Risk based adaptation to climate change

Kjell Eriksson[1,*], Peter Friis-Hansen[1]

[1] *DNV Research & Innovation, Veritasveien 1, 1363 Høvik, Norway*
** Corresponding author. Tel: +47 95468338, E-mail: Kjell.Eriksson@DNV.COM*

Abstract: Climate change is real and owners and operators of critical infrastructures need to adapt to a different environment. Decisions will have to be made under large degree of uncertainty. There are today no specific methods that combine global climate models with infrastructure design methods. Hence the uncertainty in the decisions becomes even larger.

The paper presents a method for combining state-of-the-art climate modelling, meteorological approaches, with state-of-the-art structural design methods in a decision theoretic frame. This has, to our knowledge, not been done before. The decision framework will help authorities to make complicated and critical decisions with respect to how to prepare for future changes in the environment. The work is based on the climate models used in the current and updated IPCC Reports, regional and local meteorological and oceanographic models, and the DNV Recommended Practice on environmental loads, DNV-RP-C205.

The decision theoretic frame is risk-based where expected loss will be expressed in monetary terms. The approach is applicable to critical infrastructures, power generation and transmission, and offshore oil and gas installations.

The paper will address key design parameters, likely climate change scenarios, time horizon of the infrastructure or installation in question, limitations of existing climate models, combination of global and regional climate models, how to downscale results and, ultimately, how to convert the results into a design basis.
The methodology presented in the paper is based on ongoing research partly financed by the Norwegian Research Council and partly by DNV.

Keywords: *Climate change, Adaptation, Risk management, Infrastructures*

1. Introduction

"*Every year, climate change claims lives and seriously affects much of our planet. The scale and breadth of the challenge as identified by the Climate Vulnerability Monitor is already immense. So is the explosive growth of its negative effects on human society. Everyone should be aware of the risks we are running by not tackling the climate crisis, and how simple it is in many cases to avoid damage now and tomorrow. Still, only truly urgent action will prevent increasingly irreversible harm to the earth and the life it sustains. Equally urgent support is currently needed to help populations in places most vulnerable to the worst effects of climate change. They are on today's frontlines of our common struggle with a now rapidly changing planet.*" This citation is taken from the DARA [1] homepage, where their recently published report "Climate Vulnerability Monitor 2010" is published. The *Climate Vulnerability Monitor 2010* report draws attention to approximately 350,000 lives already lost each year as a result of global warming and changes to our climate. The annual number of lives lost is forecasted to increase to nearly 1 million by year 2030. The report further estimates that US$ 150 billion is lost in today's economy as a result of climate changes. These losses will increase in the future. More than half of the total economic losses will occur in industrialized countries. Moreover, DARA estimates that around 170 countries (i.e. most of the world) have high vulnerability to climate change in at least one key impact area already today.

The evidence in the DARA report highlights that decision-makers worldwide will face huge challenges in selecting effective means for adapting costly infrastructures to the changing climate. If decision makers fail to properly adapt infrastructures in time, the potential losses may well exceed far beyond the cost of the infrastructure itself. Lost infrastructures such as part of e.g. a transport system, energy system, or vital public facilities (for instance hospitals), may paralyse society for a long time and therefore create a setback for the economy and a whole community.

What aggravates the decision making is the overwhelming amount of uncertainties that the decision maker is facing. The decision maker must not only consider uncertainties in relation to future climatic changes (temperature, storms, precipitation, waves, subsidence, etc.) and how these correlate, but also the health state of the degrading infrastructure prior to the occurrence of the events, as well as estimate direct and indirect consequences that follow. However, uncertainties are not limited to this. Mathematical models that use semi-empirical models of vegetation, soils, ice-sheets, etc., are invoked to forecast future climate change effects. These models are imprecise and will add further uncertainty into the decision problem.

The forecasting of the climate is based on four representative CO2 emission scenarios; however, we do not know which scenario that best will describe the future. Finally, it is the extreme events that govern failure of the structures, and these extremes are by nature hard to predict. Therefore, also statistical uncertainty enters the decision problem.

Although most decision-makers are increasingly concerned with the adverse impacts of climate variability and change, decision-makers rarely possess the composite knowledge needed to understand the complexity, interconnectivity, and limitations of uncertainty modelling, to make effective decisions to manage current and future climate risks. The challenge in establishing this technical understanding requires that risk-based adaptation to climate change assume a new level of integration and coordination.

DNV is currently developing a Recommended Practice (RP) for risk-based adaptation to climate change. The objective of the RP is to assist decision makers, such as public authorities, to exercise critical and sound decision-making on how to prepare and adapt to future changes in the environment. This is sought achieved through the formulation of a structured method that combines state-of-the-art climate modelling, meteorological approaches, with state-of-the-art structural design methods. The method is based on the climate models used in the current and updated IPCC Reports, regional and local meteorological and oceanographic models; and finally, it is risk-based where all uncertainties are accounted for. Such a recommended practice has, to our knowledge, never been developed before.

Since the majority of the uncertainties to a large extent are rooted in expert judgement in combination with mathematical modelling, the recommended practice will also include methods for identification of what uncertainties affect the decision making the most, and provide guidance for reducing these uncertainties. This is central since decisions made on adapting infrastructures to climate change are very costly in general; wherefore it is of paramount importance for decision-makers to identify means to effectively reduce the probability of making a wrong decision.

DNV is aware of the work undertaken by the World Meteorological Organization under the Global Framework for Climate Services (GFCS) [2]. GFCS was established by the Heads of State and Government, Ministers and Heads of Delegations present at the UN World Climate Conference-3 (WCC-3) in September 2009 with the mandate to: "*Enable better management of the risks of climate variability and change and adaptation to climate change at all levels, through development and incorporation of science-based climate information and prediction into planning, policy and practice*." As such, the GFCS activity may seem identical to the work that DNV is undertaking to establish an RP. However, the work of GFCS appears (at present) to have focus on strengthening the global observing capability of the members by optimising the density and spatial distribution of observing networks, ensuring data compatibility and increasing the quality of observations. Such work is very important to arrive at better and more reliable predictions in climate modelling, which will also be undertaken by GFCS. However, in our work on the RP, focus is on formulating a structured method that effectively will allow decision makers to effectively control and handle all uncertainties involved in the decision-making and as such to arrive at better decision. Hence, the RP and the GFCS work complement each other. At present our RP is not based on the GFCS work, but this may change in future.

In this paper we describe the general background and applied principles behind the recommended practice. The paper is compiled as follows: In section 2 the applied terminology for risk related elements are defined. Here it is argued why risk is defined as expected monetary loss. In section 3, we discuss climate modelling and how to arrive at a description of the outmost important assessment of extreme events of the climate impacts as well as the correlation among different climate impacts. Section 4 discusses the existing design principles for infrastructures. It is highlighted that extreme events for such structures have a completely different meaning than that applied in the IPCC reports. Section 5 shortly presents the risk modelling and describes how the dominating uncertainties in the model can be identified. For this set of dominating uncertainties effective uncertainty reductions can be made. In section 6, we present a graphical overview of the overall method, and finally in section 7, we summarise and conclude the expected benefits from establishing and applying the recommended practice to costly decisions on adaptation of important infrastructures to a chancing climate.

2. Risk related terminology

2.1. Risk

Intuitively a measure of risk should be some increasing function of both the probability of occurrence of the adverse event and the consequence of the adverse event represented on some numerical (monetary) scale. If an adverse event A occurs once within a year with probability p, and two or more occurrences of A within a year have negligible probability as compared to p and, moreover, the consequence of the occurrence of A can be represented by a loss L equal to a known monetary cost c, then the expected value of the yearly cost is $pc+(1-p)0=pc$, because there is no cost from A if A does not occur. There is a decision theoretical reason[i] to take this *expected cost* as the definition of the yearly risk $r(A)$ associated with the event A, i.e. $r(A)=pc$. This definition may easily be relaxed to apply for events that occur in time with frequency λ, to become $r(A)=\lambda c$.

Typically, risk analysis is performed without a clear definition of how to measure risk, and only displayed by a simple, crude colour coding. Such an approach is not sufficient to be applied for decision making of complex costly structures. In the RP we advocate for detailed modelling of both frequencies and consequences.

---

[i] The decision theoretical argument is, of course, that decisions on risk reduction initiatives are measured on monetary scale, and that risk as such directly is in agreement with the fundament of decision theory.

2.2. Vulnerability

There exist several definitions for "vulnerability" that all depend upon the type of system they relate to (e.g. technical, computer, networks, organisational and societal systems). The set of definitions all refer to *weaknesses* or *flaws* embedded within the system caused by some event combined with the capability of the environment (or external circumstances) to *exploit such weaknesses* to impair the functioning of the system [3,4,5].

The provided definitions of vulnerability are imprecise, and are not operable within the quantitative framework of the RP being established. Therefore, we define *vulnerability* as the *conditional expected loss*; that is, the risk calculated conditional on the occurrence of the unwanted event. This implies that vulnerability will be decreasing when the failure probability of any implemented barrier decreases or when the consequences decreases. This definition is operable and is in agreement with common use of the word *vulnerability*.

2.3. Resilience

There exist several definitions of resilience in literature. Within the resilience engineers there seem to be consensus along the line that is well defined by Wreathall [6]: "*Resilience is the ability of an organization (system) to keep, or recover quickly to, a stable state, allowing it to continue operation during and after a major mishap, or in the presence of continuous significant stresses*".

Unfortunately, this definition makes it difficult to measure resilience. We therefore propose the definition: "Resilience is the *ability to control* the risk that follows after a major mishap. The risk includes operational loss, emergency recovery, etc., of the continuously stressed system." This implies that resilience also can be defined as controlling the vulnerability that follows after the occurrence of the direct losses, i.e. controlling the follow consequences.

3. Climate models

The assessment of statistics on extreme events in weather variables influenced by a changing climate is of outmost importance to adaptation decisions for future infrastructures. This is a complex task. Firstly, it is difficult to estimate the extreme value statistics, since it by nature is hard to get reliable statistics of rare events from available observations. Secondly, for a changing climate, statistics based on past observations cannot directly be extrapolated, and we must rely on theories, models and past analogies. Research shows that some of the largest impacts of climate change will be through more extreme climate events [7].

The primary tool for assessing climate changes is emission scenario simulations using General Circulation Models (GCM), which in a rather coarse resolution solve the flow and energy equations for the atmosphere and oceans. Furthermore, these models are combined with semi-empirical models of vegetation, soils, ice-sheets etc, to form Earth System Models. The models are extremely costly to run at a level with reliable predictive power, which creates two types of limitations. Firstly, while they provide reasonable predictions at the large scales, they generally underestimate extremes. This is both due to the fact that the coarse resolution makes the meteorological fields unrealistically smooth and the fact that the models are too costly to run for reliable simulation of the extreme tails of the probability distributions of the meteorological fields. Secondly, the global models do not provide the probabilistic information of extreme local climate events needed for risk analysis. For the task of assessing the statistics of a specific climatologic variable, relevant for a specific location (say 10m wind over the North Sea), there are some main techniques:

Dynamical downscaling is based on Regional Climate Models (RCM) that uses GCMs as boundary conditions to simulate the state of the atmosphere in a region with a smaller grid resolution than used in the GCM. RCM models are usually defined at a grid size of 10-50 km and are able to better represent topography and land use than GCM models. However, these models inherit some of the biases of the GCM, and in most cases further statistical downscaling and adjustment is required.

Statistical downscaling techniques are needed to obtain bias-corrected, high-resolution local projections from GCM and RCM simulations. The basic idea behind statistical downscaling is to define a relationship between large scale and local scale climate variables. Presently little emphasis has been put towards downscaling of extremes.

Stochastic weather generators have been applied for downscaling precipitation and derivation of extreme value statistics. These models are typically empirical Markov chain models for generating surrogate climate variables based on parameters estimations from observations and models. Downscaling using stochastic weather generator may change the GCM results considerable. Semenov and Barrow [8] reports an increase in monthly average precipitation by up to a factor of three in some areas.

Climate statistics derives distributions based on past observations. These are based on the assumption of stationarity where past observations are used to estimate the extreme value distributions and associated risks. IPPC operates with approximately 25 GCM models, among which around 8 differ in the underlying semi-empirical models. This implies that that these models do have different competences in capturing different climate change effects in different regions. Similarly there exist of the order of 15 different RCM models that again each have their own competences and weaknesses in different areas.

One of the objectives of the RP that we are developing is to identify what climate change effects are important (for offshore structures in the first version) at different locations around the world. This is used to highlight the relevant weather features that the chosen GCMs and RCMs must be able to capture to arrive at trustworthy climate change predictions. For instance, for the Barents Sea it is important that the models capture polar lows, synoptic lows, and sea ice extent, otherwise extreme winds and waves may be grossly underestimated.

Meehl et al. [9] discussed that though the climate models can simulate many aspects of climate variability and extremes, they still are characterized by systematic simulation errors and limitations in accurately simulating regional climate such that appropriate caveats must accompany any discussion of future changes in weather and climate extremes. However, as computers become more powerful this allow for taking into account more climatological effects and at the same time increasing the grid size. However, when errors are systematic, then the increase in computer power may be of limited use.

Depending on the structures that are evaluated the climate predictions shall be evaluated for the following time periods: present, 20, 50 and 100 years forecasting. Infrastructures are typically designed for 100 year lifetime, whereas offshore structures generally have an expected lifetime of 50 years. The need for all periods for infrastructures is due to dominating uncertainties may change at the different time scales and result in a different mixture of extremes. This may initiate new failure modes to the infrastructures.

Today the climate models are evaluated only for the extreme emission scenarios (currently the A1B-scenario). This may result in too conservative adaptive measures are implemented. This may result in unjustified large investments being allocated at the expense of other initiatives not being implemented. For this reason it is desirable to have climate model runs for all emission scenarios and to assign a probability distribution over the set of analysed scenarios.

4. Design principles for infrastructures

The structural dimensioning of civil infrastructures is made according to requirements formulated in a structural design code. The code requirements are interpreted and formulated within a mathematical model for the geometric and mechanical properties of the structure and for the actions on the structure. For a carefully selected set of the (random) variables that independently contribute to that part of the mathematical model that concerns geometry, strength properties and actions, the code committee calibrates the set of (random) variables such that the design code can control the safety level of a broad class of structures for which the code is meant to cover. The variables are called *design variables*. Control over the safety level is achieved by selecting a *characteristic value* for all design variables (this is typically the 98% or 2-5% fractile value of the random variable) and calibrating *partial safety factors* that amplify the design variables such that the desired safety level is obtained.

For example, consider a simple steel rod with load that pulls at the end of the rod. Let the random strength of the rod be R and the random load be S. The critical situation is clearly when the strength is small and the load is high. Therefore the characteristic value, r_c, of the strength is defined as the 5% fractile value of R and the characteristic value, s_c, of the load takes the 98% fractile of S. The partial safety factor on r_c is γ_r and γ_s on s_c. The design equation in this example becomes:

$$g = \frac{r_c}{\gamma_r} - s_c \gamma_s \geq 0 .$$

The magnitude of the partial safety factors depend on how critical the required safety level of the structure is. Table 1 presents the required reliability (safety) index requirements for building structures.

Table 1. Example of reliability index requirements. From NKB [10].Values in parenthesis is the failure probability.

		Type of failure		
(Reference period 1 year)		Ductile with reserves	Ductile without reserves	Brittle
Safety class	Low	3.1 ($1.0{\cdot}10^{-3}$)	3.7 ($1.1{\cdot}10^{-4}$)	4.2 ($1.3{\cdot}10^{-5}$)
	Normal	3.7 ($1.1{\cdot}10^{-4}$)	4.2 ($1.3{\cdot}10^{-5}$)	4.7 ($1.3{\cdot}10^{-6}$)
	High	4.2 ($1.3{\cdot}10^{-5}$)	4.7 ($1.3{\cdot}10^{-6}$)	5.2 ($1.0{\cdot}10^{-7}$)

The table shows that the required reliability (safety) level depends both on safety class and type of failure. Both the safety class and type of failure refer to consequences of failure. The levels have been identified and validated through cost-benefit analysis of a large suite of structures. Low safety level refers to warehouses whereas the high safety class refers to grandstands and critical infrastructures. The work by NKB forms the basis for all structural codes in Scandinavia, and the principle is now also applied in the Eurocode [2] for structural design.

The table provide valuable information about the fractile level of the extreme value distribution that is of real interest. Critical infrastructures will typically be designed to reliability level of 4.2 to 4.7. It can be shown that this level corresponds to annual exceedance probabilities of the order of $1.3{\cdot}10^{-3}$ to $1.3{\cdot}10^{-5}$.

In the document IPPC [11] rare events are defined as: "*An event that is rare at a particular place and time of year. Definitions of 'rare' vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of the observed probability density function. By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense.*" It is seen that what IPPC consider as rare events significantly differs from the extreme values that is required in structural design, which is a factor of 100 to 10.000 less than the IPPC definition of rare events. The need to extend extremes far beyond what is normally classed as rare within the climatological terminology is very important and a very challenging task.

5. Risk modelling and identification of the dominating uncertainties

The risk modelling contains two interconnected parts: one is to estimate the annual probability of the structure failing and the second is to identify the spectrum of consequences that may materialise following the occurrence of unwanted events. The considered consequence spectrum shall cover both direct and indirect losses, and loss types will not only address loss of life and material losses, but shall also account for production losses and environmental losses. When estimating the indirect losses it is important to consider how the evaluated infrastructure relates and impinge on the surrounding society.

We consider three means for running the risk analysis: The first approach is to establish a Bayesian network (BN) construct for the entire problem. This approach requires a descretisation of the random variables and losses. The second is to apply a full structural reliability approach that use continuous distribution. The third approach is to apply Monte Carlo simulation to estimate the risk. This approach may be combined with the two former through discrete event simulations.

The two first approaches almost directly facilitate identification of the most dominating uncertainties as this can be extracted almost as a bi-product of the analysis. For the BN approach we use so-called *max-propagation* to identify dominating uncertainties, and for the second approach the importance factors directly provide the information. The third approach is somewhat more involved as it requires multiple runs to evaluate the 'value of information' for each random variable. Means will be identified for reducing the uncertainties for the set of variables that dominate the risk modelling, since it will be those variables influences the probability of making a wrong decision the most. Hence, this information gathering may represent a significant cost savings at limited cost.

6. Overview of the risk based method

Figure 1 presents a graphical overview of the overall method. The procedure has 6 steps. The first step is to identify a probability distribution over the emission scenarios thereafter to identify relevant GCMs and RCMs to predict the distributions of future climate. The risk analysis completed by first completing a vulnerability analysis. This facilitates future updates due to changes in emission scenarios, GCM/RCM choices, implementation of adaptation measures.

7. Summary and conclusion

Climate change is real and owners and operators of critical infrastructures need to adapt to a different environment. Climate change is analysed by different global climate models. One fundamental difference between global climate models and design codes for infrastructure is that the climate models operate with average values, whereas one needs extreme values for design codes. It should be noted that the definition of a rare event used by IPCC is fundamentally different from the definition of an extreme event in a design code. There is a significant difference in designing a roof for total of 10% more snowfall if the additional snowfall is evenly distributed throughout the winter versus if the additional snowfall is concentrated for a few days. Designing infrastructure for future climate conditions will involve handling a large number of factors with significant uncertainties. We propose to use a risk based method to handle these uncertainties, and as a means to building a bridge between the climate models and design methods used for infrastructure. More work is needed to clearly describe and quantify the characteristics of the different climate models, better understand the limitations different downscaling methods and to identify the dominating uncertainties.

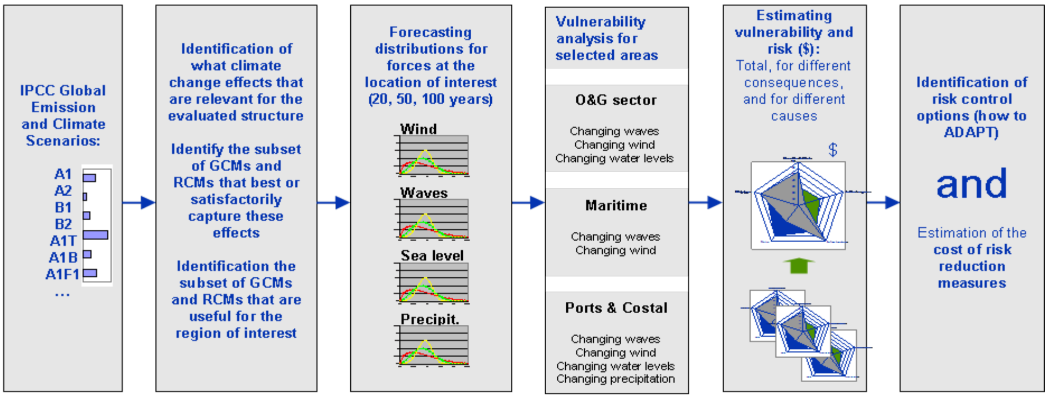

Fig. 1. Overall methodology.

References

[1] DARA, Climate Vulnerability Monitor 2010, http://daraint.org/climate-vulnerability-monitor/climate-vulnerability-monitor-2010/download-the-report/, 2010.

[2] GFCS, Position Paper on Global Framework for Climate Services. Submitted by the World Meteorological Organization. 2010. http://www.wmo.int/pages/gfcs/documents/GFCS_Position_Paper_DRAFT_REV_1_en_1.pdf

[3] ISO 27005, ISO 27000 Directory, http://www.27000.org/iso-27005.htm 2008.

[4] European Network and Information Security Agency (ENISA). www.enisa.europa.eu

[5] The Open Group (an industry consortium to set vendor- and technology-neutral open standards for computing infrastructure)

[6] Wreathall, J. Properties of Resilient Organisations. An Initial View. In Resilience Engineering Concepts and Precepts". pp. 275-285. Eds. E. Hollnagel, D.D. Woods, and N. Leveson,. Ashgate, 2008.

[7] IPCC, 2007, http://www.ipcc.ch/publications_and_data/publications_and_data.htm

[8] M.A. Semenov and E. M. Barrow, Use of Stochastic Weather Generators in the Development of Climate Change Scenarios. Climatic Change 35: 397–414, 1997.

[9] G.A. Meehl, F. Zwiers, J. Evans, T. Knutson. L. Mearns, and P. Whetton, Trends in Extreme Weather and Climate Events: Issues Related to Modeling Extremes in Projections of Future Climate Change. Bulletin of the American Meteorological Society, Vol. 81, No. 3. 2000. Pp. 427-436

[10] Nordic Committee for building structures (NKB), Recommendations for Loading and Safety Regulations for Structural Design. NKB Report No. 36, 1978.

[11] IPCC report … On extreme events and definition of rare, 2007