Comments on the USGS Report "Forecasting the Range-wide Status of Polar Bears at Selected Times in the 21st Century"

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1. Introduction

The U.S. Geological Survey recently completed nine new reports on the polar bear relevant to a listing decision under the Endangered Species Act. One of these report [1] prominently relied on Bayesian Network (BN) modeling to reach its projections about the polar bear populations at four defined ecoregions in 45, 75, and 100 years.

The purpose of this paper is to analyze the report and to provide technical insight on the modeling and methodology employed in the report. In particular, the focus of the paper is to understand how Bayesian network was applied for modeling and analyzing the polar bear status in the study. This paper will attempt to answer the following questions: What are the various factors included and how they are incorporated in the BN model? What are the uncertainties involved in the model and the resulting predictions? And what are the strengths and potential weakness of the approach?

2. Summary of the Study Documented in the Report [1]

In the report [1], two approaches were proposed to predict polar bear habitat and potential population response. First, a deterministic model of past, current, and future polar bear carrying capacity[1] (CC) was presented which assumed a linear relationship between bear density and annual average sea ice extent. Second, a stochastic model was developed based on Bayesian network structured around population stressors that could affect the factors considered in ESA decisions. The BN model combined empirical data, interpretations of data, and professional judgment of a domain expert into a probabilistic framework. The BN model incorporated information about annual and seasonal sea ice trends as well as potential effects of other population stressors such as harvest, disease, predation, and effects of increasing human activity due to ice retreat.

[1] Carrying capacity (CC) is the number of individuals an environment can support without significant negative impacts to the given organism and its environment. The carrying capacity of an environment may vary for different species and may change over time due to a variety of factors including: food availability; water supply; environmental conditions; and living space.

Based on the two approaches, the CC model predicts likely extinction of polar bear in two of the four defined ecoregions and the BN model predicts extinction of polar bear with high probability in three of the four defined ecoregions between 45 and 75 years in the future. By incorporating into the model that polar bears depend heavily on sea ice for access to their prey and other life aspects, it was noted that declines in ice habitat were the overriding factors in determining all model outcomes. In the study, the future ice condition forecasts were based largely on information derived from general circulation model[2] (GCM) projections of the extent and spatiotemporal distribution of sea ice. The model results also indicated that sea ice conditions would have to be substantially better than even the most conservative GCM projections to result in a qualitatively different outcome for any of the ecoregions.

3. Comments on the Study

First of all, I have to say that the study documented in the report did a very thorough job for polar bear population projections using a relatively complex Bayesian network model. The authors also did an extensive sensitivity analysis and came up with strong arguments that their results were relatively robust and it would require significantly different evidence in order to fundamentally alter their conclusion. However, due to the inherent uncertainty in the problem and the intrinsic weakness of the modeling technique, it's difficult to judge the validity of their conclusion.[3]

Bayesian network modeling has been used widely to describe probabilistic dependencies between variables and has been proven to be a very effective way for reasoning under uncertainty. Although this type of "model-based" approach for prediction results is cost-effective, it is well known that the method is only as good as the underlying data or domain expert that is used in deriving the model.

Also, since the polar bear's status involves complex processes, it is not only very difficult to create a model through standard knowledge engineering process, driving tests and analysis results but also almost impossible to create an accurate model for all foreseeable conditions, environmental effects, human activities, and polar bear's adaptive response. In general, if the constructed BN model is incorrect/biased or the input data supplied to the model is inaccurate, then the conclusions drawn from the model are likely to be unreliable.

Based on the report from the study, it is very difficult to judge the fidelity of the model and the accuracy of the input data and therefore not possible to measure the reliability of the resulting conclusion. Specifically, this is due to the following observations.

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[2] General Circulation Models (GCMs) are a class of computer-driven models for weather forecasting, understanding climate and projecting climate change, where they are commonly called Global Climate Models. Various versions were designed for decade to century time scale climate applications. These computationally intensive numerical models are based on the integration of a variety of fluid dynamical, chemical, and sometimes biological equations.

[3] I have also reviewed a part of the Comments of SCI/SCIF (to be filed October 22, 2007) discussing some limitations of BN modeling in the ecological area. Based on my experience and expertise with BN modeling, I generally agree with the statements from the two articles discussed in SCI/SCIF's Comments.

(1) BN was introduced to account for other stressing factors that could not have been accounted for using the CC model. However, only a single domain expert was used in the "knowledge engineering" process to model the stressing factors. It could potentially bias the BN model based on his subjective opinion.

(2) The purpose for using the BN model was to address the uncertainty inherent in the complex situation far into the future. However, the model assumes no or low adaptability of the polar bear in response to the changing and uncertain environment. Among other factors to be discussed in Section 3.2, this assumption renders the model somewhat unrealistic or incomplete.

(3) One of the key inputs to the prediction model is the result of GCM modeling and sea ice model projections of the extent of sea ice in the future. While most aspects of climate simulations have some degree of uncertainty, uncertainty in projections of Arctic climate change is particularly high. This is due to the smaller spatial scale of the Arctic and the complex processes that control the ice, and the difficulty of representing these processes in climate models [2].

Each of the issues, in addition to others, will be discussed in more detail in the following sections.

3.1 Complexity and Uncertainty in the BN Model

Bayesian network modeling has been used widely to describe probabilistic dependencies between variables. A Bayesian network is a directed acyclic graph (DAG) that includes parameters to describe the conditional probability distribution of variables. Conditional dependencies are represented by incoming arcs to each variable [3].

While this type of model-based approach for prediction results is effective, the method is only as good as the input supplied by the data or the domain expert [3]. However, it is almost impossible to create an accurate BN model for all foreseeable conditions for the complex assessment of the polar bear's status. Regardless of the quality of the data in the inputs, because of the complexity of this particular circumstance, BN modeling may not be able to predict with a high level of certainty what the actual outcome will be, particularly considering the long time horizons.

The single most critical concern about the study is the fact that there was only one subject matter expert (SME) involved in the modeling effort. Most of the BN model built in the study (including both network topology and conditional probability tables between variables) was based entirely on the judgment of the single SME.

I agree with the assessment in the report [1, p.16] that "…because BN models combine expert judgment and interpretation with quantitative and qualitative empirical information, inputs from multiple experts are usually incorporated into the structure and parameterization of a "final" model… however, we were not able to seek and incorporate the input of multiple polar bear experts. Therefore, the model presented here should be viewed as a first-generation prototype."

Furthermore, according to the report [1, p.48, Table 3], out of the 17 input nodes in the model, except the data for node B (Foraging Habitat Quantity Change) which was derived from the CC model and the data for nodes C and N (Foraging Habitat Absence Change and Shelf Distance Change) which were derived from the GCM results, data for all remaining nodes were specified by the same expert who constructed the model. It is therefore possible that the prediction results could potentially be dictated (or biased) by the knowledge of the SME.

3.2 Validity/Fidelity of the BN Model

In general, if a BN model is built and applied correctly, the mathematical aspect of the model is well understood and would not be subject to challenge or criticism. However, there are several shortcomings in the model developed for the study that deserve a closer look.

First of all, the model assumes no or low adaptability for the polar bear in response to the changing environment. However, at least some scientists believe that polar bears can adapt to climate change. Polar bears are believed to have evolved from grizzly bears some 200-250,000 years ago and were well developed as a separate species by the approximately 125,000 years ago [4]. This period was characterized by temperature fluctuations caused by entirely natural events on the same order as those predicted by contemporary climate change models. Polar bears obviously adapted to the changing environment, as evidenced by their presence today [4].

This fact was indeed recognized by the report [1, p. 5], "Polar bears, in fact, have adapted their movement strategies to accommodate a broad range of sea ice characteristics." However, the study simplified the modeling process by assuming no adaptability of polar bear as stated in the same report [1, p.9], "This approach assumes that polar bears in the future will select habitats in the same way they did between 1985-1995 despite seasonal changes in ice extent and distribution…", which is obviously not realistic.

There are several other issues in the model that could also potentially impact the accuracy of the prediction. For example, the three most important input nodes in the model (B, C, and N) are continuous variables. In the study, they were discretized in a somewhat ad hoc manner [1, p.104]. However, artificially "discretizing" the continuous variables without careful consideration could significantly degrade the accuracy of the prediction performance. In fact, a recent study [5] (of which I was a co-author) showed that even with the support of a large data set, applying a simple-minded discretization technique could cause as much as 30% error in predicting the most probable outcomes.

Another potential problematic area comes from the fact that there was a high discrepancy between the assessment results of the two outcome nodes, Numerical Response and Distribution Response. As seen in the table [1, p.68-69, Table 9], for the node Numerical Response (C4), the dominant (> 50%) outcome state was always "reduced density" in all prediction scenarios. On the other hand, with similar or less input influence, the most

dominant state for the node Distribution Response (C3) was "extirpated" in many instances. After closer examination, it is clear that this is because the conditional probability table for C3 [1, p.118] was much more heavily weighted over the tail than the one for C4 [1, p.125]. This type of inconsistency might signal a potential problem in the model.

Moreover, although the assessment results of the two responses (C3 and C4) were quite different ("extirpated" for C3 and "reduced density" for C4), the overall population outcome (D1) [1, p.66-67, Table 8], which was the combination of the two responses, was essentially the same as the distribution response (C3). The rule [1, p.126] of combining the two responses to arrive at the final overall outcome is obviously too pessimistic. It could significantly bias the final conclusion of the study.

3.3 Uncertainty in the Input Data

The main result of the study heavily relied on the GCM predictions. This is evident from the sensitivity study [1, p.93, Fig. 12] where the top three factors contribute around 75% of the explainable entropy reduction of the overall population outcome. Among the three factors, the top two (Foraging habitat quantity change and Foraging habitat absence change) are directly tied to the GCM forecast. The third variable is Geographic Area, which is obviously highly relevant to the outcome.

Although a sensitivity analysis was done in the study to evaluate the extent to which sea ice projections would have to differ to make qualitative differences in outcomes, only the range of ice conditions available from GCMs were used for the study [1, p.18]. However, the GCM model itself is uncertain and could be highly inaccurate. According to the report [1, p.23], "… The sea ice parameters we used in our polar bear models were derived from GCM outputs, which possess their own wide margins of uncertainty. Hence, the magnitude and distribution of errors associated with our sea ice parameters were unknown…"

According to another report [5, p.2] (one of the nine reports mentioned earlier), "…While all models are constructed using the same physical laws, different approximations and simplifications are used in different models, and these differences lead to different sea ice simulation outcomes… The atmosphere, ocean, and sea ice comprise a nonlinear chaotic system with a high level of natural variability unrelated to external climate forcing." Also in the same report [5, p.3], "…Even if climate models contained a perfect representation of all climate system physics and dynamics, inherent unpredictability would prevent us from issuing detailed forecasts of climate change beyond about a decade."

Casting ensemble averages from multiple GCM models as done in the study [1] allows a comparison to analogous averages from kinetic theory. However, according to a recent study [6], the climate prediction is difficult in that "the ensembles are over different spaces of invariants requiring adjustments to produce results closer to true values …. Anything that is used for models is empirically produced". Essentially, the study [6] concluded that there is no way to either verify the model or their flawed predictions.

4. Other Considerations

It is important to note that the global warming phenomenon stated in the report [1] is not new. According to a Wall Street Journal article [7] and a recent paper [8], the current earth warming trend started about 300 years ago [8] (see Figure 1). The temperature rising trend and the fluctuations within it are closely related to solar activity as shown in Figure 2 [8]. The earth temperatures are now near the 3,000-year average and obviously not unusual. What will temperatures be during the 21st century and beyond? "No one knows", according to the article [7], "Astronomers are not yet able to predict future solar activity." However, if the current trends continue, as stated in the article [7], "our environment will be much improved…..When this biological miracle stabilizes – one or two centuries in the future – it is estimated that the plant and animal population of the Earth may have doubled."

As stated in [4], "...Adaptation and transition will likely be required for every population if the projected climate change scenarios are realized. Polar bears are intelligent and quick to adapt to new circumstances and are physiologically capable of adapting to food stress…" , "They have evolved and persisted for thousands of years in a period characterized by fluctuating climate…", "no evidence exists that suggests that both bears and the conservation systems that regulate them will not adapt and respond to the new conditions." As mentioned in [4], one should "acknowledge the existing research and management structures and initiatives in place to ensure that polar bear populations persist in perpetuity."

REFERENCES

[1] Steven C. Amstrup, Bruce G. Marcot, and David C. Douglas, "Forecasting the Range-wide Status of Polar Bears at Selected Times in the 21st Century," USGS Administrative report, 2007.
[2] Eric DeWeaver, "Uncertainty in Climate Model Projections of Arctic Sea Ice Decline: An Evaluation Relevant to Polar Bears," USGS Administrative report, 2007.
[3] F.V. Jensen, Bayesian Networks and Decision Graphs, Springer Verlag, New York, 2001.
[4] M. K. Taylor, "Review of CBD Petition," submitted to the FWS, April, 2006.
[5] Wei Sun and K.C. Chang, "Probabilistic Inference using Improved Importance Sampling for Hybrid Bayesian Networks," in Proc. SPIE Defense and Security Symposium, Vol. #5809, p. 322-329, Orlando, Florida, April, 2005.
[6] Christopher Essex, Silvana Ilie, and Robert M. Corless, "Broken Symmetry and Long-Term Forecasting," *Journal of Geophysical Research*, in press, 2007.
[7] Arthur Robinson and Noah Robinson, "Global warming is 300-year-old news," *The Wall Street Journal*, Jan. 18, 2000.
[8] Arthur Robinson, Noah Robinson, and Willie Soon, "Environmental Effects of Increased Atmospheric Carbon Dioxide," *Journal of American Physicians and Surgeons*, Vol. 12, p. 79-90, 2007.

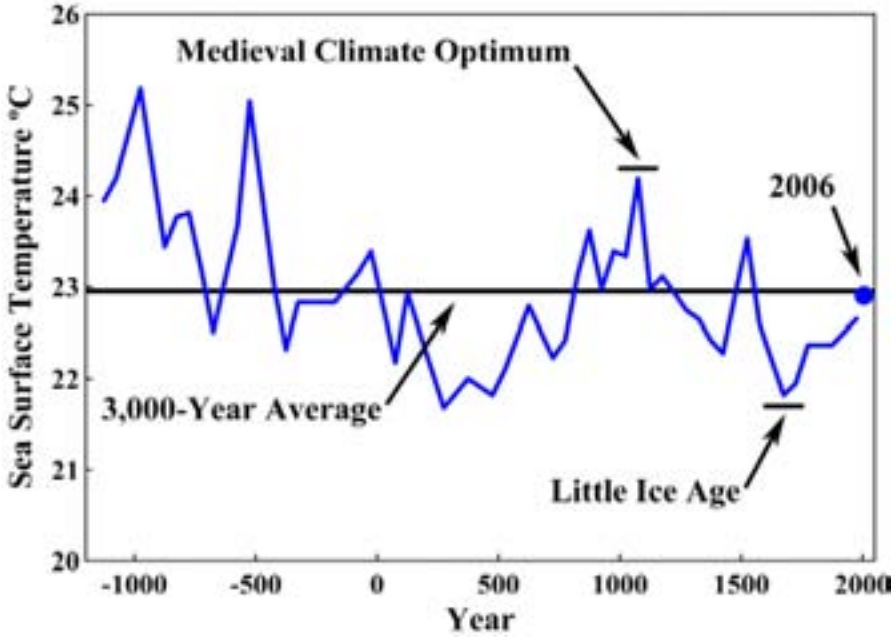

Figure 1: Surface temperatures in the Sargasso Sea, a 2 million square mile region of the Atlantic Ocean. The horizontal line is the average temperature for this 3,000-year period. The Little Ice Age and Medieval Climate Optimum were naturally occurring, extended intervals of climate departures from the mean.

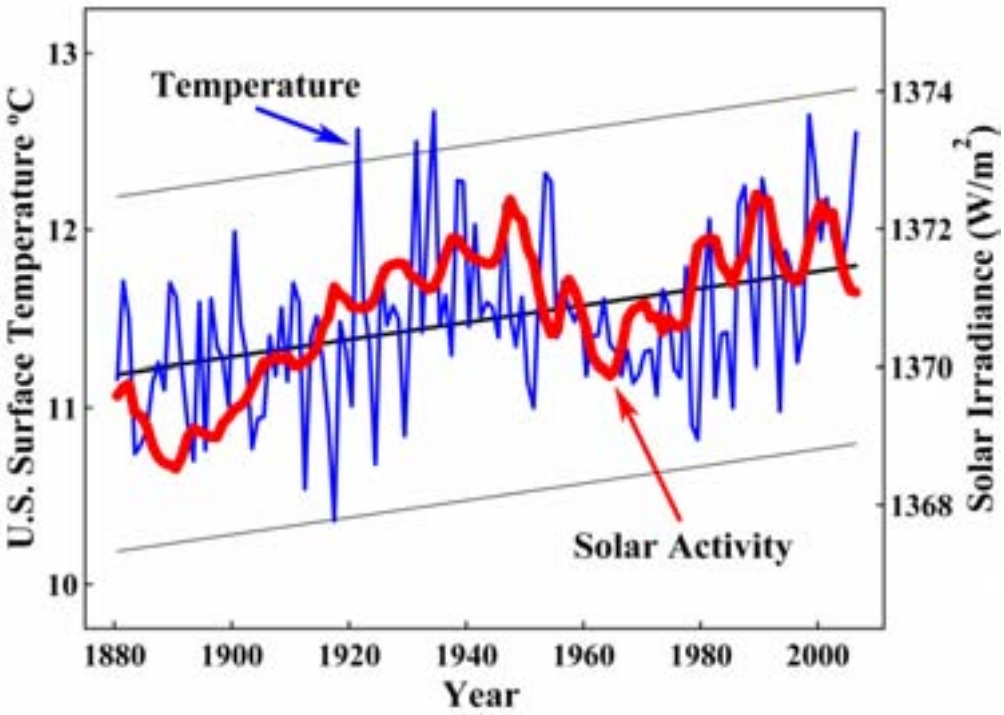

Figure 2: U.S. surface temperature as compared with total solar irradiance