Climatic Change (2008) 89:299–324
DOI 10.1007/s10584-007-9392-7

On the (im-)possibilities of defining human climate thresholds

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Received: 14 June 2006 / Accepted: 6 November 2007 / Published online: 19 February 2008

Abstract The aim of this study is to explore the way climate creates thresholds within society. Both human physiology and the human mind determine when and where climate can trigger and influence human activities. By presenting a stimulus-response model, deliberate weather- and climate- related decisions (e.g. migration, clothing) and physiological responses in daily life (e.g. sweating) are placed in a broader theoretical context. While physiological thresholds can be described quantitatively to a certain extent, subjective thresholds may be illustrated in a predominantly qualitative manner through surrogates (surveys on wants or needs). Examples from the literature on climate thresholds for humans highlight the complexity of the issue: People have different thresholds, as they do not necessarily respond to the same stimuli in the same way. At the same time, given the same stimulus, an individual may perceive it, and thus react, differently at different times in their life. In many cases, the threshold rather specifies a bandwidth or transition zone than a particular point. The level of acceptance and the cultural, technological and genetic aspects of adaptation will decide how climate may influence human well-being and contribute in setting limits to society, for example where to live, what impacts to expect, and when and what decisions to take. Knowledge of the complexity of human thresholds can be an important supplement to the analysis of peoples' vulnerability to climate change. When populations are vulnerable and thresholds are exceeded, only then will there be a measurable response.

1 Introduction

Recurrent weather extremes all over the world draw attention to the importance of climate in general, and likely anthropogenic climate change in particular, as a direct driver of human welfare, economic and social choices, and at the extreme, human survival. Throughout history, weather and climate have always acted as stimuli for human actions and triggered dangerous situations, while at the same time, opening up opportunities. There

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are cases where people were and are directly affected by climatic events, and more complex situations where climate represents only one of many influential drivers of social actions (Lamb 1995). This leads to the question of whether climatic *thresholds* beyond which a specific human action or behaviour is initiated or ends, can be specified, and ultimately how they may be measured. Two approaches may be adopted regarding the treatment of thresholds associated with human responses to climate variability and change. One approach refers to the question "Can climate thresholds for society be established or measured" and the other "Can human thresholds to climate be established or measured". This differentiation is partly a matter of semantics, i.e. how to frame the question. However, it is also a question of goal. The first question deals with the establishment and measurement of *climatic thresholds* within a particular societal context, defining a *threshold value for a climatic variable,* or a combination of climatic variables (temperature, humidity, wind, etc.) that plays a key role in the well-being of a society. For example, a temperature above a certain may be associated with heat related morbidity or mortality. Or related to seasonal climate variation, what temperature–sunshine combination makes people wear a T-shirt rather than a pullover/jacket? (Meze-Hausken 2007). It addresses the more absolute or fixed aspects of society, such as physiology like sweating, freezing, thirst, where the driver for a particular response is a change or variation in climate (Pittock and Jones 2000). The second question deals with *societal thresholds*, defined in terms of social, economic and other conditions representing the state of a society that will result in that *society reacting to a given climatic stimulus*. Here, the driver of the response is the evolution or variation in socio-economic conditions that determine whether a specified climate stress is experienced as acceptable or problematic. While climatic thresholds refer explicitly to the climatic drivers of social/individual change, societal thresholds describe conditions in the exposed (social) system. For example, a societal threshold approach might examine why a particular rainfall deficit leads to hardship for a society in 1 year, while a similar deficit in another year does not. In reality, both the climate stress and the underlying socio-economic situation will evolve and creating hazards and vulnerabilities interactively.

This paper begins by addressing the limited available literature on human climate thresholds, which by and large does not explicitly distinguish between these two approaches or questions. One rationale of this distinction relates to the primary focus for addressing a turning point. 'Climate thresholds for society' place their main research emphasis on the meteorological or climatological stimulus and have a more natural science origin while 'human thresholds to climate' accentuate the broader social-cultural baseline contributing to a turning point.

There is a third class of approaches, referred to as the engineering approach, related to the design of dams, bridges or building constructions which are affected by climate variables such as wind speed or precipitation. The design of these structures is based on calculations of tolerance (what the structures can withstand) and of the statistical return-periods of extreme events. These built structures function as intermediaries between climate and society. As they are themselves part of societal adaptation and indirectly mediate the way humans experience climate they remain outside the scope of that paper.

The scientific basis of these questions is found in Article 2 of the United Nations Framework Convention of Climate Change (UNFCCC), the stated objective of which is "…to stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent *dangerous* anthropogenic interference with the climate system". This statement has led to an extensive debate on what a "dangerous" interference with the climate system actually is. A number of papers have been published on climatic thresholds in natural biological systems (e.g. Hulme and Brown 1998; Parry et al. 1994, 1996). They focus on ecosystems or their constituent elements, discussing quantitative limits where adaptation either becomes difficult or impossible as a result of changes in temperature due to potential anthropogenic global warming. With respect to humans, many studies deal with physiological climate limits (e.g. Koppe et al. 2004). Dessai et al. (2004) in seeking to define dangerous climate change, focus on risk determination as a combination of external definition by experts and internal definition of perceived danger by individuals or societies. However, there are large gaps in our knowledge of climate thresholds relevant to human systems today, and of socio-economic thresholds for climate change in the future (Pittock and Wratt 2001; Toth and Mwandosya 2001)—no published study has attempted to combine considerations of human physiological and subjective[1] thresholds, indicating that this is no trivial task.

Many schematic models of the human consequences of climatic variability exist which emphasize the roles of vulnerability and adaptation (e.g. Jones and Boer 2005; Stern and Easterling 1999). While vulnerability refers to a state (the baseline condition) or the potential exposure to hazards with likely adverse human impacts (Brooks 2003), thresholds relate to triggers for specific reactions. People may be vulnerable to climate change, but, as long as their physiological and subjective/social–economic thresholds have not been exceeded, meaning, if they have not come to the point where they show a specific response to the climate stimulus, climate change would not have any identifiable impact on society. As an example, people may be vulnerable as a result of poverty and living in drought-prone developing regions. However, there would need to be a specific climate stimulus—alone or in combination with other factors—as the final trigger for a specific reaction, such as temporary or permanent outmigration, exceeding the resilience of individuals or societies. Adaptation, on the other hand, viewed as the ability to adjust to changed conditions (McCarthy 2001), relates to the shifting of the threshold level to a higher level, thus improving the robustness of a system (Jones and Mearns 2005).

This study of human climate thresholds is not oriented at determining the importance of climate for human response as an isolated factor. Rather, the goal is to identify the climatic circumstances as well as the contextual conditions that contribute to the existence or crossing of thresholds for specific actions. In addition, both, the “dangerous” aspect[2] referred to in the UNFCCC leading to a forced response to climate through, for example, physical acclimatisation, income generation and even human survival (climate as a push factor), and the preference response, dealing with climate as an amenity (pull factor, e.g. Frijters and Van Praag 1998; Wolpert 1996) are dealt with in this paper.

As an explorative study, the paper starts with a discussion of threshold terminology (“limit” is often used as a synonym for threshold), given the various contexts in which the term has been applied, and tries to visualize the process of approaching and exceeding a threshold for any system. Then, more specifically, a conceptual stimulus–response model is developed, focusing on how climate may create physiological and subjective thresholds to an individual. Four case-studies based on a review of the available literature supply this model with empirical material. The literature review reveals that it is necessary to move away from the concept of climatological averages (e.g. the 30-year average used by WMO)

[1] As a wider description for the human psychology, perceptions, experiences, needs and wants. See later in the text.

[2] Danger, as a function of the degree of negative effects and unacceptability of these effects, is primarily a value judgment. See Smith et al. 2001. ‘Vulnerability to Climate Change and Reasons for Concern: A Synthesis’, in J. J. McCarthy, (ed.), Climate change 2001: impacts, adaptation, and vulnerability, Cambridge University Press, Cambridge.

and a “standard person” (e.g Klima-Michel, Jendritzky 1990) when specifying human climate thresholds. As the discussion illustrates, culture and technology as well as physiological adjustment differ between regions and over time, and changes in their components modify climate related threshold levels. This complexity and the dynamics involved will assure that in most cases thresholds can be quantified only partially and are case-specific, as both the direct and indirect influences of climate on human beings and human systems differ in almost every situation. Knowledge about human climate thresholds will only provide guidelines for decision makers for emergency planning, allocation of resources for adaptation and economic development, rather than serve as a precise decision-making tool.

The perspectives discussed in this essay represent an initial effort to promote discussion of the currently somewhat vague concept of human climate thresholds. They began as a personal attempt to arrive at a coherent theoretical basis for studies of climate-related human migration, when the author was attempting to identify critical situations triggered by climatic stimuli, leading people to leave their homes. After much analysis my conclusion was that the major problem lay with the definition of what a critical situation caused by climate is: a point in time and/or situation which marks a threshold? The proposed conceptual model I am describing here, as well as the case-studies discussed, may be a starting point.

2 Definitions of thresholds

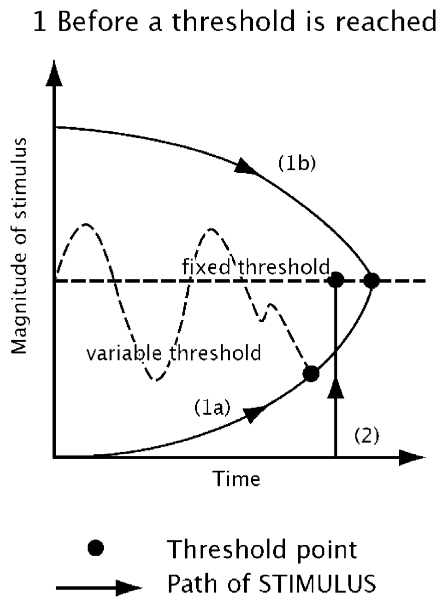
As the threshold terminology is particularly confusing, some clarity is required about its definition. The term has been widely used across different scientific schools with various meanings[3] and is only rarely operationally defined in the social sciences. One speaks of thresholds of pain, photoelectric threshold frequency, political thresholds, thresholds for stability or ecosystem thresholds. Thresholds in general determine situations where, initiated through a stimulus, something happens that otherwise would not happen. The crossing of a threshold might result in a significant reaction, or represent the start or end of an action or behaviour (e.g. the start of a riot or the melting point of ice), moving via instability out of its original equilibrium. A threshold is defined with respect to a causal stimulus and an exposure unit exhibiting a response to that stimulus. When the stimulus exceeds a certain point or value, the exposure unit reacts, and no longer functions in its usual way, either for a given time or with respect to certain elements.

A visualization of possible stimulus-response functions is depicted in Figs. 1 and 2. In Fig. 1, one can assume a fixed threshold or one which is changing over time (variable, increasing or decreasing due to system change or adaptation). The path of the stimulus which symbolises the triggering factor for a later response may emerge slowly (1 a, b) or suddenly (2), by decrease or increase in magnitude. It will then reach the variable or fixed threshold at a certain point in time, marked as circle[4]. Figure 2 illustrates the paths of the

[3] E.g. Parry 1996, Merriam-Webster’s Collegiate Dictionary http://www.m-w.com/dictionary.htm, TechEncyclopedia, http://www.techweb.com

[4] The various levels of stability, levels before a threshold is reached, are repeatedly discussed in the literature about myths or perceptions of nature, referring to different believes about the vulnerability of nature and its possibility to restore its natural balance (Holling 1979. ‘Myths of ecological stability’, in G. Smart and W. Stanbury, (eds.), Studies in Crisis Management, Butterworth, Montreal, Thompson et al. 1990, Cultural Theory. Westview Press Inc, Boulder).

Fig. 1 Schematic illustration of thresholds (before a threshold is reached). For explanation see text

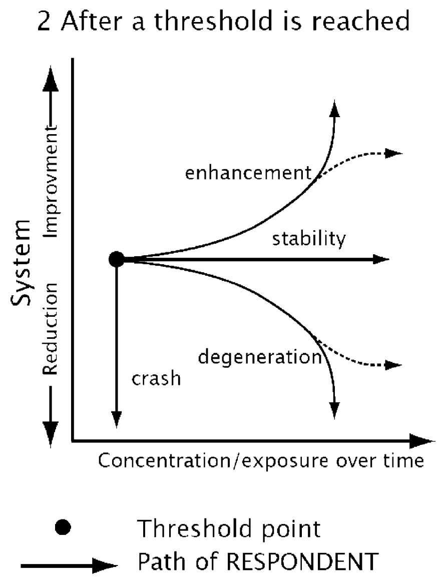


respondent after the threshold line is crossed, which is similar to models used in system ecology. The system reaches (a new level of) stability, has its functioning enhanced, degenerates, or experiences a crash, due to increased exposure over time. For example, enhancement could refer to an algal bloom in spring, during which stability is associated with optimal growth conditions in terms of the amount of precipitation, sun-light etc. The degeneration path may indicate agricultural yield reduction under a heat wave, while a sudden crash might be represented by individual human mortality due to heat stroke. In some cases, the transition across the threshold is irreversible, and a system cannot return to its prior state as the self-regulating mechanism fails (Wilson and Bryant 1997, pp.26). It may, however, recover and reach a new point of stability (dotted line in Fig. 2). In many cases, the system exhibits a memory or lagging effect in which the previous events influence the order of subsequent events (hysteresis, not shown). Another feature not evident in Fig. 2 concerns the resilience of a system, when the exposure unit restores its system balance after a certain recovery time, as well as the incorporation of the consequences of possible positive and negative feedback processes.

The threshold concept is similar to the concept of critical load. The term 'critical load' is often used in biology and ecology when referring to a threshold value for pollution. These are loading rates that are thought to approximate the capacities of the ecosystem to assimilate the pollutants (Suter and Barnthouse 1993, p.352). It is presumed that absolute values for system response can be found to establish a response function. The concept of critical loads is now accepted as a basis for political decisions on emission reductions of sulphur and nitrogen[5].

[5] Protocol on the Further Reduction of Sulphur Emissions, Oslo, on 14 June 1994, to the 1979 Convention on Long-range Transboundary Air Pollution on Further Reduction of Sulphur Emissions.

Fig. 2 Schematic illustration of thresholds (after a threshold is reached). For explanation see text



3 Human thresholds to climate

While the threshold concept presented so far is oriented strongly towards natural science, its application to the investigation of human thresholds to climate change also needs to include social science aspects. These are in many ways less easy to grasp quantitatively, as they include capacities for action and therefore resonate with the notion of knowledge (N. Steher, pers. comm.). This means that human climate thresholds are a function of a host of factors, for example, some affecting the body and depending on one's health status and age; others are determined by ideology and culture (ibid.)[6]. Thus, a specific climatic condition is not a sufficient cause for reaching a threshold which initiates a response; physiological, subjective and social conditions have also to be taken into consideration as well. Max Weber (quoted in Granovetter 1978) gives the following example: "If at the beginning of a shower a number of people on the street put up their umbrellas at the same time, this would not ordinarily be the case of action mutually oriented to that of each other, but rather of all reacting in the same way to the like need of protection from the rain." Individuals who appear to react to one another (socially determined) are actually individually responding to an external influence (weather stimulus). Still, someone's umbrella behaviour may be determined by that of others. Someone may have a new suit to protect them from rain; another has a cold and does not want to get wet, and a third one just bought a new umbrella to be tested at the first occasion.

Figure 3 presents a conceptual stimulus-response model which tries to capture these complex interactions. The STIMULUS is a climatic event, whereby the time frame of the event ranges from short-term climatic hazards or stochastic meteorological situations to slow climatic change, with or without superimposed changes in variability. In a statistical

[6] For a historical analysis of the complexity of factors contributing to thresholds of societal performance (collapse of cultures), see e.g. Diamond 2004, Collapse: how societies choose to fail or succeed. Viking, New York.

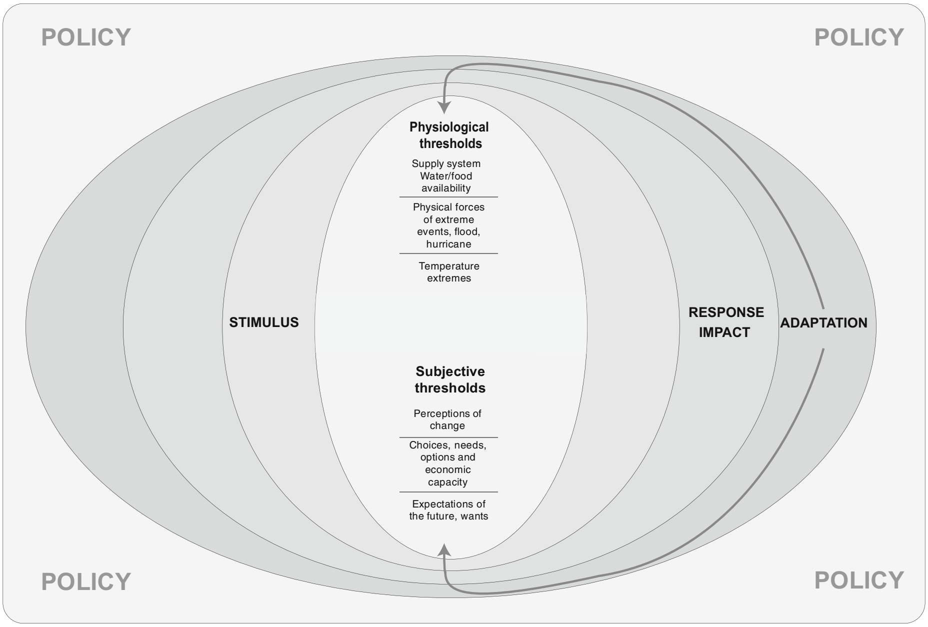


Fig. 3 Conceptual model of a stimulus-threshold-response relationship. When a stimulus reaches a threshold, it will trigger a certain response or impact. Adaptation, performed within a certain policy background, can act upon the threshold level and thus, change the (likelihood of a) response. For further explanation see text

sense, several possibilities exist if the variable is normally distributed: a) a change in the mean (e.g. increase in the number of hot days and more record hot weather, but at the same time fewer cold days); b) a change in variance (e.g. increase in probability of both hot and cold events as in the value of the extreme events); c) a combination of both, change in mean and variance, altering the occurrence of climate extremes in many different ways (Houghton 2001; Mehl et al. 2000: Fig. 2.32).

The event is described by climatic parameters such as temperature, rainfall or wind speed, alone or in combination with each other, the frequency of the anomaly and the geographical size of the affected area. In some cases, climate directly influences human physiology and the behaviour of individuals and society at large. In other cases, the influence on humans is indirect: a baseline ecosystem is perturbed by the stimulus and encounters first order impacts (bio-physical response) which affect the exposed human system (e.g. reduced permafrost in steep areas may increase avalanche danger; see e.g. Stern and Easterling 1999).

This stimulus approaches a (climatic) threshold at which tolerance levels are exceeded. This may also be associated with behavioural thresholds, i.e. qualitative changes in human behaviour (choice and timing of an action or decision). As many reactions can be viewed as secondary impacts of climate extremes and variability, a threshold can also be defined where a primary impact leads to a secondary impact, so that thresholds would be measured in terms of the extent or severity of the primary impact. PHYSIOLOGICAL THRESHOLDS to climate are encountered due to direct exposure to climate parameters such as temperature extremes, or more indirectly due to storms and floods directly harming individuals, as well as due to influences on the food and water supply-system. The SUBJECTIVE THRESHOLDS cannot be approached in a straightforward manner, thus, surrogates have to be found by e.g. mental maps, surveys or statistical relationships. These thresholds may be grouped into those related to perceptions of climate, general wants, choices and capacities of an individuals or society at large, and those related to future expectations of weather sensitive activities and situations. These surrogates reflect a broad range of subjective influencing factors for threshold determinants comprising the time horizon which the stakeholder takes into consideration for decision making: the past, the present and the future. Sometimes a threshold can be established *a priori*, through planning in advance of an event, other times only *a posteriori*, when then event has occurred (Asfaw 1984).

Exceeding a threshold, in other words experiencing an unacceptable situation or one which offers more suitable alternatives, means that the human subject experiences a response or impact. Although the distinction is somehow artificial, a RESPONSE refers to a reaction to a stimulus done *by* a system. For example, the body perspires in reaction to increased temperature, or the human skin responds to sun exposure by producing melanin. An IMPACT, on the other hand, is the direct outcome of a stimulus, i.e. something that is done *to* a system (N. Brooks, pers. comm.; e.g. damaged by a falling tree in a hurricane).

Depending on the impact, a person will try to adapt to the stimulus. ADAPTATION is the adjustment *to* a response or impact with the possible consequence of increasing/reducing the threshold level[7]. In some cases, adaptation is deliberate and planned, such as bringing an umbrella in advance, in other cases it is purely reactive, when buying the umbrella from a stall on the street as it starts to rain. Someone who does not want a tan may apply sun cream to mediate the physiological response to increased exposure of sunlight. Adaptation can be technological, cultural (habituation) or physiological (acclimatization), a combination of these elements, or simply related to postponement of decisions and actions. If the adaptation is successful, it will strengthen a system's capacity to withstand a similar stimulus (e.g. altitude climate therapy for asthmatic children), representing a reflexive learning process, as illustrated in Fig. 3, by the arrows going from adaptation to the physiological and social thresholds). Mitigation, as one form of possible adaptation (reducing greenhouse gases) can feed back to influence the stimulus as well, and thus ultimately change the threshold (or even reduce the possibility that the threshold in terms of a hazardous level will be reached), but only over relatively long timescales[8]. Thus, it is not considered as relevant in this model. The POLICY response in the conceptual model (Fig. 3) is the broader, fuzzy background in which the system operates, and which stimulates or hampers potential adaptation (e.g. institutional barriers, laws and regulations).

Presenting the stimulus-response relationship in shells, rather than with arrows, allows a dynamic perspective. It permits us to start from the inside—the thresholds factors—and relate them to the climate stimulus which evokes a certain impact or response, and then leads to some adaptation. Questions could be considered such as how a certain weather extreme influences migration decisions. Vice versa, the model could be entered from the outside, starting from the policy side and moving inward in the onion-layers. Questions

[7] In many instances in the literature, "response"is used as a synonym for adaptation in the way what one decides to do about an experienced change (e.g. building a house on poles to accommodate sea-level rise).

[8] Even in the event of a rapid reduction in CO_2 emissions, atmospheric CO_2 concentrations will continue to increase into the next century, increasing global temperature for many decades and perhaps centuries compared to pre-industrial levels. See e.g. Fig. 5 Summary for Policymakers, IPCC TAR.

may be raised such as what type of policy contributes to improving threshold levels and thus the coping capacity of a society. Nevertheless, the starting point in this model is the individual, although, with regard to adaptation to climate and possible thresholds, it is the societal response which ultimately matters. Collective behaviour emerges from the frequency distribution of the individuals and the interaction between individuals, whereby the individual response may be quite different from the societal one[9]. Even if this provides only a very simplistic explanation, any more detailed debate on the relationship between individual and society would go beyond the scope of this study.

In the following discussion, a number of examples from the literature are selected, supplying the model (Fig. 3) with empirical material (Table 1). These examples demonstrate how physiology and subjectivity influence the cause–effect relationship between climate and human impact/response. The selection of case-studies is arbitrary but presents situations in which climate variables are generally accepted as having a clear physiological or subjective influence, although all case-studies display some attributes of both.

Physiologically, humans are directly affected by climate via thermal extremes (heat and cold-waves, in combination with humidity, wind and solar radiation), water stress and events such as floods and storms. Impacts of such extreme exposure can lead to morbidity (especially resulting from heart and lung diseases), physical and psychological trauma, for example where climate extremes trigger complex disasters, and increased mortality rates (McMichael 1996; McMichael et al. 1996), as well as to acute or chronic malnutrition and vector born diseases (WHO 2003). Impacts will vary according to the individual sensitivity of the human body, where sensitivity is defined as the 'rate of change in health outcome per unit change in climate' (McMichael 1996). On a societal level, impacts will vary according to demographic factors such as the percentage of elderly people in the population and general health status. Past experiences, perceptions and expectations will affect the extent to which the climate itself determines thresholds triggering changes in behavior, management or regulations.

3.1 Thermal thresholds

There is no doubt that unclothed people without shelter are physiologically restricted from living in extreme climatic regions. Temperature sets limits for performing physical activities and for body functions in a state of rest. Within the ambient temperature range of 25 to 27°C, referred to as the "critical air temperature", an unclothed person at rest can maintain body temperature balancing heat production and heat loss (Frisancho 1993). But with long-term exposure to temperatures above 32, 35 or 40°C (depending on which literature source is cited), critical threshold for impacts on human and natural systems emerge (Cubasch and Meehl 2001). The critical temperature varies geographically, as long-term acclimatization takes place (Frisancho 1993; MacKellar et al. 1998). Because of this site specificity, there is no standard in defining e.g. heat waves (Koppe et al. 2004). The principal criterion for a heat wave is that a society is susceptible to or unable to cope with a certain temperature event (Koppe and Jendritzky 2005). The definition of a heat wave differs between European countries, some referring to temperature, in combination with

[9] See e.g. ‚Tragedy of the Commons' Hardin 1968, 'Tragedy of Commons.' Science 162, 1242-., or ‚The Prisoners' dilemma' Tucker 1950. 'Prisoner's Dilemma. Guest lecture at Department of Psychology, Standford University', discussed in Duncan, L.R. and Raiffa, H. (1957), (ed.), Games and Decisions, New York, pp. 94–102.

Table 1 Presentation of the four case-studies

Case-study	Stimulus	Physiological thresholds			Subjective thresholds			Response impact	Adaptation	Policy response
		Supply system	Physical forces of extreme events	Temperature extremes	Perceptions of change	Choices, needs, capacity	Expectations, wants			
Thermal extremes	Temperature			Heat/cold events	Time of the year, frequency (i.e. are such events "normal"?)	Shelter, heating, cooling availability, social isolation	e.g prospect of cooling later in the day	Heat stress, sickness, freezing to death, heat stroke	Buying air conditioning, thermal adjustment of the body, siesta during mid-day heat	Heat alerts, defining emergency thresholds, emergency response plans and training
Water availability	Precipitation (Temperature/ Evaporation)	Drinking water, food availability	Flooding—if precipitation excess		Unused to water deficiency/ harsh conditions	Price of water, distance to well, other indirect sources of water (e.g. milk), general health condition	Expected duration of crisis, recurrence—despair when crises return with high frequency?	Die, migrate, health problems	Building dams, resettlement, water rationing	Providing emergency help, long-term plans for building wells, resettlement, education
Tourism destination choice	Combined temperature, precipitation, cloudiness, wind		Likelihood of extreme events	Heat waves	Experiences from earlier travels, comparisons with other destinations	Destination options, economic restrictions, distance, reason for holiday	Image of destination, weather forecast	Choosing a certain destination, choosing a specific holiday type/ activity (sport/ski—culture)	Tourist: switch from camping to hotel, change expectations about destination Hotel industry: Change image/ facilities	Marketing, Adjusting tourism infrastructure Adjusting seasons—from one-season to all-year round or vice. versa.
Migration–both pull and push	Temperature, wind, precipitation (too much or too little), extreme events	Resource availability	Storms, floods, sea-level rise	Unfavourable to health or pleasure	Environmental degradation, Climate improving at prospective destination	Financial capacity, health, comfort needs for elderly, able to combine with job elsewhere	Climate change prognoses, better life quality somewhere else	Migration	Better conditions at new destination	Settlement planning, improving conditions at place of departure to reduce migration, adjustment of infrastructure demands at destination

Table 2 Criteria for releasing temperature warnings in different European countries

Country	Criteria for releasing the warning—Temperature threshold	Reference
Latvia	33°C	Air temperature
Malta	40°C	Maximum air temperature
Serbia and Montenegro	35°C–20°C	Maximum–minimum air temperature
Turkey	27°C and relative humidity >40%	Air temperature and humidity
The Netherlands	Minimum 5 days with 25°C including 3 days with 30°C or above	Maximum air temperature and duration

Examples based on (Koppe et al. 2004) and (Huynen et al. 2001)

humidity, or duration of a certain critical temperature (Table 2). This results in different temperature thresholds for initiating heat alerts through the public health authorities and national meteorological services (Koppe et al. 2004).

Heat alert temperature differs from those threshold temperatures beyond which excess mortality occurs. While threshold temperatures indicate the pure physiological temperature–mortality relationship, heat alerts are derived politically. They are based on the unique local response capacity of a region and the preparedness of its health system, as well as on factors such as the prevalence of heating/air-condition systems or housing insulation. Figure 4 presents a V-shaped relationship between temperature and mortality, and a comfort temperature range, a threshold spectrum of cold to warm regions. In both cold regions (e.g. Oslo), with low threshold temperatures, and warm/dry areas (e.g. Valencia), with a high threshold temperature, excess cardiovascular and respiratory mortality increase considerably per 1°C increase in temperature above a certain critical value (Table 3).

Experimental research (Baranowska and Gabryl 1981) has demonstrated the existence of temporal variability in thresholds above which negative health impacts occur. Categorizations such as heat load based on perceived temperature (Fanger et al. 1970; Koppe and Jendritzky 2005) or subjective thermal sensation (Blazjczyk oral pres. at ICB 2005 Baranowska and Gabryl 1981) show an inverse U-shape for temperate zones during the year (Fig. 5). This would imply that heat waves early in the summer (when physiological processes as well as dressing habits have not adjusted to the occurrence of sudden extreme) have a more drastic impact on health effects than heat waves occurring later in the season

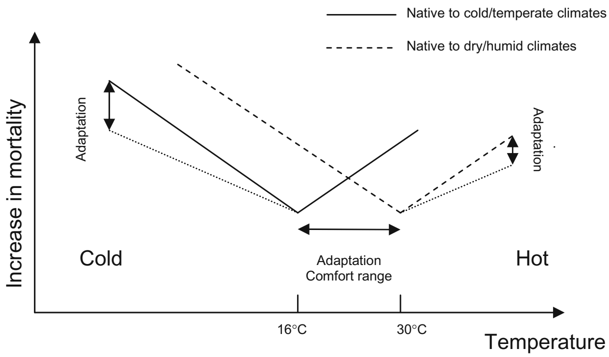


Fig. 4 V-shaped relationship between mean daily/monthly temperature and mortality. Adapted from Martens (1998), with kind permission from Elsevier Pub

Table 3 Impact of temperature on cause specific mortality: Change in mortality rate from respiratory and cardiovascular diseases per 1°C increase in temperature above the given threshold (95% confidence intervals)

Place	Temperature threshold (°C)	Respiratory mortality	Cardiovascular mortality
Oslo, Norway	10.0	4.7 (2.2, 7.1)	0.8 (−0.4, 2.0)
The Netherlands	16.5	3.11	1.13
Hungary	21.0	3.6	1.8
Valencia, Spain	24.0	5.7 (−2.9, 8.2)	2.9 (−0.4, 7.4)

(Koppe et al. 2004), Corobov oral pres. at ICB (2005)

(Sheridan and Kalkstein 2004). The converse is likely to be true for cold waves occurring early in the winter. The important factor is the relative change in temperature, rather than its absolute value. As people do not die from high temperatures, but rather from heat load, such short-term adaptation must be included in heat warning procedures (Koppe and Jendritzky 2005).

For determining critical temperature thresholds, it is essential also to take cultural factors into account, especially when estimating excess mortality due to thermal extremes. For example, Sheridan and Kalkstein (2004) found that reduced mortality in Rome during the hottest month (August) is unrelated to meteorological conditions, but the apparent result of holiday migration out of the city. Another component of human temperature thresholds is the psychological one. As a partially mental construct (Koppe et al. 2004), thermal

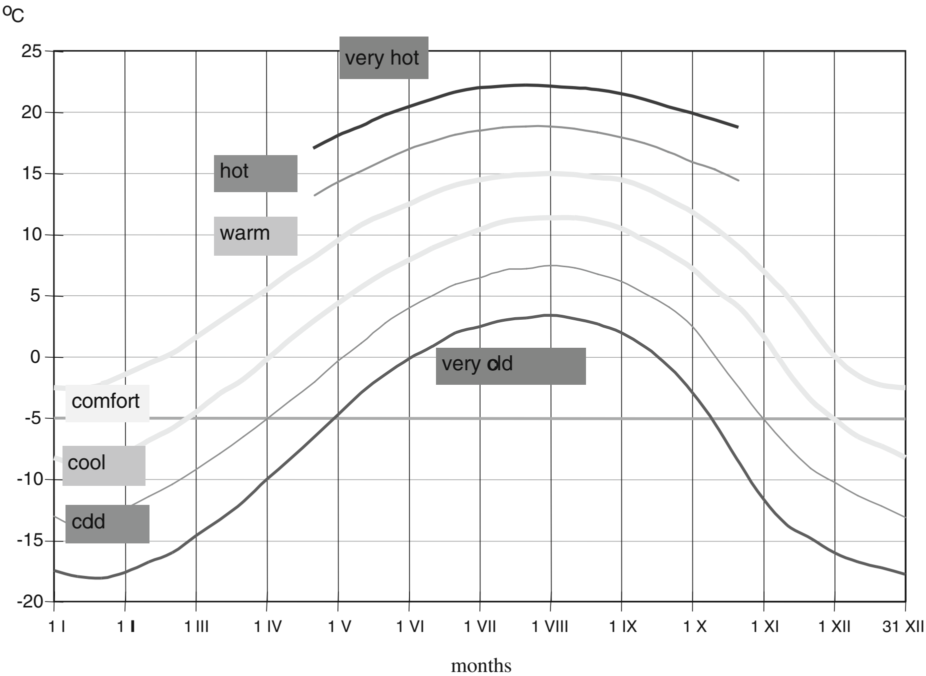


Fig. 5 Seasonal variability of thermal sensation scale (in the area of 7–8°C mean temperature in Poland). Adapted from Baranowska and Gabryl (1981)

expectation factors mean that after severe heat stress (such as during the middle of the day during summer), even a slight cooling and expectations of further cooling after sunset create perceptions of thermal comfort (Becker et al. 2003). Similarly, in Tokyo, office buildings have increased their indoor temperature from 23 to 27 degrees Celsius and people manage to adapt due to their change in expectation of comfortable temperature (De Dear, personal communication at IJB 2005). Clothing decisions are partially determined by our memory of thermal environments yesterday, and partially by what they are forecast to be like today (Morgan and de Dear 2003).

Cultural and technological adaptations to climate have not only facilitated physiological adaptation but at the same time have created new stressful conditions (Frisancho 1993). Urbanization has generated heat islands, leading to heat related mortality (Dessai 2002), even if there is not necessarily a straightforward quantitative relationship between percentage increase in mortality and 'level of urbanization' (Sheridan and Dolney 2003). Traditional house construction (enclosed courtyards and small windows in very warm areas (Bouchair and Dupagne 2003; Brooks et al. 2005), wind protected location and windowless stone walls towards the primary wind direction) have given way to modern concrete, glass and steel constructions, with the side effect of dramatically increased energy costs to maintain optimal indoor climate. For those who have resources, health reasons and available choices can lead to migration to increase human comfort in more pleasant climatic regions (Wolpert 1996), an issue which is discussed in more detail later.

3.2 Water thresholds

In dryland regions, rainfall rather than temperature is seen to be the limiting factor for human well-being and survival, as rainfall deficits can lead to serious water stress (Oldfield 2000). Water stress here means insufficient amounts of water causing dehydration (including reduced soil moisture for crops, pastures), seasonal mismatch between supply and demand, poor water quality, or water which is available but at too high labour or economic costs. Drinking water in many regions is directly related to precipitation (in terms of amount and timing), by filling reservoirs and (seasonal) rivers or by feeding glaciers with snow which provide drinking water as a result of seasonal melting. Glaciers provide drinking water in many regions, especially in the Himalaya-Hindu Kush region or in the South American Andes. Any increase of melting in the spring will result in a pattern with plenty of water in the near future followed by an abrupt shortage when glaciers have melted (Barnett et al. 2005) as water will not be replaced. People will not sustain normal body functions or guarantee healthy reproduction without a minimum amount of potable water over prolonged periods. When the water source is several kilometres away from a person's home, the minimum daily requirement is 2–4 l for drinking and cooking. Consumption is related to access, so when a water source is close to the home, total water demand, including purposes other than drinking, increases significantly by up to 20 l/day in many rural areas of developing countries[10]. The author's own field observations indicate that the Afar pastoralists in northern Ethiopia, an area with daytime temperatures in excess of 40°C, manage during periods of drought with as little as half a litre of fluid per day and water fetching distances of up to 2 days. In the same area, the recently in-migrated Tigrinian farmers who are used to a cooler climate had to leave the area during a period of acute water scarcity. They considered water access >6 h away as a threshold of endurance. These

[10] http://www.fao.org/docrep/s1250e/S1250E1d.htm#Animal handling facilities.

different thresholds may be related partly to genetic adaptation to these harsh conditions over time, and partly to available choices, expectations and experiences, or simply of acceptance of these circumstances (Ulijaszek 2001; Vargas 2001)[11].

Sufficient nutrition is another physiological requirement that is critically but indirectly influenced by climate. An adequate balance between rainfall, temperature and evaporation to enable crop production is one prerequisite for a good harvest and thus food security. Household food security is, however, very complex. As climate may play only a minor role along with factors such as trade and entitlements in determining security (Maxwell and Frankenberger 1992; Sen 1991), it is practically impossible to establish thresholds for a climatic conditions which would threaten food availability at the regional level[12].

Nonetheless, there is an important link between temperature and water thresholds, such as heat-related mortality increases due to dehydration: Sufficient fluid intake during heat-waves is essential, as water and sodium chloride, the most important physiological constituents of sweat, are necessary for cooling the body (Koppe et al. 2004).

3.3 Climate thresholds for tourism

Climate and weather is an important criterion for choosing a tourism destination (Didaskalou et al. 2004), and can determine the appeal of a location, in absolute terms or relative to other destinations. The climatic facets of tourism are related to thermal and bioclimatic[13] aspects, the nature of individual weather events (storms, rainfall) and aesthetics (sunshine, cloud cover; de Freitas 2003). For the potential tourist, the mean climate values determine the choice of destination and at what time of the year to travel, relative to the type of holiday planned (skiing, bathing, city, health). Weather forecasts and on-site experience will determine what clothes are seen as appropriate and how time is spent (in- or outdoor). For the tourist sector, climate sets limits to the overall appeal of a destination, the type of infrastructure to offer, the possible length of the tourist season and the nature of promotion and marketing campaigns.

The evaluation of a tourist climate threshold, i.e. a limit with respect to the suitability and attractiveness of a destination under current or potential future climate, is achieved by a variety of methods. Some evaluations are based on modelling behaviour on arrival or tourist expenditures as a function of weather and climate (Hamilton et al. 2005), calculating the global mean optimum temperature for tourism to be between 16.2 and 21°C (Bigano et al. 2005; Hamilton and Tol 2004; Lise and Tol 2002). Such evaluations have also identified values for individual countries. These values are not subjective perceptions of climatic comfort, but are extrapolated from the statistical relationship between tourist demand and the climatic characteristics of a country, yielding a value of the temperature of the

[11] In general, to demonstrate such an adaptation is relatively challenging. This would require separating low water needs caused by genetic differences between people and low water needs caused by differences in developmental experience and habituation, without genetic differences (Kenneth M. Weiss, personal communication).

[12] Although Tarhule and Woo (1997 found that when cumulative rainfall deficit falls below 1.3 standard deviation of the long-term mean, considerable famine occurred in Nigeria during the 20th century. (Tarhule A., and M. Woo, Towards an interpretation of historical droughts in Northern Nigeria. *Climatic Change* **37:** 601–616).

[13] As the combined effect of temperature, humidity, wind and radiation.

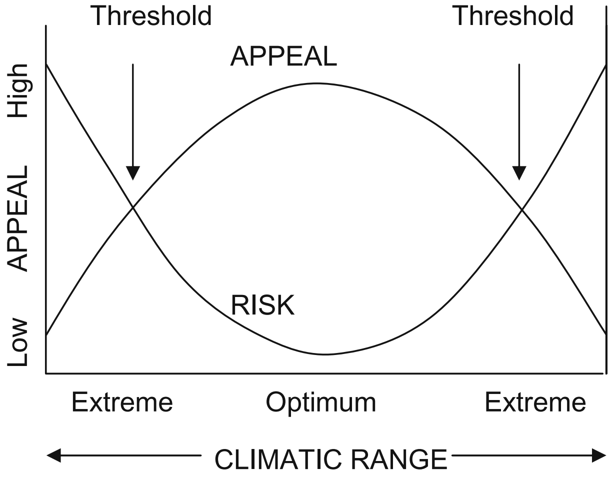


Fig. 6 Schematic representation of relationships between a climatic range and tourism potential. The climate potential of a particular location is a function of its climate and of the risks (e.g. to safety, profit, comfort) that weather may impose (de Freitas 2003). With kind permission from Springer Pub

destination country that maximises total tourist arrival in that country (Bigano et al. 2005). How these optimum temperatures may be verified, considering that many countries have both winter- and summer seasons and offer recreation activities with various dependencies on weather and climate, is difficult to comprehend. Furthermore, geographical location and remoteness also play a role in people's decisions on where to spend their holidays. de Freitas (2003) generalizes the problem by describing a climatic range in which tourism is possible for a certain location (Fig. 6). Exceeding the threshold means a high weather/climate risk related to safety and economic viability, as well as an increase in discomfort and dissatisfaction for tourists, resulting in a decrease in arrivals.

The verification of tourism thresholds can be achieved through preference studies and hypothetical choice questionnaires (Braun et al. 1999; de Freitas et al. 2004). For defining indicators of attractiveness of a certain weather type, de Freitas (2004) applies a Climate Index to Tourism (CIT). It comprises thermal, aesthetic and physical climate components where people classify a certain weather condition on a scale 1 (unacceptable) to 7 (ideal). He found that for beaches in Australia, the ideal atmospheric conditions are "slightly warm" in presence of scattered clouds and low wind (<6 m/s). Cloud cover >40% had the effect of reducing the aesthetic appeal by 30%. However, it may reasonably be expected that aesthetic thresholds for cloud cover will differ between a surfing beach in Australia and, say, a beach in western Norway: while one destination appeals through its mild lovely atmosphere, another attracts through its wild forces of nature.

Another method for defining tourism thresholds is based on thermal indices and bioclimatic considerations, (e.g. Matzarakis et al. 2005a; Matzarakis et al. 2005b). Based on the Physiological Equivalent Temperature PET[14], bioclimatic maps have been developed for the identification of e.g. climatically driven variations in the "healthiness" of resorts for

[14] PET represents a thermal index, which is based on the human energy balance of the body. PET is defined as the air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed. It includes air temperature, mean radiant temperature, air velocity and water vapour pressure. For the description of the effect of the thermal environment on humans, see: Höppe 1999, 'The physiological equivalent temperature - an universal index for the biometeorological assessment of the thermal environment.' Int J Biometeorology 43, 71–75.

various heart- and lung related diseases or areas and seasons with various levels of heat stress (Fig. 7).

Changes in climate have the potential to affect tourism thresholds, changing the suitability of a destination for a specific tourist performance (such as beach erosion due to sea-level rise, or the loss of snow in alpine zones). Modelling impacts under an assumed 1°C increase for 2025, Hamilton (2005) arrives at a turning point for a country's attractiveness as 14°C air temperature, meaning that if a cool country gets warmer, it first *attracts* more tourists, until it gets too warm and starts attracting fewer tourists. For *generating* tourists, the turning point lies at 18°C, below which fewer tourists are generated. Although such calculations are somewhat simplistic, for reasons similar to those mentioned earlier with respect to destination country temperatures and the maximisation of tourism income, it is likely that many countries which currently experience low mean temperatures will become more attractive as holiday destinations as their mean (summer) climate becomes warmer, either as a direct result of more comfortable temperatures or because their climate is more appealing that that of the countries generating tourists. Similarly, warm destinations, such as southern Spain, may become less attractive (Hamilton and Tol 2004). Figure 8 illustrates how an increase in mean temperature would affect the length of the tourist season in a maritime resort, thus shifting the seasonal thresholds further outwards. In mid-latitudes with maritime climates, the bathing season experiences a greater increase in length than the tourist season in a site with continental climate.

Nevertheless, Lise and Tol (2002) suggest that tourists probably do not care much, or only indirectly, about climate change. They simply substitute one destination for another or one travel date for another, as long as vacations are not tied to fixed seasons (school or national holidays). They may also learn to adapt to a different climatic state, thus increasing their threshold for acceptance. For the tourism industry, this substitution will certainly encourage

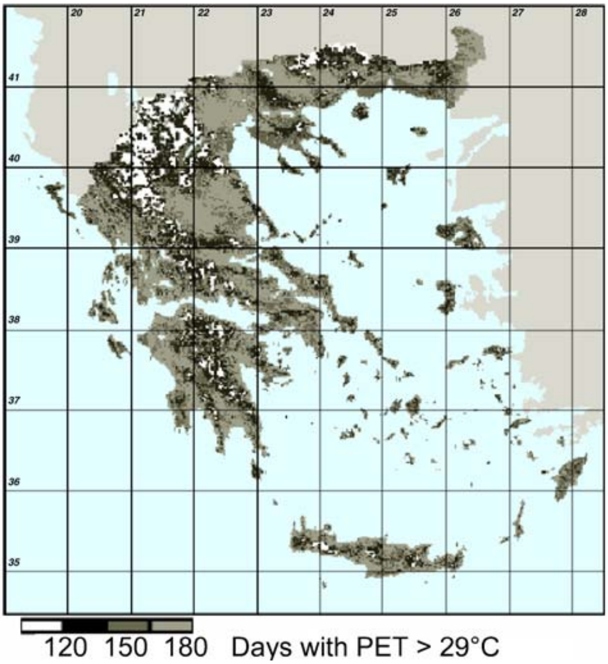


Fig. 7 Geographical distribution of the frequency of days with a physiologically equivalent temperature (PET) over 29°C in Greece. This represents thermal perception in the range of moderate to high heat stress (Didaskalou et al. 2004)

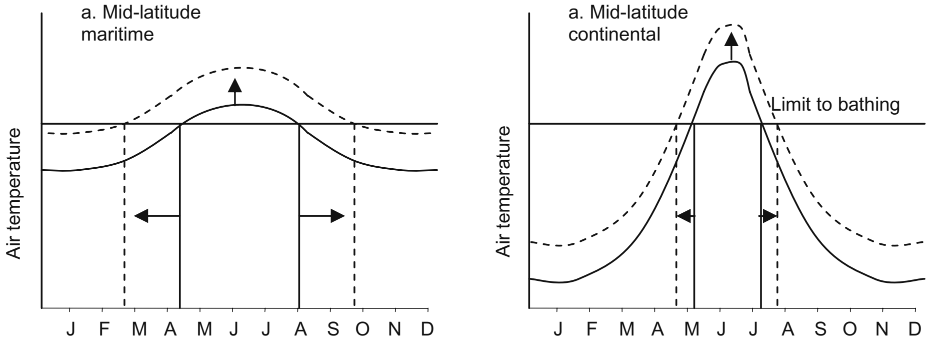


Fig. 8 Change in seasonal length for e.g. beach tourism due to incremental increase in temperature. Adapted from de Freitas (2004), with kind permission from the author

more effort in terms of marketing strategies, image correction or adjustment of infrastructure. Alpine regions with only winter-season tourism would have to offer alternative attractions or try to market another season/sector, while Mediterranean locations prone to heat waves might move their main season to the spring and autumn.

3.4 Migration thresholds

Similar to the process of selecting a suitable holiday destination, pleasure-related migration is undertaken by those who have the flexibility and capacity to do so, in order to increase their human welfare. Behavioural research on environmental preference migration reveals reasons for movements, and climate is a key factor (Svart 1996). Acting as a pull factor, climate influences health, clothing, and leisure activities, and acknowledging the vast array of other factors involved, may trigger decisions to move to another location. In a survey, desire for winter sunshine, summer weather with low humidity and afternoon temperature around 26°C, are cited as representing the most attractive climate conditions in the US, consistent with physiological research on human thermal comfort (Svart 1996). In regions with harsh climates, such as Northern Norway, a series of anomalous cold and rainy summers can trigger out-migration, as people reach their threshold of temperature acceptance, partially encouraged by TV pictures of beautiful summers in the south of the country (Mook 1978, unpublished manuscript). In the US, between 1940 and 1990, the average February temperature consumption[15] has increased from 1.44°C to 2.7°C, indicated in Fig. 9, suggesting an increase in the threshold temperature for settlement (Cragg and Kahn 1999). The nation's median location for settlement (dividing the population in half in north–south and east–west directions) shifted during those 50 years 177 km west and 120 km south to Darke, Ohio. Of this shift, the group consisting of people over 64 years in age makes the greatest contribution (ibid.), as a result of migration of this age group towards Florida, California and the general US sunbelt. Eradication of tropical diseases and introduction of air-conditioning are certainly crucial to this development (Wolpert 1996). For the elderly, as well as for people with certain chronic diseases such as rheumatism or asthma, the origin of migration may be physiological (Svart 1996), and as such, the individual threshold for migration may be lower than for the mean population.

[15] Temperature consumption here refers to the mean (February) temperature which the average US citizen experiences at his/her residence location.

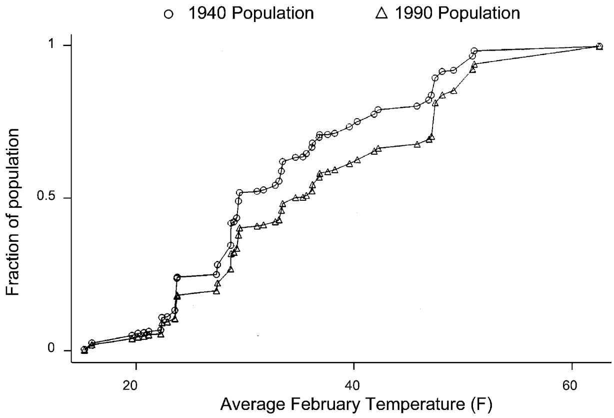


Fig. 9 Climate consumption CDF (cumulative distribution function expressed as a fraction of the population) in 1940 and 1990 in the United States, indicating that more people consume higher mean winter temperature today than some decades ago (Cragg and Kahn 1999). With kind permission from Elsevier Pub

As a substitute for measuring climate thresholds for migration related to amenity, house prices and earnings at a destination can tell us how much households are willing to pay for "optimal" climatic conditions (Cragg and Kahn 1999; Maddison and Bigano 2003). In this way, climate becomes capitalized into property prices and wages. Looking at a number of Italian cities, Maddison and Bigano (2003) calculated through a hedonic method[16] the "price" of climate variables through households' willingness to pay to relocate in a particular climatic region. They found that all households dislike high winter precipitation and high mean summer temperature. In Milan, prone to winter fog, householders are willing to pay significantly more for a marginal increase in clear sky. By calculating the utility change of living costs for a 2.5°C increase in global mean temperature, Maddison (2003) suggests an increase in amenity values for households in Northern Europe and little change in the rest of Europe. For Africa and countries close to the equator, he suggests decrease in amenity values with impacts on migration patterns. Nevertheless, there are, in many instances, certainly other factors that override climatic preferences in determining residential locations. To extract the importance of climate in monetary terms, or vice versa, determine the value of living a specific climate, needs to be seen as an economic approximation rather than a manifested measure.

Where climate is not an amenity, and thus does not invoke voluntary actions, but a necessity to income generation and survival, it is mostly intra- and interannual variability in precipitation and extreme events such as hurricanes or flooding which contribute to disaster evacuation and even permanent out-migration. Ethiopia is a famous example for drought, famine and mass-migration. There, when trying to establish a relationship between rainfall anomalies and number of migrants or affected people, a number of restrictions show up (Meze-Hausken 2004): Oral testimonies collected during the author's own field-work suggest that youngsters, whose parents once had to migrate due to extreme drought and resulting famine, but later returned, state that they are more likely and certainly faster to out-migrate permanently in the event of another rainfall failure. Thus, they may have a

[16] A Hedonic calculation is basically a regression used in economics to estimate demand or prices, adjusting for intrinsic values of a good such as substitution effects and quality adjustments. In real estate economics this would include not only the price of houses based on quality or size, but e.g. distance to city centre or, as in this case, various climate attributes (Nelson 1978, 'Residential choice, hedonic prices, and the demand for urban air quality.' Journal of Urban Economics 5, 357–369).

lower threshold than their parents in terms of what to accept as still manageable in terms of climatic anomalies, and their perceptions can aggravate a situation and even "produce" a drought (Meze-Hausken 2004). Further, it can be argued that annual rainfall deficits have a cumulative effect (Tarhule and Woo 1997), as a succession of drought years will lead to a worsening of a drought overall, especially when one refers to agricultural rather than climatological drought (Meze-Hausken 2000). This emphasizes that it is not necessarily the exceedance of the threshold itself which is important, but rather the *frequency*, in this case, re-occurrence of drought events, with which the threshold is exceeded (Arnell 2000). Thus, a threshold cannot be defined by a rainfall value alone, but in combination with intensity, frequency and regional distribution of precipitation, as well as a number of other environmental variables (e.g runoff, evaporation, requirements of the vegetation, availability of technology). Cultural differences also play an important role. For example, while farmers had to migrate during the 1984/85 drought to aid camps in a region in Northern Ethiopia (the Afar zone), pastoralists managed to stay. They slaughtered animals, lived off camel milk and accepted water fetching distances with up to 2 days march, much more than the sedentary farmers would tolerate. Places that become temporarily or permanently abandoned by one society due to perceived environmental or climatic stress may be acceptable to others, who are maybe less demanding or more adaptable. Douglas (1978) refers to this as 'the credibility about weather derived from social usage', the ability to cope with weather reinforced by people's habits and familiarity. She investigated two tribes living on opposite sides of a river in Zaire. These two societies had different agricultural calendars. The tribe which had its only agricultural activity during the dry season considered this as unbearably hot, whereas the other tribe, employing a year-round agricultural system, regarded the dry season as pleasantly cool. This indicates the presence of different thresholds in the same locality and similar climatic-environmental context. By comparing perceptions and memories of disastrous drought years in Ethiopia with meteorological data, the years remembered as worst do not always fall together with poor rainfall (Fig. 10). 2002 was declared as the worst drought in Northern Ethiopia in human memory. Nevertheless, compared to the 1984 drought, no migration movement was registered (Meze-Hausken 2004). The threshold for migration caused by rainfall deficit was lifted considerably, due to the fact of an early intervention by the official agencies and food-aid supply at the local level, as well as political stability. This proves that "climate per se is seldom the root cause of migration, but rather one more factor that exacerbates the already difficult conditions under which people attempt to cope with their changing environments" (Kritz 1990).

Both examples, tourism and migration, are certainly influenced by social factors. Granovetter (1978) describes this in his model of thresholds of collective behaviour. There, he explains that whether, and when, someone participates in an action (do/don't travel or migrate) depends on how many other people chose which alternative. Some may act early, thus having a lower threshold; some need many others to have taken action first, before acting themselves. This would indicate that the total threshold of a society cannot be described as a point value but through a spectrum with a lower and upper margin. The more rapid and intense a climate change is, the narrower such a spectrum range will probably be.

4 Discussion

Exemplified by four case-studies (thermal extremes, water availability, tourism and migration) where climate causes critical situations or acts as an opportunity factor, this

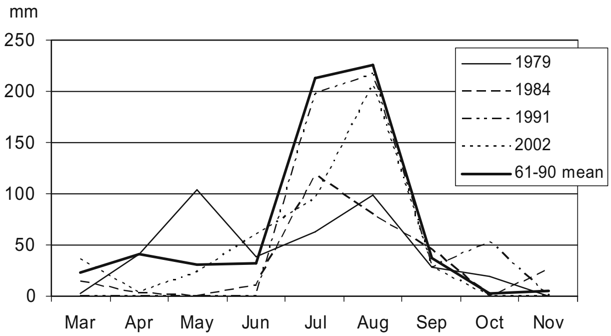


Fig. 10 Rainy season in Mekelle/North Ethiopia during extreme drought years according to human memory. 1979, which could be defined as a drought year in meteorological terms, but which was not regarded as such in peoples' perception due to little impact on livelihood, is included in the figure. It is evident that 1984 has a far-below-average total precipitation, and the lack of rain is especially visible during July and August. 1991 is very close to the mean, although data for spring rainfall, important for the availability of animal pasture, are absent. 2002 shows a late start of the rains and a lack of rain in April and May (Meze-Hausken 2004)

paper has attempted to present and discuss a conceptual model for human climate thresholds. The importance of climate thresholds arises when climate behaves differently than expected. This is due to the reactions or decisions it triggers. Although short and long timescale anomalies are a permanent feature of the climate system, decisions have to be made under insecurity as neither the strength nor duration of the anomaly can be known *a priori*. Nevertheless, while recent projections of changes in climate due to anthropogenic interference may contribute to enhanced ideas of future climate conditions, it is still speculative to what extent people's confidence in such projections will override their expectations of climate to be like in the past. The immediate question of whether it is possible to define human climate thresholds will require exploration from a variety of angles, as this literature survey shows how complex the issue is.

- Two case-studies each focused on the physiological and subjective effects of climate on humans. These variables are highly interlinked, insofar as mental state and body function influence each other. In some cases the physiological influences will outweigh the subjective and social ones, and vice versa. This important recognition can be traced back more than 2000 years, when Hippocrates (460–375 BC) proposed in his treatise on "Air, Water and Place" that knowledge about climate ought to be used to explain the psychology and physiology of human beings.
- Certain thresholds are possible to quantify, although mostly under experimental design with a *ceteris paribus* clause where other variables involved are kept constant, or by statistical analysis. Mostly, these can be defined by a range of possible outcomes, signifying a tolerance interval (Baranowska and Gabryl 1981) or threshold spectrum described by a lower and upper margin. Other thresholds may be described by narratives. While some climatic thresholds may be known in advance by experience or calculation (engineering thresholds—e.g. the amount of rainfall over time leading to river flooding in a settled area), others cannot be assessed before an event has occurred.
- Some thresholds can only be defined through subjective assessments of levels of acceptable risk and impact, as well as on expectations and experience. Furthermore the intensity of climate anomaly that people are willing to tolerate varies between

different societies. Those who have lived in a developing country may agree that one sort of climatic extreme, e.g. drought or flooding, which would be considered in Europe or the US as a "disaster", is tolerated or nearly expected as the norm by the local community. The same is valid for residents within e.g. Europe, where a snowstorm may lead to road chaos and infrastructure breakdown in one country such as southern Italy, but only to slight irregularities in Scandinavia. Events that would be considered as "extremely serious" for some are merely routine for others, suggesting that rare events have a lower level of acceptance than regular events, at least to an extent regardless of severity, due to lower preparedness. As taught in a language course for immigrants to Norway "even with snow-fall, your children are still expected to go to school". Thus, any cross-cultural and cross-regional validation of thresholds must be attempted with caution.

- Thresholds are variable in time. Changes in climatic drivers can change the frequency and magnitude of extreme events, and changes in socio-economic drivers can alter the ability to cope with such situations (Jones and Boer 2005). Adaptation can be active, relating to technological or cultural change, passive, through body response, or a combination of the two. Passive adjustment can be referred to as genetic and physiological adaptation, making survival possible in regions characterised by extreme heat or cold. As a long-term process, humans have to undergo functional adjustments to maintain thermal balance, related to the rate of metabolism, heat conservation and loss, respiration and blood circulation (Frisancho 1993, p.10). Bantu peoples in South Africa, Kalahari Bushmen or indigenous Australians are for example less susceptible to heat collapse when working in heat stress than their non-native fellows due to lower perspiration and heart rates. Inhabitants of the deserts of North Africa and Arabia on the contrary have adapted over the centuries culturally, rather than physiologically, to heat by wearing clothing that minimizes energy gains from the environment (Frisancho 1993, pp.53). Nevertheless, we have to be aware that our adaptation and thus threshold to climate may not only increase in the future (making us more adaptive), but that development in one direction may be harmful in another direction, regardless of eventual climatic change. For example, a society with a highly developed technological capacity may become more vulnerable to extreme events, at least in terms of economic damage. Changes in land-use may result in massive damage such as during the 2002 flooding in central Europe [17] Similarly, irrespective of climate change, the continuing expansion of tourism in Southern Europe will lead not only to acute water shortages over time (e.g. Spain), but could result in a higher number of casualties during heat waves, as mostly retired and sick people have become new residents in these heat prone areas. In other words, developmental trends might result in maladaptation, in which societies unwittingly make themselves more vulnerable to emerging or future climate hazards. An analysis of the 2003 European heat wave nevertheless showed that in certain regions experience of heat waves during previous years and the resulting existence of a risk management plan for hospitals public communication contributed to lower mortality rates (Kosatsky 2005). In addition, cultural factors such as an increase in social isolation of older people may contribute to vulnerability, irrespective of the meteorological condition (Sheridan and Kalkstein 2004).

[17] New Scientist 10 September 2003.

A threshold model has been suggested in this paper. Rather than presenting a definitive solution, the intention is to stimulate discussion on human–climate thresholds, supplementing the debate on human vulnerability and climate impacts. As a first approach to quantifying thresholds for policy makers, the German Advisory Council on Global Change (WBGU 2003) uses a "Tolerable Climate Window", based on a normative setting of non-tolerable climate change conditions, and determines the acceptable upper limit of absolute global warming as 2°C relative to pre-industrial temperature (based on earlier reports WBGU 1995, 1997). While this limit is assumed for both human and biological systems globally, it will definitely fail to be valid on a regional level due to substantial variations in climate impacts between regions and sectors (ibid.) and the combined effect of individual climate parameters. In addition, such a normative setting does not catch the subjective factors influencing tolerance- or threshold levels.

It can be concluded that there is no universal dose-response relationship between one climate variable, e.g. temperature, and a particular outcome, e.g. mortality (Martens 1998). Instead, thresholds are multidimensional, developing as a process over time, space and sectors. Generalising such a complex relationship involving so many variable, many of which cannot be easily quantified, is practically impossible. Glantz (1991) proposes the use of analogies, using past and present behaviour as an empirical point of departure and thus as a benchmark for future responses.

In the introduction, two ways of addressing limits to climate have been presented, either focusing on climate thresholds for society with a more bio-physical point of origin, or on human/social thresholds to climate, investigating the social vulnerability of people to climate stimuli. The case-studies have shown the high interaction between body and mind, in its widest form: perceptions that can influence physiological reactions to climate, and health requirements influencing perceptional needs and wants of climate. This interconnectedness would require that—in order to get a coherent answer to WHAT encompasses a threshold climatically, and HOW the underlying broader subjective and social structures contribute to a reaction—these two questions or approaches need to be merged. Acknowledging the complexities of the issue and its contextual conditionality and feedbacks involved, our existing knowledge of previous and current climate thresholds provides an important input to establish or modify regulations, laws and safety standards for changed future climatic conditions, based on analysis, negotiation and case-specific stimulus-response relationships. Potential changes in thresholds through endogenous and exogenous forces will require a dynamic decision making process. Issues such as adjusting the date for changing to winter tyres must be based on both climatic knowledge about the first mean frost day in the autumn, as well as on peoples' risk perception for driving on icy roads. The announcement of a crisis situation such as the 2003 heat wave in Europe needs to link temperature and rainfall data with data on human physiological responses, comfort levels, culture and behaviour (e.g. periods of peak physical activity, timing of vacations etc).

Outlook: Our current knowledge on human climate thresholds is imperfect. To follow this up, interdisciplinary work is needed which tackles natural and social science aspects simultaneously. As a start, questions could be explored such as why one society copes better with a certain climatic situation than another, based on knowledge of the culture, technology and history of a locality. But to attempt to develop generalised, universal climate thresholds, or a single universal level of "dangerous" climate change, as desired by policy makers, is hopelessly simplistic. It requires a subjective weighing up or integration of varying and sometimes conflicting interests and values, via what is essentially a political process. By applying the precautionary principle, considerations of the likelihood of global risks associated with tipping points in the Earth system, such as irreversible changes in the Earth's climate like the collapse of ice/sheets or disruption of ocean circulations will guide decision making for mitigation and adaptation actions. Any response, and thus the threshold, to perceived change now may also be affected by projections of future climate change based on science and our credibility in these projections. The beginning of a projected trend experienced already may trigger concern by confirming the likelihood of future larger changes. Indeed, one of the beneficial outcomes of climate change science may be to trigger early adaptation to prepare for greater change in the future.

Acknowledgement I would like to thank very much R. Mook, UiT, for his valuable suggestions to the improvement of this manuscript. Further thanks to many colleagues at IfG/UiB, DEV and Tyndall Center/UEA for interesting discussions on climate thresholds. C. Aall, J. Thornes and B. Balino gave comments on earlier drafts. KJ Sjöström helped kindly with several graphs. Thanks to Nick Brooks for language editing and interesting comments. Three anonymous reviewers gave constructive advice for improvement. The research has been funded by the Norwegian Research Council and the University of Bergen.

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