Systems and processes – my perception of the legacy of Klaus Hasselmann's approach to environmental science

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1. The Physics Nobel Price 2021 for Klaus Hasselmann – is there something to be learned for our community ?

Klaus Hasselmann was awarded the prestigious award in 2021, for work which he did some 40 years earlier. He shared the award with two others, among them Suki Manabe, another climate scientist. The Nobel committee referred to "for groundbreaking contributions to our understanding of complex physical systems" and specifically to their achievements in "physical modelling of Earth's climate, quantifying variability and reliably predicting global warming".

In case of Klaus Hasselmann, the recognized work was focusing on the "stochastic climate model" from 1976 and the "detection of change and its attribution to causes" (first published in 1979) as milestones. What is the legacy of his work for us? Did he enforce a paradigm-shift in our way of conceptualizing and analyzing environmental systems such as oceans and climate?

2. Paradigm shift – the PIPs-approach

My subjective answer is – yes, I believe he did. This paradigm shift was not only his work; in a sense it was already in the air; it developed over time, and as such it is hardly recognizable today. But nevertheless – there was a massive change.

Klaus Hasselmann has practiced "his" paradigm all the time, without uttering big claims, and in 1988 he published it in a hardly noticed paper – he named his concept PIPs, "Principal Interaction Patterns". The idea is that when we study a complex high-dimensional system, we need to identify a small "core" or "signal" space", and to project the overall dynamics of the full phase space (Figure 1, top), which spans very many if not infinite many degrees of freedom, on this subspace (Figure 1, bottom). This core space may depend on what we want to study – it will be different for the analysis of global warming or for the analysis of coastal morphodynamics. The myriads of processes outside the core space are disregarded and taken into account only by their expected conditional impact on the core space – in other words, parameterized.

The visible achievements, both the "stochastic climate model" and the "detection and attribution" may be seen in this concept. Also, all dynamical models are built in this way (von Storch, 2001).

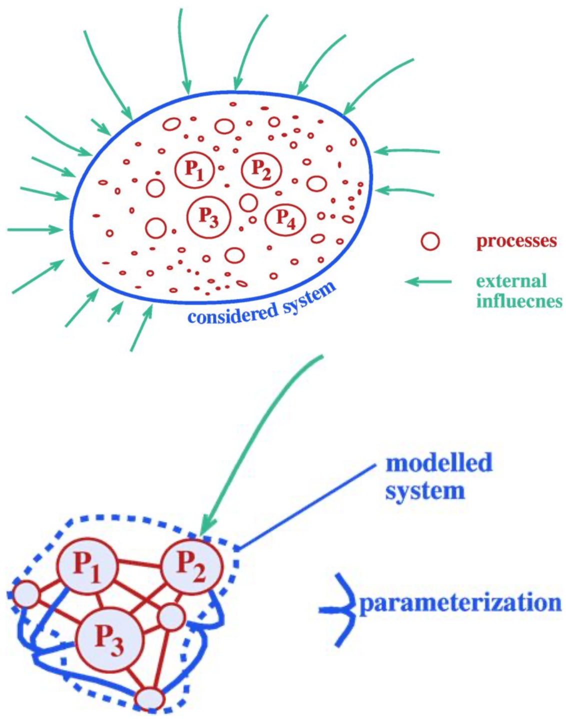

Figure 1
Top: Sketch of the full system **S,** all processes P_i and external factors F_k
Bottom,: PIP-reduction of full space to core space, a forcing of interest F and significant processes P_i, while the rest ist parametrized.

3. The role of process studies

When studying a dynamical system **S** with an Infinite state vector S, we assume that its dynamics are given by $dS/dt = \Sigma_i P_i(S)$ with very many if not infinitely many processes $P_i(S)$. When we want to „understand" **S**, we look for answers of

1) How predictable is **S**?
2) How sensitive is **S** to different external factors F_k?
3) Which processes P_i are dominant for the dynamics of **S** given the forcing F_k?

For dealing with (1) and (2) we do not necessarily need specific knowledge about the processes, but empirical (or theoretical) evidence about the variations of **S**.

Klaus Hasselmann's "stochastic climate model" (1976) dealt with (1). It recognizes the presence of in the system, and a short-term forcing. This configuration leads to the dynamical equation $\underline{S}_{t+1} = (1-\lambda)\,\underline{S}_t + \delta_t$, with a one-dimensional projection $\underline{S}$ of S, a memory parameter λ and "white noise" δ. The predictability is that of a "red" spectrum.

The second Nobel-recognized contribution of Klaus Hasselmann was his strategy of "detection and attribution" (1979 and later), which attempts to detect a "signal" in the stochastic system **S**, and to attribute one or more forcings F_k as causal. Thus, it is an approach for (2). Also in this case, specific knowledge about the processes is not needed, but only the expected conditional impact of the P's on **S.** Such knowledge can be constructed from empirical evidence or numerical experimentation with quasi-realistic models, which feature as many processes as possible.

In (3), however, specific knowledge about the processes is required. To do so in numerical experimentation, proper signal-to-noise analyses are needed to separate the relevance of the different drivers, leading to similar approaches as in (2).

In our scientific practice, a significant scientific effort is the improvement of process understanding, which is claimed to improve our quasi-realistic models by adding new processes or improving the knowledge about the functioning and sensitivity of processes. This is for (3) important, also for the continuous development of quasi-realistic models, but such additions do not automatically lead to an added value in understanding of the considered system embedded in a variety of forcings $F_{k.}$

Instead, we often see an infinite cycle of model-improvements by adding continuously new details, without shedding new light on the above mentioned three challenges.

4. Conclusion

In our community we see many process studies, often associated with a vague claim that this approach would directly lead to the understanding of the system. Indeed, "Wüst's law" (von Storch et al., 1999), according to which you find something interesting if you take a closer look, is valid, and is a strong motivation for process studies. But without theoretical or empirical expectation of what to find, we will in general be lost in a sea of details and an ocean of numbers. Given this dilemma, it is not surprising that the claim, according to which the study of processes alone would lead to system understanding, is in most cases misleading.

5. Caveat

This is my understanding of Hasselmann's legacy for us – the system is not to be conceptualized as the sum of all processes, but understanding of the system implies knowledge about predictability, of sensitivity to external forcing, and of the stochastic character of the system.

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