ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DOTTORATO DI RICERCA IN

IL FUTURO DELLA TERRA, CAMBIAMENTI CLIMATICI E SFIDE SOCIALI

Ciclo 37

Settore Concorsuale: 04/A4 - GEOFISICA

Settore Scientifico Disciplinare: GEO/12 - OCEANOGRAFIA E FISICA DELL'ATMOSFERA

CLIMATE SERVICES ECOSYSTEMS

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Esame finale anno 2025

Climate Services Ecosystems

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Submitted in partial fulfillment of the
requirements for the degree
of Doctor of Philosophy
in the Department of Physics and Astronomy

UNIVERSITY OF BOLOGNA

2025

ABSTRACT

Climate Services Ecosystems

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During the last decade climate services have been exponentially proliferating in number and diversity. Without the profound understanding, coordination and synergies among the different climate services present in a particular country, society can miss opportunities to increase resilience to climate impacts, or -what is worse- the number and diversity of disconnected climate services available to stakeholders can delay, freeze or even dismantle ongoing adaptation strategies and action plans.

Building healthy ecosystems of climate services is a way to guarantee that society enhances resilience, while optimally orchestrating the available resources. These ecosystems tend to be more robust to climate impacts than a collection of climate services focused on certain applications or just one sector, because shocks to one part of the ecosystem are redistributed and dampened through the entire network.

This PhD dissertation describes the concept and elements of climate services ecosystems and introduces the use of Network Analysis and Dynamic Causal Network Theory to compare ecosystems of climate services. This approach provides an objective way to assess potential or actual causal relationships between their elements, the dynamics of their interactions and the value of the ecosystem.

The climate services ecosystem approach assesses the value of an integrated collection of climate services, under forecasts and scenarios of a changing climate, changes in policies or interventions, changes of societal needs and limited budgets, supporting stakeholders to define what, when and how to fund climate services to enhance the resilience of communities and societies.

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Acknowledgments

The author is indebted to many people who helped her at different stages of the dissertation. With the list of names and reasons too long to include here, she hopes these generous souls will forgive her the omission.

A special mention is deserved for her partner, Dr.Angel G. Muñoz, who always supported and challenged her to move forward, swimming against currents and believe in herself despite the obstacles. *Do not let others decide on your path and, why do you care what other people think?"* have become her new live mottoes. She still remembers the first conversation they had about her PhD in Guatemala and she admits she wouldn't have come this far without his support and encouragement. I love you.

To her parents, Arcadia and José, who thought her the values of hard work, perseverance and commitment. Who supported and encouraged her in every new proposal to have "another" international experience they couldn't had. To her brothers, Juan and Antonio, who have been her role models and became fundamental pillars in her life. To her sister-in-law, Marta; and her nieces and nephew, María, Cayetana and Claudio for their constant support and love. She is forever grateful for being born in such a supporting family. To her extended family in Málaga and Navarra for their encouragement and love.

To Dr. Lisa "La Niña" Goddard, her first supervisor of this dissertation with whom she had the privilege to design and discuss the fundamental elements of this PhD thesis and who undeservedly crossed to the other side before this manuscript was completed. She will always be THE Jedi Master.

To Dr. Soret, her last supervisor, who was there to discuss aspects of the research and to provide useful and concrete suggestions. As the saying goes, what's good, when brief, is twice as good.

To Dr. Antonio Navarra who also supported the author throughout her PhD journey.

Foremost, the author would like to thank her child, Gabriel González Muñoz, 14 months old at the time of the submission, for constantly reminding his mum what the important things in life really are - just so she wouldn't loose it while finishing this PhD thesis. This was a rocking time, but he came to organize things: what matters, family, always comes first. So many sleepless nights throughout the writing of this dissertation... but none of them because of this thesis. Thank you Gabriel.

Lastly, to her friends and (former and current) colleagues for their support. To the former International Research Institute for Climate and Society (IRI) and the beautiful souls she had the privilege to meet while working there. Because science needs to work on benefit of society. To the Barcelona Supercomputing Center, for the last phase of this PhD thesis journey.

To Gabriel, Maria, Cayetana and Claudio.

Part I

Introduction

Climate services (CS) have been proliferating in the past decades among developed and developing communities (**European**; Brasseur and Gallardo, 2016; Buontempo et al., 2014; Goddard, 2016; Goddard et al., 2020; Hansen et al., 2014; C. D. Hewitt et al., 2020; Hewitt and Stone, 2021; Larosa and Mysiak, 2019; Vaughan and Dessai, 2014; Visscher et al., 2019) as societies are using climate services to support their adaptation and mitigation strategies to a changing climate (e.g. Cortekar et al., 2016; D. Scott et al., 2011). However, there is a lack of agreement on the definition of the term "Climate Service", and the need for standardization of CS within its own community (Doblas-Reyes et al., 2024). These barriers limit the optimal development of these services and they also impact the attribution of value to climate services and their implications for the overall society (WMO, 2015), limiting the optimal development of these types of services for both adaptation and mitigation purposes.

By (one of the many) definition, CS requires climate data and climate information (or knowledge) to be co-developed, translated, communicated and used (Goddard, 2016; Hewitt and Stone, 2021; Lemos et al., 2018; Vaughan and Dessai, 2014). At the center of this definition of CS lays the concepts of usability and demand-driven approach. This approach requires continuous collaboration and communication between stakeholders, including final users, scientists, purveyors and services providers (Baulenas et al., 2023; Lourenço et al., 2016) with the objective to provide science-informed or local knowledge-informed value-based outcomes for the decision-making process of particular users or communities.

The concept of CS as an outcome of the co-development process described in the previous paragraph does not happen in a linear process, but rather in a complex, dynamic and multi-dimensional fashion (Guentchev et al., 2023). Several initiatives aim to smooth that process through different pathways: the standardization of CS (Climateurope2[1],NOAA strategic Plan[2], Climate Ready Nation Initiative and Equitable

[1]http://climateurope2.eu

[2]https://www.noaa.gov/organization/budget-finance-performance/value-to-society/noaa-fy22-

Climate Service Action Plan[3]), the embedding of CS into policy, (the UK Climate Resilience Programme[4], Mission Adaptation[5]), or the reduction of the usability gap through climate science innovation (like Horizon Europe funded Impetus4Change[6] and Horizon Europe funded ASPECT[7] projects, just to mention a few).

Yet, CS have not been embraced by society at its fullest and it is common for CS to finish once the funding ends. There are several barriers identified by the academic community that can explain the reason for this: different conceptualizations of CS, along with data constrains, the need for more tailored solutions, the lack of a clear value proposition in the CS market, poor monitoring and evaluation strategies, funding issues, high level specialization of pilots, a poor understanding of what scalability is, a lack of system thinking , etc. (Guentchev et al., 2023; C. D. Hewitt et al., 2020; Woltering et al., 2019). Regardless of the reason, not having a strategic set of climate services that can support society to prepare, cope and recover form a changing climate jeopardize the adaptation and mitigation efforts of society.

Traditionally, CS have been defined and framed around a particular single application or sector, either agriculture, health, energy, water management or disaster risk management (Council, 2001; Organization, 2009)- just to mention a few. Whilst this approach can bring potential benefits such as high specialization, support for mitigation and adaptation (Allis et al., 2019; Lemos, 2015), co-benefits of articulated climate services among different sectors have not been fully assessed in the broader societal system, where these are developed and implemented. Understanding and

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[3]https://www.noaa.gov/sites/default/files/2024-04/NOAA-ECSAP-Final.pdf

[4]https://www.ukclimateresilience.org

[5]https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe

[6]https://impetus4change.eu/

[7]https://www.aspect-project.eu/

valuing the nexus between sectors during the design, development and implementation of climate services might help project and programs optimization, and eventually benefits a community, a country, an entire region or society.

The integration of CS into an ecosystem of climate services, moving from pilots and silos- climate services reality, to a system thinking, could support horizontal, vertical and functional up-scaling processes (Guentchev et al., 2023) while also helping with the orchestration of available resources. In other words, the shift into a system-thinking when designing and implementing CS can lead the limitation of these barriers.

The current scene to obtain resources for CS is more competitive than ever, and donors and investors are more and more interested in demonstrating the impact and value of CS and to understand the return of their investments (Tall et al., 2018). A first step to address these issues would be to define the rules-of-the-game and the resource allocation strategy for the orchestration of potential and actual CS interacting in a given space. That space of interactions has been defined as Climate Services Ecosystems (CSEs) (Goddard et al., 2020), due to the similarities with the ecological definition. Following the definition above of CS, the first attempt to define CSE was recently proposed (Goddard et al., 2020; GonzalezRomero et al., 2023) as -slightly modifying the business-perspective definition of Vargo and Akaka (Vargo and Akaka, 2012) - "a relatively self-contained, self-adjusting systems of resource-integrating actors connected by shared institutional goals, and mutual-value creation through exchange of climate services".

0.1 Objectives and structure of the PhD thesis

In this PhD thesis, the author's overall objective to offer an in depth analysis on the definition of CSE and to propose an evaluation framework to quantitatively assess CSEs from a perspective of resilience increase, optimization of resources and cost efficiency. More specifically, this thesis aims to: a) Provide an objective definition of what a CSE is; b) Provide a descriptive framework that allows to distinguish between what a CSE is, and what is not; c) Define the main attributes and benefits of CSEs; d) Propose an objective, quantitative framework that allows for the harmonization, evaluation and assessment of CSEs; and e) Apply the above framework to case studies based on real-life examples of CSEs.

Part I of this PhD thesis, the introduction, provides an overview of the current environment where climate services are proliferating, identifying current challenges. It also specified the objectives and the structure of this manuscript.

In Part II, this PhD thesis expands the definition of CSE and proposes the use of Theory of Directed Graph as an objective tool to analyze the relationships and connectivity of the elements (or nodes) of the CSE. In Chapter 1, the author suggests a frame of reference to identify what is and what it not a CSE. Chapter 2 describes the main attributes and benefits of CSEs and exhibits different ways how the CSE approach can increase of the resilience of their own network.

In Part III, this PhD thesis presents different methodologies to asses the integration and value of climate services in a quantitative manner. This thesis studies the term CSE from a perspective of resources optimization and value assessment by applying Network Analysis and Dynamic Causal Network Theory to analyze the interactions of the different climate services within a CSE.

Part IV of this manuscript expands on the quantitative definition of CSE described in the previous section and provides two case-studies based on real-life examples where Dynamical Causal Network Theory is applied. The first example is a CSE developed in Latin America and the Caribbean. The second example is based on the South Australia Extreme Heat and Heatwave Strategy currently being implemented in the mentioned State.

Finally, Part V presents a discussion on the CSE topic and concluding remarks.

Part II

Defining Climate Services Ecosystems

Chapter 1

Defining Climate Services Ecosystems

This chapter defines what a Climate Service Ecosystem (CSE) is and develops a frame of reference, through a flowchart system, to identify when two or more climate services are (or are not) a CSE.

1.1 Rationale

Although the term Climate Services Ecosystem is still a relatively new idea (Goddard et al., 2020; GonzalezRomero et al., 2023; Muñoz et al., 2024), the predecessors of this concept have long been established. In 2009, the World Climate Conference developed the Global Framework for Climate Services (GFCS), a UN-led initiative coordinated by WMO to guide the development and application of science-based climate information and services in support of decision-making processes in climate sensitive sectors (Services, 2023; WMO, 2014). The original GFCS Implementation Plan (WMO, 2014, section 4.6.1) referenced what is now known as the National Framework for Climate Services (NFCS), which aim to coordinate institutions at a national level and enable them to work together to co-design, co-produce, communicate, deliver and use climate services for decision-making in climate-sensitive socioeconomic sectors (WMO, 2018). This co-production among different institutions in a given country does not always happen horizontally across different sectors; instead, climate services tend to be co-developed independently and sector-oriented. The concept of CSE brings the focus to the nexus between climate services, from the same or from different sectors, and the opportunity for optimization and increase resilience as a result of that nexus, completely aligned with the goals of the NFCS and the GFCS.

1.2 What is a CSE?

In brief, a Climate Service Ecosystem (CSE) is a dynamic complex network of institutions, agents, information, knowledge, products and services functioning as a unit, at any (or across multiple) spatial or temporal scale(s). CSE presents with the objective of supporting decision-making processes to enhance the resilience of societies to a changing climate, and support countries and institutions to achieve their adaptation and mitigation goals while optimizing available resources. Similarly to natural ecosystems, CSE are self-contained and self-adjusting, having the ability to adapt in response to changes in the network or system (MilleniumEcosystemAssessment, 2003). Ideally, the more interconnected and interdependent the elements of the climate service ecosystem are, the higher the value and resilience of its network (Sawai, 2013; Watts and Strogatz, 1998, e.g.).

The characteristics of a CSE do not differ significantly from those of the climate services. A CSE needs to be demand-driven, fit-for-purpose and provide tailored information in order to satisfy the demand of its own users. It also needs to be flexible to be able to adapt to the dynamism of the needs and the climate (and non-climate) shocks, and has to provide a continuous improvement approach through feedback processes between the users, the providers and purveyors of the climate services. The elements of a CSE are interdependent of one another, presenting a mutual value creation through the establishment of shared goals and offer transparency and traceability of the information flow.

Given that the ability of a CSE to fulfill its overall objective (to be "fit-for-purpose") depends on the relationship of its elements (their interdependency), the use of Theory of Directed Graph to CSEs is of particular value as it allows to describe structural, functional and effective connectivity and interactions between the elements of the CSEs. Graphs are composed of vertices or nodes (corresponding to climate services) and edges (corresponding to pathways, or dependencies between the elements of the graph).

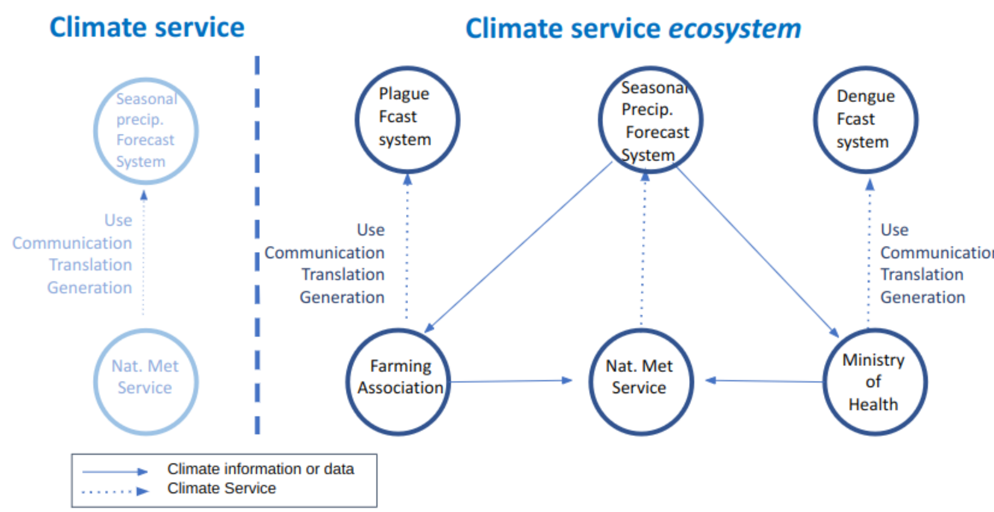


Figure 1.1: A simplified example comparing a Climate Service (CS) and a Climate Service Ecosystem (CSE).The figure on the left shows the example of a seasonal forecast system for precipitation as a climate service offered by a given National Meteorological Service, and the four pillars of climate services. The figure on the right shows a climate service ecosystem built around the same seasonal forecast system. This climate service is now used as the base for new climate services (e.g. a seasonal plague forecast system developed by a farming association and a seasonal dengue forecast system developed by the Ministry of Health).

To illustrate the idea of CSE, Figure 1.1 shows a schematic and simplified representation of a CSE involving both the agriculture and health sectors. Here, the National Meteorological Service issues a seasonal probabilistic forecast system on a monthly basis. This CS is now used as an input for a new CSs. E.g. the seasonal forecast is the base of a seasonal plague forecast system developed by a farming association and a seasonal dengue forecast system developed by the Ministry of Health. Climate services for these two sectors are usually developed in silos. The most frequent situation at the time of writing this PhD thesis is that two different projects (and donors) work with different actors -including the local National Meteorological Service- to co-produce two different services, e.g. a plague forecast system with a particular farmer association, and a dengue forecast system with the Ministry of Health, completely independent one from another. Because these two services share several common elements (in this example, the nexus is a seasonal precipitation forecast system), it is possible to optimize resources if the two separated services were part of an ecosystem of services and to understand the value of the CSE as more than just the sum of their components.

1.3 How to identify a CSE? A frame of reference

CSE are typically complex and dynamic networks that involve many information sources and types, processing steps, interactions and feedback. Identifying whether a group of two or more climate services is a CSE might not be a straightforward process given the nuances and different dynamic and complexities entangled in operational climate services. This PhD thesis proposes a frame of reference to identify whether a group of CS are a CSE or not. As exhibited in figure 1.2, in order to assess whether two or more CS conform a CSE, it is necessary to understand the environment in which each CS interacts in terms of the institutions (or agents) involved, the products or services delivered, and the information flow among the previous two elements.

A first step would be to analyze the demand of the different climate services, following the demand-centered approach of climate services. Considering simplified examples, if two CS respond to different demands, but the same institution is involved in both climate services, then that should be considered a CSE given that administrative, political or budget constrains impacting the institution will likely impact the CS too. Following the same example, if the CS respond to different demands and come from different institutions, it will be necessary to look at the information shared by the CS. If the information shared among the CS are likely to impact one another, then there is an interconnection between then and that would also form a CSE.

If two or more CS respond to the same demand, we need to analyze not only the institutions involved and the information shared, but also what type of products or services are provided by the CS. If the CS being analyzed consist on the same products but these come from different institutions then, that is considered a CSE (see figure 2.2). On the other hand, if the CS come from the same institution and provide the same product or service, that is not considered a CSE but a back-up mechanism for the CS. Back-up mechanisms are necessary for an efficient and optimal performance of the CSE, however, in order for those back-ups mechanisms to be considered a CSE, they need to cover different CS and/or institutions of the CSE.

Analyzing the value of a CSE isnt always a straight forward process. Whilst a single CS value depends on individual adaptation and mitigation efforts, moving into a CSE presents a complex dynamic. Firstly, the value of a CSE (vs CS) allows to identify inter-dependencies, feedback loops and unintended consequences, promoting a more impactful long-term solutions and smarter resource allocations. Secondly, it also prepares stakeholders with realistic expectations and strategic timing of interventions, anticipating delays and lag effects. Additionally, the value also builds from a learning and continuous improvement embedded approach in the CSE, with leverage points and scenario design that tackles root causes and provides higher return on the investment.

1.4 Summary

CSE is a complex and dynamic network of climate services that are interconnected through scientific, administrative, political, economic or demand reasons and that work as a unit to support adaptation and mitigation efforts. CSE are flexible and adapt themselves to the changes in the demand that defines them and to changes in the system due to internal or external shocks. In order to asses whether two or more climate services form a CSE, it is necessary to look at the demand of the climate services, the information flow, the institutions involved and the particular products and services provided by the climate services, as shown in the flowchart from figure 1.2. Lastly, the value of a CSE goes beyond the added value of the CS involved in it and also recognizes the efficiency of resource allocation and higher returns on strategic thinking.

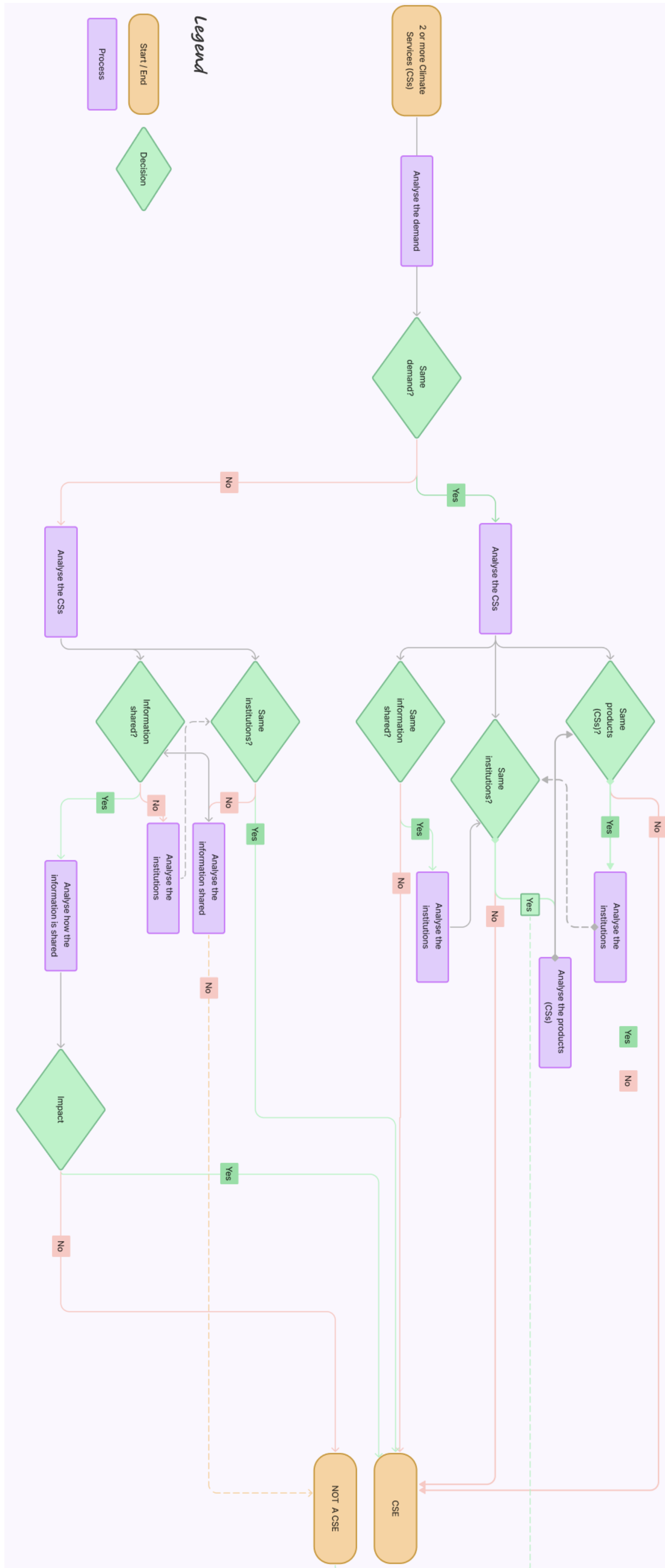


Figure 1.2: Flowchart to identify whether two or more climate services form a CSE: the analysis proposed starts with the demand, the products/services delivered, the institutions involved, and the information shared among the climate services.

Chapter 2

Attributes and benefits of Climate Services Ecosystems

Chapter 2 reflects on the attributes and the societal benefits of the CSE (resilience increase, efficiency, value increase and resources optimization) following the definition of CSE from the previous chapter.

2.1 The resilience of a CSE depends on the connectivity and interactions among its elements

The resilience of a system is defined as a vector that is time and threat-dependent and that manifests the the state of the system in relation to these (Haimes et al., 2008). It is a dynamic reality that can not be measured in units, but it is intrinsic to any ecosystems and its sustainability. However, you can compare the resilience of the CSEs and assess which one is more likely to recover from internal or external threats considering both, the cost and the necessary amount of time to recover (Haimes, 2009b). In order to assess that comparison, it is important to understand the environment and the elements of the ecosystem and the behavior (or causal relationships) of its elements under varied probabilistic conditions (Haimes, 2009a).

CSE involves interactions between different institutions, agents or sectors sharing the same climate service, information, institution or budget. As per the definition of CS defined in Chapter 1 (Commission et al., 2015; Hewitt and Stone, 2021; Vaughan and Dessai, 2014), these interactions require climate data, information or knowledge to be translated, shared, used and communicated bidirectionally, allowing for feedback processes between users and providers of climate services within the system. These interactions within the network aim to enhance its resilience, and lends efficiency and value, by optimally orchestrating the available resources (Goddard et al., 2020).

In other words, CSE tend to be more robust to climate and socio-economic impacts than a loose collection of climate services, an idea aligned with well-established results of previous studies analyzing stability and resilience in networks (e.g. Liu et al., 2022; Watts and Strogatz, 1998; X. Zhang et al., 2018). In a CSE, the shock received by the ecosystem is redistributed and dampened through part or the entire network. In a non-CSE setting, the shock is absorbed entirely by the CS, taking more time and a higher cost to recover. Interactions between CS can also contain functional redundancies (or repetition of climate services). Some of these repetitions may help to keep the equilibrium(s) of the ecosystem when dealing with changes or shocks impacting the network (positive redundancies); however, other duplication of services may decrease the optimization of resources. In order to assess the positive (or negative) impact of these repetitions, is necessary to assess the CSE, as described in section 1.3.

2.2 Efficient interactions optimize resources

Another characteristic to consider when analyzing the interactions within a CSE is the level the service contributing to the overall CSE and its efficiency. While some services or institutions make key but sporadic contributions to the ecosystem dynamics, others tend to contribute more frequently and more efficiently, in such a way that their disappearance would affect the system more significantly (MilleniumEcosystemAssessment, 2003).

Identifying multiple configurations assigning a balanced and efficient contribution to the different actors in the ecosystem is key. In complex dynamical networks like CSE, with non-linear interactions, is likely to have more than one equilibrium solution that depends on the different behaviors of their elements and the "initial conditions" of the environment they operate it (Helbing, 2013). In order to analyze comparative efficiency in CSE, the use of concepts like the Pareto efficiency (Iancu and Trichakis, 2014), allow us to acknowledge different equilibrium solutions and select the most Pareto-efficient one for that particular configuration of demand, institutions, information flows and budgets. A Pareto-efficient CSE (cf. left and right sides of Figure 2.1) implies that the allocation of climate services (and thus, resources) cannot be conducted differently without making one institution or sector worse off.

For example, the left-hand side of Figure 2.1 exhibits a non-Pareto-efficient CSE, in which two institutions from different sectors replicate the same climate service- in this example it is a seasonal forecast system for precipitation. While a duplication of climate services sometimes is necessary, in this case it results in a non-Pareto-efficient solution for the existing demand and thus, a non-optimal use of resources within the ecosystem. This outcome can also entail in an increased mistrust in these forecasts (specially if their predictions have different outcomes), the institutions involved and the scientific community overall.

In contrast, a Pareto-improved CSE is shown on the right-hand side of Figure 2.1. There, the National Meteorological and Hydrological Service, the responsible governing body, issues a seasonal forecast for precipitation that is used by a farming association to develop an index-based insurance for its associated farmers. This new paradigm further promotes specialization, orchestration of resources and a higher resilience of the ecosystem of climate services.

As mentioned earlier in this dissertation, there are cases in which the duplicity of resources or services increases the efficiency in a CSE. Figure 2.2 displays an example of such positive duplication. In this example, two institutions work together to develop a climate service. For simplicity, this dissertation assumes the CS is exactly the same seasonal precipitation forecast system. The forecast issued is directly communicated every month to the stakeholders by the two institutions, and posted in their websites, serving as a mirror or back-up option. In this case, the duplication allows for a continuation of the service in case that a shock, such as funding, impacts one of the institutions and eliminating the service in one of the institutions. In this case the duplication of services conforms a CSE since there two institutions using different resources, and offering the same CS to different communities.

For both examples, Figures 2.1 and 2.2, the CS described in the CSE use climate information at a seasonal scale. However, in any CSE, the climate information used in the CS can include different timescale rather than seasonal, and can also mix CS with climate information at different timescales. Limiting the climate information applied to a single time scale would only be a limitation if the decision-making processes is impacted by that time frame.

2.3 The added value of the CSE is also driven by the optimization of resources

The concept of value has long been a philosophical question without a straightforward answer (Perry, 1914). The utilitarian (or anthropocentric) definition of value, widely used in many disciplines, frames the paradigm of value on the principle of humans' preference satisfaction (MilleniumEcosystemAssessment, 2003). This perspective is aligned with the user-centered approach of climate services, commonly accepted in the literature (e.g., (Buontempo et al., 2018; Goddard, 2016; Goddard et al., 2014, 2020; Lu et al., 2021), just to mention a few), and it is also compatible with the concept of *utility* in Economics (Economides, 1996; Growiec et al., 2018).

Utility refers to the choices made by consumers –and usually limited by a given budget– that increases their satisfaction or benefit and, in consequence, the value or worth of a given product or service. The different possibilities of arrangements (or equilibriums) within a CSE and the different country-specific needs, make it difficult to assess and to assign a predetermine value to a CSE. The definition of value of a CSE is thus determined by the satisfaction of the existing demand for that particular ecosystem in a given point of time, which requires the co-design, co-development and co-implementation of the climate services existing in the ecosystem.

The approach presented here links the concept of value of the CSE to the concepts of risk and resilience, but it also allows to include budget constrains and resource optimization in the analysis and interpretation of CSEs. Here, the term resilience refers to the state and capacity of an CSE to adapt and respond to different hazards, or crisis under various probabilistic conditions (Haimes, 2009a, 2011). The resilience of the CSE is subject to different state conditions established in a timely manner by the interactions and characteristic of the network in that specific point of time. This makes the idea of value of the ecosystem a dynamic concept based on the needs of the stakeholders, the conditions impacting the ecosystem and the risks impacting the CSE. If either of those changes, the value of the ecosystem will need to be reassessed and,more likely than not, it will offer a different value (or resilience level) too.

The concept of risk is defined by the CSE itself, and it is directly linked to the demand (e.g. decrease the number of disease cases or deaths, decrease migrations flows, etc.). Given a level of hazard and a level of vulnerability of the CSE, a decrease of the exposure or sensitivity of the elements of the ecosystem, or an increase of their capacity to adapt will significantly reduce the risk of the ecosystem. This dynamic concept of value, risk and resilience implies that there could be multiple ways for a CSE to change over time based on the state conditions, demand, time, stakeholders, climate services and interactions of the network. Unfortunately, the amount of resources are limited and the dynamics of the CSE are also impacted by budget constraints. The proposed approach supports the value-analysis of different scenarios, allowing decision-makers to assess which is the most Pareto-efficient option (or set of options) given the existing budget constrains.

2.4 Summary

Moving from developing single individual climate services to a systematic way of understanding the interconnections of climate services in society, support the resilience and adaptation to a changing climate and makes the ecosystem more robust to internal or external shocks. The concept of resilience varies from CSE to CSE, as it depends on the demand(s) that originally suggests the organization of the CSE. Nevertheless, the optimization of resources increases the resilience of the CSE, as it allows for an increase of the efficiency. The different interactions between the climate services, bring different level of efficiencies and provide more than one equilibrium solution for the demand of the CSE in a given point of time. The value of the CSE is intrinsically liked to the concepts of resilience and risks inherent to each CSE.

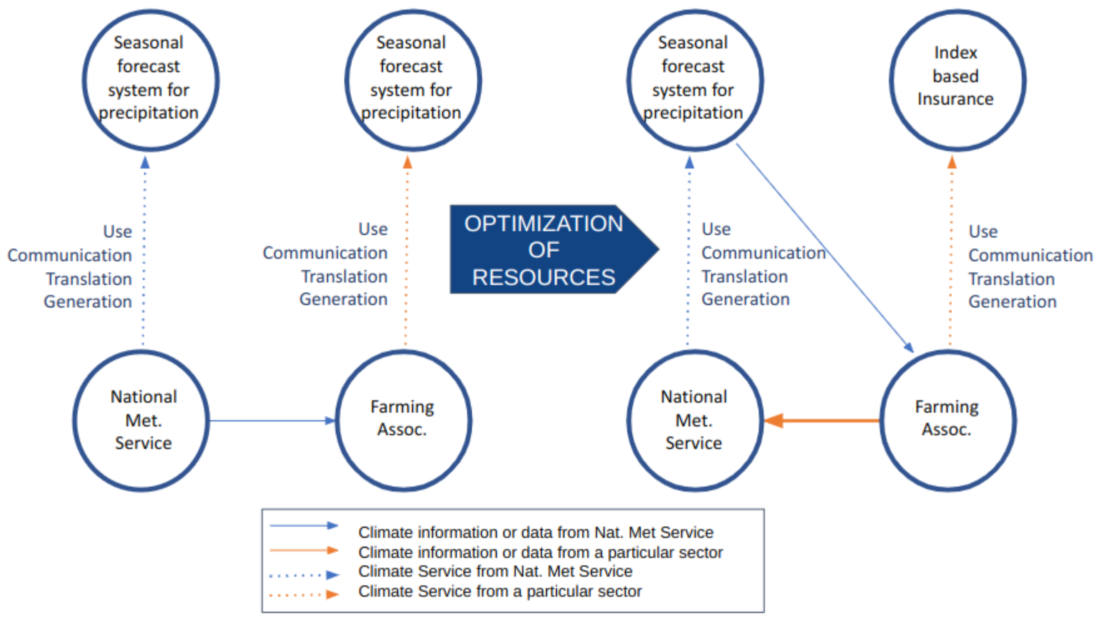


Figure 2.1: Optimization of resources for Climate Services Ecosystems (CSE). (Left) A National Meteorological Service provides a seasonal forecast system for precipitation to the general public (dotted line), and -because of a funded project- provided observed rainfall data to a particular farming association, which used the data to internally produce a different seasonal precipitation forecast system for its farmers. (Right) A National Meteorological Service provides a seasonal forecast system for precipitation which uses additional information provided by the farming association (e.g. additional observed rainfall data from a private network). Since the farming association does not need to invest time and other resources to produce an internal seasonal forecast system, it is able to co-produce with an insurance company a tailored index-based insurance product.

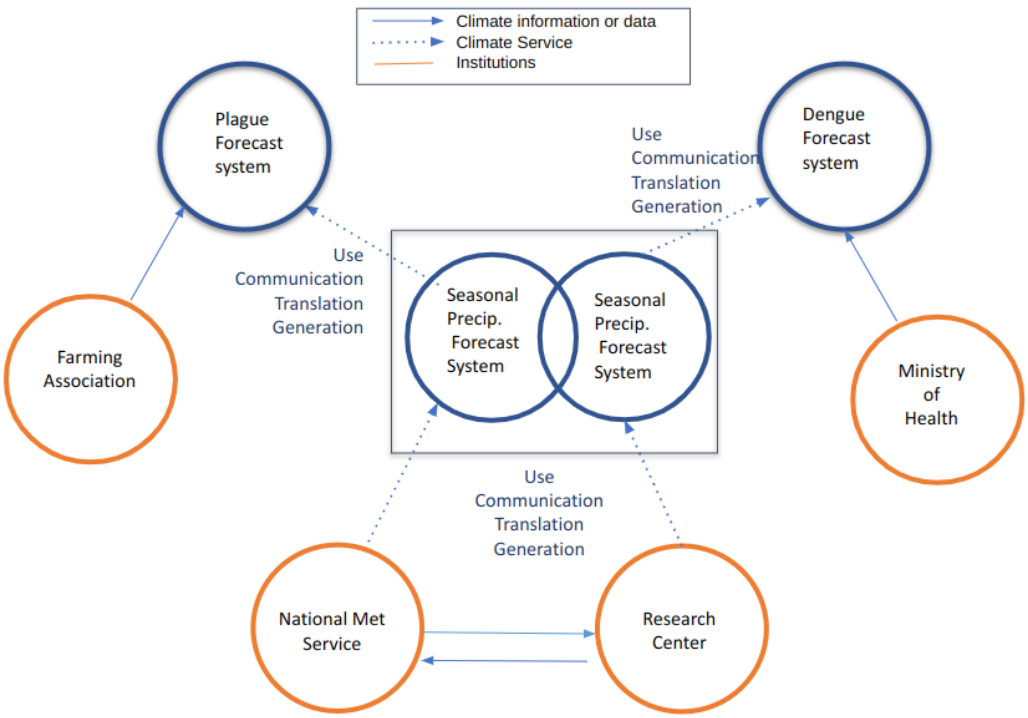


Figure 2.2: An example of positive duplication of services in a CSE.The same seasonal forecast system for precipitation is located in two different institutions (in the National Met Service, on the left; and in a research center, on the right). The forecast system is used in different climate services (a plague forecast system and a dengue forecast system, in this case).In this case, the duplication of the forecast system benefits this CSE and prevents potential failures on the previously mentioned climate services driven by technical glitches from the seasonal forecast.

Part III

A quantitative framework to analyze climate services ecosystems

Chapter 3

A quantitative framework to analyze climate services ecosystems

This chapter analyses CSEs from a diagnosis perspective, using Network Analysis and topology theory; it and also analyses changes in the network by applying Dynamical Bayesian Network theory to infer probability outcomes based on causal relationships within the networks. The ultimate objective of the proposed methodologies, is to evaluate CSE in such a way that it allows for harmonization and comparison among CSEs and supports decision-makers in the design or selection of CSEs.

3.1 Rationale

Given the definition and the characteristics and nuances of the CSEs mentioned in the sections above, it is essential to have tools that allow for the harmonization and evaluation of CSE to be able to compare and analyze them.

This dissertation proposes both, a qualitative and a quantitative way to analyze CSE. On the one hand, the qualitative analysis can be performed through the qualitative aspects of a Network Analysis. On the other hand, the quantitative analysis is performed by applying two different methodologies, Network Analysis and topology theory, or Bayesian Network Theory (among others). Whilst the Network Analysis allows for certain quantitative analysis, specially diagnosis work, the use of the Bayesian Network Theory allows to perform causal inference and obtain probabilistic outcomes that can support answering scenarios and what-if type of questions (prognosis work). While these methodologies can be applied simultaneously, it is not a necessarily a requirement to do so, and these can be exercise individually.

A qualitative analysis of an ecosystem requires the analysis of the decision-making context of the actors involved. The use of Network Analysis, from a qualitative point of view, has already been discussed extensively in the literature (e.g. Baulenas et al., 2023; Bojovic et al., 2021; Goddard, 2016; Goddard et al., 2014, 2020; Terrado et al., 2023a,b; Visscher et al., 2019, and references therein). Hence, this dissertation focuses on the quantitative application of Network Analysis and the use of Dynamical Bayesian Network Analysis.

To study the temporal evolution of the CSE and attribution of changes in the dynamics of CSEs, the paper proposes the use of a Dynamical Bayesian Network Analysis, which allows to explore causation and attribution of the impact of these changes within the network. This methodology also allows for the (re-)assessment of the value of the CSE given a shock (e.g. budget changes, merges or divisions of institutions, program implementation, etc.). The following subsections provide details on each one of these methods.

3.2 Network Analysis

Network Analysis is commonly used in a variety of fields, from medicine, biology, and social studies to financial analysis (e.g. Chen et al., 2012; Kleindorfer et al., 2009; Tajbakhsh et al., 2016; B. Zhang and Horvath, 2005). This type of analysis focuses on understanding how the combination of individual elements can create enduring, functioning networks (Borgatti et al., 2009). It looks at kinship patterns, community structures and overall relational information (J. Scott, 2017), seeking to uncover various kinds of patterns and to determine the conditions under which those patterns arise and what they imply for the network (Freeman, 2004).

Network Analysis (for a recent review see Kirschbaum, 2019) intuitively comes as an approach when dealing with climate services ecosystems. This approach helps to identify patterns within CSEs, helping to better understand which actors and services are involved, how they are connected, or how the information flows in the ecosystem. Network Analysis can also help compare different CSEs, although with some restrictions -e.g. the compared networks should have similar characteristics, such as for example the size of the CSE.

This type of analysis supports the understanding of connectivity among the nodes, and the dynamics of the CSEs in relation to potential modifications of the nodes (e.g. involved actors) and the structure of the network. In other words, Network Analysis is a useful tool to quickly summarize (or take a snapshot at a particular moment in time of) key aspects of the climate services ecosystem from a topological or network theory point of view.

Following the Social Network Analysis approach [a variety of Network Analysis, e.g. (J. Scott and Carrington, 2014)] in CSEs, information of interest can be drawn from climate services as both individual nodes, and also as sets of nodes part of the ecosystem. This approach avoids the consideration of climate services as independent silos, and promotes the analysis of CSEs considering the implications of the different climate services, institutions and information flow on the entire CSE.

Natural sciences have traditionally critiqued social network research due to its descriptive analysis and the lack of comparison with expected values from theoretical models (Borgatti et al., 2009). However, the use of Social Network Analysis for climate services ecosystems can provide value information on:

- CSE typologies. Understanding how elements affect and interact with each other, looking for types of CSE based on similarities, relationships, interactions,

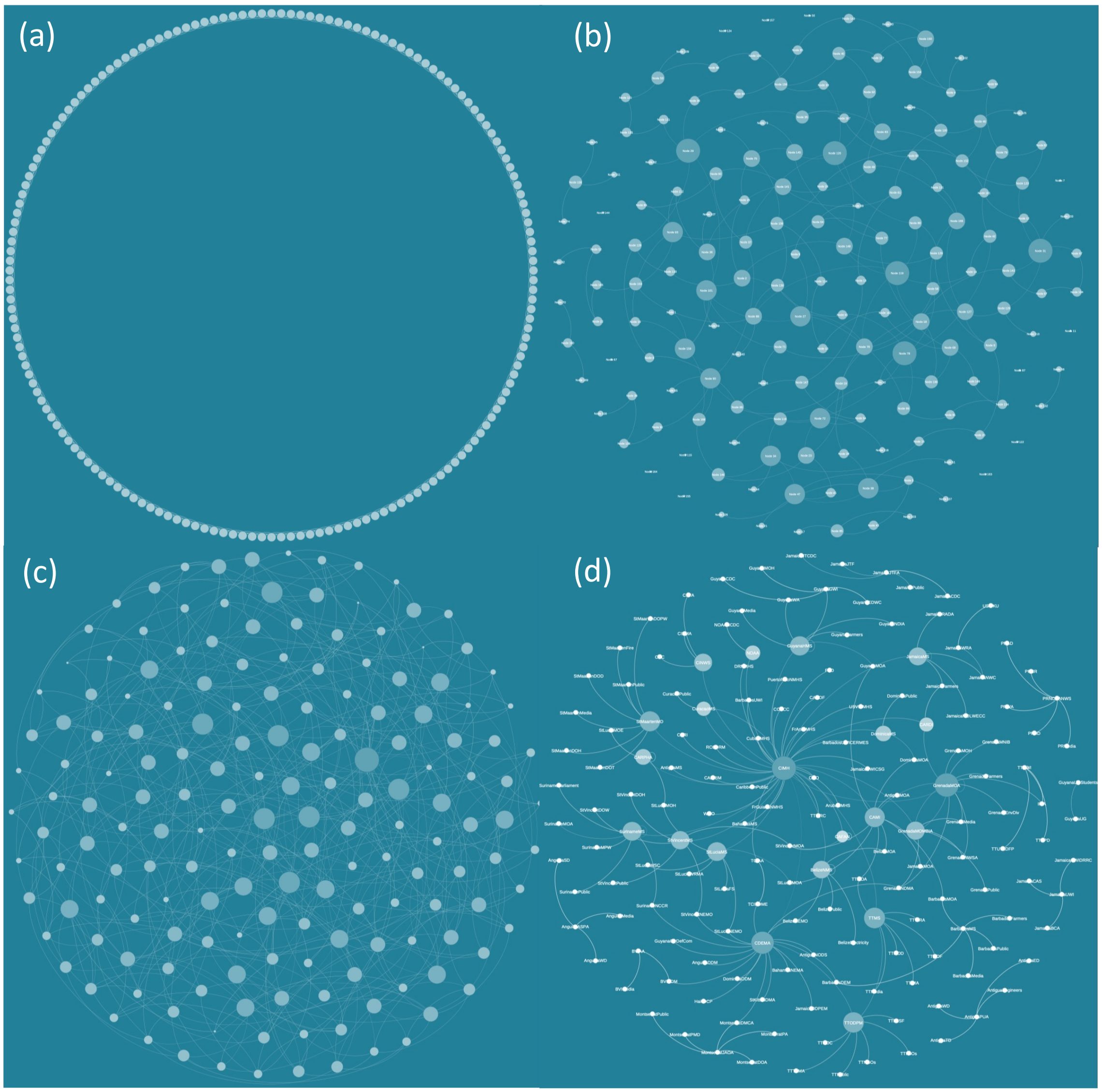


Figure 3.1: Different network connectivity examples: (a) regular lattice network, (b) small-world network, (c) Erdös-Rényi random network, and (d) real-world climate services ecosystem (data from the ACToday project, Central America region). For details see main text and Table 1.

and information flows.

- CSEs' structures, properties analysis and node outcomes based on the position of the elements.
- Centrality analysis to understand the importance of a node in the CSE network.
- Mechanisms to explain the consequences of the direct transmission of information between nodes within a CSE. The adaptation mechanism could explain how elements of the CSE become homogeneous as a result to adapt to a similar environments. The binding mechanism, on the other hand, aims to explain how environmental elements or ties can bind nodes together as to build a new node with different characteristics from its parents. The exclusion mechanism analysis the power dynamic existing in a given ecosystem.
- Estimation of past and future changes of a CSE. Associations among nodes can be inferred, allowing for the estimation of probabilities of past and future events (Pearl, 2010) or changes of the CSE, if the conditions remains the same. These association analysis can be defined in terms of a joint distribution of observed variables (Pearl, 2010).

As a simple example of the type of outcomes that can be obtained from a Network Analysis, consider the following questions: what is the most efficient network configuration to communicate climate information produced by a climate service ecosystem? how the different institutions should be interconnected? In order to answer these questions, it is necessary to look at the Average Path Length (APL) metric. The APL metric indicates how many "steps" on average are needed for a node to reach another node. It is a metric for connectivity that measures the efficiency of the transmission of information: the lower the value, the more efficient the transmission is.

In this example (see Figure 3.1), a 170-node CSE network identified in Central America by the Columbia World's Project "ACToday" (ColumbiaWorldProjects,

Table 3.1: Average path length,indicating how many steps on average can any node reach another node (a metric for connectivity), for each network exhibited in Figure 4.

Panel	Network	Average path length (APL)
(a)	Regular lattice	14.586
(b)	Erdös-Rényi (random)	0.663
(c)	Small world ($\beta = 5$ Watts-Strogatz model)	3.154
(d)	CSE in Central America	2.601

2021) is compared against three different network configurations: a regular lattice (Figure 4a) consisting of each node only connected to near-neighbor nodes, a random network (Erdös-Rényi network, Figure 4b), with completely random connections between nodes, and a small-world network (Figure 4c, defined as a $\beta = 5$ Watts-Strogatz model, (Watts and Strogatz, 1998)). The Network Analysis conducted here shows that the Central America CSE under study is topologically equivalent to a small-world network (even slighter more efficient), due to their comparatively smaller average path length (Table 1). The analysis suggests that CSE networks with high average path lengths compared with small-world networks should be re-wired (the institutional interconnections should be re-planned) in order to be more efficient in terms of communicating information produced by their climate services. Hence, Network Analysis offers ways to quantify theoretical optimal values related with different network configurations, that can be potentially translated into real-world recommendations for CSE.

However, as it has been pointed out in the specialized literature (see Kirschbaum, 2019, and references therein), Network Analysis has limitations when analyzing the temporal evolution of the network or when dealing with attribution analyses. For example, it is possible to identify through a Network Analysis a certain change in a given CSE (e.g. an increase of the scope of a climate service, the appearance or removal of a new climate services or institution), but it has limitations to identify whether that change is produced by a given project, program, budget change, an institutional arrangement or a combination of all.

3.3 Dynamical Bayesian Network Analysis

Bayesian Network Analysis (BNA) is proposed here as an alternative methodology to quantitative analyze CSE. Its aims is to infer probabilities under changing conditions withing the network like, for example, changes induced by programs, policies, budgets, institutional changes or any other external interventions that impact the CSE in one way or another. The causal assumptions that can be inferred from Bayesian Network Analysis identify relationships that remain invariant when external conditions change, allowing for the assessment of these changes, predictions of plausible scenarios and evaluation of counter-factual and testable scenarios (Pearl, 2009). The assessment of causality derived from a Bayesian Network Analysis implies that the influence of one event onto another is stable and autonomous, so the change in one of them would necessarily result on a change in the linked event.

Applying these concepts to CSEs, changes in one climate service will likely influence other climate services linked to the former. Bayesian Network Analysis combines graphs, probability and statistical modeling, allowing for the representation and analysis of the response and changes of the CSE to external or spontaneous changes (Pearl, 2009), like the ones mentioned before.

The time sensitivity of a CSE, as described in Section 2.3, may require the use of Dynamical Causal Network Theory to model the relationship between the nodes, or climate services, of a CSE. Although unnecessary when the variables are not time-dependent, a dynamical analysis brings the opportunity to model both time-dependent and time-independent nodes, if timing is a necessarily element for any of the nodes of the CSE. A CSE model may contain multiple variables representing different but (potentially) related time series. Their dependencies can be modeled leading to representations that can take multivariate time series predictions. This means that instead of using only a single time series to make a prediction, multiple time series and their interrelations can be utilized to make better predictions and analyses. The approach is illustrated in the following paragraphs.

In a CSE, the nodes can take discrete, continuous or multi-variable values, allowing for the analysis of different elements or characteristics in a CSE. A Directed Acyclic Graph (DAG), a graph with directed links and no directed cycles, represents a CSE as a system of processes and provide a causal interpretation of the changes within the network or system.

Figure 3.2 illustrates a simplified version of a CSE that involves three sectors, i.e. climate, health and agriculture, and eight different climate services (or nodes). Here, the combination of longer-term outlooks for precipitation (X_1, e.g. seasonal forecasts) and shorter ones (X_2, subseasonal forecasts) allows to put information into context (Goddard et al., 2014) for other climate services like a dengue forecast system (X_3) and an index-based insurance product (X_8). The dengue forecast system feeds into an Early Warning System (EWS) for vector-borne diseases (X_5), that unfolds into an action-based protocol (X_6) and a climate and health bulletin (X_7). Table 3.2 summarizes the sectors, variables (here nodes of the Bayesian network), and a description of the variables and functions that define each node.

Following (Pearl, 2009), here it is proposed to use a structural equation model (SEM) approach to mathematically define each node, such that:

$$x_i = \sum_{k=1} \alpha_{ik} x_k + u_i, , \qquad i = 1, ..., n \tag{3.1}$$

where the α_{ik} are regression coefficients of the model, u_n represents realizations of both random errors and the errors or disturbances due to omitted factors. The lower case symbols (e.g. x_i,u_i) in this and the following equations just serve to remind that these are particular realizations of the corresponding variables (e.g. X_i,U_i).

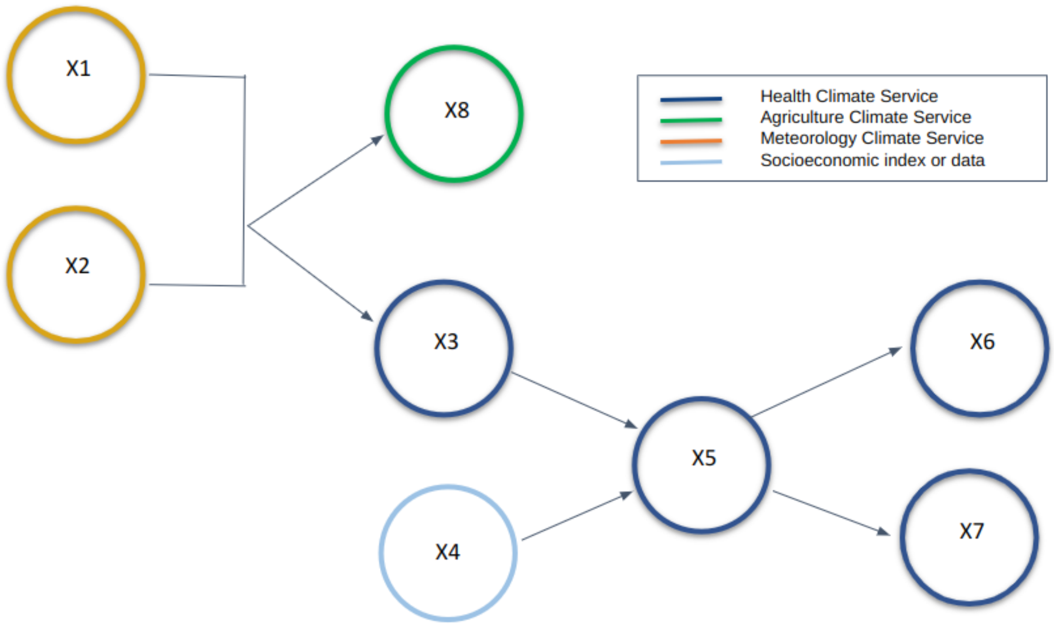


Figure 3.2: Example of a simplified CSE involving health and agriculture. See main text for details.

Table 3.2: Table exhibiting the mathematical expression of the CSE in Figure 3.2. From left to right, the columns of the table exhibit the sector, node, function and description for each element of the CSE. X_i and U_i are the model's variables and errors, respectively, as explained in the main text.

Sector	Node	Function	Description
Climate	X_1	$X_1 = f_1(\text{seasonal fcst}, U_1)$	Seasonal forecast for precipitation
Climate	X_2	$X_2 = f_2(\text{subseasonal fcst}, U_2)$	Subseasonal forecast for precipitation
Health	X_3	$X_3 = f_3(X_1, X_2, U_3)$	Dengue forecast system
Health	X_4	$X_4 = f_4(\text{socioecon data}, U_4)$	Socioeconomic index or data
Health	X_5	$X_5 = f_5(X_3, X_4, U_5)$	Early Warning System (EWS)
Health	X_6	$X_6 = f_6(X_5, U_6)$	Action-based protocol
Health	X_7	$X_7 = f_7(X_5, U_7)$	Climate and health bulletin
Agriculture	X_8	$X_8 = f_8(X_1, X_2, U_8)$	Index-based insurance

This approach allows to determine the value of each variable X_n. Applying the nonlinear, non parametric generalization of the linear SEMs, it is possible to write:

$$x_i = f_i(pa_i, u_i), \qquad i = 1, ..., n \tag{3.2}$$

where pa_i represents a realization of the Markovian parents (PA_i) of x_i, and the value of x_i responds to every possible value combination of pa_i, u_i.

The Markovian parents are the preceding variables that are sufficient for determining the probability of X_i, knowing the values of other preceding variables is redundant once we know the values pa_i of the parents set PA_i (Pearl, 2009). This concept is the essence to define the memory of the system and, instead of specifying the probability of x_i conditional on all possible realizations of its predecessors $x_1, ..., x_{i-1}$, it is only need to specify the possible realizations of the set PA_i that makes x_i dependent to pa_i (Pearl, 2009), such that:

$$P(x_i, ...x_n) = \prod_i P(x_i|x_1, ...x_{i-1}), \tag{3.3}$$

and thus

$$P(x_i|x_1, ..., x_{i-1}) = P(x_i|pa_i) \tag{3.4}$$

Putting this mathematical framework in the context of the example illustrated by Figure 3.2, the lines connecting the different nodes represent the dependency between the variables. Figure 3.2 shows a dependency between the forecasts products, both at seasonal (x_1) and subseasonal level (x_2), and the dengue forecast system (x_3) and the index-based insurance (x_8). The EWS (x_5), the action-based protocol (x_6) and the climate and health bulletin (x_7) are screen off-ed from the forecast systems described above by their Markovian parents (x_3 and x_8, respectively).

Hence, an important conclusion is that the value of the overall ecosystem is primarily based on the exchange value between Markovian-parent-related nodes. The higher the number of these interactions, the higher the value of the CSE.

3.3.1 But... why *Dynamical* Bayesian Network?

Dynamic Bayesian Network Theory expand from the Bayesian Network Theory, with the concept of time. It allows to model relationships that are time-dependent series in the same model, and also allows to model time series that are sequences from each other. This means that Dynamical Bayesian Network allows to model complex multivariate time series their relationships in the same model, allowing to include time series that behave in different ways depending on the context. For example, in the Guatemalan case study, see section 4.2, the climate information was provided at a seasonal timescale but also including monitoring systems of the precipitation level at shorter timescales. The precipitation level across these different timescales influences changes in the Dengue forecast system and thus, in the action plan. This Dynamical Bayesian Network approach allows for these conditional dependencies despite the time-dependent effect of the precipitation on the number of dengue cases and the implementatino of the action plan.

3.4 Summary

The different demands, institutions, information flows and climate services involved in CSEs, makes it difficult to assess them by only looking at qualitative information. It is necessary to use quantitative methods that allow for the harmonization and comparison between networks. Social Network Analysis (SNA) allows for the measurement and visualization of relationships within a CSE using metrics such as APL or centrality measures (to identify key players), among others. The use of one metric or another depends on the research question, but they allow for the quantification of the connection between institutions and climate services, their influence on one another, or their position within a CSE. Harmonizing CSE using these metrics, also allows to compare a given CSE with other network configurations widely studied in the literature, allowing to assess the efficiency of our network and the identification of bottlenecks for information flows.

Although SNA offers a way to quantitatively compare CSEs in terms of their efficiency and optimal values configuration, it does not allow to establish causal relationship between changes to the CSE and their impacts on the CSE. The application of Dynamical Bayesian Theory to CSEs, allows to conclude probabilities under changing conditions within the network with the capacity to establish causal relationship between these impacts or changes to programs, policies, budget changes, institutional changes or other external interventions. Additionally, the use of probability outcomes, allows to quantify the impacts of these changes throughout the entire probability distribution function and work on prognosis analysis and respond to what-if type of scenarios.

In summary, Network Analysis allows us to assess and understand the environment and the definition of the elements and their relationships in a CSE, and the application of Dynamical Bayesian Network Theory permits us to establish the causal relationship under these probabilistic and dynamic conditions and to quantitatively assess what-if scenarios regarding the changes in the probability distribution of the CSE. These two methodologies are independent and can be applied individually to assess a CSE in a qualitative or quantitative way or jointly in a complementary way.

Part IV

Case studies

Chapter 4

Case studies: application of Dynamical Bayesian Theory on real-life examples

The present chapter further explores CSEs and the application of Dynamical Bayesian Network (DBN) Theory in two different case studies. The first case study focuses on the context of the Anticipatory Action Framework of the OCHA (the Office of Coordination of Humanitarian Affairs of the United Nations) in the Dry Corridor of Guatemala. The second case study applies the Dynamical Bayesian Theory to the context of the Extreme Heat and Heatwave Strategy developed in South Australia.

4.1 Rationale

In the first case study, the manuscript applies DBN to assess the changes in the costs associated to the implementation of an Anticipatory Action Plan based on the output provided by nationally-produced seasonal forecasts that supports the CSE.

The second case study focuses on the Early Warning System for heatwaves developed in the State of South Australia. It applies a DBN analysis to calculate the full probability distribution function of the number of ambulance calls-out per day in the State. The number of call-outs is an indicator of the impact of the heatwave to the health system in the State of South Australia, and its resilience to the intensity of heatwaves.

These two case studies follow the same structure. They first start describing the socio-political context that enables the creation of the CSEs. Then, CSEs DBN-based models are described, as well as how the Dynamical Bayesian Network Theory is applied to these networks, following the methodology described in Part III of this dissertation.

4.2 Guatemala Case Study: "How much those Priority Interventions cost?" A cost assessment example

In Guatemala, during the agricultural season from May to October, El Niño years exhibit a widespread reduction of up to 20 per cent in precipitation and an average increase of 1°C in temperature (Pérez and Montes, 2024), significantly impacting the rain-fed agriculture production and the food security levels in the country. At a regional level, in the Dry Corridor, el Niño conditions tend to be associated with prolonged droughts.

The 2015-2016 El Niño had a severe impact in northern Central America. As a result, Guatemala formulated a Humanitarian Response Plan intended to target 500,000 individuals along the Dry Corridor. Such a plan mobilized around 25 million US dollars including projects focused on food assistance, acute malnutrition recovery, emergency health services, and WASH (Water, Sanitation and Hygiene) actions (Coordination of Humanitarian Affairs, 2024), and required the orchestration of efforts and resources from both national and international organizations.

Food insecurity in rural areas has increased over the past decade in Guatemala (Lane et al., 2024), making it a priority for both the National Government and International Organizations. According to the Integrated Food Security Phase Classification (IPC), between March and May 2023, 19 per cent of the analyzed population in Guatemala (17.6 million) was in a food security crisis phase (Phase 3) or above. This figure was expected to increase to 21 percent between June and August 2023 coinciding with the lean season, and then go down to 18 percent from September 2023 to February 2024 (IPC, 2023).

Similarly to 2015-2016, the food insecurity situation in 2023 required the coordination of institutions at national and international levels like CONRED (the National Civil Protection Office), SESAN (Secretariat of Food Security and Nutrition), MSPAS (Ministry of Public Health and Social Assistance), MAGA (the Ministry of Agriculture), INSIVUMEH (the National Meteorological and Hydrological Service), MIDES (Ministry of Social Development), UNICEF, WHO/PAHO (World Health Organization/Panamerican Health Organization), FAO (the Food and Agriculture Organization) or WFP (the World Food Programm).

To illustrate this particular application of Dynamic Bayesian Network Analysis in the context of climate services ecosystems, consider the case of the Anticipatory Action Framework (AAF) developed by the United Nationals Office of Coordination of Humanitarian Affairs (OCHA) for Guatemala in 2023 [1], and in particular consider the departments of Quiché, Baja Verapaz, El Progreso, Guatemala, Zacapa, Chiquimula, Jalapa y Jutiapa, the Guatemalan Dry Corridor.

The AAF Country Document contains an overall forecasting trigger (the model), the pre-agreed activation protocol and action plans (the delivery) and the pre-arranged financing (the money). As described in the OCHA's AAF, two seasonal forecast sys-

[1] https://www.unocha.org/publications/report/guatemala/anticipatory-action-framework-dry-corridor-guatemala

tems (the local one seen in Figure 4.1 and produced by INSIVUMEH -the National Meteorological Service- and the one produced by the European Centre for Medium-Range Forecasts -ECMWF) are used to trigger concrete priority interventions by sector, including food security and health, based on the outputs of the forecasts.

For the sake of simplicity, but without losing applicability, this case study follows the ecosystem of climate services represented by the network shown in Figure 4.2 as a simplified case of the OCHA's AAF. This CSE is formed by four nodes: the climate information node ("ClimateInfo"), the socio-economic information node ("SocEcInfo"), the dengue forecast node ("DengueForecast") and the early warning system node ("EWS"). The *ClimateInfo*, the *DengueForecast* and the *EWS* are interconnected climate services that establish priority intervention actions for the region of interest. The *SocEcInfo*, whilst it is not a climate service itself, provides valuable inputs for the dengue forecast system. Once the network of the EWS has been defined (the nodes and links), the Bayesian network requires a probability distribution to be assigned to each node, conditioned on its parents nodes. This can be mathematically expressed as described in equation (3.3).

In the case of this CSE in Guatemala, the ClimateInfo represents the latest seasonal forecast available for a given season. The probability distribution of this node is defined by the forecast itself, which is typically communicated based on probabilities for the below-normal, normal and above normal terciles of the distribution. In this case study, two contrasting cases are considered, and are schematically presented in Figure 4.2. Panel 4.2(a) refers to the case of a dry season, a 50 per cent probability of having precipitation below-normal (category 0 in the ClimateInfo box), 20 per cent probability of having normal precipitation, and 30 per cent probability of having above-normal precipitation. Panel 4.2(b), in contrast, describes the case of a wet -or wetter than normal- season for Dry Corridor standards, with a probability of 50 per cent for the above-normal category, whilst having normal precipitation is forecast to have a 20 per cent probability, and the below-normal precipitation category has a

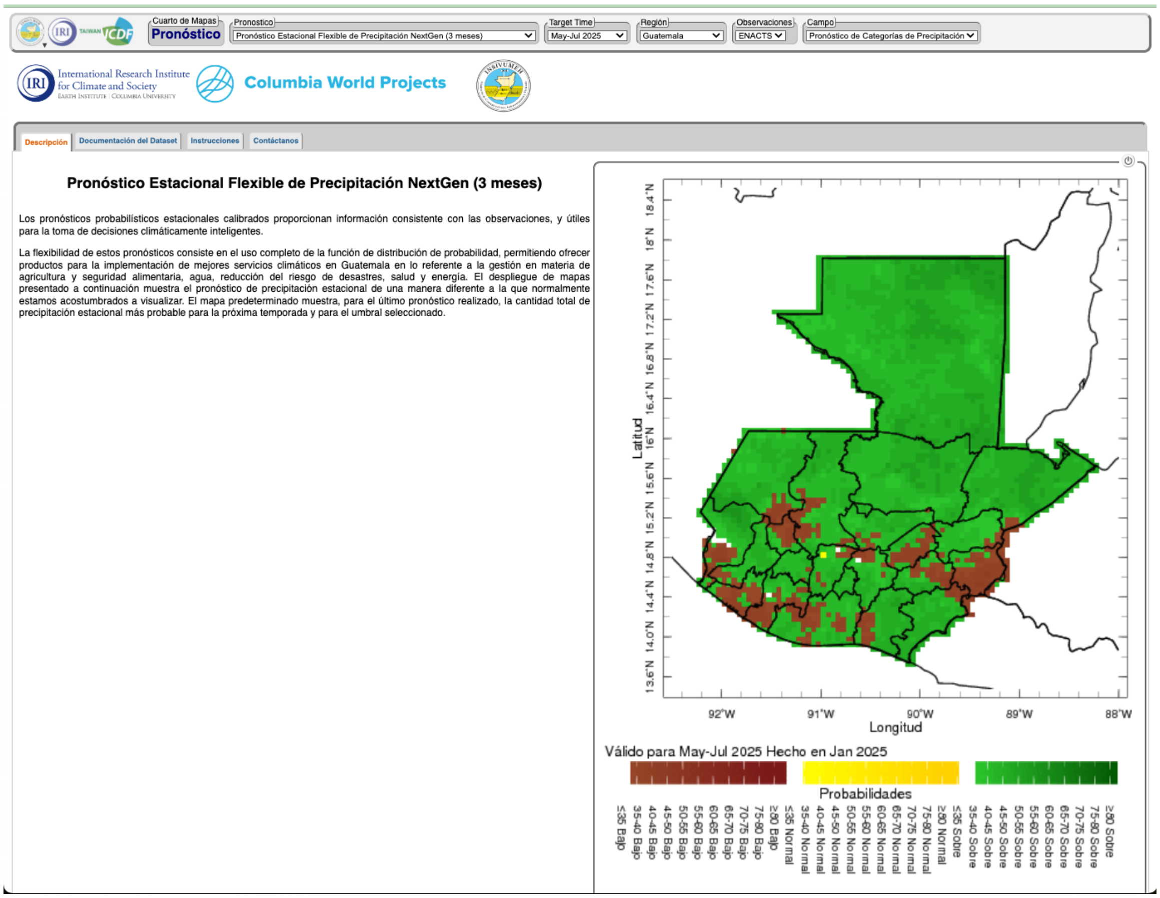
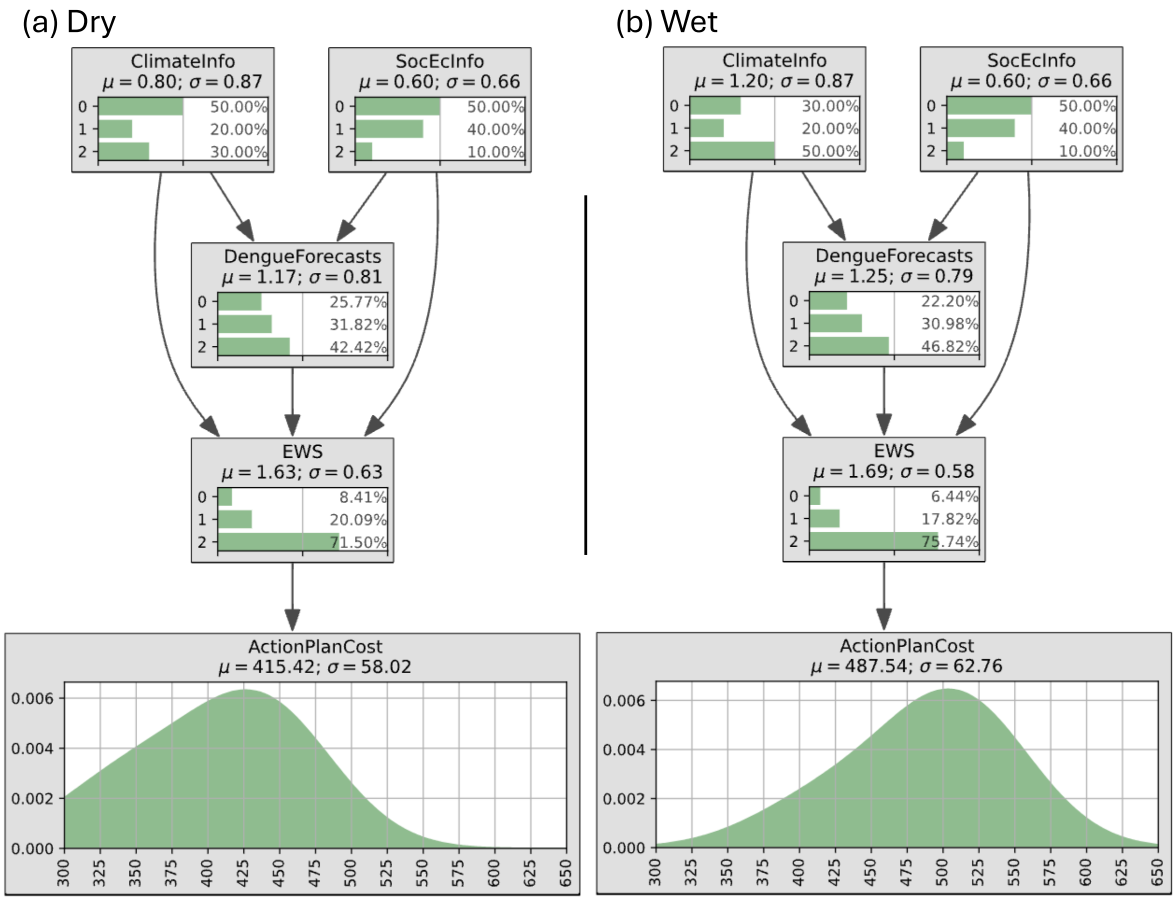


Figure 4.1: NextGen seasonal forecast system developed by INSIVUMEH, the National Meteorological and Hydrological Service, that is used in the Anticipatory Action Framework and the associated CSE as explained in Part IV. This image shows the January 2025 forecast for May-June 2025 showing the probabilities of having below normal rainfall in Guatemala. This flexible forecast system also allows to chose normal and above normal categories and their associated probabilities for each municipality in Guatemala.

Figure 4.2: Example of the use of Dynamical Bayesian Networks to assess expected costs of a set of Priority Interventions and Anticipatory Actions (node: ActionPlan-Cost) under (a) dry and (b) wet conditions, related to a climate service ecosystem involving an Early Warning System (node: EWS) that uses socio-economic information (node: SocEcInfo), climate information (both observations and forecasts; node: ClimateInfo) and dengue forecasts (node:DengueForecasts), as indicated by the arrows. The expected costs are defined in terms of the probability density function seen in the final node, while each of the other nodes exhibit probabilities (the percentages indicated in each box) of below-, near-, and above-normal categories, represented by 0, 1 and 2 in the vertical axis, respectively. For details, see text.



probability of occurrence of 30 per cent.

The SocEcInfo involves the most updated socio-economic information for the targeted region. In this example, for the ease of comparison and illustration of the approach, the SocEcInfo node and its probability distribution for below (indicated by 0 in the panel box), normal and above-normal socio-economic conditions remain the same for both the wet and the dry scenarios (Figure 4.2(a,b)). Both the climate information node and the socio-economic information node feed a dengue forecast system (DengueForecast), which then is used as an input for the EWS, along with climate information from the ClimateInfo and the SocEcInfo nodes.

The probabilistic Early Warning System is developed by combining expected conditions (in a tercile-based probabilistic approach), as indicated by the arrows in Figure 4.2 from both nodes mentioned earlier. This EWS triggers concrete actions if dry conditions (Figure 4.2a) -such as a drought-, or very wet conditions (Figure 4.2b) -such as a flood or crop-damaging intense rainfall- are expected. A high number of dengue cases can be expected both during (a) dry conditions, because humans tend to storage water during droughts, leading to suitable habitats for mosquito reproduction, and (b) wet conditions, because rainfall naturally tends to produce suitable habitats for mosquito reproduction.

Knowing the base costs related to each component of the ecosystem and that of the Priority Interventions, by changing only the probabilities related to dry (category 0) or wet (category 2) conditions in the "ClimateInfo" node, and by using equation (3.4), Dynamical Bayesian Network can help identify the expected costs of the ecosystem for dry and wet conditions, as well as other configurations, as discussed by Muñoz et al. (2024), by providing a probability density distribution of costs from which either the most probable cost (the median of the distribution), or the probability of exceedance of *any* particular threshold (i.e., exceedance of the the cost quantiles) can be computed straightforwardly by traditional Bayesian computations (as indicated, equations (3.3) or equivalently equation (3.4); for additional details and references see Chapter III).

4.3 South Australia Case Study

Historically, heatwaves have been responsible for more deaths in Australia than any other natural hazard. From 1844 to 2010, extreme heat events have killed at least 5332 people in Australia (Coates et al., 2014).

Of particular concern is the impact of heatwave on the elderly, those with pre-existing conditions, infants and vulnerable communities. According to the 2023 Intergenerational Report[2] of the Australian Bureau of Statistics, in the next forty years the number of Australians aged 65 and over will more than double, the people aged 85 and over will more than triple, and the number of centenarians is expected to increase six-fold. This is aligned with the expectation of a six-fold increase on the number of heat-related deaths in temperate Australian cities by 2050, as the frequency and intensity of heatwaves is projected to increase under climate change from global warming (Nairn and Fawcett, 2013). The impact of heatwaves can be observed across sectors and can be directly or indirectly accountable for (Nairn and Fawcett, 2013):

- increased human morbidity and mortality, particularly among the elderly and infirm,
- stress for outdoor workers;
- increased bushfire risk;
- stress in animals;
- damage to crops and vegetation and the quality of the crops, resulting in famine, nutritional deficiencies and lowered food production;
- food spoilage (e.g. result in food-borne disease like gastroenteritis)

[2] https://treasury.gov.au/sites/default/files/2023-08/p2023-435150-fs.pdf

- increased energy demand, e.g. greater demand for air conditioning; stress on energy supply infrastructure;
- increased demand for water, e.g. human consumption, cooling in power stations, and impact on water quality
- evaporative cooling in homes and offices;
- infrastructure stress: buildings, roads, rail and other infrastructure;
- shifts in tourism preferences due to higher temperatures; and
- increased risks for sporting and outdoor recreation activities

Considering the potential effects of heatwaves on people, infrastructure and the pressure they can have on the National Health System, the Bureau of Meteorology (BoM) in Australia developed a National Heatwave Framework (Meteorology of Australia, 2022) to provide the foundation for a consistent approach to heat health and heatwave warnings across Australian states and territories. This Framework aims to align the approaches to heatwave warnings taken by the Commonwealth, the States and territory governments. States and territories have different portfolio responsibilities, and *each jurisdiction* uses its own metrics, warnings thresholds, nomenclature and response processes (Meteorology of Australia, 2022).

The National Meteorological Service in Australia, BoM, uses the *Excess Heat Factor* (EHF) as part of the Australia heatwave monitoring and forecasting system. This index combines a comparison of the average temperature for a 3-day period with what would be considered hot at that location, and the observed temperatures at that location over the past 30 days (Meteorology of Australia, 2022). Using this index, BoM classifies heatwaves by their intensity. Low-intensity heatwaves are frequent during summer, however there is a low risk as most people can cope during these heatwaves. Severe heatwaves, are less frequent, and they are likely to be more challenging for vulnerable people including older people and those with medical conditions. Extreme heatwaves are rare but, are a problem for people who don't take precautions to keep cool – even for healthy people. This climate service is updated daily and is publicly available at the BoM website [3]. With each daily update, the system provides 3 overlapping 3-day forecasts (e.g., on Mondays, it provides the Monday-to-Wednesday, Tuesday-to-Thursday, and Wednesday-to-Friday forecasts; and so on for each other day of the week).

At the state level, the State of South Australia, following the national mandate, developed its own Extreme Heatwave Strategy in 2009 (Akompab et al., 2013), updating it regularly based on the lessons learned from extreme heat events (Branch, 2024). This Strategy, designed by the Disaster Management Branch and the South Australia Health Department, outlines a series of guiding principles with the aim to reduce the risk of harmful effects of extreme heat and heatwave on the health of the South Australian community and reduce the impact of the associated workload increase, surge workload and avoid the collapse of the health system in the state.

As part of the Strategy, the BoM EHF forecast is translated by the South Australia State Emergency Service (SASES) into daily bulletins with a 3-day EHF forecast per health district in South Australia (only one 3-day forecast in this case). This bulletin also contains information regarding actions to be taken per type of warnings and it is sent to Local Health Networks (LHN), Aboriginal communities, age-care service providers (public and private), transportation and communication agencies, etc.- as required by the level of warning, including general advice and information of interest for the general public. These institutions then tailor the advice to their target audience. For the case of severe and extreme heatwaves, SASES issues additional bulletins with separate warning messages for each area.

Figure 4.3 shows the CSE model exhibiting three climate services. The first one is the Excess Heat Forecast (EHF) system, issued by BoM, that predicts EHF for the State based on 3 categories: low intensity, severe intensity and extreme intensity.

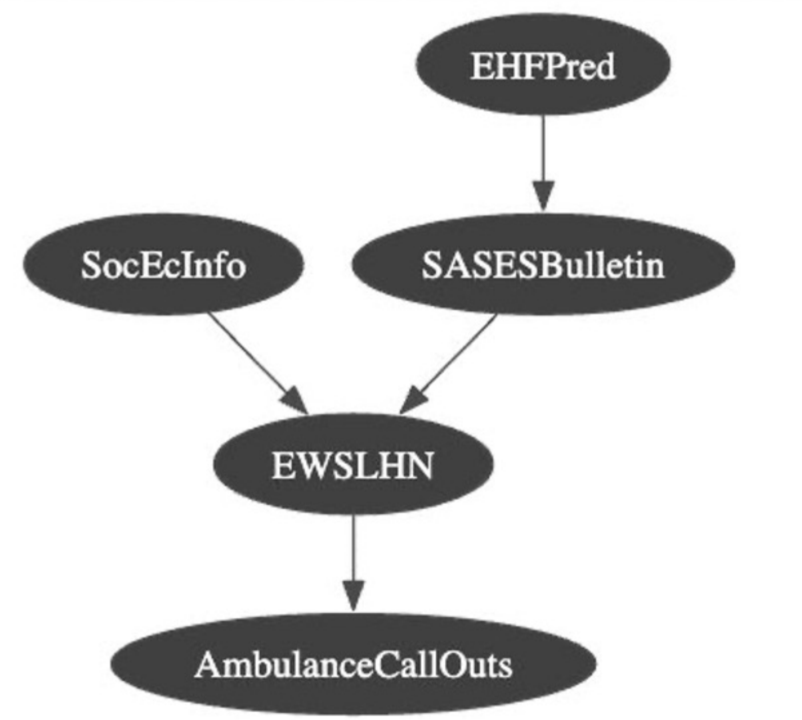
[3] http://www.bom.gov.au/australia/heatwave/

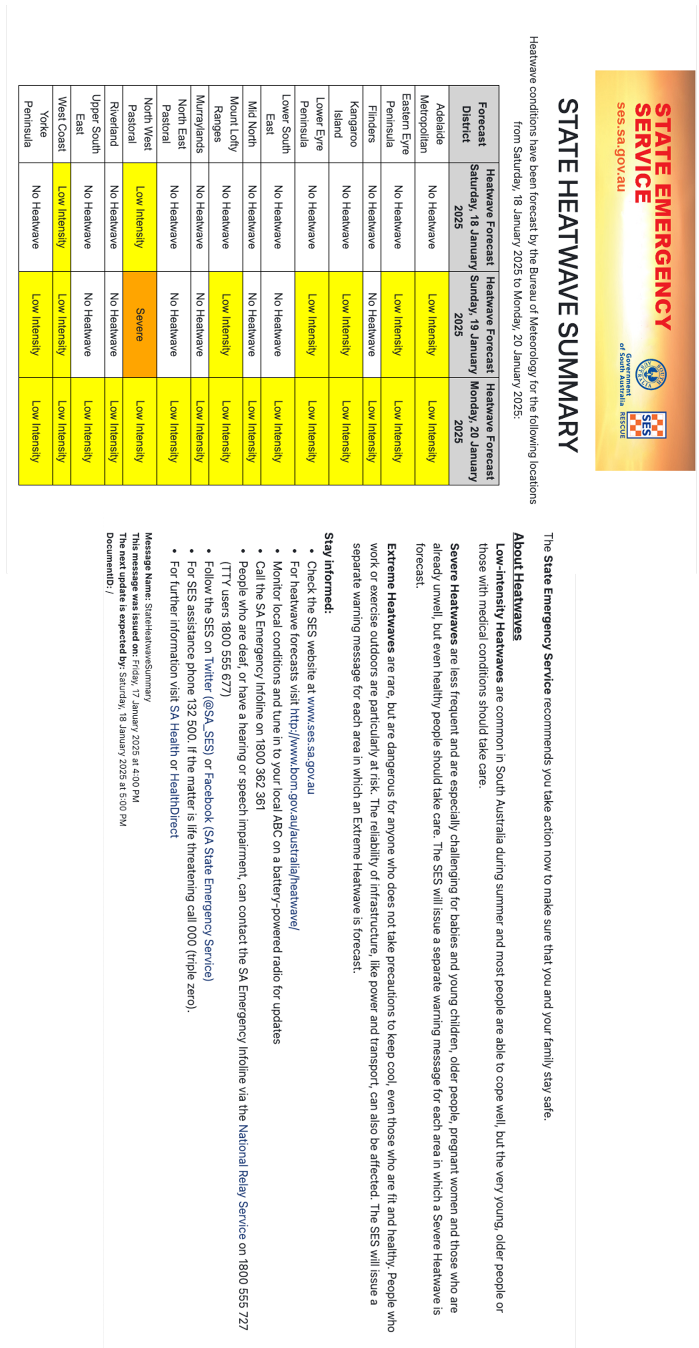
The second climate service is the SASES Heatwave Bulletin, which directly serves 10 Local Health Network (LHN) areas. It has 4 categories: no heatwave (which is not directlt included in this case study as it does not trigger any *additional* action and has no *extra* impact on the business-as-usual ambulance call-outs), and the low-intensity, severe and extreme categories. The SASES Bulletin and socio-economic information (SocEcInfo in Figure 4.3) is then used by the LHN to establish an action plan based on individual early warning system for each one of them. The EWS for the LHN areas can then support the organization of the ambulance call-outs that are triggered by the heat wave.

For the South Australia health system, an increase in temperature, together with the intensity and frequency of extreme weather and associated disasters, can impact ambulance call-outs and hospital emergency department presentation and/or admission profiles. It can also place a substantial burden upon the health system, in terms of increased number of people in care, workforce capacity and capability, as well as the cost to infrastructure and the overall state economy (Branch, 2024). In particular, the South Australia Government is concerned of the impact of heatwave in the Public Health System through an increase on poor health outcomes for vulnerable people (eg. cardiovascular, renal, and respiratory conditions, as well as mental health), those living in socio-economically disadvantaged situation and Aboriginal and Torres Strait Islander. These vulnerable communities are compromised by exposure to hotter conditions, including higher risk of death; and an increase in heat related illness, with no respite from heat with both warmer days and nights (Branch, 2024).

Research shows that a reliable indicator in the surveillance of heatwave impacts to the health system is ambulance call outs. This is because not all call outs result in a hospital admission, so call out data gives a more accurate and consistent picture of emergency health service utilization including both in the community (call out but no transportation) and in the health system (if the person is taken to hospital) (Williams et al., 2018).There are several studies that suggest that ambulance call-outs

Figure 4.3: A simplified representation of the CSE model of the Heatwave Strategy in South Australia. It includes three climate services: the Extreme Heat Factor forecast from BoM (node: EHFPred), the SASES bulletin (node: SASESBulletin) communicating the heat warning, and the Early Warning System for the 10 targeted Local Health Network areas (node: EWSLHN), which uses continuously updated socio-economic information (node: SocEcInfo) from these areas. A climate service ecosystem approach (based on Dynamical Bayesian Network Theory) has been implemented here to analyze the the impact of ambulance call outs as a stressor of the South Australia Health System.





STATE EMERGENCY SERVICE
ses.sa.gov.au

STATE HEATWAVE SUMMARY

Heatwave conditions have been forecast by the Bureau of Meteorology for the following locations from Saturday, 18 January 2025 to Monday, 20 January 2025:

Forecast District	Heatwave Forecast Saturday, 18 January 2025	Heatwave Forecast Sunday, 19 January 2025	Heatwave Forecast Monday, 20 January 2025
Adelaide Metropolitan	No Heatwave	Low Intensity	Low Intensity
Eastern Eyre Peninsula	No Heatwave	Low Intensity	Low Intensity
Flinders	No Heatwave	No Heatwave	Low Intensity
Kangaroo Island	No Heatwave	Low Intensity	Low Intensity
Lower Eyre Peninsula	No Heatwave	Low Intensity	Low Intensity
Lower South East	No Heatwave	No Heatwave	Low Intensity
Mid North	No Heatwave	No Heatwave	Low Intensity
Mount Lofty Ranges	No Heatwave	Low Intensity	Low Intensity
Murraylands	No Heatwave	No Heatwave	Low Intensity
North East Pastoral	No Heatwave	No Heatwave	Low Intensity
North West Pastoral	Low Intensity	Severe	Low Intensity
Riverland	No Heatwave	No Heatwave	Low Intensity
Upper South East	No Heatwave	No Heatwave	Low Intensity
West Coast	Low Intensity	Low Intensity	Low Intensity
Yorke Peninsula	No Heatwave	Low Intensity	Low Intensity

The **State Emergency Service** recommends you take action now to make sure that you and your family stay safe.

About Heatwaves

Low-intensity Heatwaves are common in South Australia during summer and most people are able to cope well, but the very young, older people or those with medical conditions should take care.

Severe Heatwaves are less frequent and are especially challenging for babies and young children, older people, pregnant women and those who are already unwell, but even healthy people should take care. The SES will issue a separate warning message for each area in which a Severe Heatwave is forecast.

Extreme Heatwaves are rare, but are dangerous for anyone who does not take precautions to keep cool, even those who are fit and healthy. People who work or exercise outdoors are particularly at risk. The reliability of infrastructure, like power and transport, can also be affected. The SES will issue a separate warning message for each area in which an Extreme Heatwave is forecast.

Stay informed:

- Check the SES website at www.ses.sa.gov.au
- For heatwave forecasts visit http://www.bom.gov.au/australia/heatwave/
- Monitor local conditions and tune in to your local ABC on a battery-powered radio for updates
- Call the SA Emergency Infoline on 1800 362 361
- People who are deaf, or have a hearing or speech impairment, can contact the SA Emergency Infoline via the National Relay Service on 1800 555 727 (TTY users 1800 555 677)
- Follow the SES on Twitter (@SA_SES) or Facebook (SA State Emergency Service)
- For SES assistance phone 132 500. If the matter is life threatening call 000 (triple zero).
- For further information visit SA Health or HealthDirect

Message Name: StateHeatwaveSummary
This message was issued on: Friday, 17 January 2025 at 4:00 PM
The next update is expected by: Saturday, 18 January 2025 at 5:00 PM
DocumentID: /

Figure 4.4: Bulletin with heatwave information developed by the South Australia State Emergency Service, SASES, using the Excess Heat Factor (EHF) forecast issued by the Bureau of Meteorology of Australia. The forecast produced by the Bureau is translated and communicated for each district in South Australia. This bulletin is updated on a daily basis and the climate information is shared among the other institutions participating in the South Australia Health Extreme Heat and Heatwave Strategy and the associated CSE.

are likely to increase during a heatwave in Australia (Oberai et al., 2024). Making it is necessary to optimize the planning to prepare the healthcare system to be able to cope with this situation and avoid a collapse in the ambulance service.

The demographic distribution of the population is going to have a clear effect on the number of ambulances call-outs during a heatwave. In the case of South Australia, over 70 percent of the population live in the Greater Adelaide area, alongside the coast, in the Adelaide metropolitan area, where the heat island effect retains more heat, and thus impacts more people (McGeehin and Mirabelli, 2001).

Apart from demographic data, the vulnerability of the community and socio-economic status (the SocEcInfo node) also play a relevant role on the number and distribution of ambulances call-outs. For example, the Mid North and North of the state regions have lower socio-economic statues (Statistics, 2021), that can be associated with lower health status and limited access to air conditioning (Jones and Tonts, 2003), which can increase the ambulance call-outs during a heatwave. It has also been suggested that better access to Hospitals and Emergency Departments can also have an impact on the number of ambulance call-outs (Williams et al., 2018). Regions with lower access to primary care services are more likely to use the outpatient services from hospital facilities more often than those with a more accessible primary health care services (Eckert et al., 2004).

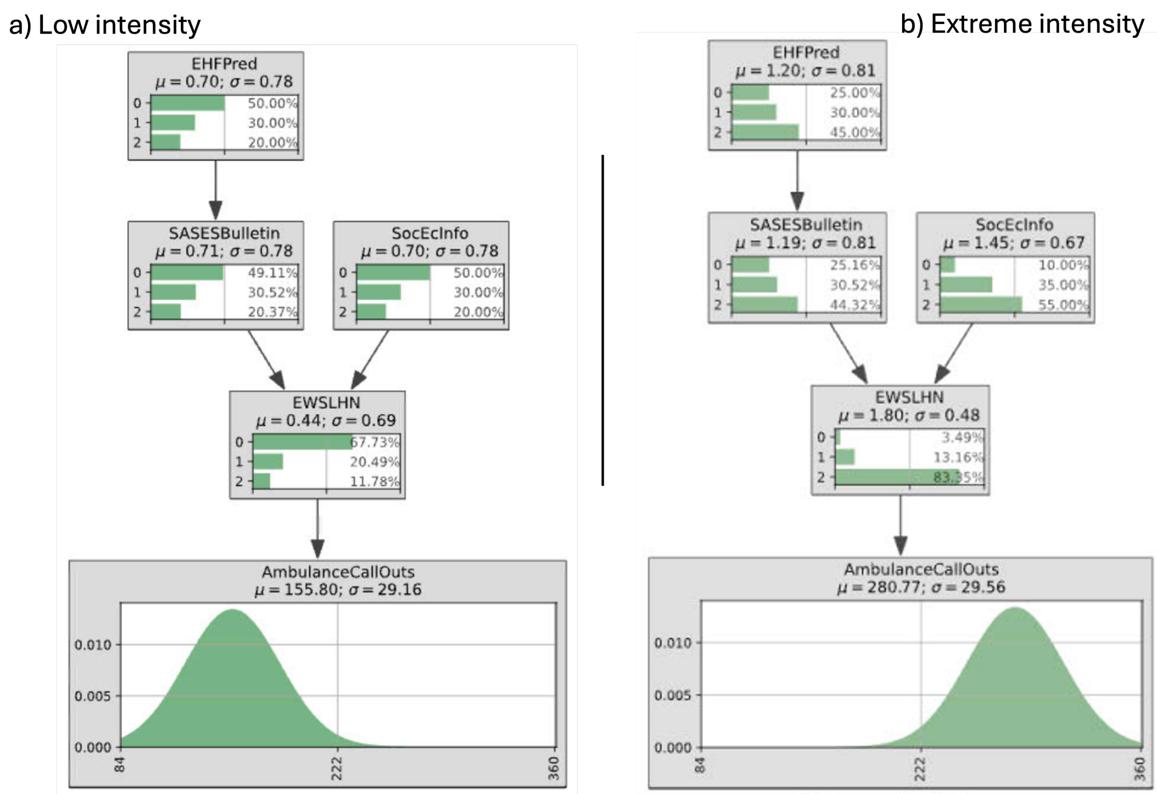
The results of the Dynamical Bayesian Network analysis are summarized in Figure 4.5, considering two contrasting cases. The low intensity scenario (Figure 4.5a) is defined here by the EHF forecast system indicating a 50 percent probability of occurrence of a low intensity forecast (category 0), a 30 percent probability of occurrence of a severe heatwaves (category 1) and a 20 percent probability of occurrence of an extreme heatwave (category 2). This forecast system feeds into the SASES Bulletin, indicating the occurrence of a low intensity heat wave (category 0) with a probability of 49 percent, a severe heatwave (category 1) with a 31 percent probability of occurrence, and an extreme heatwave (category 2) with a 20 percent probability of occurrence. The SocEcInfor indicates having 50 percent of the population having suitable or resilient conditions (category 0) to deal with the heatwave, 30 percent of the population in a medium level of vulnerability (category 1), and 20 percent of the population living under high-vulnerability conditions. The SocEcInfo node represent a vulnerability index that encompasses health status, population distribution and access to primary care and other health facilities based on indexes like the ARIA+ (Accessibility/Remoteness Index plus) [4].

The SASES Bulletin and the SocEcoInfo feeds into an EWS for LHNs that then influence the distribution of the ambulance call-out. In this scenario, a low intensity heatwave in combination with a high vulnerability environment, indicates an average of about 156 ambulance call-outs a day with a standard deviation of 30 call outs. In contrast, in the extreme heatwave scenario analyzed, the expected number of ambulance call-outs is around 280 per day (also with a standard deviation of 30 calls). Given a threshold of 250 ambulance calls per day as the critical threshold above which the system starts to be heavily stressed, the DBN analysis can easily provide the probability of stressing the ambulance system by simply computing the probability of exceeding the critical threshold. As reported by Nitschke and Tucker (2009), these values are within the range of actual ambulance call-outs reported during past heatwaves events (see Table 2 in Nitschke and Tucker (2009)).

The approach suggested in this PhD dissertation can support the preparedness, planning and capacity building for the ambulance services in South Australia and in similar scenarios elsewhere. Additional work needs to be done in relation to the individual and community awareness as a joint effort to avoid the saturation of the health system during a heatwave.

[4] https://www.abs.gov.au/statistics/standards/australian-statistical-geography-standard-asgs-edition-3/jul2021-jun2026/remoteness-structure/remoteness-areas

Figure 4.5: Example of the use of DBN to assess expected number of ambulance call-outs in a heatwave situation (node: EHFPred) under (a) a low intensity heatwave and low vulnerability level, and (b) an extreme heatwave and high vulnerability, related to a CSE involving an Early Warning System for Local Health Networks (node: EWSLHN) that uses socio-economic information (node: SocEcInfo) and climate information (node: SASESBulletin), as indicated by the arrows. The expected number of ambulance call-outs is defined in terms of the probability density function seen in the final node (see horizontal axis for the minimum, median and maximum expected callouts per day), while each of the other nodes exhibit probabilities (the percentages indicated in each box) of low, severe and extreme categories, represented by 0, 1 and 2 in the vertical axis, respectively. For details, see the main text.



4.4 Discussion

By design, the same methodology is applied to both case studies. The Bayesian Network Theory aims to infer probabilities under changing conditions withing the network. These changing conditions can be driven by changes induced by climate conditions, programs, policies, budgets, institutional changes or any other external interventions that impact the CSE. An additional value of the Bayesian Network Theory, versus other potential pathways to quantitatively asses CSEs, is the possibility to obtain a full probability distribution function associated to the changes in the demand of the CSE. Section 3.3 provides further details on the mathematical description of the methodology.

It is important to emphasize that BNA does not offer uniform metrics to compare different sets of CSE. For example, it will not be possible to use BNA to compare the Guatemala and the South Australia case studies in terms of indexes or metrics. However, DNA allows to compare CSEs that tackle similar demands and present similar contexts. For example, DBN can be used to compare the impact of different programs or projects or actions in Early Warning System CS, like the one in Guatemala, or to assess the impact of CS by implementing what-if-scenario analysis, like in the example in South Australia.

In the first case study, the demand of the CSE in Guatemala responds to the needs to provide anticipatory actions to alleviate the hunger season in the near future (less than 3 months). The seasonal precipitation forecast acts as a trigger to identify which actions are going to be implemented in the target area, and what is the cost associated to these actions.

By offering a full distribution function of the associated costs to the action plan for each climate forecast, decision makers can have information about the full range of possible costs and their probabilities,including the mean and the extreme values, and not only one particular value. This flexible format provides more information and level of uncertainty for each possible outcome. Thus, CSE analysis also becomes a tool to assess the risks of exceeding particular thresholds of interest for the decision makers and to formulate different intervention scenarios in a consistent, often comparable way. The outcome of the CSE analysis also allows for the comparison of different actions or programs and the selection of the most viable or efficient solution based on the available resources.

In the second case study, the demand of the CSE in the state of South Australia aims to avoid the saturation of the State Health System in the event of a heatwave, by using the number of ambulance call-outs as a proxy. The federal EHF forecast triggers a state-level warning bulletin that fills into the EWS of the LHN. The application of DBN in this particular CSE, allow to assess different scenarios of heatwave levels that, in combination with socio-economic information, offer a vision on the number of ambulance call-outs per day. Similarly, in this case, by offering a full distribution function of the number of ambulance call-outs decision-makers at a state level can obtain the probability of the full range of call-outs, but also the probability of having a stress Health system given a particular threshold.

Moreover, the causal assumptions that can be inferred from Bayesian Network Analysis identify relationships that remain invariant when external conditions change, allowing for the assessment of these changes, predictions of plausible scenarios and evaluation of counter-factual and testable scenarios (Pearl, 2009). Given the non-stationary characteristic of the CSE, driven by either changes of climate variable outputs or a policy or program intervention, causal networks are particularly useful in order to assess the impact of these changes in the network.

The conditional characteristic of the Bayesian Network Theory allows for the application of the storyline approach to CSEs. If there are probabilistic processes on the path towards the outcome node, or if a probabilistic prior is set as a Markovian parent, the resulting outcome from the causal network also becomes probabilistic, merging probabilities within a deterministic storyline approach (e.g. Kunimitsu et al., 2023). The storyline approach allows to assess the overall consequences of these changes and how they impact the CSE through different transmission pathways.

4.5 Summary

Concrete examples, context and a discussion was presented on the benefits of using the CSE approach and the Bayesian methodology to real-world Early Warning Systems. Given the conditional probability at the core of the Bayesian Network Theory, it is possible to assess different probabilistic scenarios of our EWS once we know a change in one of our prior probability (whether it comes from a change in climate variables, political or socioeconomic environment or budget constraints). Particularly interesting for EWS is the use of DBN, as it allows to update the CSE with time-series dependent (e.g. monitoring and forecast information) and predict the future behavior of the CSE, or even use this framework for the analysis of what-if scenarios.

Part V

Conclusions

Chapter 5

Final remarks, challenges and future areas of work

In the past 20 years, the climate services community has proliferated and evolved developing a wide and complex arena. There are a lot of challenges and barriers that has prevented the uptake of climate services for adaptation. Some authors argue that the focus on developing climate services for long-term adaptation purposes, have left shorter terms (subseasonal to interannual) overlooked, restraining the potential of climate services (Nissan et al., 2019), and the capacity of the society to adapt to a rapidly changing climate. Others blame the poor understanding of scalability (Guentchev et al., 2023) and some others the lack of system thinking (Woltering et al., 2019). Part of this expansion of climate services resembles Rostow's *Stages of Economic Growth* (Rostow, 1959). According to this theory of economic growth, there are five stages stages into the path of (economic) growth and development: 1) traditional society, 2) preconditions to take-off, 3) take-off, 4) drive to maturity and 5) age of high mass consumption. Following these ideas as a parallel, we can apply this theory to the arena of climate services and the evaluate what is needed in order to growth the field. For the sake of clarity, a brief description of each stage, in the context of climate services, is presented in the next paragraphs.

A traditional society of climate services would be the one that offers very limited sectoral applications (Rostow's *production functions*), and thus has a ceiling on the number of outputs or services, e.g. mainly focused on observations and/or weather and climate forecasts. In this stage, the potentialities of climate services are not available nor applied by the general society.

The *preconditions to take-off* stage shows new climate services and new forecast systems. There is also an increase on the modernization of products and services, but it still shows a low productivity and low mass-consumption of climate services. In the *take-off* stage, technological advances promotes growth of climate services as the normal condition. New sectors of climate services, institutions, businesses and techniques proliferate in this stage.

The *drive to maturity* stage is defined by a need of sustainability, efficiency and it depends on the economical and political priorities, rather than technological or institutional ones. There are new industries and improved technology, that allows the sphere of climate services to move beyond the original services and sectors. The *age of mass-consumption* is defined by the sovereignty of the demand and users through the loyalty of consumers of climate services. It would offer significantly higher socioeconomic impacts.

The current global state of climate services can be identified as in a *preconditions take-off* stage, although at a regional or local stages the landscape of the stages varies and is more diverse. While the stage of development can vary depending on the country and the sector of interest, at a global scale there is an increase in the rate of productive investment and an emergence of a political, economical, social and institutional frameworks to exploit the growth of the field. The climate services field has advanced well beyond the experiment and rudimentary stage of the *traditional society* and new experiments, demonstrations and pilots are used to try new approaches to climate services.

Institutional emphasis through efforts like standardization of climate services and harmonization of climate data and information is shaping the environment to increase the uptake of climate services, intending to bring-in new sectors and users into the field and ensuring equity in the field. Efforts to increase the skill of the existing (and new timescales) forecasts, and to bridge the existing gaps, challenges and barriers in the field are also intended to satisfy the existing and future demands for climate services. This "revolution", in combination with the climate crisis the world is facing, and the financial constrains we leave in, makes it urgent to integrate efforts within the climate services sphere, developing CSEs, to increase the uptake, to promote the democratization and sustainability of climate services, to seek a higher efficiency and distribution of resources, while being able to satisfy the needs of the most vulnerable population and a rising demand of climate justice.

Despite the benefits of CSEs identified in previous chapters of this PhD thesis, like the orchestration of resources, the value and resilience increase or the uptake of climate services, there are also risks associated to any interconnected network, and thus, inherited in a CSE. Systemic risks represent the possibility of having interdependent failures in our network (Helbing, 2013). For example, a non-cooperative behavior among the institutions that form the CSE, can be the cause of fundamental changes in CSEs limiting its benefits. Looking at the current political scene, more often than not, ideology plays a significant role on the development of climate services within and outside the network . For example, the U.S withdrawal from the Paris agreement under the Trump administration surely impacts the national US policy, but it also places a burden in other countries where the withdraw implies a reduction of climate finance assistance. Additionally, cascade effects driven by a strong interdependency among institutions or climate services can result in large vulnerability to perturbations in CSE with strong correlations (Helbing, 2013).

It is important to be aware of these risks and limitations when planning CSEs. Literature on network systems suggests different possibilities to confront these risks and to make the network more resilience to (negative) perturbations. The first measure is to ensure consistent feedback mechanisms from users to avoid suboptimal and sub-efficient equilibrium (Helbing, 2012). Another important principle is to have at least one backup system that runs in parallel to the main system (Axelrod and Cohen, 2008). Lastly, working with reduced CSE, following the example from ecological systems and pursuing sparser networks (Haldane and May, 2011), can help to reduce the contagious effects of the perturbation in the CSE.

Another constraint when using the CSE approach can be the limited understanding of the relationships between the climate services, the insitutions and actors. Not having a clear interpretation on which are the relevant nodes and how the information flows between them can result in an overestimation or underestimation of the analysis of the CSE. Additionally, the DBN methodology described in this PhD manuscript does not allow to compare nor rank CSEs with different demand as there arent established metrics or indexes associated to them.

Chapter 6

Conclusions

The main purpose of climate services is to respond to the demands of society by supporting decision-making processes to adapt and mitigate the effects of a changing climate. The value of climate services resides on the relevance, accessibility, usability, precision, timelines, accuracy and reliability of that respond.

However, it is still common to see climate services being developed with a focus on the supply-side and the academic perspective, rather than on the needs and requirements of the communities. These perspectives bring important limitations to the value of the services and the tools developed. For example, it is fairly common for climate services to be of no further use after their conception-to-deployment phase because of a limited (or wrong) understanding of the demand (making the climate service unfit for purpose), or because the deployments are requested by donors and projects to happen in a specific time-frame, rather than responding to the pace of the final users. These, and others, supply-side perspectives eventually bring negative return-to-investments in projects, as they leave unfit (and thus unused) climate services, they erode the trust from users but also from the general public (and potential new users), increasing the chances of failing for adaptation and mitigation strategies (and thus the intrinsic value of the climate service itself) and, more importantly, leaving communities' needs and demands unheard and invisibilized.

The characteristics of climate services vary depending on several factors, like the existing demand, the scale, the field, the location and the budget available, among others. However, they are likely to be influenced by the interactions with many other climate services, institutions and/or agents in that same (or different) scale, field, and location. CSEs bring the concept of biological ecosystems to the climate services arena, serving as a way to assess how climate services interact among each other, developing an opportunity for optimization of resources, increasing the resilience of society and the value of the climate services and going beyond understanding climate services in isolation.

The concept of CSE brings a novel perspective of understanding the realm of climate services in an integrative and unifying approach to optimize resources and increase resilience, in a context of limited resources, changing needs and constant shocks. While there might be other perspectives to analyze climate services ecosystems (e.g. a governance point of view), this PhD dissertation presents the perspective of optimization of resources and value assessment in a cohesive way, understanding the impact of climate services in society from an connected system perspective rather than silos, offering quantitative ways to identify and analyze these ecosystems.

By using a "systems thinking" perspective to show the connections between different climate services (including institutions, products and information flows), different actors can recognize how their actions and contributions interact with different parts of the ecosystem and influence the overall outcomes and value. This transparency can enhance trust and accountability and inform adaptation, mitigation and risk-management strategies proactively. CSE also supports a more efficient orchestration of resources by identifying key nodes, feedback mechanisms, bottlenecks and opportunities within the ecosystem. This can aid to make informed decisions about resource allocation, optimization and efficiency of the CSE. CSEs are dynamic and adaptable to changes and need to have redundancy and backup mechanisms that ensure service continuity even in the case of negative perturbations.

The use of DBN to assess CSE brings a novelty to the current network analysis. DBN allows to infer the causal relationship between the elements of the CSE model and quantify different scenarios based on probability changes in the network (driven by changes to programs, policies, budget changes, institutional changes, climate events or other external interventions). Additionally, the use of probability outcomes, allows to quantify the impacts of these changes throughout the entire probability distribution function.

Part VI

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