An Evaluation of Surface Atmospheric Changes over the Arctic Ocean for 2000–09 Using Recent Reanalyses

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**ABSTRACT:** The authors examine five recent reanalysis products [NCEP Climate Forecast System Reanalysis (CFSR), Modern-Era Retrospective Analysis for Research and Applications (MERRA), Japanese 25-year Re-analysis Project (JRA-25), Interim ECMWF Re-Analysis (ERA-Interim), and Arctic System Reanalysis (ASR)] for 1) trends in near-surface radiation fluxes, air temperature, and humidity, which are important indicators of changes within the Arctic Ocean and also influence sea ice and ocean conditions, and 2) fidelity of these atmospheric fields and effects for an extreme event: namely, the 2007 ice retreat. An analysis of trends over the Arctic for the past decade (2000–09) shows that reanalysis solutions have large spreads, particularly for downwelling shortwave radiation. In many cases, the differences in significant trends between the five reanalysis products are comparable to the estimated trend within a particular product. These discrepancies make it difficult to establish a consensus

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on likely changes occurring in the Arctic solely based on results from re-analyses fields. Regarding the 2007 ice retreat event, comparisons with remotely sensed estimates of downwelling radiation observations against these reanalysis products present an ambiguity. Remotely sensed observations from a study cited herewith suggest a large increase in downwelling summertime shortwave radiation and decrease in downwelling summertime longwave radiation from 2006 and 2007. On the contrary, the reanalysis products show only small gains in summertime shortwave radiation, if any; however, all the products show increases in downwelling longwave radiation. Thus, agreement within re-analysis fields needs to be further checked against observations to assess possible biases common to all products.

KEYWORDS: Arctic

1. Introduction

Sea ice is a key component of the Arctic Ocean physical system and can control the exchange of heat, water, momentum, and gases at the sea surface. Changes in the albedo of the surface brought on by changes in the ice cover over very large areas are a major factor in global climate change. The summer extent of the Arctic sea ice cover, widely recognized as an indicator of climate change (Hassol 2005), has been declining for the past few decades. The ice pack is also thinning. Based on submarine measurements, the ice draft is reported by Rothrock et al. (1999) to have thinned by 40% from the 1960s and 1970s to the 1990s.

The September sea ice coverage minimum of 2012 is the lowest areal extent since the start of the satellite multichannel passive-microwave record, reaching new record minima in both ice extent (ocean area with ice concentration of at least 15%) and ice area (cumulative area of actual ice coverage) (Parkinson and Comiso 2013). A combination of several years of ice reduction and a strong storm that entered the central Arctic in early August 2012 and broke up the main ice pack are likely reasons behind this decline (Parkinson and Comiso 2013; Zhang et al. 2013). For the previous record in September 2007, the sea ice cover reached a record minimum of 4.2 million km$^2$, which was 1.6 million km$^2$ or 23% less than the record set in September 2005 (Stroeve et al. 2008). This retreat was particularly pronounced in the East Siberian, Chukchi, and Beaufort Seas. There are several possible causes of the dramatic loss, the key factor being thinning of sea ice in recent decades (Holloway and Sou 2002; Lindsay and Zhang 2005; Maslanik et al. 2007; Stroeve et al. 2008; Perovich et al. 2008), as well as enhanced solar heating of the ocean (Perovich et al. 2007; Kay et al. 2008). Other factors include the combined effects of increased air temperature, changes in ocean currents and seawater temperature, radiative fluxes, wind forcing, and ice albedo feedback (Lindsay and Zhang 2005; Shimada et al. 2006; Serreze et al. 2007; Steele et al. 2008; Polyakov et al. 2010).

Atmospheric reanalyses are widely applied in Arctic research to study climate variability and trends (Serreze and Francis 2006, 2007; Jakobson and Vihma 2010; Cullather and Bosilovich 2012); to better understand large-scale circulation and teleconnection patterns (Thompson and Wallace 1998); and to provide boundary conditions for ocean, sea ice, land surface, and regional atmospheric models. In data-sparse areas such as the Arctic, reanalyses are arguably the best available source of integrated information on the four-dimensional structure of the atmosphere
although this is not necessarily true for all variables. The first global reanalyses included the National Center of Environmental Predictions–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996), its improved version by NCEP and the U.S. Department of Energy (DOE) (Kanamitsu et al. 2002), and the 15-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-15) (Gibson et al. 1997) and ERA-40 (Uppala et al. 2005) products. Comparisons against observations from the Arctic have revealed, however, major problems in each reanalysis: large errors exist in many variables including near-surface air temperature, specific humidity, and wind speed and direction (Walsh and Chapman 1998; Tjernström and Graversen 2009; Screen and Simmonds 2010).

To improve these products, extensive work has recently been carried out in producing new reanalyses, such as the Interim ECMWF Re-Analysis (ERA-Interim) (Dee et al. 2011), the Japanese Meteorological Agency Climate Data Assimilation System [JCDAS; which is continuation of the Japanese 25-year Reanalysis Project (JRA-25; Onogi et al. 2005)], the NCEP Climate Forecast System Reanalysis (CFSR) (Saha et al. 2010), and the National Aeronautics and Space Administration (NASA) Modern-Era Retrospective Analysis for Research and Applications (MERRA) (Rienecker et al. 2011). In general, these new reanalyses apply better horizontal and vertical resolution, better sea ice and land surface schemes, more extensive assimilation of satellite data, and more sophisticated assimilation methods. Several recent studies have evaluated these new reanalyses in the Arctic (Lüpkes et al. 2010; Cullather and Bosilovich 2012; Screen and Simmonds 2010). Some studies have evaluated the impact of sea ice on overlying atmospheric conditions (e.g., Porter et al. 2012; Tetzlaff et al. 2013); however, an assessment of reanalyses-derived atmospheric conditions on sea ice solutions has not been undertaken. While the aforementioned reanalyses products are global solutions, a higher-resolution regional Arctic reanalysis called the Arctic System Reanalysis (ASR) has also been recently made available (D. Bromwich and K. Hines 2008, personal communication).

With a declining trend in sea ice cover over the past few decades and increasing frequency of extreme events such as the 2007 and 2012 sea ice minima, good knowledge of near-surface atmospheric fields is needed to better understand the climate conditions within the data-sparse Arctic. Since reanalysis products provide estimates in both space and time at high resolutions, especially for the Arctic, we investigate them from both atmospheric and oceanic perspectives and give answers to the following questions: First, can they be used to analyze patterns of variability in near-surface atmospheric fields at interannual to decadal time scales? Specifically, do different reanalysis products show consistent decadal trends in near-surface variables? Second, do they show agreement in surface atmospheric conditions during extreme events such as the extensive decline of sea ice during 2007 and 2012?

In this paper we mainly focus on atmospheric variables that influence the oceanic heat budget and hydrography as well as the near-surface atmospheric heat budget in the Arctic: namely, downwelling shortwave and longwave radiation, air temperature, and relative humidity. These near-surface variables are also particularly chosen as they are extensively used by the ocean and sea ice modeling communities as boundary conditions or lateral forcing. While wind speed also affects the ocean heat flux, its discussion is briefly mentioned here and deferred to
investigation of momentum and freshwater fluxes, which will be presented as part of another article. We evaluate five recent reanalysis products (CFSR, MERRA, JRA-25, ERA-Interim, and ASR) for 1) consistency in near-surface atmospheric trends for the last decade and 2) fidelity of these atmospheric variables for the 2007 sea ice retreat extreme event. The outcome of this analysis will provide baseline information on the applicability of these reanalyses solutions for studying decadal climate patterns and extreme events in the Arctic and highlight possible inconsistencies in near-surface fields important for determining the state of the atmosphere–ocean–sea ice Arctic system.

2. Data and methods

We consider five recent reanalysis products—namely, CFSR, MERRA, ERA-Interim, JRA-25, and ASR—for our analysis. CFSR uses a global, high-spatial-resolution (≈40 km) coupled atmosphere–ocean–land surface–sea ice model. This reanalysis is designed to provide initial conditions for historical forecasts and operational NCEP climate forecasts. CFSR utilizes the NCEP Operational Global Forecast System (GFS) model coupled with the Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model, version 4 (MOM4) and sea ice model. Atmospheric observations are assimilated via the three-dimensional variational data assimilation (3DV AR Gridpoint Statistical Interpolation (GSI) system. The CFSR utilizes the Rapid Radiative Transfer Model (RRTM) (Mlawer et al. 1997). A more detailed description is provided in Saha et al. (2010).

NASA's MERRA reanalysis is a 1/2° × 1/3° resolution product based on the Goddard Earth Observing System, version 5 (GEOS-5) Data Analysis System (DAS; Bosilovich 2008). GEOS-5 ODAS, which is the ocean reanalysis, couples the GEOS-5 atmospheric general circulation model (AGCM), MOM4, and the Los Alamos Sea Ice Model (CICE). This global reanalysis takes advantage of a variety of recent satellite observations, such as NASA’s Earth Observing System (EOS), with a focus on improving estimates of the Earth’s hydrological cycle. The radiation parameterizations used in MERRA are documented in Chou et al. (2001). More detailed information about MERRA is provided through documentation available online (at http://gmao.gsfc.nasa.gov/research/merra/pubs/).

ERA-Interim is the recent ECMWF reanalysis (≈80-km spatial resolution), created in preparation for the next-generation extended reanalysis to replace the former ERA-40 reanalysis. Improvements include higher resolution and 4DVAR assimilation scheme. ERA-Interim uses ECMWF’s Integrated Forecast System (IFS) as its atmospheric model (Berrisford et al. 2009). ERA-Interim also utilizes the RRTM as its radiation transfer scheme (Mlawer et al. 1997). Further details on ERA-Interim system and performance can be found in Berrisford et al. (2009) and are described in numerous ECMWF newsletters.

JRA-25 is the product (≈120-km spatial resolution) from the Japan Meteorological Agency (JMA). A primary goal of JRA-25 is to provide a consistent and high-quality global reanalysis dataset with improved coverage and quality of analysis in the Asian region. JRA-25 uses the JMA Global Spectral Model and utilizes a 3DVAR assimilation scheme. JRA-25 reanalysis from 1979 to 2004 was transitioned to JMA Climate Data Assimilation System (JCDAS) onward of 2005 using the same data assimilation system of JRA-25. Since we use both JRA-25
(2000–04) and JCDAS (2005–09) fields, for consistency we refer to them both as JRA-25. More details can be found in Onogi et al. (2005).

While the four reanalysis products described above are global reanalyses, the ASR is a regional reanalysis focused on the Arctic. It uses the polar Weather Research and Forecasting Model (pWRF) and assimilates Arctic data using the WRF-VAR scheme. It also uses the RRTM similar to CFSR and ERA-Interim. Being regional in focus, the ASR final solution is being produced at 10-km resolution; however, at present only an interim 30-km product has been made publicly available. Because of its regional focus, ASR solutions are at higher resolutions than any of the global reanalyses products. Further details and documentation are available online (at http://polarmet.osu.edu/ASR/index.html).

Because all these reanalysis products are of different spatial resolutions and available for different time spans, we chose to analyze the common period of the last decade (i.e., 2000–09), when data from all the products are available. Prior to analysis, we averaged the reanalyses output into monthly means for each year for downwelling longwave and shortwave radiation, 2-m air temperature, and relative humidity. We conducted a linear least squares fit (LSF) on anomalies computed from differences between monthly values and corresponding 10-yr climatological monthly value at each grid point. We note that the trend analysis is conducted at the native spatial resolution of each reanalysis product. A comparison of trends from different reanalysis solutions is presented in section 3.

To compare reanalysis products and their influence in estimating sea ice during an extreme event, we investigate the potential impact of downwelling radiative fluxes on sea ice in 2007. We follow the analysis from Kay et al. (2008), who suggest that an increase in downwelling shortwave radiation due to reduced cloud cover may have been a major contributor to the drastic sea ice decline of 2007. Based on satellite- and ground-based observations, they show that summertime downwelling shortwave radiation increased by 32 W m⁻² from 2006 to 2007 over the western Arctic Ocean. To compare the same, we compute differences in summertime (mean from 15 June to 15 September) radiation between 2006 and 2007 for the western Arctic (180°–120°W, 70°–90°N) for each considered reanalysis product. Furthermore, we compare 2007 summertime radiation with other years in our study period (2000–09) for both the western Arctic and the full Arctic basin (180°W–180°E, 70°–90°N). Our analysis of the 2007 sea ice retreat is provided in section 4. The results of our analysis are discussed in section 5.

### 3. Trends

Each of the five reanalysis solutions shows large differences in spatial patterns of significant trends in downwelling shortwave radiation fields (Figure 1) for the last decade. CFSR, MERRA, and ERA-Interim show a significant negative shortwave radiation trend ($\approx -0.75 \pm 0.06$ W m⁻² yr⁻¹) in the Chukchi Sea; however, their spatial signatures are different. MERRA also shows a positive trend ($\approx 1 \pm 0.08$ W m⁻² yr⁻¹) north of the Canadian Archipelago, which is weakly observed in JRA-25. The JRA-25 shortwave radiation field does not show significant trends for most of the region. The ASR solution seems to differ from all other solutions and shows significant decline in shortwave radiation ($\approx -1.5 \pm 0.12$ W m⁻² yr⁻¹) in the Nordic and Barents Seas. A comparison of magnitudes for significant trends
across the five models is not possible, because no common locations are found to conduct an analysis.

Trends in downwelling longwave radiation (Figure 1) generally show significant increases over the Russian sector of the Arctic (Chukchi, Laptev, East Siberian, and Kara Seas) in most products, but MERRA shows an increase of greater than $2 \pm 0.18 \text{ W m}^{-2} \text{ yr}^{-1}$ in the Chukchi over the past decade, whereas CFSR, ERA-Interim, and JRA-25 increases vary from 0.5 to 1.5 W m$^{-2} \text{ yr}^{-1}$. The ASR solution seems to show largest significant increases in the Nordic and Barents Seas with increases of over 1 $\pm 0.06 \text{ W m}^{-2} \text{ yr}^{-1}$. The JRA-25 solution shows positive trends in the Barents and Kara Seas and also a portion of the Nordic seas, and hence its spatial patterns are closer to the patterns observed in the ASR than other reanalysis products. A comparison of magnitudes of significant trends across the five models in common locations such as the Chukchi Sea shows largest differences of $1.3 \text{ W m}^{-2}$ between MERRA and ASR, which in many locations are as large as the trend itself in the ASR model. Similar differences are found in the Kara and Barents Seas. Thus, for both shortwave and longwave radiation, CFSR, MERRA, and ERA-Interim seem to show similar spatial patterns in trends; however, MERRA shows enhanced trends compared to other solutions. Spatial patterns in trends of the ASR radiation solution differ from most other solutions.

Trends in near-surface air temperature (Figure 2) seem to follow similar spatial patterns as the downwelling longwave radiation. MERRA and ERA-Interim show warming of $0.25 \pm 0.01 \degree \text{C yr}^{-1}$ around most of the Arctic, especially along the Russian sector. CFSR shows a weaker warming trend of $0.15 \pm 0.01 \degree \text{C yr}^{-1}$.
confined to the western Arctic, Chukchi Sea, and Kara Sea. JRA-25 displays warming all along the Russian sector although the warming is more pronounced in the eastern Arctic ($\approx 0.25^\circ \pm 0.02^\circ$C yr$^{-1}$) in comparison to the western Arctic ($\approx 0.15^\circ \pm 0.01^\circ$C yr$^{-1}$). ASR shows a warming trend in the Beaufort Sea, which is not seen in any other reanalysis product. ASR also does not show significant warming trends along the Russian Arctic, which are seen in all other reanalysis products with varying spatial extent. Furthermore, ASR solutions display a cooling trend along eastern Greenland, which is not seen in other solutions. A comparison of trends of air temperature at common locations such as the Barents Sea shows the largest differences of 0.42°C yr$^{-1}$ between MERRA and JRA-25. This difference is as large as the estimated trend in MERRA for these locations. Substantial uncertainties in Arctic surface temperatures have vital impacts on the global average temperature trends (Curry 2014).

Trends in near-surface humidity (Figure 2) show similar spatial patterns as air temperature, with increasing moisture around most of the Arctic and particularly pronounced along the Russian sector in CFSR, MERRA, ERA-Interim, and JRA-25. The ASR trend in humidity shows a distinct increase in humidity along the western Arctic and a decrease along the eastern coast of Greenland, but no significant trends are seen along the eastern Arctic. The magnitudes of significant trends at common locations for near-surface humidity are comparable in most

![Figure 2. Significant trends (different from zero at the 95% significance level using one-sided hypothesis test) in (top) 2-m air temperature ($^\circ$C yr$^{-1}$) and (bottom) specific humidity (kg kg$^{-1}$ yr$^{-1}$) from 2000 to 2009 for five reanalysis products. Most of the reanalyses show significant increases in both air temperature and humidity over the past decade over large areas in the Arctic. However, a significant cooling and low moisture trend is seen in the Bering Sea region west of Alaska.](image)
regions. The largest differences in trends are observed in the Chukchi region between CFSR and ASR ($3.2 \times 10^{-5} \text{ kg kg}^{-1} \text{ yr}^{-1}$).

In general, 2-m air temperature and humidity solutions for ASR seem to differ from the other four reanalyses. The one commonality among all the reanalyses is the significant cooler and drier conditions within the Bering Sea over the past decade. All the solutions show at least $-0.2^\circ \pm 0.01^\circ \text{C yr}^{-1}$ decrease in temperature and $-2 \times 10^{-5} \pm 3 \times 10^{-6} \text{ kg kg}^{-1} \text{ yr}^{-1}$ decrease in humidity (Figure 2). The cooler and drier conditions within the Bering Sea are associated with a period of cooling in the Bering Strait from 2005 onward (Zhang et al. 2010), with the winter of 2008 being one of the coldest on record. Zhang et al. (2010) suggest that this cooling is due to a decline in downwelling longwave radiation in the area, which is in agreement with significant decreasing trends in longwave radiation as seen in reanalysis products discussed here (Figure 1). In summary, analysis of trends over the Arctic for the past decade shows that five different reanalysis solutions have large spreads, particularly for downwelling shortwave radiation, longwave radiation, air temperature, and to a lesser extent humidity. The source of these differences in the reanalysis products could likely be due to factors such as different assimilation schemes, frequency of assimilation, radiative transfer schemes, cloud parameterizations, datasets being assimilated, and changing data streams, among others.

4. Factors affecting sea ice decline in 2007

The sea ice decline of 2007 was a significant departure from the long-term sea ice trend (Stroeve et al. 2008). A look at the sea ice concentrations for the period from 2000 to 2009 show general agreement among all reanalyses, with positive anomalies during late summer–fall in the early part of the decade followed by the anomalously negative (5%–10%) decline during 2007 (Figure 3). The reanalyses, however, show large differences in their winter and springtime estimates. It must be noted that the sources of sea ice concentration estimates represented by the reanalyses are different. For instance, CFSR and MERRA have dynamic sea ice models, which are coupled to the ocean and atmosphere and assimilate sea ice data (Saha et al. 2010; Rienecker et al. 2011), and thus the sea ice is simulated. On the contrary, sea ice concentrations in JRA-25 are derived from Centennial in situ Observation-Based Estimates (COBE), which are “prescribed” as boundary conditions to the atmospheric model (Onogi et al. 2005). Similarly, ERA-Interim and ASR also use prescribed sea ice datasets (Dee et al. 2011; Bromwich et al. 2010). Thus, comparing sea ice concentrations among these reanalysis products is nontrivial because of differences in the way they are applied or derived. We thus focus on near-surface variables that affect sea ice concentrations from these reanalyses to understand possible forcing mechanisms for the 2007 decline.

Among several hypotheses for this decline, Kay et al. (2008) suggest that reduced cloudiness and enhanced shortwave downwelling radiation were associated with the 2007 sea ice loss. To study the event, they analyzed radar-based CloudSat and lidar-based Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) data for cloud cover, downwelling longwave radiation, and downwelling shortwave radiation for the western Arctic ($180^\circ–120^\circ\text{W}, 70^\circ–90^\circ\text{N}$). They report that cloud cover reduced by 16% from 2006 to 2007, which in turn increased summertime
Figure 3. Monthly-mean anomalies of sea ice concentration (%) from 2000 to 2009 for the Arctic (70°–90°N). The five reanalysis products show considerable variations in their solutions; however, all the reanalyses show the anomalous sea ice decline in 2007.
downwelling shortwave radiation by 32 W m\(^{-2}\). They also suggest that downwelling longwave radiation reduced by 4 W m\(^{-2}\) from 2006 to 2007. We follow their analysis to test the reliability of reanalysis solutions in reproducing near-surface atmospheric conditions during this extreme event. In particular, we look at patterns in downwelling shortwave and longwave radiation within the western Arctic.

Monthly-mean anomalies of downwelling shortwave radiation for the five reanalysis products in the western Arctic are presented in Figure 4. Large discrepancies are seen among the five solutions over the full analysis period (2000–09). For example, CFSR and ASR show positive springtime anomalies (months 4–6) of >15 W m\(^{-2}\) during 2000, whereas JRA-25 and ERA-Interim show weaker positive anomalies of \(\approx 5\) W m\(^{-2}\) and MERRA shows even weaker anomalies. There are instances of large positive anomalies in MERRA and ASR, which are absent in other products, and JRA-25 shows a sustained positive anomaly during summer of 2009, whereas the other fields show mostly negative anomalies. However, the one consistent signal represented by all the reanalysis solutions is that 2007 was not an anomalously high summer. Another common pattern is a springtime negative anomaly in 2006 followed by a summertime positive anomaly, which is most pronounced in the ASR fields. The shortwave radiation patterns from the five reanalyses do not provide, however, any consistent indications of either preconditioning in 2006 or an instantaneous increase in 2007 to trigger the icemelt event of 2007. On the contrary, downwelling longwave radiation shows anomalously high values during late summer–early fall 2007 for all the reanalyses (Figure 5). Furthermore, most of the year-to-year variability in the reanalysis solutions shows agreement with each other. The years of 2000, 2001, and 2004 seem to show anomalously low downwelling longwave radiation, whereas 2006 and 2007 show an increase in longwave radiation.

This analysis thus far suggests that downwelling shortwave radiation does not show any anomalous behavior in 2007, whereas downwelling longwave radiation displays an anomalous increase during 2007. To further investigate the radiation fields in the different reanalyses, we present the differences in summertime (average from 15 June to 15 September) downwelling shortwave and longwave radiation between 2007 and 2006 (Figure 6). The differences in shortwave radiation show small gains or losses for most of the Chukchi and Laptev Seas. The western Arctic, Kara, and Nordic Seas show gains in radiation. However, the shortwave gains in the western Arctic are much below the 32 W m\(^{-2}\) gain suggested by Kay et al. (2008). In fact, CFSR and MERRA show losses in shortwave radiation, whereas ERA-Interim, JRA-25, and ASR show slight gains on the order of \(\approx 4\) W m\(^{-2}\). Thus, reanalyses that do show gains are an order of magnitude weaker than those estimated from remotely sensed data. On the other hand, all five reanalyses show a large gain (>10 W m\(^{-2}\)) in downwelling longwave radiation in the central Arctic and Chukchi Seas. The western Arctic does show smaller gains compared to the Russian sector; however, each of the reanalyses shows increases ranging from 7.7 to 3.8 W m\(^{-2}\). These increases are once again in contrast to results from Kay et al. (2008), who suggest a decrease of 4 W m\(^{-2}\) in downwelling longwave radiation from 2006 to 2007.

Differences in 10-m winds between reanalyses products might also affect respective ocean heat fluxes as well as the sea ice cover (in reanalyses that simulate sea ice). A comparison of 10-m zonal and meridional winds from 2000 to 2009
Figure 4. Monthly-mean anomalies of downwelling shortwave radiation (W m$^{-2}$) from 2000 to 2009 for the western Arctic (180°-120°W, 70°-90°N). The five reanalysis products show considerable variations in their solutions. Shortwave radiation estimates do not show any large anomalous patterns in 2007; however, 2006 shows anomalously low summertime shortwave radiation values in all the reanalysis solutions.
Figure 5. Monthly-mean anomalies of downwelling longwave radiation (W m$^{-2}$) from 2000 to 2009 for the western Arctic (180°–120°W, 70°–90°N). The five reanalysis products show some temporal variations in their solutions as well as in amplitudes; however, in general, they seem to agree with each other. Longwave radiation estimates show positive anomalous patterns during summer and fall of 2007.
suggests good general agreement for CFSR, MERRA, ERA-Interim, and JRA-25 but large differences particularly for zonal winds for ASR (not shown). In 2007, both meridional and zonal speeds were anomalously high during February–March in almost all reanalyses, a period coincident with the seasonal sea ice maxima. The impact of these strong winds on sea ice concentration in 2007 is unclear from the reanalyses, because of the way sea ice is prescribed (or assimilated), as described earlier.

5. Discussion and summary

Our analysis presents an ambiguity between remotely sensed downwelling radiation observations and atmospheric reanalysis solutions. Remotely sensed observations presented by Kay et al. (2008) suggest that decreased cloud cover led to significant increases in shortwave radiation, which in turn was associated with enhanced sea ice melting from 2006 to 2007. In contrast, the reanalysis products show only small gains in summertime shortwave radiation, if any (CFSR and MERRA show losses); however, all the products show increases in downwelling longwave radiation. A limitation of the Kay et al. (2008) analysis is that it is confined to the western Arctic. If the region of interest is the Siberian and Laptev Seas sectors of the eastern Arctic (120°–180°E, 70°–90°N), then our analysis would show summertime differences between 2007 and 2006 for shortwave radiation to be –13, –20, –2, –8, and –11 W m⁻² and for longwave radiation to be 13, 18, 10, 14, and 15 W m⁻² for CFSR, MERRA, ERA-Interim, JRA-25, and ASR.
respectively. Thus, in the Siberian and Laptev Seas sectors, reanalysis products all show increases in longwave radiation and decreases in shortwave radiation. For other seasons, longwave radiation dominates the Arctic radiation budget because of large solar zenith angles, high surface albedos, and limited light conditions (Curry et al. 1996). On an Arctic basin level (Figure 7), downwelling summertime shortwave radiation anomalies are mostly weak with periods of strong negative anomalies during 2006 and 2007 in comparison to other years for all the re-analyses, and similarly all the reanalyses exhibit anomalous increases in 2007 longwave radiation (not shown).

Our results based on reanalysis products suggest that longwave radiation dominated the Arctic radiation budget in the summertime for 2007, whereas shortwave radiation was anomalously low. These findings agree with Francis et al. (2005), who use satellite-based observations to suggest that downwelling longwave radiation fluxes account for a large percentage—approximately 40% on average—of the variability in perennial ice extent from 1979 to 2004. They noted that, in the Beaufort/Chukchi Sea area, increasing ice retreat is consistent with strong positive trends in spring downwelling longwave radiation, which appear to be caused by substantial increases in precipitable water, cloud amount, and surface temperature. They postulated a positive feedback system where, under melting, open water will likely be warmer than the ice it replaced and thus be a stronger emitter of longwave radiation. Cloud bases would absorb this energy, warm, and emit more radiation back toward the surface. They also found that anomalies in the downwelling shortwave flux were negatively correlated with ice retreat anomalies in the Arctic at all lags: that is, positive (negative) shortwave flux anomalies are associated with more (less) ice.

Another perspective is that of arctic feedback amplification such as preconditioning (Porter et al. 2012): that is, declining sea ice prior to 2007 would increase turbulent heat fluxes from the ocean to the atmosphere, resulting in vertically deep heating and moistening of the Arctic atmosphere. This warmer and moister atmosphere would increase cloud cover and thus the radiative flux (increased downwelling longwave), which could subsequently affect the sea ice concentrations in 2007. Such an amplification does not seem to appear in the reanalyses as sea ice concentrations are anomalously high or neutral during the summer–fall sea ice minima of 2006 (Figure 3). Furthermore, differences in 2006 sea ice concentrations among the reanalyses do not appear to be correlated with patterns of shortwave radiation (Figure 7), but amplification after the sea ice decline of 2007 is likely, as described by Porter et al. (2012).

On a further cautionary note, cloud parameterizations within reanalysis models are known to have biases. Walsh et al. (2009) suggest that reanalysis models simulate the radiative fluxes well only when the cloud fraction is simulated correctly. However, the systematic errors of climatological reanalyses cloud fractions are substantial. Cloud fraction and radiation biases show considerable scatter, both in the annual mean and over a seasonal cycle, when compared to observations. Large seasonal cloud fraction biases have significant impacts on the surface energy budget. Persistent low-level cloud fraction in summer is particularly difficult to capture in the reanalysis models, creating biases in the shortwave radiation flux that can exceed 160 W m⁻² (Walsh et al. 2009). Similarly, Tjernström et al. (2008) suggest negative biases in downwelling radiation by comparing six regional models from the Arctic Regional Climate Model Intercomparison (ARCMIP) project against observations from the Surface Heat Budget of the Arctic Ocean.
Figure 7. Monthly-mean anomalies of downwelling shortwave radiation (W m$^{-2}$) from 2000 to 2009 for the entire Arctic for 70°-90°N. The five reanalysis products show amplitude differences as well as temporal variations in their solutions. However, they seem to agree that summertime shortwave radiation in both 2006 and 2007 was anomalously low.
(SHEBA) experiment. They show poor correlations between model cloud properties and observations. Most models underestimate the presence of high clouds and the modeled low clouds are too thin and displaced downward. Thus, similar shortcomings in internal model cloud parameterizations might make their radiative flux estimates closer to each other; however, these estimates might be biased when compared against observations.

Regarding the analysis of decadal trends in near-surface atmospheric variables for the 2000–09 period, we observe large spreads in estimates for the five reanalysis products. In most regions within the Arctic, the trends differ considerably in magnitude and spatial pattern, well beyond respective statistical uncertainties, thus failing to provide a consistent perspective of estimated decadal changes in near-surface atmospheric conditions. These differences make it difficult to establish a consensus on changes in near-surface atmospheric conditions from seasonal to longer time periods, without which a reliable narrative is difficult to establish for concerned stakeholders. Although our analysis period is limited to 10 years, one might anticipate similar discrepancies to be present at longer time scales. Even if there are instances when all the reanalysis products show consistent trends, such as the significant cooler and drier conditions in the Bering Sea over the past decade, the agreement may not necessarily establish a “consensus” view, as demonstrated by our discussion of changes in summertime downwelling radiative fluxes from 2006 to 2007. Comparative analysis with observations can provide a further check on possible biases in reanalysis products.

In general, several studies (both cited here and uncited) compute trends from either one reanalysis product for comparison with other models or observational products. In most such cases, trends of near-surface atmospheric variables are computed by taking a spatial mean over a region of interest. However, our study suggests that it is advisable to investigate such trends in multiple reanalyses and possibly at their native spatial resolutions to investigate how they compare to each other and against observations where possible. Such an exercise would likely establish a better understanding about the fidelity of these trends. On another note, the ocean modeling community is encouraged to do the same when choosing reanalysis products for deriving air–ice and air–sea fluxes, as implicit biases in their long-term variability can affect ocean model integrations on similar time scales.

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