CHARACTERISATION OF WET-BULB TEMPERATURES ON THE EAST COAST OF INDIA

by

Jenix

(2016-20-020)

THESIS
Submitted in partial fulfilment of the
requirements for the degree of
B.Sc. – M.Sc. (Integrated) Climate Change Adaptation
Faculty of Agriculture
Kerala Agricultural University

COLLEGE OF CLIMATE CHANGE AND
ENVIRONMENTAL SCIENCE
VELLANIKKARA, THRISSUR – 680 656
KERALA, INDIA
2021

DECLARATION

I, Jenix (2016-20-020) hereby declare that this thesis entitled **"Characterisation of wet bulb temperatures on the East coast of India"** is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award to me of any degree, diploma, associate-ship, fellowship or other similar title, of any other University or Society.

Vellanikkara	Jenix
Date:	(2016-20-020)

CERTIFICATE

Certified that this thesis entitled **"Characterisation of wet bulb temperatures on the East coast of India"** is a record of research work done independently by Ms. Jenix under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to her

Vellanikkara
Date:

Dr. Joy Merwin Monteiro
(Major Advisor, Advisory Committee)
Assistant Professor
Earth and Climate Science,
Indian Institute of Science Education
and Research, Pune

CERTIFICATE

We, the undersigned members of the advisory committee of Ms. Jenix, a candidate for the degree of B.Sc.– M.Sc. (Integrated) Climate Change Adaptation agree that the thesis entitled **"Characterisation of wet bulb temperatures on the East coast of India"** may be submitted by Ms. Jenix, in partial fulfilment of the requirement for the degree.

Dr. Joy Merwin Monteiro
(Major Advisor, Advisory Committee)
Assistant Professor,
Earth and Climate Science,
Indian Institute of Science Education and Research, Pune

Dr. P. O. Nameer
(Member, Advisory Committee)
Dean, College of Climate Change and Environmental Science KAU, Vellanikkara

Dr. T. K. Kunhamu
(Member, Advisory Committee)
Professor and Head (Silviculture and Agroforestry),
College of Forestry,
KAU,Vellanikkara

Dr. M. Shaji
(Member, Advisory Committee)
Assistant Professor (Wildlife Sciences),
College of Forestry, KAU,
Vellanikkara.

External Examiner
(Name and Address)

ACKNOWLEDGEMENT

I extend my sincere gratitude to my major guide **Dr. Joy Merwin Monteiro** Assistant Professor, Earth and Climate Science, Indian Institute of Science Education and Research, Pune, for his patience, reassurance and constant guidance throughout the research. I wholeheartedly thank him for his support during my learning curve.

Furthermore, I would like to thank my advisory members; **Dr. T. K. Kunhamu**, Professor and Head, Silviculture and Agroforestry, College of Forestry, KAU,Vellanikkara, **Dr. M. Shaji**, Assistant Professor, Wildlife Sciences, College of Forestry, KAU, Vellanikkara for their suggestions and encouragement.

I express my thanks to **Dr. P. O. Nameer**, Dean, College of Climate Change and Environmental Science, KAU, Vellanikkara and a member of the advisory committee, for giving me this opportunity, motivating and encouraging me for the timely submission of this thesis.

I take this opportunity to thank Dr. Neethi V Rao, PhD, Health Policy and Systems, Research Consultant, Adjunct Faculty, Institute of Public Health, Bengaluru for improving this work with her suggestions and ideas.

I cordially thank Kerala Agricultural University, College of Cli-

mate Change and Environmental Science (CCES) and Indian Institute of Science Education and Research, Pune for their resources and support for the completion of this thesis.

My heartfelt gratitude to all my classmates (batch of 2016) for inspiring me and cheering me at every step of my research.

I express my sincere indebtedness towards my entire family for their love and blessings.

Jenix

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Chapter 1

INTRODUCTION

While it is well known that weather and climate play an important role in social and economic activity, there is an increasing recognition that extreme weather events such as floods, droughts, heat and cold waves disproportionately impact society. Even though such events happen rarely, they can cause huge loss of life and property.

South Asia is home to a large and dense human population, and this makes the region especially vulnerable to extreme events. While floods and droughts dominate the news due to their highly visible nature, heat waves have also been responsible for a significant number of deaths and sickness. Due to the fact that heat waves are not visible, they are termed as the "silent killer"[1].

India has had a long history of research into heat waves, beginning

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[1] `https://www.noaa.gov/stories/excessive-heat-silent-killer`

in the middle of the previous century (Raghavan, 1966). The India Meteorological Department (IMD) has a system of heat wave warnings based on local air temperature, which is modified based on geographical considerations such as coastal or hilly regions. The categories by IMD states, heat waves are declared when

1. Based on maximum dry bulb temperature, when it reaches
   (a) 40° Celsius for plains and 30° Celsius for hilly regions
   (b) 40° Celsius for coastal stations
   (c) 45° Celsius or more irrespective of region
2. Based on departure from normal
   (a) If normal maximum temperature of a station is less than or equal to 40° Celsius
      i. A departure of 5° to 6° Celsius from normal is considered as a heat wave
   (b) If the normal maximum temperature of a station is more than 40° Celsius
      i. A departure of 4° to 5° Celsius from normal is considered as a heat wave

However it is only in the past 5-6 years that the relationship between heat and human health has been recognized in India at the policy level, with the development of the Heat Action Plan in Ahmedabad in 2014 (Knowlton et al., 2014).

The fundamental relationship between heat and human health lies in the fact that regulation of body temperature is essential to the proper functioning of various physiological processes. The human body is adaptable to change; its physiological functions are so that it allows homeostasis. Even with these intrinsic abilities seasonal weather episodes such as heat waves pose a huge threat for human survival (Sherwood and Huber, 2010; Raymond et al., 2020). Heat waves are weather phenomena that result in extremely high temperature conditions over land causing dangerous impacts on vulnerable communities (Robinson, 2001). Heat wave reported deaths in India marked higher death compared to many other potential natural calamities (Rohini et al., 2016). Satyanarayana and Rao 2020 showed that incidence of heat wave episodes over Southeast India were observed only after 1970, and stated that, the heat wave events over these regions as a possible repercussions of then course of global warming. Variegated and substantial consequences of these events signifies social challenges for the years ahead (Raymond et al., 2020).

Since one of the important mechanisms of losing heat in humans is through loss of latent heat of evaporation by sweating, defining heat waves over regions of high humidity requires the additional consideration of humidity along with temperature, and such events cannot be studied without referring to effects on humans (Robinson, 2001). Elevated moisture content in the atmosphere during heat wave conditions impairs the ability of human body to adjust through thermoregulation (Li, 2020). Different studies identified different indexes relating humidity and temperature to human discomfort, but the interpretation of physiological limits provide a better understanding with wet bulb temperature (Sherwood and Huber, 2010; Monteiro and Caballero, 2019; Coffel et al., 2017).

The wet bulb temperature T_w is defined as the temperature at which a parcel of air containing a given amount of water vapour q comes to thermodynamic equilibrium with a reservoir of water in an insulated container. Equilibrium is reached by evaporating more water into the air parcel, causing its temperature to reduce and specific humidity to increase. Eventually, the air parcel reaches saturation no further change in its temperature or specific humidity is observed. The temperature at which this equilibrium is reached is defined as the wet bulb temperature. If the air parcel is already saturated, then further evaporation and cooling does not occur, and T_w is equal to the dry bulb temperature T. Therefore, in a region with high environmental humidity, the human body cannot lose heat via evaporation of sweat, leading to higher discomfort.

The study conducted by Raymond et al. (2020) highlighted the fact that of wet bulb temperature above threshold levels already cross dangerous levels in certain parts of the world in the current climate. They observed these unbearable episodes to be clustered near South Asia, Middle East and coastal southwest North America.They also found out that regions adjacent to coasts, with constrained ocean air flow (such as gulf or bay), are nearer to the sources of terrestrial heat fluxes along with moisture laden maritime air are hot- spots for wet bulb temperature higher than 31°Celsius. Thinking ahead, beneficiaries and associated officials require a much better understanding of the changing climate and extreme events at a local and at a regional level (Ganguly et al., 2009), easing the decision making processes for adaptation and policy interventions.

In the current thesis, we focus on understanding the climatological and extreme patterns of wet bulb temperature along the east coast of India, particularly in Telangana, Andhra Pradesh and Tamil Nadu. We utilise station data and ERA5 datasets for the analysis. Chapter

3 describes the methods we followed to accomplish the objective. A detailed description of the analysis is described in chapter 4, while chapter 6 summarises the results.

Chapter 2

LITERATURE REVIEW

2.1 Extreme event theory

The most severe impacts of changes in climate are identified with increased recurrence and intensity of extreme climate and weather episodes (Sura, 2011). Given a distribution of any variable V, increases in extreme values of V can occur due to either an increase in its mean value or the variance. Katz and Brown (1992) looked into this question and concluded that changes in the extremes is more sensitive to changes in the variance as compared to the mean. Thus, any study of extreme events must also consider changes to the variance as well as the mean values. When we assess the risk of increased heat waves in the future, the skewness of the distribution and how it is likely to change becomes important to assess. A negatively skewed (or "short warm tai") distribution is likely to have a much larger increase in risk of temperatures exceeding a certain threshold as compared to a positively skewed distribution (Loikith et al., 2018). Thus, in general, it is important to understand more characteristics of the distribution of any climate variable of interest than just the mean or median when we need to understand the changes in risk.

2.2 South Asian heat waves

Heat waves over India are usually pre-monsoon events, having higher incidence over east coast, north, northwest and central parts (Ratnam et al., 2016). Satyanarayana and Rao (2020) showed the heightened exposure of extreme temperature conditions over South east India (even though having mean temperatures lower than that of Northeast and North India), is mainly due to larger irregularities in temperature over these regions. Small and large-scale events associated with the advancement of heat waves were researched in many previous studies (Rohini et al., 2016; Satyanarayana and Rao, 2020; Ratnam et al., 2016; Sandeep and Prasad, 2018).

2.3 Dry vs. humid heat

Wet bulb temperature characterisation is important to assess the impact on living beings, whose vulnerability changes with humidity and temperature (Raymond et al., 2020). Extreme wet bulb temperature events associated with heat waves were studied at different regions of South West Asia (Monteiro and Caballero, 2019; Pal and Eltahir, 2016) and South East Asia (Li, 2020). These studies highlights events in the past and projections over regions vulnerable to higher wet bulb temperature. Both wet bulb temperature near the threshold and severely lower than threshold can have significant impacts on most humans (Im et al., 2017).

Wet bulb temperature is more responsive towards changes in moisture content than to changes in dry bulb temperature across warmer regions (Raymond et al., 2017). Studies conducted by Raymond et al. in 2020 and Monteiro and Caballero in 2019 also showed the dominant influence of specific humidity over temperature for the changes in wet bulb temperature. The seasonality in humidity across the country varies with seasonal fluctuations in temperature and air flow (Jaswal and Koppar, 2011). Jaswal and Koppar showed specific humidity having maximum mean values are at regions along the coastlines during warmer months in India.

Living systems can cope with heat wave events having high wet bulb temperatures only for small time periods provided there is enough time for readjustment (Sherwood and Huber, 2010). Sherwood and Huber discussed the survivable limit of wet bulb temperature for humans to be near to 35°C (it is important that core body temperature and mass of mammals are taken into account while determining the threshold value). It is so that if and when the wet bulb temperature values crosses the predetermined value without sufficient recovery time the impacts are to be significant (Pal and Eltahir, 2016).

Severe surface heating can trigger start deep convection in the atmosphere, meaning it is very likely that very high wet bulb values will be compensated by cloud formation followed by rain (Raymond et al., 2020). However, processes that subdue deep convection (comprising adiabatic and diabatic descent) were to be constant over a region it can lead to extreme ambient surface conditions (Coffel et al., 2017; Pal and Eltahir, 2016).

The study conducted by Byrne and O'gorman in 2013 try to understand the trends in continental surface humidity in climate change projections. They show that due to the small gradients in free tropospheric potential temperatures, the surface moist static energy over land and ocean remain the same in the presence of active convection. Since the land surface is moisture limited, increases in surface moist static energy must be driven by surface temperature changes in this scenario. Thus, there is a disproportionate change in surface temperature, and a corresponding reduction in relative humidity over land as compared to the oceans under global warming.

However these studies have concentrated mainly on extreme high wet bulb temperature and the possibility of it crossing the threshold in accordance with warming of the planet and the potential aftermath of such events on ecosystem as a whole. However, it is well known in the literature that temperature variability is also an important factor in deciding the vulnerability of human populations to heat stress (Cheng et al., 2014; Guo Yuming et al., 2016). No similar studies has been carried out to understand the vulnerability of populations to variability in wet bulb temperature, T_w. Similarly, while there have been a number of studies analysing dry bulb temperature extreme events over South Asia and their drivers, no similar studies have been carried out for wet bulb temperature extremes.

Chapter 3

MATERIALS AND METHODS

3.1 Thermodynamics of moist air

Air at a particular temperature can hold only a certain amount of water vapour (saturation), this capacity increases with increasing temperature (Caballero, 2014). This means that at elevated temperature conditions, the relative humidity of air, defined as the ratio of the specific humidity and the saturation specific humidity at a given temperature, decreases at constant pressure. This also implies that at constant pressure, if the temperature is reduced, it eventually reaches saturation without any additional moisture influx. The temperature at which an air parcel reaches saturation is known as its dew point temperature ($\mathrm{T_d}$).

As described previously, the wet bulb temperature T_w or adiabatic saturation temperature of an air parcel is the temperature achieved when the air parcel achieves thermodynamic equilibrium with a reservoir of water under adiabatic conditions. This temperature is equal to the dry bulb temperature T only when the air parcel is fully saturated. In all other cases, the air parcel will cool down due to evaporation, and T_w is necessarily lower than T (Caballero, 2014).

To derive wet bulb temperature T_w, we need to consider the conservation of moist enthalpy of the air parcel. To recall, enthalpy is defined as the heat content of a system. For an air parcel which contains water vapour, this includes the enthalpy of dry air as well as the chemical potential due to the presence of water vapour. The former is defined as $c_{pd}T$ and the latter is defined as $L_v w$ per unit amount of mass of dry air. The terms in this equation are defined below.

If a parcel initally is at a temperature T and contains a water vapour mixing ratio of w, the moist enthalpy is given by

$$c_{pd}T + L_v w \tag{3.1}$$

where c_{pd} is the specific heat of dry air at constant pressure, w is the mixing ratio of water vapour, and L_v is the latent heat of evaporation.

If we allow evaporation into the parcel until it reaches saturation while simultaneously cooling the parcel to compensate for the evaporative cooling, the final moist enthalpy will be given by

$$c_{pd}T_w + L_v w_s(T_w) \tag{3.2}$$

where T_w is the wet bulb temperature and $w_s(T_w)$ is the saturation mixing ratio at the temperature T_w.

The psychrometric equation is obtained from equating the above two equations

$$c_{pd} \times (T - T_w) = L_v \times (w_s(T_w) - w) \tag{3.3}$$

3.1.1 Data collection and method

The data was collected from the Hadley Centre Integrated Surface Database (HadISD version 3.1.1.202006p; (Dunn, 2019)) contributed by the UK Met office Hadley. The data-set consists of quality controlled sub daily data-set for various climatology variables from 1950-11-09 till 2020-06-30. The station data for south Asia was identified from which time series data-set for temperature, dew point temperature and station level pressure for eastern coastal stations of India as Network Common Data Form (netCDF files) were retrieved. The data reported 3 hourly values for all three variables. Calculating wet bulb temperature required all three variables at the same hour. The procedure involved removal of potential errors caused by NAN (Not

A Number) values in all three variables. This comprised the station data.

Along with which, most recently generated climate reanalysis by European Centre for Medium-Range Weather Forecasts (ECMWF), ERA5 was also used to carry out analysis. ERA5 included sub daily data-sets for land-surface, sea-state and atmospheric variables together with measures of uncertainty. Data-set covered period from 1950 till 2020 (at the time of data retrieval). The three variables; dry bulb temperature, dew point temperature and station level pressure for entire South Asia was subsetted. The data was accessible at Climate Data Store on a latitude-longitude grid at 0.25° x 0.25° resolution (Hersbach et al., 2020).

3.2 Calculation of wet bulb temperature T_w

1. The wet bulb temperature, T_w was calculated by solving the psychrometric equation;

$$(T - T_w) \times \frac{c_{pd}}{L_v} = w_s(T_w) + w \tag{3.4}$$

   where c_{pd} is the isobaric specific heat of dry air, L_v is the enthalpy of latent heat of condensation of water vapour, T is the dry bulb temperature, w is the mixing ratio and w_s is the saturated mixing ratio at T_w.

2. Saturated vapour pressure e_s is calculated using the Hyland and Wexler formula (over water) (Vömel, 2016)

$$\log e_s = \frac{-0.58009906 \times 10^4}{T} + 0.13914993 \times 10^1 - 0.48640239 \times 10^{-1} \times T + 0.41764768 \times 10^{-4} \times T^2 + -0.14452093 \times 10^{-7} \times T^3 + 0.65459673 \times 10^1 \times \log T \tag{3.5}$$

where T is the dry bulb temperature.

3. Saturated specific humidity q was calculated using the equation;

$$q = \frac{M_w}{M_d} \times \frac{e}{p - (0.378 \times e)} \tag{3.6}$$

where, $\mathrm{M_w}$ and $\mathrm{M_d}$ is the molar mass of wet and dry air respectively, p is the pressure and e is the vapour pressure

4. Mixing ratio w was taken as saturated specific humidity at dew point temperature T_d. That is replacing T in equation 3.5 with T_d, then finding out saturation specific humidity. Whereas saturated mixing ratio w_s was taken as saturated specific humidity at wet bulb temperature T_w.

Since the equation 3.3 included the term $w_s(T_w)$, that required wet bulb temperature in prior, Newton-Raphson method was used. Meaning, wet bulb temperature was solved by finding root of the equation 3.4. Newton-Rapshon method is a technique used to find the zero of a function by providing an initial value. Here we used corresponding dew point temperature ($\mathrm{T_d}$) to every dry bulb temperature T, as the staring point.

A python script was developed incorporating the above mentioned equations. Using scipy, numpy, pandas, matplotlib and xarray libraries, a function was written which took dry bulb temperature, pressure and dew point temperatures as input and gave wet bulb temperature as output. Detailed python code is provided in section 6. Further, a quality control on the calculated variable was done prior to our analysis. For instance, checking the consistency of maximum and minimum values occurring on a daily and seasonal timescale.

3.3 Area of study

A prominent intra annual variability of heat waves in east coast India with intensity increasing each heat wave were observed by Sandeep and Prasad (2018). Hence we concentrated our study area along the east coast of India extending from longitude of 78.067° East to 83.3° East and latitude of 10.765° North to 18.767° North. The chosen region covers 12 stations spread across Andhra Pradesh, Telangana and Tamil Nadu. Stations included are:

1. Ramagundam
2. Hyderabad
3. Visakhapatnam Walt
4. Kakinada
5. Machilipatnam
6. Kurnool
7. Nellore
8. Anantapur
9. Madras

10. Cuddalore
11. Coimbatore
12. Tiruchchirappalli

The stations are plotted in Figure 3.1. Stations were selected based on the data availability.That is, only stations with all data required for the calculation – dew point temperature, dry bulb temperature and station level pressure – were selected. Further, only stations having greater than 65000 (approx) valid data points were selected. The analysis was conducted for the years 1995 to 2020 since data gaps in the selected stations was minimal for this time period. These stations are grouped into coastal stations:

1. Kakinada
2. Machilipatnam
3. Nellore
4. Madras
5. Cuddalore
6. Vishakapatnam

and inland stations:

1. Anantapur
2. Kurnool
3. Hyderabad
4. Ramagundam
5. Coimbatore
6. Tiruchchirappalli

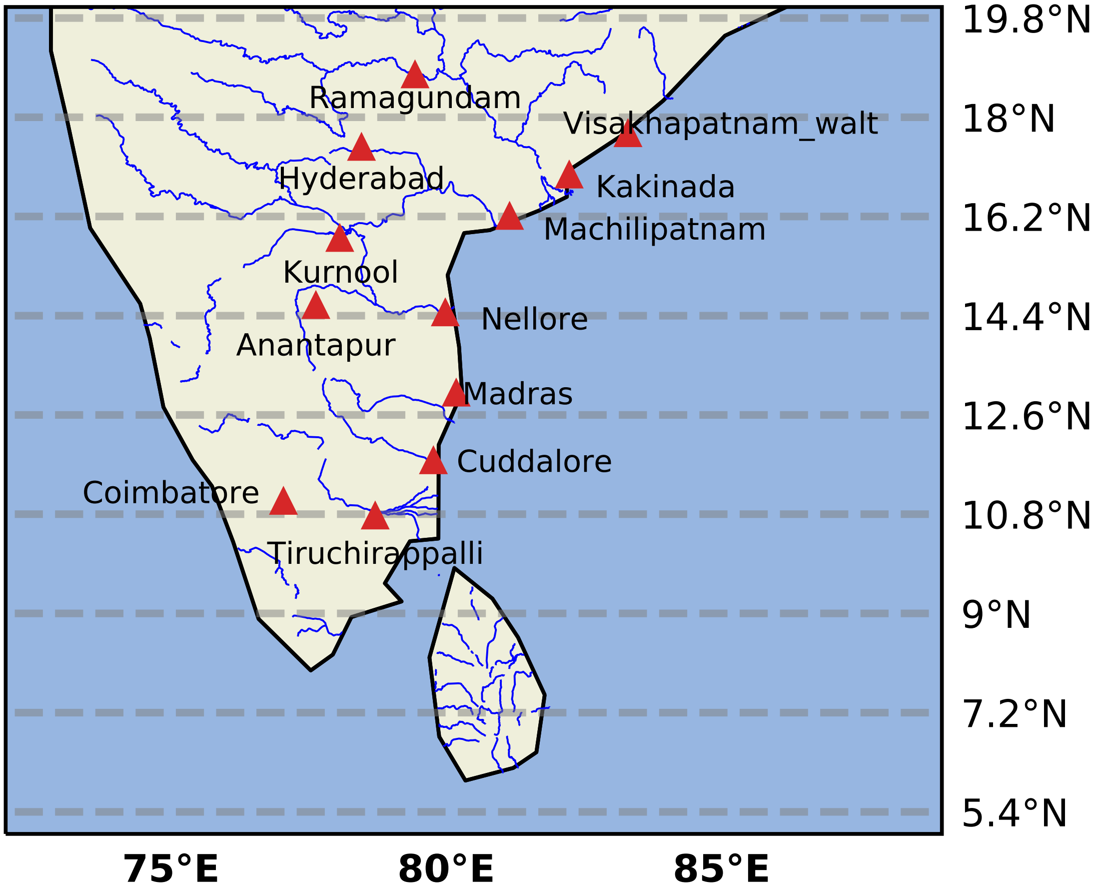

Figure 3.1: Locations of 12 stations considered for this study

Chapter 4

RESULTS AND DISCUSSION

4.1 Seasonal Cycle

For all the stations in the region of interest, we plot the seasonal variations in dry bulb temperature, specific humidity and wet bulb temperature to identify relationships between the three variables and identify months with high variability and extremes.

4.1.1 Dry bulb temperature

Figure 4.1 shows the seasonal variations of dry bulb temperature across the given stations. All inland stations except Coimbatore and Tiruchchirappalli show a marked season cycle in temperatures, with a clear difference between the hot pre-monsoon months of April-early June as compared to the monsoon months starting from late June. Ananta-

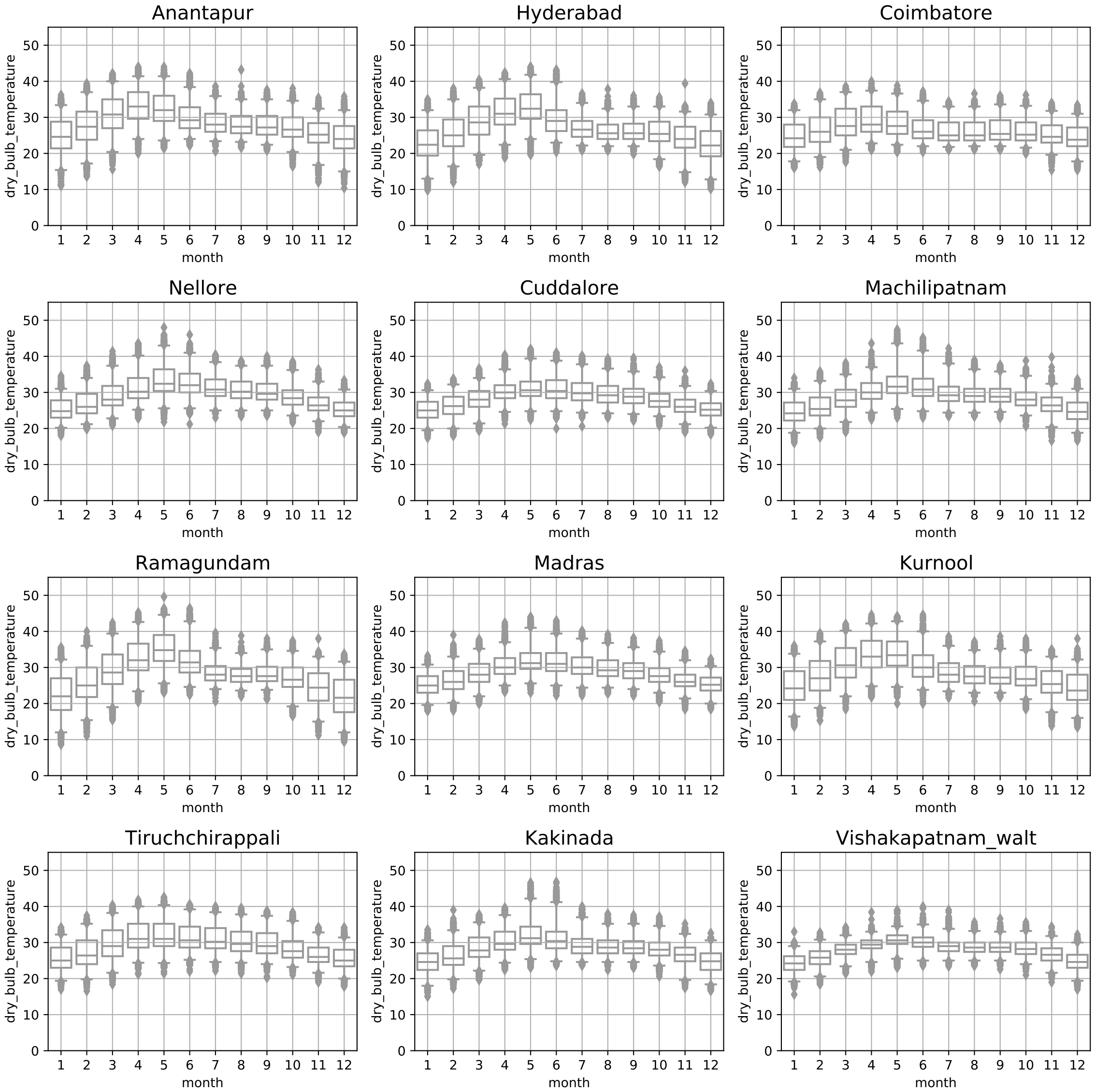

Figure 4.1: Dry bulb temperature box plot: Each box-whisker plot shows month wise hourly dry bulb temperatures (with a period of three hours) for all the stations for 24 years (1995-2020). The whiskers of the vertically aligned box plot is adjusted to 1st and 99th percentile. Grey diamonds are outliers

pur and Coimbatore have April as the warmest month as compared to other inland stations where May is the warmest month. As expected, the stations further inland such as Anantapur, Hyderabad and Ramagundam exhibit a more pronounced seasonal cycle as compared to the other inland stations.

In contrast, the coastal stations have a more muted seasonal cycle due to the high thermal capacity of the sea nearby. In all coastal stations, the highest median temperature is observed in May.

In most stations, the variability of temperature (as indicated by the size of the boxes or the interquartile range) is lowest during the monsoon season. The interquartile range (IQR) increases post monsoon and remains high until May. Thus, April and May are months with a high median value as well as a large IQR, indicating that these months have a higher incidence of extreme temperatures. Similarly, the occurrence of extremely high temperatures (as indicated by the upper whisker and outliers beyond the whisker) is more likely in April, May and June, with May usually being the month with higher number of extremes in most stations. The observed spread (indicated by the distance between the whiskers) was between 20 to 35 degrees Celsius for most stations, except for Ramagundam it reached up to 40° Celsius.

4.1.2 Daily maximum and minimum temperatures

In comparison with the daily temperatures, the daily maximum temperatures shown in Fig. 4.2 show a much smaller IQR, though the median values are obviously higher than that for daily temperatures. During the months of April-June, the occurrence of negative extremes (i.e, cooler daily maximum temperatures) is more likely, as indicated by the fact that the negative whisker is much further away from the median as compared to the positive whisker. The exceptions to this pattern are the coastal stations in Andhra Pradesh – Machilipatnam, Kakinada and Vishakapatnam – where the occcurrence of positive and negative extremes are quite similar, though the variability in Vishakapatnam is far less pronounced as compared to the other two stations.

Daily minimum temperatures are shown in Fig. 4.3. Except during monsoon months, the occurrences of positive extremes were more likely compared to the negative extremes at inland stations. Whereas a symmetry in daily minimum temperatures observed at coastal stations all throughout the year. A lower variability in daily minimum temperatures observed during the monsoon period for all the stations. A broader IQR for stations Anantapur, Hyderabad, Rmagundam and Kurnool observed in the given period.

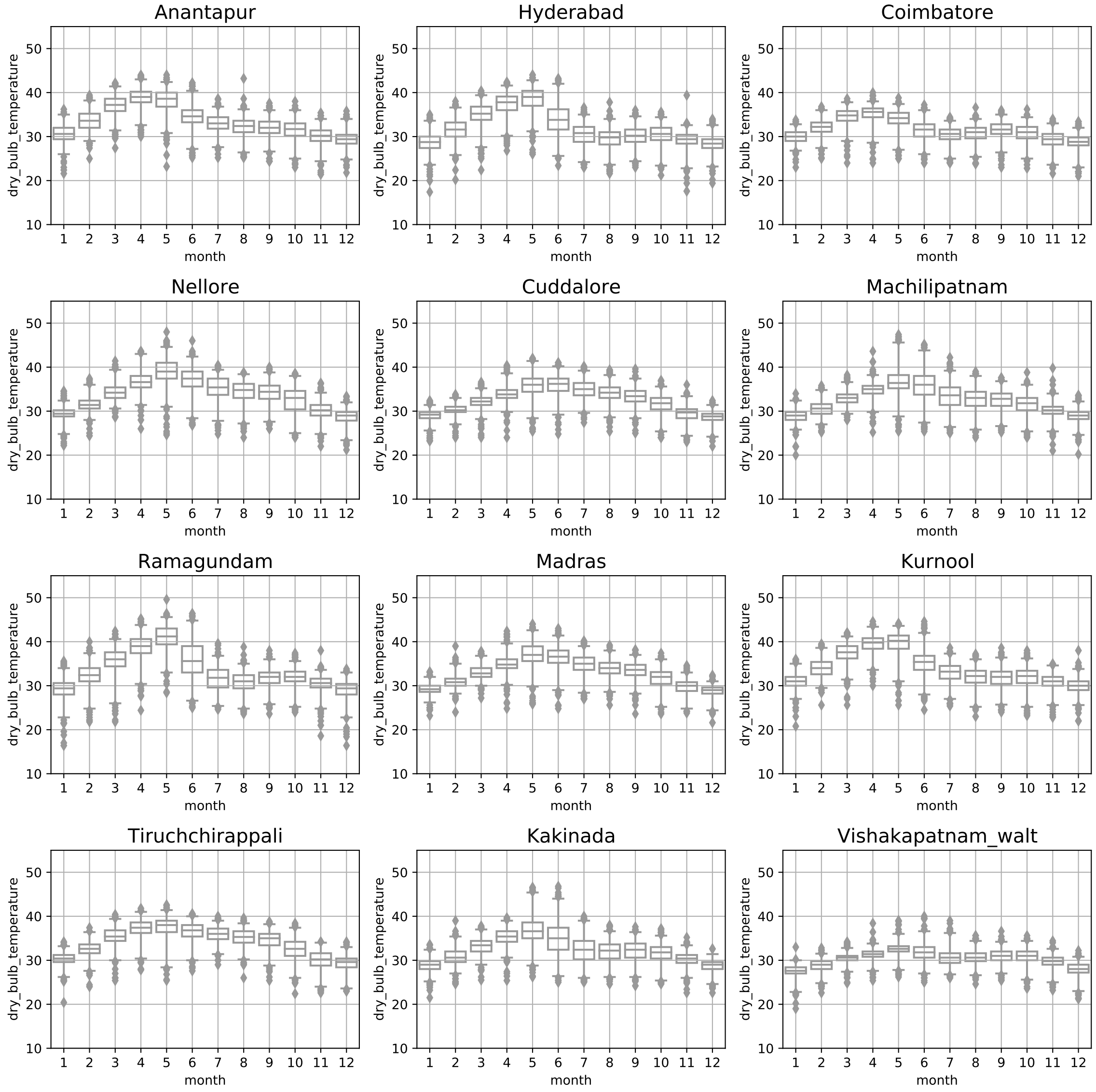

Figure 4.2: Daily maximum temperature box plot: Each box-whisker is adjusted to 1^{st} and 99^{th} percentiles. The middle line through the box shows where the median of the data lies. Outliers are marked by individual grey diamonds. Inter quartiles (values within the edges of the rectangle box-whisker) convey where the 50 percentage of the data lies. The data is plotted for all the stations for a period of 24 years (1995-2020).

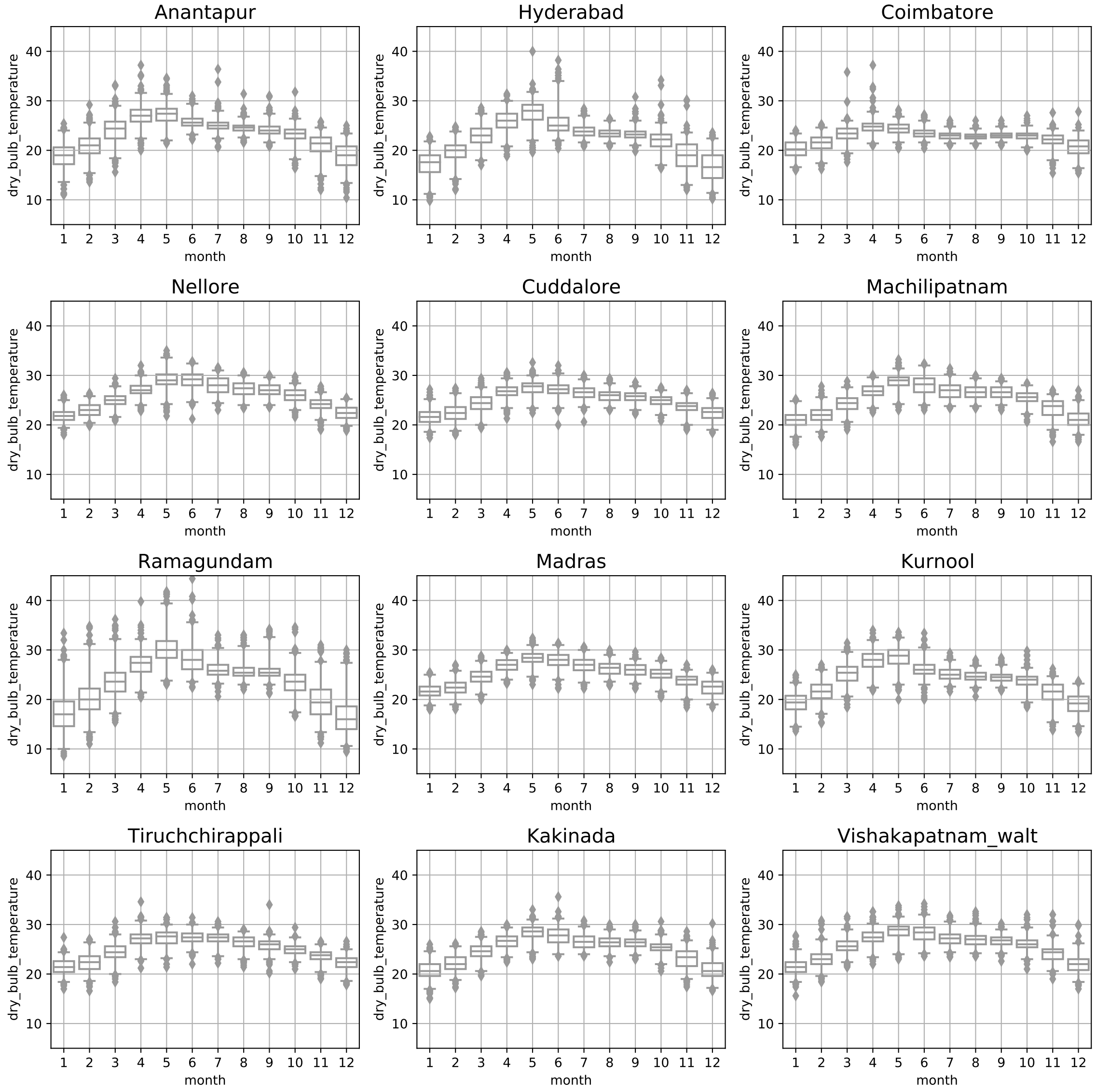

Figure 4.3: Daily minimum temperature box plot: Each box-whisker is adjusted to 1st and 99th percentiles. The middle line through the box shows where the median of the data lies. Outliers are marked by individual grey diamonds. Inter quartiles (values within the edges of the rectangle box-whisker) convey where 50 percentile of the data lies. The data is plotted for all the stations for a period of 24 years (1995-2020)

4.1.3 Specific humidity

Figure 4.4 shows specific humidity variations throughout the year for the given time period. Two peaks for median values were to be seen, one during the month of May and the second during the month of September, however values are slightly higher during former compared to latter. This seasonal pattern is prominent across all station except at Kurnool, Hyderabad and Ramagundam where the peak were seen usually during the month of September alone. Overall, the stations can be grouped into two broad categories – those which have specific humidity maxima at both the beginning and end of the summer monsoon (May and September) and those which have single maxima at the end of the monsoon.

The IQR were observed between 9 and 20 for all inland stations whereas for coastal stations it were in between 10 and 22. However, the IQR shrunk during the monsoon period for most of the stations (Anantapur, Hyderabad, Coimbatore, Ramagundam, Kurnool, Kakiknada and Visakhapatnam). A larger IQR was observed during the winter and pre-monsoon months at all inland stations. In contrast, the coastal stations exhibit a large IQR was largest during the pre-monsoon and monsoon seasons, apart from the winter months.

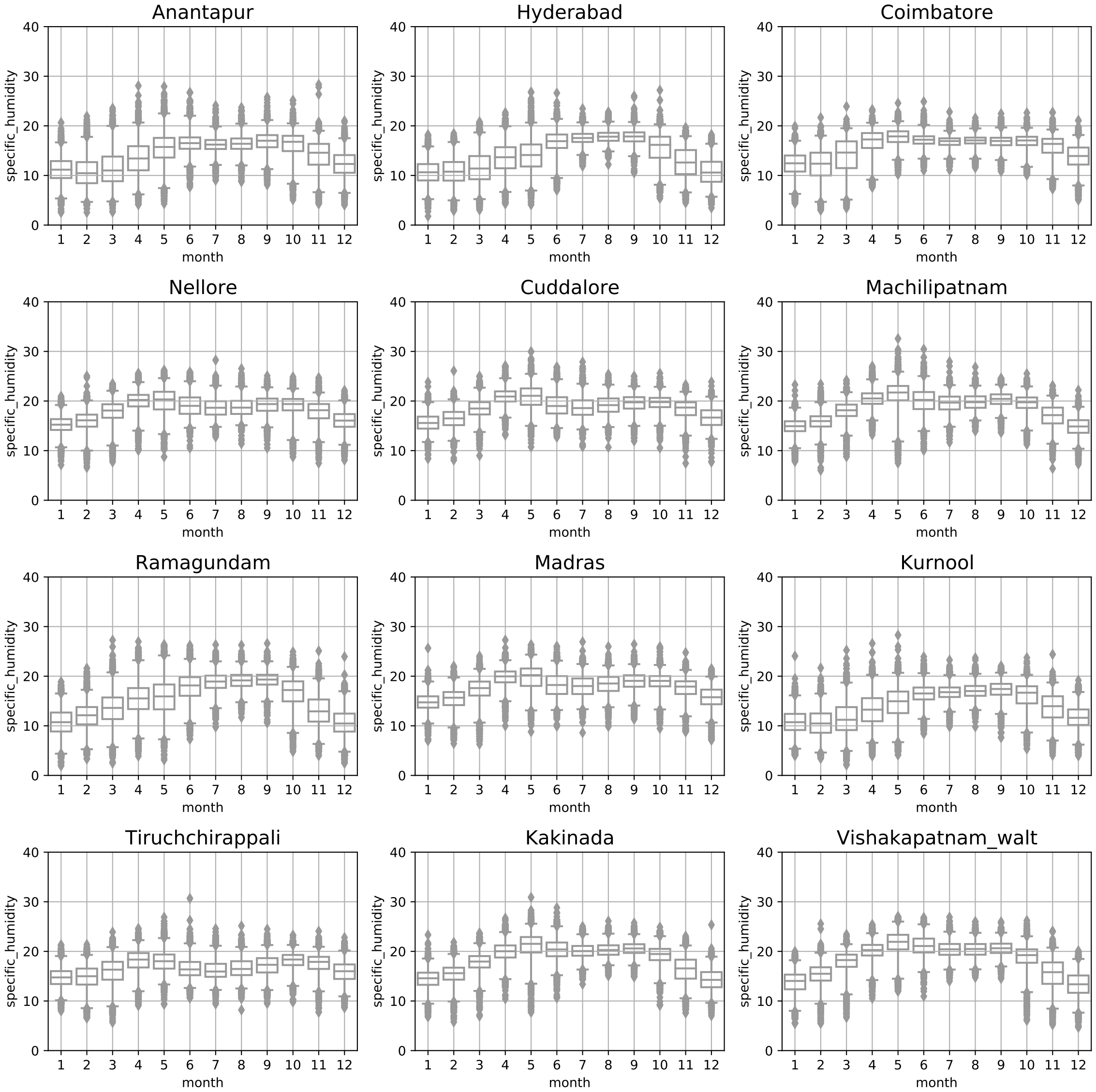

Figure 4.4: Specific humidity box plot: Each box-whisker is adjusted to 1^{st} and 99^{th} percentiles. The middle line through the box shows where the median of the data lies. Outliers are marked by individual grey diamonds. Inter quartiles (values within the edges of the rectangle box-whisker) convey where the 50 percentage of the data lies. The data is plotted for all the stations for a period of 24 years (1995-2020)

The spread about the median is nearly symmetric for inland stations all throughout the year. In contrast, the coastal stations exhibit an asymmetric distribution with a longer negative tail. This asymmetry is particularly pronounced in the winter and pre-monsoon months, and is highest for Kakinada, Machilipatnam and Vishakapatnam. Therefore, the probability of negative extremes in specific humidity is higher in these stations. This is contrast to the temperature, where positive extremes are more probable, especially during the pre-monsoon months. As we will see, this asymmetry is also reflected in the wet bulb temperature, which is very sensitive to changes in specific humidity.

4.1.4 Wet bulb temperature

Figure 4.5 shows the wet bulb temperature values across all stations. Pronounced seasonality in wet bulb temperature values were again visible at inland stations except at Tiruchchirapalli. Median values were higher during the month of May at Anantapur and Coimbatore. For Tiruchchirapalli and Kurnool it were highest in April and September respectively. Hyderabad and Ramagundam exhibit a peak that spans three months, from August until September.

Coastal stations exhibit weaker seasonality, and higher median

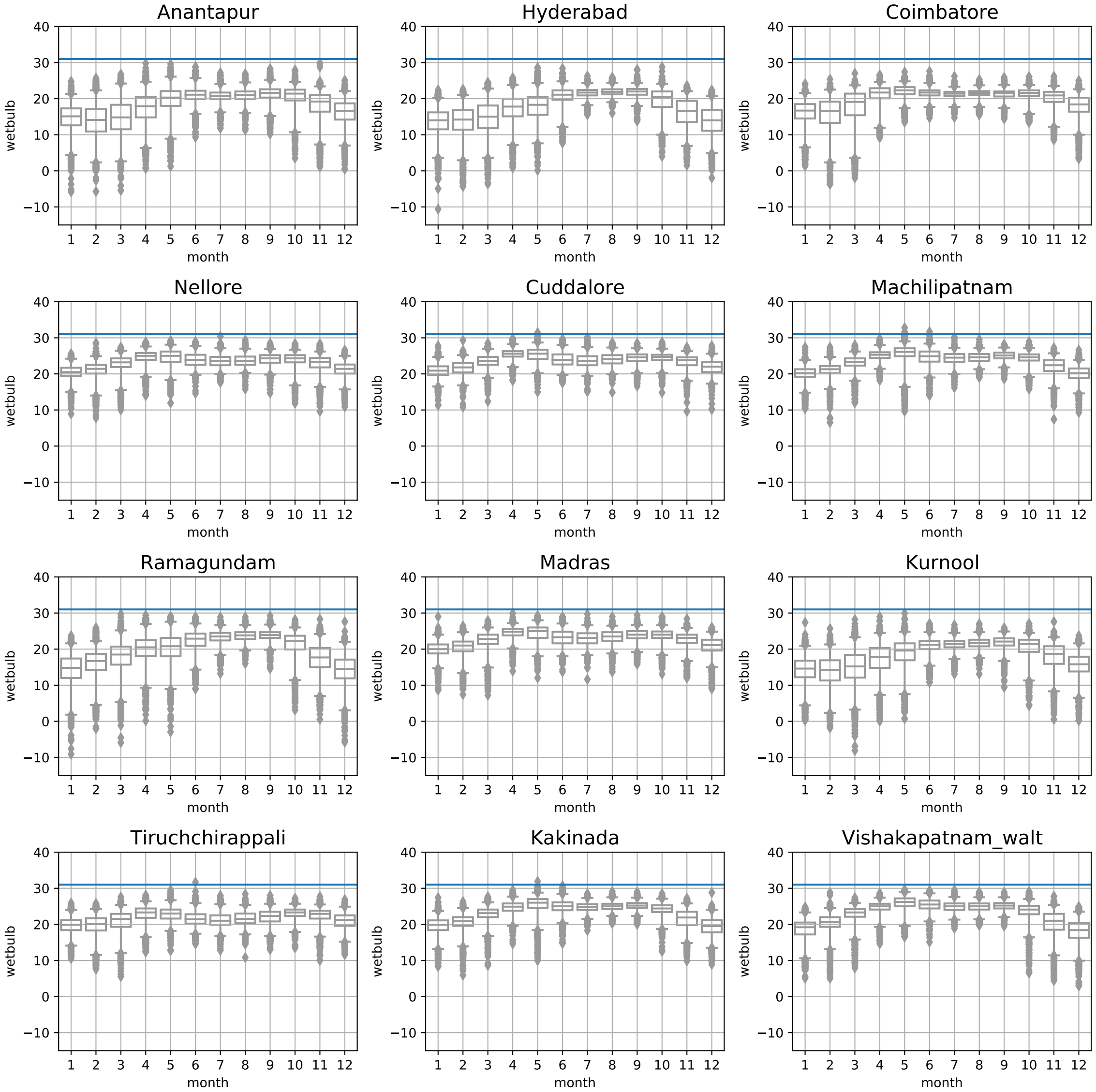

Figure 4.5: Wet bulb temperature box plot: Each box-whisker is adjusted to 1st and 99th percentiles. The middle line through the box shows where the central values of the data lie. Outliers are marked by individual grey diamonds. Horizontal line in blue, marks the threshold where labour capacity is diminished. Inter quartiles (values within the edges of the rectangle box-whisker) convey where the 50 percentage of the data lies. The data is plotted for all the stations for a period of 24 years (1995-2020)

values were observed during May at all stations. Higher variability in wet bulb temperature values were observed at all inland stations, from October until May. Although coastal stations depicted the same seasonal pattern (larger spread from post monsoon till June), the values showed lesser variation.

A reference value of 31 degrees Celsius for wet bulb temperatures was taken. This is the lower limit of wet bulb temperature threshold that, considering an exerting body, ensures added heat could leave the system without resulting in hypothermia (Sherwood and Huber, 2010). Machilipatnam, Kakinada, Cuddalore, Tiruchchirappalli exceeded this threshold in the month of May (Machilipatnam crossed this value both in May and June) within the chosen time period, here onwards will be known as extreme stations.

The IQR for coastal stations lies closer to this threshold value throughout the year between 19° and 28° Celsius. During the monsoon months of June till September a large reduction in the IQR of wet bulb temperature values were seen at all stations. The IQR range were highly constrained between 20 and 24 degrees Celsius for inland stations, except at Hyderabad and Ramagundam, where it was between 21 and 24 degrees Celsius.

4.1.5 Daily maximum and minimum wet bulb temperatures

The daily maximum for wet bulb temperature is shown in Fig. 4.6. Wet bulb temperatures above 15° Celsius were observed at coastal stations (including the outliers beyond the whiskers) except in Kakinada and Visakhapatnam, where it ranges from 8 degrees Celsius and above. However during the monsoon period the values ranged between 20° and 31° Celsius. Except during the monsoon period, positive and negative extremes were found further away from the median across all inland stations. Conversely, a symmetry in the positive and negative extremes were observed during the monsoon period at all the stations however values were far more restricted.

Note that the negative extremes at stations in Andhra Pradesh and Telangana during the pre monsoon period had a much longer whisker.

At coastal stations the entire range of daily maximum T_w values lies between 20° and 30° Celsius during the months from April till September (keeping in the mind the attributes of extreme stations).

Daily minimum temperatures as shown in the Fig. 4.7, at the inland stations never seem to cross 25° Celsius except in Ramagundam during April till September, although the negative extremes extend below zero degrees Celsius for these stations. Coastal stations on the other hand had a upper limit below 30° Celsius and lower limit of 10° Celsius during pre-monsoon and monsoon period, and a lower limit of 5° Celsius for rest of the months.

Machilipatnam and Kakinada exhibit much larger negative extremes during May as compared to the other coastal stations. This behaviour is due to the fact that these stations also exhibit large negative extremes of specific humidity during May, and wet bulb temperatures are quite sensitive to variations in specific humidity. We note that this large variability is not observed in daily maximum T_w described in the previous section. Thus, these stations have a fairly stable daily maximum with the possibility of large variations in the daily minimum values.

4.2 Large scale picture

To place the above results from station data into a larger context, we plot the mean wet bulb temperatures over the South Asian region using ERA5 data.

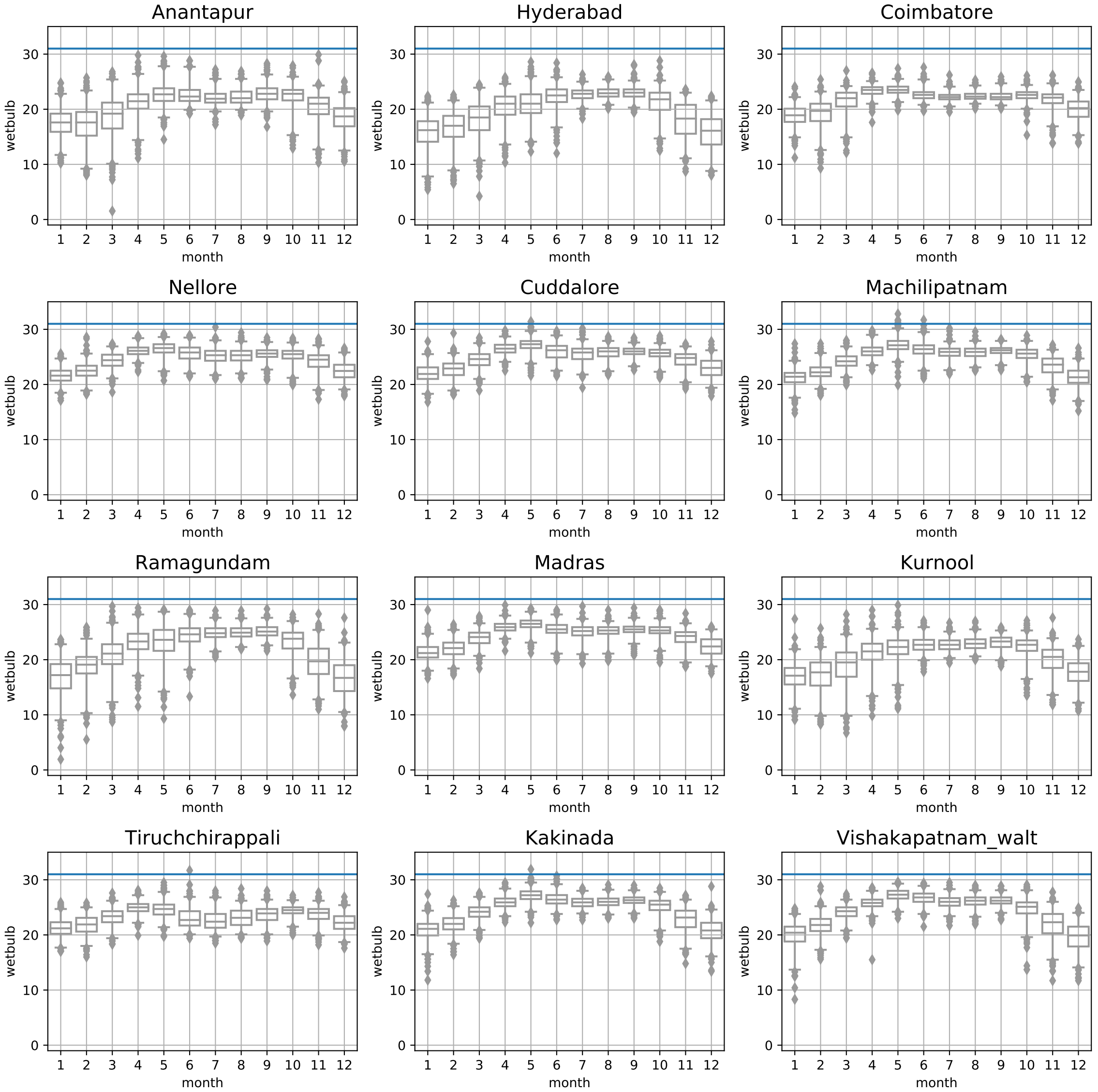

Figure 4.6: Daily maximum wet bulb temperature box plot: Each box-whisker is adjusted to 1st and 99th percentiles. The middle line through the box shows where the median of the data lies. Outliers are marked by individual grey diamonds. Inter quartiles (values within the edges of the rectangle box-whisker) convey where the 50 percentile of the data lies. The data is plotted for all the stations for a period of 24 years (1995-2020)

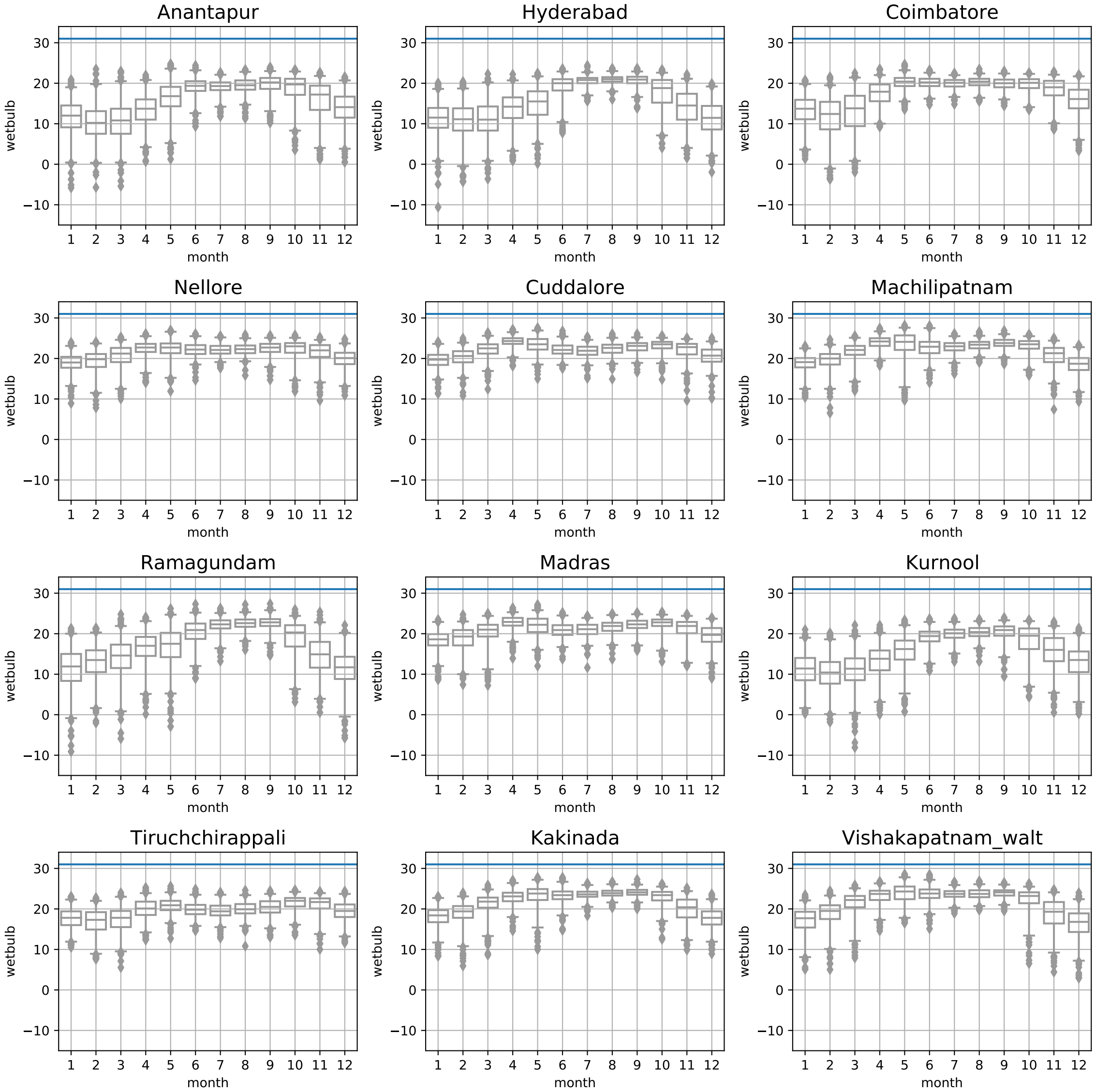

Figure 4.7: Daily minimum wet bulb temperature box plot: Each box-whisker is adjusted to 1st and 99th percentiles. The middle line through the box shows where the median of the data lies. Outliers are marked by individual grey diamonds. Inter quartiles (values within the edges of the rectangle box-whisker) convey where 50 percentage of the data lies. The data is plotted for all the stations for a period of 24 years (1995-2020)

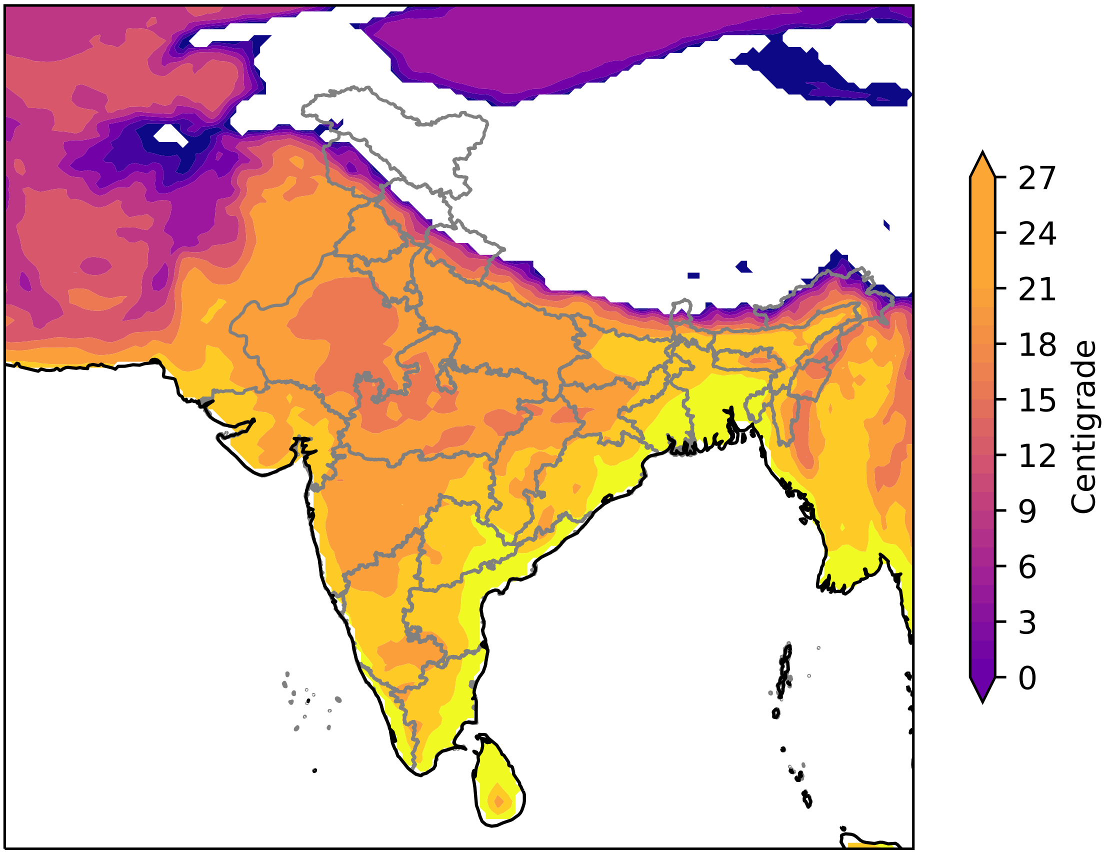

Figure 4.8: Climatological mean of the daily maximum T_w for the month of April for the period 1980-2019. T_w has been calculated using the same algorithm as for the station data. Negative values of T_w, usually found in the high altitude regions of the Himalayas and Tibet have been masked.

April

Larger parts of South Asia during the month of April showed the mean value of daily maximum wet bulb temperature above 18° Celsius (and never beyond 28° Celsius at any region), as shown in the Fig. 4.8. The coastal regions displayed a higher mean values for wet bulb temperatures T_w, followed by the interior regions. This pattern is visible at either side of the Indian peninsula, however the eastern coastal regions bordering the Bay had relatively higher climatological mean for daily maximum T_w values and covered larger spatial area. Regarding the regions under study (Andhra Pradesh, Tamil Nadu and Telangana) thus exhibited two different ranges of mean values.

Bangladesh exhibited the highest T_w of all the regional countries during April. Across India, lowest values for mean T_w were observed in parts of Rajasthan, Madhya Pradesh and at the border of Jharkhand and Chhatisgarh, value ranged between 16° and 20° Celsius.

May

Figure 4.9 shows the mean T_w over the region during May. Most of South Asia exhibits T_w above 20° Celsius. The observed T_w ranges from 20° Celsius along the east coast of India to 20° Celsius in central-northwest regions of India. Bangladesh exhibits the highest T_w of all

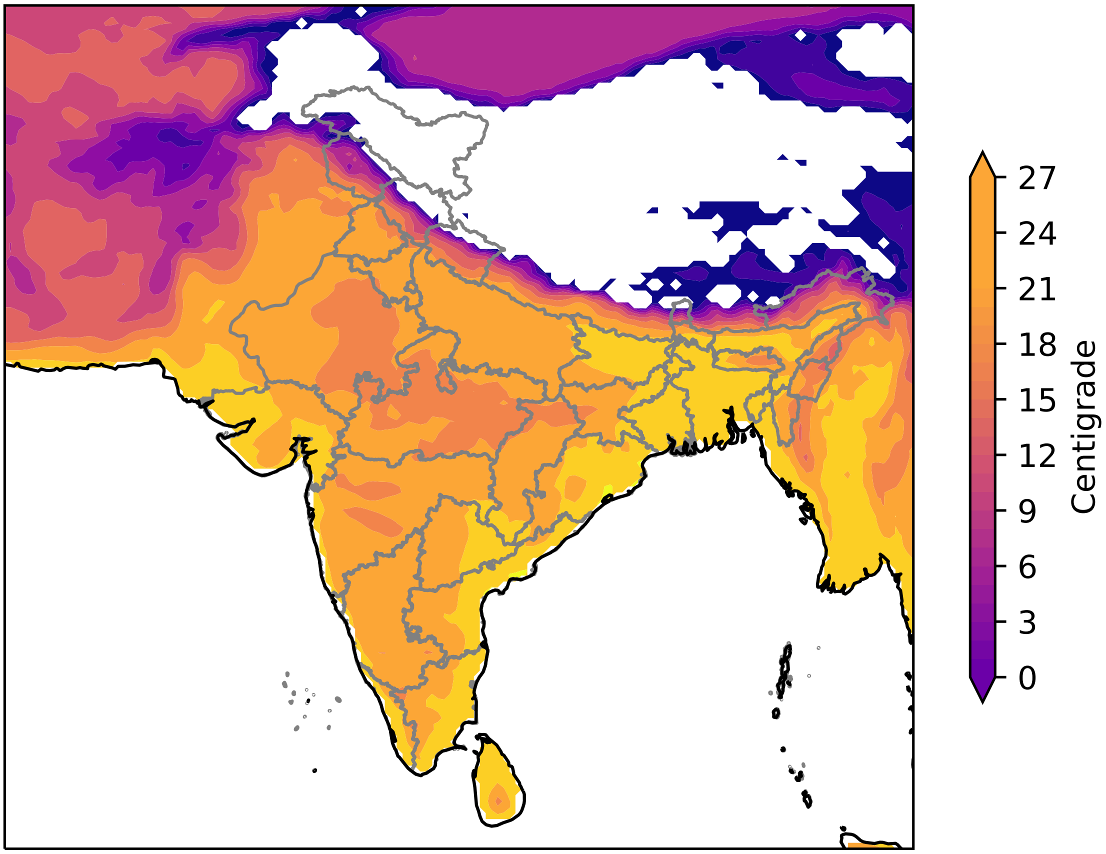

Figure 4.9: Climatological mean of the daily maximum T_w for the month of May for the period 1980-2019. T_w has been calculated using the same algorithm as for the station data. Negative values of T_w, usually found in the high altitude regions of the Himalayas and Tibet have been masked.

the regional countries during May.

There is a regional minimum spanning Rajasthan and Madhya Pradesh, whereas the regions of maximum T_w are found mainly along the east coast of India and Bangladesh, and a smaller region spanning Gujarat and Southern Pakistan. The highest T_w in excess of 27° Celsius are observed in coastal regions of Andhra Pradesh, Orissa and West Bengal. Remarkably, the west coast of India does not exhibit any such T_w maxima.

June

The climatological mean for daily maximum wet bulb temperature exhibit only three ranges of values compared to April and May across India as evident from the Fig. 4.10. A maxima along the eastern coastal region, Gujarat, regions bordering southern Pakistan, North and North Eastern India. And a minima of around 18 ° and 20 ° Celsius at southern Karnataka. The rest of the regions falls between the range 23 ° and 25.4 ° Celsius.

Regionally, Southern Pakistan, Northwest and central India, Bangladesh and Myanmar during the month of June showed a higher mean T_w daily maximum values. Along the east coast, West Bengal and Bangladesh remains at higher T_w values nearing to 28° Celsius.

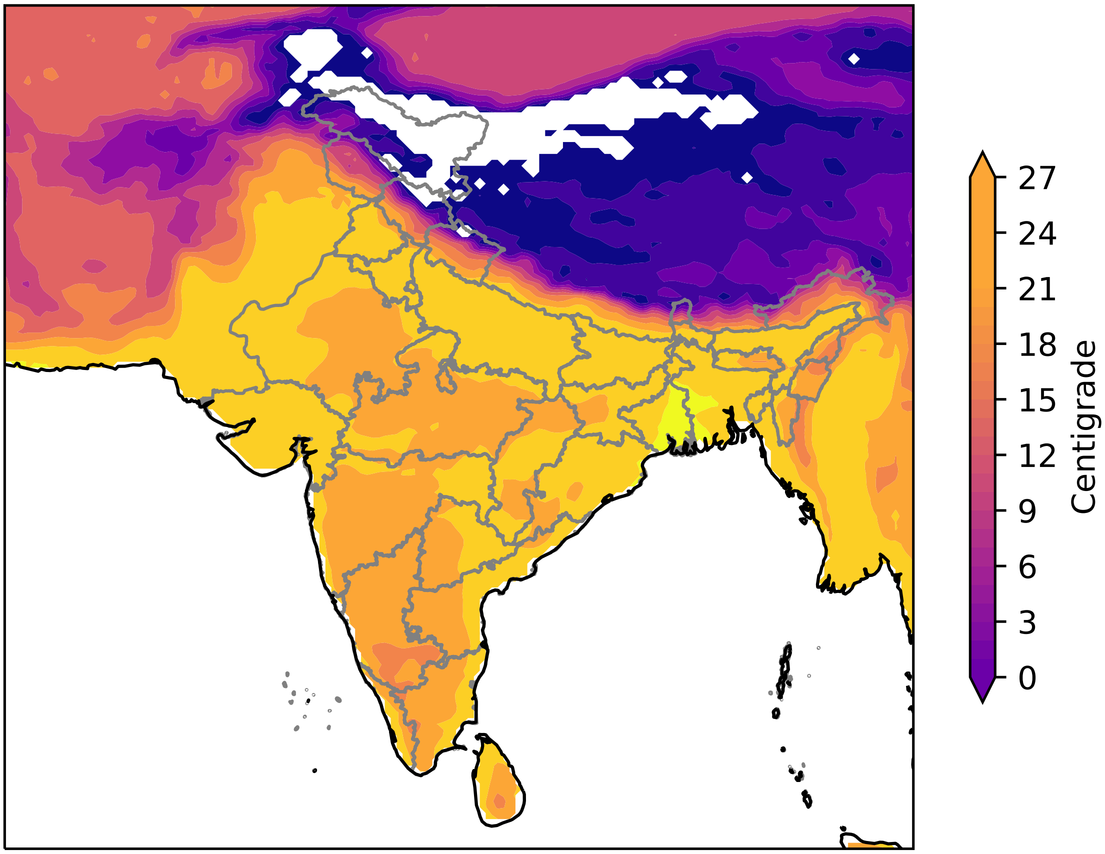

Figure 4.10: Climatological mean of the daily maximum T_w for the month of June for the period 1980-2019. T_w has been calculated using the same algorithm as for the station data. Negative values of T_w, usually found in the high altitude regions of the Himalayas and Tibet have been masked.

4.3 Analysis of heat waves

To understand the dynamics of wet bulb temperature extremes, we choose four stations: Machilipatnam and Kakinada (coastal), Ramagundam and Hyderabad (inland) . These stations were chosen based on the previous seasonal analysis where it was observed that these stations have high median values as well as large variations in the daily minimum wet bulb temperatures.

Here we choose four heat wave years and four non heat wave years as representatives to see if there is a systematic difference in the dynamics of wet bulb temperatures. These eight years were chosen on the basis of the criteria set by IMD, Mandal et al. (2019) identified heat wave events at different regions over India. From those events identified for south east India, we selected four heat wave years: 1998, 2003, 2012 and 2015 and four normal years: 2000, 2001, 2004 and 2014 from their study.

4.3.1 Heat wave years

Coastal stations

Wet bulb temperature variations for Machilipatnam and Kakinada are shown in Figs. 4.11 and 4.12 respectively. In both stations, the daily

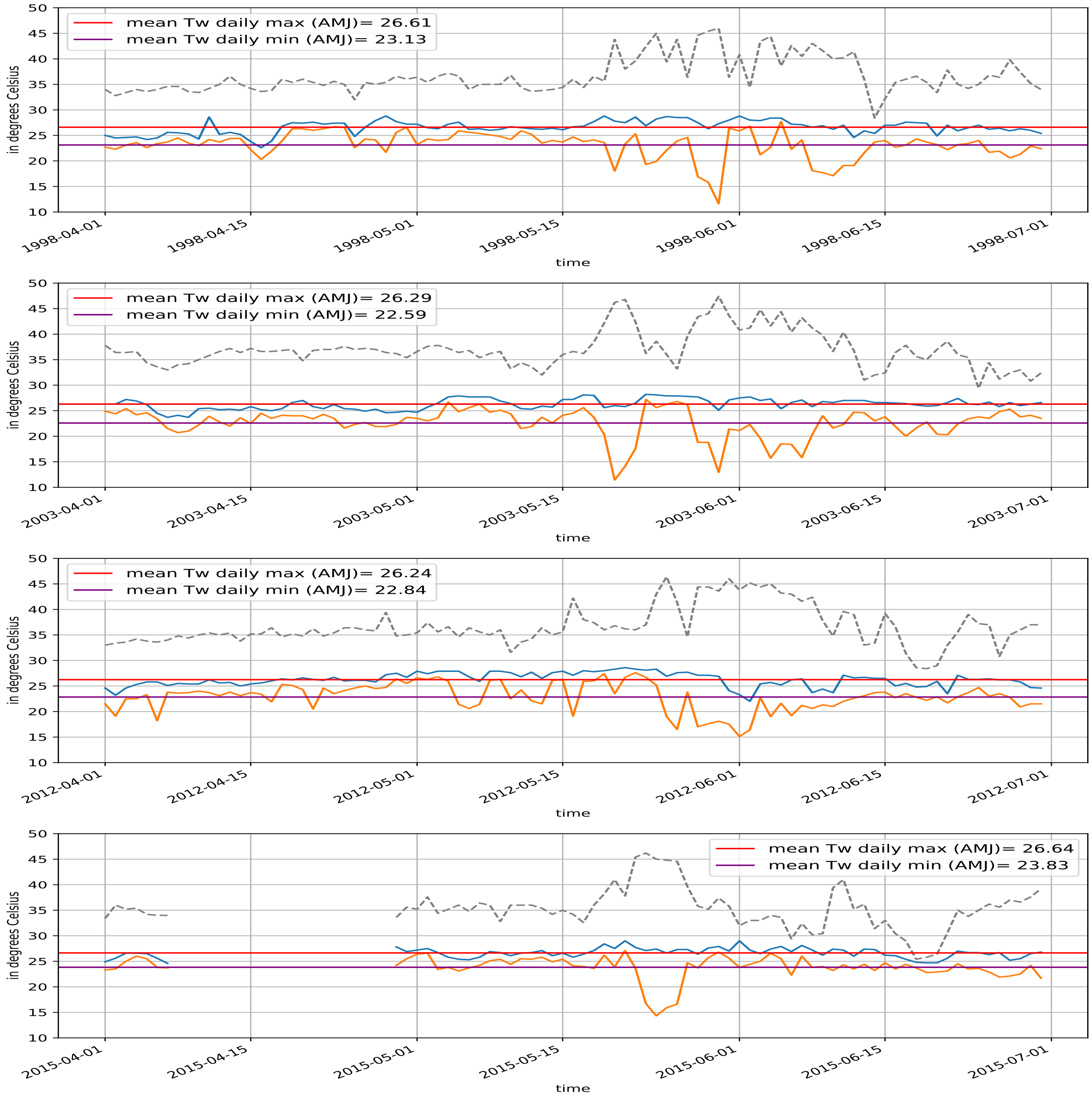

Figure 4.11: Daily maximum and minimum wet bulb temperatures at station Machilipatnam for the years 1998, 2003, 2012 and 2015 (top to bottom). Values were plotted for the months April, May and June. The blue and orange line in each plot indicates maximum and minimum wet bulb temperatures respectively. Daily maximum dry bulb temperature is shown in dashed grey line. Mean daily maximum and daily minimum wet bulb temperatures for the months April, May and June for the years are indicated by red and violet lines respectively.

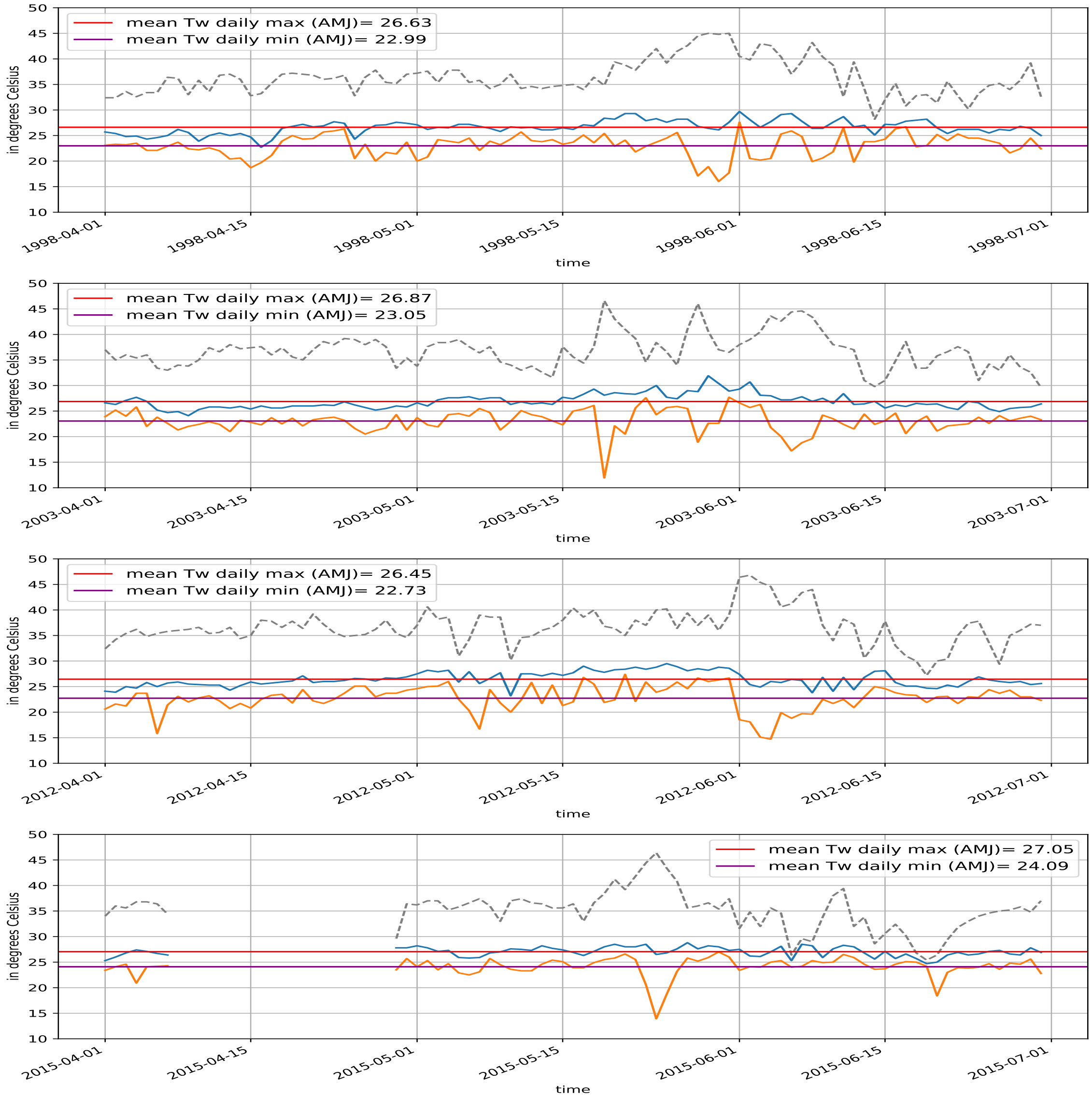

Figure 4.12: Daily maximum and minimum wet bulb temperatures at station Kakinada for the years 1998, 2003, 2012, 2015 (top to bottom). Values were plotted for the months April, May and June. The blue and orange line in each plot indicates maximum and minimum wet bulb temperatures respectively. Daily maximum dry bulb temperature is shown in dashed grey line. Mean daily maximum and daily minimum wet bulb temperatures for the months April, May and June for the years are indicated by red and violet lines respectively.

maximum wet bulb temperature varies very little from the mean, with departures rarely exceeding 3-4°C. The positive departures from the mean of the daily maximum wet bulb temperature is more pronounced for Kakinada as compared to Machilipatnam. Similarly, Kakinada exhibits the highest wet bulb temperature of around 32°C in 2003.

On the other hand, there are large variations in the daily minimum wet bulb temperatures in both stations during years when heat waves occurred. daily minima can change from the mean values by as much as 10°C. This indicates that heat waves are characterized by large diurnal variations in wet bulb temperatures. Since wet bulb temperatures are very sensitive to variations in specific humidity, this indicates large changes in specific humidity over the span of a single day. Furthermore, variability in daily minimum wet bulb temperatures are often related to increases in dry bulb temperature. Thus, elevated dry bulb temperatures (traditionally defined as heat waves) are accompanied by a large decrease in specific humidity, which results in the wet bulb temperatures actually decreasing during this period. While we have not explored the reasons for this relationship between wet and dry bulb temperatures in this thesis, we expect that moist maritime air is being replaced by dry continental air in these stations during heat waves.

Inland stations

For the interior stations of Ramagundam and Hyderabad, the daily maximum and minimum wet bulb temperatures are shown in Figs 4.13 and 4.14 respectively. The mean values of daily maximum and minimum are much lower than the coastal stations, and the daily maximum is strongly constrained like in the coastal stations. Variation about the mean is also observed during heat waves, but both daily maximum and minimum vary, ensuring that the diurnal variability of wet bulb temperatures are much lower as compared to the coastal stations. Unlike the coastal stations, the variability in wet bulb temperatures is not related to changes in dry bulb temperatures.

Daily dry bulb temperatures at Ramagundam and Hyderabad were found beyond 40° Celsius mostly from May till early June. The maximum temperatures observed during a heat wave are about 5° Celsius above this mean value. While the maximum dry bulb temperatures observed in the coastal stations during a heat wave are also similar (45° Celsius), the mean value is around 35° Celsius, resulting in an increase of 10° Celsius or more. This further lends support to the hypothesis that maritime air is being replaced by continental air during heat waves.

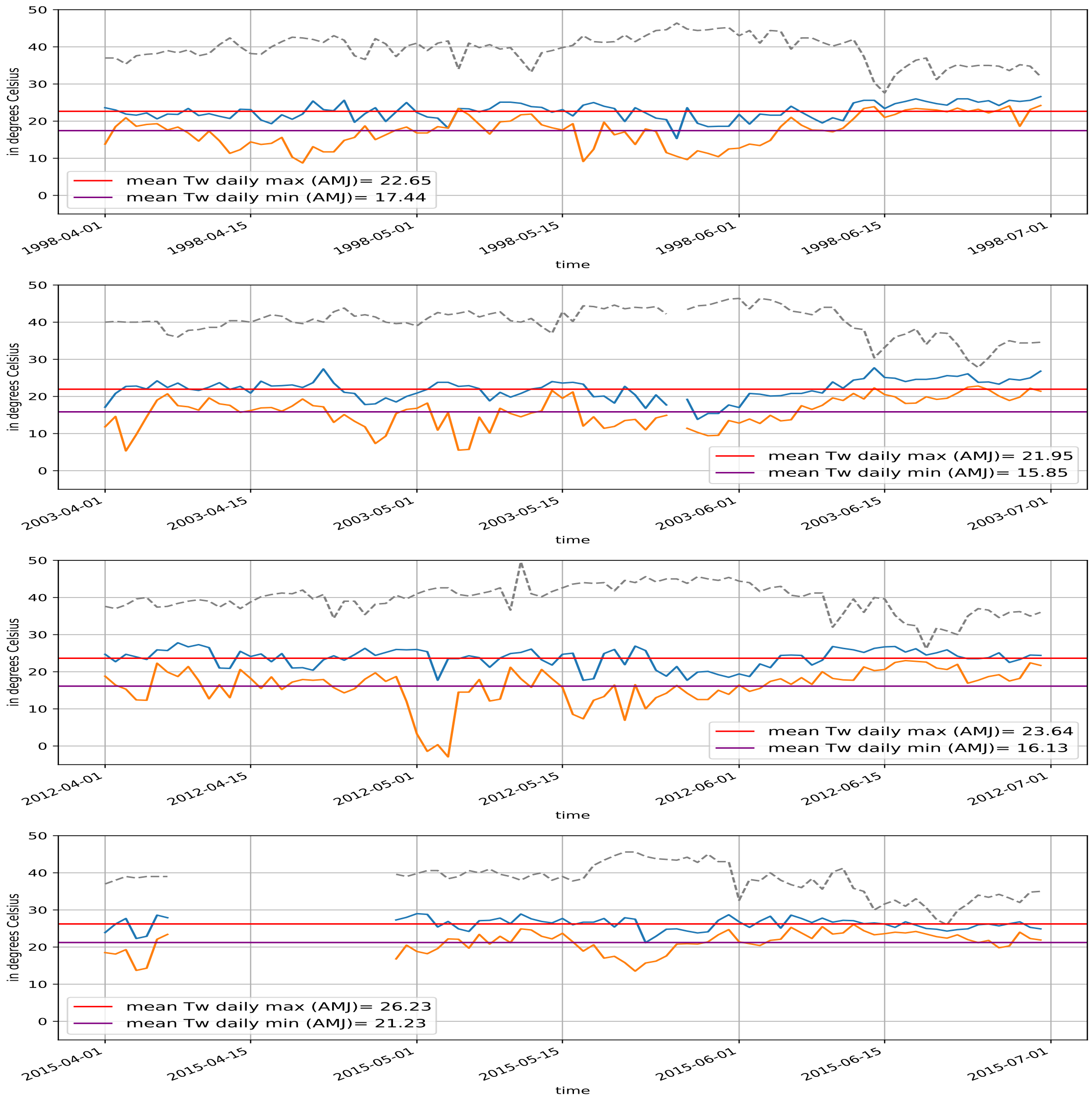

Figure 4.13: Daily maximum and minimum wet bulb temperatures at station Ramagundam for the years 1998, 2003, 2012, 2015 (top to bottom). Values were plotted for the months April, May and June. The blue and orange line in each plot indicates maximum and minimum wet bulb temperatures respectively. Daily maximum dry bulb temperature is shown in dashed grey line. Mean daily maximum and daily minimum wet bulb temperatures for the months April, May and June for the years are indicated by red and violet lines respectively.

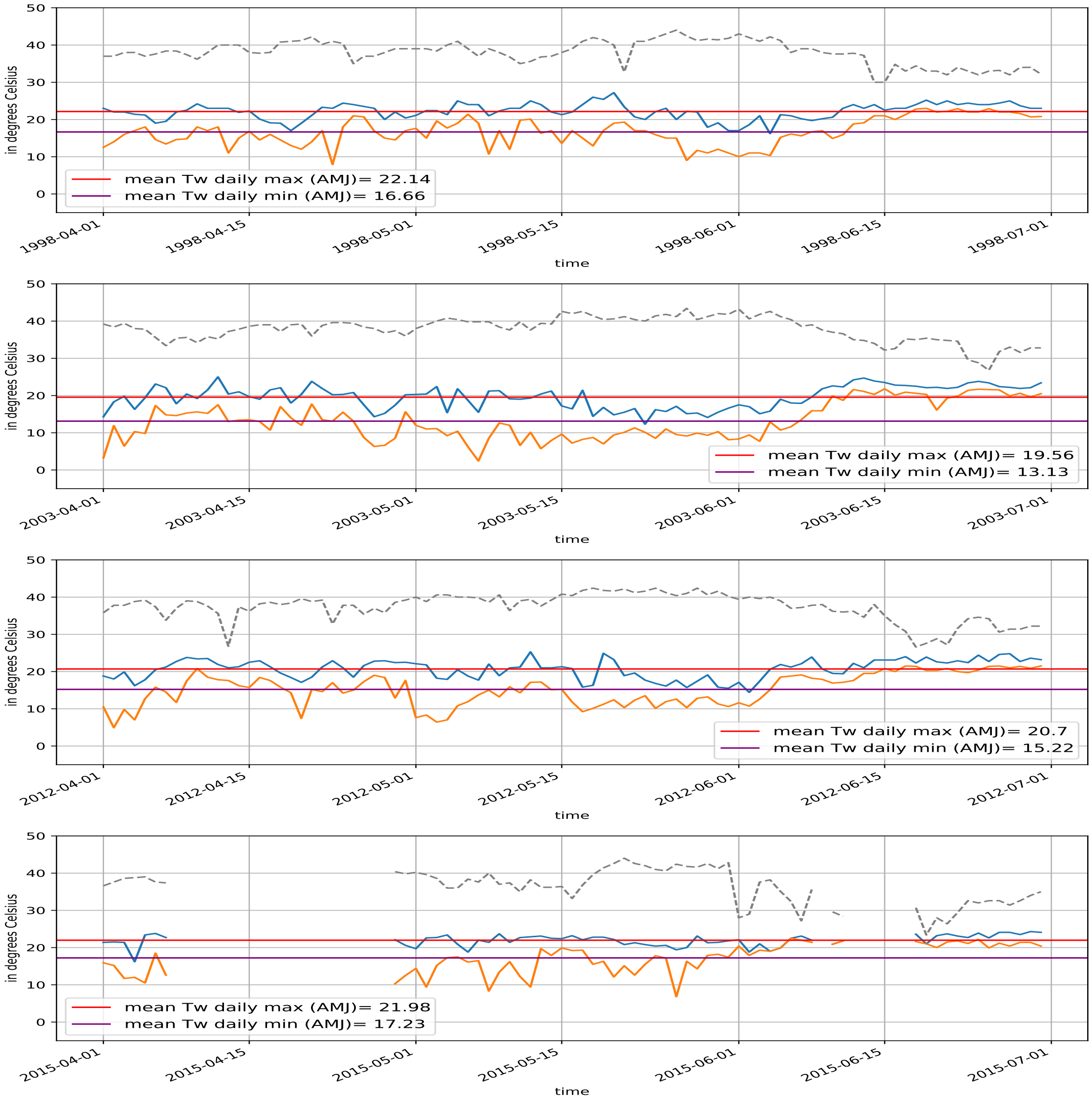

Figure 4.14: Daily maximum and minimum wet bulb temperatures at station Hyderabad for the years 1998, 2003, 2012, 2015 (top to bottom). Values were plotted for the months April, May and June. The blue and orange line in each plot indicates maximum and minimum wet bulb temperatures respectively. Daily maximum dry bulb temperature is shown in dashed grey line. Mean daily maximum and daily minimum wet bulb temperatures for the months April, May and June for the years are indicated by red and violet lines respectively.

4.3.2 Non heat wave years

Coastal stations

Diurnal variation in wet bulb temperatures in the figure 4.15 and 4.16 were much lesser for both Machilipatnam and Kakinada compared to heat wave years. At Kakinada, both daily maximum and daily minimum values were observed to be closer to the mean values with a departure of about 2° to 3° Celsius. Whereas for Machilipatnam both maximum and minimum temperatures were comparatively farther away from the mean values with a departure of around 8° Celsius.

Daily dry bulb temperatures during these years were less compared to that of heat wave years. The number of days with dry bulb temperature values crossing 40° Celsius are also less. Even though there is variation in dry bulb temperatures, the diurnal changes in wet bulb temperatures are much lower than in heat wave years, suggesting that the heating is more local in nature, and does not involve large changes in specific humidity.

Inland stations

The daily maximum and minimum wet bulb temperatures at Hyderabad and Ramagundam are shown in Figs. 4.17 and 4.18. The diurnal

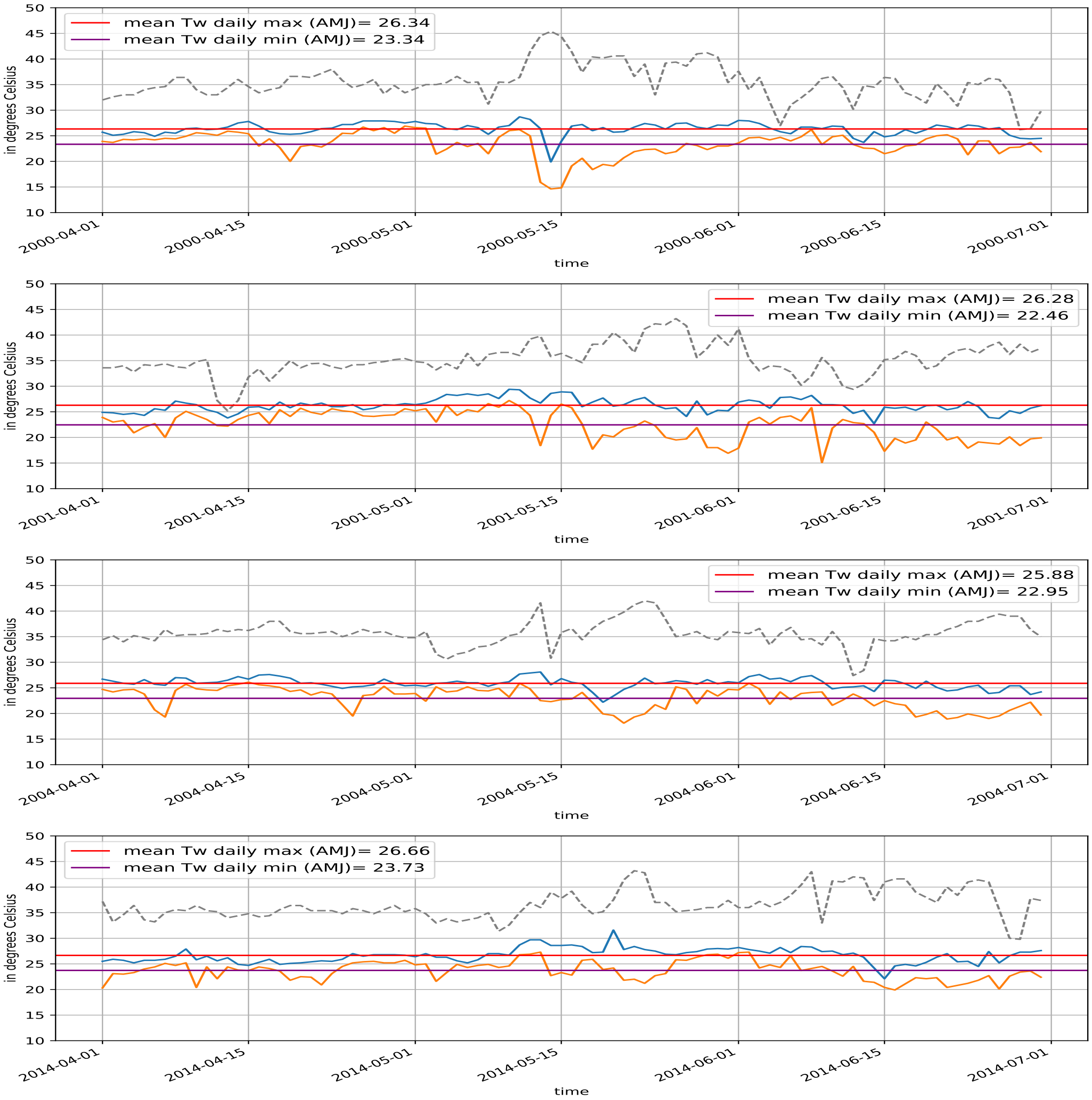

Figure 4.15: Daily maximum and minimum wet bulb temperatures at Machilipatnam station for the years 2000, 2001, 2004 and 2014 (top to bottom). Values were plotted for the months April, May and June. The blue and orange line in each plot indicates maximum and minimum wet bulb temperatures respectively. Daily maximum dry bulb temperature is shown in dashed grey line. Mean daily maximum and daily minimum wet bulb temperatures for the months April, May and June for the years are indicated by red and violet lines respectively.

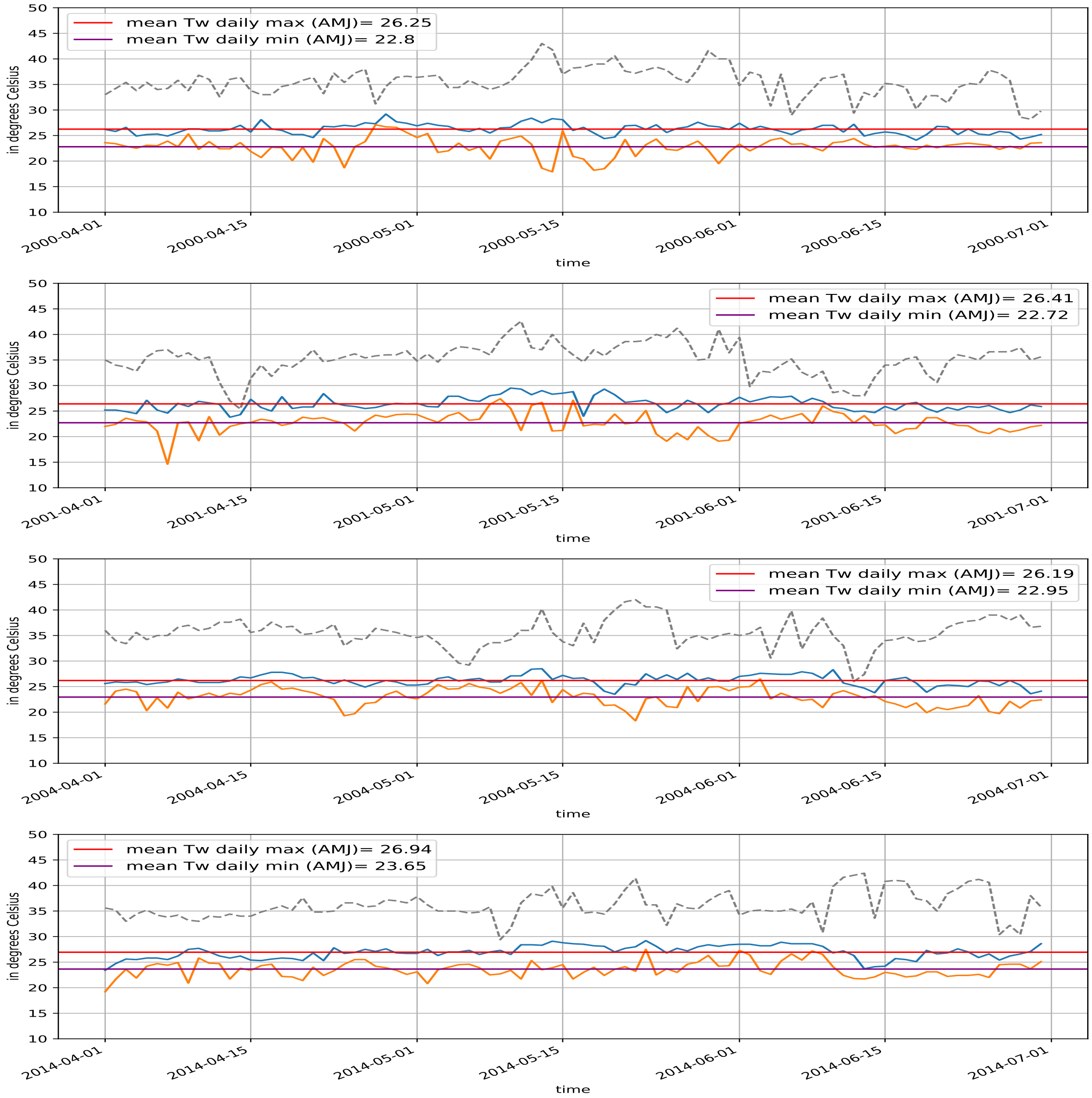

Figure 4.16: Daily maximum and minimum wet bulb temperatures at Kakinada station for the years 2000, 2001, 2004 and 2014 (top to bottom). Values were plotted for the months April, May and June. The blue and orange line in each plot indicates maximum and minimum wet bulb temperatures respectively. Daily maximum dry bulb temperature is shown in dashed grey line. Mean daily maximum and daily minimum wet bulb temperatures for the months April, May and June for the years are indicated by red and violet lines respectively.

variability of wet bulb temperatures is not different from that observed during heat wave years, suggesting that the variations in specific humidity is not linked to increases in temperature. Thus, we conclude that coastal stations have much lower variability of wet bulb temperatures in the absence of dry bulb temperature variability, whereas inland stations do not exhibit any such relationship.

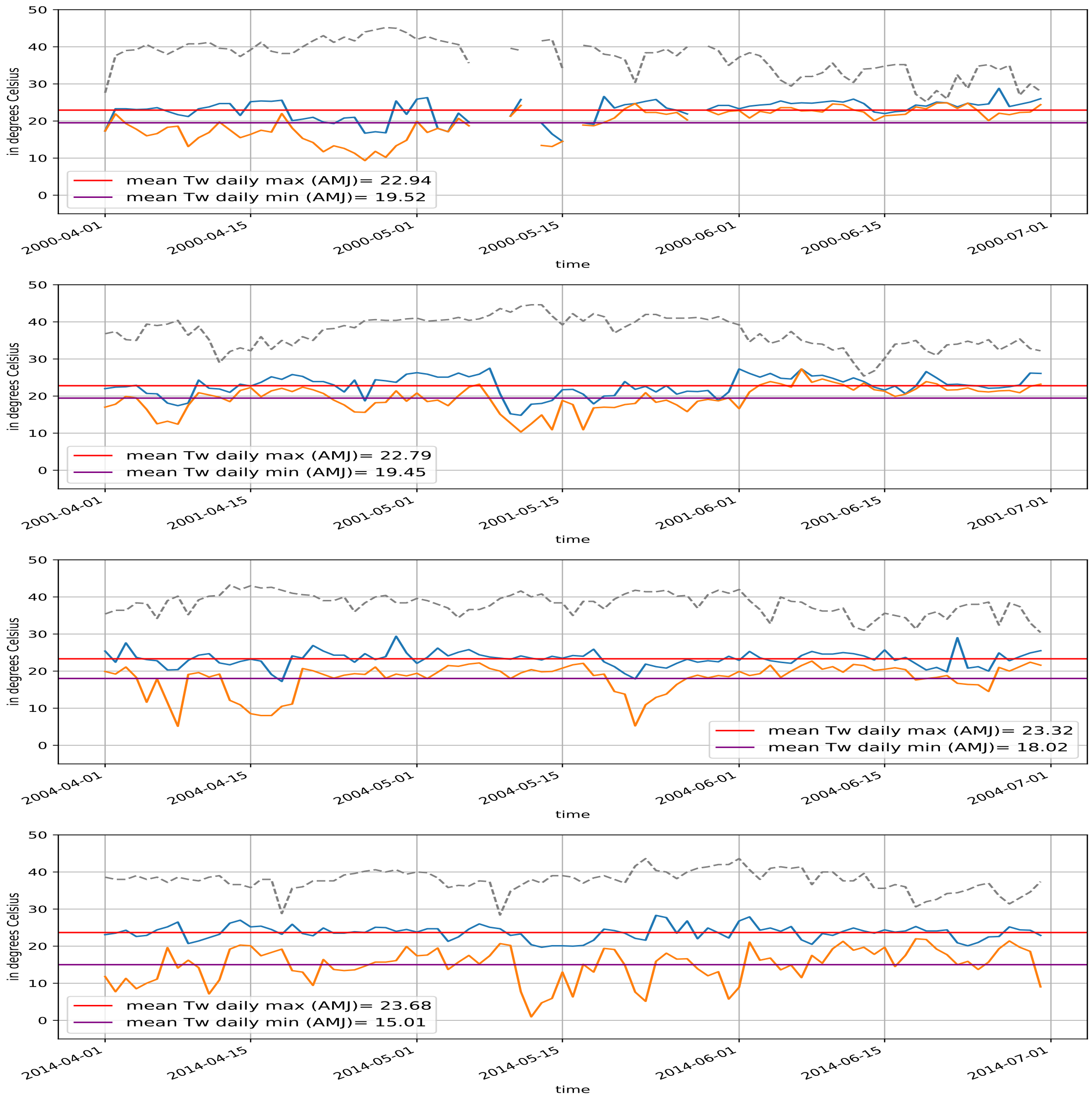

Figure 4.17: Daily maximum and minimum wet bulb temperatures at Ramagundam station for the years 2000, 2001, 2004 and 2014 (top to bottom). Values were plotted for the months April, May and June. The blue and orange line in each plot indicates maximum and minimum wet bulb temperatures respectively. Daily maximum dry bulb temperature is shown in dashed grey line. Mean daily maximum and daily minimum wet bulb temperatures for the months April, May and June for the years are indicated by red and violet lines respectively.

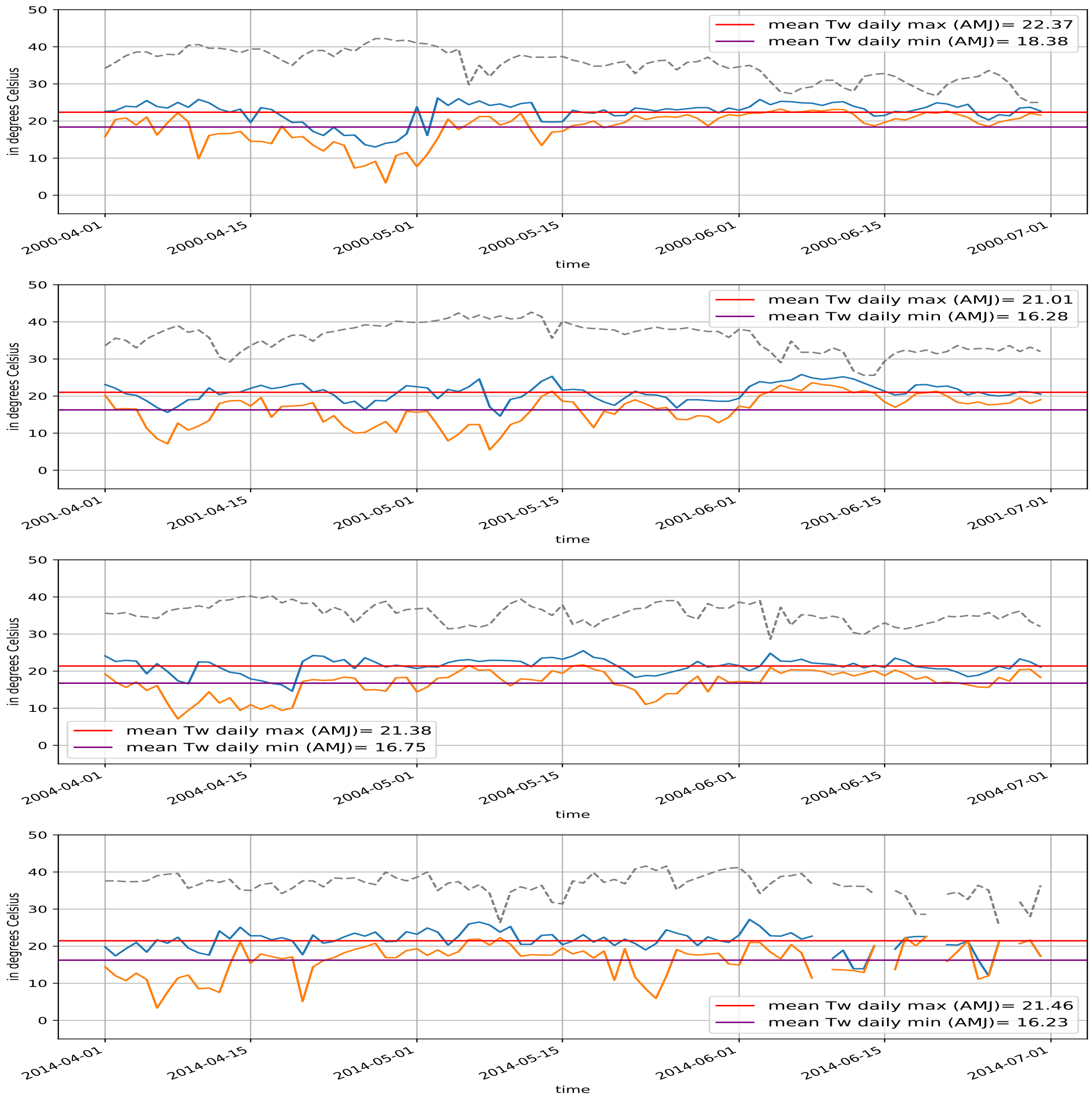

Figure 4.18: Daily maximum and minimum wet bulb temperatures at Hyderabad station for the years 2000, 2001, 2004 and 2014 (top to bottom). Values were plotted for the months April, May and June. The blue and orange line in each plot indicates maximum and minimum wet bulb temperatures respectively. Daily maximum dry bulb temperature is shown in dashed grey line. Mean daily maximum and daily minimum wet bulb temperatures for the months April, May and June for the years are indicated by red and violet lines respectively.

Chapter 5

DISCUSSION

Ratnam et al. (2016) attributed heat waves over the east coastal regions to the anomalous circulation regimes in the tropical pacific. This in response alters the low level wind patterns, owing to further changes in the weather systems. Warm air advecting from the north-west India accentuates surface layer heating at the east coast. The land and sea breezes are sources for temperature regulations near the coast. During heat waves, sea breezes weakens as part of altered wind regimes and leaves the land completely dry without regulating the high temperature levels that onsets over these region during summer. This is evident from the Figs. 4.11 and 4.12. Where we find there is a dipping of wet bulb temperatures when the dry bulb temperatures falls into the category of heat waves (described by IMD).

Heat related deaths during the 2015 heat waves over India were around 2422, of which about more that 1422 deaths were reported from the state Andhra Pradesh (Guleria, 2018). The daily maximum temperatures did in fact cross 45° Celsius, refer Fig. 4.11, 4.12 and 4.13 for the year 2015. It is also important to note that the daily maximum temperature of 40° Celsius was attained, that is about a rise of 10° Celsius occurred within a span of around three days at Machilipatnam and Kakinada. Although similar variations in dry bulb temperature were also exhibited in the rest of the years we chose as heat wave years, the number of deaths reported in these years were never as high as that reported in 2015.

If we were to look at 2015 heat wave events based on extreme wet bulb temperatures, we could see that the daily maximum wet bulb temperatures barely crossed 28° Celsius and the number of days where wet bulb temperature were above the mean value is also small, ref Figs. 4.11, 4.12 and 4.13 for the year 2015. However wet bulb temperature diurnal variations for these years provide a better health related perspective. To discuss further regarding health is beyond the scope of this thesis. However we highlight the necessity to include wet bulb temperature variations while discussing heat waves over these regions.

Chapter 6

SUMMARY AND CONCLUSION

Indian land mass during the pre-monsoon period, when there is a direct solar heating from the transitioning sun towards the North, together with its geographical location (near to equator) where there is less temperature gradient makes these regions vulnerable to heat wave episodes. Identifying heat wave events with daily maximum dry bulb temperature extremes alone make most parts of the Indian subcontinent highly vulnerable. However it is evident from recent studies that it is not just temperature that contributes to such adverse impacts on community in question, other factors (meteorological and non meteorological aspects) adds to the impacts of matter at hand. IMD categorises heat waves on the basis of daily maximum temperature alone, it does not take into account for all other factors that affects human health on a daily scale yet alone account for the cumulative impacts of heat stress. Hence ambiguities in understanding the entire heat wave episodes and by extension less efficient adaptation strategies.

In this thesis, we looked at the pattern of dry bulb temperature, specific humidity and wet bulb temperature in the region under study over a period of 25 years (1995-2020). The selected stations were grouped into two groups: coastal and inland stations. We observed the months where these variables peaked and showed higher variability. We found the pre monsoon period having a higher chances of positive extreme for dry bulb temperature. Wet bulb temperature on the other hand showed a higher chances of extremes during April-June. We observed a link between specific humidity and wet bulb temperature.

We then identified the wet bulb temperature patterns during the warmer months across the three states Andhra Pradesh, Telangana and Tamil Nadu. Which then was used to characterise heat waves across these regions. Since the scientific community understood that heat waves needs to be addressed in regard to moisture content along with dry bulb temperatures, studies thus concentrated on threshold levels and the excess of a metrics above such a limit, which is usually considered to be 35 °C.

However from this study we conclude that it is not just the wet bulb temperature exceeding such a limit that needs to be accounted but also the variations of variables require to be considered. Meaning, the climatological mean provide an understanding of what values of a variable (here, wet bulb temperature) the community is accustomed to (that is of course excluding the health conditions). An unprecedented changes in climate conditions causes distress (often influencing cellular and humoral immunity) (Xu et al., 2014). Thereby the variations either above the mean and below the mean needs to be evaluated.

We found that heat waves over East coast regions are linked to changes in specific humidity which thus influences the diurnal changes of dry and wet bulb temperatures. It is thus implied that a combination of dry bulb temperature and wet bulb temperature changes is necessary while describing heat wave events across east coast stations.

We understand that our study is highly region specific. But it also put light into the need for more such studies in order to make the heat action plan for different states more efficient. Since heat wave impacts are highly predicated on the community and region. We hence try to convey that monitoring changes in dry bulb temperature to disseminate heat wave warnings for entire India is insufficient, since impacts and effects are region specific.

Appendices

Chapter A

Python script for the calculation of wet bulb temperature

```
#!/usr/bin/env python
# coding: utf-8

# In[1]:



#importing libraries

import numpy as np
import xarray as xr
import matplotlib.pyplot as plt
import netCDF4
import pandas as pd
from metpy.units import units
from metpy import constants
from scipy.optimize import fsolve, root
```

```
from scipy import optimize


# In[2]:


# station data vishakaptnam navy netcdf file

file = xr.open_dataset(’hadisd.3.1.1.202006p_19310101-20200701_431490-99999.nc’)


# In[3]:


# removing nan values

my_temperature=file.temperatures
my_temperature[my_temperature==my_temperature.flagged_value]=np.nan
my_dewpoint=file.dewpoints
my_dewpoint[my_dewpoint==my_dewpoint.flagged_value]=np.nan
my_pressure=file.stnlp
my_pressure[my_pressure==my_pressure.flagged_value]=np.nan

mask=np.logical_and(~xr.ufuncs.isnan(my_temperature).values,~xr.ufuncs.isnan(my_pressure).values)
mask=np.logical_and(mask, ~xr.ufuncs.isnan(my_dewpoint).values)


# In[4]:

```

```

# modified variables without nan values

valid_dewpoint=file.dewpoints[mask]
valid_temperature=file.temperatures[mask]
valid_pressure=file.stnlp[mask]


# In[5]:


triple_point=273.15
temperature=valid_temperature + triple_point # converted to kelvin
pressure=valid_pressure*100   # converted to pascals
dewpoint_temperature=valid_dewpoint + triple_point  #converted to kelvin


# In[6]:


""" using constants from metpy """

cpd=constants.dry_air_spec_heat_press
latent_heat=constants.water_heat_vaporization

print(cpd)
print(latent_heat)

cpd_lv = np.array((cpd/latent_heat).to(’1/degK’)).item()
cpd_lv
```

```


# In[7]:


""" defining functions for saturation vapour pressure and saturation specific humidity
at temperture
saturation vapour pressure is found using the Hyland and Wexler formulation
using the formula
Log es =  -0.58002206e4 / T                [4]
              + 0.13914993e1
              - 0.48640239e-1 T
              + 0.41764768e-4 T^2
              - 0.14452093e-7 T^3
              + 0.65459673e1 Log(T)
with temperature in kelvin; saturation vapour pressure is obtained in pascals



"""
def saturation_vapour_pressure(temperature):
  return np.exp((-0.58002206e4 / temperature) + 0.13914993e1 -(0.48640239e-1*temperature)
  +(0.41764768e-4*(temperature**2)) - (0.14452093e-7*(temperature**3))
  + 0.65459673e1*np.log(temperature))

```

```
print(saturation_vapour_pressure(temperature))  # in pascals


# In[8]:


"""
saturation specific humidity is obtained using the formula
saturation specific humidity=E*es/pressure-es
where epsilon E =621.97
specific humidity is essentially dimensionless ; if to compare with another formula check with g/kg
pressure is in pascals and es is calculated in pascals
"""

def saturation_specific_humidity(temperature,pressure):
  es=saturation_vapour_pressure(temperature)  # in pascals
  return (621.97*es)/(pressure-es)

specific_humidity=saturation_specific_humidity(dewpoint_temperature,pressure)  #specific humidity at dewpoint

print(saturation_specific_humidity(dewpoint_temperature,pressure))


# In[9]:


"""
the psychrometric equation is solved for obtaining tw values
(T-Tw)*cpd/lv=ws(Tw)-w
```

```
here w is the ambient mixing ratio calculated at dewpoint temperature and pressure
ws is the saturation mixing ratio at wet bulb temperature
"""

def wet_bulb(tw, temperature, specific_humidity, pressure):
  return (temperature-tw)*(cpd_lv)   + (
          specific_humidity - saturation_specific_humidity(tw, pressure))

my_tw = root(wet_bulb, dewpoint_temperature.values,
             args=(temperature.values, specific_humidity.values, pressure.values),
             method='krylov'
            )
my_tw

#wet_bulb in kelvin
```

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Abstract

We studied dry bulb temperature, specific humidity and wet bulb temperature patterns across 12 stations along the east coast of India. Station data together with ERA5 data are used to analyse the dynamics of these variables. We focus on pre-monsoon period for characterising heat wave events. We find that these events are linked to large changes in specific humidity in the coastal stations. The study established that the daily maximum wet bulb temperatures were quite stable for heat wave years whereas variations in daily minimum temperatures caused by the changes in specific humidity had a much larger role. In contrast, the difference between changes in maximum and minimum wet bulb temperatures in inland stations is much smaller. We thus suggest that heat exposure during heat waves is very different in these two kinds of situations and has implications for preventive measures during heatwaves.