^{-2}$ differs from the Carroll (1982) value of $+18 \text{ W m}^{-2}$.
The surface radiative flux differences at South Pole are further examined using the observations of Dutton et al. (1989), who recorded daily mean radiative flux components from April 1986 until February 1988. Over this period, the surface net radiative flux for both MERRA and observation is positive for most of the year but becomes negative in summer months as seen in Fig. 11. Over the 22 month period, the downwelling longwave radiative flux is consistently less than observation by an average 24 W m\(^{-2}\). This difference is apparent in the comparison of daily values in Fig. 11. Large biases are also found in the MERRA net shortwave radiative flux in spring and summer. For the month of January, the net downward shortwave flux is overestimated by 20 W m\(^{-2}\) in 1987, and by 23 W m\(^{-2}\) in 1988. A minor part of the shortwave bias is associated with the MERRA surface albedo, which is fixed over land ice at 0.775. Observed monthly averages at South Pole indicate an albedo of between 0.80 and 0.89. These differences in the shortwave flux partially cancel the downwelling longwave underestimate in summer. It may be seen from Fig. 11 that some of the day-to-day variability in the downwelling longwave radiative flux is reproduced in MERRA. By subtracting a 30-day running mean from each time series to remove the annual cycle, the two curves have a correlation of 0.70.

Table 2 presents a comparison of net surface flux values for the south polar cap. Both the ERA-I and the CFSR correctly depict a near-zero annual net flux field over the Antarctic ice sheet, while regions of opposite sign in MERRA \(F_{\text{sf}}\) fortuitously cancel. Monthly values of surface radiative flux components from CFSR and ERA-I are compared to 1986-1988 values from Dutton et al. (1989) for the South Pole. The ERA-I collection begins in 1989, so 1989-2005 averages were used. In general, the monthly net surface radiative fluxes of the three reanalyses are more similar to each other than to observation. The net upward radiative flux is overestimated by 18 W m\(^{-2}\) for MERRA, 16 W m\(^{-2}\) for ERA-I, and 20 W m\(^{-2}\) for CFSR. Similar
to MERRA, a large part of the ERA-I difference is due to an underestimate of the downwelling longwave component. For the annual average, the ERA-I downwelling longwave flux is underestimated by 15 W m$^{-2}$. For the CFSR, the upwelling longwave flux is overestimated for winter months March to September by 21 W m$^{-2}$, and this provides a significant contribution to annual net flux differences. Both ERA-I and CFSR have variable surface albedos at South Pole, however the ERA-I value approximates the MERRA fixed value, while the CFSR value averages 0.84 during summer months.

The spatial patterns of Fig. 5b are of interest over the Southern Ocean. In the annual mean, MERRA indicates a net loss of energy from the ocean to the atmosphere south of 60°S which increases in magnitude near the continent. Farther north there is a marked asymmetry within the 50°S-60°S zone, with net energy loss from the ocean to the atmosphere in the Pacific sector and energy gains elsewhere. Embedded within the Pacific sector are two regions of net energy gain from the atmosphere to the ocean which correspond to meanderings of the Antarctic Polar Front— as it crosses the Southeast Indian Ridge near 145°E, and the Pacific-Antarctic Ridge near 145°W (e.g., Moore et al., 1999). Josey (2009) noted the zonal asymmetry in the net surface heat flux in NCEP and ECMWF reanalyses but found that coupled models produce a more zonally uniform field. Josey (2009) concluded that the sign of annual mean surface heat exchange over much of the region is not known. The net surface flux from ERA-I and CFSR reanalyses in Southern high latitudes differ with MERRA. The coastal zone of heat loss from the ocean to the atmosphere in both the ERA-I and CFSR is more closely confined near the continent than in MERRA. Similar to MERRA, the ERA-I indicates an annual mean net positive energy flux from the ocean to the atmosphere in the Pacific Ocean sector of the 50°S-60°S zone, while
the CFSR indicates negative values between 0 and −15 W m$^{-2}$ that are smaller in magnitude than for the rest of the zone.

The annual cycle of the net surface flux for the Southern Ocean is shown in Fig. 3c. Using ECMWF operational analyses overlapping the period of the ERBE study, Okada and Yamanouchi (2002) examined the atmospheric energy budget for the region bounded by 60°S and 70°S. Okada and Yamanouchi estimated the surface energy budget as the residual using TOA ERBE radiation and analyses divergence terms. A seasonal asymmetry in the net surface flux was highlighted, which was found to abruptly peak in May with a maximum value of 116 W m$^{-2}$. Okada and Yamanouchi (2002) attributed this asymmetry to the latent heat release resulting from sea ice formation. As seen in Fig. 3c, the MERRA surface energy flux over the Southern Ocean sea ice domain is also asymmetric and peaks in May at 98 W m$^{-2}$, however the maximum is not as striking as was found for the ECMWF analyses. In examining the autumnal surface turbulent fluxes in MERRA, it is found that the total latent heat flux is a maximum for the domain in April with 33 W m$^{-2}$. The latent heat flux then diminished over ice covered winter months, with a second maxima in November of 28 W m$^{-2}$. The MERRA sensible heat flux reaches its annual maximum in May of 21 W m$^{-2}$ and generally reflects the shape of surface net flux. The asymmetry in the annual cycle for the MERRA net surface flux as shown in Fig. 3c is principally due to seasonal changes in the sensible heat flux. In reanalyses, sea ice cover is prescribed from observational fields. The latent heat flux arising from ice formation is manifest as the net conductive flux at the atmosphere-ice interface. In this context, MERRA and the results of Okada and Yamanouchi (2002) are broadly consistent.
4. Summary and Discussion

MERRA reproduces the basic patterns of energy flow in the polar atmosphere as they are known. As shown in Fig. 3, the polar regions are marked by a convergence of energy from lower latitudes for all months, and a loss of energy at the top of the atmosphere for the most of the year. In the Arctic, reductions in the TOA shortwave radiative flux in autumn produce a negative tendency in the atmospheric column total energy throughout the period August through January, which is moderated by contributions from the net surface flux and increased energy transport from lower latitudes in winter (Serreze et al., 2007). In the Antarctic, this seasonal progression is less sinusoidal, with the net TOA radiative flux remaining negative throughout the year, and an extended winter period in the energy budget components extending from April to September.

Despite reproducing these essential components, MERRA energy budgets for the Arctic and Antarctic contain substantial errors owing to overly simplistic physical parameterizations, including sea ice albedo, the surface heat budget over permanent land ice, and cloud radiative properties. Difficulties in MERRA with sea ice characteristics are not dissimilar from those described in Bretherton et al. (2000) for ECMWF analyses produced during SHEBA, and indeed the discrepancies in surface shortwave radiative fluxes are similar. Spring is a critical period for evaluation of surface flux fields in the Arctic, and differences between MERRA shortwave surface radiative fluxes with observation are most prominent in May. Over the data sparse Southern Ocean, discontinuities in the time series of TOA radiative fluxes coincide with the introduction of AMSU satellite data in November 1998 and are therefore spurious. Elsewhere, interannual variability of the analysis increments term $\Delta N_A(E)$ is large but not as easily linked to changes in the observing system. Additional characterization of analysis increments, including
their vertical distribution, and MERRA cloud properties are conspicuous points for further evaluation.

MERRA nevertheless compares favorably to previous studies of energy budget components produced from state and dynamical variables. These vertical integrals are pre-computed quantities in MERRA, and are not readily available from contemporary reanalyses.

Atmospheric energy convergence and the spatial distribution of transport along the 70° parallel compare closely with previous studies in the Northern Hemisphere, while estimates for the south polar cap are qualitatively similar but may also been seen as an update to studies based on earlier analyses. The total atmospheric energy tendency in polar regions also compares favorably to previous studies.

Credible estimates of the atmospheric energy budget in polar regions continue to be a significant challenge due to changes in the observing system and complex energy feedback mechanisms that are associated with the high latitudes. Evaluation using both representative point location observations and previous area-averaged estimates such as those used in this study are valuable for providing a straightforward appraisal of new reanalyses. The MERRA system is an important product due to its alternative construction, including a non-spectral background model and its emphasis on NASA satellite products. An important concept used in MERRA is the employment of analysis increments for identifying differences between observations and the background analysis system. Inconsistencies in atmospheric budgets are quantified in the analysis increments, which is one means of measuring uncertainty. ERA-I and CFSR reanalyses are found to utilize seasonal variations in sea ice albedo and have realistic annual mean surface heat fluxes over ice sheets. However these collections are also found to have significant discrepancies with observed surface and TOA energy fluxes. In particular, sensible heat fluxes
from CFSR are large in comparison to SHEBA observations, while all three reanalyses overestimate the annual surface net radiative flux at South Pole by 16 to 20 W m\(^{-2}\). These disagreements underscore the challenge of the high latitude energy budget problem.

A general criticism of reanalyses is that they are produced with the intent of providing the best representation of conditions for a given time without consideration for the impact of heterogeneous observations on temporal variability (Thorne and Vose, 2010). This intent nevertheless has practical, scientific application. Additionally, reanalyses may be seen as part of a spectrum of products for climate study ranging from heterogeneous observations to model simulations, which include AMIP fields and sparse data reanalyses (e.g., Compo et al., 2006). As part of that continuum, the analysis increments in MERRA provides a quantification of differences between observations and the background system. Changes in the spatial and temporal variability of the analysis increments imply changes to the observing system, which should be carefully treated in evaluating time series. MERRA is a valuable record for examining the polar atmosphere when these cautions are exercised.

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collection was obtained from the National Climate Data Center. This study was funded by grants from the NASA Modeling Analysis and Prediction Program (MAP) and the NASA Energy and Water cycle Study (NEWS) to the second author.

APPENDIX

Representation of the Atmospheric Energy Budget Using MERRA Variables

The following MERRA variables are given as follows.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>DQVDT_DYN</td>
<td>Vertically integrated water vapor tendency for dynamics</td>
<td>kg m(^{-2}) s(^{-1})</td>
</tr>
<tr>
<td>DQVDT_PHY</td>
<td>Vertically integrated water vapor tendency for physics</td>
<td>kg m(^{-2}) s(^{-1})</td>
</tr>
<tr>
<td>DQVDT_ANA</td>
<td>Vertically integrated water vapor tendency for analysis</td>
<td>kg m(^{-2}) s(^{-1})</td>
</tr>
<tr>
<td>DQIDT_DYN</td>
<td>Vertically integrated ice water tendency for dynamics</td>
<td>kg m(^{-2}) s(^{-1})</td>
</tr>
<tr>
<td>DQIDT_PHY</td>
<td>Vertically integrated ice water tendency for physics</td>
<td>kg m(^{-2}) s(^{-1})</td>
</tr>
<tr>
<td>DQIDT_ANA</td>
<td>Vertically integrated ice water tendency for analysis</td>
<td>kg m(^{-2}) s(^{-1})</td>
</tr>
<tr>
<td>DQVDT_CHM</td>
<td>Artificial “filling” of water vapor</td>
<td>kg m(^{-2}) s(^{-1})</td>
</tr>
<tr>
<td>DQVDT_FIL</td>
<td>Artificial “filling” of frozen water</td>
<td>kg m(^{-2}) s(^{-1})</td>
</tr>
<tr>
<td>DKDT_DYN</td>
<td>Vertically integrated kinetic energy tendency for dynamics</td>
<td>W m(^{-2})</td>
</tr>
<tr>
<td>DKDT_PHY</td>
<td>Vertically integrated kinetic energy tendency for physics</td>
<td>W m(^{-2})</td>
</tr>
<tr>
<td>DKDT_ANA</td>
<td>Vertically integrated kinetic energy tendency for analysis</td>
<td>W m(^{-2})</td>
</tr>
<tr>
<td>DHDT_DYN</td>
<td>Vertically integrated (c_pT_v) tendency for dynamics</td>
<td>W m(^{-2})</td>
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<tr>
<td>DHDT_PHY</td>
<td>Vertically integrated (c_pT_v) tendency for physics</td>
<td>W m(^{-2})</td>
</tr>
<tr>
<td>DHDT_ANA</td>
<td>Vertically integrated (c_pT_v) tendency for analysis</td>
<td>W m(^{-2})</td>
</tr>
<tr>
<td>DPDT_DYN</td>
<td>Potential energy tendency for dynamics</td>
<td>W m(^{-2})</td>
</tr>
<tr>
<td>DPDT_PHY</td>
<td>Potential energy tendency for physics</td>
<td>W m(^{-2})</td>
</tr>
<tr>
<td>DPDT_ANA</td>
<td>Potential energy tendency for analysis</td>
<td>W m(^{-2})</td>
</tr>
<tr>
<td>CONVKE</td>
<td>Vertically integrated convergence of kinetic energy</td>
<td>W m(^{-2})</td>
</tr>
<tr>
<td>CONVCPT</td>
<td>Vertically integrated convergence of virtual enthalpy</td>
<td>W m(^{-2})</td>
</tr>
<tr>
<td>CONVPHI</td>
<td>Vertically integrated convergence of geopotential</td>
<td>W m(^{-2})</td>
</tr>
<tr>
<td>SWTNT</td>
<td>TOA outgoing shortwave flux</td>
<td>W m(^{-2})</td>
</tr>
<tr>
<td>SWGNT</td>
<td>Surface net downward shortwave flux</td>
<td>W m(^{-2})</td>
</tr>
<tr>
<td>LWTUP</td>
<td>Upward TOA longwave flux</td>
<td>W m(^{-2})</td>
</tr>
<tr>
<td>LWGNT</td>
<td>Net downward longwave flux at the surface</td>
<td>W m(^{-2})</td>
</tr>
<tr>
<td>EFLUX</td>
<td>Latent heat flux (positive upward)</td>
<td>W m(^{-2})</td>
</tr>
<tr>
<td>HFLUX</td>
<td>Sensible heat flux (positive upward)</td>
<td>W m(^{-2})</td>
</tr>
<tr>
<td>PRECSN</td>
<td>Frozen precipitation at the surface</td>
<td>kg m(^{-2}) s(^{-1})</td>
</tr>
</tbody>
</table>
A tendency may be expressed as the sum of dynamics, physics, and analysis variables. For example, the tendency of vertically integrated water vapor (precipitable water) is expressed using MERRA variables as follows.

\[ \frac{\partial W_{(v)}}{\partial t} := DQVDT\_DYN + DQVDT\_PHY + DQVDT\_ANA \]  

Equation (2) is represented as follows.

\[ \frac{\partial A_E}{\partial t} := L_v \cdot (DQVDT\_DYN + DQVDT\_PHY + DQVDT\_ANA) \\
+ L_f \cdot (DQIDT\_DYN + DQIDT\_PHY + DQIDT\_ANA) \\
+ DHDT\_DYN + DHDT\_PHY + DHDT\_ANA \\
+ DPDT\_DYN + DPDT\_PHY + DPDT\_ANA \\
+ DKDT\_DYN + DKDT\_PHY + DKDT\_ANA \]  

Equation (3) is represented as:

\[ \nabla \cdot \overline{\bar{F}_A} := -(L_v \cdot DQVDT\_DYN - L_f \cdot DQIDT\_DYN) \\
+ CONVKE + CONVCPT + CONVPHI \]  

Equations (4) and (5) are represented as follows.

\[ R_{top} + F_{sfc} := (SWTNT - LWTUP) \cdot (SWGNT + LWGNT) \\
+ EFLUX + HFLUX + L_f \cdot PRECSN \]  

The contribution of spurious residuals in the energy term is represented as:

\[ Q_{NUM} := i \cdot DKDT\_DYN + CONVKE + CONVPHI \\
+ DKDT\_GEN \cdot DPDT\_DYN \cdot TEFIXER \]  

The remainder of equation (1) is given as follows.

\[ L_v \frac{\partial W_v}{\partial t} \bigg|_{CHM} + \left[ L_v \frac{\partial W_v}{\partial t} - L_f \frac{\partial W_i}{\partial t} \right]_{FIL} + A_{\overline{\overline{E}}} := \\
L_v \cdot DQVDT\_CHM + (L_v \cdot DQVDT\_FIL - L_f \cdot DQIDT\_FIL) \\
+ (L_v \cdot DQVDT\_ANA \cdot L_f \cdot DQIDT\_ANA + DHDT\_ANA \\
+ DKDT\_ANA + DPDT\_ANA) \]


Table 1. Components of the MERRA atmospheric energy budget for regions defined in Fig. 1, in W m\(^{-2}\). The surface flux \(F_{sfc}\) discounts latent heating from solid precipitation. The standard deviation over the 1979-2005 time period is indicated in parentheses.

Table 2. MERRA, CFSR, and ERA-I 1989-2005 average TOA and surface energy flux values for regions defined in Fig. 1, in W m\(^{-2}\). The standard deviation over the time period is indicated in parentheses.

Figure 1. Regions of study for (a.) the Northern Hemisphere and (b.) the Southern Hemisphere. Bold line indicates the 70° parallel. Continental areas are shaded gray.

Figure 2. Average MERRA analysis increments field for the atmospheric energy budget (variable \(ANA(E)\)) for (a.) the Northern Hemisphere and (b.) the Southern Hemisphere. The contour interval is 20 W m\(^{-2}\). The zero contour is indicated with a solid black line.

Figure 3. Annual cycle of atmospheric energy budget components in MERRA for (a.) north polar cap, (b.) south polar cap, and (c.) the Southern Ocean domain, in W m\(^{-2}\). Bars indicate plus and minus the standard deviation for the period 1979-2005.
Figure 4. Average monthly meridional energy transport from MERRA (a.) across 70°N, contoured every 5·10⁹ W m⁻¹, and (b.) 70°S, contoured every 3·10⁹ W m⁻¹. Positive values indicate northward transport.

Figure 5. Annual average net surface heat flux from MERRA (positive upwards). Contours are plotted with an interval of 20 W m⁻² and for the levels −10, −5, 0, 5, and 10 W m⁻². The zero contour is indicated with a solid black line.

Figure 6. Monthly averaged surface albedo (gray) and upwelling shortwave radiative flux (dark) for SHEBA observed (solid) and corresponding MERRA values (dashed) for October 1997 to September 1998, in W m⁻². “Tower” values are from downward-pointing pyranometer measurements, while “line albedo” values are from surface measurements along a 300m line.

Figure 7. Near-surface hourly air temperature from SHEBA and corresponding values from MERRA for the period 1 February 1998 to 30 June 1998, in degrees C.

Figure 8. Time series of monthly averaged near-surface station air temperature anomaly and corresponding MERRA values for Barrow (left, 71°N, 157°W) and Jan Mayen (right, 71°N, 9°W), in degrees C.

Figure 9. Hourly (a.) precipitable water and (b.) liquid water path from SHEBA microwave radiometer and corresponding MERRA values, in mm.
FIGURE 10. Average annual time series for near surface station temperature and corresponding MERRA values for (a.) Amundsen-Scott (90°S), and (b.) Scott Base (78°S, 167°E), in degrees C. Bars indicate the standard deviation of monthly values over the period 1979–2005.

FIGURE 11. Time series of daily downwelling longwave flux and the net downward flux from Dutton et al. (1989) and corresponding values from MERRA for 90°S, in W m\(^{-2}\).
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TABLE 2. MERRA, CFSR, and ERA-1 1989-2005 average TOA and surface energy flux values for regions defined in Fig. 1, in W m\(^{-2}\). The standard deviation over the time period is indicated in parentheses.

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FIGURE 1. Regions of study for (a.) the Northern Hemisphere and (b.) the Southern Hemisphere. Bold line indicates the 70° parallel. Continental areas are shaded gray.
Figure 2. Average MERRA analysis increments field for the atmospheric energy budget (variable $A\text{NA}_{(E)}$) for (a.) the Northern Hemisphere and (b.) the Southern Hemisphere. The contour interval is 20 W m$^{-2}$. The zero contour is indicated with a solid black line.
FIGURE 3. Annual cycle of atmospheric energy budget components in MERRA for (a.) north polar cap, (b.) south polar cap, and (c.) the Southern Ocean domain, in W m\(^{-2}\). Bars indicate plus and minus the standard deviation for the period 1979-2005.
Figure 4. Average monthly meridional energy transport from MERRA (a.) across 70°N, contoured every $5 \times 10^9$ W m$^{-1}$, and (b.) 70°S, contoured every $3 \times 10^9$ W m$^{-1}$. Positive values indicate northward transport.
Figure 5. Annual average net surface heat flux from MERRA (positive upwards). Contours are plotted with an interval of 20 W m$^{-2}$ and for the levels $-10$, $-5$, $0$, $5$, and $10$ W m$^{-2}$. The zero contour is indicated with a solid black line.
Figure 6. Monthly averaged surface albedo (gray) and upwelling shortwave radiative flux (dark) for SHEBA observed (solid) and corresponding MERRA values (dashed) for October 1997 to September 1998, in W m$^{-2}$. “Tower” values are from downward-pointing pyranometer measurements, while “line albedo” values are from surface measurements along a 300m line.
FIGURE 7. Near-surface hourly air temperature from SHEBA and corresponding values from MERRA for the period 1 February 1998 to 30 June 1998, in degrees C.
FIGURE 8. Time series of monthly averaged near-surface station air temperature anomaly and corresponding MERRA values for Barrow (left, 71°N, 157°W) and Jan Mayen (right, 71°N, 9°W), in degrees C.
Figure 9. Hourly (a) precipitable water and (b) liquid water path from SHEBA microwave radiometer and corresponding MERRA values, in mm.
FIGURE 10. Average annual time series for near surface station temperature and corresponding MERRA values for (a.) Amundsen-Scott (90°S), and (b.) Scott Base (78°S, 167°E), in degrees C. Bars indicate the standard deviation of monthly values over the period 1979–2005.
Figure 11. Time series of daily downwelling longwave flux and the net downward flux from Dutton et al. (1989) and corresponding values from MERRA for 90°S, in W m⁻².