Final report

Updating Shipping Route Data for the Heat Stress Risk Assessment (HSRA) Model Project Report

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Abstract

The overarching goal of this project is to improve heat stress support for the Australian red meat livestock export program. This research was commissioned and managed by LiveCorp in conjunction with Meat & Livestock Australia (MLA). There is a strong relationship between the 2-metre Wet-Bulb Temperature (WBT) and heat stress livestock experience along international shipping routes. Therefore, the project objective is to build an up-to-date climatology of WBT along MLA's shipping routes between Australia and Middle Eastern and Asian ports.

The European ERA5 climatological data was used to provide the base data. The WBT climatology for the region's shipping routes to Middle Eastern and Asian ports was derived from this dataset. The ERA5 data was processed and bias-corrected using a quantile-to-quantile bias correction technique, focussing on the bias correction of the highest WBT percentiles as this is the climatological data critical to the identification of heat stress risks for livestock shipments across large oceanic areas.

Comparisons between the original (2003 to 2008) port and route WBT climatologies – as used by the original HotStuff model - and the 2011-2020 climatologies - as developed in this project – are also included in this report.

The benefit to the industry is the availability of the most up-to-date climatology of WBT at 30-kilometre resolution along the main shipping routes used by Australian exporters, with the ability to add new routes as needed. An additional bonus is the provision of the observed linear trends in WBT associated with climate change through the period 2011-2020, allowing the WBT climatologies to be adjusted as needed in future years to cater for climate change effects.

Executive summary

Background

The Australian Standards for the Export of Livestock (ASEL) 2.3 — which have been in place since 2011 — were reviewed in 2018-19, focusing on setting requirements to ensure animals are fit to export from Australia and their health and welfare risk is managed throughout the export voyage. The purpose of the review was to ensure the standards remain fit for purpose and reflect the latest science.

The ASEL technical review committee consulted widely in forming its views. Based on information received and the committee's own analysis, they recommended several changes to the standards to help ensure the welfare of animals entering the live export supply chain are maintained.

The committee recommended a key change concerning circumstances where a heat stress risk assessment (HSRA) must be conducted. This was reviewed extensively, and the recommendation effective 1 November 2020 is that an HSRA will be required for all export voyages that cross the equator. Previously the HSRA was only required for any livestock export shipment to and through the Middle East.

As a result of the recommendation for an HSRA for all voyages crossing the equator, there is a requirement for shipping routes and port data within the model to be updated. The current heat stress risk assessment (HSRA) model relies on historical weather data to predict risk, which has not been updated since its development in the early 2000s. This report addresses the heat stress data, specifically monthly wet-bulb temperature (WBT) climatological data, required to satisfy these recommendations as they apply to shipping routes from Australia to Middle Eastern and Asian ports north of the equator.

Comparisons were conducted between the original (2003 to 2008) port and route WBT climatologies – as used by the original HotStuff heat stress risk assessment model - and the 2011-2020 climatologies developed in this project. Most Middle Eastern ports have experienced rises in WBT for most months during the past two decades. However, trends with the route data were found to be lower, with some apparent slight reductions in the 98th percentile WBT between the original (2003) HotStuff Northern and Southern Persian Gulf and Red Sea routes. These slight reductions are attributable to the different methodologies used to generate the highest WBTs for the two key routes.

The results of these analyses will be used by livestock exporters operating out of Australia to better manage their stock selection and stocking levels and the timing of voyages on a variety of shipping routes and destination ports where heat stress can be an issue at certain times of the year.

Objective

The objective of this report is to provide the technical description of how up-to-date monthly WBT climatological statistics — based upon bias-corrected ERA5 data for the period 2011-2020 — were produced. This is critical information needed to inform livestock exporting operators out of Australia of the likely heat stress risks for the oceanic component of shipping routes to key Middle Eastern and Asian destination ports. The actual WBT datasets described here are separately provided to the MLA and are being integrated into the new version of the HSRA model.

This report complements the reports prepared by Buckley (2021) — W.LIV.2017: "Final Report Collection and Validation of Island & Selected Additional Coastal Ports for Oceanic Bias Correction of ERA5 WBTs for the HSRA Model", W.LIV.2017 "Final Report Middle Eastern and West Asian Port Climatologies" and W.LIV.2017 "Final Report South & East Asian Port Climatologies" that provide the WBT climatologies for destination ports across the Middle East and Asian ports north of the equator.

This analysis and bias correction were undertaken by Drs Cindy L. Bruyère and James M. Done at the US National Center for Atmospheric Research (NCAR) / University Corporation for Atmospheric Research (UCAR), with assistance from Dr Bruce Buckley, Weather Australia, using the European Re-Analysis – 5 (ERA5) datasets. The ERA5 datasets are the highest quality reanalysis data available across the oceanic regions of interest.

Methodology

The availability of detailed climatological WBT data along the shipping routes used by the livestock exporters operating out of Australian ports is limited. The previous version of the Heat Stress Risk Assessment (HSRA) model utilised quality-controlled voluntary observing ship (VOS) data, aggregated into 5-degree latitude/ 10-degree longitude bins at monthly time steps. However, this data is known to suffer from poor quality humidity data, and there are large oceanic areas where the data is sparse. The last analysis of this dataset was also completed in the early 2000s. With the rapidly warming climate we live in, this oceanic climatology urgently needed updating.

The highest quality meteorological/climatological dataset spanning all the shipping routes used by Australian livestock exporters is the European Reanalysis Dataset, version 5. The ERA5 data was processed with the cumulative density functions generated for every grid point across the domain of interest - 50^{o}N to 45^{o}S, 20^{o}E to 165^{o}E. This domain covers the shipping routes to destination ports north of the equator across the Middle East and Asia.

The ERA5 data was then compared to high-quality observational data across the analysis domain and bias-corrected.

Comparisons between the original port weather station WBT climatologies, which uses data spanning 1998 to 2008 (see W.LIV.0267 Detailed Temperature and Humidity Climatology for Middle east Ports 2009), and the most recent observational data (spanning 2011 to 2020) were undertaken. For this comparison, we used the 98th percentile data for both periods for each month of the year and for the key Middle Eastern Ports in the original version of HotStuff. These results are included in Appendix 2.

The old (2003 HotStuff) and new (ERA5) Persian Gulf and Red Sea route WBT calculations use different datasets and methodologies. The original HotStuff model used aggregated Voluntary Observing Ship (VOS) data placed into large bins. Near-equatorial bins were 5^{o} latitude by 10^{o} longitude (approximately 605,000 square kilometres each). In the Red Sea and Persian Gulf, the data was aggregated into 5^{o} latitude bands. VOS data is known to have significant limitations regarding humidity measurements, and these limitations are described in the results section. The original route design was direct from Australia to the Gulf of Oman and the Gulf of Aden. The southern routes departed from Fremantle, while the northern departure location was undisclosed (most likely Darwin). Additionally, the original HotStuff model used VOS data recorded within a 500km range of the destination ports as the "destination" WBT values. These "destination" values differ from the port WBT climatologies, which use weather station observations from high-quality weather stations near the destination ports. The highest 98th percentile WBT from any of the large bins through which the routes cut was extracted. The intercept of this value and the "destinations" 98th percentile value was used as the HotStuff 98th WBT for each route. Additionally, the original HotStuff model applied a normal distribution to the VOS data then added a +1^{o}C adjustment to the mean to make the mean VOS data align better with the destination port data.

The ERA5 route data used the highest 98th percentile WBT from 0.25^{o} grid points (i.e., data points separated by approximately 30km at equatorial latitudes) and thus were far more targeted to the routes of interest. The routes were those supplied by LiveCorp and reflect the current ship routes used by ships to the Persian Gulf and Red Sea. These comprise a series of route segments that go along specified traffic separation lanes. A piracy avoidance strategy also shifted routes further east to a point just southwest of Sri Lanka before heading towards traffic separation zones leading into the Gulf of Aden. Therefore, neither the routes nor the data aggregation methods are directly comparable. The implications of this are discussed in the results section. The detailed comparisons are included in Appendix 3.

Results/key findings

The research project demonstrated that quantile-quantile bias-corrected ERA5 WBT data can accurately represent the actual WBT climatology — as defined by the numerous weather station validation climatologies that lie across the routes traversed by livestock from Australia to the Middle East and Asian ports. Bias-corrected WBT climatologies were produced for each percentile from 1% to 100% (including 99.9%), for each month of the year, and every grid point in the domain.

The climate change-induced trends in the WBTs were also quantified across the domain. These vary by location, with both positive and negative trends identified. The most substantial increases were found to occur in the Middle East, with the effects most prominent in the months of September and October.

The detailed comparisons between the port weather station 98th percentile data produced using the data spanning 1998 to 2008 with the most recent analyses spanning the period 2011-2020 for selected key Middle Eastern ports are contained in Appendix 2. The changes were not uniform in space and time. Overall, there were increases in WBT for all ports and most months of the year, in some cases by over 2.0^{o}C. There is evidence of a broadening of the highest heat stress periods for these ports and increasing WBTs at the hottest time of the year.

The comparisons between the original HotStuff route WBT 98th percentiles and the new ERA5 WBT percentiles revealed modest decreases in the 98th percentile WBT — in the vicinity of 0.4 to 1.4^{o}C for the Fremantle to Kuwait route. Differences were greatest in the northern hemisphere cool season (November to March) when the WBT data used to determine the HotStuff route values came from the largest aggregation bins close to the equator. The smallest differences were in June and July, when the highest WBT data came from within the confined Persian Gulf region. In addition, the original HotStuff model applied a normal distribution to the VOS data then added a +1^{o}C adjustment to the mean to make the mean VOS data align better with the destination port data at that time (see Maunsell 2003).

When looking at these changes, it should be noted that the ERA5 climatological datasets were bias-corrected for the highest parts of the WBT distributions against the high-quality weather station data across the Middle Eastern ports and selected island weather stations to ensure the ERA5 data matched the highest quality WBT observations as closely as the data allows. Appendix 3 (Fig. A3.4) shows the CDFs for the key validation island and coastal weather stations of Gizan (southern Red Sea), Djibouti (western Gulf of Aden), Abu Musa and Siri Islands (Persian Gulf). The bias-corrected ERA5 data matches the observed WBT distributions in each case within 0.5°C, which demonstrates the effectiveness of the quantile-quantile bias-correction technique in matching the ERA5 and observational WBT distributions at the higher end of their distributions. On the other hand, the VOS data was not bias-corrected against reference weather stations. Further, the quality control process did remove incorrect outliers but did not account for systematic problems with VOS WBT observations and the fact that the WBT distributions are not exactly normally distributed.

One of the authors of this report used to supervise the management of VOS ships operating out of NSW. Recurring issues were found with the measurements of WBTs onboard ships, including:

- The water reservoir used to keep the wicks of the wet-bulb thermometers moist tended to run dry;
- The muslin that draws water from the reservoir up to the wet-bulb thermometer sensor tends to be changed less frequently than required (daily or more often in windy or rough conditions), leading to the muslins being either dirty or contaminated by salt; and
- The requirement to use the thermometers in the screen on the sheltered side of the ship's bridge (one side tends to be in the sun with extra heating experienced off the metal superstructure of the ship, the other side in the shade) was not always adhered to, and the screens themselves were not aspirated, which can lead to anomalous readings.

All of the above observational problems led to erroneously high recorded WBTs. WBTs that in many cases approach the dry-bulb temperature. This distorts the VOS 98th percentile WBTs upwards. Also, note that the WBTs selected using the large bin sizes in the original HotStuff model will use the highest reported WBT from anywhere within the very large areas of the bins, even if these locations are not close to the routes followed by the ships enroute to the Middle East. The +1°C adjustment of the VOS mean temperatures will also have led to more elevated WBTs. In comparison, the ERA5 WBT distributions were systematically bias-corrected against high-quality observational data.

Therefore, the authors are confident that the bias-corrected ERA5 data, which does not suffer from the limitations experienced using the aggregated VOS data, provides a significantly more accurate and up to date product than that contained in the original HotStuff model.

Benefits to industry

The Australian livestock export industry now has access to the latest and most accurate WBT climatologies along every route used between Australia and the Middle East and Asian ports across time, along with updated destination port WBT climatologies. This will allow industry to have greater confidence in quantifying the heat stress risks along the routes and to the destinations of interest across all times of the year. In addition, the industry will be able to optimise stocking densities and stock selection types with greater confidence and better manage voyage timing as a result of this new and improved analysis.

The industry also has quantitative evidence that there are ongoing increases in the WBTs along several key routes and for many of the destination ports due to ongoing climate change effects. Therefore, the observed trends can be incorporated into heat stress risk assessments in the coming years as the WBT climatologies continue to change.

Future research and recommendations

As climate change is accelerating, the results of this and the companion studies should be updated in approximately five years as the statistics of wet- and dry-bulb temperatures will have changed by that time. WBTs can be expected to rise for most locations where heat stress risks are most likely as the climate warms, and hence the risk of heat stress will also worsen. Conversely, there will be a gradual decline in the risk of cold stress for most locations.

To account for climate change over the next five years, it is recommended that either a climate change adjustment of approximately +0.5°C be added to the 98th percentile values of WBT or a higher threshold of WBT from the ERA5 and port data be used for heat stress risk purposes. This could either be the 99th percentile or the 99.9th percentile values.

The ERA5 data will allow for analysis at higher than monthly temporal resolution. The data can also be used to evaluate duration and frequency of extreme WBT events and how these might change in the future.

ERA5 and weather station data could also be used to update the WBT acclimatisation zones across Australia, utilised to assess the degree of livestock acclimatisation to heat stress prior to export. The current acclimatisation zones appear to be using data approximately two decades old and, with a changing climate, may no longer be as representative as they were at the time they were produced.

It is also possible higher resolution reanalysis datasets will become available in the coming years. If and when they do, the climatological WBT analyses may be repeated if there is evidence that improved data resolution will yield meaningful improvement in heat stress risk estimations.

Future research to investigate the ability and value arising from dynamic and statistical models that predict actual WBT probabilities along key shipping routes may be of value. Dynamic predictors that consider the current state of the atmosphere and oceans along the shipping routes and at destination ports may be of value if a dynamic tool for assessing heat stress risks can be shown to improve management of trade heat stress risk over the existing system.

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1. Background

The Australian Standards for the Export of Livestock (ASEL) 2.3 — which have been in place since 2011 — were reviewed in 2018–19, focusing on setting requirements to ensure animals are fit to export from Australia and their health and welfare risk is managed throughout the export voyage. The purpose of the review was to ensure the standards remain fit for purpose and reflect the latest science.

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Comparisons were conducted between the original (2003 to 2008) port and route WBT climatologies – as used by the original HotStuff heat stress risk assessment model - and the 2011-2020 climatologies developed in this project. Most Middle Eastern ports have experienced rises in WBT for most months during the past two decades. However, trends with the route data were found to be lower, with some apparent slight reductions in the 98th percentile WBT between the original (2003) HotStuff Northern and Southern Persian Gulf and Red Sea routes. These slight reductions are attributable to the different methodologies used to generate the highest WBTs for the two key routes.

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2. Objective

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Climatologies" and W.LIV.2017 "Final Report South & East Asian Port Climatologies" that provide the WBT climatologies for destination ports across the Middle East and Asian ports north of the equator.

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3. Methodology

3.1 Application of ERA5 climatological data to support oceanic heat stress risk assessment

The availability of detailed climatological WBT data along the shipping routes used by the livestock exporters operating out of Australian ports is limited. The previous version of the Heat Stress Risk Assessment (HSRA) model utilised quality-controlled voluntary observing ship (VOS) data, aggregated into 5-degree latitude / 10-degree longitude bins at monthly time steps. However, this data is known to suffer from poor quality humidity data, and there are large oceanic areas where the data is sparse. This can lead to uncertainties in the WBT cumulative density functions, especially at the higher parts of the distributions where knowledge of the true values is most important. The last analysis of this dataset was also completed in the early 2000s. With the rapidly warming climate we live in, this oceanic climatology urgently needed updating.

The highest quality meteorological/climatological dataset spanning all the shipping routes used by Australian livestock exporters is the European Reanalysis Dataset, version 5. This is described in more detail in the next paragraph and in the reference. The ERA5 data was processed with the cumulative density functions generated for every grid point across the domain of interest - 50°N to 45°S, 20°E to 165°E. This domain covers the shipping routes to destination ports north of the equator across the Middle East and Asia.

The ERA5 data was then compared to high-quality observational data across the analysis domain and bias-corrected.

3.1.1 Use of ERA5 Data

To generate a consistent, gridded dataset of various percentile values of WBT, the ERA5 (ERA5, Hersbach et al. 2020) dataset is used. ERA5 is a reanalysis of historical data available hourly from 1979 to the present on an approximately 30km (0.25 degree) global grid. ERA5 data are dynamically consistent in time and space, making it suitable for this climatological assessment.

The destination port climatological data used in the shipping route WBT bias corrections is described in the reports "W.LIV.2017 Final Report Middle Eastern and West Asian Port Climatologies MLA Confidential" and "W.LIV.2017 Final Report South and East Asian Port Climatologies MLA Confidential". In addition, these port climatologies were supplemented with island and selected coastal climatological datasets to ensure those regions most susceptible to oceanic heat stress were validated against an adequate number of high-quality weather station datasets — as described in "W.LIV.2017 Final Report Collection and Validation of Island and Selected Additional Coastal Ports for Oceanic Bias Correction".

Bias corrections were then applied to all the analysed ERA5 WBT data using the weather stations' detailed WBT climatologies included in the above reports as the reference dataset. The methodology for developing and applying these bias corrections are described in the next section.

3.1.2 Comparisons between observed station data and the corresponding ERA5 gridded data

Most of the validation weather stations (90%) WBTs correlate very well (r > 0.8; Pearson Correlation Coefficient) with the nearest WBT data points extracted from the ERA5 analysis datasets (Fig. 1). These correlations were calculated from the hourly (where available) observational time-series data and the corresponding ERA5 hourly time-series. A couple of example hourly time-series plots (column 1), with the corresponding PDFs/CDFs (columns 2 and 3), are shown in Fig, 2. Red represents observations and blue ERA5 reanalysis. It is clear from these examples that — in most cases — the reanalysis data match the observed time-series data very well.

However, there are outliers. Some of these have very good meteorological and data resolution explanations for why the weather station data should not correlate well with the reanalysis datasets—for example, Diego Garcia airport weather station and Aqaba.

Figure 1: Correlation of stations' hourly time-series observational data and corresponding ERA5 hourly time-series data.

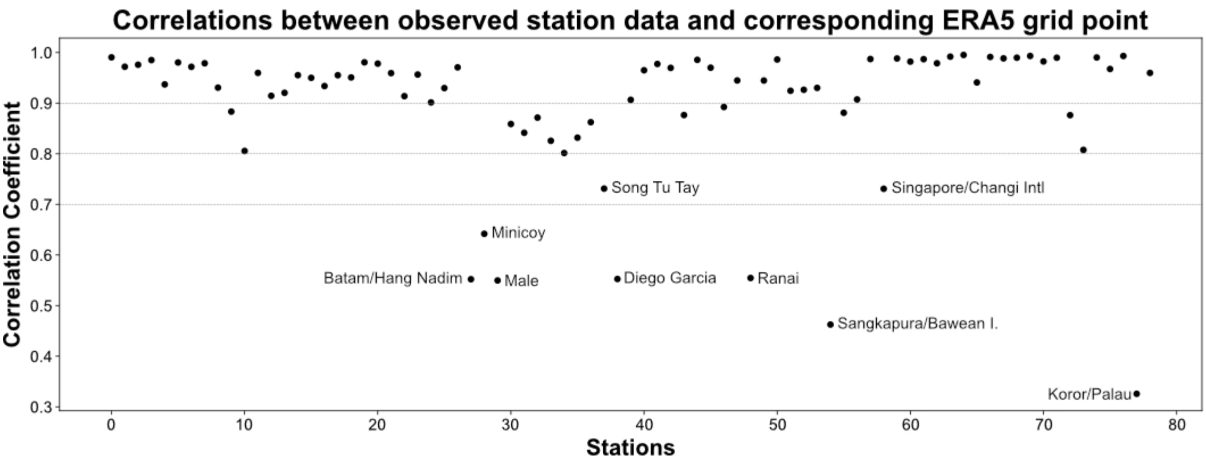
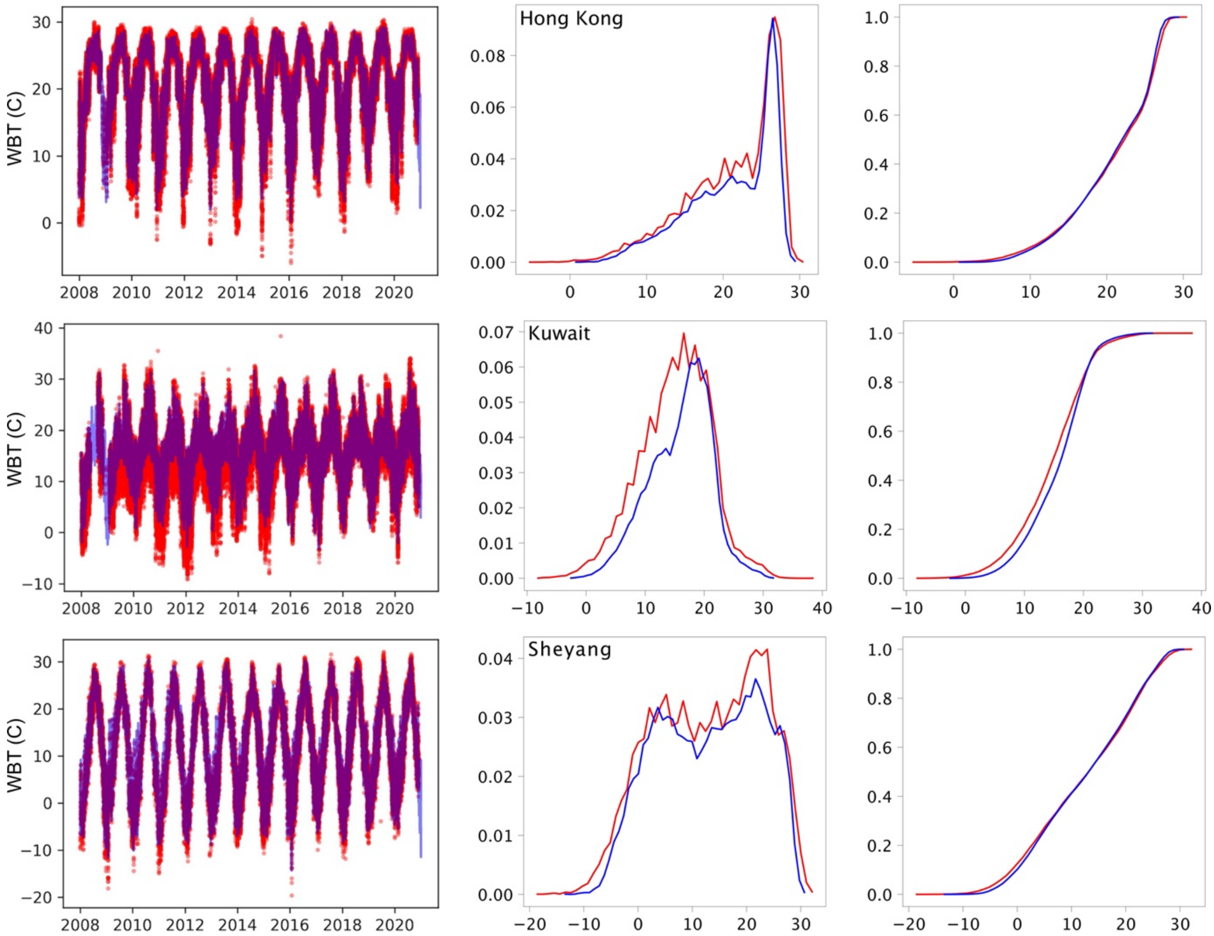


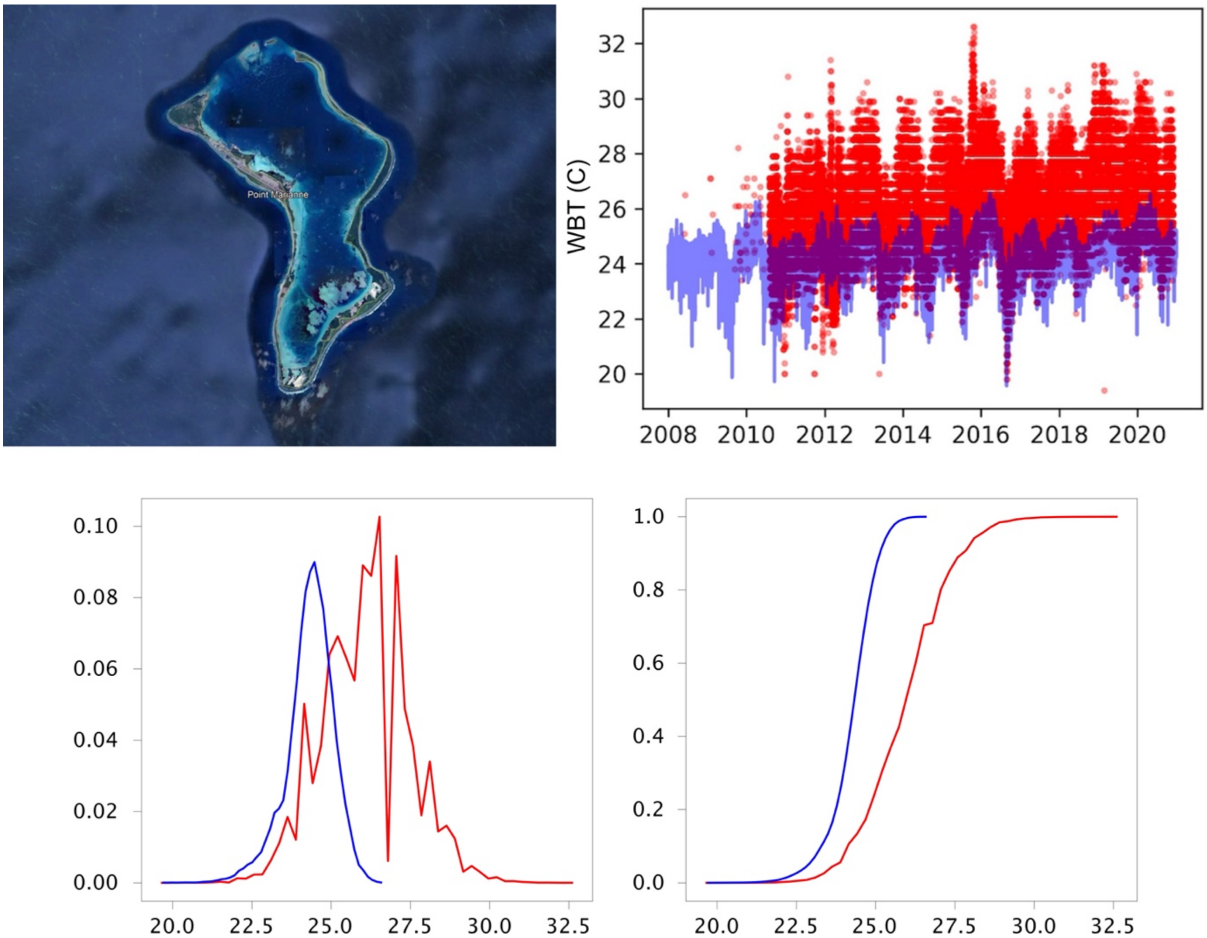
Figure 2: Example hourly observed (red) and ERA5 (blue) time-series data (column 1). The corresponding PDFs and CDFs generated using this data are shown in columns 2 and 3. Again red indicates observational data and blue ERA5 data.



The Diego Garcia airport weather station might not provide a good representation of the surrounding oceanic area in light wind situations as the weather station captures the adjacent lagoon WBT environment more than the surrounding open ocean area (Fig. 3, top left image). This regions' prevailing winds from March to November tend to be from the southeast. The weather station is located at the International Airport on the western side of the coral atoll, adjacent to a large, almost entirely enclosed, lagoon. The waters within the lagoon are likely to be ~2^{o}C warmer than those outside the lagoon during periods of light winds as there is limited water exchange with the open ocean.

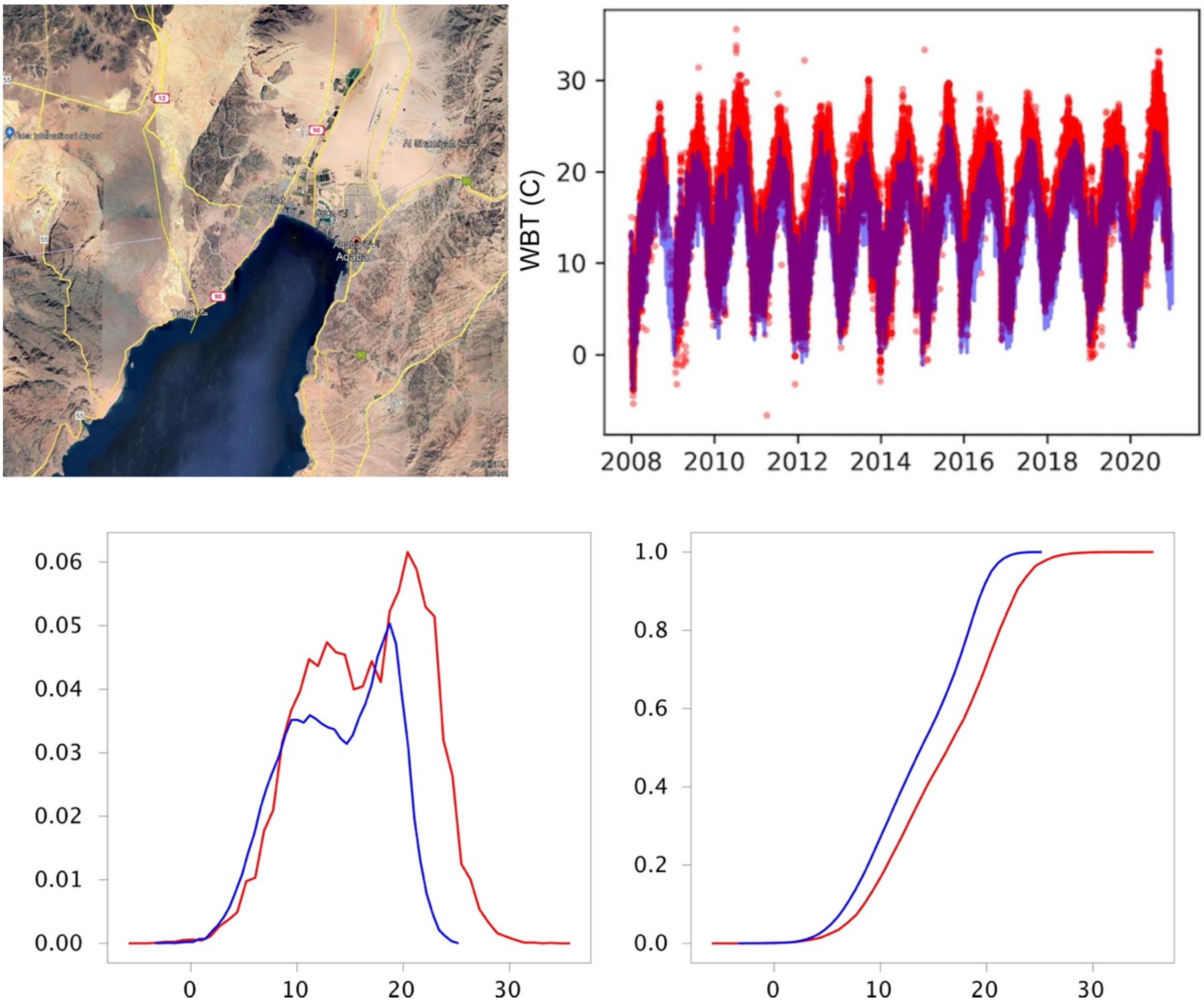
Additionally, the shallow lagoon would retain heat better than the open ocean where the incoming energy is mixed through a greater depth. Therefore, it is expected that the observed Diego Garcia WBTs would be higher than over the open ocean during the periods of highest WBT.

Figure 3: Google Earth image showing Diego Garcia Airport adjacent to and on the western side of an almost fully enclosed lagoon (top left). The hourly station (red) and ERA5 (blue) time-series data is shown on the top left, with the corresponding PDF (left) and CDF (right) on the bottom.



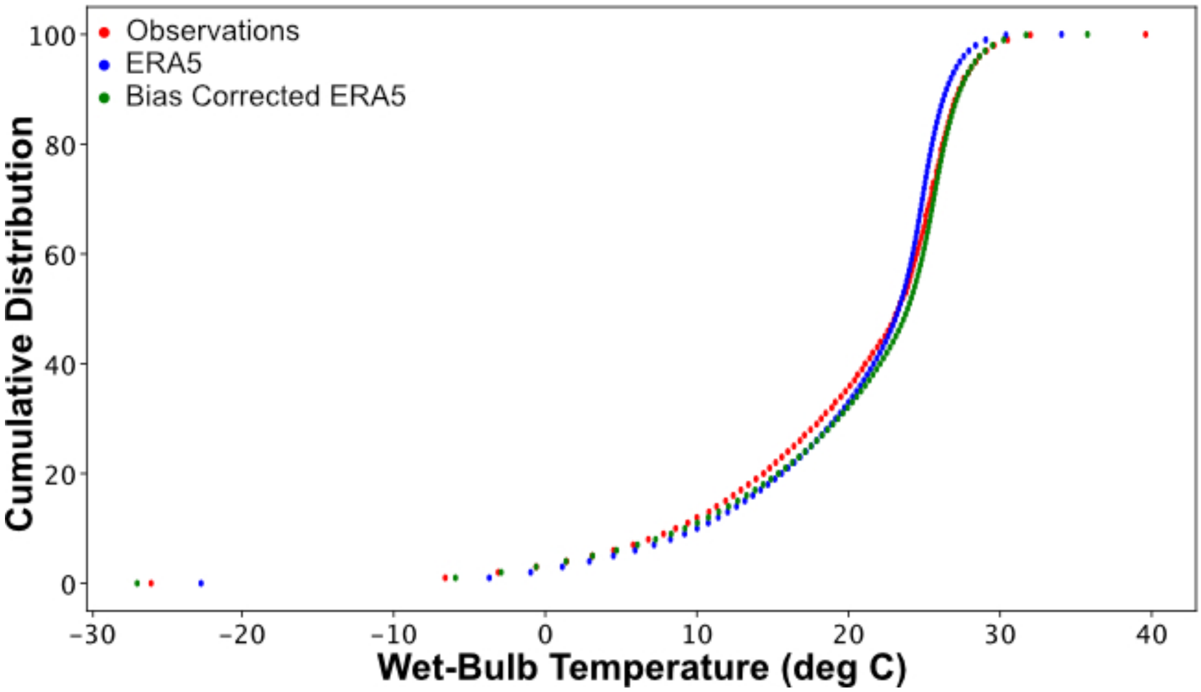
Aqaba (Fig. 4, top left) is another location where the bias between the ERA5 data and the weather station data is large. Aqaba is located at the northern end of the Gulf of Aqaba, which is only 6 km wide for the final 10 kilometres leading into the port. The grid point resolution of the ERA5 data is approximately 30 km. Hence, the reanalysis is not able to resolve the finer scale detail of the WBT climatology at this location — representing the surrounding desert areas rather than the Gulf waters. However, as the port WBT climatology is considered accurate — and with ships delivering to this port taking only 4.5 hours to traverse the length of the Gulf of Aqaba after leaving the Red Sea — the limitation of the ERA5 dataset at this particular location should have little effect on the heat stress risk estimates for livestock. The destination port climatology will capture this destination's actual heat stress risk.

Figure 4: Google Earth image showing Aqaba at the northern end of the Gulf of Aqaba (top left). The Gulf of Aqaba is only 6km across within 10km of the port, below the 30km grid spacing of the ERA5 data. The hourly station (red) and ERA5 (blue) time-series data is shown on the top left, with the corresponding PDF (left) and CDF (right) on the bottom.



The cumulative distribution — generated from all hourly time-series station data — compared to ERA5 (Fig. 5, red and blue dots) shows that, especially at the tail end of the distribution, ERA5 systematically underestimates WBTs. Various statistical bias correction methods are available to improve these systematic biases in model output (Li et al., 2019). Some commonly used bias correction methods include linear scaling, variance scaling, and quantile-quantile mapping. In this case, the most appropriate bias correction method is quantile-quantile mapping. For this method, a quantile-specific transfer function — determined by the difference between simulated and observed empirical cumulative distribution functions (CDFs) — is applied to the reanalysis data to match percentiles between the model outputs and observations. Note that the bias-correction is calculated using CDFs developed from all station data to ensure uniform application to all ERA5 grid points and prevent overfitting. This method has the advantage of correcting the mean and variance while also improving the entire distribution. The improvement provided by this method is shown in the green dots in Fig. 5, which match the observed WBT distributions very well at the higher end of the distribution, where the accuracy of the data is most important for heat stress risk assessment purposes.

Figure 5: Cumulative distribution of the WBT distributions for all observations (red dots), the nearest ERA5 grid points to the weather stations (blue dots), and the bias-corrected ERA5 data (green dots).



Using the individual station CDFs — as shown in the right-hand column in Figure 2 — it is possible to quantify the extent that the extreme WBT values — per station — is under/overestimated by the ERA5 data. Fig. 6 shows the differences between each station's observed and reanalysis WBT data. The three rows show the differences in the 95, 98, and 99% WBT values. Differences before/after bias correction are shown on the left/right panels. The orange to red arrows shows differences larger than 2°C, compared to observations. The direction of the arrow indicates whether the reanalysis is under/overestimating the WBTs. The plots show several stations where the reanalysis underestimates the WBTs by more than 2°C. Not surprisingly, these are the same stations where the correlations are lower. Bias correcting the reanalysis data improved the underestimations significantly (see examples in Fig. 7a), with only Aqaba and Diego Garcia still showing bigger differences (Fig. 6 and Fig 7b). As discussed earlier, the station location contributes to the Diego Garcia differences, and the ERA5 grid resolution explains the Aqaba differences. As such, we would also expect that the bias-correction method will not force these stations back to the observed values, as that would suggest the bias-correction model is overfitting.

All other weather stations closely matched the ERA5 data once the bias corrections had been applied, with very good correlations for the important higher percentiles of the WBT distributions — those between the 90th and 100th percentiles. The appendix provides plots showing the cumulative frequency distributions for the weather stations compared to the ERA5 data before and after bias correction.

Figure 6: Difference in the 95/98/99% wet-bulb temperature values between ERA5 and station observations (per station) for the raw ERA5 data (left) and the bias-corrected (right) data. The direction of the arrow indicates whether the reanalysis is under/overestimating the wet-bulb temperatures. Colours indicate the severity of under/overestimation.

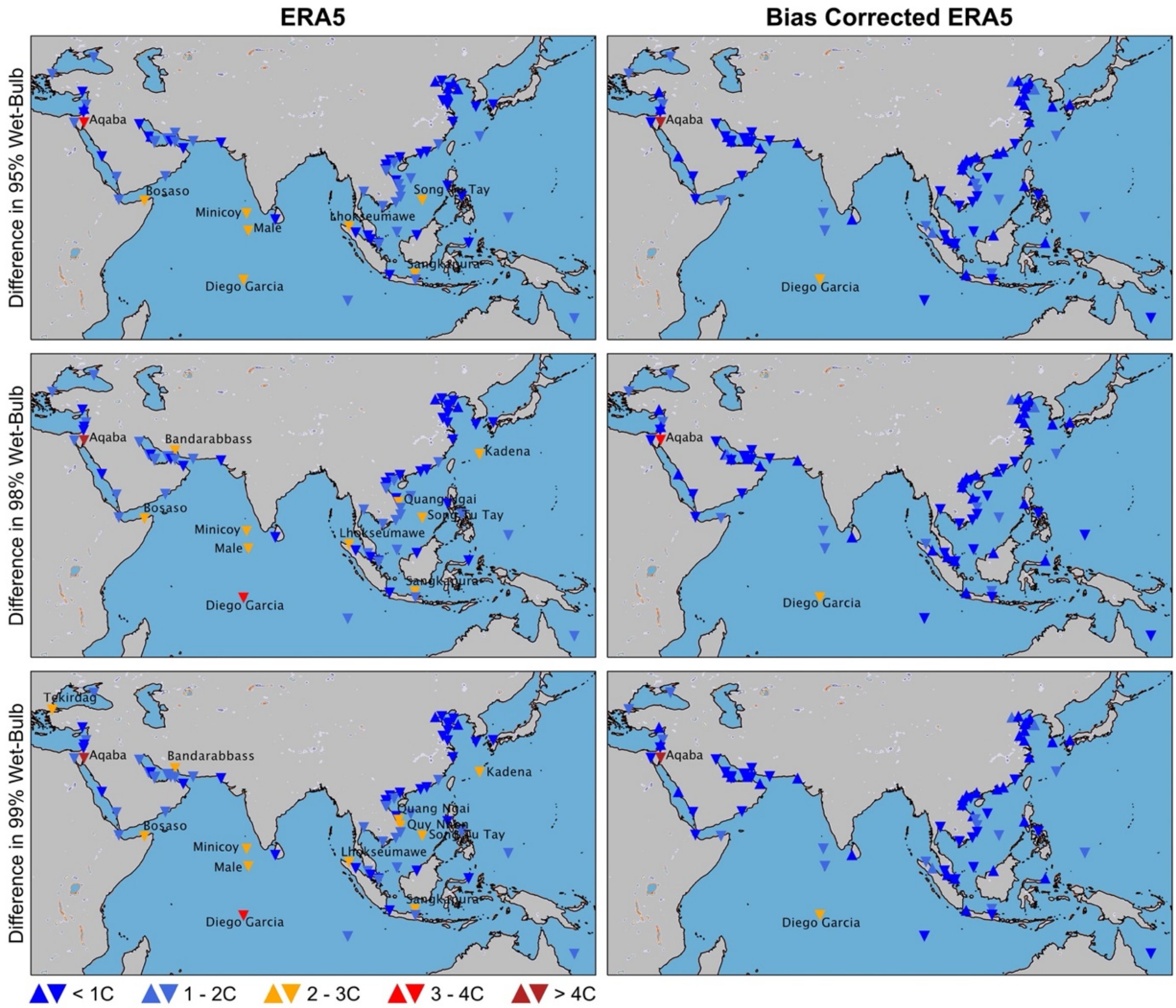


Figure 7a: Examples show how the bias correction method improves station PDF and CDF profiles. Observations are in red, ERA5 in blue and bias-corrected ERA5 in green.

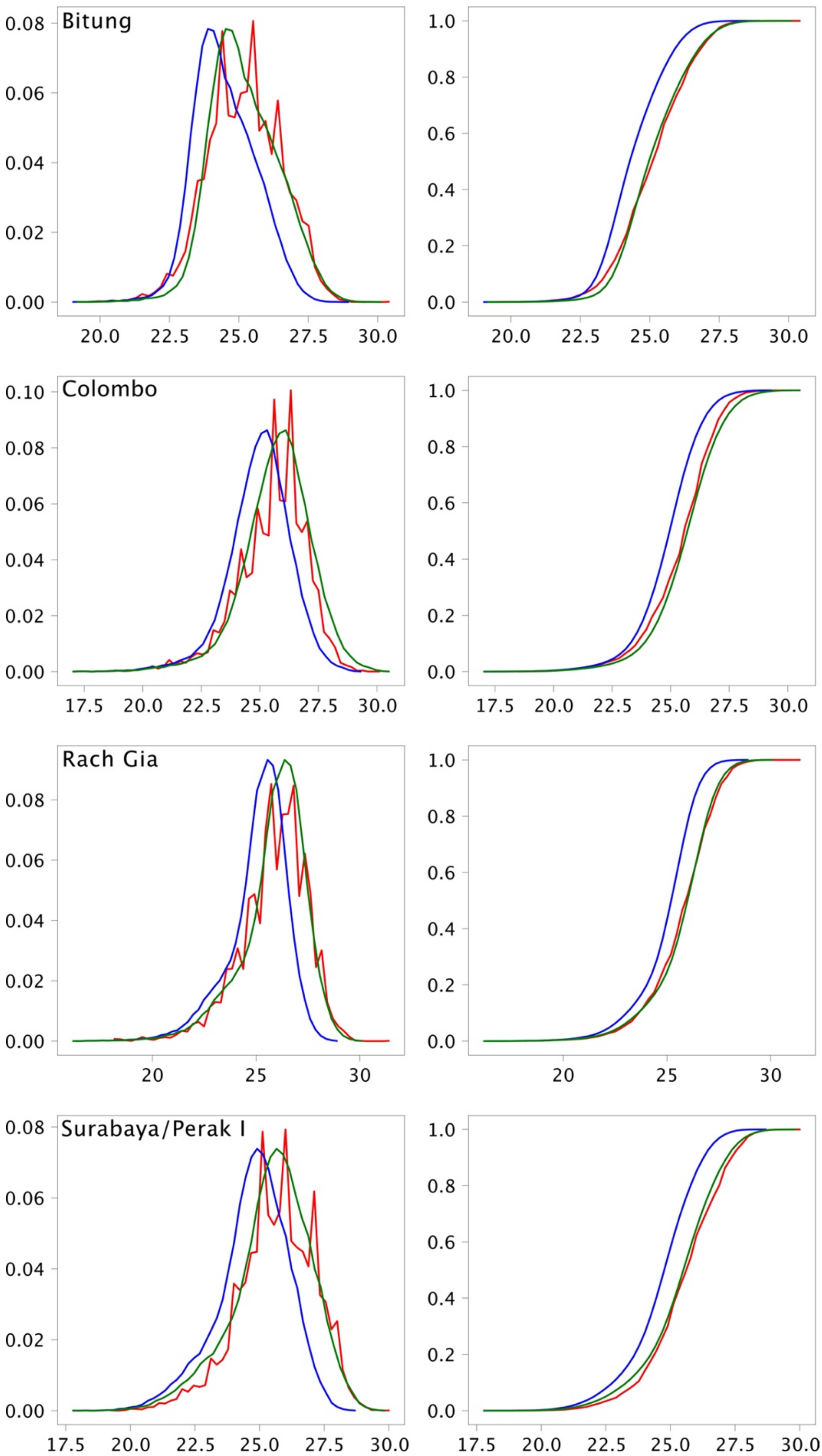
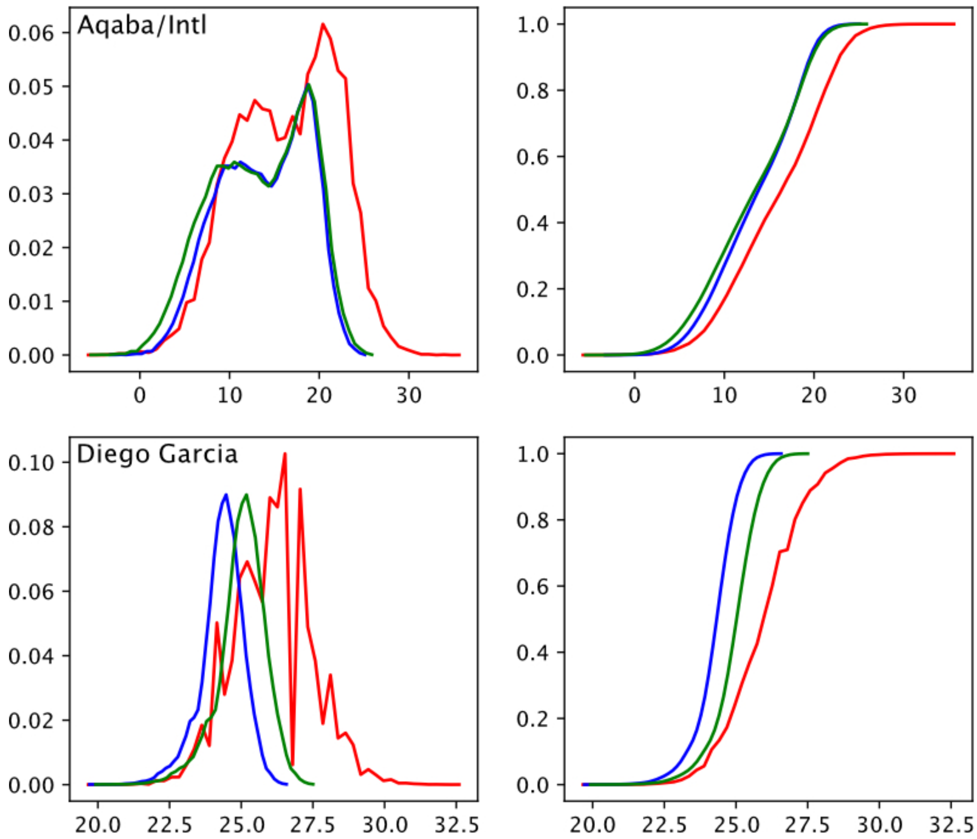


Figure 7b: Showing that the bias-correction model does not overfit for the Aqaba and Diego Garcia stations. PDFs are shown on the left and CDFs on the right. Observations are in red, ERA5 in blue and bias-corrected ERA5 in green.



4. Results

4.1 ERA5 WBT Climatologies and Bias Corrections

4.1.1 WBT Climatologies Focussing upon the 2011-2020 Decade

Research into heat stress risk assessments — as they affect Australian livestock and the HSRA model utilised by Australian livestock exporters — has shown that the 98th percentile value of WBT is most useful for characterising heat stress risks along shipping routes to the Middle East and Asia. The analyses undertaken by NCAR/UCAR spanned the entire probability distribution, and values have been derived for every percentile — from 1 to 100%. The gridded datasets and the shipping route data provided to the MLA contain all the percentiles for each month of the year for every grid point. For simplicity and relevance, the discussion of results that follows concentrates on the 98th percentile results.

Fig. 8 provides maps across the whole domain of the 98% monthly WBT data, calculated using the bias-corrected 2011–2020 reanalysis dataset. Figs 9 and 10 provide zoomed-in views of two areas of particular interest, the Middle East and East Asia. These plots clearly show that the highest WBT areas are in the Middle East, spanning the period from June to September.

Figure 8: 98% monthly WBT data, calculated using the 2011-2020 ERA5 dataset. Units are degree C.

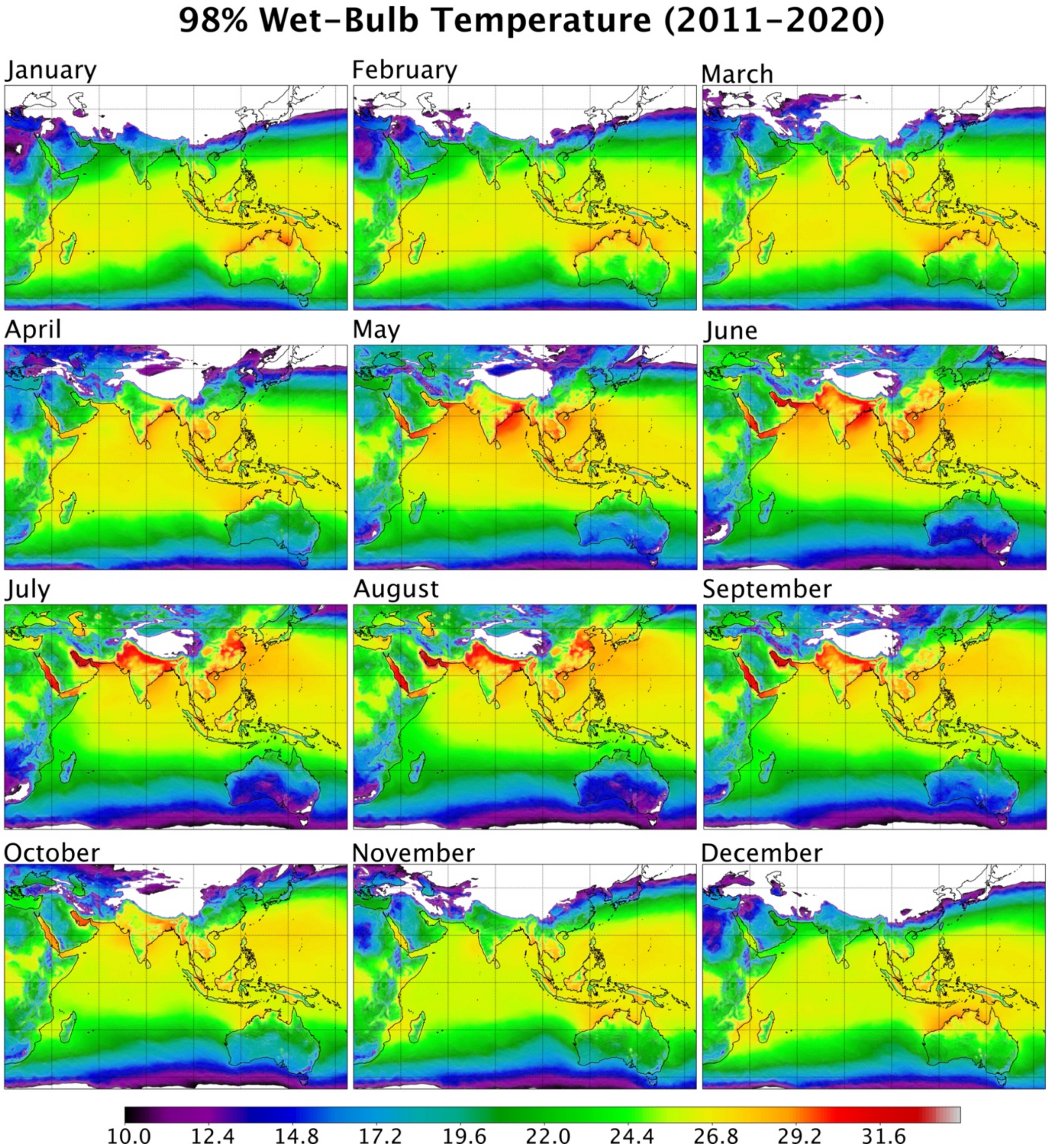


Figure 9: Same as Figure 6, but this provides a zoomed-in view of the Middle East area of interest.

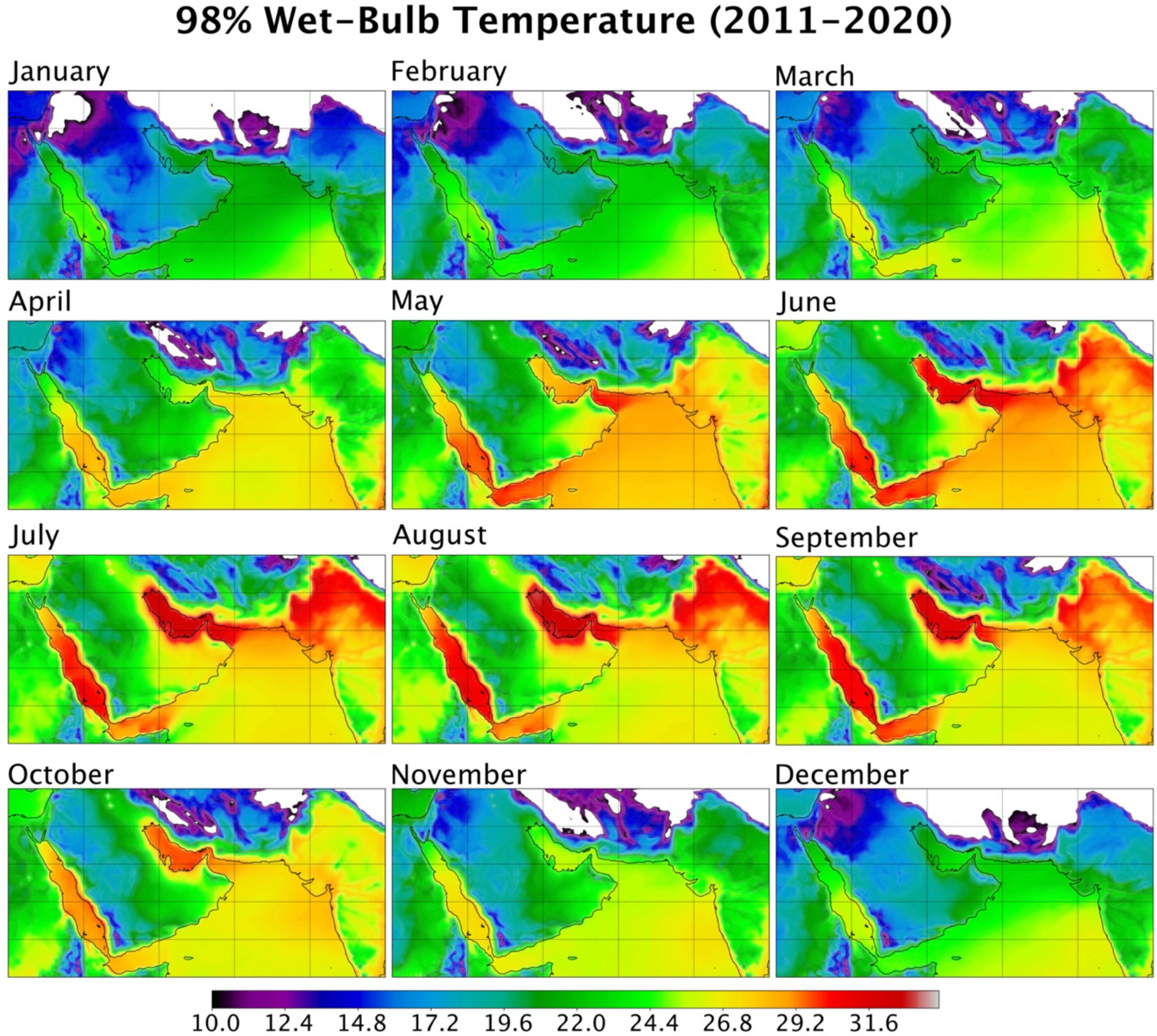


Figure 10: Same as Figure 6, but this provides a zoomed-in view of the East Asia area of interest.

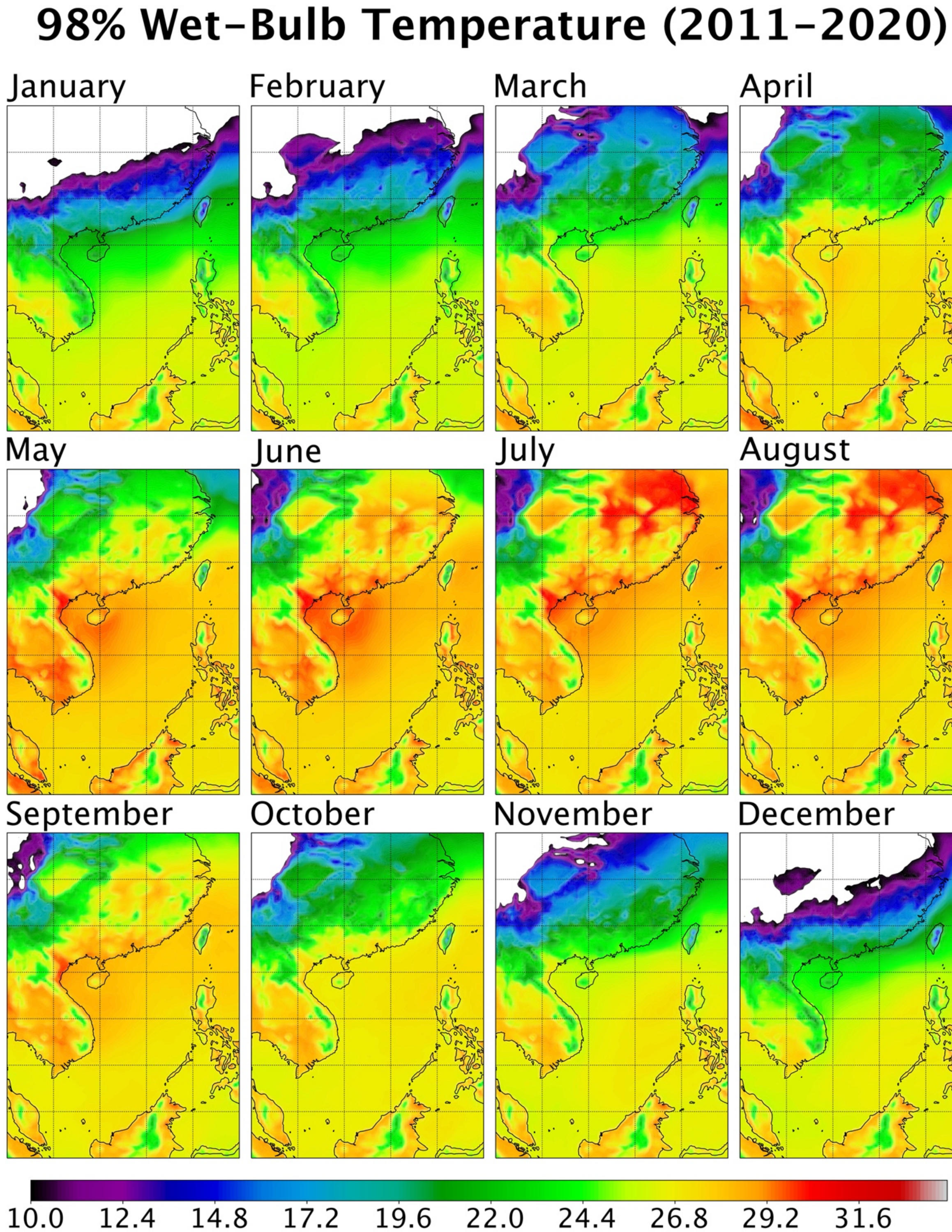
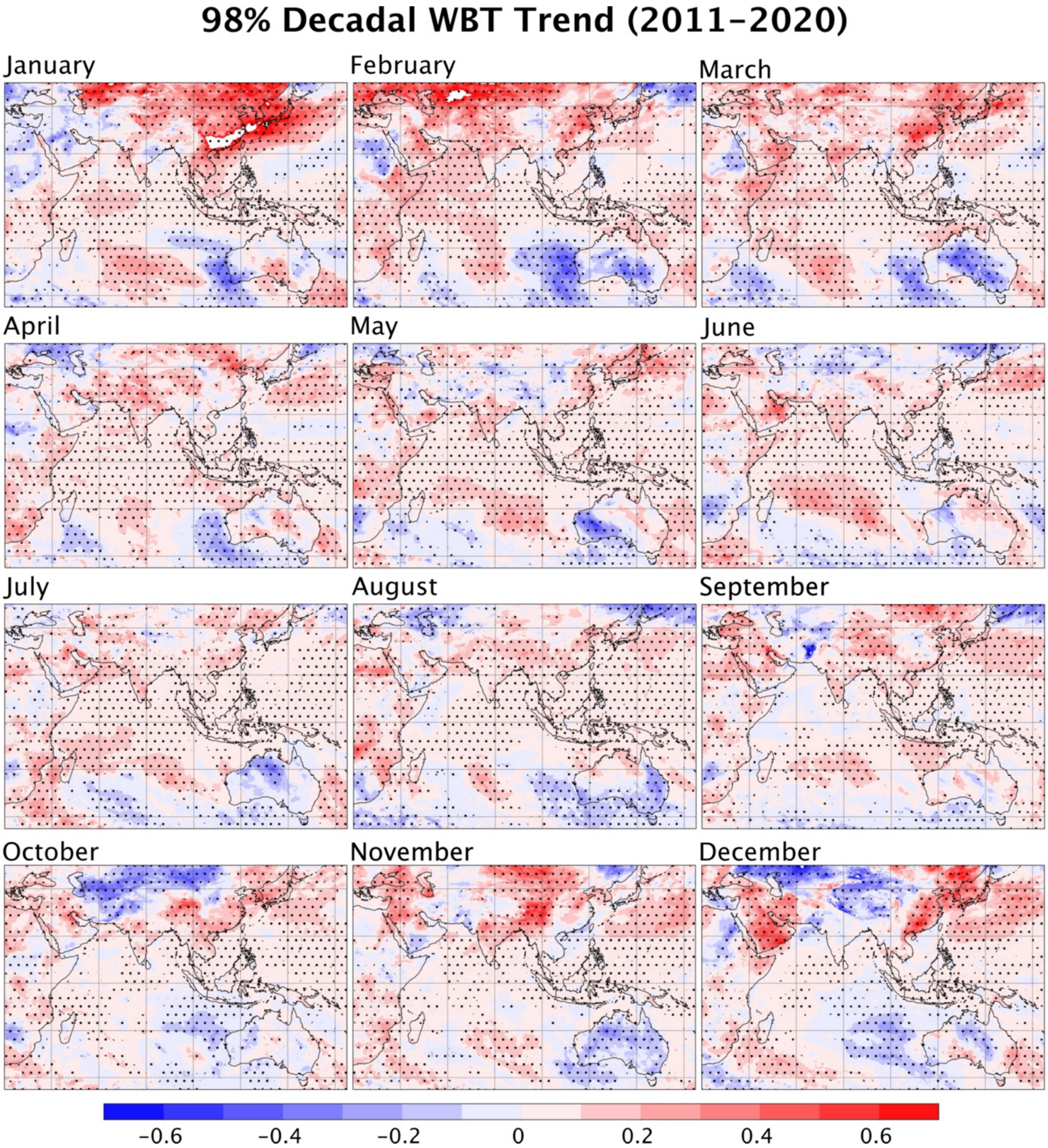


Figure 11: Decadal trend in 98% WBT using the 2011-2020 ERA5 dataset. Units are degrees C/decade. Stippling indicates areas where the trends are significant at the 95% level.



While the absolute WBT plots indicate the expected monthly percentile values in any area, it does not explain the changes any area has experienced over the last decade(s). Fig. 11 shows the decadal trend for the 98% WBT over the period 2011–2020. The stippling on this plot indicates the areas where the trend is significant at the 95% level. We can see both positive and negative trends through the domain and for different times of the year. The area with the highest WBT values — the Middle East — has mostly a positive trend of up to 0.5°C over the last decade. The WBT trend over the last 40 years has also been positive, with the highest trend values recorded during the most recent (2011–2020) decade (not shown). This trend likely has a climate change contribution, and it is reasonable to assume that we can expect a continued climate change influence through the coming decade.

This dataset now allows us to extract detailed monthly WBT information for any shipping route for any percentile of WBT, for example, Fremantle to Kuwait through the Strait of Hormuz, as shown in Fig. 12. The numbers on the map indicate the waypoints along the route. The mapping of data from the original bias-corrected ERA5 grid to the route waypoints uses a process to select the highest WBTs from the bias-corrected ERA5 gridded data within 25km of each waypoint to ensure the WBT values along the routes do not under-represent the heat stress risks.

Fig. 13 shows the monthly 98% WBT (top), the 2011–2020 monthly decadal trend values along this route (middle), and the change in decadal trend values (for September) over the last four decades (bottom). The y-axis represents the waypoints along the route. The highest WBTs along this route are in the Persian Gulf from July to September. The monthly decadal trend (for 2011–2020) is shown in the middle plot in Fig. 13. Filled circles indicate that this trend is significant at the 95% level. Along this shipping route, the largest increases in WBT have been observed in September, followed by October and in the Persian Gulf region. The final plot in the series (bottom, Fig. 13) shows the change in the decadal trend — for September — over the last four decades. Again, the biggest changes are in the Persian Gulf. More striking is the change in decadal trends in this area, with trends increasing from near 0^{o}C/decade (1981–1990) to over 0.5^{o}C/decade for the most recent decade.

In some months, notably the southern hemisphere summer and autumn, in the region from Fremantle north to around 20^{o}S there has been a slight reduction in oceanic WBTs for the 98th percentile. This is tentatively attributed to the fact that this region is experiencing warmer and drier winds off the Western Australian continent for greater periods of time through the hotter months of the year, with a reduction in the frequency of frontal events that historically produce longer periods of onshore winds.

Figure 12: Example shipping route from Fremantle to Kuwait. The numbers indicate waypoints along the route and correspond to the X-axis in Figure 13.

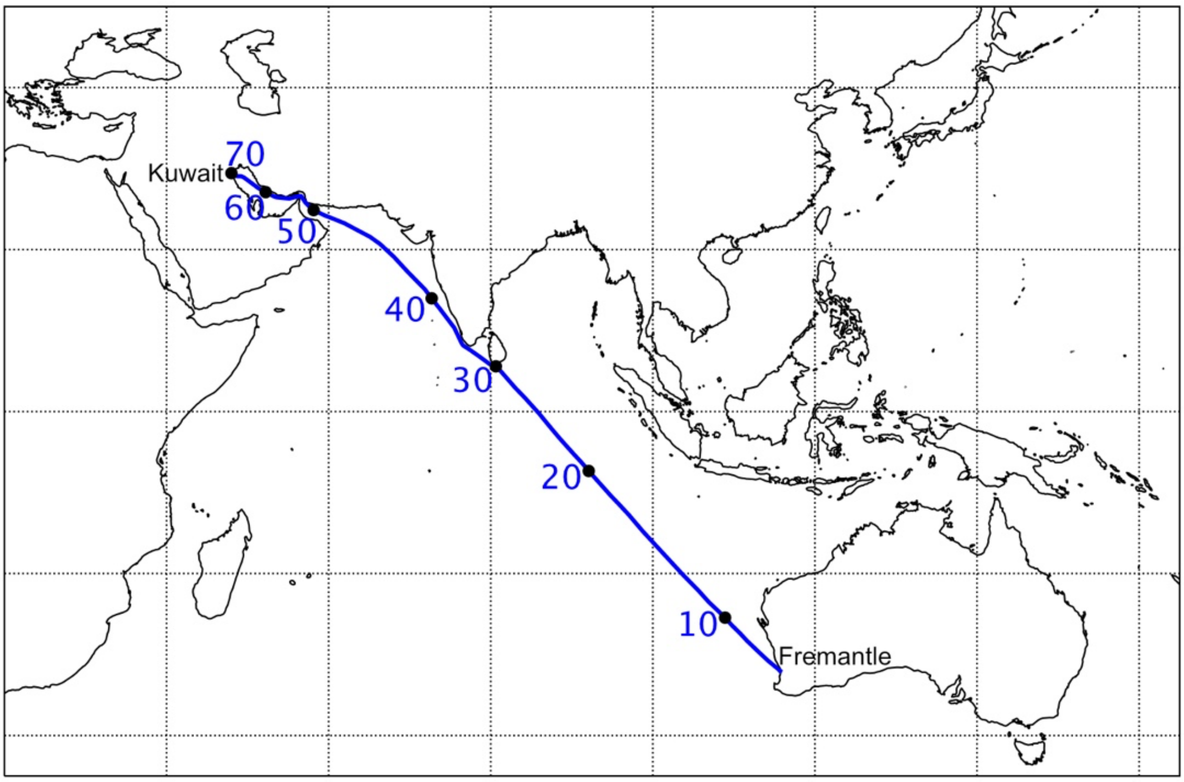
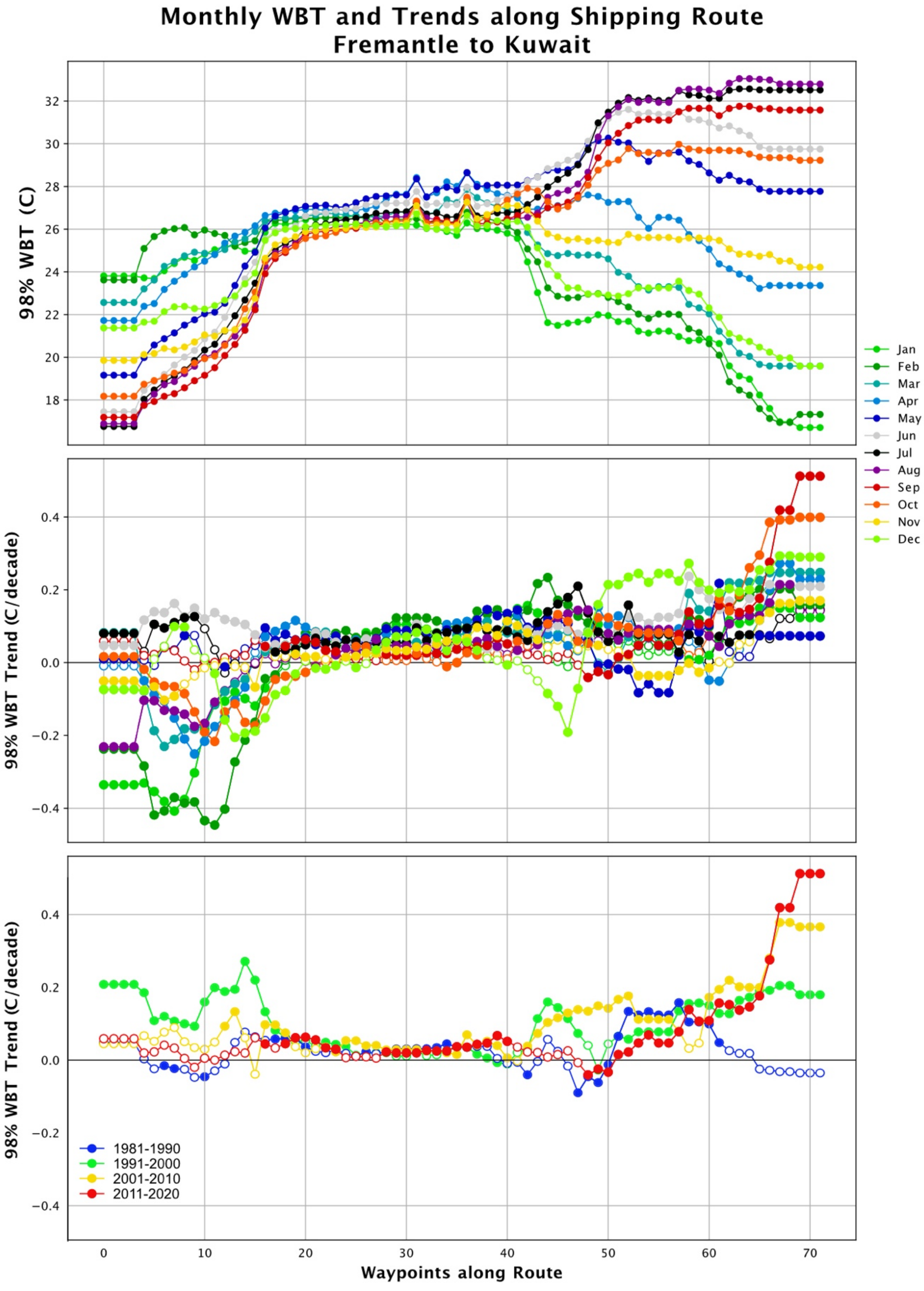


Figure 13: Monthly 98% WBT (calculated from the 2011–2020 averages) along the shipping route Fremantle to Kuwait (top). The monthly 2011–2020 decadal trends at each of the waypoints are shown in the middle. The September trends for each decade since 1981 are shown on the bottom. In the top two figures, colour indicates the month, while it indicates decades in the bottom plot. For the trend plots (middle and bottom), the solid circles indicate that the trend is significant at the 95% confidence level.



The ERA5 bias-corrected WBT data has been provided to the MLA for every percentile across the entire analysis domain. The data were also mapped to the shipping routes provided to the research team. Note that for the remapping process, the highest ERA5 WBT value from the gridded analyses that was within 0.25 degrees of the shipping route waypoints was used in every case. This was done to prevent WBT values from grid points that could lie over land — particularly dry inland desert areas that are common throughout the Middle East — from being mapped to a shipping route. This prevents the possibility of an anomalously low WBT value being used along the shipping routes.

The comparisons between the original HotStuff route WBT 98th percentiles and the new ERA5 WBT percentiles revealed modest decreases in the 98th percentile WBT — in the vicinity of 0.4 to 1.4°C for the Fremantle to Kuwait route. Differences were greatest in the northern hemisphere cool season (November to March) when the WBT data used to determine the HotStuff route values came from the largest aggregation bins close to the equator. The smallest differences were in June and July, when the highest WBT data came from within the confined Persian Gulf region. In addition to this, the original HotStuff model applied a normal distribution to the highest half of the VOS data then added a +1°C adjustment to the mean to make the mean VOS data align better with the destination port data at that time (see Maunsell 2003).

When looking at these changes, it should be noted that the ERA5 climatological datasets were bias-corrected for the highest parts of the WBT distributions against the high-quality weather station data across the Middle Eastern ports and selected island weather stations to ensure the ERA5 data matched the highest quality WBT observations as closely as the data allows. Appendix 3 shows the CDFs for the key validation island and coastal weather stations of Gizan (southern Red Sea), Djibouti (western Gulf of Aden), Abu Musa and Siri Islands (Persian Gulf). The bias-corrected ERA5 data matches the observed WBT distributions in each case within 0.5°C, which demonstrates the effectiveness of the quantile-quantile bias-correction technique in matching the ERA5 and observational WBT distributions at the higher end of their distributions. On the other hand, the VOS data was not bias-corrected against reference weather stations. Further, the quality control process did remove incorrect outliers but did not account for systematic problems with VOS WBT observations and the fact that the WBT distributions are not exactly normally distributed.

One of the authors of this report used to supervise the management of VOS ships operating out of NSW. Recurring issues were found with the measurements of WBTs onboard ships, including:

- The water reservoir used to keep the wicks of the wet-bulb thermometers moist tended to run dry;
- The muslin that draws water from the reservoir up to the wet-bulb thermometer sensor tends to be changed less frequently than required (daily or more often in windy or rough conditions), leading to the muslins being either dirty or contaminated by salt; and
- The requirement to use the thermometers in the screen on the sheltered side of the ship's bridge (one side tends to be in the sun with extra heating experienced off the metal superstructure of the ship, the other side in the shade) was not always adhered to, and the screens themselves were not aspirated, which can lead to anomalous readings.

All the above observational problems lead to erroneously high recorded WBTs - WBTs that in many cases approach the dry-bulb temperature. This distorts the VOS 98th percentile WBTs upwards. Also, note that the WBTs selected using the large bin sizes in the original HotStuff model will use the highest reported WBTs from anywhere within the very large areas of the bins, even if these locations are not close to the routes followed by the ships enroute to the Middle East. The +1°C adjustment of the VOS mean temperatures will also have led to more elevated WBTs. In comparison, the ERA5 WBT distributions were systematically bias-corrected against high-quality observational data.

5. Conclusions

5.1 Key findings

The research project demonstrated that quantile-quantile bias-corrected ERA5 WBT data can accurately represent the actual WBT climatology — as defined by the numerous weather station validation climatologies that lie across the routes traversed by livestock from Australia to the Middle East and Asian ports. Bias-corrected WBT climatologies were produced for each percentile from 1% to 100%, for each month of the year, and every grid point in the domain.

The climate change-induced trends in the WBTs were also quantified across the domain. These vary by location, with both positive and negative trends identified. The most substantial increases were found to occur in the Middle East, with the effects most prominent in the months of September and October.

5.2 Benefits to industry

The Australian livestock export industry now has access to the latest and most accurate WBT climatologies along every route used between Australia and the Middle East and Asian ports, along with updated destination port WBT climatologies. This will allow the industry to have greater confidence in quantifying the heat stress risks along the routes and to the destinations of interest. In addition, the industry will be able to optimise stocking densities and stock selection types with greater confidence as a result of this new and improved analysis.

New routes can also be mapped to the gridded datasets provided to the MLA when the need arises.

6. Future research and recommendations

As climate change is accelerating, the results of this and the companion studies should be updated in approximately five years as the statistics of wet- and dry-bulb temperatures will have changed by that time. WBTs can be expected to rise for most locations where heat stress risks are highest as the climate warms, and hence the risk of heat stress will also worsen. Conversely, there will be a gradual decline in the risk of cold stress for most locations.

To account for climate change over the next five years, it is recommended that either a climate change adjustment of approximately +0.5°C be added to the 98th percentile values or a higher threshold of WBT from the ERA5 and port data be used for heat stress risk purposes. This could either be the 99th percentile or the 99.9th percentile values.

The ERA5 data will allow for analysis at higher than monthly temporal resolution. The data can also be used to evaluate duration and frequency of extreme WBT events and how these might change in the future.

It is also possible higher resolution reanalysis datasets will become available in the coming years. If and when they do, it may be of value to redo the climatological WBT analyses if there is evidence that more accurately defined heat stress risks can bring material benefit to the management of heat stress by the trade.

Future research should also investigate the ability of dynamic and statistical models to predict the actual WBT probabilities along key shipping routes, providing a more dynamic tool for assessing heat stress risks considering the current state of the atmosphere and oceans along the shipping routes and at destination ports.

7. References

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Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D. and Simmons, A. (2020). "The ERA5 global reanalysis." Quarterly Journal of the Royal Meteorological Society, 146(730), 1999-2049.

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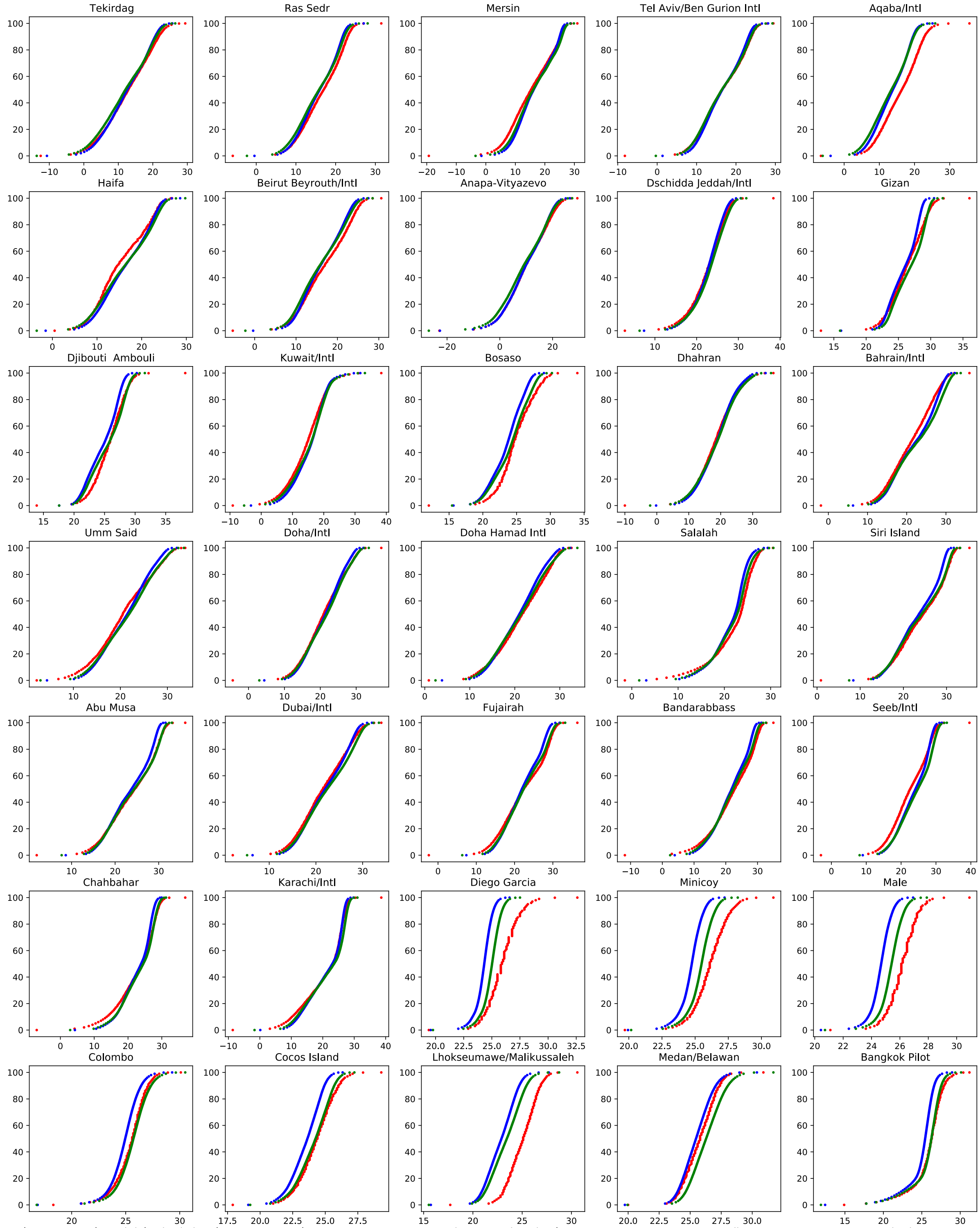
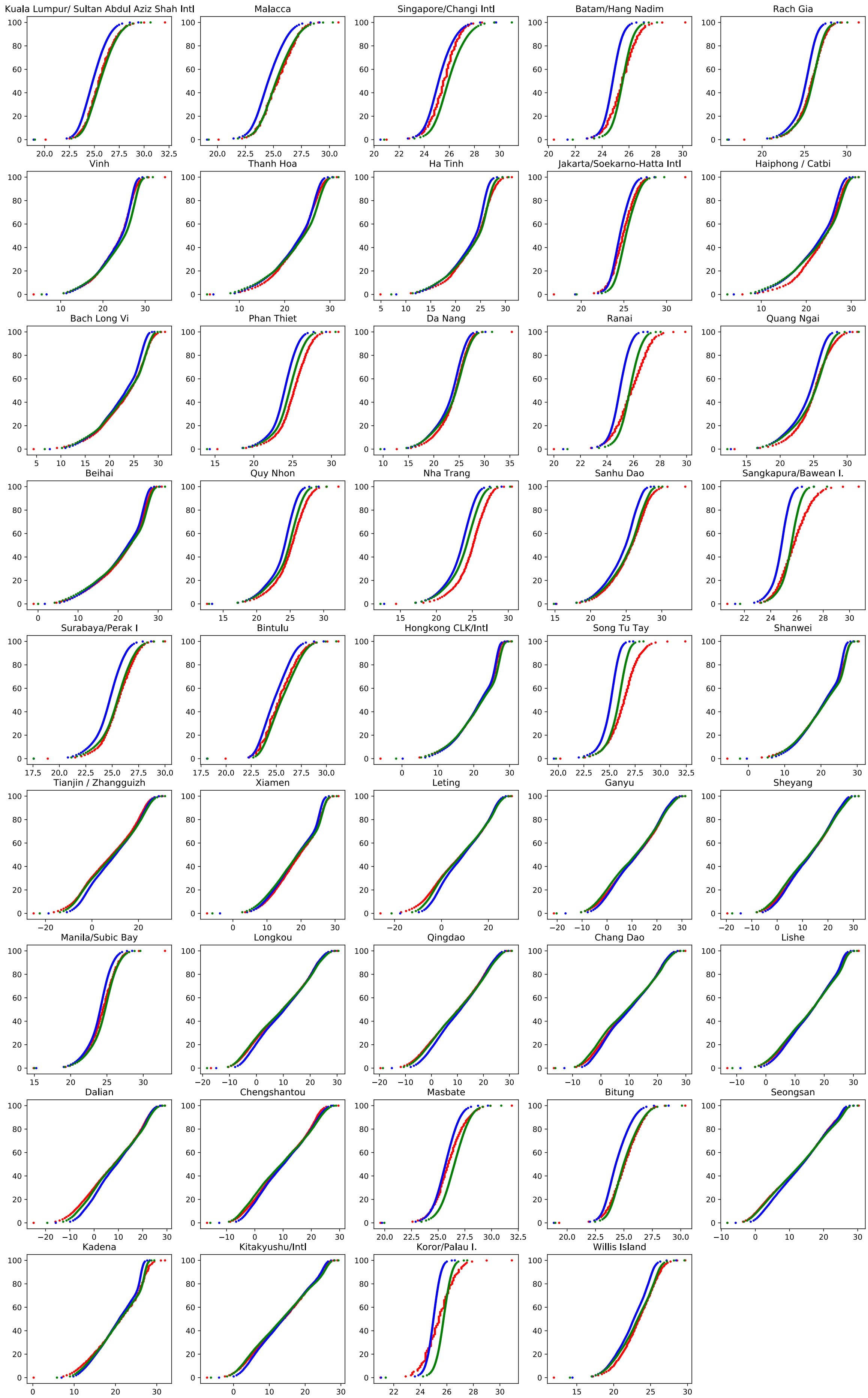
Maunsell Australia Pty Ltd (2003) Project LIVE.116 Development of a heat stress risk management model. MLA

Appendix 1: Observed & ERA5 Cumulative Frequency Distributions:

Figure A1.1: WBT CDFs: Observed (Red) - ERA5 (Blue) - Bias corrected (Green)




Kuala Lumpur/ Sultan Abdul Aziz Shah Intl
Malacca
Singapore/Changi Intl
Batam/Hang Nadim
Rach Gia
Vinh
Thanh Hoa
Ha Tinh
Jakarta/Soekarno-Hatta Intl
Haiphong / Catbi
Bach Long Vi
Phan Thiet
Da Nang
Ranai
Quang Ngai
Beihai
Quy Nhon
Nha Trang
Sanhu Dao
Sangkapura/Bawean I.
Surabaya/Perak I
Bintulu
Hongkong CLK/Intl
Song Tu Tay
Shanwei
Tianjin / Zhangguizh
Xiamen
Leting
Ganyu
Sheyang
Manila/Subic Bay
Longkou
Qingdao
Chang Dao
Lishe
Dalian
Chengshantou
Masbate
Bitung
Seongsan
Kadena
Kitakyushu/Intl
Koror/Palau I.
Willis Island

Appendix 2: Port WBT Trends 2008 Report to 2021 Report

Appendix 2 summarises the trends in the 98th percentile monthly WBTs for the key destination Middle Eastern ports for shipments of livestock from Australia. The tables that follow show the changes in the most critical 98th percentiles for heat stress risk assessment purposes between the original data (published in 2008 with observational data spanning periods that typically ran from 1998 to 2008) and the most recent analyses (published in 2021 that use data from the same locations but span the decade 2011 to 2020). Note that there are even larger changes to the WBTs when looking at the maximum recorded values, meaning the changes in extremes are greater than at the 98th percentile. The most recent data is contained in the report “W.LIV.2017 Final Report Middle Eastern and West Asian Port Climatologies”, provided to the MLA in July 2021.

These trends are essentially the observed changes in the WBT observations from the nearest high-quality weather stations to the destination ports, usually from adjacent international airport weather stations, primarily associated with the rapidly changing climate of this region.

Some comments on the observed trends follow.

Kuwait

The main changes involve a deepening of the heat low over the Arabian Peninsula earlier in the hot season. This leads to a more persistent and drier NNW wind through February to April. Then the heat lows shift northwards sooner in summer, which leads to an earlier increase in WBTs in July which sees the greatest increase in WBTs. Finally, WBTs are declining more slowly in November due to the longer-lived Arabian Peninsula heat low.

Table A2.1: Monthly 98th percentile WBT differences between the 2020 port analyses and the 2008 analyses for Kuwait.

Month	Port WBT 2008 statistics	Port WBT 2020 statistics	Port WBT Differences from 2020 to 2008
January	16.7	16.8	0.1
February	19.7	17.2	-2.5
March	20.4	19.4	-1.0
April	22.9	21.4	-1.5
May	22.2	23.2	1.0
June	24.1	23.1	-1.0
July	25.7	29.2	3.5
August	29.7	29.9	0.2
September	27.1	28.6	1.5
October	25.1	26.1	1.0
November	18.6	22.6	4.0
December	19.6	18.6	-1.0

Bahrain

The changes in the WBT 98th percentiles are generally less marked at Bahrain. However, there is a large decline in April as the heat low over the Arabian Peninsula deepens prior to its northward shift in May, when a more modest series of higher WBTs can be seen. The decline in WBTs leaving the hot season is slower, although the onset of stronger drier NNW winds in December is evident, as seen at Kuwait.

Table A2.2: Monthly 98th percentile WBT differences between the 2020 port analyses and the 2008 analyses for Bahrain.

Month	Port WBT 2008 statistics	Port WBT 2020 statistics	Port WBT Differences from 2020 to 2008
January	19.2	19.1	-0.1
February	18.3	19.5	1.2
March	21.5	21.3	-0.2
April	27.2	23.8	-3.4
May	26.9	27.2	0.3
June	28.5	29.2	0.7
July	31.0	31.5	0.5
August	31.7	31.6	-0.1
September	30.5	30.7	0.2
October	27.7	28.6	0.9
November	23.8	24.9	1.1
December	22.9	21.1	-1.8

Dhahran

Dhahran exhibits one of the most consistent and relatively significant increases in WBTs throughout the year. The exception is May, where the WBT barely changes – right at the point of transition between the lower humidity of the cooler season and the high humidity of the hottest season. Much of this difference is probably due to the warming of the Gulf of Salwa and its northern approaches, increasing the WBTs over Dhahran.

The only month where the WBTs have declined is in the cool season month of December, when the NNW winds will be peaking, tending to reduce the influence of the higher sea temperatures of the Gulf of Salwa.

Table A2.3: Monthly 98th percentile WBT differences between the 2020 port analyses and the 2008 analyses for Dhahran.

Month	Port WBT 2008 statistics	Port WBT 2020 statistics	Port WBT Differences from 2020 to 2008
January	16.4	18.5	2.1
February	16.9	19	2.1
March	18.6	20.6	2.0
April	21.5	23.4	1.9
May	26.3	26.4	0.1
June	27.2	28.2	1.0
July	30.0	32.1	2.1
August	30.6	33	2.4
September	29.1	31.1	2.0
October	26.1	28.4	2.3
November	22.1	24.8	2.7
December	21.2	19.9	-1.3

Doha

Doha has experienced the fastest increase in WBTs in the shoulder season of May to June, highlighting the earlier deepening of the Arabian Peninsula heat low and its earlier movement northwards. The lengthening of the high WBT season can also be seen in the August to September period, where the Persian Gulf's heating exacerbates the heat stress and slows its decline into the winter months.

The only months which have experienced minimal change in the WBTs are the months of December and January, at the height of the winter period when the NNW winds are most persistent.

Table A2.4: Monthly 98th percentile WBT differences between the 2020 port analyses and the 2008 analyses for Doha.

Month	Port WBT 2008 statistics	Port WBT 2020 statistics	Port WBT Differences from 2020 to 2008
January	19.9	19.7	-0.2
February	19.5	20.1	0.6
March	20.5	21.6	1.1
April	23.2	24.2	1.0
May	25.8	27.9	2.1
June	28.0	29.6	1.6
July	31.0	31.8	0.8
August	30.9	32.1	1.2
September	30.1	31	0.9
October	27.9	28.6	0.7
November	24.0	25.2	1.2
December	21.5	21.6	0.1

Dubai

Dubai / Jebel Ali Port has experienced increases in WBT throughout the year, with the hottest time of the year – June to August, experiencing increases near 2°C. However, the largest increase in any month occurred in the late winter month of February, attributed to the earlier deepening and northward movement of the Arabian Peninsula heat low. This has shifted the driest month of the year earlier in the year to January.

It is also notable that the length of the high heat stress period is starting to extend into September, where an increase in the 98th percentile WBT has reached 1.6°C.

Table A2.5: Monthly 98th percentile WBT differences between the 2020 port analyses and the 2008 analyses for Dubai.

Month	Port WBT 2008 statistics	Port WBT 2020 statistics	Port WBT Differences from 2020 to 2008
January	19.3	20.1	0.8
February	18.2	20.8	2.6
March	21.3	22.2	0.9
April	23.5	24.5	1.0
May	26.7	27.9	1.2
June	29.0	30.8	1.8
July	29.5	31.6	2.1
August	30.1	31.8	1.7
September	28.9	30.5	1.6
October	27.8	28.8	1.0
November	24.0	24.5	0.5
December	21.0	21.9	0.9

Appendix 3: Comparisons between HotStuff 2003 and ERA5 Route WBTs

This appendix (Appendix 3) provides the results of the comparisons between the newly created bias-corrected ERA5 98th percentile WBT distributions mapped to newly defined shipping routes for the four shipping routes developed in the original 2003 HotStuff heat stress risk management project.

The original (2003) HotStuff Heat Stress Risk model provided a single WBT value for every month of the year for four routes from Australia to the Middle East. The value provided was the highest 98th percentile Voluntary Observing Ship (VOS) WBT value from any part of any of the grid boxes transected by either the southern or northern shipping routes to the Persian Gulf and the Red Sea for each month of the year. It should be noted that the precise routes used to determine these values could not be determined. However, Figure A3.1 from the original report illustrates the basis for determining the WBT values. In the original approach, the VOS ship median values were also increased by 1.0^{o}C, which would also have affected the 98th percentile values.

The current project utilises newly specified route segments provided by LiveCorp that cover all expected shipping routes from Australia to Middle Eastern, western, southern and east Asian ports for livestock exports. These new routes take into account real-world route limitations imposed by mandated traffic separation zones in busy shipping areas, individual countries' territorial waters boundaries, the presence of reef systems and islands, and routes that avoid potential piracy incidents off the east African coast (for those routes leading into the Gulf of Aden and the Red Sea).

For this comparison, the southern Australian port of origin was taken to be Fremantle, and the northern port of origin was assumed to be Darwin. The Persian Gulf destination was chosen as Kuwait, being the northern-most Persian Gulf port, with the northern Red Sea port of Abadiyah used as the destination port. These routes are illustrated in Figures A3.2 and A3.3. The Galle (Sri Lanka) location was used as a convenient way to define the connection points between various shipping route segments.

It should be emphasised that the HotStuff shipping routes are not the same as these shipping routes as the original HotStuff routes are not viable in today’s world for the reasons mentioned above.

The comparisons between the HotStuff (2003) route WBT values and those for the ERA5 analyses are shown in Tables A3.1 through A3.4 for the Persian Gulf (North and South) and Red Sea (North and South) routes. Although the non bias-corrected ERA5 data can be below the observed cumulative distribution functions, applying the bias corrections makes the data almost precisely overlay the observed distributions, especially around the 98th to 99th percentiles. This indicates the ERA5 data is well calibrated to the high-quality observation stations at the western end of the Gulf of Aden, the southern Red Sea and western approaches to the Strait of Hormuz.

Note that the bias-correction method was designed to not overfit, and thus the ERA5 data might differ slightly from observations. Further, note the limitations of the methodology and with the accuracy of the VOS data as discussed in the “Results” section.

At the 98th percentile level, the comparisons indicate that the ERA5 data tend to be below that of the original HotStuff model for the peak of the hot season. However, closer inspection of the data indicates the original 98th percentile HotStuff WBT values more closely resemble the 99th percentile ERA5 data.

The reasons for the differences have been discussed in more detail in the results section but include factors such as the warm bias of the VOS observations due to the observational practices commonly experienced on these ships, the fact that the highest WBTs are drawn from much larger areas that the ERA5 data, and that the routes have significant differences with the Southern HotStuff routes passing over the equatorial Indian Ocean to southern Arabian Sea warm areas while the Galle to Gulf of Aden route skirts to the north of this warm area in the milder half of the year for the northern hemisphere.

The authors of this report believe the bias-corrected ERA5 dataset to be the superior dataset in this respect, and the differences between the two techniques can be explained for the reasons given above.

Figure A3.1: Map showing the boundaries of the Southern and Northern shipping routes to the Persian Gulf and the Red Sea used to define the HotStuff (2003) northern and southern shipping routes, with the VOS oceanic grid boxes included as the underlay. (Maunsell 2003)

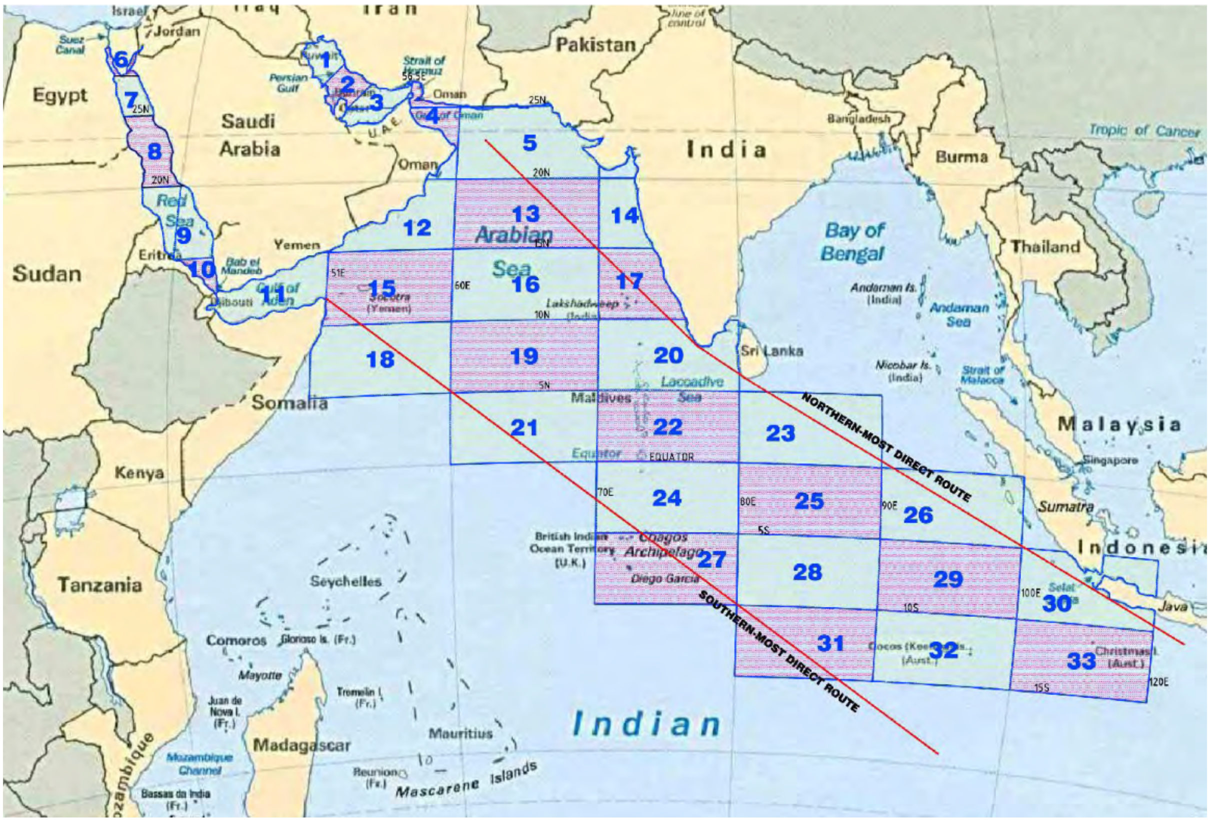


Figure A3.2: Map showing the Fremantle to Kuwait and Darwin to Kuwait (Persian Gulf) shipping routes used in the ERA5 WBT mapping in this project. Source: LiveCorp 2022.

Figure A3.3: Map showing the Fremantle to Abadiyah and Darwin to Abadiyah (Red Sea) shipping routes used in the ERA5 WBT mapping in this project. Source: LiveCorp 2022.

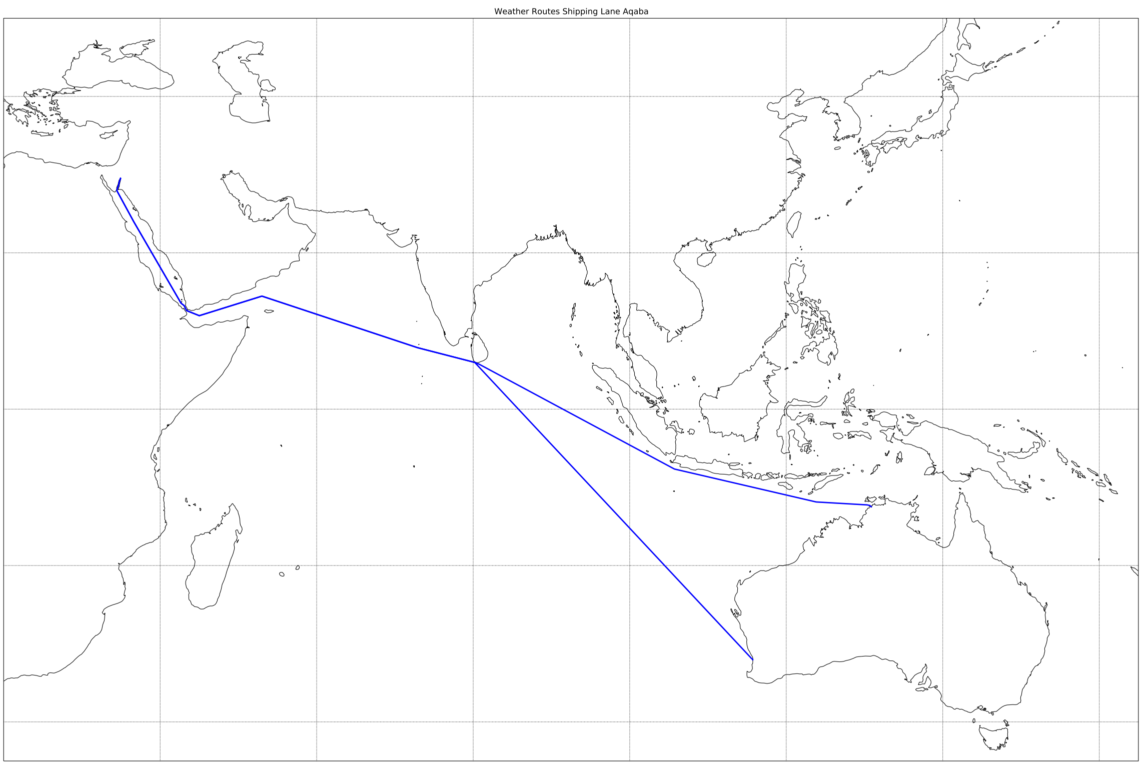


Figure A3.4: Graphs showing the PDFs (left) and CDFs (right) of the WBTs for the weather stations at Gizan (Red Sea), Djibouti (Ambouli Airport), Siri Island and Abu Musa Island. Observations are in red, ERA5 in blue and bias-corrected ERA5 in green.

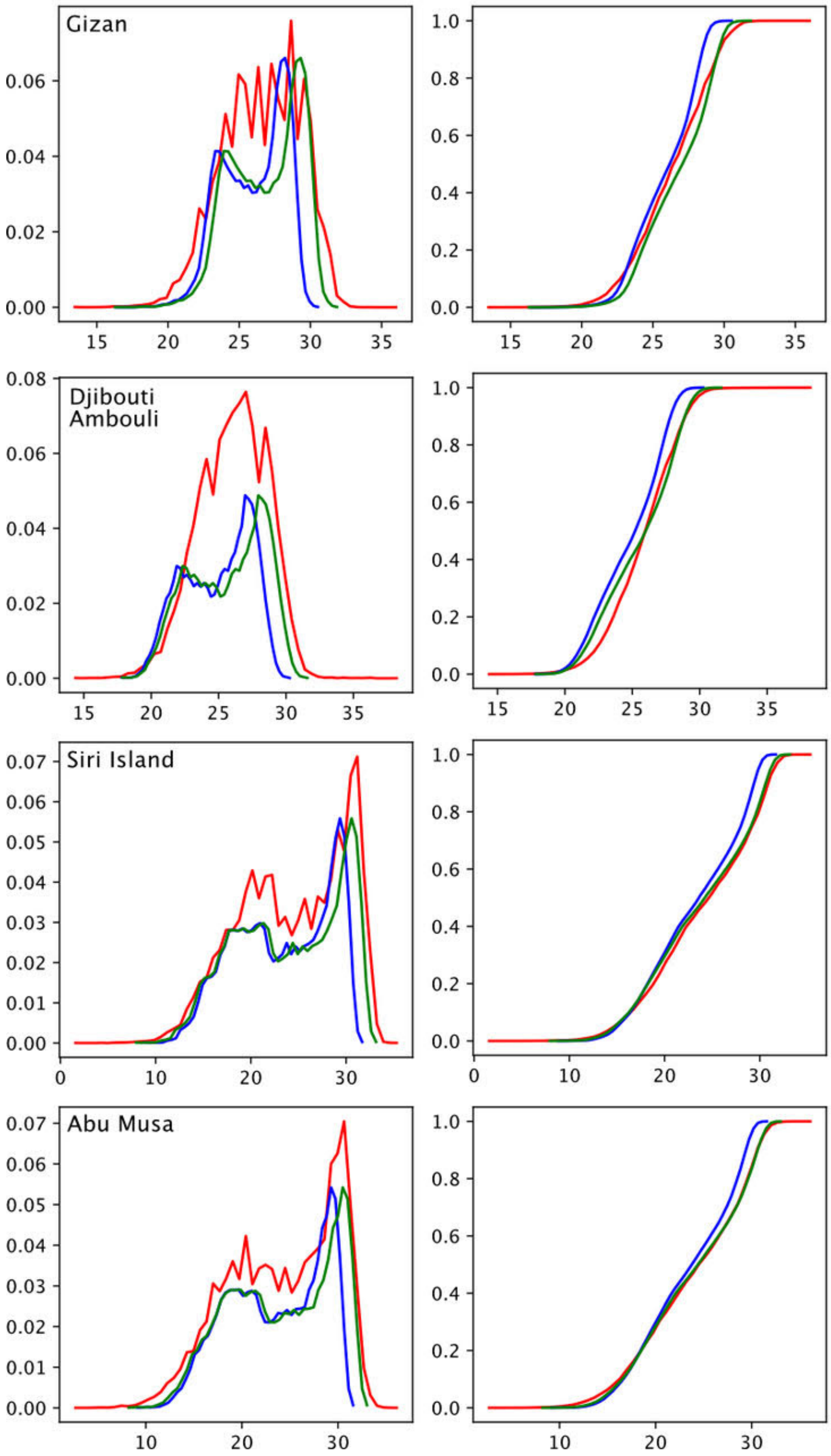


Table A3.1: Table comparing the original HotStuff 98th percentile WBT statistics with the new ERA5 WBT statistics for the Persian Gulf (North) shipping route.

Month	HotStuff WBT	ERA5 WBT	Difference
January	27.6	28.7	1.1
February	28.0	28.8	0.8
March	29.0	28.9	-0.1
April	29.5	27.9	-1.6
May	31.4	30	-1.4
June	32.8	31.6	-1.2
July	33.0	32.7	-0.3
August	34.0	33.1	-0.9
September	33.0	31.9	-1.1
October	30.6	30	-0.6
November	28.0	28.3	0.3
December	28.0	28.7	0.7

Table A3.2: Table comparing the original HotStuff 98th percentile WBT statistics with the new ERA5 WBT statistics for the Persian Gulf (South) shipping route.

Month	HotStuff WBT	ERA5 WBT	Difference
January	28.0	26.6	-1.4
February	28.1	26.8	-1.3
March	29.2	27.9	-1.3
April	29.7	28.6	-1.1
May	31.4	30.3	-1.1
June	32.7	31.6	-1.1
July	33.0	32.6	-0.4
August	34.0	33.1	-0.9
September	33.0	31.8	-1.2
October	30.6	30	-0.6
November	28.6	27.3	-1.3
December	28.0	26.7	-1.3

Table A3.3: Table comparing the original HotStuff 98th percentile WBT statistics with the new ERA5 WBT statistics for the Red Sea (North) shipping route.

Month	HotStuff WBT	ERA5 WBT	Difference
January	28.0	28.7	0.7
February	29.0	28.8	-0.2
March	29.0	28.9	-0.1
April	29.4	28.4	-1.0
May	30.4	30.2	-0.2
June	31.2	30.3	-0.9
July	32.4	30.3	-2.1
August	32.3	30.5	-1.8
September	31.8	30.8	-1.0
October	31.0	29.2	-1.8
November	29.0	28.3	-0.7
December	28.0	28.7	0.7

Table A3.4: Table comparing the original HotStuff 98th percentile WBT statistics with the new ERA5 WBT statistics for the Red Sea (South) shipping route.

Month	HotStuff WBT	ERA5 WBT	Difference
January	28.6	26.2	-2.4
February	28.8	26.5	-2.3
March	28.9	27.2	-1.7
April	29.0	28.4	-0.6
May	30.4	30.1	-0.3
June	31.2	30.3	-0.9
July	32.4	30.3	-2.1
August	32.3	30.5	-1.8
September	31.8	30.8	-1.0
October	31.0	29.2	-1.8
November	29.0	27.4	-1.6
December	28.3	26.7	-1.6