P1.7

EVALUATION OF THE NCEP/NCAR AND ECMWF 15-YR REANALYSES OVER THE DATA SPARSE ARCTIC OCEAN

Sheng-Hung Wang[1,2*], Jennifer A. Francis[3], and David H. Bromwich[1,2]
[1] Polar Meteorology Group, Byrd Polar Research Center, The Ohio State University, Columbus, OH
[2] Atmospheric Sciences Program, Department of Geography, The Ohio State University, Columbus, OH
[3] Institute of Marine and Coastal Sciences, Rutgers University, New Brunswick, NJ

1. Introduction

The two most widely used reanalysis data sets are the collaborative effort of the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) Reanalysis (hereafter, abbreviated to NNR) (Kalnay et al. 1996; Kistler et al. 2001), and the European Centre for Medium-Range Weather Forecasts (ECMWF) 15-year Reanalysis (ERA-15) (Gibson et al. 1999). Both reanalyses have been evaluated extensively for a variety of fields (e.g., Bromwich et al. 2000). Many aspects of the reanalysis data are high quality over regions with sufficiently dense data. However, the accuracy of reanalyses is uncertain over areas with sparse data, particularly at high latitudes.

The atmospheric hydrologic cycle over the Arctic basin has a significant impact on the mass balance of the sea ice cover. North Atlantic conditions are intimately related to the Arctic ice and freshwater discharges through the Fram Strait (Mysak et al. 1990). The resulting variability in the North Atlantic thermohaline circulation can potentially impact global climate (Broecker 1997; Bromwich et al. 2000; Serreze and Hurst 2000). However, the presence of a floating ice field prevents the collection of reliable measurements of atmospheric moisture and precipitation in the Arctic region. In particular, measurements of solid precipitation are highly inaccurate when winds are strong, although statistical correction methods have been developed (Goodison et al. 1998; Yang 1999). Gauge-based measurements are also subject to blowing snow around the measurement sites. These limitations have led the exploration of the atmospheric moisture budget method, precipitation minus evaporation/sublimation (P-E), using reanalysis data.

Using atmospheric reanalyses, Cullather et al. (2000) computed P-E from atmospheric moisture flux convergence as well as obtaining the same quantity from forecast P and E. These P-E estimates were compared with observations and previous studies to assess the potential for using these numerical data in the Arctic region. The spatial distribution of the mean annual P-E from the ERA model forecasts is in a qualitative agreement with estimates, while the NNR model performs less well. For both models, the average forecast and computed P-E values poleward of 70 ° N are not hydrologic balance. Serreze and Hurst (2000) have examined the NCEP/NCAR and ERA forecast precipitation in comparison to an improved gauge-based climatology. Both reanalyses captured the major spatial features of annual mean precipitation and general aspects of the seasonal cycle, while both were found to underestimate annual values over the Atlantic side of the Arctic.

The accuracy of reanalysis wind fields is also of concern when applying atmospheric moisture budget equation (P-E) method in the Arctic region. Francis (2002) averaged rawinsonde data from two Arctic field programs (the Coordinated Eastern Arctic Research Experiment, CEAREX, and the Lead Experiment, LeadEx), which were not assimilated into both reanalyses, and compared them to reanalysis wind products for five layers between 1000 and 300 hPa. Both reanalyses exhibit large average biases and are significantly too westerly and too northerly. On average, total wind speeds are too strong by 25 to 65 % relative to rawinsonde data.

This study undertakes a comprehensive evaluation of the accuracy of components in the atmospheric moisture budget equation by comparing the two independent observed data sets of Francis (2002), CEAREX and LeadEx, to the NNR and the ERA-15 results over the Arctic Ocean. Both average conditions and , for the first time, variability are considered.

2. Data

Rawinsonde data sets from CEAREX and LeadEx were obtained from J. Francis. The pre-quality-control observation counts have been examined for both experiments to be sure both data sets were not assimilated into reanalysis models. The CEAREX was conducted from the Norwegian ship Polarjørn over the Norwegian Sea and adjacent ice pack from September 1988 through April 1989 (CEAREX Drift Group 1990; NSIDC 1991). LeadEx was conducted during the period of 24 March 1992 to 2 April 1992. The objective of the LeadEx was to study the effects of open leads, which are created by the deformation of the ice pack, on the Arctic Ocean and atmosphere (LeadEx Group 1993). The experiment took place on and around an ice camp in the Beaufort Sea, approximately 300 km northeast of Deadhorse, Alaska. The rawinsonde data were measured at approximately 0000 and 1200 UTC each day for both experiment sites.

3. Comparisons

The atmospheric moisture budget equation can be written as

---

[*] *Corresponding author address*: Sheng-Hung Wang, Polar Meteorology Group, Byrd Polar Research Center, The Ohio State University, 1090 Carmack Road, Columbus, OH 43210.
e-mail: wang@polarmet1.mps.ohio-state.edu

$$P - E = -\frac{\partial W}{\partial t} - \nabla \cdot \frac{1}{g}\int_{P_{top}}^{P_{sfc}} q\boldsymbol{V}\,dp,$$

where W is precipitable water, q is specific humidity, $\boldsymbol{V}$ is horizontal wind vector, P_{sfc} is surface pressure, and P_{top} is the pressure of top air column. However, the highest available level of humidity data is 300 hPa for NNR and 10 hPa for ERA-15. Thus, P_{top} for all three data sets (the CEAREX, NNR and ERA-15) has been set to 300 hPa for comparison purposes in this study. Each component of the atmospheric moisture budget equation in NNR and ERA-15 will be examined and compared to the CEAREX observations. The highest available data for the LeadEx is about 800 hPa, therefore, only wind components for the LeadEx were compared to reanalysis data.

(1) *Upper air winds*

For the CEAREX rawinsondes, on average, both reanalyses generally overestimate the u components (stronger westerly wind) and underestimate the v components (stronger meridional flow from the north) in magnitude (see Fig. 1). For the average u component, ERA-15 starts to diverge from CEAREX above the 600-hPa level, whereas NNR has large differences above the 925-hPa level. For the average v component, NNR agrees better with CEAREX than ERA-15. Regarding the wind component variability, both reanalyses show positive correlations with the CEAREX data. The correlation coefficients between 12-hourly rawinsonde and ERA-15 (R mostly > 0.6) are higher than NNR (R . 0.1) and highly significant ($p < 0.01$), with the exception of the 1000 hPa level. The biases at 1000 hPa may be caused by the differences between the model surface pressures and real surface pressures. The significant t-tests of differences show that the ERA-15 average winds have a much better agreement with the observed average winds, especially for the u components. In contrast, both u and v components show that there is a significant difference between NNR and the CEAREX observations.

The comparison between the LeadEx data and both reanalyses shows that NNR slightly overestimates and ERA-15 slightly underestimates the easterly flow at the 925 and 850 hPa levels on average. Both NNR and ERA-15 have strong positive correlations, R > 0.65 for NNR and R > 0.90 for ERA-15, with the 12-hourly LeadEx data at significance levels $p < 0.01$. There are no significant differences ($p > 0.90$) for the average u components between LeadEx and both reanalyses. For the average v components of the LeadEx data, both reanalyses underestimate the southerly flow by about 1 m s^{-1}. The magnitudes of biases, percentage wise, are larger than for the CEAREX data. The correlation coefficients between rawinsonde and two reanalyses show that they are highly correlated with each other. This result suggests that both models well simulated the variability of u and v components, but the strength of average v components is about 80 % off during the period of LeadEx.

The results shown here disagree partly with Francis (2002). Francis combined both experimental data sets without considering their variability and compared them to NNR and ERA-15 reanalyses using a pressure-weighted averaging scheme. Both NNR and ERA-15 show large average biases in the u (too westerly) and v (too northerly) components in relation to the CEAREX rawinsondes. The result of this study shows that NNR simulated too strong westerly and northerly flows, which agrees with Francis results. However, ERA-15 generally produces smaller biases and simulates much better variability than NNR during the CEAREX experiment. Both reanalyses also exhibit a better agreement with observations during the LeadEx period than the CEAREX period (not available from Francis analysis). Overall, the ERA-15 reanalysis data set provides a much more realistic representation of the winds than the NNR during both experimental periods.

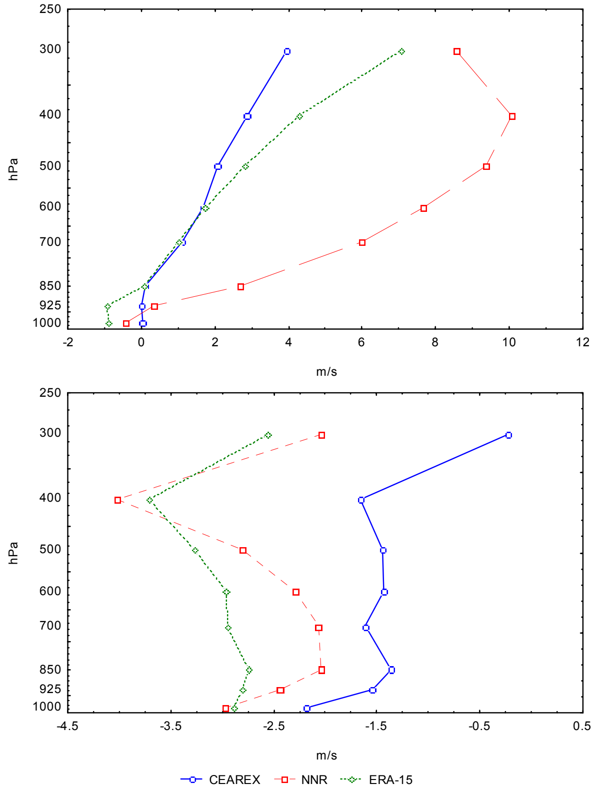

Fig. 1. Average values of upper air wind components for the CEAREX and both reanalysis data sets (in unit m/s): (a) u components; and (b) v components.

(2) *Specific humidity and precipitable water*

At the surface level, discrepancies are present during the winter and early spring. Both reanalyses are much drier than the CEAREX observations. However, NNR and ERA-15 reasonably simulated the humidity field for the remainder of the period. At upper levels (500 and 850 hPa), both reanalyses tend to underestimate the specific humidity field. On average, ERA-15 produced a 40 to 60 % lower specific humidity than rawinsondes throughout the experiment period. In contrast, NNR has a better agreement with observations, with about a 15 to 30 % negative bias. The magnitude of biases between NNR and CEAREX is much smaller than for the ERA-15 data set. However, both reanalyses well capture specific humidity variability as seen by Table 1.

Table 1. The correlation coefficients between the CEAREX monthly mean specific humidity and both reanalysis at surface, 850 hPa and 500 hPa ($p < 0.01$).

	Surface	850 hPa	500 hPa
NNR	1.00	0.94	0.70
ERA-15	0.96	0.90	0.93

Figure 2 shows the average column-integrated water vapor amounts (precipitable water) for each month. From the above analysis, both reanalyses generally underestimate the specific humidity at each level, especially for ERA-15 data. These discrepancies in the specific humidity field are clearly reflected in the differences of precipitable water. NNR shows a good agreement with the observations during early months of the experiment, but does less well in the later months. On the other hand, ERA-15 was about 1 to 2 kg m^{-2} lower than the CEAREX for most months of the experiment. Both reanalyses tend to show increased differences as the mean temperature increases. The correlation coefficients between the CEAREX/NNR and the CEAREX/ERA-15 are 0.97 and 0.96 for monthly means, respectively.

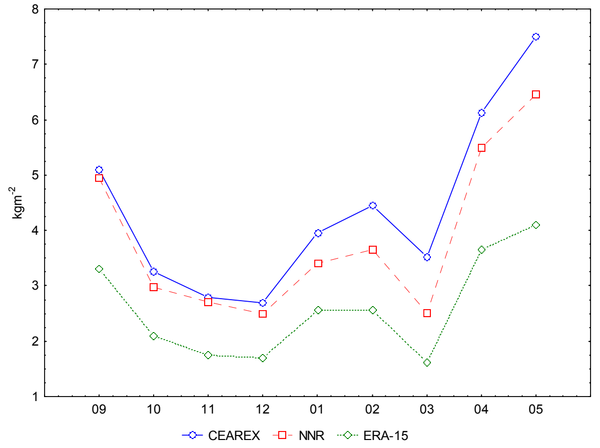

Fig. 2. Monthly average of precipitable water (in unit kg m^{-2}) for the CEAREX and both reanalysis data sets.

(3) *Horizontal fluxes*

Horizontal moisture flux (qV) can be considered as two parts: mean flux and eddy flux. Mean zonal and meridional fluxes for each individual month are plotted in Figs. 3a and 3b. For zonal mean flux, ERA-15 is clearly much closer to the observations than NNR. Both directions and magnitudes were simulated well by ERA-15 for most months, with the exception of April 1989. In contrast, NNR simulated much stronger westerly flow which transported much more moisture into the experiment area. In Fig. 3b, the moisture was transported from the north ($v < 0$)in early months and became weaker or southerly ($v > 0$)during later months of the experiment. NNR often oversimulated meridional flux for most cases, moreover, NNR even produced opposite directions to observations in a couple of months. In contrast, the meridional fluxes simulated by ERA-15 were much closer to the the CEAREX results than NNR during the period of experiment. The majority of differences are within 3 kg m^{-1} s^{-1}. These results are in agreement with the discussions above. The differences of mean fluxes result from the composite biases of average wind and specific humidity fields.

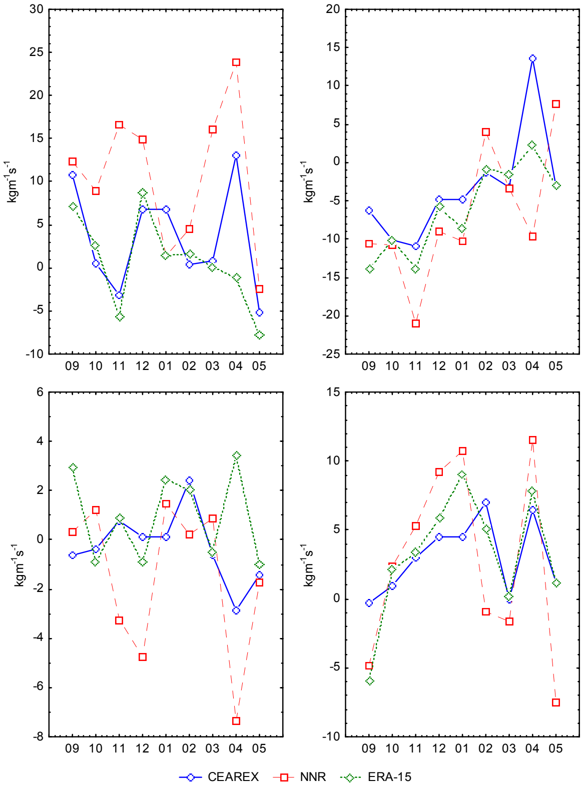

Fig. 3. Monthly moisture fluxes for the CEAREX and both reanalysis data sets (in unit kg m^{-1} s^{-1}): (a) for zonal mean fluxes; (b) for meridional mean fluxes; (c) for zonal eddy fluxes; and (d) for meridional eddy fluxes.

Zonal and meridional transient eddy fluxes are shown in Figs. 3c and 3d. Zonal eddy fluxes (Fig. 3c) were close to zero in the early months, becoming more active during the later period of the experiment. ERA-15 generally has a better agreement with observations in most cases, but displays large discrepancies in a few isolated cases. For instance April 1989, the CEAREX had

2.9 kg m^{-1} s^{-1} eddy flux from the east and ERA-15 simulated 3.4 kg m^{-1} s^{-1} from the west. The directions of eddy fluxes oppose one another and have a 6.3 kg m^{-1} s^{-1} difference in magnitude. Meridional eddies during the CEAREX period (Fig. 3d) show the two most active months are February and April of 1989, which were both simulated by ERA-15 but only one (April 1989) by NNR. Both reanalyses exhibit a tendency to oversimulate the magnitude of the meridional eddy flux in most months. The results indicate that ERA-15 captures much more co-variability of the wind and moisture fields than NNR during the CEAREX experimental period, and this is consistent with the wind component variability analysis presented earlier .

5. Conclusions and Discussions

Reanalysis products exhibit great potential for climate studies. One main characteristic of reanalysis data is that the models use a fixed assimilation procedure and incorporate a variety of observation sources. Although reanalysis data are theoretically preferred for climate studies, we display some problems and limitations in the Arctic region. Each reanalysis has its own strengths and weaknesses in different fields. ERA-15 has a good agreement with observations in most fields despite some biases. In contrast, there are serious problems with the NNR in some fields at higher latitudes. This study highlights some of the shortcomings in the reanalysis data.

In upper air wind field, the observations are expected to have larger magnitudes for u and v components than the smoothed and interpolated reanalysis data. However, we show it is not the case for this study. NNR usually simulated stronger average zonal flows during both experiment periods, but ERA-15 produced a much better relationship with rawinsondes. Both reanalyses display large discrepancies in simulations of the average v components. Regarding the differences in the upper air wind field, both reanalyses exhibit strong agreements in the average heights and temperature fields. The average height differences between observations and reanalyses are small, within 20 m, for most cases. For temperature comparisons, reanalyses produced colder temperatures at the surface and warmer temperatures at upper levels. For the moisture field, both reanalyses produce drier specific humidity and precipitable water at the CEAREX site, which agrees with previous Arctic studies (Bromwich et al. 2000; Serreze and Hurst 2000). Both mean and transient eddy fluxes can be strongly influenced by the simulations of the wind field. Generally, zonal fluxes are simulated better than meridional fluxes, particularly by ERA-15. For wind component variability, ERA-15 clearly outperforms NNR. Overall, ERA-15 performs much better than NNR during the two experiment periods.

Acknowledgment

This research was funded by National Science Foundation grants OPP-9907549 and OPP-9910334.

References

Broecker, W. S., 1997: Thermohaline circulation, the Achilles heel of our climate system, will man-made CO$_2$ upset the current balance? *Science*, **278**, 1582-1588.

Bromwich, D. H., R. I. Cullather, and M. C. Serreze, 2000: Reanalyses depiction of the Arctic atmospheric moisture budget. In Lewis, E. L. (ed.), *The Fresh Water Budget of the Arctic Ocean*, Kluwer Academic Publishers, 163-196.

CEAREX Drift Group, 1990: CEAREX Drift Experiment. *Eos*, Transactions, American Geophysical Union, **71**, 1115-1118.

Cullather, R. I., D. H. Bromwich, and M. C. Serreze, 2000: The atmospheric hydrologic cycle over the Arctic Basin from reanalyses. Part I: Comparison with observation and previous studies. *J. Climate*, **13**, 923-937.

Francis, J. A., 2002: Validation of reanalysis upper-level winds in the Arctic with independent rawinsonde data. *Geophys. Res. Lett.*, **29**, No. 9, 1-4.

Gibson, J. K., P. Kållberg, S. Uppala, A. Hernandez, A. Nomura, and E. Serrano, 1999: ERA depiction. ECMWF Re-Analysis Project Report Series. *1. ERA-15 Description (Version 2 - January 1999)*, 84 pp. [Available from ECMWF web page, http://www.ecmwf.int].

Goodison, B. E., P. Y. T. Louie, and D. Yang, 1998: WMO solid precipitation measurement intercomparison, final report. *WMO/TD - No. 872*, WMO, Geneva, 212 pp.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, A. Leetmaa, B. Reynolds, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K.C. Mo, C. Ropelewski, J. Wang, Roy Jenne, and D. Joseph, 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.*, **77**, 437-472.

Kistler, R., E. Kalnay, W. Collins, S. Saha, G. White, J. Woollen, M. Chelliah, W. Ebisuzaki, M. Kanamitsu, V. Kousky, H. van den Dool, R. Jenne, and M. Fiorino, 2001: The NCEP-NCAR 50–year reanalysis: Monthly means CD-ROM and documentation. *Bull. Amer. Meteor. Soc.*, **82**, 247-268.

LeadEx Group, 1993: The LeadEx Experiment. *Eos*, Transactions, American Geophysical Union, **74**, 393-397.

Mysak, L. A., D. K. Manak, and R. F. Marsden, 1990: Sea-ice anomalies observed in the Greenland and Labrador seas during 1901-1984 and their relation to an interdecadal Arctic cycle. *Clim. Dynamics*, **5**, 111-133.

NSIDC, 1991: Coordinated Eastern Arctic Experiment (CEAREX), 1988-1989. Document file on NSIDC's CD-ROM titled *Eastern Arctic Ice, Ocean and Atmosphere Data, Volume 1: CEAREX-1, version 1.0, 8/91*. [Available from NSIDC web page, http://nsidc.org/data/docs/daac/nsidc0020_cear ex.gd.html].

Serreze, M. C., and C. M. Hurst, 2000: Representation of mean Arctic precipitation from NCEP-NCAR and ERA reanalyses. *J. Climate*, **13**, 182-201.

Yang, D., 1999: An improved precipitation climatology for the Arctic Ocean. *Geophy. Res. Lett.*, **26**, 1625-1628.