Differences between the mean temperature of climate models compared to weather station (and derived) data in coastal cells.

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Introduction

We have recently produced a report on the maximum monthly temperature (Tmax) in coastal cells where the Tmax of the land in coastal cells is reduced by the Tmax of the water in that cell. As many people live along the coast, this reduction in Tmax of coastal cells can also reduce the impact we are studying – the impact of heat on working people. We have also produced a report on Tdew again focussing on coastal cells. Early indications were that Tmean for coastal cells had good agreement with weather stations and CRU and this report was initiated to confirm this

In this report we use Tmean as the monthly average of the daily average temperature in a ½ X ½ grid cell. While Tmax is the most important term in determining heat stress, Tmean also plays a significant role especially when the daily variation in temperature is small such as for tropical countries.

This report only considers coastal cells, because in our impact measure (work hours lost) we found the largest issues were with the data along the coast where large populations live. The special feature of coastal cells is that they are part land and part water. The land heats up more quickly than the water so in the warmer months of the year, the way the grid cell temperature is measured and what it is used for becomes important. Large populations live and work near the coast, and they experience the land temperature in that grid cell – as measured by weather stations which are mainly on land. Satellite data averages the temperature in the grid cell which can be depressed by up to 3C by the cooler water. This is clearly shown in the Tmax report (B lemke 2021). We do not expect these large errors in Tmean because the land and sea are much more likely to have the same Tmean value while the Tmax and Tmin are strongly affected over the course of 24 hours by the rapid heating (or cooling in winter) of the land.

Method:

We have developed a table of ½ x ½ degree grid cell Tmean data for various models so they can be directly compared. This table has monthly Tmean data averaged over 10 years 2001 to 2010 for all models we use and for weather stations (GSOD 2020): CRU TS 3.36 (CRU 2019/20), GFDL2b, HadGEM2b, GFDL3b, UKesm3b (ISIMIP 2020/21) and ERA5 (ERA5 2021). We included the EWEMBI model (ISIMIP 2020/21) used to bias correct ISIMIP2b data and based on the CRU data; and the W5E5 model (ISIMIP 2020/21) used for bias correction of ISIMIP3b and based on CRU (for land cells) and ERA5 (for ocean cells).

Stage 1: Grid cell comparisons

For this first stage all grid cells that did not have a good weather station within them were removed. We deemed a good weather station as one that had over 80% completeness of days per annum. Each grid cell had an associated land percent, population, altitude, latitude and longitude. As we are not interested in Tmean for colder regions, we excluded all weather stations in the polar circle (north and south of 66.5 degrees) and all grid cells and weather stations above 1000m. We also excluded cells where the altitude difference between weather stations and the grid cell altitude was more than 500m because the lapse rate with altitude decreases the temperature between 5-10C per 1000m. We only considered coastal cells that had less than 80% land because we found that the proportion of water in a cell included water in lakes and large rivers which are not likely to have the same cooling effect as a large body of ocean. The 80% land threshold we used for coastal cells eliminates most of the small lakes and rivers from our coastal analysis. In stage 1, coastal cell Tmean from weather stations was compared to that of CRU to see whether CRU could be used as a substitute for weather stations for climate model comparisons. CRU is derived from weather stations (B Lemke 2021 CRU errors) but is more useful, because it covers more cells especially in large cities because often the NOAA weather station is in one city grid cell and there is no weather station in the neighbouring highly populated grid cells. Gridded CRU data also allows for a better comparison with other gridded model data because land areas are being compared to the same land area rather than to single points. The land area comparison averages the altitude in the area so we can relax the less than 500m altitude difference criteria used for weather stations which may be on a high mountain in the grid cell. Again, the polar regions and grid cells over 1000m were excluded and we only considered coastal grid cells with 80% or less land.

Starting off with 68940 land-based grid cells, once all grid cells with more than 80% land were removed we ended with 7475 grid cells. When polar cells (above 66.5 latitude) are removed 6866 coastal cells remained. When all grid cells and weather stations above 1000m were removed 6791 cells remained. This is the data used for CRU comparisons.

For weather station comparisons we added the restrictions that only those grid cells that had a good weather station in them (80% completion rate) were used which lowered the count to 920 grid cells. The final restriction was that we only used weather station and grid cell data where there was less than 500m difference in altitude and that left us with about 900 grid cells with full data for most months of the year.

In pursuing our studies we found faulty weather stations and faulty CRU data. These are documented in a separate report (B Lemke 2021 CRU errors). Removing these had negligible overall affect on our data except to the maximum and minimum model deviations from CRU or weather station data.

Stage 2: Country comparison
Country data coastal data was compared similar to the comparison for Tmax so we could make a direct comparison. The names of the country occupying a grid cell was stored in our table in an approximate form: for boundary cells, the cell was assigned to the country with the largest area in the boundary cell. Polar regions and grid cells over 1000m were excluded and we only considered coastal grid cells with 80% or less land.

RESULTS

Results (stage 1a): coastal cell Tmean from models compared to Tmean from weather stations.

A quick check of this data is shown in Figure 1 which shows the Tmean(CRU) minus Tmean(weather station) for 5% bins from 0 to 80% land cover.

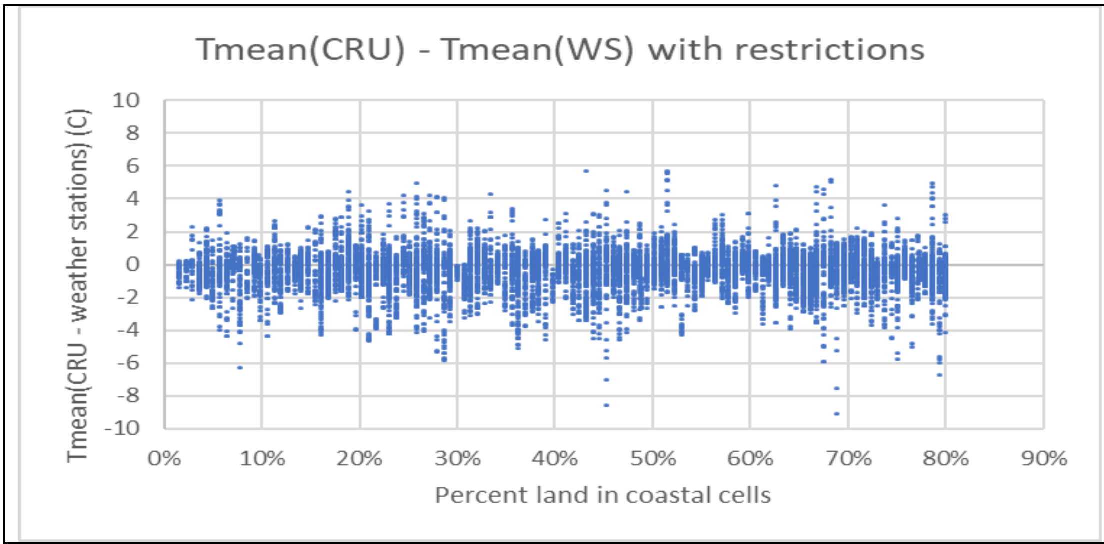

Figure 1 Tmean(CRU) minus Tmean(weather stations) vs percent land cover in coastal cells with the restrictions: no polar weather stations, no weather stations above 1000m only grid cells with weather stations and where the weather station altitude differed by less than 500m from the grid cell altitude. All grid cells deemed as coastal with less than 80% land in them.

By comparing Figure 1 with a similar graphic in the Tmax report, it can immediately be seen that the scatter is far less with the 2C scatter in this graphic looking like the 5C scatter in the Tmax graphic. The faulty CRU grid cells and weather stations that have been previously identified have not been removed as removing then was found to make a negligible difference (less than 0.001 for the mean).
The mean and standard deviation of CRU Tmean temperature compared to those of weather stations are shown in Table 1 along with the mean and standard deviations described in the Tmax and Tdew reports.

Table 1 comparison of the difference between the CRU and weather stations (WS) for all months 2001-2010 for Tmax and Tdew (B Lemke 2021 Tdew report, Tmax report) and Tmean

Model minus WS all months 2001 to 2010	Mean	Standard deviation
Tmax(CRU) minus Tmax(WS)	0.01	1.46
Tmean(CRU) minus Tmean(WS)	-0.34	1.19
Tdew(CRU) minus Tdew(WS)	-0.17	1.35

Table 1 has interesting results. The Tmean(CRU) minus Tmean(weather stations) has a low standard deviation indicating a good match, but the offset for Tmean is greater than for Tmax and Tdew. CRU data is based solely land weather station data. It is unlikely to be affected by cooler seas in that grid cell. It could be that most weather stations are located at the fringe of urban areas where there is still some influence of urban heat island (UHI) effects while CRU data could well remove much of the UHI by considering weather stations further afield. The 0.34 (CRU less than weather stations) offset needs to be kept in mind when comparing with modelled data.

Results (stage 1b): coastal cell Tmean from models compared to Tmean from CRU.
For Tmax(models) the largest errors were for Tmax(model) being too low – lower than Tmax(CRU). Hence we set up the same comparison for Tmean so we can directly compare the results of Tmean and Tmax over the full range of land coverage (see Figure 2).

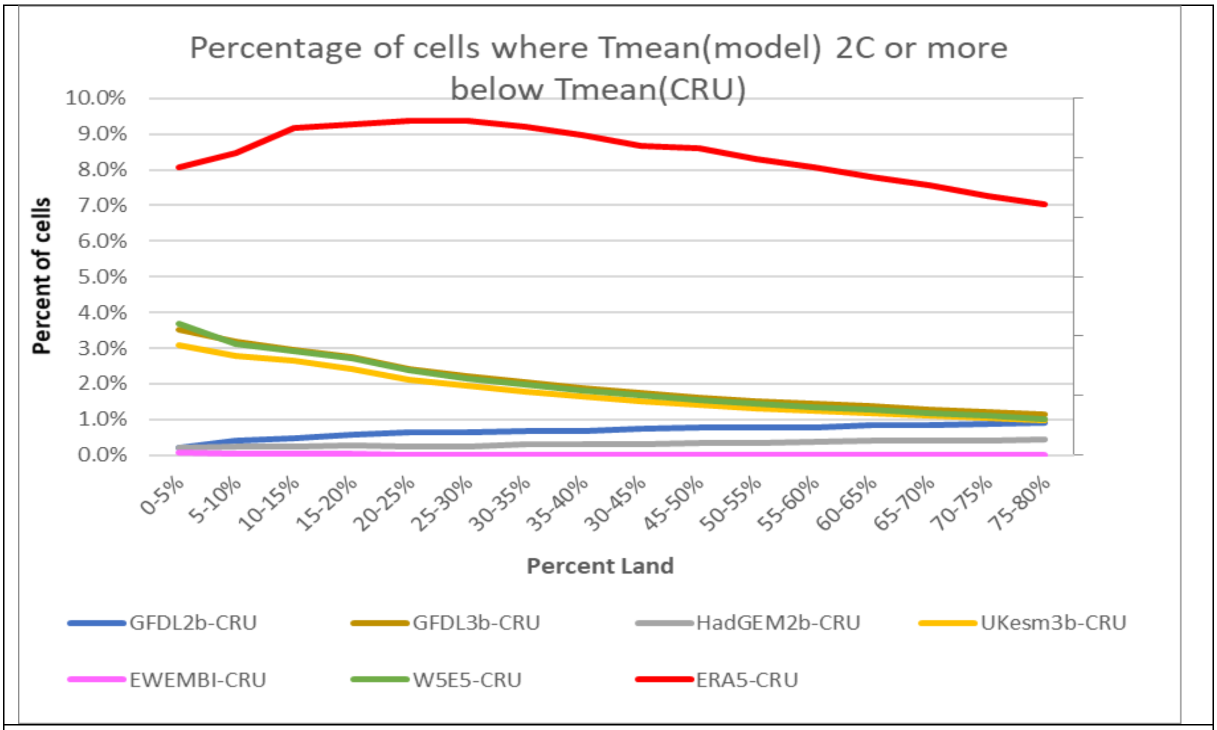

Figure 2a Percentage of coastal cells in each 5% land area bin where model **Tmean** is more than 2C below **Tmean**(CRU). Monthly averages 2001 to 2010. GFDL3b line is hidden behind W5E5 line.

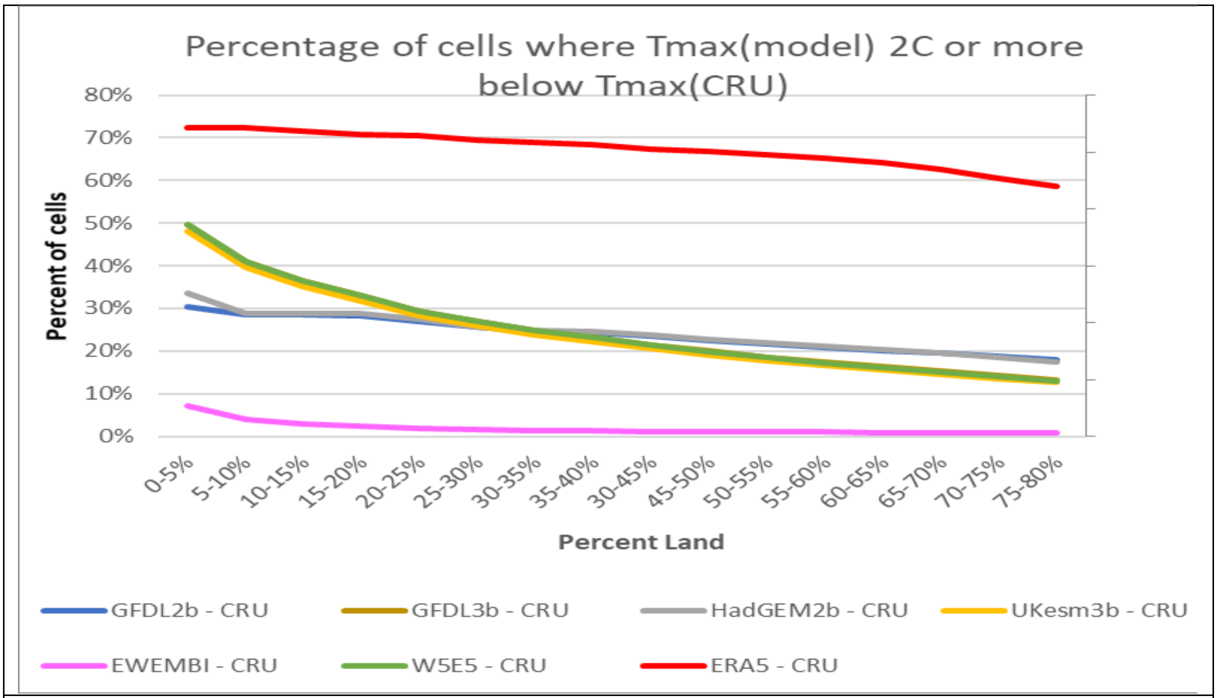

Figure 2b Percentage of coastal cells in each 5% land area bin where model **Tmax** is more than 2C below **Tmax**(CRU). All data 10 year monthly averages 2001 to 2010

It is clear by comparing Figure 2a and Figure 2b that the depression of coastal cell temperatures is very much less for Tmean than for Tmax. While Tmean(ERA5) still has the greatest depression of all the models, a 2C depression only occurs for about 9% of coastal cells while for Tmax(ERA5) it occurs for about 60-70% of coastal cells. Tmean(ISIMIP) depression is very small, mostly affecting less than 2% of coastal cells.

The main concern for us was the population in the coastal cells that where Tmean was at least 2C too low compared to CRU data. As we were only considering the ISIMIP models in our impact analysis we removed ERA5, EWEMBI and W5E5 populations from the graphics so one could more clearly see the population in the four ISIMIP models. This is shown for Figure 3a and 3b for Tmean and Tmax.

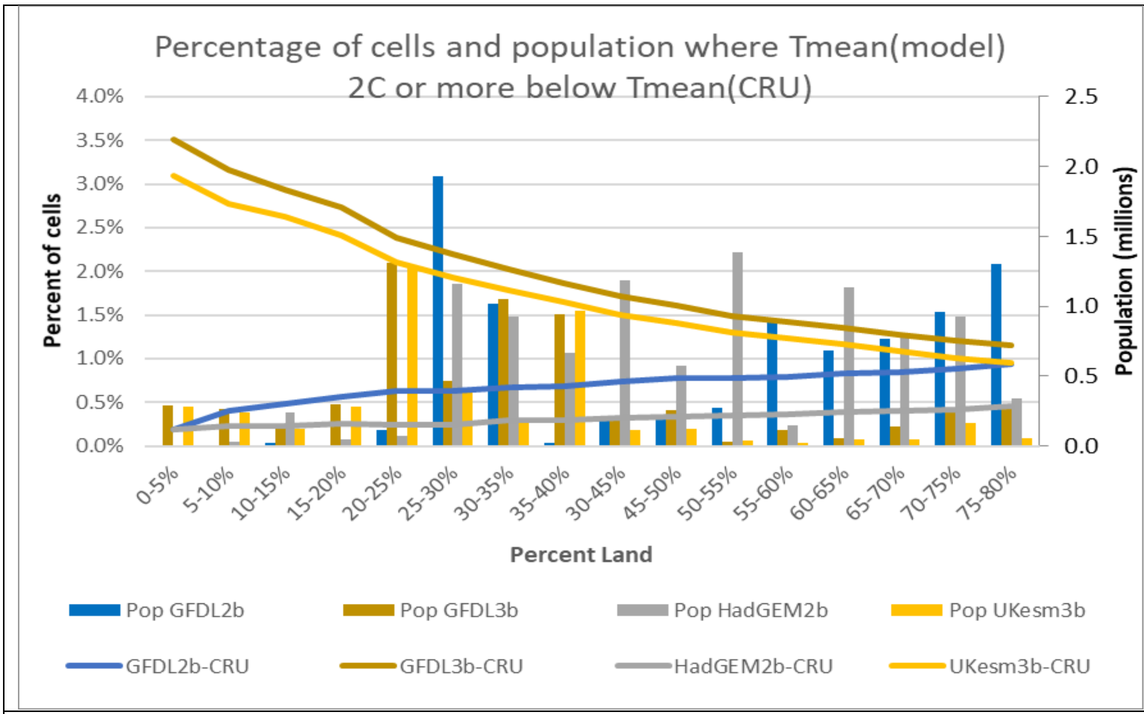

Figure 3a Left axis: Percentage of coastal cells in each 5% cell land area bin where **Tmax**(model) is more than 2C below **Tmax**(CRU). Right axis: Population in each land percent bin with **Tmean**(model) 2C or more below **Tmean**(CRU) shown by the vertical clustered column bars.

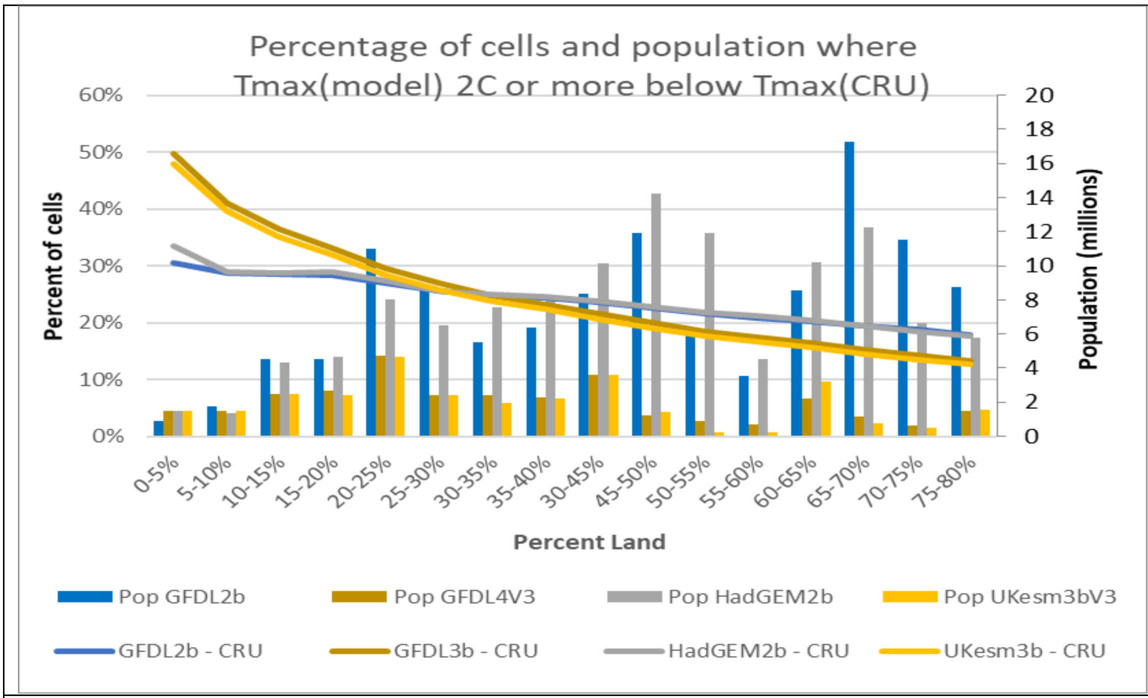

Figure 3b Left axis: Percentage of coastal cells in each 5% cell land area bin where **Tmax(**model) is more than 2C below **Tmax**(CRU). Right axis: Population in each land percent bin with **Tmax**(model) 2C or more below **Tmax**(CRU) shown by the vertical clustered column bars.

Figures 3a and 3b show that for both the number of ISIMIP cells less than 2C lower than CRU and the population in those cells are an order of magnitude smaller for Tmean than for Tmax. It also shows that the number of coastal cells that have Tmean different from CRU is higher for ISIMIP3b, but the population in those aberrant cells is lower in ISIMIP3b than for ISIMIP2b. Tmean(ISIMIP3b) has a large population in the 20-25% land bin and on investigating this originated in north easterly grid cell of Bahrain with a large population (over 1M in the grid cell) and with Tmean(ISIMIP3b) being about 2C lower than Tmean(Bahrain weather station), while the Tmean(ISIMIP2b) values are about the same as for the Tmean(Bahrain weather station).

Also the too low Tmax(GFDL2b) in the 65-70% land area bin from Chennai (B Lemke ISIMIP2b report 2019) which raises the population in that Tmax bin is considerably reduced in Tmean(GFDL2b) showing that this error was caused by faulty bias correction for Tmax only (S Lange 2019).

Table 2 shows the result when Tmean(CRU) is subtracted from the models (including EWEMBI and W5E5) The Tmean when the Tmean(model) has the highest difference from Tmean(CRU)is indicated in the table by "Max". When Tmean(CRU) has the highest difference from the Tmean(model) this is indicated by "Min" in the table. The 90 percentile is the Tmean value where 10% of the largest Tmean(model) are higher than the Tmean(CRU) and the 10 percentile is where 10% of the largest Tmean(CRU) are higher than Tmean(model).

Table 2 Comparing coastal grid cell Tmean from models with CRU for summer months in the northern and southern hemisphere and tropics. The table shows the mean difference from the Tmean(CRU), the maximum and minimum difference, the 90 percentile and 10 percentile and the standard deviation for each of the climate zones. Note that "Max" means the largest Tmean(model) in excess of Tmean(CRU) and "Min" means the largest Tmean(CRU) in excess of the Tmean(model)							
Coastal cells	GFDL2b-CRU	GFDL3b-CRU	HadGEM2b-CRU	UKesm3b-CRU	EWEMBI-CRU	W5E5-CRU	ERA5-CRU
Latitude= 23.4 to 66.6 (North of Tropics). June + July + August. n=7881							
Max	2.30	4.83	2.85	4.86	2.36	4.57	6.61
90Perc	0.83	0.61	1.17	0.91	0.11	0.31	0.84
Average	-0.04	-0.19	0.18	0.04	-0.01	-0.17	-0.93
10Perc	-0.95	-1.00	-0.67	-0.89	-0.13	-0.72	-3.15
Min	-2.80	-7.43	-2.81	-7.81	-2.36	-7.88	-14.17
SD	0.68	0.84	0.72	0.89	0.18	0.74	1.71
Latitude= -66.6 to -23.4 (South of Tropics). January + February + December. n=1542							
Max	1.44	3.28	2.01	3.30	0.74	2.77	4.71
90Perc	0.72	0.70	0.88	0.83	0.06	0.41	0.65
Average	0.07	0.04	0.11	0.19	-0.09	-0.05	-0.71
10Perc	-0.55	-0.50	-0.50	-0.39	-0.36	-0.46	-2.41
Min	-1.42	-4.68	-1.31	-4.11	-1.30	-4.52	-6.98
SD	0.48	0.68	0.53	0.67	0.19	0.63	1.31
Latitude= -23.4 to 23.4 (Tropics). March + April + May. n=6723							
Max	0.10	0.02	0.21	0.08	-0.06	-0.06	-0.35
90Perc	1.40	4.14	1.86	4.25	0.88	4.01	8.49
Average	0.51	0.55	0.61	0.59	0.02	0.35	1.11
10Perc	-0.39	-0.58	-0.20	-0.51	-0.22	-0.51	-1.68
Min	-1.86	-8.23	-1.93	-8.04	-1.63	-7.97	-8.46
SD	0.38	0.67	0.38	0.67	0.16	0.64	1.28
Latitude= -23.4 to 23.4 (Tropics). September + October + November. n=6723							
Max	1.86	6.53	1.66	6.62	0.94	6.56	6.52
90Perc	0.56	0.44	0.60	0.53	0.02	0.32	0.98
Average	0.10	0.01	0.18	0.08	-0.07	-0.05	-0.30
10Perc	-0.41	-0.54	-0.29	-0.49	-0.24	-0.55	-1.47
Min	-2.28	-4.79	-1.99	-4.29	-2.34	-4.74	-6.27
SD	0.40	0.58	0.37	0.59	0.16	0.57	1.13
Global (excluding polar regions). All months n = 63240							
Max	5.07	12.08	6.88	12.17	3.51	11.64	13.16
90Perc	0.83	0.90	1.04	1.14	0.06	0.51	2.05
Average	0.09	0.11	0.24	0.26	-0.03	0.05	0.11
10Perc	-0.71	-0.70	-0.56	-0.58	-0.19	-0.43	-1.62
Min	-5.15	-8.23	-4.27	-8.04	-2.64	-7.97	-9.11
SD	0.73	0.89	0.78	0.93	0.17	0.77	1.66

What stands out in table 2 is that all average Tmean(model-CRU) are very close to 0 (within +/-0.2) except ERA5 which is +/- 1C from 0. The EWEMBI model has the least difference from the CRU data except in the tropics where it is about 0.45C higher than the CRU data. Again the EWEMBI model performs very well with its average value very close to that of CRU and also with a small standard deviation.

The monthly variation of Tmean for all the models is shown graphically in Figure 4a, 4b and 4c.

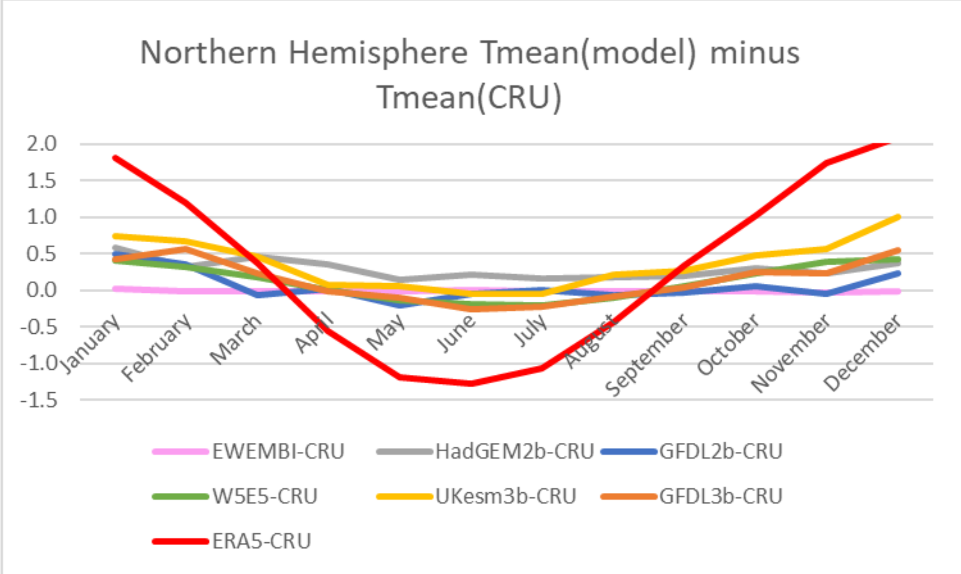

Figure 4a Northern Hemisphere Tmean difference of the 7 models from CRU

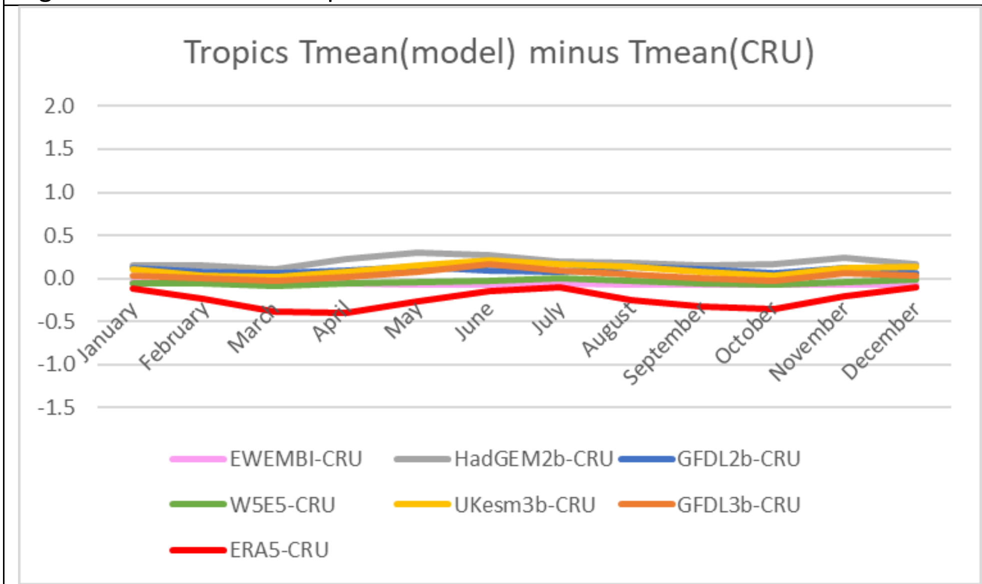

Figure 4b Tropics Tmean difference of the 7 models from CRU

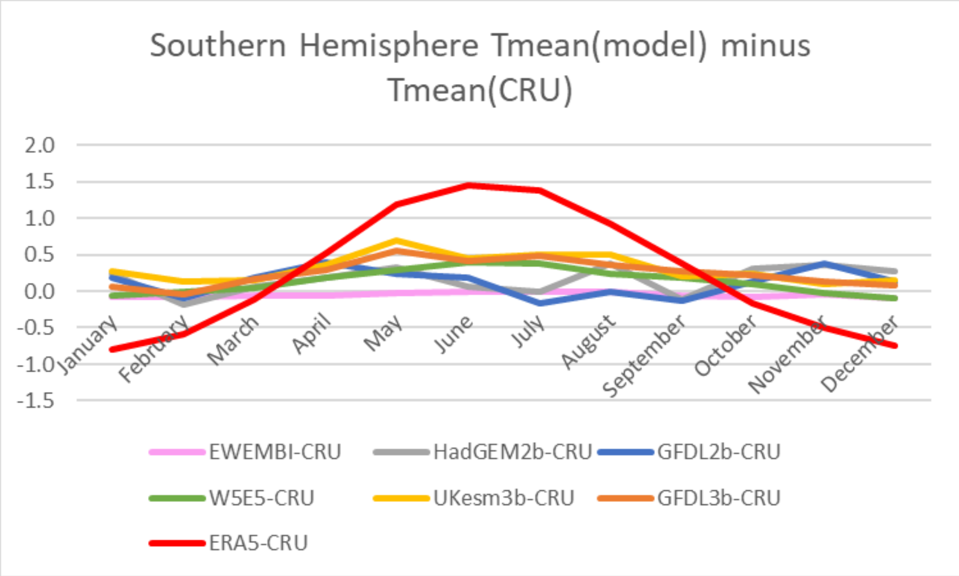

Figure 4c Southern Hemisphere Tmean difference of the 7 models from CRU

It is clear from figures 4a-4c that for most months the deviation of Tmean for all models except ERA5 from the Tmean of CRU is less than 0.5C. Tmean(ERA5), on the other hand, is about 1.5C warmer in the winter months and 1.5C cooler in the summer months. The swing in ERA5 for Tmean is about the same as for Tmax, but the 2C cooler offset observed for Tmax (see figure 5) is not apparent for Tmean. One can surmise from this that the average monthly sea temperatures in summer are cooler in summer hence lowering the average of coastal grid cells that include water by about 1.5-2C. While in winter the average sea temperature is warmer than the average land temperature raising the grid cells that include water by about the same amount. This occurs for both Tmax and Tmean. Over and above that, the large 2C offset shown in Figure 5 for Tmax in the northern hemisphere also includes the effect of the cooling influence of the water as the land is heated during the day in the coastal cells.

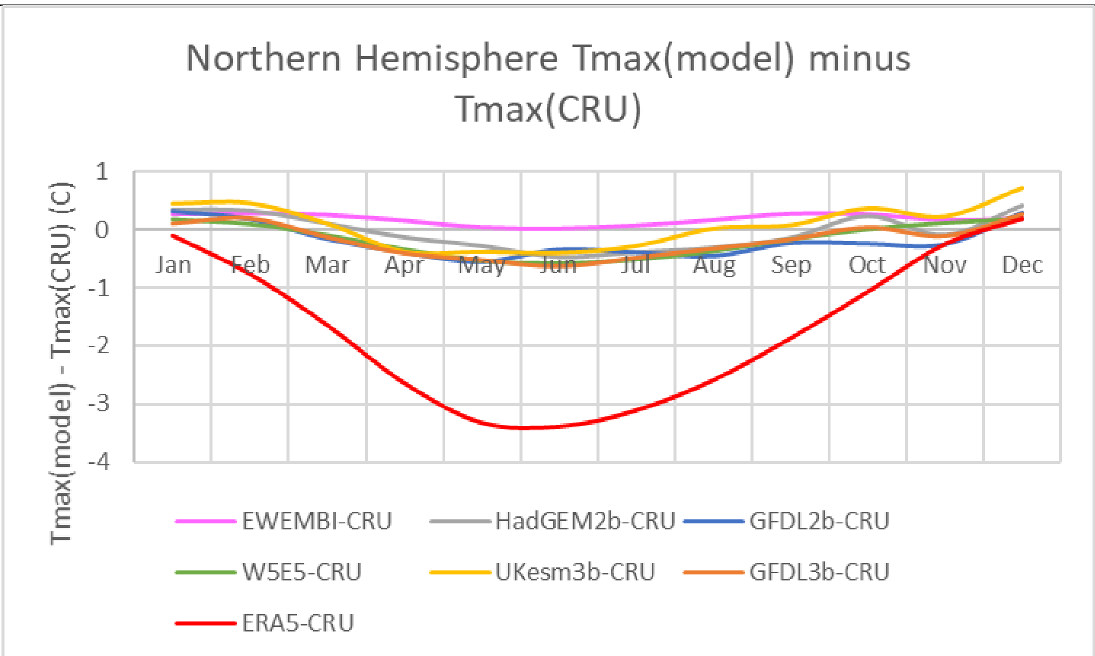

Figure 5 Northern Hemisphere Tmax difference of the 7 models from CRU

Results Stage 2 Comparing Tmean for Coastal Grid cells in countries.

The difference between the model data and CRU for coastal cells in all countries was determined in this section. While 202 countries have a coastline, about 25% of these are small island states. In this section, while data is available for each month separately, the results shown are for all global coastal cells for all months. This is because some countries have all 12 months where the Tmean difference is high so by limiting to only some months (different for each hemisphere) this does not give a good representation of the overall impact of coastal Tmean depression. Since we are focusing on population effects, the other important factor to note (see figure 3a) is that some coastal grid cells have a very large difference in Tmean(model-CRU) but have a very small population, while others have a small difference in Tmean(model-CRU) but a high population. A country population weighted Tmean was therefore included in the analysis.

Part 2a Tmean difference values only

The number of countries where Tmean(model) was less than Tmean(CRU) on **average** by 1C or more for all that country's coastal cells was GFDL2b=1, GFDL3b=12, HadGem2b=3 and UKesm3b=13. Note that the 1C difference indicate an acceptable difference for our impact work.

The countries that figured on this list except for ERA5 were all Island countries (see also table 3): Curacao, Dominica, Isle of Man, Kiribati, Saint Kitts and Nevis, Maldives, Montserrat, Norfolk Island, Saint Helena, Saint Pierre and Miquelon, Sao Tome and Principe, Tokelau, Tuvalu, Saint Vincent and Grenadines, Vanuatu, Samoa.

ERA5 had 36 countries where the average coastal Tmean(ERA5) varied from Tmean(CRU) by 1C or more.

Table 3. Number of countries with coastlines where the average (for all coastal cells) of Tmean(model) was different from Tmean(CRU) by 1C or more. Names of those countries where the average difference is 1C excluding those small island nations listed in the text above.

	Tmean(GFDL 2b – CRU)	Tmean(GFDL 3b – CRU)	Tmean(HadGEM 2b – CRU)	Tmean(UKesm 3b – CRU)	Tmean(ERA5 – CRU)
Number of countries	1	12	3	13	36
Countries with Tmax difference of all cells > 1C Excluding small island states	Only small island states	Only small island states	Only small island states	Only small island states	Albania, Benin Bahrain, Gabon Ghana, Gambia Guinea-Bissau, Honduras, Croatia, Montenegro, Namibia, Peru, Qatar, Sudan Senegal, Somalia Taiwan, Ukraine, Western Sahara

Part 3b Population weighted Tmean difference.

When population weighting is introduced, many of these small island countries are not significant in their impact because of their low population. So we multiplied the Tmean(model - CRU) by the population IN EACH grid cell and then repeated the averaging of all coastal cells in each country. For example, if the Tmean difference is 2C then a population of 100,000 in a grid cell will give a 200,000 person-degree difference.

If the country average of all coastal cells Tmean(model)*Population is different from Tmean(CRU)*Population by 100k person-degrees or more, the number of countries were as follows: GFDL2b=16, GFDL3b=18, HadGem2b=17, UKesm3b=18. See Table 4 for more detailed data but where a 200k person-degrees criteria was used so the table did not become too large. Countries with just 1 coastal cell were excluded.

For ERA5 there were 38 countries where the country average of all coastal cells when Tmax(model - CRU)*Population was over +/-100,000.

Table 4. Name of countries including their affected coastal populations where the coastal cell population weighted average Tmean(model) differed from Tmean(CRU) by over the 2k person-degree threshold. The values in the models*Population columns are in bold-italics where for the models where the threshold is exceeded. Positive values of Tmean(model - CRU) *Population indicates Tmean(model)> Tmean(CRU) while a negative values indicates Tmean(CRU)>Tmean(model) when population weighted. Country population for 2010. (The World Bank Group 2020).

Country	Coastal Populat^n	Country Populat^n	GFDL2bDiff *Populat^n	GFDL3bDiff *Populat^n	HadGEM Diff *Populat^n	UKesm Diff *Populat^n	ERA5 Diff *Populat^n
Bahrain	0.62	1.24	***-0.25***	***-0.63***	0.04	***-0.53***	***-0.62***
Côte d'Ivoire	0.76	20.53	0.19	0.07	***0.22***	0.06	***-0.73***
Ghana	0.15	24.78	0.04	-0.02	0.05	-0.01	***-0.24***
India	0.89	1234.28	0.15	-0.03	***0.24***	0.00	***-0.79***
Israel	2.42	7.62	***-0.56***	***-0.82***	-0.07	-0.15	***0.21***
Kuwait	0.59	2.99	***-0.41***	***-0.26***	***-0.24***	-0.09	***-0.59***
Nigeria	0.34	158.50	0.03	-0.01	0.08	-0.01	***-0.32***
Pakistan	0.24	179.42	-0.06	-0.05	0.00	-0.03	***-0.22***
Peru	0.22	29.03	0.07	0.09	0.16	0.12	***-0.21***
Qatar	0.21	1.86	-0.13	-0.10	-0.05	-0.07	***-0.28***
Senegal	0.24	12.68	0.03	-0.09	-0.06	-0.04	***-0.40***
Singapore	3.40	5.08	***0.67***	***-0.36***	***1.08***	-0.04	***-2.12***
Taiwan	0.46	23.19	0.16	-0.03	***0.32***	0.15	***1.01***
Viet Nam	0.73	87.97	0.05	-0.07	0.17	0.03	***-0.22***

Table 4 shows that all the countries listed have issues when using ERA5 Tmean data while only Bahrain, Israel, Kuwait and Singapore have issue when using the ISIMIP3 data. Note that this excludes small island states which have low populations.

Conclusion.

The first part of this report showed that Tmax(CRU) was a good substitute for Tmax(weather stations) in comparing model data to the best real (historical) data provided the small offset of 0.34C with CRU less than weather stations in remembered. CRU covers more coastal grid cells (6791) than just weather station data (900 grid cells).

In general the average of Tmean(ISIMIP-CRU) = 0.17C (table 2) is about the same as the average of Tmax(ISIMIP-CRU) = -0.14C and the standard deviation of Tmean(model-CRU) = 0.83C is about half that of Tmax(model-CRU) = 1.51C. For ERA5 the average and standard deviation of Tmean(ERA5-CRU) is 0.11C and 1.66 while Tmax(ERA5-CRU) it is -2.16C and 2.29C.

When models are compared with CRU at a country level, Tmean(ISIMIP) has on average 18 countries with 100k difference in person-degrees while for Tmax(ISIMIP) this number is 70. For Tmean(ERA5) there are 38 countries where this criteria is exceeded and 121 countries exceed this criteria for Tmax(ERA5).

Overall, if ISIMIP3b is being used there are no serious issues with Tmax and Tmean in the calculation of population impacts like work hours lost using WBGT. The only exceptions being small island states and Singapore, Kuwait, Hong Kong, Israel and Bahrain. However caution needs to be used when using ERA5 for coastal cells when calculating impacts on land based activities as both Tmax(ERA5) and Tmean(ERA5) have many countries where there is a large population weighted difference in coastal cells.

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