Institute for Social and Environmental Transition-International
SUMMARY REPORT

DA NANG, VIETNAM:
CLIMATE CHANGE IMPACTS ON HEAT STRESS BY 2050

Sarah Opitz-Stapleton
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ISET THE ROCKEFELLER FOUNDATION ACCCRN Asian Cities Climate Change Resilience Network COHED

Institute for Social and Environmental Transition
www.i-s-e-t.org

Key Findings

Hot, humid days and nights contribute to heat stress, heat-related deaths, reduced labor productivity and can exacerbate poverty. While everyone can be negatively impacted by extreme heat, certain people such as workers, especially those working outdoors in the sun or engaging in physical labor, the elderly and those with chronic illnesses, children and pregnant women are particularly at risk of suffering harm during such hot spells. Climate change is causing temperatures to increase around the globe, and leading to an increase in the number of hot days and nights.

Da Nang is a tropical city in which the humidity rarely drops below 60%; the humidity is always high. Humidity and lack of wind can make a day or night feel even hotter than what the thermometer registers, and as the body experiences increasing difficulty in cooling itself through sweating. Heat stress indices have been developed to describe how hot it actually feels to people based on humidity, temperature and physical activity, among other factors. We developed a heat stress index for Da Nang to measure how the number of hot days and nights has changed in the past (1970-2011) and how climate change might increase these in the near future (2020-2049).

The Vietnam Ministry of Health (MOH) regulations specify that temperatures in a work environment should not exceed 34°C for light work (desk-based jobs) or 30°C for heavy work (construction, outdoor labor, etc.) when the humidity is 80% or lower. At humidity higher than 80%, the temperature thresholds are even lower because dangerous heat stress conditions can rapidly develop and endanger workers' health. Over the period of 1970-2011, there were an average 210 (295) days per year in which the heat index was equal to or greater than the MOH's recommendations of 34°C (30°C) for light (heavy) labor. On average, the number of days per year in which the heat index exceeds 34°C has increased by approximately 5 days per decade.

Multi-model projections of future day and night ambient temperatures and heat index values under nearly all climate change scenarios show continued warming through 2050. Warming is most pronounced in the months leading up to (April and May) and just after (September through November) the hot season, though the hot season will also get warmer. Because of these increases in ambient temperature, the heat index during the day begins to continually average above 40°C during May through September, creating dangerous working conditions for both outdoor and indoor workers. The median heat index during the day is not likely to fall below 35.1°C during any season by 2050, putting both outdoor and indoor workers at risk of heat stress unless a variety of coping mechanisms are adopted. Nighttime temperatures and heat indices are also likely to increase, not allowing individuals to recover while they sleep. When factoring urban heat island effects, future heat stress in Da Nang could be significant.

The rapid construction of buildings and roads, additional cars and air conditioning in Da Nang are trapping heat in the city – this is known as the urban heat island effect and can make temperatures in the urban core up to 10°C warmer than the surrounding rural areas. The potential for urban heat effects on future heat indices is profound. Outdoor workers in urban areas will be at significant risk of heat stroke and, possibly, death in the hot season if their localized heat index approaches 45 to 55°C and their employers do not allow them to rest and take protective measures.

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Acronyms

ACCCRN	Asian Cities Climate Change Resilience Network
CMIP5	Apparent Temperature
AT	Coupled Model Intercomparison Project Phase 5
COHED	Centre For Community Health And Development
CSIRO	Commonwealth Scientific and Industrial Research Organisation
GCM	General Circulation Model
IMHEN	Institute of Meteorology, Hydrology and Environment
IPCC	Intergovernmental Panel on Climate Change
ISET	Institute For Social And Environmental Transition
ILSSA	Institute for Labour, Science and Social Affairs (MOLISA)
MOH	Ministry Of Health
MOLISA	Ministry Of Labour, Invalids And Social Affairs
MONRE	Ministry of Natural Resources and Environment
RCM	Regional Circulation Model
RCP	Representative Concentration Pathway
WBGT	Wet Bulb Globe Temperature

Climate Change Impacts on Heat Stress by 2050 in Da Nang, Vietnam

Introduction

Hot weather has long been recognized as detrimental to human health and labor productivity by the scientific, health and labor research communities. Despite this recognition, implementation and updating of existing health policy mechanisms, and public and business awareness of the health and labor risks associated with extreme heat remain low (Nguyen, 2013; Zeng et al., 2012; Huang et al., 2011). Capacities for accessing, perceiving and understanding heat risks, and taking appropriate actions are diverse and strongly linked with socioeconomic status, culture and ability to participate politically – similar to capacities related to dealing with other natural hazards and building resilience to climate change (IPCC 2012).

As the reality and significance of climate change begins to permeate discussions across many policy and decision making spheres – from the community-level through international negotiations – many are recognizing the importance of heat stress, extreme heat and its impact on labor productivity. These are not the only health risks that are being altered by a changing climate; shifts in the transmission and range of zoonotic and vector-borne diseases, direct threats of mortality and morbidity related to hazards like flooding or typhoons, malnutrition due to food insecurity and other types of health impacts should be anticipated (Smith et al. 2014; Moore et al. 2012; McMichael et al. 2006). Some of these health threats, such as those related to food insecurity or malaria have traditionally garnered more research and policy attention than heat stress. Recent efforts are now calling greater attention toward the importance of heat stress, but much work is still needed in many locations, where monitoring and communication of weather conditions (early warning) as well as general awareness of weather-health impacts and precautions, remain low. Still further work needs to be done in finding context-appropriate responses for dealing with heat and in exploring the inter-linkages between various health impacts and knock-on effects, such as how reduced labor productivity could lead to lower crop yields (and thus food insecurity) as farmers are physically unable to tend to their crops or to loss of household incomes and inability to seek medical care.

Figure 1: Location of Da Nang in Vietnam's central coast (left figure) and a simple land use map showing the drastic terrain (coast to mountains) over a short distance. The terrain influences Da Nang's local climate in a manner not captured by climate models, requiring downscaling for climate change studies.

This study focuses on three main action research activities related to heat stress in the city of Da Nang, Vietnam: 1) improving awareness among the city's businesses and residents about heat stress and building capacities for reducing heat exposure, particularly at work; 2) coordinating with the Public Health Department and local businesses to improve monitoring of unhealthy heat conditions and devise appropriate responses; and, 3) to assess trends in heat stress conditions and project how climate change might alter these by 2050 through the creation of a simple heat index that the health department can calculate and then use to warn the city's residents about heat risk. The project falls under the Asian Cities Climate Change Resilience Network (ACCCRN) program umbrella.

Heat Index
An approximate measurement of how hot a person feels given weather conditions, physical activity and clothing.

The project is being led by the Center for Community Health and Development (COHED) in coordination with a number of public health and labor entities, with support by the Institute for Social and Environmental Transition-International (ISET) for the third activity. This report summarizes the development of the heat index and how climate change is likely to alter the number of hot days and nights in Da Nang, the length of the hot season, and increase overall temperatures. It concludes with a discussion of some of the implications for heat stress and labor productivity, and highlights additional critical (in the authors' opinions) research needs that are not within the scope of this study.

The creation of heat indices and methodologies for doing so are not novel, and it would be both redundant and a waste of time to try to create a new 'innovative' heat index. What is novel about the work is that the heat index is being developed in coordination with a broad range of stakeholders to assist in policy development and the implementation of climate resilient responses. The meteorological and climatological communities have developed a standard set of heat indices, however, they are often not good at communicating their utility to health departments, businesses or the broader public or in conveying heat-health risks. *The true value and innovation of the heat analysis in this project lies in it being a climate service in support of a climate resilience process, designed to meet specific user-identified needs.* It is in the application of the index, and its ultimate usefulness and adoption by the Ministry of Health (MOH) or other health agencies, businesses and residents, that its innovation lies. Furthermore, projecting how the heat index might change in the future due to climate change IS innovative and an important contribution to the climate science community; such efforts are underway in multiple studies for locations around the world. As COHED continues their work in Da Nang, they will be able to monitor how the heat index is being used, what aspects are confusing to different stakeholders, and be able to evolve and/or develop new approaches for conveying the heat risk that the index represents.

Background

Da Nang is a city with a tropical (hot and humid) climate dominated by a dry season that lasts roughly from April to August, and a wet season from September to March. The humidity rarely drops below 60% in the city, averaging roughly 80% and the mean annual temperature is 25.9°C. As the city has experienced rapid development in the past few decades, the large number of buildings and roads, more cars and air conditioners are trapping excess heat in the city and making it hotter than the surrounding agricultural lands. This so called 'urban heat island effect' can make Da Nang's dense urban areas up to 10°C warmer than the surrounding rural areas, as seen in other cities (Mohan et al. 2013). The naturally hot and humid climate, coupled with the urban heat island, can create extreme heat conditions that have a broad range of negative impacts on the city's residents and workers.

Hot, humid days and nights contribute to heat stress and heat-related deaths, along with a decrease in labor productivity. While everyone can be negatively impacted by extreme heat, certain people such as workers, especially those working outdoors in the sun or engaging in physical labor, the elderly and ill, children and pregnant women are particularly at risk of suffering harm during such hot spells. Workers in buildings with poor ventilation, no air conditioning or fans, and/or operating heat-generating machinery (e.g. sewing machines, manufacturing, or many computers) may find that indoor temperatures exceed the ambient outside temperature (IPCC 2012). Consecutive days and nights of extreme heat sap workers' strength, exacerbate underlying health conditions, and can lead to heat stress and increased risk of death.

The Vietnam Ministry of Health (MOH) has set work temperature recommendations urging special precautions for when **ambient temperature** (what a standard meteorological thermometer measures) and humidity reach particular thresholds. For outdoor workers, such as construction workers, street vendors, farmers or fisherfolk, the MOH (2002) urges caution when air temperature is 30°C or warmer and humidity measures up to 80%. Indoor workers engaged in light labor, e.g. desk-based work, are theoretically able to handle temperatures of up to 34°C and humidity up to 80% (MOH 2002). While these temperature and humidity thresholds definitely do lead to dangerous conditions for most workers, how hot it feels to an individual and their ability to cope with it depends on a number of other factors. Such factors include a person's underlying health and nutritional status, age, clothing type, level of labor activity (all coping mechanisms), ability to cool off in the evening, and exposure to sunlight and wind (meteorological conditions. Numerous studies indicate that a broader range of **apparent temperatures** – how hot it feels to a person – should be considered than the MOH's thresholds when developing precautionary measures for protecting people's health and productivity during hot seasons.

The meteorological and climatological communities in various countries have devised a number of **heat indices** to more accurately reflect the actual temperatures a healthy person is physiologically experiencing under particular weather conditions. The next section discusses the history of a few commonly used heat indices, common assumptions and precautions in interpreting each, and provides examples of how they are used.

Heat Indices

Health research indicates that a variety of health impacts begin to emerge through a broad range of air temperature and humidity conditions, especially if the individual is engaged in physical activity (; Smith et al. 2014). At temperatures of 27°C and a relative humidity of 40%, healthy individuals may begin to experience increasing fatigue and irritability if they are exposed to such conditions for a couple of hours or more and/or engaged in physical activity (**Figure 2 and Table 1**). A healthy person engaged in heavy physical labor, such as a construction worker or farmer may begin experiencing heat stress at heat indices of 26°C (Kjellstrom et al. 2009; Parsons, 2006). Individuals with cardiac, respiratory or chronic health conditions like diabetes, cancers or autoimmune disorders, those taking certain medications, children, elderly and pregnant women may have lower thresholds at which they begin to suffer adverse health effects (Luber and McGeehin 2008). Furthermore, the impacts of heat stress may accelerate much more rapidly for such populations as weather conditions worsen than for healthy populations. *Because working populations can comprise pregnant women, those with chronic health conditions or older workers, we advise a lowering of heat index thresholds to trigger employer safety measures*[1].

[1] In this study however, we used MOH's thresholds of 34°C for indoor workers. We do urge reconsideration of this threshold toward a range to accommodate different health conditions and workers of advanced age.

Caution
Extreme Caution
Danger
Extreme Danger

Relative Humidity (%)	temperature (°C)																
	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
40	27	28	29	30	31	32	34	35	37	39	41	43	46	48	51	54	57
45	27	28	29	30	32	33	35	37	39	41	43	46	49	51	54	57	
50	27	28	30	31	33	34	36	38	41	43	46	49	52	55	58		
55	28	29	30	32	34	36	38	40	43	46	48	52	55	59			
60	28	29	31	33	35	37	40	42	45	48	51	55	59				
65	28	30	32	34	36	39	41	44	48	51	55	59					
70	29	31	33	35	38	40	43	47	50	54	58						
75	29	31	34	36	39	42	46	49	53	58							
80	30	32	35	38	41	44	48	52	57								
85	30	33	36	39	43	47	51	55									
90	31	34	37	41	45	49	54										
95	31	35	38	42	47	51	57										
100	32	36	40	44	49	54											

Figure 2: A simple heat index table from the U.S. National Oceanic and Atmospheric Administration (NOAA) describing an approximate relationship between air temperature and humidity and how hot it feels. At prolonged exposure or strenuous activity, the likelihood of a person experiencing heat stress is demarcated by the colors yellow to red. The table does not include wind or solar radiation effects (NWS 2014).

Table 1: Range of heat index values at which a healthy person doing strenuous physical activity or with prolonged exposure will begin experiencing health impacts (NWS 2014).

Celsius	Health Impacts
27 – 32 °C	**Caution:** fatigue possible with prolonged exposure and activity. Continuing activity could result in heat cramps.
32 – 41 °C	**Extreme caution:** heat cramps and heat exhaustion are possible. Continuing activity could result in heat stroke.
41 – 54 °C	**Danger:** Heat cramps and heat exhaustion very likely. Heat stroke is possible with continue activity.
Over 54 °C	**Extreme danger:** heat stroke is imminent and can cause fatalities.

While much of the health-heat impacts research focuses primarily on the interaction of ambient temperature and humidity, exposure to sunlight, heat radiating from nearby surfaces (e.g. off of roads or walls) and the presence of wind alter the temperatures a person experiences. Being outside in full sunlight can increase the heat index by up to 8°C. Breezy or windy conditions[2] will decrease the heat index as the wind facilitates the evaporation of sweat and helps to cool a body. High humidity inhibits evaporative cooling from sweat. A number of heat indices (e.g. Predicted Heat Strain Model, Universal Thermal Climate Index, Effective Heat Strain Index, etc.) have been developed to account for a broader range of meteorological conditions and assumptions around physical activity, clothing, and body mass (Epstein and Moran 2006; Lemke and Kjellstrom 2012).

[2] Up to a certain point, windy conditions will help cool a person. In hot, dry climates, a strong wind can actually make conditions feel hotter because the winds are usually warm and/or can lead to dehydration, which inhibits a person's ability to sweat. This caveat is not applicable to Da Nang's situation as it is a humid climate.

The most common heat indices used internationally are the Apparent Temperature and the Wet Bulb Globe Temperature.

Apparent Temperature

The Apparent Temperature (AT) is a heat index that was created by Robert Steadman in 1984 after years of research by multiple investigators into the extent to which humidity and high temperatures combine to create heat-related health impacts for an active person (Steadman 1979a; 1979b). Indoors, a person is only exposed to heat and humidity, while outdoors a person may be exposed to wind and net radiation. After further refinement, and incorporation of factors like clothing, level of physical activity, atmospheric pressure, skin thermal resistance and sweating, Steadman derived an empirical relationship between many of these variables to create the AT (Steadman 1984). The formulas represent a mathematical model of heat balance in a human body.

Net Radiation
The combination of direct sunlight, the heat reflected off of different surfaces like roads and buildings, and the heat these re-emit.

There are three AT formulas: one for indoor, one for outdoors in the shade, and one for outdoors in the sun.

(Indoor): $AT_{in} = -1.3 + 0.92T + 2.2p$

(Outdoor, shade): $AT_{out} = -2.7 + 1.04T + 2p - 0.65v$

(Outdoor, sun): $AT_{out,sun} = -1.8 + 1.07T + 2.4p - 0.92v + 0.044Q$

(vapor pressure): $p = 6.112\exp\ \hat{}(\frac{17.67T}{243.5+T})$

Where AT and T (ambient temperature) are in °C
p is vapor pressure in kPa and dependent on relative humidity and air temperature. It is empirically derived. We used Bolton's (1980) formula.
and *v* is the wind speed measured at 10m above ground in m/s

There is no single formula that can accurately describe how hot it actually feels to a person because each person is different and it is not possible to account for all factors – like amount of skin exposed, how much a person is sweating or their metabolism. However, Steadman's formula is considered to be universally appropriate and is used, with a few modifications, by a number of meteorological organizations around the world like the U.S. National Weather Service or Australia's Bureau of Meteorology working in conjunction with public health departments to issue heat warnings.

Wet Bulb Globe Temperature

The Wet Bulb Globe Temperature (WBGT) is a heat index developed by U.S. Army and Marine Corps to protect soldiers working outdoors (heavy physical activity), with heavy clothing in high heat, humidity and sunny conditions in the 1950s (Yaglou and Minard 1957). It has been widely adopted by a number of industrial and sports associations, militaries and codified under the International Labor Organization's standard as ISO 7243. There are several different versions of the WBGT (Curtis and Gallagher undated; Mochida et al. 2007), with parameters modified for clothing, and the original formula being:

(Indoors or Outdoors, shade): WBGT = 0.7Tnwb + 0.3Tg

(Outdoors, sun): WBGT = 0.7Tnwb + 0.2Tg + 0.1T

Where *Tnwb* is the natural wet-bulb globe temperature and is measured by a special thermometer bulb covered by wetted cotton and is exposed to solar radiation and wind. It simulates sweating conditions.

Tg is the black globe temperature and is measured by a special thermometer coated in black to incorporate solar radiation and wind. It simulates sun exposure on skin.

T is the ambient temperature

The WBGT requires non-standard meteorological instruments in order to be calculated, using variables often not collected by meteorological agencies (BOM 2010). Special and expensive instruments requiring constant and proper calibration are needed to collect the values; most meteorological agencies do not operate the necessary equipment. Furthermore, while the black globe temperature and natural wet-bulb temperature values can be approximated from standard meteorological variables – air temperature, wind speed, relative humidity, pressure – the approximations are considered inaccurate and likely to lead to over- or under-estimations of actual heat conditions and its limitations and use are being questioned by researchers (BOM 2010; Budd 2008; Epstein and Moran 2006). Neither are there any standardized equations for approximating WBGT from standard meteorological variables, unlike AT. Due to its widespread adoption by various labor standard organizations, however, it will take a while before other, more accurate and easily measured heat indices are adopted.

Methodology

As just described, AT and WBGT are the most commonly used heat-indices. Both were developed to account for physiological factors – approximations of sweating, clothing, metabolic rate, etc. – and meteorological conditions. However, only the AT can be directly calculated from standard meteorological variables. WBGT must be approximated from these, and in doing so, biases are introduced into the calculation that can lead to uncertainties about whether a heat safety threshold has been exceeded or not. For these reasons, and the fact that global climate models do not make projections of the Tnwb or Tg, we decided to use the AT heat index for this study. This section describes the steps involved in assessing historical trends in ambient temperature and the AT, and projecting how climate change may increase both in the future.

Step 1: Collect and clean historical and projected meteorological data

We collected daily data for the following variables in order to calculate AT: minimum temperature, maximum temperature, relative humidity, and 10-meter wind speed. Data over the historical period 1970-2011 were collected from meteorological records compiled from a number of sources (See **Table 2**). The projected values of these variables over the period 2020-2049 were downloaded from six general circulation models (GCMs), two emission scenarios each, from the IPCC's Coupled Model Intercomparison Project Phase 5 (CMIP5) data portal (See **Table 2**). These variables were downscaled (described in Step 3) for calculating the potential future range of heat index values.

It is not possible to measure ambient temperature at every single point in the city. Furthermore, due to the way the city is constructed, different radiative (how materials absorb and re-emit heat) properties of surfaces like brick, tin, concrete, trees or asphalt, and local hotspots due to autos and air conditioning units, temperatures can vary significantly throughout Da Nang. For these reasons, we take the conditions measured at two to five weather stations, averaged them and use this dataset as an area-averaged approximation of citywide conditions. Data from limited number of stations (2) were available in the 1970s – early 1990s, with the station network expanding up to ~5 (that we could access) by the late 1990s through 2011. Missing data were interpolated from the ERA Interim reanalysis project (Dee et al. 2011) and NCEP Reanalysis project (Kalnay et al. 1996). The data were cleaned and underwent several quality control checks that are standard for meteorological and climatological data. It took a few months to compile this area-averaged dataset, due to the spotty records in between 1970-1994.

Climate model data

No single climate model will ever be able to project the *exact* changes in rainfall, temperature, or other climate variables in any given year or period in the future for any part of the world. This is because no one knows exactly what emissions, populations, and land-use changes might occur in the future, and due to the limitations and assumptions of the models themselves. GCMs project how the climate might change, given changes to these human-controlled factors, which are accounted for as representative concentration pathways (RCPs) in the IPCC 5th Assessment models (van Vuuren et al. 2011). Because no single model can project exact changes to an area's climate, it is necessary to use projections from multiple GCMs, each driven by a couple of RCPs, to capture the possible range and trend of changes. Furthermore, climate is a description of an area's average weather over a period of time, typically 30 years. Therefore, climate change analysis involves comparing the statistics of an area's particular weather as projected for a period in the future that is at least 30 years long, with a period of historical climate of the same length.

We had originally hoped to be able to use higher resolution climate model output from the Vietnam Climate Futures project – a collaborative climate modeling effort between Vietnam's Institute of Meteorology, Hydrology and Environment (IMHEN), the University of Science-Vietnam National University and Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) – to develop the downscaled projections for this heat stress project. See: http://climatetool.vnclimate.vn/. This data would have been preferable as it used RCMs, climate models run at a higher resolution, that are better at capturing more local interactions between the land, ocean and atmosphere than GCMs and better at representing the seven climatic regions of Vietnam. We could not get access to the underlying, daily data for the four variables we need, and later found out that the analysis associated with the Futures project was not yet complete – UNDP calls were issued in August 2014 for completing the project. This was much too late for us.

We also examined the possibility of using projection data from the Land Use and Climate Change Interactions in Central Vietnam (LUCCi) project, a collaborative research effort between several universities in central Vietnam, IMHEN and some German universities (Laux et al., 2012). See: http://leutra.geogr.uni-jena.de/vgtbRBIS/metadata/start.php. The project has collated weather station data for multiple stations in the central region and done dynamical downscaling of certain variables. While we used the historical station data to augment and correct our station data, we could not use the projection data. Too few GCMs were used in the downscaling (only 1 GCM) for capturing the potential range of climate futures; as previously discussed, projections from multiple GCMs are needed. Therefore, we had to downscale variables from the IPCC CMIP5 project directly, rather than use variables from various ongoing climate modeling projects within Vietnam.

An ensemble set of projected, daily variables was formed using projections from 6 GCMs, each running RCP 4.5 (low emissions) and RCP 8.5 (business as usual, high emissions). The models' simulations of historical values covering the period 1970-1999 were also downloaded from the IPCC CMIP5 archive. This gave us a total of 12 ensemble members against which to compare future minimum and maximum temperature, relative humidity and wind speed with past, measured values, and to correct the biases in the model values.

Table 2: Datasets and models used for estimating changes to Da Nang's extreme heat days

Dataset/Model	Data Provider	Description
ERA-Interim NCEP Reanalysis	European Centre for Medium-Range Weather Forecasting NOAA/OAR/ESRL PSD, Boulder Colorado	High-resolution daily datasets from observations 1979-2011 (Dee et al. 2011) Coarse resolution daily datasets from 1970 – 1980 (Kalnay et al. 1996)
Station-level: • Da Nang & nearby stations	Center for Hydro Meteorological Service at South Central Provinces (Vietnam) Global Summary of the Day & Global Historical Climatology Network – National Climatic Data Centers (USA)	Daily data from observations
CMIP5: • BCC-CSM1.1(m) • CanESM2 • CSIRO-MK3.6.0 • MIROC-ESM • MPI-ESM-MR • NCAR-CCSM4	Beijing Climate Center, China Met Administration Canadian Centre for Climate Modelling & Analysis Commonwealth Scientific & Industrial Research Organization (CSIRO)/ Queensland Climate Change Centre of Excellence Japan Agency for Marine-Earth Science & Technology, Atmosphere & Ocean Research Institute (University of Tokyo), and National Institute for Environmental Studies Max Planck Institute for Meteorology (MPI-M) National Center for Atmospheric Research	Simulated daily variables: • Historical (1960-2005) • RCP 4.5 (2006-2055) • RCP 8.5 (2006-2055) All downloaded from CMIP5 Multi-Model Ensemble Dataset: http://pcmdi9.llnl.gov/esgf-web-fe/

Step 2: Model Skill and Bias Testing

Natural Variability
The natural season-to-season, year-to-year and decadal variability an area's climate experiences that is not caused by humans.

While multiple models must be used in estimating potential changes to an area's climate, it is necessary to use some skill tests to ensure that the selected models are able to replicate key historical statistics for that area if the modeling efforts are focused on the near-term (out to 2050s) changes. This is because strong climate change signals that consistently appear on top of natural variability are not likely to emerge in an area until the 2050s or so, depending on the part of the globe (Kirtman et al. 2013). If a climate model does a poor job of replicating an area's seasonal or annual statistics, there is likely to be considerable error in its near-term projections.

The GCMs selected for this study do a decent job of replicating daily maximum and minimum temperatures in all months over the period 1970-1999. However, all of the models have a cold bias in most months, except for Can-ESM and Miroc-ESM, which have a hot bias in the March-May season.

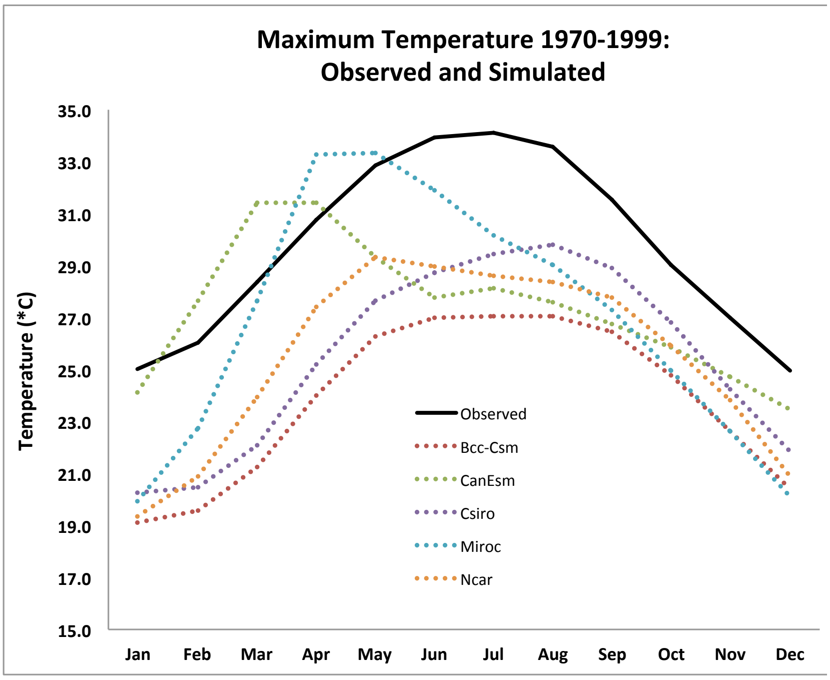

Figure 3: GCM simulated daily maximum temperatures compared with observed over 1970-1999. The GCMs are generally able to replicate seasonality, but tend to have a cold bias. Both Can-ESM and Miroc-ESM over-estimate daily maximum temperatures in March and April.

Another way of testing the models' skill and checking for their biases is to run a *correlation test between the models' simulated daily values and the observed daily values*. A high correlation indicates that the models do a fairly good job of replicating the observed and are representing most of the large-scale land-ocean-atmosphere processes that influence Da Nang's climate. A low correlation implies that the models are not. While it is important to check that the model means are close to the observational means (**Figure 3**), it is also important to check the models' skill in replicating higher order moments like standard deviation. *Standard deviation is a measure of the area's climate variability, due to both natural processes and climate change.* A model should be able to do a decent job of replicating variability, but will always over- or under-represent variability because the scale of the model projection scale is larger than the city scale. Another metric of model skill is the *root-mean-square error (RMSE) – how far the model's simulated values are on average from the observation values*.

Taylor Diagrams are one means of visualizing all three skill tests – correlation, standard deviation (variability) and RMSE – on a single figure. **Figure 4** displays the Taylor Diagrams comparing the models' simulated minimum and maximum temperatures, relative humidity and surface wind with the observed values between 1970-1999. The models do a good job of replicating temperature, but a poor job of relative humidity and surface wind. Even though the models replicate temperature well, they still have some cold biases in certain months and do not capture the full range of natural variability (standard deviation) seen in the observed datasets. These discrepancies and the reasons why are explained in the next step on downscaling.

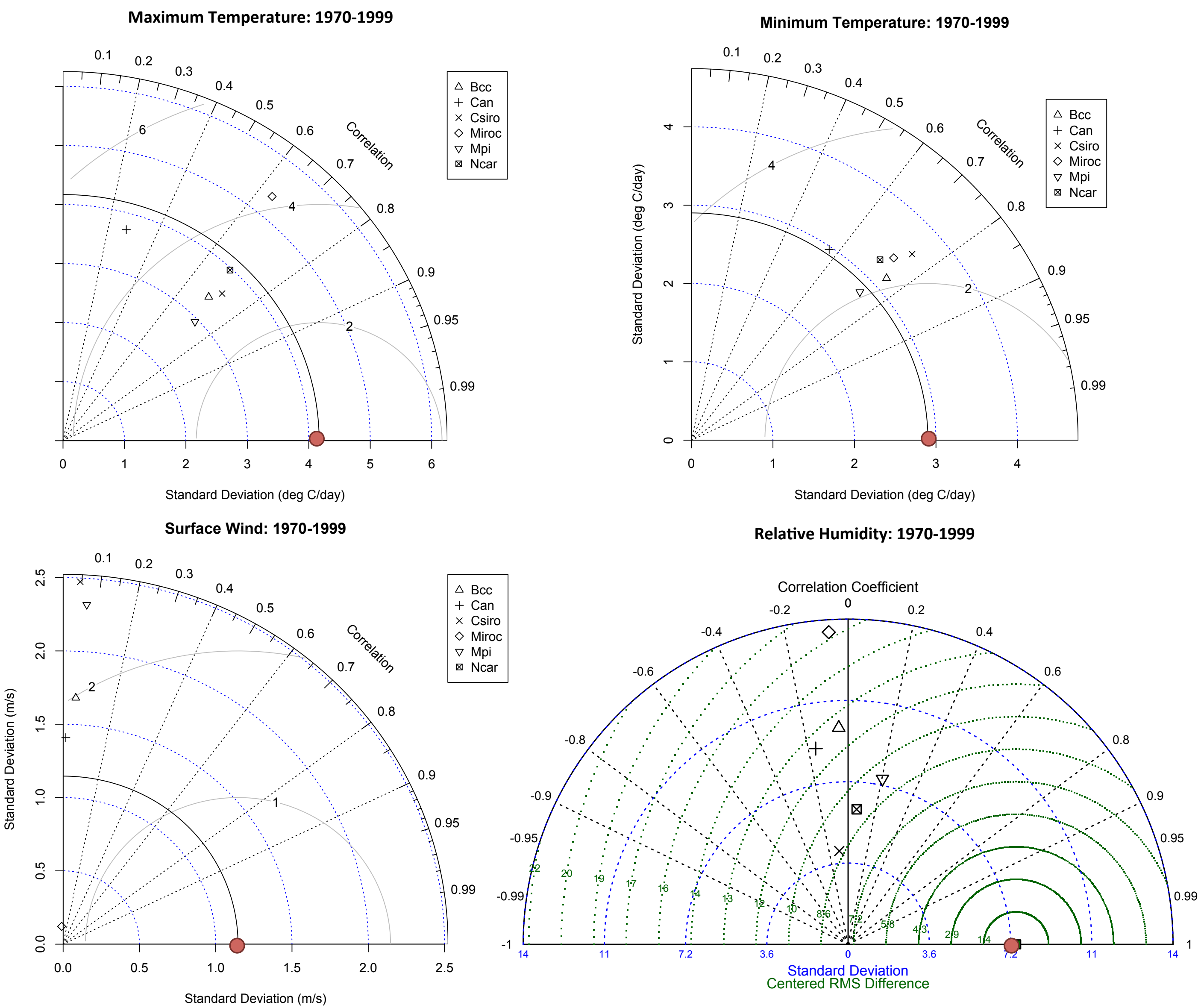

Figure 4: Models' skill at replicating the four daily climate variables needed to calculate the heat index – minimum and maximum temperature, relative humidity and surface wind. In these Taylor Diagrams, a way of representing three skill metrics on a single graph, we can see that the models do a good job of replicating temperatures. They have high correlations (~0.6 to 0.8), standard deviations (between the blue arcs) within 1°C of the observed sd (red dot), and RMSE (between black arcs) of between 2-3°C. These statistics give us greater confidence in the models' near-term projections.

The models do not do a good job of replicating Da Nang's relative humidity or surface winds. In fact, when Da Nang's relative humidity is high, the models replicate it as being low (negative correlation).

Step 3: Downscaling

GCMs model the interactions between the land, ocean and atmosphere that influence climate, but they do so on a large-scale, typically between ~100 to ~300km. As a result, they cannot fully capture local climate processes, such as the city-scale (~5-50km) and will over- or under-represent variables like temperature or precipitation and not accurately reproduce local variability. We have just seen this to be the case in step 2. As a result, it is necessary to downscale – find a relationship between the large-scale model values and the local observation values – and correct for the biases (too hot, too cold, etc.) in the model values.

We employed a quantile-quantile mapping technique to statistically downscale the four variables and correct for model bias without losing the important climate change signals embedded in the model projections. There are many methods for downscaling and bias correcting GCM output; these methods fall into either a dynamical or statistical downscaling category (Opitz-Stapleton and Gangopadhyay 2011; von Storch et al. 2000; Wilby et al. 2004). There are so many journal articles written about various methods, the assumptions and pros and cons of each, that we are not going to discuss them here.

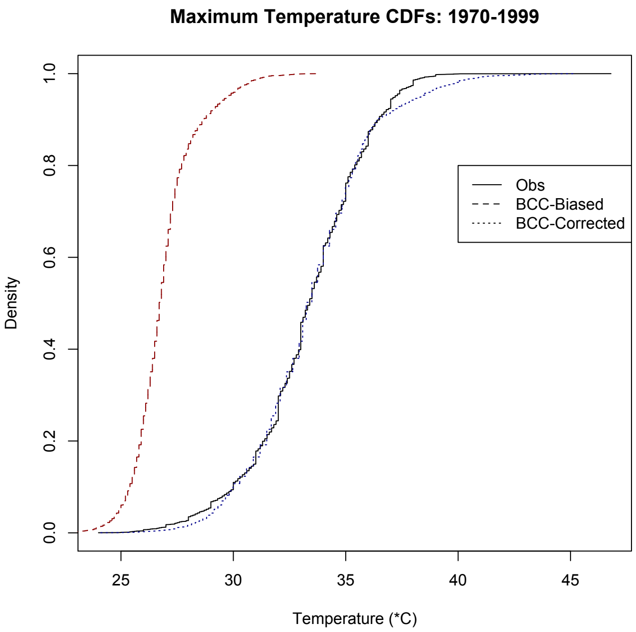

Figure 5: Quantile mapping plot showing a biased model (red) and downscaled model (dots) in comparison with the observed (solid black).

The quantile mapping method has been used in a number of climate change studies, typically to downscale temperature and precipitation (Quintana-Segui et al. 2011; Hashimo et al. 2007; Gudmundsson et al. 2012). The method involves developing a transfer function from the cumulative distribution function (CDF) of the model simulations to match the CDF of the observation data (**Figure 5**). In order to account for the possibility that climate change will alter the variability and the skew of the distribution over time, in addition to the mean, we used the equidistant mapping method proposed by (Li et al. 2010). We used a linear transfer function after testing other transfer functions to find out the best possible fit over the historical period and used this to shift the projections:

$$x_{m,adj} = x_{m,fut} + F_{obs}^{-1}\left(F_{m,future}\left(x_{m,fut}\right)\right) - F_{m,past}^{-1}\left(F_{m,fut}\left(x_{m,fut}\right)\right)$$

where x_m = the model variable, *adj* is the downscaled value and *fut* is the uncorrected model variable

F = a transfer function derived either from the observation data or from the model data

We downscaled each variable separately according to Li et al., coded in R (v.3.1.1 'Sock it to Me') and drawing from the 'qmap' package (Gudmundsson et al. 2012). These downscaled, bias-corrected variables were then used to calculate a range of possible future ATs and see how climate change might alter temperatures and heat indices in Da Nang by 2050.

Step 4: Calculation of Future AT Heat Index

We calculated the range of possible AT in the future using the downscaled variables from Step 3, and the formulas for AT described previously. In keeping with convention (Dunne et al. 2013; Sherwood and Huber 2010), we did NOT calculate the historical or projected heat index for outdoor conditions of sun and wind.

1. This is because calculating net radiation – the combination of incoming short-wave and long-wave radiation, its absorption, reflection and re-radiation from all the surfaces in the city – are very difficult to do and we did not have the necessary historical data to make such calculations.
2. Furthermore, GCMs do not simulate net radiation; estimating future radiation would introduce further uncertainty into the projections and the radiation component only accounts for 0.4% of the variance in the AT equations.

It is therefore standard practice to neglect projecting AT or WBGT conditions outdoor in the sun. Also, due to the poor bias correction fit for downscaling the surface winds (the models tended to significantly over-estimate surface winds in Da Nang, leading to an artificial cooling of the outdoor shade heat index), we decided to calculate a heat index only for indoor conditions. However, it is easy to remember that prior research has established that full sun conditions can make the heat index up to 8°C hotter than when in the shade and that wind will have a cooling effect. In the future, the MOH or local meteorological agency can calculate both outdoor AT heat indices using observation data (solar radiation and 10 meter wind speed from the meteorological agency) and the formulae provided.

We then analyzed how the range of projected (2020-2049) minimum and maximum ambient temperatures, and daytime and nighttime ATs, changed when compared with the observed values over the period 1970-1999. We calculated the following; he results are presented in the next section:

- Number of days per year in which the heat index exceeds 34°C
- Number of nights per year in which the heat index exceeds 28°C
- Changes in ambient day and night temperatures
- Changes in the length of the hot season

Climate Change Impacts on Heat Stress

As with many places around the world, climate change is projected to increase the number of hot days and nights in Da Nang, increase the length of the hot season and lead to greater numbers of heat waves in the city. All of these shifts will have profound impacts on people, livestock, health, water, agriculture and a number of other systems. The implications of current heat stress conditions on health and labor productivity have been well studied (Srinavin and Mohamed 2003; Pantavou et al. 2011), but projecting how climate change might alter future heat stress conditions is a topic that has only begun to be researched in the past decade (Huebler et al. 2007; Roy et al. 2011). Many questions remain about understanding the health and labor productivity implications of future heat stress, what adaptive actions can be taken to reduce health impacts and how the tradeoffs of particular actions (e.g. air conditioning protects individuals against heat stress and enables them to work, however, the machines release massive amounts of heat and can increase the urban heat island effect if many buildings have them).

Historical Trends: 1970-2011

Da Nang is a rapidly developing and expanding city, located in a hot and humid climate. While the people living and working in the city and surrounding areas are acclimated to warmer conditions than would be people from say, Norway, there are still hard physiological limits to which any person can adapt. Any heat index values approaching a human body skin temperature of 35°C (core temperature of 37°C), particularly for sustained periods, can lead to negative health impacts. As seen in **Figure 2** and **Table 1** a healthy person engaged in moderate physical activity can begin experiencing fatigue, irritability and difficulty concentrating at heat index values ranging between 26 to 32°C. Outdoor workers engaged in construction, fishing, farming or street vendors fall into this category. These heat index ranges are applicable to unhealthy individuals not engaged in physical labor – those with cardiac, respiratory, chronic illnesses, malnutrition, diabetes or other conditions. These people, as well as older individuals, children and pregnant women have lower heat tolerance. As heat index temperatures rise, healthy workers engaged in light activity, such as working at a desk, are negatively impacted. Indoor workers doing physical labor – manufacturing, sewing in factories, cleaning and heavy housework – will begin suffering negative health effects at the same ranges as outdoor workers. All of these factors have to be considered when assessing potential climate change impacts on heat stress.

Hot Days

Between 1970 and 2011, there were an average of 210 (295) days per year in which the heat index was equal to or greater than the MOH's recommendations of 34°C (30°C) for light (heavy) labor. On average, the heat index is 4°C warmer than the ambient temperature (**Figure 5**). Interestingly, while the number of days per year in which the heat index exceeded 30°C remained fairly steady, the number of days exceeding 34°C has been increasing as a proportion of the total number of days over 30°C. On average, the number of days per year exceeding 34°C has increased by approximately 5 days per decade. This implies that the number of very hot days is increasing faster than over all gradual temperature increases. Maximum day temperatures are increasing at an average rate of ~0.1°C per decade for Da Nang, which is consistent with other studies (Nguyen et al. 2014, Dao et al. 2013).

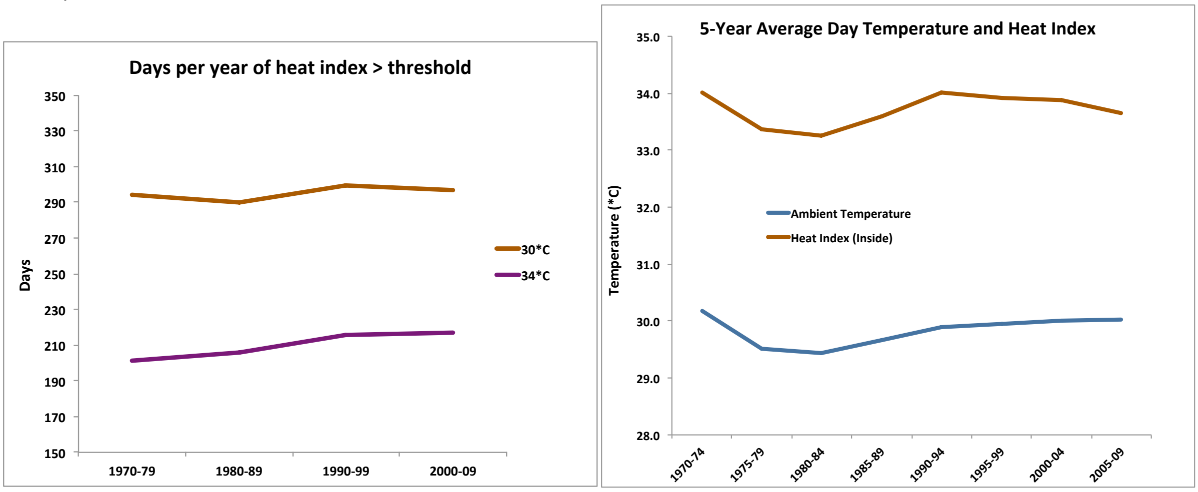

Figure 6: Trends in historical heat index exceeding critical work thresholds specified by MOH. The number of days per year at the 30°C has remained fairly constant, but the number of days exceeding 34°C has increased an average of 5 days per decade. The number of very hot days is increasing faster than overall temperature increases.

Hot Nights

The number of nights in which the heat index exceeds 28°C remained constant over 1970-1993, but appears to have decreased around 1993 (see **Figure 6**). Overall, average nighttime ambient temperatures have declined by about 0.3°C between 1970-2011, with most of the downward trend happening after 1993.

We speculate that the downward trend seen since 1993 is partially due to the amount of data missing prior to this year, though some of it appears to be happening naturally as shown in the station records. There was considerable missing daily data from the station datasets[3] between 1976-1993 that we had to fill using the ERA-Interim datasets and some NCEP Reanalysis data for the period 1976-1978. We found that while the ERA datasets were highly correlated with the daily minimum temperatures, they did exhibit a hot bias that could have artificially inflated the number of very hot nights. The NCEP Reanalysis data is of very coarse resolution (~278.3 km spacing) and was used to approximate missing days, also introducing a bias. After 1993, when station records became more complete, the true number of very hot nights can be assessed and it does appear that the downward trend does continue. It is beyond the scope of this study to speculate why this downward trend exists or what is causing it. We do not expect it to continue in the future however, as climate change is likely to cause nights to warm faster than days.

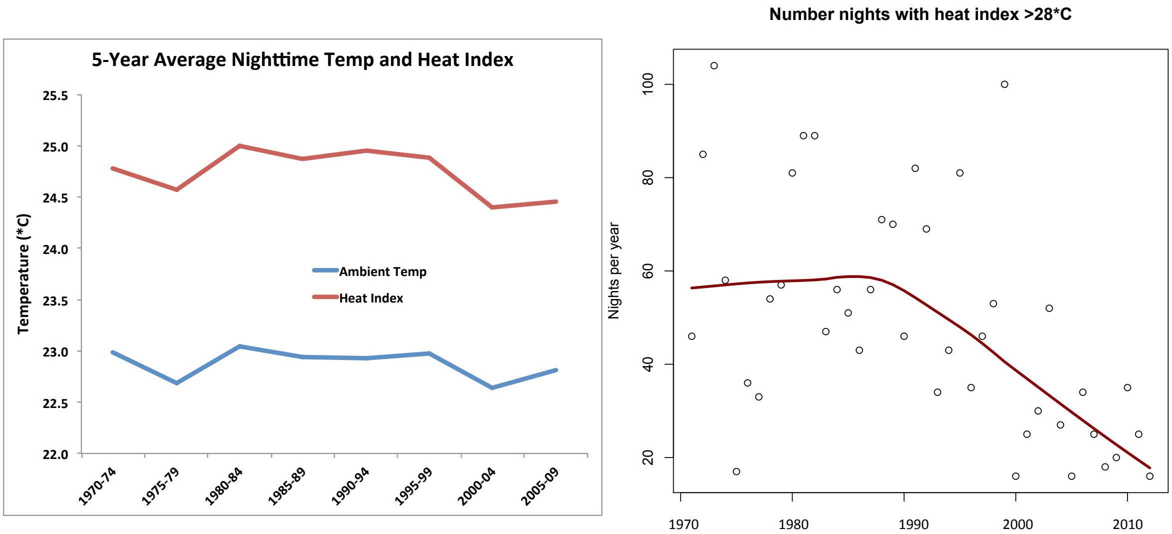

Figure 7: Trends in average nighttime temperatures and average heat values between 1970-2011 (left figure) and trends in the number of very hot nights where the heat index exceeds 28°C over the same period (right figure). The declining trend in very hot nights is significant at the 95th percentile and begins roughly around 1993. See accompanying text for possible explanation of the declining trend in very hot nights.

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[3] Due to low station density, data gaps as a legacy of the war and rebuilding period, and the diversity of Da Nang's terrain going from sea to mountains over a short distance, it was difficult to run some of the standard data quality checks on the historical dataset. Homogenity tests are needed to remove artificial trends that can creep into station data, such as it appearing to be much hotter or cooler over a particular period if a tree or building is put up near the weather station. However, conducting such tests and removing artificial trends requires being able to compare enough near-by weather stations against each other and see if they all show the same trend or not. We could not run these tests for data prior to 1993 due to low station density (we only had one station for the whole period, and partial data from 2 other stations between 1970-1993).

Both ERA-Interim and NCEP Reanalysis are gridded datasets in which observation data from multiple sources – weather stations, ships, radiosonde, etc. – is compiled and analyzed to produce area-averaged climate data for each grid space. The spatial resolution of each grid is an approximation of the whole area's climate; local features like Da Nang's urban heat island are blurred in the datasets. However, they are sometimes the only way to approximate an area's historical climate when station data are incomplete or hard to access.

Climate Change Projections: 2020-2049

Projections of future day and night ambient temperatures and heat index values under nearly all climate change scenarios show continued warming through 2050 (**Figure 8** and **Table 3**). Warming is most pronounced in the months leading up to (April and May) and just after (September through November) the hot season, though the hot season will also get warmer. Because of these increases in ambient temperature, the heat index during the day begins to continually average above 40°C during May through September, creating dangerous working conditions for both outdoor and indoor workers. The median heat index during the day is not likely to fall below 35.1°C during any season by 2050, putting both outdoor and indoor workers at risk of heat stress unless a variety of coping mechanisms are adopted. It is only during the early spring that the models are not showing significant increases in ambient day and night temperatures, which translate into only small changes in day and nighttime heat indices. It is still possible for temperature increases to happen in the early spring (upper edge of the shaded blue area) under the high emissions scenario RCP 8.5[4]. The increase in night temperatures and heat index values is significant (**Table 3**) and implies that individuals will not be able to physiologically recover from working during hot days.

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[4] While RCP 8.5 is considered the high emission scenario in the most recent IPCC climate modeling efforts, it is also considered the 'business-as-usual' scenario in which humanity makes no efforts to reduce emissions. It assumes we keep emitting at the same rate of yearly increase in emission amounts as we currently are doing, hence the business-as-usual designation. RCP 4.5 represents the low emission pathway and is essentially unachievable because it assumes we begin reducing emissions immediately.

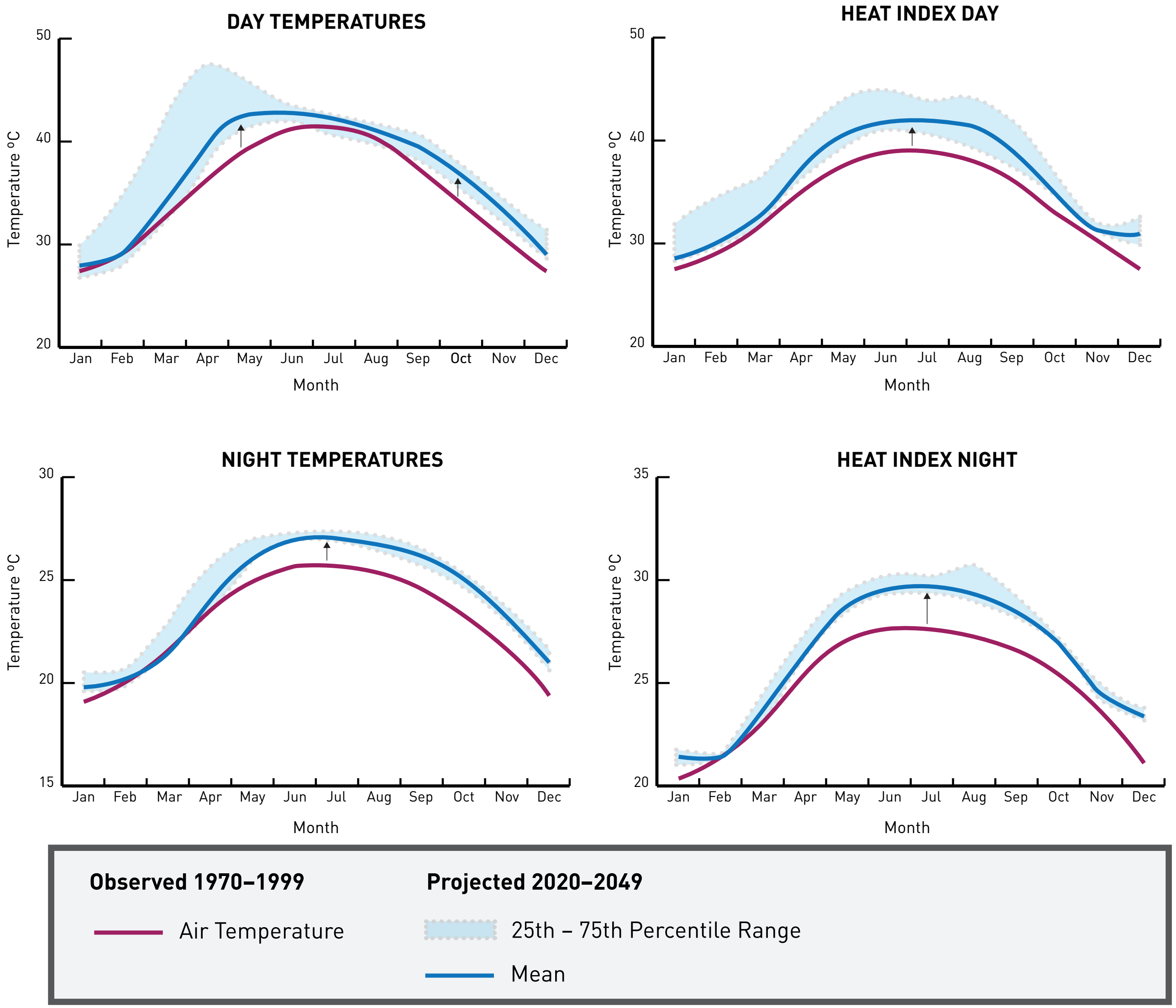

Figure 8: Climate change is highly likely to lead to increases in day and night ambient temperatures (a and b) in all months, except for the early spring, by 2050 when compared with the historical period. Heat index values are also expect to increase (high confidence with all models and emission scenarios agreeing on the increase). Dangerous working conditions are quite likely between May-Sept., when the mean heat index is not likely to drop below 40°C during the day and nights will be uncomfortable.

The red lines show the mean ambient and heat index temperatures over 1970-1999. The blue line shows the mean projected ambient and heat index values over 2020-2049. The blue shaded region shows the potential range of increase according to the model spread (interquartile range). Note the temperature scale difference between some graphs.

Table 3: The average seasonal ambient and heat index temperatures at day and night over the historical period (1970-1999) and the projected increases in the future (2020-2049). The projected temperatures are presented as ranges showing the model spread, with the median model value in brackets []. For example, the average ambient day temperature during DJF 1970-1999 was 25.3°C. Over 2020-2049, it is projected to increase anywhere from 0 to 2.7°C with a median projected value of [25.8°C]. The example is highlighted in yellow in the table.

Ambient Temperature (°C)				
	Daytime		Nighttime	
	1970-1999	2020-2049	1970-1999	2020-2049
DJF	25.3	0 to 2.7° [25.8]	19.6	0.4 to 1.3° [20.3]
MAM	30.7	0.9 to 6.1° [32.2]	23.4	0.2 to 1.8° [23.8]
JJA	33.9	0 to 1.3° [34.1]	25.6	1.0 to 1.7° [26.7]
SON	29.2	0.9 to 2.5° [30.8]	23.2	1.3 to 1.8° [24.9]
Heat Index (°C)				
DJF	28.1	1.2 to 5.1° [35.1]	21.0	0.9 to 1.3° [22.1]
MAM	34.9	1.0 to 5.5° [40.5]	25.3	0.8 to 1.9° [26.4]
JJA	38.7	1.5 to 5.6° [43.0]	27.5	1.7 to 2.9° [29.4]
SON	33.1	1.3 to 3.7° [36.8]	25.2	1.1 to 1.8° [26.5]

The number of days (nights) in which the heat index exceeds 34°C (28°C) is also expected to increase dramatically under all climate change scenarios. *If the daytime heat index threshold of 30°C is used (relevant to outdoor workers), it is exceeded almost continuously by 2050.* The types of change in ambient temperature are consistent with previous projections by MONRE (MONRE 2011). During the day, the heat index historically was ~3 to 6°C warmer than the ambient temperature. Because of climate change, the daytime heat index is likely to be up to 5.6°C hotter than it was in the past. The length of the hot season is now likely to extend from March through October by 2050, two to three months longer than in the past. Nighttime heat index temperatures during the hottest months (June to August) are not likely to drop below an average of 29.4°C, reducing recovery capacity at night while sleeping and exacerbating pre-existing health conditions like diabetes or high blood pressure. **Figure 9** displays the projected changes in numbers of days (nights) per year that the heat index exceeds important thresholds.

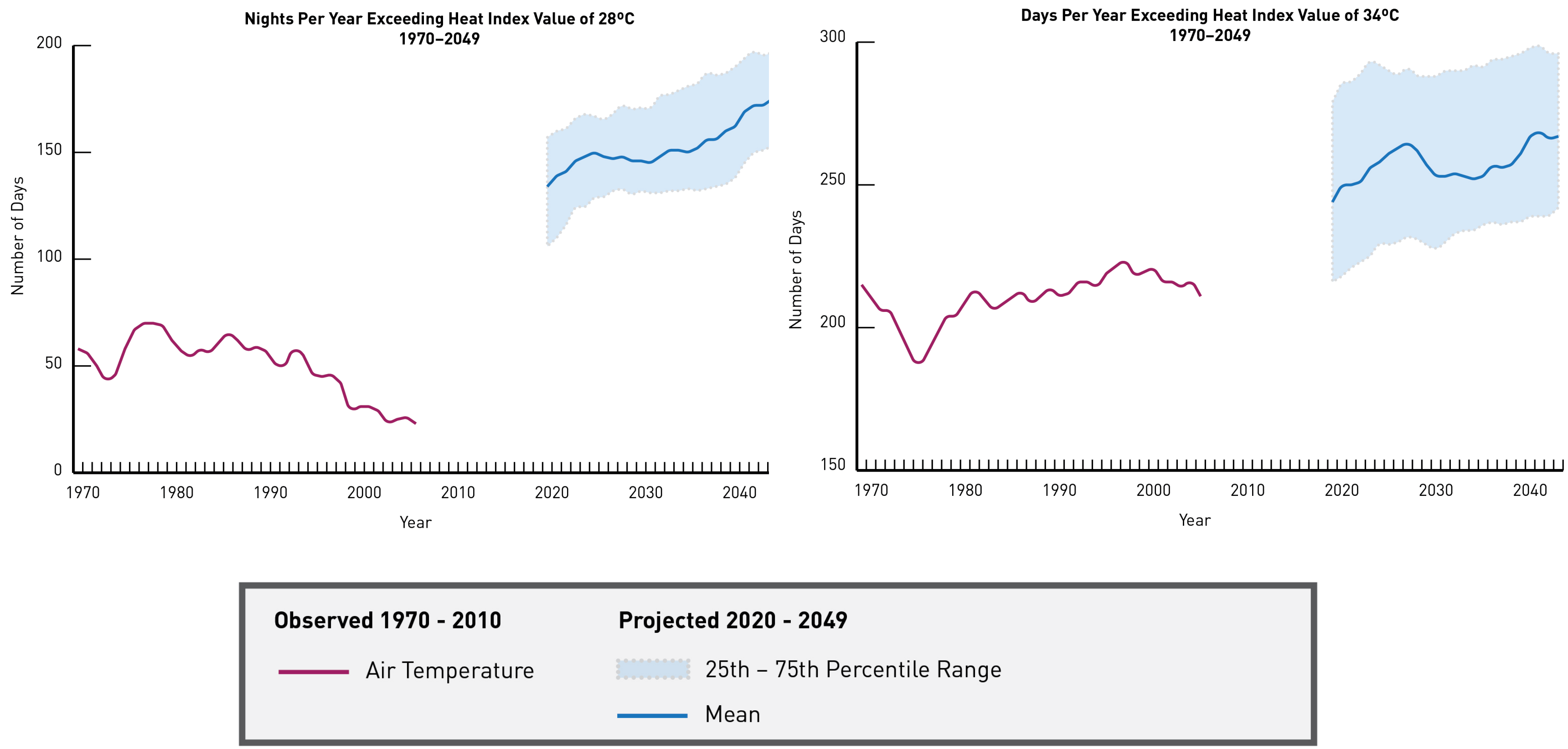

Figure 9: Changes in the number of nights (left figure) and days (right figure) per year in which the heat index exceeds the critical thresholds of 28°C (night) and 34°C (day). The red line displays the historical values, while the solid blue line shows the mean model projection value. The blue shading around the solid blue line shows the possible range of change in the future. Note the downward trend in very hot nights between 1993-2011, which was discussed in the text. The downward trend is not expected to continue in the future. Climate change will make nights hotter and it more difficult for people to recover from hot temperatures during the day.

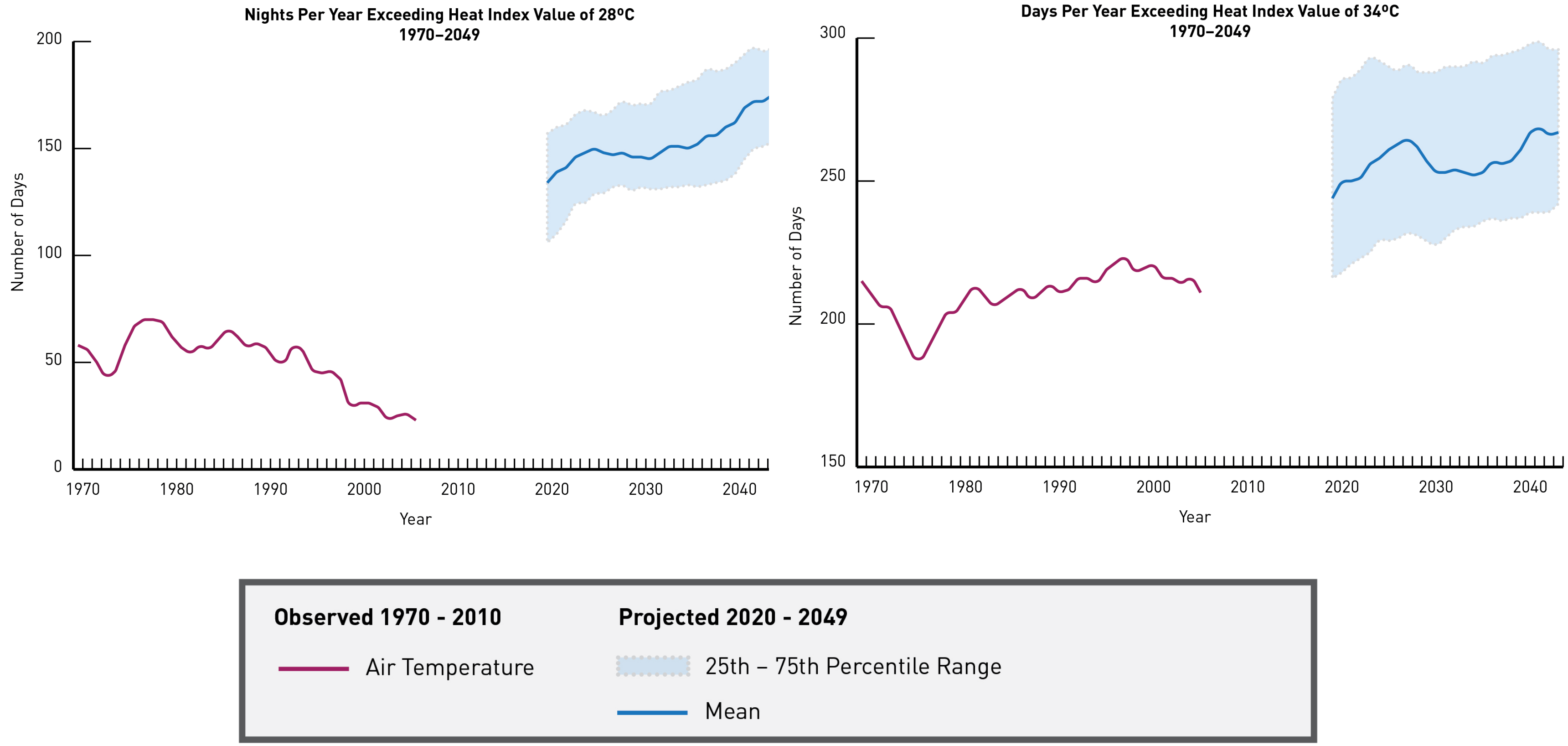

Figure 9: Changes in the number of nights (left figure) and days (right figure) per year in which the heat index exceeds the critical thresholds of 28°C (night) and 34°C (day). The red line displays the historical values, while the solid blue line shows the mean model projection value. The blue shading around the solid blue line shows the possible range of change in the future. Note the downward trend in very hot nights between 1993-2011, which was discussed in the text. The downward trend is not expected to continue in the future. Climate change will make nights hotter and it more difficult for people to recover from hot temperatures during the day.

Summary

This study confirmed that temperatures have increased in the past few decades and that climate change will lead to more heat waves, a longer hot season, and stressful working temperatures in the future for Da Nang. The number of very hot days in which the heat index exceeds 34°C, the threshold currently set by Vietnam's Ministry of Health at which indoor workers engaged in light, desk-based work, has been increasing in the past few decades, though the number of nights in which the heat index exceeded 28°C decreased. According to projections from multiple GCMs, each running a low (RCP 4.5) and high (RCP 8.5) emission scenario, climate change is highly likely to increase day and night ambient and heat index temperatures. In the future, average heat index temperatures during the day are likely to be ~35°C or higher in all seasons – this will have a profound impact on human health and the labor productivity of Da Nang's workers. The length of the hot season is likely to increase by two to three months a year by 2050.

A previous study by COHED revealed that awareness of precautions for dealing with heat stress remains low. Certain populations, such as women-headed households or the self-employed, are at particular risk of suffering from heat stress and lost labor under today's climate conditions because they have fewer resources for taking time off in the middle of the day to rest or to invest in different cooling strategies like air conditioning (Dao et al. 2013). Construction workers, agricultural laborers, street vendors and fishermen (all outdoor workers), and indoor workers engaged in manufacturing or sewing, or those in poorly ventilated and constructed buildings will be particularly hard hit. Many workers currently have little bargaining power within the workplace to ask for cooling measures, breaks or protective clothing; without these things in the future, they will consistently be unable to meet the productivity demands of their employers.

As both day and night temperatures continue to climb due to climate change, as well as an increase in the area influenced by the city's urban heat island effect due to development and land use change, passive cooling measures like opening windows or hanging wet sheets for evaporative cooling will become less effective. People will need air conditioning, at least at night, in order to recover from the impacts of heat stress they suffered while working during the day. Poorer populations that currently rely on such measures will be hit particularly hard by the projected increases in ambient and heat index temperatures. These populations, particularly if they are migrants, often rent cheap housing without adequate ventilation, active cooling measures like air conditioners, and little insulation. These buildings retain heat at night and, under future warmer nighttime temperatures, will not allow low-income laborers to recover from heat stress they experienced during the day. As health impacts mount due to climate change, and people find that their labor productivity decreases, particularly poor populations may find themselves locked into a poverty spiral.

At the same time, while air conditioning will become increasingly necessary to improve working conditions for indoor workers and for people at night, outdoor workers do not have this luxury. New strategies (beyond the scope of ISET's research component) will need to be explored for helping to protect outdoor workers. Additional research also needs to be done to understand the potential impacts of increasing usage of air conditioners on Da Nang's urban heat island. If more buildings are equipped with air conditioners, which generate a lot of heat, this will raise urban heat temperatures and increase the daytime and nighttime heat index in a manner that was beyond the scope of this study to investigate. Because of the urban heat island effect, augmented by increased air conditioning and automobile use, some pockets of Da Nang might locally be up to 10°C warmer than the city-averaged heat index. Outdoor workers in these pockets will be at significant risk of heat stroke and, possibly, death in the hot season if their localized heat index approaches 45 to 55°C and their employers do not allow them to rest and take protective measures. Accounting for localized

urban heat island effects in the heat index warnings issued by the responsible agency, and holding employers accountable for protecting workers' health, will become increasingly important.

COHED is working with a number of partners, including the Da Nang Preventative Medicine Centre and the Institute for Labour, Science and Social Affairs (MOLISA), to improve the capacity of low-income laborers in dealing with increasing temperatures under climate change. Measures to increase awareness among employers and laborers, as well as a range of adaptive measures, are needed to improve the capacities of Da Nang's residents in dealing with increasing heat threats. COHED and other project partners will be using the heat index information generated from this study activity to inform their efforts on improving heat capacity in Da Nang.

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