Too Hot!
An Epidemiological Investigation of Weather-Related Mortality in Rural India

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This thesis is dedicated to my mother.
You are my inspiration.
Life is like weather - sometimes hot, sometimes cold and sometimes windy...

-Vijendra Ingole
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Abstract

Background

Most environmental epidemiological studies are conducted in high-income settings. The association between ambient temperature and mortality has been studied worldwide, especially in developed countries. However, more research on the topic is necessary, particularly in India, given the limited evidence on the relationship between temperature and health in this country. The average global temperature is increasing, and it is estimated that it will go up further. The factors affecting vulnerability to heat-related mortality are not well studied. Therefore, identifying high-risk population subgroups is of particular importance given the rising temperature in India.

Objectives

This research aimed to investigate the association of daily mean temperature and rainfall with daily deaths (Paper I), examine the relationship of hot and cold days with total and cause-specific mortality (Paper II), assess the effects of heat and cold on daily mortality among different socio-demographic groups (Paper III) and estimate the effect of maximum temperature on years of life lost (Paper IV).

Methods

The Vadu Health and Demographic Surveillance System (HDSS) monitors daily deaths, births, in-out migration and other demographic trends in 22 villages from two administrative blocks in the rural Pune district of Maharashtra state, in western India. Daily deaths from Vadu HDSS and daily weather data (temperature and rainfall) from the Indian Meteorological Department were collected from 2003 through 2013. Verbal autopsy data were used to define causes of death and classified into four groups: non-infectious diseases, infectious diseases, external causes and unspecified causes of death. Socio-demographic groups were based on education, occupation, house type and land
ownership. In all papers, time series regression models were applied as the basic approach; additionally, in Paper III, a case-crossover design and, in Paper IV, a distributed lag non-linear model (DLNM) were used.

**Results**

There was a significant association between daily temperature and mortality. Younger age groups (0-4 years) reported higher risk of mortality due to high and low temperature and heavy rainfall. In the working age group (20-59 years), mortality was significantly associated only with high temperature. Mortality due to non-infectious diseases was higher on hot days (>39°C), while mortality from infectious diseases and from external causes were not associated with hot or cold days. A higher heat-related total mortality was observed among men than in women. Mortality among residents with low education and those whose occupation was farming was associated with high temperature. We found a significant impact of high temperature on years of life lost, which confirms our results from the previous research (Papers I-III).

**Conclusion**

The study findings broadened our knowledge of the health impacts of environmental exposure by providing evidence on the risks related to ambient temperature in a rural population in India. More specifically, the study identified vulnerable population groups (working age groups, those of low education and farmers) in relation to high temperature. The adverse effect of heat on population is preventable if local human and technical capacities for risk communication and promoting adaptive behavior are built. Furthermore, it is necessary to increase residents’ awareness and prevention measures to tackle this public health challenge in rural populations.

**Keywords**

Temperature, heat and cold, mortality, education, socioeconomic status, occupation, rural population, India.
Original Papers

This thesis is based on the following papers. Papers I and II were published in open access journals, so no permission was required to reprint. Papers III and IV are manuscripts.


**Abbreviations**

- **CI**: Confidence Interval
- **DF**: Degree of Freedom
- **DLNM**: Distributed Lag Non-linear Model
- **DOW**: Day of Week
- **FRA**: Field Research Assistants
- **GAM**: Generalized Additive Model
- **GLM**: Generalized Linear Model
- **HDSS**: Health and Demographic Surveillance System
- **ICD**: International Classification of Diseases and Related Health Problems
- **IMD**: Indian Meteorological Department
- **INDEPTH**: International Network for the Demographic Evaluation of Populations and their Health
- **IPCC**: Intergovernmental Panel of Climate Change
- **KEM**: King Edward Memorial
- **LMIC**: Low and Middle Income Countries
- **NCD**: Non-Communicable Diseases
- **NOAA**: National Oceanic and Atmospheric Administration
- **OR**: Odds Ratio
- **RR**: Relative Risk
- **SES**: Socio-Economic Status
- **VA**: Verbal Autopsy
- **VRHP**: Vadu Rural Health Program
- **WHO**: World Health Organization
- **YLL**: Years of Life Lost
Summary in Swedish

Sammanfattning

Bakgrund

Kunskaper inom det miljömedicinska forskningsområdet inhämtas i huvudsak från höginkomstländer idag, trots stora skillnader i livsbetingelser och exponeringar i dessa områden jämfört med i fattigare delar av världen. Sambanden mellan lufttemperatur och dödlighet har noggrant kartlagts i höginkomstländer, men i mindre utsträckning i utvecklingsländer. Det finns ett ytterligare behov av forskning i länder såsom Indien, där extremt höga temperaturer återkommande uppmäts. Speciellt viktigt är det att inhämta nya kunskaper i dessa regioner för att bättre förstå konsekvenserna av en förändrad klimatsituation. Bestämningsfaktorer för känslighet och sårbarhet i relation till varierande temperaturer i dessa regioner saknas ofta. Det är därför av stor vikt att identifiera faktorer som sammankopplas med ökad risk för sjukdom och dödsfall till vid temperaturextremer i dessa befolkningar.

Syfte

Det här forskningsprojektet syftade till att kartlägga sambanden mellan: dödsfall och dygnets temperatur och nederbörd (arbete I), dödlighet och orsaksspecifik dödlighet och extrema temperaturer (arbete II), hur dödlighet i relation till värme och kyla påverkas av sociala faktorer (arbete III), samt hur mycket temperaturen uppskattas påverka antalet förlorade levnadsår (arbete IV).

Metoder

Vadu hälsodemografiska monitoreringssystem (Vadu HDSS) övervakar löpande födsslag, dödsfall, in- och utflyttning och andra demografiska trender i 22 samhällen i två administrativa områden på landsbygden i distriktet Pune i regionen Maharashtra i västra Indien. Dödsfall på dygnssnivå inhämtades från Vadu HDSS för perioden 2003-2013. Uppmätta dygnsvärden av utomhustemperatur och nederbörd inhämtades för samma period från Indiens meteorologiska institut.

**Resultat**


**Slutsats**


**Nyckelord**

Temperatur, värme, kyla, dödsfall, utbildning, socioekonomi, yrke, landsbygd, Indien.
व्यक्तिभूति
पालकधर्म
पालकधर्म भारतीय का ज्ञानदाता अध्ययन उच्च आय वाली परिस्थितियों में किया गया है। परिवेश के तापमान और मृदुलता के बीच के संबंध का अध्ययन मुनियार भारत में, विशेष रूप से भारत में, जहां तापमान और स्वास्थ्य के बीच के संबंध को सीमित प्रमाण के रूप में देखा गया है। अभिनव तापमान बढ़ रहा है और अनुमान है कि यह और अधिक बढ़ेगा। तापमान-संबंधी मृदुलता के प्रति अतिसंवेदनशीलता पर आस पर आस करने वाले कारकों पर ध्यान करने का अधिकतम तापमान का अनुमान लगाना (पेपर IV)।

अध्ययन प्राप्ति:

अध्ययन प्राप्ति हृदय स्वास्थ्य और जनसंभावनीय निगरानी प्राप्ति (एडीएसएस), पश्चिमी भारत के महाराष्ट्र राज्य के ग्रामीण पुरूष जिले में दो तारखके से २२ गांवों में दैनिक मौत, जम, गैर के अंदर - वह स्वास्थ्य और अन्य जनसंभावनीय परिवर्तनों पर नज़र रखती है। २००३ से २०१३ के दौरान हड़प्पा दूरदर्शण दूरदर्शन, दैनिक पत्रों की संख्या और भारतीय मौसम विषयों से दैनिक मौसम के अंकों को (तापमान और ध्वनि) उपयोग किया गया। मौसमी निवेश इंटरनेशनल का उपयोग मृदुलता का कारण निर्धारित करने के लिए किया गया और इसको तारख में से ज्यादा किया गया - नौ-संबंधकों रोग, संक्रमक रोग, मृदुलता के सावधानी कारण और अन्तिदिक कारण सामाजिक जनसंभावनीय समुदाय शिक्षा, ज्वालास्वास्थ्य, भाषा का प्रकाश और पुरुष के स्वास्थ्य से आधार पर बनाए गए थे। सभी पेपरों में हड़प्पा दूरदर्शन मॉडल को बुनियादी नज़रें के तौर पर लाया किया गया था; और पेपर III में केस-क्रॉस-ओवर डिजाइन और पेपर IV में हड़प्पा दूरदर्शन लैंग-लीमिटेड मॉडल (डीएसएसएस) का उपयोग किया गया था।

परिणाम

परिणाम दैनिक तापमान और मृदुलता के बीच उल्लेखनीय संबंध है। हालांकि आयु के समूहों में (०-४ वर्ष) अधिक और (५-९ वर्ष) अधिक तापमान और भारी वर्ष के कारण मृदुलता का जोखिम अधिक पाया गया। इसके साथ में, पालकधर्म के बीच उल्लेखनीय संबंध (२००३ से २०१६) रोग, गैर-संबंधकों रोग, संक्रमक रोग, मृदुलता के साथ जुड़ा नहीं रहा। गैर-संबंधकों रोग का अधिकतम होना वाली मीटर की अंधकार या ध्वनि (३९ डिग्री से अधिक) जबकि संबंधकों रोग के कारण इलाज और आरोग्य के साथ तापमान होने वाली मीटर की जंतुता में दो दिनों में जोखिम नहीं रहा। कुल मृदुलता दर में गैर-संबंधकों रोगों की घटना में अधिक हो गई। कच्ची भाषा वालों के विवाहित और खेती का व्यवसाय करने वालों में मृदुलता दैनिक तापमान से संबंधित पाया गया। गैर-संबंधकों रोग के कारण नज़रें (नाबर ऑफ डायरेक्ट लॉस्ट ड्रीम ड्रीम्स) का उपयोग किया गया था।

उपसंहार

उपसंहार के लिए अध्ययन एवं खोजों के नतीजों के आधार पर साहित्य व्यवसाय के परिवर्तन, अन्तर्राष्ट्रीय अन्तराष्ट्रीय स्वास्थ्य और शासन, जनसंभावनीय मौसम और संबंधित पश्चात्तापित परिस्थितियों के साथ जोड़ देने की जरूरत है। इससे से संबंधित व्यक्ति, अन्तर्राष्ट्रीय अन्तर्राष्ट्रीय स्वास्थ्य और शासन, जनसंभावनीय मौसम और संबंधित परिस्थितियों के साथ जोड़ देने की जरूरत है।
Chapter 1: Introduction

This research explores the effects of ambient temperature on health in a rural setting in western India. This section provides the background to the study with a global overview of climate change and health. It also highlights the need to study the vulnerability of the rural population to environmental exposure. The section then reviews the existing evidence on the effects of exposure to temperature on human health. The thermophysiology of heat and human health, i.e. physiological mechanisms, is explained. This is followed by the epidemiology of temperature-related mortality. Then, a section on social and demographic factors and their vulnerability to ambient temperature follows. Finally, the section ends with the study objectives of the research conducted.

Background

Global climate change is expected to cause an increase in the frequency and intensity of heat waves [1]. Climate change and its potential impacts on health are increasingly drawing attention in both developed and developing countries. The health of the population depends on optimal functioning of the biosphere’s ecological and physical systems, also referred to as life-support systems, which, in turn, are influenced by both natural and anthropogenic activities. However, the increasing carbon emissions and air pollution and the accompanying global warming and increase in natural disasters may affect these activities [1, 2]. Global climate change is expected to affect human health via different pathways, scales and directness, as well as time lags. The more direct impacts on health include those due to changes in exposure to extreme weather conditions (heat and cold waves, storms and floods), and indirect effects include changing distributions of infectious disease vectors and displacements of populations [3]. However, this evidence base is largely from developed countries. This is especially due to the lack of population data and priority given to such research in low- and middle-income countries [4].
India represents one-sixth of the world’s population, which is supported on 1/50 of the world’s land and 1/25 of the world’s water [5]. With an increasing population (~1.2 billion) and rate of urbanization, India is undergoing enormous change. Additionally, climate change is expected to pose an overwhelming stressor that will magnify existing health threats. India has a rapidly growing economy. About 64% of the population are in the working age group; more than 90% of these people work in the informal economy, mainly in the small- and medium-size agricultural sector and services [6]. About 73% of the rural population in India does not have access to fresh water, and 74% do not have sanitary toilets. Potable water availability in India is also a concern; available water is expected to decrease from 1,820 m³ per capita to <1,000 m³ by 2025 in response to the combined effects of population growth and climate change [7]. The Intergovernmental Panel of Climate Change (IPCC) special report on extreme events and disasters stated that the average as well as the minimum and maximum temperatures in India are expected to increase in the future [1]. India has experienced a series of heat waves in the past, which reveals their potential for impacts on mortality. In 1998, the state of Odisha faced an unprecedented heat wave (45.4-47.6°C) situation, as a result of which 2042 people lost their lives [8]. In another instance, 1421 people were killed in Andhra Pradesh from a heat wave in 2003 [9]. Effects included hospitalization because of heatstroke, suffering of livestock and severe drought in some regions that affected both health and agriculture [9]. Research reported 1344 excess deaths during the 2010 heat wave in the city of Ahmedabad, India [10]. The western states in India show an increase in the frequency of high heat-stress events that occur regularly over a period of a couple of weeks [11]. Many of the predicted effects of climate change (heat waves, floods, etc.) are likely to become a reality in India and indeed have also been experienced recently. The summer of 2016 was the hottest summer on record in India, with the highest ever-recorded temperatures (51°C) [12].

Low- and middle-income countries are responsible for only a small percentage of global greenhouse gas emissions; however, the adverse health effects associated with climate change will likely fall
disproportionately on their populations [13]. In India, agricultural workers, mainly men, work long hours in the fields and are exposed to high temperatures. There are several other sectors that are yet to be explored in terms of the effect of high temperatures on health. There are many interwoven issues, including the existing laws and guidelines, regulatory mechanisms, the relationship between the management and workers and the socio-economic conditions of the workers, which compel them to undertake such work in spite of adverse conditions [14]. Some groups working in rural and semi urban-based industries, such as ceramics and pottery and iron works, are potentially at risk of high heat exposure during peak summer months. There is no formal regulatory guideline yet available in the country to determine the maximum limit of exposure of the workers [15, 16].

**Thermophysiology**

The physiological basis for the effects of heat on humans is well understood. The body has a sophisticated thermoregulatory system to maintain its temperature. It produces heat through metabolic activity—the higher the level of activity, the higher the heat produced. Of the total energy generated by the body, only a small proportion is used to perform mechanical work, while the greatest proportion is released as heat. If heat generation and heat input are greater than heat output, the body temperature rises and vice versa. When the ambient temperature reaches or exceeds the human core temperature of 37°C, there are potentially adverse physiological effects, posing risk to some organ systems and also making it progressively harder to maintain work productivity [17]. The impact of weather variability on human health, particularly all-cause mortality, has been studied extensively. Relatively little is known, however, about physiological and cultural adaptation to climate change [18].

**Epidemiology of temperature-related mortality**

Exposure to hot and cold temperatures has long been recognized as a threat to human health, and, in the last decade, this association has been intensely studied by the research community [19].
Epidemiological studies have shown the temperature-mortality relationship to be either J-, U-, or V-shaped, indicating increased risk in cold and hot weather [20]. Many diseases are influenced by the ambient weather condition and/or display strong seasonality [19]. Hot and cold temperatures significantly increase mortality rates around the world, but which temperature indicator is the best predictor of mortality is not known. The increase of interest in this area of research has been encouraged by episodes of extreme weather, characterized by an exceptional increase in mortality and other adverse health outcomes. Mostly, these known events have been reported as public health disasters, for example the Chicago heat waves in July 1995 or those in France during August 2003 [21, 22]. A number of epidemiological studies have examined high temperatures in relation to all-cause and cause-specific (e.g. non-accidental) deaths and to other health outcomes such as emergency visits and hospital admissions [23, 24]. In fact, heat waves are the biggest cause of weather-related fatalities in many cities, responsible for more deaths annually than any other form of extreme weather events (e.g. floods, storms) [25]. Ultimately, the vulnerability to heat and cold exposure is an individual phenomenon; researchers have found variations from one person, neighbourhood, city and region to the next [26, 27]. Living and working in extreme climatic conditions constitutes an obvious potential risk to health [28].

A years of life lost is an indicator of premature mortality that accounts for the age at which deaths occurred by giving greater weight to deaths at younger ages [29]. A years of life lost is a measure of disease burden that uses the life expectancy at death [29]. Overall, most studies have examined temperature impacts in terms of excess deaths or mortality risks [30]. Assessing the temperature impact on years of life lost is more appealing to policymakers when communicating the actual burden of temperature-related mortality. It is also more relevant from a health economics perspective, especially in relation to projection of health burdens and associated costs under scenarios of future climatic change [29]. Furthermore, many low- and middle-income countries have strong underlying social and population dynamics, such as the
rapid aging of the population, an increase in urbanization, demographic transition and change in disease and mortality patterns, e.g. an increase in non-communicable diseases [31]. If the association between temperature and mortality were high only in the elderly with a short life expectancy, this would potentially be seen as less of a public health concern [29, 31-34].

**Socio-demographic factors and health impacts of temperature**

In order to effectively implement preventive measures such as early warning systems and organizational changes in the health sector during heat waves, it is important to identify the groups most susceptible to waves of heat and cold [35, 36]. Heat-related mortality risk differs by age and sex. The elderly are more vulnerable to heat than younger people because of changes in their thermoregulatory system [18]. There is a research gap in the age group at which vulnerability increases in different populations (climate, culture, infrastructure, etc.) [18]. Research has consistently shown that heat waves and high ambient temperatures affect the elderly population to a greater degree than the younger population [35]. However, the evidence for other age groups is more difficult to interpret [37]. Many studies have shown that women are affected by heat more than men, but a few other studies have found no such difference [18]. On the other hand, men appear more at risk of dying from a heat stroke because they are more likely to be active in hot weather [38]. Commonly, work-related heat exposure, thermal and ambient temperature and their physiological impact are associated with social and demographic parameters [39]. In many studies, it has been shown that increasing temperatures also affect the working population and lead to more work-related injuries. In many areas of tropical countries, the maximum temperature during the summer is around 40°C, and even this is increasing over time. The population of western India confronts frequent heat emergencies, with high risk of mortality and morbidity [40]. An additional 3-5°C will make agriculture and construction work very difficult during the hottest periods in most of the cities [16]. Previous research has shown
that in developed countries, work in the agriculture and construction sectors increases the risk of environmental heat being associated with mortality [41]. Social and demographic parameters, occupational heat exposure and access to resources were related to increased vulnerability [39]. However, this issue has not been explored sufficiently in developing countries [42]. Work-related heat stress has been studied in a handful of settings in India, e.g. outdoors under the sun, in poorly ventilated indoor workspaces and near furnaces [14]. Therefore, research is needed to achieve a better understanding of the multiple factors (including social and environmental drivers) and their interaction with heat exposures in the agricultural and manufacturing industry in order to improve the health and safety of workers while maintaining worker productivity [16]. Research has also addressed socio-economic differences in vulnerability, partly related to pre-morbidity. Individuals with low incomes are more likely to have chronic diseases or other medical risk factors such as mental illness, which modify the risk of heat-related mortality [41]. Low income is also related to adverse housing conditions, which increase health risks [43]. Several high-risk populations have been identified. These include the elderly with specific pre-existing diseases or individuals of low socio-economic status who take certain medications, as well as socially isolated people [35].

More research is needed to improve our understanding of modifying factors such as housing condition, technological changes, local topography, urban design and behavioural parameters [23]. The prevailing high temperatures and the generally low socio-economic status in tropical developing countries indicate that these regions might be most vulnerable to a rise in temperature, promoted by climate change and global warming [44]. Therefore, integration of social, demographic and environmental data with health outcome data will contribute to a more comprehensive understanding, which will help identify sustainable health solutions [45].
Need for weather-related studies in low- and middle-income countries

Mortality from heat waves and other extreme weather events is a significant public health problem that is likely to worsen in the future [4]. The need for the design of effective intervention strategies thus becomes even more important in the face of current and future climate change [14]. A better understanding of the relationship between weather conditions and population-level mortality in a country such as India could contribute to the development of such prevention strategies. Recognition that climate change may amplify occupational heat-related health risks with related impacts on productivity, especially in developing countries, is yet to develop. A systems approach focusing on health outcomes is critical to the success of future research in this area [46]. Most of the studies focus on heatstroke deaths, and these have been associated with occupational exposure at construction sites, agricultural sites and hot industrial jobs, which require heavy work [41]. Therefore, workers in hot environments must also be educated regarding the heat stress [6]. Heat stress associated with climate change has been examined in relation to heat wave effects on the general population. Retrospective studies investigating climate variability and health dominate the literature, leaving predictive and prospective studies related to climate change open to be explored [45]. In cases where the data already exist, more work is needed to identify and access this type of long-term data, creating uniform repositories. Therefore, the Health and Demographic Surveillance Sites (HDSS) platform offered a unique opportunity to utilize individual information that is rarely available in developing countries [47].

INDEPTH Climate and Mortality Working Group

The International Network for the Demographic Evaluation of Populations and Their Health (INDEPTH) is an initiative that conducts longitudinal surveillance of population data in low- and middle-income countries (LMICs). It supports organizations for the setting up
of independently operating surveillance sites in Africa, Asia and Oceania [48]. INDEPTH, together with a number of south-north collaborating institutions, initiated a research and capacity-strengthening workshop in Nouna, Burkina Faso, in February 2011 (Figure 1). Fifteen out of the 42 HDSSs sites were represented during this one-week workshop. The aim of the group was to work towards a special issue for the journal Global Health Action that would focus on the relationship between weather conditions and mortality in HDSS areas. This activity was labelled CLIMO (Climate and Mortality). Afterwards, a second workshop was organized in Accra, Ghana, in May 2012. The objective of the second workshop was to help the participants develop their writing and scientific presentation skills in order to meet the standards of the upcoming scientific supplement in Global Health Action. The facilitator group included the INDEPTH Network secretariat, Ghana; Umeå University, Sweden; Heidelberg University, Germany; London School of Hygiene and Tropical Medicine, UK; Virginia University, USA; and the Nouna Health Research Centre, Burkina Faso [49].

Figure 1: INDEPTH CLIMO (Climate and Mortality) Working Group Participants in Burkina Faso, February 2011.
The scope of the PhD research work

Figure 2 explains the conceptual framework of this PhD research work. Ambient temperature is an important determinant of mortality [50]. There are direct and indirect pathways that affect human health: heat waves, cold waves, and rainfall [51]. We assessed the association of total mortality with temperature and rainfall in Paper I. The effect of hot and cold days on cause-specific mortality was investigated in Paper II. How weather-related mortality is modulated by occupation, education and other socioeconomic factors was assessed in Paper III. The impact of maximum temperature on years of life lost was investigated in Paper IV (Multisite collaborative project in high-, middle-, and low-income settings, of which Vadu HDSS is part). The PhD research work is structured around four distinct interlinked research papers mainly focused on total mortality. The conceptual framework highlights the potential health outcomes associated with environmental exposures. It also emphasise preventive actions, indicating that surveillance, adaptation and prevention are essential.

Figure 2: Conceptual framework of the PhD research work.
Aims and objectives

The overall aim was to assess weather-related mortality in a rural population in the Vadu HDSS area, western India.

1. To investigate the short-term association of temperature and rainfall with daily mortality in different strata of age and sex (Paper I).
2. To estimate the effects of heat and cold on total and cause-specific mortality (Paper II).
3. To estimate the effects of heat and cold on mortality among different socio-demographic groups (Paper III).
4. To investigate the relationship between temperature and years of life lost (Paper IV).
Chapter 2: Materials and methods

This chapter starts with the study location and setting of the population and environmental data. A detailed description of the statistical methods used in this thesis follows.

Study location and setting

The Vadu Health and Demographic Surveillance System (HDSS) is situated in a rural area between latitude 18°30 to 18°47 N and longitude 73°58 to 74°12 E, covering a 232-km² geographical area (Figure 3). Vadu HDSS covers 22 villages from two tehsils (confined blocks), 14 villages from Shirur and eight villages from Haveli, in the Pune District of Maharashtra state in western India [52].

A major national road passes through the area, and five villages fall in the industrial zone. The main occupation and source of income is farming [53]. Health facilities in this study area include both public and private health services. A rural hospital and a primary health centre (PHC) are in the public health sector. The private health sector has several small general hospitals and clinics. Health care is easily accessible, and most residents seek care in the private sector, which is largely not regulated by the government [54].
Figure 3: Vadu HDSS area, Pune District, India [55].
Vadu Rural Health Program

Dr. Banoo Coyaji initiated the Vadu Rural Health Program (VRHP) in the late 1970s due to the need for good health care facilities in the Vadu area during an epidemic of diarrhoea (Figure 4). She started delivering primary health services with a team of a few doctors from King Edward Memorial (KEM) Hospital in Pune. The mission of this program is to ‘Provide evidence-based, sustainable and rational health care solutions for the rural population using globally relevant community-based ethical research’ [56]. This program provides primary health care for a geographically defined population of about 130,000 individuals residing in 22 villages. The Shirdi Saibaba Rural Hospital is situated in the Vadu village, which provides a secondary medical facility to the population (Figure 5). VRHP is conducting many clinical trials, disease burden studies and social and environmental research in public health [53].

Figure 4: Vadu Rural Health Program, Vadu Bk, Pune, India.
INDEPTH Network: Better health information for better health policy

The Vadu HDSS has been a member centre of INDEPTH Network since 2002. The International Network for the Demographic Evaluation of Populations and Their Health (INDEPTH) conducts longitudinal surveillance for monitoring and evaluation of population health in low- and middle-income countries. The detailed conceptual structure of the dynamic cohort model is described in Figure 6. The INDEPTH HDSS sites collect the data from entire communities over extended time periods; thus, they more accurately reflect the health and population problems in LMICs. Currently, there are 46 member centres observing through 53 HDSS field sites the life events of over three million people in 20 LMICs in Africa, Asia and Oceania [48].
Vadu Health and Demographic Surveillance System (HDSS)

In essence, core HDSS data has provided dynamic information about the population at an individual level, within the geographically defined Vadu HDSS area, since the baseline census in 2002. Field research assistants (FRAs) visit every household in all villages to record demographic events. These events include births, deaths, in-migrations, out-migrations and pregnancies within the Vadu HDSS area and have been recorded twice a year since 2003 [57]. Each event is recorded using questionnaires administered by the FRAs, who are also local residents. In this thesis, information on age, sex, date of death, occupation and education of the deceased person was retrieved from the HDSS database.

Verbal autopsy data

All deaths within the study area are recorded and subjected to verbal autopsy (VA). Verbal autopsy is an instrument for identifying the cause of death on the basis of structured interviews with relatives of the deceased. Information obtained in these interviews is used to determine the likely cause of death [47, 58]. Trained field research assistants administered the verbal autopsy questionnaire for all deaths.
within the Vadu HDSS area. These data were collected within four weeks after each death occurred. VA were conducted for all deaths in the area, and each death was then assigned a cause of death and an ICD-10 code (International Classification of Diseases-10). In Paper II, we have used the mortality data of 2302 deaths for which verbal autopsy was performed. ICD-10 codes were assigned by a physician and are displayed in Table 1. We have only used data for the population aged 12 years and older due to fact that VA data were available for this age group at the time of the study.

**Socio-demographic data**

A socio-economic status (SES) survey was conducted in 2004, in which information on household-salient features of assets owned by households was recorded. The questionnaire contained 29 ordinal variables, e.g. house type, ownership of appliances, transport and livestock, ownership of agricultural land, etc. The status of ownership of agricultural land was available for each family, and it was used in this thesis to define individual socioeconomic status. We grouped ownership of agricultural land into three classes: owning five acres or more of agricultural land was considered high SES, owning less than five acres of land was medium SES and owning no agricultural land was low SES. Another variable was the house type; the locally defined terms used to identify types of homes are “pucca”, “semi-pucca” and “kachha”. Houses made with a mud floor, a thatched roof and walls painted with mud or cow dung are called kachha houses, and houses that use material similar to kachha coupled with some material used for permanent structures such as walls with stones but still painted with mud or tin walls but definitely no concrete roof are called semi-pucca houses. Houses made with a tiled floor, a tin or concrete roof and walls plastered with cement are called pucca houses (Figure 7). We classified all houses into either kachha (also including semi-pucca) or pucca.
Finally, education was classified into three classes: no education or uncompleted primary school (low), completed primary school (medium) and completed secondary school or higher (including college and university) (high education).

Weather data

The climate of India is comprised of a wide range of weather conditions across the geographic scale. Daily weather data were obtained from the Indian Meteorological Department (IMD) in Pune for the study period. The IMD designates four climate seasons: Winter, summer or pre-monsoon, monsoon or rainy season and post monsoon. Winter lasts from November to February and is followed by a summer that lasts up to early June. The monsoon season starts from early June and continues until the beginning of October. The latter part of October is
the post-monsoon season. After February, the temperature rises rapidly until April or May, which correspond to the hottest months. Toward the end of the monsoon season in October, there is a slight increase in the day temperature, but the nights become progressively cooler.

Based on each study objective, we have used different meteorological data. In Paper I, the mean daily temperature and cumulative daily precipitation from January 2003 to May 2010 was used. Daily maximum temperature data was used for the period January 2003 to December 2012 for Paper II and Paper IV. We used daily maximum temperature due to the fact that this variable had the least number of missing observations and errors. For Paper III, the daily mean temperature for the study period from January 2004 to December 2013 was obtained from the National Oceanic and Atmospheric Administration (NOAA) (http://www.ncdc.noaa.gov).

**Definition of heat days and cold days**

There is no standard definition of heat and cold with regard to health impacts [59]. A definition of heat wave or a cold wave always considers the combination of the intensity and the duration of a high or low temperature period [60-62]. Many studies on temperature-health relationships are focused on the analysis of specific episodes of heat events [18].

In Paper II, we adopted a percentile approach for identifying hot days and cold days [30, 63-65]. Daily maximum temperatures above 39ºC (98th percentile) were defined as hot days, and cold days were defined as days with maximum temperatures below 25ºC (2nd percentile).
Table 1: Climatological information for Pune city over a 30-year period.

<table>
<thead>
<tr>
<th>Month</th>
<th>Mean Daily Minimum Temperature (°C)</th>
<th>Mean Daily Maximum Temperature (°C)</th>
<th>Mean Total Rainfall (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>11.6</td>
<td>30.2</td>
<td>1.6</td>
</tr>
<tr>
<td>Feb</td>
<td>12.7</td>
<td>32.3</td>
<td>1.1</td>
</tr>
<tr>
<td>Mar</td>
<td>16.3</td>
<td>35.8</td>
<td>2.7</td>
</tr>
<tr>
<td>Apr</td>
<td>20.1</td>
<td>37.9</td>
<td>13.6</td>
</tr>
<tr>
<td>May</td>
<td>22.3</td>
<td>37.2</td>
<td>33.3</td>
</tr>
<tr>
<td>Jun</td>
<td>22.8</td>
<td>32.0</td>
<td>120.4</td>
</tr>
<tr>
<td>Jul</td>
<td>22.0</td>
<td>28.1</td>
<td>179.0</td>
</tr>
<tr>
<td>Aug</td>
<td>21.3</td>
<td>27.6</td>
<td>106.4</td>
</tr>
<tr>
<td>Sep</td>
<td>20.6</td>
<td>29.2</td>
<td>129.1</td>
</tr>
<tr>
<td>Oct</td>
<td>18.9</td>
<td>31.7</td>
<td>78.8</td>
</tr>
<tr>
<td>Nov</td>
<td>14.8</td>
<td>30.5</td>
<td>28.6</td>
</tr>
<tr>
<td>Dec</td>
<td>11.8</td>
<td>29.3</td>
<td>5.3</td>
</tr>
</tbody>
</table>

(Source: http://worldweather.wmo.int/en/city.html?cityId=535)

In Paper III, we defined hot and cold periods based on summer months and winter months. However, we did not consider the rainy and post-rainy seasons in our analysis as it was beyond the scope of the objective.
Statistical methods and analyses

Table 2 summarizes the study objectives, datasets and main statistical methods used in the four research papers. The preferred method to investigate temperature-mortality associations is the time series regression method [50, 66-69].

Table 2: Overview of materials and methods used in the PhD research.

<table>
<thead>
<tr>
<th></th>
<th>Study 1</th>
<th>Study 2</th>
<th>Study 3</th>
<th>Study 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Objectives</strong></td>
<td>To investigate the short-term association of temperature and rainfall with mortality</td>
<td>To estimate the effects of hot and cold days on total and cause-specific mortality</td>
<td>To estimate the effects of heat and cold on mortality among different socio-demographic groups</td>
<td>To estimate the impact of daily maximum temperature on years of life lost</td>
</tr>
<tr>
<td><strong>Study population (Deaths)</strong></td>
<td>1661</td>
<td>2303</td>
<td>3079</td>
<td>3394</td>
</tr>
<tr>
<td><strong>Statistical methods</strong></td>
<td>Poisson regression model</td>
<td>Quasi-Poisson regression model</td>
<td>Conditional logistic regression model (Case-crossover study design)</td>
<td>Distributed lag non-linear model (DLNM)</td>
</tr>
</tbody>
</table>

The main statistical method used in Paper I was Poisson regression and in Paper II quasi-Poisson regression. Another proposed method for investigating the effects of temperature on health outcomes is the case-crossover design, which we applied in Paper III [24, 44, 70, 71]. Daily deaths in the population subgroups were analysed by demographic characteristics (education, occupation, etc.). The analysis was conducted during summer and winter months using a time-stratified case-crossover study design.
In Paper IV, we applied a distributed lag non-linear model (DLNM) to estimate the association between daily maximum temperature and years of life lost (YLL). The effect of a specific exposure event of temperature is not limited to the period when it is observed, but it is also delayed. This is one of the challenges in modelling the association between an exposure and an outcome, specifying the distribution of the effects at different lags after the event. DLNM are widely used to model the association of exposure and health outcomes, as they allow the main effect to vary according to both temperature and lags [72, 73].

In the Poisson regression model, it is essential to control for long-term trends in order to effectively separate them out from the short-term associations between exposure of interest and outcome. Natural and cubic spline functions were used to smoothly model the long-term patterns. It was necessary to capture seasonal patterns in a way that was allowed to vary from one year to the next. In this method, the series of daily counts of deaths and ambient levels of temperature were compared while controlling for potential confounding variables such as long-term and seasonal trends. The standard regression model assumes Poisson responses, allowing for over-dispersion [50, 69]. In Paper I, the association between daily mean temperature, daily cumulative rainfall and daily mortality was examined using a time series Poisson regression model during the period 2003-2010. Exposure-response functions were estimated linearly for temperature and rainfall and indicated little deviation from linearity. Potential delayed effects of the weather variables on mortality were assessed in different lag strata. The aim was to avoid collinearity introduced by having several highly correlated explanatory variables in the regression model [57]. The following model was used in this analysis:

\[
\text{Deaths} \sim \text{Poisson (mean)} \\
\log \text{(mean)} = \text{intercept} + s(\text{temperature}_t) + s(\text{rainfall}_t) + s(\text{time}_t, \text{df}=6 \text{ per year})
\]

where ‘s’ denotes a cubic spline function with ‘df’ number of degrees of freedom, and ‘t’ denotes the time of observation.

A similar method was used in Paper II to examine the association of
hot and cold days with daily counts of total and cause-specific deaths, respectively. We estimated the relationship between hot and cold days and mortality in the lag periods of 0 (same day) and 0–4 days. Additionally, we assessed in sensitivity analyses the relationship between hot and cold days and daily deaths using a logistic regression model to check the robustness of the quasi-Poisson model given the large number of days with zero deaths [55]. The mathematical formula of the model is given as follows:

Deaths ~ Poisson (mean_t)

log (mean_t) = intercept + \beta_1 X_{i,t} + \text{ns}(\text{time}_t, \text{df}= 5 \text{ per year}) + \text{other covariates}

where ‘ns’ denotes a natural cubic spline function with ‘df’ number of degrees of freedom, \beta_1 is the regression coefficient for the indicator variable X_i marking heat/cold extremes, and ‘t’ denotes the time of observation, and other covariates include weekdays.

In Paper III, analyses were carried out in two stages. In the first stage, we used a quasi-Poisson regression model to examine the association of heat and cold with daily death counts. We estimated the relationship between heat and cold and total mortality with a lag of 0-1 days in summer and 0-13 days in winter. A natural cubic spline function was used to assess the functional form of the temperature-mortality relationship and to adjust for season and time trends, allowing six degrees of freedom (df) per year. In the second stage, the dose-response relationship between temperature and mortality was explored for all deaths and for population subgroups based on the heat and cold function from the exploratory analysis using a time stratified case-crossover study design [24, 70, 74]. Controls for each case were selected for the same year, month and day of the week as the own cases. Conditional logistic regression analysis was performed for each subgroup separately for hot (summer months) and cold (winter months) periods.

In Paper IV, we used the DLNM method to assess the impact of maximum temperature on YLL at seven study sites, including Vadu HDSS. The DLNM framework allows for modelling of non-linear
relationships in the dimension of the predictor as well as its lag. This method employs the concept of cross-basis, which is a joint modelling of the basis functions of the predictor variable and its lag. We created a DLNM for maximum daily temperature with a natural cubic spline basis (two degrees of freedom), capturing both non-linear effects and the lag dimension. We modelled lags up to two weeks. Since daily years of life lost were not normally distributed, we applied a quasi-Poisson regression model. A natural cubic spline function of time trend allowing eight degrees of freedom per year was included to capture long-term trends and seasonality of years of life lost and included the day of week. The model equation used for estimating the effect of maximum temperature on years of life lost for HDSS sites was as follows:

\[
\text{YLL} \sim \text{Poisson (mean}_t) \\
\log(\text{mean}_t) = \text{intercept} + f(\text{temp}_t, \text{lagdf}=2, \text{vardf}=2) + s(\text{time}_t, \text{df}=8 \text{ per year}) + \text{DOW}_t + \text{HEAP}_t \\
\]

where \(\log(\text{mean}_t)\) is the expected number of years of life lost at day \(t\), \(f\) is the cross-basis function of maximum temperature and its lag dimension with \(\text{vardf}\) and \(\text{lagdf}\) degrees of freedom, \(s\) is the smooth function of time with degrees of freedom given by \(\text{df}\), respectively, \(\text{DOW}_t\) is controlling for the day of week and \(\text{HEAP}_t\) for heaping days (only at HDSS sites). The cross-basis function of maximum temperature was centred at the median value for the site.

**Ethical consideration**

The ethical approval for this PhD research was obtained from KEM Hospital Research Centre Ethics Committee. This study analysed population data from Vadu HDSS, which did not contain information providing individual identification. The usage of available HDSS data did not need a separate ethical permission for this PhD research.
Chapter 3: Results
This chapter presents the study results according to each of the four papers.

**Ambient air temperature, rainfall and daily deaths—understanding the association**

The short-term association of daily mean temperature and cumulative rainfall with daily mortality was assessed in the Vadu HDSS area during the study period from January 2003 to May 2010. The frequency table of daily deaths stratified by age and sex is presented in Table 3. The total number of daily deaths included in this analysis was 1,662.

Table 3: Frequency of daily mortality by age and sex in Vadu HDSS, 2003-2010.

<table>
<thead>
<tr>
<th>Age group</th>
<th>N</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-4 years</td>
<td>46</td>
<td>3</td>
</tr>
<tr>
<td>5-19 years</td>
<td>62</td>
<td>4</td>
</tr>
<tr>
<td>20-59 years</td>
<td>627</td>
<td>38</td>
</tr>
<tr>
<td>&gt;=60 years</td>
<td>927</td>
<td>56</td>
</tr>
<tr>
<td>Men</td>
<td>954</td>
<td>57</td>
</tr>
<tr>
<td>Women</td>
<td>708</td>
<td>43</td>
</tr>
<tr>
<td>Total</td>
<td>1,662</td>
<td>100</td>
</tr>
</tbody>
</table>
Table 4 displays the descriptive statistics of the daily meteorological parameters of the Pune airport weather station. Figure 8 presents the association between daily mean temperature, rainfall and daily total mortality. The relationship between rainfall and total mortality showed increased risk in lags up to two weeks. Exponentiation of the log relative risk estimates indicates that both high and low daily mean temperature was highly associated with total mortality in lag periods of 0-1 and 2-6 days. However, the rainfall impact in short lag periods 0-1 and 2-6 days on total mortality was non-significant, but had higher effects in the lag period 7-13 days. At lags of up to two weeks, temperature was associated with decreases in total mortality. A strong association between daily mortality in age group 0-4 years and daily mean temperature was found in lag 0-1 and 2-6 days. Increases in rainfall were also significantly associated with mortality among children within two weeks’ delay (figure 9). Rainfall at a short lag did not show any association with mortality among children. In the age group 20-59 years, increases (lag 0-1 day) and decreases (lag 2-6 days) in mean temperature were associated with higher mortality. The association of rainfall and mortality indicated an upward direction with increases in rainfall at lag 0-1 day and, in particular, a strong significant association in the two-weeks lag (Figure 10). The elderly appeared susceptible when there was increased rainfall with a lag up to two weeks. However, there were no strong apparent patterns associated with daily mean temperature in this group (age 60 years and above).
The observed relationship in men and women shows that women were more vulnerable to rainfall in two-week lags compared to men (Figure 11).

Figure 8: Association of daily mortality, daily mean temperature and rainfall in Vadu HDSS, 2003–2010 (dark line is log of relative risk and dotted line is 95% confidence interval), adopted from Paper I.
Figure 9: Association of mortality with daily temperature and rainfall in the age strata of 0–4 years in Vadu HDSS, 2003–2010 (dark line is log of relative risk and dotted line is 95% confidence interval), adopted from Paper I.
Figure 10: Association of mortality with daily temperature and rainfall in the age strata of 20–59 years in Vadu HDSS, 2003–2010 (dark line is log of relative risk and dotted line is 95% confidence interval), adopted from Paper I.
All-cause and cause-specific mortality and high and low temperatures

In this study, we investigated the effects of heat and cold on total mortality, infectious disease mortality, non-infectious disease mortality and external causes of death between 2003 and 2012. Table 5 presents the total number of daily deaths and cause-specific deaths (ICD-10 codes). The most frequent common causes of deaths in the infectious disease category included gastroenteritis, amoebiasis and sepsis. Non-infectious diseases made up the largest disease group and consisted mainly of acute myocardial infarction, stroke, acute renal failure, asthma and chronic ischaemic heart disease. External causes of death and unspecified causes of death were composed of unspecified injuries, intentional self-harm and accidents were the main causes of deaths in this group.
Table 5: Descriptive statistics of causes of deaths with ICD-10 codes for common diseases in Vadu HDSS, 2003-2012.

<table>
<thead>
<tr>
<th>Disease class</th>
<th>ICD-10 codes</th>
<th>Cause of Death</th>
<th>Most frequent diseases</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-infectious</td>
<td>C00-D48</td>
<td>Neoplasms</td>
<td>Acute myocardial infarction, stroke, acute renal failure, asthma and chronic ischaemic heart disease</td>
<td>1175</td>
</tr>
<tr>
<td>diseases</td>
<td>E00-E90</td>
<td>Endocrine, nutritional and metabolic diseases</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>F00-F99</td>
<td>Mental and behavioural disorders</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>G00-G99</td>
<td>Diseases of the nervous system</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>H00-H95</td>
<td>Diseases of the eye and adnexa</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>K00-K93</td>
<td>Diseases of the digestive system</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>L00-L08</td>
<td>Infections of the skin and subcutaneous tissue</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>M00-M03</td>
<td>Diseases of the musculoskeletal system and connective tissue</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Infectious</td>
<td>A00-B99</td>
<td>Certain infectious and parasitic diseases</td>
<td>Gastroenteritis, amoebiasis and sepsis</td>
<td>296</td>
</tr>
<tr>
<td>diseases</td>
<td>J00-J99</td>
<td>Diseases of the respiratory system</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>L00-L08</td>
<td>Infections of the skin and subcutaneous tissue</td>
<td></td>
<td></td>
</tr>
<tr>
<td>External</td>
<td>S00-T98</td>
<td>Injury, poisoning and certain other consequences of external causes</td>
<td>Intentional self-harm and accidents</td>
<td>309</td>
</tr>
<tr>
<td>causes</td>
<td>V01-Y98</td>
<td>External causes of morbidity and mortality</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unspecified</td>
<td>R00-R99</td>
<td>Symptoms, signs and abnormal clinical and laboratory findings, not elsewhere classified</td>
<td>Unspecified deaths</td>
<td>522</td>
</tr>
<tr>
<td>causes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Deaths</td>
<td></td>
<td></td>
<td></td>
<td>2303</td>
</tr>
</tbody>
</table>

There were in total 144 hot days (98th percentile, >39ºC) and 44 cold days (2nd percentile, <25ºC) during the study period. We estimated the relative risks for all-cause and cause-specific mortality with hot and cold days. All-cause mortality and heat days were associated at lag 0 (RR = 1.33; 95% CI: 1.07-1.60). There was also a statistically significant association between hot days and non-infectious disease mortality on
the same day (lag 0 day) (RR = 1.57; 1.18-2.10). Even in longer lags up to four days, we found that non-infectious disease mortality was associated with hot days (RR = 1.34; 1.04–1.90). However, infectious disease mortality in lags 0 and 0-4 days (RR = 1.15; 0.58-2.28 and RR = 0.93; 0.52-1.65) and external causes of death (RR = 1.48; 0.89-2.48 and RR = 0.99; 0.62-1.58) were not associated with hot days. The relative risk in men on hot days (lag 0) was found to be 1.38. However, no statistical significance was found among women (RR = 1.24; 0.86-1.79). The relative risk of mortality in the age group of 12-59 years was 1.43 on hot days (lag 0). There was no significant association between cold days and total and cause-specific mortality over lags 0 and 0-4 days. Relative risks with 95% confidence intervals stratified by cause, age and sex are presented in Table 6 and 7.

Table 6: Association of hot days with mortality stratified by cause of death, age and sex, Vadu HDSS, 2003–2012, adopted from Paper II.

<table>
<thead>
<tr>
<th>Hot Days</th>
<th>Lag 0</th>
<th>Lag 0–4 Days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RR</td>
<td>95% CI</td>
</tr>
<tr>
<td>All-cause mortality</td>
<td>1.33</td>
<td>1.07–1.60</td>
</tr>
<tr>
<td>Non-infectious disease mortality</td>
<td>1.57</td>
<td>1.18–2.10</td>
</tr>
<tr>
<td>Infectious disease mortality</td>
<td>1.15</td>
<td>0.58–2.28</td>
</tr>
<tr>
<td>External causes of mortality</td>
<td>1.48</td>
<td>0.89–2.48</td>
</tr>
<tr>
<td>All-cause mortality in men</td>
<td>1.38</td>
<td>1.05–1.83</td>
</tr>
<tr>
<td>All-cause mortality in women</td>
<td>1.24</td>
<td>0.86–1.79</td>
</tr>
<tr>
<td>All-cause mortality in age group 12–59 years</td>
<td>1.43</td>
<td>1.02–1.99</td>
</tr>
<tr>
<td>All-cause mortality in age group 60+ years</td>
<td>1.27</td>
<td>0.94–1.70</td>
</tr>
</tbody>
</table>

(RR = Relative risk; CI = confidence interval; bold numbers indicate statistical significance).
Additionally, we conducted sensitivity analyses using a logistic regression model and found similar results as with the quasi-Poisson regression model. Conversely, the effects were slightly higher than those with the quasi-Poisson model for hot days. In lags 0 and 0–4 days, we found relative risks of 1.70 and 1.44 in non-infectious disease mortality. Moreover, logistic regression models also obtained non-significant results for the effects of cold days for lags 0, 0–4 and 0–14 days. Detailed results are presented in the appendix of Paper II.

Table 7: Association of cold days with mortality stratified by cause of death, age and sex, Vadu HDSS, 2003–2012 (relative risks with 95% confidence intervals), adopted from Paper II.

<table>
<thead>
<tr>
<th>Cold Days</th>
<th>Lag 0</th>
<th>Lag 0–4 days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RR</td>
<td>95% CI</td>
</tr>
<tr>
<td>All-cause mortality</td>
<td>1.14</td>
<td>0.79–1.66</td>
</tr>
<tr>
<td>Non-infectious disease mortality</td>
<td>0.99</td>
<td>0.55–1.72</td>
</tr>
<tr>
<td>Infectious disease mortality</td>
<td>1.48</td>
<td>0.65–3.38</td>
</tr>
<tr>
<td>External causes of mortality</td>
<td>0.26</td>
<td>0.03–1.92</td>
</tr>
<tr>
<td>All-cause mortality in men</td>
<td>1.18</td>
<td>0.73–1.89</td>
</tr>
<tr>
<td>All-cause mortality in women</td>
<td>1.12</td>
<td>0.63–1.97</td>
</tr>
<tr>
<td>All-cause mortality in age group 12–59 years</td>
<td>1.15</td>
<td>0.67–2.00</td>
</tr>
<tr>
<td>All-cause mortality in age group 60+ years</td>
<td>1.12</td>
<td>0.71–1.86</td>
</tr>
</tbody>
</table>

(RR = Relative risk; CI = confidence interval; bold numbers indicate statistical significance).
Socio-environmental factors and susceptible groups in the population

To identify vulnerable population groups in the Vadu HDSS area, we estimated the effects of the daily mean temperature during summer and winter on the daily total mortality among different socio-demographic groups during the study period from January 2004 to December 2013. A non-linear association was found between total mortality and daily mean temperature with an upward slope above a threshold of 31°C. Temperature above this threshold was significantly associated with daily total mortality (OR = 1.48; 1.04-2.09) during the summer period with a lag of 0-1 day. We observed higher heat-related risks (OR = 1.70; 1.03-2.81) in the farming occupation group than in other occupation groups. Resident work in the manufacturing industry indicated high OR (2.08; 0.64-6.78). Individuals with low education also showed high risk (OR = 1.66; 1.01-2.73). The findings indicated that women had higher heat-related risks than men (OR = 1.93; 1.07-3.48 in women, and OR = 1.29; 0.83-1.99 in men, respectively).

However, during the winter season, a linear association between temperature and mortality was found within up to two-week lags. There were some population subgroups with no statistically significant effects from cold. Total mortality was associated with lower temperature within a lag period of 0-13 days (OR = 1.06; 1.00-1.12). The effects of cold during winter on residents working in housework showed OR = 1.09; 1.00-1.19). The elderly people (age 80+ years) had a higher risk (OR = 1.13; 0.97-1.33) than younger ones (OR = 1.05, 0.98-1.13). Detailed results of all subgroups are displayed in Table 8 (summer) and Table 9 (winter).
Table 8: Mortality risk in summer (lag 0-1 day), per 1°C increase above the threshold 31°C, by age, sex and other demographic parameters during 2004-2013 in Vadu HDSS, India.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>No.</th>
<th>Percent</th>
<th>OR</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>All Deaths</strong></td>
<td>3079</td>
<td>100</td>
<td><strong>1.48</strong></td>
<td><strong>1.04-2.09</strong></td>
</tr>
<tr>
<td>Age 15-67</td>
<td>1,892</td>
<td>61.45</td>
<td>1.51</td>
<td>0.97-2.35</td>
</tr>
<tr>
<td>Age 68-80</td>
<td>732</td>
<td>23.77</td>
<td>1.40</td>
<td>0.69-2.89</td>
</tr>
<tr>
<td>Age 80+</td>
<td>455</td>
<td>14.78</td>
<td>1.48</td>
<td>0.60-3.65</td>
</tr>
<tr>
<td><strong>Sex</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>1,861</td>
<td>60.44</td>
<td>1.29</td>
<td>0.83-1.99</td>
</tr>
<tr>
<td>Female</td>
<td>1,218</td>
<td>39.56</td>
<td><strong>1.93</strong></td>
<td><strong>1.07-3.48</strong></td>
</tr>
<tr>
<td><strong>Occupation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Farming</td>
<td>1,131</td>
<td>36.74</td>
<td><strong>1.70</strong></td>
<td><strong>1.03-2.81</strong></td>
</tr>
<tr>
<td>Housework</td>
<td>1,388</td>
<td>45.09</td>
<td>1.17</td>
<td>0.61-2.24</td>
</tr>
<tr>
<td>Manufacturing work</td>
<td>230</td>
<td>7.47</td>
<td>2.08</td>
<td>0.64-6.78</td>
</tr>
<tr>
<td>Other</td>
<td>107</td>
<td>7.21</td>
<td>1.61</td>
<td>0.45-5.71</td>
</tr>
<tr>
<td>Service work</td>
<td>222</td>
<td>3.48</td>
<td>0.89</td>
<td>0.18-4.39</td>
</tr>
<tr>
<td><strong>Agricultural land ownership</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High (&gt;= 5 acres land)</td>
<td>730</td>
<td>32.6</td>
<td>2.18</td>
<td>0.99-4.79</td>
</tr>
<tr>
<td>Medium (&lt; 5 acres land)</td>
<td>1,011</td>
<td>45.15</td>
<td>1.38</td>
<td>0.82-2.32</td>
</tr>
<tr>
<td>Low (no land)</td>
<td>498</td>
<td>22.24</td>
<td>1.25</td>
<td>0.44-3.58</td>
</tr>
<tr>
<td><strong>House Type</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kachha (poor quality)</td>
<td>901</td>
<td>40.24</td>
<td>1.87</td>
<td>0.99-3.54</td>
</tr>
<tr>
<td>Pucca (high quality)</td>
<td>1,338</td>
<td>59.76</td>
<td>1.35</td>
<td>0.82-2.25</td>
</tr>
<tr>
<td><strong>Education Group</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low (no or uncompleted primary school)</td>
<td>1,360</td>
<td>44.17</td>
<td><strong>1.66</strong></td>
<td><strong>1.01-2.73</strong></td>
</tr>
<tr>
<td>Medium (completed primary school)</td>
<td>1,094</td>
<td>35.53</td>
<td>1.75</td>
<td>0.94-3.26</td>
</tr>
<tr>
<td>High (completed secondary school)</td>
<td>625</td>
<td>20.3</td>
<td>0.86</td>
<td>0.36-2.02</td>
</tr>
</tbody>
</table>

*Conditional logistic regression model (OR = odds ratio; CI = confidence interval; bold numbers indicate statistical significance).*
Table 9: Mortality risk in winter (lag 0-13 days) per 1 °C decrease in mean temperature by age, sex and other demographic parameters during 2004-2013 in Vadu HDSS, India.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>No.</th>
<th>Percent</th>
<th>OR</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
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<td>100</td>
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</tr>
<tr>
<td>Age 15-67</td>
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<td>61.45</td>
<td>1.05</td>
<td>0.98-1.13</td>
</tr>
<tr>
<td>Age 68-80</td>
<td>732</td>
<td>23.77</td>
<td>1.05</td>
<td>0.94-1.16</td>
</tr>
<tr>
<td>Age 80+</td>
<td>455</td>
<td>14.78</td>
<td>1.13</td>
<td>0.97-1.33</td>
</tr>
<tr>
<td><strong>Sex</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>1,861</td>
<td>60.44</td>
<td>1.05</td>
<td>0.98-1.13</td>
</tr>
<tr>
<td>Female</td>
<td>1,218</td>
<td>39.56</td>
<td>1.05</td>
<td>0.97-1.16</td>
</tr>
<tr>
<td><strong>Occupation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Farming</td>
<td>1,131</td>
<td>36.74</td>
<td>1.06</td>
<td>0.97-1.16</td>
</tr>
<tr>
<td>Housework</td>
<td>1,388</td>
<td>45.09</td>
<td>1.09</td>
<td>1.00-1.19</td>
</tr>
<tr>
<td>Manufacturing work</td>
<td>230</td>
<td>7.47</td>
<td>0.86</td>
<td>0.64-6.78</td>
</tr>
<tr>
<td>Other</td>
<td>107</td>
<td>3.48</td>
<td>1.06</td>
<td>0.87-1.27</td>
</tr>
<tr>
<td>Service work</td>
<td>222</td>
<td>3.48</td>
<td>1.10</td>
<td>0.84-1.45</td>
</tr>
<tr>
<td><strong>Agricultural land ownership</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High (&gt;= 5 acres land)</td>
<td>730</td>
<td>32.6</td>
<td>1.06</td>
<td>0.95-1.19</td>
</tr>
<tr>
<td>Medium (&lt; 5 acres land)</td>
<td>1,011</td>
<td>45.15</td>
<td>1.04</td>
<td>0.95-1.14</td>
</tr>
<tr>
<td>Low (no land)</td>
<td>498</td>
<td>22.24</td>
<td>1.02</td>
<td>0.89-1.16</td>
</tr>
<tr>
<td><strong>House Type</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kachha (poor quality)</td>
<td>901</td>
<td>40.24</td>
<td>1.04</td>
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<tr>
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</tr>
<tr>
<td><strong>Education Group</strong></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
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<tr>
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<td>1.04</td>
<td>0.96-1.14</td>
</tr>
<tr>
<td>High (completed secondary school)</td>
<td>625</td>
<td>20.3</td>
<td>1.08</td>
<td>0.96-1.22</td>
</tr>
</tbody>
</table>

Conditional logistic regression model (OR = odds ratios; CI = confidence interval; bold numbers indicate statistical significance).
Years of life lost and temperature

This study assessed the association between maximum temperatures and years of life lost (YLL) at seven study sites (India, Africa, USA and Sweden). Here, only results of the Vadu HDSS site (study period 2003-2012) are presented. The summary statistics of deaths, years of life lost and temperature are presented in Table 10. During this period, there were a total of 3394 deaths recorded with a daily maximum YLL of 568.

Table 10: Summary statistics of weather and deaths during study period 2003-2012.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Min.</th>
<th>Max.</th>
<th>Mean</th>
<th>2nd</th>
<th>5th</th>
<th>95th</th>
<th>98th</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deaths</td>
<td>0</td>
<td>24</td>
<td>0.9</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>YLL</td>
<td>0</td>
<td>568.2</td>
<td>24.3</td>
<td>0</td>
<td>0</td>
<td>91.8</td>
<td>128.8</td>
</tr>
<tr>
<td>Daily mean temperature</td>
<td>15.4</td>
<td>34.9</td>
<td>25.1</td>
<td>18.6</td>
<td>19.8</td>
<td>30.7</td>
<td>31.5</td>
</tr>
<tr>
<td>Daily minimum temperature</td>
<td>2.7</td>
<td>28</td>
<td>18.2</td>
<td>8.5</td>
<td>9.8</td>
<td>24</td>
<td>24.7</td>
</tr>
<tr>
<td>Daily maximum temperature</td>
<td>21.1</td>
<td>42.4</td>
<td>32.0</td>
<td>25.3</td>
<td>26.6</td>
<td>38.8</td>
<td>39.9</td>
</tr>
</tbody>
</table>

Figure 12 displays the distribution of YLL and daily maximum temperature over several years. The average daily mean temperature over the study period was 25.1°C. We found a clear, immediate heat effect of daily maximum temperature on YLL, increasing gradually above 33°C. Relative risk at the 95th percentile (38.8°C) was highest at shorter lags and decreased afterwards (Figure 13). Overall, higher temperature was associated with YLL in the Vadu HDSS area and this results confirms the previous findings (Papers I-III). We did not find a significant effect of cold at the 5th percentile (26.6°C).
Figure 12: Means of daily maximum temperature and years of life lost per month over 10 years in the Vadu HDSS area, India.

Figure 13: Association between temperature and years of life lost in the Vadu HDSS area.

(The first row shows relative risk (RR) with 95% confidence intervals by temperature, cumulative over all lags; the second and third rows show lagged effects at the 5th and 95th percentiles of temperature, respectively).
Chapter 4: Discussion

Although there is ample research on the impact of weather on human health, there remains a persistent research gap in developing countries and low-resource settings around the globe. The main aim of this research was to investigate the association between ambient air temperature, rainfall and daily deaths among a rural population living in western India. Additionally, the study explored the social and demographic indicators associated with heat- and cold-related mortality. Furthermore, cause-specific deaths were analysed using verbal autopsy data to assess their relationship with high and low temperatures. Our study showed that non-communicable disease mortality was highly associated with hot days. When analysing social and demographic parameters, our quantification showed that farmers and working age groups were at higher heat-related risks during summer than other subgroups. Education and housing also emerged as important predictors of vulnerability for heat-related mortality within the study population. Finally, in our multisite study on years of life lost and temperature, we found that there were associations with daily maximum temperature.

Effects of temperature on total mortality

We set out to determine the associations between daily mortality and observations of daily mean temperature and cumulative rainfall in the first study. These associations indicated that high daily mean temperature had immediate effects in terms of mortality, particularly at lags of 0-1 days (heat effect) and 2-6 days (cold effect). Strong statistically significant relationships between rainfall and mortality were found in lag 7-13 days. This means that high-heat events may produce immediate increases in mortality, while anomalous rain events increased mortality for the two weeks following the event. In lag 0, we observed that hot days (>39°C) were associated with an increased total mortality by 33%. In the summer period, with lag 0-1, the temperature-mortality relationship was non-linear with an upward slope above 31°C. These findings are consistent with previous studies on weather and mortality in developing countries [15, 49, 75-78].
Another study from India, which examined the relationship between weather and deaths across Indian districts between 1957 and 2000, showed that hot days were significantly associated with increases in mortality within a year of their occurrence. The effects were only observed for rural populations, supporting our results. The study did not find any effects for urban populations [78]. Research in resource-poor settings in Asia and Africa found similar results when studying weather conditions and mortality [49].

Some research suggests that high and low temperatures have different lag effects, and, generally, the effects of cold days have longer delays than those of hot days [79, 80]. However, we assessed lags up to 14 days and found non-significant results, confirming that there was neither an immediate nor delayed impact of cold on mortality in this population. A reason for this may be the threshold for cold, defined as temperatures that are relatively high compared to studies from temperate countries [55].

Studies often examine the relative risks of heat-related mortality, but the absolute measure of years of life lost is also useful [29, 32, 81]. YLL is an informative measure for assessing the health impacts from weather compared to mortality risk, as it accounts for the age at death. We found that the association between temperature and years of life lost in Vadu HDSS is non-linear, with increased YLL with higher temperatures. The impact of temperature at the 95th percentile (38.8°C) on YLL was largest in shorter lag periods. These results confirmed our previous findings, which showed that temperature-related mortality risk increases with little delay at higher temperatures. However, studies from developed countries showed that both high and low temperatures are associated with YLL [29].

In our multisite paper, we found at the Kenyans sites, Kisumu and Nairobi HDSS, low temperature impacts on YLL. Another low-income setting, Nouna HDSS in Burkina Faso, showed that relative risk increased only with high temperature, while no cold effect was observed. Similar results were found in Vadu HDSS.
Age and sex
Risk among young children was high in relation to heat, cold and rainfall, thus indicating higher susceptibility in young children compared to other age groups. Adults aged 20-59 years were determined to be most affected shortly following temperature events, supporting research in the Matlab HDSS population in Bangladesh [82]. Our results also show that heat was associated with increased mortality also in the age group 12-59 years (Paper II) and in the age group 15-67 (Paper III, summer season, although non-significant). Thus, the three papers gave similar results for the population group at working age.

Our oldest group, aged 80+ had a higher cold-related mortality than younger adults in the cold season (Paper III). Several studies have supported similar evidence that indicates that elderly individuals are the most susceptible group [83].

Sex differences in weather susceptibility varied across our studies. In Paper III, which included residents aged 15 and older, it was women who were more vulnerable to heat than men; while in Paper II (aged 12 and older), the opposite was the case. Effects of low temperatures on mortality, on the other hand, were similar in men and women (Papers II and III).

There was little evidence for an effect of hot days on mortality among women and the elderly (Paper II). These results contradict previous research, which shows that these are particularly vulnerable population groups [18, 85-86]. This might be because most evidence is available for developed countries and the effects might be greater on younger age groups in developing countries. Other studies reported higher excess mortality in women in the United States and the United Kingdom, supporting our current findings [18, 71, 87].

Only the first of our studies investigated the role of rainfall for mortality. We found larger effects at longer lags on mortality among women than among men. Previous studies demonstrated that heavy rainfall is associated with waterborne diseases in India and Bangladesh [83, 88-90]. Extreme rainfall is a potential risk factor for certain
diseases, including diarrhoea, dengue, malaria and cholera [91, 92]. It is reasoned that due to heavy rainfall, floodwater contaminates drinking water, resulting in an increase in mortality due to cholera, dysentery and other water-borne diseases [83].

**Cause-specific deaths and the effects of heat and cold**

In Paper II, we assessed the relationship between extreme high and low temperatures and cause-specific mortality using verbal autopsy data. There is very limited research on cause-specific mortality and extreme temperatures in rural parts of India due to the unavailability of data. We observed that, like all-cause mortality, deaths by non-infectious diseases are associated with heat days. Our study population had high rates of non-infectious disease mortality due to cardiovascular diseases (e.g. cardiac arrest, myocardial infarction), respiratory diseases (specifically asthma) and kidney disease (acute renal failure). This finding supports the results from Bangladesh with a similar setting, where cardiovascular and other non-communicable diseases are more prevalent causes of death in males, causing them to be more susceptible to adverse heat effects [31]. The mechanism is that heat and cold can impair the human body and its physiological processes in innumerable ways, while also interacting with pre-existing conditions and chronic diseases. For exposure to heat and cold, the primary concern is alteration of the body’s core temperature beyond a healthy range [26]. High body temperature is associated with increased heart and respiratory rates. Evidence showed that not only heat strokes but also cardiac disease and renal impairment are associated with heat [26, 93, 94]. Although, as one study showed, heat-related deaths were generally higher in urban population in developed countries, other studies observed larger relative risks during heat events in rural populations [26].

In our study, there was no significant impact of heat on mortality by infectious diseases and external causes of death. This result is not consistent with studies from developed countries, which showed that mortality due to respiratory infections and external causes was
strongly associated with hot weather [95]. This might be because the limited number of deaths in our study population restricted the statistical power. For external causes of death, for example, we found a comparably large immediate effect of heat (RR = 1.48), but the association was statistically non-significant. Another reason could be that weather effects on infectious diseases might be delayed over more than two weeks, which was the longest lag we investigated.

**Socio-demographic factors and heat- and cold-related mortality**

Social and demographic parameters, occupational heat exposure and access to resources (e.g. water or health information) are likely to increase vulnerability [42]. More research is important to improve our understanding of the modulating factors such as housing quality, technology, local topography, urban design and behaviour and to improve the assessment of the capacity to adapt to current and future climates [23, 52]. This gap in knowledge motivated our subsequent study of socio-economic and demographic factors in association with heat- and cold-related mortality (Paper III). Population sensitivity towards extreme temperature varies with acclimatization, demographics and socioeconomic characteristics. There are very few studies that have examined socioeconomic inequalities that affect the relationship between temperature and mortality [96]. In our study, there were some groups more susceptible to heat; e.g. those working in agriculture and individuals with low education had a higher level of risk of dying during summer months.

There is evidence regarding the relationship between heat-related mortality and SES in India and China [8, 87, 97]. In our study population, individuals who had not completed primary school showed a high risk of effects from heat during the summer period. These associations may exist because people with little or no education may be less aware of the health risks from heat. They are also more likely to work in outdoor environments or in the agriculture field, while those with higher levels of education are more likely to work in offices. In the United States and China, scientists found that a low education level
intensified the temperature-mortality relationship [84, 96, 98-100]. Education, occupation and land ownership are indicators of socio-economic status (SES), which might be related to housing type/quality-limited access to health care. Residents who owned large amounts of agricultural land (more than five acres) were the most vulnerable to heat impacts, probably because they were more likely to work on agricultural farms and to be exposed to high ambient air temperature. Housing characteristics have also been related with heat-health outcomes [101]. In our study, individuals living in kachha houses (low-quality material) had a higher heat-related mortality risk during summer months than those living in high-quality houses (pucca), although both effects were statistically non-significant. In the Chicago heat waves in 1995 and 1999, housing characteristics were not found to be significant characteristics of vulnerability after controlling for other factors [21, 87, 102]. The Vadu HDSS kachha house types might increase indoor heat, but they may also be associated with other socio-economic factors such as income or occupation that impact mortality. Some results were not statistically significant due to small death counts, making their interpretation and conclusions less certain. This group is at working age, and the high mortality risk might be due to occupational heat stress. Research in developed countries showed that work in agriculture and construction increases the risk of heat-associated mortality [82].

In the cold season, overall results showed a 6% increase in total mortality per 1°C decrease in temperature in the lag period of 0-13 days. The cold effects on residents working in housework (indoor) were higher than on those working in farms (outdoor) and other occupations. This may be due to traditional practices of biomass burning for cooking purposes, which may contribute to indoor air pollution [103, 104]. Cold effects on other population subgroups (residents of working age, low education and farmers) were not highly associated with mortality.
Study strengths and limitations

This study has a number of strengths and limitations that we acknowledge. The HDSS platform offered a unique opportunity to utilize individual information that is rarely available in developing countries [47]. In Paper II of this thesis, we have considered only those deaths for which verbal autopsy has been done among those aged 12 years and older. Therefore, the results might be different for younger children. The verbal autopsy (VA) data could also face challenges of recall bias of relatives of the deceased and uncertainty introduced by the physicians coding the causes of deaths. However, the VA process offers an opportunity to conduct cause-specific analysis. SES data was collected in 2004, and we linked that data with the mortality dataset from 2004-2013. During this period, there were possibilities of change in SES and thus potential misclassification of socio-economic variables at the time of death.

The small sample size of observation led to large numbers of days with zero deaths and limited the statistical power of the analysis. Further the large number of statistical test throughout Paper I-IV increases the risk of detection of false significant associations.

The temperature measurements were obtained from a monitoring station located about 20 km outside the study area. This may not accurately represent the actual individual exposures, creating a potential underestimation of true associations. Many studies used humidity, apparent temperature and air pollution as confounding factors, but we did not have this data for the study area. We mainly used daily maximum temperature as the exposure variable, since these data were the only available, which may cause bias in the interpretation of the results. Meteorological data was collected from two different sources—one from IMD weather stations and another from the NOAA (online source) website.

While studying YLL, we assumed that deaths occurring in association with temperature are comparable to other deaths in terms of conditional life expectancy. This assumption may be further investigated.
Notwithstanding these study limitations, the study provides novel evidence to demonstrate the need for measures to mitigate the effects from environmental exposures. More notably, the study contributes to unique understanding of the weather-related health burden among rural populations in western India.

**Policy implications and future direction of the study**

The study findings draw the attention of policymakers to prioritise national and regional level health research on weather and health for countries such as India. Our study established evidence of a relationship between heat and mortality in low-resource settings. Simple preventive measures can be used during routine HDSS data collections to avoid negative effects of heat in rural populations. Our study points to vulnerable groups in the rural community. These groups can be targeted for interventions, to plan and prioritise resources and to evaluate health intervention in resource-scarce communities. Our study provides an understanding of the mediating influence of the social and physical environment (e.g. working and housing condition). To further refine the findings of these studies, there is a need to improve environmental monitoring and surveillance systems in developing countries. Research initiatives could focus on long-term data collection on climate-related mortality with the aim of understanding current weather sensitivity and predicting future scenarios. Our study findings have multiple potential policy implications for middle- and low-income countries and highlight the need for multidisciplinary collaboration of different stakeholders to tackle the challenges of environmental exposures in rural populations. There is a need to create awareness among vulnerable population groups regarding the health risks of exposure to temperature and rainfall.

Improved methods for monitoring health indicators, including enhanced surveillance of diseases that are sensitive to weather, should be developed to detect and respond to the effects of weather on human health. There is a critical need for capacity building to improve
surveillance and monitoring and, in turn, to detect changes in mortality that may be a result of global climate change. However, surveillance systems alone are not sufficient to prevent illness, and continued efforts to develop projection models should be implemented. At the same time, national efforts should be undertaken to create awareness of the health effects of extreme temperature exposure to the rural population through initiatives like campaigns involving institutions such as schools, community groups and social groups. Involvement of local decision makers is critical in recognizing the risk to their communities and effectively deploying preventive measures at the community level. The short-term measures at the community level could include public health response systems such as education campaigns regarding temperature variation-related symptoms. Therefore, future interventions (e.g. health education) targeting specific population groups such as agricultural and other outdoor workers may reduce vulnerability to extreme heat in rural India.
Chapter 5: Conclusion

The study findings broadened our knowledge of the health impacts of environmental exposure by providing evidence on the risks related to ambient temperature in a rural population in India. This study utilises the unique opportunity that is accessible by the Vadu Health and Demographic Surveillance System to conduct environmental health research. This research served to identify population groups at risk of weather-related effects as a basis for possible environmental health interventions. Results suggest a prioritisation of programs specifically on non-communicable diseases. The study also identified vulnerable population groups (low education and farmers) in relation to ambient temperature.

The effect of heat on the population is preventable if local human and technical capacities are increased for risk communication and prevention measures. These should aim at increasing residents’ awareness and at promoting adaptive behaviour in order to tackle this public health challenge in rural India.

This study clearly indicates the value of the HDSS data for exploring climate-disease exposure-response relationships. There is great potential to further refine these analyses to identify susceptible groups and hazardous climate-related events, so as to increase the resilience of the rural communities to these impacts.
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References


