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Systematic Improvements of Reanalyses in the Arctic (SIRTA)

A White Paper



Great Arctic Cyclone of 2012, Imaged by Aqua MODIS, August 7, 2012.

Systematic Improvements of Reanalyses in the Arctic (SIRTA)

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Executive Summary

This white paper on atmospheric reanalyses, with a focus on issues related to Arctic reanalyses, was requested in May 2015 by the IARPC (Inter-agency Arctic Research Policy Committee) Principals. Their charge was:

- Evaluate the state, utilization, limitations and potential utility of the current Arctic reanalyses;
- Inventory and assess the currently planned operational and experimental observations of the Arctic system to improve reanalyses;
- Examine reanalyses products and forecast models for potential improvement; and
- Assess the potential utility of YOPP and CMIP6 as focal points to facilitate progress.

The IARPC Staff subsequently asked NASA and NOAA to appoint individuals to co-lead an IARPC Collaborations working group. The co-authors, selected by NOAA and NASA, are the chairs of the working group. The working group held four open meetings for the community to share ideas and provide input to the white paper. This paper is a result of those meetings.

Reanalyses are retrospective, gridded depictions of the atmosphere. Reanalyses are generated through a statistical adjustment of a prior, short-term numerical forecast to available observations during the period of the forecast. The data include radiance information from available satellites and in situ observations, including land stations, marine observations, aircraft, rawinsonde, and profiler data. Compared to mid-latitudes, the Arctic has a paucity of in situ observations. Additionally, both infrared and microwave satellite sensors have difficulty in profiling the lower atmosphere over snow- and ice-covered surfaces, and geostationary satellites do not cover the high latitudes.

Improving reanalyses will help in nearly all aspects of Arctic systems research. In the Arctic, the uses of reanalysis have included physical process-related investigations, and the evaluation of weather and climate models. Reanalyses are also used as boundary conditions for a variety of other models, including those for the regional Arctic atmosphere, ocean circulation and sea ice, land surface, ice sheets, and biogeochemistry. Importantly, they are also used in the production of satellite-derived data sets. Reanalyses are critical for understanding the Arctic climate system

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due to the lack of conventional data sources. Potentially, reanalyses are powerful tools that may be used to address major scientific questions, including Arctic predictability and polar/midlatitude climate interactions. Many Arctic system studies and applications cannot be conducted without reanalyses. Reanalyses are limited in particular in the Arctic by the limited observing system and by model deficiencies. Chronic issues that affect several reanalyses include errors in near-surface air temperatures; the treatment of atmospheric moisture, including precipitation and clouds; and unphysical discontinuities in reanalysis time series. Reanalyses continue to be used – in spite of known shortcomings – because of their consistent, gridded format in time and space.

Current and planned observations of the Arctic may be broadly distinguished by those that may be directly incorporated into reanalyses and those that are designed to illuminate Arctic processes. The latter may be used indirectly in the evaluation of reanalyses, and in particular the background model that supplies its first guess. Both applications of the observations are critical to the improvement of reanalyses and Arctic process understanding.

Current Arctic observing systems can play a key role in the quality of reanalyses because this part of the world generally has sparse data. Such data are only useful to reanalysis generation if it is encoded into standard formats and accompanied by information such as measurement error characteristics. We find that methods for the incorporation of new or novel observations into reanalyses are problematic and need to be remedied in a comprehensive manner. Reanalysis developers need to be engaged with the Arctic observing community in order for systematic improvement to occur.

The working group has identified the following topics that will potentially improve Arctic reanalyses:

- Performance of the next generation of reanalyses focused on the entire Arctic.
- Development of prediction of clouds at spatial resolutions used by reanalyses and for mixed phase, liquid water, and ice clouds, as well as the prediction of aerosols and their impacts on cloud formation.
- Coordinated observation-modeling-reanalysis-forecasting activities.
- Daily rawinsonde observations for the central Arctic Ocean.
- Assessment of key in situ Arctic observing system components.
- Identification of new and past observations not used in prior Arctic reanalyses and suitable for assimilation.
- Better atmospheric remote sensing over ice and snow.
- Arctic reanalysis intercomparison and evaluation.

- Refinements to analysis and forecast systems that are most necessary to improve surface analyses.
- Development of strongly coupled data assimilation methodologies.
- Facilitation of education and outreach to Arctic communities should be encouraged to provide compelling visualizations of the changing Arctic based on improved Arctic reanalyses.

1. Introduction

This white paper on atmospheric reanalyses, with a focus on issues related to Arctic reanalyses, was requested in May 2015 by the IARPC Principals. The IARPC (Interagency Arctic Research Policy Committee) Staff Group subsequently asked NASA and NOAA, the two agencies which requested the formation of the working group, to appoint individuals with expertise in the area of reanalyses to co-lead an IARPC Collaborations working group. The working group held four open meetings for the community to share ideas and provide input to the white paper. An online town hall was also convened for final community comment prior to completion of the white paper.

The working group's charge was to:

- Evaluate the state, utilization, limitations and potential utility of the current Arctic reanalyses;
- Inventory and assess the currently planned operational and experimental observations of the Arctic system to improve reanalyses;
- Examine reanalyses products and forecast models for potential improvement; and
- Assess the potential utility of YOPP and CMIP6 as focal points to facilitate progress.

The white paper serves several purposes: explain the importance of reanalyses to Arctic research; indicate how researchers can make their data more readily useful when future reanalyses are generated; and describe some of the strengths and weaknesses in reanalyses for potential Arctic-related users.

Section 2 provides essential background on reanalyses. Section 3 provides an overview of the common types of observations that are assimilated into reanalyses. This section also provides information on the issues for using new data sources in future reanalyses, and what sort of observations would be most helpful in such reanalyses. Section 4 gives an assessment of current-generation reanalyses, surveying the literature on such assessments and how well they represent specific physical processes. Particular areas where current-generation reanalyses perform sub-optimally are identified. Section 5 provides guidance on future directions for reanalyses. How will development strategies change, including the use of higher-resolution models, new observation types, coupled ocean-land-atmosphere-cryosphere reanalyses, and potential developments in assimilation methods? Section 6 concludes the white paper with a list of potential improvements to Arctic reanalyses.

2. Background on Reanalyses

Section Summary

This section provides potential reanalysis users with some general background on reanalyses, including: (a) a list of current reanalyses; (b) the underlying mathematical techniques used to produce reanalyses; (c) the methodological challenges and data challenges, and (d) a review of the literature on use of reanalyses, with a focus on Arctic reanalysis.

Reanalyses are *retrospective analyses*. Table 1 provides a list of available reanalyses and the periods that they cover. “Retrospective” here indicates that the analyses are available not just for current conditions, but also for years, decades, or even centuries in the past. “Analyses” indicate that a gridded depiction of the state of the system is provided. For atmospheric reanalyses, these would include winds, temperatures, and humidities not just at the surface but at many levels above the surface. Reanalyses are generated through a statistical adjustment of a prior, short-term numerical forecast to available observations during the period of the forecast. The adjustment heavily weights the observations where they are plentiful and accurate, and it largely preserves the prior forecast estimate where the observations are inaccurate or missing. Reanalyses also typically provide estimates for other variables, such accumulated precipitation and surface energy fluxes, but commonly these are generated strictly from the forecast and are not statistically adjusted to the newly available observations.

Reanalyses serve many purposes; section 1.4 provides details of many of the uses relevant to Arctic research. However, reanalyses are also produced for other purposes, including retrospective forecast initialization (Saha et al. 2010, Hamill et al. 2013) and global climate and climate variability monitoring (Compo et al. 2011). Many users may assume that such global reanalyses can be used in a straightforward manner for the diagnosis of Arctic characteristics and their changes, but only a few are designed specifically for such a purpose (e.g., Bromwich et al. 2016, Liu et al. 2014). Users of reanalyses for Arctic processes should thus be aware of issues in reanalysis generation as discussed in this white paper.

In the remainder of the introduction, we provide the reader with some context regarding the challenges associated with the components used in the generation of reanalyses: the observations, the numerical forecasts, and the assimilation method itself. We follow this with a review of Arctic reanalysis uses, and finally with a description of the content in the rest of the white paper.

Table 1. List of atmospheric reanalyses. Grid spacing is based on the longitudinal spacing at 70°N. See appendix 1 for descriptions of the associated acronyms.

	Period	Type	Grid Spacing	Reference
NCEP/NCAR	1948-ongoing	Global	213 km, L28	Kalnay et al. (1996)
ERA-15	1979-1993	Global	125 km, L31	Gibson et al. (1997)
NCEP DOE II	1979-2015	Global	213 km, L28	Kanamitsu et al. (2002)
ERA-40	1957-2002	Global	125 km, L60	Uppala et al. (2005)
JRA-25	1979-2004	Global	125 km, L40	Onogi et al. (2007)
NCAR CFDDA	1985-2005	Global	44 km, L28	Rife et al. (2010)
NCEP CFSR	1979-2011	Global	35 km, L64	Saha et al. (2010)
CFSv2	2011-ongoing	Global	23 km, L64	
ERA-Interim	1979-ongoing	Global	52 km, L60	Dee et al. (2011)
MERRA	1979-2015	Global	56 km, L72	Rienecker et al. (2011)
JRA-55	1958-2012	Global	63 km, L60	Kobayashi et al. (2015)
MERRA-2	1980-ongoing	Global	56 km, L72	Bosilovich et al. (2016)
NOAA NARR	1979-2014	Regional	32 km, L45	Mesinger et al. (2006)
CBHAR	1979-2009	Regional	10 km, L49	Zhang et al. (2016)
ASR	2000-2012	Regional	30 km, L71	Bromwich et al. (2016)
v.2			15 km, L71	
HIRLAM EURO4M	1989-2010	Regional	22 km, L60	Dahlgren et al. (2016)
NOAA-CIRES 20CR	1908-1958	Sfc pres.	213 km, L28	Compo et al. (2011)
v.2c	1851-2011			
ERA-20C	1900-2010	Sfc pres.	125 km, L91	Poli et al. (2016)

2.1 Challenges in current data assimilation methodologies

To understand challenges associated with assimilation methodologies, some background is necessary. The underlying mathematical procedures used in data assimilation are varied, but thankfully the mathematical statement of the problem is generally agreed upon (Lorenz 1986). The common assumptions in data assimilation are as follows: the precise state of the atmosphere is unknowable, but an optimal estimate is possible through combinations of available data, the numerical forecast(s), and recent observations. Underlying this optimal combination is an assumption that the input data are unbiased, or that they have been adjusted prior to the assimilation to make the data unbiased. Further, errors are commonly assumed to be Gaussian, that is, modeled with a bell-shaped curve. More formally, let's define a model state vector $\mathbf{x} = [x_1, \dots, x_n]$, where the n components are the gridded values of temperature, wind components, humidities, and so forth. It's common in modern data assimilation systems for n to be order 10^7 or larger. We then seek a model state \mathbf{x} that represents the best compromise between forecasts and observations, each weighted according to their relative error statistics. This can be expressed as a functional:

$$J(\mathbf{x}) = \frac{1}{2} (\mathbf{x}_b - \mathbf{x})^T (\mathbf{P}_b)^{-1} (\mathbf{x}_b - \mathbf{x}) + \frac{1}{2} (\mathbf{y} - \mathcal{G}(\mathbf{x}))^T \mathbf{R}^{-1} (\mathbf{y} - \mathcal{G}(\mathbf{x}))$$

In this equation, \mathbf{x}_b refers to the vector describing the first guess, or “background” model state at a particular time. If the observations are distributed over a “window” or period of time, then commonly \mathbf{x}_b refers to the background at the beginning time in the window. \mathbf{P}_b is the background-error covariance, a matrix description of the magnitude of errors expected for each component of the state and the relationships of errors between state components. Errors are assumed Gaussian, with zero mean. \mathbf{y} is a vector describing the recently available observations during this window of time. \mathbf{R} is the covariance matrix for the observations, describing their errors and relationships of errors between the observations. Expected observation errors are usually assumed Gaussian as well, with zero mean expected value. $\mathcal{G}(\cdot)$ is an operator that both evolves the forecast state from the beginning of the window to the times of each observation, and it converts the state to the observation type. For example, this conversion might involve changing model forecast temperatures and humidities into the same radiances units as observed for a particular satellite observation. Finally, $J(\mathbf{x})$ is the overall functional we seek to minimize; the first term in the functional penalizes the analysis deviations from the background forecast, and the second term penalizes the deviations from the observations. Essentially, this equation states that we seek a model state that is a compromise between the background forecast and the observations, with that compromise reflecting their relative error statistics. In areas where observations are plentiful and/or accurate, the analyzed state \mathbf{x} will be drawn toward those observations. In data voids or regions where observations are inaccurate, the background forecast will largely be preserved.

There are multiple ways to estimate this state \mathbf{x} . One common way is applying the calculus of variations to find the minimum of the functional (e.g., Le Dimet and Talagrand 1986, Courtier et al. 1994, Rabier et al. 2000); this commonly involves the use of iterative methods. In meteorological parlance, this is known as four-dimensional variational analysis or “4D-Var.” Another modern method is the use of Kalman-type filters, with the most common variant for meteorological applications being the “ensemble Kalman filter” (Evensen 1994, Houtekamer and Mitchell 1998, Hamill 2006). The solution method is akin to multiple regression analysis (Anderson 2003). In recent years, researchers have increasingly tried to hybridize the two methods, for each has attractive aspects (e.g., Hamill and Snyder 2000, Buehner et al. 2010ab, Clayton et al. 2013).

With this background, we can now consider some of the scientific limitations of these approaches. The most severe limitation is the relatively limited ability of the methods to produce high-quality analyses in the presence of non-Gaussian error distributions. For example, cloud liquid water distributions are often strongly non-Gaussian. In a meteorological environment where there is potential instability, with a slightly lower surface temperature, clouds may not develop if there is a capping inversion. With just slightly warmer temperatures, deep convection may develop, and cloud liquid water values become very large. If this cloud liquid water is part of the state vector, the data assimilation system will struggle to produce realistic results. There are some more novel proposed methods for data assimilation that permit non-Gaussian distributions, methods such as “particle filters” (e.g., Gordon et al. 1993; Doucet et al. 2001), but

they have their own limitations (Snyder et al. 2008) and are not yet in widespread use with high-dimensional states common in geophysical state estimation.

As emphasized previously, there is also a strong assumption that the forecasts and observations have zero-mean expected error, i.e., that they are unbiased. This assumption, regrettably, is commonly violated. If multiple types of observations are available in a given area, some without bias and some that potentially have bias, then it can be possible to use past differences to “bias-correct” the observations that may be contaminated with bias before they are used in the assimilation system. Bias correction of forecasts is more difficult; ideally, biased forecasts are addressed by improving the forecast model directly, but statistical adjustment of the forecast may also be possible (Bloom et al. 1996, Dee 2005).

A final challenge is the computational expense. Previously, it was mentioned that the first guess forecast(s) can be computationally expensive to generate. For data assimilation, the input and output of substantial quantities of high-resolution data can limit the computational performance, as can memory. Ideally, the full model state over the time window of the observations will be readily available in fast memory, as will be all the observations and the error covariances. In practice, it is impossible to hold all this information in the fastest memory, and it is often challenging to split the overall computation into smaller segments that can be parallelized over many processors. The efficient swapping of information to and from the fast memory and the parallelization of the assimilation procedure are often the rate-limiting step of the assimilation process, the bottleneck that is in the way of faster, more accurate analyses.

2.2 Challenges with the use of observations in reanalyses

Consider now some of the key challenges in using observations to define a gridded estimate of the state of the atmosphere. These challenges include:

(a) **Representativeness.** The observations may be point measurements, such as the temperature observed by a weather balloon at a particular pressure level. The gridded analysis is intended to estimate the average state of a grid volume. There is thus a “representativeness” error associated with the point measurements, quantifying statistically how well they represent the state of that volume. The larger the analysis grid box, the larger the representativeness error. More generally, quantification of errors, whether they are due to representativeness or instrument design, must be characterized and provided to the data assimilation system.

(b) **Data inhomogeneity.** Observations are distributed non-uniformly in time and space. We desire, say, an analysis at a regular gridded set of locations over the earth every three hours, but the observations are clustered over population-dense areas over land, or they may have measured the atmospheric state in between the three-hourly analysis times. For example, a “polar-orbiting” weather satellite orbits the earth at a relatively low altitude every ~101 minutes, sampling a particular location near the equator roughly twice a day and near the poles much more often. It generates scanned data continuously, not only at every third hour. Satellites may provide ample data in some regions (e.g., clear air) but are generally unsuitable for assimilation

in other regions (e.g., cloudy regions due to the challenges associated with accurate characterization of cloud emissivity). The data assimilation system must also be able to properly utilize the observations at times slightly offset from the analysis time.

(c) **Indirectness.** Observations may not directly measure the quantity being analyzed. For example, weather satellites observe upwelling radiances at a particular frequency or in a frequency band. These are indirectly related to the temperature through some vertical depth of the atmosphere, but they are not measuring the temperature at a particular latitude, longitude, and elevation, as the gridded analysis must.

(d) **Unusefulness.** Observations may have been collected with other purposes in mind, such as to provide insight into the dynamics of a particular physical process. Perhaps a researcher is interested in the distribution of cloud droplet sizes in order to understand the processes for generating clouds and precipitation. Such observations may provide little information that can be leveraged to analyze winds, temperatures, and humidities.

(e) **Bias.** A common assumption in data assimilation methodologies is that the observations are unbiased, with zero mean error. Perhaps the instrument produces data with systematic over- or under-estimates of temperature or even more complicated biases by scene-type (e.g., different biases over ocean, land, and ice). Before being used, such biases should be quantified and ameliorated.

(f) **Data corruption.** Observations may have unexpectedly large errors. An instrument may malfunction, and the data assimilation system should be able to detect when an observation is clearly unrealistic and discard it.

(g) **Network non-stationarity.** The sum total of the observations, i.e., the “observation network,” changes over time. In the recent past we have added more and more satellite data; thirty years ago we had little more than surface observations and weather balloons. Prior to the late 1940’s, we had no weather balloons. While new information is desirable, reanalysis users may be using the data to detect trends. A particular variable, say stratospheric temperature at a particular location, may have been largely un-observed prior to the advent of microwave radiances around the year 2000. Hence, in the absence of observations the analysis may reflect the prior forecast and its errors. When the new satellite data are assimilated, suddenly observational data are available, and the temperature state at that particular location can now be more accurately estimated. This could result in an unrealistic jump in the state of reanalyses at that location, complicating the interpretation of trends from reanalysis data.

(h) **Data availability.** Observations must be available and in the form used by the reanalysis software; if they were generated by a particular researcher but never put into the database of observations to be assimilated, they cannot positively affect the reanalyses.

(i) **Correlation of errors.** Observations may have been assumed to have independent errors, when in fact they do not. If two observations have correlated errors when the reanalysis system

has assumed they were uncorrelated, the system will over-weight the influence of these observational data.

(j) **Profusion.** Satellites may provide more data than can be effectively used. They may provide data at such a fine spatial resolution, or sampling so many different frequencies, that the assimilation procedure cannot use them all and generate a state estimate without undue computational expense. Some types of satellite data in cloudy regions must be eliminated from future use.

2.3 Challenges with the use of forecast information in reanalyses

The other main type of information used in data assimilation is a forecast, or sometimes multiple forecasts. The prior forecast is important in providing an initial gridded estimate of the state, and in regions with sparse observations, the forecast is heavily weighted. Some common challenges with the forecast data include:

(a) **Inaccuracy due to computational expense.** The higher the resolution of the forecast (i.e., the smaller the grid spacing), the more computationally expensive it is to generate the forecast. Also, the more the forecast model includes complex representations of the effects of sub-grid-scale phenomena (known as “parameterizations” in the language of weather prediction), the more computationally expensive the simulation. In recent years, data assimilation schemes have also commonly relied on the computation of ensembles of prior forecasts in order to provide not only an estimate of the most likely forecast state but also to quantify the uncertainty in that estimate. Here, the more members generated, the smaller the sampling error of uncertainty estimates. This further increases the computational expense of generating the underlying forecasts.

(b) **Bias.** Though modern forecast models are computationally expensive, it is still common for them to include simplified representations of the physical processes; a forecast model cannot represent the interaction of the winds with every mountain, every tree, every blade of grass. Even if they could, the physical laws governing those interactions may be known imperfectly. Consequently, the prior numerical forecasts are sometimes biased, i.e., the forecasts are systematically too warm or too cold, too wet or too dry. The underlying data assimilation procedure commonly assumes that the forecasts are unbiased, and if this bias is not ameliorated, the bias will be reflected in the reanalyses.

(c) **Diminished representation of smaller scales of motion.** Suppose the assimilation procedure is generated on a grid with points separated by ~ 10 km. The underlying numerical methods used in the forecast model make it difficult to properly model the amplitude and phase speed of waves near the scale of the grid; commonly for a grid spacing of Δx , waves smaller than $6-8 \Delta x$ are mis-modeled and consequently strongly damped. Hence, the forecasts used in the assimilation are lacking in variability at the smaller scales of motion, and in the absence of dense observational data, the resulting analyses will lack this variability as well.

2.4 Uses of reanalyses for Arctic research

We now turn our attention to common uses of reanalyses in the Arctic. Knowledge of the large-scale atmospheric state provided by reanalyses is often crucial to understanding the drivers of atmospheric variability and change and the interactions between the atmosphere and other climate system components (sea ice, land ice, ocean, and the biosphere). Reanalyses provides continuous and consistent meteorological information in space and time; despite known deficiencies, they represent our synthesis or the best estimate of atmospheric state, and in some cases they provide the only available estimate. Because of the wide array of uses and the enormous importance of atmospheric conditions to all atmospheric problems, the accuracy and fidelity of reanalyses is one of the most important challenges and biggest limiting factors in climate science. Improving reanalysis would help almost all avenues of Earth system study.

Reanalysis uses range from understanding the linkages between short-time scale processes (e.g., Zelinka and Hartman 2009; Taylor 2014) as well as weather and climate variability and associated water vapor and cloud feedbacks (e.g., Bony et al. 2004; Bony and Dufresne 2005; Su et al. 2006; Brown et al. 2016). Reanalysis has helped to further our understanding of extratropical cyclones and specifically evaluating their structure within climate models (e.g., Catto et al. 2010; Naud et al. 2012). Reanalysis products have also been used to inform science requirements for future satellite missions (e.g., Wielicki et al. 2013). Globally available atmospheric state information is critical for understanding linkages between atmospheric processes, such as clouds, and meteorological variability (e.g., Li et al. 2014a). Reanalysis data products also have applications in the assessment and attribution of trends in many variables such as surface temperature, precipitation, and evaporation (e.g., Bronnimann et al. 2012; Vose et al. 2012; Zhang et al. 2012; Boisvert et al. 2015). Reanalysis atmospheric state information has many modeling applications for regional climate models, cloud resolving models, and large eddy simulation models (e.g., Dethloff et al. 1996; Rinke et al. 2006; Schoetter et al. 2012; Fettweis et al. 2013).

Meteorological reanalyses are vital to studies of Earth's energy budget. Trenberth et al. (2009) extensively used reanalysis-derived radiative and surface turbulent fluxes to analyze Earth's global energy budget. NASA Clouds and Earth's Radiant Energy System (CERES; Wielicki et al. 1996) data products use reanalyses in their surface radiative flux data products (e.g., Rutan et al. 2009). Global, vertical temperature and humidity information from reanalyses have been used to drive radiative transfer calculations that further our knowledge of the surface radiation budget and water cycle (L'Ecuyer et al. 2008; Kato et al. 2010; Kato et al. 2011) including the influence on Greenland surface melt (e.g., Van Tricht et al. 2016). Reanalysis data sets played a key role in constraining the observed state of the global energy budget and water cycle in the early 21st Century (Rodell et al. 2015; L'Ecuyer et al. 2015).

Reanalysis may be most critical for understanding the Arctic climate system due to the lack of conventional data sources. Studies of atmospheric variability in the Arctic and interactions between the atmosphere and other components of the Arctic and global climate system rely critically on reanalysis data products (e.g., Ogi and Wallace 2007; Francis et al. 2009; Serreze

and Barry 2011; Hegyi and Deng 2011; Stroeve et al. 2012; Deng et al. 2013; Li et al. 2014b; Hassanzadeh and Kuang 2015). Specifically, reanalysis data sets played a critical role in our understanding of the contributions from the atmospheric circulation, clouds, ocean, and sea ice state to the 2007 sea ice minimum (Serreze et al. 2007; Schweiger et al. 2008a, Kay et al. 2008; Ogi and Wallace 2012; Dong et al. 2014; Letterly et al. 2016). Reanalysis data sets are at the forefront of the current debate over the impacts of rapid Arctic climate change on the mid-latitude jet stream and extreme weather events (Francis and Vavrus 2012; Barnes 2013; Screen and Simmonds 2013; Screen 2013; Francis and Vavrus 2015; Overland et al. 2015; Screen et al. 2015; Francis and Skific 2015). Reanalysis serves as an important data source for constraining Arctic Ocean clouds and radiative fluxes (e.g., Kay and L'Ecuyer 2013), the Arctic large-scale energy budget (e.g., Serreze et al. 2007), as well as on the surface turbulent fluxes (Inoue et al. 2011; Boisvert et al. 2012; Boisvert et al. 2013; Chaudhuri et al. 2014). Further, reanalyses played a role in the investigation of potential feedbacks between sea ice and Arctic clouds (e.g., Schweiger et al. 2008a; Cuzzone and Vavrus 2011; Barton et al. 2012; Taylor et al. 2015). Reanalysis data sets also serves as an important component of climate model evaluation (e.g., Randall et al. 2007; Gleckler et al. 2008; Flato et al. 2013, Barton et al. 2014; Cesana et al. 2015). Reanalyses have also been used for studying the Greenland ice sheet mass balance by providing surface temperature and precipitation estimates as well as serving as forcing to regional climate model simulations and analysis (e.g., Fettweis et al 2013; Tedesco et al. 2013; Lim et al. 2016). Comparative studies have been performed on sea-ice trends from reanalyses (Chevallier et al. 2016) and other quantities such as temperature and clouds (e.g. Jakobson et al. 2012, Lindsay et al. 2014, Bauer et al. 2014, Simmons and Poli 2015).

These example uses of and comparisons of reanalysis are far from exhaustive, but they do exemplify how atmospheric reanalyses are one of the most important sources of atmospheric state information used within climate science literature. Due to the lack of traditional observations in the Arctic, the importance of reanalyses to further scientific understanding and attributing reasons for the rapid and unprecedented changes in surface temperature, sea ice, and land ice is more critical in the Arctic than any other region.

3. Reanalyses and Observations

Section Summary

The observational record is critical to the reanalyses; the data quality and assimilation as well as the numerical model determine the accuracy of the reanalysis product.

Observations from both conventional instruments and satellites are important for reanalysis.

Continued collection and reprocessing of data records, and accessing the strengths, limitations and uncertainties of the reprocessed observations is required to improve the usefulness of the observational data in reanalysis, in particular for the data-sparse Arctic region.

New potential observations over the Arctic are important for the Arctic reanalysis, which provides clues for our further understanding of the Arctic changes.

Reanalysis depends upon both historical and operational archives of observations and newly reprocessed sets of observations being produced at meteorological research centers around the world. The challenge in using observations for reanalysis has been discussed in the previous chapter, including representativeness, data inhomogeneity, indirectness, unusefulness, bias, data corruption, network non-stationarity, data availability, correction of errors, and profusion. The data considered for global reanalyses include but are not limited to: (a) the best catalogues of data from the Research Data Archive (RDA) at NCAR (National Center for Atmospheric Research), USA; NCEI (the National Centers for Environmental Information), USA; NESDIS (National Environmental Satellite, Data, and Information Service), USA; NSIDC (National Snow and Ice Data Center), USA; and the Nansen Center, Norway; and (b) the reprocessed modern datasets from operational centers (Bureau of Meteorology, Australia; the European Centre for Medium-Range Weather Forecasts; Europe Space Agency; European Organisation for the Exploitation of Meteorological Satellites; Japan Meteorological Agency; and NOAA National Centers for Environmental Prediction, USA).

3.1. Observations currently assimilated

A reanalysis reverts to model forecast data in the absence of observations. Hence, characteristics of the observing system are critical to the ability of the reanalysis system to depict conditions. Typically, a reanalysis combines many types of observations, with the majority of data obtained from satellite observations. In the Arctic, meteorological conditions may impede the use of satellite data at low levels of the atmosphere. For thermal sensors, the cold lower troposphere creates ambiguity in distinguishing clear and cloudy-sky conditions. Passive microwave sensing is useful for detecting the presence of surface ice cover and for estimating atmospheric temperatures. However, the inability to correctly assign a surface emissivity impedes the use of these sensors in much of the Arctic troposphere. As a result,

reanalyses are least aggressive in using satellite radiance data near the surface in polar regions. This places an added importance on non-radiance data sources and unbiased estimates from the first-guess forecast. Figure 1(a,b) shows the spatial and temporal variability of non-radiance observations over the Arctic. These observations, as listed below, include land stations, drifting buoys, aircraft and profiler observations. Two forms of satellite-derived non-radiance observations are of importance in the Arctic: atmospheric motion vector data derived from Moderate Resolution Imaging Spectroradiometer (MODIS) data (Key et al. 2003, Bormann and Thepaut 2004) and wind data obtained from active microwave radar sensors (scatterometer). While the location of receiving stations in high latitudes provides added coverage for scatterometer data in the Arctic, few sensors are active during most of the MERRA period 1979-2015. A snapshot of the in situ observing system shown in Fig. 1(a) shows the significant coverage over land surfaces, particularly northern Europe and Alaska. Beyond 70°N, however, surface observations become restricted to those of the International Arctic Buoy Program (Colony and Rigor 1993). Note the coverage is greater on the North American side of the Arctic. It should be clear from Fig. 1 that the Arctic is a region of in situ data scarcity. Apart from the atmospheric motion and stratospheric aircraft data, the amount of in situ data is less than one-quarter of that available in midlatitudes. As July 2007 was part of the International Polar Year, the number of in situ observations for the month is greater than for other times in the reanalysis period. Below is a summary of the observations currently assimilated in the global and/or regional systems.

3.1.1. Conventional observing systems

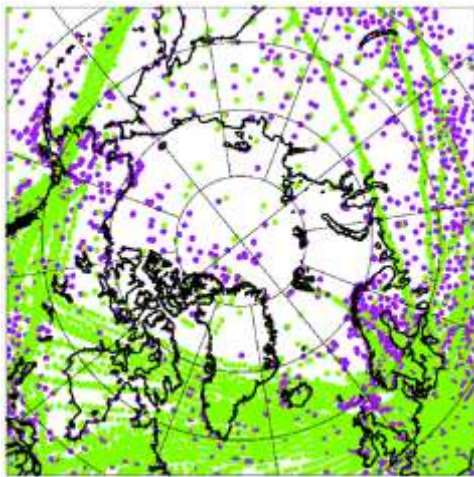
The conventional observing system is crucial for reanalyses before the satellite era; even after the satellite era it still serves as an indispensable constraint to the atmospheric reanalysis and data are used to correct biases in other observing systems. Conventional observations include *in situ* measurements from radiosondes, pilot balloons, aircraft, and wind profilers, and from ships, drifting buoys, and land stations, as summarized below.

- *Surface observations from land stations:* snow depth, pressure, near-surface air temperature, relative humidity and wind (speed and direction)
- *Ships and drifting buoys:* pressure, near-surface temperature, relative humidity and wind (speed and direction)
- *Radiosondes and pilot balloons:* In situ measurements of upper air temperatures, wind (speed and direction), and specific humidity
- *Aircraft and ACARS (Aircraft Communications Addressing and Reporting System) data:* Upper air temperatures, wind (speed and direction), and specific humidity
- *Wind Profiler:* Wind speed and direction
- *METAR (Meteorological Aviation Report) automated reports:* Temperature, dew point, wind (speed and direction), precipitation, cloud cover, cloud heights, visibility, and barometric pressure
- Point estimates of sea-level pressure extracted from a manual analysis; created at the Australian *Bureau of Meteorology*

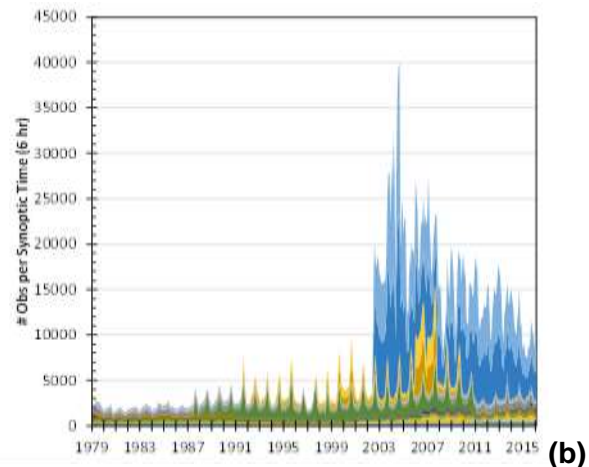
3.1.2. Satellite radiance-based observing systems

The majority of the observations used for reanalysis originates from satellites and increases over time. Satellite observations include radiance measurements (quantified as brightness temperatures) from polar-orbiting and geostationary sounders and imagers. Most satellite radiance data require substantial adjustments for bias so that they can be usefully assimilated in the reanalysis system (e.g. Saha et al 2010, Dee et al, 2011). Below is a list of the sources of satellite radiance data.

- *TOVS (TIROS Operational Vertical Sounder) radiances*
- *MSU (Microwave Sounder Unit) radiances (recalibrated)*
- *ATOVS (Advanced TIROS Operational Vertical Sounder) radiances*
- *GOES (Geostationary Operational Environmental Satellite) radiances*
- *Aqua AIRS (Atmospheric Infrared Sounder), AMSU-A/B (Advanced Microwave Sounding Unit-A/B), HIRS (High-Resolution Infrared Sounder), and AMSR-E (Advanced Microwave Scanning Radiometer Earth Observing System) data*
- *MetOp (Meteorological Operation) Infrared Atmospheric Sounding Interferometer, AMSU-A and Microwave humidity sounder data*
- *CHAMP/COSMIC (Challenging Mini-satellite Payload and Constellation Observing System for Meteorology Ionosphere and Climate) GPS (Global Positioning System) radio occultation data*



(a)



(b)

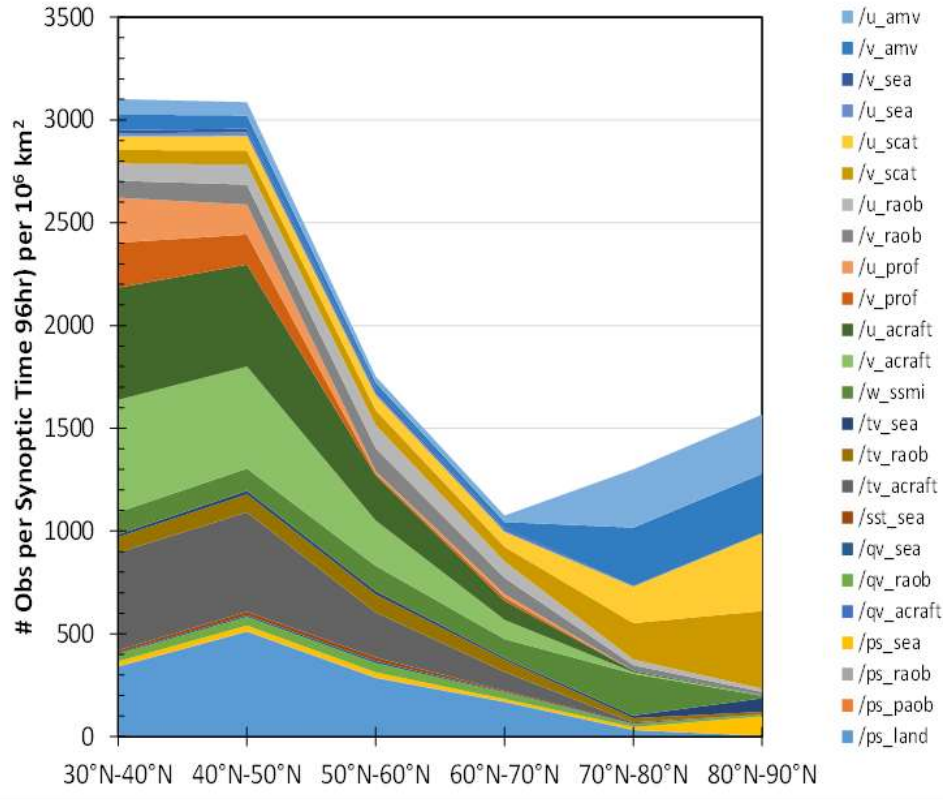


Figure 1. (a) The spatial distribution of MERRA in situ observations for 00UTC 19-July 2007, determined from a gridded $\frac{1}{2}^\circ$ summary of input data (Bosilovich et al. 2015). Surface observations from land stations and marine platforms are indicated in purple. Upper air aircraft, rawinsonde, and profiler data are indicated in green. A 10° latitude by 30° longitude grid is indicated. (b) The number of non-radiance observations per synoptic time for the north polar region ($70^\circ\text{N} - 90^\circ\text{N}$) from MERRA reanalysis, averaged per month. (c) The number of non-radiance observations per synoptic time per 10^6 km^2 from MERRA reanalysis for July 2007, averaged for 10-degree latitude zones. Non-radiance observations include satellite-derived atmospheric motion vectors (amv), station pressure (land), marine-observed wind and pressure (sea), scatterometer-derived wind (scat), rawinsonde wind, temperature, and pressure (raob), wind profiler (prof), and aircraft wind and temperature (acraft).

3.1.3. Other satellite data

Other satellite data include atmospheric motion vectors derived from geostationary satellites; scatterometer wind data; ozone retrievals from various satellite-borne sensors; and snow cover, sea ice concentration, and sea surface temperature data, as summarized below.

- *Ocean surface wind datasets from the European Space Agency ERS-1/AMI (European Remote Sensing Satellite-1 Active Microwave Instrument) and the ERS-2/AMI, the NASA QuickSCAT/SeaWinds Scatterometer, and the NRL (Naval Research Laboratory) WindSat scatterometer data*
- *Atmospheric motion vectors derived from geostationary satellite imagery; the imagery in GTS (Global Telecommunication System) from GOES, METEOSAT, and GMS (Geosynchronous Meteorological Satellite) satellites; and MODIS polar wind data*

- *SSM/I (Special Sensor Microwave Imager) ocean surface wind speed derived from the SSM/I brightness temperature data*
- *Ozone retrieved from Solar Backscattered UltraViolet; Global Ozone Monitoring Experiment on ERS-2; and Ozone Monitoring Instrument, Total Ozone Mapping Spectrometer and Scanning Imaging Absorption Spectrometer for Atmospheric Cartography*

3.1.4. Other analysis data

- *IMS (Interactive Multisensor Snow and Ice Mapping System) snow cover:*
- *Precipitation from the Climate Prediction Center (CPC) Merged Analysis of Precipitation and CPC unified global daily gauge analysis*
- *Ocean waves height from ERS-1, ERS-2, Environmental Satellite, Jason-1, and Jason-2*
- *Sea ice concentration*
- *Sea surface temperature*

3.2. Process and criteria for including observations and data formats

Observations are essential for reanalysis products, as their quality and availability ultimately determine the accuracy that can be achieved. It is not always easy to determine which observations should be used in the reanalysis; dealing with the complexities and uncertainties in the observing system, including data selection, quality control and bias correction, can have a crucial effect on the quality of the reanalysis data. In general, all observations used in reanalyses are subject to a suite of quality control and data selection steps (e.g. Dee et al. 2011). If the data are unreliable, or cannot be usefully interpreted by the data assimilation system, they may be excluded.

For example, in ERA-Interim reanalysis the following data are excluded:

- All near-surface wind observations over land (because of concerns of representativeness);
- Surface pressure observations over high terrain (again, representativeness);
- Radiosonde observations below the (smoothed) model surface;
- Near-surface relative humidity observations at nighttime or over high terrain (known to be unrealistic);
- Radiosonde specific humidity observations in extreme cold conditions ($T < 193\text{K}$ for RS-90 sondes, $T < 213\text{K}$ for RS-80 sondes, $T < 233\text{K}$ otherwise).

Another example, because it is very difficult to assimilate 2m temperature (T2m) over land, CFS reanalysis did not assimilate T2m; ERA-40 only postprocessed the observed T2m into their output. The following questions should always be considered before an observational data set goes into the reanalysis.

- What types of observations are used?

- What are the time constraints (availability) for observations?
- What types of data are restricted from reanalyses?
- What should be done about data inconsistency due to instrument change?
- What data format is used?
- What should be done to deal with non-standard observations and difficulty in assimilation?
- Which global set of reanalysis is used to drive the regional reanalysis for the boundary conditions?

Regarding data format, currently the Binary Universal Form for the Representation of meteorological *data* (BUFR) is the only internationally recognized WMO standard observation format, which was designed specifically for the storage and transmission of observed data, and has been adopted in one way or another by all major NWP centers over the last thirty years. As part of an NWS modernization during the 1990's, most of the data processing within National Centers for Environmental Prediction (NCEP) was converted to use BUFR and General Regularly-distributed Information in Binary form (GRIB) as the basic formats for observations and gridded products, and remains to this day. All previous NCEP reanalyses, as well as the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis, MERRA and Japan Meteorological Agency projects have used BUFR for observation transmission or processing, or both. BUFR and GRIB have greatly facilitated and expedited international exchanges of large datasets for reanalysis intercomparison and other purposes. Seeking new approaches in storing and processing observations is an active area of research and development, especially given the advances made and anticipated in computer hardware and storage technologies. The quest to develop relational data processing for observation databases, in particular, is in progress. It is very likely that the bit string fundamentals and the self-describing storage organization, which are the part and parcel of the BUFR format, will remain important while NWP operations transition to a new world of database interactivity.

3.3. Identify new or potential observations for inclusion

As seen in Fig. 1, the Arctic is a region of observational data scarcity. In general, observational data may be distinguished as information that can be directly assimilated into the reanalysis product, and observations that are not but are otherwise useful for validation or are conducive to model development. Both of these types of observations are critically important to the development of reanalysis. More observations for direct input into reanalyses are desirable. Satellite observations partially compensate for in situ data scarcity, but these data are affected by many factors, such as cloudiness for passive infrared sensors. New observing systems must be robust, easy to maintain, and be able to operate in harsh conditions. Quality checking should be done appropriately at each processing stage. All these are important parts of assembling a high quality data source. It is recognized that there is a considerable amount of Arctic observing data – obtained from in situ observations and other sources – that is not currently being assimilated. Potentially, Arctic researchers may have collections of observations taken from field studies that may be considered for inclusion in future reanalyses. New types of observations must be codified, securely transmitted and archived in order to be useful for reanalysis. For reanalyses, the inclusion of new observation types requires the generation of numerical

operators for the data assimilation process. Essentially, this requires a characterization of the measurement, including its uncertainty. Standard meteorological observations such as rawinsonde measurements are conducive to data assimilation, while more non-standard measurements are not. In the assimilation of new observations, reanalyses are constrained by expertise, time, and cost. The cost of their development may be substantial, measured in person-years of effort. If the observations are extensive and provide measurements of aspects of the system state that were previously unobserved, the subsequent improvement in reanalysis quality is considered worth the time and effort to develop new observation operators. If the observations are low quality or redundant, and do not provide information to improve a system state that is already well defined, then it is probably not worth much extra effort. As noted previously, many standard observations of near-surface variables are not incorporated in all reanalyses. These include observed gauge precipitation, which is problematic in polar regions, and near-surface air temperatures over land, which are difficult to obtain and reconcile with the surface energy budget computation and with local topographic differences with the assimilating model. The degree of impact on reanalysis is related to the observation's spatial representativeness and duration.

Two main avenues for incorporating new sources of data are through the Global Telecommunication System (GTS), and through reanalysis access to established data repositories, notably the Research Data Archive (RDA) at the National Center for Atmospheric Research. We find that both avenues are likely to be problematic for the incorporation of novel observations into future reanalyses.

Ideally, all potential observations should be sent via the GTS. This is the most reliable means for potential assimilation, and perhaps the only means for inclusion into ongoing reanalyses. However, the procedures for transmission are complex, and it seems unlikely that this complexity would be easily surmounted in the course of preparing for field work.

Data repositories such as the RDA were accessed during the production of early reanalyses (e.g., Kalnay et al. 1996). But subsequent reanalyses typically rely on the data that had been previously obtained, rather than re-accessing these repositories. Thus any information subsequently placed in these repositories is likely not part of newer reanalyses. It would seem necessary to have a mechanism to identify valuable, new observations for reanalyses to be constructed. It may be necessary for this topic to be generally addressed in a manner not limited to the Arctic, perhaps through the WCRP Data Advisory Council (WDAC).

Briefly, we comment on several Arctic observing systems and their significance in relation to reanalyses.

- The Greenland Climate Network (GC-Net) refers to a network of automatic weather stations on the Greenland Ice Sheet, which was started in 1995 (Steffen and Box 2001). GC-Net observations are not provided over the GTS; for this reason they are not incorporated into many reanalyses (for example, Fig. 1). GC-Net data have been used in the assessment and improvement of the ice sheet surface representation in reanalyses (Cullather et al. 2014),

and are widely used for other studies of the Greenland Ice Sheet. Assimilation of GC-Net pressure data is likely to be beneficial to reanalyses, particularly for the varied surface conditions on the southern part of the ice sheet. A critical assessment of data quality needs to be undertaken to understand the uncertainty of other variables, which has been identified as being problematic (e.g., Hanna et al. 2014).

- The International Arctic Buoy Program (IABP, Coloy and Rigor 1993) has deployed buoys regularly since 1992, with roughly 12 to 30 operating in any given year (Rigor et al. 2000). These data are available via the GTS. Arctic buoys are the primary source of in situ observational data for the central Arctic for reanalyses, as well as NWP (numerical weather prediction). As with GC-Net, a continued assessment of data quality would be valuable.
- Icebreaker-based studies, including SHEBA (Tjernström and Graversen 2009, Cullather and Bosilovich 2012), ASCOS (Wesslén et al. 2014, de Boer et al. 2014), ACSE (Tjernström et al. 2015), SeaState (Thompson 2015), and potentially MOSAiC (Barber et al. 2015), are valuable studies for the evaluation of reanalyses. This is due to the typical availability of full atmospheric column measurements that are made, which allow for a detailed understanding of processes for model and reanalysis diagnosis. These studies are also generally sustained over periods ranging from several weeks to a year. In particular, surface energy budget assessments over the pack ice are important for assessing the impact of changes in model cloud parameterizations.
- Aircraft studies, including Operation IceBridge (OIB, Medley and Lawrence 2011) and the Arctic Radiation-IceBridge Sea and Ice Experiment (ARISE, Smith et al. 2016), have been used to assess reanalysis representations of physical processes including annual accumulation and Arctic cloud physics. While preliminary, the data obtained from ARISE appear to have been useful for understanding current shortcomings in reanalysis model physics.
- Long-term energy flux stations, including Atmospheric Radiation Measurement sites in Alaska and the International Arctic Systems for Observing the Atmosphere (IASOA, Uttal et al. 2016), are used as key validation points for surface energy fluxes. The value of these observations is in the longevity of the sites, but also in the representativeness of the measurements to the surrounding area (Starkweather et al. 2013). Measurements of surface fluxes are important for understanding the impact of cloudiness on the reanalysis.

There are other activities planned which may also have bearing on improving reanalyses in the Arctic. Preliminary planning has occurred for the Year of Polar Prediction (YOPP), an international effort to improve environmental prediction capabilities for the polar regions (Goessling et al. 2016). These efforts include intensive observing periods. Potentially, YOPP could include well-posed forecast and analysis experiments. Although much remains unresolved, YOPP objectives are consistent with those needed for the improvement of reanalyses. This includes interaction between modelers and observationalists in order to understand relevant issues with the observing system, and the identification of areas where analyses and models need to improve.

Ana4mips (Reanalysis for Model Intercomparison Projects) is a project to collect data from selected major reanalysis efforts. Each dataset is reformatted similarly to facilitate comparison

with each other and with the CMIP models (Potter et al. 2014). This would aim to provide an end-to-end system for the comparative study of the major reanalysis projects. This would be very useful for identifying and understanding differences between reanalyses in the Arctic, and elsewhere.

Finally, the NOAA Arctic Test Bed (ATB) has been designated to focus on mitigation science and technology gaps in the Arctic as well as forecast challenges. The ATB aims to maintain awareness of scientific advances and new techniques for improved data-analysis and forecasting. These activities address current challenges for reanalyses in the Arctic.

4. Assessment of Current Reanalyses

Section Summary

Reanalyses are widely used in Arctic research despite known flaws.

Many reanalysis studies and applications cannot be conducted via other means.

The evaluation of Arctic reanalyses is typically performed anecdotally.

Reanalyses suffer from chronic issues: the treatment of atmospheric moisture including precipitation and clouds, near-surface air temperatures, and temporal discontinuities.

A variety of Arctic atmospheric phenomena are not spatially resolved by current global reanalyses.

Artificial temporal discontinuities occur from the segmented processing of reanalyses, changes in the observing system, and abrupt changes in boundary conditions.

Segmented processing requires rapid, accurate initialization, which may be difficult or impossible for some aspects of the cryosphere. Reanalyses containing these features may cover shorter periods or require longer processing time.

Discontinuities resulting from changes in the observing system are an area of active investigation. Methods to constrain reanalyses by other means, such as global mass budgets, are being investigated. Model bias is thought to be an important source of these discontinuities.

As indicated in the Section 2, atmospheric reanalyses are widely used in Arctic research and have been useful for a variety of studies. These include physical process-related investigations, such as the examination of the large scale circulation (Thompson and Wallace 1998, Hurrell et al. 2003), and the identification of mechanisms related to the changing sea ice cover (Ogi and Wallace 2007). They have been used in the evaluation of models, including global climate

models used by the IPCC (Flato et al. 2013, Walsh et al. 2002, Kay et al. 2012). Reanalyses have also been used as boundary conditions for a variety of models, including those for the Arctic regional atmosphere (Rinke et al. 2006, Fettweis et al. 2013, Ettema et al. 2009), ocean circulation and sea ice (Kreyscher et al. 2000), land surface (Qian et al. 2006), ice sheets (Rutt et al. 2009, Stone et al. 2010), and biogeochemistry (Manizza et al. 2009). Importantly, they are also used in the production of satellite-derived data sets (Kato et al. 2013, Wang and Key 2003). Many reanalysis studies and applications cannot be conducted via other means. Reanalyses continue to be used – in spite of known shortcomings – because of the information that they provide and because of their consistent, gridded format in time and space (Rienecker et al. 2012).

The evaluation of reanalyses is typically performed anecdotally in the context of these uses. Reanalyses are also evaluated against new or unique observational data such as in field studies (Wesslén et al. 2014, Jakobson et al. 2012). Assessments may also occur by production centers in the course of introducing a new reanalysis (Bromwich et al. 2016, Cullather and Bosilovich, 2011). Each of these methods is limited by resources and the availability of independent, validating data. Reanalyses are complex and voluminous; their evaluation relies to considerable degree on external assessments. Studies evaluating multiple variables from two or more reanalyses over an extended period of time represent a substantial effort and are generally rare.

For the Arctic, evaluations of early reanalyses – NCEP/NCAR and ERA-15 (Table 1) – focused mainly on surface temperature and precipitation due to the availability of comparative, in situ observations and the considerable interest in the trend of these variables. Atmospheric budget quantities were also investigated as an important metric for understanding reanalyses (e.g., Adams et al. 2000, Walsh and Chapman 1998). Over the course of an atmospheric model integration, properties including moisture, mass, and energy are strictly conserved (e.g., see Fig. 2). The ingestion of new observations into the system at the analysis time breaks this conservation. The lack of conservation in a reanalysis is attributable to inconsistencies between model and observations (Dee et al. 2014). In early reanalyses, the Arctic surface moisture flux (the net of precipitation minus evaporation) derived from the analysis and from the background model differed by around 35% of the analysis value (Bromwich et al. 2000). The more recent ERA-Interim has been found to differ by only around 7% (Jakobson and Vihma 2010). The bulk of this reduction appears to be due to improvements in physical processes in the model: specifically the annual cycle of sea ice albedo, which alters evaporation over the sea ice zone (Bretherton et al. 2000). In general, more recent reanalyses provide a reduction of atmospheric budget imbalances as compared to earlier versions due to improvements in physical representations in models and in the assimilation system. Reductions in these imbalances are a main focus of reanalysis development. In the course of ensuing evaluations, a number of issues have been identified as being endemic to several reanalyses and may be termed as chronic problems. These are briefly described below.

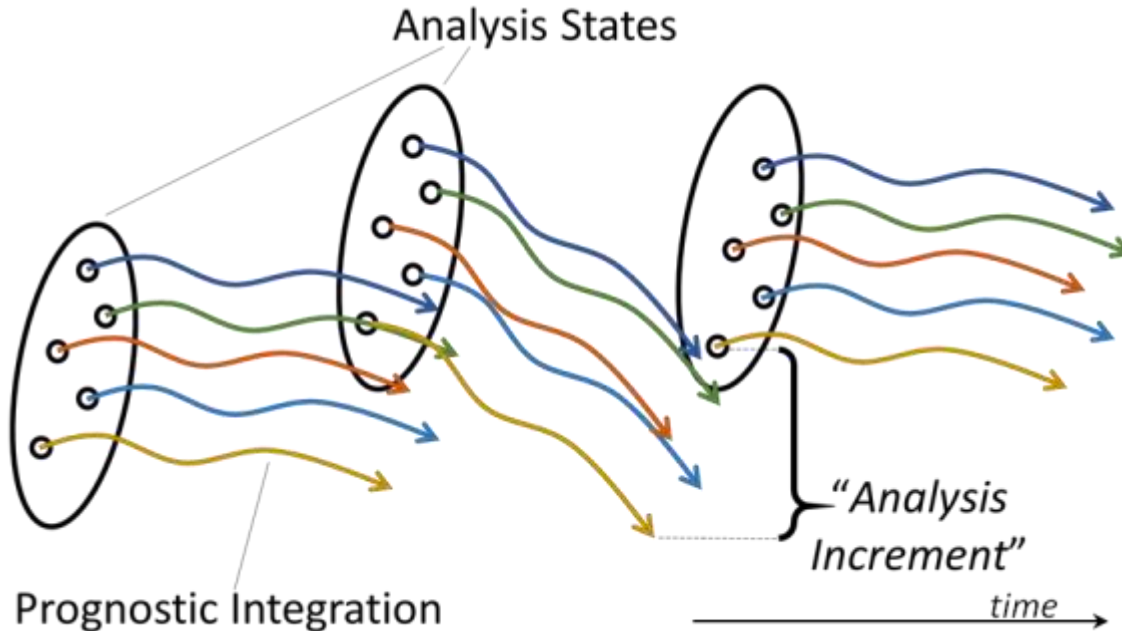


Figure 2. Schematic of a reanalysis system cycle.

4.1 Atmospheric moisture

Evaluations of reanalyses in the Arctic have consistently revealed difficulties in the representation of atmospheric moisture (Serreze et al. 2012, Sotiropoulou et al. 2015, Walsh et al. 2009, Lindsay et al. 2014, Jakobson et al. 2012, Serreze and Hurst 2000). Atmospheric moisture is a significant variable in the climate system. Through the assimilating model, moisture feeds back into other variables, including precipitation, evaporation, and the representation of **clouds** and resulting radiative fluxes, which affect temperature and other variables in the atmospheric column. As indicated previously, imbalances in the atmospheric moisture budget have been reduced in newer reanalyses through better model physical parameterizations. But this has not reduced the considerable spread among reanalysis for average precipitation and evaporation in the Arctic (Cullather and Bosilovich 2011). These differences are generally largest during the spring transition season. Among multiple reanalyses, cloud amounts and resulting surface radiative fluxes also show considerable spread (Walsh et al. 2009, Lindsay et al. 2014). The largest differences have been associated with shortwave radiative fluxes in the summer period. Assessments have shown that when the cloud cover is well represented, biases in radiative fluxes are small. Difficulties with the accurate representation of cloudiness and cloud processes are not limited to reanalyses in the Arctic, but are associated with a wide variety of models (de Boer et al. 2014, Wesslén et al. 2014) and climates (Flato et al. 2013). The Arctic is particularly challenging due to the presence of multiple phases of moisture, including large amounts of super-cooled liquid water (Morrison et al. 2012). The phase of cloud moisture has a substantial influence on resulting radiative fluxes. There is also significant stratification in Arctic cloud cover, such that vertical resolution is important (Luo et al. 2008). Recent efforts have focused on complex cloud parameterizations in which the cloud

particulate distribution as well as the moisture amount are determined (Morrison et al. 2012, Barahona et al. 2014). These methods provide an explicit determination of cloud phase as opposed to a simple thresholding based on ambient temperature. However, these methods also rely on adequate information on the distribution of aerosols, which can be challenging to obtain for reanalysis. Recent studies have suggested difficulty with advanced cloud representations in producing adequate surface fluxes (Luo et al. 2008, Sotiropoulou et al. 2015). Additional observational and modeling work is needed to understand best methods for Arctic cloud representations in reanalyses.

4.2 Air temperatures

Near-surface air temperatures are of obvious interest because of recent changes in Arctic conditions. It is known that reanalyses substantially disagree in both averaged Arctic temperatures for the annual cycle and in the long-term trend (Lindsay et al. 2014; Fig. 3). Figure 3 shows considerable range among available reanalyses, even for the large north polar region (70°N-90°N). The range becomes smaller in the later period. Seasonally, these differences are largest in winter, when observed temperatures significantly differ from the melting point, and there is a general tendency for reanalyses to be too warm in winter and too cold in summer relative to observations. Some reanalyses, including ERA-Interim, JRA-25, and JRA-55, assimilate observed 2-m temperatures. In the ERA-Interim system, these temperatures are also allowed to feed back onto the 3-dimensional assimilated fields. For other reanalyses, land station-observed near-surface air temperatures have not been assimilated because they are dispersed differently than other data on the GTS. This provides a challenging problem for near real-time analyses and necessitates a separate development for reanalysis. In the reanalysis model, the surface skin temperature is generally solved for over land and sea ice, while the sea surface temperature is a specified boundary condition over open water. The reasons for differences among reanalyses are complex but are related to the respective surface types.

Issues with temperatures over sea ice are related to how the surface is physically represented in the model, and the limited observational information available to characterize the surface. In computing the surface temperature via the energy budget, variables such as sea ice thickness and ice albedo are not assimilated, but must be prescribed or simulated. Most current reanalyses prescribe these variables, and the resulting representation of sea ice is generally simplistic. Processes within the boundary layer over sea ice also pose a considerable challenge for reanalyses in the absence of regular observations. Comparisons with in situ measurements have shown that reanalyses contain large errors in the vertical profiles of air temperature and humidity (Jakobson et al. 2012).

The surface representation over polar ice sheets has historically received less attention by reanalyses centers. A primary issue for Greenland surface temperatures is the use of invalid topographic boundary data which, in some reanalyses, may be in error by 600 m or more over large parts of the ice sheet (Cullather et al. 2016). Developments by regional modeling groups indicate an adequate representation of surface snow hydrology and a prognostic snow albedo

are necessary for the reasonable representation of surface conditions (Fettweis et al. 2013, Ettema et al. 2009).

There has been relatively less study of reanalyses in Arctic boreal forest and tundra zones. Most of the information used in model representations in these regions dates to the BOREAS field campaign (Sellers et al. 1997). The representation of terrestrial snow cover varies considerably among reanalyses (Bromwich et al. 2007), including heat conduction through the snowpack (Niu et al. 2011), snow metamorphism processes, and the subsequent impact on surface albedo. Precipitation amount and phase also play a role in differences among reanalyses. In recent global reanalyses, additional constraint has been provided to the terrestrial land surface. This is done either by correcting the land surface model for errors in screen-level observed temperatures and relative humidity (ERA-I), or by constraining soil moisture via the use of an observed precipitation (CFSR, MERRA-2), as noted in section 2. The Arctic presents a particular challenge to both of these methods due to the paucity of surface station data and the large uncertainty in observed precipitation. For these reasons, the constraint of soil moisture through the use of observed precipitation is currently restricted to lower latitudes. Other sources of uncertainty, including atmospheric moisture, clouds, and boundary layer processes, are present in the surface energy budget computation over all three surfaces. As seen in Fig. 1, the subarctic boreal zone lies between the dense midlatitude surface station network and specialized, non-radiance satellite derived products used in the high Arctic. Thus there are compelling reasons to explore methods for reanalysis improvement in these areas (e.g., Sellers et al. 2012).

4.3 Spatial resolution

Due to the high-latitude convergence of meridians, it is commonly assumed that the spatial resolution of reanalyses is less problematic in the Arctic than for other regions. But high spatial resolution is necessary for research purposes in the Arctic for several reasons. The Arctic is a location of complex topography with substantial contrast over short spatial scales between the ocean surface and steep coastal areas of the Canadian Arctic Archipelago, Norway, the Alaska Range, and the escarpment of the Greenland Ice Sheet, among other locations. In assessing local weather and climate conditions, these contrasts become significant. Recent, focused attention has been given to surface conditions over Greenland, including the characterization of surface melt in summer. This requires spatial resolution sufficient to resolve surface features, such as the equilibrium line that separates the accumulation and ablation zones. Studies have suggested a grid spacing of a few 10s of km is necessary (Ettema et al. 2009) which, as seen in Table 1, is beyond the resolution of many global reanalyses. For these reasons, as well as the inadequate representation of surface physical processes, the assessment of polar ice sheets was ceded to regional climate modeling in recent IPCC reports (Meehl et al. 2007, Church et al. 2013). Other phenomena requiring high spatial resolution associated with Greenland include the katabatic and barrier wind flows (Moore et al. 2016). Additionally, high latitudes are associated with mesoscale processes such as polar lows, which have horizontal scales of 200 to 1000 km (Rasmussen and Turner 2003). In general, these mesoscale circulations, which are considered key features of the Arctic climate, are not resolved in global reanalyses (Claud et al. 2007). The

case for higher spatial resolution is made by the need for examining these features, as well as requirements for boundary forcing of several types of models, including dynamic ice sheets (Schlegel et al. 2013) and mesoscale ocean integrations (Jung et al. 2014). These reasons provide a motivation for regional reanalyses (Bromwich et al. 2016) and for higher spatial resolution in global reanalyses.

4.4 Temporal discontinuities

Time series of chosen variables over the period covered by a reanalysis are especially desirable in studies for purposes of understanding recent Arctic climate variability, evaluating trends, examining precedence of selected phenomena, and for evaluating covariability among a selection of quantities. Reanalyses are proposed as useful for homogenizing the available observational record, but these products have contained notable failures. Artificial discontinuities arise for several reasons.

Because of the amount of processing required, reanalyses are often integrated in temporal sections – known as streams – to improve production efficiency. The merging of these streams into a unified time series may result in abrupt changes due to initial conditions used, which may not match with the end of the prior stream. Time scales of the synoptic atmosphere are generally on the order of days to weeks, but information may accumulate and linger in selected areas of the represented climate system, such as the upper atmosphere or – particularly – deep soil layers where the annual cycle wave may not penetrate (Wang et al. 2011). In these parts of the system, data assimilation provides less of a constraint. Regions of observational data scarcity such as the Arctic are more prone to abrupt changes resulting from the stitching of reanalysis streams. To improve initial conditions at the beginning of each stream, some amount of system spin-up may be allotted. The spin-up period would then be discarded when the streams are merged. But this spin-up time is limited by computational resources. Additionally, spin-up for the first chronological stream subtracts from the overall length of a reanalysis. The time required for spin-up in a reanalysis system is related to the system's complexity and is not straightforward. Less expensive methods for initialization may be employed. For example, initial conditions may be obtained from operational analyses which are similar to the system being used for reanalysis. Computational efficiency is a particular challenge in the move towards coupled reanalyses as it is unlikely that abrupt changes in the ocean state between streams can be avoided. Additional complexity in the modeled cryosphere, where rapid initialization is problematic, such as the representation of permafrost, sea ice thickness, firn and glaciated land all pose substantial challenges to segmented reanalysis processing. The alternative is to use non-segmented reanalyses.

A second source of artificial discontinuities is changes in the observing system. For in situ observations in data-sparse locations, the termination, introduction, relocation, or a change in instruments or procedures for a reporting station may affect reanalyses locally. Changes in remote sensing instrumentation occur periodically and may have a large-scale or global impact on a system. The degree of homogenization with the introduction of a new observing system is dependent in part on its compatibility with current observations, including spatial and temporal

observing changes, the assessment of error and other instrument characteristics, and biases of the background model. Perhaps the most notable discontinuity found in early reanalyses is the transition to the satellite era in 1979 (Fig. 3; Trenberth and Smith 2005). More recent, notorious discontinuities found in contemporary reanalyses include the introduction of the Advanced Microwave Sounding Unit in 1998 (Robertson et al. 2011). It has been speculated that these types of discontinuities mostly result from model bias, where the system reverts to an unphysical climatology in the absence of specific observations. Alternatively, it may be suggested that even a system with a perfect background model will not represent irregularly timed events without observations. Thus introducing or removing an observing system will alter the representation of such events in reanalysis. In this context, the discontinuity provides a measure of the uncertainty of a reanalysis given limited observations. Efforts to address discontinuities have relied on an advanced understanding of instrument characteristics and its impact on the system, but the total effect is difficult to anticipate prior to a reanalysis integration. A recent focus has been on constraining the reanalysis system through a global conservation of dry air and moisture in addition to observations (Takacs et al. 2016). These methods remain an active area of investigation.

A third source of discontinuity is associated with boundary conditions. In their present form, atmospheric reanalyses are dependent on supplied boundary conditions, including sea ice and sea surface temperatures, aerosols, and trace gas constituents. Regional reanalyses also rely on global reanalyses for lateral boundary conditions. For sea ice and sea surface temperatures, fields are often produced by systems not directly related to an atmospheric reanalysis. But, as with atmospheric reanalyses, they are produced in the context of their own system limitations, including observational scarcity, instrument uncertainty, and observing system discontinuities. While the problem gives an appearance of tractability, the requirements for reanalysis boundary condition data sets are severe and not always completely attained. They must span the entire length of the reanalysis, be homogeneous, and be consistent with complementary boundary data. For example, it is necessary for sea ice concentration to have consistency with sea surface temperatures. Atmospheric reanalyses may extend beyond the duration of a single boundary condition data set, so that it may be necessary to stitch together several products, which may also incur erroneous temporal artifacts (Wang et al. 2011). This source of discontinuity points to a need for extended, homogeneous reconstructions of these fields. The current limitations of boundary condition data sets are one motivation for coupled atmosphere-ocean reanalyses.

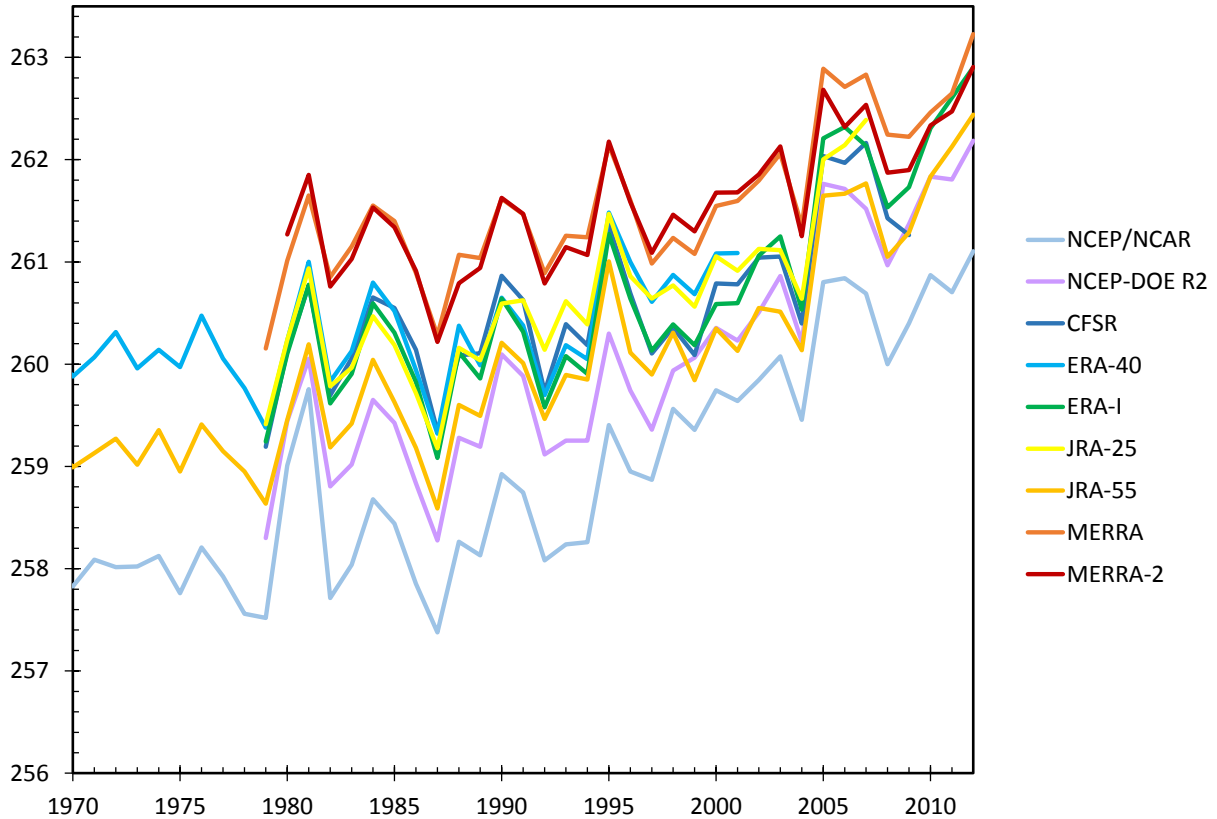


Figure 3. Time series of annual 2m air temperature (K) averaged for the north polar region (70°N–90°N) from nine global reanalyses.

5. Future Development of Arctic Reanalyses

Retrospective analyses (or reanalyses) provide a synthesis of the state and evolution of the Arctic climate system that is undergoing rapid change most likely as a result of anthropogenic forcing. The system components are the atmosphere, the Arctic Ocean consisting of ice covered and ice free regions, the snow-covered and frozen northern land areas that surround the Arctic Ocean and through which flow the major rivers that empty into the Arctic Ocean and help sustain the sea ice cover, and the Greenland ice sheet. The southern boundary of the “Arctic” is not well defined.

Reanalyses discussed here include those of the atmosphere typically coupled with a land surface model but with specified ocean and sea ice conditions, and fully coupled atmosphere-land-ocean-sea ice syntheses. The atmospheric reanalyses, in particular, can either have a global or regional focus, and most often span the start of the modern satellite era (in 1979) to the present. The century-scale reanalyses that rely on assimilation of surface observations, and ocean reanalyses that include the sea ice cover and specify atmospheric conditions, are not considered here. Areas of needed development are summarized in the next 3 paragraphs.

Regionally focused reanalyses centered on the Arctic aim to improve on global atmospheric reanalyses with higher horizontal resolution and better vertical resolution near the surface.

Better regional physics dealing with mixed phase clouds and the stable boundary layer is often employed, but many recent parameterization improvements need to be implemented. Data assimilation for atmosphere, land, sea ice, and Greenland are targeted at more observational usage and exploitation of new data types; for example, ASR has a comprehensive specified treatment of Arctic sea ice in terms of variable fraction, sea ice thickness, snow cover on sea ice, and seasonal albedo evolution due to melt pond formation (Bromwich et al. 2016). Data products should be focused on regional applications. Extreme weather (e.g., precipitation), temporal evolution (e.g., diurnal cycle), frequency statistics, and mesoscale and orographic phenomena (e.g., mountain precipitation) are better characterized by regional reanalyses (see http://www.rmets.org/events/regional-reanalysis-adding-detail-past-0?dm_i=2PRB%2C6Z2Z%2CU5PL5%2CLU9L%2C1) but have hardly been exploited. Regional reanalyses can inform the global reanalyses about desirable improvements to their treatment of Arctic physics and data assimilation.

Coupled atmosphere-ocean-sea ice-land reanalyses, both global and regional, are either under development or are being contemplated (Compo et al. 2016). Needed research includes development of fully coupled data assimilation, well posed and balanced initial conditions for all coupled models, and assurance of continuity between processing streams. Arctic focus topics are complete characterization of the Arctic Ocean and its sea ice cover, better treatment of snow covered land (e.g., accurate snow water equivalent descriptions) and permafrost regions, and capturing the seasonal freshwater discharge of the major northward flowing Arctic rivers (Ob, Yenisey, Lena, MacKenzie) that has a large impact on the stability of the sea ice cover. Coupled reanalysis potentially offers a better surface representation and improved ice/ocean/atmosphere coupled processes. Discontinuities from boundary ocean SST and sea ice data sets may also be eliminated. But with exceptions, ocean reanalyses in the Arctic have been uneven (Chevallier et al. 2016). Thus, the overall benefits of coupled reanalyses remain to be seen.

The Integrated Earth System Analysis (IESA) framework calls for coupled global reanalyses that include atmosphere, land surface, ocean, sea ice, aerosols, greenhouse gases, and reactive gases that influence air quality (Busalacchi and Kraucunas 2009). Arctic-specific aspects that need to be developed beyond those described under coupled reanalyses include deposition of black carbon on snow and treatment of the carbon cycle for the Arctic landscape.

6. Potential Improvements to Arctic Reanalyses

The following potential enhancements to Arctic reanalyses have been extracted from the prior sections dealing with background on reanalyses, reanalyses and observations, assessment of current reanalyses, and future development of Arctic reanalyses.

- There is compelling justification to undertake the next generation of reanalyses focused on the entire Arctic. Areas with R&D needs include making all Arctic data amenable to reanalysis use; the development of improved physical parameterizations in the underlying forecast model; the development of advanced data assimilation methods for the

atmosphere, sea ice, land surface, and Greenland Ice Sheet; and making computational capacity improvements that will permit extremely high atmospheric horizontal resolution (i.e., well into the non-hydrostatic domain, 5 km or less) to capture the topographic forcing and spatial gradients with fidelity. This approach will take advantage of the full spatial and temporal information from remote sensing products and will inform local communities about climate change affecting them.

- Development is needed to accurately predict mixed phase, liquid water, and ice clouds at spatial resolutions used by reanalyses, as well as the prediction of aerosols and their impacts on cloud formation. Dedicated field campaigns (surface based and airborne) are desirable to collect tailored observations characterizing the full annual cycle, especially targeting cloud condensation and cloud ice nuclei concentrations. Cloud prediction is one of the greatest impediments for much improved Arctic atmospheric modeling (process to Earth System models) and the production of reliable Arctic reanalyses.
- Joint observation-modeling-reanalysis-forecasting activities would be useful. Interaction between observers and modelers is important for understanding observational uncertainty and improving the model representation of physical processes. One activity that is in the advanced planning stage is the Year of Polar Prediction (YOPP), 2017-2019. Following the example of the Year of Tropical Convection (YOTC), a computer archive of all analyses, reanalyses, forecasts and observations during YOPP, and research using the archive to isolate model errors in the Arctic would be beneficial.
- Science suggests that reanalyses would be improved by expanding the sparse in situ station observing network. In particular, there is a need for daily rawinsonde observations for the central Arctic Ocean. There is an additional need for long-term (all-season) surface energy budget (radiative plus turbulent fluxes) monitoring for the evaluation of reanalyses in the sub-Arctic boreal zone region.
- Assessment of key in situ Arctic observing system components would be valuable. Observation characterization and quality control for automatic weather station and buoy observations would be useful for reanalyses. In particular, buoy data are recognized as a critical observing system for the Arctic, and it is vital that these observations be used correctly in reanalyses.
- Identification of new and past observations suitable for new Arctic reanalyses has substantial merit. This activity would include: (1) identify the availability, quality, and potential use of accumulated in situ observations from field studies and other means that are not presently being assimilated; (2) identify mechanisms for which future such observations would be incorporated, either through repository, GTS, or other means; (3) assess the potential use of other types of novel Arctic observations including MISR cloud track winds, GPS integrated precipitable water, and GRACE-derived land soil moisture; and (4) include groups such as the WCRP Data Advisory Council.

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- Research to improve atmospheric remote sensing techniques over ice and snow would increase the reliability of Arctic reanalyses. A particular focus for the Arctic is on the assimilation of satellite sounder data over sea ice covered by low-level stratus cloud. Research centered on improving methods for retrieving the maximum usable meteorological information for these locations would be useful.
- Arctic reanalysis intercomparison and evaluation reveal their strengths and weaknesses. To facilitate intercomparison in important new ways, reanalysis centers need to provide vertically-integrated atmospheric transports and convergence of mass, moisture, and energy. Intercomparison and evaluation activities including the [Ana4MIPS](#) program with the Earth System Grid project, and the [Climate Data Guide](#) at NCAR should continue to be developed.
- Given that a large percentage of reanalysis users are concerned with surface conditions (temperature, precipitation, winds, ice state, and so forth), and given that surface states in reanalyses are often biased, improvements to analysis and forecast systems will improve surface analyses. Questions that need to be addressed include: (a) What model and assimilation developments in the research community are ready for advanced testing and use in next-generation reanalyses? (b) What are there major gaps in our knowledge of Arctic surface and near surface processes? (c) How to remedy gaps in knowledge and develop improved parameterizations to remedy forecast bias? (d) Are new observation platforms necessary, and if so, what are the most key observations?
- Strongly coupled data assimilation methodologies are the foundation for the IESA framework for reanalyses. "Strongly coupled" reanalyses are clearly desirable for the Arctic, so as to better exploit the sparse observations. With strongly coupled assimilation, observations from the ocean or ice or land can affect the atmospheric state estimate, and atmospheric observations can change the ocean, ice, and land state. This potentially leads to improved consistency in the analyses of state components and the ability to leverage more observational data to improve the estimates of the atmospheric state. While a strongly coupled methodology is desirable, it is at the frontier of assimilation and modeling research. If the forecast interactions are mis-modeled between state components, the influence of observations from one state component on another will be mis-estimated. Hence, strong coupling will provide a very useful diagnostic of the quality of physics at interfaces and will help determine which physical parameterizations are in greatest need of improvement.
- Improved Arctic reanalyses will facilitate education and outreach to Arctic communities via compelling visualizations of the changing Arctic based on reanalyses. The great power and promise of reanalyses is only realized when a wide and diverse community including stakeholders is able to make appropriate use of these data.

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Appendix 1

Acronyms

4D-Var:	Four Dimensional Variational Analysis
ACARS:	Aircraft Communications Addressing and Reporting System
AIRS:	Atmospheric Infrared Sounder
AMI:	Active Microwave Instrument
AMSR-E:	Advanced Microwave Scanning Radiometer Earth Observing System
AMSU-A/B:	Advanced Microwave Sounding Unit-A/B
ARISE:	Arctic Radiation-IceBridge Sea and Ice Experiment
ASCOS:	Arctic Summer Cloud Ocean Study
ATB:	Arctic Test Bed
ATOVS:	Advanced TIROS Operational Vertical Sounder
BOREAS:	Boreal Ecosystem Atmosphere Study
BUFR:	Binary Universal Form for the Representation of meteorological data
CFS:	Climate Forecast System
CHAMP:	Challenging Mini-satellite Payload
CIRES:	Cooperative Institute for Research in Environmental Sciences
CMIP:	Coupled Model Intercomparison Project
CMIP6:	Coupled Model Intercomparison Project Phase 6
COSMIC:	Constellation Observing System for Meteorology Ionosphere and Climate
CPC:	Climate Prediction Center
DOE:	Department of Energy
ECMWF:	European Centre for Medium-Range Weather Forecasts
EOSDIS:	Earth Observing System Data and Information System
ERS:	European Remote Sensing Satellite
EURO4M:	European Reanalysis and Observations for Monitoring project
GC-Net:	Greenland Climate Network
GMAO:	NASA Global Modeling and Assimilation Office
GMS:	Geosynchronous Meteorological Satellite
GOES:	Geostationary Operational Environmental Satellite
GPS:	Global Positioning System
GRACE:	Gravity Recovery and Climate Experiment
GRIB:	General Regularly-distributed Information in Binary form
GTS:	Global Telecommunication System
HIRS:	High-Resolution Infrared Sounder
IARPC:	Inter-agency Arctic Research Policy Committee
IASOA:	International Arctic Systems for Observing the Atmosphere
IMS:	Interactive Multisensor Snow and Ice Mapping System
IPCC:	Intergovernmental Panel on Climate Change
LANCE:	Land, Atmosphere Near real-time Capability for EOS
METAR:	Meteorological Aviation Report
METEOSAT:	European Space Agency geosynchronous Meteorological Satellite

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MetOp:	Meteorological Operation
MISR:	Multi-angle Imaging SpectroRadiometer
MODIS:	Moderate Resolution Imaging Spectroradiometer
MOSAIC:	Multidisciplinary drifting Observatory for the Study of Arctic Climate
MSU:	Microwave Sounder Unit
NASA:	National Aeronautics and Space Administration
NCAR:	National Center for Atmospheric Research
NCDC:	National Climate Data Center
NCEP:	National Centers for Environmental Prediction.
NESDIS:	National Environmental Satellite, Data, and Information Service
NOAA:	National Oceanic and Atmospheric Administration
NRL:	Naval Research Laboratory
NSIDC:	National Snow and Ice Data Center
NWP:	Numerical Weather Prediction
QuikSCAT:	Quick Scatterometer
RDA:	Research Data Archive
SHEBA:	Surface Heat Budget of the Arctic Ocean
SSM/I:	Special Sensor Microwave Imager
SSMIS:	Special Sensor Microwave Imager Sounder
TIROS:	Television and Infrared Observation Satellite
TOVS:	TIROS Operational Vertical Sounder
WCRP:	World Climate Research Programme
WDAC:	WCRP Data Advisory Council
WMO:	World Meteorological Organization
YOTC:	Year of Tropical Convection
YOPP:	Year of Polar Prediction

Acronyms of Reanalyses

20CR:	NOAA-CIRES 20th Century Reanalysis
ASR:	Arctic System Reanalysis
CBHAR:	Chukchi-Beaufort High-Resolution Atmospheric Reanalysis
CFDDA:	NCAR Global Climate Four-Dimensional Data Atmospheric Reanalysis
CFSR:	NCEP Climate Forecast System Reanalysis
CFSv2:	NCEP Climate Forecast System, version 2
ERA-15:	15-yr ECMWF Re-Analysis
ERA-20C:	ECMWF's 20th Century Re-Analysis
ERA-40:	40-yr ECMWF Re-Analysis
ERA-Interim:	ECMWF's Interim Re-Analysis
HIRLAM EURO4M:	High Resolution Limited Area Model reanalysis of the EURO4M project
JRA-25:	25-yr Reanalysis of the Japan Meteorological Agency
JRA-55:	55-yr Reanalysis of the Japan Meteorological Agency
MERRA:	Modern-Era Retrospective Analysis for Research and Applications

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MERRA-2: Modern-Era Retrospective Analysis for Research and Applications,
version 2.
NARR: NOAA North American Regional Reanalysis
NCEP DOE II: Second Reanalysis of the NCEP and the DOE Atmospheric Model
Intercomparison Project
NCEP/NCAR: Reanalysis of NCEP and NCAR