6.8 EVALUATION OF BALLOON TRAJECTORY FORECAST ROUTINES FOR GAINS

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1. INTRODUCTION

The Global Air-ocean IN-situ System (GAINS) is a global observing system designed to augment current environmental observing and monitoring networks (Girz et al. 2001). GAINS is a network of long-duration, stratospheric platforms carrying onboard sensors and hundreds of dropsondes for acquisition of meteorological, air chemistry, and climatic data over oceans and remote land regions of the globe. Two vehicles comprise the GAINS network—superpressure balloons and remotely-operated aircraft (ROA). The 33.5-m diameter superpressure balloons will carry payloads of 350 kg and remain aloft for a period of 6-12 months at altitudes from 18.3 to 22.9 km. Remotely-operated aircraft, which are expected to play a role in providing year-round global coverage in the Northern Hemisphere, midlatitudes, and polar regions, also carry hundreds of kilograms of payload, but for shorter periods.

Vital to meeting the goal of an operational program is completion of a rigorous set of laboratory and field tests of balloon shell and payload instrumentation. A flight of up to 48 hours has recently been conducted and is discussed in a companion paper (Girz et al. 2002); flights with durations of several days to weeks are planned. Proper evaluation of these test flights requires recovery of the balloon and payload, thus the need to know their flight path and landing site. Software utilizing observational and numerical model sources has been developed for trajectory prediction, with four versions currently in use. Here, we describe the methods employed by the software and the differences of each version, and discuss the results of an evaluation of predicted trajectories for the period 1-30 May 2001.

2. SOFTWARE

In late 1998, the first of several versions of software was developed for computation of predicted balloon trajectories using winds from rawinsonde observation data. This software uses simple linear extrapolation to predict balloon position in 1-min increments. Given a launch site (latitude, longitude and elevation), ascent and descent rates and flight duration, the balloon is assumed to simply advect along with the wind. No consideration is given for aerodynamic drag, loss of lift due to helium diffusion, or vertical oscillation due to density changes resulting from the day-night radiation cycle. Ascent and descent rates are assumed constant throughout the flight. Although overly simplistic as a result of these assumptions, we expect that the predictions based on this software will nonetheless prove useful in flight planning and recovery operations.

The software produces two ASCII text files. The first contains 1-min incremental balloon positions (latitude and longitude) used for mapping the trajectory. The second file contains a 1-min incremental listing of computational information, including balloon altitude, corresponding pressure level, nearest site ID and wind direction and speed

The first version, known as Version 7, uses wind observations from the twice-daily National Weather Service rawinsonde balloon launches for the predictions. Soundings from each North American site are interpolated to 10-mb vertical levels, and winds from the nearest site and pressure level are used for prediction of the balloon's 1-min incremental movement. The nearest raob site is re-computed after each prediction. Because launches are planned from Tillamook, Oregon, the sounding derived from the RUC-2 model (Benjamin et al. 1998) for the METAR site near Tillamook is included in the rawinsonde file.

Inaccuracies in the predictions from Version 7 come from a variety of sources. First, spatial distribution of rawinsonde stations (on the order of 200 km or more) mean that winds for each site are unrealistically assumed to exist over a wide area surrounding that site. For predicted flights with durations greater than a few hours, the 12-h temporal resolution also unrealistically assumes that winds remain static over that period. We expect that Version 7 will be most useful for predicting flights of less than 3 h launched soon after synoptic launch times (0000 and 1200 UTC), and close to raob sites.

Version 8 was developed soon after Version 7 and also utilizes the observations from the rawinsonde network. The soundings are again interpolated to 10-mb vertical levels, but the observations at each level are objectively analyzed to a regular latitude-longitude grid prior to use for balloon trajectory prediction. The analysis performed is a simple 4-pass Gaussian scheme developed by F. Caracena in the late 1980s, and has a mean grid spacing of 62 km over the continental U.S. (personal communication).

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The finer spatial resolution of Version 8 reduces the inaccuracies due to station spacing, but temporal resolution remains unchanged and as a result, Version 8 is also best suited for short flights launched close to the synoptic data times. Both Versions 7 and 8 are also sensitive to missing observations and levels. For example, a balloon predicted to float eastward from Tillamook eventually needs to use winds from the Boise, Idaho, sounding. If these are missing, the winds used from launch will continue to be used for an unrealistic distance. The preprocessing, which produces the objective analysis, performs a check of data distribution at each 10-mb level. The data "center of mass" and mean nearest-neighbor distances are computed; levels with skewed centers of mass or wide station distribution are excluded from use in trajectory calculations. These temporal and spatial distribution issues may be resolved through the use of numerical model analyses and forecasts in trajectory prediction.

Versions 9, 10, and 11, developed over the past two years, utilize model output from the Eta, AVN and RUC-2 models, respectively. Version 9, originally written to use the 32-km Eta output, is undergoing modifications to use the 22-km Eta output, and is not included in this study.

Version 10 uses the analysis and forecast output from the Global AVN model (NOAA/NCEP, 2001). This model, using a 1x1 degree horizontal grid spacing and 26 vertical levels from the surface to 10 mb, is initialized four times per day, and yields forecast output at 3-h intervals to 72 hours. The temporal resolution allows for better prediction of balloon trajectory for flights longer than a few hours; we are testing whether the spatial resolution will be adequate for reasonably accurate trajectory prediction. Because this model is global in scope, it will prove useful for prediction of flights launched from points outside the continental US and those whose duration causes the balloon to float great distances.

Version 11 of the software performs the trajectory prediction using the analysis and forecast output (in isobaric form) from the 40-km RUC-2 model (Benjamin et al. 1998). The RUC-2 model is initialized hourly with forecast output at 1, 2, 3, 6, 9 and 12 hours from initialization. Its spatial and temporal resolutions are the best of any model currently available, and the initializations are based upon a wide variety of observational data, including ACARS and satellite-derived parameters.

Unlike Versions 7 and 8, which predict using wind data for a single synoptic time (Fig. 1a), the model versions use the winds from the initialization and model forecasts that encompass the duration of the predicted flight. The point at which the wind data used switch from initialization to the first forecast period, and from forecast to forecast, is determined by the temporal midpoint between each successive valid time. For example, a 4-h predicted flight using Version 11 (RUC-2) will use the initialization, and 1-, 2-, and 3-h forecast data (Fig. 1b). The initialization is used to the midpoint between initial time and 1 h, or 0.5 h; the 1-h forecast used from 0.5 h to 1.5 h (the midpoint between 1-h and 2-h forecasts), and so on, concluding with the 6-h forecast winds for the predicted period from 4.5 hours to balloon landing.

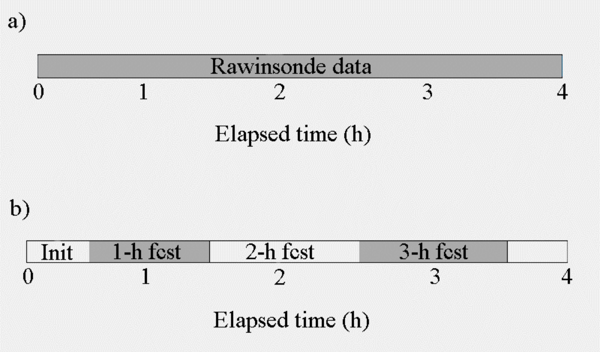

Fig. 1. Wind data segments for 4-h flight predicted with versions 7 and 8 (a) and Version 11 (b).

3. EVALUATION METHODOLOGY

The purpose of this study is to evaluate the accuracy of each of the software versions against "true" balloon paths. Resource constraints have not permitted us to launch balloons twice daily to obtain these actual balloon trajectories. Because of the completeness of the data which comprise the RUC-2 hourly initializations, we have chosen to use trajectories predicted by Version 11 using a series of RUC-2 hourly initializations as the "baseline" trajectory for comparison against the predictions from the various versions. Forecast and baseline predictions were computed for launches from Tillamook, Oregon (45.42°N 123.81°W) at 0000 and 1200 UTC for each day in the period 1-30 May 2001 with the following flight parameters: Flight durations of 3 h for Versions 7 and 8 (rawinsonde), 48 h for Version 10 (AVN) and 12 h for Version 11 (RUC-2). Ascent and descent rates were 2.5 m s^{-1} and 3.1 m s^{-1}, respectively. The differences in predicted locations were computed minute-by-minute for each version. Results appear in the next section.

4. ANALYSIS

For this preliminary study, we used several methods to evaluate the differences between forecast and baseline trajectories. Radial difference magnitudes between baseline and forecast trajectory position were plotted at 1-h increments for each version. Directional biases were determined by plotting latitudinal versus longitudinal errors for 3-h and 12-h flights. Tables of quartile and median values were constructed to locate potential outliers. Additionally, forecast and baseline latitude and longitude values were plotted separately to determine the correlation for each version. The next section discusses comparisons of Version 7 and 8 results and Version 10 and 11 results.

5. VERSIONS 7 AND 8 RESULTS

As expected, trajectory differences were found to increase with time for both Version 7 and Version 8 (Figs. 2 and 3). Maximum difference at 3 h for Version 8 (100 km) is one-half the magnitude of the Version 7 (201 km) difference, indicating the value of the interpolation scheme.

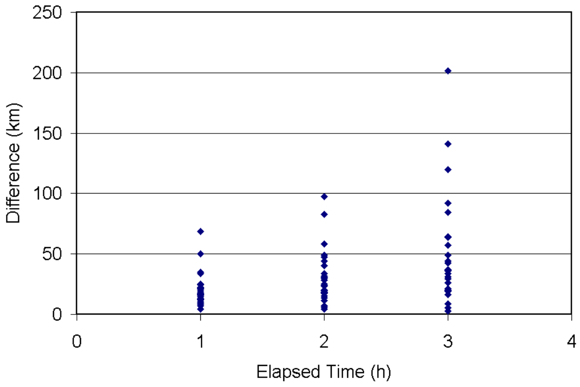

Fig. 2. Trajectory differences (forecast – baseline) by hour for Version 7.

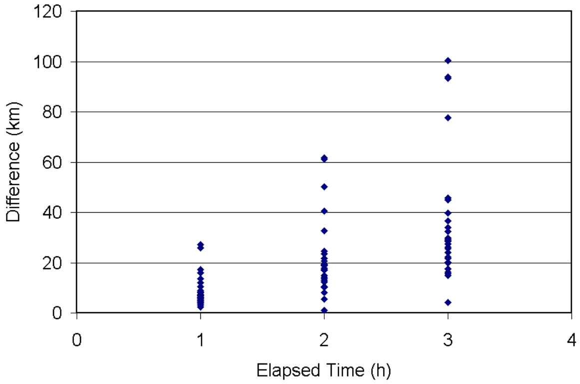

Fig. 3. As in Fig. 2 except for Version 8.

Comparisons of median and quartile values of the distribution in Figs. 2 and 3 (Table 1) show similar results. By all measures, differences are alway smaller for Version 8 for all flight durations.

TABLE 1. Quartile values (km) for Versions 7 and 8.

	1 h		2-h		3-h	
	V 7	V 8	V 7	V 8	V 7	V 8
Max	68.6	27.2	97.3	61.6	201.5	100.5
3rd Q	21.5	8.9	33.4	21.7	55.2	36.6
Med	16.0	6.4	23.5	17.2	36.2	28.5
1st Q	12.0	4.3	18.1	13.5	22.5	20.1
Min	4.2	2.2	4.5	1.0	2.6	4.2

When the latitudinal and longitudinal differences are compared, both versions show a tendency for a northeast bias at 3 h (Figs. 4 and 5). While no significant change in meridional error is noted, the use of objectively-analyzed wind data greatly decreased the median zonal errors, from 12.45 to 1.89 km, or by about 85%.

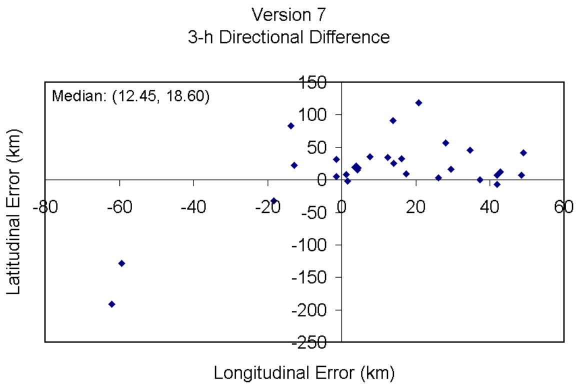

Fig. 4. Directional difference distribution for 3-h flights predicted by Version 7.

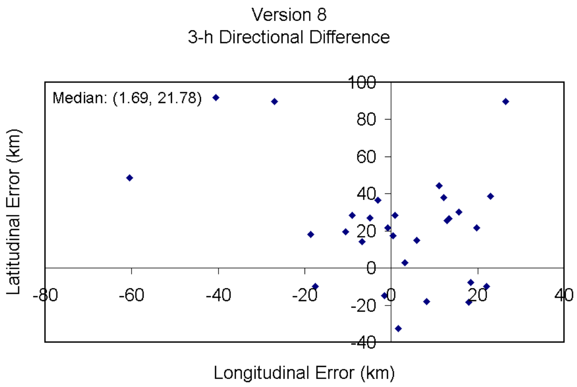

Fig. 5. As in Fig. 4, except for Version 8.

Correlation of baseline and predicted latitude position (Figs. 6 and 7) at 3 h also show marked improvement in Version 8. Figures 8 and 9 show that longitude correlation is also improved to a lesser degree.

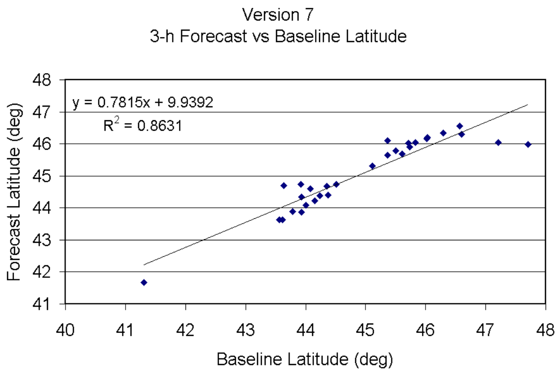

Fig. 6. Latitude scatterplot for Version 7 at 3 h.

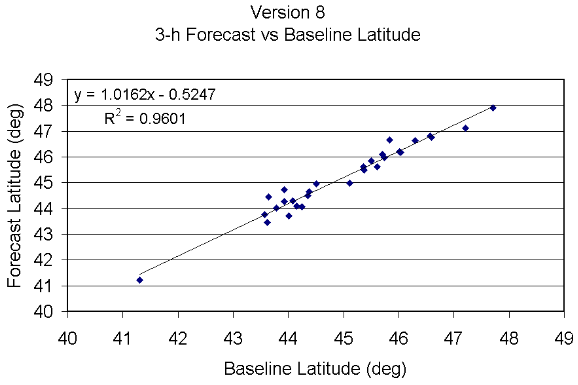

Fig. 7. As in Fig. 6, except for Version 8.

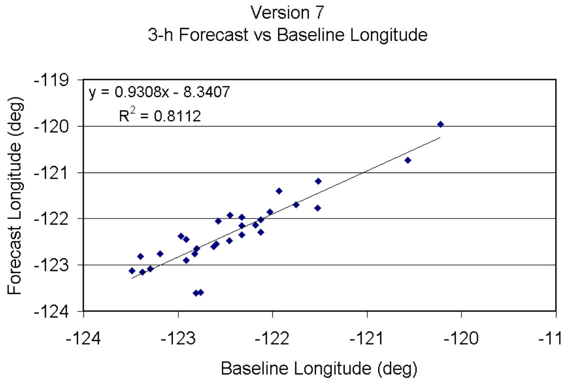

Fig. 8. Longitude scatterplot for Version 7 at 3 h.

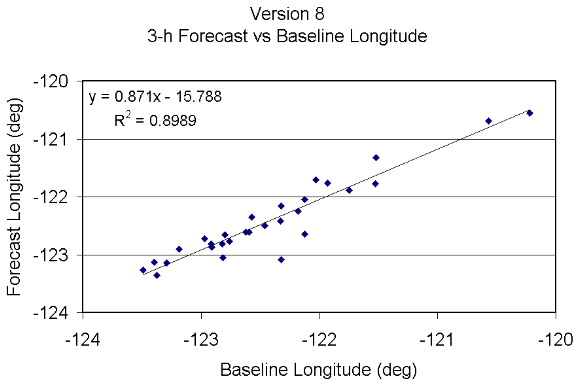

Fig. 9. As in Fig. 8 except for Version 8.

6. VERSIONS 10 AND 11 RESULTS

For 48-h (Fig. 10) and 12-h (Fig. 11) trajectory forecast differences continue to diverge with time. Flights predicted using Version 10 show three outliers (Fig. 10). The length of the predicted flights for Version 10 (48 h) causes overlap in the chronological series of RUC-2 initializations on consecutive days. For this reason, we considered the possibility that the outliers resulted from anomalous wind data in one or more of the initializations. The data, however, do not bear this out, indicating that the outliers occurred on predicted flights 15 days apart. Reasons for these outliers are under investigation.

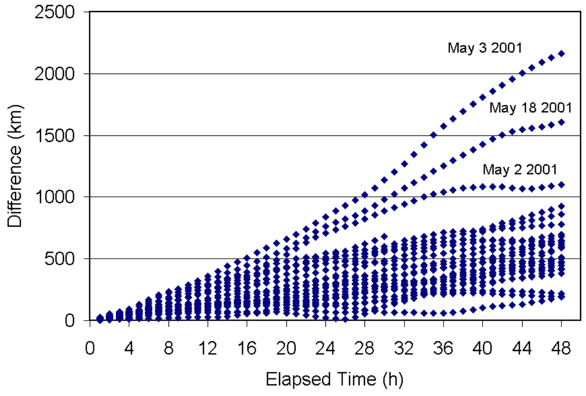

Fig. 10. Trajectory difference (forecast – baseline) by hour for Version 10.

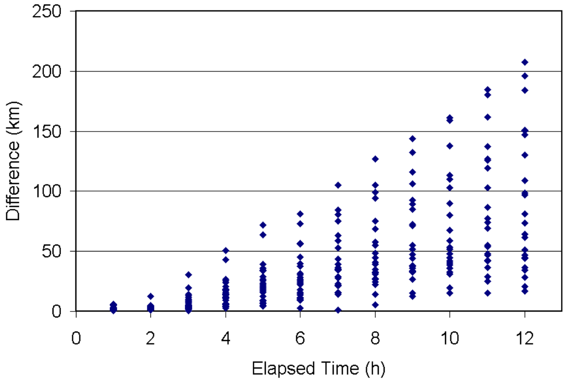

Fig. 11. As in Fig. 10, except for Version 11.

Table 2 shows that Version 11 is a better predictor of balloon position, with a median error approximately half that for Version 10 at 12 h. Also note the improvements in position of Version 10 and Version 11 at 3 h (Table 2) for the upper end of these distributions.

TABLE 2. Quartile values (km) for Versions 10 and 11.

	3-h		6-h		12-h	
	V 10	V 11	V 10	V 11	V 10	V 11
Max	71.0	30.5	169.1	81.2	359.7	207.3
3rd q	47.3	9.9	97.7	39.2	239.2	134.5
Med	38.8	7.0	83.4	26.3	137.6	68.8
1st q	31.9	3.7	53.3	14.9	110.5	44.6
Min	8.2	0.5	18.0	2.6	25.5	16.8

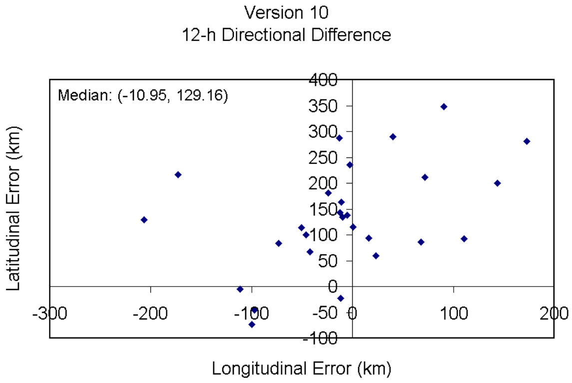

Fig. 12. Directional difference distribution for 3-h flights predicted by Version 10.

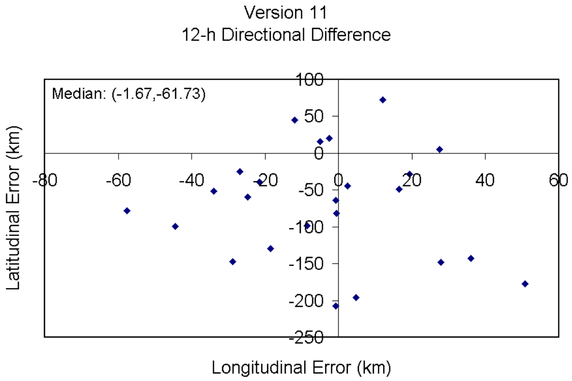

Fig. 13. As in Fig. 12, except for Version 11.

Directional differences vary between these two models. Version 10 shows a northwest bias, while Version 11 data for May 2001 indicate a slight southwest bias (Figs. 12 and 13). Both versions show good correlation in terms of latitude (Figs. 14 and 15), but Fig. 16 shows poor correlation in the longitude values for Version 10 in comparison to Version 11 (Fig. 17). This indicates greater differences in the zonal component of the AVN and baseline wind data, perhaps a result of grid space disparity (111.1 km vs. 40 km at 45° latitude).

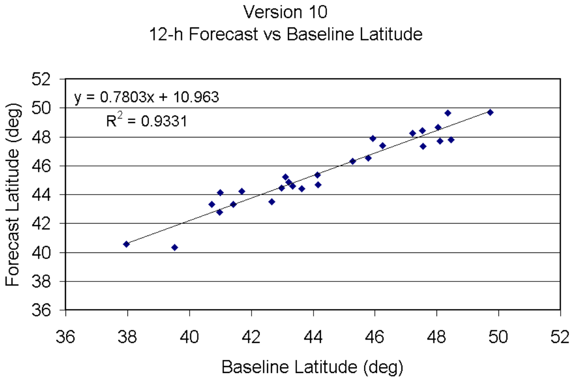

Fig. 14. Latitude scatterplot for Version 10 at 12 h.

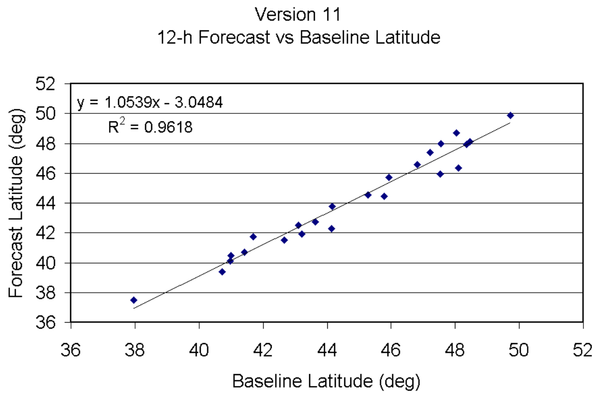

Fig. 15. As in Fig. 14, except for Version 11.

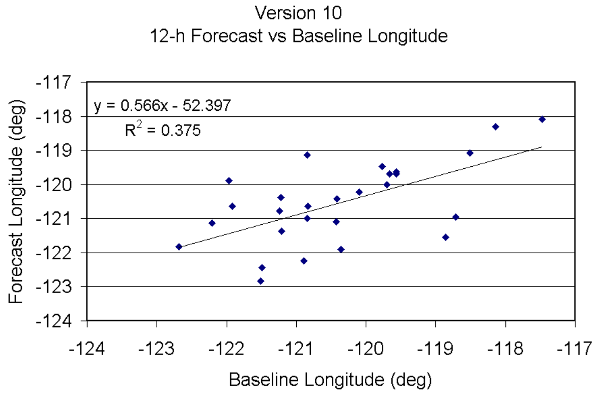

Fig. 16. Longitude scatterplot for Version 10 at 12 h.

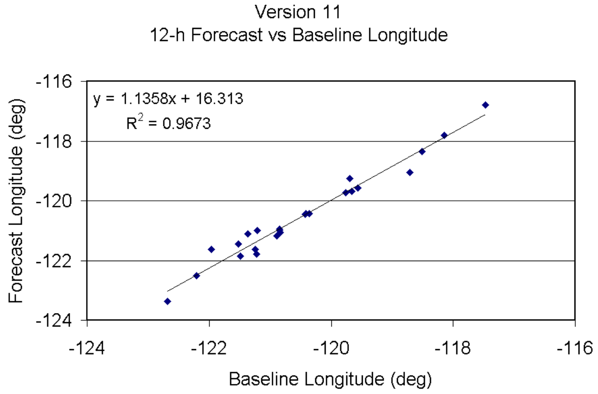

Fig. 17. As in Fig. 16, except for Version 11.

7. SUMMARY

We have developed a set of useful tools for examining trajectory predictions and assessing differences as a function of input wind data. The temporal (and in part, spatial) limitations of single soundings (Version 7) constrain their use to flights of 3 h or less. Spatial interpolation of raobs (Version 8) improve the comparison, but are still temporally limited. These limitations are overcome by the dynamical consistency of numerical weather models. However, large differences between the AVN (Version 10) and RUC-2 (Version 11) forecasts even at 3 hours may be an indication of the coarseness of the AVN grid.

Wind trajectories, of course, are not actual balloon trajectories. Actual trajectories are influenced by various physical considerations, particularly float altitude which depends on density arising from day-to-night differences in short and long wave radiation. A truer assessment of these trajectories and the input winds will be possible with an actual flight.

Further study is needed to determine whether the magnitude of errors found in this May 2001 study period is typical for other months and whether any seasonal biases can be detected.

8. REFERENCES

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