Some roles of physics in climate science and sustainability with examples in Southern Africa

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Abstract. Physics is well embedded in climate and sustainability science, and its contributions are expanding. This work aims to illustrate a few of the surprising or growing roles of physics, providing very short outlines of case studies of relevance to Southern Africa. Two disasters highlight attribution science, the scarcity of data in southern Africa, and the need for functioning Early Warning systems. Longer-term forecast of El Niño-linked drought is needed, and the non-linear nature of El Niño system models Southern Oscillation is mentioned. This introduces some contributions of theoretical physics to the theory of climate and a challenge in computational physics in models for Africa. The use of quantum physics in countering the spread of malaria is mentioned. Finally, since the Southern Ocean climate system affects both southern Africa and the global circulation profoundly, an example of physics applied to understanding ice mechanics is provided. A simple systematic way of finding gaps by linking physics to climate and sustainability science is proposed, in preparation for future work.

1 Introduction

The change in the Earth's climate is a threat to all its inhabitants, and the evidence for this statement is accumulating steadily [1-5]. The monthly global average surface temperature remained over 1.5 °C higher than preindustrial values for 12 consecutive months up to June 2024 [6]. We are at a watershed where the decisions made in the next five years will determine the future of humanity. While physics is embedded in many current initiatives, this paper aims to provide a few examples of pure and applied physics (especially theoretical and computational physics) in climate science and sustainability, and to provide a few illustrations relevant to Southern Africa in the global context.

This paper is not intended to cover the widely spread existing research in, or about, the Southern African region. Instead, this short article is prompted by the creation by the IUPAP[1] of Working Group 21 (WG21) to promote the unique roles that physics can, and should, play in these sciences, as physicists respond to the climate crisis and the threats to the future of the planet. The initiative is relevant to Sustainable Development Goal 13, Climate action, and the International Decade of Sciences for Sustainable Development. It is not the intention of WG21 to perform research, since many international bodies exist to do this. WG21 can, however, promote action among members. Institutes, departments, scientists and companies are respectfully acknowledged but very few can be mentioned in this small set of illustrations, including, for example contributors to IPCC[2] Reports [1].

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[1]International Union of Pure and Applied Physics IUPAP WG21, Physics for climate change action and sustainable development,
[2] Intergovernmental Panel on Climate Change

1.1 *Structuring the interaction between two extensive fields*

In understanding the current roles of physics in this context, it may be useful to find links between physics sub-disciplines and the components of climate and sustainability science, treated as a driver and an area of application. As a first exercise, for selected cases links have been made between developments in physics or related to physics, and at least one application area in the climate context. For test purposes a single publication has been used in selected cases. Data-backed analysis of literature is becoming considerably more widely used, and validation of the results of automated studies is improving. It may be possible to stimulate new and original physics by enabling visualisation that makes gaps in knowledge more easily identifiable. Some simple diagrams have been used to demonstrate how such a study might be structured. For initial demonstration purposes, the fields of physics are taken as those for which IUPAP has designated commissions, affiliated commissions or working groups, and the fields of climate science and sustainability are adopted from the structure of IPCC reports.

It is noted that much of climate, sustainability and regenerative development lies outside the academic journal base and is usually published in the form of peer-reviewed reports. Reports that are fundamental in assisting physicists to navigate the field might be cited [1 – 5, 7]. The sustainability space, which is deeply dependent on physics, is more difficult to navigate and systematise and is not attempted here.

2 Case study examples

2.1 *Attribution of extreme events to anthropogenic forcing and the Kwa-Zulu Natal floods of April 2022*

On 11-12 April 2022, the eThekwini region of Kwa-Zulu Natal (KZN), South Africa, experienced nearly 300 mm of rainfall in 24 hours, extreme flooding, over 430 fatalities, and serious damage to infrastructure and housing [8]. The South African Weather Service (SAWS) and the eThekwini municipality issued warnings, but with limited effect: the warnings were not received by all, many people did not know what to do, and there was a disproportionate effect on marginalised communities [8, 9].

The case is a good illustration of the use of the relatively new science of attribution and is one in which Southern African authors are active [8, 9]. The likelihood of occurrence of extreme events can be derived as a function of intensity for the natural (pre-industrial) climate from, for example, the ERA5 observational data [10]. The actual, or present, climate and probable future climate can also be modelled. The World Weather Attribution Protocol [11] defines the methods acceptable in the chain of reasoning that leads from observation, through model analysis, model evaluation, and eventually to communication statements. The probabilities of an event with intensity above a certain threshold can be compared between the natural climate and the actual climate (Figure 1). The conclusions of the study included an assessment that the return time of the event is about 20 years in the present climate but would have been about 40 years in a climate 1.2°C cooler.

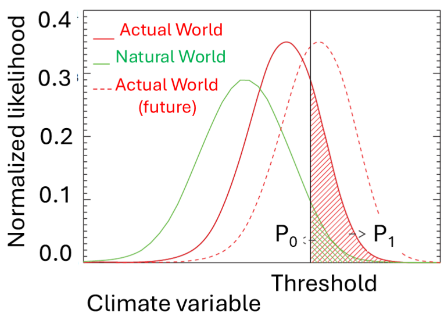

Figure 1: An illustration of the Probability Density Functions of a climatic variable. The probabilities of exceeding a prespecified threshold (P1 and P0) are represented by the hatched areas [12] (Image: CC-BY-4.0).

Contributions from fields of physics are mapped the left side of Figure 2. Physicists may be able to identify potentially productive gaps among these areas of study. Physicists also make impact in the direct applications of instrumentation, earth observation, ground station data, disaster risk assessment and reduction, and the effectiveness of Early Warning Systems (EWS) [9]. There is scope for physics in the determination of what constitutes an extreme event (currently defined in meteorological terms as an event that is rare at a particular place and time of year [1], Glossary) and in defining thresholds in atmospheric or oceanic parameters. Extending the thinking in terms of the full function of EWS, socio-ecological systems are the most critical factor in the success of EWS: "an extreme event should not mean that there has to be a disaster"[3]. Physics community initiatives could consider combining localized disaster warning with indigenous knowledge systems, and applying theory of change in terms of the real needs of a community and the long-term goals and conditions needed for survival and success.

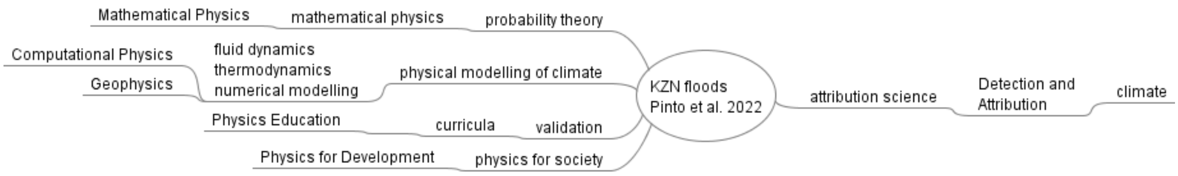

Figure 2: Contributions from fields of physics through Pinto *et al.* (2022)[8] to climate science.

2.2 Data scarcity

The example of the KZN floods, above, illustrates the scarcity of reliable data in South Africa [8]. To provide reasonable predictions and analyses, time-dependent temperature and precipitation data is a critical input. The KZN analysis [8] indicates that daily rainfall data available for South Africa was not sufficiently gap-free and did not cover enough decades (1950-2022); only 70 stations of the 194 SAWS stations in the study were able to provide data of the quality required for attribution. The availability and quality of high-quality persistent data is low and has been declining in Africa and Southern Africa (see [13] Figure 7.1 on the graphic contrast between Europe and Africa in the number of stations per unit area). SAEON, the South African Environmental Observation Network, is now active increasing observation sites and EWS effectiveness through collaborations with communities [14]. Disaster Risk Reduction requires action throughout southern African nations for realistic national science policy and implementation in an all-of-government model, and scientific organisations have a distinct role to play in science diplomacy and communication.

2.3 Modelling and non-linear systems: the Southern African drought of 2024 and ENSO

In February, 2024, less than 20% of the expected rainfall was experienced, and a prolonged drought took place in Zimbabwe, Zambia, Malawi, Angola, Mozambique and Botswana [15]. Crops failed among rain-fed subsistence farms and food insecurity affected an estimated 71 million people by November 2024 [16]. Climate attribution studies of this event indicated multiple drivers, notably concluding that the El Niño event was a key driver, and that the prolonged drought was twice as likely during El Niño years [15].

Understanding the teleconnections between El Niño events and southern Africa in a warmer world requires global and mesoscale modelling [17] and shows correlation of El Niño events with low southern African rainfall (except in south-eastern regions). Prediction of an El Niño event can be made at present with reasonable confidence from observations between 6 and 12 months before July, and impacts are observed between November and March. The need for warning at longer lead-times is clear. In terms of a physical understanding, the proposal that the El Niño Southern Oscillation (ENSO) can be conceptually modelled as a non-linear system was first made in 1986 by Vallis [18], seeking a physics-based model for the qualitative aspects of the system. A set of three equations similar to the Lorentz equations, based on three variables (east and west ocean temperatures and a wind-driven current velocity), was able to produce ENSO-like behaviour. Vallis models continue to provide a basis for research.

General Circulation Models (GCMs) have potential to make predictions at time scales greater than 9 months, possibly up two years, the time scale being limited by computational costs [19]. A knowledge of the underlying non-linear physics describing ENSO makes it clear that initial conditions are critical, and therefore that pooling multiple models in an ensemble may obscure the development of El Niño events [19].

2.4 The theory of climate: complex systems and stochastic dynamics

The Nobel Prizes in Physics awarded in 2021 illustrated the fact that pure physics has made fundamental contributions in unexpected ways. Parisi, receiving the award "for the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales", had been investigating Ising networks and spin glasses, of which P.W. Anderson said "the history of spin glass may be the best example I know of the dictum that a real scientific mystery is worth pursuing to the ends of the Earth for its own sake, independently of any obvious practical important or intellectual glamour" [20]. Parisi developed the calculation of macroscopic

[3] M.M. Bopape (SAEON), 21 July 2025, https://www.youtube.com/watch?v=vxWBjW1X6Mg

thermodynamic properties using replicated partition functions and a new long-range order parameter, eventually demonstrating the role of random fluctuations in controlling Earth's climate states over long epochs [21], and redefining the link between weather and climate (Figure 3). Hasselmann addressed a stochastic model relating short-time scale perturbations of weather to long time scale drift, or climate [22] (Figure 2), and was awarded the Nobel Prize for the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming" together with Manabe [23], who developed the fundamental models for an atmosphere in thermal equilibrium with convection.

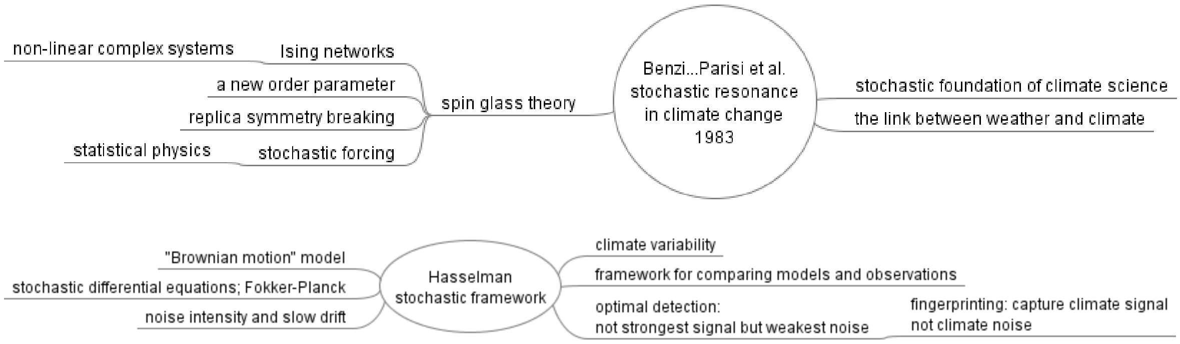

Figure 3: (*top*) Complex system links to the theory of climate in the work of Parisi [21] (*bottom*) stochastic differential equations applied to climate variability by Hasselman [22].

2.5 GCMs and Earth System Models: fluid dynamics, thermodynamics and computational physics
The fundamental formulation of Manabe [23] underpins the GCMs and Earth System Models (ESMs) which now pose challenges for physicists and engineers in, for example, atmospheric turbulence, multiscale modelling, and cryosphere-ocean-atmosphere interaction. GCM and ESM predictions concerning Southern Africa made in 2021 include more frequent and intense multi-year droughts (as experienced in 2024), more frequent and intense heat waves with impact on human health and mortality (as quantified by the Lancet Countdown 2025 [24]), and more intense tropical cyclones (now seen as more frequent landfalls over Mozambique [4]).

The development of an African ESM is an essential tool for quantifying climate tipping points for the continent [3, 25]. A gap of interest lies in modelling African thunderstorms. Considerable progress has been made in the northern hemisphere in modelling specific thunderstorm instances where reflectivity observations from Doppler Ku-band radar are available. Turbulent Large Eddy Simulations at this scale provide remarkably good models in comparison, showing the existence of a hydraulic jump above supercell thunderstorms at the tropopause [26]. These simulations are computationally expensive, but may lead to reasonable sub-grid models.

2.6 Infectious and vector-born diseases: quantum physics
There is abundant evidence of the profound influence of pollution and climate change on health [24], including, for example, the spreading of the areas affected by malaria [27]. X-ray diffraction and synchrotron studies provide target protein structures and the Protein Data Bank [28] provides open access to this data. Among the tools of rational drug design is Density Functional Theory (DFT). Quantum mechanics now plays a routine role not only in condensed matter physics but in seeking treatments and vaccines for infectious diseases and DFT methodology is widely used in Africa; training in electronic structure modelling has taken place through many initiatives across Africa over more than two decades[4]. An example in the use of DFT for ligand-protein interaction energy calculation is the search for malaria treatments or vaccines [29]. In these initiatives, computational physicists find themselves well-prepared to join teams which stretch through the spectrum of physicists and biochemists to clinicians.

2.7 Polar science and the cryosphere: ice mechanics, computational physics and remote observation
The Southern Ocean can be considered to control climate in the southern one-third of the world [30]. Southern Africa's marine economies are profoundly influenced by the Southern Ocean climate system and the Southern Annular Mode (SAM), an oscillation on the scale of decades in the natural climate. At present, we are in a positive phase of the SAM ([30] and [31], Ch. 4, Fig. 4.27), the Westerly winds have strengthened, and both the Westerlies and the Antarctic Circumpolar Current have contracted towards the pole. Model projections indicate

[4] Including African School on Electronic Structure Methods and Applications https://www.asesma.org/

that increased atmospheric CO_2 is likely to prolong this phase, increasing CO_2 degassing from the major carbon sink in the Southern Ocean, increasing upwelling of warm Circumpolar Deep Water, increasing ice shelf recession and influencing the latitude of the Intertropical Convergence Zone [30]. Antarctic research is therefore of significant importance to Southern Africa.

South African research entities[5] carry out exploration of Southern Ocean and Antarctic conditions and climate. Most ice properties are measured in Arctic conditions, offering Southern Africa geographic advantage and scope in determining material properties, structure and texture, historic climatic conditions and sea ice dynamics in the field and through computational models [32]. Ice drift studies reveal drivers of Southern Ocean dynamics [33].

3 Conclusions

The small sample of cases above illustrate some valuable contributions of physics as a fundamental science in its own right, as well as a partner in transdisciplinary work. An aim of this small study was to show some of the expanding roles of physics, highlighting some less frequently mentioned aspects and successes, and seeking gaps in which physicists may make effective contributions. The KZN floods were shown to focus on attribution science, the need for a systematic approach to data scarcity and engagement with community-centred Early Warning Systems. The 2024 southern African drought showed the need to understand the El Niño oscillation and the impact of non-linear dynamics in the field. Theoretical physics is well-established in Southern Africa, and therefore the link from the theory of climate to theoretical physics has been highlighted. Computational physics and computational modelling have been briefly covered in the context of Africa. In countering the impacts of climate change on malaria, quantum physics is now a routinely used tool. The impact of the Southern Ocean on southern African climate requires sustained research which involve applied physics and its related technologies.

In seeking ways to find productive research and application gaps by linking physics to impact in the present crisis, a simple mapping of relations between physics and climate science and sustainability science has been shown. It is possible that this method is amendable to an automated analysis of literature.

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