Klaus Hasselmann: Recipient of the Nobel Prize in Physics 2021

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https://doi.org/10.1093/acrefore/9780190228620.013.931

Published online: 22 November 2022

Summary

Klaus Hasselmann and Syukuro Manabe shared one half of the 2021 Nobel Prize in Physics for their achievements in "physical modelling of Earth's climate, quantifying variability and reliably predicting global warming." The Swedish Academy asserted: "Klaus Hasselmann created a model that links together weather and climate, thus answering the question of why climate models can be reliable despite weather being changeable and chaotic. He also developed methods for identifying specific signals, fingerprints, that both natural phenomena and human activities imprint in the climate. His methods have been used to prove that the increased temperature in the atmosphere is due to human emissions of carbon dioxide."

Klaus Hasselmann is best known for founding the Max Planck Institute for Meteorology in Hamburg, where he implemented his ideas on quantifying internal variability in the climate system and its components ("stochastic climate model"), and on devising a methodology to separate "noise," that is, variability not provoked by external drivers, from a "signal" reflecting the impact of such external drivers. In this way, he introduced a paradigm shift from a deterministic view of the climate system to a genuinely stochastic one. This proved instrumental in detecting anthropogenic climate change beyond natural variability ("detection") and in demonstrating that the ongoing change could not be explained without a dominant role of elevated atmospheric levels of greenhouse gases ("attribution"). Hasselmann and Manabe initiated the construction of two of the leading quasi-realistic climate models featuring not only an atmosphere and ocean but also the carbon cycle. These achievements were recognized by the Nobel Prize.

The spectrum of themes where Klaus Hasselmann left significant footprints extends far beyond climate dynamics, covering a wide range of geophysical topics. By the time he entered the field of climate research, Hasselmann had already produced groundbreaking work on the modeling and predicting of ocean surface waves. He and his wife led the development of a third-generation wave model, versions of which are in operational use today at major numerical weather prediction centers around the world, including the European Centre for Medium-Range Weather Forecasts (ECMWF) in Europe and the National Oceanic and Atmospheric Administration (NOAA) in the United States. After his retirement, Hasselmann considered his contribution to geophysical issues of climate and climate change sufficient and chose to focus on two different topics. One concerned the coupling of societal decision making with the geophysical system. A second concerned Hasselmann's interest in elementary particle physics, which dates back to his work in the 1960s when he described nonlinear resonant wave-wave interactions by means of Feynman diagrams. Following early ideas by Kaluza and Klein, Hasselmann pursued a deterministic, unified field theory of particles and fields, which he termed "metron theory." It remains incomplete, and given Hasselmann's age may never be completed by himself, but may have to await a smart young physicist to take on the challenge.

Keywords: Klaus Hasselmann, Nobel Prize in Physics 2021, stochastic climate model, detection and attribution, wave modeling and prediction, metrons

Subjects: Modeling

The Nobel Prize in Physics 2021

Klaus Hasselmann was awarded the 2021 Nobel Prize in Physics for work which he did some 40 years earlier (figure 1). He shared half of the award with climate scientist Syukuro Manabe, the other half being awarded to theoretical physicist Giorgio Parisi. The Nobel Committee cited "groundbreaking contributions to our understanding of complex physical systems" and, in the case of the two climate scientists, specifically their achievements in "physical modelling of Earth's climate, quantifying variability and reliably predicting global warming." The recognition of Klaus Hasselmann's work focused on the "stochastic climate model," published in 1976, and the "detection of change and its attribution to causes" (first published in 1979) as milestones:

> Klaus Hasselmann created a model that links together weather and climate, thus answering the question of why climate models can be reliable despite weather being changeable and chaotic. He also developed methods for identifying specific signals, fingerprints, that both natural phenomena and human activities imprint in the climate. His methods have been used to prove that the increased temperature in the atmosphere is due to human emissions of carbon dioxide.
>
> (Royal Swedish Academy of Sciences, 2021)

In his Nobel Prize lecture, Klaus Hasselmann himself sketched his achievements and their significance for science, the public, and policymaking.[1]

When the Nobel Prize was announced, many observers took it as proof that climate science was finally accepted as "physics" (e.g., Hegerl, 2022; Källen, 2022), which would have two major implications. First, skeptical claims that human-made climate change would just be a speculation by meteorologists and other earth scientists were refuted; instead, both, the theory and the empirical assertion that climate change is real are based on hard physics and can hardly be questioned anymore. Second, climate science would be "knighted" as real and worthy science, on par with physics. In any case, the prize had significant implications for both the public and the intrascience perception of the field of climate science.

One could, however, also argue that the award recognizes scientific constructions, with significance beyond the field of climate science; for instance, the finding of the stochastic climate model, according to which any not too nonlinear geophysical system governed by memory and forced by short-term fluctuations will form low-frequency variations, without being subject to a specific low-frequency forcing. This is a remarkable adaptation of Brownian motion or the random walk concept to the climate system and will likely find fruitful applications in other areas of geosciences, such as morphodynamics or glacier dynamics. Another is that the analysis of a complex, high-dimensional, and heterogenous system may be pursued productively and with much insight by partitioning the full phase space into a small (i.e., reduced-order) signal space, for which state matters, and a noise-space, for which the statistics conditioned by the state in the signal space matter (see the subsection "Climate Dynamics, Statistics, and Change.").

Figure 1. Klaus Hasselmann and his wife and coworker, Susanne Hasselmann in December 2021. Copyright: Nobel Prize Outreach.

Photo: Bernhard Ludewig.

Data and Evidence

This article relies on 30 and more years of cooperation and friendship between Klaus Hasselmann, Hans von Storch, and Patrick Heimbach, and three major sources, namely

- K. Hasselmann, 2021: Nobel Prize lecture,

- H. von Storch and D. Olbers, 2007: interview with Klaus Hasselmann, and H. von Storch, 2022: *From Decoding Turbulence to Unveiling the Fingerprint of Climate Change: The Science of Klaus Hasselmann*.[2]

Not surprisingly, in the aftermath of the Nobel Prize, many articles have been published, which not only shed light on various details of the achievements of the laureate but also to some extent tell anecdotes on Hasselmann’s life and personality, such as Källen (2022), von Storch et al. (2021), Hegerl (2022), Cavaleri and Janssen (2022), von Storch (2022), Song and Wu (2022), Bensley (2022), and Franzke et al. (2022).

Scientific Career of Klaus Hasselmann

Klaus Hasselmann was born on October 25, 1931 in Hamburg, Germany and emigrated to England with his family in 1934 because of the Nazi regime. In Welwyn Garden City, England, he went to school, where he received the Cambridge Higher School Certificate in 1949 as his final high school exam (Bendsley, 2022). This period was formative for Klaus, who still considers himself as kind of English and who counts in English.

As a German, he was not permitted to study at Cambridge University. In 1949, he and his family returned to his hometown, Hamburg, where he did an internship at a company engaged in mechanical engineering until he enrolled at Hamburg University in May 1950, studying physics and mathematics. He concluded his studies in 1955 with a “Diplom” on a thesis on turbulence. He spent the next 2 years as a doctoral student at the University of Göttingen and the Max Planck Institute for Fluid Dynamics Research. He was formally supervised by the institute’s director, Walter Tollmien, but essentially was left on his own. He concluded this period with his dissertation in July 1958: *Über eine Methode zur Bestimmung der Reflexion und Brechung von Stoßfronten und von beliebigen Wellen kleiner Wellenlängen an der Trennungsfläche zweier Medien*.

In August 1957, Klaus returned to Hamburg to the Institute of Naval Architecture at the University of his old mentor, Karl Wieghard, before spending almost 3 years at the Institute for Geophysics and Planetary Physics of the Scripps Institution of Oceanography, University of California, San Diego, where he met and began a lifelong friendship with Walter Munk (von Storch & Hasselmann, 2010). During that time, in 1963 he took part in a classic field campaign to measure swell propagation across the Pacific Ocean (Snodgrass et al., 1966), being conveniently stationed for 3 months in Hawai’i together with his wife, whom he had married in 1957 (figure 1), Susanne Hasselmann. Vivid accounts of his time are given in von Storch and Hasselmann (2010) and von Storch (2022). A half-hour documentary was also produced detailing the experiment and its results, an exquisite early example of outreach.[3]

In February 1963, Klaus received his “Habilitation” in Hamburg, which was a necessary requirement for a young scientist in Germany to continue his academic career. He became lecturer in late 1964, full professor in 1966, and department director in 1969 at the Institute of Geophysics of the University of Hamburg. His stay in Hamburg was interrupted by extended overseas positions, first as visiting fellow at the University College, Cambridge University, United Kingdom, and as Doherty Professor at the Woods Hole Oceanographic Institution (WHOI) in Massachusetts.

During this first period of his career, Klaus Hasselmann's attention was mostly, but not exclusively, focused on all kinds of waves, in particular ocean surface gravity waves (wind waves and swell), with both theoretical work for deriving the standard spectrum of waves and their dynamics, but also field work which led to the so-called JONSWAP spectrum. Remarkably, as a theoretical physicist, Klaus happily and easily worked with numerous observational field programs, both as designer and analyzer of the details of the results. His research was widely recognized early on, receiving a series of prestigious awards, such as the Carl Christiansen Commemorative Award in 1963, the James B. Macelwane Medal of the American Geophysical Union in 1964, the Academic Award for Physics from the Academy of Sciences in Göttingen in 1970, and the Sverdrup Medal of the American Meteorological Society in 1971.

In 1974, all this changed when he was offered by the president of the Max Planck Society, Reimar Lüst, to build a Max Planck Institute for Meteorology. As usual with these institutes, Hasselmann was given very wide latitude in setting up his institute in terms of the research agenda and his staff, but it was expected that he would approach the issue of man-made climate change. In 1975, the institute was founded, and he remained director until his retirement in 1999, during most of his tenure in a direct managing role. When he succeeded in building the German Climate Computing Centre (DKRZ) next to his Max Planck Institute, he also assumed the position of the scientific director of that institution.

During this time, Klaus continued his work on ocean waves, together with his wife Susanne. Eventually they succeeded at installing an operational forecast system at the European Centre for Medium-Range Weather Forecasts (ECMWF) in Reading, England, based on Klaus' "Grundgleichungen," a closed theory of its source terms, and the assimilation of satellite-based real-time data. However, this important and successful work occupied only a minor part of his time and attention; instead, the climate problem became more and more important, with the key achievement being the conceptualization that climate variability would have its sources in both internal and external drivers. The dynamic behavior of the internal drivers were found to be well approximated by his "stochastic climate model," put forward in 1976; the task of how to practically determine the external components of the variations in the sea of "noise" (internally generated variations) was a second major achievement. Two decades later, this became famous as "detection and attribution" when the Intergovernmental Panel on Climate Change (IPCC) in 1995 recognized the fingerprint of ongoing climate change caused by human emissions of greenhouse gases. These two achievements laid the foundation for awarding Klaus, decades later, the 2021 Nobel Prize in Physics. During this second phase of Klaus Hasselmann's career, he was honored with many more awards, including the Förderpreis für die Europäische Wissenschaft of the Körber-Stiftung in 1990 (together with Lennart Bengtsson and Bert Bolin), the Vilhelm Bjerknes Medal of the European Geophysical Society in 2002, and the BBVA Foundation Frontiers of Knowledge Award in 2009 (see von Storch, 2022 for a complete list).

Hasselmann's seminal papers related to climate, the stochastic climate model and the detection and attribution concept, may both be seen as rooted in his paradigm of splitting the full phase space of climate variability into two separate spaces, one a low-dimensional signal-space, or PIP-space, and the other a high-dimensional noise space—as outlined in another seminal paper on principal interaction patterns in 1988. Beyond these highly impactful publications, Klaus' creative mind generated a wealth of other research ideas to be pursued by members of the Max Planck Institute, and with Klaus generously sharing with or conferring to others the credit for many of these ideas.

In the decade leading up to his retirement, and the time thereafter, he spent less time on waves and climate but focused on a topic he has been interested in all his life, a unified particle theory—the "metrons." This work made significant progress, and in recent years, he and his wife had worked on a book spelling out the concept, but given age and health, the work slowed and finally came to a halt without having achieved the recognition it may deserve.

The Elephant

When talking to colleagues with different topical backgrounds about Klaus Hasselmann, it quickly becomes obvious that the interests and achievements of Klaus Hasselmann are very broad—broader than many were aware of. In preparing the book on Klaus (von Storch, 2022), the authors noticed that the old Indian parable of the blind humans and the elephant applies well, with Klaus Hasselmann being the elephant and his colleagues the blind humans.[4] His colleagues recognize only a subset of his interests, potentials, and achievements. A cartoon (figure 2) captures seven such different themes, but more are likely hidden in the elephant's shadow. In the following, the authors try to summarize some of these themes. More detailed accounts are given in the book compiled by von Storch (2022).

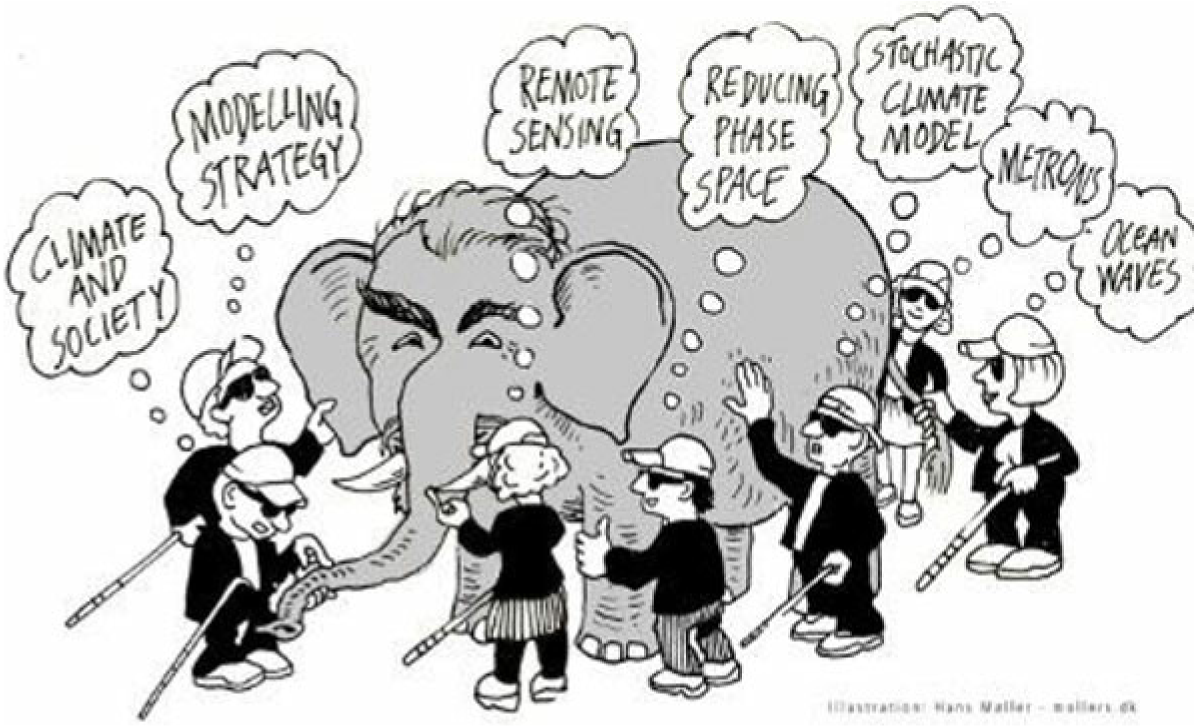

Figure 2. The blind humans and the elephant.

Drawing by Hans Møller.

Climate Dynamics, Statistics, and Change

The work sketched in the following motivated the awarding of the 2021 Nobel Prize in Physics.

To understand climate dynamics, focusing solely on developing numerical models and conducting simulation-based experiments is as insufficient as to exclusively formulate hypotheses and theories on a piece of paper. Klaus Hasselmann's approach to the field of climate dynamics recognized the need to do both at the same time, that is, to be able to simulate climate variability and to perform numerical experimentation (because the empirical evidence is insufficient, and does not allow experimentation), but also to order the components of the climate system with practically an infinite number of inhomogeneous degrees of freedom according to significance.

A cubic meter of gas has practically an infinite number of degrees of freedom, but they are homogeneous because the gas consists of an ensemble of identical actors, and theoretical physicists have learned to deal with such a challenge. In the case of climate, the "actors" are not identical. Two-dimensional turbulence exists with storms and eddies, three-dimensional turbulence in boundary layers, and there are planetary cells and convective cells, gravity and baroclinic waves, raindrops, plants, and so on. Indeed, the climate system is open—and in the course of time, the set of state variables considered in climate models has steadily expanded, in parallel with ever-increasing computing power.

Full models of atmospheric or oceanic dynamics, or of the coupled system and thus of climate dynamics, are based on process-based equations of motion (conservation and constitutive laws), that is,

$$\frac{d\psi}{dt} = \sum_i p_i(\psi), \tag{1}$$

with a large vector of state variables ψ and many representations of processes p_i. In many cases, these representations are parametrizations, that is, a conditional expectation of the effect of the process on the resolved scales. Such processes include advection, convection, friction, dissipation, turbulence, tides, gravity waves, internal and external sources and sinks, and so on.

Colleagues expected Klaus Hasselmann to construct such models when he founded his Max Planck Institute of Meteorology and to install a powerful computer right away. But he did not.[5]

Instead, he began to work with paper and pen and designed his stochastic climate model (Hasselmann, 1976):

$$\frac{d\psi}{dt} = \lambda\psi + \delta, \tag{2}$$

with one state variable ψ and a stochastic white noise process δ.[6] If $\lambda \geq 0$ the stochastic process ψ is nonstationary, but with $\lambda < 0$, it is statistically stationary, and its variability is described by a red-noise spectrum. Thus, ψ will show long-term variations, which are not forced by a specific external driver. Of course, in both cases, deterministic external forcing may be present as well.

Note that Equation 2 is fundamentally different from Equation 1—the two terms on the right side do not represent processes, but properties of the system, namely memory and short-term forcing, independent of how, and by which processes, these effects are generated.

Named stochastic *climate* model, most considered this finding to be relevant for climate dynamics, and only for climate dynamics. Several studies have demonstrated the power of the stochastic climate model (in particular Frankignoul & Hasselmann, 1977; Lemke, 1977). The model may well be used for all stationary, not too nonlinear systems with memory (the $\lambda\psi$-term) and forced by short-term fluctuations. This finding, if not theorem, specifies that in all such systems, unprovoked long-term variations will emerge—red noise—and any analysis of changes in such a system must discriminate between internal variations and possible changes caused by external drivers. This is the *detection and attribution* problem (Hasselmann, 1979, 1993; see this section).

The general strategy was to build hierarchies of models, with Equation 1 as the most complex one, and Equation 2 the simplest, to identify how detailed the models need to be in order to describe certain phenomena and links. The simple models (Equation 2) represent *understanding*, while detailed simulations are best conducted with models of the type represented in Equation 1.

Given the noisy character of the dynamics and the enormous number of degrees of freedom in the process-based representation in Equation 1, a straightforward analysis of observed data and of simulations or numerical experiments with climate models of Equation 2 is practically impossible. In order to cast a manageable problem, one must limit the number of degrees of freedom or, in other words, reduce the phase space.

This insight that detailed modeling must be done in the full phase space, or better, in the largest phase space available on the given computing and storing mainframe, was part of Klaus Hasselmann's thinking early on, but also that the analysis should be conducted in a reduced phase space. Most of the time he did this without making it explicit. But in 1988, he eventually formulated this principle in his PIPs and POPs paper (Hasselmann, 1988). In this ansatz, he postulated the presence of a small signal space described by simple equations, which governs the main aspects of the dynamics, while the rest is considered a noise space. The statistics of the noise space are conditioned by the state in the signal space, and the impact of the noise space components on the signal space are realizations of these conditional statistics. The few dimensions of the signal space, given by patterns, are the principal interaction patterns (PIPs). The concept is sketched in figure 3. An important difference between PIPs and POPs, on the one hand, and the more conventional principal component analysis (or empirical orthogonal functions), on the other, is that the coefficients associated with the PIPs and POPs are governed by a set of ordinary differential equations describing a low-order dynamical system, and that the optimal patterns are inferred from minimizing the misfit between the time derivatives of the full versus the reduced-order state.

The dynamics of the signal space that is given by a multivariate version of Equation 2 amounts to stochastically forced damped traveling and standing oscillations, named principal oscillations patterns, or POPs (Hasselmann, 1988; von Storch et al., 1988). For the most general PIP concept, nontrivial examples have hardly been identified so far except for the common usage of parametrizations in quasi-realistic climate models, where the noise space includes all subgrid-scale variability. However, the POP concept, which is based on a multivariate model of Equation 2, was used to deconstruct and predict the Madden and Julian oscillation (MJO), the life cycle of baroclinic storms, and the El Niño-southern oscillation (ENSO).

This approach, of splitting the full phase space into a small signal space and a large noise space, permits an ordering of the dimensions of the system considered, with significant active ones in the signal space and passive components, the influence of which is limited to their statistics but not their state. The determination of the signal space requires a meaningful hypothesis of the key components of the system, either by using conceptual models or empirical analysis (as suggested in the PIPs and POPs paper).

For one's understanding, the splitting of the phase space introduced a paradigmatic shift, which made a robust analysis of climate variability and dynamical understanding possible—and, indeed, the Nobel Prize acknowledged such a significant progress.

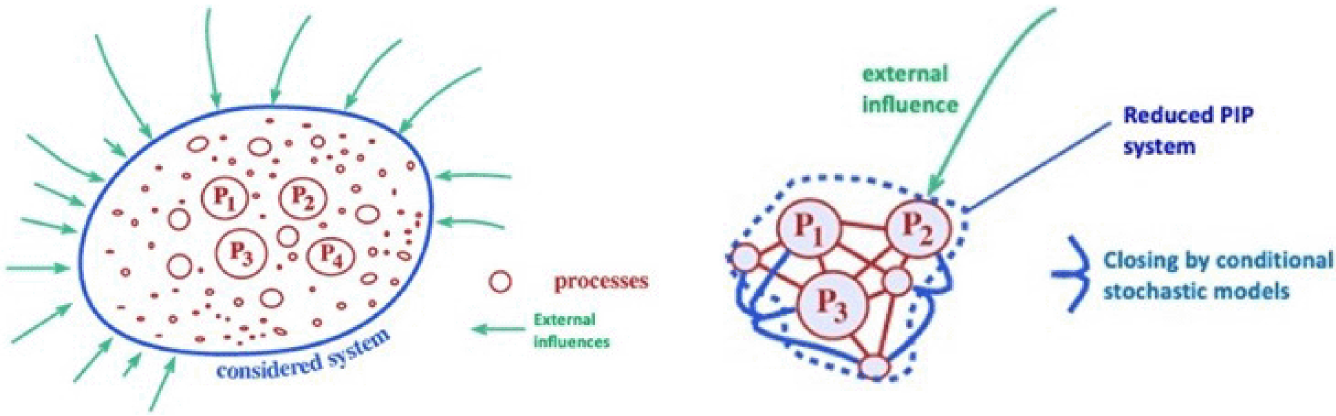

Figure 3. Sketch of the full phase space with infinite processes and external forcing, and of the reduced signal space, with reduced number of processes and forcings, and the closing by conditional stochastic models.

A special application of the idea to determine a subspace, within which the significant dynamics takes place, is contained in the detection and attribution (D&A) ansatz (Hasselmann, 1979, 1993). This D&A shorthand stands for "detecting non-internally generated change" and "attribution of such change to most plausible causes."

The detection part takes the form of a statistical hypothesis test, with the null hypothesis that the recent change is drawn from a distribution of changes in an undisturbed climate. When this hypothesis is rejected with a small risk of error, then the alternative hypothesis is accepted, according to which the climate, which generated the recent change, is not undisturbed, but influenced by an external forcing. To improve the a priori chances for a successful rejection of the null hypothesis, the number of degrees of freedom must be massively reduced—here again, one has a small signal space and a large noise space. In practice, the signal space is spanned by a small number of guessed response patterns to the assumed driver — often, elevated greenhouse gas concentrations, as suggested by climate models. Klaus Hasselmann suggested to further enhance the power of the statistical test by considering the expected signal-to-noise-ratio and to determine guess patterns with maximum expected signal-to-noise ratios. This "optimal fingerprint" method was originally implemented (e.g., Hegerl et al., 1996), but later only rarely used, as the signal, in terms of thermal variables, turned out to be strong enough also without this optimization.

A possible, but unproven cause of misdetection is that the estimation of the level of variability of the "normal" climate could be insufficient — for instance, because the empirical evidence is too limited or the model output, which supposedly characterizes the normal climate, is biased. In most cases, both issues must be accepted as unavoidable reservations, and time will tell if they are significant or not.

The attribution part too consists of the performance of a statistical hypothesis test, but the "success" is not given by a rejection of the null hypothesis, but by a nonrejection — which is: The recent change is consistent with a climate, which is modified by a certain combination of external forcing, as suggested by climate models. Obviously, the attribution evidence is weaker than the stringent detection part; this is unavoidably so because it cannot be excluded that a forcing is at work, of which science is not (yet) aware of. Thus, a positive attribution is subject to alterations if new mechanisms associated with the observed "detected" change are presented or if model-generated expectations of effects must be modified.

The D&A methodology has matured in recent years and has been applied to various state variables, such as temperature, rainfall, and air pressure (IDAG, 2005). The D&A concept played a prominent role in the Intergovernmental Panel on Climate Change (IPCC) assessment of the reality of human-made climate change (IPCC SAR, 1995). While in earlier years, analyses were most of global character, recently more regional studies have been published (e.g., Barkhordarian et al., 2018).

Ocean Surface Waves—Dynamics and Forecasting

Klaus Hasselmann had the leading role in virtually all aspects of ocean wave research, from basic theory, to spearheading field campaigns for empirical spectral model selection and calibration, to the algorithmic development of skillful global wave models, to the conception of a satellite nonlinear wave spectral retrieval algorithm and data-efficient mode of satellite operation, to laying the foundation for operational numerical wave prediction as practiced today worldwide via modern data assimilation techniques. He thus provided intellectual leadership from fundamental theory all the way to practical application, combining deep theoretical insight, skill in devising quasi-controlled field experiments, the right intuition required to rendering skillful wave modeling and prediction feasible, as well as ingenuity in making surface wave spectral retrievals from satellite practical for numerical wave prediction. Much of the successes are also due to Hasselmann's generosity and ability to bring together and motivate the international communities to jointly solve these difficult problems (JONSWAP, IWEX, SWAMP, MARSEN, WAMDI; see this section).

The basic insight, which enabled all of the following, was that the growth of wind waves and generation of swell, in terms of intensity, period, and direction, is not merely a matter of the forcing wind, but also due to an energy exchange among the different waves. His approach, encapsulated in his "Grundgleichungen," was confirmed in experimental campaigns, foremost JONSWAP (Hasselmann et al., 1973). National and international cooperative networks in the 1970s, such as the Sonderforschungsbereich Meeresforschung (SFB 94) in Hamburg or Sea Wave Modeling Project by the SWAMP Group (1985), led to the development of computer models and eventually to the first numerical predictions in 1981 at the German weather service. From this, later the service of trans-ocean ship-routing advising developed.

Following attempts at characterizing basic statistical properties of ocean waves for the purpose of prediction during the Second World War by H. Sverdrup and W. Munk (1943, declassified 1947), a more rigorous approach emerged which cast ocean wave dynamics as a transport (or balance) equation for the evolution of two-dimensional directional wave energy spectra. These were the "Grundgleichungen der Seegangsvoraussage" (Hasselmann, 1960). They provide a complete description for the evolution of the spectral energy balance of a two-dimensional surface wave field that is subject to three source terms: energy input due to wind (S_{in}), conservative nonlinear spectral energy transfer (S_{nl}), and energy dissipation (S_{diss}). Casting the numerical wave prediction problem in such a way set the wave research community up for advancing the science over the subsequent decades along the lines of these three overarching source terms. As early as 1960, Hasselmann formulated the vision of fast, accurate wind sea and swell prediction using suitable codes for "electronic digital devices."

In what is perhaps the most significant contribution to ocean wave research, Hasselmann developed a theory for the term $S_{nl,}$: Borrowing concepts from nonlinear scattering theory (Hasselmann, 1962, 1963a, 1963b) as well as the Feynman diagram formalism developed for describing the interaction among elementary particles (Hasselmann, 1966), he derived a closed expression for the nonlinear resonant wave-–wave interactions among wave quadruplets. An attempt had previously been made by Phillips (1960) and Longuet-Higgins (1962), but considering only a perturbation expansion to third order for interacting wave triplets, which do not admit resonance for the dispersion relation of surface gravity waves. Previously, Phillips (1957) and Miles (1957) had also developed theories on the momentum input to surface waves by the wind, providing the basis for the source term $S_{in.}$

That this nonlinear source term plays a central role in describing wave growth of windsea spectra and the ultimate generation of low-frequency swell was corroborated in the Joint North Sea Wave Project (JONSWAP; Hasselmann et al., 1973). A particular ingenuity of JONSWAP consisted of the fact that—absent the ability to create wave generation via wind input over 10s of kilometers under controlled wind conditions in a laboratory—geometric settings provided by nature were used (figure 4). JONSWAP enabled the study of wave growth and decay under quasi-controlled, fetch-limited conditions, which led to a more accurate description of windsea spectra and swell generation.

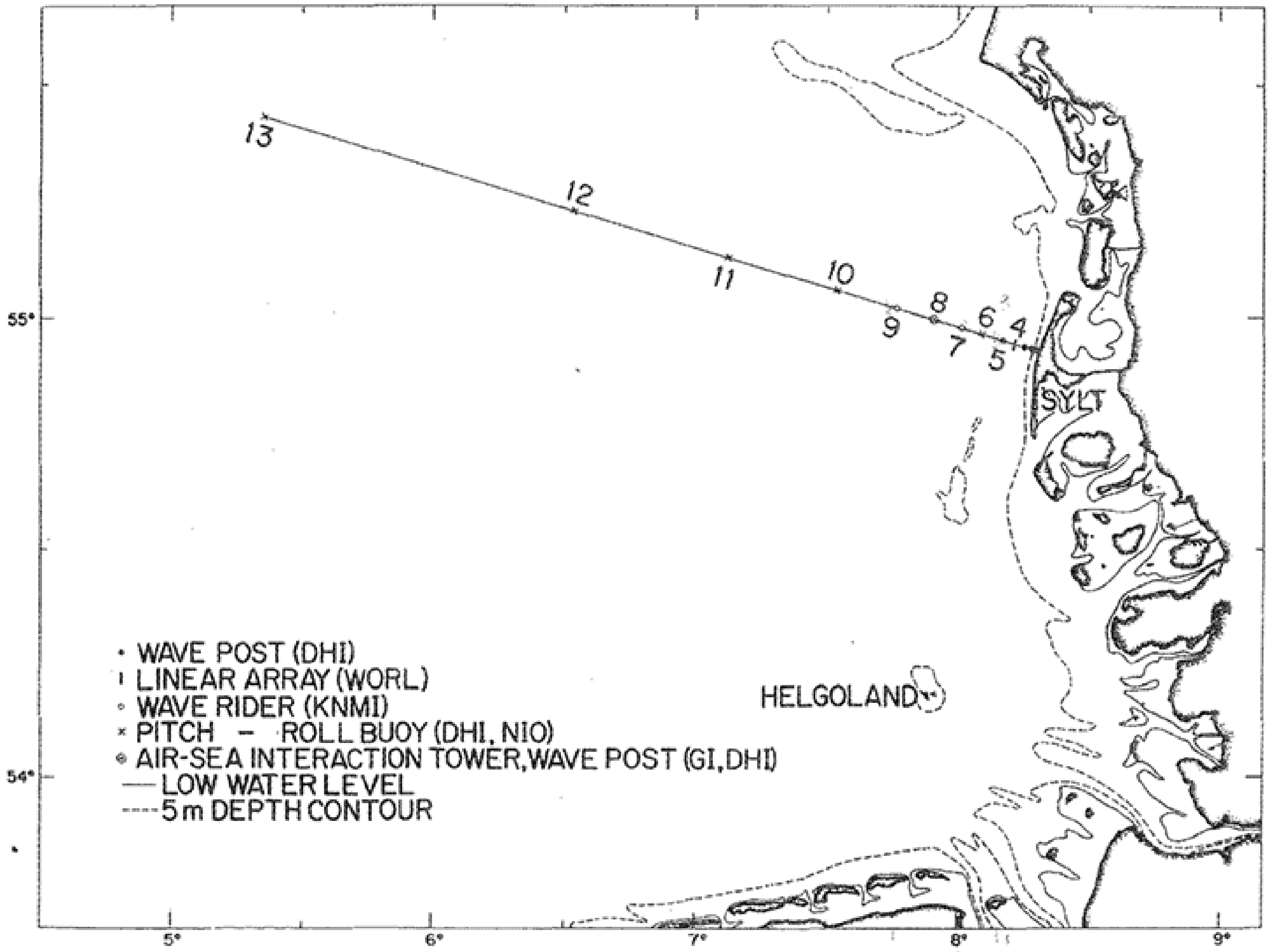

Figure 4. Experimental design of the JONSWAP experiment, conducted in the German Bight in 1969 (Hasselmann et al., 1973).

Knowledge of a detailed wave spectral shape for wind waves would enable testing different theories regarding the balance among the three different source terms and the evolution from short to long waves. Based on similarity theory, Kitaigorodskii (1961) had proposed a general form and power law which required as input only a single fetch parameter and friction velocity. Measurements of wave spectra for fully developed seas led Pierson and Moskowitz (1964) to a refinement of Kitaigorodskii's general form. The JONSWAP experiment revealed that more parameters were required to describe the wave spectrum; in particular, that the shape of the spectrum needed to be altered, compared to the Pierson-Moskowitz spectrum, to account for an enhancement of spectral energy near its peak. Crucially, the measurements provided strong confirmation of the role of nonlinear energy transfer — not previously considered — for the maintenance of the spectral peak, for the energy transfer from high to low frequencies, and ultimately for the generation of low-frequency (long-wavelength) swell. The central role of the nonlinear resonant energy transfer is sketched in figure 5, taken from Hasselmann et al. (1973). The source term S_{nl} acts to extract energy from the main part of the spectrum and redistribute it toward low and high frequencies. The former mechanism, in particular, is responsible for the generation of long swell. Thus, energy is removed at low frequencies of the spectrum through advection out of the domain, whereas at high frequencies local dissipation is assumed to counter the energy transfer.

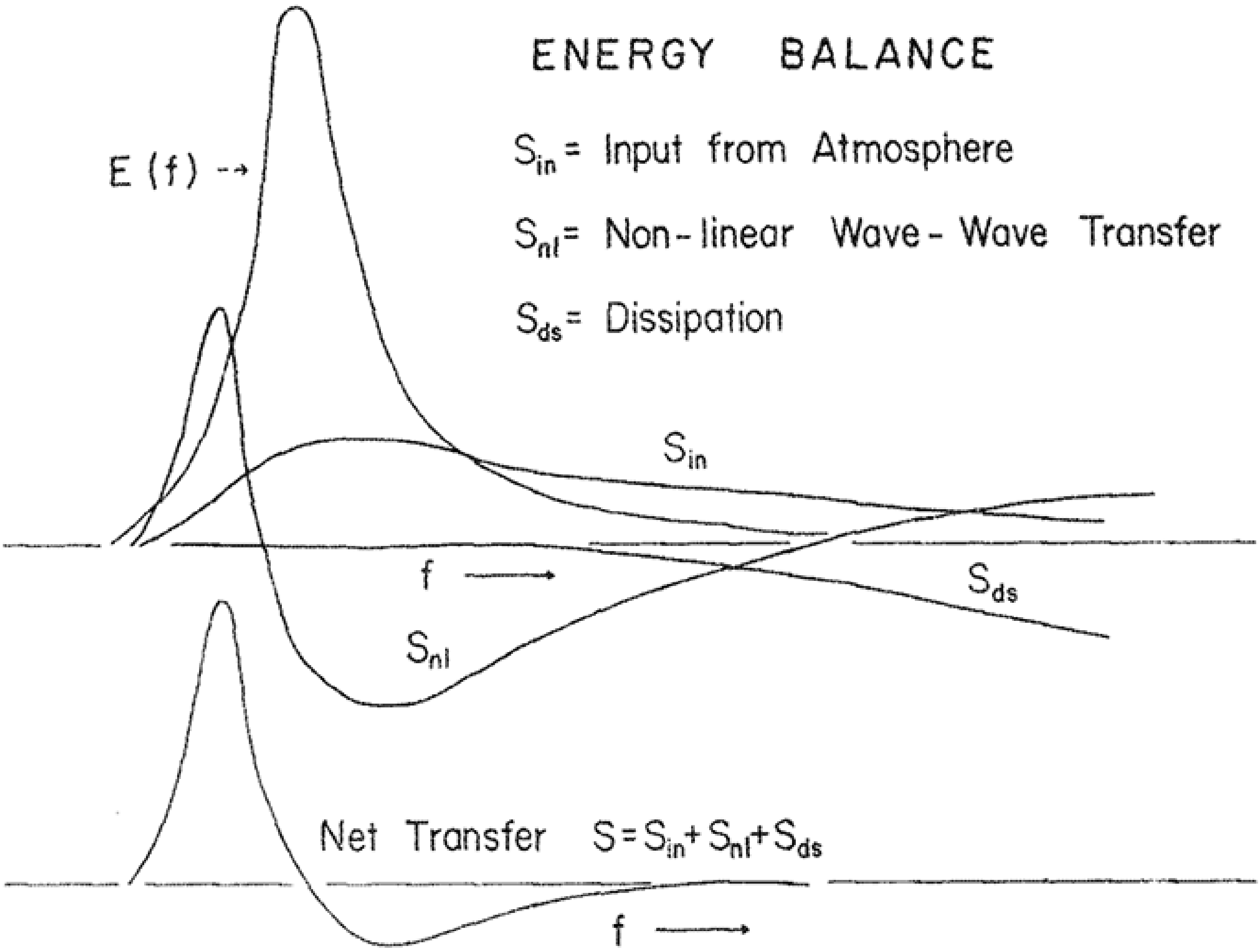

Figure 5. Schematic of the contribution of the different source terms, *S*, to the spectral energy balance in shaping the full spectrum *E(f)*. From Hasselmann et al. (1973).

JONSWAP was the first of many efforts organized by Hasselmann to bring together the community to solve a complex scientific problem. Another was the sea wave modeling project by the SWAMP Group (1985), set up in 1979. Coincident with the realization by the SWAMP group that existing second-generation wave models remained deficient, Klaus recognized that forthcoming, ocean-dedicated earth-observing satellites, notably the first European remote sensing satellite ERS-1, offered the prospect of quasi-synoptic wave data for forecasting applications. In turn, those data could only be fully exploited in conjunction with skillful reliable wave models. To realize this vision, major developments were required in modeling and remote sensing. Together with his wife Susanne, Klaus proceeded to guide the community on both fronts.

At the Max Planck Institute, the "Seegangsgruppe," led by Susanne, became a center of gravity for the development of a third-generation wave model that culminated in the WAve Model (WAM) (WAMDI Group, 1988). A major breakthrough here consisted of the development of a numerically efficient, yet more accurate treatment of the six-dimensional Boltzmann collision integral that accounts for the nonlinear resonant wave–wave interactions (Hasselmann & Hasselmann, 1985). Key local and international contributors included Eva Bauer, Heinz Günther, P. A. E. M. Janssen, Gerbrand Komen, Vince Cardone, Luigi Cavaleri, and Mark Donelan. The numerical algorithms underlying WAM form the backbone of most operational wave forecasting models in use to this day at leading numerical weather prediction centers worldwide, including at ECMWF ("HRES-WAM") in Europe and at NOAA (WAVEWATCH-III) in the United States.

Fundamental and practical difficulties needed to be overcome to make surface wave spectral retrievals from satellites workable and operational.

1. First, it was recognized that wave motions distorted radar images of a synthetic aperture radar (SAR). Once again, following pioneering early work (Hasselmann, 1971), Hasselmann convened the community in the marine remote sensing (MARSEN) experiment (Hasselmann et al., 1985). Based on these results as well as work by Werner Alpers and Claus Brüning in Hamburg, Klaus and Susanne derived an algorithm for inverting the nonlinear mapping between the distorted SAR image spectrum and the desired surface wave spectrum (Hasselmann & Hasselmann, 1991), which was eventually implemented as a retrieval algorithm for ERS-1 (Hasselmann et al., 2013).
2. A second problem was the fact that data transmission of full SAR images over the global ocean was impractical in a continuous form. Solving this problem, Hasselmann devised the so-called ERS-1 SAR "imagette mode," which operated over the ocean, taking small subimages ("imagettes") at periodic intervals, and which could be stored on board awaiting transmission when in line of sight of a receiving station. Hasselmann also spearheaded the framework for formally assimilating the wave retrievals into a model (Hasselmann, 1985).

Hasselmann's wave research extended beyond surface gravity waves to a broad spectrum of geophysical wave phenomena. Having a keen interest, beyond theoretical considerations, in real data, Klaus spent time in the analysis of geophysical time series and in the development of practical analysis tools. Early on, during Klaus's stay in La Jolla, this included the analysis of higher-order moments of wave spectral characeristics (Hasselmann et al., 1963), of the generation of microseisms (Hasselmann, 1963c), and of the superresolution of tidal line spectra (Munk & Hasselmann, 1964).

During his stay at Woods Hole Oceanographic Institution (WHOI) in the early 1970s, Klaus also developed an interest in internal gravity waves. Taking advantage of observational capabilities at WHOI, motivated by a recent report on the lack of field observations by Wunsch (1971), and with the experience that he had gained in leading JONSWAP, in 1973 Klaus initiated, together with Ferris Webster, the internal wave experiment (IWEX) campaign, consisting of a large triangular array of current meters and thermistors to measure the internal wavenumber-frequency spectrum in the main thermocline in the Sargasso Sea, alongside Mel Briscoe, Claude

Frankignoul, Terrence Joyce, Peter Müller, Dirk Olbers, and Jürgen Willebrand. The goal of the campaign was to test the Garrett and Munk (1975) spectrum. Much of the subsequent analysis of the IWEX field data did not involve Klaus directly (Briscoe, 1975, 1977; Frankignoul & Joyce, 1979; Müller et al., 1978; Olbers et al., 1976).

Building the Hamburg Powerhouse of Climate Science

As already mentioned, the intellectual and scientific achievements of Klaus Hasselmann were accompanied, and to some extent enabled, by networking and by building a thriving scientific environment in Hamburg. It began with the Sonderforschungsbereich Meeresforschung of the German Science Foundation in 1972; in 1975, Hasselmann's position was considerably empowered when he was given "his" institute, the Max Planck Institute for Meteorology. In an initial phase, he and his coworkers, such as Peter Lemke, Dirk Olbers, Claude Frankignoul, and Jürgen Willebrand, laid the theoretical foundations for a modern, empirically and theoretically informed climate science. Among these were most of the achievements sketched in the section "Climate Dynamics, Statistics, and Change," the fundamental importance of which were recognized some 40 years later by the Nobel Prize in Physics.

After this initial phase, around 1982 Hasselmann initiated the buildup of a climate modeling capability by coupling a conventional atmospheric general circulation model with a new, advanced ocean circulation model (large-scale geostrophic; Maier-Reimer et al., 1993). Such a system was good to study the internal variability in the climate system, but in order to render the system adequate for studying anthropogenic climate change, Hasselmann also initiated models of the carbon cycle, at first of the ocean (HAMOCC; Maier-Reimer, 1993; Maier-Reimer & Hasselmann, 1987). Later on, this was combined with the coupled atmosphere-ocean model (Cubasch et al., 1992).

This activity required a high-performance computing and archiving system designed for the use of such models and for storing the large amounts of data produced. Consequently, Hasselmann persuaded the German Ministry for Science and Technology and the regional partners of Hamburg University, the Alfred Wegener Institute in Bremerhaven and the GKSS Research Center in Geesthacht, together with the Max Planck Society, to found and fund the German Climate Computing Centre (DKRZ) in 1988. Hasselmann became director of the DKRZ, while Wolfgang Sell was responsible for the technical setup and operation.

In about 1990, the modeling activities were further bolstered when Lennart Bengtsson, the former director of the European Centre for Medium-Range Weather Forecasts (ECMWF) in Reading, United Kingdom, became codirector of the Max Planck Institute. Under the leadership of Bengtsson, the modeling system at Max Planck Institute became one of the few leading models worldwide. It was used regularly in all the Intergovernmental Panel on Climate Change (IPCC) assessments of the knowledge of climate variability and climate change. The Max Planck Institute was involved from the beginning in the IPCC process through Ulrich Cubasch.

Following the success of climate modeling in producing consistent scenarios of future anthropogenic climate change and the analysis based on Hasselmann's concepts of separating noise from signal, it became clear that for the public and for policymaking, the challenge would be the impact of climate change on georisks (natural hazards), such as storm surges, on ecosystems and on society and the economy. Hasselmann himself engaged in developing simple coupled climate-and-society models (Hasselmann & Hasselmann, 1998; Hasselmann et al., 1997), while after some experimenting with risks and ecosystems, he outsourced these issues by pushing for the creation of the Potsdam Institute for Climate Impact Research, headed by Hans-Joachim Schellnhuber, and, less prominently, by having Hans von Storch at the GKSS Research Center work on issues of coastal climate impacts.

In 1999, Hasselmann retired as director of both the Max Planck Institute for Meteorology and the DKRZ. His successor was Guy Brasseur, who left after a few ýears, followed by Jochem Marotzke. His "lieutenants" took over responsibilities at other institutions, such as Martin Heimann, who became director of the Max Planck Institute of Biogeochemistry in Jena, and Mojib Latif, who became head of research at GEOMAR Kiel. Many became professors at universities, such as Jürgen Willebrand in Kiel, Gabriele Hegerl in Edinburgh, Ulrich Cubasch in Berlin, Christoph Heinze in Bergen, Hans Graf in Cambridge, and Patrick Heimbach in Austin, Texas. Previously, Peter Lemke and Dirk Olbers had moved to the Alfred Wegener Institute in Bremerhaven, and Hans von Storch to the former GKSS but now named Hereon Research Center in Geesthacht.

During his time at the helm, his institute became one of the world's leading climate research institutions. His success and "drag" also led in his regional partner institutions to significantly enhancing their scientific focus and output—which became visible when a few years later a consortium carried by Hamburg University, Max Planck Institute, Hafencity Universität, and GKSS Research Center was selected in a competitive process to become a center of excellence—initially named CLISAP and today CLICCS. Additionally, an informal network named Klimacampus Hamburg was created where additional partners joined, such as the Hamburg branch of the German Weather Service and the Technical University of Hamburg.

There are two interesting aspects, which have nothing to do with the scientific achievements, but with the personality of Klaus Hasselmann. One is his general disinterest in media. He hardly became visible in the media, with the exception in 1995 when the IPCC recognized that the proof of the reality of the anthropogenic cause of ongoing climate change was based on his method. In principle, he acknowledged the legitimacy of public interest in science and its significance for society and policymaking. However, engagement with media demands attention and time. Klaus solved this by asking two colleagues, Mojib Latif and Hartmut Grassl, to take over — which they did, successfully, and to everybody's satisfaction. The net effect was that Klaus Hasselmann was hardly known to the public when he was suddenly catapulted into the limelight by the Nobel Prize.

A second aspect is that his scientific papers were hardly published in the purportedly high-impact scientific journals *Science* and *Nature*. Every now and then, he submitted something to these journals, but in most cases, he failed to pass the criteria of broad interest (as do most).

Metrons, the Real but Unfinished Challenge

Fundamental physics was perhaps the strongest intellectual passion of Klaus Hasselmann since very early in his career, but one which he decided he could not pursue as a profession because he was suspicious of mainstream theoretical physics. Klaus first gained an interest in theoretical particle physics when he discovered in the mid-1960s that his theory of nonlinear resonant wave-wave interactions could be framed in terms of Feynman diagrams (Hasselmann, 1966), which in turn were developed for describing the interaction among elementary particles in quantum field theory. His deep insights into "wave-wave" interactions and their descriptions in terms of particle-particle scattering theory led him to pursue an alternative, nonconventional program of a unified theory of particles and fields.

The established interpretation of quantum mechanics in particular, according to which processes at the microscopic level were fundamentally limited to a statistical description (the wave function), ran counter to Klaus's intuition, as did the "imprecise demarcation" between classical and quantum phenomena. In this he echoed the skepticism that had motivated Einstein, Podolsky, and Rosen (EPR) to formulate their paradox and to suggest quantum mechanics to be an incomplete theory (Einstein et al., 1935). Already a decade before, Einstein had considered the merit of a "unified field theory" (e.g., Einstein, 1923). Hasselmann was convinced that the unfinished program pursued by Einstein would hold the key to a deeper understanding of fundamental physics. Hasselmann further believed that modern theories remained unsatisfactory. For example, the standard model of elementary particle physics requires 18 "free parameters" and is unable to provide the mass hierarchy of elementary particles from first principles. These shortcomings motivated him to pursue his own program to develop a unified deterministic theory of particles and fields, which he termed the "metron model," and which he finally wrote down in a series of papers some three decades after he started this work (Hasselmann, 1996a, 1996b, 1997a, 1997b). His metron program rests on several ideas.

First, Hasselmann sought to resolve the wave-particle duality by postulating soliton solutions to Einstein's nonlinear field equation. The soliton would act like a linear wave in its far field (i.e., a manifestation of the classical gravitational and electromagnetic fields), but would behave strongly nonlinearly near its core, thus exhibiting particle-like properties (mass, charge, spin, weak and strong coupling constants). This solution, termed "metron" (***metr***ic solit***on***), would overcome difficulties of interpretation as it unified both particle-like and wave-like behavior within the same, well-defined microphysical object (rather than a probability distribution). Effects of quantization, such as discrete atomic energy spectra, would be represented by resonant interactions between scattered far-field waves and particle trajectories.

The Metron Model: Elements of a Unified Deterministic Theory of Fields and Particles, Part 1

Table I: Relation between Metron and Quantum Field Theoretical Picture of Microphysical Phenomena

Phenomenon	*Quantum Field Theory*	*Metron Model*	*Sections*
Particles	Defined statistically	Trapped-mode solutions of field equations	Part 1, Sec. 4 Part 2, Sec. 5
Fields	Defined statistically in conjunction with particles by system state	Form nonlinear particle core, experienced as far fields	Part 2, Sec. 4 Part 4
Lagrangians	Derived from postulated gauge symmetries	Inferred from n-dimensional gravitational Lagrangian	Part 2, Sec. 4, Part 4
Physical constants	Postulated	Derived from metron solutions with postulated periodicities	Part 2, Sec. 5, Part 4
Bell's theorem	Violates time symmetry of both theories, not applicable to reversible microphysical phenomena		Part 3, Sec. 4
Wave-particle duality	Statistical interpretation; nonexistence of "objective" fields and particles	Explained by periodic de Broglie far fields of "objective" particles	Part 3, Secs. 5 and 6
Atomic spectra	Eigensolutions of Maxwell-Dirac system	Same as QED at lowest order augmented by Bohr-orbiting electrons	Part 3, Sec. 6
Absorption and emission	Secular (resonant) perturbations of system state	similar formalism for classical fields	Part 3, Sec. 6
Divergences	Renormalization	? (should not arise)	—
Standard Model	Summarizes particle spectrum, 19 empirical parameters	General structure reproduced for given symmetries of metron solutions; parameters determined by solutions	Part 4
Gauge symmetries	Postulated	Inferred from geometrical symmetries of metron solutions and invariance with respect to coordinate transformations	Part 2, Sec. 4, Part 4, Sec. 4
Particle interactions	S-matrix formalism	Not discussed, similarity to S-matrix formalism anticipated from analogy with optical absorption and emission	Part 3, Sec. 6

Figure 6. Relation between the metron and quantum field theory picture of microscopic phenomena and summary of the four-part series of papers laying out the metron program (from Hasselmann 1996a).

Second, Hasselmann used as a starting point to the fundamental equations of motion the concept of a higher-dimensional generalization of general relativity developed in the 1920s by Theodor Kaluza (1921) and Oskar Klein (1926). Similar to Minkowski's (1909) work in which he unified electromagnetism and special relativity within a four-dimensional geometric space-time theory, the Kaluza-Klein approach consisted in unifying general relativity and electromagnetism within a five-dimensional generalization of Einstein's equation of general relativity. Hasselmann postulated the soliton to be the solution to a higher ($4 + D$) dimensional generalization of Einstein's equations in matter-free space (proposing dimensions $D = 8$ or $D = 9$). Analogous to the compactification approach, albeit different in detail, Hasselmann postulated the extra dimension to be harmonic (i.e., periodic but avoiding a cylindric topology required by compactification).

Importantly, analogous to the energy-momentum field tensor arising as a geometric property (i.e., from the metric tensor and its derivatives) of the five-dimensional Kaluza-Klein theory, in Hasselmann's program all four fundamental forces arise geometrically from the curvature of the space-time extra dimension and mixed space-time extra-dimension components. Two more key characteristics are as follows:

1.

No source terms occur in the field equations such that "the curvature is not produced by prescribed mass fields, but is a self-generated feature of the nonlinear field equations themselves."

2. "The coupling constants and symmetries are not postulated in the basic field equations, but follow from the specific geometrical properties of the metron solutions" (Hasselmann, 1996a).

The ***D***-dimensional nonlinear vacuum equations were thus free of physical constants, and Hasselmann's ambition was to derive these constants, in particular the spectrum of observed particle masses, from solutions to the equations, thus overcoming the shortcomings of the standard model. Conceptual differences between the metron model and quantum field theory, as perceived by Hasselmann, are summarized in figure 6.

Hasselmann's metron program has to contend with several challenges and open questions:

1. Being effectively a hidden-variable theory, the metron program violates Bell's theorem (a generalization of the EPR paradox) on the nonexistence of deterministic hidden-variable theories (Bell, 1964). Hasselmann countered this apparent contradiction by pointing out that Bell's theorem requires the existence of an arrow of time (forward-causality), but which is not present at the basic level of the field equations describing the microscopic phenomena, since they are invariant under time reversal (see Hasselmann, 2013 for a more detailed discussion of entanglement).
2. Hasselmann sought to explain the discreteness of the observed particle spectrum as a solution to the model, but at present this remains an unsolved problem.
3. The success of the metron program rests critically on the ability to find soliton-like solutions postulated by Hasselmann to the ***D***-dimensional vacuum field equations. Together with his wife, Susanne, Klaus Hasselmann dedicated part of his retirement from the Max Planck Institute to this problem. Despite some progress toward computing the metron solution for the simplest possible particle, the electron (Hasselmann, 2013; Hasselmann & Hasselmann, 2003), and plans to publish further results in a book, this project remains unfinished.
4. An interesting question that remains open is whether the metron model would lead to new predictions of phenomena in elementary particle physics that have not yet been predicted and that could provide a critical test of the theory through experiment.

A confirmation (or falsification) of Hasselmann's program remains outstanding. With the recognition of Hasselmann's achievements via the Nobel Prize in Physics, it is hoped that the physics community will take a closer look at his metron program and conduct an appraisal of its potential merits. Hasselmann himself was realistic in his 2006 interview: "Once the theory is published in accepted journals, it will become either accepted or rejected. This is as it should be. I am not really concerned about the outcome, which is beyond my control" (von Storch & Olbers, 2007). Regardless, Hasselmann's work, from the theory of turbulence, waves, and stochastic processes in geophysical systems, climate dynamics, to elementary particle physics, has come full circle, making fundamental contributions to a wide range of grand challenges in physics.

Acknowledgment

The authors had valuable comments on a draft version of this article from Susanne Hasselmann and Carl Wunsch.

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Notes

1. See Nobel Prize Lecture *<https://www.youtube.com/watch?v=UF8PBXkCtko&feature=emb_imp_woyt>*.

2. Nobel Prize Lecture *<https://www.youtube.com/watch?v=UF8PBXkCtko&feature=emb_imp_woyt>* ; *GKSS Report 2007/5*; Interview with Klaus Hasselmann *<http://hvonstorch.de/klima/Media/interviews/hasselmann.pdf>* ; Springer, *From Decoding Turbulence to Unveiling the Fingerprint of Climate Change: The Science of Klaus Hasselmann* *<https://*

doi.org/10.1007/978-3-030-91716-6> . The book includes the interview, summarizes the scientific work of Klaus Hasselmann, and provides personal accounts of many of Klaus Hasselmann's coworkers and friends. The book also contains a publication list and a list of awards. The publication repository of the Max Planck Society offers pdfs of most of Klaus Hasselmann's publications *<https://pure.mpg.de/cone/persons/resource/persons37172>*.

3. Waves across the Pacific *<https://www.youtube.com/watch?v=MX5cKoOm6Pk>*

4. E.g., Blind Men and an Elephant *<https://en.wikipedia.org/wiki/Blind_men_and_an_elephant>*

5. See Interview with Klaus Hasselman *<http://hvonstorch.de/klima/Media/interviews/hasselmann.pdf>*

6. Or, more generally, a process of short-term variations.