## NOTES AND CORRESPONDENCE

# Evaluation of the NCEP–NCAR and ECMWF 15- and 40-Yr Reanalyses Using Rawinsonde Data from Two Independent Arctic Field Experiments*

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ABSTRACT

Many aspects of reanalysis data are of high quality over regions with sufficiently dense data, but the accuracy is uncertain over areas with sparse observations. NCEP–NCAR reanalysis (NNR) and ECMWF 15/40-Yr Re-Analysis (ERA-15 and ERA-40) variables are compared to two independent rawinsonde datasets from the periphery of the Arctic Ocean during the late 1980s and early 1990s: the Coordinated Eastern Arctic Research Experiment (CEAREX) and the Lead Experiment (LeadEx). The study is prompted by J. A. Francis who found that the NNR and ERA-15 upper-level winds are very different from those observed during these two field experiments.

All three reanalyses display large biases in comparisons of the wind components and wind speeds with CEAREX observations, particularly above the 500-hPa level, but exhibit smaller discrepancies with respect to the LeadEx data, generally consistent with the previous findings of J. A. Francis. However, all three reanalyses well capture the wind variability during both experiment periods. For the geopotential height, temperature, and moisture fields, the reanalyses demonstrate close agreement with the CEAREX rawinsonde observations. From comparisons with surrounding fixed rawinsonde stations and examination of the average vertical wind speed shear, it is concluded that the CEAREX upper-level wind speeds (especially above the 500-hPa level) are erroneous and average about half of the actual values. Thus, this evaluation suggests that the three reanalyses perform reliably for tropospheric-state variables from the edge of the Arctic Ocean during the modern satellite era.

## 1. Introduction

The concept of reanalysis has been described by Trenberth (1995) and Kalnay et al. (1996). Reanalysis represents an effort to remove spurious trends in archived operational analyses that are associated with the evolving data assimilation system. The remaining temporal variability is either real or the result of changes to the observational network (Cullather et al. 2000). The primary goal of reanalysis is to provide global quality-controlled datasets of analyzed and forecast fields for the research community. The two most widely used reanalysis datasets are the collaborative effort of the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) Reanalysis (NNR; Kalnay et al. 1996; Kistler et al. 2001), and the European Centre for Medium-Range Weather Forecasts (ECMWF) 15-yr Re-Analysis (ERA-15; Gibson et al. 1999). Both reanalyses have been evaluated extensively for a variety fields. The ECMWF started a

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new 40-yr Re-Analysis project (ERA-40) in 1999, and completed it in early 2003. The ERA-40 dataset 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.

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. On average, total wind speeds are too strong by 25%–65% relative to these rawinsonde data.

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 datasets 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. For the first time, both average conditions and variability are considered.

## 2. Data

The original rawinsonde datasets from CEAREX and LeadEx, which were used in Francis (2002), were obtained from J. A. Francis at the Institute of Marine and Coastal Sciences, Rutgers University, in New Brunswick, New Jersey. However, the highest available data for LeadEx, used by Francis (2002), is around the 770-hPa level (<2 km). Therefore, the original partial LeadEx dataset from J. A. Francis has been replaced by the complete LeadEx dataset obtained from O. Persson at the Environmental Technology Laboratory (ETL) of the National Oceanic and Atmospheric Administration (NOAA) in Boulder, Colorado. Figure 1 shows the geographic locations of the CEAREX and LeadEx experiment sites. The pre–quality control observation counts, using the NCEP's Web tool (available online at http://nomad2.ncep.noaa.gov/ncep_data/), have been examined to be sure that both experimental datasets were not assimilated into the NNR. An equivalent tool is not available for the ECMWF reanalyses, but the NNR dataset was very similar to that used by ECMWF for their reanalyses. CEAREX was conducted from the Norwegian ship *Polarbjørn* over the Norwegian Sea and adjacent pack ice from September 1988 to May 1989 [CEAREX Drift Group 1990; National Snow and Ice Data Center (NSIDC) 1991]. The primary goal of CEAREX was to study the momentum, heat, and biomass exchanges of the eastern Arctic Ocean, in an effort to better understand the mesoscale structure and interactions between the sea ice, ocean, and atmosphere in and adjacent to the marginal ice zone. LeadEx took place on and around an ice camp in the Beaufort Sea, approximately 300 km northeast of Deadhorse, Alaska, from 16 March to 25 April 1992. The objective of LeadEx was to study the effects of open leads, which are created by deformation of the pack ice, on the Arctic Ocean and the atmosphere (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.

Three reanalysis datasets, NNR, ERA-15, and ERA-40, are used in this study. The NNR consists of analyses that are available four times a day (at 0000, 0600, 1200 and 1800 UTC) at a T62 horizontal resolution (approximately 210 km) and 28 sigma levels in the vertical (Kalnay et al. 1996; Kistler et al. 2001). The NNR data were obtained from National Weather Service (NWS) Climate Prediction Center (CPC) reanalysis project (available online at http://www.cpc.ncep.noaa.gov/products/wesley/reanalysis.html). ERA-15 is produced 4 times daily using a spectral numerical weather prediction model at T106 horizontal resolution (approximately 125 km) with 31 hybrid levels in the vertical from 1979 to 1993 (Gibson et al. 1999). The ERA-40 project covers the period from September 1957, when a major improvement was made to the atmospheric observing system in preparation for the International Geophysical Year 1957–58, to August 2002. The model 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). The basic analyzed variables include not only the conventional meteorological fields, but also stratospheric ozone and ocean wave and soil conditions. ERA-40 can be thought of a second-generation reanalysis, in contrast to the first-generation reanalysis systems used for NNR and ERA-15. Both ERA-15 and ERA-40 datasets were provided by the University Corporation for Atmospheric Research (UCAR) Data Support Section (DSS; see online at http://dss.ucar.edu). All three reanalysis datasets are available at 2.5° × 2.5° resolution at the surface (or near surface) and upper levels for our study periods.

For comparison purposes, both CEAREX and

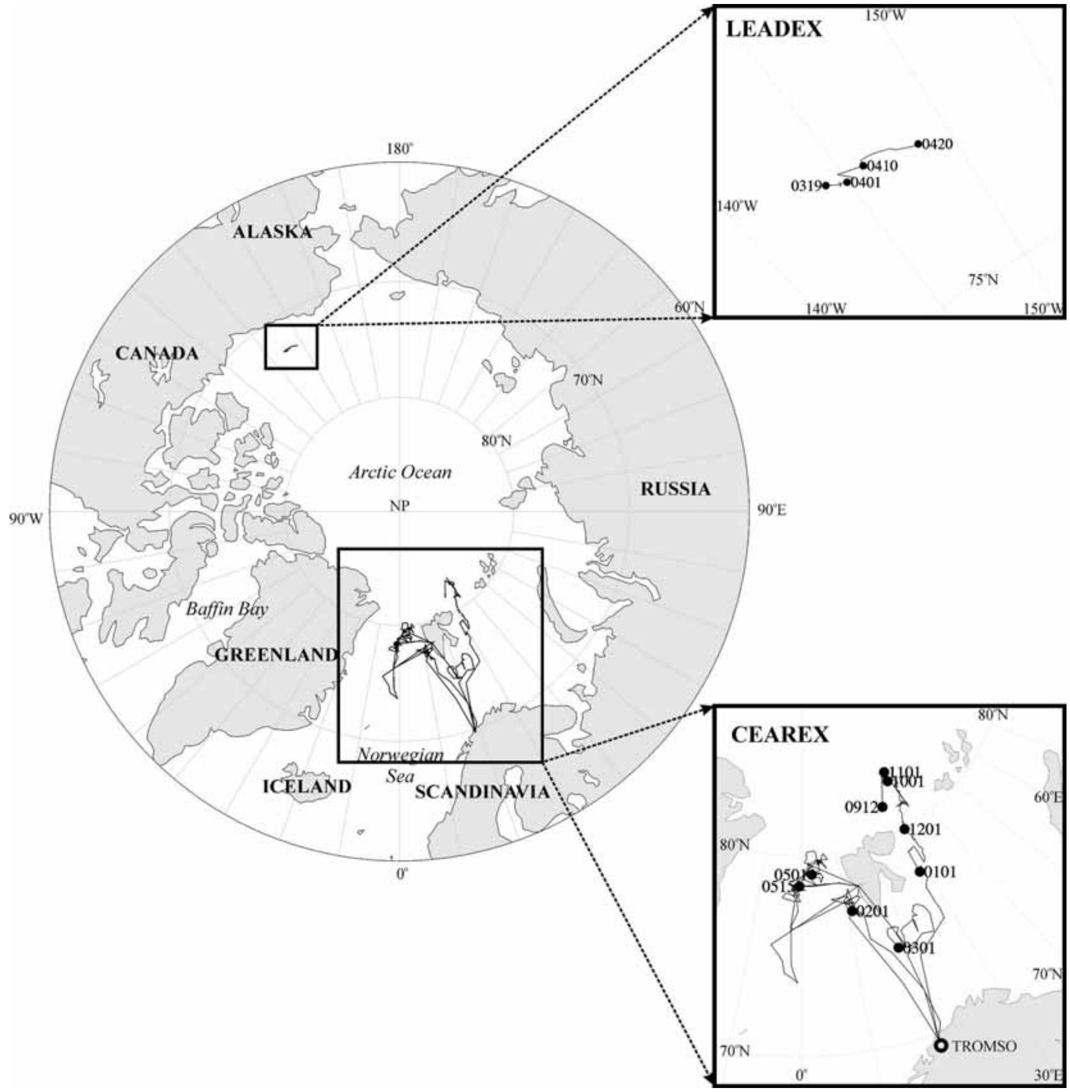


FIG. 1. The geographic locations of CEAREX and LeadEx experiments. CEAREX was measured from Sep 1988 to May 1989, and LeadEx was conducted from 16 Mar to 25 Apr in 1992. Selected dates of measurements are marked (in MMDD format) next to site locations in subpanels. For example, 0912 indicates 12 Sep.

LeadEx datasets were vertically interpolated to the following levels: surface, 1000, 925, 850, 700, 600, 500, 400, and 300 hPa. For each chosen level, the five closest rawinsonde data within 5 hPa were linearly interpolated for each variable, excluding extreme outliers. All three reanalysis datasets were spatially interpolated to the drift locations by using a bilinear algorithm, and linearly interpolated to rawinsonde launch times. Because LeadEx data cover a very short time period (about 40 days), only LeadEx wind variables are discussed in this study.

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; most of these observations were assimilated into the reanalyses. Data from drifting ice islands, ships, and aircraft dropsondes have been assembled in a separate archive (not used in this study). 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 primary object of the archive is to provide long-term comprehensive data for meteorological and climatological research in the Arctic region. The HARA dataset was obtained from the NSIDC. Only HARA stations with complete records during the experiment periods have been chosen for this study.

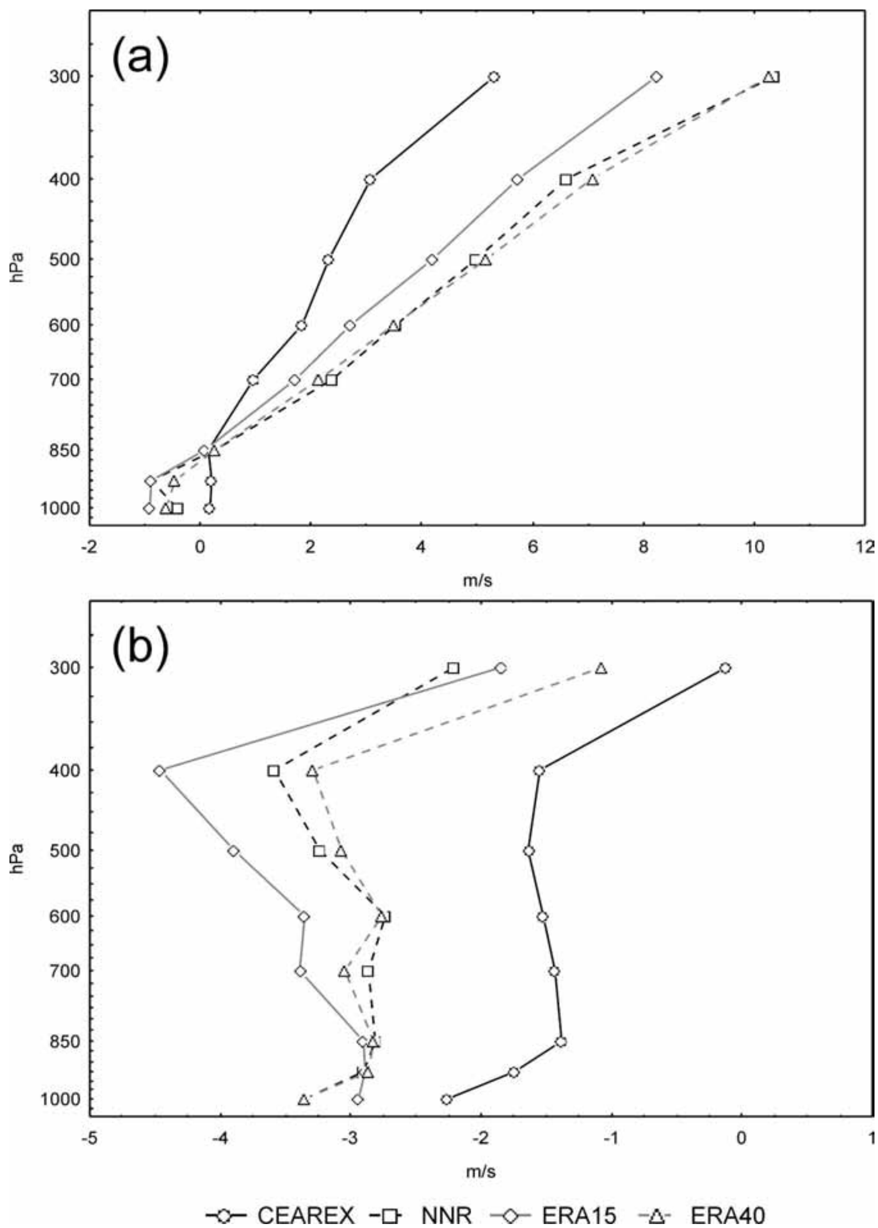


FIG. 2. Average values of upper-air wind components (m $s^{-1}$) for CEAREX and reanalyses: (a) $u$ and (b) $v$ components.

## 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 (LeadEx figures not shown). The biases, mean square errors (mses) and correlation coefficients ($r$) for both experiments are listed in Tables 1 and 2, with associated significance tests.

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, although the ERA-15 average zonal winds show closer agreement with CEAREX than NNR and ERA-40 data. 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. The $t$-test results for the average $v$ components indicate there is a significant difference between

TABLE 1. Means, biases, mses, and correlation coefficients ($r$) of winds (m $s^{-1}$) between CEAREX and reanalyses for (a) $u$ and (b) $v$ components, and (c) wind speeds. Bias (reanalyses − observation) and correlation values significant at the 99% confidence level are boldface ($t$ test with $p$ value $< 0.01$).

1a.

| Level | CEAREX | NNR | | | | ERA-15 | | | | ERA-40 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (hPa) | Mean | Mean | Bias | Mse | $r$ | Mean | Bias | Mse | $r$ | Mean | Bias | Mse | $r$ | Count |
| 1000 | 0.17 | −0.41 | −0.59 | 7.07 | **0.24** | −0.92 | −1.09 | 7.05 | **0.25** | −0.62 | −0.79 | 6.95 | **0.28** | 237 |
| 925 | 0.20 | −0.89 | **−1.09** | 5.34 | **0.48** | −0.89 | **−1.09** | 5.10 | **0.52** | −0.47 | −0.67 | 4.97 | **0.53** | 346 |
| 850 | 0.15 | 0.28 | 0.14 | 4.42 | **0.61** | 0.08 | −0.07 | 4.29 | **0.62** | 0.28 | 0.13 | 4.17 | **0.66** | 346 |
| 700 | 0.97 | 2.38 | **1.40** | 4.90 | **0.66** | 1.73 | **0.76** | 4.49 | **0.67** | 2.13 | **1.16** | 4.61 | **0.71** | 338 |
| 600 | 1.85 | 3.55 | **1.70** | 5.00 | **0.73** | 2.72 | **0.87** | 4.54 | **0.73** | 3.49 | **1.65** | 4.96 | **0.76** | 311 |
| 500 | 2.34 | 4.98 | **2.64** | 6.10 | **0.71** | 4.20 | **1.86** | 5.44 | **0.73** | 5.18 | **2.84** | 6.17 | **0.75** | 273 |
| 400 | 3.08 | 6.63 | **3.55** | 7.04 | **0.73** | 5.74 | **2.65** | 6.36 | **0.75** | 7.09 | **4.00** | 7.25 | **0.79** | 168 |
| 300 | 5.32 | 10.37 | **5.06** | 7.85 | **0.78** | 8.26 | **2.95** | 6.78 | **0.82** | 10.28 | **4.96** | 7.56 | **0.84** | 46 |

1b.

| Level | CEAREX | NNR | | | | ERA-15 | | | | ERA-40 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (hPa) | Mean | Mean | Bias | Mse | $r$ | Mean | Bias | Mse | $r$ | Mean | Bias | Mse | $r$ | Count |
| 1000 | −2.26 | −3.35 | **−1.09** | 4.48 | **0.63** | −2.94 | −0.68 | 4.28 | **0.65** | −3.35 | **−1.09** | 4.29 | **0.66** | 237 |
| 925 | −1.74 | −2.90 | **−1.16** | 4.28 | **0.82** | −2.88 | **−1.14** | 4.36 | **0.83** | −2.87 | **−1.13** | 4.14 | **0.84** | 346 |
| 850 | −1.38 | −2.81 | **−1.43** | 4.26 | **0.82** | −2.90 | **−1.52** | 4.31 | **0.83** | −2.82 | **−1.44** | 4.12 | **0.85** | 346 |
| 700 | −1.44 | −2.86 | **−1.43** | 4.40 | **0.83** | −3.38 | **−1.95** | 4.32 | **0.86** | −3.04 | **−1.61** | 4.00 | **0.89** | 338 |
| 600 | −1.53 | −2.74 | **−1.21** | 4.83 | **0.86** | −3.36 | **−1.83** | 4.87 | **0.87** | −2.76 | **−1.23** | 4.47 | **0.90** | 311 |
| 500 | −1.63 | −3.23 | **−1.60** | 5.06 | **0.86** | −3.89 | **−2.26** | 5.32 | **0.88** | −3.07 | **−1.44** | 4.74 | **0.91** | 273 |
| 400 | −1.54 | −3.59 | **−2.05** | 6.51 | **0.78** | −4.46 | **−2.91** | 6.98 | **0.81** | −3.29 | **−1.75** | 6.20 | **0.83** | 168 |
| 300 | −0.12 | −2.20 | **−2.08** | 5.47 | **0.89** | −1.85 | −1.73 | 5.68 | **0.90** | −1.07 | −0.95 | 4.82 | **0.91** | 46 |

1c.

| Level | CEAREX | NNR | | | | ERA-15 | | | | ERA-40 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (hPa) | Mean | Mean | Bias | Mse | $r$ | Mean | Bias | Mse | $r$ | Mean | Bias | Mse | $r$ | Count |
| 1000 | 6.87 | 6.55 | −0.32 | 5.44 | **0.31** | 6.34 | −0.54 | 5.34 | **0.34** | 6.58 | −0.29 | 5.29 | **0.35** | 237 |
| 925 | 5.48 | 8.18 | **2.70** | 4.90 | **0.51** | 8.31 | **2.82** | 4.86 | **0.53** | 8.21 | **2.73** | 4.54 | **0.59** | 346 |
| 850 | 5.05 | 8.12 | **3.07** | 4.75 | **0.56** | 8.13 | **3.07** | 4.68 | **0.60** | 8.17 | **3.12** | 4.52 | **0.64** | 346 |
| 700 | 5.49 | 9.01 | **3.52** | 5.36 | **0.58** | 8.90 | **3.41** | 5.13 | **0.58** | 9.11 | **3.62** | 5.07 | **0.65** | 338 |
| 600 | 5.88 | 10.01 | **4.13** | 5.87 | **0.63** | 9.88 | **4.00** | 5.48 | **0.64** | 10.22 | **4.34** | 5.64 | **0.71** | 311 |
| 500 | 6.82 | 11.46 | **4.64** | 6.65 | **0.65** | 11.33 | **4.52** | 6.20 | **0.72** | 11.82 | **5.00** | 6.51 | **0.77** | 273 |
| 400 | 7.92 | 13.29 | **5.37** | 7.41 | **0.71** | 13.42 | **5.50** | 7.37 | **0.75** | 13.85 | **5.93** | 7.69 | **0.79** | 168 |
| 300 | 7.79 | 14.45 | **6.66** | 8.50 | **0.80** | 13.63 | **5.84** | 7.91 | **0.81** | 14.13 | **6.34** | 8.20 | **0.86** | 46 |

the CEAREX and all three reanalyses ($p < 0.01$) at all levels. However, all three reanalyses reasonably capture the pattern of the average $v$-component vertical profile; $r = 0.78$, 0.54, and 0.93 for NNR, ERA-15, and ERA-40, respectively.

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 (Tables 1a,b). Regarding the wind component variability, all three reanalyses show high positive correlations with the CEAREX data, with the exception of the 1000-hPa level. The discrepancy at 1000 hPa may be caused by the differences between the model surface pressures and real surface pressures. The correlation coefficients between 12-hourly rawinsonde and ECMWF reanalyses are generally higher than NNR results and highly significant ($p < 0.01$), although the differences are small (about 2% higher for ERA-15 and 6% higher for ERA-40). ERA-40 demonstrates the best correlation skill among the three reanalysis datasets.

The time series for both $u$ and $v$ components at each level were also examined. The time series plots for $u$ and $v$ components for CEAREX at 500 hPa are shown in Figs. 3a,b. For the $u$ component, Fig. 3a shows some substantial differences between CEAREX and the reanalyses with individual differences exceeding 20 m $s^{-1}$ (e.g., the observation at 2225 UTC 26 December 1988,

TABLE 2. Same as in Table 1, but between LeadEx and reanalyses.

2a.

| Level | LeadEx | NNR | | | | ERA-15 | | | | ERA-40 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (hPa) | Mean | Mean | Bias | Mse | $r$ | Mean | Bias | Mse | $r$ | Mean | Bias | Mse | $r$ | Count |
| 1000 | −4.37 | −3.92 | 0.45 | 2.94 | **0.90** | −3.86 | 0.51 | 2.88 | **0.90** | −4.58 | −0.21 | 2.85 | **0.90** | 70 |
| 925 | −3.24 | −3.42 | −0.18 | 3.11 | **0.90** | −2.86 | 0.37 | 2.89 | **0.92** | −2.76 | 0.48 | 2.90 | **0.92** | 74 |
| 850 | −1.98 | −2.22 | −0.24 | 3.09 | **0.90** | −1.70 | 0.28 | 2.98 | **0.91** | −1.17 | 0.81 | 2.89 | **0.92** | 73 |
| 700 | −0.14 | 0.27 | 0.41 | 3.34 | **0.86** | −0.07 | 0.08 | 3.17 | **0.87** | 1.45 | **1.60** | 3.27 | **0.90** | 72 |
| 600 | 1.19 | 1.50 | 0.31 | 3.59 | **0.82** | 0.78 | −0.42 | 3.42 | **0.84** | 2.74 | **1.55** | 3.25 | **0.89** | 71 |
| 500 | 2.91 | 2.90 | −0.01 | 4.11 | **0.78** | 2.04 | −0.87 | 3.72 | **0.83** | 4.10 | **1.19** | 3.57 | **0.86** | 71 |
| 400 | 5.08 | 4.47 | −0.61 | 4.64 | **0.79** | 3.92 | −1.16 | 4.00 | **0.85** | 5.70 | 0.62 | 3.30 | **0.90** | 71 |
| 300 | 6.49 | 5.84 | −0.65 | 3.56 | **0.89** | 5.96 | −0.53 | 2.85 | **0.93** | 6.56 | 0.80 | 2.14 | **0.96** | 69 |

2b.

| Level | LeadEx | NNR | | | | ERA-15 | | | | ERA-40 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (hPa) | Mean | Mean | Bias | Mse | $r$ | Mean | Bias | Mse | $r$ | Mean | Bias | Mse | $r$ | Count |
| 1000 | −0.04 | −1.24 | **−1.20** | 2.35 | **0.79** | −1.64 | **−1.60** | 2.49 | **0.83** | −0.74 | **−0.71** | 2.02 | **0.83** | 70 |
| 925 | 1.23 | 0.07 | **−1.16** | 2.48 | **0.88** | 0.20 | **−1.03** | 2.33 | **0.89** | 1.23 | 0.00 | 1.86 | **0.91** | 74 |
| 850 | 1.38 | 0.24 | **−1.13** | 2.54 | **0.88** | 0.30 | **−1.07** | 2.44 | **0.89** | 1.16 | −0.21 | 1.96 | **0.92** | 73 |
| 700 | 1.83 | 0.71 | **−1.12** | 2.69 | **0.90** | 1.05 | **−0.78** | 2.34 | **0.92** | 0.41 | **−1.42** | 2.26 | **0.95** | 72 |
| 600 | 1.95 | 0.84 | **−1.11** | 2.82 | **0.91** | 1.60 | −0.35 | 2.80 | **0.89** | 0.22 | **−1.73** | 2.82 | **0.94** | 71 |
| 500 | 2.16 | 1.28 | **−0.88** | 2.73 | **0.93** | 1.88 | −0.28 | 3.14 | **0.91** | 0.30 | **−1.86** | 3.35 | **0.93** | 71 |
| 400 | 2.39 | 1.27 | **−1.12** | 3.11 | **0.94** | 1.67 | −0.71 | 3.41 | **0.93** | 0.66 | **−1.73** | 3.32 | **0.95** | 71 |
| 300 | 2.58 | 1.83 | −0.75 | 2.72 | **0.96** | 2.42 | −0.17 | 2.45 | **0.96** | 2.82 | 0.23 | 2.24 | **0.97** | 69 |

2c.

| Level | LeadEx | NNR | | | | ERA-15 | | | | ERA-40 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (hPa) | Mean | Mean | Bias | Mse | $r$ | Mean | Bias | Mse | $r$ | Mean | Bias | Mse | $r$ | Count |
| 1000 | 6.91 | 6.31 | −0.61 | 2.75 | **0.84** | 6.90 | −0.01 | 2.52 | **0.87** | 7.12 | 0.20 | 2.56 | **0.86** | 70 |
| 925 | 7.50 | 6.67 | −0.83 | 2.90 | **0.85** | 6.56 | **−0.94** | 2.78 | **0.87** | 7.04 | −0.45 | 2.63 | **0.88** | 74 |
| 850 | 7.53 | 6.41 | **−1.12** | 2.73 | **0.84** | 6.44 | **−1.09** | 2.75 | **0.84** | 6.87 | −0.66 | 2.45 | **0.87** | 73 |
| 700 | 7.57 | 6.28 | **−1.29** | 2.80 | **0.82** | 6.58 | **−0.99** | 2.51 | **0.85** | 7.45 | −0.12 | 2.30 | **0.86** | 72 |
| 600 | 8.03 | 6.76 | **−1.27** | 3.00 | **0.78** | 7.11 | **−0.92** | 2.77 | **0.79** | 17.94 | −0.09 | 2.87 | **0.79** | 71 |
| 500 | 9.34 | 8.57 | −0.77 | 3.27 | **0.73** | 8.50 | −0.84 | 3.20 | **0.75** | 9.25 | −0.09 | 3.56 | **0.74** | 71 |
| 400 | 11.32 | 10.37 | −0.95 | 3.93 | **0.75** | 10.40 | −0.92 | 3.80 | **0.77** | 11.15 | −0.18 | 3.59 | **0.80** | 71 |
| 300 | 12.18 | 11.50 | −0.68 | 3.27 | **0.86** | 11.87 | −0.32 | 2.70 | **0.90** | 12.27 | 0.09 | 2.29 | **0.93** | 69 |

observation No. 199 in Fig. 3a). The NNR time series often has larger biases. On average, both NNR and ERA-40 similarly overestimate the average zonal wind speed (2.64 m $s^{-1}$ for NNR and 2.84 m $s^{-1}$ for ERA-40) and display similar mses (Table 1a). A $t$ test between NNR and ERA-40 ($p > 0.1$) indicates there is no significant difference between those two reanalyses at the 500-hPa level, however, ERA-40 ($r = 0.75$) better captures the zonal wind variability than NNR ($r = 0.71$). The bias between NNR and ERA-15 (NNR − ERA-15) is 0.78 m $s^{-1}$ significant at $p < 0.01$, but they are highly correlated ($r = 0.95$). For meridional flow ($v$ components), all three reanalyses exhibit some disagreement with the observed soundings (Fig. 3b). The correlation coefficients between CEAREX and the reanalyses (0.86, 0.88, and 0.91 for NNR, ERA-15, and ERA-40, respectively) are highly positive, indicating that all three reanalyses correctly resolve the variability of meridional flow but not the CEAREX magnitude (Table 1b). On average, reanalyses produce nearly 1.8 m $s^{-1}$ stronger northerly flow. ERA-40 shows the lowest bias and mse with the highest correlation value among the three reanalyses.

For wind speed comparisons (Table 1c), all three reanalyses display large biases and mses at all levels above 1000 hPa, and the differences and mses increase with height. The percentage of significant differences between reanalyses and CEAREX observations, defined as exceeding the CEAREX measurement accuracy of 4 m $s^{-1}$ (Francis 2002), increase from less than 30% at the surface to more than 65% at the 300-hPa level. By contrast, the reanalyses show positive corre-

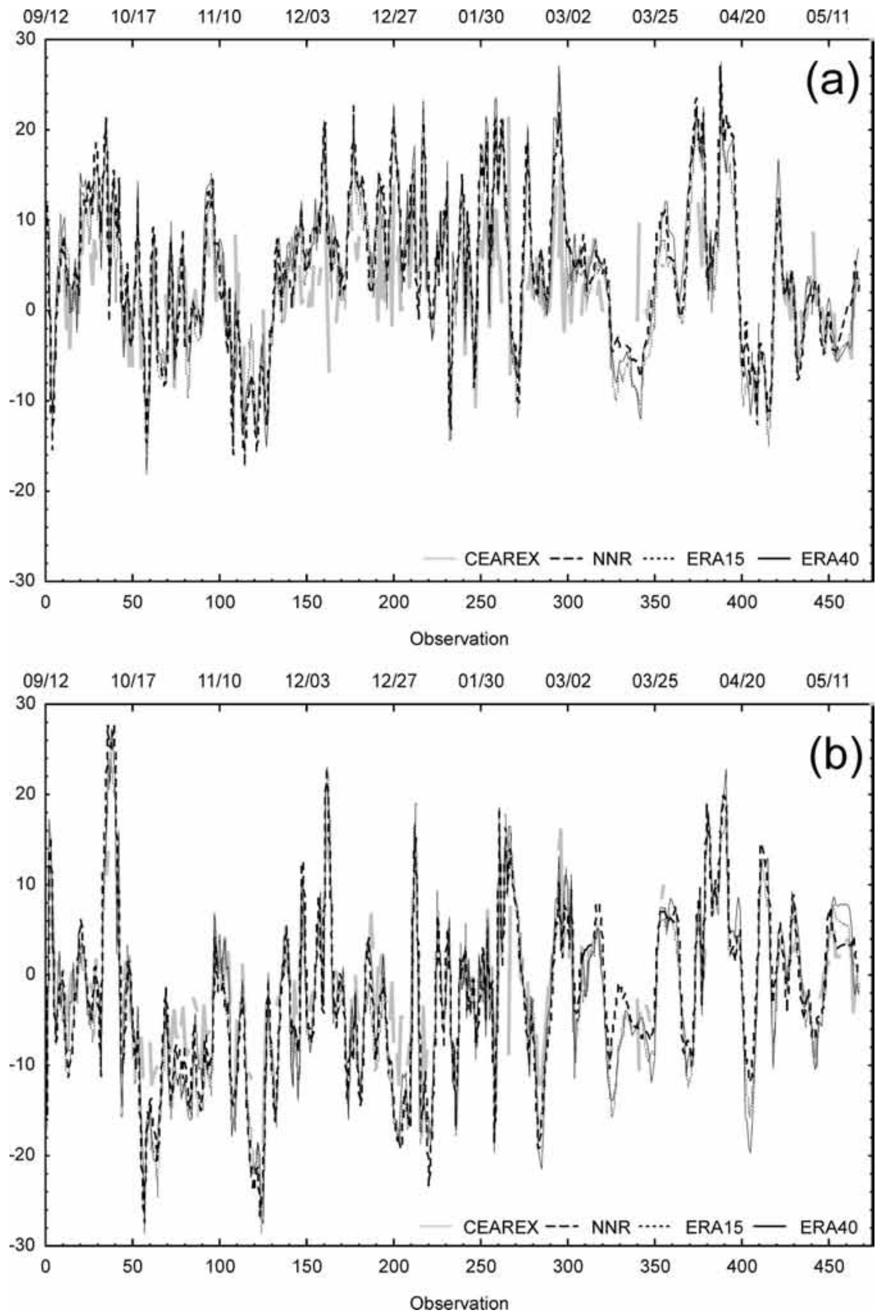


FIG. 3. Time series plot of wind components (m $s^{-1}$) at the 500-hPa level for CEAREX and reanalyses for (a) $u$ and (b) $v$ components. Observation count is shown on the bottom of the $x$ axis. The dates associated with every 50 observations are marked on the top of each plot.

lations 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.

The differences of $u$ components between the LeadEx data and the three reanalyses can be found in Table 2a. ERA-40 displays stronger westerly flow at most levels. However, the biases and mses between observations and reanalyses are relatively small and consistent throughout atmosphere. The significance tests indicate that there are no significant differences for the average $u$ components between LeadEx and three reanalysis datasets at most levels. All three reanalyses have strong positive correlations, $r > 0.77$ for NNR, $r > 0.82$ for ERA-15, and $r > 0.85$ for ERA-40, with the 12-hourly LeadEx data with significance levels of $p < 0.01$.

For the average $v$ components of the LeadEx data (Table 2b), NNR underestimates the southerly flow by about 1.0 m $\mathrm{s}^{-1}$ (about 40% less than the CEAREX biases) with high correlation coefficients (about 5%–10% higher than for CEAREX) at most levels. In contrast to NNR, ERA-15 demonstrates better skill with respect to bias and ERA-40 with respect to variability. On average, ERA-15 displays a better agreement with rawinsondes at upper levels and ERA-40 at lower layers. This result suggests that all three reanalyses well resolve the variability of the $u$ and $v$ components during the LeadEx period.

The time series plots of $u$ and $v$ components for the LeadEx at upper levels have been examined (figures not shown). For $u$ components, all three reanalyses have good agreement with rawinsondes, with the NNR displaying a slightly better approximation (smaller biases) to the observations than both ECMWF reanalyses, however, both ERA-15 and ERA-40 demonstrate better skill in capturing the variability. The discrepancies between the LeadEx soundings and all three reanalyses are not statistically significant at most levels.

Unlike CEAREX (large biases and good correlations), LeadEx has much smaller biases and higher (5%–10%) correlations in the wind speed comparisons (Table 2c). The discrepancies between rawinsonde and reanalyses 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 better during the LeadEx period than during the CEAREX period.

### *b. Specific humidity and precipitable water*

The CEAREX monthly mean specific humidity for surface and upper levels (850 and 500 hPa) are plotted in Figs. 4a–c. At the surface level (Fig. 4a), both ECMWF reanalyses show close agreement with 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 (Fig. 4b), both ERA-15 and ERA-40 outperform NNR, with small negative biases ($-0.01$ g $\mathrm{kg}^{-1}$) for ERA-15 and small positive biases (0.03 g $\mathrm{kg}^{-1}$) for ERA-40. Again, NNR (with an average bias of $-0.11$ g $\mathrm{kg}^{-1}$) tends to underestimate the specific humidity. On average, NNR has a 20%–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 of $-0.01$ g $\mathrm{kg}^{-1}$) with the observations at the 500-hPa level (Fig. 4c). Both ECMWF reanalyses (0.03 g $\mathrm{kg}^{-1}$ for ERA-15 and 0.03 g $\mathrm{kg}^{-1}$ for ERA-40) tend to overestimate the monthly average specific humidity, with positive biases of 20%–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 0.95 at most levels. By contrast, the correlation coefficients between 12-hourly observations and three reanalyses are lower. For example at 500 hPa, the correlation coefficients are 0.77, 0.81, and 0.82 for the NNR, ERA-15, and ERA-40, respectively. This result shows that all three reanalyses capture the variability of specific humidity on the monthly time scale. However, on the 12-hourly or daily basis, the agreement between observations and reanalyses drops significantly. ERA-40 has a better specific humidity representation than the NNR and ERA-15 data.

Figure 4d shows the average column-integrated water vapor amounts (precipitable water) for each month. Precipitable water is defined as

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

where $w$ is precipitable water, $q$ is specific humidity, $p_{\mathrm{sfc}}$ is surface pressure, and $p_{\mathrm{top}}$ is the pressure at the 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, $p_{\mathrm{top}}$ of all four datasets (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 dataset. 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 $\mathrm{m}^{-2}$, occurred in March 1989. On the other hand, ERA-15 was about 0.2–0.5 kg $\mathrm{m}^{-2}$ 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 $\mathrm{m}^{-2}$. The correlation coeffi-

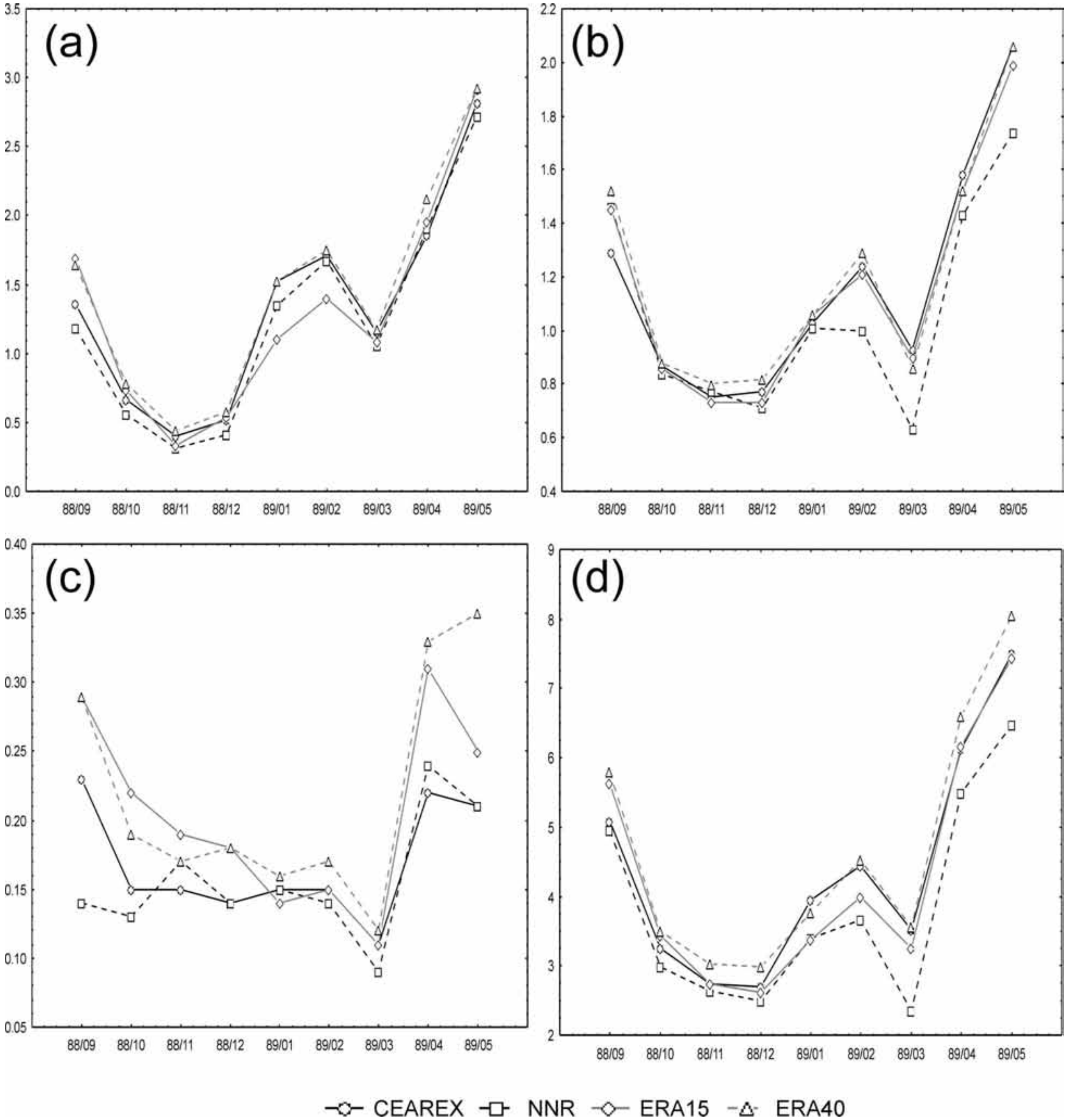


FIG. 4. Monthly average specific humidity (g $kg^{-1}$) and precipitable water (kg $m^{-2}$) for CEAREX and reanalyses (a) surface specific humidity, (b) 850-hPa specific humidity, (c) 500-hPa specific humidity, and (d) precipitable water.

cients 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. The observed variables have been averaged for each month and compared to the NNR, ERA-15, and ERA-40 datasets.

The mean temperatures for each month at surface and at upper levels (850 and 500 hPa) are shown in Figs. 5a–c. During the first few months at the surface level (Fig. 5a), the NNR underestimated the mean temperature by approximately 2°–3°C and both ECMWF reanalyses tend to overestimate it by a similar amount.

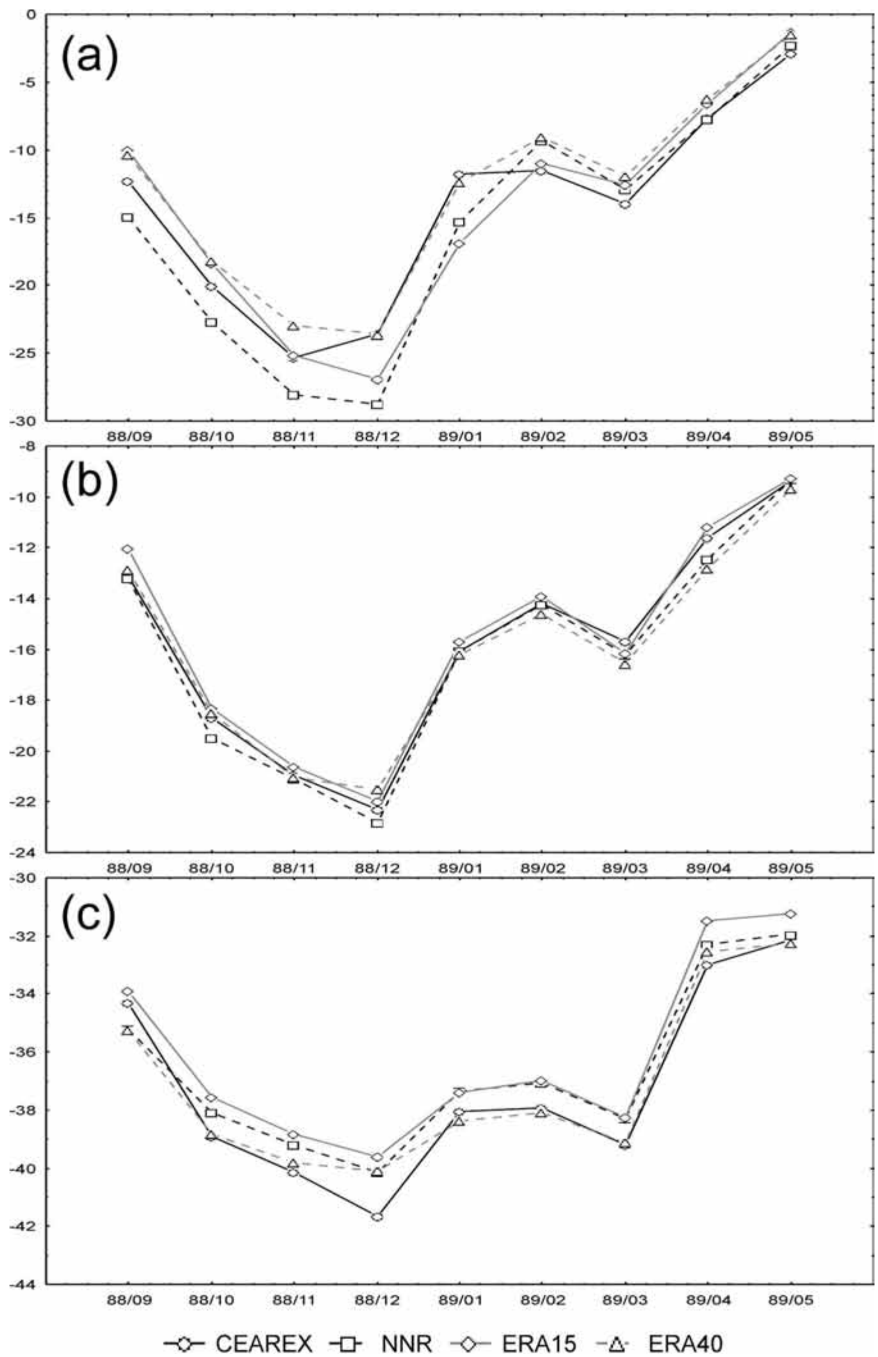


FIG. 5. Monthly mean temperature (°C) for CEAREX and reanalyses at (a) the surface, (b) the 850-hPa level, and (c) the 500-hPa level.

Mean surface temperatures are about 1°–2°C lower than all three reanalysis datasets 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 displays the best skill, with the lowest root-mean-square error (rmse) 1.7°C (cf. 2.8°C for NNR and 2.4°C for ERA-15) and the highest correlation coefficient 0.99, among the three reanalysis datasets.

At lower-tropospheric levels (925, 850, and 700 hPa, only 850 hPa is shown in Fig. 5b), 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,

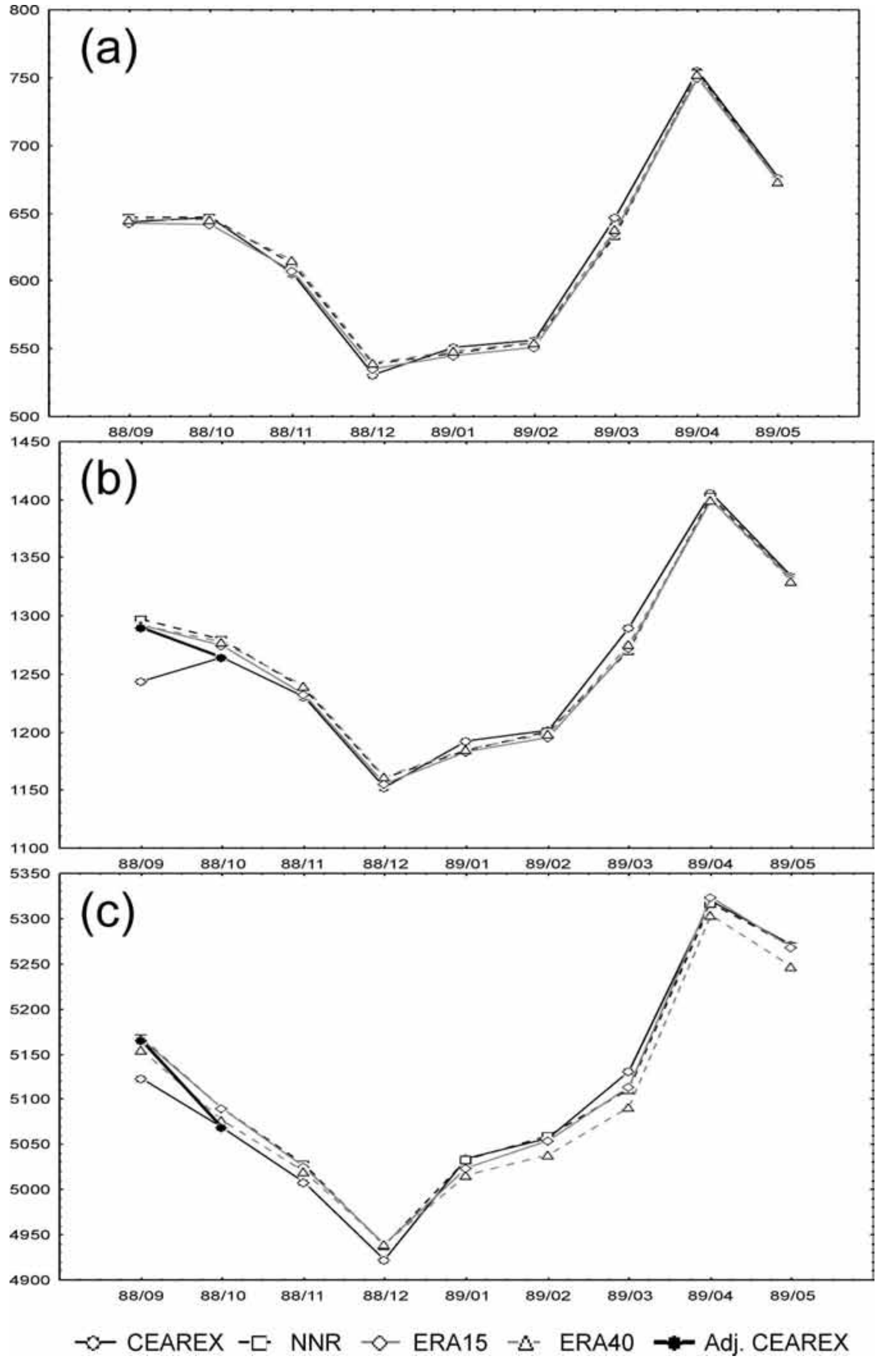


FIG. 6. Monthly average heights (m) for CEAREX and reanalyses at the (a) 925-, (b) 850-, and (c) 500-hPa level.

ERA-15, and ERA-40 monthly mean temperatures and the observations at 850 hPa are −0.4°, 0.2°, and −0.2°C. Correlations between 12 hourly observations and reanalysis values are 0.95, 0.96 and 0.96, respectively. The reanalyses at upper levels (600, 500, and 400 hPa, only 500 hPa is shown in Fig. 5c) are warmer than the observations, with the average monthly differences at 500 hPa being 0.7°, 1.2°, and 0.2°C; 12-hourly correlations are 0.92, 0.93, and 0.93, respectively. The difference between reanalyses and soundings also increases slightly as the pressure decreases. Overall, all three reanalyses well simulate the temperature field. ERA-40 generally exhibits the best skill among the three reanalysis datasets.

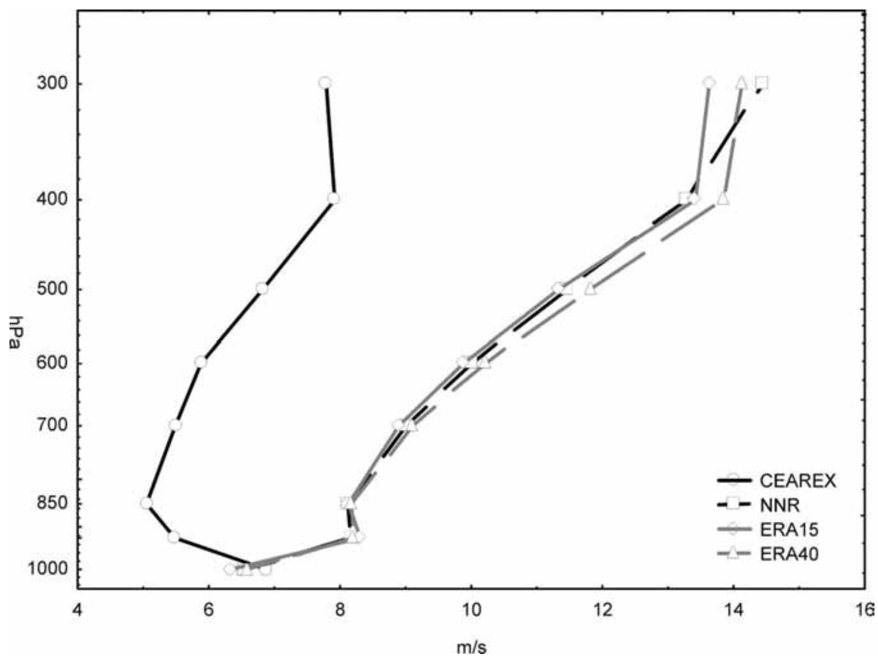


FIG. 7. Average wind speed (m $s^{-1}$) profile for CEAREX and the reanalyses.

Figures 6a–c show the average geopotential heights of the CEAREX and three reanalyses for each month at 925-, 850-, and 500-hPa levels. The largest biases can be found during the first month, which is caused by the error of the 1150 UTC 21 September 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 m for 850 hPa and 43.4 m for 500 hPa (Figs. 6b,c). After the first month of the experiment, the biases between soundings and reanalyses are less than 10 m (<1%), a small 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 m at the 850-hPa level; and 4.2, −3.1, and −10.1 m at the 500-hPa level. The significant negative difference between CEAREX and ERA-40 at the 500-hPa level is likely caused by the known cold bias in ERA-40 at lower-tropospheric levels (Bromwich et al. 2002). The 12-hourly CEAREX observations and all three reanalyses are also highly correlated with each other ($r \approx 0.97$ for 850 hPa and $r \approx 0.98$ for 500 hPa) with high confidence ($p < 0.01$).

## 4. Discussion and conclusions

Reanalysis products exhibit great utility for climate studies. The main characteristics of reanalysis data are use of a fixed data assimilation scheme and incorporation of a wide variety of observation types. Although reanalysis data are theoretically preferred for climate studies, we display some differences between observations and three different reanalyses during the CEAREX and LeadEx periods. Each reanalysis has its own strengths and weaknesses in different fields. ERA-40 has the best agreement with observations for most fields despite some biases, whereas NNR generally exhibits the largest differences and the lowest correlations among the three reanalyses.

The results shown here disagree partly with Francis (2002). Francis combined both experimental datasets 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, which agrees with Francis's 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 from Francis's analysis). To extend Francis's evaluation, we show that the ERA-40 reanalysis dataset provides a more realistic representation of the winds than the other two reanalyses, especially NNR, during both experimental periods.

The largest discrepancy between the observations

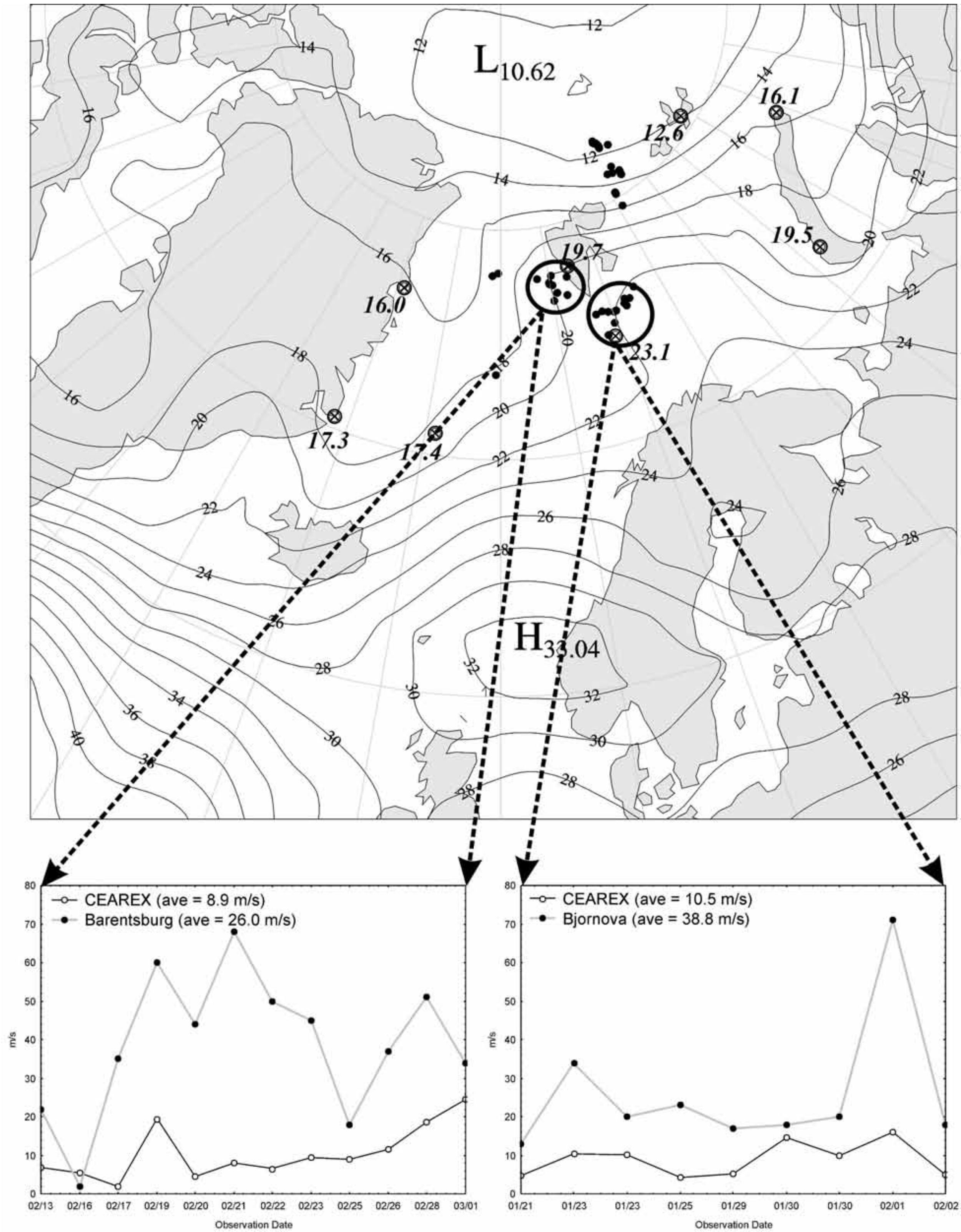


FIG. 8. Average 300-hPa ERA-40 wind speed (contours in m $s^{-1}$) for 46 cases of CEAREX observations. The locations of *Polarbjørn* are plotted as solid dots on the map. The locations of HARA stations are also marked on the map as circles with an x. The average 300-hPa wind speed for HARA stations during 46 cases are shown next to the locations. CEAREX and HARA wind speed for cases near Barentsburg and Bjørnova are plotted in the two subpanels.

TABLE 3. Same as in Table 1, but between *Haakon Mosby* observations and reanalyses.

3a.

| Level | HM | NNR | | | | ERA-15 | | | | ERA-40 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (hPa) | Mean | Mean | Bias | Mse | $r$ | Mean | Bias | Mse | $r$ | Mean | Bias | Mse | $r$ | Count |
| 1000 | 0.52 | −0.91 | −1.43 | 3.90 | **0.74** | −0.70 | −1.22 | 3.40 | **0.80** | −0.18 | −0.70 | 2.68 | **0.88** | 30 |
| 925 | −0.93 | −0.80 | 0.13 | 3.89 | **0.87** | 0.59 | **1.52** | 3.97 | **0.88** | −0.42 | 0.51 | 2.89 | **0.93** | 86 |
| 850 | 0.53 | 0.99 | 0.47 | 3.94 | **0.88** | 1.44 | 0.91 | 4.11 | **0.86** | 0.80 | 0.27 | 3.15 | **0.93** | 86 |
| 700 | 3.30 | 3.54 | 0.24 | 4.38 | **0.89** | 3.58 | 0.28 | 3.49 | **0.94** | 3.70 | 0.40 | 3.11 | **0.95** | 83 |
| 600 | 4.49 | 5.15 | 0.66 | 4.38 | **0.89** | 4.32 | −0.17 | 3.70 | **0.92** | 5.04 | 0.55 | 3.05 | **0.95** | 79 |
| 500 | 5.20 | 6.57 | 1.37 | 5.16 | **0.91** | 5.12 | −0.08 | 4.54 | **0.92** | 6.32 | **1.12** | 3.78 | **0.95** | 78 |
| 400 | 5.28 | 7.31 | **2.04** | 5.56 | **0.91** | 5.73 | 0.46 | 4.50 | **0.93** | 7.23 | **1.96** | 3.99 | **0.97** | 76 |
| 300 | 6.58 | 7.62 | 1.04 | 3.76 | **0.96** | 6.21 | −0.36 | 4.06 | **0.94** | 7.81 | **1.24** | 3.12 | **0.97** | 73 |

3b.

| Level | HM | NNR | | | | ERA-15 | | | | ERA-40 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (hPa) | Mean | Mean | Bias | Mse | $r$ | Mean | Bias | Mse | $r$ | Mean | Bias | Mse | $r$ | Count |
| 1000 | −2.57 | 0.05 | **2.62** | 4.94 | **0.69** | −0.40 | **2.17** | 4.49 | **0.73** | −0.65 | **1.92** | 3.63 | **0.84** | 30 |
| 925 | −0.97 | 0.16 | 1.13 | 4.52 | **0.85** | −0.39 | 0.58 | 3.75 | **0.89** | −0.94 | 0.03 | 3.02 | **0.93** | 86 |
| 850 | 2.01 | 2.05 | 0.04 | 4.39 | **0.82** | 1.53 | −0.48 | 3.44 | **0.89** | 1.47 | −0.54 | 3.46 | **0.89** | 86 |
| 700 | 2.90 | 3.72 | 0.82 | 3.86 | **0.83** | 2.76 | −0.14 | 3.01 | **0.90** | 3.23 | 0.33 | 2.97 | **0.91** | 83 |
| 600 | 3.76 | 4.57 | 0.81 | 3.43 | **0.90** | 3.25 | −0.51 | 2.28 | **0.96** | 3.66 | −0.11 | 2.43 | **0.95** | 79 |
| 500 | 3.48 | 5.27 | **1.80** | 4.21 | **0.89** | 3.65 | 0.18 | 2.83 | **0.94** | 3.89 | 0.42 | 2.89 | **0.94** | 78 |
| 400 | 4.20 | 6.17 | **1.97** | 4.48 | **0.90** | 4.97 | 0.77 | 3.45 | **0.93** | 4.68 | 0.48 | 3.03 | **0.94** | 76 |
| 300 | 6.33 | 7.13 | 0.80 | 3.33 | **0.93** | 6.14 | −0.20 | 3.52 | **0.92** | 6.35 | 0.02 | 2.37 | **0.97** | 73 |

3c.

| Level | HM | NNR | | | | ERA-15 | | | | ERA-40 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (hPa) | Mean | Mean | Bias | Mse | $r$ | Mean | Bias | Mse | $r$ | Mean | Bias | Mse | $r$ | Count |
| 1000 | 7.66 | 5.32 | **−2.34** | 3.46 | **0.68** | 4.97 | **−2.70** | 3.87 | **0.59** | 5.29 | **−2.37** | 3.40 | **0.70** | 30 |
| 925 | 10.30 | 7.34 | **−2.96** | 4.51 | **0.70** | 8.93 | **−1.37** | 4.24 | **0.54** | 9.20 | **−1.10** | 3.38 | **0.73** | 86 |
| 850 | 9.67 | 6.58 | **−3.10** | 4.59 | **0.74** | 7.98 | **−1.70** | 4.16 | **0.67** | 8.31 | **−1.36** | 3.40 | **0.78** | 86 |
| 700 | 10.18 | 8.12 | **−2.06** | 4.48 | **0.80** | 9.05 | **−1.13** | 3.29 | **0.89** | 9.31 | **−0.87** | 2.99 | **0.90** | 83 |
| 600 | 11.02 | 9.35 | **−1.67** | 3.91 | **0.88** | 9.66 | **−1.36** | 3.08 | **0.93** | 10.08 | **−0.95** | 2.56 | **0.95** | 79 |
| 500 | 12.58 | 10.75 | **−1.84** | 4.49 | **0.88** | 11.06 | **−1.52** | 3.82 | **0.91** | 11.34 | **−1.24** | 3.47 | **0.92** | 78 |
| 400 | 13.57 | 12.07 | **−1.49** | 5.03 | **0.88** | 12.77 | −0.80 | 3.80 | **0.92** | 12.68 | −0.88 | 3.82 | **0.92** | 76 |
| 300 | 13.17 | 12.67 | −0.51 | 3.42 | **0.96** | 12.64 | −0.53 | 3.61 | **0.95** | 12.84 | −0.34 | 2.62 | **0.98** | 73 |

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. 7) 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 region 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 850-hPa level.

Figure 8 shows the average wind speed field for ERA-40 and the average speeds at local HARA stations during the 46 available 300-hPa CEAREX soundings, 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,

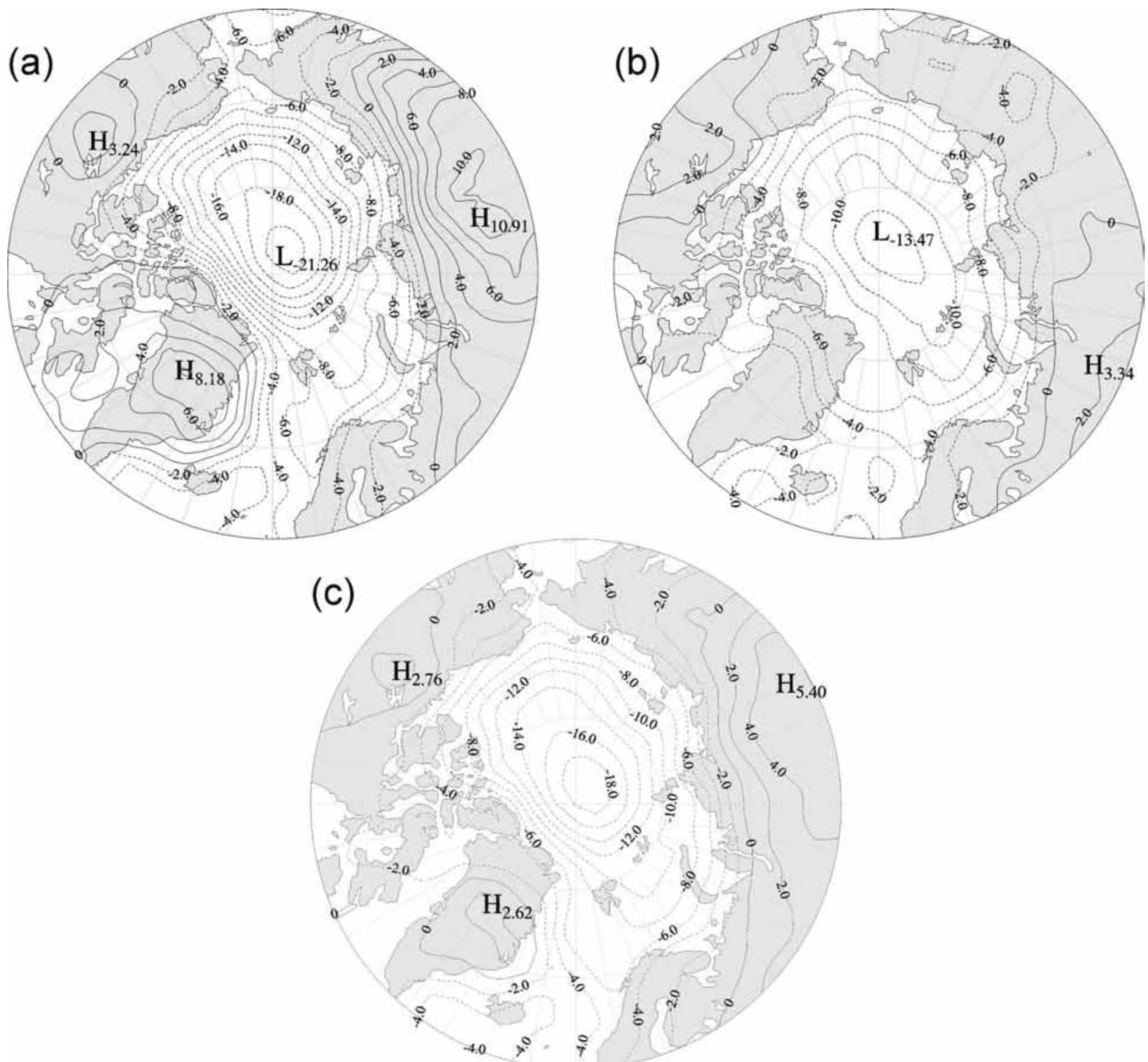


FIG. 9. 500-hPa geopotential height differences (m) between ERA-40 and NNR (ERA-40 minus NNR) from 1979 to 1996: (a) DJF, (b) JJA, and (c) annual average.

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. 8). During part of the CEAREX period, another ship the *Haakon Mosby* was in the vicinity of Bjørnova and south of Svalbard, Norway. The *Haakon Mosby* participated in the Seasonal Ice Zone Experiment (SIZEX) from 25 February to 23 March 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*. Wind speeds from the three reanalyses are slightly weaker than the observed values from *Haakon Mosby* (Table 3c); there is no evidence of discrepancy in vertical wind speed shear between the reanalyses and *Haakon Mosby* observations, especially from 700 to 300 hPa. In general, there is no bias in the reanalysis wind components (Tables 3a, b) in relation to *Haakon Mosby* observations, and the observed temporal variability is very well resolved by the reanalyses throughout the atmospheric column. The results indicate that the upper-level winds (especially above the 850-hPa level) obtained by the CEAREX *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 *Polarbjørn* measurement errors, in part, because VIZ Corporation is no longer in business.

In addition to wind field comparisons, all three reanalyses agree closely with the observed CEAREX heights and temperatures. The heights differences between observations and reanalyses are small for most cases except for those associated with the known lower-tropospheric cold bias in ERA-40 (Bromwich et al. 2002; discussed further below). For the temperature comparisons, reanalyses generally produced colder temperatures (1°–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.

The results demonstrate that the CEAREX *Polarbjørn* upper-level winds are erroneous. Thus, we disagree with Francis's (2002) conclusion that the upper-tropospheric wind speeds in NNR and ERA-15 suffer from a serious high bias. In fact, these reanalyses along with ERA-40 display good agreement with rawinsonde winds from surrounding fixed stations. In addition to the wind comparisons, we find that the temperature, humidity and geopotential fields from both CEAREX and LeadEx (not shown) are well reproduced in terms of bias and variability. We conclude that reanalyses are a suitable and possibly a primary tool for study of Arctic climate.

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 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. In particular, 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 [e.g., the High Resolution Infrared Radiation Sounder (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 (see the ECMWF online document at http://www.ecmwf.int/research/era/Data_Services/section3.html). Comparison between the 500-hPa heights in ERA-40 and NNR confirms that the ERA-40 cold bias starts at the beginning of HIRS assimilation in 1979 and ends in 1996. The difference between ERA-40 and NNR for this period at the center of the Arctic Ocean is about 21 m in December–January–February (DJF; Fig. 9a) and near 13 m in June–July–August (JJA; Fig. 9b). For the annual average (Fig. 9c), ERA-40 is up to 18 m lower than NNR at the 500-hPa level. These 500-hPa differences are confirmed by the reanalyses comparison with CEAREX and LeadEx observations presented here, and are almost entirely due to the negative height bias in ERA-40. Current ECMWF plans call for a rerun of the modern satellite era (1979 to the present). The polar meteorological community has high expectations that the enhanced ERA-40 can improve studies of the Arctic and Antarctic climate.

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