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A RE-EVALUATION OF UPPER TROPOSPHERIC WINDS IN REANALYSES NEAR SVALBARD

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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 fields. The European Centre started a new reanalysis project (ERA-40) in 1999, and completed it in early 2003. The ERA-40 data set covers the period from September 1957 to August 2002, overlapping the earlier ERA-15 (Simmons and Gibson 2000). Many aspects of the reanalysis data are of high quality over regions with sufficiently abundant data. However, the accuracy of reanalyses is uncertain over areas with sparse data, particularly at high latitudes.

Recently, Francis (2002) used rawinsonde data from two Arctic field programs, which were not assimilated into NNR and ERA-15, and compared them to reanalysis wind products for five layers between 1000 and 300 hPa. Both reanalyses exhibit large biases and are significantly too westerly and too northerly relative to these rawinsonde data. In addition, total wind speeds are too strong by 25 to 65 %.

This study undertakes a more comprehensive evaluation of the accuracy of reanalysis atmospheric variables (wind components, as well as temperature, geopotential height and moisture fields) by comparing the two independent observed data sets of Francis (2002), the Coordinated Eastern Arctic Research Experiment (CEAREX) and the Lead Experiment (LeadEx), to the NNR and ERA-15 over the Arctic Ocean. The analysis is extended by considering the performance of ERA-40. Both average conditions and variability are considered.

2. Data

The rawinsonde data sets from CEAREX and LeadEx were obtained from J. Francis at the Institute of Marine and Coastal Sciences, Rutgers University, in New Brunswick, New Jersey. Figure 1 shows the geographic locations of the CEAREX and LeadEx experiment sites. CEAREX was conducted from the Norwegian ship *Polarbjørn* over the Norwegian Sea and adjacent pack ice from September 1988 through May 1989 (CEAREX Drift Group 1990; NSIDC 1991). LeadEx was conducted from March 16 to April 25, 1992 on and around an ice camp in the Beaufort Sea, approximately 300 km northeast of Deadhorse, Alaska (LeadEx Group 1993). The rawinsonde data were measured at approximately 0000 and 1200 UTC each day for both experiments, with additional launches conducted during abnormal weather conditions.

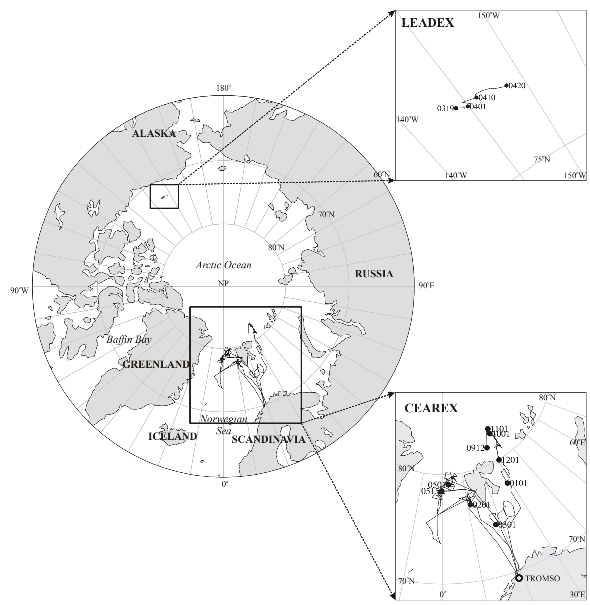

Fig. 1. The geographic locations of CEAREX and LeadEx experiments. Selected dates of measurements are marked (in MMDD format) next to site locations on sub-panels. For example, 0912 indicates September 12.

Three reanalysis data sets, NNR, ERA-15 and ERA-40 are used in this study. The NNR consists of analyses which are available four times a day at a T62 horizontal resolution (approximately 210 km) and 28 sigma levels in the vertical. The NNR data were obtained from National Weather Service (NWS) - Climate Prediction Center (CPC). ERA-15 is produced four times daily using a spectral numerical weather prediction (NWP) model at T106 horizontal resolution (approximately 125 km) with 31 hybrid levels in the vertical during 1979 to 1993. ERA-40 has T159 spatial resolution (nominally about 85 km) in the horizontal and with 60 levels in the vertical located between the surface and a height of about 65 km (Simmons and Gibson 2000). Both ERA-15 and ERA-40 data sets were provided by the University Corporation for Atmospheric Research (UCAR) Data Support Section

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(DSS). All three reanalysis data sets are available at 2.5° x 2.5° resolution at the surface (or near-surface) and upper levels for our study periods.

For comparison purposes, both CEAREX and LeadEx data sets were vertically interpolated to the following levels (surface, 1000, 925, 850, 700, 600, 500, 400 and 300 hPa for CEAREX; and surface, 1000, 925 and 850 hPa for LeadEx). The highest available data for LeadEx is around the 770 hPa level, therefore only wind components for LeadEx were compared to reanalysis data. For each chosen level, the five closest rawinsonde data within 5 hPa were used to interpolate each variable, excluding extreme outliers. All three reanalysis data sets were spatially and temporally interpolated to the drift locations and rawinsonde launch times.

The Historical Arctic Rawinsonde Archive (HARA) contains all available rawinsonde data (including temperature, pressure, wind and humidity) from fixed-position (mostly land) stations poleward of 65° N; these observations were assimilated into the reanalyses. Data from drifting ice islands, ships, and aircraft dropsondes have been assembled in a separate archive. HARA covers from the beginning of station record through mid 1996; most stations commenced soundings in the late 1950s (Kahl et al. 1992; Serreze and Shiotani 1997). The HARA data set was obtained from the National Snow and Ice Data Center (NSIDC).

3. Comparisons

a. Upper level winds

The observed rawinsonde wind data have been converted into u- and v-components for comparison purposes. Figure 2 shows the mean values of u- and v-components for the CEAREX rawinsondes and three reanalyses.

For the CEAREX rawinsondes, on average, reanalyses generally overestimate the u-components (stronger westerly winds) and the v-components (stronger meridional flow from the north) in magnitude. For the average u-components (Fig. 2a), the three reanalyses start to diverge from CEAREX above the 850 hPa level, and the differences increase steadily with height. The vertical profile of the mean v-components (Fig. 2b) clearly shows that NNR and both ECMWF reanalyses (ERA-15 and ERA-40) display more northerly values than the observations throughout the troposphere. However, all three reanalyses reasonably capture the pattern of the average v-component profile; $r = 0.78$, 0.54 and 0.93 for NNR, ERA-15 and ERA-40 respectively. T-tests of average u-component differences show that there are significant differences between all three reanalyses and observations ($p < 0.25$), although the ERA-15 average zonal winds show better agreement with CEAREX than NNR and ERA-40 data. In contrast, the results for the average v-components indicate there is a significant difference between the CEAREX and all three reanalyses ($p < 0.01$) throughout the troposphere.

For wind speed comparisons, all three reanalyses display large biases at all levels above 1000 hPa, and the differences increase with height. By contrast, the reanalyses show positive correlations with observations that are highly significant, especially ERA-40. These results indicate that the reanalyses demonstrate good skill in capturing the CEAREX wind speed variability but not the magnitude.

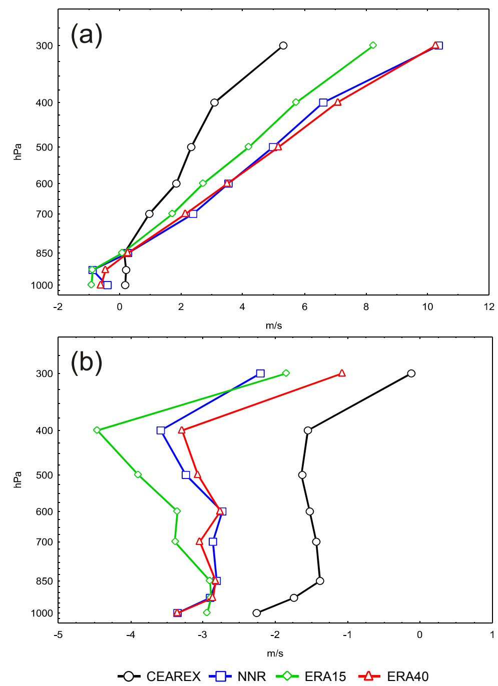

Fig. 2. Average values of upper air wind components (m s^{-1}) for CEAREX and reanalyses: (a) u components; and (b) v components.

The comparisons of u-components between the LeadEx data and the three reanalyses show that NNR slightly overestimates and both ERA-15 and ERA-40 slightly underestimate the easterly flow at the 925 and 850 hPa levels on average. All three reanalyses have strong positive correlations, $r > 0.90$ for NNR, $r > 0.91$ for ERA-15 and $r > 0.92$ for ERA-40, with the 12-hourly LeadEx data with significance levels $p < 0.01$. There are no significant differences ($p < 0.01$) for the average u-components between LeadEx and three reanalysis data sets.

For the average v-components of the LeadEx data, both NNR and ERA-15 underestimate the southerly flow by about 1.0 m s^{-1}, similar to the CEAREX biases. The correlation coefficients between rawinsonde observations and the two reanalyses show that they are highly correlated with each other ($r > 0.88$). In contrast to NNR and ERA-15, ERA-40 displays the best skill among the three reanalysis data sets, with the lowest bias and the highest correlation coefficient. This result suggests that all three reanalyses well resolve the variability of the u- and v-components, but the average v-components for the NNR and ERA-15 are about 1.0 m s^{-1} too small during the LeadEx period.

Unlike CEAREX (large biases and high correlations), LeadEx has much smaller biases in the wind speed comparisons. These discrepancies are very small and negligible ($p < 0.01$) in some cases. Again, all three reanalyses demonstrate skill in capturing the wind speed variability. This suggests that the reanalyses perform well during the LeadEx period.

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-components (too northerly) in relation to the CEAREX winds. The result of this study shows that NNR produces too strong westerly and northerly flows, which agrees with Francis' results. However, ERA-15 generally has smaller biases and better variability than NNR. Both reanalyses also exhibit better agreement with observations during the LeadEx period than the CEAREX period (not available in Francis' results). To extend Francis' analysis, we show that the ERA-40 reanalysis data set provides a more realistic representation of the winds than the other two reanalyses, especially NNR, during both experimental periods.

b. Specific humidity and precipitable water

The CEAREX monthly mean specific humidity for surface and upper levels (850 and 500 hPa) have been compared to three reanalyses. At the surface level, both ECMWF reanalyses show close relationships to the CEAREX soundings. Small discrepancies are present during the late winter and early spring for the NNR, when it is drier than the CEAREX observations. However, the NNR reasonably captured the humidity field for the remainder of the period. At the 850 hPa level, both ERA-15 and ERA-40 outperform NNR, with small negative biases (-0.01 g kg^{-1}) for ERA-15 and small positive biases (0.03 g kg^{-1}) for ERA-40. Again, NNR (with average bias -0.10 g kg^{-1}) tends to underestimate the specific humidity. On average, NNR has a 20 to 40 % lower specific humidity than the rawinsondes during the latter half of the CEAREX experiment period. In contrast to the surface and 850 hPa, NNR has a better agreement (smaller biases, -0.01 g kg^{-1}) with the observations at the 500 hPa level. Both ECMWF reanalyses (0.04 g kg^{-1} for ERA-15 and 0.05 g kg^{-1} for ERA-40) tend to overestimate the monthly average specific humidity, with positive biases of 15 to 30 %. The biases for ERA-40 are slightly larger than ERA-15. Most correlation coefficients between CEAREX monthly mean specific humidity and three reanalyses are greater than 0.90. By contrast, the correlation coefficients between 12-hourly observations and three reanalyses are much lower. For example at 850 hPa, the correlation coefficients are 0.53, 0.58 and 0.63 for the NNR, ERA-15 and ERA-40, respectively. This result shows that all three reanalyses well capture the variability of specific humidity on the monthly time scale. However, on the 12 hourly or daily basis, ERA-40 has a better specific humidity representation than the NNR and ERA-15 data.

The average column-integrated water vapor amounts (precipitable water) for each month are also compared. Precipitable water is defined as

$$w = \frac{1}{g}\int_{P_{top}}^{P_{sfc}} q \, dp,$$

where w is precipitable water, q is specific humidity, P_{sfc} is surface pressure, and P_{top} is the pressure of top of the air column. However, the highest available level of humidity data is 300 hPa for NNR, 10 hPa for ERA-15 and 1 hPa for ERA-40. Thus, P_{top} of all four data sets (the CEAREX, NNR, ERA-15 and ERA-40) has been set to 300 hPa for comparison purposes in this study. From the above analysis, both NNR and ERA-15 reanalyses generally underestimate the specific humidity throughout the CEAREX experiment period, especially the NNR data set. The precipitable water of NNR shows better agreement with the observations during early months of the experiment, but does less well in the later months. The largest negative bias, approximately 1.2 kg m^{-2}, occurred in March 1989. On the other hand, ERA-15 was about 0.2 to 0.5 kg m^{-2} lower than CEAREX for most months. ERA-40 displays small positive biases during earlier and later months. The discrepancies in the specific humidity field at each level are clearly reflected in the differences of precipitable water. The monthly mean differences between NNR, ERA-15 and ERA-40 and the observations are -0.55, -0.08 and 0.27 kg m^{-2}. The correlation coefficients for monthly mean precipitable water between the CEAREX and the NNR, ERA-15 and ERA-40 are 0.97, 0.98 and 0.99, respectively.

c. Temperature and geopotential height fields

In addition to the wind and moisture fields, temperatures and geopotential heights observed during CEAREX are also examined. Each variable has been averaged for each individual month and been compared to the NNR, ERA-15 and ERA-40 data sets.

During the first few months at the surface level, the NNR underestimated the mean temperature by approximately 2 to 3 °C and both ECMWF reanalyses tend to overestimate it by a similar amount. Mean surface temperatures are about 1 to 2 °C lower than all three reanalysis data sets for the second half of the experiment period. The agreement between observations and reanalyses improves in the warmer season (open water) as compared to the colder months (sea ice region). The ERA-40 display the best skill, with the lowest root mean square error (RMS) 1.7 °C (contrast to 2.8 °C for NNR and 2.4 °C for ERA-15) and the highest correlation coefficient 0.99, among the three reanalysis data sets.

At lower tropospheric levels (925, 850 and 700 hPa), all three reanalyses resolve the mean temperature well, with the differences between soundings and reanalyses much less than 1 °C for most cases. The average differences between NNR, ERA-15 and ERA-40 monthly mean temperatures and the observations at 850 hPa are -0.3, 0.3 and -0.2 °C. Correlations between 12 hourly observations and reanalysis values are 0.89, 0.88 and 0.89, respectively. The reanalyses at upper levels

(600, 500 and 400 hPa) are warmer than the observations, with the average monthly differences at 500 hPa being 0.6, 1.1 and 0.1 °C; 12 hourly correlations are 0.91, 0.92 and 0.92, respectively. The difference between reanalyses and soundings also increases as the pressure level decreases. For instance, there is a 3 °C difference between rawinsonde data and ERA-40, the closest reanalysis to the observation, at 400 hPa in December 1988. Regardless of these discrepancies, all three reanalyses well simulate the temperature change patterns. The ERA-40 generally exhibits the best skill among the three reanalysis data sets.

For the monthly mean geopotential heights of the CEAREX at 925, 850 and 500 hPa levels, the largest biases can be found during the first month, which is caused by the error of September 21, 1150 UTC observation. This error could have resulted from various factors (e.g., human, instrumental or decoding errors). If we exclude this outlier in our study, the differences drop significantly, 56.1 meters for 850 hPa and 43.4 meters for 500 hPa. After the first month of the experiment, the biases between soundings and reanalyses are less than 20 meters (< 1 %), a negligible discrepancy, and highly correlated with each other ($r > 0.99$). The monthly mean average difference between NNR, ERA-15 and ERA-40 and the observations are: 0.2, -2.8 and -0.1 meters at the 850 hPa level; and 4.2, -3.1 and -10.1 meters at the 500 hPa level. The 12-hourly CEAREX observations and all three reanalyses are also highly correlated with each other ($r \approx 0.96$ for 850 hPa and $r \approx 0.98$ for 500 hPa) with high confidence ($p < 0.01$).

4. Discussion and Conclusions

The largest discrepancy between the observations and the three reanalyses can be found in the upper wind comparisons, especially during the CEAREX period. For upper level winds, the observations are generally expected to have larger magnitudes of u- and v-components than the smoothed and interpolated reanalysis data. Here, we show it is not the case for this study. All three reanalyses have stronger zonal flows during CEAREX and display discrepancies in the v-components during both experiment periods. The discrepancies tend to increase with height. However, all reanalyses well capture the rawinsonde variability, especially ERA-40.

The average wind speed profile for CEAREX (Fig. 3) exhibits a relatively small vertical wind shear. In contrast, all three reanalyses display much stronger wind speeds as height increases. In addition to vertical wind shear discrepancies, all three reanalyses agree with each other. The marked meridional thermal gradient of the marginal ice zone sampled by CEAREX indicates from thermal wind considerations that the wind speed should increase with height and that the reanalyses are more likely to be accurate. This raises a question as to the accuracy of the CEAREX upper level winds, particularly above the 500 hPa level.

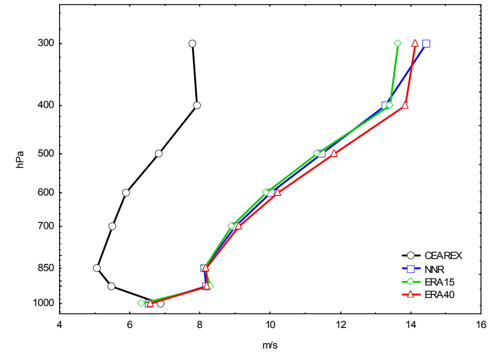

Fig. 3. Average wind speed (m s^{-1}) profile for CEAREX and the reanalyses.

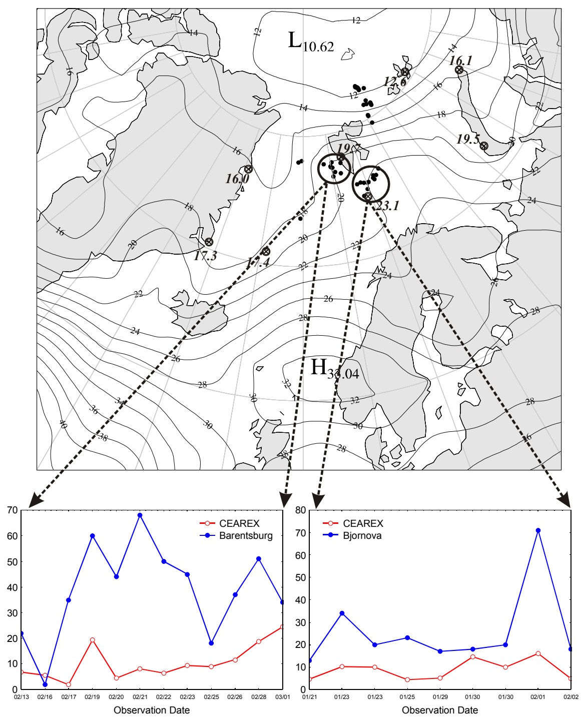

Fig. 4. Average 300 hPa ERA-40 wind speed (contours in m s^{-1}) for 46 cases of CEAREX observations. The locations of *Polarbjørn* are plotted as solid dots on the map. The locations of HARA stations are also marked on the map. The average 300 hPa wind speed for HARA stations during 46 cases are shown next to the locations. CEAREX and HARA wind speed (in m s^{-1}) for cases near Barentsburg and Bjørnova are plotted in the two sub-panels.

Figure 4 shows the average wind speed field for ERA-40 and the average speeds at local HARA stations during the 46 available 300 hPa CEAREX cases, and a reasonably close fit is evident at the HARA sites. The average wind speed for CEAREX during these 46 cases is 7.8 m s^{-1}, which is about half the average reanalysis values interpolated to the CEAREX locations (14.4 m s^{-1} for NNR, 13.6 m s^{-1} for ERA-15 and 14.1 m s^{-1} for ERA-40). Comparisons between CEAREX winds and those from Barentsburg and Bjørnova when the *Polarbjørn* was nearby reveal much lower 300 hPa wind speeds than at the fixed rawinsonde sites (Fig. 4).

During the CEAREX period, another ship the *Haakon Mosby* was in the vicinity of Bjørnova and south of Svalbard. The *Haakon Mosby* participated in the Seasonal Ice Zone Experiment (SIZEX) from February 25 to March 23, 1989. Both ships used the same Omega tracking scheme (Lange 1985) to measure the upper level winds, although the equipment came from different manufacturers (VIZ Corporation for the *Polarbjørn* and Väisäla for the *Haakon Mosby*). We applied similar analyses to the data obtained from the *Haakon Mosby*. A weak vertical wind shear and large differences between reanalyses and observations at upper levels are not present. The results indicate that the upper level winds (especially above the 500 hPa level) obtained by the *Polarbjørn* are much too weak on average but reflect much of the actual variability. We have not been able to determine the cause of these measurement errors. Thus, we disagree with Francis' (2002) conclusion that the upper tropospheric wind speeds in NNR and ERA-15 suffer from a serious high bias.

All three reanalyses agree closely with the observed CEAREX heights and temperatures. The heights differences between observations and reanalyses are small, within 20 m, for most cases. For temperature comparisons, reanalyses generally produced colder temperatures (1 to 2 °C) at the surface during earlier months, and warmer temperatures (about 1 °C) at the surface during the second half of the experiment and at upper levels in most months. For the moisture field, the NNR and ERA-15 reanalyses are slightly drier in terms of specific humidity and precipitable water at the CEAREX site, which agrees with previous Arctic region studies (Bromwich et al. 2000; Serreze and Hurst 2000). By contrast, ERA-40 is much closer to the CEAREX moisture observations.

Overall, ERA-40 performs better than NNR and ERA-15 during the two experiment periods. Several other aspects of the quality of the ERA-40 reanalysis in relation to ERA-15 were discussed at a 2001 ECMWF workshop. The results show that there are substantial improvements in some fields. For instance, Bromwich et al. (2002) found that the atmospheric moisture budget (P-E) of ERA-40 is much closer to hydrologic balance than ERA-15 for the Arctic region. Some problems still exist in the ERA-40 products. For example, there is a lower tropospheric cold bias in ERA-40 centered over ice-covered oceans in both the Arctic and the Antarctic, which is related to the assimilation of infrared satellite sounder temperature information (HIRS) and perhaps the cloud clearing algorithm over sea ice (Bromwich et al. 2002). According to ECMWF, changes to the thinning, channel-selection and quality control of the HIRS data that were introduced for analyses from 1997 onward to reduce the tropical precipitation bias have also virtually eliminated the polar cold bias. Current ECMWF plans call for a rerun of the modern satellite era (1979 to present). The polar meteorological community has high expectations that the enhanced ERA-40 can improve studies of Arctic and Antarctic climate.

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