Environmental Modelling and Simulation for Naval Ships

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Synopsis

The existing HVAC system on board Landing Platform Docks (LPD)s, has been designed to operate in mild tropical environmental conditions such as the Mediterranean. This means that when the ship operates in extreme hot climates such as the Arabian Gulf and the Red sea region, the HVAC system is over loaded and cannot maintain the required design conditions. This results in uncomfortable and difficult working conditions for the ship's occupants, and causes problems with equipment overheating, and overloading of cooling plants. In order to assess options for improving the HVAC system, an environmental model that is capable of dynamically simulating the environment inside the ship is created. The model takes into account weather data based on ship location and time, ship structure and insulation, sun location and shading effects, internal heat gains from equipment and people, and the performance of the HVAC systems; which includes chillers, cooling coils, heaters, controllers, etc. The environmental model is used to assess options for improving the HVAC system to accommodate extreme tropical conditions. The model also forms an environmental baseline for the ship that can be used for assessing the impact of any change in the operational profile of the ship.

Keywords: HVAC; Environmental modelling; Thermal dynamic simulation; CFD

1. Introduction

LPDs have been designed to operate in mild tropical conditions 31°C Dry Bulb (DB), 26°C Wet Bulb (WB), this means that when these ships operates in areas with extreme hot climates (44°C DB, 29°C WB) such as the Arabian Gulf the HVAC system is over loaded and cannot maintain the required internal design conditions, resulting in uncomfortable and difficult working conditions for the ship's occupants, and causes problems with equipment overheating, and overloading of cooling plants.

In order to assess options for improving the HVAC system an environmental model of the ship is created. The environmental model includes the ship structure and insulation, people and equipment heat load and a detailed representation of the HVAC system.

Options for improving the HVAC system to accommodate extreme tropical conditions that are assessed in this study include lowering the chilled water supply temperature and pre-cooling the fresh air supplied to the ship using coolers in the AFU's.

A Computational Fluid Dynamics (CFD) analysis is also undertaken to assess the impact of lowering the chilled water temperature on compartment comfort.

The model also forms an environmental baseline for the ship that can be used in the future for assessing the impact of any modification such as increasing ship company, changing compartment usage or installing/upgrading equipment; it can also be to assess the impact of operating in different geographical locations and environments.

The behaviour of the environmental model has been validated by using data from a report (Ross, 2004) containing results from tropical habitability trial which were undertaken when the ship was commissioned.

Author Biography,
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Younus specialises in the design and analysis of marine systems. His research interests include improving HVAC systems and auxiliary cooling systems for ships.

2. Creating the Environmental Model

The environmental model of the ship is created using Dynamic Thermal Simulation software (IES VE 2017) which takes into account the following features;

1. Weather data based on ship location and time (from integral database),
2. Ship structure and insulation,
3. Performs shadow simulation across any day or time range at any global location,
4. Internal heat gains which include; lighting, people latent and sensible heat and equipment heat load,
5. The application of profiles for simulating people's movement in the ship and equipment operating frequency,
6. Modelling of the HVAC system which includes chillers, cooling coils, heaters, controllers, etc,

The ship and compartments geometry is modelled by importing DXF files for each deck. The DXF files were then converted to 3D geometry and insulation and construction material is applied to each individual compartment bulkhead deck and deck head.

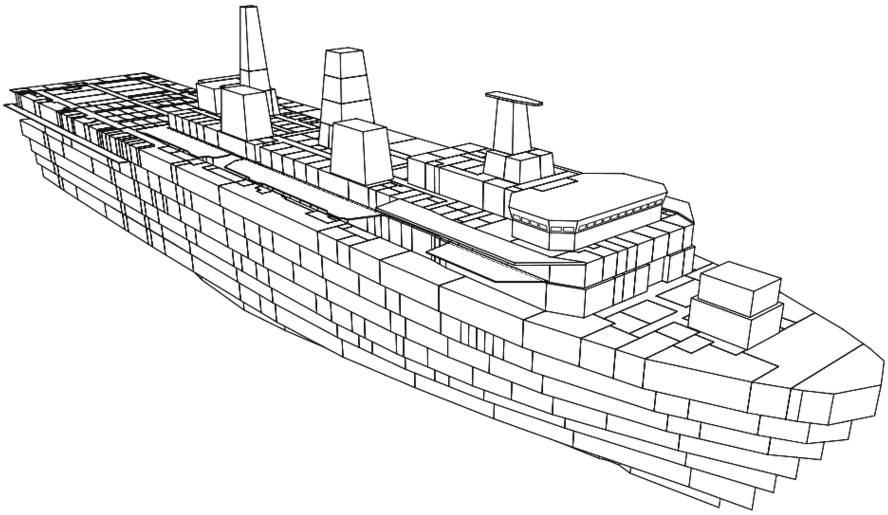

Figure 1: ISO view of the modelled ship geometry

Figure 1 shows the modelled ship geometry. All external surfaces below the water line have been set to a profile which can easily be used for changing the seawater temperature to suit the location of the ship.

The simulation of shadows and solar exposure can be undertaken from any sun position defined by date, time, orientation, site latitude and longitude. Figure 2 shows a snap shot for a shading simulation.

Internal heat gains for people, lighting and equipment are assigned for each space with a profile so the value of these heat gains can be controlled for a different time of day or year using daily, weekly and yearly profiles values were obtained from the LPD Contract Specification 500 Annex C. (LPD Contract Specification, 1996).

Each compartment is assigned the relevant occupancy profile; this enables the simulation of people's movement in the ship. Figure 3 shows the occupancy profile for a working area, the dining halls and cabins. The occupancy profiles show that cabins are occupied at 19:00-07:00 and 16:00-18:00 hours, dining halls are occupied at 07:00-08:00, 12:30-13:30 and 18:00- 19:00 and working areas are occupied between 08:00 and 16:00. From the figure it can also be seen that at any point of time the summation of the three profiles is one; this means that people will not be duplicated during the simulations.

The HVAC system is modelled by using a schematic component-based interface which enabled the modelling of the actual properties of cooling coils, heaters, fans chilled water plants and controllers. The interface also enables the linking of the HVAC system the relevant compartments in the model by using duct and room components. Figure 4 shows part of the HVAC model.

The HVAC system on the ship does not have a recirculating ducting system, this means that when air is supplied to compartments from an ATU the return air flows is generally through passageways, stairwells and lobbies back to the ATU. As most of these passageways and lobbies are shared by a number of ATUs, air supplied by one ATU will end up in another ATU via the returned air. Therefore such compartments and passageways were all inter-connected in the model.

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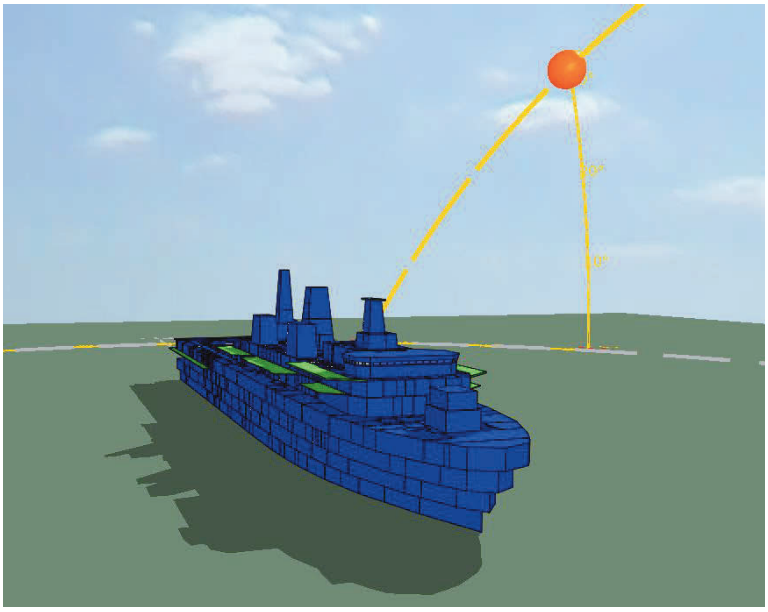

Figure 2: shading and sun exposure simulation

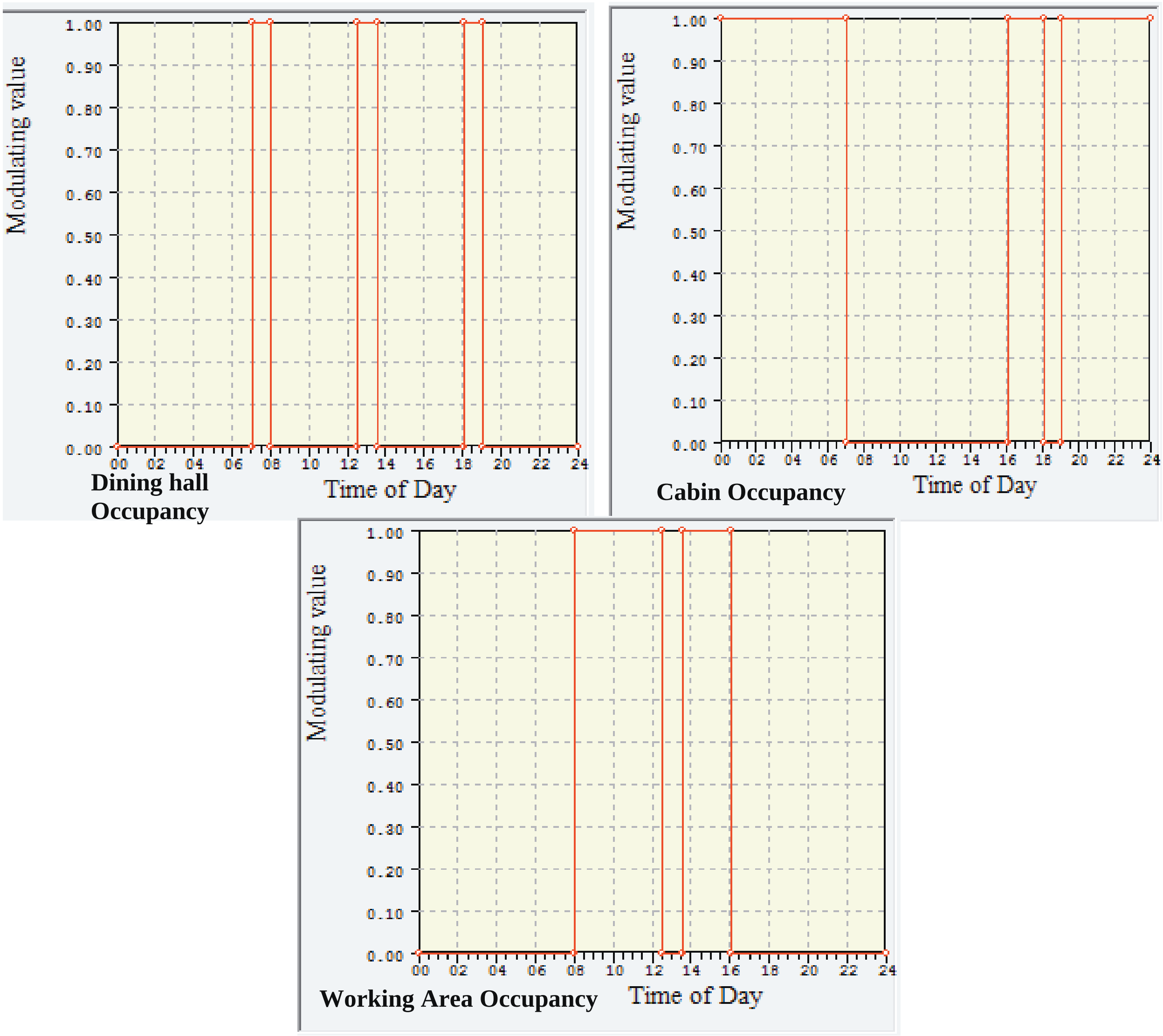

Figure 3: Occupancy profiles

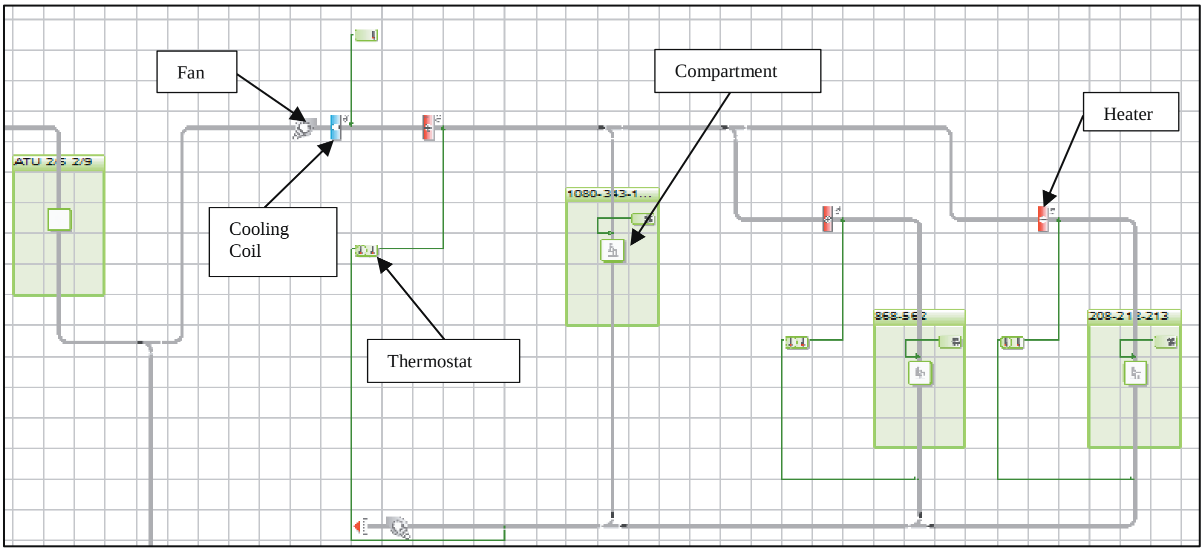

Figure 4: HVAC system components

3. Simulations and results

3.1. Design conditions

In order to simulate the condition for which the ship was designed, it was important to find a location with matching maximum ambient conditions that could be used in the simulation. From Figure 5 it can be seen that the maximum generic ambient conditions for a coastal region in the Mediterranean i.e. Tripoli on the 29th Aug, match the summer design conditions specified for the ship (31°C DB, 26°C WB).

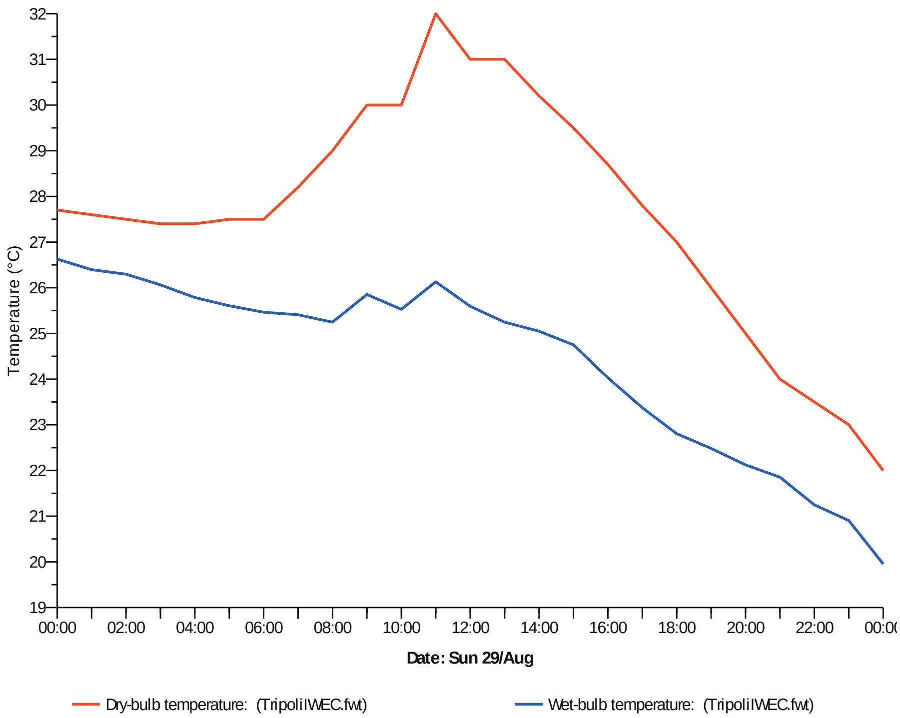

Figure 5: Weather data 29/Aug (Tripoli)

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The results showed that most of the compartment temperatures were below the internal design limits (29.5°C DB) with the exception of a few.

The results of the chilled water maximum load are listed in Table 1. From the table it can be seen that all the chillers have a reasonable margin when compared to the design capacity (BR 7911 (501)1, 1999), with the exception of the Operations Complex which only has a margin of 2.0 %.

Table 1: Design condition, chillers capacity

Chilled Water System	*Maximum Load (kW)*	*Design Capacity (kW)*	*Chiller Margin (kW)*	*Chiller Margin %*
Non-Essential	1673.4	2218.0	544.6	25%
Operations Complex	341.0	347.9	6.9	2%
Radar Complex	105.4	121.0	15.6	13%
Forward Weapons	47.1	53.3	6.2	12%
AFT Weapons	45.1	71.8	26.7	37%

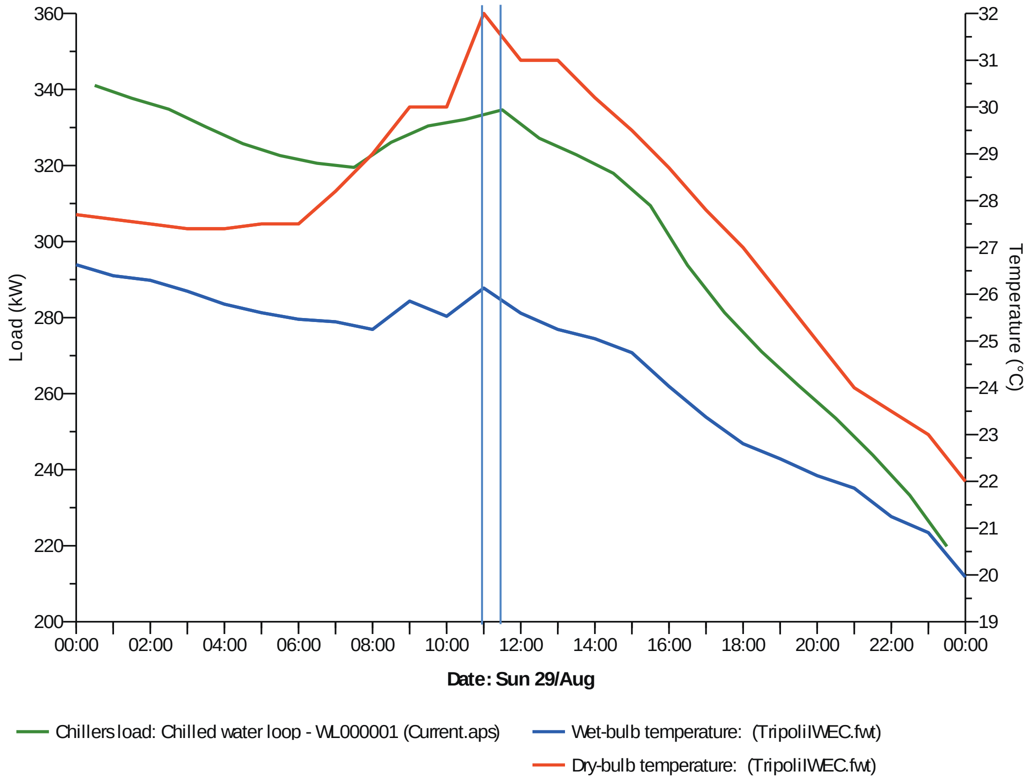


Figure 6: Ambient conditions and Operations Complex chiller load

Figure 6 shows the change in the operations complex chiller load with the ambient dry bulb and wet bulb temperatures. From the graph it can be seen that the maximum chiller load, lags the maximum ambient temperature by 15 minutes. This is because the simulation takes into account the behaviour of the thermal mass of the ship.

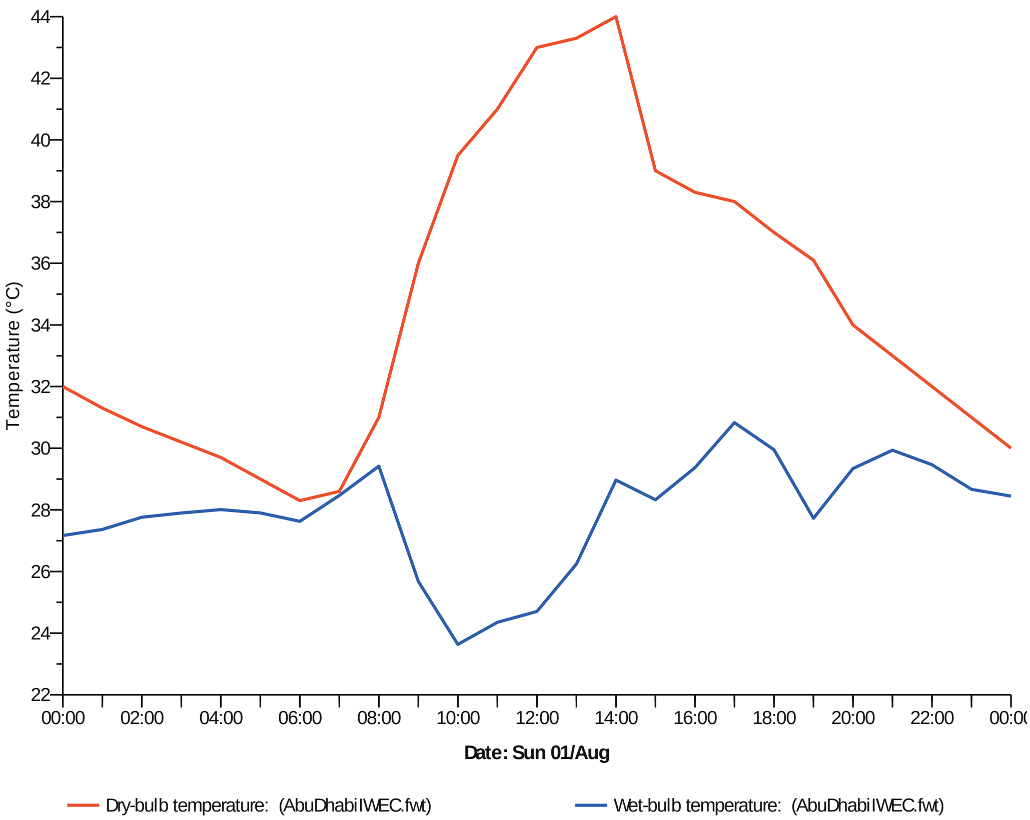
Another result that can be obtained from the simulation is the CO_2 concentration in spaces. Table 2 shows the CO_2 concentration levels in a few selected compartments.

Table 2: CO_2 concentration

Compartment	*CO_2 concentration (ppm)*
Compressor Room (LP)	494
Machinery Control Room	521
Compressor Room (HP)	472
Officer's Cabin	1645
Officer's Cabin	1631
Officer's Cabin	1645

3.2. Extreme Tropical conditions

One of the most extreme summer conditions LPDs operate in, is the Arabian Gulf, and one location with high dry bulb and wet bulb ambient temperatures that occur at the same time, is the coastal city of Abu Dhabi. Therefore, for this simulation the weather file for Abu Dhabi was used. Figure 7 shows the dry bulb and wet bulb temperatures for Abu Dhabi on 1st August.



Dry-bulb temperature (°C)	44.0
Wet-bulb temperature (°C)	29.0

Figure 7: Weather data 01/Aug (Abu Dhabi)

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Using the temperatures for Abu Dubai the results show that 75 compartments exceed the internal design temperature limit with some compartments experiencing temperatures as high as 40°C. This shows that conditions are very uncomfortable for living and working.

Table 3 shows the maximum chiller load in summer, from the table it can be seen that the operations complex chiller is operating above its design capacity. This means that the chiller cannot deliver chilled water at the required temperature (set chilled water supply temperature). Figure 8 shows a graph for the 5 chillers chilled water supply temperature, from the graphs it can be seen that the Operations Complex chiller supply water temperature rises to 8.8°C, which means that the chiller cannot remove the required heat from the system. The result also shows that the FWD Weapons chiller is running slightly above its rated capacity.

By comparing the operations complex chiller load graph throughout the day, with the ambient dry and wet bulb temperatures in Figure 9, it can be seen that the change in wet bulb temperature, affects the operations complex chiller more than the change in ambient dry bulb temperature.

Table 3: Extreme summer conditions chiller capacity

Chilled Water System	*Chiller Load (kW)*	*Design Capacity (kW)*	*Chiller Margin (kW)*	*Chiller Margin %*
Non-Essential	2057.2	2218	160.8	7%
Operations Complex	400.5	347.9	-52.6	-15%
Radar Complex	114.5	121	6.5	5%
Forward Weapons	53.4	53.3	-0.1	0%
AFT Weapons	49.9	71.8	21.9	30%

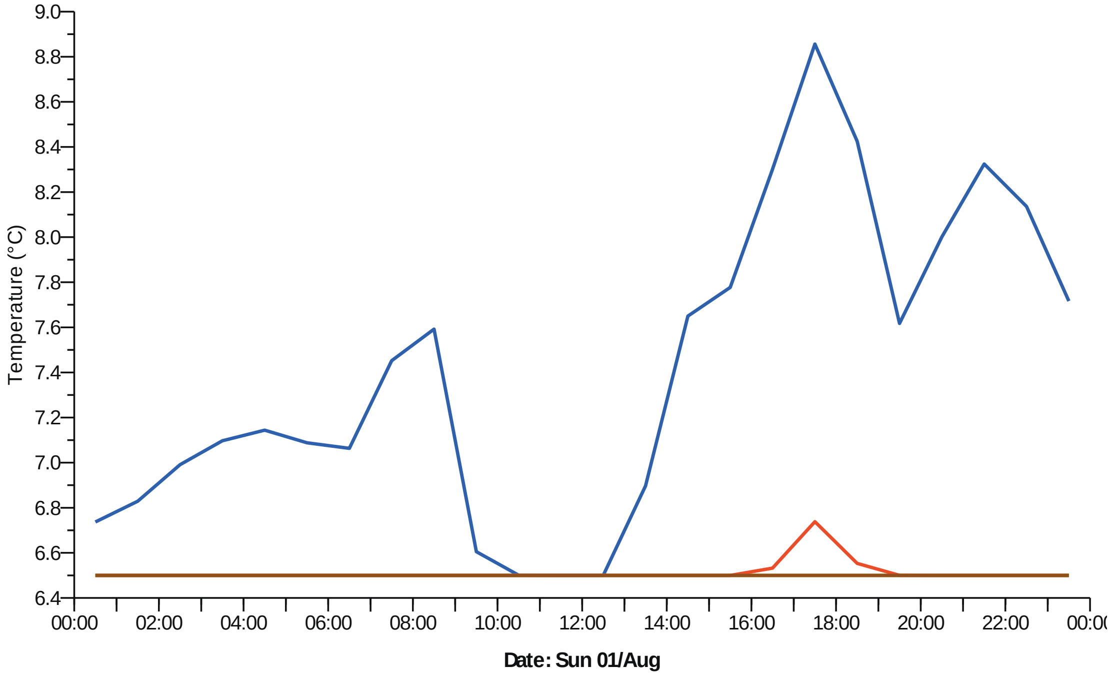
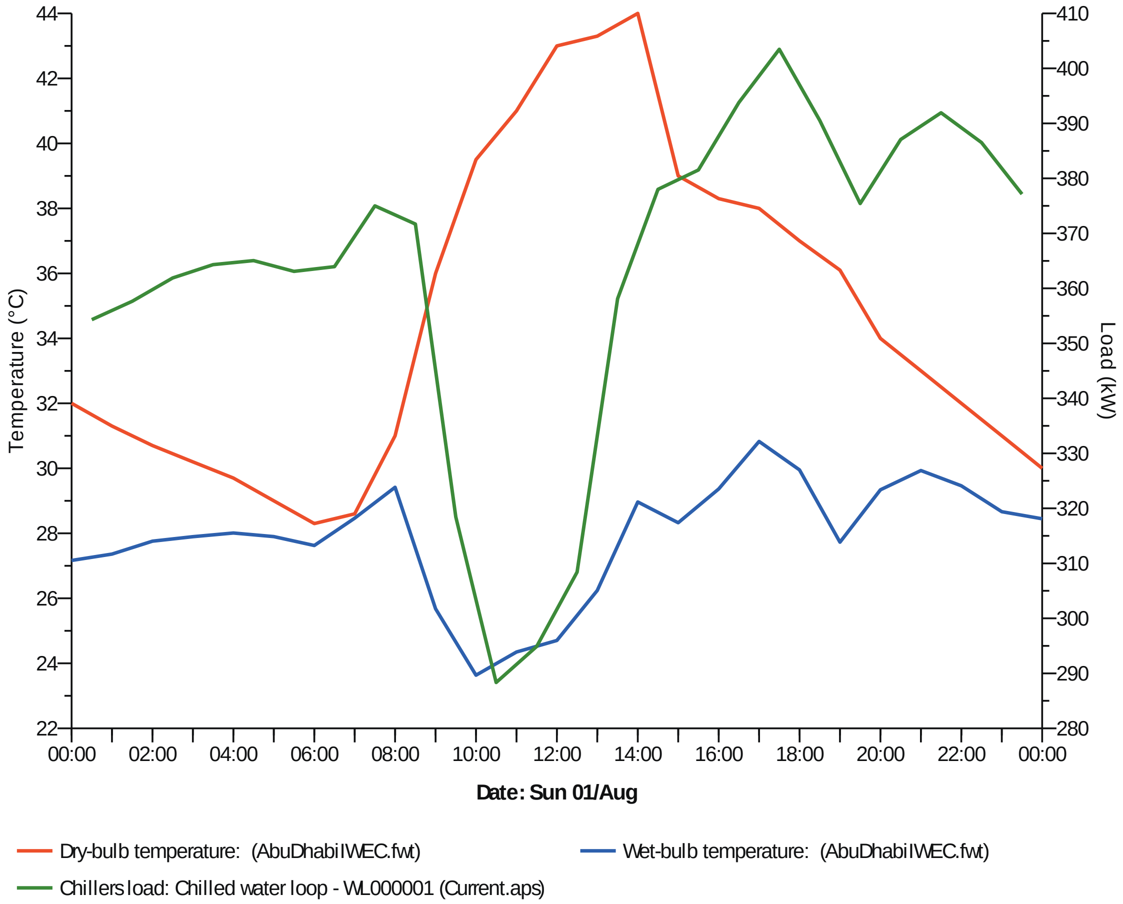


Figure 8: Chilled water leaving temperature 01/Aug (Abu Dhabi)



Dry-bulb temperature (°C)	37.5
Wet-bulb temperature (°C)	30.39
Chiller load (kW)	400.196

Figure 9: Ambient conditions and Operations Complex chiller load 01/Aug Abu Dhabi

The performance of a selection of ATU cooling coils is listed in Table 4. These cooling coils are rated to give a dry bulb leaving temperature of 15°C (BR 7911(403)5, 2001), and from the table it can be seen that the leaving air dry bulb temperature for some cooling coils is as high as 20°C, which means that they are underrated for these conditions.

Table 4: ATU cooling coil performance

ATU No	*Design Capacity (kW)*	*Actual Load (kW)*	*Air leaving Temp (°C)*	*Water ΔT (°C)*
1/1	76.5	67.5	12.2	6.4
1/2	58.2	57.4	14.7	7.1
1/5	82.4	117.5	20.4	9.9
1/7	74.2	94.2	17.6	8.9
1/9	21.5	20.8	14.2	7.3
1/13	124.4	171.3	20.3	9.6

4. System improvement strategies/options

There are a range of measures that could be considered to upgrade the HVAC system on board the ship to operate in extreme hot conditions, ranging from reducing the chilled water temperature, to improving the insulation in selected compartments and undertaking a minor redistribution of air in selected ATU ventilation systems.

Reducing the chilled water supply temperature will reduce the air supply temperature to the compartments, therefore the difference in enthalpy between the supply and exhaust air will increase, as a result the air flow supplied to the compartment will have a greater cooling effect (ASHRAE, 2000). This will eliminate the need to increase the air flow rate and potentially the ducting size and ATU fan sizes throughout the ship.

Reducing the chilled water supply temperature will also increase the difference between the supply and return temperature. The increase in temperature difference will result in a higher cooling capacity without the need to upgrade the chilled water flow rate and hence upgrade the pipe work and pump.

Eliminating the need to upgrade the ducting, fans, CW piping and pumps throughout the ship would have significant cost savings. The chiller electrical power consumption will increase as its efficiency will reduce at lower chilled water supply temperatures (Wulfinghoff, 2004), this increase in chiller power consumption is offset by the reduced electrical consumption of fans and pumps.

A number of scenarios were simulated to assess the effect of reducing the chilled water supply temperature, and pre-cooling the fresh air by using coolers in the AFU's on the environmental condition of the ship. The results from these simulations identified that some spaces are over cooled and others are under cooled, so the air supply to these spaces (21 in total) has been redistributed. The results also identified that the main source of heat for some compartments, which were above the design limit, is due to internal and external heat conduction. Therefore it is proposed that the insulation of these compartments (nine in total) is increased to 75 mm in thickness.

After the model was updated with the revised insulation thickness, and the air flow to selected compartments was redistributed, the environmental conditions in these compartments were significantly improved. This configuration was used as a baseline for the simulation of alternative options.

Once a baseline model was established two viable options were identified as having the potential to improve system performance. These options were modelled and simulations run and the results assessed for their effectiveness.

4.1. Option A

Option A; uses the design chilled water supply temperature of 6.5°C, and fresh air cooling coils located in the AFU compartments with 15.0°C dry bulb air leaving temperature for pre cooling the fresh air before it enters the ATUs. This option would require the installation of a cooling coil in each AFU, and the upgrade of each AFU fan. Also eight ATU cooling coils, will have to be upgraded. Additionally the Non-Essential and the Operations Complex chillers will have to be upgraded.

4.2. Option B

Option B; uses a supply temperature of 4.0°C for the Non-Essential and Operations Complex chillers. All other chillers are kept at a chilled water supply temperature (CWST) of 6.5°C.

The results from simulating Option B show that, only 25 spaces are above the internal temperature threshold and most of these spaces are passageways, lobbies or stores.

For Option B the Non-Essential and Operations Complex chillers will have to be replaced, all other chillers have adequate capacity and don't need to be replaced, providing they are operating at their design capacity, as they are only required to operate at a CWST temperature of 6.5°C. In terms of cooling coils this option would only require the upgrading of six cooling coils.

Table 5 shows a comparison between compartment temperatures, which are above the internal design limits at the original design conditions, before any modification is made and at extreme topical conditions after the modifications in Option B are implemented.

Table 5: Compartments initially above the internal design limit

Compartment	*Ambient (31.0°C DB, 26°C WB) Design Conditions*	*Ambient 44.0°C DB 29°C WB with CWST 6.5°C*	*Ambient 44.0°C DB, 29°C WB with CWST4°C (Option B)*
Electrical Equipment Space Mast 2	32.12	35.97	25.35
Electrical Equipment Space Mast 1	32.82	39.31	28.09
Fwd. Weapons Room	30.19	32.84	27.74
JRS Recreation Space	28.53	32.07	27.09
Senior Rating Pantry	32.02	34.19	29.18

Table 6: Option B chillers capacity and CWST

Chilled Water System	*Design Capacity (kW)*	*Chiller Load (kW)*	*Chillers Margin (kW)*	*Chillers Margin %*	*CWST (°C)*
Non-Essential	2218	2283.8	-65.833	-3%	4.0
Operations Complex	347.9	437.8	-89.936	-26%	4.0
Radar Complex	121	113.5	7.455	6%	6.5
Forward Weapons	53.3	49.6	3.715	7%	6.5
AFT Weapons	71.8	49.2	22.563	31%	6.5

From Table 6 it can be seen that for this option both the Non-Essential and Operations Complex chillers will have to be upgraded all other chillers have adequate capacity and don’t need to be replaced as they are only required to operate at a CWST temperature of 6.5°C.

Option B is the preferred option as it provides more comfortable internal environmental conditions at extreme tropical ambient conditions. This option is also more economical as there is no requirement to install fresh air cooling coils in the AFU compartments which would also require fan upgrades and major chilled water piping work. Also the total chiller capacity required for this option is less than Option A.

5. CFD Analysis

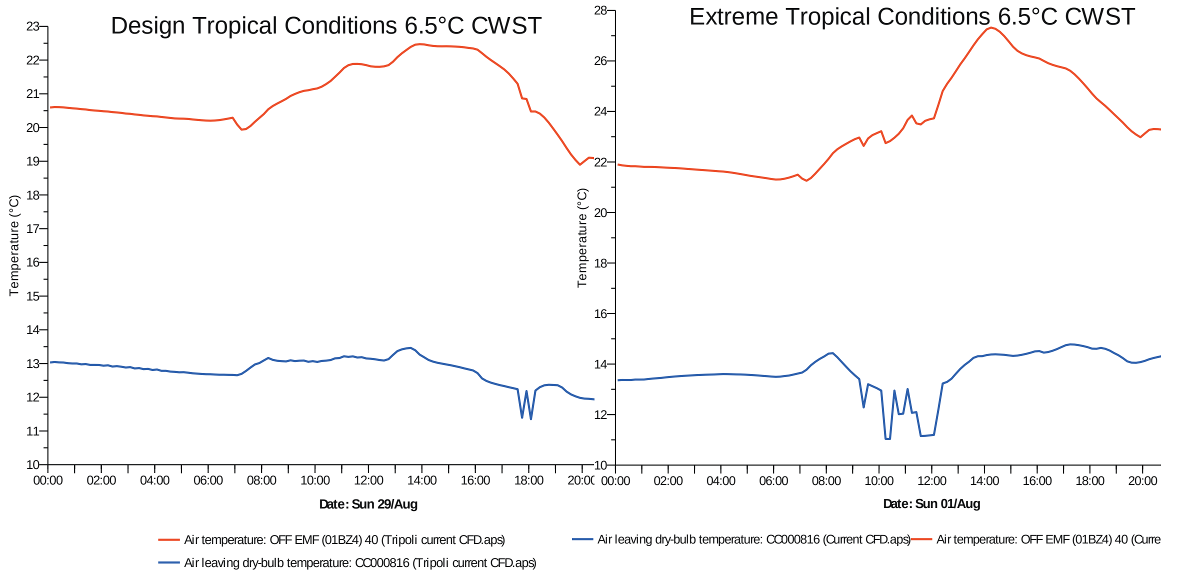
This section presents the results from a CFD analysis that was undertaken, to assess the effect of lowering the chilled water supply temperatures on compartment comfort. For this analysis an officer’s cabin is selected for the assessment.

5.1. 6.5°C Chilled Water Supply Temperature

The results from the dynamic thermal analysis of the ship model for two simulations were imported, and used as boundary conditions for the CFD analysis; the first is the simulation at the design ambient condition (31°C DB, 26°C WB), and the second is the simulation at extreme tropical conditions (44°C DB, 29°C WB), with a CWST of 6.5°C (ship in current state).

Figure 10 shows the officer cabin compartment air temperature and air supply temperatures for the two simulations.

Figure 11 shows the temperature contour plots of the CFD analysis for the selected officer cabin, at design and extreme tropical conditions respectively, when a CWST of 6.5°C is used. From the two temperature plots, it can be seen that temperature around the bed and at mid compartment height, is between 24 - 22°C, for the design conditions and 27-25°C, for the extreme tropical design conditions.



Variable Name	Ambient 31°C DB, 26°C WB	Ambient 44°C DB, 29°C WB
Air supply temperature (°C)	13.26	14.78
Compartment temperature (°C)	22.47	27.32

Figure 10: Officer Cabin compartment air temperature and HVAC system air supply temperatures CWST 6.5°C

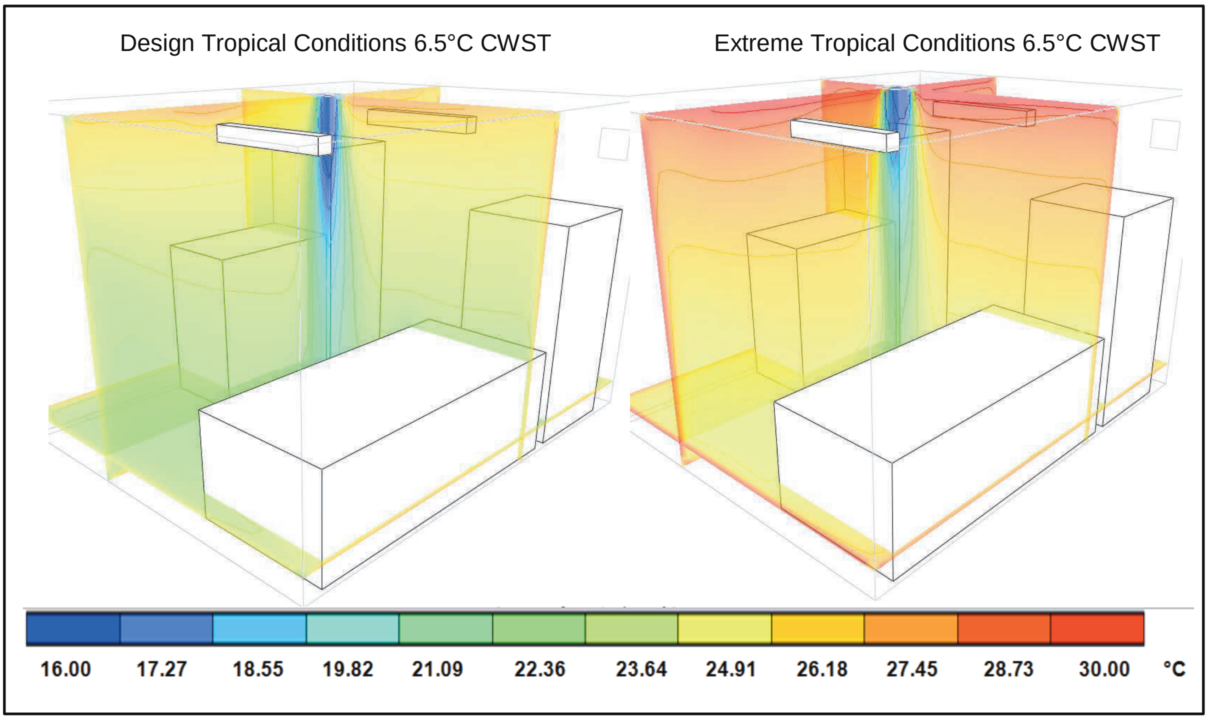
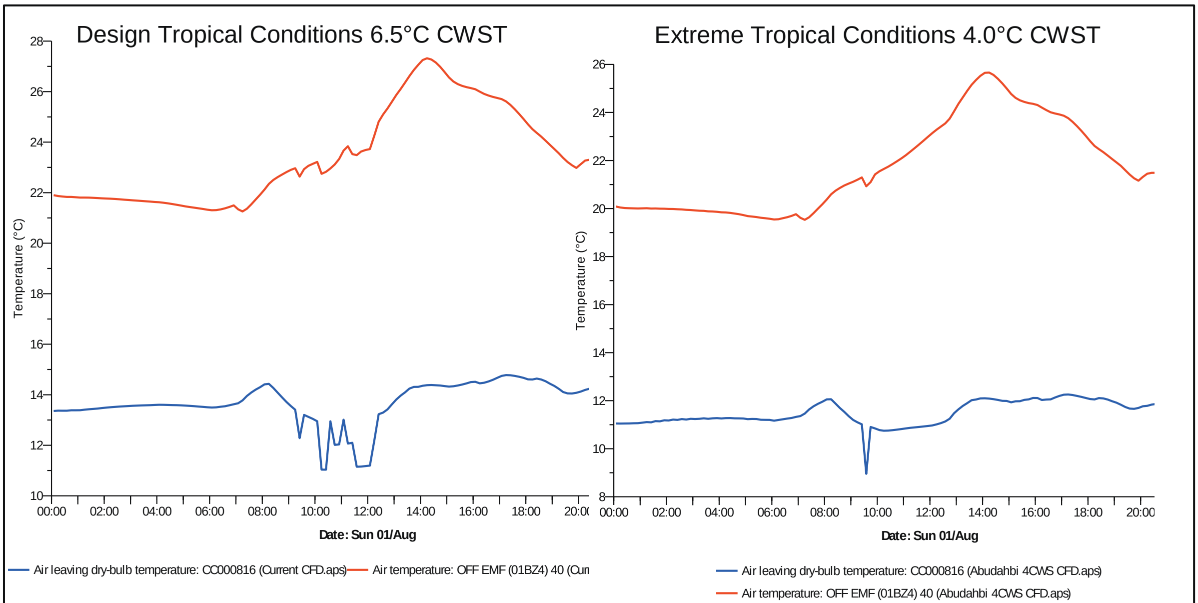


Figure 11: Temperature plot -Officer Cabin comparison between Design conditions and Extreme tropical conditions CWST 6.5°C.

5.2. 4.0°C Chilled Water Supply Temperature

The results from the dynamic thermal analysis of the ship model, for the simulation at, the extreme topical conditions (44°C DB, 29°C WB) (Abu Dhabi 01/Aug), with a CWST of 4.0°C, were imported and used as boundary conditions in the CFD analysis.

Figure 12 shows the officer cabin compartment air temperature, and air supply temperatures, for the 4.0°C CWST extreme tropical conditions, and the design conditions simulations.



Variable Name	Ambient 31°C DB, 26°C WB CWST 6.5°C	Ambient 44°C DB, 29°C WB CWST 4.0°C
Air supply temperature (°C)	14.26	12.1
Compartment temperature (°C)	22.47	25.65

Figure 12: Officer Cabin compartment air temperature and HVAC system air supply temperatures when CWST at extreme tropical conditions is 4°C.

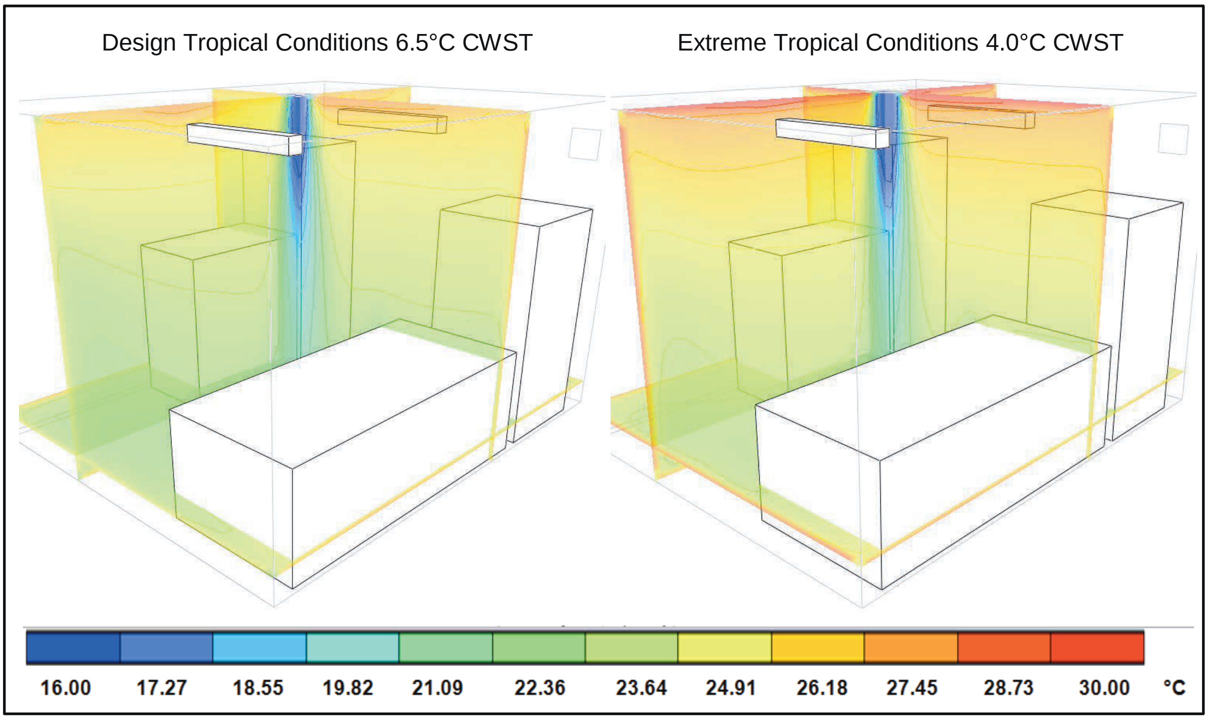


Figure 13: Temperature plot -Officer Cabin comparison between Design conditions and Extreme topical conditions with CWST of 4.0°C.

Figure 13 show the temperature contour plots of the CFD analysis for the selected officer cabin, at design conditions (CWST 6.5°C), and extreme tropical conditions, when the CWST is set to 4.0°C. From the two temperature plots, it can be seen that the temperature around the bunk bed, and at mid compartment height is between 24 - 22°C for the design conditions, and 25-22°C for the extreme tropical design conditions

From this CFD analysis it can be seen that the reduction in the temperature of the air supplied to the compartment due to reducing the CWST to 4.0°C in extreme tropical conditions, will not have a negative impact on the comfort of the compartment, on the contrary it will enhance the comfort of the compartments as it brings the conditions and temperature distribution around the compartment, closer to the original design state scenario.

6. Validation of the ship environmental model

A report (Ross, 2004) containing results from tropical habitability trial, has been used to validate the environmental model of the ship. The trial results contain compartment temperatures, air flow rates, and chilled water flow rates.

6.1. Configuration of HVAC System

In order to validate the model, the HVAC system in the model was modified to suit the actual system configuration during the trial. The following modifications were made;

1. Air flow to all compartments was modified to equal the air flow readings taken during the trial. The exhaust air flow and the fresh air supply to each ATU have not been recorded during the trial and therefore, the percentage of air supply to each ATU has been based on design values.
2. Chilled water flow rate to all cooling coils were modified, to the values recorded during the trial.

In order to simulate the ambient conditions during the trial (32°C DB, 27°C WB), it was important to find a location that is close to where the trial was undertaken, and has ambient conditions that are close to the recoded values. So a weather file for Miami Florida was chosen, the file was then modified so the dry bulb and wet bulb conditions, matched the conditions of the trial. The wet bulb and dry bulb conditions for the modified day, are shown in Figure 13.

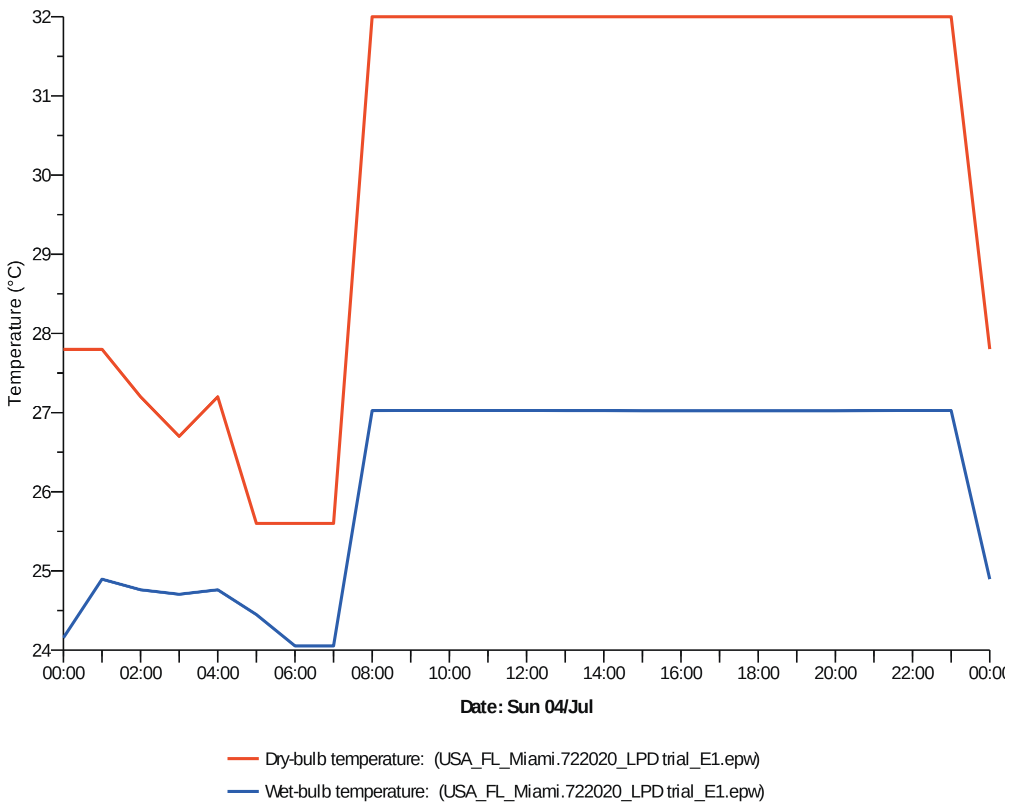


Figure 14: Modified weather data for Miami Florida

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6.2. Tropical Trial Results

Table 7 shows a comparison between the actual compartment temperature readings recorded on the tropical trial and the model results. The table lists the compartments that have close correlation when comparing the model to the trial data.

Table 7: Model results with close correlation to trial data

Compartment	*Trial Temp °C*	*Model Temp (°C)*	*ΔT Temp (°C)*
Crew Shelter	20	20.36	0.36
Weapons Workshop	23.6	23.1	-0.5
Officers Cabin	22.9	22.5	-0.4
Officers Cabin	22.8	22.3	-0.5
Deck Store	26.1	25.3	-0.8
Officers Cabin	21.1	22	0.9
W.C.	24.6	25	0.4

Table 8 lists a selection of compartments where the model results do not correlate to the tropical trial recorded compartment temperatures. All these compartments have high estimated equipment wild heat applied to the model, and therefore, the compartment temperature results from the model are higher. This means either, the values estimated are too high, or when the trial was undertaken, not all the electrical equipment in the compartments was operated.

Because the air flow to the compartment is known and the ambient conditions are the same the temperature difference between the trial and the model results can be used to estimate the wild heat from equipment during the trial using Equation (1).

$$Q = m^{\cdot} \times C_p \times \Delta T \quad (1)$$

Where; Q is the difference in equipment wild heat, ΔT is the difference between the trial and the model result temperature, $m^{\cdot}$ is the mass flow rate of air supplied to the compartment, and C_p is the specific heat capacity of air in the compartment.

Table 8: Model results with poor correlation to trial data

Compartment	*Trial Temp °C*	*Model Temp °C*	*ΔT Temp °C*	*Model Equipment Wild Heat (W)*
Electrical Equipment	20.7	26	5.3	1,600.0
Bridge	20.3	22.9	2.6	10,400.0
Command Support System Annexe	23.9	31.6	7.7	2,280.0
Radar Office	20.6	25.6	5	12,000.0
AFT Weapons Equipment Room	23	30	7	8,055.0
Flying Control Office	23	25.7	2.7	4,480.0

The model has been updated with the corrected wild heat values for the selected compartments and then re-simulated.

Table 9 shows the corrected equipment wild heat values and the corresponding temperatures for each of the selected compartments. From the table it can be seen that the difference between the trial compartment temperature and the model results has reduced significantly.

This method of correcting the equipment wild heat by comparing actual trial data to the model temperature, can be used to estimate the wild heat for equipment that does not have OEM wild heat data if the equipment is operated at, or close to, its maximum power.

The validation of the environmental model has shown that the behaviour of the model accurately represents that of the actual ship under the conditions, future work has been scheduled to validate the model across a range of other conditions using the ship current configuration.

Table 9: Model results after the correction of equipment wild heat values

Compartment	*Trial Temp °C*	*Model Temp °C*	*ΔT Temp °C*	*Corrected equipment Wild Heat (W)*
Electrical Equipment	20.7	21.7	1	944.9
Bridge	20.3	20.5	0.2	6,063.2
Command Support System Annexe	23.9	23.8	-0.1	727.7
Radar Office	20.6	20.6	0	2,250.0
AFT Weapons Equipment Room	23	23.15	0.15	3,485.4
Flying Control Office	23	23.1	0.1	2,954.0

7. Conclusions

By creating an environmental model for a Naval Ship, it was possible to assess the environmental conditions under a variety of ambient conditions and operational scenarios. The model was also successfully used to assess proposed improvements to the HVAC system by undertaking dynamic simulations.

The simulation of the environmental model of LPDs, at extreme tropical conditions shows that, 75 compartments exceed the internal design temperature limit. The results also show that the Operations Complex chiller load is above its rated capacity.

The results from these simulations also identified that some spaces are over cooled, and others are under cooled, so the conditions in theses spaces can be significantly improved by redistributing the supply air. The results also identified that the main source of heat for some compartments, which were above the design limit is predominantly due to internal and external heat conduction, and the conditions in these compartments would benefit from additional insulation to the bulkheads and Deck-heads.

By upgrading the capacity of the Non-Essential and Operations Complex chillers, and reducing the CWST to 4.0°C, the supply temperature to most of the ship compartments is reduced by 2°C. This reduction in air supply temperature has a positive impact on the environmental conditions of the whole ship.

A CFD analysis has shown that reducing the air supply temperature to the compartments by 2°C, will not have a negative impact on the comfort of the compartment, on the contrary it will enhance the comfort of the compartments as it brings the conditions, and temperature distribution around the compartment closer to the desired design limits.

The validation of the environmental model, against the tropical trial has shown that the behaviour of the model accurately represents that of the actual ship under these conditions, future work has been scheduled to validate the model across a range of other conditions using the ship current configuration.

This model can also form an environmental baseline for the ship, which can be used in the future, for managing the environmental margins, and assessing the impact of any modification such as; an increase in ship occupancy, installing electrical equipment or operating in a new location.

8. Acknowledgment

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10. Glossary of terms

AFU : Air Filtration Unit.
ATU : Air Treatment Unit.
BR : Book of Reference.
CFD : Computational Fluid Dynamics.
CW : Chilled Water
CWST : Chilled Water Supply Temperature.
DB : Dry Bulb.
HVAC : Heating Ventilation and Air Conditioning.
LPD : Landing Platform Dock.
WB : Wet Bulb.

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