ARMY RESEARCH LABORATORY

Wind Radar, Microwave Profiler, and GPS Data Fusion for Mesoscale Modeling

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radiometrics CORPORATION

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1. Artillery Corrections with Temperature and Wind Profilers

Radiosondes are traditionally used to provide atmospheric temperature and wind profile corrections for artillery targeting and battlefield weather forecasting. However, logistical requirements for radiosonde operations limit their use during battlefield conditions. In order to ease logistical demands and obtain continuous temperature, humidity, cloud liquid and wind profile measurements, the US Army is considering mobile temperature and wind profiling using radiometry and radar. This study was conducted to estimate improvements in artillery accuracy that could be obtained if continuous temperature and wind profiling observations are available.

We calculated statistics of artillery targeting corrections based on mesoscale forecasts, and forecasts plus microwave profiler and wind profiler soundings. Radiosonde soundings were assumed to define the true state of the atmosphere. We used microwave profiler (MP), wind profiler (WP), and radiosonde data from the DOE ARM Southern Great Plains Central Facility near Lamont, Oklahoma. The MP provides temperature profiles up to 10 km height and the WP provides wind profiles up to 16 km height. AER Inc. performed analysis and forecasting using the MM5 mesoscale model <http://rain.mmm.ucar.edu/mm5> under subcontract to Radiometrics. Their analyses were based on radiosonde, wind profiler and other background data. Forecasts initialized with the analysis were provided at 3 to 12 hour intervals up to 48 hours. Profiles are based on the following data:

- Radiosonde
- Forecast
- WP-sensed wind plus forecast temperature and forecast wind > 16 km
- MP-sensed temperature plus forecast winds and forecast T > 10 km
- MP temperature and WP wind plus forecast temperature > 10 km and forecast wind > 16 km

Forecast temperatures and winds are included in cases where there are no measurements since only the forecasts would be available during battlefield operations when radiosonde data are not available. Trajectories calculated for the radiosonde are assumed to be ground truth or zero error. The trajectory for the forecast atmosphere represents the case where no additional measurements are available after forecast initialization. Trajectories including wind profiler and microwave profiler measurements represent artillery accuracy corrections based on these measurements.

Atmospheric & Environmental Research Inc. (AER) provided radiosonde, microwave profiler, wind profiler, and 10 km MM5 forecast soundings during March 2000. Dr. Thomas Nehrkorn, AER Meteorological Scientist, led the modeling and forecast work. Forecasts during this period were based on 3 March 12:00 analysis for the 4-5 March forecasts, and 19 March 00:00 analysis for the 19-20 March forecasts. Trajectory analyses were performed by Rosemary Wells in Bob Lieske's group at Aberdeen Proving Ground. Radiometrics staff compiled the target impact coordinates from the trajectory analyses.

AER performed additional analysis and forecasting for 8, 14, 19, 22 and 26 June, for 1 and 4 August, and for 1, 22 and 25 September 2001. However, the microwave profiler temperature retrievals were degraded during this period. We found that the DOE had not calibrated the microwave profiler at Lamont for more than 6 months. They found good stability in the instrument during the first several months of calibrations and had therefore discontinued the recommended monthly calibration procedure. Microwave profiler calibration in December, 2001, showed that profile retrievals would have been significantly degraded. We could recalibrate the microwave profiler using radiosonde observations during cloud free conditions. The original microwave profiler data could then be reprocessed to obtain accurate temperature profile retrievals. However, this would be beyond the scope of the current work. Therefore, this report is limited to 19 cases in March 2000 when the microwave profiler was properly calibrated.

Resulting artillery miss distances vs. forecast length for forecast and observed profiles are provided in Table 1 and Figure 1. Details of each trajectory analysis including down range, cross range, and total miss distances are provided in Appendix A. Trajectory analyses were conducted by Dr. Robert Lieske, Chief of Firing Tables, U.S. Army Aberdeen Proving Ground. Profiles and trajectory miss distance plots for all cases are shown in Appendix B.

Table 1. Average trajectory miss distances and length of forecast for all cases.

Artillery Miss Distance Results						
		Miss distance (m)				**Forecast**
date (2000)	**time (UT)**	**fc**	**mp**	**wp**	**wp+mp**	**(hr)**
4-Mar	0:00	359	205	197	44	12
4-Mar	12:00	339	278	220	163	24
5-Mar	0:00	368	325	169	119	36
5-Mar	12:00	290	263	204	176	48
19-Mar	3:00	101	105	80	78	3
19-Mar	9:00	239	181	97	43	6
19-Mar	12:00	239	142	64	29	9
19-Mar	15:00	177	87	116	24	12
19-Mar	18:00	174	81	213	111	15
19-Mar	21:00	359	269	251	157	18
20-Mar	0:00	235	154	114	65	21
20-Mar	3:00	235	165	260	153	24
20-Mar	6:00	223	154	163	57	27
20-Mar	9:00	111	133	190	129	30
20-Mar	12:00	159	173	128	31	33
20-Mar	15:00	140	267	162	29	36
20-Mar	18:00	24	144	314	160	39
20-Mar	21:00	131	19	280	159	42
21-Mar	0:00	264	172	169	44	45
	average:	**219**	**175**	**178**	**93**	**25**
	stdev:	**97**	**78**	**69**	**56**	**14**

The average miss distance for an average 25-hr forecast was 219 m (97 m stdev), with 19 cases studied. Combined wind and microwave profiler corrections provided an average miss distance of 93 m (56 m stdev), an improvement factor of 2.4 in miss distance. This translates into an improvement factor of 5.5 for artillery impact area. More modest miss distance improvement factors of 1.2

were found for either temperature profile corrections or wind profile corrections alone.

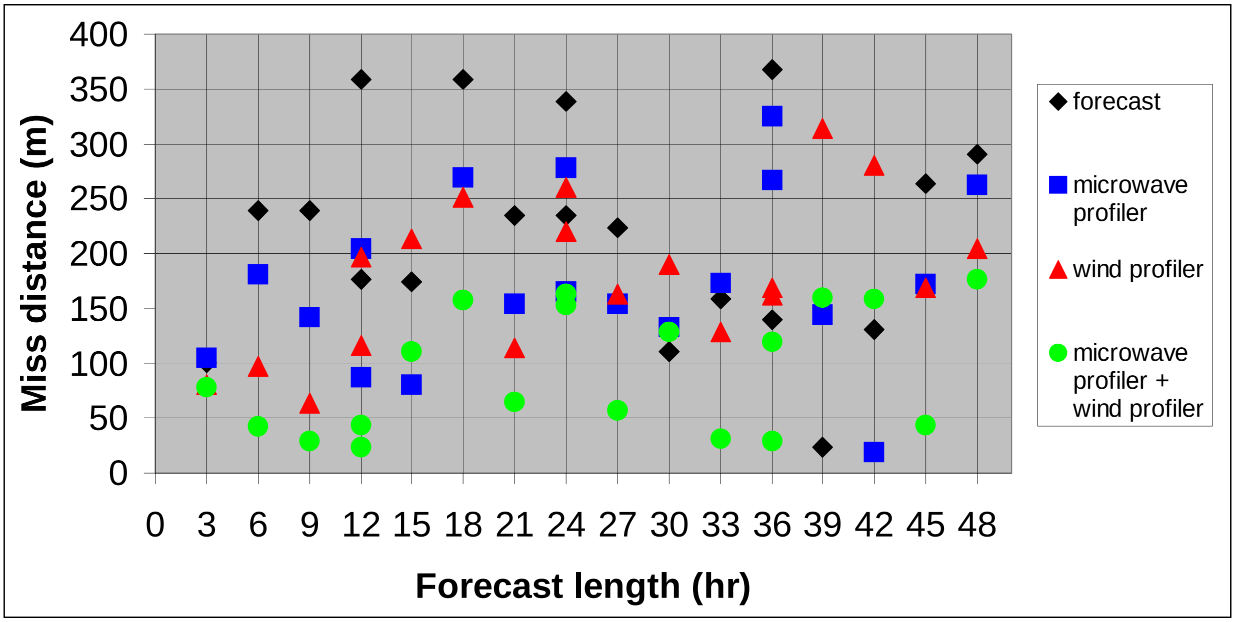

Figure 1. Miss distances vs. forecast length and correction method for all cases.

Miss distances associated with the various correction methods were found to be insensitive to forecast length for forecast length of 6 hours or more, as shown in Figure 1. However, this result is based on only one 3-hr and one 6-hr forecast, and additional short term comparisons are needed.

2. Discussion

We studied potential improvements in long-range artillery accuracy that could be obtained if local measurements of atmospheric temperature and wind are available from microwave and wind profilers. The measurements were obtained from a 440 MHz wind profiler operated by NOAA's Forecast Systems Laboratory at Lamont, Oklahoma, and from a Radiometrics TP/WVP-3000 microwave profiler operated by the Department of Energy's Atmospheric Radiation Monitoring (ARM) program at its Southern Great Plains Facility 10 km southwest of Lamont. In addition, radiosonde observations at Lamont were obtained from ARM.

High resolution (10-km) analysis and forecasting was provided by AER Inc., based on radiosonde, surface met, and background information. The radiosonde measurements were assumed to define the true state of atmospheric temperature and wind. Trajectory calculations based on forecast temperature and wind provided downrange and crossrange miss distances for long-range (~30 km) artillery (Appendix A). Calculations based on radiosonde profiles were assumed to give zero miss distances. Thus, the forecast miss distances represent the best corrections that would be available using state-of-the art analysis and forecasting based on a local radiosonde launch. The study occurred in an area (Oklahoma) where high accuracy forecasting can be obtained as a result of benign topography and availability of high quality background and surface meteorological information.

During battlefield conditions in remote areas low quality background and surface meteorological data would degrade the forecasts. We would expect miss distances based on forecast profiles to be larger than the miss distances obtained in this study. In addition, strong topographic effects could also degrade battlefield forecast accuracy. We would expect larger improvements during battlefield conditions than those obtained in this study.

AER was able to provide high quality forecasts in Oklahoma using relatively dense radiosonde and surface meteorological information and background analysis provided by NCEP. In battlefield conditions in remote locations the quality of meteorological information and analysis is likely to poor. As a result, battlefield forecasts may be of lower quality and improvements in miss distances would be expected to be larger.

It should be possible to significantly improve the results in this study by:

- Direct assimilation of radiometer brightness temperatures
- Advanced radiometric observation and retrieval methods
- Using refractivity gradient information from wind profilers

Direct Brightness Temperature Assimilation. Instead of using microwave and wind profiler measurements directly for trajectory calculations, the raw measurements could be assimilated into models. The model profiles could then be used to calculate trajectory information. Similar steps were taken in satellite radiometry to improve forecasting. At first, vertical temperature and humidity profiles were retrieved from satellite radiometer measurements. The profiles were assimilated into models, with mixed results. After assimilating raw satellite radiance measurements directly into models, general forecast improvements were seen.

Potential improvement can clearly seen for the 09:00 19 March 2000 temperature profile shown on page 6 of Appendix B. Near 10 km height the MP temperature profile is ~6 K colder than observed by the radiosonde. If MP brightness temperatures were assimilated directly into the model, the resulting error would be much smaller. Error would be reduced because upper level temperatures would converge with forecast instead of climatological values.

Advanced Radiometric and GPS Methods. Advanced observation and retrieval methods can improve the accuracy of radiometric profile retrievals. By observing at various elevation angles, temperature profile error can be reduced to 1 K up to heights of 3 km (Westwater et al., 1999). Local tropospheric profile observations can be augmented by slant GPS measurements (Braun et al., 2001; 2002). Slant GPS delays can be observed near zero elevation angle where the GPS ray extends more than 100 km in the boundary layer. A GPS satellite rises or sets every 15 minutes, providing the opportunity for slant measurements at various azimuth angles. These passive measurements can potentially extend local forecast capability to regional scale. Slant GPS combined with microwave profiling can provide high resolution three dimensional water vapor analysis (MacDonald et al., 2002).

Refractivity Gradient Information. Raw wind profiler data contains information on the magnitude of the refractivity gradient at the top of the boundary layer. The top of the boundary layer is typically the place where the radiometric temperature profile has the largest error (Gueldner and

Spaenkuch, 2001). This error can potentially be reduced by using refractivity gradient information from the wind profiler. Progress on this approach is a topic of the COST720 Workshop in Europe in Aquila, Italy, 18-21 June 2002.

3. Radiosonde Accuracy

In this study we assumed that the radiosonde temperature and wind profiles are free from error. However, radiosonde temperature measurements may have 1 K error or more at the surface that increases error with height, and the radiosonde wind measurements typically have 3-5 m/sec error. If these errors were properly taken into account, the relative accuracy obtained from temperature and wind profile measurements could improve by a small amount.

4. Mobile Radiometric and Wind Profiling

Mobile radiometric and wind profiling capabilities have been demonstrated. The Mobile Integrated Profiling System (MIPS) developed by Prof. Kevin Knupp at the University of Alabama at Huntsville is shown in Figure 2. MIPs provides high resolution temperature, humidity, cloud liquid (Ware et al., 2002) and wind observations that are useful for high resolution forecasting. Traditional radiosonde-based methods provide limited temporal resolution and logistical complexity. Mobile profiling systems can be combined with slant GPS methods to extend local wind, temperature, moisture and visibility analysis and forecasting to regional scales (MacDonald et al., 2001). In particular, high resolution nuclear, biological and chemical (NBC) dispersion modeling can be greatly improved by this type of dense spatial and temporal observations. A commercial boundary layer profiling system is shown in Figure 3.

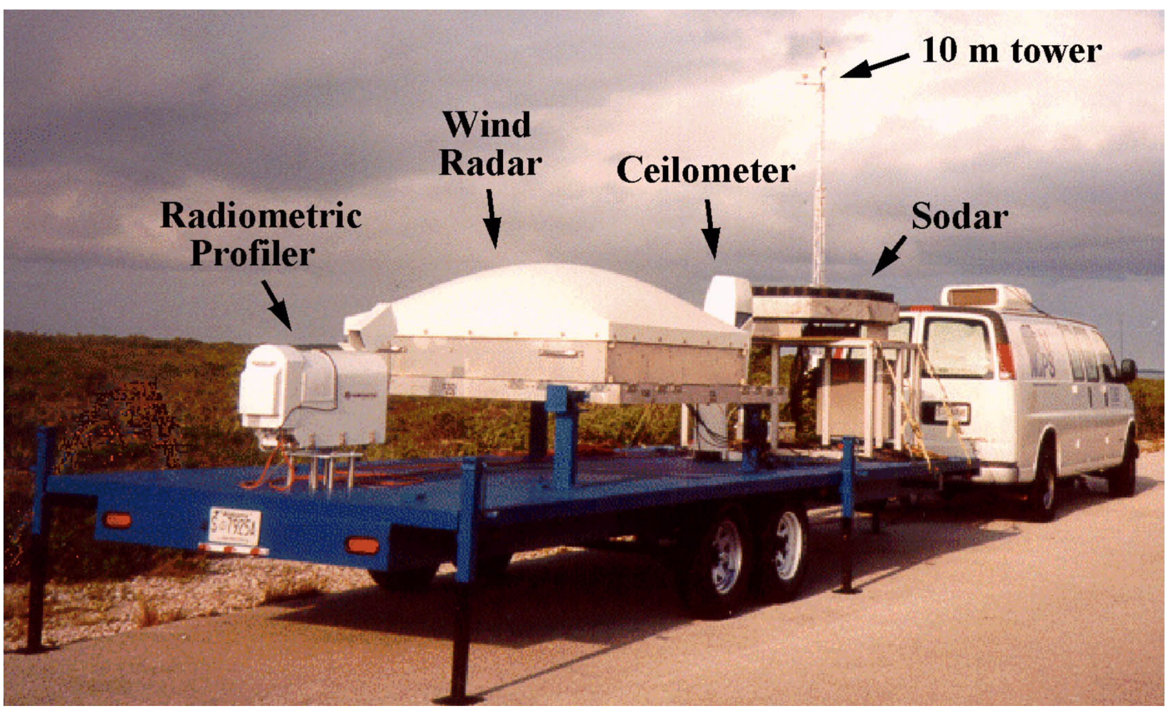

Figure 2. Mobile Integrated Profiling System (MIPS) developed by the University of Alabama.

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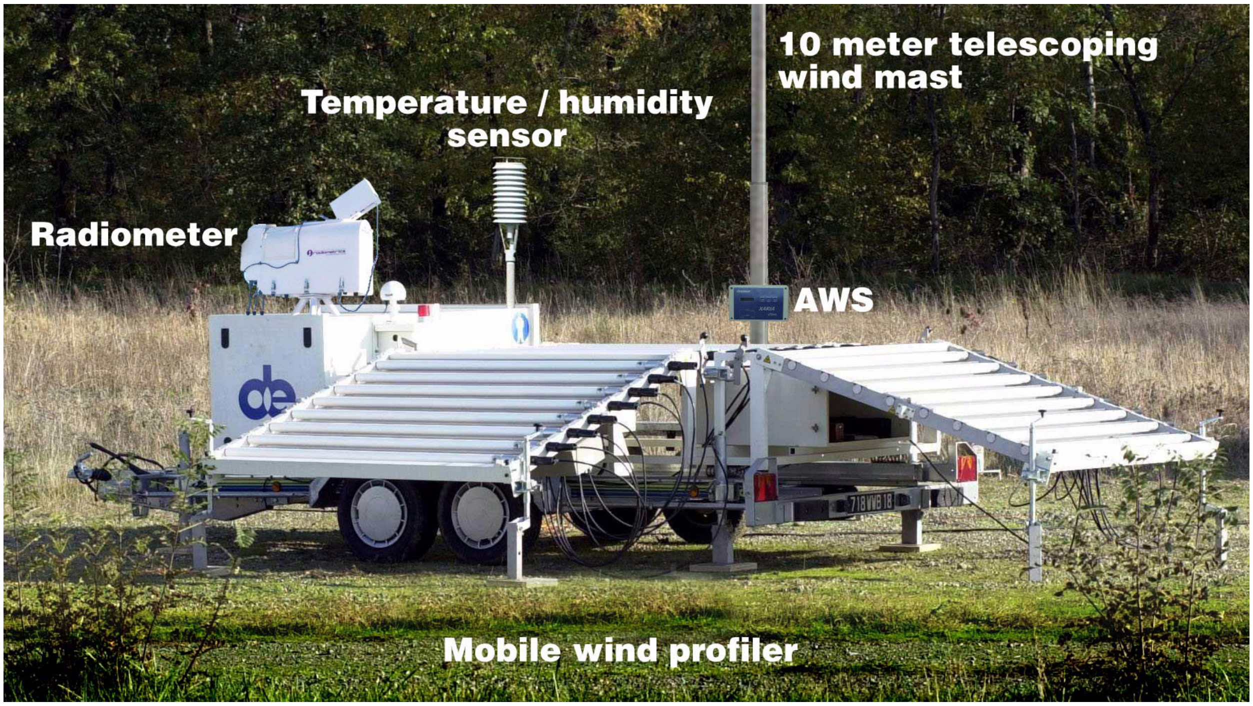

Figure 3. Mobile profiler offered commercially by Degreane, Inc.

5. Summary and Conclusions

We conducted a preliminary study of temperature and wind profile corrections for artillery compared with corrections based on radiosondes and forecasts. Nineteen cases were analyzed during March 2002 at Lamont, Oklahoma. The average forecast duration was 25 hours. We found that miss distances for combined wind and temperature profile corrections were 93 m, compared with 219 m for corrections based on forecasts (standard deviations were 56 and 97 m respectively). This corresponds to a miss distance improvement factor of 2.4, and an impact area improvement factor of 5.5. Miss distances appeared to be insensitive to forecast duration for forecasts of 6 hours or more. However, more short term case studies are needed to confirm this result.

We expect improvements in miss distances if radiometric brightness temperature observations are assimilated directly into models, with advanced radiometric observation and retrieval methods, and with the use of wind profiler refractivity gradient measurements. We also expect additional improvements in battlefield conditions at remote locations where sparse data and topography are likely to degrade forecast accuracy.

Mobile temperature, humidity, cloud liquid and wind profiling systems are now commercially available. The promising preliminary results in this report show the potential for these systems in military and civilian applications. Local tropospheric wind, temperature and moisture measurements can be extended to regional scales if they are combined with slant GPS methods. This will allow military and civilian users to move away from logistical complexity and limited temporal resolution associated with current radiosonde-based systems.

6. References

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Appendix A

Long-range (~30 km) artillery downrange, crossrange, and total miss distances calculated from the profiles shown in Appendix B by Dr. Robert Lieske, Chief of Firing Tables, U.S. Army Aberdeen Proving Ground.

		Downrange		Crossrange		miss
Sounding		(meters)		(meters)		distance
type	date/time	distance	delta	distance	delta	(meters)
sonde	3/4/2000 0:00	31,909	0	707	0	0
forecast		31,550	-359	683	-24	359
mp		31,704	-204	694	-12	205
wp		31,711	-197	715	9	197
wp+mp		31,871	-38	729	22	44
sonde	3/4/2000 12:00	31,868	0	760	0	0
forecast		31,530	-338	750	-10	339
mp		31,590	-278	754	-6	278
wp		31,648	-220	756	-4	220
wp+mp		31,705	-163	760	0	163
sonde	3/5/2000 0:00	32,297	0	1,296	0	0
forecast		31,967	-330	1,134	-162	368
mp		32,014	-283	1,137	-159	325
wp		32,130	-167	1,320	24	169
wp+mp		32,181	-116	1,322	25	119
sonde	3/5/2000 12:00	32,253	0	1,660	0	0
forecast		31,979	-274	1,564	-96	290
mp		32,007	-246	1,566	-94	263
wp		32,054	-199	1,615	-45	204
wp+mp		32,083	-170	1,617	-44	176
sonde	3/19/2000 3:00	32,382	0	1,605	0	0
forecast		32,360	-22	1,703	98	101
mp		32,373	-9	1,709	104	105
wp		32,386	5	1,525	-80	80
wp+mp		32,400	18	1,530	-75	78
sonde	3/19/2000 9:00	32,351	0	1,112	0	0
forecast		32,115	-236	1,070	-41	239
mp		32,174	-177	1,076	-36	181
wp		32,255	-97	1,125	13	97
wp+mp		32,312	-39	1,130	18	43

Appendix A

		Downrange		Crossrange		miss
Sounding		(meters)		(meters)		distance
type	date/time	distance	delta	distance	delta	(meters)
sonde	3/19/2000 12:00	32,191	0	881	0	0
forecast		31,952	-238	862	-20	239
mp		32,049	-141	869	-12	142
wp		32,127	-63	890	8	64
wp+mp		32,216	26	896	14	29
sonde	3/19/2000 15:00	32,019	0	610	0	0
forecast		31,844	-175	636	26	177
mp		31,940	-80	644	34	87
wp		31,904	-115	614	4	116
wp+mp		31,999	-21	622	12	24
sonde	3/19/2000 18:00	32,030	0	332	0	0
forecast		31,863	-167	379	47	174
mp		31,974	-56	390	59	81
wp		31,820	-210	369	38	213
wp+mp		31,931	-99	381	49	111
sonde	3/19/2000 21:00	32,396	0	553	0	0
forecast		32,071	-325	401	-153	359
mp		32,167	-229	412	-142	269
wp		32,145	-251	566	12	251
wp+mp		32,241	-155	576	23	157
sonde	3/20/2000 0:00	32,436	0	649	0	0
forecast		32,226	-210	544	-104	235
mp		32,316	-121	553	-95	154
wp		32,335	-102	700	51	114
wp+mp		32,412	-24	709	61	65
sonde	3/20/2000 3:00	32,445	0	897	0	0
forecast		32,278	-166	731	-167	235
mp		32,389	-55	742	-156	165
wp		32,189	-256	851	-47	260
wp+mp		32,296	-149	863	-35	153
sonde	3/20/2000 6:00	32,622	0	1,252	0	0
forecast		32,460	-162	1,099	-153	223
mp		32,566	-56	1,108	-143	154
wp		32,459	-163	1,249	-2	163
wp+mp		32,565	-57	1,258	7	57

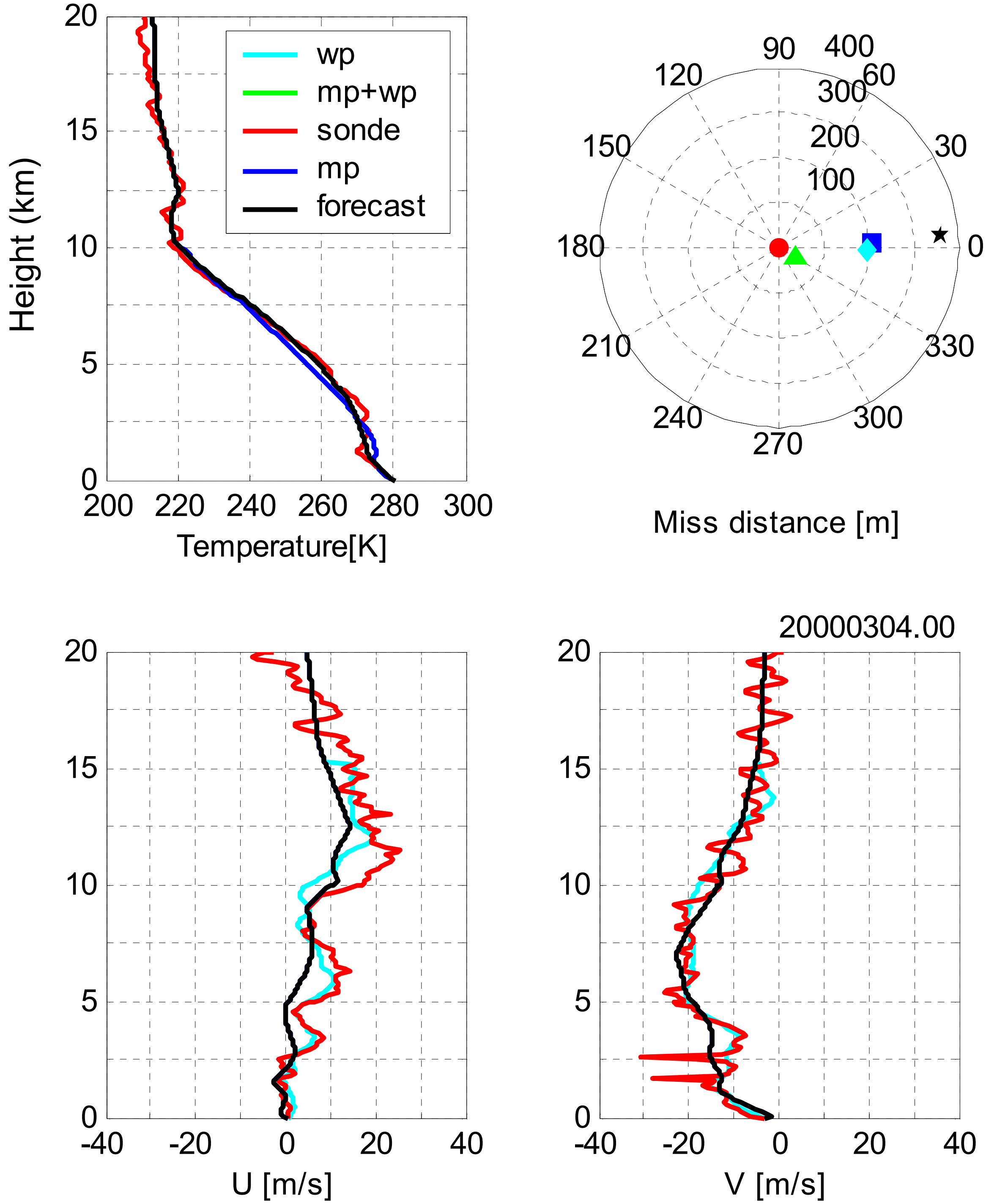
Appendix A

		Downrange		Crossrange		miss
Sounding		**(meters)**		**(meters)**		**distance**
type	**date/time**	**distance**	**delta**	**distance**	**delta**	**(meters)**
sonde	3/20/2000 9:00	32,622	0	1,416	0	0
forecast		32,630	8	1,305	-111	111
mp		32,703	81	1,311	-105	133
wp		32,445	-177	1,488	71	190
wp+mp		32,519	-103	1,494	77	129
sonde	3/20/2000 12:00	32,709	0	1,391	0	0
forecast		32,658	-50	1,543	151	159
mp		32,779	71	1,549	158	173
wp		32,583	-126	1,415	23	128
wp+mp		32,707	-1	1,422	31	31
sonde	3/20/2000 15:00	32,609	0	1,614	0	0
forecast		32,737	127	1,672	58	140
mp		32,869	259	1,679	65	267
wp		32,448	-161	1,597	-17	162
wp+mp		32,582	-28	1,606	-8	29
sonde	3/20/2000 18:00	32,817	0	1,778	0	0
forecast		32,817	0	1,801	24	24
mp		32,957	141	1,809	31	144
wp		32,503	-314	1,759	-19	314
wp+mp		32,657	-159	1,764	-13	160
sonde	3/20/2000 21:00	32,979	0	1,879	0	0
forecast		32,849	-130	1,891	11	131
mp		32,986	7	1,897	18	19
wp		32,724	-255	1,763	-116	280
wp+mp		32,865	-114	1,769	-110	159
sonde	3/21/2000 0:00	33,004	0	1,847	0	0
forecast		32,776	-228	1,979	133	264
mp		32,902	-102	1,985	138	172
wp		32,837	-167	1,873	26	169
wp+mp		32,973	-32	1,878	31	44

Appendix B

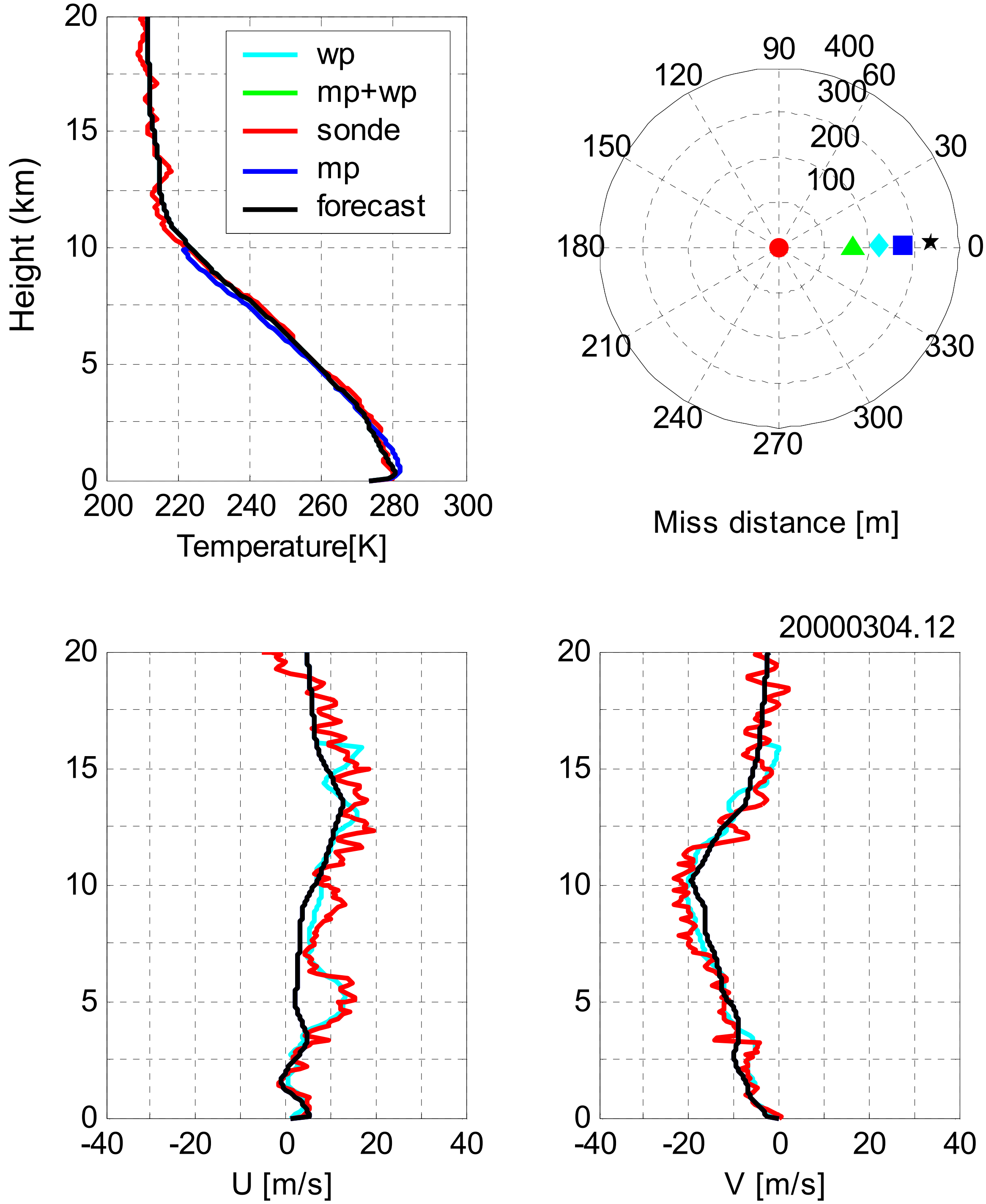
Atmospheric temperature and wind profiles from radiosondes, forecasts, and a wind profiler and microwave profiler at Lamont, Oklahoma, and long-range (~30 km) artillery target miss distances for trajectory calculations based on the various profiles are shown in the figures on the following pages.

Appendix B



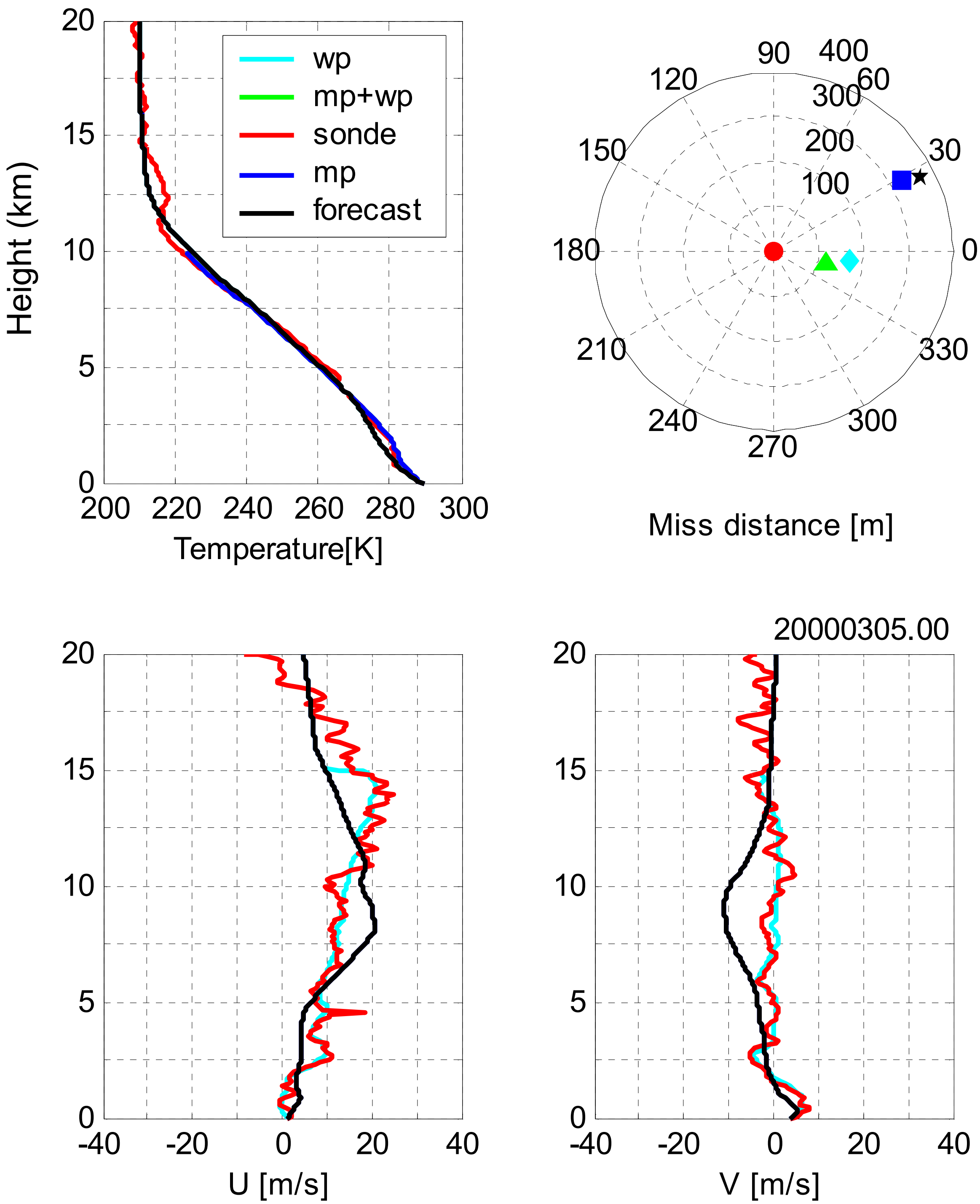
wp
mp+wp
sonde
mp
forecast
Height (km)
Temperature[K]
Miss distance [m]
20000304.00
U [m/s]
V [m/s]

Appendix B



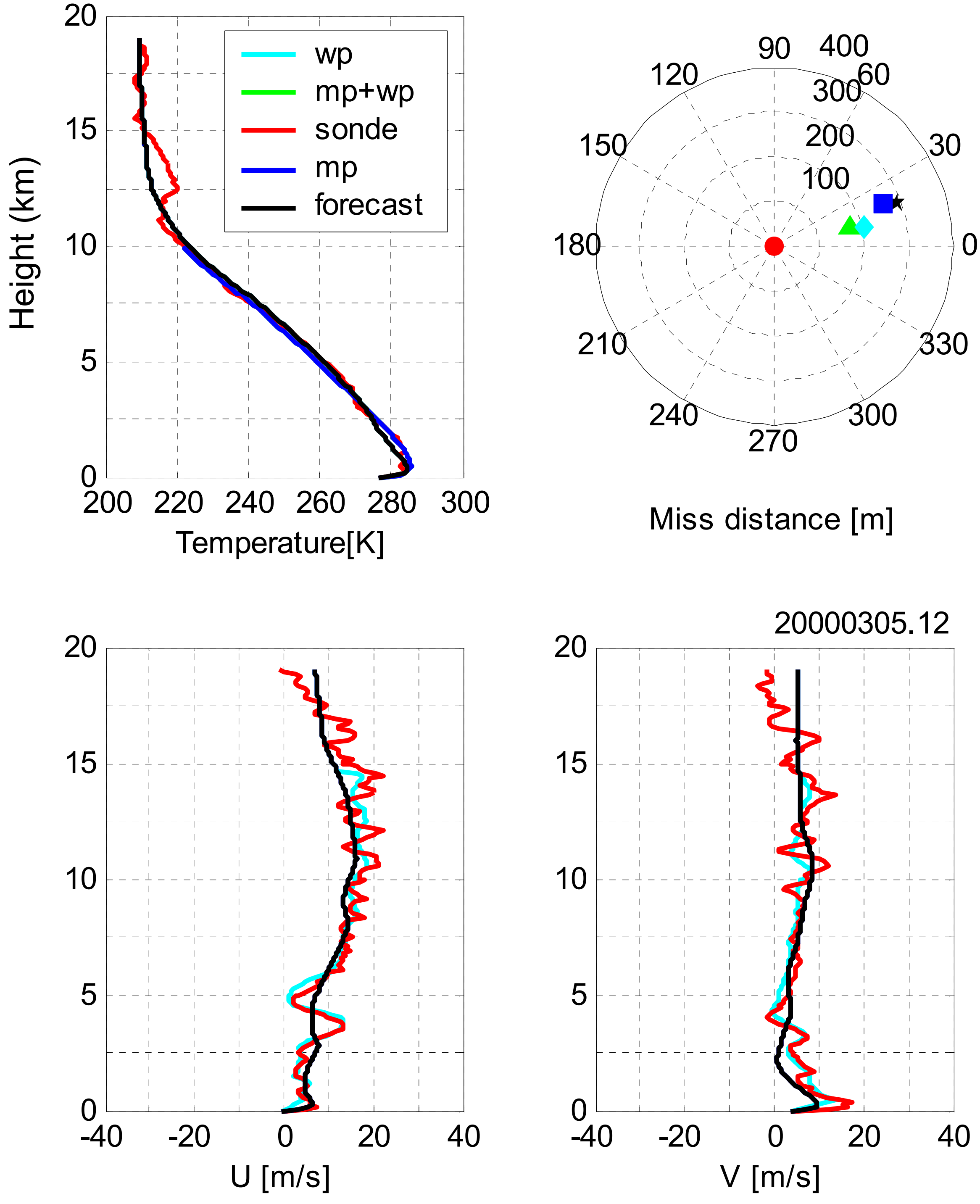
wp
mp+wp
sonde
mp
forecast
Height (km)
Temperature[K]
Miss distance [m]
20000304.12
U [m/s]
V [m/s]

Appendix B



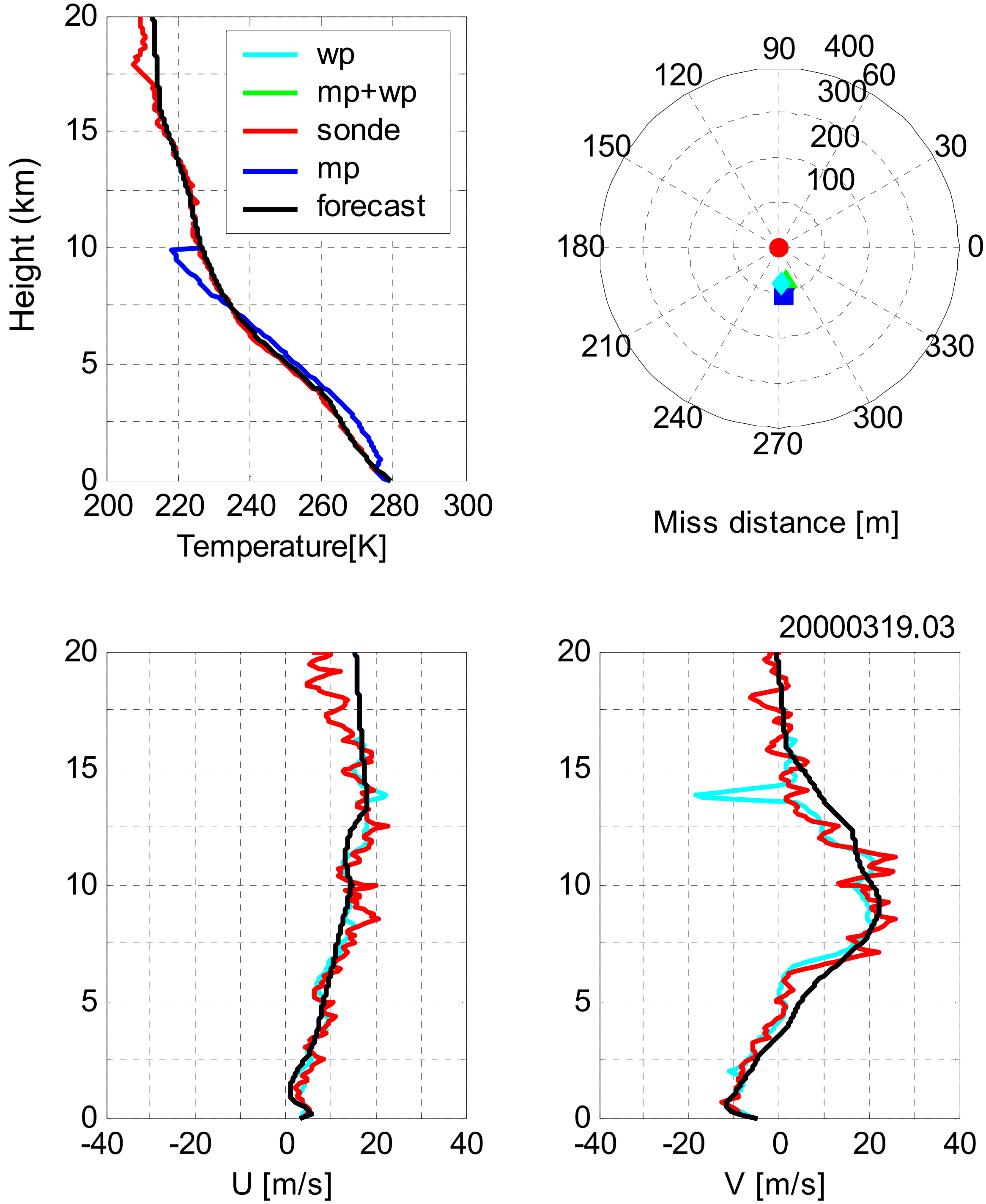
wp
mp+wp
sonde
mp
forecast
Height (km)
Temperature[K]
Miss distance [m]
20000305.00
U [m/s]
V [m/s]

Appendix B



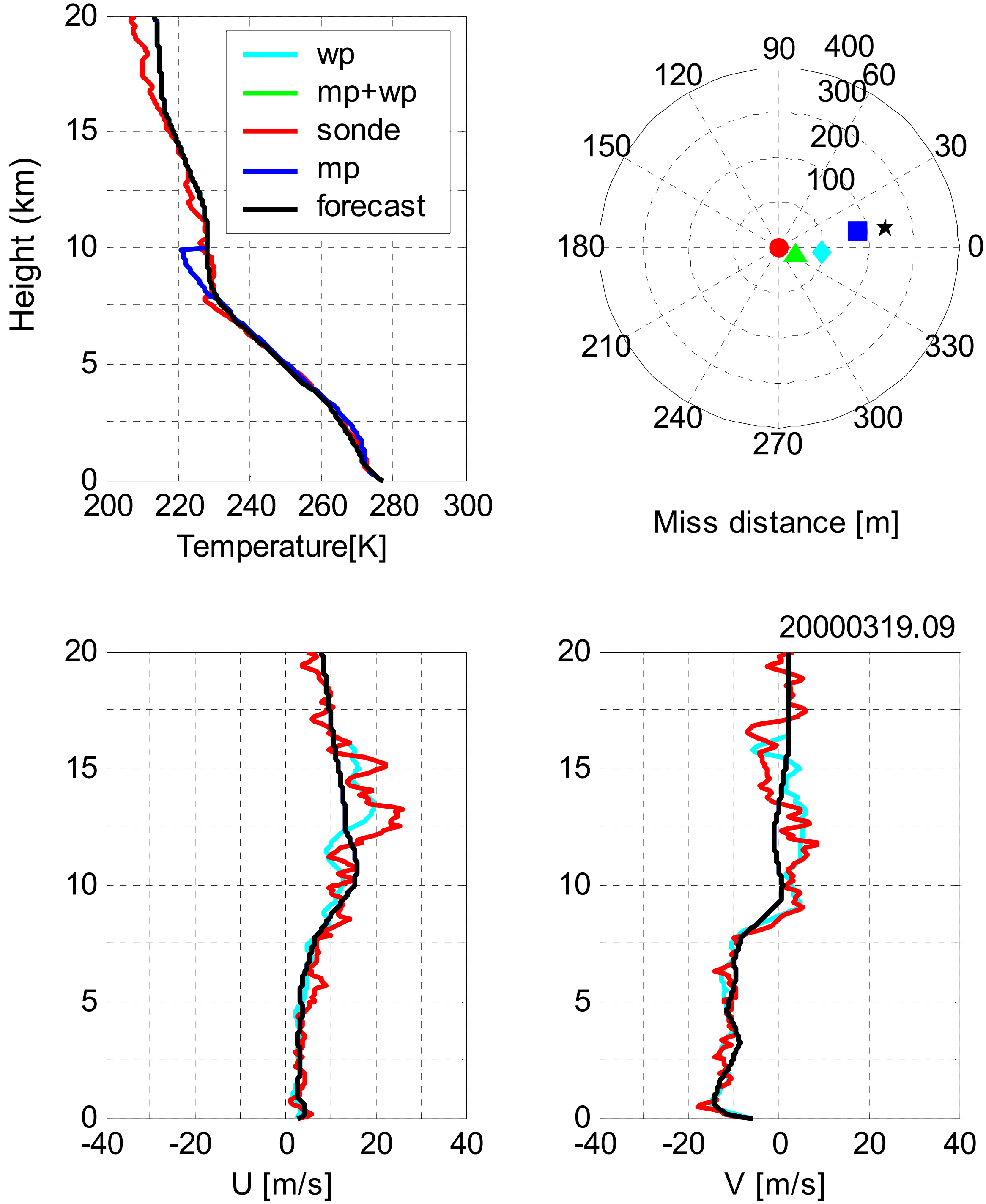
20
15
10
5
0
200 220 240 260 280 300
Temperature[K]
Height (km)
wp
mp+wp
sonde
mp
forecast
90
400
120
60
300
200
150
30
100
180
0
210
330
240
300
270
Miss distance [m]
20000305.12
-40 -20 0 20 40
U [m/s]
V [m/s]

Appendix B



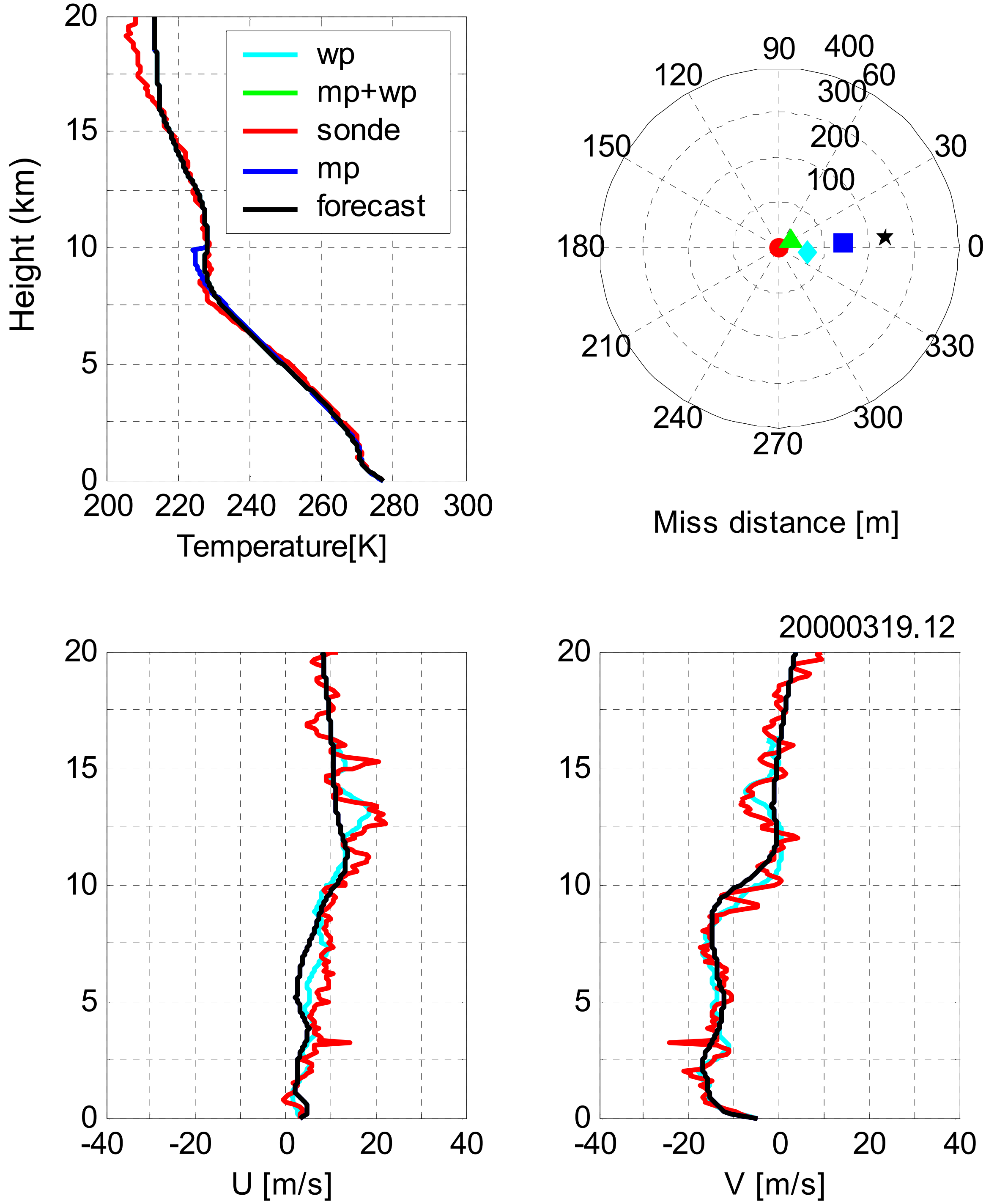
wp
mp+wp
sonde
mp
forecast
Height (km)
Temperature[K]
Miss distance [m]
20000319.03
U [m/s]
V [m/s]

Appendix B



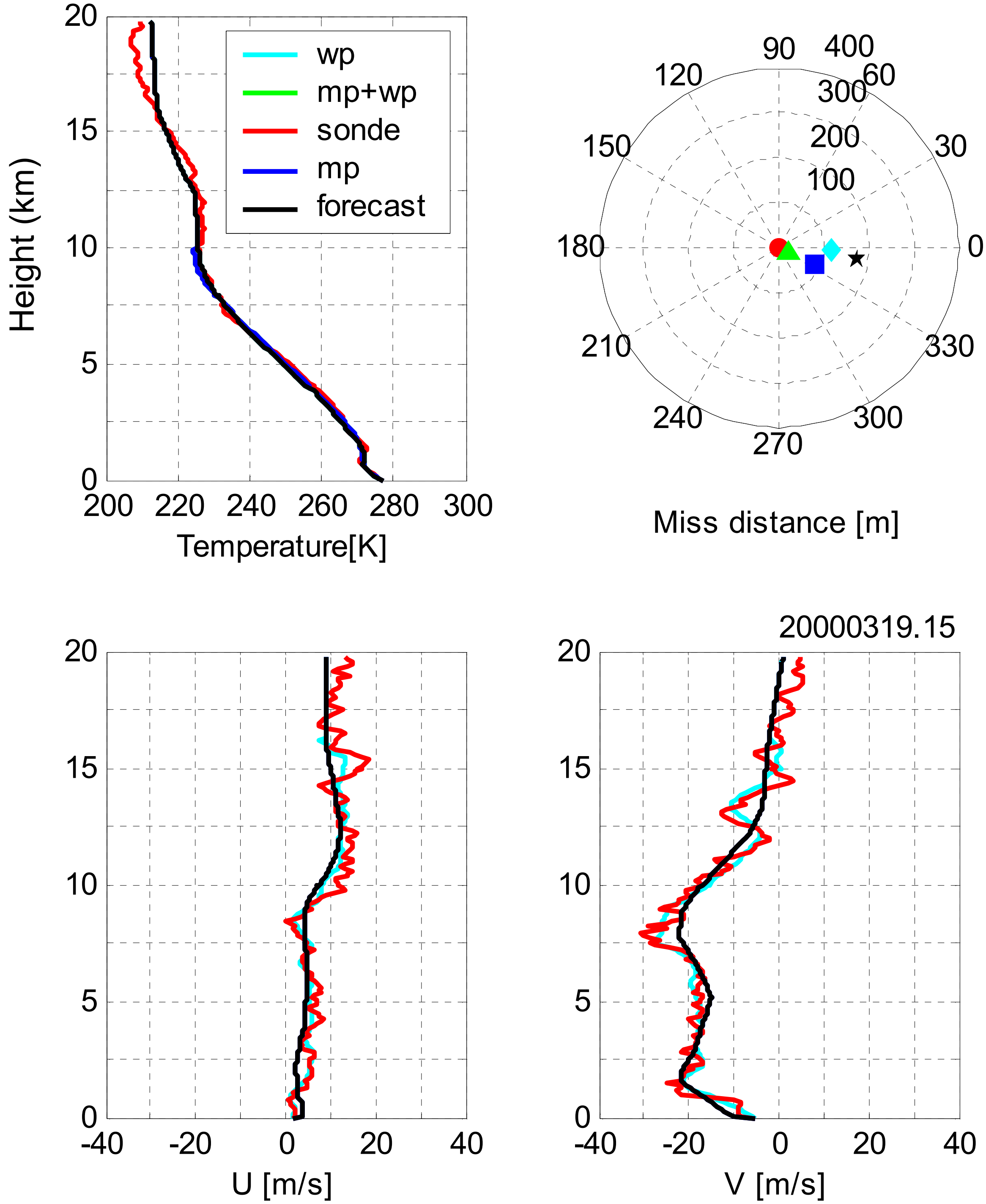
wp
mp+wp
sonde
mp
forecast
Height (km)
Temperature[K]
Miss distance [m]
20000319.09
U [m/s]
V [m/s]

Appendix B



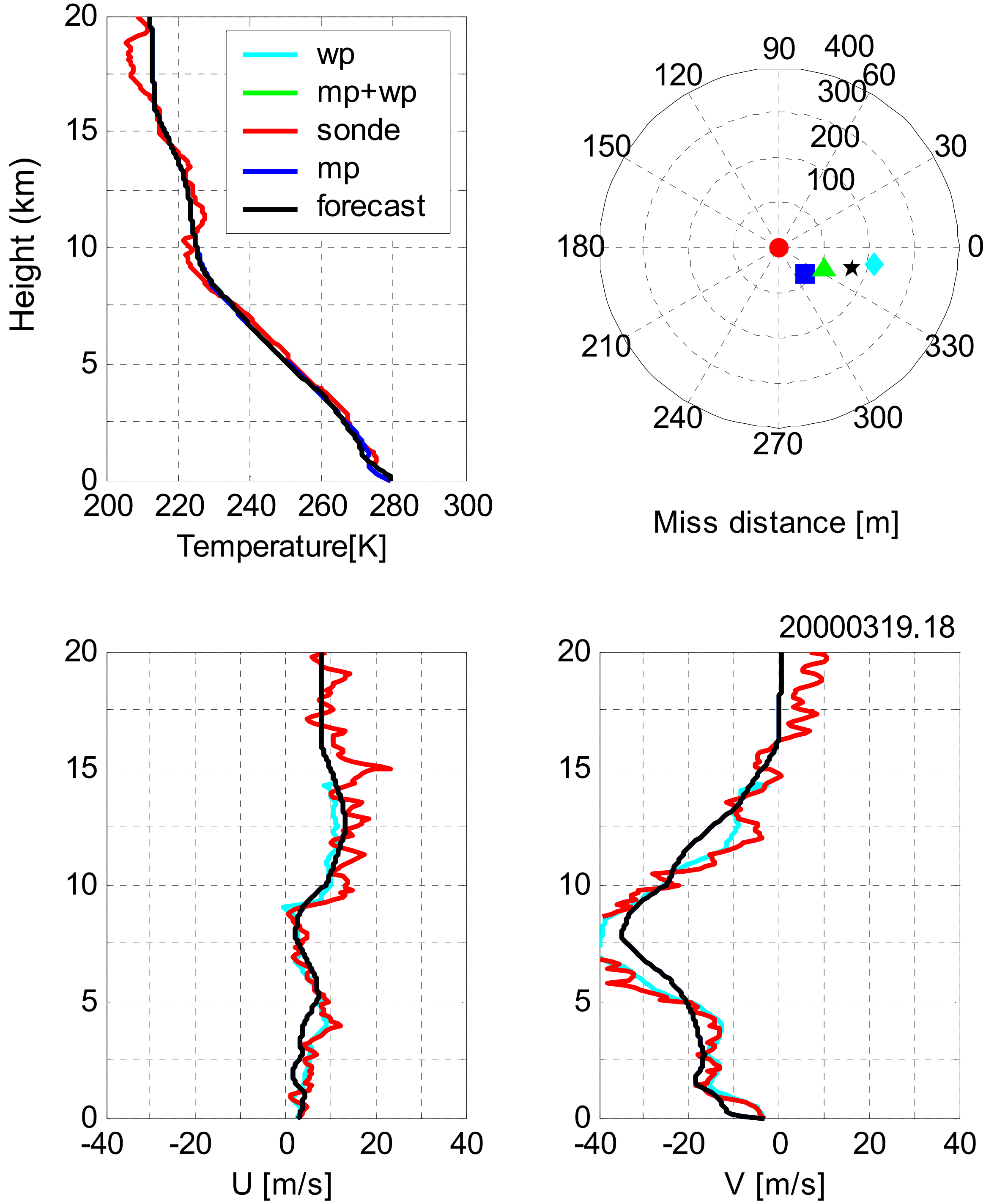
Height (km)
Temperature[K]
wp
mp+wp
sonde
mp
forecast
Miss distance [m]
20000319.12
U [m/s]
V [m/s]

Appendix B



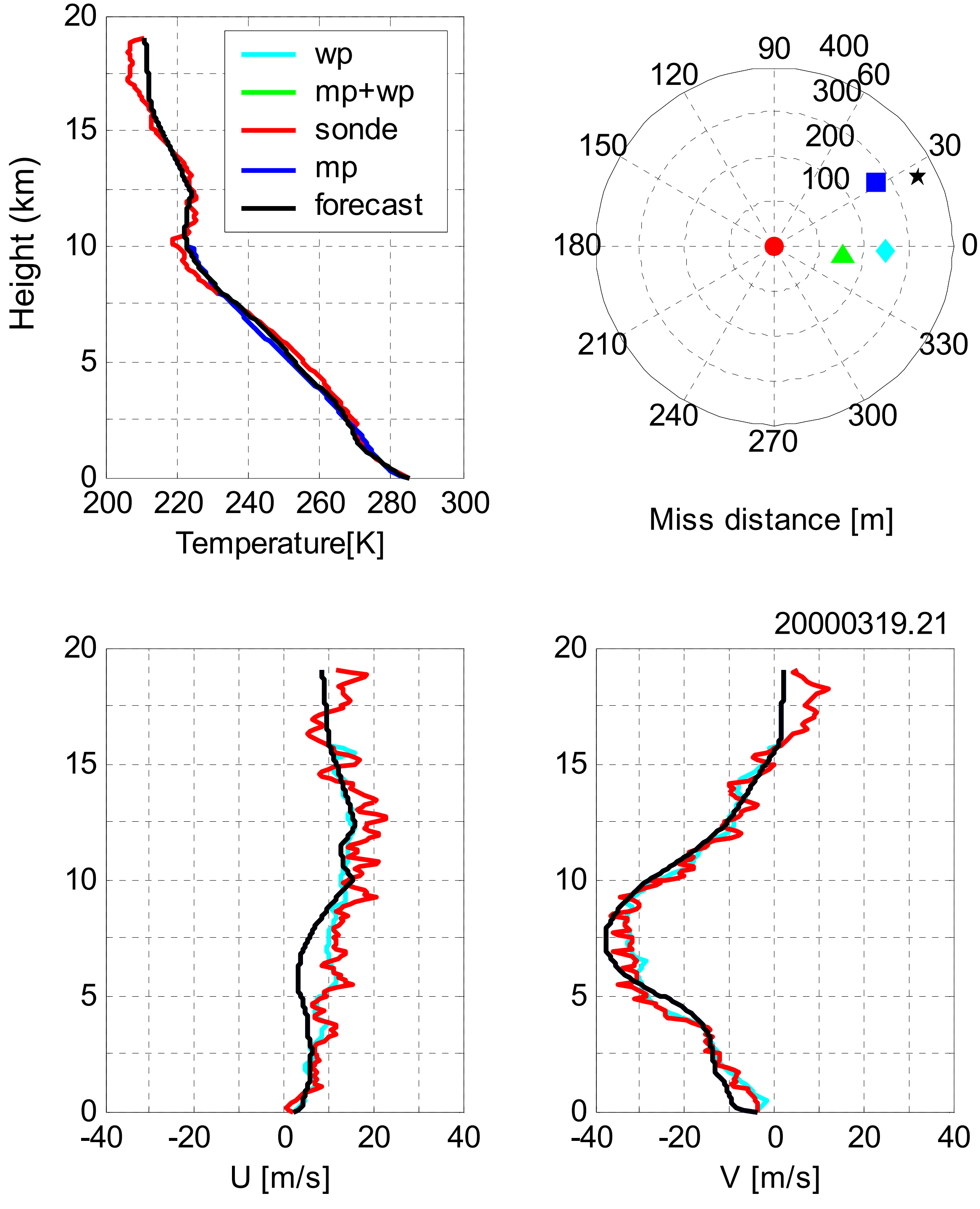
wp
mp+wp
sonde
mp
forecast
Height (km)
Temperature[K]
Miss distance [m]
20000319.15
U [m/s]
V [m/s]

Appendix B



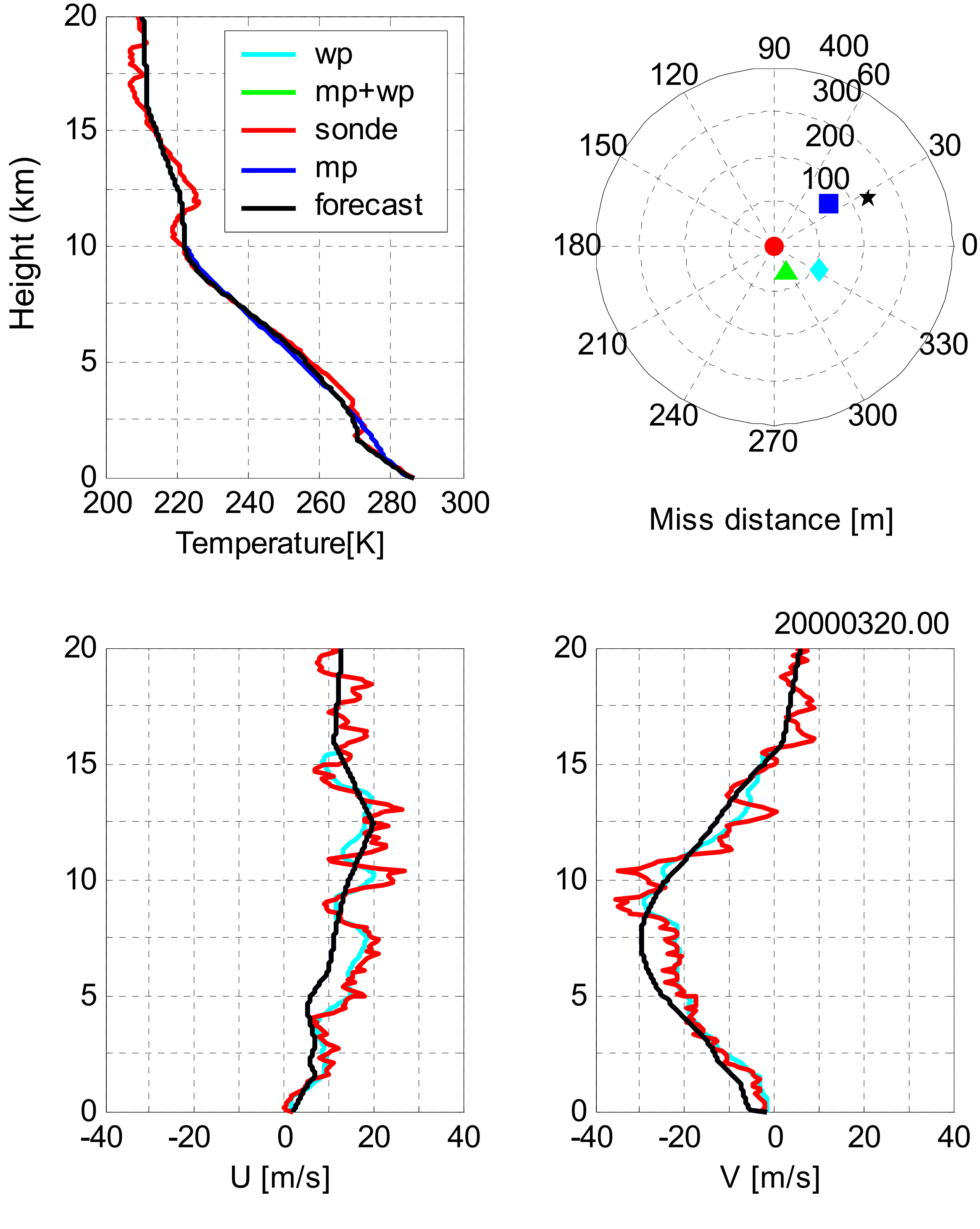
Height (km)
Temperature[K]
wp
mp+wp
sonde
mp
forecast
Miss distance [m]
20000319.18
U [m/s]
V [m/s]

Appendix B



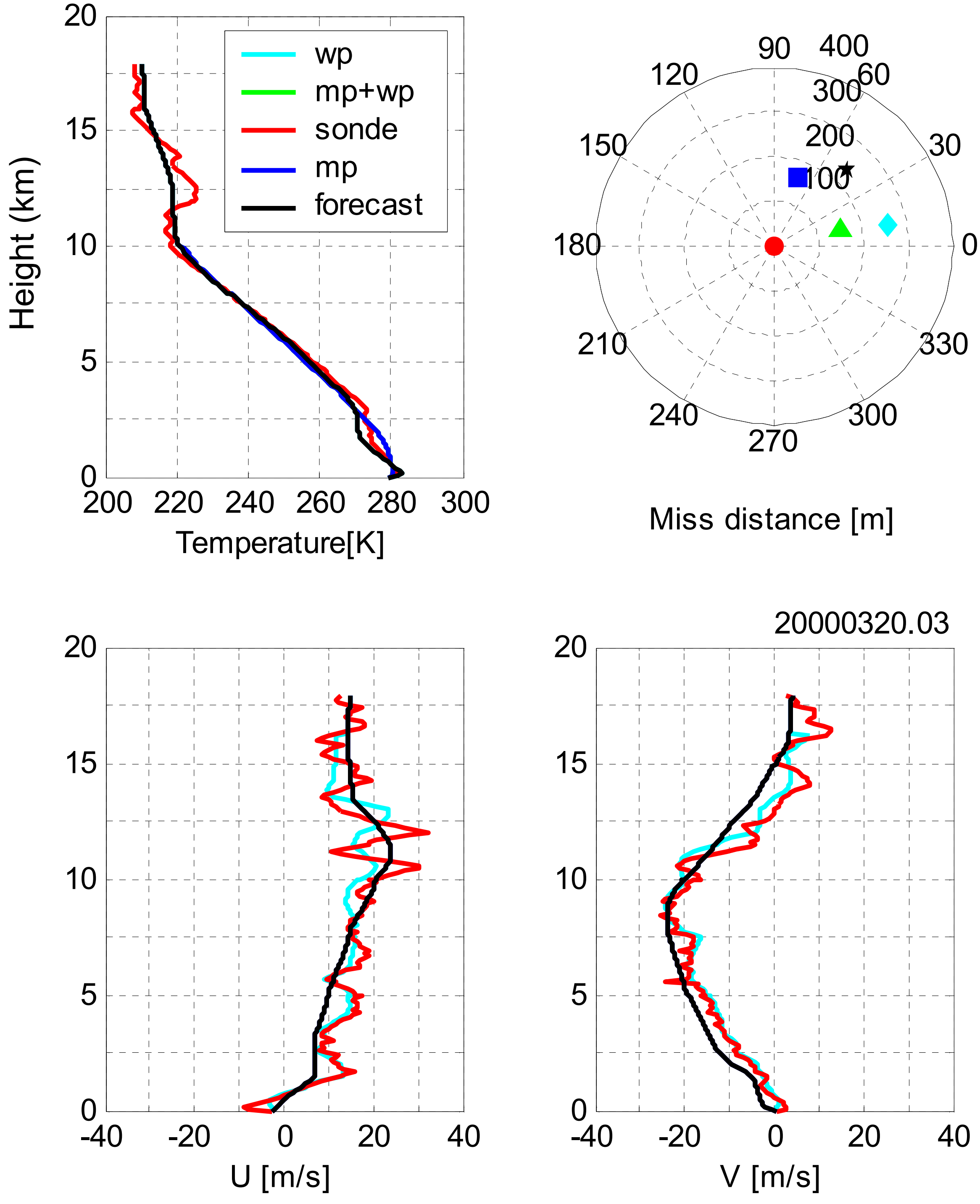
wp
mp+wp
sonde
mp
forecast
Height (km)
Temperature[K]
Miss distance [m]
20000319.21
U [m/s]
V [m/s]

Appendix B



wp
mp+wp
sonde
mp
forecast
Height (km)
Temperature[K]
Miss distance [m]
20000320.00
U [m/s]
V [m/s]

Appendix B



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sonde
mp
forecast
Height (km)
Temperature[K]
Miss distance [m]
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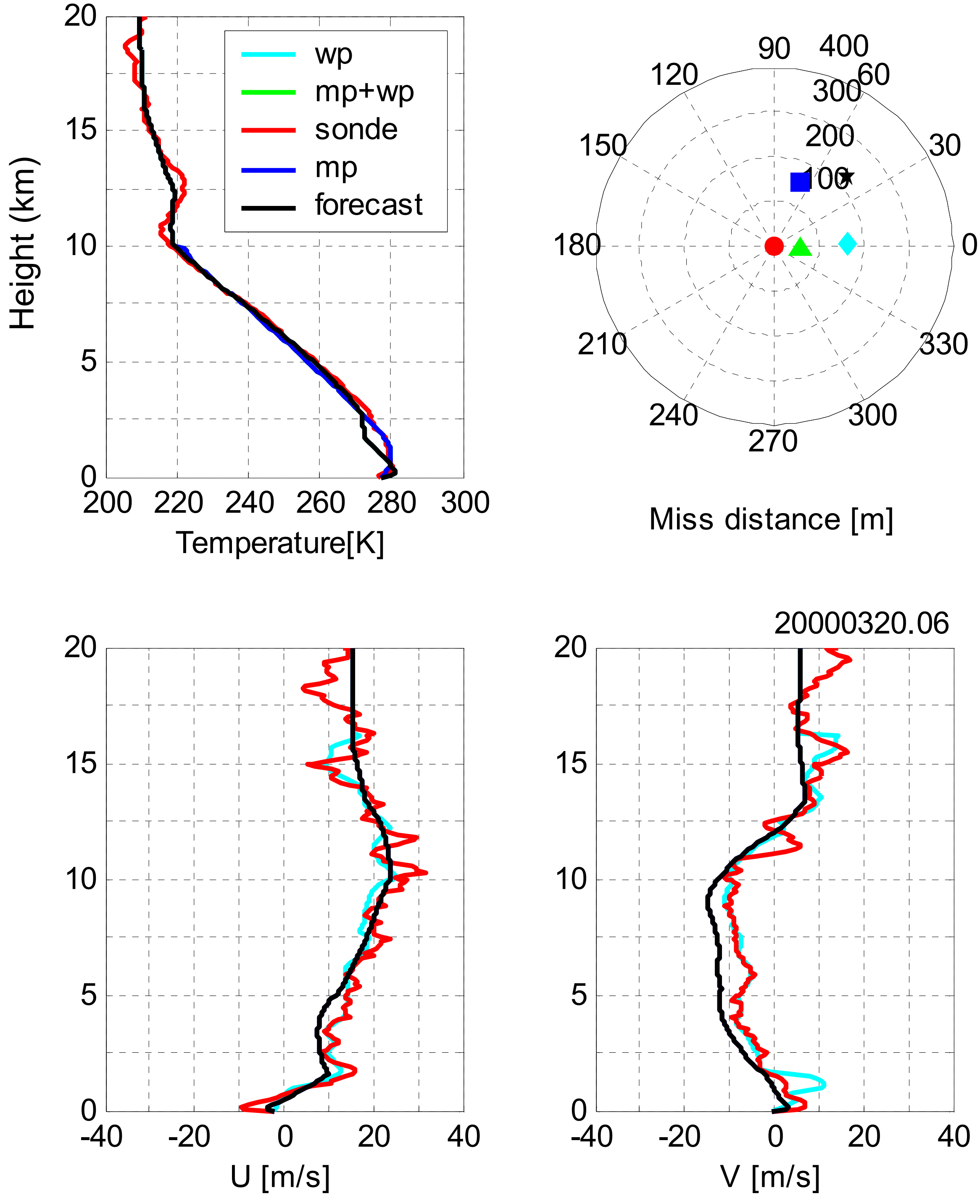
U [m/s]
V [m/s]

Appendix B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forecast
Height (km)
Temperature[K]
Miss distance [m]
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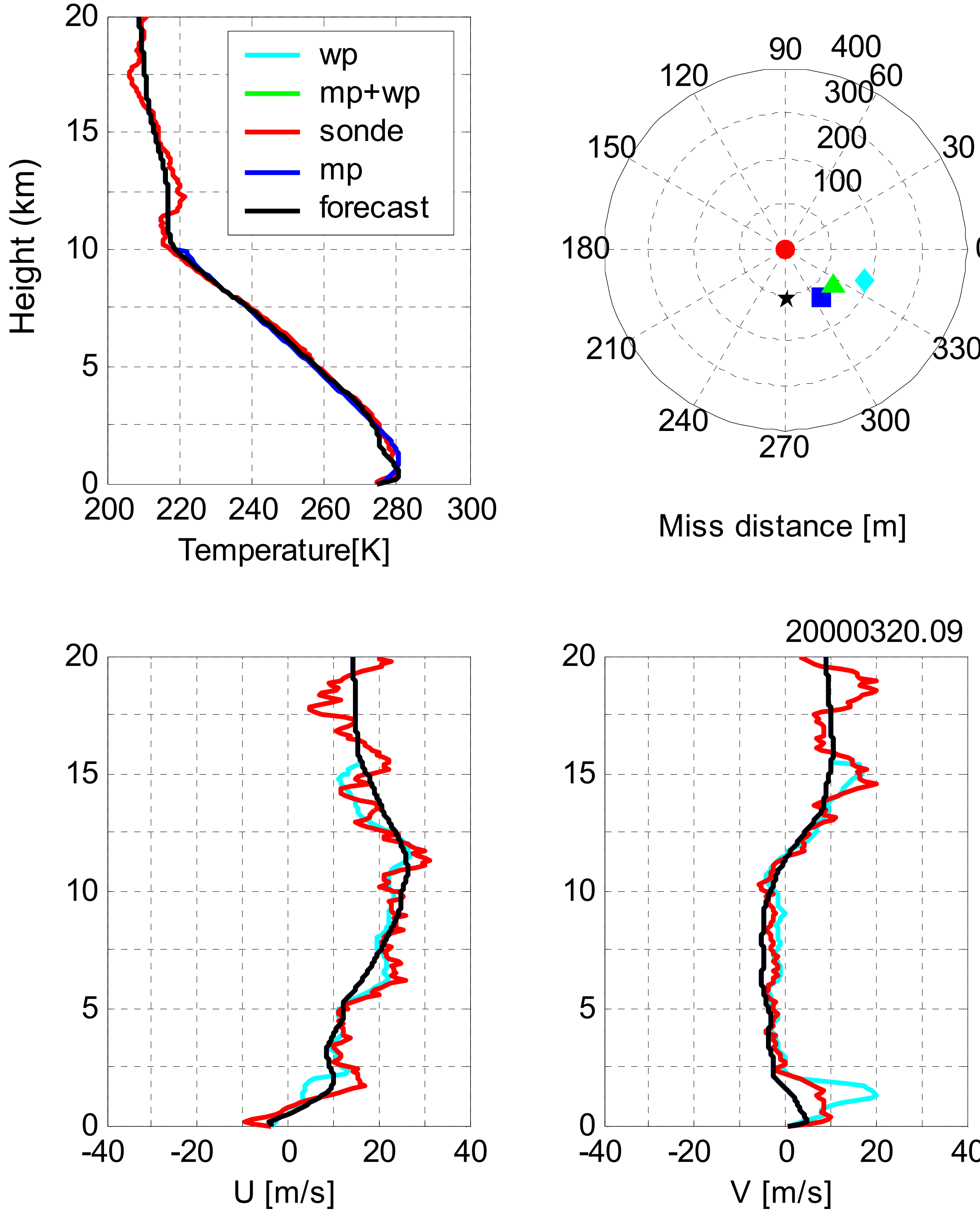
U [m/s]
V [m/s]

Appendix B



Height (km)
Temperature[K]
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mp+wp
sonde
mp
forecast
Miss distance [m]
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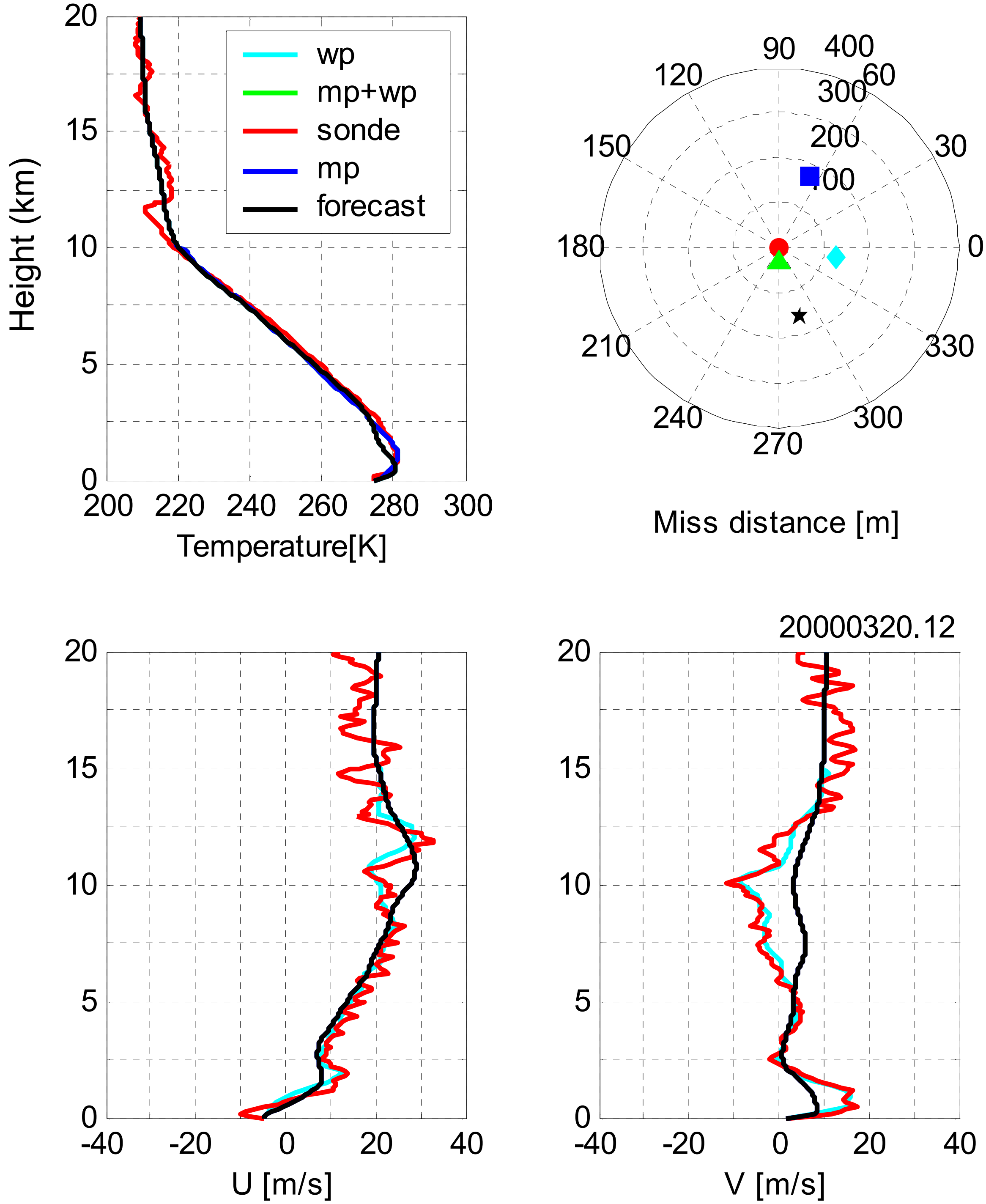
U [m/s]
V [m/s]

Appendix B



wp
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sonde
mp
forecast
Height (km)
Temperature[K]
Miss distance [m]
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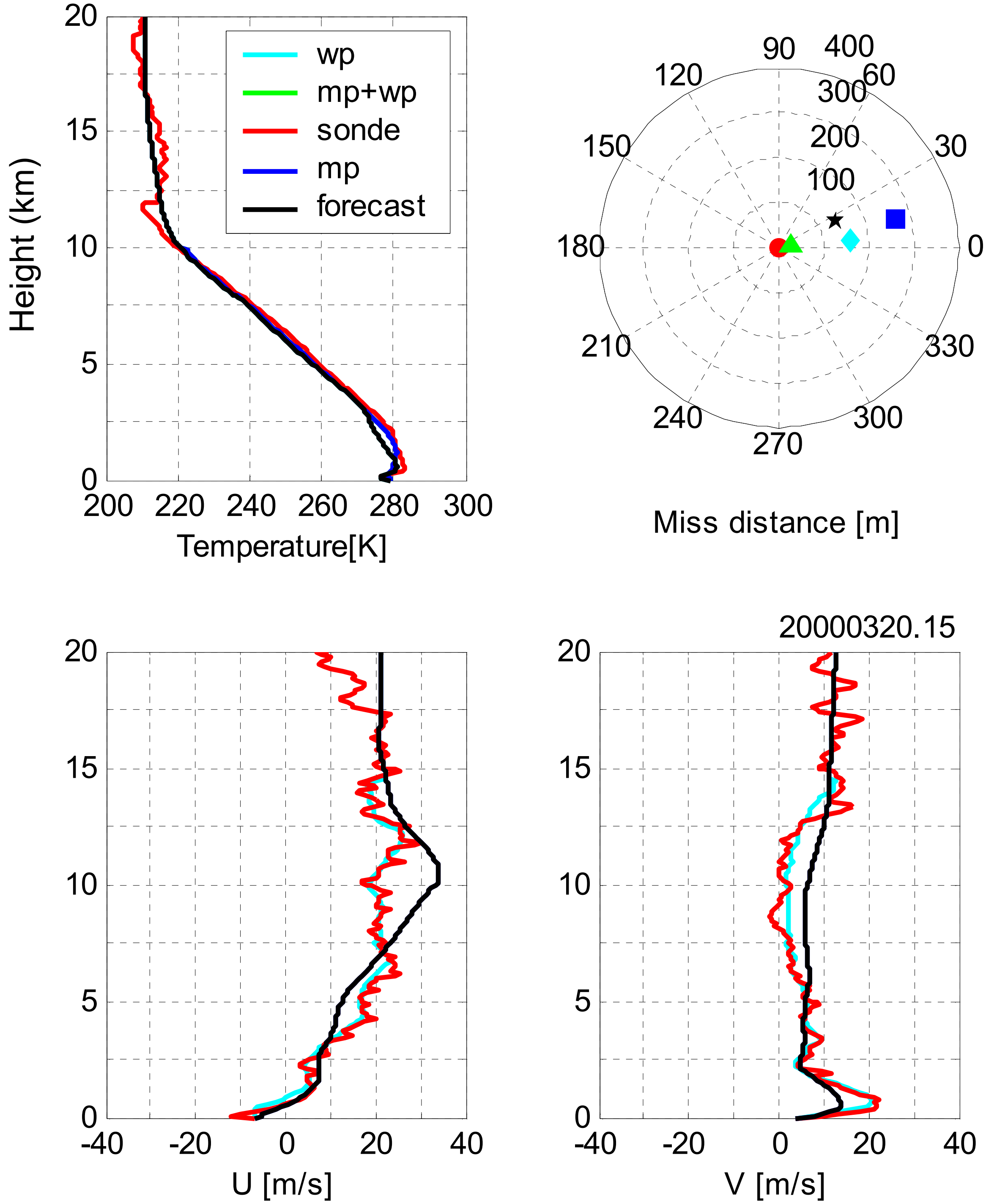
U [m/s]
V [m/s]

Appendix B



wp
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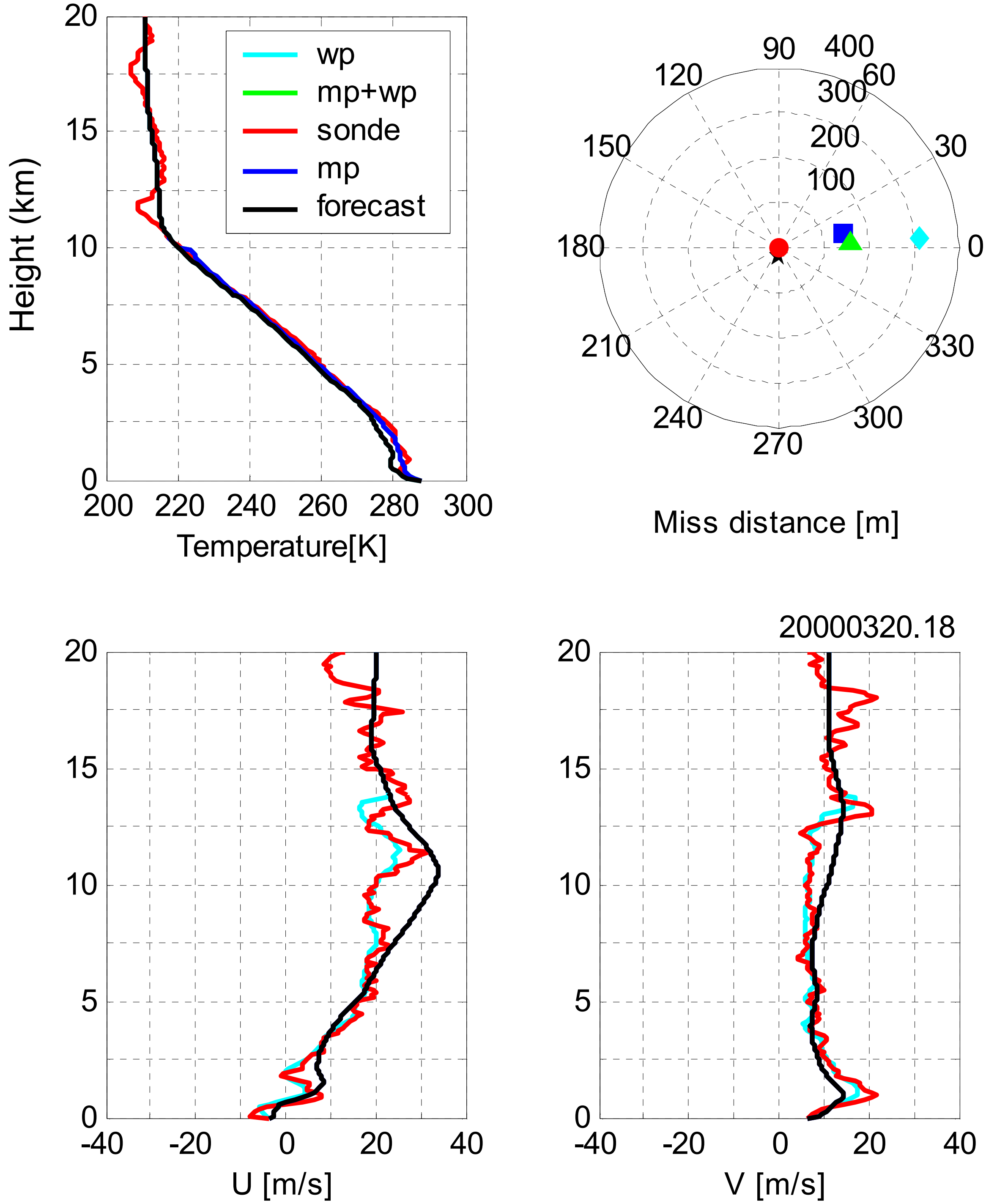
sonde
mp
forecast
Height (km)
Temperature[K]
Miss distance [m]
U [m/s]
V [m/s]
20000320.15

Appendix B



wp
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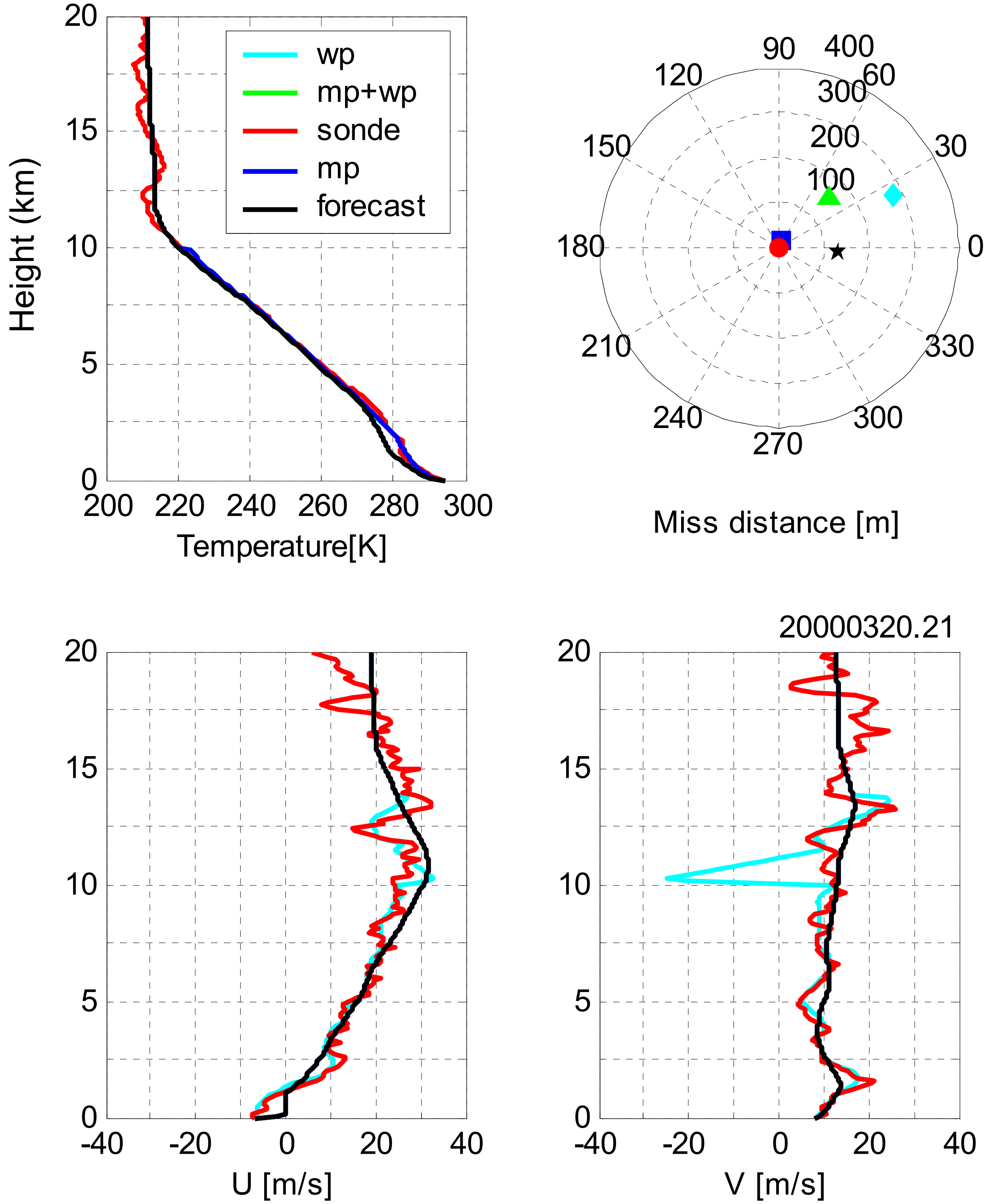
sonde
mp
forecast
Height (km)
Temperature[K]
Miss distance [m]
20000320.18
U [m/s]
V [m/s]

Appendix B



wp
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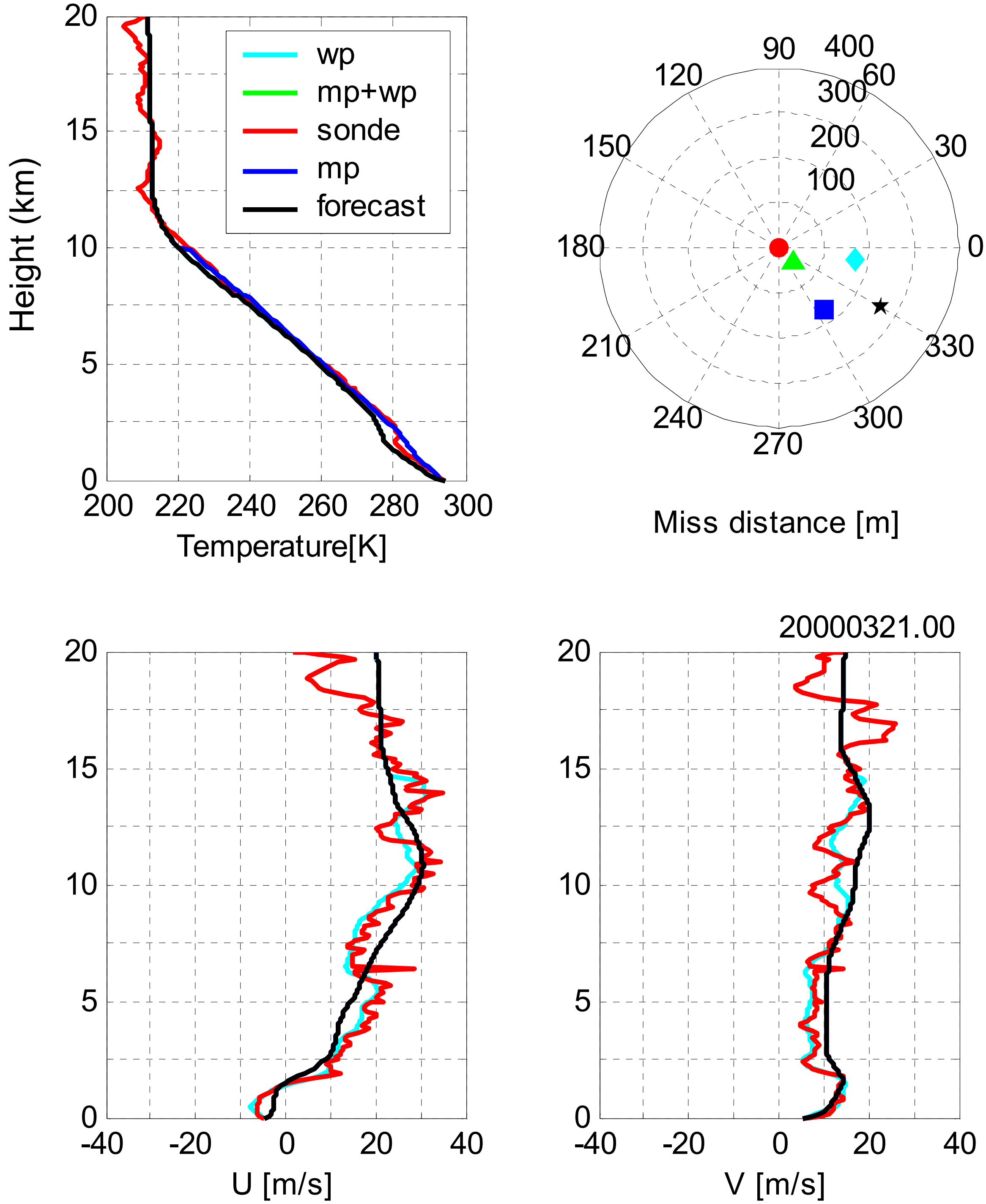
sonde
mp
forecast
Height (km)
Temperature[K]
Miss distance [m]
20000320.21
U [m/s]
V [m/s]

Appendix B



wp
mp+wp
sonde
mp
forecast
Height (km)
Temperature[K]
Miss distance [m]
20000321.00
U [m/s]
V [m/s]