Assimilating All-Sky Infrared Brightness Temperatures in an Ensemble Data Assimilation System using a Nonlinear Bias Correction Method

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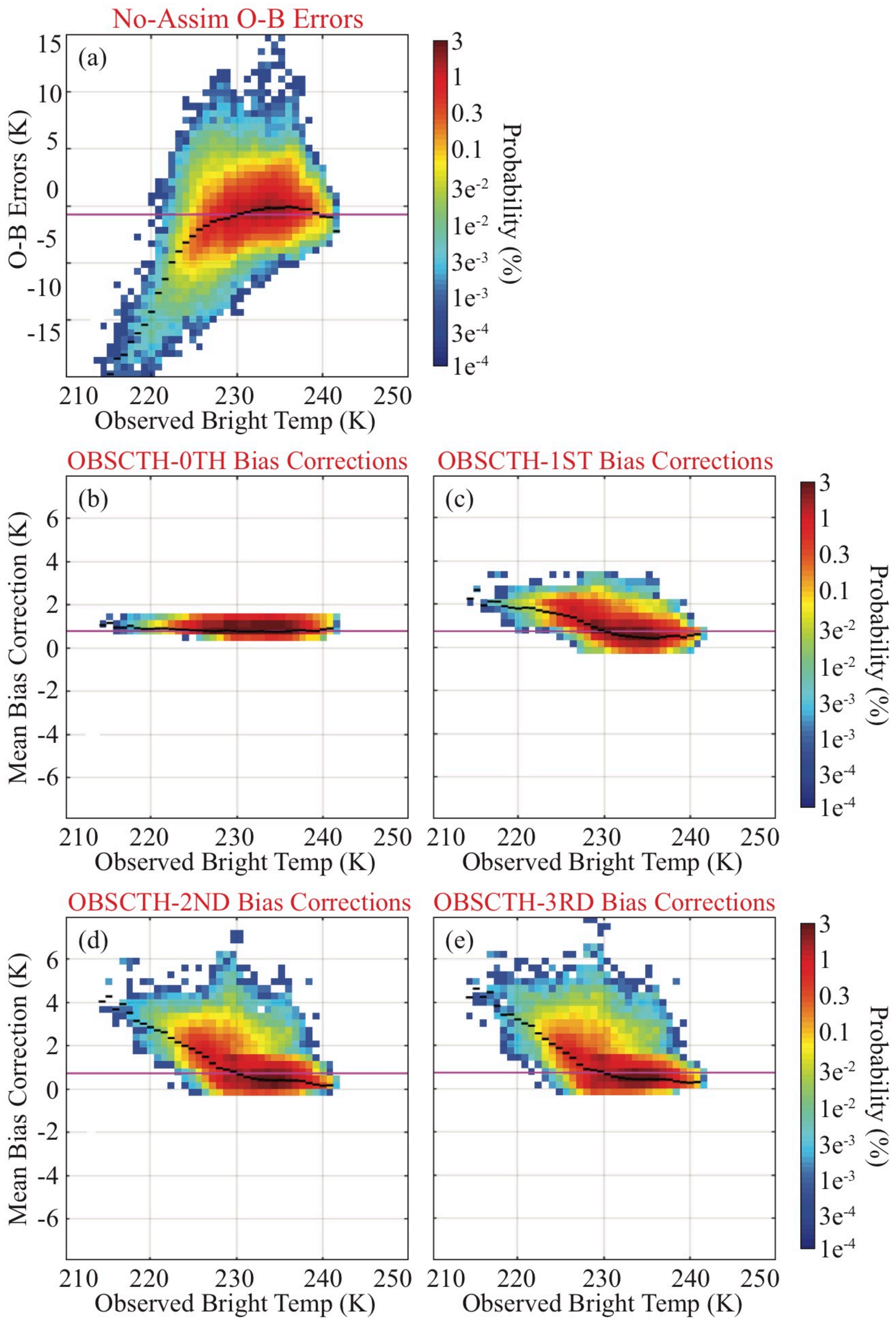
Introduction

Satellite infrared brightness temperatures from geostationary sensors provide valuable information about clouds and water vapor with high spatial and temporal resolution. The assimilation of all-sky infrared brightness temperatures is challenging however due to the presence of non-Guassian errors that can be introduced by limitations in the forward radiative transfer models used to compute the model-equivalent brightness temperatures and the inability of the NWP model to properly simulate cloud properties. Bias correction (BC) methods are therefore necessary to remove the biases from these observations prior to their assimilation. BC methods typically assume that a linear relationship exists between the observation-minus-background (OMB) departures and a given set of predictors. Though previous studies have shown that linear BC methods are able to effectively remove biases from clear-sky satellite observations, these methods are suboptimal if the observation bias varies as a nonlinear function of some predictor. Indeed, Otkin et al. (2018) showed that nonlinear conditional biases are more likely to occur in cloud-affected observations, which necessitates the development of BC methods that can capture complex error patterns in all-sky observations. Their study also showed that cloud-sensitive predictors, such as the cloud top height or the brightness temperatures themselves, are most effective at removing biases from all-sky infrared observations. In this study, we build upon their work by assessing the ability of linear and nonlinear BC predictors in the context of all-sky infrared brightness temperature assimilation to improve short-range (1-h) forecasts in an ensemble DA system.

Methodology

In this study, we advance efforts to assimilate all-sky infrared brightness temperatures from the cloud and water vapor sensitive 6.2-μm band on the SEVIRI sensor using a pre-operational version of the Kilometer-scale Ensemble Data Assimilation (KENDA) system run at the German Deutscher Wetterdienst. Experiments were run in which the nonlinear bias correction (NBC) method developed by Otkin et al. (2018) was used to remove systematic biases from the all-sky observations prior to their assimilation. Conventional observations and all-sky infrared brightness temperatures were actively assimilated at hourly intervals during a 3-day period from 28-31 May 2014 on the COSMO-DE domain containing 2.8-km horizontal resolution. Two baseline experiments were performed, including ones in which the all-sky SEVIRI observations were either not assimilated (No-Assim) or were assimilated without using bias correction (No-BC). Other experiments were performed to examine the impact of using different orders of Taylor series expansions to remove the biases from the observations, ranging from a 0^{th} order (constant) correction to linear (1^{st} order), quadratic (2^{nd} order), and cubic (3^{rd} order) corrections. These experiments were performed using the observed cloud top height (OBSCTH) as the predictor, with the results shown in the left column below. A second set of experiments was performed to assess the ability of various bias predictors, such as satellite zenith angle (SATZEN), vertically-integrated water content (IWC), and observed brightness temperature (OBSBT), to improve the assimilation performance when a 3^{rd} order bias correction was used. These results are shown in the middle column below. A final set of experiments examined the utility of symmetric bias predictors (the average of the observed and simulated quantities), with those results shown in the right column. For each experiment, the impact of the infrared brightness temperatures and NBC method was assessed using the prior fits to radiosonde observations (shown in the tables) and through inspection of the brightness temperature bias corrections and innovations.

Linear and Nonlinear BC Experiments



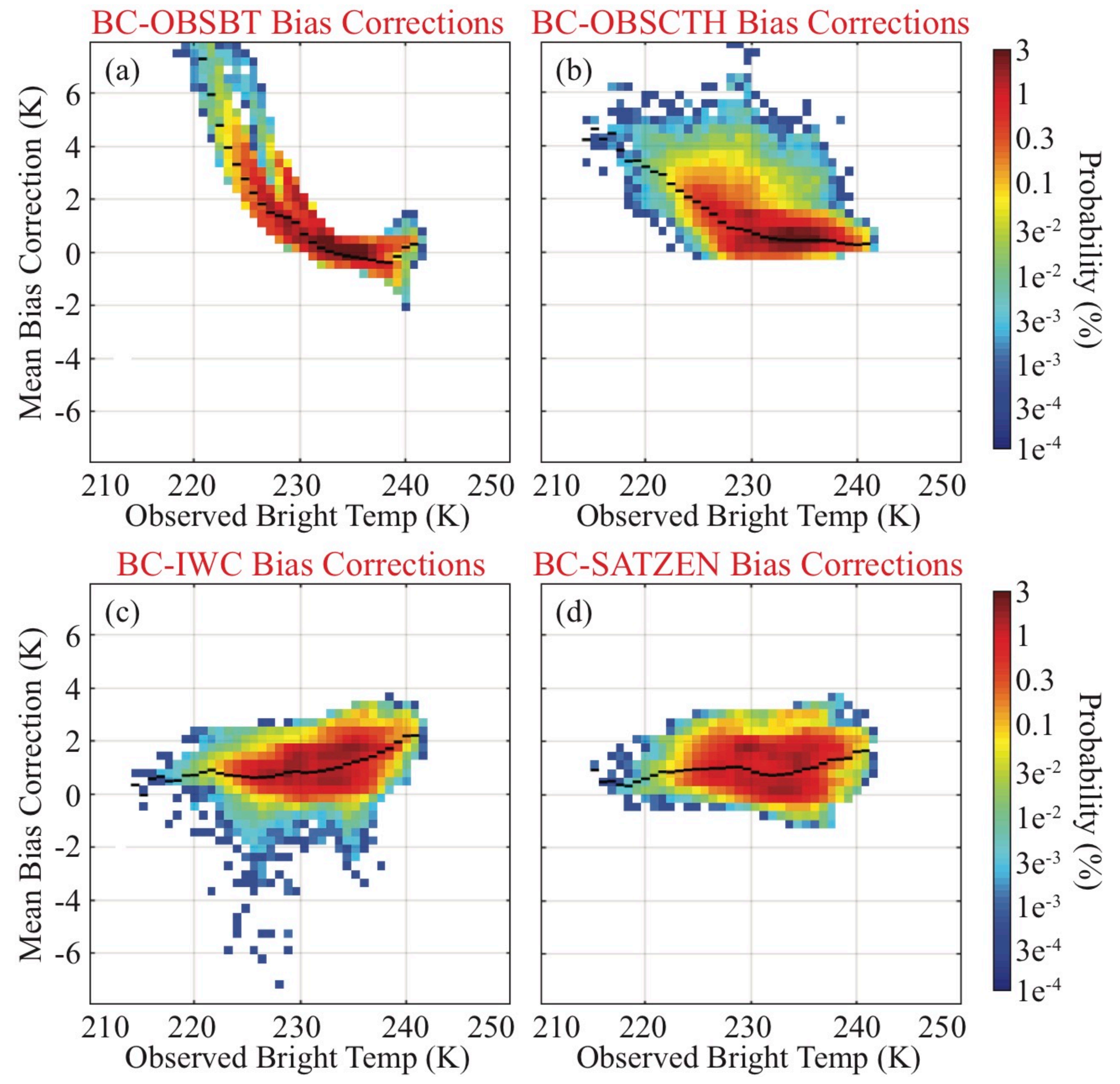
Experiment	U	V	T		RH	
	RMSE	RMSE	RMSE	BIAS	RMSE	BIAS
OBSCTH-0TH	-0.2%	-0.2%	-0.1%	-4.7%	-0.6%	-36.2%
OBSCTH-1ST	-0.7%	-0.1%	-0.3%	-3.1%	-0.9%	-29.1%
OBSCTH-2ND	-0.9%	-0.5%	-0.3%	-5.0%	-1.5%	-25.6%
OBSCTH-3RD	-1.0%	-0.8%	-0.2%	-1.3%	-1.8%	-30.2%

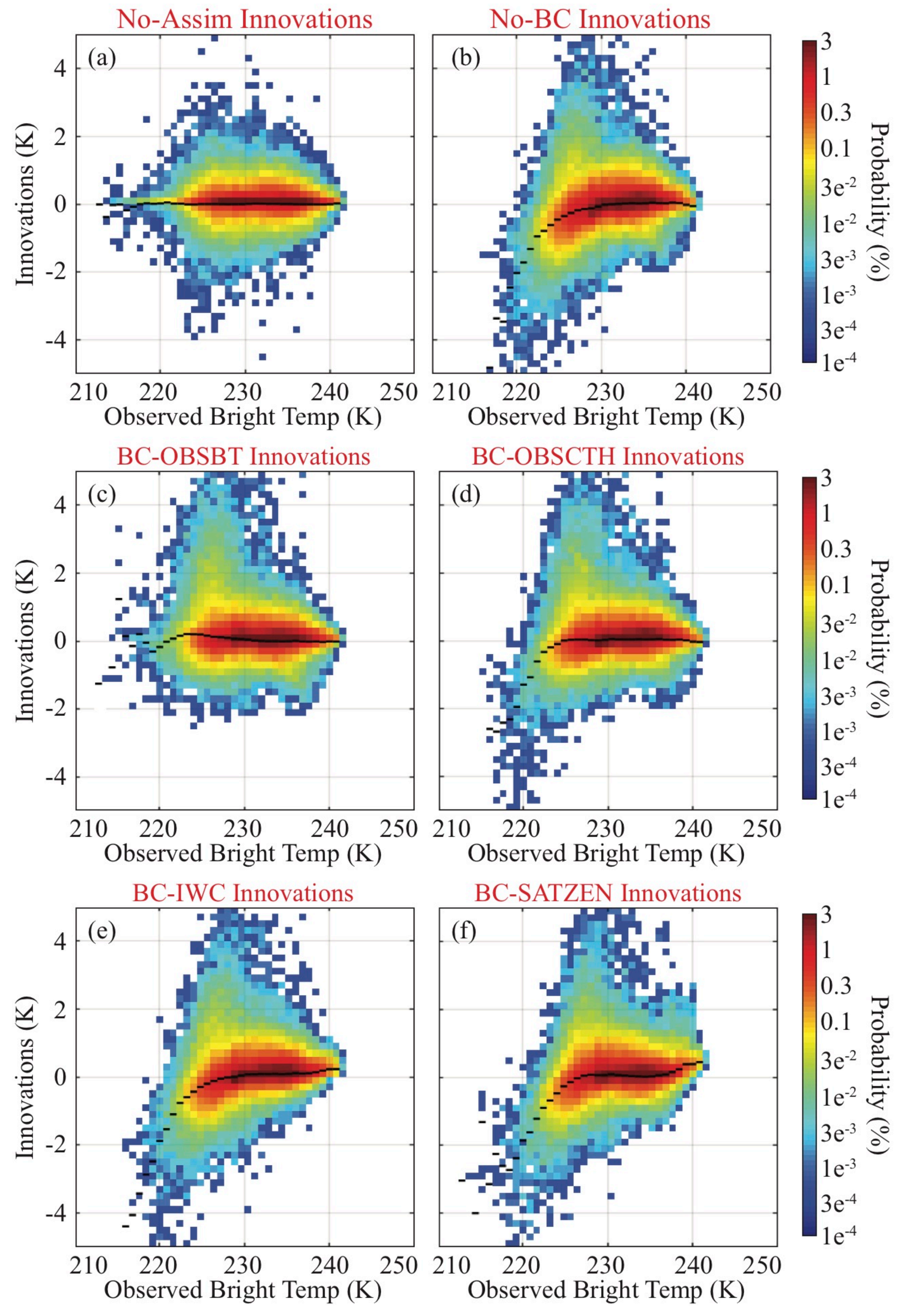
Results, Part 1

Linear and Nonlinear BC Experiments: The No-Assim experiment exhibits small biases for warmer brightness temperatures that transition into larger negative biases for the colder temperatures. The OBSCTH_0TH experiment has a very narrow range of BCs because the single predictor can only remove the constant bias from the distribution. More accurate BCs are obtained during the 1st order experiment in the middle right panel, as indicated by the slightly larger BCs for colder brightness temperatures. The BCs become even larger when the 2^{nd} and 3^{rd} order nonlinear bias predictors are used in the bottom row. The table shows that the radiosonde statistics are much more accurate when BC is applied to the satellite observations, with the largest impact on the relative humidity field. There is also a distinct advantage to using the higher order BC terms. For example, the RMSE for the wind and relative humidity observations steadily decrease as the bias predictor goes from the 0^{th} order to the 3^{rd} order. Overall, these results show that more accurate results are obtained when the higher order nonlinear predictors are used.

Different Bias Correction Predictors: Inspection of the 2-D distributions of the ensemble mean BCs (middle column, top) shows that the BC patterns for the OBSCTH and OBSBT experiments are flipped compared to the OMB departure distribution from the No-Assim experiment (left column, top). This means that the OBSBT and OBSCTH predictors are able to account for the nonlinear, cloud-dependent conditional biases in that distribution. In contrast, the BC-IWC and BC-SATZEN experiments have much smaller BCs for the lowest brightness temperatures that then become larger for higher brightness temperatures. This behavior shows that it is necessary to use BC predictors sensitive to the CTH. Inspection of the mean innovations (middle column, bottom) reveals that the large conditional biases for the lower brightness temperatures are strongly corrected during the No-BC, BC-IWC, and BC-SATZEN experiments, whereas the mean innovations are much smaller during the BC-OBSBT and BC-OBSCTH experiments. The smaller innovations during the BC-OBSBT and BC-OBSCTH experiments were likely beneficial because they limited potential imbalances in the model due to large analysis increments. This positive impact is also demonstrated by the larger error reductions for the radiosonde observations (bottom table) when the cloud top sensitive bias predictors are used.

Different Bias Correction Predictors





Experiment	U	V	T		RH	
	RMSE	RMSE	RMSE	BIAS	RMSE	BIAS
BC-OBSBT–No-BC	-0.9%	-1.4%	-0.2%	-3.1%	-1.2%	-15.6%
BC-OBSCTH–No-BC	-1.0%	-0.8%	-0.2%	-1.3%	-1.8%	-30.2%
BC-IWC–No-BC	-0.2%	0.0%	-0.1%	-3.2%	-0.9%	-45.2%
BC-SATZEN–No-BC	-0.1%	-0.1%	-0.1%	-4.5%	-1.4%	-38.2%

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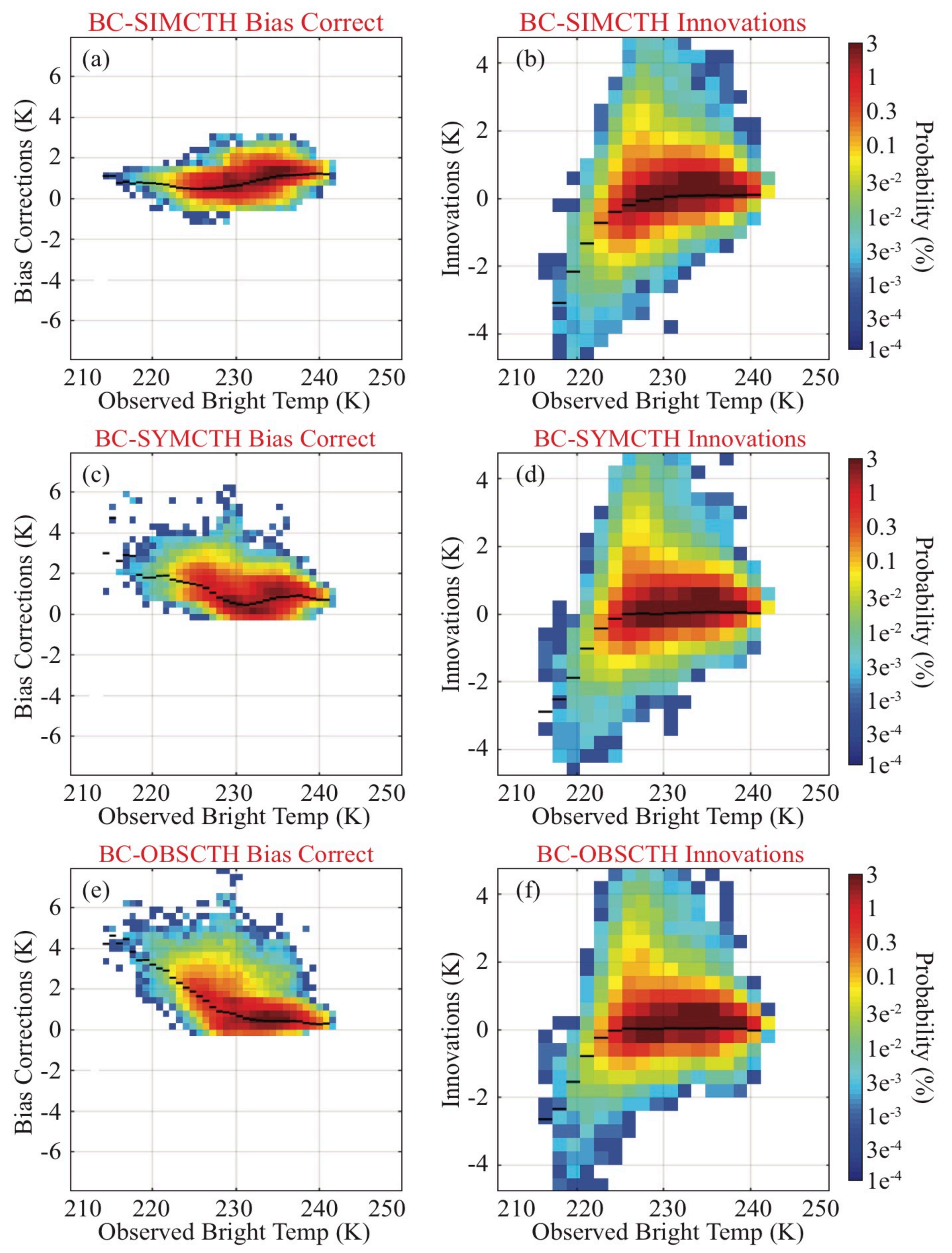
Symmetric BC Predictor Experiments



Experiment	U	V	T		RH	
	RMSE	RMSE	RMSE	BIAS	RMSE	BIAS
BC-OBSBT–No-BC	-0.9%	-1.4%	-0.2%	-3.1%	-1.2%	-15.6%
BC-SYMBT–No-BC	-0.1%	0.0%	-0.1%	-2.0%	-1.0%	-29.6%
BC-SIMBT–No-BC	1.0%	1.3%	-0.6%	-1.1%	-0.8%	-55.8%

Results, Part 2

Symmetric BC Predictor Experiments: To explore the utility of symmetric bias predictors, two additional sets of experiments were performed where the observed (BC-OBSBT, BC-OBSCTH), simulated (BC-SIMBT, BC-SIMCTH), or symmetric (BC-SYMBT, BC-SYMCTH) quantities for the CTH and BT predictors were used to remove the bias from the infrared brightness temperatures. Comparison of the BC distributions (left) reveals a relatively flat pattern during the BC-SIMCTH experiment, which shows that the SIMCTH predictor was unable to account for the large negative biases for brightness temperatures <230 K. The smaller BCs for the lower brightness temperatures during this experiment stand in sharp contrast to the much larger BCs during the BC-OBSCTH experiment. Because the symmetric predictor is simply the mean of the observed and simulated quantities, the distribution during the BC-SYMCTH experiment is a hybrid of the BC-OBSCTH and BC-SIMCTH distributions. As such, the smaller BCs for the lower brightness temperatures due to the impact of the model-simulated quantity leads to larger innovations than occurred during the BC-OBSCTH experiment. Inspection of the radiosonde summary statistics (table above) shows that the error reductions for the radiosonde observations are smaller during the BC-SYMBT experiment than they are during the BC-OBSBT experiment. Likewise, when the CTH predictors are used (not shown), the most accurate analyses are obtained when the observed quantity is used. A possible reason for the relatively poor performance during the symmetric bias predictor experiments is that, with the exception of relative humidity, the error reductions are consistently smaller when the simulated predictors are used. Inclusion of the simulated predictor value when computing the symmetric bias predictor is not beneficial. Instead, it is more effective to simply use the observed quantity as the bias predictor.

Conclusions

Comparison of the various predictors showed that those sensitive to the location of the cloud top had the largest positive impact on the model background based on improved fits to the radiosonde observations. The observed CTH and BT predictors were the best overall because their use not only led to the smallest relative humidity errors, but also led to the largest error reductions for the wind speed observations. Additional experiments showed that it was beneficial to use higher order nonlinear BC terms to remove the bias from the all-sky infrared brightness temperatures. Another set of experiments revealed that symmetric bias predictors do not improve the model analyses as effectively as the observed predictors do by themselves.