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EUCOS Space-Terrestrial Study Final Report: Observing System Experiments from the winter 2004 - 2005 and summer 2005

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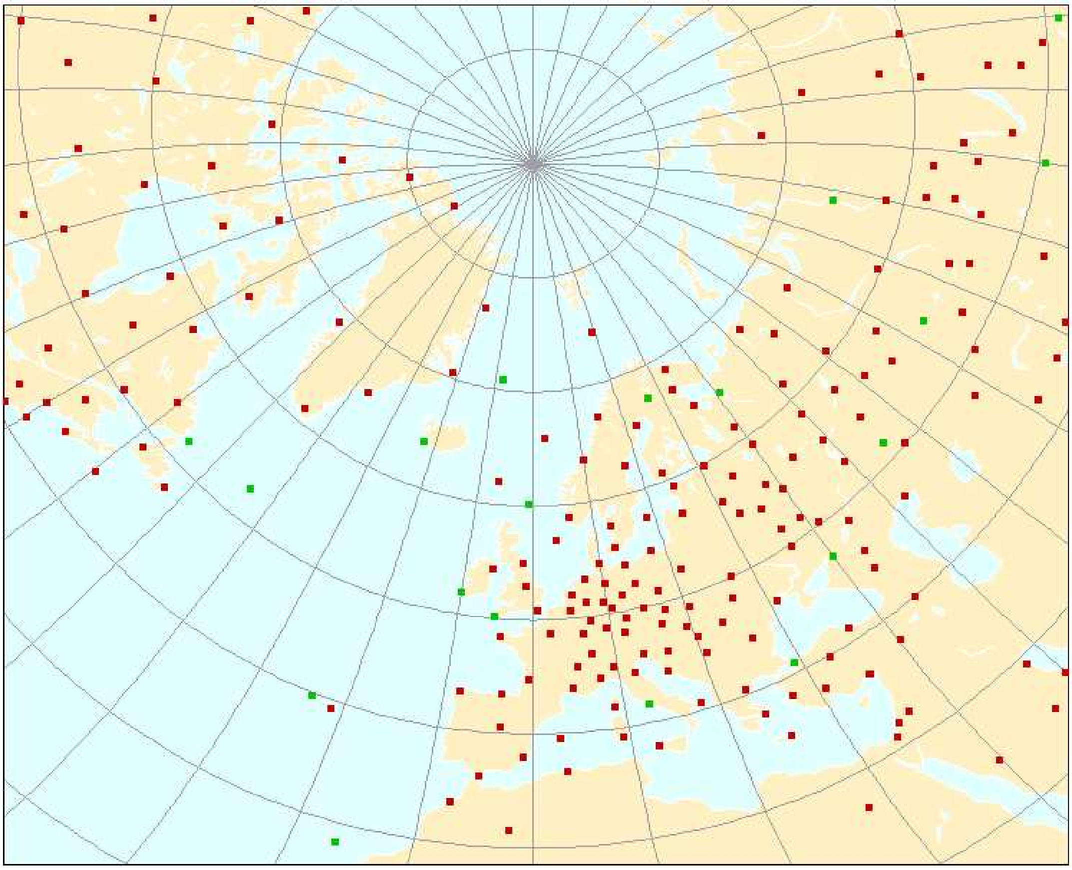

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Title

EUCOS Space-Terrestrial Study Final Report: Observing System Experiments from the winter 2004 - 2005 and summer 2005

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Abstract

This report presents results from 10 HIRLAM impact experiments for two 1 month periods in December/January 2004/05 and August 2005. The purpose of the experiments was to study how different conventional observation types affect the HIRLAM 20km assimilation and forecasting system of the Norwegian Meteorological Institute, as well as the correspondig quality of forecasts. The study was initied by the EUMETNET EUCOS programme as part of the EUCOS Space-Terrestrial Studies. Radiosonde wind and temperature profiles and observations from Aircraft (AIREP/AMDAR) are found to have a substantial positive impact on the HIRLAM 20km forecasts over the 2 specified 1 month verification periods. A slight, but significant, positive impact is also found from the E-ASAP ship radiosondes.

Keywords

Numerical Weather Prediction, Observations, Data Assimilation

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1 Introduction

In the EUCOS Space-Terrestrial study a series of Observing System Experiments (OSEs) is carried out to assess analysis and forecast impact using different observational scenarios. The aim of the terrestrial part of the study, to which this report is a contribution, is to establish the impact, in the European context, of selected terrestrial observation data of varying density, over and above what we get from current space-based data. This is done by sequentially adding conventional observations from e.g. aircraft, radiosonde (including ASAP) and surface data onto a system where a full set of space-based observations is used.

To assess the specific effect of each part of the conventional observation network, the EUCOS Space-Terrestrial study group has designed a "Baseline" and several "experiment" scenarios in which observation types are added and removed. The "Baseline" scenario contains all available remote sensing observations and a minimum set of conventional observations:

- All current satellite observations (radiances, cloud drift winds and scatterometer winds)
- The GUAN (GCOS Upper Air Network) radiosonde network
- The GSN (GCOS Surface Network) SYNOP network (hourly observations)
- Hourly buoy observations (no SHIP data)

This Baseline scenario with a minimum observation system defined by the GCOS (Global Climate Observing System) observation sets, serves as a reference, and each experiment scenario had one or more additional conventional observation type added to the Baseline. Also, a "Control" scenario with all available observations was designed, which is close to what is used operationally at met.no. The experiment scenarios contain the following observation types in addition to the Baseline set-up:

1. Baseline
2. Baseline + All available aircraft observations (AIREPs, AMDARs)
3. Baseline + All available radiosonde wind observations
4. Baseline + All available radiosonde wind and temperature observations
5. Baseline + All available Wind Profiler observations
6. Baseline + All available radiosonde humidity, wind and temperature observations
7. Baseline + All available radiosonde and Aircraft wind and temperature observations
8. Baseline + All available in-situ observations (The full observing system)
9. Baseline + All available E-ASAP radiosonde observations, E-ASAP ships only
10. Baseline + All available E-ASAP radiosonde observations, including MIKE and EKOFISK

2 Results

The Baseline and the experiments were run for 2 verification periods of 1 month each, from 15th of December 2004 until 19th of January 2005, and from 1st to 31th August 2005. There was a spin-up period of 10 days prior to each verification period. At the Norwegian Meteorological Institute, the HIRLAM model was used for these experiments. The model has 20 km horizontal resolution and 40 vertical layers, and covers Europe, the Arctic and a large part of the North Atlantic. The lateral boundaries to the HIRLAM experiments are from the ECMWF global model, using the EUCOS Control run with all available observations.

The HIRLAM set-up used here was very close to what is used operationally at the Norwegian Meteorological Institute, except that for some observation types, like Atmospheric Motion Vectors and winds from the European Wind Profiler Network, all observations within the assimilation window of 6 hours around analysis time are used in the analysis. This puts more weight on these observations than would be the case for a real-time model run, which currently runs with a cut-off time for observations of 2hrs 15min. However, as this is only a problem for a small fraction of the total amount of observations, the effect of this is regarded as minimal on the overall result.

The forecasts are run in sequence; each analysis using the previous 6 hour forecast as a first guess. A full 48 forecast is done for the midnight cycle only. This differs from the operational model setup, where the analysis at each cycle starts from a digital blending of the most recent ECMWF analysis and a short time HIRLAM forecast.

For verification, the forecasts originating from the midnight cycle are used. The forecasts are verified at the main synoptic hours (0Z, 6Z, 12Z, 18Z). Only EWGLAM observations are used in the verification. The RMS error and Bias between the reference observations and the model forecasts is calculated.

Each of the EUCOS experiments is compared with the Baseline run. If the experiment has a significantly smaller Root Mean Squared (RMS) error than the Baseline, the experiment is considered to be better than the Baseline.

2.1 Surface parameters - MSLP, T2m and FF10m

For the surface parameters Mean Sea Level Pressure, 2 meter temperature and 10 meter wind, the Baseline run has higher Root Mean Square (RMS) error than each of the 9 experiments conducted, with the exception of scenario 5 (add Wind Profilers). This is true for both verification periods. The Control scenario, where all available observations are included, has the lowest RMS error compared to the Baseline (figures 1 and 2). The figures show the RMS error and Bias of the forecasts compared to surface observations from the European Working Group on Limited Area Modeling (EWGLAM) station list, which is a limited set of observing stations located in Europe which are considered to have a certain quality and representativeness.

These error statistics are shown both as a function of forecast length and as daily contributions to the total RMS error. Also shown is the mean difference between the RMS errors, with error bars indicating 1 standard deviation. [1] Finally, the vertical distribution of RMS error in some key parameters, compared to radiosondes from the EWGLAM station list, is shown.

[1] Please note that the vertical axis of the significance plots are opposite for the winter and summer period. This means that, for a scenario to score significantly better than the Baseline, the curve should be ABOVE zero for the winter run, and BELOW zero for the summer run. The latter was the agreed convention in the study group, but unfortunately this was decided too late to be effectuated for the winter period.

In the following we focus on the signal in Mean Sea Level Pressure (MSLP). The signal in the other surface parameters is generally the same, but weaker than for MSLP. Results for all parameters are shown at the end of this report (from figure 29)

Radiosondes are the most important contributors to lowering the RMS error in the surface parameters (figures 3,4a and 5a). The improvement by adding more radiosondes is quite significant. Wind and Temperature seem to be equally important, while humidity does not seem to have much added effect.

This shows that radiosondes are still - also in the presence of an increasing number of new satellite data - essential for the forecast quality of the HIRLAM model in use at the Norwegian Meteorological Institute.

For the winter period, combining non-GUAN radiosondes and AIREPs improves the scores even more (figures 3 and 5b). This effect is not so clear for the summer period (figures 4b and 5b)

Adding Wind Profilers to the system results in significantly worse RMS scores for all surface parameters (figures 3, 4c and 5c). The impact is distributed evenly over the verification period. This datatype has not been used at the Norwegian Meteorological Institute prior to this study, and the negative impact of this data type is probably caused by non-optimal error handling and quality checks. More investigation is needed before we can say for certain if this data is valuable for the HIRLAM analysis system.

The experiments with E-ASAP radiosondes show that the few extra radiosondes from data sparse ocean regions do have an impact on the overall verification of the surface parameters (figures 3, 4c and 5d). For the winter period, the time series of the RMS scores show that for shorter periods at the start of January, the E-ASAP ship radiosondes had a positive impact on the RMS error. This coincides with a period of large synoptic activity in the North Atlantic, with 3 storm centers reaching Scandinavia in one week. However, for the winter period as a whole they seem to have a slightly negative impact on the overall MSLP score. For the summer period, the E-ASAP ships show a small, but significant positive contribution to the forecast quality. This is also the case for an added experiment for the winter period, where E-ASAP ships + sondes from OWS MIKE and the oil rig EKOFISK are used.

2.2 The middle atmosphere - Z, T, RH and FF

Figures 6 and 7 show the vertical distribution of RMS error for the parameters Z (Geopotential height), T (Temperature), RH (Relative Humidity) and FF (Wind) for the same EUCOS scenarios as discussed above. The model output is verified against radiosondes from the EWGLAM list.

For Geopotential height, the Non-GUAN radiosondes and AIREPs contribute in a positive way through the whole vertical column and for all forecast times (figs 6 and 7, a+b). The European Wind Profilers (figs 6c and 7c) lead to higher RMS error for the whole atmospheric column in the winter, but slightly lower RMS error between 500 and 300 hPa for the summer. For the winter period the E-ASAP radiosondes have a neutral to slightly positive impact for the first 24 hours of the forecasts, but for longer forecasts the impact is negative.(figs 6d). For the summer period, however, there is a small, but significant positive impact for the whole atmosphere for all forecast lengths (fig 7d). Also, if the stations MIKE and EKOFISK are included for the winter period, the positive impact remains also in the 48 hour forecasts (fig 37).

The atmospheric temperature estimate is most improved by adding radiosondes (figs 6a and 7a). Combining Aircraft with the Non-GUAN radiosondes, further reduces the RMS errors (figs

6b and 7b), especially during winter.

For the winter period, the impact on Relative Humidity is not as clear as for geopotential height. For most of the scenarios the impact is neutral below 850 hPa, and then neutral to slightly positive. The largest positive impact is found for the 6 hour forecasts. Unfortunately, due to some technical error, Relative Humidity information was not stored for the summer period.

All scenarios have a neutral or positive effect on the RMS wind error below 400 hPa, except for scenario 5 (add EWPs) where there is a clear negative impact (figs 6c and 7c).

3 Some weather situations

In addition to the summary statistical scores presented, we also discuss some weather situations in more detail. One general motivation for studying specific cases is that for the overall scores, there is no extra weight on extreme weather events, which are the most important phenomena to forecast correctly. Also, if there are large analysis differences over ocean areas, it will not be well picked up by the EWGLAM station network; the stations being mainly situated over Central Europe. Such cases can possibly be identified and assessed on weather maps.

Generally with observing system experiments with one month duration over a limited area as presented here, one can also find limited time periods where there are particularly large contributions to the differences in verification scores between the scenarios. It might be of interest to locate such incidences in the verification timeseries presented in Figures 3 and 4 to see what type of situation is responsible for these differences.

3.1 Winter period situation

The timeseries of RMS errors for the winter situation presented in Fig. 3 shows a peak in the errors around 17 December 2004 and another one around 9 January 2005. The latter peak was within a period where 3 intense storms hit Scandinavia. In Norway these storms were named “Gudrun”, “Haarek” and “Inga”. These storms reached Scandinavia on 8, 11 and 13 January 2005, respectively, and caused considerable damage.

3.1.1 The Scandinavian storm ”Gudrun”, 20050108 12UTC

Here we look closer into the situation during the first of the three storms, “Gudrun” which hit the coast of Norway the 8th of January 2005. Figure 8 shows the position of the storm center from the first appearance in the model area on January 7th, until it landed and weakened on the evening of January 8th. The overlying satellite image is valid at 11:40UTC on the 8th of January. Figure 9 shows the 12 hour forecasts valid at 12UTC the 8th of January for the Control and Baseline experiments. We see that in this case even for as short forecast range as 12 hours there are significant differences between the scenarios. The center of the storm over Southern Norway is too shallow and too far east in the Baseline run compared with verifying SYNOPS. The Control forecast is in better agreement with the observations. Adding E-ASAP ships to baseline (also including EKOFISK and weathership Mike) is shown in Fig. 10, and these observations are able to improve the forecasted location and strength of the low significantly. Adding aircraft observations to Baseline (Figure 11) alters the shape of the low, but it is still too weak, and now the position is too far south. Adding non-GUAN radiosondes (Fig. 12) contributes positively by placing the center more in agreement with the surface observations.

However, the center is still slightly too shallow compared to the observations and the Control run.

The relative merit of the various scenarios in this case is generally in agreement with the statistical verification results shown above. In addition one notes the good effect of adding the soundings at Weathership Mike, Ekofisk platform and E-ASAP ships in this case.

3.2 Summer period cases

On the summer period verification statistics timeseries in Fig. 4, we find relatively high values of RMS errors in the period 5-10 August. We have therefore had a closer look at the weather situation at a time within that period. In addition we discuss a situation of a strong low pressure system Northwest of Scotland on 24 August.

3.2.1 Low over Northeast Europe, 20060809 00UTC

Since a peak is found in the forecast verification errors in the period of 5-10 August, we have looked closer at the weather situation in that period. There is not particularly strong synoptic activity at the time, but some activity over continental Europe where much of the EWGLAM verification network is located, and a low is developing over Northeast Europe.

First we present 24 hours forecasts valid at 9 August 00 UTC. In Fig. 13 we present the control run compared with the analysis performed by the forecaster. The situation is generally well captured by the control run, but the low pressure center is located too far north and is too weak. In the baseline scenario in Fig. 14 we find a slightly larger displacement of the center of the low, and the weak low pressure center over Denmark is less well captured.

Adding radiosonde wind, Fig. 15, and also adding radiosonde temperature, Fig. 16 seem to improve the description of the low pressure center slightly relative to the baseline as could be expected. The experiment adding E-ASAP ships, Fig. 17, does not seem to be an improvement over the baseline in this case.

In the 48 hours forecasts for the control (Fig. 18) and baseline (Fig. 19) valid 24 hours later we see that the differences found in the 24 hours forecasts have developed further. The baseline experiment seem to develop a stronger low, but it is too strong and displaced, causing apparently larger errors than in the control run.

3.2.2 Low West of Scotland, 20060824 00UTC

From the summer period we have also looked closer on a situation with a marked low pressure system West of Scotland the 24th of August 2006. There is a weak maximum in the verification errors around that time, but significant forecast errors in this situation are over the ocean and not captured by the EWGLAM network.

In the baseline run, Fig. 20 the low pressure center is too weak and slightly displaced to the east. In Fig. 21 we show the results when adding E-ASAP ships upon the baseline, and in this case these data provides an improvement in the forecasted strength of the low pressure center. Also adding radiosonde wind and temperature and aircraft, Fig. 22, brings a clear further improvement.

However the addition of the rest of the observation network (more surface observations, moisture data) in the control run, Fig 23, actually seems to produce a slightly worse forecast of the low.

4 Summary and conclusions

The case studies performed, also cases investigated which are not presented in this report, generally confirm results concerning the overall merits of the various scenarios found in the EWGLAM verification statistics. We have also noted some cases of developments over ocean with good influence of added E-ASAP data.

It is demonstrated that the conventional upper-air observations have a large positive effect on the forecast quality in the operational setup at the Norwegian Meteorological Institute. The Control experiment with the full combined observing system verifies significantly better than the minimum system used in the Baseline scenario, even in the presence of all available satellite data.

Radiosondes are still a major contributor to the forecast quality. Wind and Temperature are equally important, while for the summer period, humidity had little added effect. The gain in quality from new satellite data sources and fast delivery systems such as the Eumetsat Advanced Retransmission System, can not outweigh the loss from receiving fewer radiosondes at present.

The results from scenarios 2 and 6 show that AMDARs and AIREPs profiles complement the radiosondes and further improve the forecast skill of the HIRLAM model. This is clearest for the winter period, whereas for the summer it seems that the added impact of these observations is much smaller.

With the present tuning of the assimilation system, there was no improvement from adding Wind Profilers to the system (in fact it led to a decrease in forecast skill). More work on tuning and quality checks is probably necessary if we are to benefit from this data source. It is not clear whether this should be considered a data assimilation problem or an observation preprocessing problem.

The results from scenario 9 (including the E-ASAP network) show that even the very limited number of radiosondes located in data sparse regions in the oceans can have a significant impact on the forecasts. This signal is clearest for the summer period, whereas for the winter period as a whole the impact of the E-ASAP network is neutral. However, during the period with large synoptic activity in January they seem to contribute in a positive way, and also, with the inclusion of the sondes on EKOFISK and OWS MIKE, the E-ASAP network has an overall positive impact.

The study clearly shows the benefit of the various observation types supported by EUCOS in the regional model used at the Norwegian Meteorological Institute. The quantification of the various impacts given here can, together with cost assessments for the various components, assist the development of a future cost-effective observing system for regional weather forecasting.

List of Figures

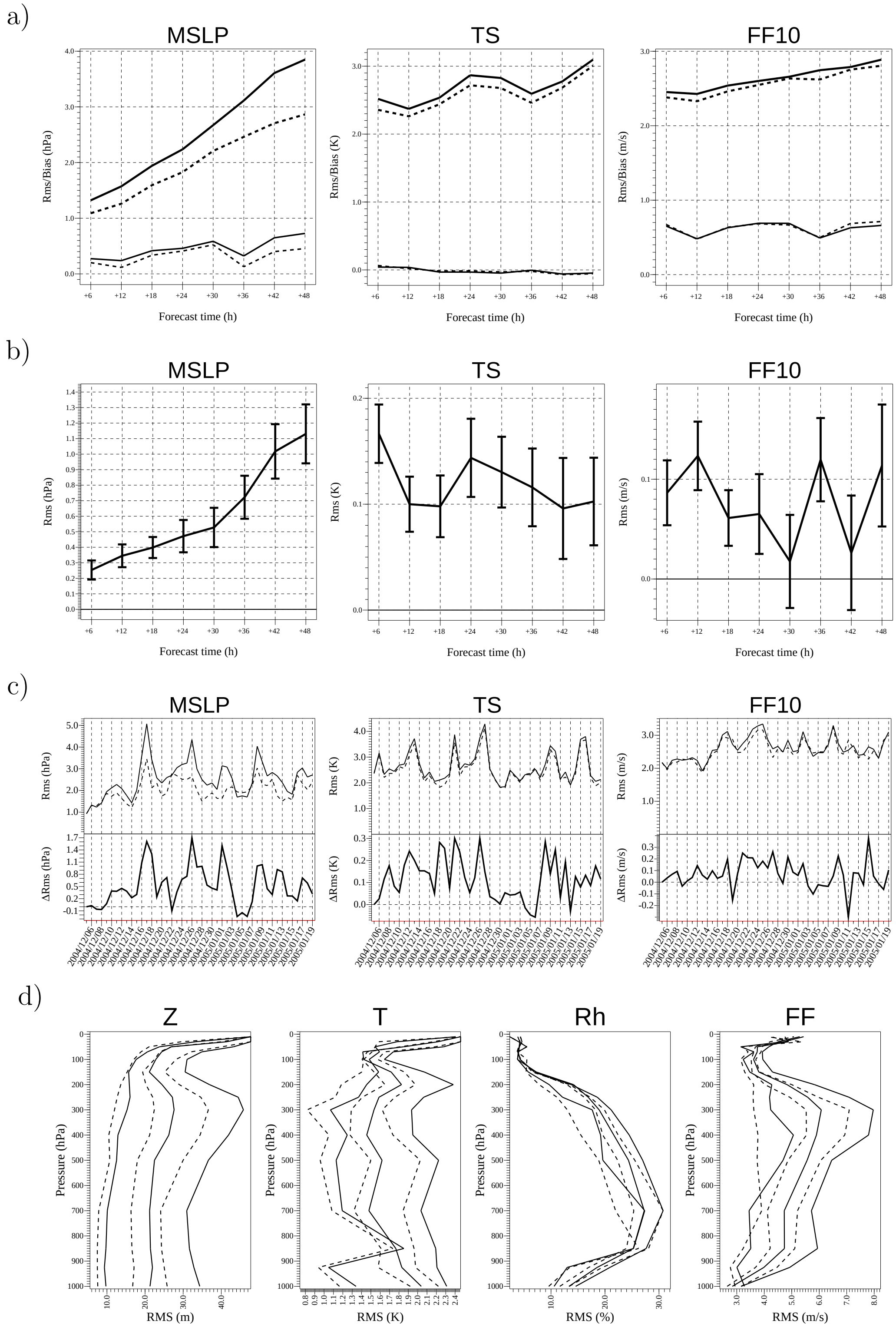


Figure 1: WINTER PERIOD Scenario 8 - the Control experiment (dashed) compared to Baseline (solid). a) RMS error (upper curves) and Bias (lower curves)as a function of forecast length. b) Mean RMS error difference (BAS-CTR). c) Time series of the daily contribution to the errors in MSLP, T2m and FF10. To score better than the Baseline, the experiment should be below the Baseline in the upper panel, and correspondingly on the positive side in the lower panel. d) Vertical profiles of RMS error for forecast lengths (+6h, +24h, +48h).

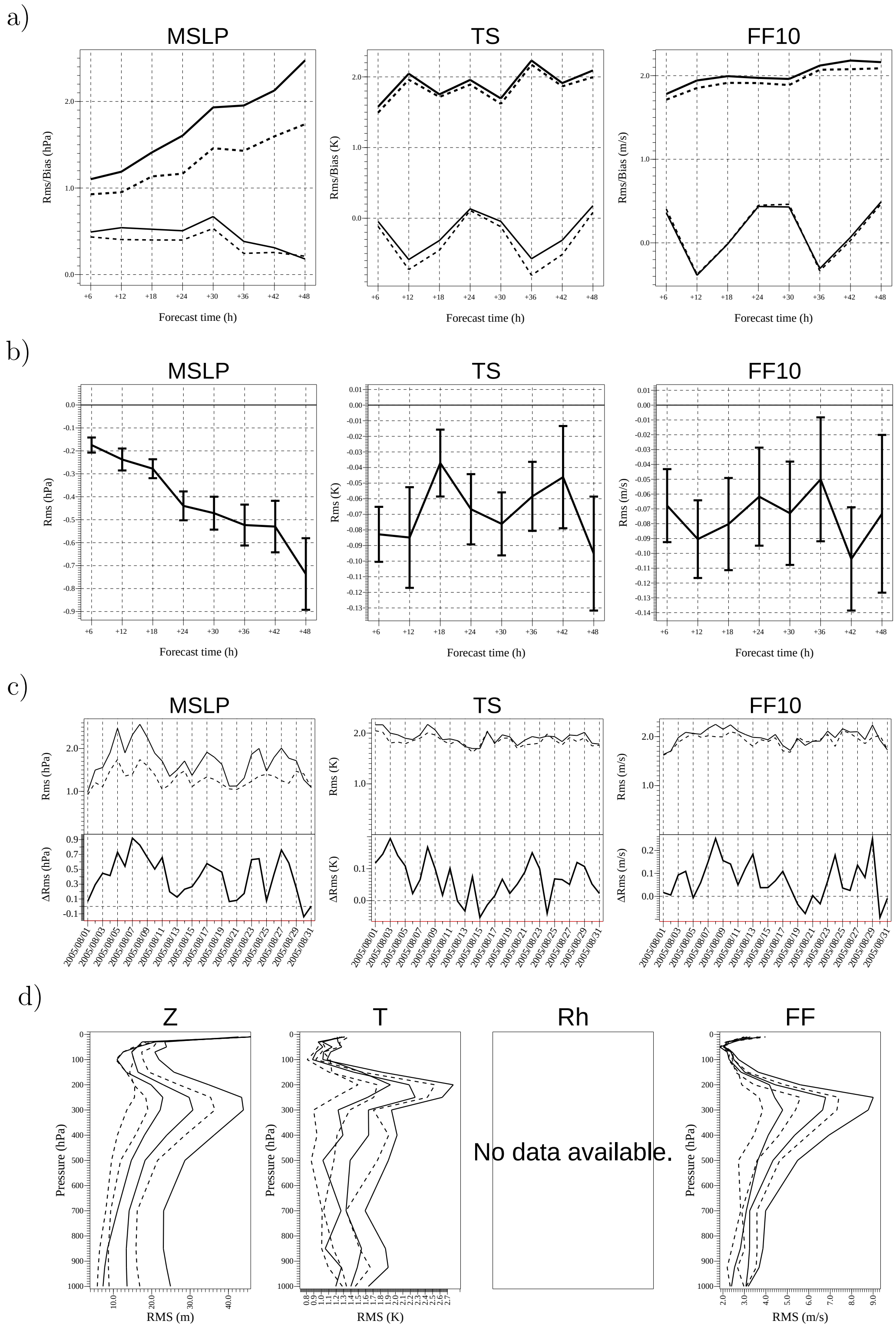
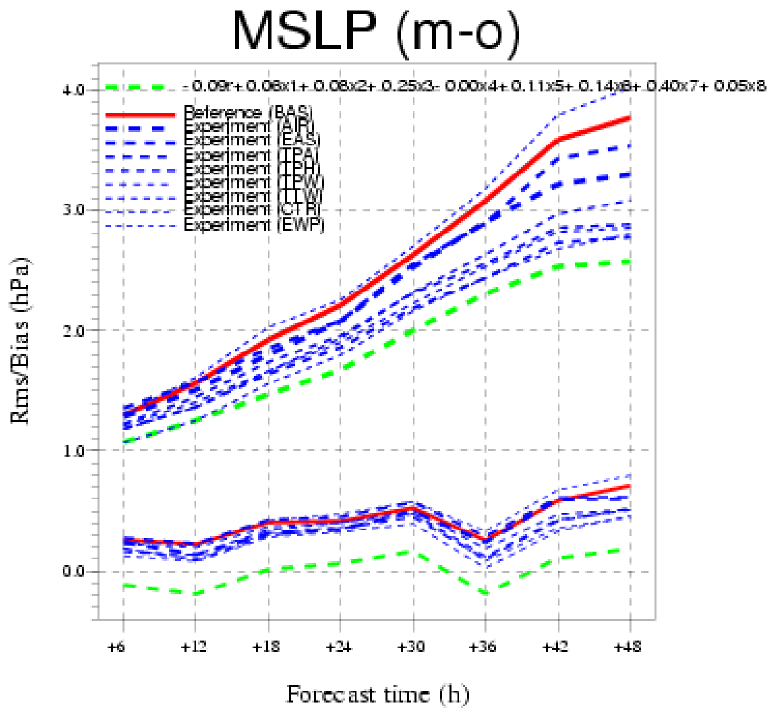
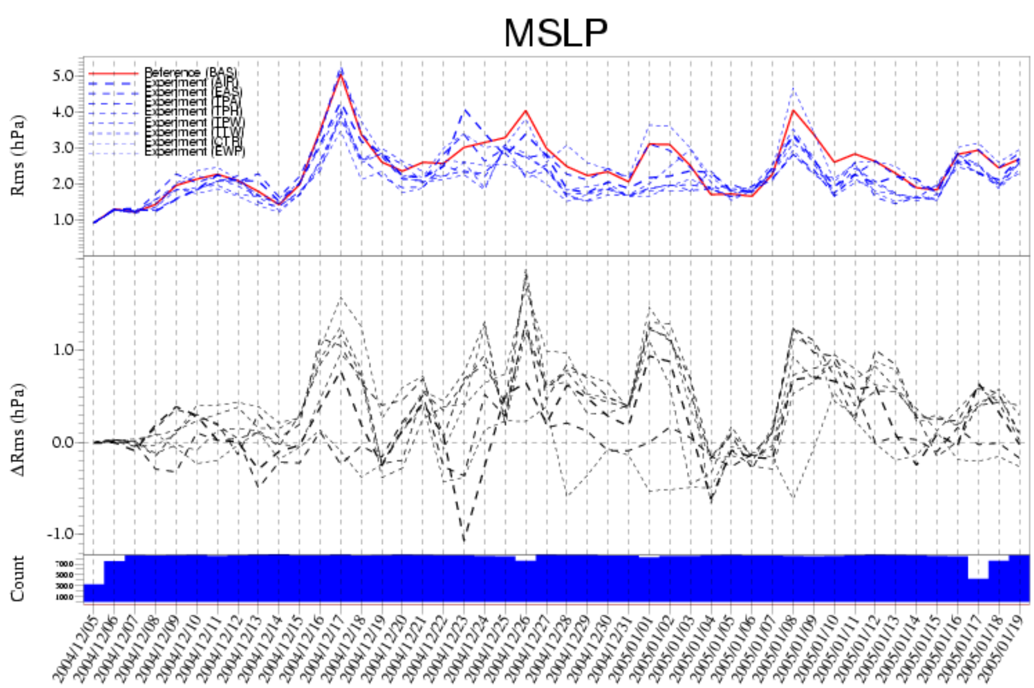


Figure 2: SUMMER PERIOD Scenario 8 - the Control experiment (dashed) compared to Baseline (solid). See figure 1 for details. (Please note that the vertical axis of the significance plots (b) are opposite for the winter and summer period. This means that, for a scenario to score significantly better than the Baseline, the curve should be ABOVE zero for the winter, and BELOW zero for the summer period.)



a) From 2004/12/05 06:00: 0.00 to 2005/01/19 18:00: 0.00



b) From 2004/12/05 06:00: 0.00 to 2005/01/19 18:00: 0.00

Figure 3: WINTER PERIOD. a) RMS error (upper curves) and Bias (lower curves) of MSLP as a function of forecast length. Baseline (Solid red line) vs All EUCOS Scenarios (dashed blue lines). b) Time series of the daily contribution to the errors in MSLP (upper panel), and the difference in RMS between the Baseline and the 8 EUCOS scenarios (lower panel). (The different EUCOS scenarios are, from the top: Scenario 1 (BAS - Baseline), scenario 2 (AIR - Add aircraft), scenario 9 (EAS - Add E-ASAP network, incl MIKE,EKOFISK), scenario 6 (TPA - aircraft + radiosonde wind+temp), scenario 7 (TPH - radiosonde wind+temp+hum), scenario 3 (TPW - radiosonde wind), scenario 4 (TTW - radiosonde wind+temp), scenario 8 (CTR - Control, the full system), and scenario 5 (EWP - add wind profilers). The dashed green line is the theoretical linear combination of all the experiments verifying optimally.)

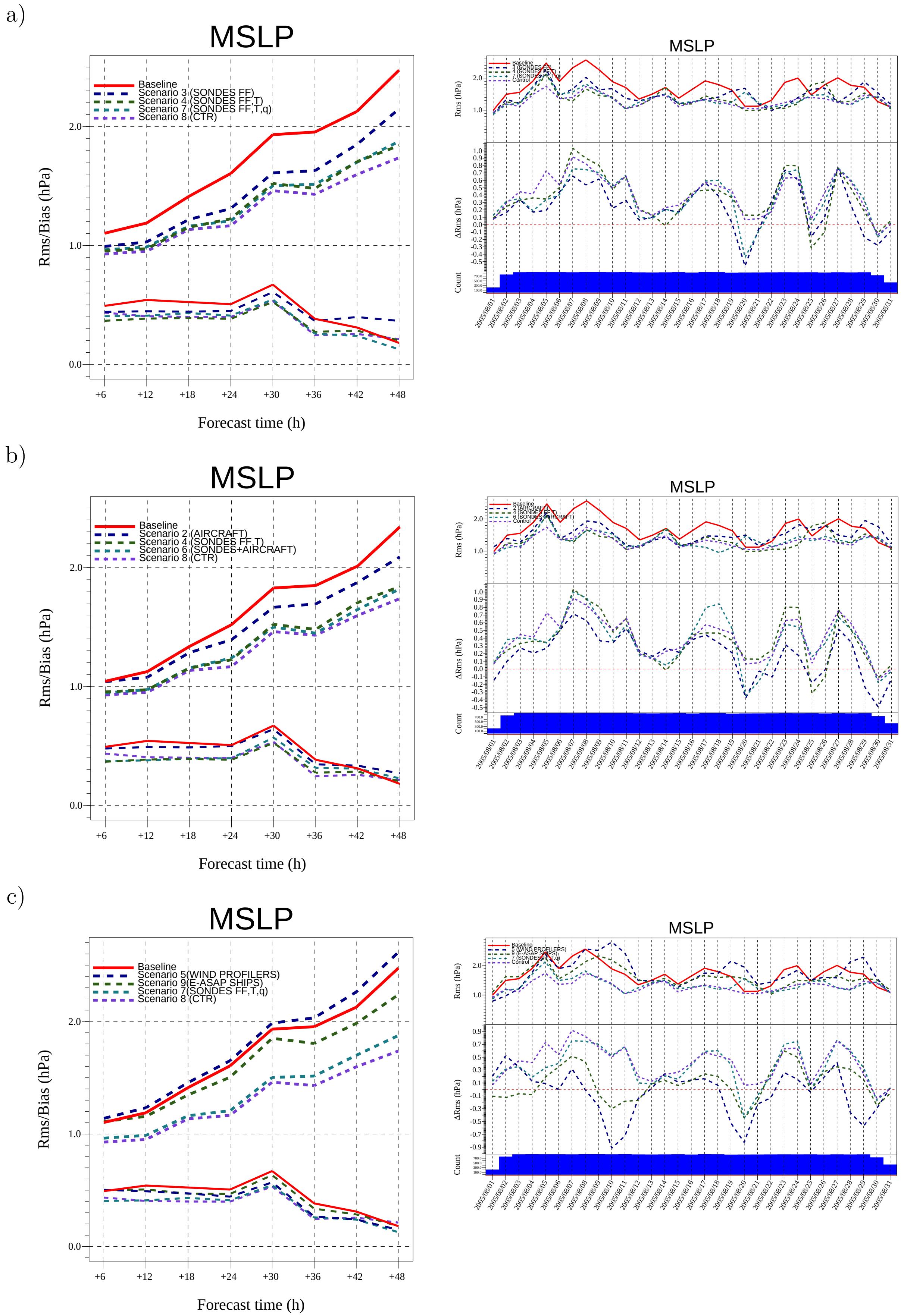


Figure 4: SUMMER PERIOD experiments with a) Radiosondes, b) Aircraft data and c) E-ASAPs and Wind Profilers. Baseline (Solid red line) and Control (dashed purple) are plotted in all figures.

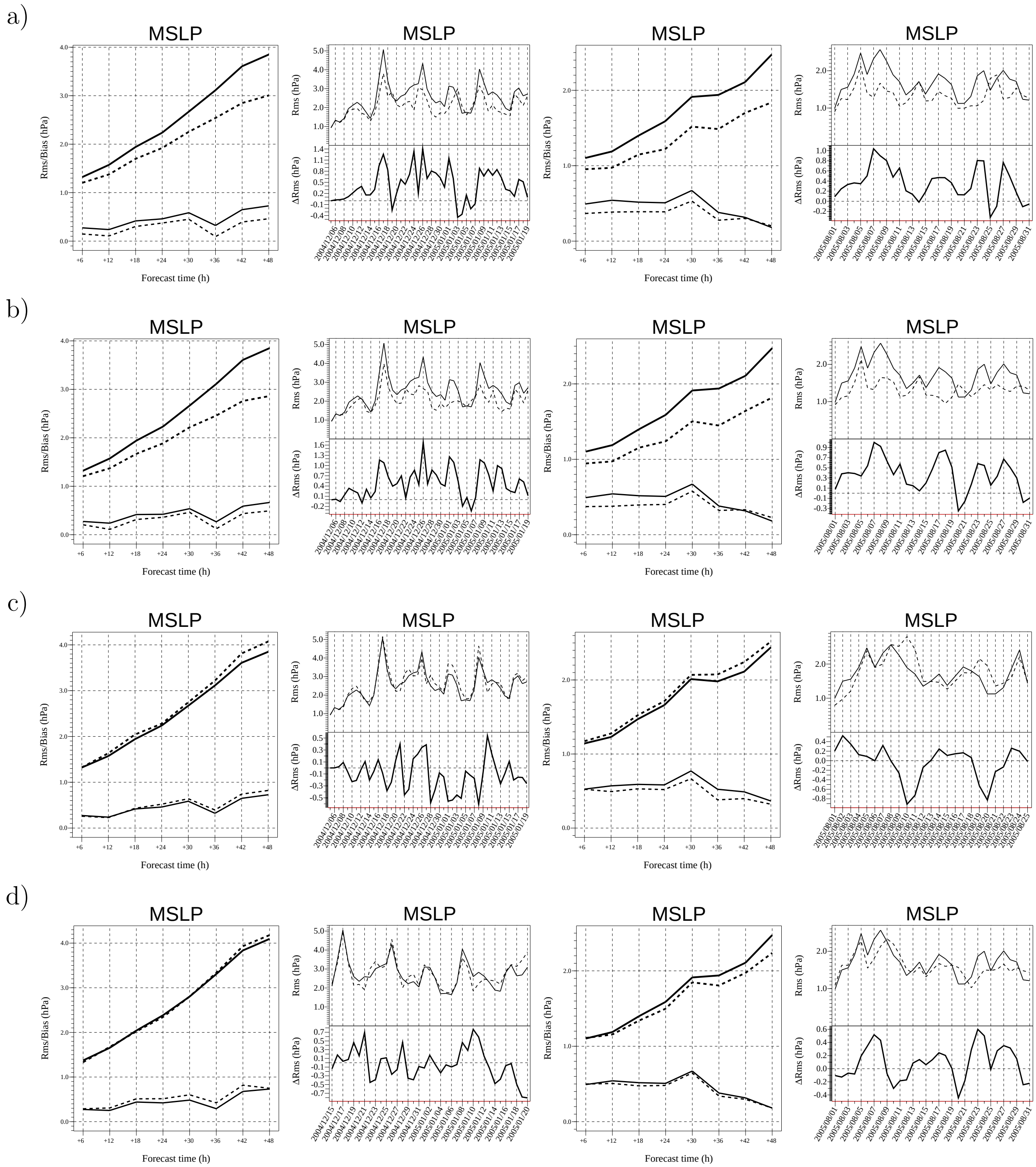


Figure 5: a) Scenario 4 - Add Radiosonde temperature and wind. b) Scenario 6 - Add Radiosonde and Aircraft temperature and wind. c) Scenario 5 - Add European Wind Profilers. d) Scenario 9 - Add E-ASAP ship Radiosondes. Left panels: WINTER, Right panels: SUMMER.

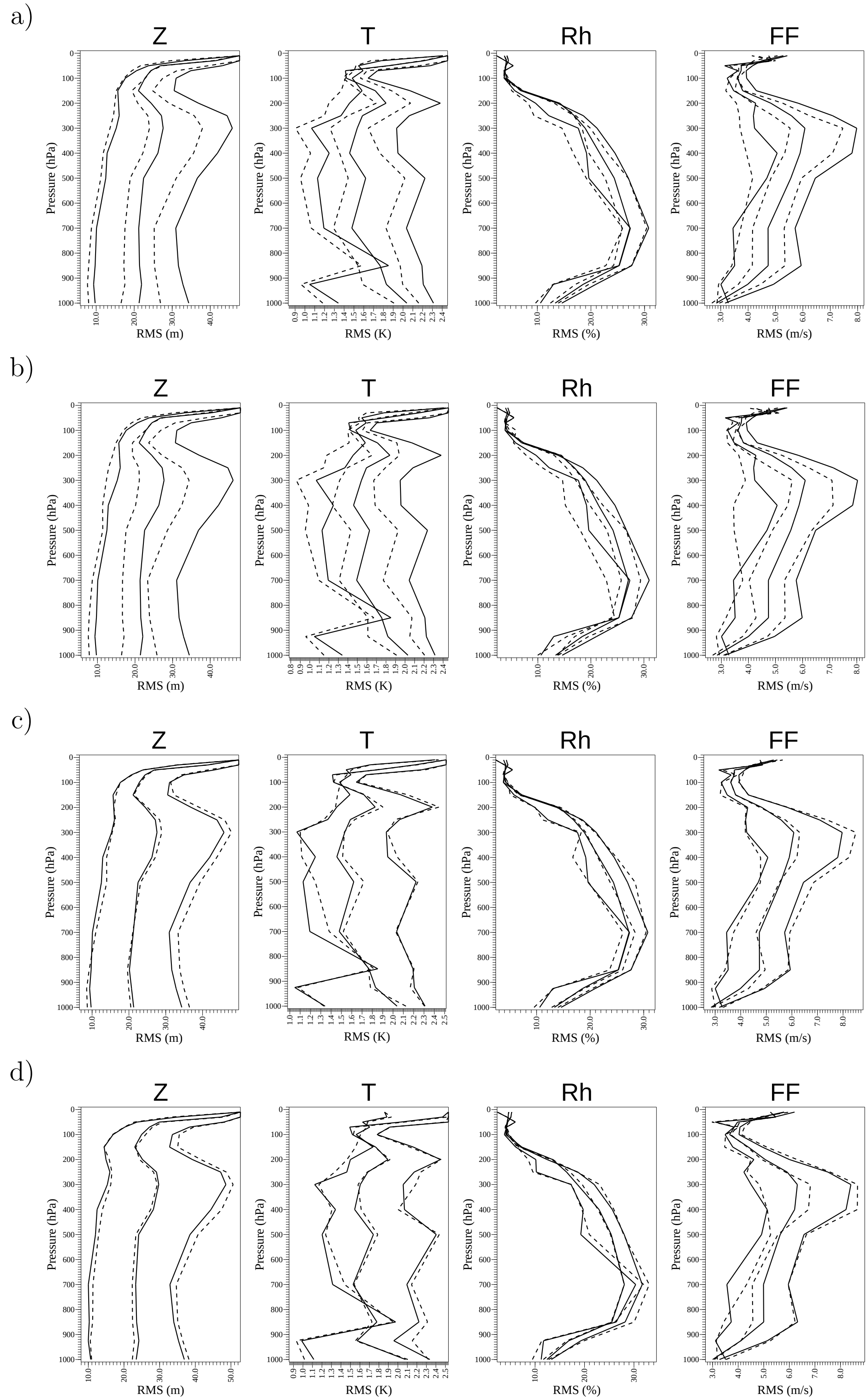


Figure 6: WINTER PERIOD. Vertical profiles of RMS error for forecast lengths (+6h, +24h, +48h). Same scenarios as in figure 5.

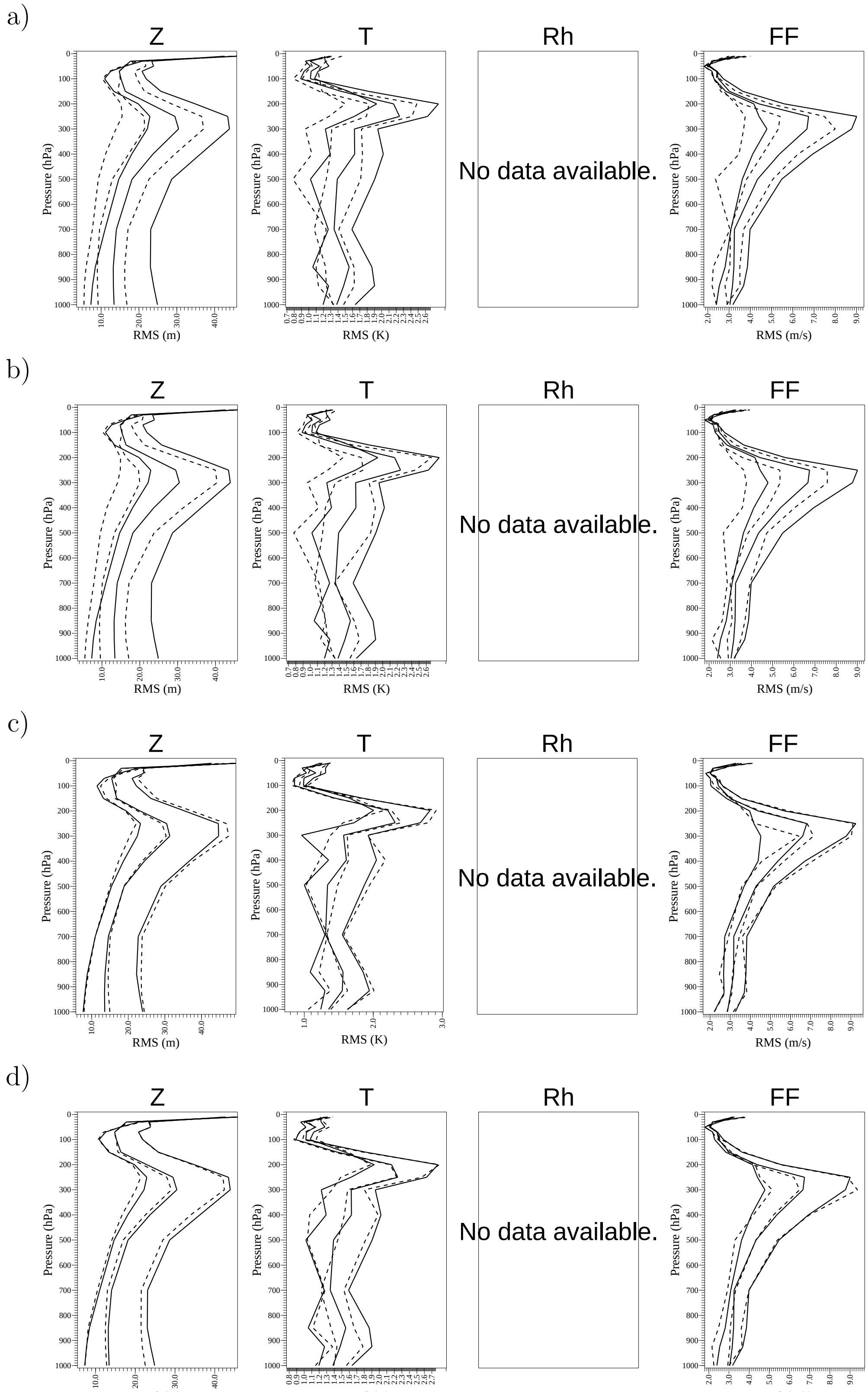


Figure 7: SUMMER PERIOD. Vertical profiles of RMS error for forecast lengths (+6h, +24h, +48h). Same scenarios as in figure 5. Unfortunately, RH information is missing for the summer period.

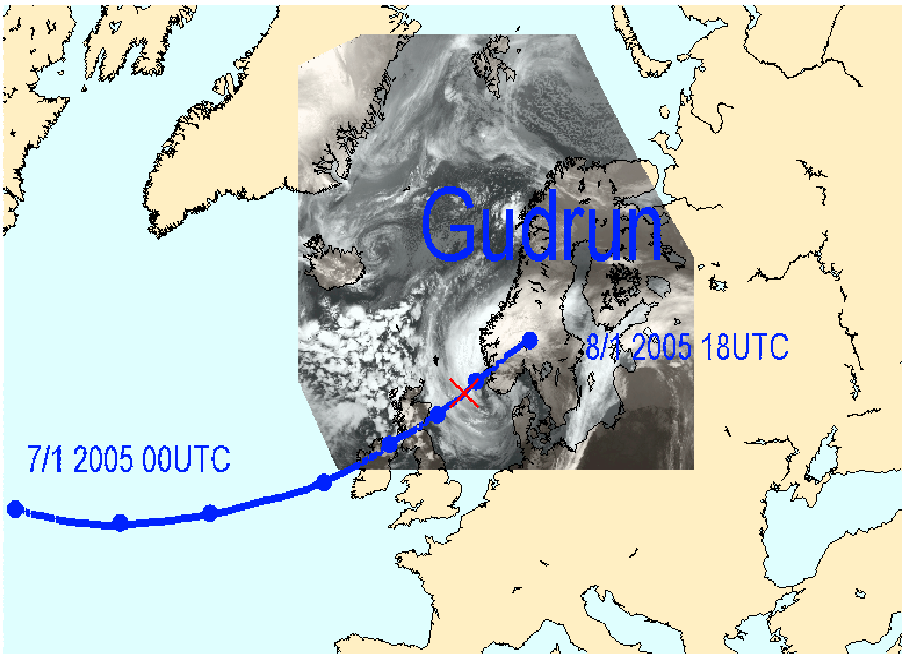


Figure 8: The track of the Scandinavian storm "Gudrun". The positions of the low pressure centre are indicated with blue dots at 6 hours intervals. The satellite image is valid at 11:40UTC on the 8th of January, and the position of the storm at that time is indicated with the red cross.

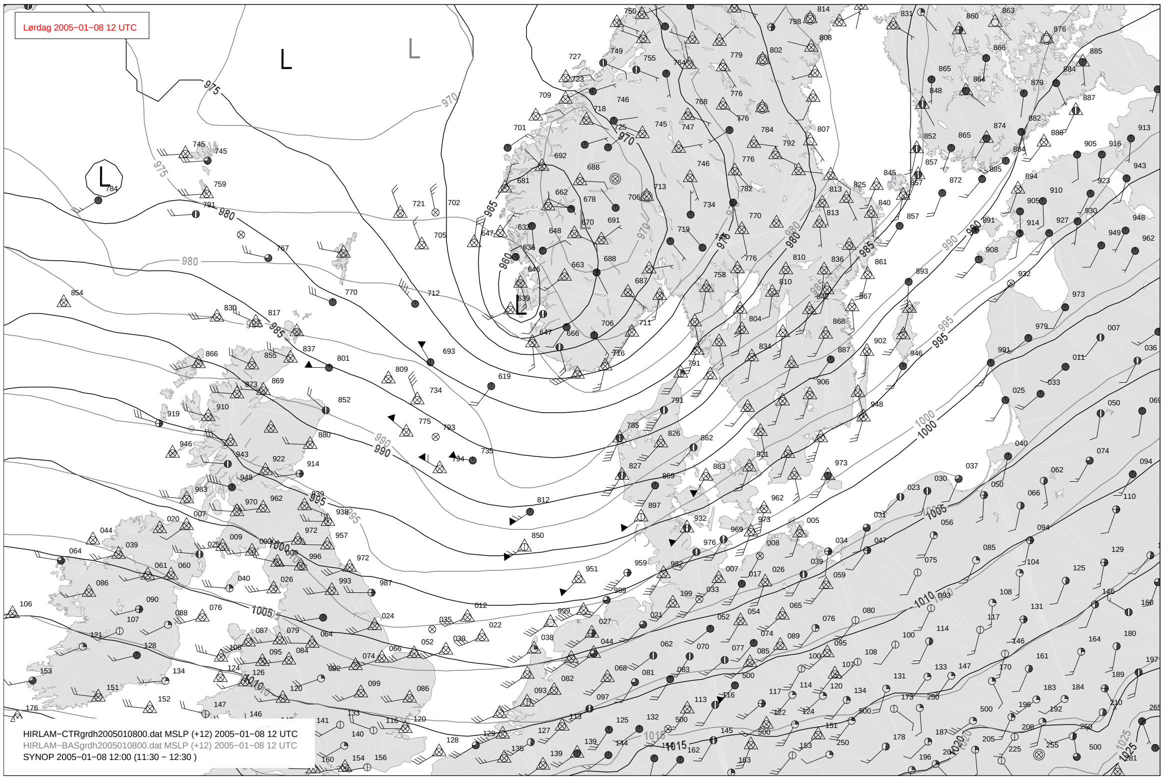


Figure 9: Forecast valid at 20050108 12UTC. Scenario 1 (BAS) in grey, Scenario 8 (CTR) in black.

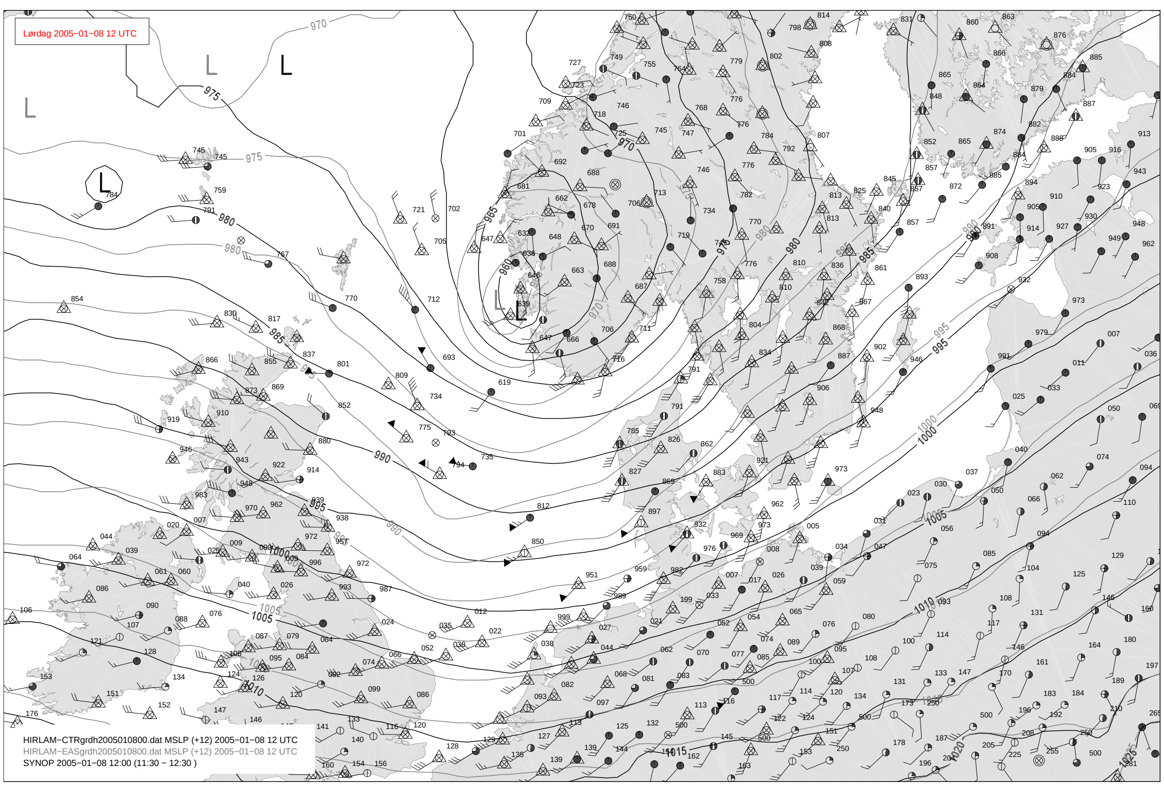


Figure 10: Forecast valid at 20050108 12UTC. Scenario 10 (Add E-ASAP incl Mike and Ekofisk, EAS) in grey, Scenario 8 (CTR) in black.

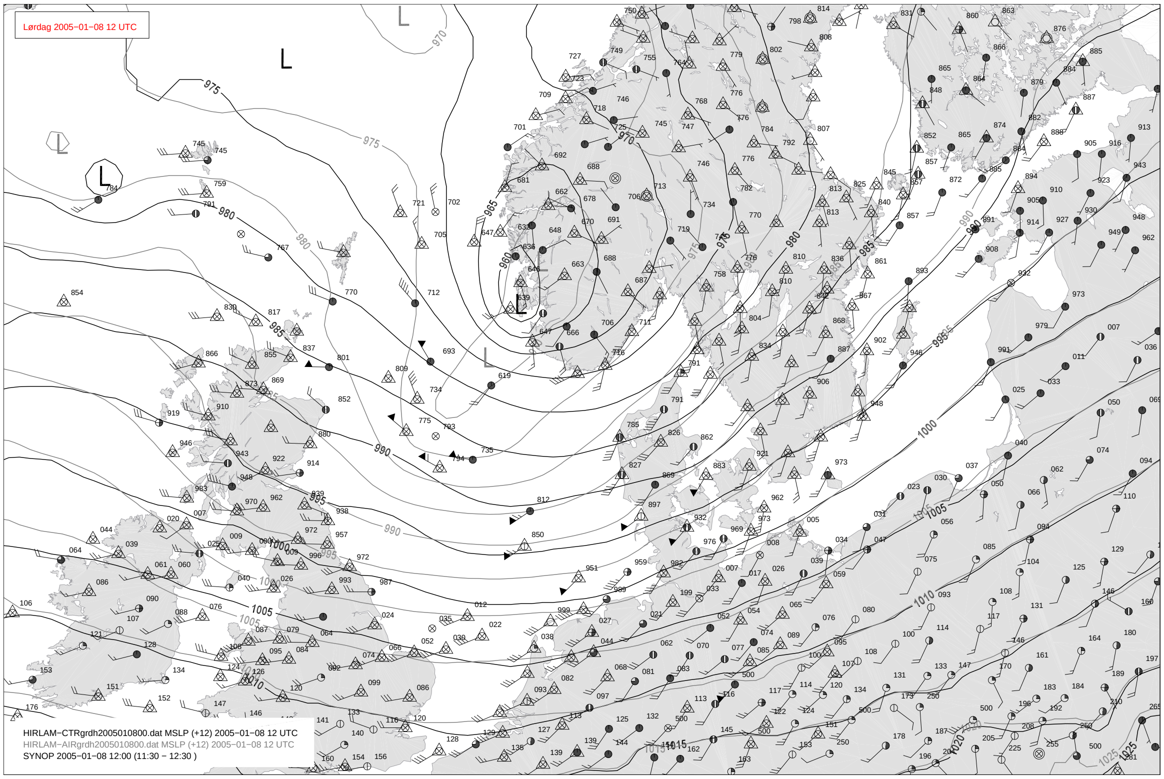


Figure 11: Forecast valid at 20050108 12UTC. Scenario 2 (Add AIREPs) in grey, Scenario 8 (CTR) in black.

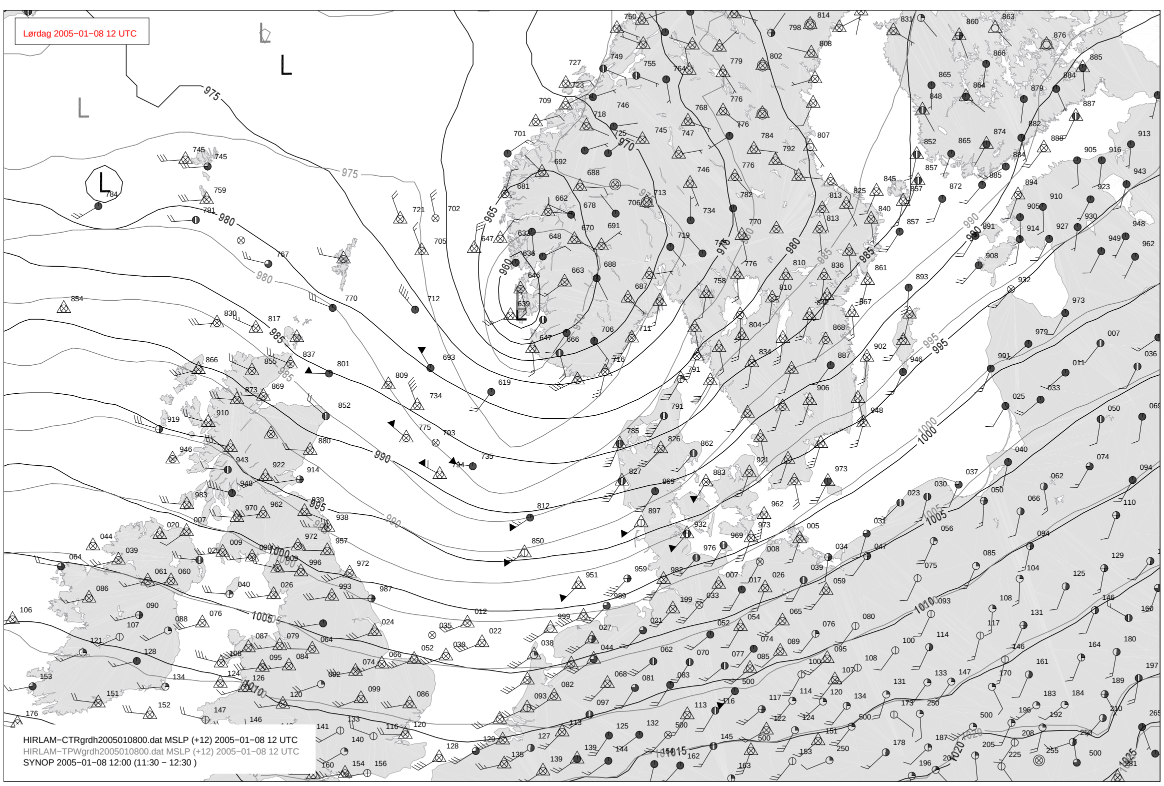


Figure 12: Forecast valid at 20050108 12UTC. Scenario 3 (Add Radiosonde Wind) in grey, Scenario 8 (CTR) in black.

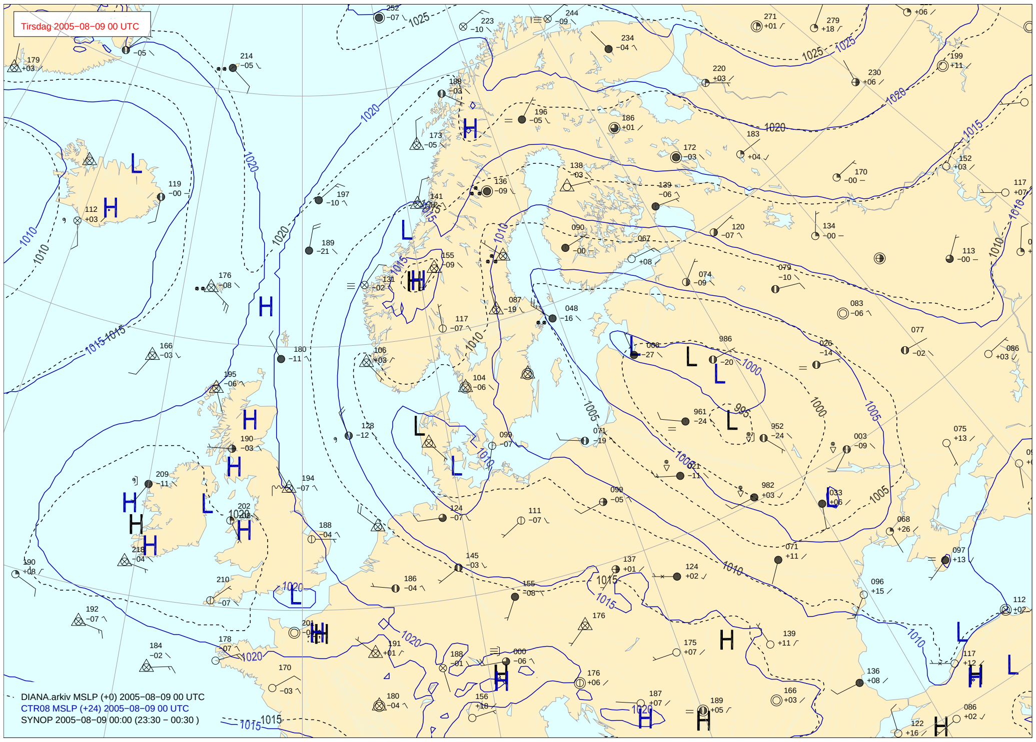


Figure 13: 24 hours forecast valid at 20050809 00UTC. Control. Solid lines: Sea level pressure. Dashed: Forecaster's pressure analysis. Some observations also included.

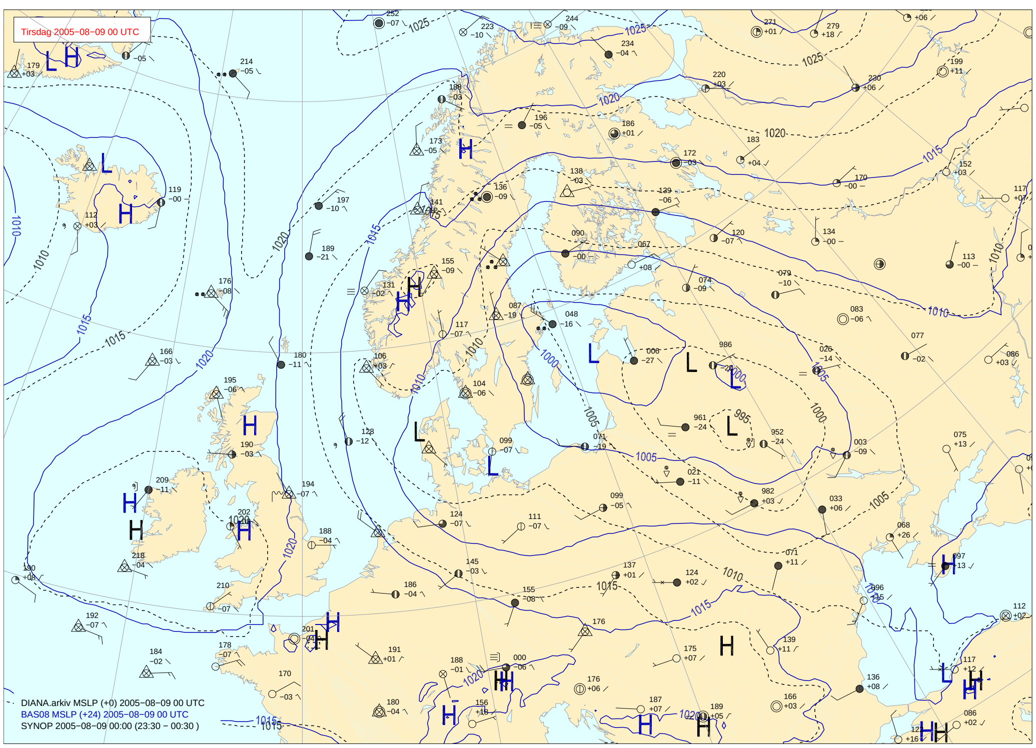


Figure 14: 24 hours forecast valid at 20050809 00UTC. Baseline. Solid lines: Sea level pressure. Dashed: Forecaster's pressure analysis. Some observations also included.

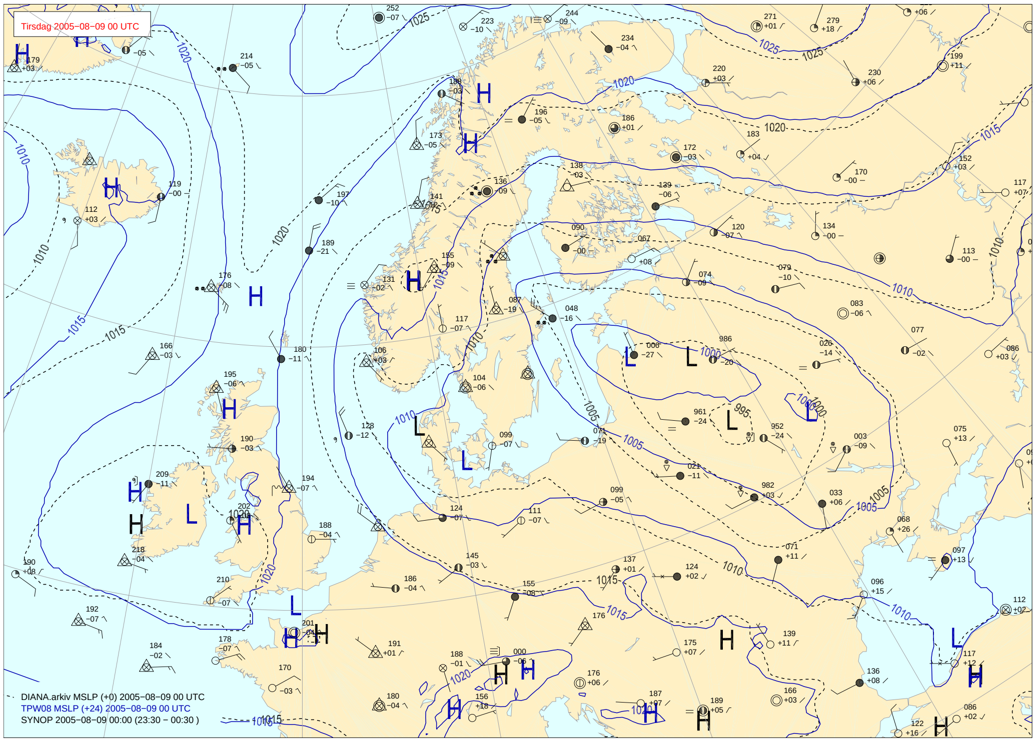


Figure 15: 24 hours forecast valid at 20050809 00UTC. Scenario 3: Baseline, add radiosonde wind. Solid lines: Sea level pressure. Dashed: Forecaster's pressure analysis. Some observations also included.

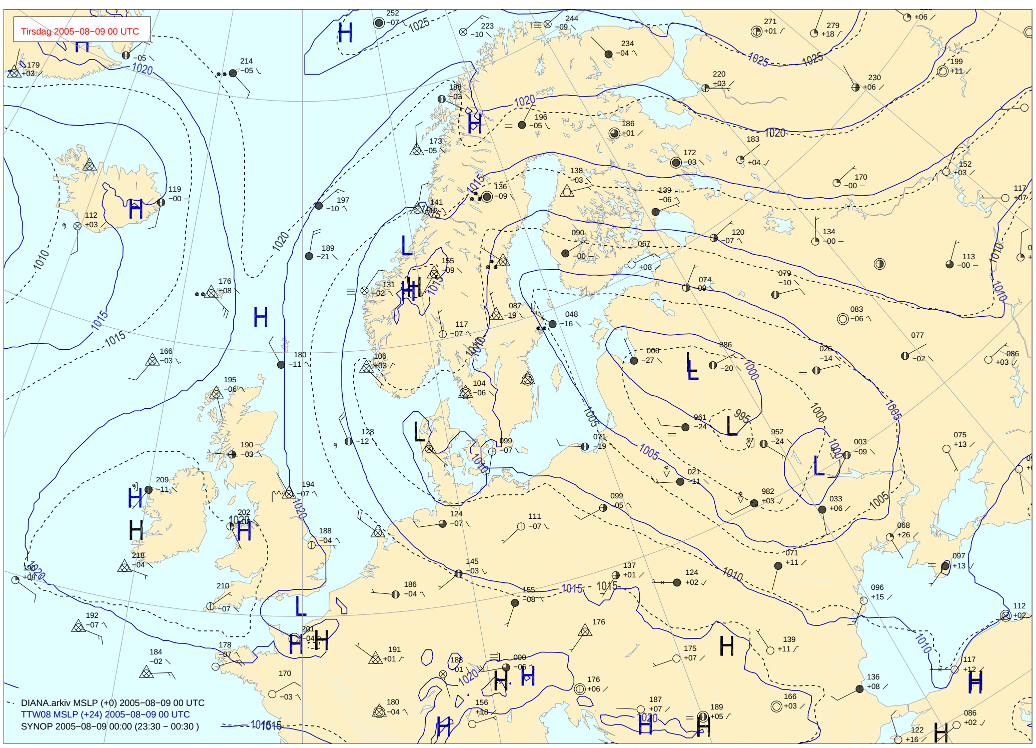


Figure 16: 24 hours forecast valid at 20050809 00UTC. Scenario4: Baseline, add radiosonde wind and temperature. Solid lines: Sea level pressure. Dashed: Forecaster's pressure analysis. Some observations also included.

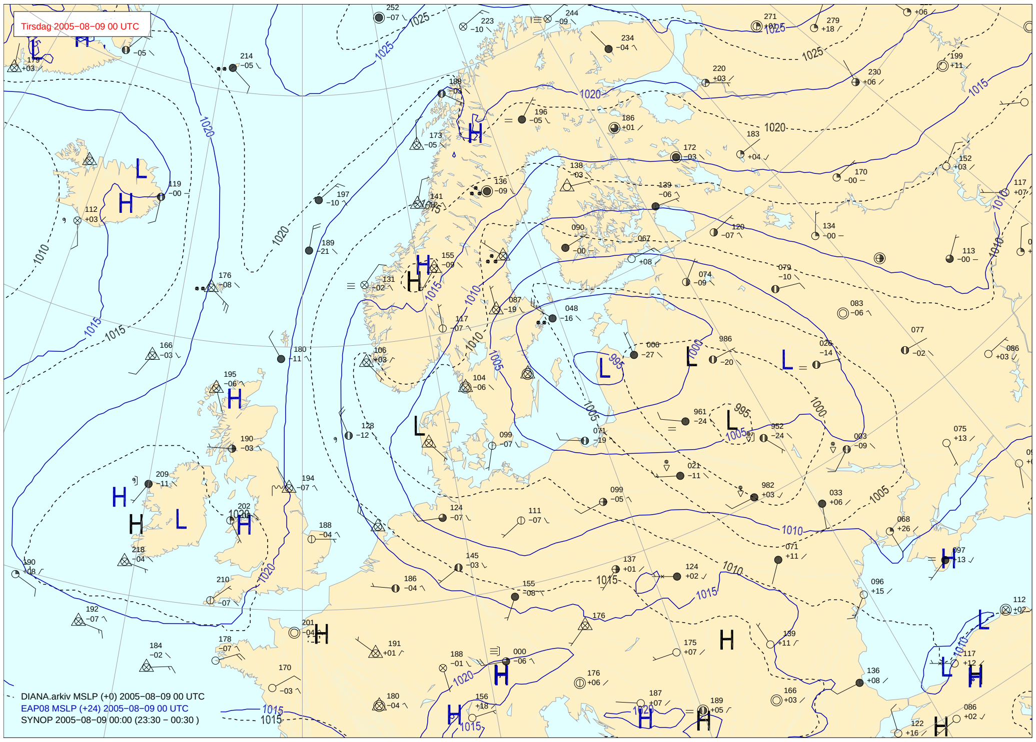


Figure 17: 24 hours forecast valid at 20050809 00UTC. Scenario 9: Baseline, add E-ASAP ships. Solid lines: Sea level pressure. Dashed: Forecaster's pressure analysis. Some observations also included.

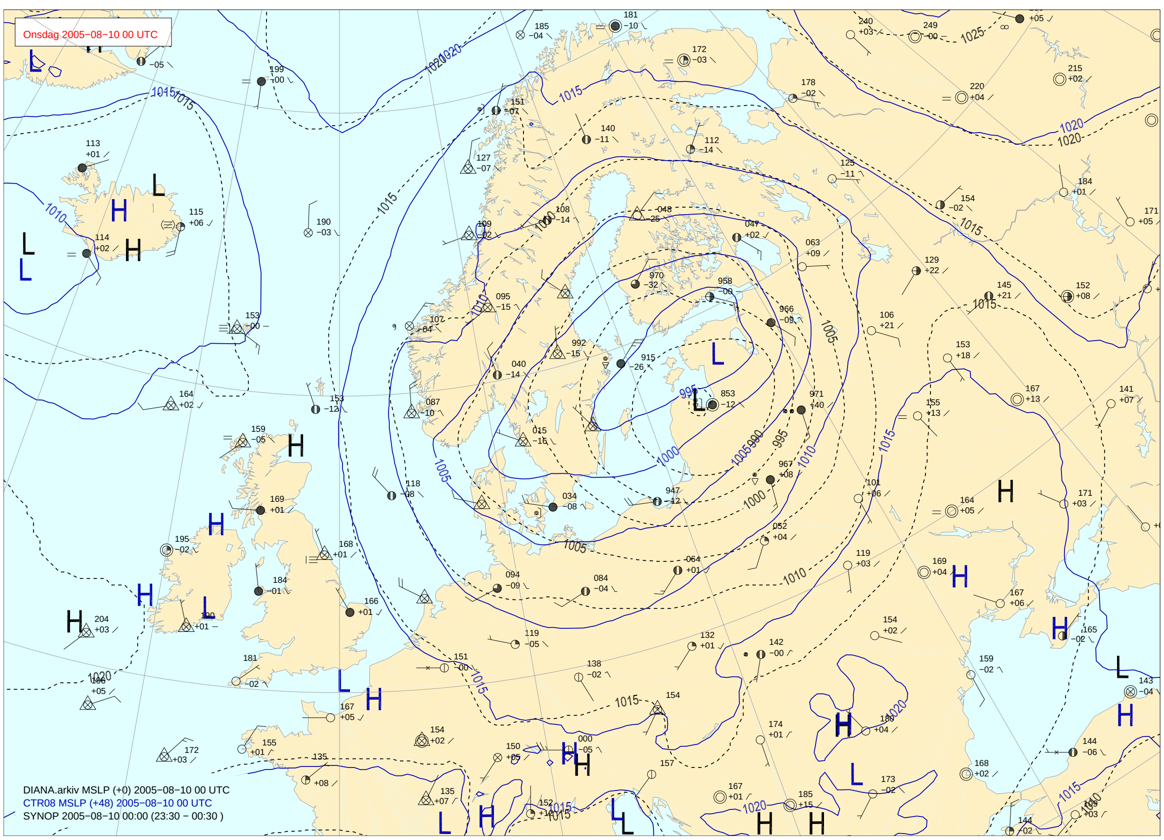


Figure 18: 48 hours forecast valid at 20050810 00UTC. Control scenario. Solid lines: Sea level pressure. Dashed: Forecaster's pressure analysis. Some observations also included.

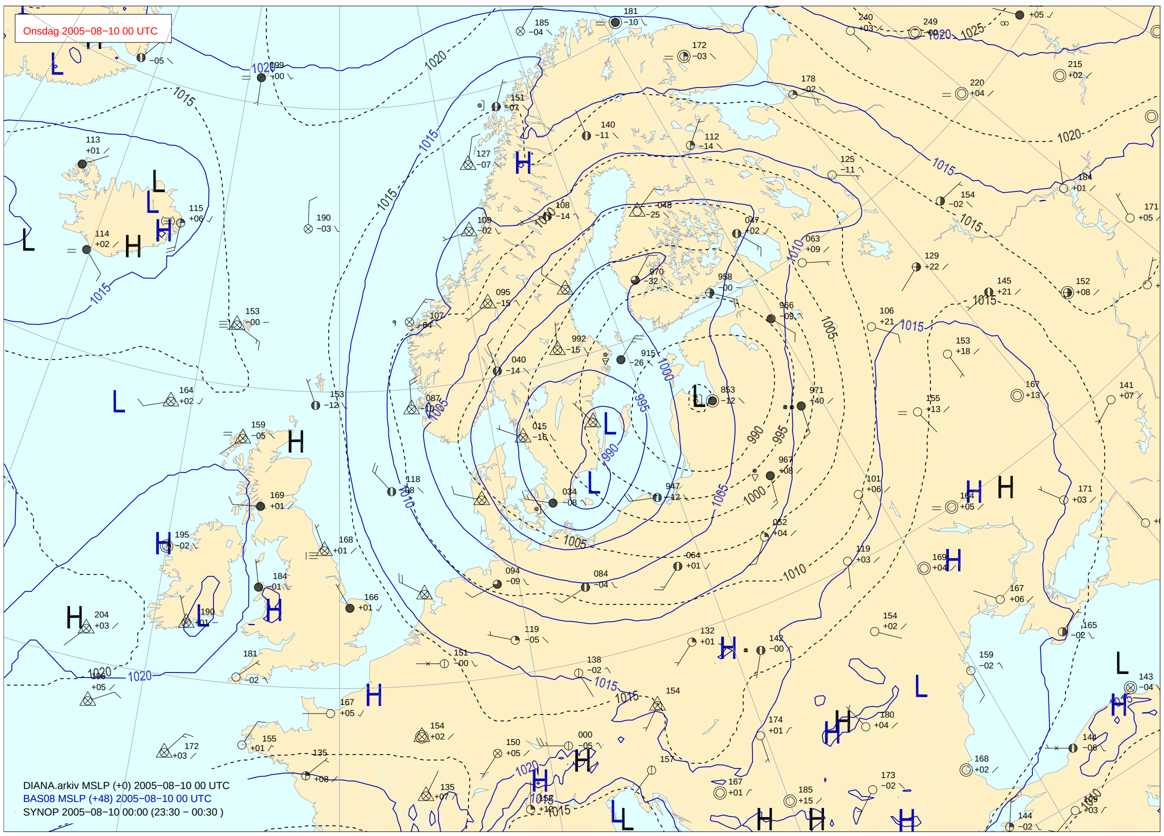


Figure 19: 48 hours forecast valid at 20050810 00UTC. Baseline scenario. Solid lines: Sea level pressure. Dashed: Forecaster's pressure analysis. Some observations also included.

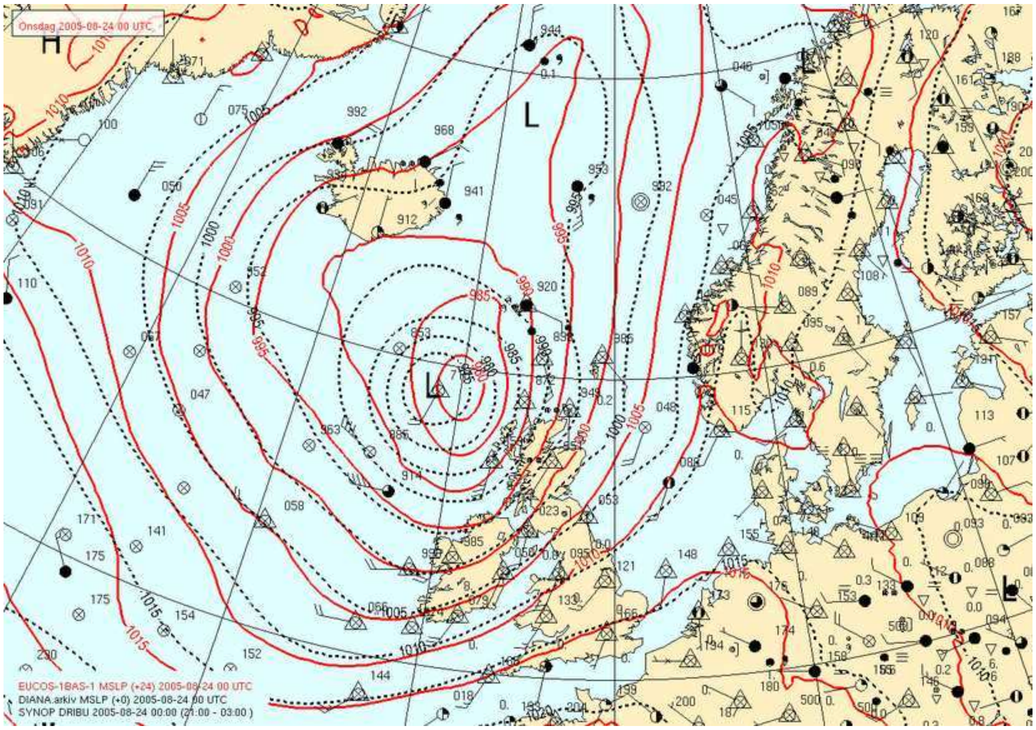


Figure 20: Baseline experiment: 24 hours forecast valid at 20050824 00UTC. Solid lines: Sea level pressure. Dashed: Forecaster's pressure analysis. Some observations also included.

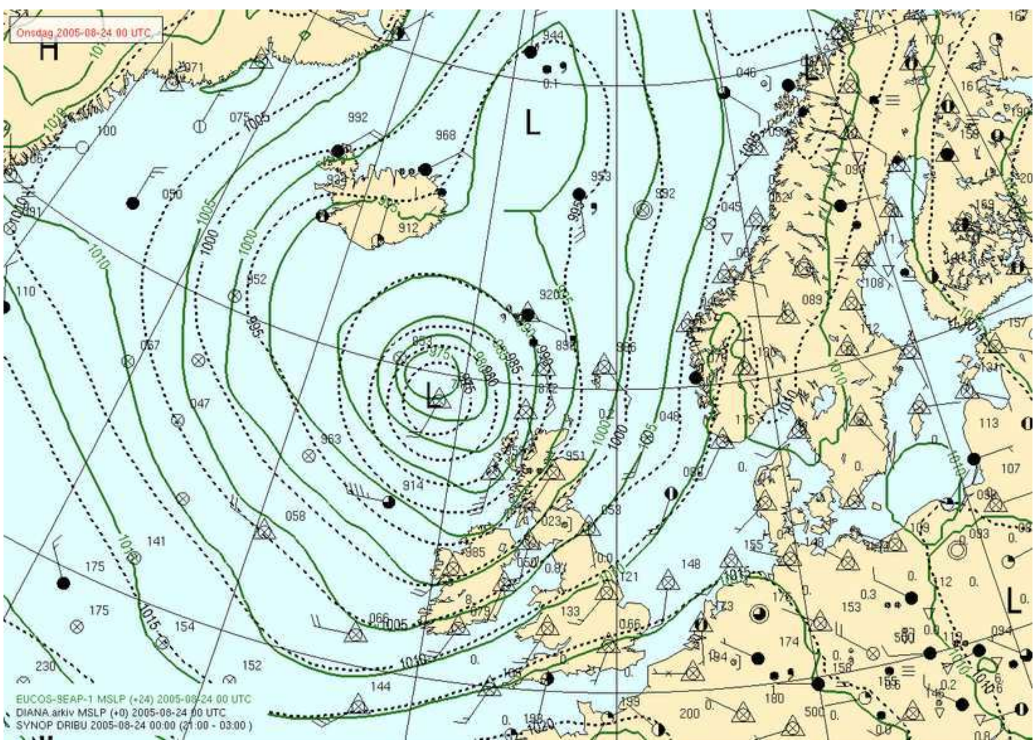


Figure 21: Experiment 9, added E-ASAP ships to baseline: 24 hours forecast valid at 20050824 00UTC. Solid lines: Sea level pressure. Dashed: Forecaster's pressure analysis. Some observations also included.

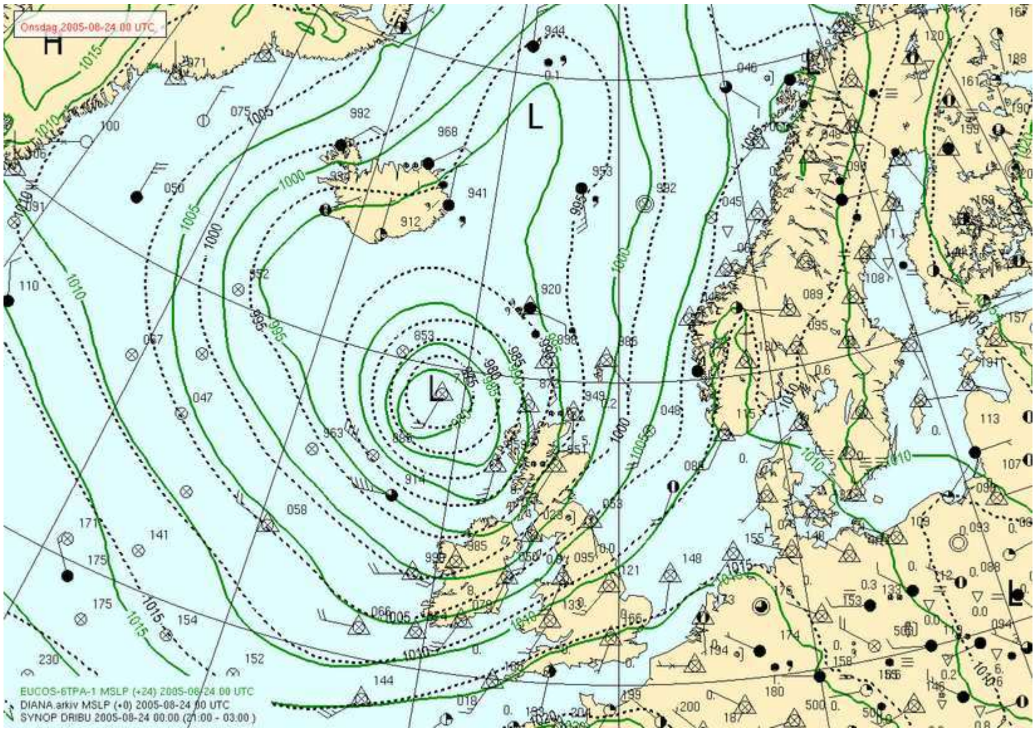


Figure 22: Experiment 6, added radiosonde wind and temperature and aircraft to baseline: 24 hours forecast valid at 20050824 00UTC. Solid lines: Sea level pressure. Dashed: Forecaster's pressure analysis. Some observations also included.

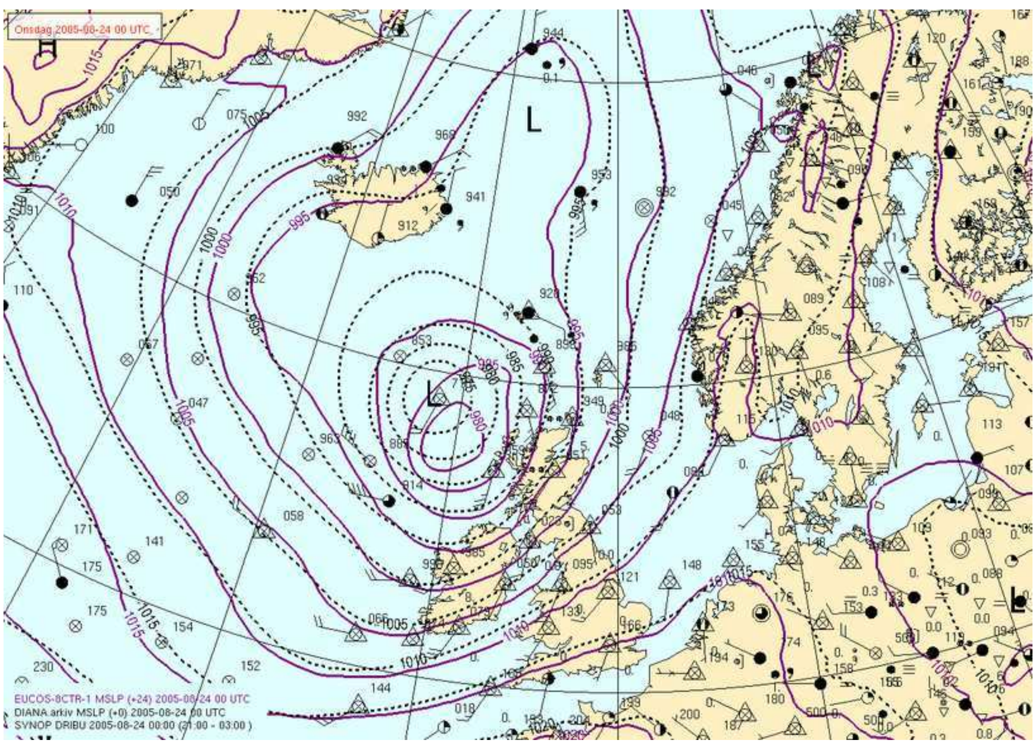


Figure 23: Control experiment: 24 hours forecast valid at 20050824 00UTC. Solid lines: Sea level pressure. Dashed: Forecaster's pressure analysis. Some observations also included.

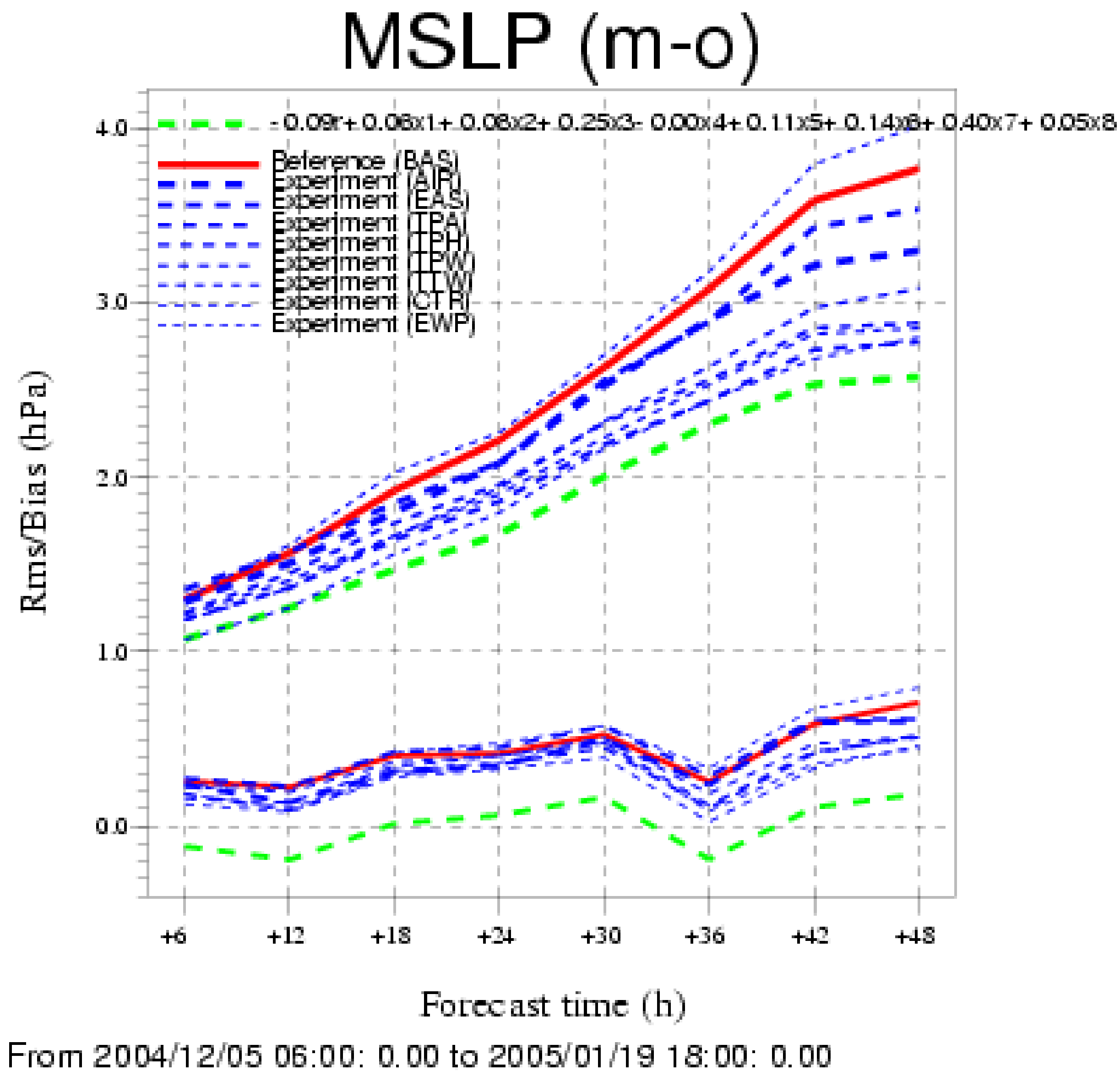


Figure 24: WINTER PERIOD, RMS error (upper curves) and Bias (lower curves) of MSLP as a function of forecast length. Baseline (Solid red line) vs All EUCOS Scenarios (dashed blue lines). The different EUCOS scenarios are, from the top: Scenario 1 (BAS - Baseline), scenario 2 (AIR - Add aircraft), scenario 9 (EAS - Add E-ASAP network, incl MIKE,EKOFISK), scenario 6 (TPA - aircraft + radiosonde wind+temp), scenario 7 (TPH - radiosonde wind+temp+hum), scenario 3 (TPW - radiosonde wind), scenario 4 (TTW - radiosonde wind+temp), scenario 8 (CTR - Control, the full system), and scanario 5 (EWP - add wind profilers). The dashed green line is the optimal combination of all the experiments.

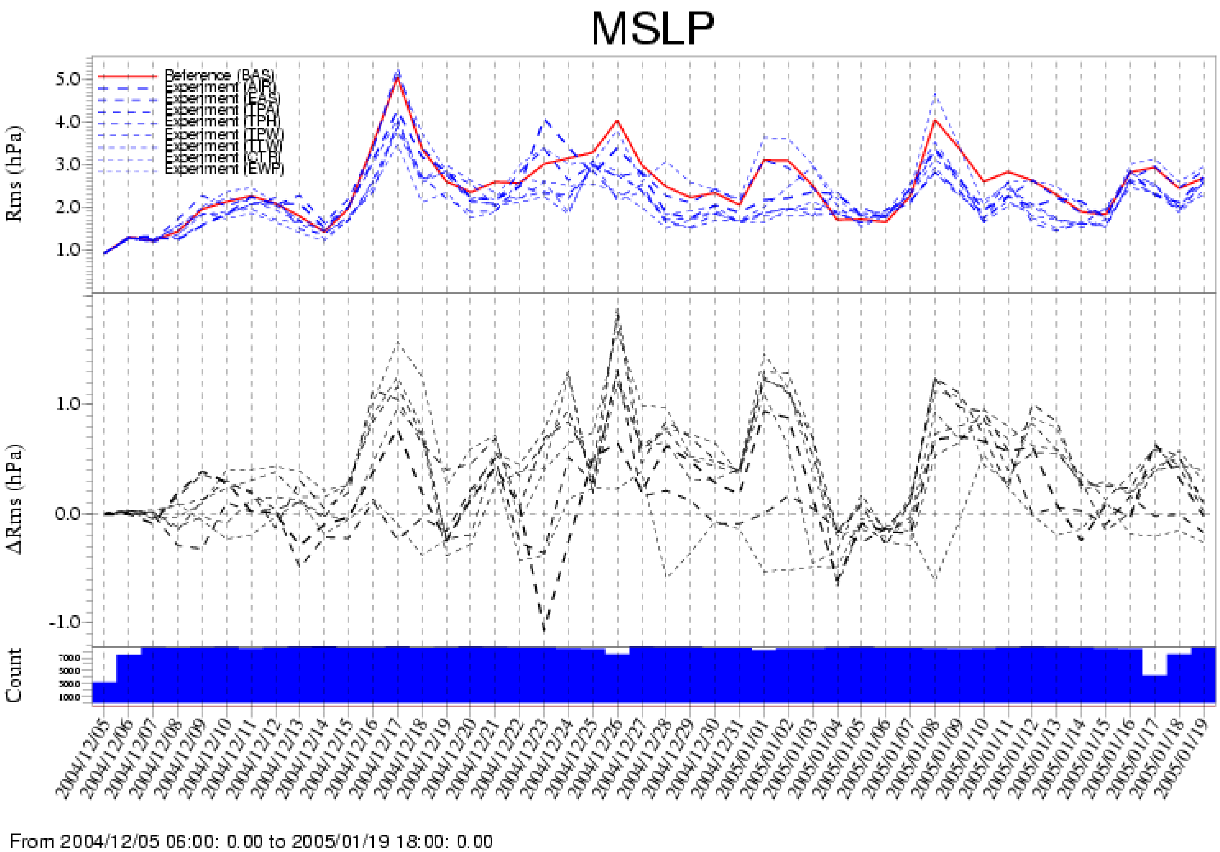
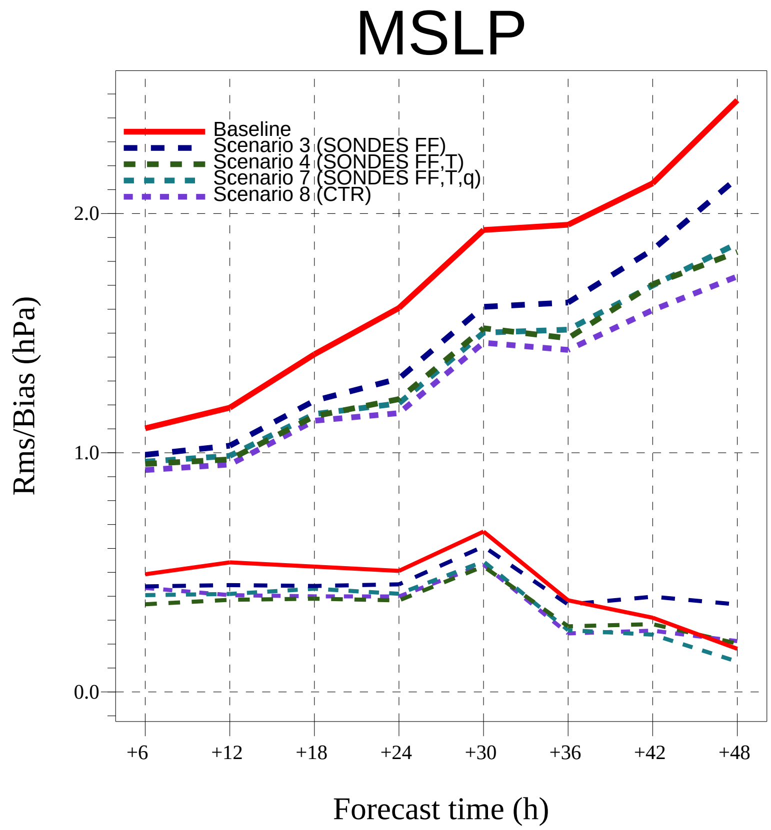


Figure 25: WINTER PERIOD: Time series of the daily contribution to the errors in MSLP (upper panel), and the difference in RMS between the Baseline and the 8 EUCOS scenarios (lower panel). To score better than the Baseline, the experiment curves should be below the solid red line in the upper panel, and correspondingly on the positive side in the lower panel. See fig 3 for further details on the different EUCOS scenarios.



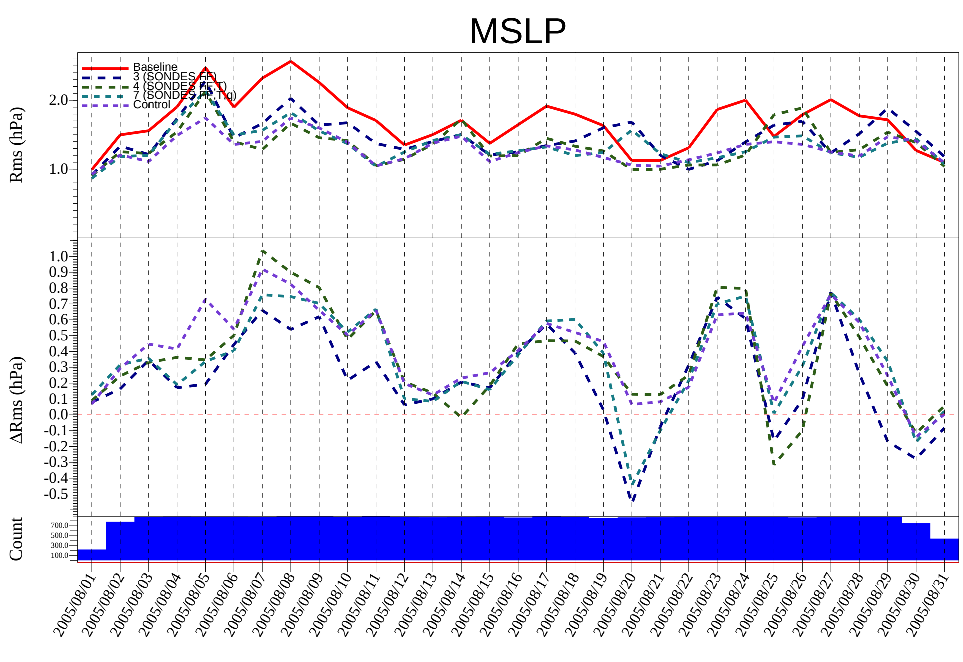


Figure 26: SUMMER PERIOD experiments with Radiosondes. Baseline (Solid red line) vs Scenario 3-Sondes FF (Blue), 4-Sondes FF,T (dark green line), 7-Sondes FF,T,q (light green) and Control (purple). TOP: RMS error and Bias of MSLP as a function of forecast length. BOTTOM: Time series of the daily contribution to the errors in MSLP.

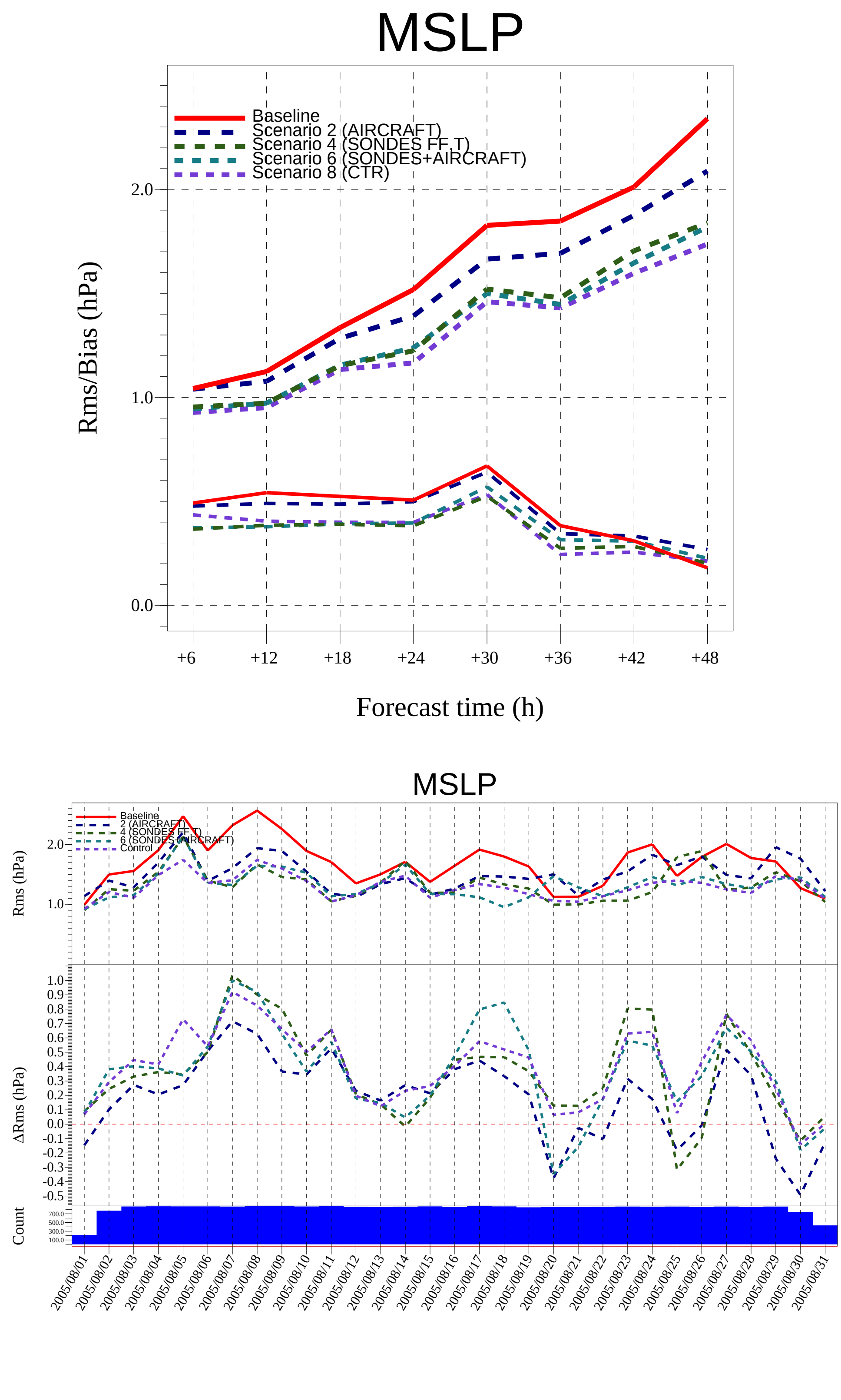
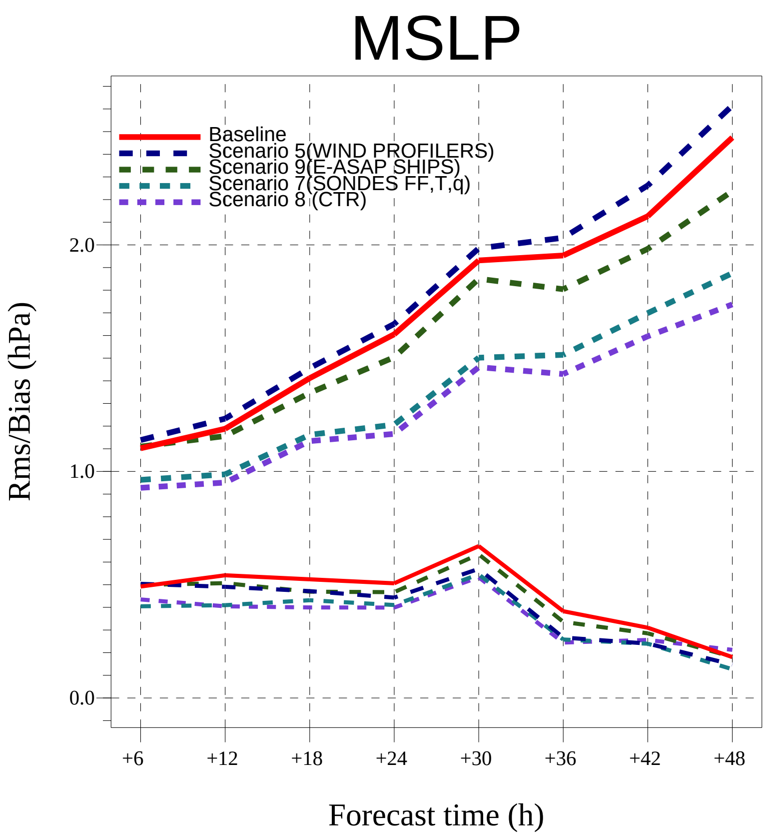


Figure 27: SUMMER PERIOD experiments with Aircraft data (AIREPS/AMDARS). Baseline (Solid red line) vs Scenario 2-Aircraft (Blue), 4-Sondes FF,T (dark green line), 6-Sondes+Aircraft (light green) and Control (purple).



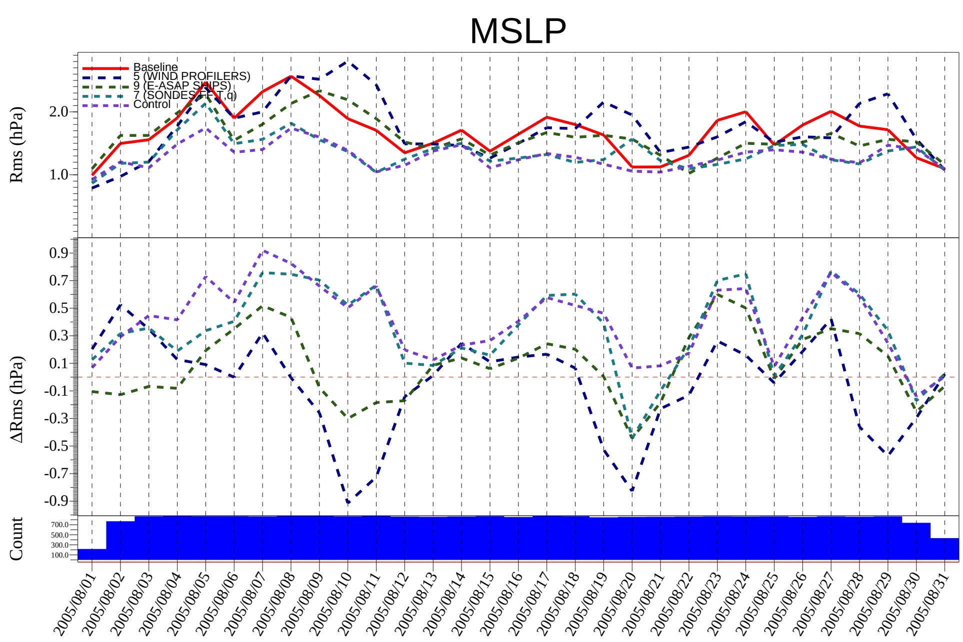


Figure 28: SUMMER PERIOD experiments with E-ASAPs and Wind Profilers. Baseline (Solid red line) vs Scenario 5-EWPs (Blue), 9-E-ASAPs (dark green line), 7-Sondes FF,T,q (light green) and Control (purple).

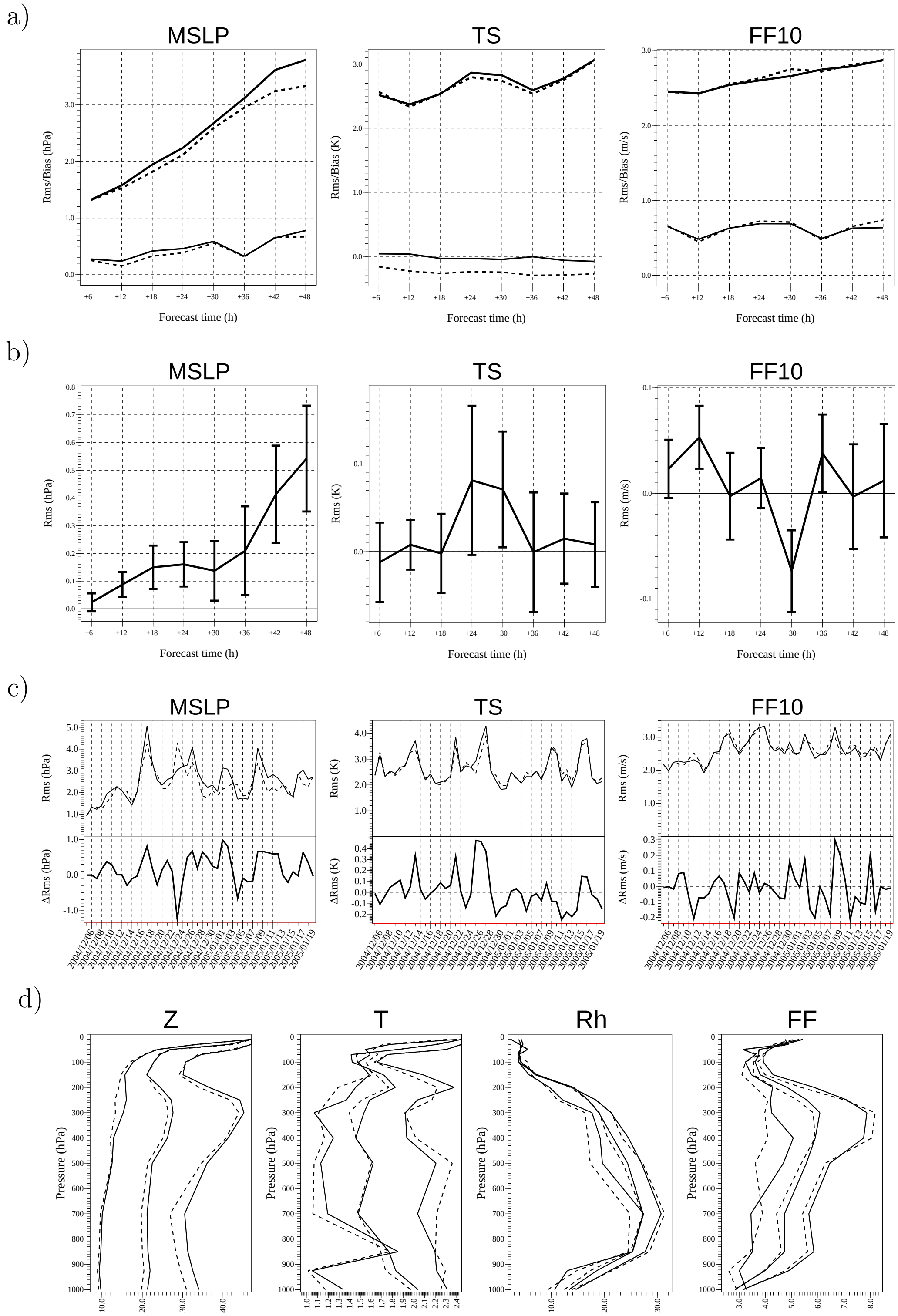


Figure 29: WINTER PERIOD Scenario 2 - Add Aircraft data (dashed) compared to Baseline (solid). a) RMS error and Bias as a function of forecast length. b) Mean RMS error difference (BAS-AIR). c) Time series of the daily contribution to the errors in MSLP, T2m and FF10. d) Vertical profiles of RMS error for forecast lengths (+6h, +24h, +48h). (Please note that the vertical axis of the significance plots (b) are opposite for the winter and summer period. This means that, for a scenario to score significantly better than the Baseline, the curve should be ABOVE zero for the winter period, and BELOW zero for the summer period.)

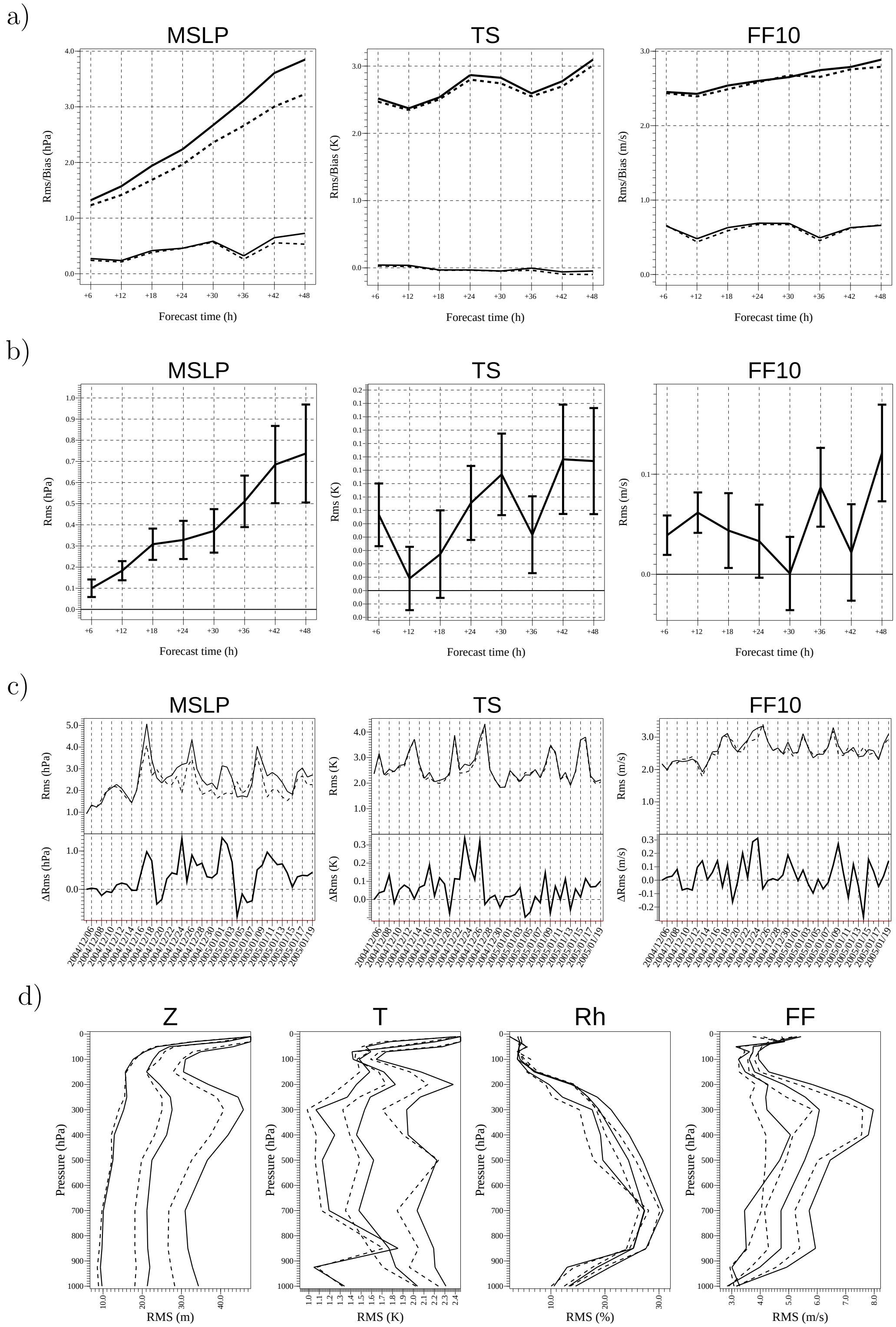


Figure 30: WINTER PERIOD Scenario 3 - Add Radiosonde Wind (dashed) compared to Baseline (solid). See figure 29 for further explaination.

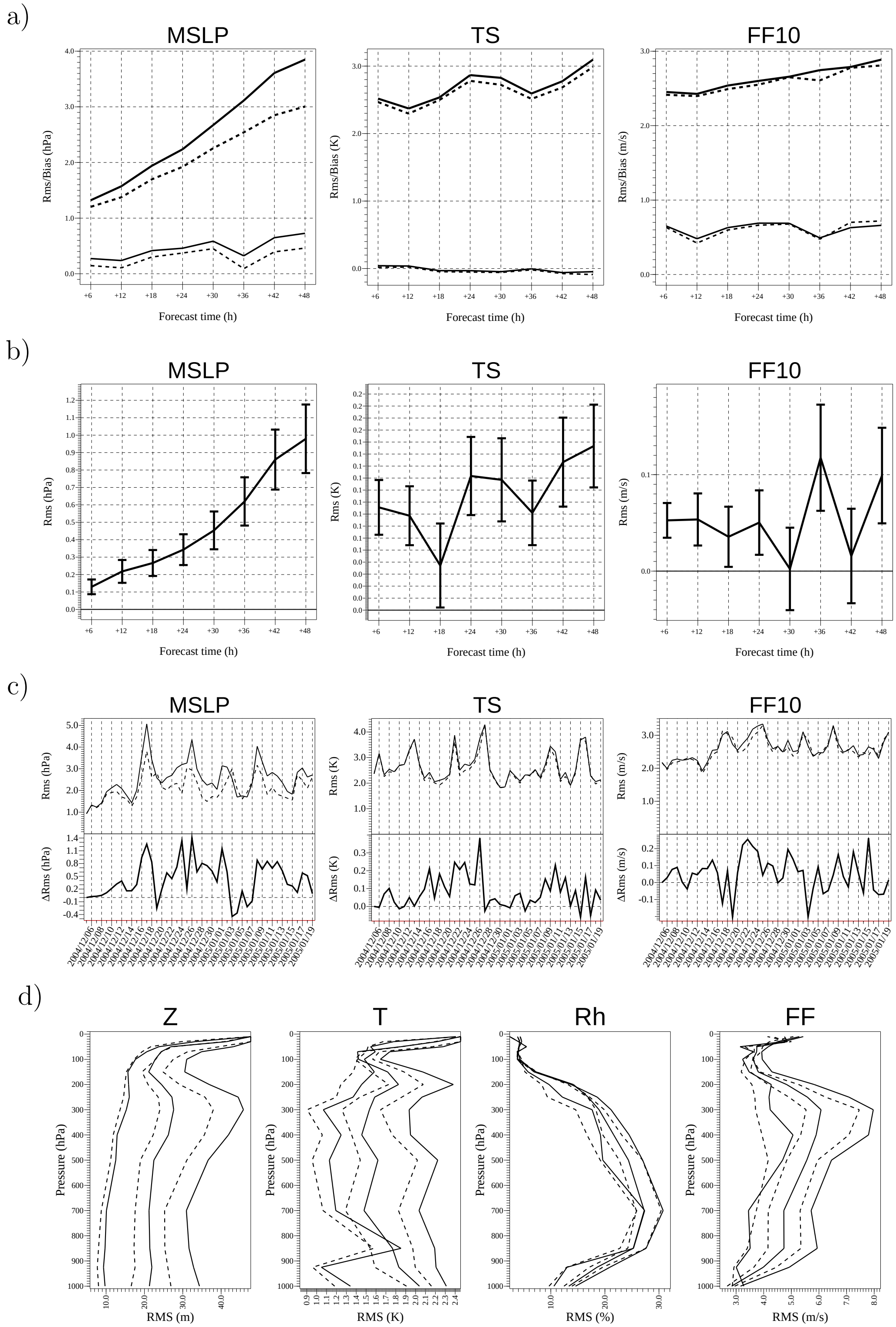


Figure 31: WINTER PERIOD Scenario 4 - Add Radiosonde Wind and Temperature (dashed) compared to Baseline (solid). See figure 29 for further explaination.

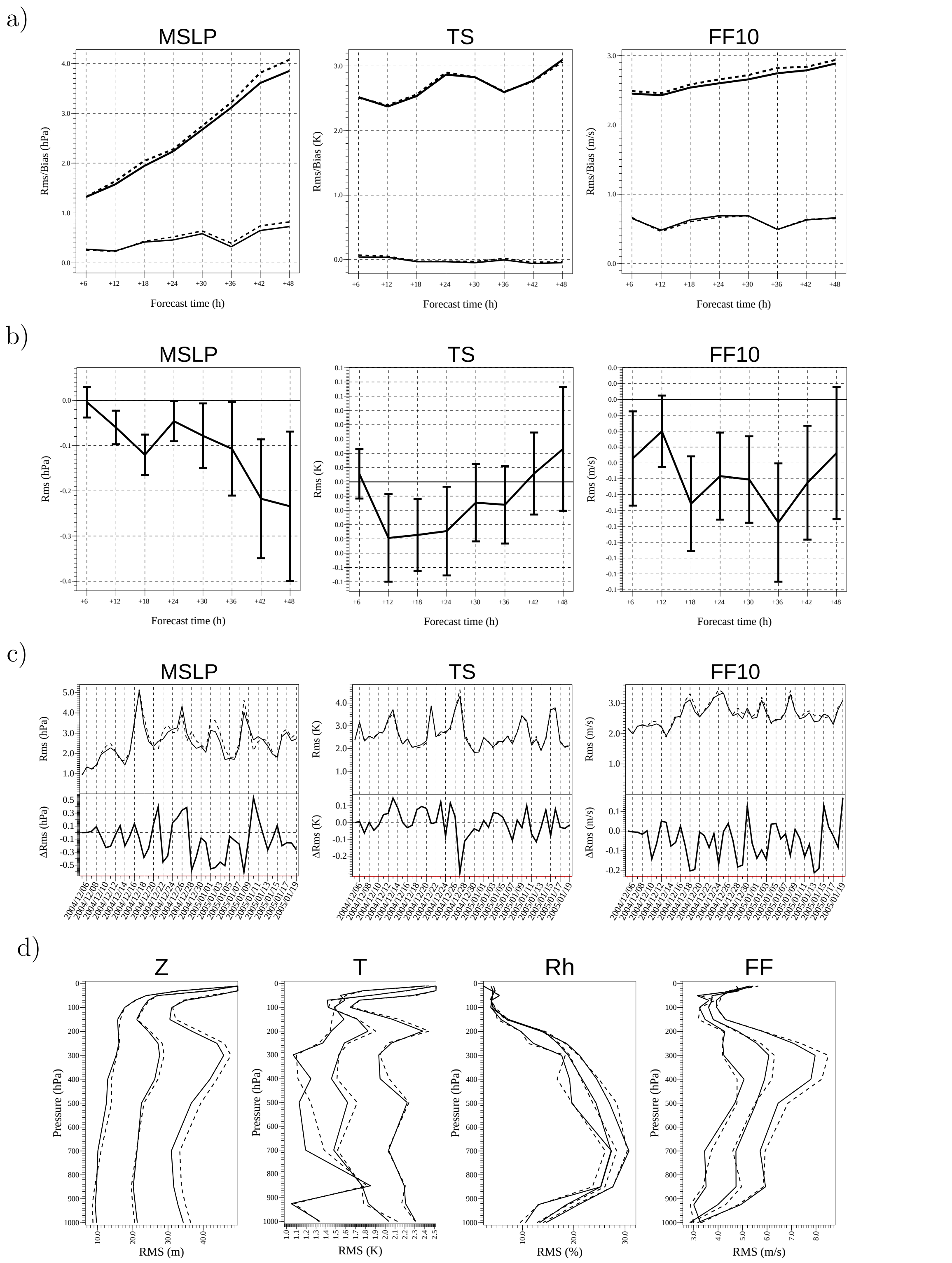


Figure 32: WINTER PERIOD Scenario 5 - Add Wind Profilers (dashed) compared to Baseline (solid). See figure 29 for further explaination

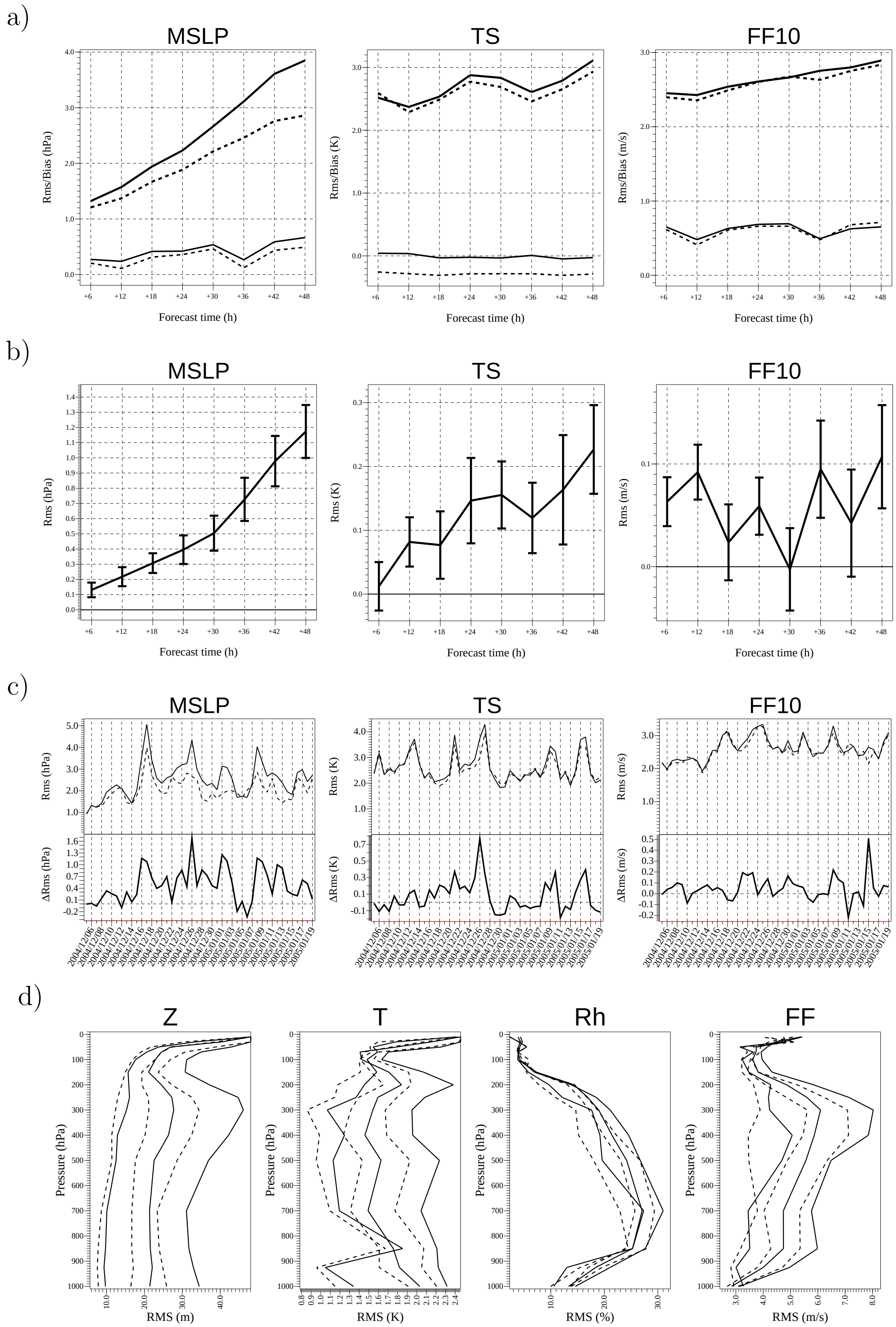


Figure 33: WINTER PERIOD Scenario 6 - Add Wind and Temperature from Aircraft and Radiosondes (dashed), compared to Baseline (solid). See figure 29 for further explaination

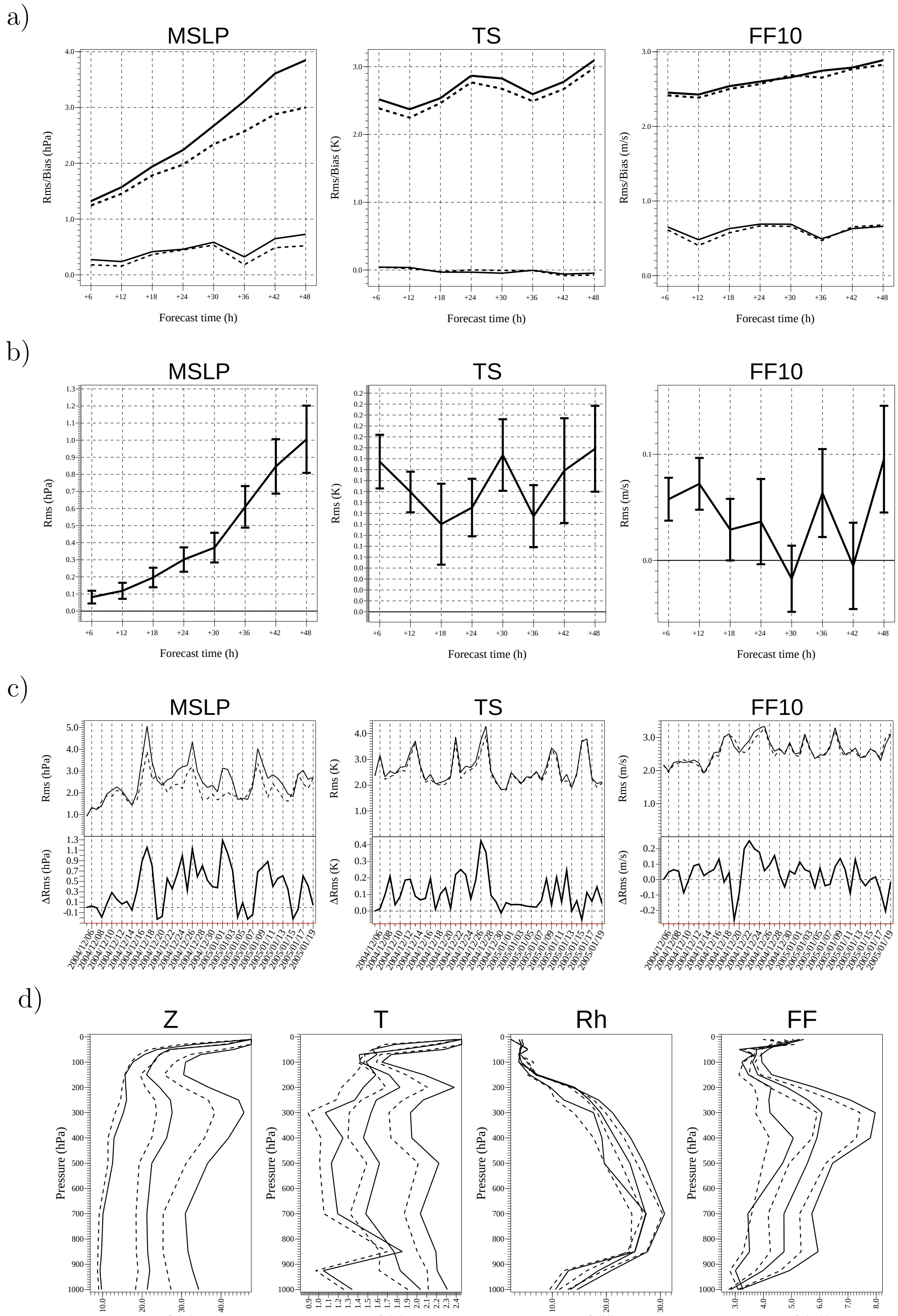


Figure 34: WINTER PERIOD Scenario 7 - Add Radiosond Wind, Temperature and Humidity (dashed), compared to Baseline (solid). See figure 29 for further explaination

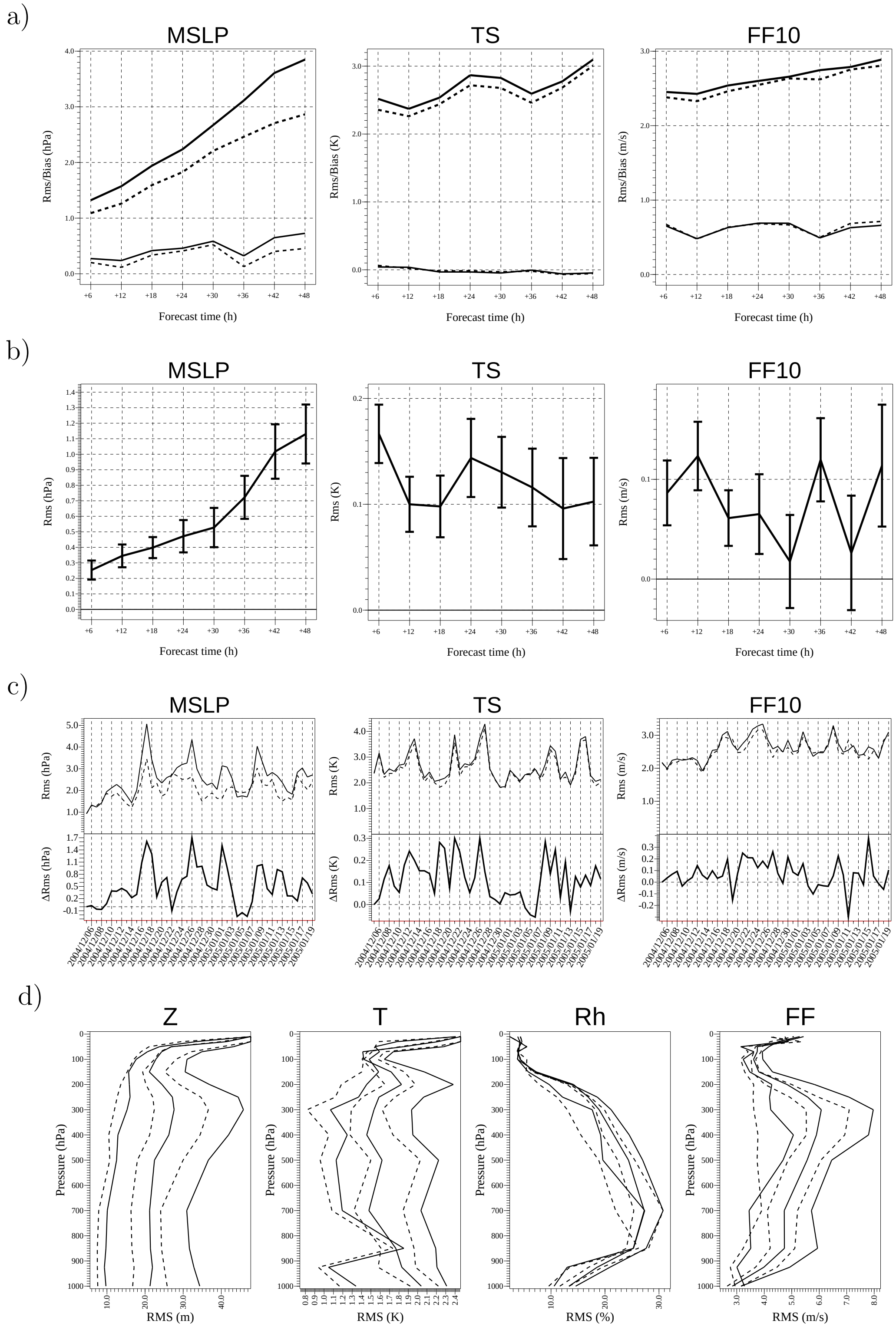


Figure 35: WINTER PERIOD Scenario 8 - the Contol experiment (dashed) compared to Baseline (solid). See figure 29 for details.

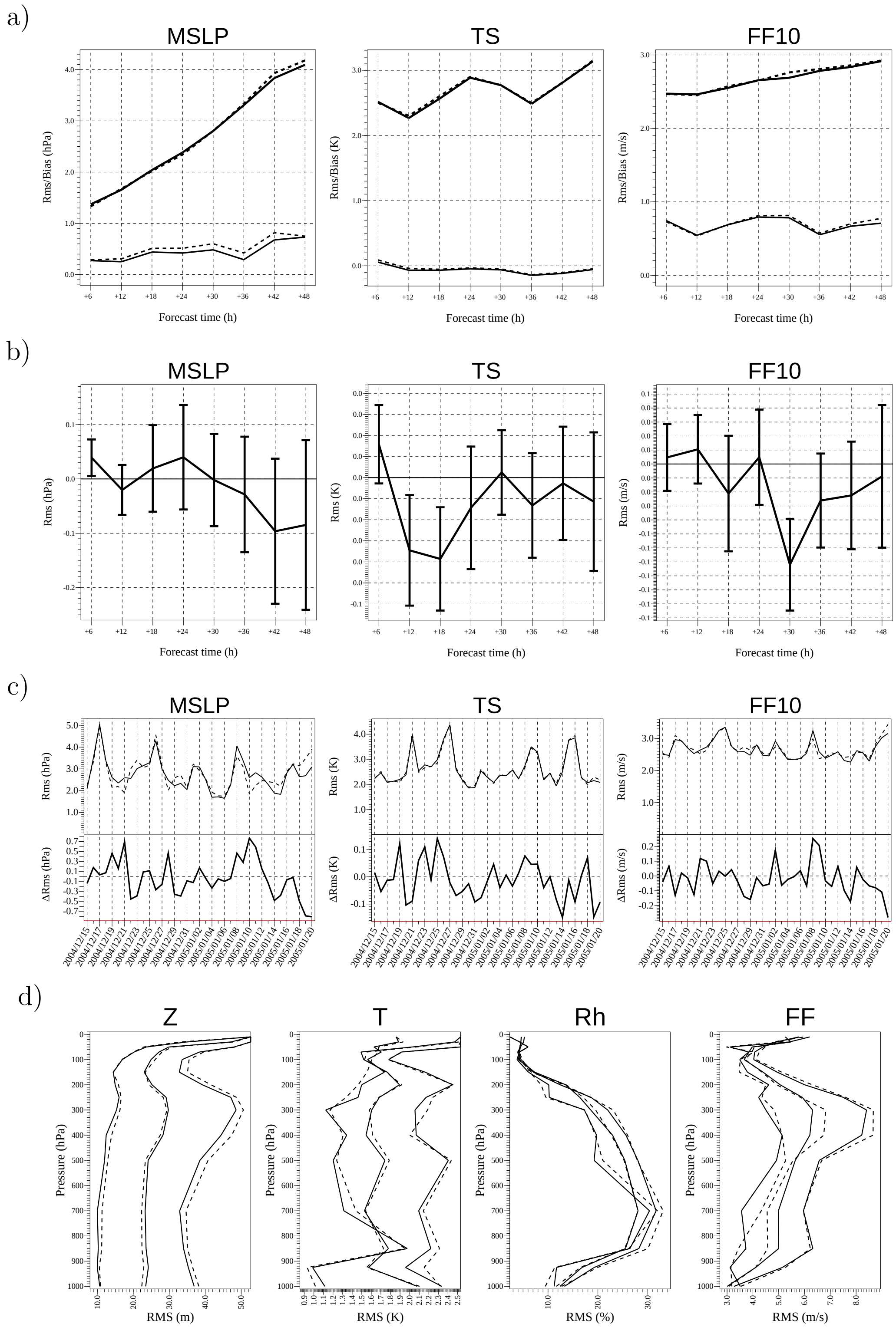


Figure 36: WINTER PERIOD Scenario 9 - Add E-ASAPs, ships only (dashed) compared to Baseline (solid). See figure 29 for details.

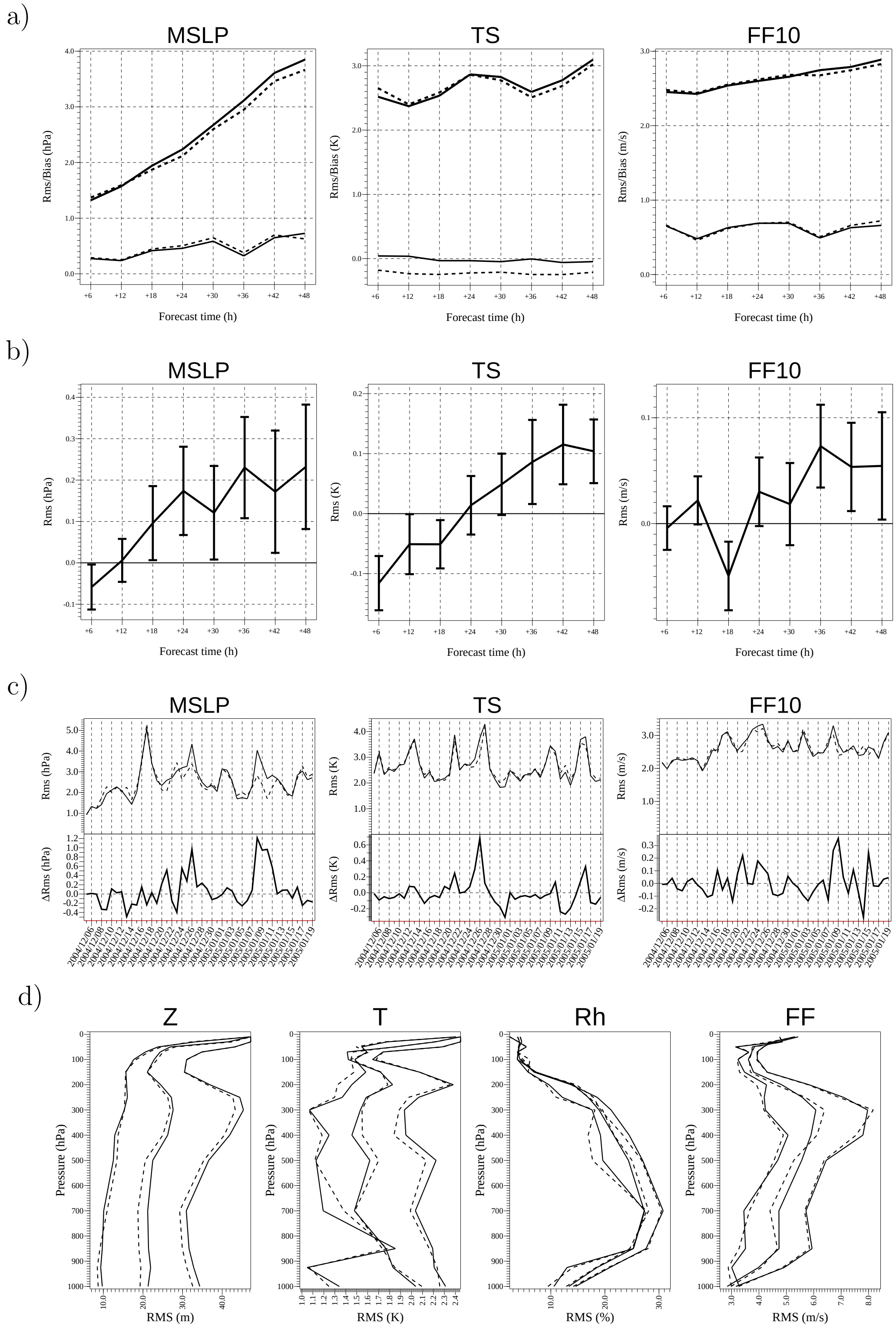


Figure 37: WINTER PERIOD Scenario 10 - Add E-ASAPs , incl. MIKE, EKOFISK (dashed) compared to Baseline (solid). See figure 29 for details.

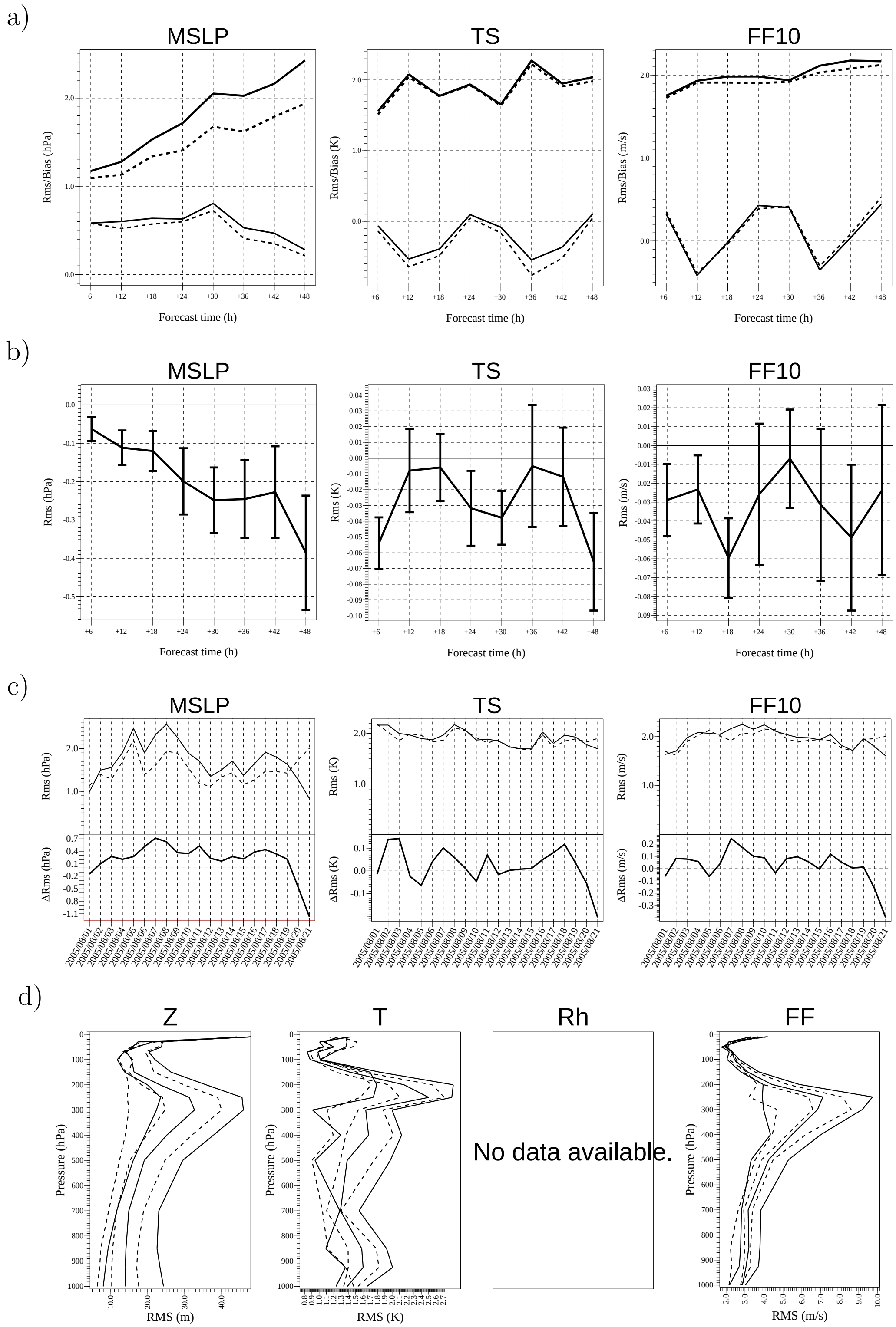


Figure 38: SUMMER PERIOD Scenario 2 - Add Aircraft data (dashed) compared to Baseline (solid). a) RMS error and Bias as a function of forecast length. b) Mean RMS error difference (AIR-BAS). c) Time series of the daily contribution to the errors in MSLP, T2m and FF10. d) Vertical profiles of RMS error for forecast lengths (+6h, +24h, +48h).(Please note that the vertical axis of the significance plots (b) are opposite for the winter and summer period. This means that, for a scenario to score significantly better than the Baseline, the curve should be ABOVE zero for the winter period, and BELOW zero for the summer period.) Unfortunately, RH data is not available for the summer period.

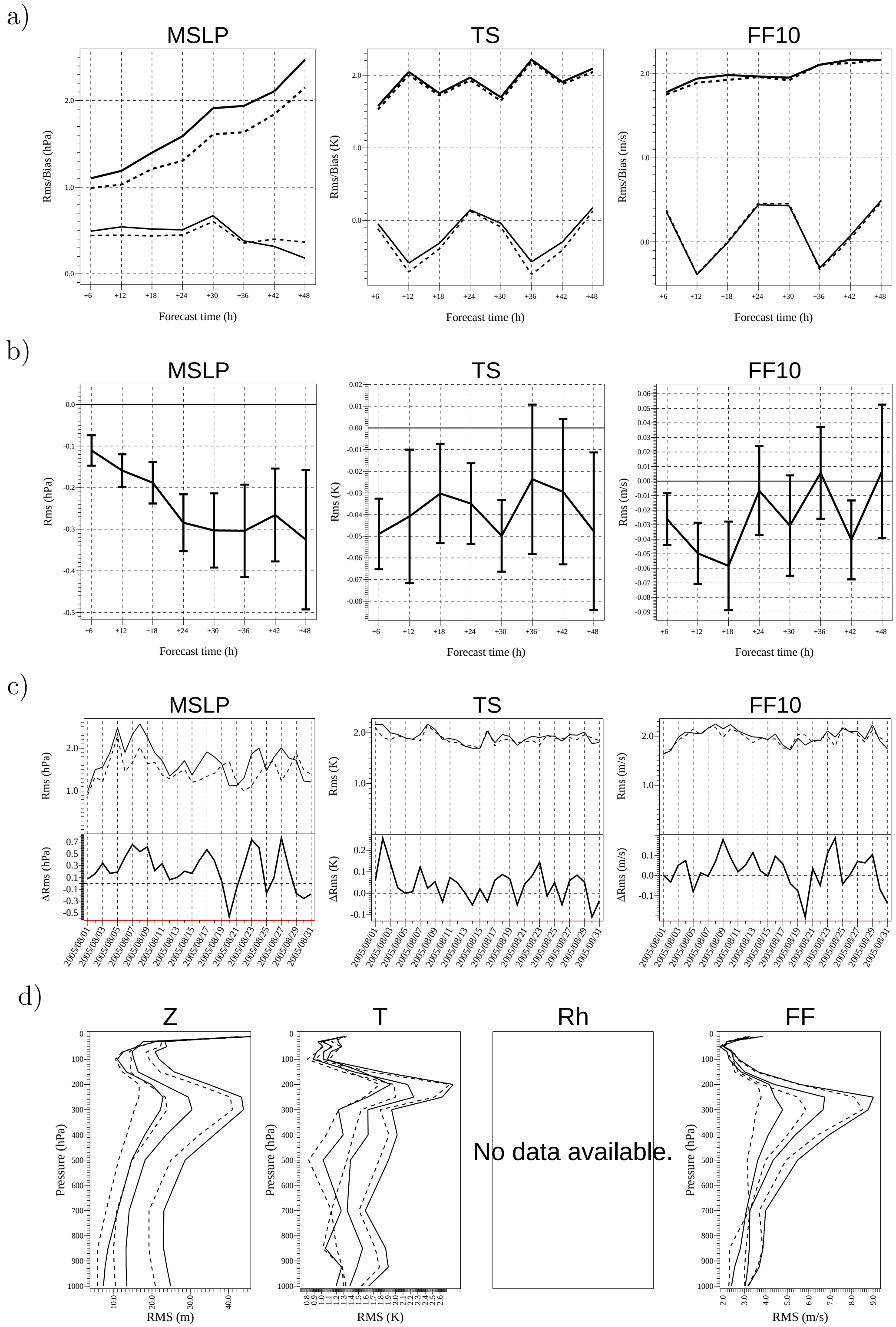


Figure 39: SUMMER PERIOD Scenario 3 - Add Radiosonde Wind (dashed) compared to Baseline (solid). See figure 38 for details.

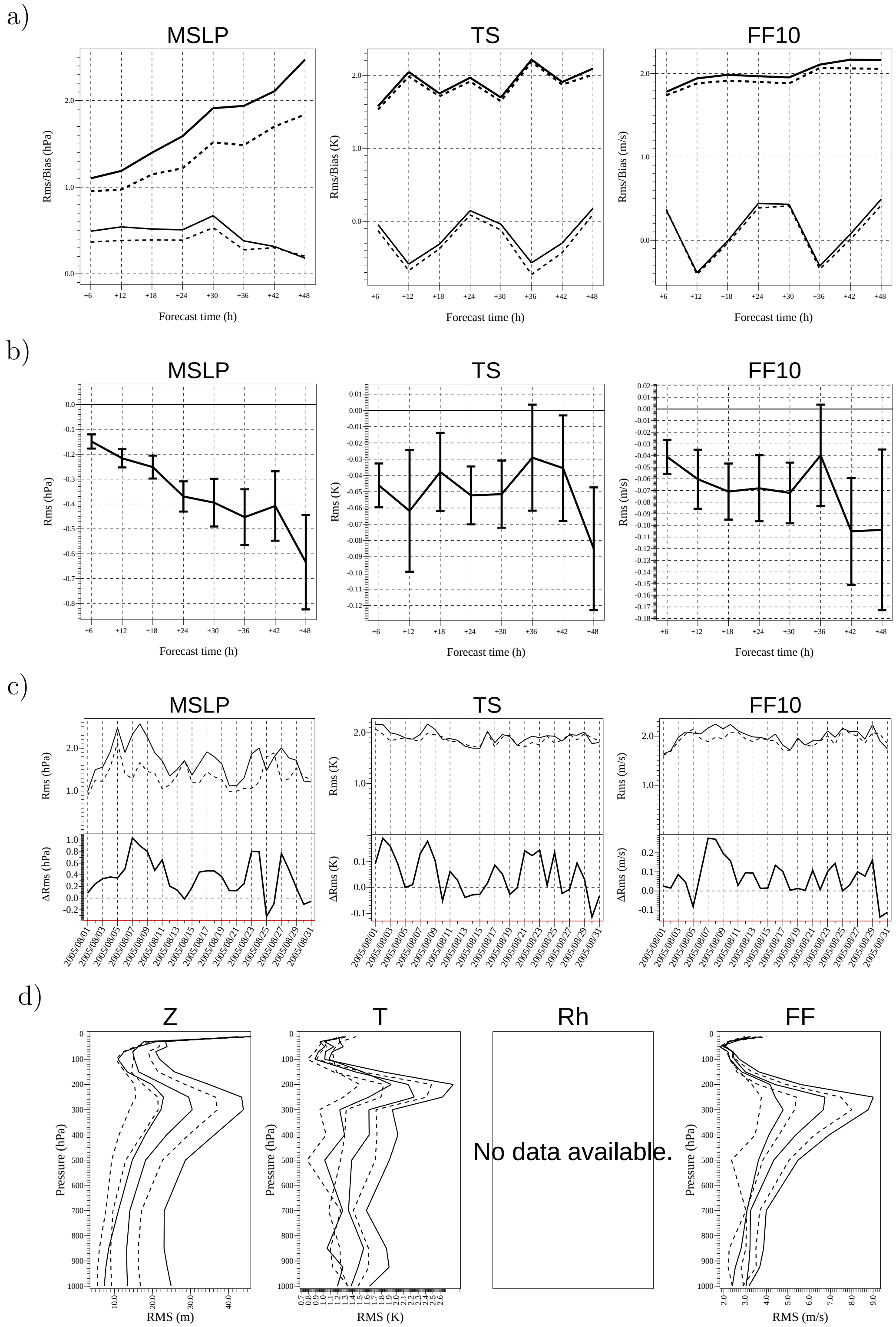


Figure 40: SUMMER PERIOD Scenario 4 - Add Radiosonde Wind and Temperature (dashed) compared to Baseline (solid). See figure 38 for details.

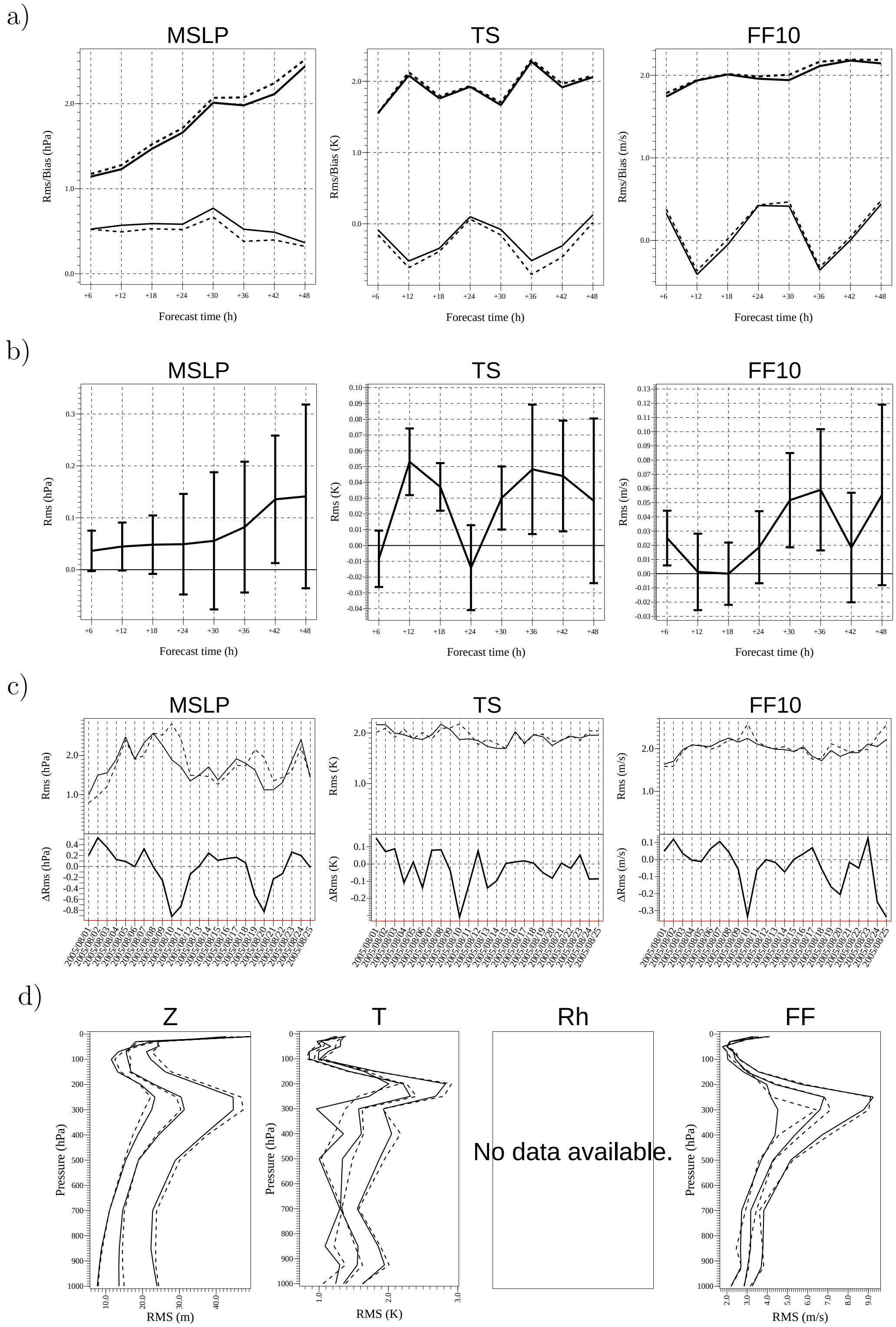


Figure 41: SUMMER PERIOD Scenario 5 - Add Wind Profilers (dashed) compared to Baseline (solid). See figure 38 for details.

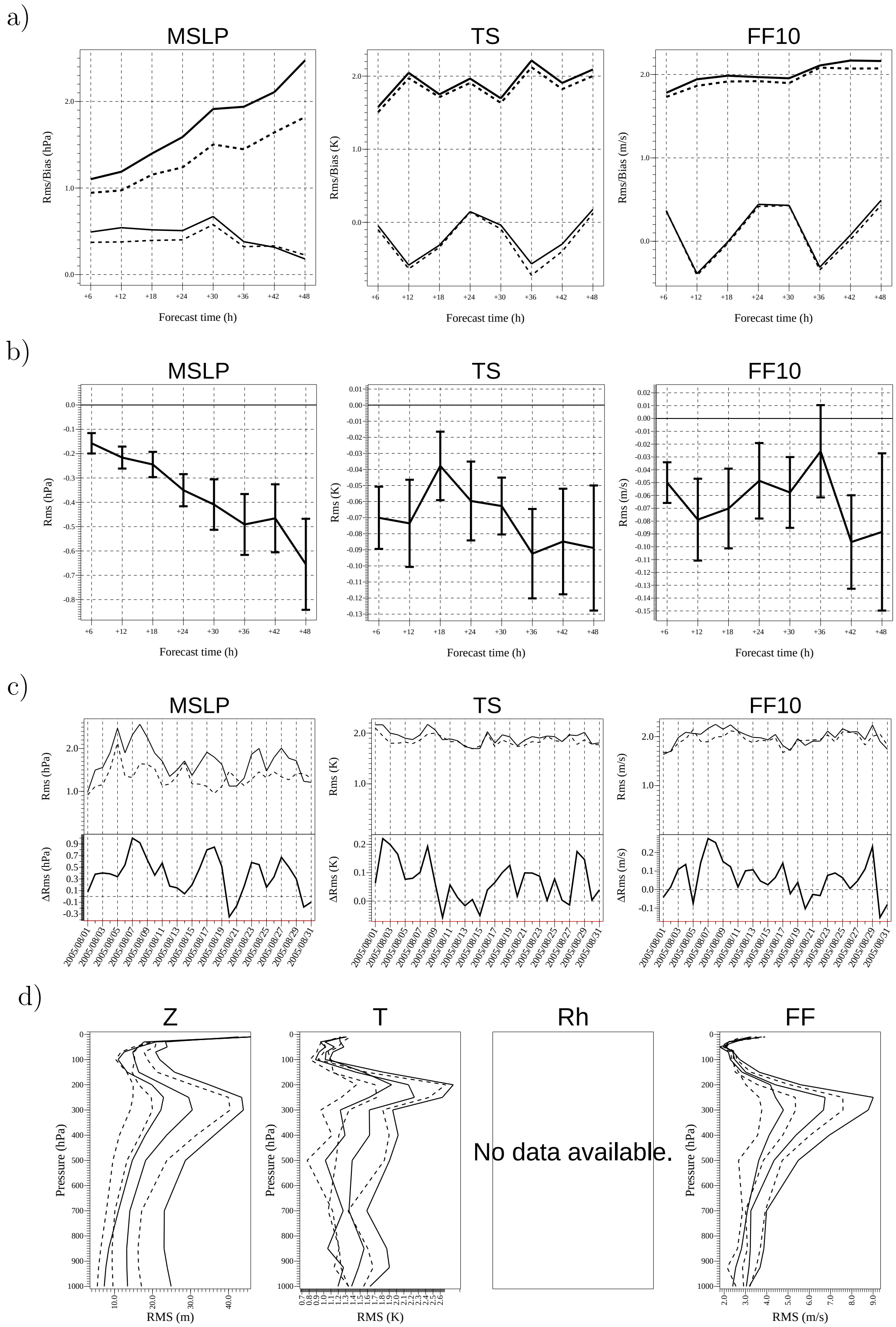


Figure 42: SUMMER PERIOD Scenario 6 - Add Wind and Temperature from Aircraft and Radiosondes (dashed) compared to Baseline (solid). See figure 38 for details.

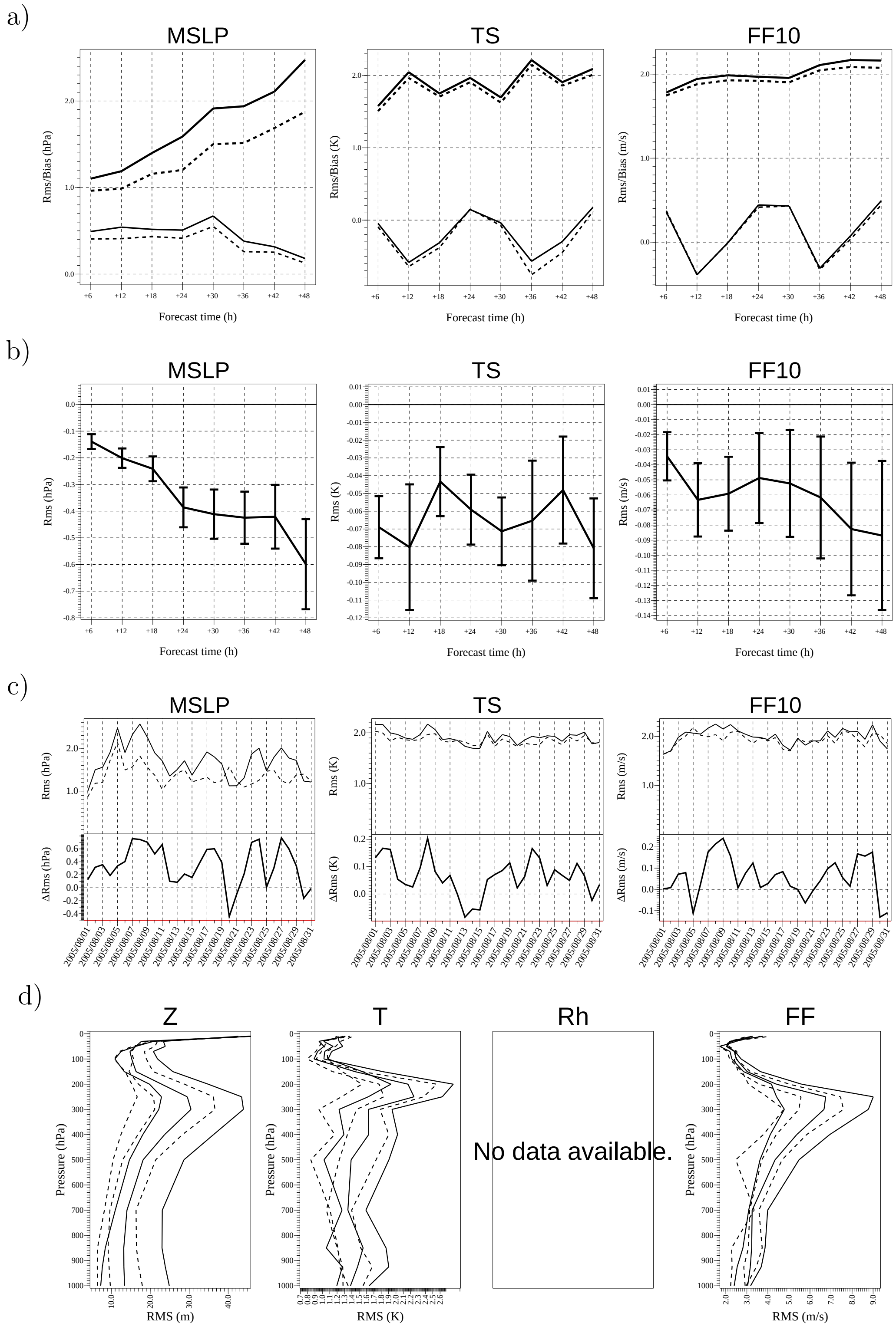


Figure 43: SUMMER PERIOD Scenario 7 - Add Radiosonde Wind, Temperature and Humidity (dashed) compared to Baseline (solid). See figure 38 for details.

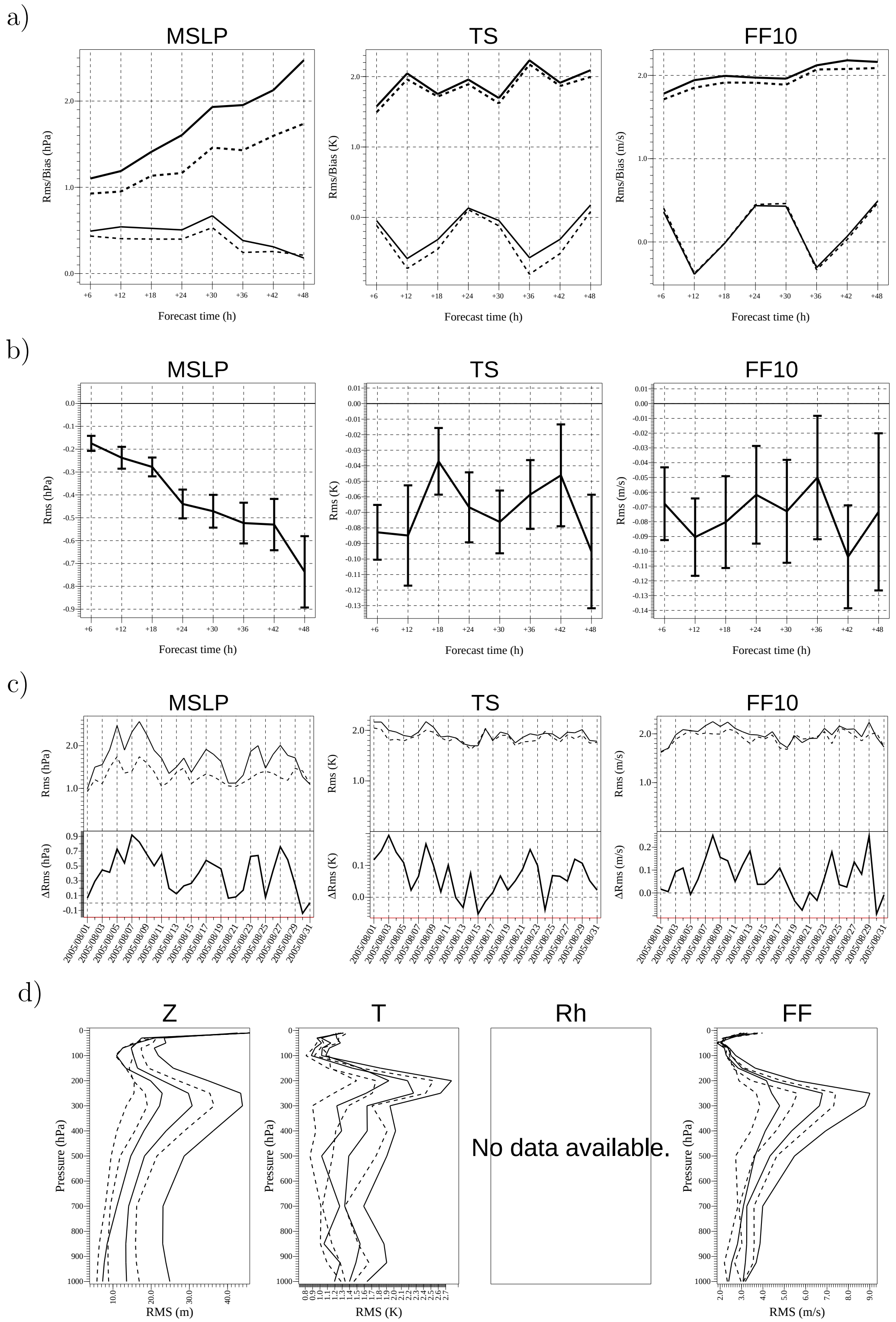


Figure 44: SUMMER PERIOD Scenario 8 - the Contol experiment (dashed) compared to Baseline (solid). See figure 38 for details.

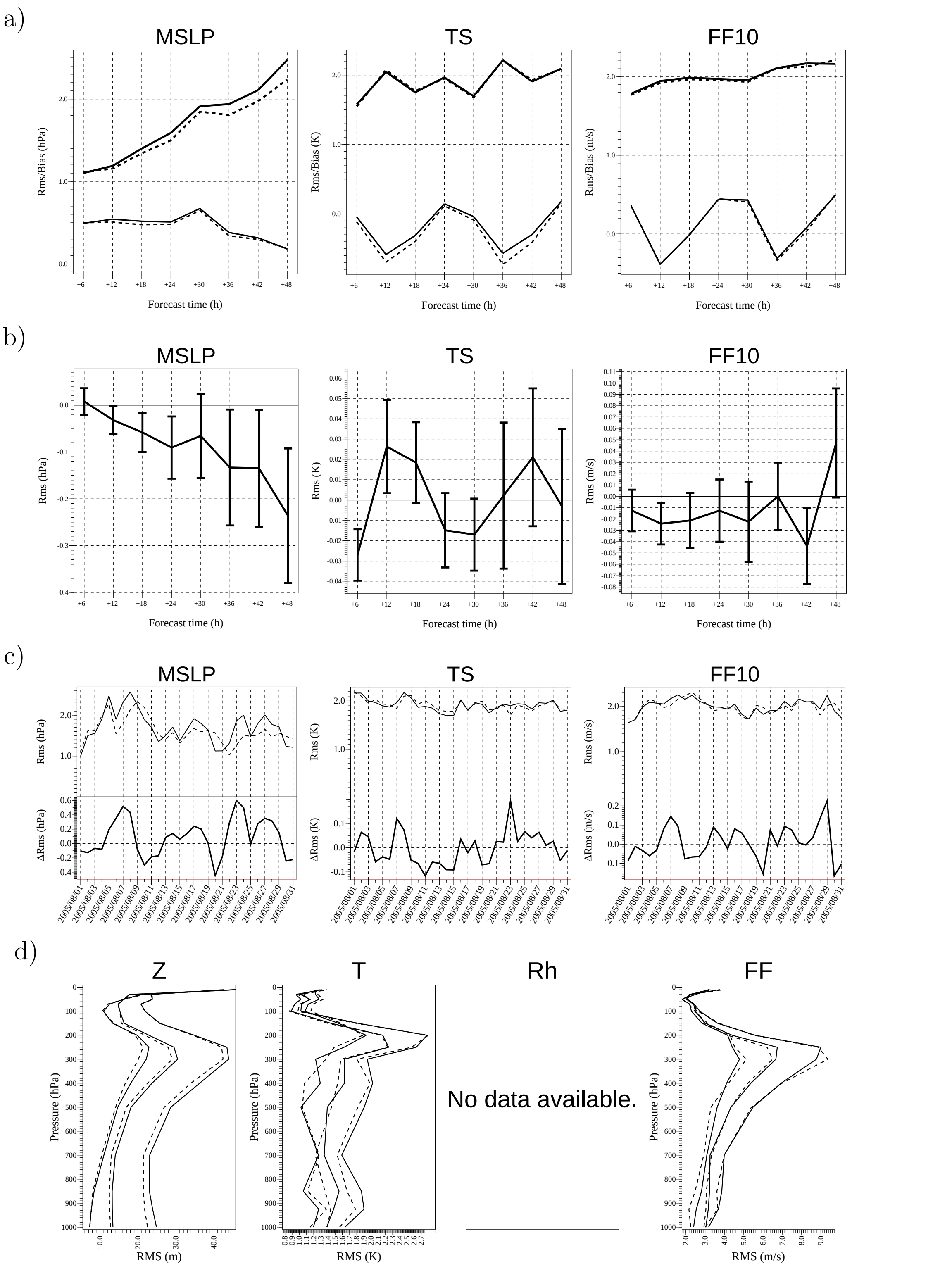


Figure 45: SUMMER PERIOD Scenario 9 - Add E-ASAP ships (dashed) compared to Baseline (solid). See figure 38 for details.