

## Reply to Wiin-Nielsen's comment

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Wiin-Nielsen observes that the value of the variance of the fluctuations for which a substantial amplification of the thermal response to the forcing can take place is quite large. Moreover, he points out that the choice of the value of the heat capacity coefficient can influence the value of the variance for which the above-mentioned amplification takes place. Wiin-Nielsen concludes that the theory developed by Nicolis (1982) although correct mathematically, does not seem to explain the natural phenomenon in the sense that the parameter values utilized are not realistic.

Wiin-Nielsen is correct in pointing out that high values of the variance  $q^2$ , are needed. The main reason for this, however, is not in the choice of the heat capacity,  $C$ , but in the fact that the zero-dimensional model (Crafoord and Källén, 1978) used to illustrate the theory gives rise to a large distance between stable climatic states. Despite the periodic lowering of the potential barrier by the periodic forcing, one therefore still needs substantial fluctuations in order to "tunnel" between the present-day climate and the glacial climate.

I was well-aware of this peculiarity, which is shared by all known zero-dimensional energy balance models subject to the constraint that they give realistic values for the albedo. My principal

goal, however, was to identify the physical mechanisms responsible for the amplification of an external forcing by the system's dynamics, and arrive in this way at a better understanding of the rôle of externally and internally generated factors in climatic change. To achieve this, it was essential to first consider simple models in which an exhaustive analytic treatment, free of ambiguities, could be carried out. In short, my analysis should be regarded as a *qualitative* one. I believe that the objective pursued amply justifies the interest of this latter type of approach. This essential point of the work is not touched upon in Wiin-Nielsen's comment, which is addressed to the quantitative aspects of the problem.

It would of course be worthwhile to obtain quantitative answers. To this end, one should use more sophisticated models as, for instance, one-dimensional energy-balance models with judiciously parameterized surface albedo feedback and infrared cooling terms, or models involving the energy-ice extent coupling. It should, however, be realized that this would confront us with very hard mathematical problems. In any case, such possibilities constitute a challenge to be met by future investigations.

### REFERENCES

- Crafoord, C. and Källén, E. 1978. A note on the condition for existence of more than one steady-state solution in Budyko-Sellers type models. *J. Atmos. Sci.* 35, 1123-1125.
- Nicolis, C. 1982. Stochastic aspects of climatic transitions—response to a periodic forcing. *Tellus* 34, 1-9.