ZUERICH CLIMATE AND WEATHER
ACM40080 PROJECT 3

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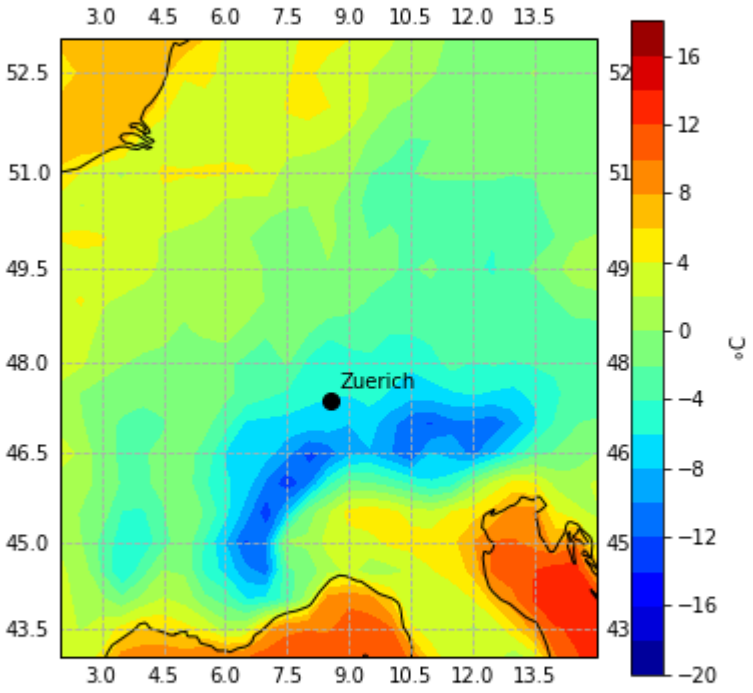

FIGURE 1. kwbc Forecasted '2m' Temperature on 08/12/20 at 00:00

1. Introduction

This report consists of two sections. First, we look at daily '2m' temperature forecasts from nine different meteorological centres for the period 08/12/2020 to 07/01/2021 and compare these to the actual observed temperatures. We'll calculate four skill scores for each day, and overall: bias, RMSE, ACC and rank histogram. Any sytematic errors will reveal themselves here. We'll then remove a systematic error from the ensemble of nine forecsats and re-calulate the skill scores.

In the second section, we will analyse climate models for Zuerich from two centres: the French National Centre for Meteorological Research (CNRM) and the Irish Centre for High-End Computing (ICHEC). First we will assess the accuracy of each model by comparing their temperature predictions for a historic time period (1979-2006) to the observed data. Then we'll look to the future. For each model we have daily temperature projections corresponding to two emissions scenarios of different severity. We'll compare projections for the period 2070-2100 to the observed 1979-2006 period in order to assess predicted climate temperature change.

2. Ensemble Forecasts

As mentioned before, we'll be looking at nine different forecasts for Zuerich from 08/12/2020 to 07/01/2021. Here are the nine meteorological centres/locations and their abbreviations:

ammc - Melbourne
babj - Beijing
cwao - Montreal
dems - New Delhi
ecmwf - European Centre for Medium-Range Weather Forecast
kwbc - US National Weather Service
rjtd - Tokyo
rksl - Seoul
vabb - New Delhi

While the forecasts provide temperature values four-times daily, we simply take the mean daily temperature and work with one temperature value per day. Below, you can see linegraphs displaying the forecasted temperatures alongside the observed. Also included is the 'poor man's ensemble' (pme), i.e. the equally weighted average of the nine forecasts calculated daily.

We'll then finish up by combining the two models as, as far as we're concerned, they are equally likely, and get the projected change in temperature for the two scenarios.

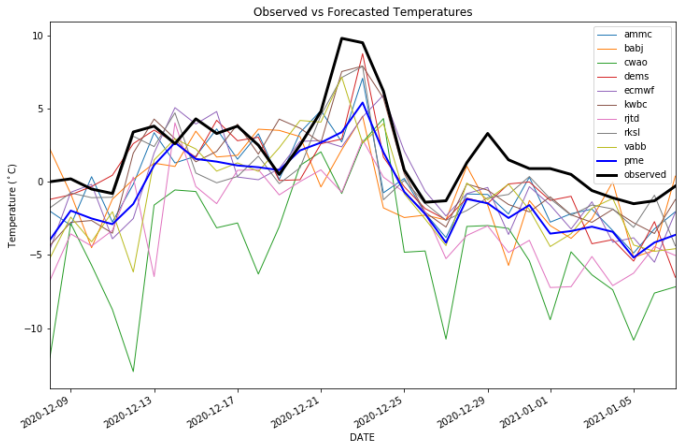

Figure 2. Observed vs Forecasts

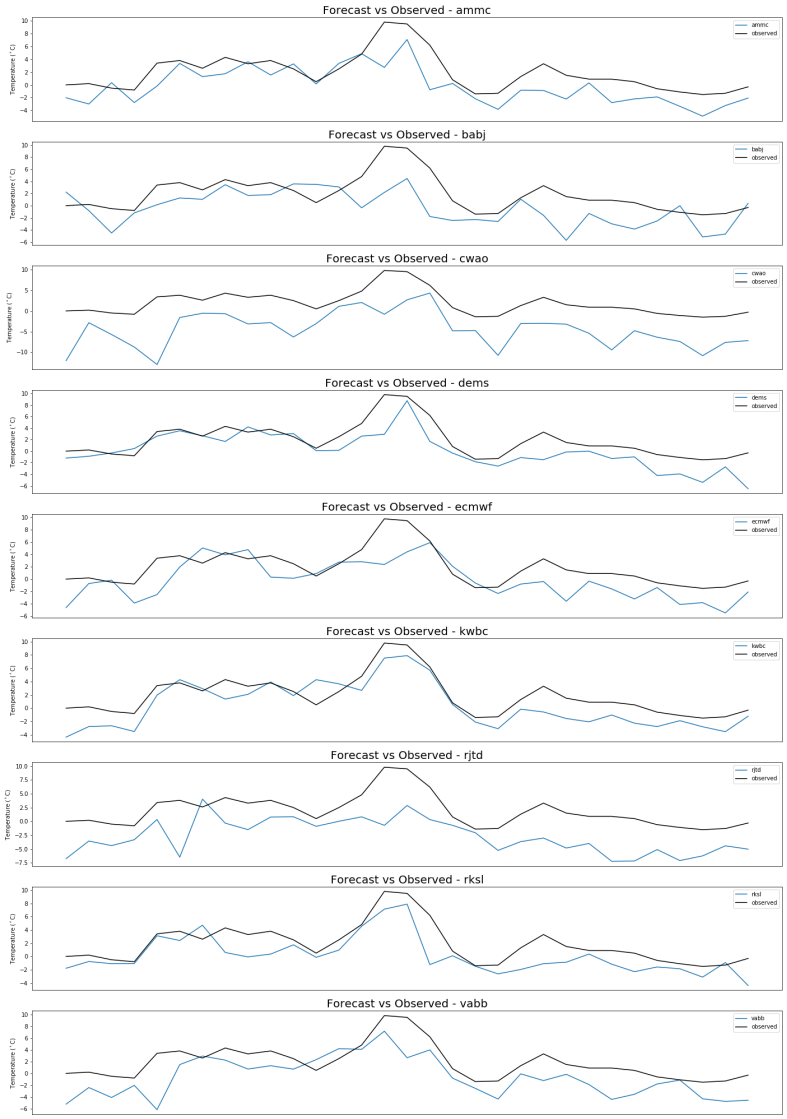

FIGURE 3. Observed vs Individual Forecasts

Already we can make a significant observation. The forecasted temperatures seem to fall below the observed temperatures the vast majority of the of the time. This will be evident as we look at bias. The poor man's ensemble seems to track the observed shape rather well, though it's always too low.

2.1. **Bias.** Bias is simply the average error. We compute the daily errors for each forecast ($forecast - observed$), average these over the month to get the overall bias for each forecast, and then average these over all forecasts to get an overall bias for the ensemble.

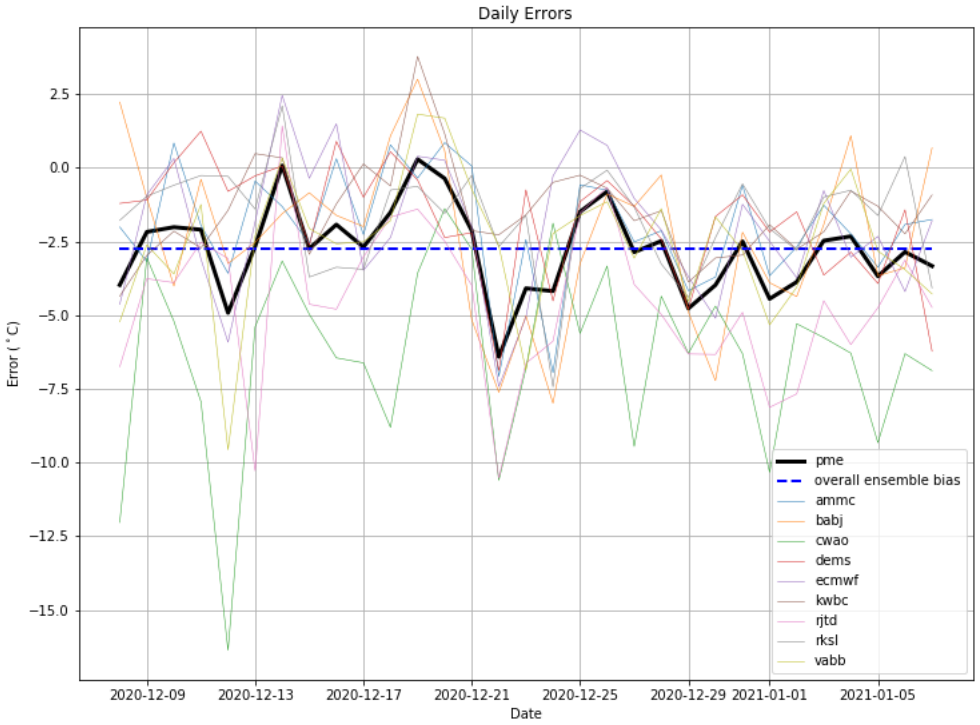

FIGURE 4. Daily Errors

	Ammc	Babj	Cwao	Dems	Ecmwf	Kwbc	Rjtd	Rksl	Vabb	Mean
Bias	-2.02	-2.31	-6.36	-1.79	-1.99	-1.46	-4.56	-1.71	-2.56	-2.75

FIGURE 5. Forecast Biases

The least biased forecast is kwbc, at -1.46. The most biased is cwao, at -6.36. The mean overall bias is $-2.75°C$. This is a rather significant figure, and so might

be indicative of systematic error. Later on, we'll remove the bias and reassess the skill of the ensemble.

2.2. **RMSE.** RMSE (Root-Mean-Square Error) is the standard deviation of the residuals, or daily errors. While a forecast might have low bias, its variance could be very high, as its positive and negative errors might cancel out. The closer the RMSE is to 0, the more skillful the forecast. Below you'll see a bar chart and table dsiplaying the RMSE of each forecast.

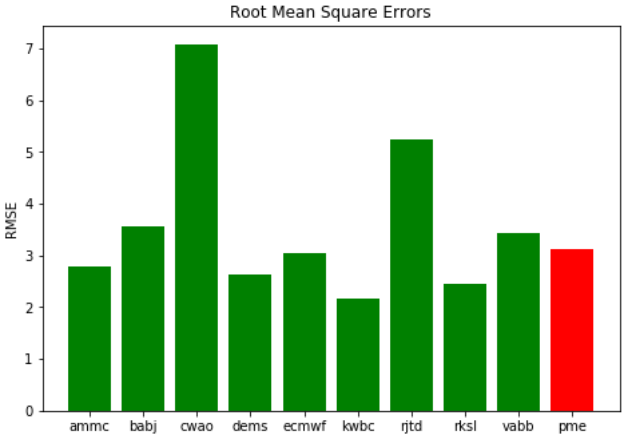

FIGURE 6. RMSE Barchart

	Ammc	Babj	Cwao	Dems	Ecmwf	Kwbc	Rjtd	Rksl	Vabb	Pme	Mean
RMSE	2.78	3.55	7.09	2.62	3.04	2.15	5.24	2.46	3.42	3.12	3.55

FIGURE 7. RMSE Table

The forecast with lowest RMSE is kwbc, at 2.15. The forecast with greatest RMSE is cwao, at 7.09.

The mean RMSE averaged across the nine forecasts is 3.55. The poor man's ensemble RMSE is 3.12, which places it sixth best among the nine forecast RMSEs.

2.3. **ACC.** ACC (Anomaly Correlation Coefficient) takes the local climate into account. It removes the climate average from both the observed and forecasted temperatures. The closer the ACC value is to 1, the better the skill of the forecast. The climatology coefficient for these calculations was determined using a 'rolling window'of observations from 1981 to 2010.

There is considerable variety in the ACC values of the nine forecasts, ranging from 0.18 for rjtd to 0.78 for kwbc. cwao again scored poorly here with 0.21. The mean ACC averaged across the nine forecasts is 0.480, while the poor man's ensemble yields an ACC of 0.504.

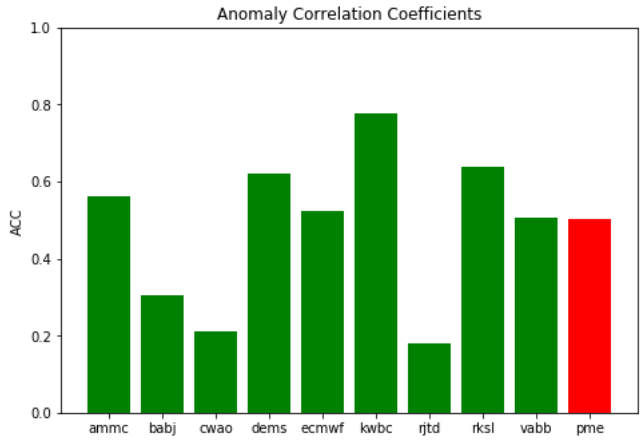

FIGURE 8. ACC Barchart

	Ammc	Babj	Cwao	Dems	Ecmwf	Kwbc	Rjtd	Rksl	Vabb	Pme	Mean
ACC	0.56	0.30	0.21	0.62	0.52	0.78	0.18	0.64	0.51	0.50	0.48

FIGURE 9. ACC Table

2.4. **Rank Histogram.** For the rank histogram, the ranking of the observed temperature (1-10) among the forecasted temperatures is recorded for each of the 31 days, and the frequency of each ranking is displayed in a histogram, which you'll find below.

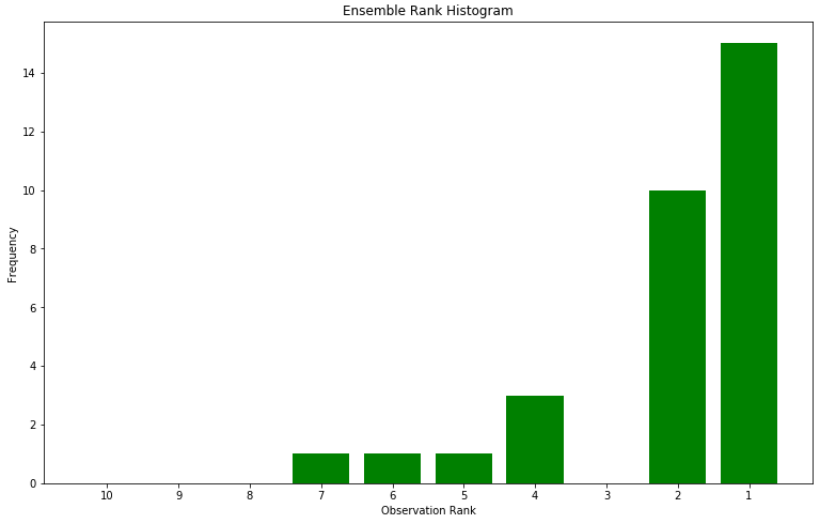

FIGURE 10. Rank Histogram

A rank histogram belonging to a consistent, reliable forecast will be relatively evenly distributed. That is far from the case in this instance.
The rank histogram clearly shows that the ensemble is negatively biased, with the observed temperature ranking first or second 25 days out of the 31.

Summary:
Based on the above, it's evident that there is significant underlying negative bias in the forecasts over the period 08/12/20 to 07/01/21. It's also clear that the most skillful forecast is kwbc, while the least skilled is cwao. The poor man's ensemble ranks somewhere in the middle.

2.5. **Systematic Errors.** It is clear up to this point that most of our forecasts are not very good. A factor in this may be underlying systematic errors in the models. The easiest systematic error to rectify is bias. As discussed earlier, all forecasts are negatively biased to varying extents. The mean bias across the nine forecasts was found to be $-2.75°C$. Hence, to correct for bias, we'll subtract this amount from each forecast and recalculate each skill score.

Bias-Corrected Bias:

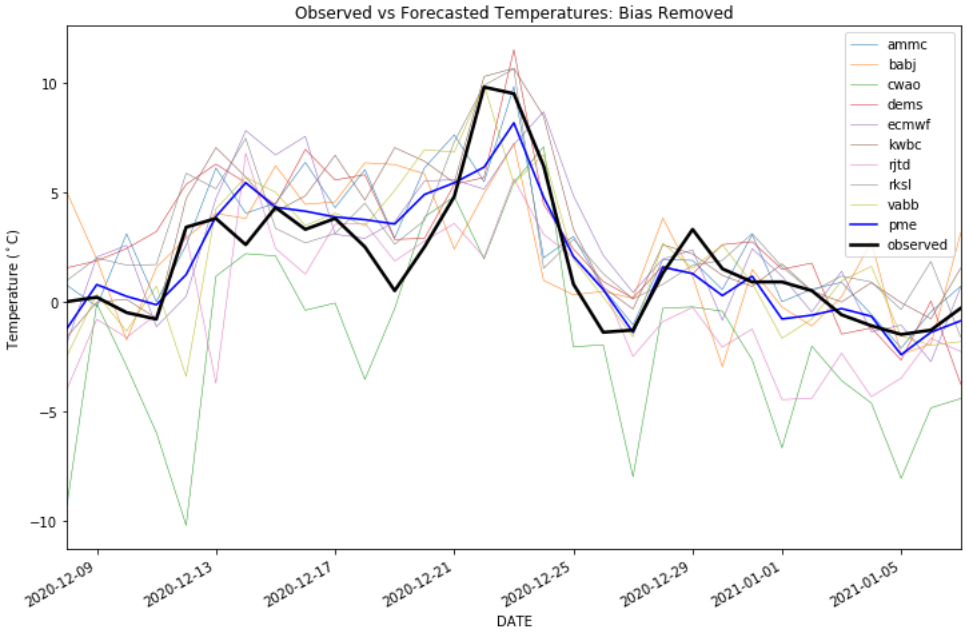

FIGURE 11. Bias-Removed Forecasted and Observed Temperatures

We see in figure **??** that the blue 'poor man's ensemble' line now matches the observed data quite well. Its bias is now, of course, 0, having subtracted the overall average bias. The biases of the nine adjusted forecasts are shown in the table in figure **??**, with the daily errors plotted in figure **??**.

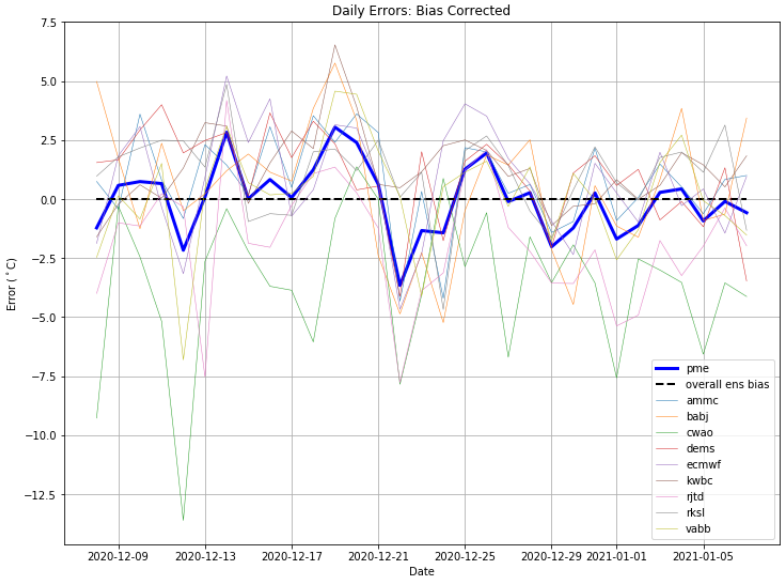

FIGURE 12. Bias-Corrected Forecast Daily Errors

	Ammc	Babj	Cwao	Dems	Ecmwf	Kwbc	Rjtd	Rksl	Vabb	Mean
Bias	0.73	0.45	-3.61	0.96	0.76	1.30	-1.81	1.04	0.19	0

FIGURE 13. Bias-Corrected Bias Table

Bias-Corrected RMSE:

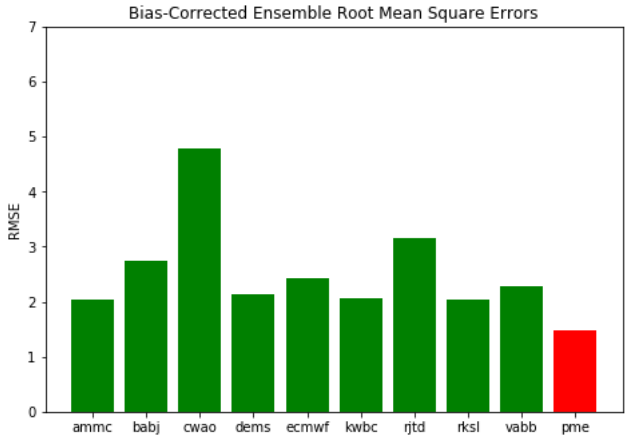

FIGURE 14. Bias-Corrected RMSEs

The overall reduction in RMSE is evident in the bias-correced case. The mean RMSE has reduced from 3.55 to 2.51.

	Ammc	Babj	Cwao	Dems	Ecmwf	Kwbc	Rjtd	Rksl	Vabb	Pme	Mean
RMSE	2.05	2.74	4.77	2.14	2.41	2.05	3.15	2.04	2.27	1.47	2.51

FIGURE 15. Bias-Corrected RMSE Table

Interestingly, the bias-corrected poor man's ensemble has the lowest RMSE of all, at 1.47.

Bias-Corrected ACC:

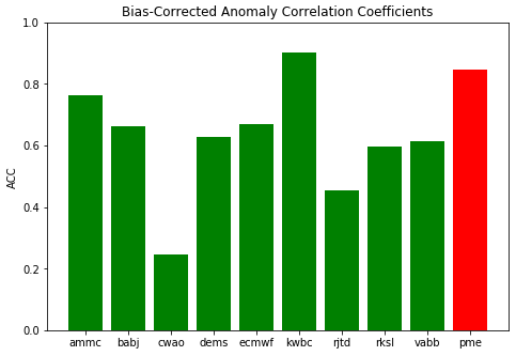

FIGURE 16. Bias-Corrected ACCs

	Ammc	Babj	Cwao	Dems	Ecmwf	Kwbc	Rjtd	Rksl	Vabb	Pme	Mean
ACC	0.76	0.66	0.25	0.63	0.67	0.90	0.45	0.60	0.61	0.85	0.62

FIGURE 17. Bias-Corrected ACC Table

With the removal of bias has come all-round improvementl of ACC. The mean ACC is now 0.62, up from 0.48.

The poor man's ensemble now has an ACC of 0.85, up from 0.50, and places second among the nine forecasts, behind only kwbc.

Bias-Corrected Rank Histogram:

The bias-corrected rank histogram is, surprise-surprise, no longer biased. That said, it still does not reflect an ideal ensemble. Its distribution is concentrated in the middle, meaning it's overconfident, but this is a significant improvement on what we had before correcting for bias.

This last statement is true in general. Subtracting the mean overall bias from the forecasts has led to significant improvements in each skill score.

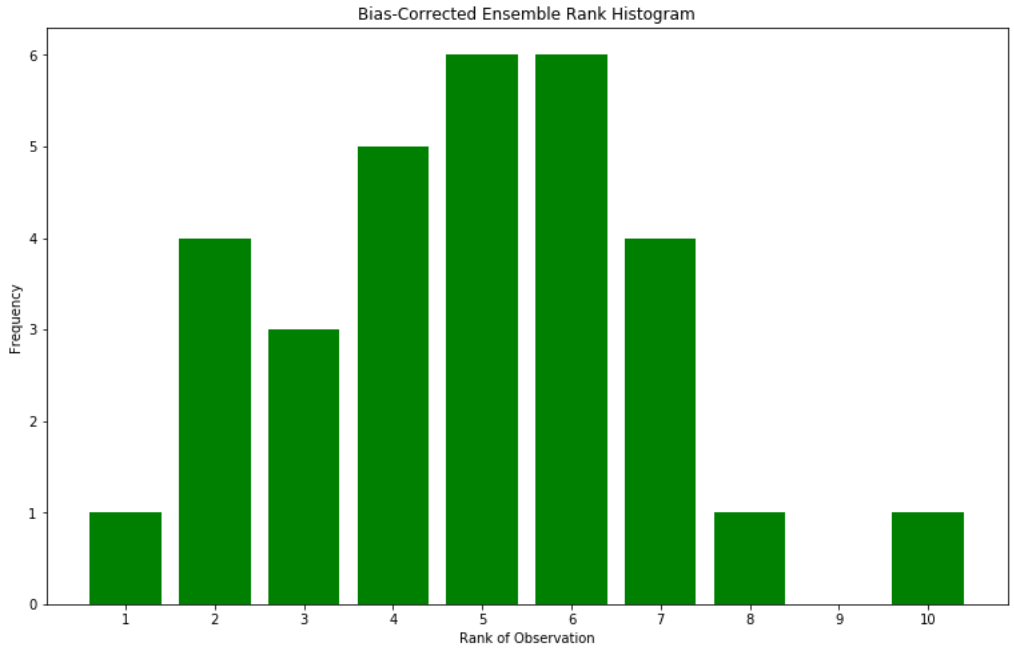

FIGURE 18. Bias-Corrected Rank Histogram

Correcting for bias has led to the improvements of essentially all skill scores. kwbc still performs among the best, particularly in RMSE and ACC, while cwao remains the least skillful by far.

Rather than subtracting the overall average bias from all forecasts, we could have subtracted from each forecast its own bias. This would lead to greater precision again. Another way to go would be to assign weights to the individual forecasts according to their skill, and use as a forecast the weighted average of the overall ensemble. In this instance, kwbc performed well, so we would assign it a large weight, while cwao performed poorly, so we would assign it a small weight, or perhaps even exclude it from the ensemble.

Caveat: This 31-day period is a small sample size. We tailored the ensemble to best match this period. Further analysis of the tailored ensemble on other sample dates throughout a year/years would be needed to properly assess its skill.

3. Climate Projections

As mentioned in the introduction, here we will be working with six datasets: three sets of temperature projections belonging to climate models from two research centres, the French National Centre for Meteorological Research (CNRM) and the Irish Centre for High-End Computing (ICHEC). The first of the three datasets contains the model's projections over the historical period 1979-2006. For each model, the projections will be compared to the actual observed temperatures from that period to assess how well each represents the climate of Zuerich.

The other two datasets contain temperature projections for the future period 2070-2100.
One of these projects temperatures in the RCP4.5 emissions scenario. From Wikipedia: RCP 4.5 is described by the IPCC as an intermediate scenario. RCP 4.5 is more likely than not to result in global temperature rise between $2°C$, and $3°C$, by 2100. Many plant and animal species will be unable to adapt to the effects of RCP 4.5 and higher RCP.
The third dataset projects temperatures in the RCP8.5 emissions scenario. From Wikipedia: In RCP 8.5 emissions continue to rise throughout the 21st century. This is generally taken as the basis for the worst case climate change scenario.
For each scenario and each model, we'll compare the projections over the 2070-2100 period to the observed 1979-2006 period and look at the projected temperature changes.

3.1. **Historical Climate Projections.**

Below you'll see a plot of the average monthly temperatures from 1979-2006 for each of the models and the observed.

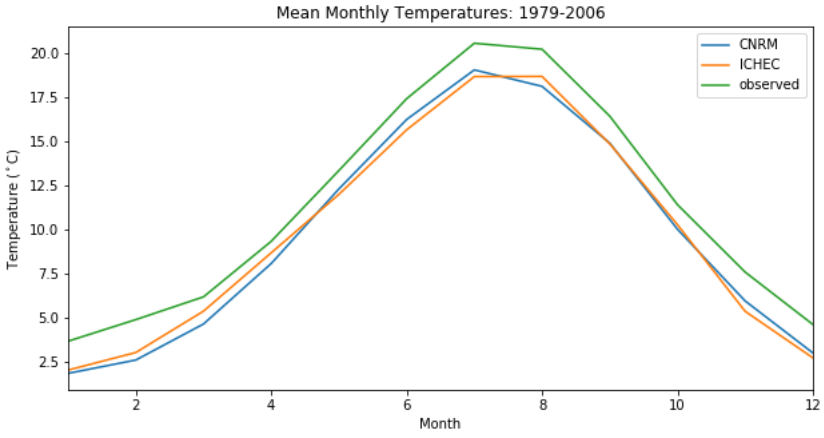

Figure 19. Mean Monthly Temperatures from 1979 to 2006: models and observed

While there's very little separating the two models, it's clear that they both consistently underestimate the temperatures throughout the year. The bias corresponding to CNRM is -1.57, while the bias corresponding to ICHEC is -1.53. I suspect there may be systemic error at play here.

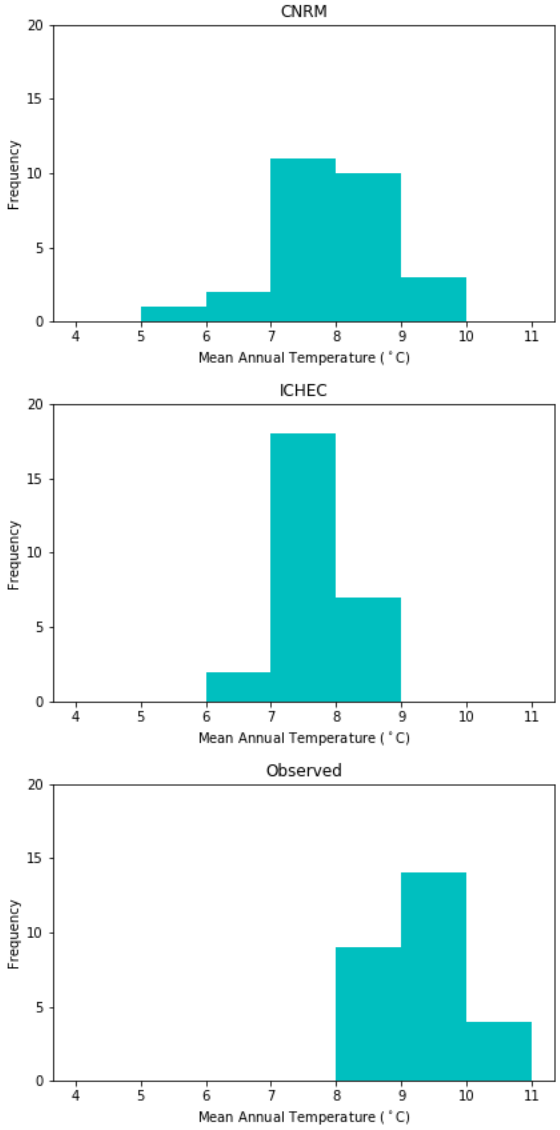

FIGURE 20. Frequency of Mean Annual Temperatures from 1979 to 2006: models and observed

From figure **??**, we can see that CNRM has a high range of mean annual temperatures, while ICHEC is less widely distributed, but both are to the left of the observed. However, if ICHEC were to be shifted up a little bit, it would match

the observed rather well.

We'll now consider, for each model, the overall mean, the standard deviation, extreme values and skewness, and compare to the observed data.

	CNRM	ICHEC	Observed
Mean	7.96	7.71	9.28
Standard Deviation	7.47	6.76	7.45
Minimum	-20.71	-19.33	-18.10
Maximum	26.95	25.79	27.40
Skewness	-0.21	-0.18	-0.11

FIGURE 21. Models vs Observed Stats (1979-2006)

Looking at the stats in figure **??**, it's still hard to conclude which of the models best fits the observed data. I think they would both model the observed climate very well if bias were removed.

3.2. **Future Climate Projections.** We'll look at the monthly average temperatures for 2070-2100 from each of the four models, alongside that of the observed data from 1979-2006. We'll then look at the monthly average temperature changes with respect to the observed data for each of the four.

For each projection, we will compute the overall average projected temperature across the 30 years. We will subtract the overall average historical temperature from the overall average projected temperature, giving us the projected change in temperature for each model and scenario.

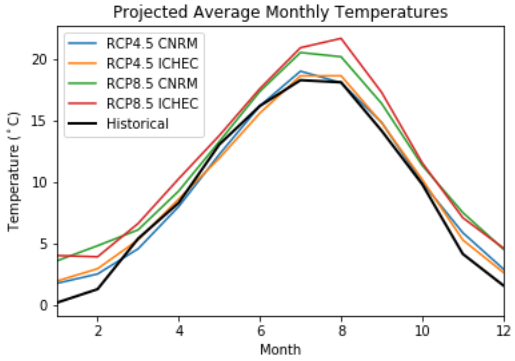

FIGURE 22. Projected Average Monthly Temperatures (2070-2100)

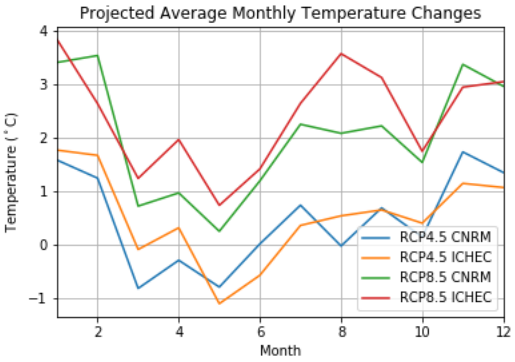

FIGURE 23. Projected Average Monthly Temperature Changes (2070-2100)

The two models are quite similar in their RCP4.5 projections, seeing negative change in the Spring months, which is surprising, and positive change in Autumn/Winter. For RCP4.5, the average temperature changes across the twelve months for CNRM and ICHEC are increases of $0.45°C$ and $0.50°C$ respectively

Annual Mean Temperature	°C
Historic Observed	9.24
RCP4.5 ICHEC	9.69
RCP8.5 CNRM	9.75
RCP8.5 ICHEC	11.27
RCP4.5 CNRM	11.64

Annual Mean Temperature Changes	°C
RCP4.5 ICHEC	0.45
RCP8.5 CNRM	0.50
RCP8.5 ICHEC	2.03
RCP4.5 CNRM	2.40

FIGURE 24. Projected Average Monthly Temperatures and Temperature Changes (2070-2100)

While there is greater disparity between the two RCP8.5 models, the projected temperature changes for both are significantly greater than RCP4.5. From figure **??**, it seems that ICHEC predicts greater temperature change than CNRM for most of the year. For RCP8.5, the average temperature changes across the twelve months for CNRM and ICHEC are increases of $2.03°C$ and $2.40°C$ respectively

The trends of the projected temperature changes are roughly the same shape for all four models. The Autumn/Winter months see the greatest temperature change, while temperatures in Spring see the smallest change.

If we are to consider the two models to be of equal importance, it would make sense to average them to obtain one figure each for the projected temperature changes.
For RCP4.5, the 'ensemble' average temperature change is $0.48°C$.
For RCP8.5, the 'ensemble' average temperature change is $2.21°C$.

From what I've read about the different RCP scenarios and projections in a global sense, it seems that other areas may be worse-affected by climate change than Zuerich.