Climate science – is it a sub-field of physical science?

Hans von Storch[1], Armin Bunde[2] and Nico Stehr[3]
[1]Institute of Coastal Research, GKSS Research Center and KlimaCampus, University of Hamburg, [2]Institute of Theoretical Physics, University of Giessen, Germany,
[3]Zeppelin University, Friedrichshafen, Germany

Abstract: As an initial educated look tells us, the scientific analysis of climate is mostly a physical science discipline. The object of climate science is not a social construct but part of the real world that is governed by physical principles, such as conservation of energy, momentum and mass in hydrodynamics. Thus, the climate science field comprises the "physics of the climate system". None the less, this is only part of the story; another significant part of the set of issues represented by "climate" is deeply embedded in social and cultural processes. Thus, climate science is a genuinely trans-disciplinary scientific field, which poses special challenges and approaches requiring the skills of both physical scientists as well as social and cultural scientists.

1 Orientation

In following sections, the physic-nes of climate science is discussed. In a *first* section, we discuss the historical development of the concept of climate leading us from an anthropocentric view to a strictly physical worldview, and one that is now moving once again towards a more anthropocentric view – this time concerning not only the impacts but also the drivers. In a *second* section, a series of physical issues, from modelling, over parameterizations, impossibility of experimentation and data problems are discussed. In the *third* section, the concept of post-normal science is introduced, which is related to high uncertainties in the field of the physics of climate, and the high stakes on the societal side. Here, at the boundary between science and policy, new dynamics emerge, which have little to do with physics; dynamics which depend on culture and history, on opposing interests ands world views. A brief concluding section argues for the need of a trans-disciplinary approach to climate in order to assist in developing policies consistent with physical insights and cultural and social constraints.

2 History of climate science

Historically, „climate" was considered part of the human environment. Alexander von Humboldt ([1845] 1846:323-324) in 1845 in his book *Cosmos, A Sketch of a Physical Description of the Universe* defined climate as the sum of physical influences, brought upon humans through the atmosphere: "The term climate, taken in its most general sense, indicates all the changes in the atmosphere, which sensibly affect our organs, as temperature, humidity, variations in the barometrical pressure, the calm state of the air or the action of opposite winds, the amount of electric tension, the purity of the atmosphere or its admixture with more or less noxious gaseous exhalations, and, finally, the degree of ordinary transparency and clearness of the sky, which is not only important with respect to the increased radiation from the earth, the organic development of plants, and the ripening of fruits, but also with reference to its influence on the feelings and mental condition of men".

Thus, like astronomy, climate in much of 19th century discourse was subject to an anthropocentric view. The global climate was little more than the sum of regional climates (cf. Hann, 1903), and the challenge was to faithfully describe regional climates by measuring and mapping the statistics of their weather. Not surprisingly, a large body of information was generated, dealing with the impacts of climate on people and societies. It was the time of the prominence of the prespective of climatic determinism (Fleming, 1998; Stehr and von Storch, 1999 and 2010). At the turn of the 19th and 20th centuries,more physical questions were formulated (e.g. Friedmann, 1989; see also the systematic approach presented by Arrhenius, 1908), and meteorology and oceanography became "physics of the atmosphere" and "physics of the ocean". Climate was no longer primarily considered an issue of the field of geography, but of meteorology and oceanography, and climate science became "physics of climate" (e.g., Peixoto und Oort, 1992).

Since the 1970s the notion that unconstrained emissions of greenhouse gases into the atmosphere generated by human actities will lead to significant changes of climatic conditions – a theory first proposed by Svante Arrhenius (1896) – was supported by evidence of a broad warming and finally embraced by the majority of climate scientists, as is documented for example in the series of Assessment Reports by the Intergovernmental Panel of Climate Change (IPCC). In the 1990s the issue became the absolutely dominant topic in climate sciences (Weart, 1997; 2010). Climate research became almost exclusively research into human-made climate and its impacts.

Unnoticed by most climate scientists, the developments in the last decades represent a return to the original but transformed *anthropocentric* view of the issue of climate (Stehr und von Storch, 2010): In contrast to the perspective of "climatic determinism", it was no longer the idea that climate *determines* the functioning and fate of societies, but that climate *conditions* human societies (Stehr and von Storch, 1997).

3 Methodical challenges of the Physics of Climate

The pillars of the success story of physics in the last two centuries are the unbiased observation and description of natural phenomena, the reproducibility of experimental data, and the mathematical description of the empirical results leading to a generalization of the experimental results and the elucidation of the underlying basic laws of nature. Perhaps the most prominent example is the Newtonian classical mechanics which Newton developed on the basis of Kepler´s observations and Galilei´s gravity experiments. Another example is electrodynamics which was established by Maxwell and based on the experimental and theoretical work by Coulomb, Volt, Ampere, Gauss and others. Like Newtons equations, the celebrated Maxwell equations describe comprehensively all (classical) electrical and magnetic phenomena, and not only those that they aimed to describe initially. Among others, Maxwells theory led to the recognition that light is an electrodynamic phenomenon.

Prerequisites of the success of physics were:

- the departure from the anthropocentric view of life that for the first time allowed an unbiased view onto the natural phenomena (like planetary motion),
- a new practise of publication: the protagonists did no longer (like the alchemists) hide their results but made them available to the public, allowing colleagues to reproduce (or falsify) them, and finally
- the norm of checking a theoretical hypotheses experimentally. In the case of conflicting theories, an *experimentum crucis* is needed to decide which theory is correct. Perhaps the most important experimentum crucis is the Michelson experiment on the velocity of light, which forms the basis for Einstein´s theory of relativity.

When we look at the climate system, we encounter different “compartments”, such as atmosphere, ocean, sea ice, land surface including river networks, glaciers and ice sheets, but also vegetation and cycles of substances, in particular greenhouse gases (Figure 1). An important element of the dynamics is given by fluiddynamics of the atmosphere, ocean and ice, which are described by simplified Navier-Stoker equations. However, due to the unavoidable discrete description of the system, turbulence can not be described in mathematical accuracy, and the equations need to be “closed” – the effect of friction, in particular at the boundaries between land, atmosphere and ocean, need to be “parameterized” (e.g., Washington and Parkinson, 2005).

Additional equations describing the flow and transformations of energy are needed – part of this may be described by the first law of thermodynamics, the conservation of energy. In these equations we find source and sink terms, which are related to phase changes (condensation, for instance) and the interaction of cloud water and radiation. These processes often take place at smallest scales and require additional state variables (such as the size spectrum of cloud droplets). Again, such processes can not be taken care of explicitly – and need to be “parameterized”. Interestingly, a similar concept is used in physics, named the Mori-Zwanzig formalism (Zwanzig, 1960), developed independently at about the same time as in atmospheric sciences – a similarity unknown to the two communities, it seems.

This issue of parameterization is difficult to understand (Müller and von Storch, 2004). The basic idea is to split the state variables, say Ψ, into two components, $\Psi = \underline{\Psi} + \Psi'$ with $\underline{\Psi}$ representing that part of Ψ, which is well represented with the given spatial resolution (say, 100 km), and Ψ' being the unresolved part of smaller spatial scale. The equations are then approximately written as $d\underline{\Psi}/dt = F(\underline{\Psi}) + G(\Psi')$. Here, $F(\underline{\Psi})$ describes the influence of the resolved part $\underline{\Psi}$ on the future development von $\underline{\Psi}$, whereas $G(\Psi')$ describes the influence of the non-resolved part, which is of course unknown. A conventional truncation of the equations would lead to $d\underline{\Psi}/dt = F(\underline{\Psi})$, and the non-resolved part would have no influence. Since this will not be acceptable – the small scale turbulence and the associated friction can not be neglected – another approximation is used, namely $G(\Psi') = H(\underline{\Psi})$. The latter is the “parameterization”.

The idea with the parameterization is that it would carry the information, which is to be expected from the small scales Ψ^* when the resolved state is $\underline{\Psi}$. Or more precisely, $G(\Psi')$ is considered a random variable, which is conditioned by the resolved part $\underline{\Psi}$. Practically, $G(\Psi')$ can be determined empirically – by observing the distribution of $G(\Psi')$ when the large-scale state is $\underline{\Psi}$. $H(\underline{\Psi})$ can then be a random realization of this distribution of $G(\Psi')$, or the $\underline{\Psi}$-conditional expectation of $G(\Psi')$.

The usage of parameterizations is normal practice in climate models, and they have turned out to make such models capable of describing the present climate, the ongoing change and historical climates. It is plausible that the parameterizations are valid “closures” also in a different climate (after all, in terms of physical (but not societal) magnitudes, any climate change would represent only a very minor change), but the final evidence for this belief will be available only after the expected changes have taken place, have been observed and analysed.

There are two aspects of parameterizations, which are worth to be mentioned.

One is a linguistic aspect, namely that in the language of climate modellers, parameterizations are named “physics”, a short hand for “unresolved physical processes”. For a person uncommon with the culture of climate sciences, this terminology may go with the false connotation that parameterizations would be derived from physical principles. While the functional form of the parameterization $H(\underline{\Psi})$ may be motivated by a physical plausibility argument, the specific parameters used are either guessed, fitted to campaign or laboratory data or to make the model skilful in reproducing the large scale climate $\underline{\Psi}$. Thus, the word “physics” points to semi-empirical “tricks”.

Another aspect of parameterizations is that they are no universal formulation but depend on the spatial resolution chosen. When the model is changed to run on a higher resolution, the parameterizations need to be reformulated or re-specified. There is no rule how to do that, when the spatial resolution is increased – which means that the difference equations do not converge towards a pre-specified set of differential equations, or, in other words: there is nothing like a set of differential equations describing the climate system per se, as is the case in most physical disciplines. In climate science, there are only useful approximations, which depend on the spatial resolution of the system. This aspect causes many misunderstandings, in particular among mathematicians and physicists who often enough demand to see “the equations”.

The business with non-unique differential equations and the need to close the system by adopting parameterizations may already make the field different from mainstream physics. But there are other issues, which make climate science “different” from physics, when we consider only the classical physical dimension of climate.

Unlike most physics disciplines climate can not be associated with spatial and temporal scales in a certain limited range – instead climate varies on all spatial scales (on Earth) and extends across several magnitudes of time scales, from short term events, measured in minutes, via time scales of decades and centuries, to geological times scales of millennia and more years. If we look at the relevant processes in the climate components atmosphere and ocean, we find a continuum of scales, as displayed in Figure 2. The implication is that there are hardly independent observations from different locations, and the temporal memory extends across many decades of years.

As a practical rule, the World Meteorological Organization (WMO) has mandated hundred or more years earlier that 30 year time intervals would represent “normal climatic conditions”; every 30 years new normals are determined. If we accept this somewhat arbitrary number of 30 years, we have to wait about 30 years to get a new realization of the climate system, which is at least somewhat independent of previous states. Thus, tests of hypotheses, derived from historical data, using new data are hardly possible.

Real experiments, in the sense of paired configurations, which differ in a limited number of known details, are of course also not possible in the real world (as in any other geophysical set-up).) However, with quasi-realistic models, who serve as a kind of virtual laboratory, it is possible to perform real experiments, for instance on the effect of clouds, physiographic details but also on elevated greenhouses gas concentrations in the atmosphere. Independent realisations can be generated; extended long simulation are possible so that the weather noise may be reduced and the looked after signals of a imposed experimental change in the system may be more easily isolated. The problem is, of course, that even if the models share indeed many properties with reality, it is unproven if the specific model response is realistic.

Real forecasts are also hardly possible: even if we are able to prepare a successful forecast for the coming 10 or 30 years, we can not claim “success” of our prediction scheme, because a single success may also have taken place by coincidence. Determining the skill of a forecast scheme needs many independent trials, as in case of weather forecasting. Given the long time scale in climate variability allows no robust estimate of the skill of our methods to explore the future.

Indeed, in recent years sometimes real predictions are tried with dynamic climate models, with lead times of one or a few decades (e.g., Keenlyside, 2011). The logic behind such forecasts is that the details of the emissions do not really matter for such a time horizon - as long as they exhibit some increase in the coming decades of years. A first attempt of forecasting the next 10 years (in this case 2000-2009) was in the year 2000 published by Allen et al. (2000) – now, ten years later, this prediction can be compared with the actual recent development. The scenario prepared by Hansen et al. in (1988) was retrospectively by Hargreaves (2010) considered a forecast, and compared with the recent development (Figure 3). In both cases (Figure 3), the future was well predicted. For the coming decades, a reduced warming has been predicted in an experimental forecast effort by Keenlyside et al. (2008).

Most outlooks of possible future climatic developments take the form of conditional predictions – assumed developments of greenhouse gas emissions/concentrations and other factors are used as external drivers in climate models (e.g., von Storch, 2007). As such they are scenarios, namely possible future developments, and not predictions, namely most probable developments (cf. discussion in Bray and von Storch, 2009). Such scenarios are often falsely labelled as “predictions” in the media, and even by some research institutions. They are prepared with *quasi-realistic climate models* (e.g., Müller and von Storch, 2004), often abbreviated by GCM (which historically stands for General Circulation Models and not for Global Climate Models)

To summarize: most future outlooks available to the scientific community and presented to the general public are not descriptions of most probable futures (predictions) but plausible consistent and possible futures (scenarios or projections). In a few cases, real predictions have been prepared for the nearer future, and they have turned out to point into the right direction.

While this is encouraging, such sporadic successes can not be considered as significant evidence for the general validity of climate models. At the same time, evidence is not available that would positively disqualify such models of being valid tools to study man-made climate change.

The lacking option of doing experiments prevents many uncertainties to be decided – as for instance the *climate sensitivity* (temperature increase after equilibration when CO2 concentrations are doubled). Indirect evidence is used for improving the estimate of such uncertain quantities, but some uncertainty remains and thus a certain range of interpreting results and perspectives differently.

Because of the long waiting time for getting a new realization of the climate system, climate science must rely on historical "instrumental" data, data which have been measured for often quite different purposes, under different conditions, with different instruments and standards. Alternatively, proxy data may be used, for instance data on tree growth or ice accumulation, which may have „recorded" aspects of the geophysical environment.

The "*instrumental*" data usually suffer from "inhomogeneities" (e.g., Jones, 1995; Karl et al., 1993). An example is provided by Lindenberg et al. (2010), who examined statistics of wind-speed recorded at five locations along the German North Sea coast. The diagram shows periods, when the wind-speeds co-varied to large extent, whereas at other times, marked by dashed line, the statistics began to deviate strongly. These deviations are mostly related to relocation of the instruments due to various reasons. Such effects are common in "raw" data time series, and at least in modern data sets well documented.

Indeed, it may be a good rule of thumb that almost all time series, extending across several decades of years, suffer from some inhomogeneities – the more easily detectable inhomogeneities are "abrupt", such as those in Figure 4, but the more difficult to detect are continuous changes. An example is the effect of continuous urbanization which can be separated from the natural variability only within large error bars (Lennartz and Bunde, 2009).

Before using such data in climate analysis, the series have to be "homogenized" (e.g., Peterson et al., 1998). For scientists and lay people, with insufficient insight into the contingencies of climate data, this significant hurdle is hardly recognized. Therefore, it happens every now and then that publications show surprising results, which in the end display changing data recording practises and not changes in the climate system. A nice example is the conjectured increase of the absolute number of deep cyclones in the last century which is due to an insufficient data knowledge (Schinke, 1992). Also, contributors on weblogs often ask for "raw data", with the implicit suspicion that somebody may have tampered with the raw data in order to obtain preconceived results. This is in most cases not a wise approach – because of these invisible inhomogeneities (cf., Böhm, 2010).

„*Proxy*"-data have other problems (Briffa, 1995). The main problem is that the proxies, for instance growth rings in trees, or annual layers of sedimented material, record not only some climate parameters, such a summer temperature, but also other influences. The fundamental problem is that only part of the variability in the proxies is related to climate variability, in particular temperature. The proportion of variability, which may be related to climate drivers, differs in time, and the empirically derived transfer functions may show different amplitudes for different time scales. The famous problem of the hockeystick-named temperature reconstruction, which was based mostly on tree-rings, had much to do with the dis-uniform representation of long-term and short term variability. An interesting exchange about proxy-methodologies and robust claims-making is provided by a series of papers, comment and replies by Christiansen et al. (2009), Rutherford et al. (2010) and Christiansen et al. (2010).

To summarize: „Data“ is a complex issue in climate research. Historically collected “instrumental” data suffer from inhomogeneities, related to changing observational, archival and analytical practises. Indirect proxy-data provide information about changing physical conditions, but compete with other unknown influences – so that stationarity and time-scale dependence of the information content of such data are an issue. More expertise about the process of using instruments and of storing influences in indirect data is required.

4 The socio-cultural context

There is another set of factors that makes the science of climate immediately „different“ from other scientific fields – namely that climate research, the issues, results and individuals – are firmly embedded into socio-historical, socio-cultural and socio-economic contexts. This is already illustrated by virtue of the fact that most, perhaps almost all, of present climate research activities are related to the issue of anthropogenic climate change and its impact on the natural environment and society.

The main issue in the societal context concerns the statistics of weather (in atmosphere and ocean) and its changes, such as the frequency and intensity of extreme events as storms, heat waves and flooding. Weather statistics are significant data for societies, its infrastructure and inhabitants because they contain important information about possible impacts (and adaptive measures to deal with them) and options for keeping a check on the drivers (mitigation). Both strategies in response to a changing climate, that is, reducing emissions and reducing vulnerability, are subjects of a wide range of scientific fields including the engineering sciences, hydrology, law, geography, policy sciences, ecology and social sciences.

Thus, climate research has significant attributes beyond physics. The extra-physical science attributes of climate research are linked to the joint presence of two factors. One factor is high uncertainty about the “facts” of climate dynamics, ranging from the climate sensitivity, to regional specification, to the presence of other social drivers and to future options of dealing with emissions and impacts. The other factor concerns the societal response to climatic conditions, how we interpret and deal with climate related processes. Our ordinary everyday understanding of climate is closely related to our way of life mediated of course by the way in which the mass media communicate climate issues; references to climate and climate change in public communication may be employed for example as a tool to legitimate changes to our way of life, or, in the opposite sense, as a means to defend dominant worldviews.

Under these circumstances but not only because of the embedness of the nature of our understanding of climate in everyday life, climate science becomes along with other modern scientific fields “post normal” (Funtovicz and Ravetz, 1985; Bray and von Storch, 1998). A broad range of essentially contested terms and explanations enter the public arena and compete for attention, accounts that may also be brought in position to give credence to different world views and legitimacy to political and economic interests.

There seem to be two major, contending classes of explanations of the climate and climate change (von Storch, 2009). One, which we label as "*scientific construct*" of human-made climate change, describes that processes of human origin are influencing the climate – that human beings are changing the global climate.[1] In almost all localities, at present and in the foreseeable future, the frequency distributions of the temperature continue to shift to higher values; sea level is rising; amounts of rainfall are changing. Some extremes such as heavy rainfall events will change. The driving force behind alterations beyond the range of natural variability is above all the emission of greenhouse gases, in particular carbon dioxide and methane, into the atmosphere, where they interfere with the radiative balance of the Earth system.

The scientific construct is widely supported within the relevant scientific communities, and has been comprehensively formulated particularly thanks to the collective and consensual efforts of the UNO climate council, the "IPCC."[2] Of course, there is not a complete consensus on all aspects of the construct in the scientific community, so that speaking of "the scientific construct" is somewhat of a simplification. What is consensual and enumerated in the previous paragraph is the core of the scientific construct.

A different conception of climate and climate change may be labelled the *social or cultural construct* (cf. Stehr and von Storch, 2010). In the context of this concept, climate and weather patterns are also changing, the weather is for instance less reliable than it was before, the seasons less regular, the storms more violent. Weather extremes are taking on catastrophic and previously unknown forms.

What causes these changes in weather patterns? A variety of economic reasons and psychological motives tend to be adduced, for example, sheer human greed and simple stupidity. The mechanism that is at work may be described as follows: Nature is retaliating and striking back. For large segments of the population, at least in Central and Northern Europe, this mechanism producing climate change is taken-for-granted. In older times, and even sometimes today, adverse weather patterns were the prompt response of the gods angered by human sins (e.g., Stehr and von Storch, 2010).

The cultural construct of climate and changing weather patterns takes many different forms depending on the traditions in a society, its developoment and dominant

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[1] The position of so-called „climate sceptics“ is not discussed here because there is no consistent body of knowledge of "skeptic" climate science but merely a collection of various, often highly contested issues that range from detailed matters to much more general assertions, e.g., that greenhouse gases would have no significant impact on climate. The absence of a consistent body of assertions does not imply in principle that the questions raised by "sceptics" might not in one or the other instance be helpful to constructively move the science of climate forward.

[2] The support among climate scientists seems indeed very broad, when related to the key assertions just listed (cf. Bray and von Storch, 2007). Whether the emergence of errors in Working Group (WG) 2, and possibly WG3, of 4th Assessment Report (AR4) of IPCC, which so far all point towards a dramatization, and after it became known that a key data set (CRU) could no longer be reproduced because of some original data having been "lost", will have implications for this support within climate science and the general scientific community remains to be seen.

aspirations - but what is described above as the everyday concept of climate and weather represents something like a standard core of such statements.

Obviously, the scientific construct in hardly consistent with such cultural constructs.

In this postnormal-situation where science cannot make concrete statements with high certainty, and in which the evidence of science is of considerable practical significance for formulating policies and decisions, this science is impelled less and less by the pure “curiosity” that idealistic views glorify as the innermost driving force of science, and increasingly by the usefulness of the possible evidence for just such formulations of decisions and policy (Pielke, 2007b). It is no longer being scientific that is of central importance, nor the methodical quality, nor Popper’s dictum of falsification, nor Fleck’s idea of repairing outmoded systems of explanation (Fleck, 1980); instead, it is social and political utility of knowledge claims that carry the day. Not correctness, nor objective falsifiability, occupies the foreground, but rather social acceptance and social utility.

In its post normal phase, science thus lives on its claims, on its staging in the media, on its affinity and congruity with socio-cultural constructions. These knowledge claims are not only raised by established scientists, but also by other, self-appointed experts, who often are bound to special interests. Representatives of social interests seek out those knowledge claims that best support their own position. One need only recall the *Stern* report (see the critique by Pielke (2007a) or Yohe and Tol (2008)), or the regular press releases of US Senator Inhofe.

5 Conclusions

Two major conclusions about the science of climate, and the knowledge about climate may be drawn:

The scientific construct is mostly based on a physical analysis of climate and developed by natural scientists. It describes the left two blocks in Figure 5. In as much as the relevant actors, the climate scientists are also part of society and not immune to dominant societal conceptions of the nature and the impact of climate and climate change on human conduct, they tend to embed their analysis, especially in efforts to communicate their knowledge to policy makers and society at large in ways which are attentive to the socio-cultural construct of climate and climate change. It is not surprising that in this postnormal-situation scientists concerned about the impact of the greenhouse gases, in their desire to save the world, may develop some bias towards an overdramatization. The discussion itself often resembles more a religious than a physics discussion where the non-believers (of the role of the greenhouse gases and their impact) are called “deniers”.

One therefore is able to surmise that the transfer of the scientific construct into the societal realm goes along with a subtle transformation of the climate knowledge, by blending the scientific construct with the socio-cultural construct (the middle blocks in Figure 5).

Obviously, the situation is not quite that straightforward, it is not easily deconstructed and the interrelations of scientific and everyday construct are difficult to dissemble. To comprehend and disentangle the multiple interactions of science and society in the case of our understanding of climate and climate change is nonetheless a real and worthy scientific and practical challenge. It needs a transdisciplinary approach, bringing together scientists with a solid background in the physics, and scholars who understand societal and knowledge dynamics (Pielke, 2007b).

If this helps to implement a better climate policy, with an efficient constraining of climate change and socio-culturally acceptable measures of mitigation and adaptation, needs to be seen. Summing up, climate science is and should be much more than just the physical analysis.

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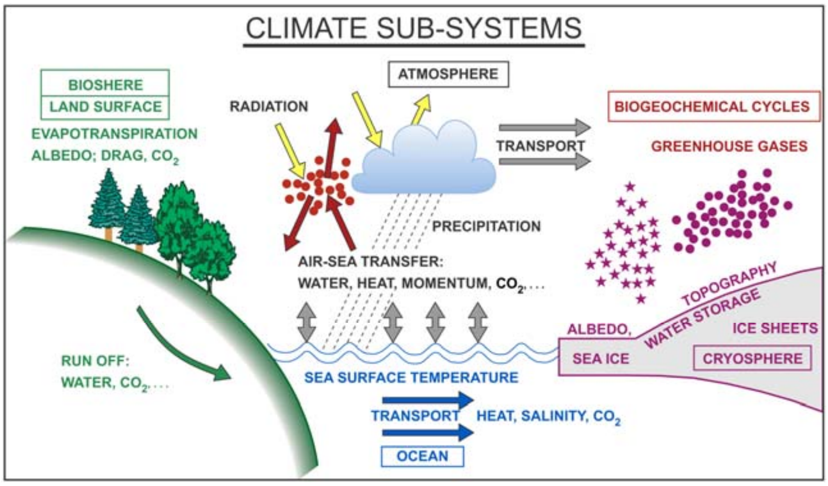

Figure 1: Schematic sketch of processes and variables in the climate system

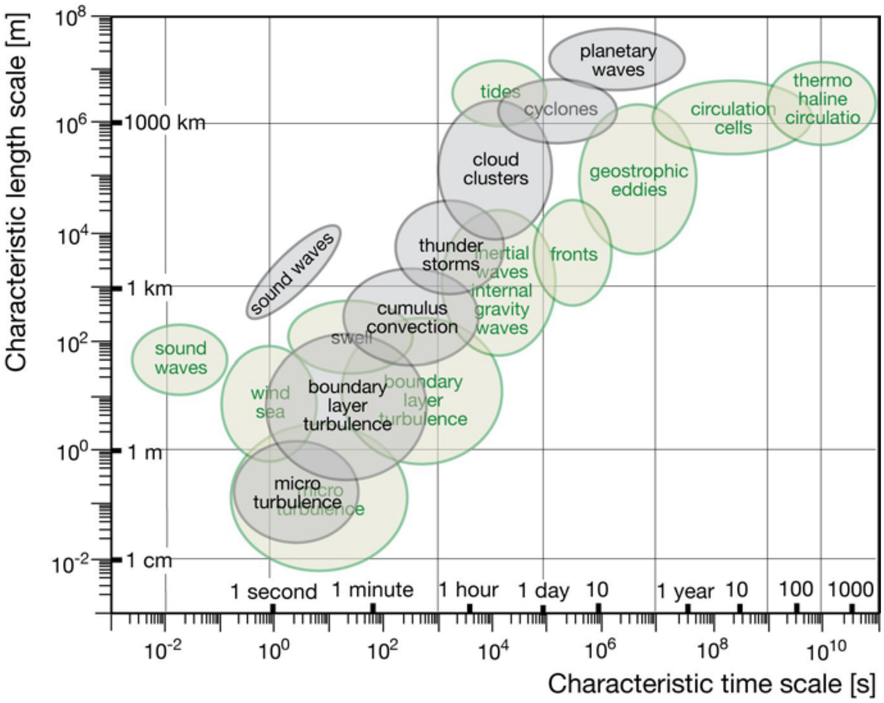

Figure 2: Spatial and temporal scales of processes in the climate components atmosphere and ocean.

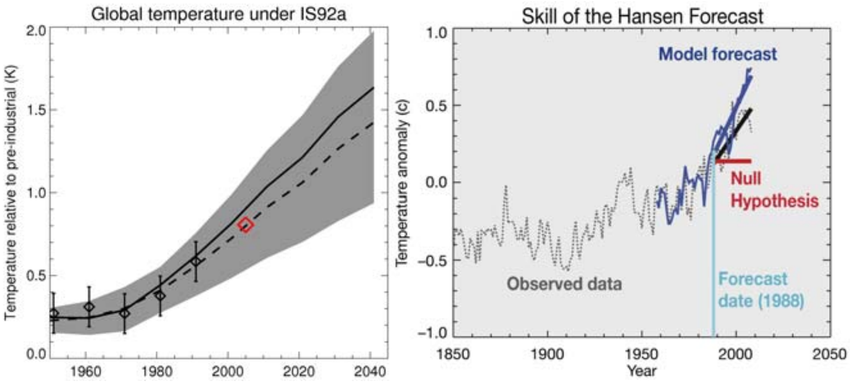

Figure 3: **Left:** Allen et al.'s (2000) forecast of global temperature made in 1999. Solid line shows original model projection. Dashed line shows prediction after reconciling climate model simulations with the HadCRUT temperature record, using data to August 1996. Grey band shows 5-95% uncertainty interval. Red diamond shows observed decadal mean surface temperature for the period 1 January 2000 to 31 December 2009 referenced to the same baseline. **Right:** Hansen's scenario published in 1988 as a prediction up to 2010 (Hargreaves, 2010).

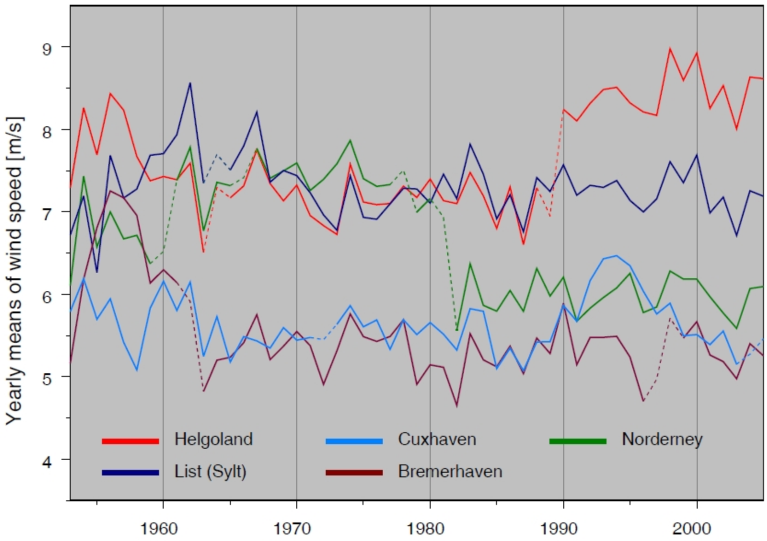

Figure 4: Yearly means of wind speed measurements from five synoptic near coastal stations. Dashed lines label years with known station relocations. (Lindenberg et al., 2010)

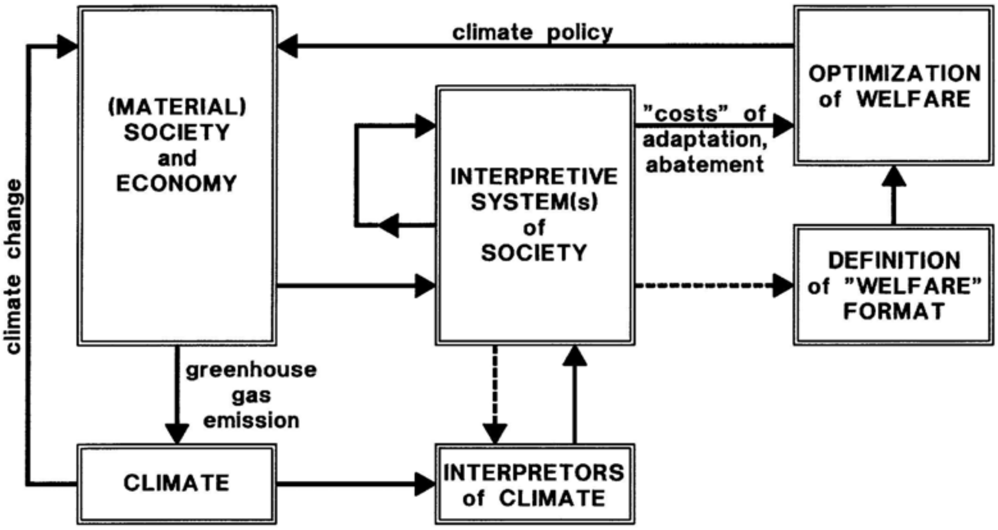

Figure 5: The perceived climate and society model (Stehr and von Storch, 2010)