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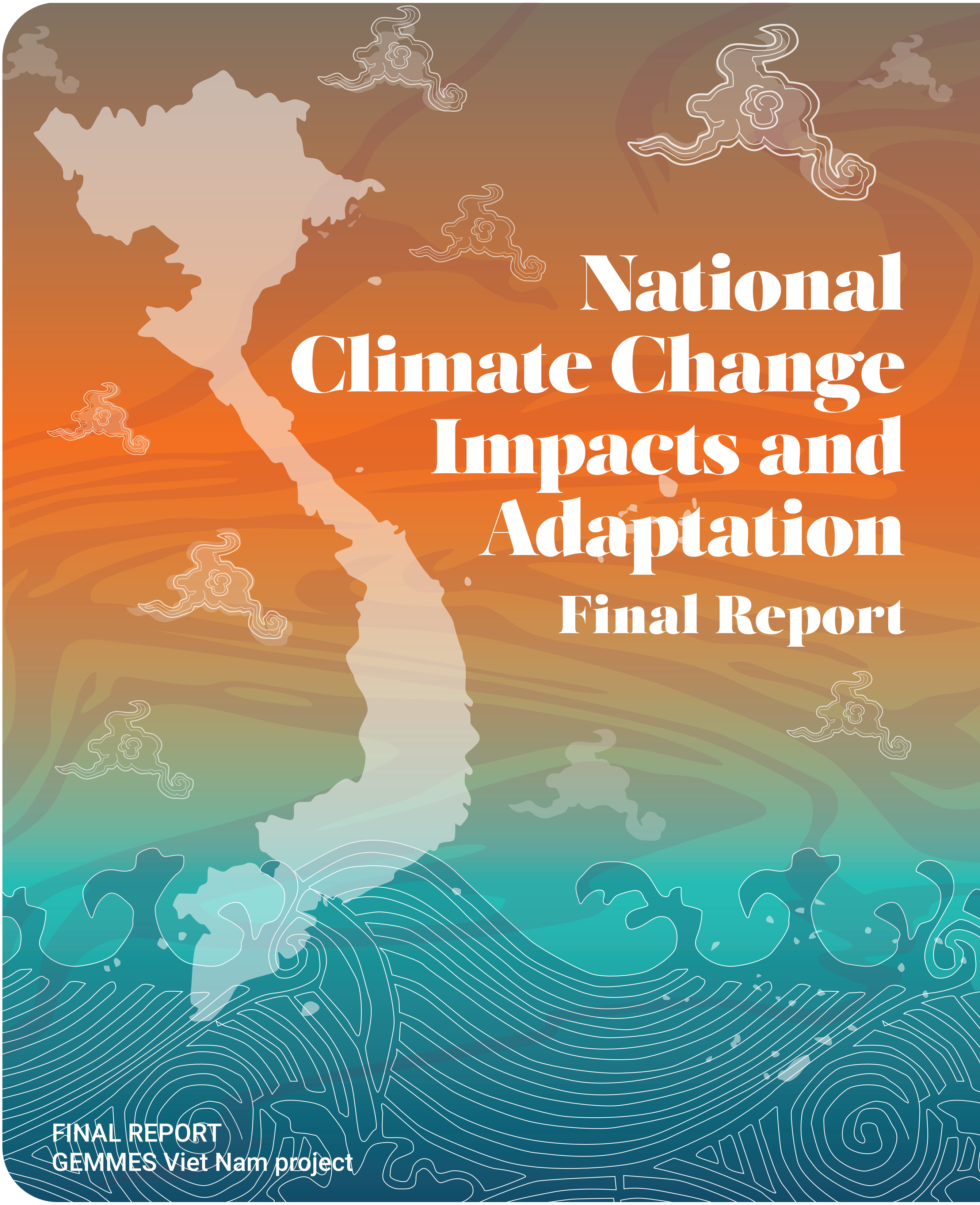

National Climate Change Impacts and Adaptation

Final Report

FINAL REPORT
GEMMES Viet Nam project

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PREFACE

Within the framework of the study on the socio-economic impacts of climate change in Viet Nam and strategies for adaptation (GEMMES Viet Nam), French and Vietnamese researchers have produced this Report which defines different socio-economic scenarios for Viet Nam by 2050 in the context of climate change.

This Report proposes relevant solutions to support a climate-resilient economic development pathway for Viet Nam. It clearly confirms the potential significant impacts of climate change on Viet Nam if global temperatures were to increase by 1,5°, 2° or even 3°C above the preindustrial period. In line with the commitments of Viet Nam at the COP26, the report confirms the urgent necessity to switch from a fossil-driven economy to an efficient low-carbon one. The report investigates, with different scenarios, Viet Nam's potential for a green transition, with a net-zero target, while also contributing to the sustainable development goals (SDG) of the country.

AFD has actively worked in collaboration with the Department of Climate Change in the implementation of the GEMMES Viet Nam project. Beyond this project, both parties wish to continue deepening their fruitful collaboration in order to contribute to the commitments of the international community to respond to climate change, with net-zero emission targets by 2050.

We would like to thank French researchers for their close collaboration with Vietnamese researchers to produce this specific report, and more generally in the implementation of the GEMMES project. Given the elements provided by this Macroeconomic Report, we hope that this reference document will be useful to researchers, policy makers and sectoral stakeholders.

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LỜI NÓI ĐẦU

Trong khuôn khổ hợp tác chương trình nghiên cứu tác động kinh tế - xã hội của biến đổi khí hậu ở Việt Nam và chiến lược thích ứng với biến đổi khí hậu (GEMMES), các nhà khoa học Pháp và Việt Nam đã xây dựng Báo cáo vĩ mô nhằm xác định các kịch bản kinh tế - xã hội của Việt Nam trong bối cảnh biến đổi khí hậu từ nay đến 2050.

Báo cáo đề xuất các giải pháp phát triển kinh tế, xã hội gắn với chống chịu tác động của biến đổi khí hậu ở Việt Nam. Báo cáo cũng mô tả về mức độ nghiêm trọng của những tác động mà biến đổi khí hậu có thể gây ra cho Việt Nam nếu nhiệt độ toàn cầu tăng lên 1,5°C, hoặc 2° hoặc thậm chí 3°C so với thời kỳ tiền công nghiệp. Gắn với những cam kết của Việt Nam tại COP26, báo cáo khẳng định tính cấp thiết phải chuyển đổi từ một nền kinh tế dựa vào nhiên liệu hóa thạch sang một nền kinh tế hiệu quả hơn với mức phát thải các-bon thấp.

Báo cáo nghiên cứu tiềm năng dưới những kịch bản khác nhau về chuyển đổi xanh của Việt Nam để đạt mục tiêu đạt phát thải ròng bằng «0», đồng thời là nền tảng để đạt được những mục tiêu phát triển bền vững của Việt Nam.

AFD đã tích cực phối hợp với Cục Biến đổi khí hậu trong suốt quá trình triển khai thực hiện chương trình GEMMES Việt Nam. Không chỉ giới hạn ở báo cáo chuyên biệt này, hai bên sẽ tiếp tục phát triển các hoạt động hợp tác mới và đi vào chiều sâu trong bối cảnh Việt Nam đang nỗ lực thực hiện những cam kết cùng cộng đồng quốc tế ứng phó với biến đổi khí hậu, đưa mức phát thải ròng về «0» vào năm 2050.

Chúng tôi trân trọng cảm ơn các nhà khoa học Pháp đã phối hợp chặt chẽ với các nhà khoa học Việt Nam trong quá trình xây dựng báo cáo nói riêng và trong triển khai thực hiện chương trình GEMMES nói chung. Với những nội dung được nêu trong Báo cáo vĩ mô hy vọng sẽ là tài liệu tham khảo hữu ích cho các nhà nghiên cứu, hoạch định chính sách và các nhà quản lý trong các lĩnh vực có liên quan.

Tiến sỹ Tăng Thế Cường
Cục trưởng
Cục Biến đổi Khí hậu
Bộ Tài nguyên và Môi trường Việt Nam

Hervé Conan
Giám đốc Quốc Gia
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PRÉFACE

Dans le cadre du programme d'étude sur les impacts socio-économiques du changement climatique au Viet Nam et les stratégies d'adaptation associées (GEMMES Viet Nam), les chercheurs français et vietnamiens ont réalisé ce Rapport qui définit différents scénarios socio-économiques du Viet Nam à l'horizon 2050 dans le contexte du changement climatique.

Ce Rapport propose des solutions pertinentes en appui à une trajectoire de développement économique résilient au changement climatique pour le Viet Nam. Il confirme clairement l'importance des impacts potentiels du changement climatique au Viet Nam si les températures mondiales augmentaient de 1,5°, 2° ou même 3°C par rapport à l'ère préindustrielle. En lien avec les engagements pris par le Viet Nam à la COP26, le rapport confirme la nécessité urgente de passer d'une économie basée sur les énergies fossiles à une économie bas-carbone efficace. Le Rapport étudie, selon différents scénarios, le potentiel de transition verte du Viet Nam, avec l'objectif net zéro, tout en contribuant également aux objectifs de développement durable (ODD) du pays.

L'AFD a activement travaillé en collaboration avec le Département du Changement climatique dans la mise en œuvre du projet GEMMES Viet Nam. Au-delà de ce Rapport spécifique, les deux institutions sont désireuses de continuer à approfondir leur fructueuse collaboration afin de contribuer aux engagements de la communauté internationale pour répondre au changement climatique, avec l'objectif du net-zéro émission en 2050.

Nous tenons à remercier les chercheurs français pour leur collaboration étroite avec les chercheurs vietnamiens dans la réalisation de ce rapport en particulier, et dans la mise en œuvre du projet GEMMES en général. Compte tenu des éléments du Rapport Macro-économique, nous espérons que ce document de référence sera utile pour les chercheurs, les décideurs politiques ainsi que les acteurs des secteurs concernés.

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PREFACE

At COP26, Viet Nam positioned itself at the forefront of an emerging coalition of the willing, opening an era of rapid structural change for the country. Net zero objectives today cover most of the world, including the major developed and emerging economies, as well as many developing nations. The announcement – at COP26 – by Vietnamese Prime Minister Phạm Minh Chính of an ambitious net zero horizon in 2050, came at a strategic moment. The GEMMES Viet Nam COP26 special assessment report has already extensively developed the multiple macro-financial constraints and multi-dimensional vulnerabilities resulting from inevitable climate impacts at the national level.

On the occasion of COP27, this new Climate and Adaptation macroeconomic exposure report marks one of the two final outcomes of the GEMMES Viet Nam project. It also goes a step beyond the COP26 report in several dimensions. On the climate side first, it develops a new set of climate scenarios using the latest CMIP6 global circulation models from the latest IPCC report of 2022, and investigates the full range of climate uncertainties downscaled over Viet Nam.

Second, the report also looks at the industrial and technological opportunities in a "green race" scenario. Viet Nam starts the journey from a difficult position of high-emission intensity compared to the rest of the world, as well as a high exposure to potential climate impacts. But its technological capabilities for green innovation are also quite positive, providing a narrow path towards green industrial development for the country.

Finally, a dynamic assessment of climate impacts as well as adaptation strategies at the macro economic level is provided. Viet Nam's industrial and development strategy in the face of climate change will thus have to navigate between macro-financial constraints, multi-dimensional vulnerabilities due to inevitable impacts, its current dependency on a high-emission path, and its very strong technological perspectives in green industries.

This second final report from the GEMMES Viet Nam project contributes to a preliminary assessment of Viet Nam's climate and adaptation exposures at a decisive time in its alignment with the Paris Agreement.

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LỜI NÓI ĐẦU

Tại COP26, Việt Nam đã tự khẳng định vị trí dẫn đầu trong một liên minh mới xuất hiện, sẵn sàng mở ra một kỷ nguyên đất nước có những thay đổi cơ cấu nhanh chóng. Ngày nay, mục tiêu phát thải ròng bằng không liên quan đến hầu hết thế giới, từ những nền kinh tế phát triển và mới nổi, cũng như nhiều quốc gia đang phát triển. Tuyên bố tại COP26 của Thủ tướng Việt Nam Phạm Minh Chính về một mục tiêu phát thải ròng bằng không vào năm 2050 được đưa ra vào một thời điểm chiến lược. Báo cáo đánh giá đặc biệt COP26 của dự án GEMMES Việt Nam đã đưa ra được các hạn chế tài chính vĩ mô và tính dễ bị tổn thương đa chiều do các tác động khí hậu không thể tránh khỏi ở cấp quốc gia.

Xuất bản cùng thời điểm của COP 27, bản báo cáo mới cập nhật về kinh tế vĩ mô thích ứng và khí hậu là một trong hai kết quả cuối cùng của dự án GEMMES Việt Nam. Nội dung báo cáo COP27 cũng rộng hơn báo cáo COP26 ở nhiều khía cạnh. Về mặt khí hậu, trước tiên, báo cáo đã phát triển một tập hợp các kịch bản khí hậu mới bằng cách sử dụng các mô hình hoàn lưu khí hậu toàn cầu CMIP6 mới nhất từ báo cáo mới nhất của IPCC năm 2022, đồng thời nghiên cứu toàn bộ các yếu tố bất thường về khí hậu ở Việt Nam.

Thứ hai, báo cáo cũng xem xét các cơ hội công nghiệp và công nghệ trong kịch bản "cuộc đua xanh". Việt Nam bắt đầu cuộc đua này từ một vị trí bất lợi do có tần suất phát thải cao so với phần còn lại của thế giới, cũng như phải chịu nhiều tác động tiềm ẩn của khí hậu. Nhưng tiềm năng công nghệ của quốc gia cho đổi mới xanh cũng khá tích cực, tạo ra một khe cửa nhỏ hướng tới phát triển công nghiệp xanh cho đất nước.

Cuối cùng, báo cáo cũng đưa ra một đánh giá năng động về tác động khí hậu cũng như các chiến lược thích ứng ở cấp độ kinh tế vĩ mô. Theo đó, chiến lược phát triển và công nghiệp của Việt Nam đối mặt với biến đổi khí hậu sẽ phải điều hướng giữa các hạn chế tài chính vĩ mô, các yếu tố dễ bị tổn thương nhiều chiều do các tác động không thể tránh khỏi, sự phụ thuộc hiện tại vào lộ trình phát thải cao, và các triển vọng công nghệ mạnh mẽ của đất nước trong lĩnh vực công nghiệp xanh.

Báo cáo cuối cùng thứ hai này từ dự án GEMMES Việt Nam góp phần đánh giá sơ bộ mức độ phơi nhiễm với khí hậu và thích ứng của Việt Nam vào thời điểm quyết định, trong việc thực hiện Thỏa thuận Paris về khí hậu.

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PRÉFACE

Lors de la COP26, le Viet Nam s'est positionné à l'avant-garde d'une coalition émergente de pays volontaires, ouvrant une ère de changements structurels rapides pour le pays. Les objectifs net zéro couvrent aujourd'hui la majeure partie du monde, y compris les principales économies développées et émergentes, ainsi que de nombreuses nations en développement. L'annonce – lors de la COP26 – par le Premier ministre vietnamien Phạm Minh Chính d'un ambitieux horizon net zéro en 2050, est arrivée à un moment stratégique. Le rapport spécial d'évaluation GEMMES Viet Nam COP26 a déjà largement développé les multiples contraintes macro-financières et les vulnérabilités multidimensionnelles résultant des impacts climatiques inévitables au niveau national.

À l'occasion de la COP27, ce nouveau rapport sur l'exposition macroéconomique au climat et à l'adaptation constitue l'un des deux résultats finaux du projet GEMMES Viet Nam. Il va également plus loin que le rapport COP26 à plusieurs égards. Sur le plan climatique, tout d'abord, il élabore une nouvelle série de scénarios climatiques à l'aide des derniers modèles climatiques globaux CMIP6 du dernier rapport du GIEC de 2022, et étudie l'ensemble des incertitudes climatiques à l'échelle du Viet Nam.

Deuxièmement, le rapport examine également les opportunités industrielles et technologiques dans un scénario de «course verte». Le Viet Nam part d'une position difficile, à savoir une intensité en émissions élevée par rapport au reste du monde, ainsi qu'une forte exposition aux impacts climatiques potentiels. Mais ses capacités technologiques en matière d'innovation verte sont également très positives, ce qui ouvre au pays une voie étroite vers le développement industriel vert.

Enfin, une évaluation dynamique des impacts climatiques ainsi que des stratégies d'adaptation au niveau macroéconomique est fournie. La stratégie industrielle et de développement du Viet Nam face au changement climatique devra donc naviguer entre les contraintes macro-financières, les vulnérabilités multidimensionnelles dues aux impacts inévitables, sa dépendance actuelle à l'égard d'une trajectoire à fortes émissions, et ses très fortes perspectives technologiques dans les industries vertes.

Ce deuxième rapport final du projet GEMMES Viet Nam contribue à une évaluation préliminaire des risques climatiques et d'adaptation du Viet Nam à un moment décisif de son alignement sur l'Accord de Paris.

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CONTENT

Part 1

Statistical downscaling and probabilistic projections for climate risk analysis in Viet Nam

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Abstract

The latest downscaling activities in Viet Nam have been mainly based on the dynamical approach for a limited number of Global Climate Models (GCMs) of the Coupled Model Intercomparison Project Phase 3 (CMIP3) and Phase 5 (CMIP5). To date, no attempt to downscale the latest GCMs of the CMIP Phase 6 (CMIP6) has been done in Viet Nam. In this part, we first apply the Bias Corrected Spatial Disaggregation (BCSD) statistical method to downscale the outputs of 31 CMIP5 and 35 CMIP6 GCMs for inland Viet Nam. The new sets of data, including four variables: daily precipitation, daily average, and maximum and minimum temperatures, are at 10-km spatial resolution and respectively called CMIP5-VN and CMIP6-VN. CMIP5-VN and CMIP6-VN cover the historical period of 1980–2005 and 1980–2014, and the future projection period until 2100 with four Representative Concentration Pathways (RCPs; RCP2.6, 4.5, 6.0, and 8.5) and seven Shared Socioeconomic Pathways (SSPs; SSPs 1-1.9, 1-2.6, 2-4.5, 3-7.0, 4-3.4, 4-6.0, and 5-8.5) scenarios, respectively. Then, we establish the joint probability density functions (PDFs) of temperature and precipitation change over the 21st century for every region in Viet Nam using the surrogate/model mixed ensemble (SMME) method. The new SMME data facilitates the assessments of local and regional climate change risks, including tail risks, which are known to have low probability but severe consequences. We recommend the use of these CMIP5-VN, CMIP6-VN, SMME-CMIP5, and SMME-CMIP6 datasets for studies on climate change assessment, as well as into climate change impacts on socio-economic activities in Viet Nam.

Tóm tắt

Các nghiên cứu gần đây nhất về chi tiết hóa các kịch bản khí hậu cho Việt Nam chủ yếu dựa trên phương pháp tiếp cận động lực đối với một số lượng hạn chế các mô hình khí hậu toàn cầu (GCMs) từ Dự án đối sánh mô hình kết hợp giai đoạn 3 (CMIP3) và giai đoạn 5 (CMIP5). Cho đến nay, chưa có nghiên cứu nào về chi tiết hóa các kết quả mô hình toàn cầu mới nhất từ dự án CMIP giai đoạn 6 (CMIP6) được thực hiện tại Việt Nam. Trong phần này, trước tiên chúng tôi áp dụng phương pháp thống kê Hiệu chỉnh sai số và Phân rã không gian (BCSD) để chi tiết hóa đầu ra của 31 mô hình CMIP5 và 35 mô hình CMIP6 cho phần đất liền Việt Nam. Bộ dữ liệu mới, bao gồm bốn biến: lượng mưa ngày, nhiệt độ trung bình, nhiệt độ cực đại và cực tiểu ngày, có độ phân giải không gian 10 km, được gọi tương ứng là CMIP5-VN và CMIP6-VN. CMIP5-VN và CMIP6-VN bao gồm giai đoạn quá khứ 1980–2005 và 1980–2014, và giai đoạn dự tính trong tương lai cho đến năm 2100 với bốn kịch bản đường nồng độ tiêu biểu RCPs (RCP2.6, 4.5, 6.0 và 8.5) và bảy kịch bản kinh tế xã hội chia sẻ SSPs (SSP1-1.9, 1-2.6, 2-4.5, 3-7.0, 4-3.4, 4-6.0 và 5-8.5). Tiếp đó, chúng tôi thiết lập các hàm mật độ xác suất (PDF) của sự thay đổi nhiệt độ và lượng mưa trong thế kỷ 21 cho mọi vùng ở Việt Nam bằng phương pháp SMME (thay thế/ tổ hợp pha trộn có trọng số các mô hình). Bộ dữ liệu SMME mới rất hữu ích cho việc đánh giá các rủi ro biến đổi khí hậu tại địa phương và khu vực, bao gồm cả rủi ro cực đoan vốn có xác suất xuất hiện thấp nhưng hậu quả lại nghiêm trọng. Bộ dữ liệu CMIP5-VN, CMIP6-VN, SMME-CMIP5 và SMME-CMIP6 mới được xây dựng hiện có thể truy cập trực tuyến và miễn phí. Chúng tôi khuyến nghị sử dụng các bộ dữ liệu này cho các nghiên cứu về đánh giá biến đổi khí hậu, cũng như các tác động của biến đổi khí hậu đối với các hoạt động kinh tế - xã hội ở Việt Nam.

Résumé

Les dernières analyses de réduction d'échelle (downscaling) des scénarios climatiques au Viet Nam ont été principalement basées sur l'approche dynamique, pour un nombre limité de modèles climatiques mondiaux (GCM) du projet d'intercomparaison de modèles couplés phase 3 (CMIP3) et phase 5 (CMIP5). À ce jour, aucune tentative de réduction d'échelle des derniers GCMs de la phase 6 du CMIP (CMIP6) n'a été effectuée au Viet Nam. Dans cette partie, nous appliquons d'abord la méthode statistique de correction de biais et de désagrégation spatiale (BCSD) pour réduire l'échelle des sorties de 31 GCMs du CMIP5 et 35 GCMs du CMIP6 pour l'intérieur du Viet Nam. Les nouvelles bases de données, comprenant quatre variables (précipitation quotidienne, température moyenne, maximale et minimale quotidiennes du température), avec une résolution spatiale de 10 km et appelées respectivement CMIP5-VN et CMIP6-VN. CMIP5-VN et CMIP6-VN couvrant la période historique de 1980–2005 et 1980–2014, et la future période de projection jusqu'en 2100 avec quatre voies de concentration représentatives (RCP ; RCP2.6, 4.5, 6.0 et 8.5) et sept voies de socioéconomiques partagées (SSP ; SSP1-1.9, 1-2.6, 2-4.5, 3-7.0, 4-3.4, 4-6.0 et 5-8.5), respectivement. Ensuite, nous établissons les fonctions de densité de probabilité conjointes (PDF) du changement de température et de précipitations au cours du 21e siècle pour chaque région du Viet Nam en utilisant la méthode SMME (surrogate model mixed ensemble). Les nouvelles données SMME facilitent les évaluations des risques locaux et régionaux liés au changement climatique, y compris les risques extrêmes, dont on sait qu'ils ont une faible probabilité mais des conséquences graves. Nous recommandons l'utilisation de ces ensembles de données CMIP5-VN, CMIP6-VN, SMME-CMIP5 et SMME-CMIP6 pour des études sur l'évaluation du changement climatique, ainsi que sur les impacts du changement climatique sur les activités socio-économiques au Viet Nam.

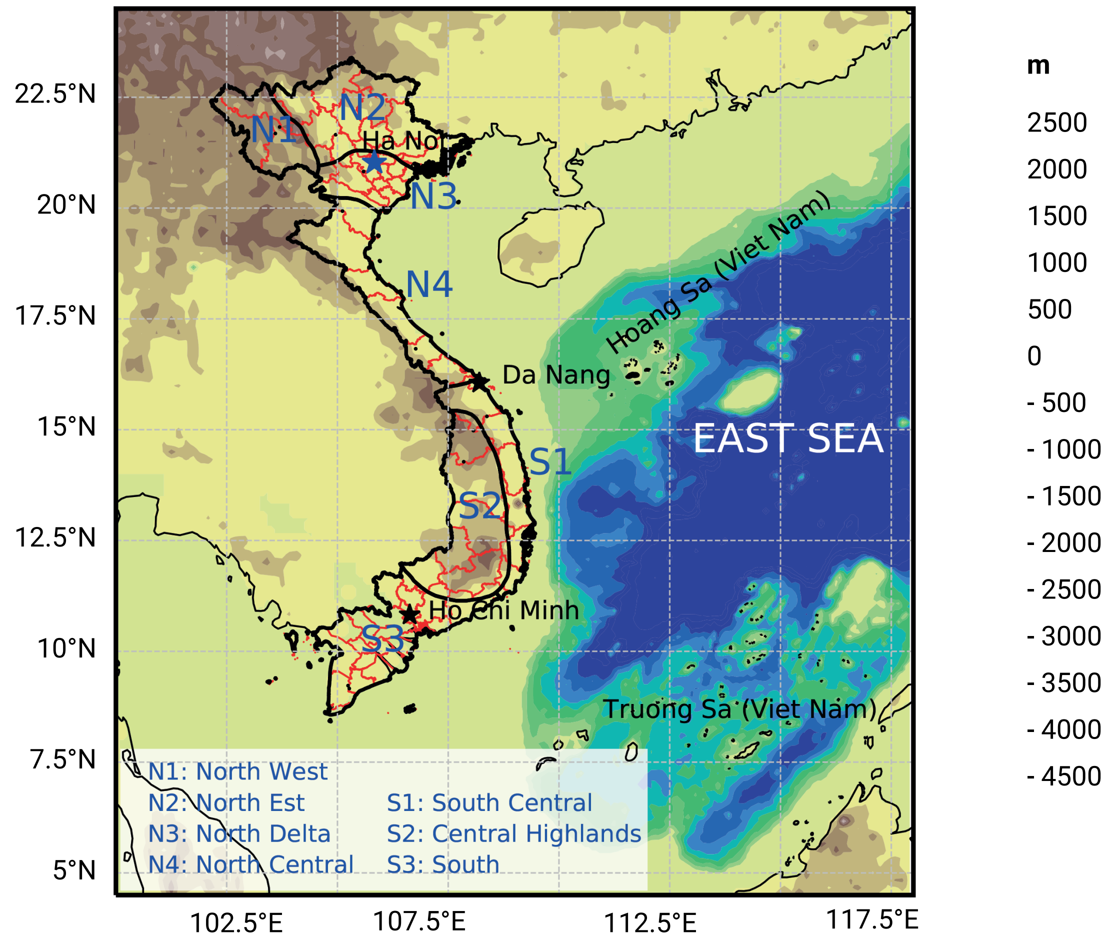
1. Introduction

Located in the tropical region in Southeast Asia, on the eastern side of the Indochina peninsula with a long coastline of about 3,260 km, Viet Nam is among the countries that have been severely impacted by climate change [MONRE, 2016]. Based on specific criteria for radiation, temperature and rainfall, Viet Nam is divided into seven climatic regions [Nguyen & Nguyen, 2004; Phan *et al.*, 2009], including the northwest (denoted as R1), the northeast (denoted as R2), the Red River Delta (denoted as R3), the north central (denoted as R4), the south central (denoted as R5), the central highlands (denoted as R6), and the south region (denoted as R7) [Figure 1.1].

In recent years, the Ministry of Natural Resources and Environment (MONRE) has published several reports on climate change and sea-level rise scenarios for Viet Nam [MONRE, 2009; 2012; 2016; 2021], which provide information on observed and projected trends for climate and sea-level rise in Viet Nam. It is to be noted that building climate change scenarios for the country involves downscaling the output of Global Climate Models (GCMs) for various global greenhouse gas (GHG) scenarios. The MONRE reports published in 2009 and 2012 applied the Special Report on Emission Scenarios (SRES) [Nakicenovic *et al.*, 2000], which were used in the Third and the Fourth Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC) [IPCC, 2001; 2007]. With respect to the latest MONRE reports [MONRE, 2016; 2021], the GHG scenarios applied are the Representative Concentration Pathways (RCPs) [van Vuuren, 2011] that were used in the Fifth Assessment Report of IPCC [IPCC, 2013], while the early reports [MONRE, 2009; 2012] used the statistical approach to downscale the outputs from the Global Climate Models (GCMs) of the Coupled Model Intercomparison Project Phase 3 (CMIP3). The 2012, 2016 and 2021 editions of the report gradually switched to the dynamical approach. However, although it has the advantage of well representing the local-scale feedback and dynamical processes [Seaby *et al.*, 2013; Tangang *et al.*, 2020], dynamical downscaling is an extremely computationally demanding method. Thus, in the 2021 MONRE report, only a limited number of 14 downscaling experiments for temperature and five for rainfall were used, which could limit the range of possible projected climates in the future. It is worth noting that prior to the works conducted within the framework of the GEMMES Viet Nam project, no attempt to downscale the latest CMIP6 GCMs has been done in Viet Nam.

In this chapter, we first present a primary study to develop new high-resolution climate scenarios over Viet Nam from a large number of CMIP5 and CMIP6 GCMs based on a statistical downscaling approach thanks to its advantages of being simple and not requiring huge computer resources. The new datasets, hereinafter referred to as CMIP5-VN and CMIP6-VN, consist of daily near-surface mean temperature (T2m, maximum temperature (Tmax), minimum temperature (Tmin), and rainfall (R). Previous studies indicated the performance of different statistical methods that could be comparable to dynamical downscaling [*e.g.* Salathé, 2003; Widmann, *et al.* 2003; Maurer & Hidalgo, 2008]. Among those methods, Wood *et al.* (2004) stated that the bias correction and spatial disaggregation (BCSD) approach is reliable and effective for downscaling temperature and precipitation data. Thus, the BCSD downscaling method has been used for the present study. For CMIP5, the downscaling has been conducted for

[Figure 1.1]
Topography of Viet Nam and surrounding areas



The seven climatic regions and administrative provincial boundaries of Viet Nam are also displayed.

31 GCMs with four RCPs (RCP2.6, 4.5, 6.0 and 8.5). It should be noted that the latest MONRE reports [MONRE 2016; 2021] have only the projected results from two RCPs (RCP4.5 and RCP8.5) due to the limited number of dynamical downscaling experiments as a result of associated limited computation times. For CMIP6, the downscaling has been conducted for 35 GCMs under different Shared Socioeconomic Pathways (SSPs) scenarios, including the SSP1 (Sustainability), SSP2 (Middle of the Road), SSP3 (Regional Rivalry), SSP4 (Inequality) and SSP5 (Fossil-fueled Development) pathways [Riahi *et al.*, 2017]. Details of the BCSD methodology, as well as the validation and projection results for CMIP5 and CMIP6 ensembles, are presented in Section 1.2.

It would be important to highlight that the projected results from CMIP5, CMIP6 GCMs and their downscaling products are still based on a limited number of model products. Such results and products are an ensemble of opportunities and were not designed for neither capturing the full probability distribution nor considering all the sources of uncertainty. Moreover, GCMs are often known to underestimate the likelihood of extreme climate impacts. There are two major challenges that need to be overcome in the risk assessment of climate change: i) the risk of an undesired event is described by its probability of occurrence and its consequences; and, consequently, ii) assessments of local and regional climate change risks, require the consideration of the entire range of possible probabilities and consequences of future outcomes, including tail risks, which are known to have low probability but severe consequences.

In view of the above, this chapter establishes the joint PDFs of temperature and precipitation change over the 21st century for every region in Viet Nam, using the surrogate/model mixed ensemble (SMME) method [Rasmussen *et al.*, 2016]. SMME is an integrated assessment model that both gives probability weights to GCMs and represents the tail risks that are not captured by them. The different steps to conduct the SMME and associated probabilistic results are presented in Section 1.3 and the Conclusions and key recommendations are outlined in Section 1.4.

2. BCSD downscaling for CMIP5 and CMIP6 GCMs

For reporting purposes, the figures and results presented in this section are extracted or modified from two manuscripts prepared by Tran-Anh *et al.* (2022a) for the CMIP5 downscaling, and Tran-Anh *et al.* (2022b, to be submitted) for the CMIP6 downscaling, under the framework of the present GEMMES project.

2.1 Data prepared for the downscaling

Observed gridded dataset

Daily observed rainfall and temperatures, including near-surface mean (T2m, daily maximum (Tmax), and minimum (Tmin) for the period 1980–2014, are obtained, respectively, from 581 and 147 stations of the Viet Nam Meteorological and Hydrological Administration (VMHA) [Figure 1.1]. Then, the observed station data are interpolated onto a 0.1° × 0.1° gridded dataset (hereinafter referred to as OBS) using the Spheremap [Willmott *et al.*, 1985] and Kriging [Switzer, 2014] techniques for rainfall and temperature variables, respectively. Among various popular interpolation techniques, such as Cressman [Cressman, 1959], Inverse Distance Weighted [Shepard, 1968] or Kriging [Switzer, 2014], the Spheremap method shows advantages in creating rainfall gridded distribution [Nguyen-Xuan *et al.*, 2016]. Besides, the Kriging method is more suitable for interpolating continuous spatial variables such as temperature [Sluiter, 2009; Wu and Li, 2013]. The newly created gridded OBS dataset is subsequently used to bias-correct GCM data, validate the downscaled products, and estimate future Viet Nam climate patterns.

Data from CMIP5 and CMIP6 GCMs

The CMIP is an international experimental protocol coordinated by the World Climate

[Table 1.1]
List of 31 CMIP5 GCMs considered in this study

No.	CMIP5 Model	Country	Grid Resolution (in degrees)		Availability (* means Yes)			
			Longitude	Latitude	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
1	ACCESS1-0	Australia	1.250	1.875	NA	*	NA	*
2	ACCESS1-3	Australia	1.250	1.875	NA	*	NA	*
3	BCC-CSM1-1	China	2.791	2.813	*	*	*	*
4	BCC-CSM1-1-M	China	2.791	2.813	*	*	NA	*
5	BNU-ESM	China	2.791	2.813	*	*	NA	*
6	CanESM2	Canada	2.791	2.813	*	*	NA	*
7	CCSM4	USA	0.942	1.250	NA	*	*	*
8	CESM1-BGC	USA	0.942	1.250	NA	*	NA	*
9	CESM1-CAM5	USA	0.942	1.250	*	*	*	*
10	CMCC-CM	Italy	0.748	0.750	NA	*	NA	*
11	CNRM-CM5	France	1.401	1.406	*	*	NA	*
12	CSIRO-Mk3-6-0	Australia	1.865	1.875	*	*	*	*
13	GFDL-CM3	USA	2.000	2.500	*	*	NA	*
14	GFDL-ESM2G	USA	2.023	2.000	*	*	*	*
15	GISS-E2-H	USA	2.000	2.500	*	*	*	*
16	GISS-E2-H-CC	USA	2.000	2.500	NA	*	NA	*
17	GISS-E2-R	USA	2.000	2.500	*	*	*	*
18	GISS-E2-R-CC	USA	2.000	2.500	NA	*	NA	*
19	HadGEM2-CC	UK	1.250	1.875	NA	*	NA	*
20	HadGEM2-ES	UK	1.250	1.875	*	*	NA	*
21	IPSL-CM5A-LR	France	1.897	3.750	*	*	NA	*
22	IPSL-CM5A-MR	France	1.268	2.500	*	*	*	*
23	IPSL-CM5B-LR	France	1.895	3.750	NA	*	NA	*
24	MIROC-ESM	Japan	2.791	2.813	*	*	*	*
25	MIROC-ESM-CHEM	Japan	2.791	2.813		*	*	*
26	MIROC5	Japan	1.401	1.406	*	*	*	*
27	MPI-ESM-LR	Japan	1.865	1.875	*	*	NA	*
28	MPI-ESM-MR	Japan	1.865	1.875	*	*	NA	*
29	MRI-CGCM3	Japan	1.121	1.125	*	*	NA	*
30	NorESM1-M	Norway	1.895	2.500	*	*	*	*
31	NorESM1-ME	Norway	1.895	2.500	NA	*	NA	*
Total number of available models for each RCP					20	31	12	31

NA: not available.

[Table 1.2]
List of 35 CMIP6 GCMs considered in this study

No	CMIP6 Model	Country	Horizona resolution (latitude x longitude, in degrees)	Historical	SSP1 -1.9	SSP1 -2.6	SSP2 -4.5	SSP3 -7.0	SSP4 -3.4	SSP4 -6.0	SSP5 -8.5
1	ACCESS-CM2	Australia	1.88°x1.25°	x	NA	x	x	x	NA	NA	x
2	ACCESS-ESM1-5	Australia	1.88°x1.25°	x	NA	x	x	x	NA	NA	x
3	AWI-CM-1-1-MR	Germany	0.93°x0.94°	x	NA	x	x	x	NA	NA	x
4	BCC-CSM2-MR	China	1.13°x1.13°	x	NA	x	x	x	NA	NA	x
5	CAMS-CSM1-0	China	1.13°x1.12°	o	NA	NA	NA	NA	NA	NA	NA
6	CAS-ESM2-0	China	2.81°x2.81°	o	NA	o	NA	o	NA	NA	o
7	CESM2	USA	1.41°x1.42°	o	NA	o	O	o	NA	NA	o
8	CESM2-WACCM	USA	1.25°x0.94°	o	NA	o	NA	o	NA	NA	o
9	CIESM	China	1.25°x0.94°	x	NA	x	x	NA	NA	NA	x
10	CMCC-ESM2	Italy	1.25°x1.25°	x	NA	x	x	x	NA	NA	x
11	CNRM-CM6-1-HR	France	1.25°x0.94°	x	NA	x	x	x	NA	NA	x
12	CNRM-ESM2-1	France	0.50°x0.50°	x	x	x	x	x	x	x	x
13	CanESM5	Canada	1.41°x1.39°	x	x	x	x	x	x	x	x
14	EC-Earth3	Europe	0.70°x0.70°	x	NA	x	x	x	NA	NA	x
15	EC-Earth3-Veg	Europe	0.70°x0.70°	x	X	x	x	x	NA	NA	x
16	FGOALS-f3-L	China	1.25°x0.80°	o	NA	o	NA	o	NA	NA	o
17	FGOALS-g3	China	2.00°x2.03°	x	x	x	X	x	x	x	x
18	FIO-ESM-2-0	China	1.25°x1.25°	x	NA	o	NA	NA	NA	NA	o
19	GFDL-ESM4	USA	1.00°x1.00°	x	x	x	x	x	NA	NA	x
20	GISS-E2-1-G	USA	2.50°x2.50°	x	x	x	x	x	x	x	x
21	HadGEM3-GC31-LL	UK	1.88°x1.88°	x	NA	x	x	NA	NA	NA	x
22	HadGEM3-GC31-MM	UK	0.83°x0.56°	x	NA	x	NA	NA	NA	NA	x
23	IITM-ESM	India	1.88°x1.89°	o	NA	o	NA	O	NA	NA	o
24	INM-CM5-0	Russia	2.00°x1.50°	x	NA	x	x	x	NA	NA	x
25	IPSL-CM6A-LR	France	2.50°x1.27°	x	x	x	X	x	x	x	x
26	KACE-1-0-G	Korea	1.88°x1.88°	o	NA	o	NA	o	NA	NA	o
27	MCM-UA-1-0	USA	3.75°x2.24°	o	NA	o	NA	o	NA	NA	o
28	MIROC-ES2L	Japan	1.41°x1.41°	x	x	x	x	x	NA	NA	x
29	MIROC6	Japan	2.81°x2.77°	x	x	x	x	x	x	x	x
30	MPI-ESM1-2-HR	Germany	0.94°x0.94°	x	NA	x	x	NA	NA	NA	x
31	MRI-ESM2-0	Japan	1.13°x1.13°	x	x	x	x	x	x	x	x
32	NESM3	China	1.88°x1.88°	x	NA	x	x	NA	NA	NA	x
33	NorESM2-MM	Norway	1.25°x0.94°	o	NA	o	o	o	NA	NA	o
34	TaiESM1	Taiwan	1.25°x0.94°	o	NA	NA	NA	o	NA	NA	o
35	UKESM1-0-LL	UK	1.88°x1.25°	x	x	x	x	x	NA	NA	x.

Notes: x Available for both precipitation and temperature / o Only precipitation / NA Not available

Research Programme (WCRP) for producing and studying the outputs of global climate models (GCMs). The CMIP Phase 5 (CMIP5) and Phase 6 (CMIP6) provide the scientific ground for the IPCC Fifth Assessment Report (AR5) [IPCC, 2013] and the latest IPCC Sixth Assessment Report (AR6) [Arias *et al.*, 2021], respectively.

In the CMIP5 project, a number of climate models run one historical simulation and four RCPs future scenarios. The RCP scenarios are developed based on the future estimated radiative forcing, covering a period up to the year 2100 or later [van Vuuren *et al.*, 2011]. The four RCPs consist of RCP2.6 (a scenario characterized by a low radiative forcing level), RCP4.5 and RCP6.0 (medium stabilization scenarios), and RCP8.5 (a high radiative forcing scenario), representing different pathways upon the projected impacts of land use and emission of greenhouse gases (GHGs). Accordingly, RCP2.6 expresses a low GHG concentration scenario in the future with radiative forcing estimated at 2.6 W/m^2 by 2100, and so forth with the other RCPs [Moss *et al.*, 2010].

The new state-of-the-art climate projections for the coming decades, called CMIP Phase 6 (CMIP6) [Eyring *et al.*, 2016], provide the underlying scientific ground for the latest IPCC AR6 [Arias *et al.*, 2021]. The Shared Socioeconomic Pathways (SSPs) scenarios used in AR6 include: SSP1 (Sustainability); SSP2 (Middle-of-the-Road); SSP3 (Regional Rivalry); SSP4 (Inequality); and SSP5 (Fossil-fueled Development) pathways [Riahi *et al.*, 2017]. The CMIP6 future scenario GCM experiments are classified into core priority groups, including; i) the tier-1 experiments with and ii) the tier-2 experiments with SSPs 1-1.9, 4-3.4, 4-6.0 and 5-3.4 [Zhao *et al.*, 2021].

Daily rainfall and temperatures (T2m, Tmax, Tmin) from 31 CMIP5 GCMs [Table 1.1] and 35 CMIP6 GCMs [Table 1.2] are obtained via the Earth System Grid Federation portal (ESGF), https://esgf-node.llnl.gov.

For CMIP5 (CMIP6), the historical simulations for the period 1980–2005 (1980–2014) are used as the basis to construct statistical relationships between the high-resolution OBS dataset and the coarse resolution GCMs. Those relationships are further used to statistically downscale the projected CMIP5 (CMIP6) GCM variables for the period 2006–2100 (2015–2099) under RCPs 2.6, 4.5, 6.0, and 8.5 (the SSPs 1-1.9, 1-2.6, 2-4.5, 3-7.0, 4-3.4, 4-6.0, and 5-8.5, combination of both tier-1 and tier-2 except 5-3.4 due to model availability).

2.2 BCSD downscaling methodology

The BCSD method [Wood, 2002; Wood *et al.*, 2004] has been applied to the GCM outputs to create a fine-scale daily climate dataset over Viet Nam. The BCSD is a bias-correct and trend-preserving statistical downscaling algorithm widely used to construct high-resolution precipitation and temperature data from the coarse resolution of GCMs. BCSD consists of three major steps: i) data pre-processing; ii) bias correction (BC); and iii) spatial disaggregation (SD). Data pre-processing aims to detrend the temperature variables, so their raw climatic trend remains unchanged during the bias correction process, although detrending is not necessary for precipitation data.

The BC step follows the quantile mapping (QM) method of Maurer and Hidalgo (2008), which corrects the biases in GCM data using observations. For each grid cell and each month, the cumulative distribution functions (CDFs) for both observations and historical GCM simulations are separately generated for all climate variables (P, Tmax, Tmin, T2m). A quantile mapping of each variable is constructed by comparing the CDFs of the model and observation data at all probability ranges for the historical period. Then, the biases in the GCM monthly outputs are corrected by transforming them with a transfer function (TF) to the corresponding observational data of the same CDF quantile. Those TFs are assumed to be stable through the historical and future periods in BCSD, which are also applied to correct the projected climate variables for the future. After the BC step, the previously saved climatic trends of temperatures are separately added back to the BC model data for the historical and future periods. Then, the climatological mean bias adjustment between the GCM and the OBS temperature at each grid point is subsequently applied, producing the final BC temperature data.

In the SD step, the BC model data are interpolated to the observational resolution (0.1°×0.1°) following a three-step procedure: **i)** the additive and multiplicative change factors for temperature and precipitation (P) estimated between the BC GCM fields and observed climatology are spatially translated to the targeted high-resolution using the bilinear interpolation method (BIP); **ii)** the BC high-resolution GCM data are constructed by adding (for Tmax, Tmin, and T2m) or multiplying (for R) the high-resolution change factors and the observed climatology; and **iii)** the monthly BC fields of the future are temporally disaggregated to daily scale by randomly choosing a respective month from the observations and additively (for T) and multiplicatively (for P) shifting its daily values to reproduce the monthly BC data.

The implementation of the BCSD approach for CMIP5 (CMIP6) GCMs contains two main phases as follows:

– Phase 1 – Historical period: The climatological fields of the training period 1980–1995 (1980–2004) from the OBS and CMIP5 (CMIP6) GCMs are used to develop the TFs between the model outputs and observations. Then, the BCSD is applied to the testing period 1996–2005 (2005–2014), and the results, hereinafter referred to as BCSD-CMIP5 (BCSD-CMIP6), are compared with the OBS to examine the performance of the BCSD.

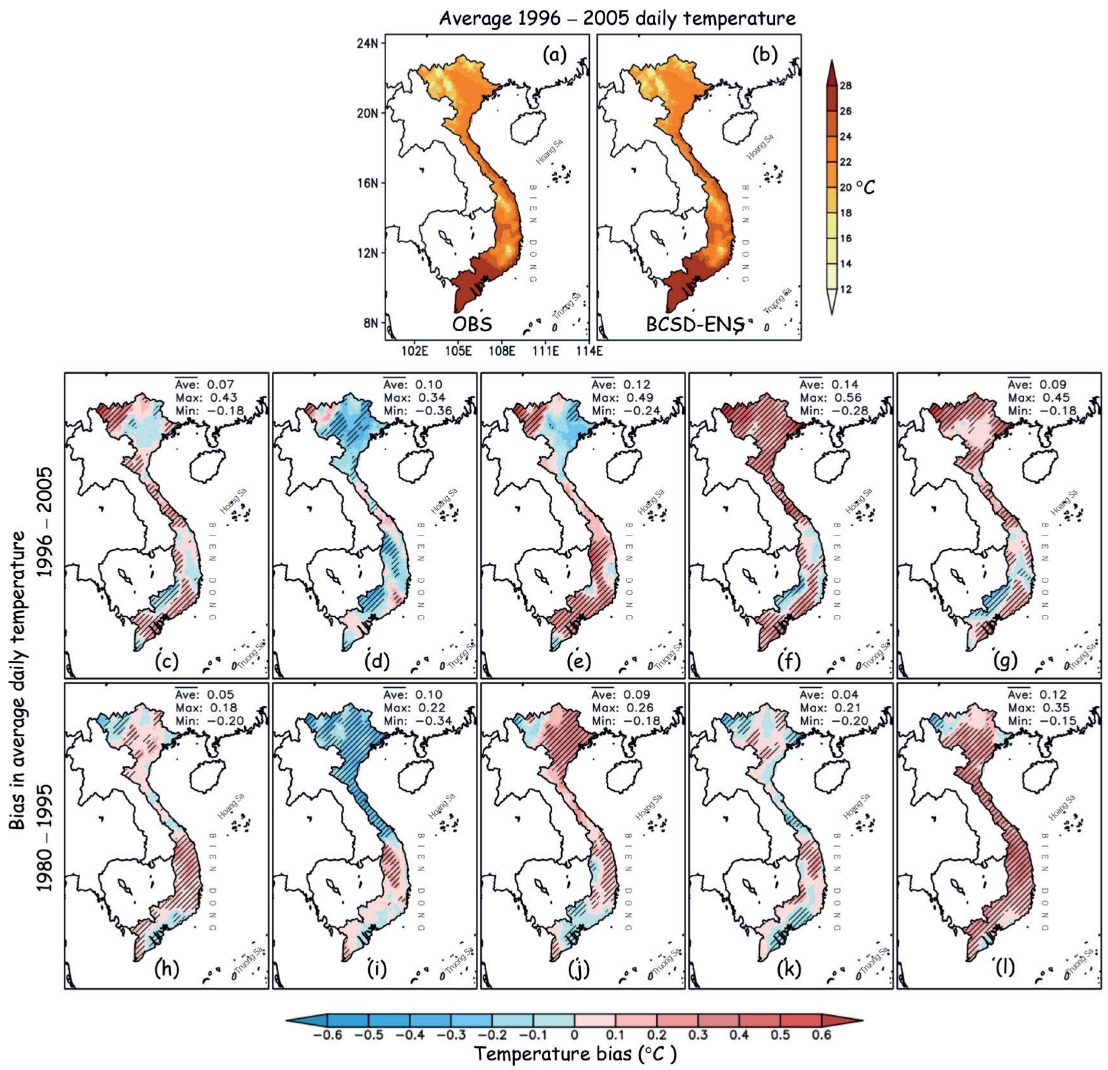
– Phase 2 – Future period: To maximize the construction period of the BCSD approach, the total of 26 (35) years period from 1980 to 2005 (2014) is used to bias correct the CMIP5 (CMIP6) GCM projections and to guide the spatial disaggregation for the future period 2006–2099 (2015–2099). The BCSD is applied to all CMIP5 (CMIP6) GCM models and RCPs (SSPs) scenarios listed in Table 1.1 [Table 1.2] to generate the targeted CMIP5-VN (CMIP6-VN) dataset.

2.3 Validation of the BCSD downscaling

The CMIP5-VN dataset

We first evaluate the spatial distribution of annual temperature obtained from the ensemble mean of 31 BCSD downscaled CMIP5 models (hereinafter referred to as CMIP5-ENS) over the independent period 1996–2005 [Figure 1.2(a,b)], which finds that there is a good agreement between the simulated temperature patterns and observed data. The model ensemble can sensibly resolve the subtle and smooth temperature transition between regions, with a relatively higher temperature in Southern Viet Nam and a lower temperature

[Figure 1.2]
Spatial distribution of average temperature and biases in Viet Nam



The average 1996–2005 temperature by OBS (a) and BCSD-ENS (b); the biases of CMIP5-ENS compared to OBS for the testing period 1996–2005 (c-g) and the training period 1980–1995 (h-i). Hatching patterns show the regions where over two-thirds of the CMIP5 models have the same bias sign as BCSD-ENS. Figure modified from Tran-Anh *et al.* (2022a).

in mountainous areas in the North and Central Highlands. The biases indicated in Figure 1.2(c-i) [Figure 1.2(h-l)] are relatively small, ranging between [-0.34°C, 0.35°C] ([-0.36°C, 0.56°C]) for the training (testing) period. The average annual bias over Viet Nam is 0.05°C for the training period, slightly less than the value of 0.07°C for the testing period. Seasonal temperature biases are generally larger than the annual average bias [Figure 1.2(c-l)]. For each season, the temperature bias range is higher in the northern regions ([-0.36°C, 0.56°C]) than in the southern regions ([-0.2°C, 0.3°C]), suggesting that the QM accuracy might be sensitive to the magnitude of annual and seasonal ranges of temperature. It is worth noting that over the regions with large CMIP5-ENS biases, the BC-GCMs generally show a strong agreement in their bias tendency, *i.e.* at least two-thirds of the model members have the same bias sign with the CMIP5-ENS.

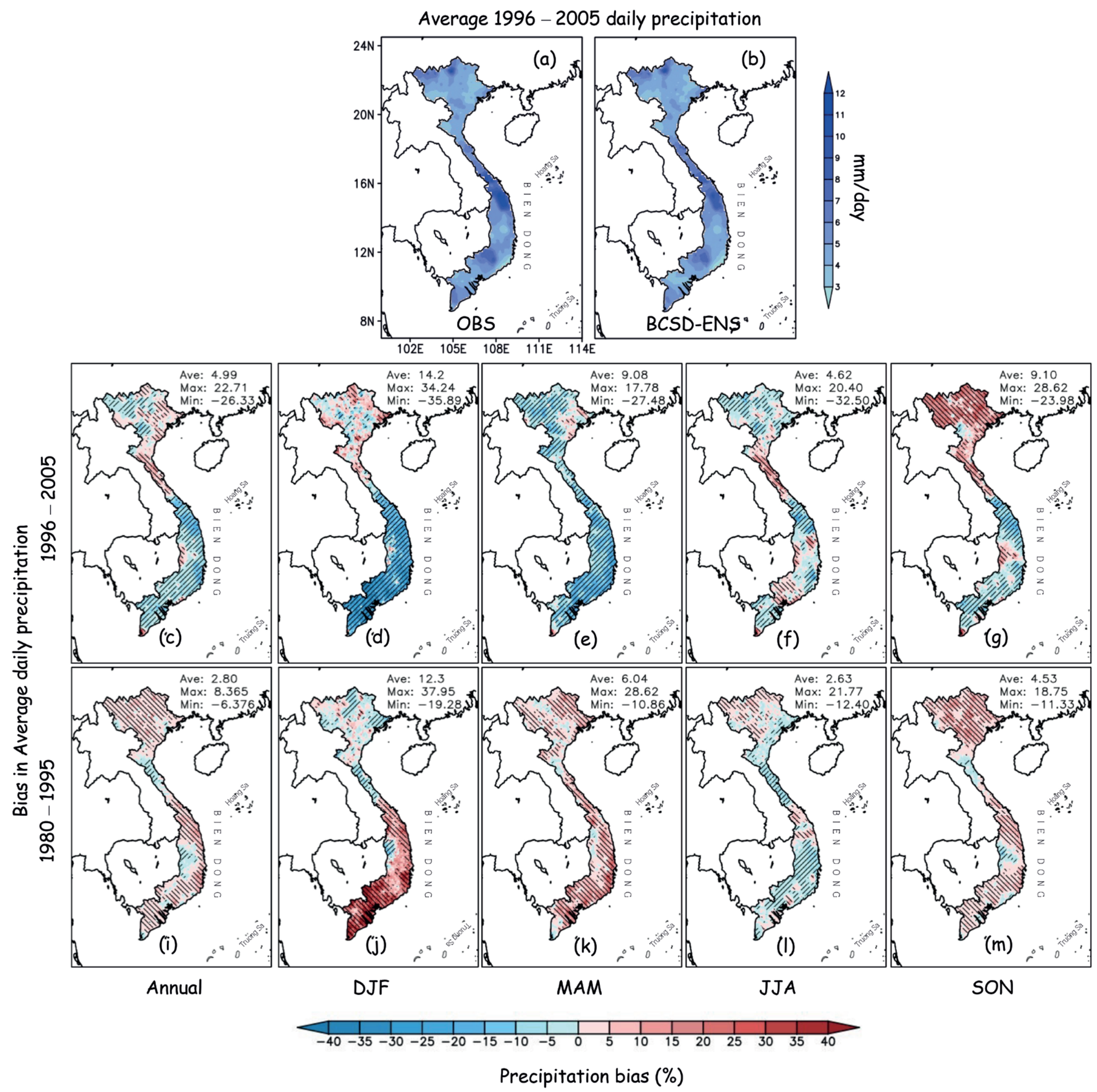
The CMIP5-ENS biases in maximum and minimum daily temperature (figures not shown) are relatively higher than those in average daily temperature for both annual and seasonal averages. For those two variables, the difference between cold and warm bias patterns becomes more intense.

The BCSD outputs for precipitation also show a good agreement with OBS, partly illustrated by the average bias of 4.99% for the testing period [Figure 1.3(a-c)]. Locations of the rainfall centres in Viet Nam (*e.g.* in the north, central and south of central highlands) are well represented by the CMIP5-ENS [Figure 1.3(a-b)]. Although the bias patterns are distributed differently between seasons and regions, the CMIP5-ENS in the testing period tends to underestimate precipitation by up to -36% in the South Central, Central Highlands and South regions, and overestimate precipitation by up to 28% in the north, particularly in September-October-November (SON) [Figure 1.3(d-g)]. For the training period 1986–1995, the CMIP5-ENS results [Figure 1.3(i-l)], with an annual average bias of 2.8%, are better than those for the testing period. Winter season rainfall exhibits the largest bias ranges among all seasons in the BCSD results for both training (-19.28%–27.95%) and testing (-35.89%–34.24%) datasets. It is worth mentioning that relatively small absolute biases may appear as significant percentage biases in regions and seasons with dry (*i.e.* little rainfall) conditions, for example, in December–January–February (DJF). Since precipitation usually has more considerable spatial and temporal variability than temperature, the bias ranges of BC precipitation (in percentage) are much larger than that of temperature.

The ability of the CMIP5-ENS in reproducing the seasonal cycle is illustrated in Figure 1.4, where temporal correlations between the BC outputs and OBS for the independent period are displayed. The average correlation values are very high – 0.998 and 0.97 for temperature and precipitation, respectively – indicating a good agreement between the CMIP5-ENS and OBS [Figure 1.4(a, c)]. Although the simple BIP downscaled CMIP5 GCMs ensemble (BIP-ENS) also shows good seasonal cycles, with average correlations of 0.97 and 0.88, respectively, for temperature and precipitation [Figure 1.4(c, d)], the BCSD-ENS exhibits noticeably better results in all regions.

The reproducibility of the BCSD outputs for the seasonal cycles of temperature and precipitation is further investigated in Figure 1.5 by comparing the CMIP5-ENS, the BIP-ENS and 31 individual CMIP5 models downscaled by both methods, and OBS for all seven climatic sub-regions. Significant agreements in seasonal temperature variation between the BCSD outputs and OBS are clearly illustrated with low root mean square error (RMSE) values, ranging from 0.26°C in the south region to 0.45°C in the northwest. While it is difficult to distinguish the seasonal cycles of the CMIP5-ENS from OBS, the differences between the BIP-ENS and OBS are clear. The BIP-ENS products generally underestimate autumn-winter rainfall from the northwest to north central

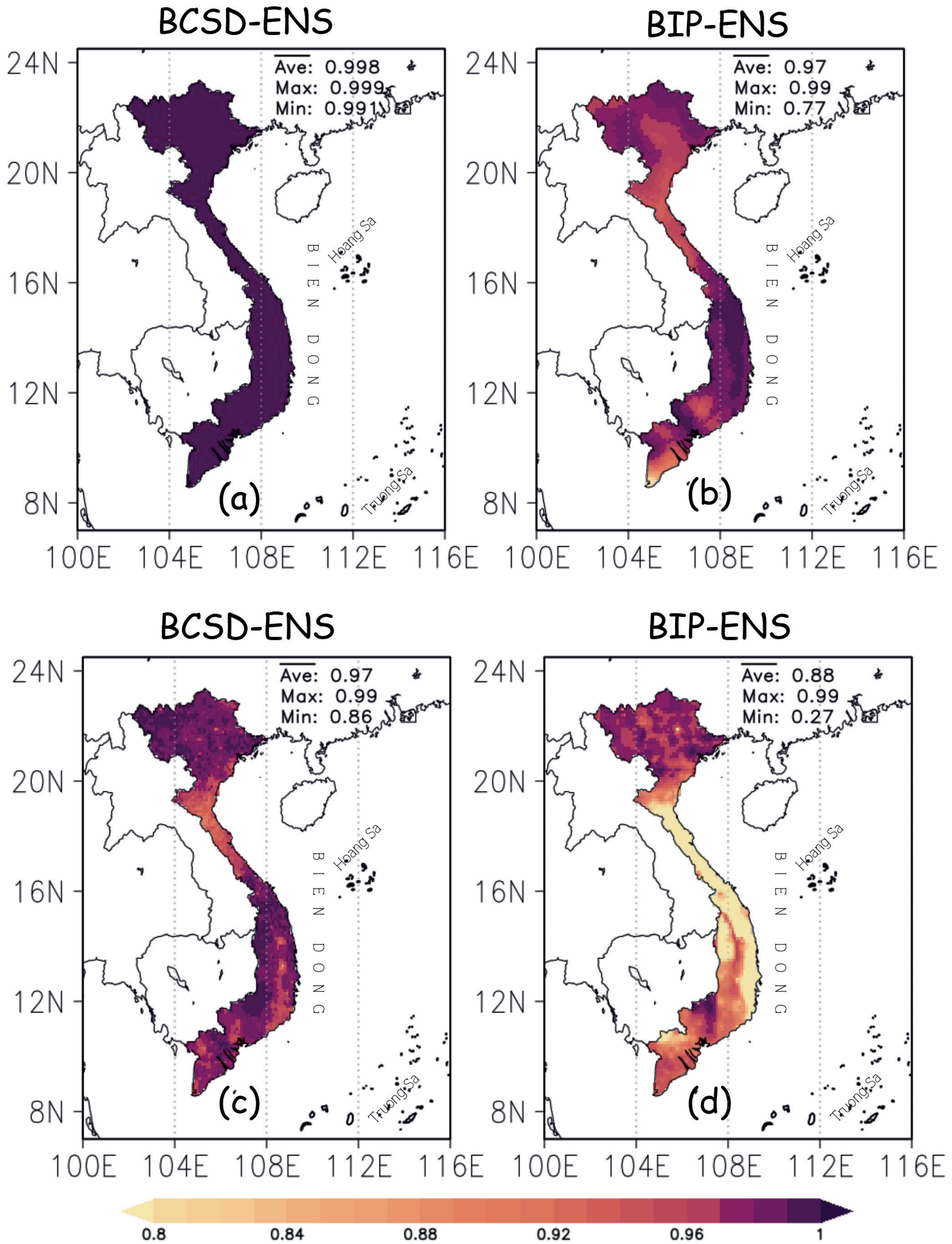
[Figure 1.3]
Spatial distribution of average precipitation and biases in Viet Nam



The average 1996–2005 precipitation by OBS (a) and BCSD-ENS (b); the biases of CMIP5-ENS compared to OBS for the testing period 1996–2005 (c-g) and the training period 1980–1995 (h-i). Hatching patterns show the regions where over of the CMIP5 models have the same bias sign as BCSD-ENS.
Figure modified from Tran-Anh *et al.* (2022a).

[Figure 1.4]

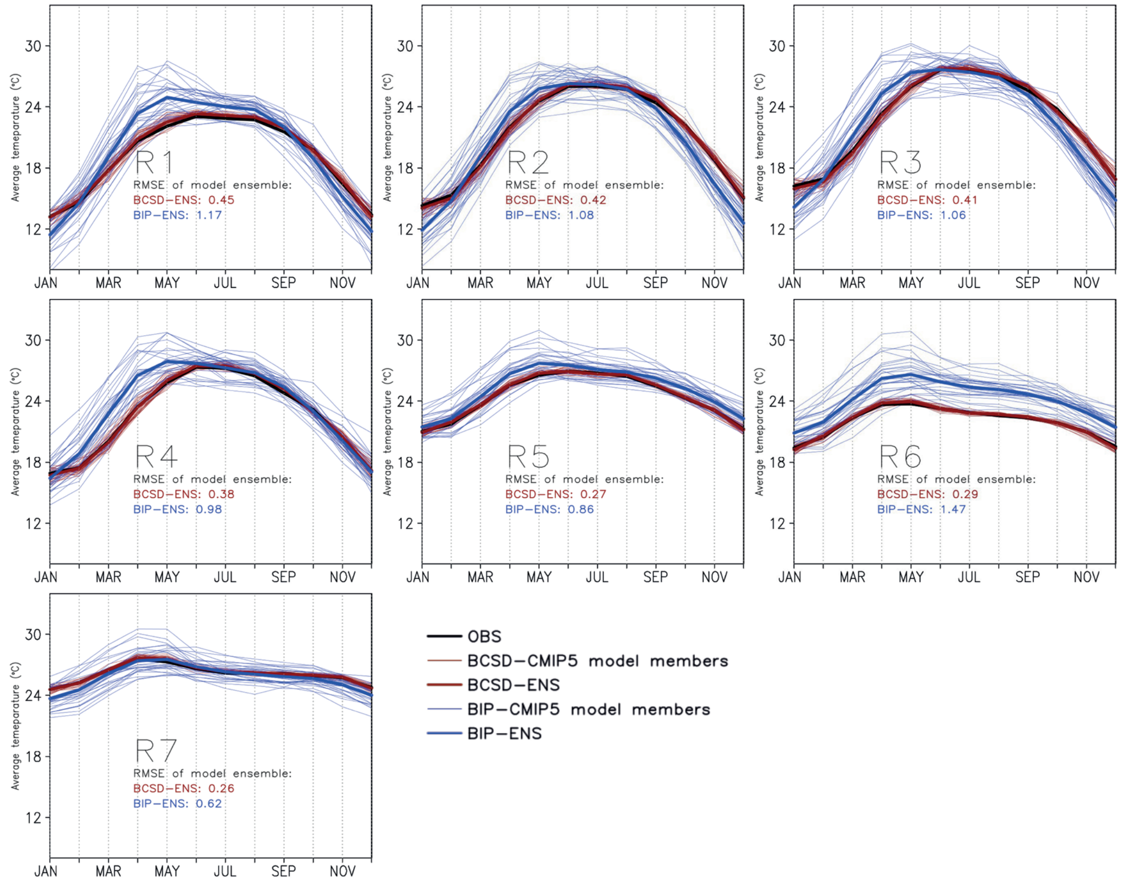
Correlations between the downscaled/interpolated ensemble products and the gridded observational dataset for temperature and rainfall



Temporal correlations of the 1996–2005 seasonal cycle between the CMIP5-ENS (left) and BIP-ENS (right) with OBS for temperature (a, b) and precipitation (c, d).
Figure modified from Tran-Anh *et al.* (2022a).

[Figure 1.5]

Seasonal temperature cycles for the seven climatic sub-regions for the period 1996–2005



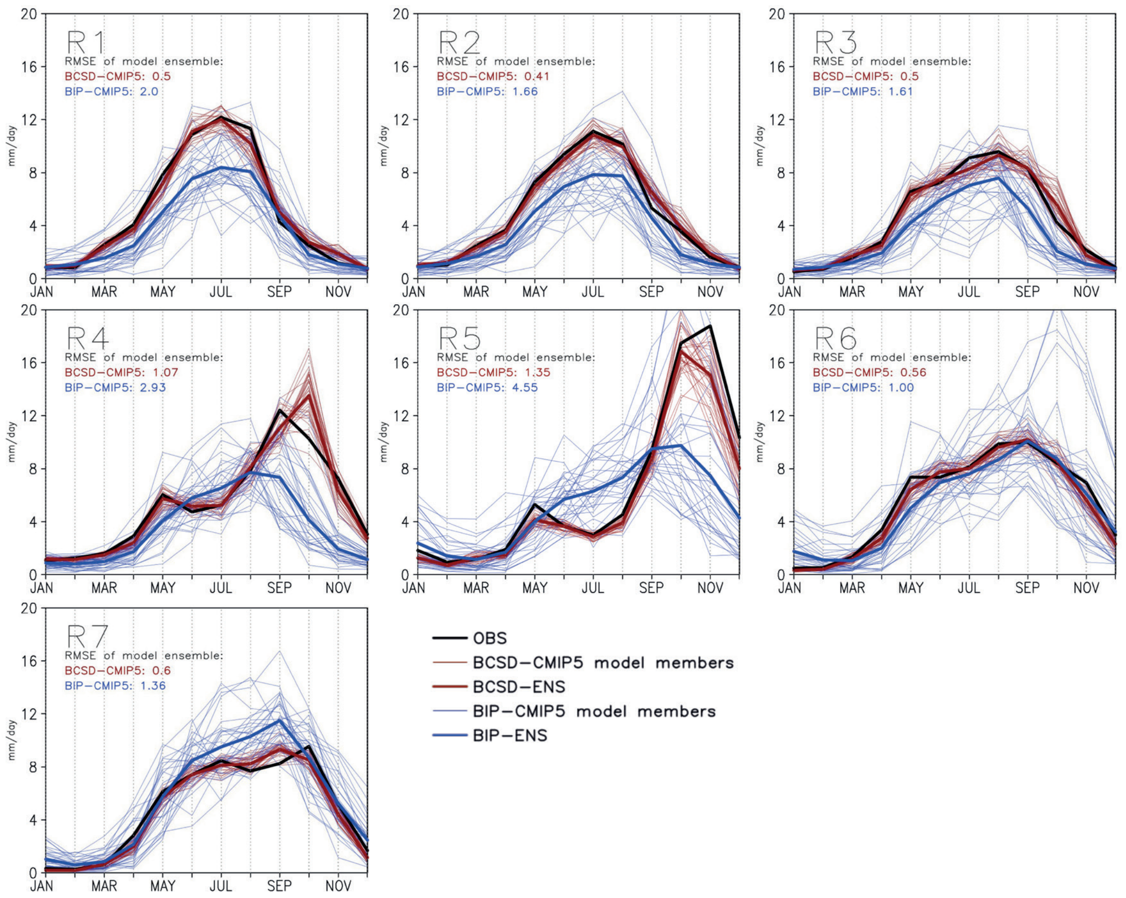
Seasonal temperature cycles for the seven climatic sub-regions for the period 1996–2005 by OBS (black), 31 downscaled individual CMIP5 model members by BCSD (dim red), and BIP (dim blue), and two models ensemble mean, the CMIP5-ENS (dark red) and the BIP-ENS (dark blue). Mean square errors (MSE) of the CMIP5-ENS and BIP-ENS are also indicated.
Figure modified from Tran-Anh *et al.* (2022a).

and consistently overestimate rainfall in the remaining months and regions. Since the variations among the BIP members are much larger than among the BCSD members, the RMSEs of the BIP-ENS results, ranging from 0.62°C in the south to 1.47°C in the central highlands, are much larger than those of the CMIP5-ENS.

Figure 1.6 shows the good performance of the BCSD downscaled results in reproducing the observed seasonal precipitation cycles. The BCSD outputs can well capture the phase and amplitude of the seasonal cycles over all the climatic sub-regions, including R4 (north central) and R5 (south central), where the rainy season starts late in the last months of

[Figure 1.6]

Seasonal precipitation cycles for the seven climatic sub-regions for the period 1996–2005



Seasonal precipitation cycles for the seven climatic sub-regions for the period 1996–2005 by OBS (black), 31 downscaled individual CMIP5 model members by BCSD (dim red), and BIP (dim blue), and two models ensemble mean, the CMIP5-ENS (dark red) and the BIP-ENS (dark blue). Mean square errors (MSE) of the CMIP5-ENS and BIP-ENS are also indicated.
Figure modified from Tran-Anh *et al.* (2022a).

the year. Both BCSD and BIP downscaling results exhibit higher dispersions in months with higher precipitation amounts. The average RMSEs are relatively small for the CMIP5-ENS, ranging from 0.5 mm per day in R1 (northeast) and R3 (north delta) to 1.35 mm per day in R5. In all regions, the BCSD RMSEs are significantly lower than BIP (1.0–4.55 mm per day).

In summary, this subsection has demonstrated the overwhelming performance of the BCSD downscaling method for temperature and precipitation over Viet Nam. For each CMIP5 GCM and the ensemble mean, the BCSD outperforms the simple BIP method over almost all territories of Viet Nam.

The CMIP6-VN dataset

For the CMIP6-VN dataset, we first demonstrate the capability of the downscaled products in capturing the patterns of average temperature over Viet Nam. The climatology derived from the ensemble mean of 25 BCSD downscaled CMIP6 GCMs (hereinafter referred to as CMIP6-ENS) is compared with OBS for the training (1980–2004) and testing periods (2005–2014) [Figure 1.7(a-d)]. There are good similarities between the CMIP6-ENS and OBS in both periods. The biases for the training [Figure 1.7(e-i)] and testing [Figure 1.7(j-n)] periods are relatively small and range between -0.13°C–0.41°C and -0.33°C–0.49°C, respectively, during the year.

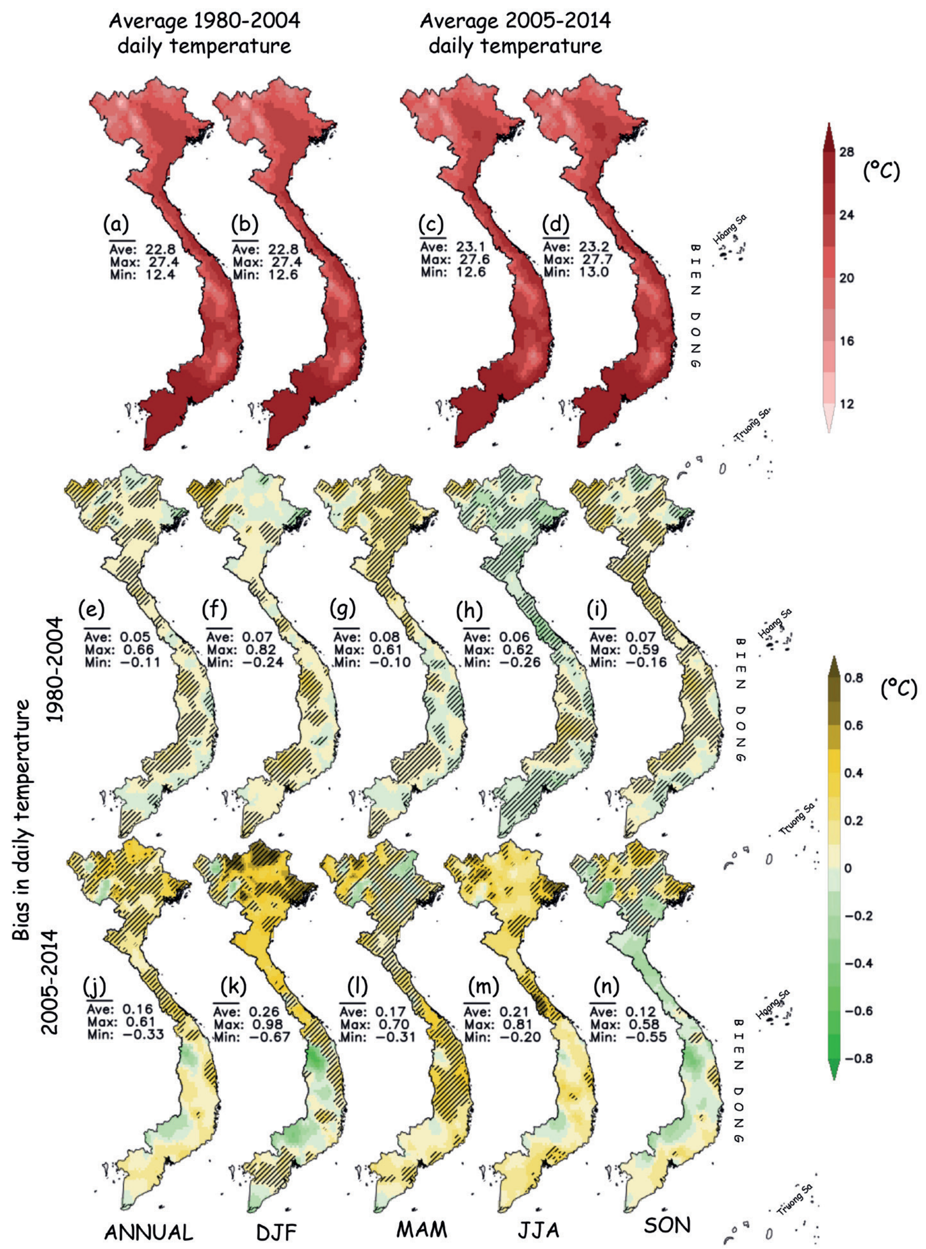
Seasonal temperature biases are more extensive than the annual average bias [Figure1.7(f-i, k-n)]. Generally, the seasonal temperature bias range in the northern regions is higher than in the southern regions. Besides, there is a strong agreement on the bias tendency of BC-GCMs. The regions where over two-thirds of the model members share the same sign of bias account for the majority areas of Viet Nam, especially in the training period.

In addition, the biases of CMIP6-ENS for maximum and minimum daily temperatures are generally higher than those for average daily temperature in both annual and seasonal values (figures not shown).

Figure 1.8 shows that the CMIP6-ENS precipitation agrees well with OBS. There are relatively low average annual biases, respectively, of 2.17% and 5.23% in the training and testing periods, [Figure 1.(e, j)] Locations of dry regions (*i.e.* the northeast and south of the south central) and the wet regions (*i.e.* north of the northeast and central) are accurately captured by the BCSD outputs [Figure 1.8(a-d)]. The simulation biases are non-uniformly distributed between seasons and regions, and generally larger in the testing period than in the training period. The CMIP6-ENS precipitation for the dry season of December-January-February (DJF) exhibits the largest bias compared to the other seasons. The DJF biases could reach 30.38% in the Central Highlands and-50.41% in the south during the testing period, and 24.9% in the north and -8.37% in the central highlands during the training period [Figure 1.8(f, k)].

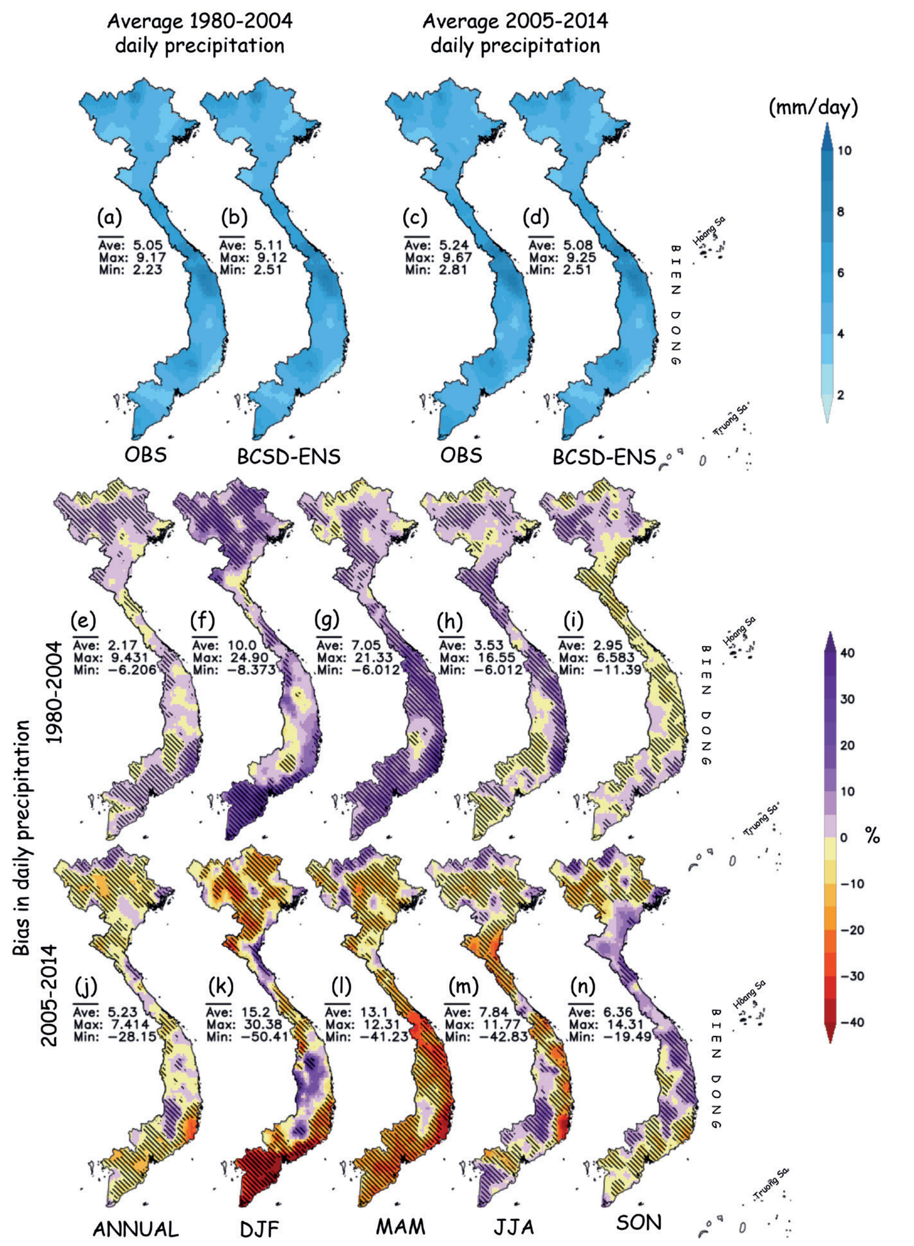
The reproducibility of the CMIP6-ENS for seasonal cycles is examined by calculating the temporal correlations between the simulations and observation [Figure 1.9]. The average correlation values for the testing period are very high, over 0.994 for temperature and 0.982 for precipitation, indicating the good performance of the downscaled products [Figure 1.9(d,h)]. The overall performance of the CMIP6-ENS is slightly better in the training period than in the testing period. The simple BIP downscaled CMIP6 GCMs ensemble (BIP-ENS) also shows a good agreement with OBS, which is partly illustrated by the high correlation coefficients of 0.976 and 0.926 for the seasonal cycles of temperature and precipitation, respectively, in the testing period [Figure 1.9 (c,g)]. The CMIP6-ENS generally exhibits better performance compared to the BIP-ENS. The skill of the CMIP6-ENS in reproducing the seasonal cycle is also better for temperature than for precipitation.

[Figure 1.7]
Spatial distribution of the average temperature and biases in Viet Nam



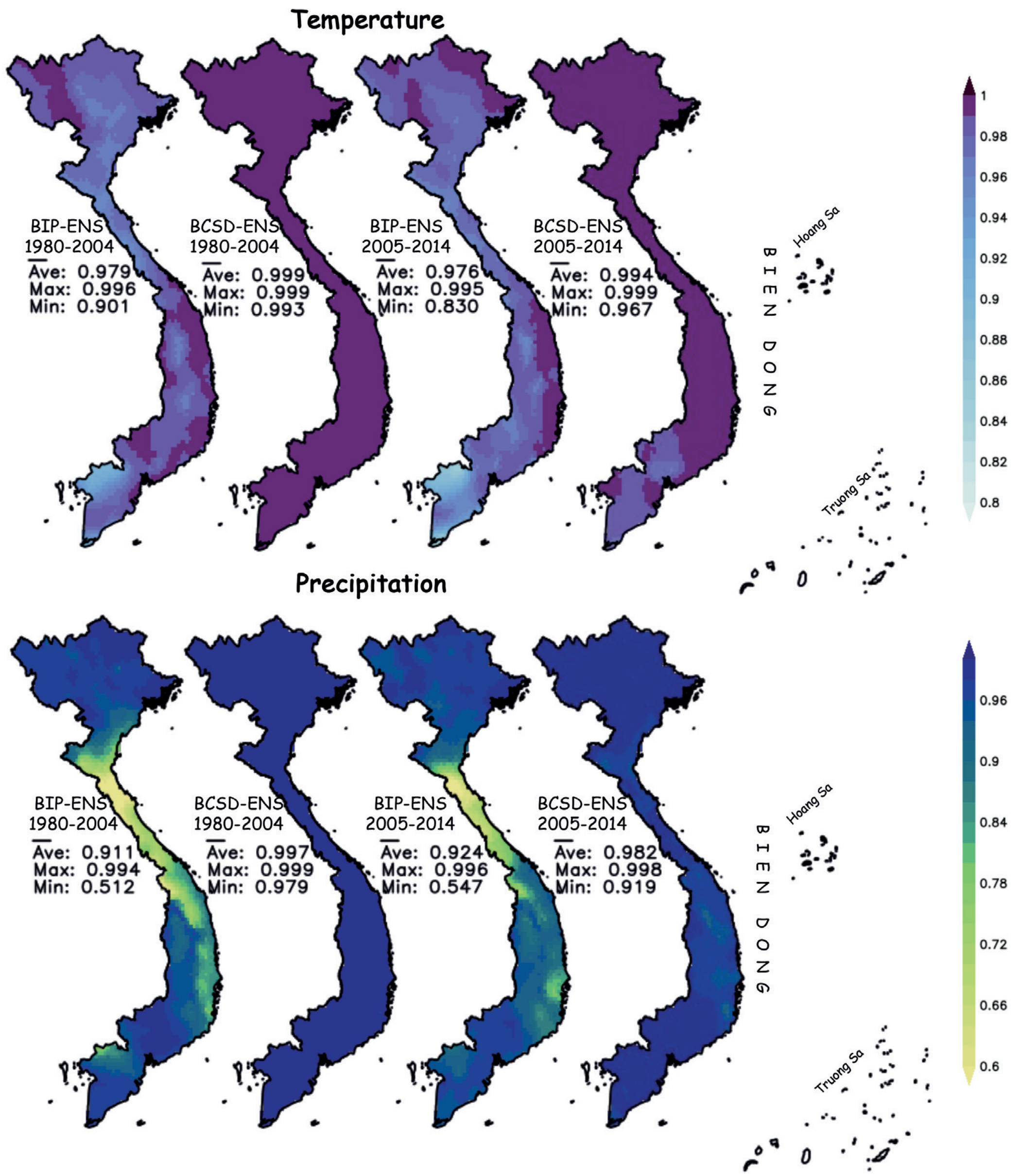
Spatial distribution of the average temperature in Viet Nam according to OBS and CMIP6-ENS; (a, b) and (c, d) indicate the average temperature of 1980–2004 and 2005–2014 by OBS and CMIP6-ENS, respectively; (e-i) and (j-k) show the biases of CMIP6-ENS compared to OBS for the training period 1980–2004 and the testing period 2005–2014. The hatched lines show the regions in which more than two-thirds CMIP6 models have the same sign as BCSD-ENS.
Figure modified from Tran-Anh *et al.* (2022b).

[Figure 1.8]
Spatial distribution of the average precipitation and biases in Viet Nam



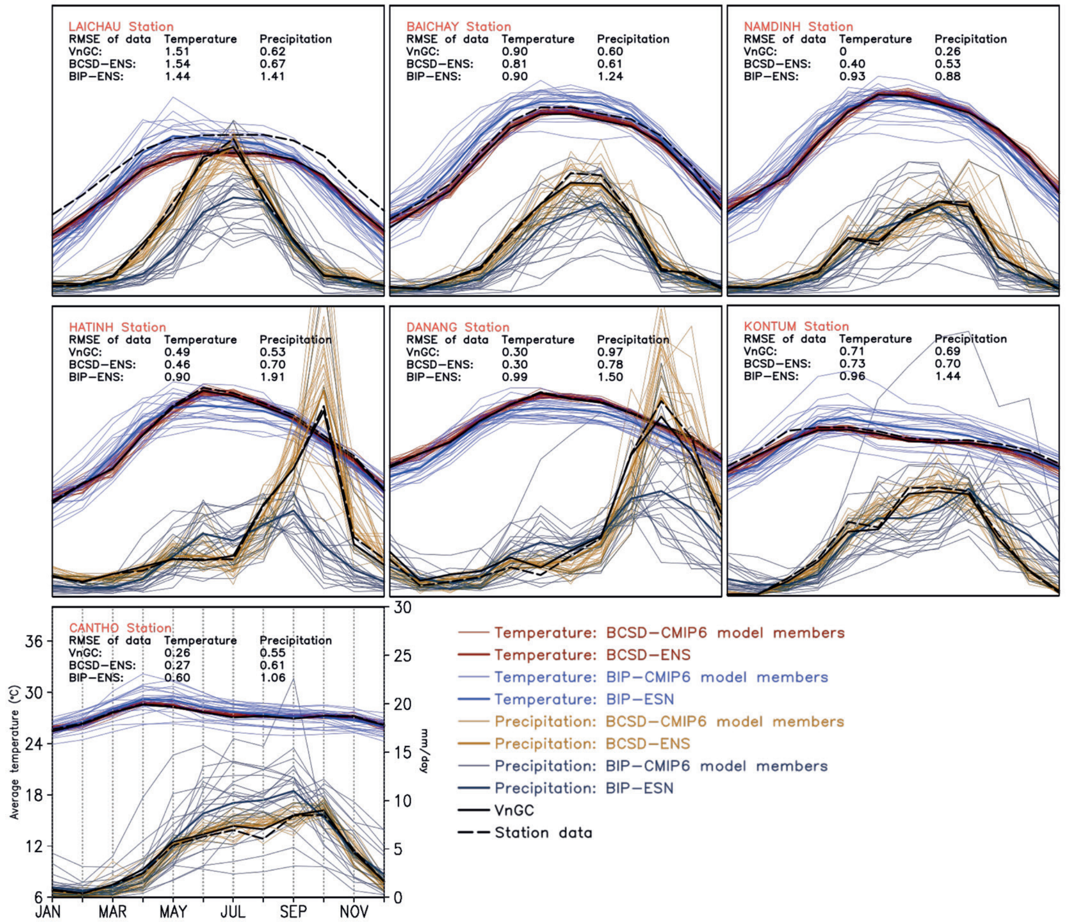
Spatial distribution of the average precipitation in Viet Nam according to OBS and CMIP6-ENS; (a, b) and (c, d) indicate the average temperature of 1980–2004 and 2005–2014 by OBS and CMIP6-ENS, respectively; (e-i) and (j-k) show the biases of CMIP6-ENS compared to OBS for the training period 1980–2004 and the testing period 2005–2014. The hatched lines show the regions in which more than two-thirds CMIP6 models have the same sign as BCSD-ENS.
Figure modified from Tran-Anh *et al.* (2022b).

[Figure 1.9]
Correlations between the downscaled/interpolated ensemble products and the gridded observational dataset for temperature and rainfall



Temporal correlations of the temperature (upper) and precipitation (lower) seasonal cycles between the BCSD-ENS and BIP-ENS with OBS for the training period 1980–2004 (two left figures) and testing period 2005–2014 (two right figures).
Figure modified from Tran-Anh *et al.* (2022b).

[Figure 1.10]
Comparison of the seasonal temperature/precipitation cycles according to station data



Comparison of the seasonal temperature/precipitation cycles according to station data, OBS, BCSD models and their ensemble mean, and BIP models and their ensemble mean for seven station locations in the period 2005–2014. Values of mean square errors (MSE) of OBS, BCSD-ENS, and BIP-ENS are also displayed.
Figure modified from Tran-Anh *et al.* (2022a).

In Figure 1.10, the CMIP6-ENS, the BIP-ENS, the downscaled individual models by both BCSD and BIP methods, and OBS were compared to examine the ability of the downscaled products to reproduce the seasonal temperature cycles. The comparison was conducted at seven stations randomly taken from the list of stations located in the seven climatic sub-regions [Figure 1.10], including Lai Chau (northwest), Bai Chay (northeast), Nam Dinh (Red River Delta), Ha Tinh (north central), Da Nang (south central), Kon Tum (central highlands) and Can Tho (south). There are good agreements between OBS and the observed station data, illustrated by low RMSE values ranging from 0.26°C in Can

Tho to 1.51°C in Lai Chau. Figure 1.10 also shows the good agreement between OBS and the BCSD outputs. The RMSE values between the CMIP6-ENS and OBS are small, *e.g.* only 0.3°C in Da Nang. On the other hand, the BIP-ENS generally overestimates spring-summer temperature in the northern part of Viet Nam and consistently underestimates autumn-winter temperature in the remaining months and regions. Given that the variations among BIP members are larger than among BCSD members, the RMSEs of the BIP-ENS, ranging from 0.6°C in Da Nang to 1.44°C in Lai Chau, are also larger than those of the CMIP6-ENS.

The good performance of the BCSD results in reproducing the observed seasonal precipitation cycles is also illustrated in Figure 1.10, where the CMIP6-ENS well reproduces OBS. The BCSD outputs can effectively capture the temporal variation and amount of rainfall in all stations, including Ha Tinh (north central) and Da Nang (south central), where the rainy season comes between two to three months later than the other regions of the country. In months with high rainfall amounts, the dispersions among the downscaled products are also larger. The average RMSEs of the CMIP6-ENS outputs, ranging from 0.53 mm per day (Nam Dinh) to 0.78 mm per day (Da Nang), are much smaller than those of the BIP outputs (0.88–1.91 mm per day). The BCSD outputs consistently outperform the BIP outputs in all regions and seasons.

We subsequently compare the BCSD and BIP products to OBS in terms of temperature and precipitation seasonal cycles over seven sub-climatic regions. Results also show the good performance of the BCSD outputs (figure not shown). The BCSD method continues to outperform the BIP method.

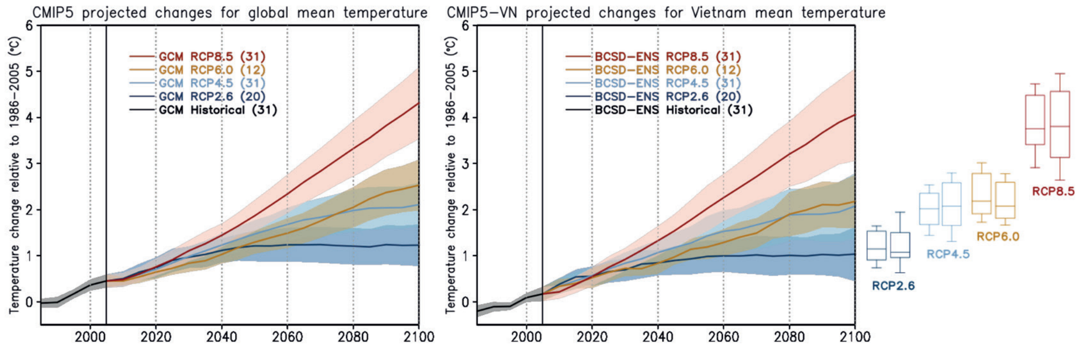
2.4 Future projections with the BCSD

Future projections with the CMIP5-VN dataset

Future global (obtained from the CMIP5 GCMs) and Viet Nam (obtained from the CMIP5-VN) warming levels over the 21st century compared to the baseline period (1986–2005) are shown in Figure 1.11. While the average warming trends in Viet Nam are slightly smaller, the warming variability there is larger than the global average for all RCPs at the end of the century. The average temperature in Viet Nam increases by 1.3±0.52°C under RCP2.6 and by 3.85±0.85°C under RCP8.5. The model variability for each RCP is generally larger in Viet Nam than that of the global scale, except for the RCP6.0 scenario which has a limited number of models. It is worth mentioning that results for Viet Nam are aligned with the latest IPCC AR6, which concluded with high confidence that future warming in Southeast Asia (including Viet Nam) will be slightly less than the global average [Gutiérrez *et al.*, 2021].

The progress of global warming in the seven climatic sub-regions of Viet Nam at the end of the 21st century is illustrated in Figure 1.12, where the CMIP5-ENS temperature seasonal cycles of the future 2080–2099 and baseline 1986–2005 periods are compared. Results indicate that regional mean temperatures, which vary between regions, are projected to increase by 1.10°C–1.37°C under RCP2.6 and by 3.11°C–3.70°C under RCP8.5. The warming in the northern regions (R1–R4) is more intense than in the south (R5–R7), by 0.10°C and 0.31°C warmer on average under RCP2.6 and RCP8.5, respectively. In the northern re-

[Figure 1.11]
Projected temperature changes relative to the baseline period 1986–2005



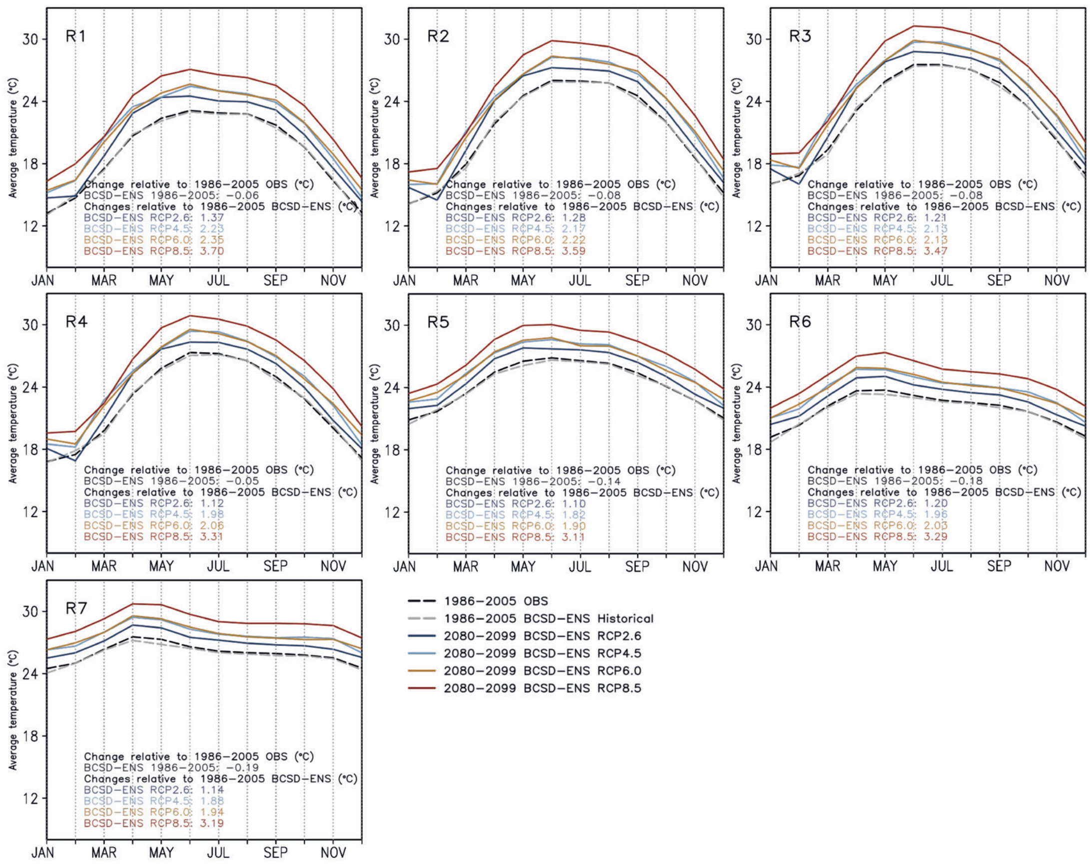
Projected temperature changes relative to the baseline period 1986–2005 based on the CMIP5 GCMs and CMIP5-VN data for global average (left) and Viet Nam (right), respectively. Five-year moving averages are applied. Colored lines show the ensemble means of the models and colored shaded areas present the uncertainty ranges (±1 standard deviation) for each RCP. The number of models used for each RCP is shown in brackets. Box plots on the right display the occurrence statistics (quartile, median, 10th and 90th percentile) for warming levels on the global scale (left boxes) and in Viet Nam (right boxes) at the end of the 21st century 2080–2099. Figure modified from Tran-Anh *et al.* (2022a).

gions, projected temperature increases are about 0.44°C–0.76°C higher in summer than in winter for all RCPs. Our findings correlate fairly well with MONRE (2016)'s results, which were based on a limited number of dynamical downscaling experiments and projected more severe warming conditions in the northern regions than in the southern regions of Viet Nam.

Projection of CMIP5-VN precipitation change in Viet Nam related to the 1986–2005 period is illustrated in Figure 1.13. Contrary to the clear increasing temperature trends across all models, the trends of precipitation contain more uncertainties [Figure 1.13a]. The average precipitation in the far future 2080–2099 is projected to generally increase by 1.16±7.1% under RCP2.6 and by 4.41±9.2% under RCP8.5. The uncertainties increase with time and become the largest under the high greenhouse gas concentration scenario RCP8.5. Over Viet Nam, the CMIP5-ENS shows a slight increasing precipitation trend, except for some small areas in the North and South (Central Viet Nam) under RCP2.6 (RCP6.0) [Figure 1.13(b–e)]. There is a more robust agreement of the CMIP5-VN products on the increasing precipitation trend in Central Viet Nam (including R4 and the northern parts of R5 and R6) under RCP4.5 and RCP8.5 than in the remaining regions and scenarios.

The slight changes in the projected mean precipitation at the end of the 21st century are also demonstrated by the slight increases in the average seasonal precipitation over the seven climatic sub-regions (figures not shown). The average changes of the CMIP5-ENS vary from 0.31% to 3.54% under RCP2.6 and from 2.10% to 9.50% under RCP8.5. In the dry months, only a small increase or decrease

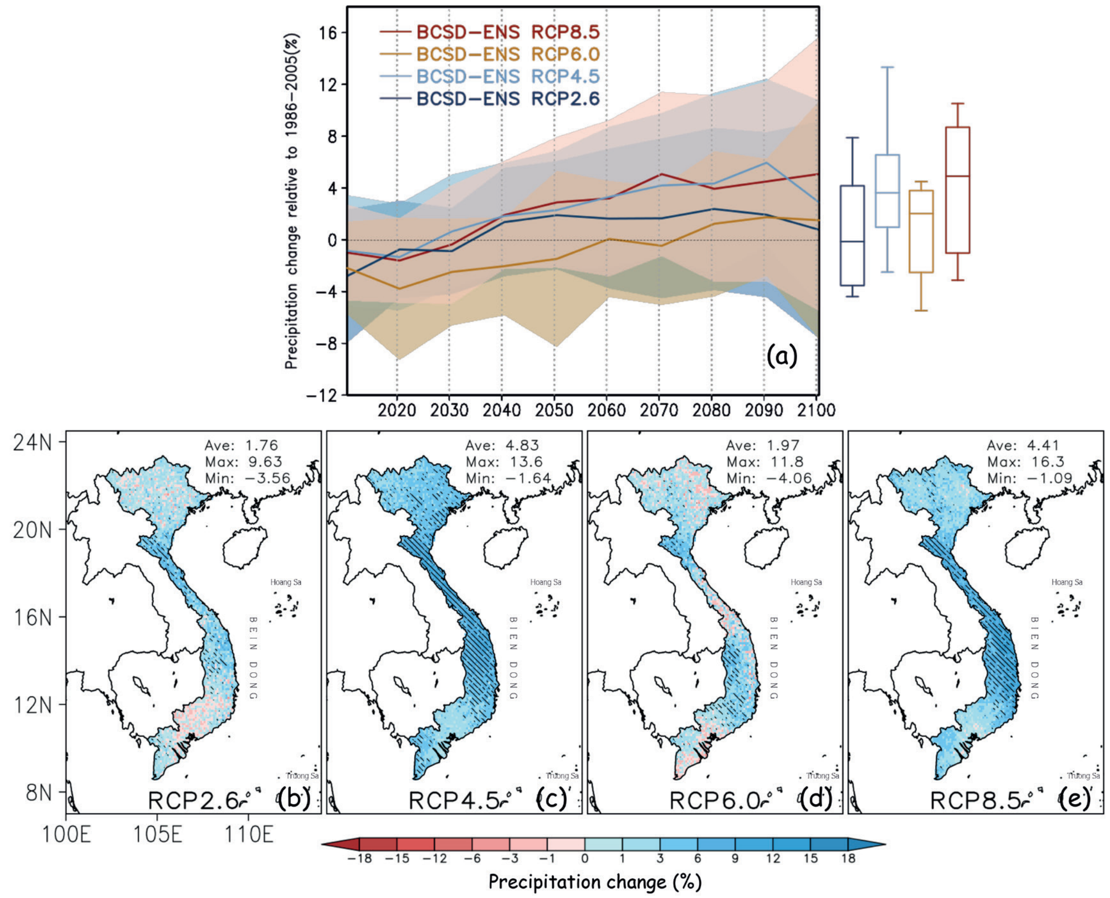
[Figure 1.12]
Seasonal temperature cycles for the seven climatic sub-regions



Comparison between the seasonal temperature cycles of the CMIP5-ENS and OBS over the seven climatic sub-regions of Viet Nam. Black and grey dashed lines respectively represent the OBS and CMIP5-ENS cycles for 1986–2005, while color lines represent the future 2080–2099 seasonal cycles for each RCP. Average changes between the future 2080–2099 CMIP5-ENS and the 1986–2005 OBS with the historical 1986–2005 CMIP5-ENS are also displayed.
Figure modified from Tran-Anh *et al.* (2022a).

in future rainfall can cause a large percentage change. For example, the CMIP5-ENS rainfall is projected to increase by 35% in February under RCP6.0 and to decrease by -25% in March under RCP8.5 in the South region (R7); however, the average monthly rainfall values of R7 in these months are less than 0.5 mm per day, which are very small. There is a tendency of rainfall reduction in the dry months, particularly during March-April-May, suggesting that dry conditions are exacerbated in the future, especially under RCP8.5. On the other hand, more rainfall is projected from June to the end of the year in most climatic sub-regions under all RCPs. In particular, rainfall is projected to increase under RCP4.5 and RCP8.5 by

[Figure 1.13]
Projected precipitation changes in Viet Nam under different RCPs



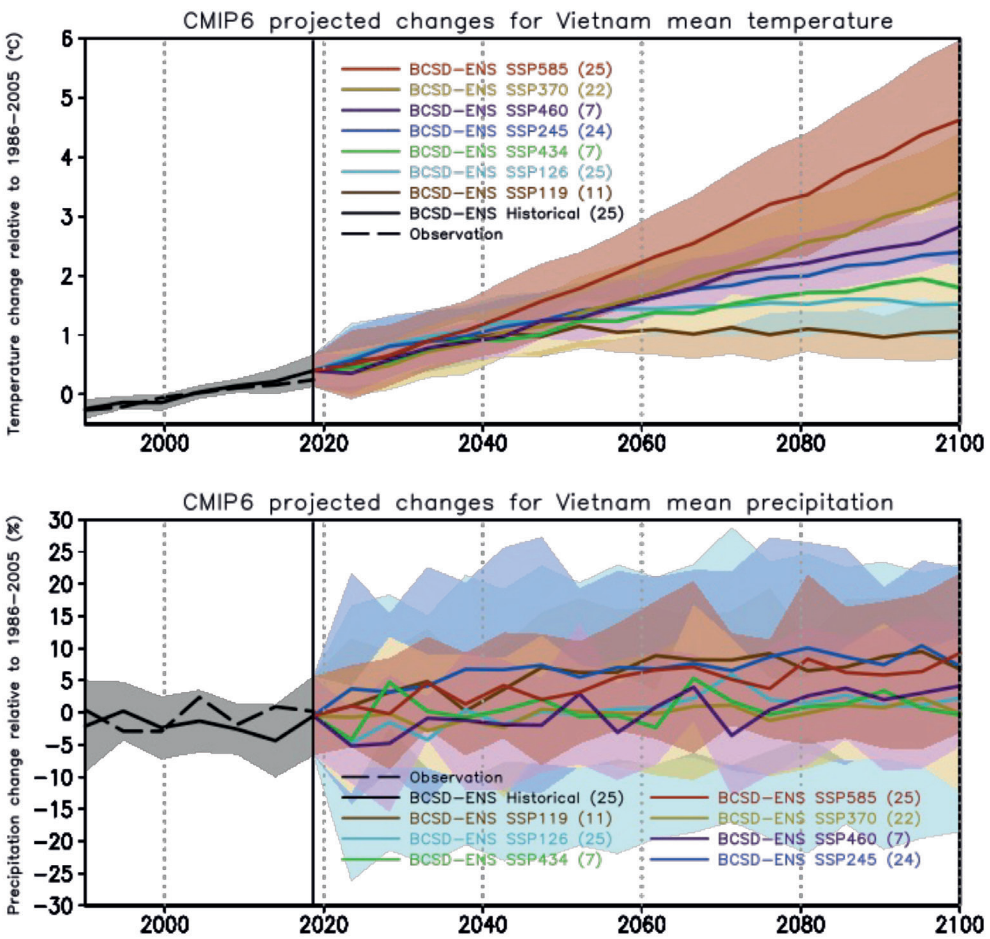
(a) Colored lines present the 10-year moving average of the CMIP5-ENS and colored shaded areas show the uncertainty ranges (±1 standard deviation). Box plots on the right display the occurrence statistics (quartile, median, 10th, and 90th percentile) for precipitation changes at the end of the 21st century 2080–2099. (b, c, d, e). Distribution of change patterns between the 2080–2099 and 1986–2005 periods derived by the CMIP5-ENS. The hatching lines show the regions where over two-thirds of BCSD-CMIP5 models have the same bias sign as the CMIP5-ENS.
Figure modified from Tran-Anh *et al.* (2022a).

more than 10% in north central (R4), and by 5–20% in south central (R5) from September to November, which are the months with the highest rainfall of the year, suggesting more extreme rainfall events in the future in these regions.

Future projection with the CMIP6-VN dataset

The final CMIP6-VN dataset has been built using all 35 years of observation (1980–2014) for bias correcting the GCMs data. The un-

[Figure 1.14]
Comparison of the CMIP6-ENS data with OBS during the historical period (1980–2014) and the future scenarios (2015–2099)



Five-year moving averages are used. Colored lines show the ensemble means of the models and colored shaded areas represent the areas of uncertainty (1 standard deviation) for each RCP. The number of models used for each RCP is given in brackets.
Figure modified from Tran-Anh *et al.* (2022b).

certainty among BCSD downscaled CMIP6 GCMs for the historical (1986–2014) and future periods (2015–2099), illustrated by one standard deviation away from the ensemble mean, is displayed in Figure 1.14. The average dispersion of the BCSD downscaled products in the historical period is relatively small, *i.e.* ±0.21°C for temperature and ±5.1% for precipitation. Similar to the future projection by the CMIP5-VN dataset, a clear warming trend toward the end of the 21st century is projected by all SSPs in the CMIP6-VN dataset, along

with the growth of model uncertainty. The projected warming levels for the period 2080–2099 found in the CMIP6-ENS are generally larger than in the CMIP5-ENS in all radiative forcing-equivalent scenarios, *i.e* 0.46°C larger in SSP5-8.5 than in RCP8.5. The CMIP6-ENS shows a slightly increasing precipitation trend over Viet Nam in the late 21st century with large uncertainties.

In summary, this is the first time in Viet Nam that a study on downscaling CMIP6 GCMs has been conducted. The CMIP6 downscaled data has been validated and an associated manuscript submitted [Tran-Anh *et al.*, 2022b, submitted]. The CMIP6 and CMIP6 downscaled data can be downloaded and used free of charge at the following address: http://remosat.usth.edu.vn/~thanhnd/Download/dat_GEMMES_WP1/.`

3. Probabilistic projections

Section 1.2 has introduced the BCSD products for CMIP5 and CMIP6 GCMs. It should be noted, however, that those downscaling products are still based on a limited number of models. As mentioned in Section 1.1, these are an ensemble of opportunities and were not made for either capturing the full probability distribution or taking into account all the sources of uncertainty. Besides, GCMs are often known to underestimate the likelihood of extreme climate impacts. Therefore, to better assess local and regional climate change risks, it is imperative to consider the entire range of possible probabilities and consequences of future outcomes, including tail risks, which are known to have low probability but severe consequences.

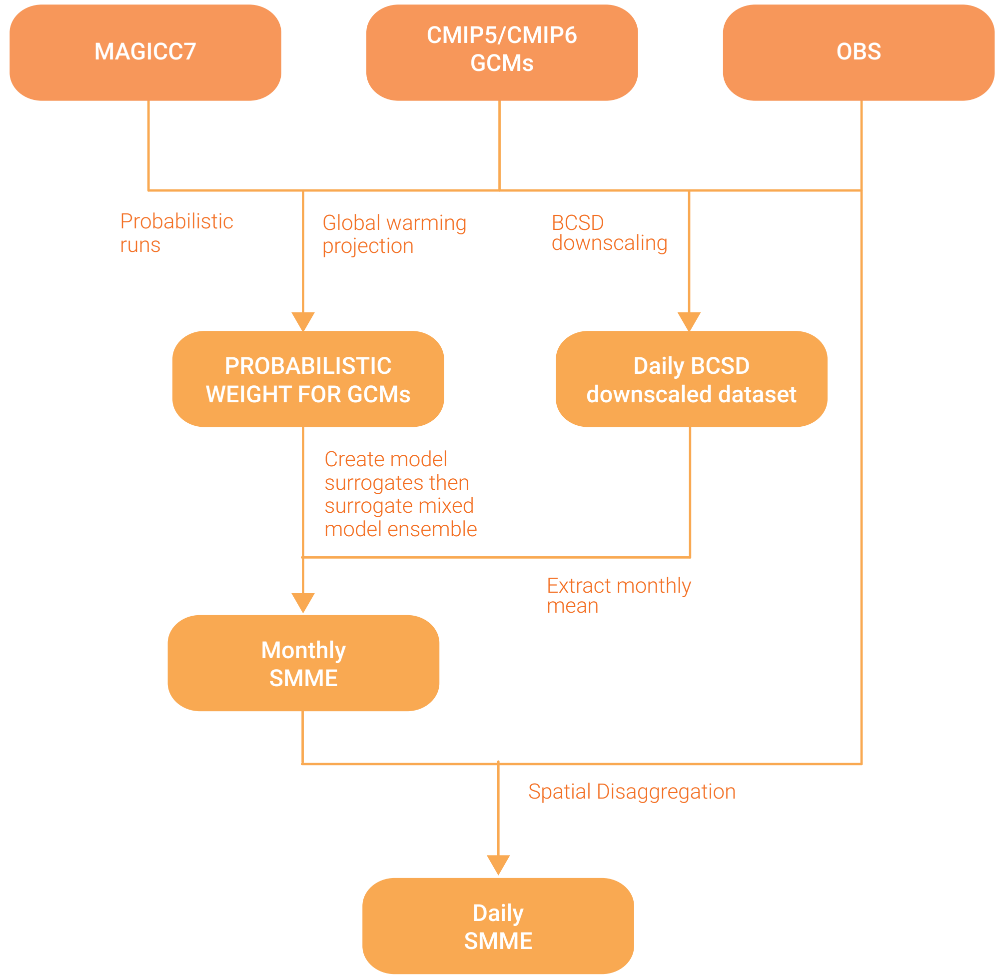
In this section, we establish the joint PDFs of temperature and precipitation change over the 21st century for every region in Viet Nam using the surrogate/model mixed ensemble (SMME) method [Rasmussen *et al.*, 2016]. SMME is an integrated assessment model that both gives probability weights to GCMs and represents the tail risks that are not captured by them. The methodology for conducting the SMME and associated probabilistic results are presented below.

3.1 Methodology for probabilistic projections

The SMME model is constructed by the following steps:
1] The Model for the Assessment of Greenhouse Gas Induced Climate Change version 7 (MAGICC7) [Meinshausen *et al.*, 2020] is used in a probabilistic setting to calculate the projections of global mean temperature over the 21st century for all SSPs to ensure all future uncertainties are captured, including the tails of the probability distribution;
2] The probabilistic projections of global mean temperature derived from MAGICC7 are used to weight the CMIP6 GCMs;
3] The model surrogates that fully cover the tails of the probability distribution are constructed; and
4] The SMME model is estimated by combining the probabilistic weighted GCMs which were already downscaled to 10-km resolution using the BCSD method.

The probabilistic projection method by Rasmussen *et al.* (2016) is adopted to build the future climate scenarios for Viet Nam by creating the surrogate/mixed model ensemble (SMME). The major steps to creating the SMME model are presented in Figure 1.15.

[Figure 1.15]
Major steps to creating the SMME model



Starting with the estimation of the probability distribution of global mean temperatures over the 21st century from an Simple Climate Model (SCM), the projections of global mean temperature change are used to weight GCM outputs and to inform the construction of model surrogates to cover the tails of the SCM probability distribution that are missing from the GCM ensemble. The SMME method requires an ad hoc selection of the patterns used to create the surrogate models. The patterns and residuals of models associated with higher-probability global temperature projections have greater weights. In this study, the SMME method uses the SCM global mean temperature change for 2080–2099 as the target for the probability distribution but may deviate from the SCM distribution at other time points. The detailed steps of the SMME method are described in Figure 1.15.

Global mean temperature

Projections of global mean temperature GCMs are calculated using MAGICC [Meinshausen *et al.*, 2011; Meinshausen *et al.*, 2020] in probabilistic mode. MAGICC is an SCM that represents hemispherically averaged atmosphere and ocean temperature and the globally averaged carbon cycle. MAGICC does not simulate internal climate variability or precipitation, both of which require more complex models. The distribution of input parameters for MAGICC that we employ has been constructed from a Bayesian analysis that is based upon historical observations of hemispheric land and ocean surface air temperature, ocean heat content, estimates of radiative forcing [Meinshausen *et al.* 2009], and the Equilibrium Climate Sensitivity (ECS) probability distribution from the IPCC AR5 and AR6 [Friedlingstein *et al.*, 2011; Meinshausen *et al.*, 2020; Tebaldi *et al.*, 2021]. The probability distributions of climate sensitivity from AR5 and AR6 are based on several lines of information. The differences in climate sensitivity between MAGICC and the IPCC assessment reports in part reflect sampling and the constraints needed to fit historical observations within the MAGICC model structure. The tails of the global mean temperature distribution are vulnerable to extreme scenarios produced by MAGICC and are not robust. Extreme outcomes, such as the 99th percentile, exceed the capabilities of the simple model and are not showed. For each RCP and SSP scenario, we use MAGICC in probabilistic mode with 600 runs. Different versions of MAGICC are used, such as MAGICC6, which is compatible with the CMIP5 dataset, and the recently released MAGICC7, which was developed based on the CMIP6 dataset. Because of underlying structural uncertainties in the SCM, a sample size beyond 600 runs does not yield much additional precision [Rasmussen *et al.*, 2016].

Pattern fitting

The pattern-fitting method presented here parallels the description given by Rasmussen and Kopp (2015): Assuming that forced climate change can be approximated as linear in the long-term (30-year) running average of global mean temperature, for each GCM model and scenario i and each at station j, we fit the deviation from the 1980–2010 reference levels for seasonal temperature and precipitation to the linear model following Rasmussen and Kopp (2015) and Mitchell (2003). Hence, **ΔT** is the running-average change in global mean temperature relative to the reference period (1980–2010), **k** is the estimated seasonal pattern, bi,j is the observed historical mean, and **ε(t)** is an estimated temporal pattern of unforced variability. For local precipitation patterns, unforced variability is greater than that of local temperature, with a weaker correlation with global mean temperature.

$$y_{i,j}(\Delta T,t)=k_{i,j}\Delta T + b_{i,j}+\varepsilon_{i,j}(t) \qquad \text{(Eq.1.1)}$$

Surrogate mixed model ensemble

The SMME method was used in Houser *et al.* (2015) and originally described in Rasmussen and Kopp (2015). First, the unit interval [0, 1] is divided into 10 bins, but not of equal width; the tails of the intervals are allocated more bins to ensure sampling of the part that is not captured by the GCMs. The bins are centred at the 4th, 10th, 16th, 30th, 50th, 70th, 84th, 90th, 94th, and 99th percentiles. The bounds and centre of each bin are assigned corresponding quantiles of global mean temperature from the MAGICC6 and MAGICC 7 outputs. Likewise, the CMIP5 and CMIP6 global mean temperature are placed into bins on the basis of the projected change in global mean temperature in 2080–2099 compared to 1980–2010.

If there are fewer than two GCMs in a bin, model surrogates are produced to raise the total number of models and surrogates to two. Model surrogates are generated by taking the MAGICC projected annual global mean temperature time series that corresponds to the bin's middle quantile. In the case where there is no CMIP output available in the bin, two models having global mean temperature projections close to the bin are selected and, where possible, one model having a net increase in rainfall over Viet Nam, and another a net decrease (or lesser increase). For bins with a single GCM, a model is selected with a precipitation pattern that is either identical or complementary to the one in the bin. Lastly, the patterns from the selected models are scaled by the global mean temperature projection and the same model's residuals are added, creating a surrogate model that includes both forced change and unforced variability. Tables 1.3–1.4 and Tables 1.6, 1.7 list the CMIP5 and CMIP6 models used to generate each pattern as well as their respective global mean temperature bin assignments.

The models and surrogates in the final probability distribution are weighted equally in each bin such that the total weight of the bin corresponds to the target distribution for 2080–2099 temperatures. For example, if four models are in the bin centred at the 30th percentile, bounded by the 20th–40th percentiles, each will be assigned a probability of 20%/4 which is equal to 5%. Thus, the projected distribution for global mean temperature approximates the target. The probabilistic projection model ensemble for Viet Nam, SMME-CMIP5 and SMME-CMIP6, respectively created based on the BCSD CMIP5-VN and CMIP6-VN dataset.

The SMME data are available at the following address:
http://remosat.usth.edu.vn/~thanhnd/Download/dat_GEMMES_WP1/SMME

3.2 Future probabilistic projections

Probabilistic projections for Viet Nam future climate with the SMME-CMIP5

From the MAGICC6 projections, the RCP4.5 and RCP8.5 scenarios yield the 5th–95th percentile of the global mean temperature increases in 2080–2099 above the 1986–2005 levels of 1.04–3.36°C and 2.41–6.30°C, respectively. However, the warming levels indicated by the original selected CMIP5 GCMs for the corresponding time period only span 1.17°–2.90°C in RCP4.5 [Table 1.3] and 2.59–5.00°C in RCP8 [Table 1.4]. Thus, the CMIP5-GCMs fail to capture both the lower-end and upper-end quantiles of the global warming distribution. The surrogates or 'scaled' models are created based on the available CMIP5 models and assigned to the bins that were not captured by the CMIP5 GCMs. The SMME-CMIP5 models are created for both RCP4.5 and RCP8.5 scenarios and for the period 2080–2099, covering the 5th, 17th, 25th, 50th, 83rd, and 95th percentile regions.

[Table 1.3]

Selected patterns and SMME probability weights used for RCP4.5

'Scaled' models are surrogate models used to capture the respective quantile of the temperature distribution

SMME bin	Model	Quantile	SMME weight	2080–2099 Global ΔT (°C)	2080–2099 Viet Nam ΔP (%)
1	Scaled-GFDL-ESM2G	0.04	0.0400	1.03	6.00
1	Scaled-GISS-E2-R-CC	0.04	0.0400	1.03	-1.14
2	Scaled-GFDL-ESM2G	0.10	0.0200	1.13	6.61
2	Scaled-GISS-E2-R-CC	0.10	0.0200	1.13	-1.25
3	GFDL-ESM2G	0.12	0.0400	1.17	6.83
3	GISS-E2-R-CC	0.19	0.0400	1.28	-1.42
4	GISS-E2-R	0.21	0.0667	1.32	-2.42
4	GISS-E2-H-CC	0.31	0.0667	1.49	1.05
4	GISS-E2-H	0.38	0.0667	1.62	1.13
5	bcc-csm1-1-m	0.43	0.0200	1.69	1.54
5	MRI-CGCM3	0.44	0.0200	1.70	6.71
5	NorESM1-M	0.44	0.0200	1.72	14.99
5	CESM1-BGC	0.44	0.0200	1.72	7.71
5	MPI-ESM-LR	0.45	0.0200	1.73	4.57
5	IPSL-CM5B-LR	0.45	0.0200	1.73	0.83
5	bcc-csm1-1	0.45	0.0200	1.76	-0.67
5	CCSM4	0.49	0.0200	1.83	2.56
5	MPI-ESM-MR	0.50	0.0200	1.85	3.36
5	MIROC5	0.51	0.0200	1.89	7.62
6	CNRM-CM5	0.61	0.0167	2.06	7.48
6	ACCESS1-3	0.71	0.0167	2.25	10.66
6	CMCC-CM	0.72	0.0167	2.29	4.51
6	CMCC-CMS	0.74	0.0167	2.34	6.32
6	IPSL-CM5A-LR	0.75	0.0167	2.36	4.91
6	CSIRO-Mk3-6-0	0.75	0.0167	2.37	-4.13
6	BNU-ESM	0.75	0.0167	2.37	-0.33
6	ACCESS1-0	0.76	0.0167	2.38	2.69
6	IPSL-CM5A-MR	0.77	0.0167	2.40	3.23
6	HadGEM2-CC	0.78	0.0167	2.42	0.34
6	CESM1-CAM5	0.79	0.0167	2.45	14.03
6	CanESM2	0.80	0.0167	2.50	7.97
7	MIROC-ESM	0.82	0.0267	2.57	-2.27
7	MIROC-ESM-CHEM	0.85	0.0267	2.66	-3.87

SMME bin	Model	Quantile	SMME weight	2080–2099 Global ΔT (°C)	2080–2099 Viet Nam ΔP (%)
7	HadGEM2-ES	0.87	0.0267	2.74	4.79
8	GFDL-CM3	0.89	0.0200	2.90	16.25
8	Scaled-MIROC-ESM-CHEM	0.90	0.0200	2.93	-4.25
9	Scaled-GFDL-CM3	0.96	0.0300	3.49	19.51
9	Scaled-MIROC-ESM-CHEM	0.96	0.0300	3.49	-5.07
10	Scaled-GFDL-CM3	0.99	0.0100	4.22	23.64
10	Scaled-MIROC-ESM-CHEM	0.99	0.0100	4.22	-6.14

[Table 1.4]

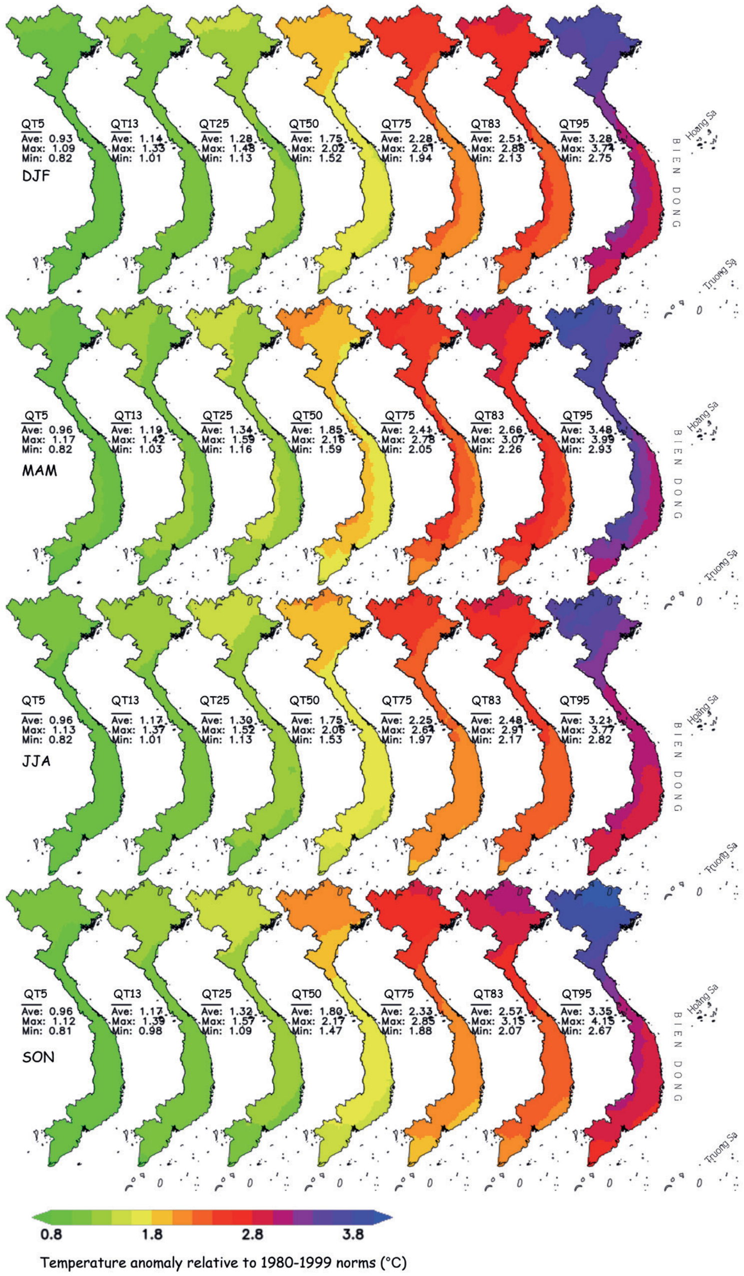
Selected patterns and SMME probability weights used for RCP8.5

'Scaled' models are surrogate models used to capture the respective quantile of the temperature distribution

SMME bin	Model	Quantile	SMME weight	2080–2099 Global ΔT (°C)	2080–2099 Viet Nam ΔP (%)
1	Scaled-GISS-E2-R	0.04	0.0400	2.36	-12.80
1	Scaled-GISS-E2-R-CC	0.04	0.0400	2.36	0.13
2	Scaled-GISS-E2-R	0.10	0.0200	2.54	-13.77
2	Scaled-GISS-E2-R-CC	0.10	0.0200	2.54	0.14
3	GISS-E2-R-CC	0.12	0.0400	2.59	0.14
3	GISS-E2-R	0.13	0.0400	2.61	-14.15
4	GISS-E2-H-CC	0.26	0.0400	2.93	7.72
4	GFDL-ESM2G	0.26	0.0400	2.94	6.44
4	GISS-E2-H	0.28	0.0400	2.99	2.28
4	MRI-CGCM3	0.39	0.0400	3.25	10.12
4	NorESM1-M	0.39	0.0400	3.26	20.85
5	IPSL-CM5B-LR	0.46	0.0222	3.43	-2.32
5	bcc-csm1-1-m	0.47	0.0222	3.45	1.01
5	MIROC5	0.48	0.0222	3.48	6.31
5	bcc-csm1-1	0.49	0.0222	3.53	2.71
5	MPI-ESM-MR	0.52	0.0222	3.62	7.10
5	CNRM-CM5	0.52	0.0222	3.64	7.14
5	CESM1-BGC	0.52	0.0222	3.66	9.83
5	MPI-ESM-LR	0.53	0.0222	3.67	7.80
5	CCSM4	0.55	0.0222	3.78	10.60
6	ACCESS1-3	0.65	0.0154	4.09	-5.39
6	CSIRO-Mk3-6-0	0.66	0.0154	4.12	-4.23
6	CESM1-CAM5	0.67	0.0154	4.19	7.34
6	ACCESS1-0	0.67	0.0154	4.19	-5.03
6	CMCC-CM	0.70	0.0154	4.30	9.60
6	CMCC-CMS	0.72	0.0154	4.41	5.39
6	IPSL-CM5A-MR	0.74	0.0154	4.50	6.79
6	BNU-ESM	0.74	0.0154	4.50	6.02
6	CanESM2	0.77	0.0154	4.65	3.66
6	IPSL-CM5A-LR	0.77	0.0154	4.65	-2.27
6	HadGEM2-CC	0.77	0.0154	4.68	-5.89
6	MIROC-ESM	0.78	0.0154	4.74	-5.20
6	GFDL-CM3	0.80	0.0154	4.82	11.40
7	HadGEM2-ES	0.80	0.0400	4.84	-0.70
7	MIROC-ESM-CHEM	0.83	0.0400	5.00	-7.10
8	Scaled-GFDL-CM3	0.90	0.0200	5.56	13.16
8	Scaled-MIROC-ESM-CHEM	0.90	0.0200	5.56	-7.90
9	Scaled-GFDL-CM3	0.96	0.0300	6.53	15.46
9	Scaled-MIROC-ESM-CHEM	0.96	0.0300	6.53	-9.29
10	Scaled-GFDL-CM3	0.99	0.0100	8.20	19.40
10	Scaled-MIROC-ESM-CHEM	0.99	0.0100	8.20	-11.65

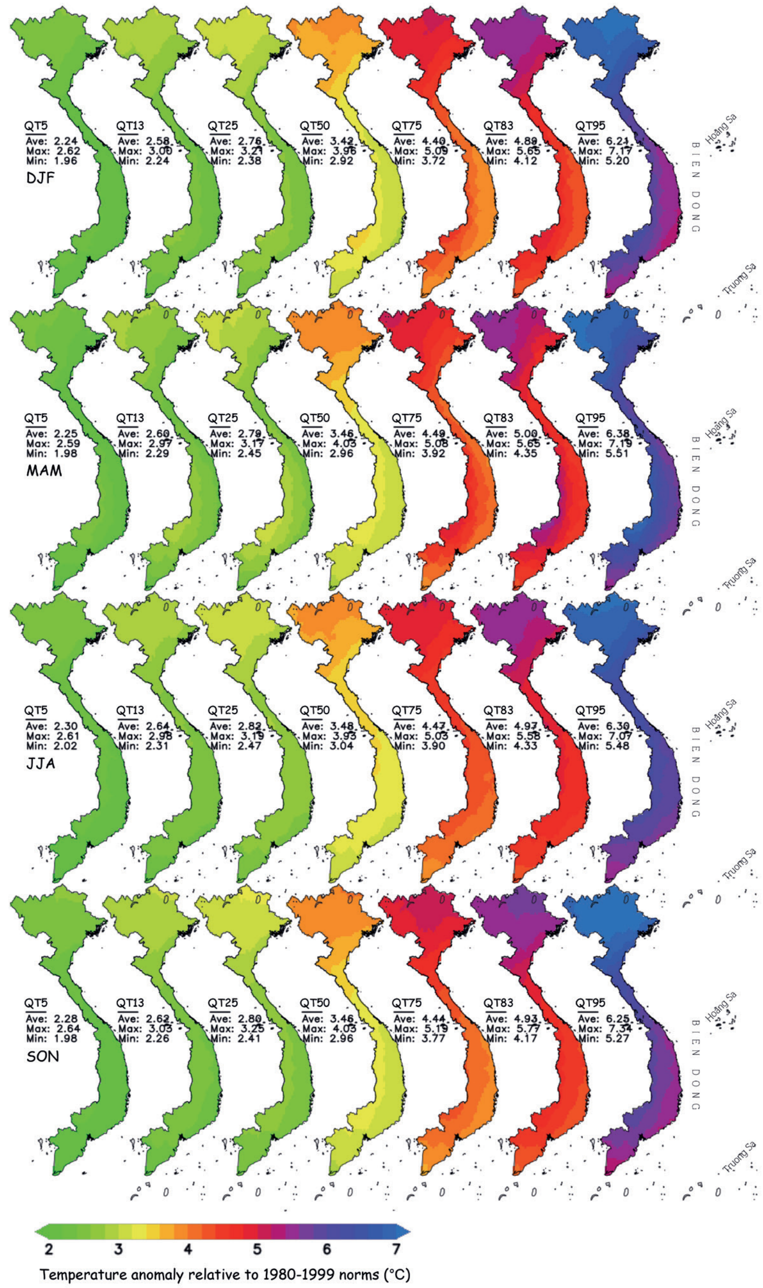
The probabilistic projections by the SMME-CMIP5 for average temperature change in Viet Nam under RCP4.5 and RCP8.5 for all seasons related to the 1980–1999 norms are illustrated in Figure 1.16 and Figure 1.17. Under both RCP4.5 and RCP8.5, the large warming ranges of the 5th–95th percentiles indicate the large uncertainty of future warming projection. For example, the JJA 5th–95th warming ranges are 1.13–3.77°C and 2.61–7.07°C under RCP4.5 and RCP8.5, respectively. Generally, the SMME-CMIP5 shows comparable warming patterns between DJF and JJA under both RCP4.5 and RCP8.5, in which the warming trends are strongest in the north, then gradually decrease to the central and weakest in the south. At the upper percentiles, such as the 95th percentile, the warming difference between the north and the south is more pronounced, where temperature increase in the north could be 1.08°C warmer than in the south. The warming trends nationwide are also projected larger in JJA than in DJF. For JJA, the averaged warming levels between 5th–95th percentiles under RCP4.5/RCP85 vary from 0.96–3.21°C to 2.3–6.3°C, marginally higher than the corresponding warming ranges of 0.93–3.28°C/2.24–6.21°C in DJF. The average projected temperature increases in MAM, varying from 0.96°C to 3.48°C under RCP4.5 and from 2.25°C to 6.38°C under RCP8.5, exhibit the largest values among all seasons.

[Figure 1.16]
Average seasonal temperature anomaly in 2080–2099 relative to the 1980–1999 period under RCP4.5



From left to right and from top to bottom are 5th, 13th, 25th, 50th, 75th, 83rd, 95th quantiles; and DJF, MAM, JJA and SON of the CMIP5-VN SMME.

[Figure 1.17]
Average seasonal temperature anomaly in 2080–2099 relative to the 1980–1999 period under RCP8.5



From left to right and from top to bottom are 5th, 13th, 25th, 50th, 75th, 83rd, 95th quantiles; and DJF, MAM, JJA and SON of the CMIP5-VN SMME.

The projections for possible changes in seasonal precipitation in seven sub-climatic regions under RCP4.5 and RCP8.5 relative to the 1986–2005 norms are also shown in Table 1.5. While the increasing trends of precipitation are found under both RCP4.5 and RCP8.5 at the end of the 21st century, the percentage changes are larger from September to February (SONDJF) than from March to July (MAMJJA) in all regions. For example, at the 50th percentile, regional average precipitation changes are larger for SONDJF than for MAMJJA by 9.24% under RCP4.5 and by 12.59% under RCP8.5. Under extreme warming conditions presented by the 5th–95th percentiles, regional averaged precipitation changes vary significantly, from 10.9°C to 21.9% (0.16–6.4%) and from 13.4°C to 21.9% (1.56–6.4%) in DJF (JJA) under RCP4.5 and RCP8.5, respectively. Generally, the increasing trend of precipitation at the end of the 21st century is more pronounced in DJF and JJA than in MAM and SON under RCP4.5 and RCP8.5. At all percentiles, more rainfall is also projected in the southern provinces than in the northern provinces in DJF and JJA under both RCP4.5 and RCP8.5. Particularly, at the 95th percentile under RCP8.5, rainfall increases by 35.5% (south) and up to 64.4% (central highlands) for DJF and by 0.7% (south) up to 15.5% (south central) for JJA.

Probabilistic projections for Viet Nam future climate with the SMME-CMIP6

Table 1.6 and Table 1.7 respectively show the patterns of the CMIP6 model and surrogate models used to build the SMME-CMIP6. Contrary to the selected CMIP5 GCMs that failed to capture both the left and right tails of the global warming distributions [Table 1.3 and Table 1.4], the selected CMIP6 GCMs well capture these distributions. In the period 2080–2099, the CMIP6 ensemble projects the global warming ranges of 1.81–4.36°C under SSP2-4.5 and 3.13–6.96°C under SSP5-8.5, which are close to the ranges of the global mean temperature indicated by MAGICC7, *i.e.* 1.64–4.53°C under SSP2-4.5 and 2.17–7.6°C under SSP5-8.5. Therefore, most of the bins are captured by at least two CMIP6 GCMs, leading to the small number of surrogate models generated for building the SMME in both SSP2-4.5 (four models) and SSP4-8.5 (five models). With the SMME-CMIP6, the number of the covered percentiles is similar to the SMME-CMIP5.

The probabilistic projections for temperature increase at the end of the 21st century over Viet Nam by the SMME-CMIP6 under SSP2-4.5 and SSP5-8.5 are illustrated in Figure 1.18 and Figure 1.19, respectively. The warming level differences between the 5th and 95th percentiles under SSP2-4.5 and under SSP5-8.5 are relatively large, indicating the large uncertainty of future projections. For example, the increases in JJA average temperature are 1.88–3.41°C under SSP2-4.5 and 3.22–6.02°C under SSP5-8.5. Compared to the baseline 1980–2010 period, the seasonal average temperature might increase by 1.71–3.68°C under SSP2-4.5 and 2.93–6.26°C under SSP5-8.5 at the end of the 21st century. The seasonal temperature is projected to increase considerably in all seasons under both scenarios and tends to increase more in MAM and JJA than in SON and DJF. MAM has the largest warming trend among seasons, *i.e.* 3.68°C under SSP2-4.5 and 6.26°C under SSP5-8.5.

[Table 1.5]
Median values and percentile ranges of projected regional seasonal precipitation changes (%) under RCP4.5 and RCP8.5 for 2080–2099 relative to 1986–2005

Region	DJF			MAM			JJA			SON		
	50	17-83	5-95	50	17-83	5-95	50	17-83	5-95	50	17-83	5-95
RCP4.5												
Northwest	5.43	2-9.6	0.9-13.9	3.58	-0.6-8.8	-2.1-14-1.08	-1.8−-0.2	-2.1-0.7	6.24	4.4-8.5	3.8-10.7	
Northeast	5.57	2.8-9	1.8-12.5	3.63	0.9-7	0-10.4-2.27	-2.4−-2.2	-2.4−-2	5.18	3.9-6.8	3.5-8.4	
Red River Delta	5.15	2.3-8.7	1.3-12.3	2.70	-1-7.3	-2.4-120.68	-0.7-2.3	-1.1-4	8.16	7.2-9.4	6.9-10.6	
North Central	5.80	3.1-9.2	2.1-12.6	3.38	1.2-6.1	0.4-8.96.07	3.4-9.4	2.4-12.8	9.35	8.3-10.7	7.9-12.1	
South Central	25.22	20.7-30.8	19.1-36.5	0.37	3.1−-3	4.1−-6.58.34	4.7-12.8	3.5-17.3	5.94	3.7-8.8	2.8-11.6	
Central Highland	33.94	30-38.8	28.6-43.8	-3.48	-0.6−-7	0.4−-10.6	5.29	2.5-8.7	1.5-12.2	5.98	3.4-9.2	2.4-12.5
South	22.87	23.4-22.2	23.6-21.6	-8.37	-3.9−-13.9	-2.4−-19.4	0.49	-0.4-1.6	-0.8-2.8	3.79	1.8-6.3	1.1-8.8
RCP8.5												
Northwest	-6.19	-5.1−-8	-4.7−-9.7	-1.04	-1.8-0.4	-2.2-1.70.28	-0.8-2.2	-1.3-3.9	8.10	6.8-10.5	6.2-12.6	
Northeast	-6.41	-5.2−-8.5	-4.7−-10.4	1.72	0.7-3.5	0.3-5.2-0.46	-1.5-1.3	-1.9-2.9	8.49	7-11.2	6.3-13.6	
Red River Delta	-2.10	-1.6−-2.9	-1.5−-3.6	-3.37	-3.4−-3.4	-3.4−-3.4	0.97	0.1-2.6	-0.3-4	12.60	10.7-15.9	9.9-19
North Central	2.82	2.3-3.8	2-4.7	0.49	0-1.4	-0.3-2.35.71	4.6-7.6	4.2-9.4	14.16	12-18	11.1-21.4	
South Central	39.73	34.1-49.6	31.9-58.5	-0.49	1−-3.2	1.6−-5.69.12	7.2-12.5	6.5-15.5	10.41	8.5-13.7	7.8-16.7	
Central Highland	47.51	42.4-56.4	40.4-64.4	-4.91	-3.3−-7.7	-2.7−-10.2	5.49	4.2-7.8	3.7-9.8	10.05	8-13.6	7.2-16.9
South	32.58	30.9-35.5	30.3-38.1	-14.84	-11−-21.6	-9.4−-27.7	-0.53	-0.5−-0.6	-0.4−-0.7	6.33	4.9-8.9	4.3-11.2

[Table 1.6]

Selected patterns and SMME probability weights used for SSP2-4.5

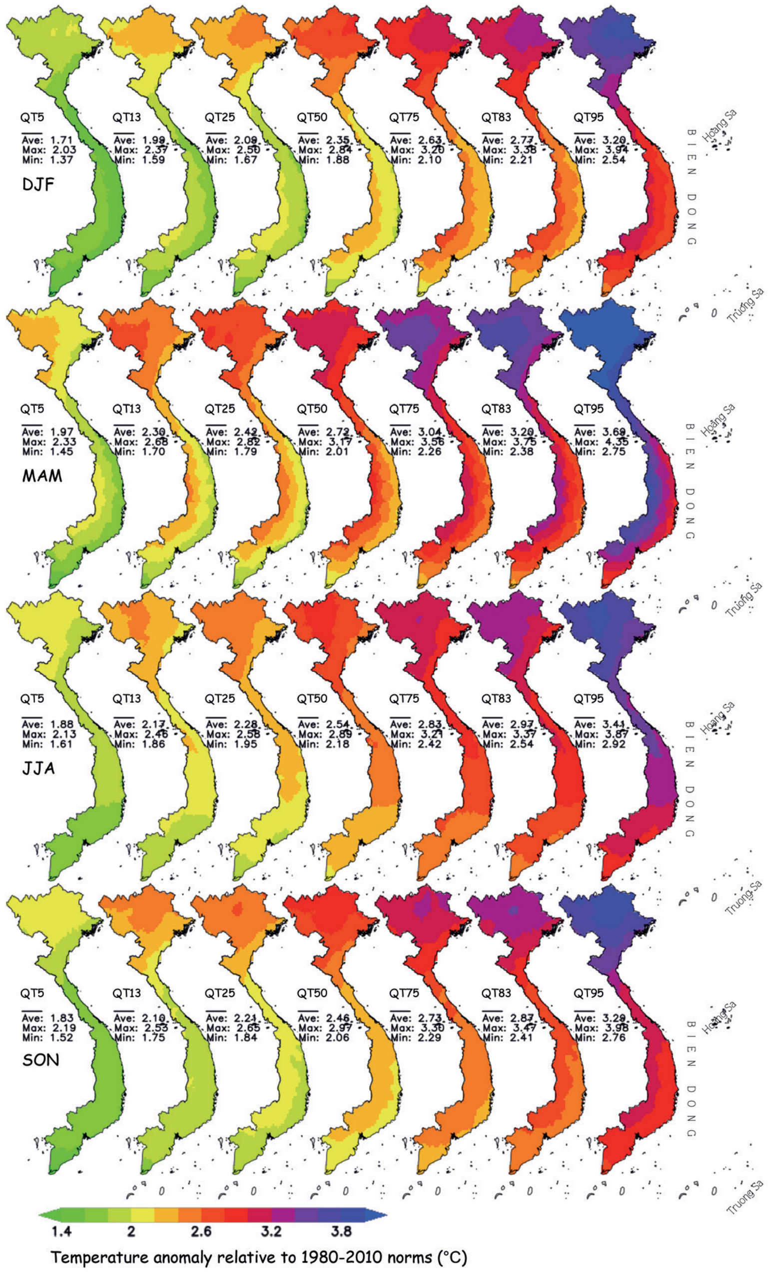
SMME bin	Model	Quantile	SMME weight	2080–2099 Global ΔT (°C)	2080–2099 Viet Nam ΔP (%)
1	FGOALS-g3	0.015	0.0160	1.81	-4.86
1	INM-CM5-0	0.017	0.0160	1.84	10.56
1	MIROC6	0.020	0.0160	1.85	14.33
1	MPI-ESM1-2-HR	0.023	0.0160	1.86	5.52
1	GFDL-ESM4	0.043	0.0160	1.97	7.14
2	MIROC-ES2L	0.088	0.0200	2.10	13.86
2	CNRM-CM6-1-HR	0.088	0.0200	2.11	-6.78
3	GISS-E2-1-G	0.142	0.0400	2.23	-9.87
3	AWI-CM-1-1-MR	0.180	0.0400	2.31	10.50
4	BCC-CSM2-MR	0.207	0.1000	2.33	1.90
4	MRI-ESM2-0	0.218	0.1000	2.35	-1.76
5	NESM3	0.455	0.0400	2.62	19.60
5	EC-Earth3-Veg	0.492	0.0400	2.66	11.57
5	CNRM-ESM2-1	0.530	0.0400	2.70	1.08
5	ACCESS-ESM1-5	0.580	0.0400	2.75	11.74
5	CIESM	0.598	0.0400	2.77	7.59
6	EC-Earth3	0.687	0.0667	2.88	4.69
6	IPSL-CM6A-LR	0.695	0.0667	2.89	1.28
6	CMCC-ESM2	0.717	0.0667	2.92	7.82
7	Scaled-HadGEM3-GC31-LL	0.840	0.0400	3.11	-0.02
7	ACCESS-CM2	0.850	0.0400	3.14	4.97
8	Scaled-CanESM5	0.900	0.0200	3.35	12.68
8	Scaled-HadGEM3-GC31-LL	0.900	0.0200	3.35	-0.02
9	CanESM5	0.920	0.0300	3.42	12.93
9	HadGEM3-GC31-LL	0.967	0.0300	3.67	-0.02
10	Scaled-HadGEM3-GC31-LL	1.000	0.0100	4.05	-0.03
10	UKESM1-0-LL	1.000	0.0100	4.36	10.21

[Table 1.7]

Selected patterns and SMME probability weights used for SSP5-8.5

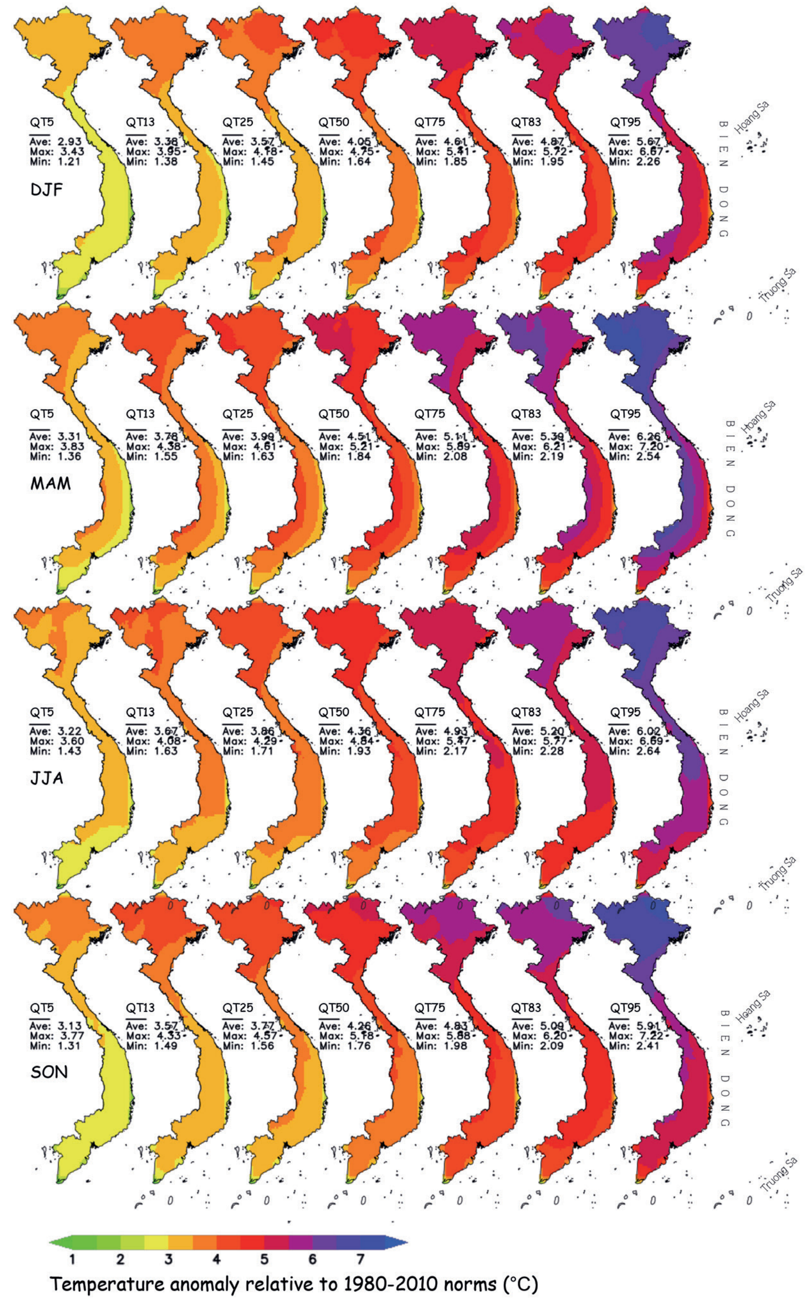
SMME bin	Model	Quantile	SMME weight	2080–2099 Global ΔT (°C)	2080–2099 Viet Nam ΔP (%)
1	INM-CM5-0	0.02	0.0160	3.13	13.97
1	FGOALS-g3	0.02	0.0160	3.17	0.21
1	MPI-ESM1-2-HR	0.04	0.0160	3.33	7.13
1	GFDL-ESM4	0.07	0.0160	3.42	0.38
1	MIROC6	0.07	0.0160	3.45	7.58
2	Scaled-GISS-E2-1-G	0.10	0.0200	3.60	-1.25
2	MIROC-ES2L	0.11	0.0200	3.62	13.74
3	GISS-E2-1-G	0.12	0.0400	3.67	-1.28
3	BCC-CSM2-MR	0.17	0.0400	3.81	1.57
4	MRI-ESM2-0	0.24	0.0667	3.99	0.14
4	CNRM-CM6-1-HR	0.26	0.0667	4.02	-0.95
4	AWI-CM-1-1-MR	0.27	0.0667	4.04	4.84
5	ACCESS-ESM1-5	0.45	0.0667	4.37	1.49
5	CMCC-ESM2	0.51	0.0667	4.49	9.54
5	CNRM-ESM2-1	0.58	0.0667	4.60	-1.19
6	EC-Earth3-Veg	0.63	0.0667	4.69	20.36
6	NESM3	0.64	0.0667	4.71	24.41
6	EC-Earth3	0.75	0.0667	4.97	16.99
7	ACCESS-CM2	0.81	0.0267	5.12	8.93
7	IPSL-CM6A-LR	0.84	0.0267	5.25	3.03
7	CIESM	0.86	0.0267	5.36	15.04
8	Scaled-CIESM	0.90	0.0200	5.58	15.65
8	Scaled-HadGEM3-GC31-LL	0.90	0.0200	5.58	-1.61
9	HadGEM3-GC31-LL	0.95	0.0200	6.00	-1.73
9	CanESM5	0.96	0.0200	6.17	6.15
9	UKESM1-0-LL	0.97	0.0200	6.36	9.49
10	Scaled-HadGEM3-GC31-LL	0.99	0.0100	6.96	-2.01
10	Scaled-UKESM1-0-LL	0.99	0.0100	6.96	10.40

[Figure 1.18]
Average seasonal temperature anomaly in 2080–2099 relative to the 1980–2010 period under SSP2-4.5



From left to right and from top to bottom shown are 5th, 13th, 25th, 50th, 75th, 83rd, 95th quantiles; and DJF, MAM, JJA and SON of the SMME-CMIP6.

[Figure 1.19]
Average seasonal temperature anomaly in 2080–2099 relative to the 1980–2010 period under SSP5-8.5



From left to right and from top to bottom shown are 5th, 13th, 25th, 50th, 75th, 83rd, 95th quantiles; and DJF, MAM, JJA and SON of the SMME-CMIP6.

Similar to the SMME-CMIP5, the SMME-CMIP6 also projected the warming trend in the northern areas is stronger than that in the southern areas, usually 0.5–1°C hotter at all quartiles and seasons under SSP2-4.5, and 0.8–2°C under SSP5-8.5. Since the south region has the least warming trend nationwide, the northeast regions suffer the strongest temperature increase. However, the projected warming range in the SMME-CMIP6 is noticeably narrower than that in the SMME-CMIP5, *i.e.* 1.71–3.68°C/2.93–6.26°C under SSP2-4.5/SSP5-8.5 and 0.93–3.48°C/2.24–6.38°C under RCP4.5/RCP8.5. In all scenarios and all seasons, the warming levels at the lower percentiles (*i.e.* the 5th percentile) in the SMME-CMIP6 are consistently higher than those in the SMME-CMIP5, while the opposite is found in the upper percentiles (*i.e.* the 95th percentile).

The probabilistic projections for rainfall over the seven climatic-sub regions of Viet Nam by the SMME-CMIP6 are shown in Table 1.8. Although total rainfall is projected to slightly increase by the end of the 21st century [Figure 1.14], its tendency is different between seasons where rainfall might increase in JJA, DJF, and SON and decrease in MAM. Rainfall is projected to increase strongest in SON in all regions under both scenarios. For example, the SON increases of the 5th–95th percentiles range from 7.5 to 11.5% (10–18.5%) in the south region to 14.1–20.1% (26–39.1%) in the Red River Delta under SSP2-4.5 (SSP5-8.5). DJF ranks second in terms of large rainfall increases. However, DJF rainfall tends to increase more in the south than in the north by 7.6–10.6% under SSP2-4.5 and 12.2–17.5% under SSP5-8.5. JJA rainfall tends to increase by about 7–8% throughout the country under both scenarios. During MAM, rainfall is projected to decrease under all scenarios in all regions, especially from the Central Highland to the southern areas, where rainfall at the 95th percentile may decrease by 28.1%. The decreasing trend of rainfall in MAM in the SMME-CMIP6 is also found in the SMME-CMIP5 with less intensity. Besides, the increasing trend of rainfall in the far future is more pronounced in the SMME-CMIP6 than that in the SMME-CMIP5.

4. Conclusions and Recommendations

One of the important highlights of this Chapter is the successful application of the BCSD statistical downscaling method, from which two detailed sets of high-resolution (~10-km) climate scenarios for Viet Nam have been built with the inputs of 31 and 35 CMIP5 and CMIP6 GCMs, respectively. With the BCSD method applied to the CMIP5 GCMs' outputs, future GHG concentration scenarios are not limited to only RCP4.5 and RCP8.5, as conducted in the MONRE's published scenarios [MONRE 2016; 2021] but are also for RCP2.6 and RCP6.0, which are the scenarios that have not been addressed in previous studies in Viet Nam. Moreover, this is the first time in Viet Nam that a study on downscaling CMIP6 GCMs has been conducted. The CMIP5 and CMIP6 downscaled data have been validated and a manuscript for CMIP5 has been published [Tran-Anh *et al.*, 2022a] and another will be submitted soon [Tran-Anh *et al.*, 2022b, to be submitted). The CMIP6 and CMIP6 BCSD downscaled data is available for free at the following address: http://remosat.usth.edu.vn/~thanhnd/Download/dat_GEMMES_WP1/

Regarding the downscaling efforts in Viet Nam to date, the projections were generally still bounded by the driving GCMs results.

[Table 1.8]

Median values and percentile ranges of projected regional seasonal precipitation changes (%) under SS02-4.5 and SSP5-8.5 for 2080–2099 relative to 1986–2005

Region	DJF			MAM			JJA			SON		
	50	17-83	5-95	50	17-83	5-95	50	17-83	5-95	50	17-83	5-95
SSP2-4.5												
Northwest	13.65	9.6–18.2	6.5–22.9	-5.98	-6.5–-5.4	-6.9–-4.8	9.28	7.7-11.1	6.4-13	14.40	12.8-16.3	11.5-18.2
Northeast	15.25	10.3–20.8	6.5–26.6	-7.16	-7.1–-7.3	-7–-7.4	6.97	5.7-8.4	4.7-10	12.80	11.5-14.2	10.6-15.7
Red River Delta	13.10	9.5–17.2	6.7–21.5	-8.73	-9.1–-8.4	-9.3–-8	6.87	5.7-8.3	4.7-9.7	16.69	15.2-18.4	14.1-20.1
North Central	13.80	11.5–16.5	9.7-19.2	-11.21	-10.9–-11.5	-10.7–-11.8	6.03	4-8.3	2.5-10.6	18.44	16.9-20.2	15.7-22
South Central	22.33	18.9–26.2	16.3-30.2	-15.14	-12.4–-18.3	-10.3–-21.5	-0.09	-1.1-1	-1.8-2.2	12.08	11.6-12.6	11.3-13.1
Central Highland	21.82	20.1–23.8	18.8-25.8	-15.34	-13.1–-17.9	-11.4–-20.5	5.57	3.9-7.5	2.6-9.4	12.95	12-14	11.3-15.1
South	16.75	17.8–25.5	18.7-34.3	-19.77	-16.1–-23.9	-13.4–-28.1	8.98	6.9-11.4	5.2-13.9	9.22	8.2-10.4	7.5-11.5
SSP5-8.5												
Northwest	7.67	8.6–6.6	9.1-5.6	0.71	-1.1-2.9	-2.2-5	8.96	8-10.1	7.4-11.3	27.61	24.4-31.5	22.3-35.3
Northeast	9.20	9.2–9.2	9.2-9.1	-0.26	-2.2-2.1	-3.5-4.4	9.86	8.2-11.9	7.1-13.8	26.33	23.2-30.1	21.2-33.7
Red River Delta	6.52	8.1–4.6	9.2-2.6	-3.74	-5.1–-2.1	-6–-0.5	4.51	4.2-4.9	3.9-5.3	31.36	28.1-35.3	26-39.1
North Central	7.18	8.4–5.7	9.2-4.3	-8.17	-9.2–-7	-9.8–-5.8	3.55	2.4-5	1.6-6.3	29.50	26.5-33.1	24.5-36.7
South Central	29.29	27.5–31.5	26.3-33.6	-14.39	-13.4–-15.6	-12.7–-16.9	-1.75	-3.2-0	-4.1-1.7	16.01	13.8-18.7	12.3-21.3
Central Highland	37.19	35.3–39.4	34.1-41.6	-13.60	-12.7–-14.7	-12.1–-15.8	7.36	5.1-10	3.7-12.7	21.86	19.1-25.1	17.4-28.4
South	14.84	15.3–24.3	15.5-33.8	-17.24	-15.5–-19.4	-14.3–-21.5	8.18	6.3-10.4	5.1-12.6	13.49	11.4-16	10-18.5

The CMIP5 or CMIP6 GCMs are ensembles of opportunities and were not made for either capturing the full probability distribution or considering all the sources of uncertainty. Besides, GCMs are often known to underestimate the likelihood of extreme climate impacts. Thus, in this chapter, we have introduced for the first time the probabilistic projections for Viet Nam using the surrogate/model mixed ensemble (SMME) method [Rasmussen *et al.*, 2016]. The SMME-CMIP5 and SMME-CMIP6 datasets have been successfully built and is available for free at the following address: http://remosat.usth.edu.vn/~thanhnd/Download/dat_GEMMES_WP1/SMME

The SMME datasets can represent the tail risks which are known to have low probability but severe consequences. Therefore, the SMME-CMIP5 and SMME-CMIP6 could better take into account the extreme risks that may occur in the future.

Recommendations

1] We recommend the potential use of the daily and high-resolution (10-km) CMIP5-VN, CMIP6-VN, SMME-CMIP5, and SMME-CMIP6 datasets, which were generated under the framework of the GEMMES project, for studies on climate change assessment, as well as into climate change impacts on socio-economic activities in Viet Nam.

2] It should be recalled that climate change scenarios always include uncertain factors that are associated with GHG scenarios, limited perception in global and regional climate systems, scenario-building methods and climate models, etc. Therefore, when using climate change scenarios for purposes such as impact assessment or policy making, it is essential to consider and carefully analyse the uncertainty range of future climate.

3] When using the information on climate change and sea-level rise scenarios, users are advised to carefully consult the 2015 Law on Hydrology and Meteorology of Viet Nam (https://vanbanphapluat.co/law-no-90-2015-qh13-hydrometeorology) to ensure that the use of information is in accordance with the regulations.

4] The BCSD approach applied in this Chapter requires a good-gridded observation dataset to bias correct the CMIP GCMs. We have successfully collected the daily data of rainfall and temperatures (T2m, Tmax, and Tmin), respectively, from 581 and 147 stations for the period 1980–2014. These were then interpolated onto a 0.1° × 0.1° gridded dataset using the Spheremap and Kriging techniques for rainfall and temperature variables, respectively. In the near future, more updated station data should be collected, and a more sophisticated interpolation/assimilation technique should be considered to build a new version of the gridded observation dataset.

5] Besides the four variables rainfall, T2mean, Tmax, and Tmin, we often receive requests from other research groups, particularly the impact communities, to provide high-resolution downscaled products for other variables, such as humidity, radiation, evapotranspiration, and wind speed and direction, etc. Therefore, it is highly recommended that the downscaling processes for other variables be considered in a further study.

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Part 2

Viet Nam's green industrial path between carbon and climate exposures

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Abstract

At COP26, Viet Nam positioned itself at the forefront of the global race towards net zero emissions, opening an era of rapid structural change for the country. Viet Nam starts this journey from a position of high-emission intensity compared to the rest of the world. In the electricity, gas and water sector, while the world emits less than 2.5 kg of CO_2 per US dollar, Viet Nam emits almost 15 kg of CO_2 per US dollar. The same pattern is verified in other industries. In the textiles and wearing apparel, as well as in metal products, Viet Nam emits about 2.5 kg of CO_2 per US dollar, whereas the world median is inferior to 1 kg per US dollar. The country also has a relatively high exposure to sunset industries in terms of external, fiscal and socio-economic constraints. A low Social Protection Coverage adds to the potential social impact of a rapid transition. At the same time, Viet Nam belongs to the most exposed countries to climate impacts confirming its own specific interest to lead the global 'green race'. A cross-sectoral exposure analysis shows some significant potential impacts of a 2°C world in terms of external, fiscal and socio-economic effects. But Viet Nam also shows very promising industrial and technological opportunities in a 'green race' scenario. When compared to other Southeast Asian nations, or even to Asian developed economies such as Korea, Viet Nam shows very important green opportunities in the less complex green products, but also some promising opportunities in more complex products, which usually bring with them the best job opportunities and technical capabilities. In the recent decade, Viet Nam had the fastest increasing green complexity index among South-East Asian economies, and one of the highest green complexity potential. Developing a robust green industrial and development strategy in the face of climate change requires deploying the right mix of policies to support diversification in those priority sectors.

Tóm tắt

Tại COP26, Việt Nam đã định vị mình ở vị trí dẫn đầu trong cuộc đua toàn cầu hướng tới «phát thải ròng bằng 0», mở ra kỷ nguyên thay đổi cơ cấu nhanh chóng cho đất nước. Việt Nam bắt đầu hành trình này từ một vị trí phát thải nhiều so với phần còn lại của thế giới. Trong lĩnh vực điện, khí đốt và nước, trong khi thế giới thải ra chưa đến 2,5 kg CO_2/đô la thì Việt Nam thải ra gần 15 kg CO_2/đô la. Các ngành khác cũng có mức phát thải tương tự. Trong lĩnh vực dệt may, cũng như các sản phẩm kim loại, Việt Nam thải ra khoảng 2,5 kg CO_2/đô la, trong khi mức trung bình toàn cầu là dưới 1,0 kg/đô la. Một số ngành công nghiệp trong nước cũng đang đối mặt với các rủi ro về các ràng buộc bên ngoài, rủi ro tài khóa và rủi ro kinh tế xã hội. Tỷ lệ bao phủ bảo trợ xã hội thấp làm tăng thêm tác động xã hội tiềm tàng của quá trình chuyển đổi nhanh chóng. Đồng thời, Việt Nam là một trong những quốc gia chịu nhiều tác động của khí hậu nhất, điều này khẳng định mối quan tâm cụ thể trong việc dẫn đầu "cuộc đua xanh" toàn cầu này. Một phân tích liên ngành đánh giá mức độ rủi ro đã chỉ ra một số tác động tiềm tàng về các ràng buộc bên ngoài, tài khóa và kinh tế xã hội đáng kể khi nhiệt độ tăng lên 2°C. Nhưng Việt Nam cũng đưa ra những cơ hội công nghiệp và công nghệ rất hứa hẹn trong một kịch bản «cuộc đua xanh» toàn cầu. So với các quốc gia Đông Nam Á khác, hay thậm chí các nền kinh tế phát triển châu Á như Hàn Quốc, Việt Nam không chỉ có cơ hội triển vọng trong việc phát triển các sản phẩm xanh ít phức tạp hơn, mà còn cơ hội ở các sản phẩm phức tạp hơn, nhìn chung mang lại cơ hội việc làm tốt nhất và trình độ kỹ thuật tốt nhất. Trong thập kỷ qua, Việt Nam đã có mức tăng trưởng chỉ số phức tạp xanh nhanh nhất trong số các nền kinh tế Đông Nam Á, và là một trong những quốc gia có tiềm năng phức tạp xanh cao nhất. Xây dựng chiến lược phát triển mạnh mẽ và công nghiệp xanh trong bối cảnh đối diện với biến đổi khí hậu đòi hỏi phải triển khai kết hợp các chính sách phù hợp để hỗ trợ đa dạng hóa trong các ngành ưu tiên này.

Résumé

Lors de la COP26, le Viet Nam s'est positionné à l'avant-garde de la course mondiale vers le «net zéro», ouvrant ainsi une ère de changement structurel rapide pour le pays. Le Viet Nam entame ce voyage en partant d'une position de forte intensité d'émissions par rapport au reste du monde. Dans le secteur de l'électricité, du gaz et de l'eau, alors que le monde émet moins de 2,5 kg de CO_2 par dollar américain, le Viet Nam émet près de 15 kg de CO_2 par dollar américain. Le même schéma se vérifie dans d'autres secteurs. Dans le secteur du textile et de l'habillement, ainsi que dans celui des produits métalliques, le Viet Nam émet environ 2,5 kg de CO_2 par dollar américain, alors que la médiane mondiale est inférieure à 1,0 kg par dollar américain. Le pays est également relativement exposé aux industries en déclin en termes de contraintes externes, fiscales et socio-économiques. Une faible couverture de protection sociale ajoute à l'impact social potentiel d'une transition rapide. En même temps, le Viet Nam fait partie des pays les plus exposés aux impacts climatiques, ce qui confirme son intérêt spécifique à mener cette «course verte» mondiale. Une analyse transsectorielle de l'exposition montre certains impacts potentiels importants d'un monde à 2°C en termes d'effets externes, fiscaux et socio-économiques. Mais le Viet Nam présente également des opportunités industrielles et technologiques très prometteuses dans un scénario de «course verte» globale. Comparé à d'autres nations d'Asie du Sud-Est, ou même à des économies développées asiatiques comme la Corée, le Viet Nam présente des opportunités industrielles très importantes dans les produits verts moins complexes, mais aussi des opportunités prometteuses dans les produits plus complexes, qui apportent généralement les meilleures opportunités d'emploi et les meilleures capacités techniques. Au cours de la dernière décen-

nie, le Viet Nam a connu la croissance la plus rapide de l'indice de complexité verte parmi les économies d'Asie du Sud-Est, et l'un des potentiels de complexité verte les plus élevés. L'élaboration d'une solide stratégie de développement et d'industrie verte face au changement climatique nécessite de déployer le bon dosage de politiques pour soutenir la diversification dans ces secteurs prioritaires.

1. Introduction

Viet Nam is often presented as one of the countries most affected by climate change. In a special COP26 assessment report of the GEMMES Viet Nam project submitted to the Minister of Ministry of Natural Resources and Environment (MoNRE) Trần Hồng Hà, Espagne *et al.* (2021a) investigate the potential macroeconomic damages to the Vietnamese economy up to 2050 under different climate change scenarios, together with some adaptation options. On the same day the report was presented at COP26, Vietnamese Prime Minister Phạm Minh Chính announced a net zero objective for the Vietnamese economy in 2050. It is already clear that this ambitious announcement of greenhouse gas (GHG) emission reductions, combined with the prospective climate impacts, will require strong structural change in the process of industrialization and modernization of Viet Nam.

At the same time, decarbonization processes can also offer unique opportunities depending on one country's current technological capabilities, as well as macroeconomic strategies. The opportunities for Viet Nam in terms of green growth have been assessed by the Ministry of Planning and Investment, and different net zero trajectory options have been analyzed by MoNRE in an updated version of the Viet Nam National Climate Change Strategy. In this light, we propose a quantitative assessment of the relationships between climate change, climate policies and a greener industrialization process for Viet Nam, in international comparison as well as in projections to 2050.

The first step in this direction is to assess Viet Nam's exposure to low-carbon transition with respect to three dimensions – external, fiscal and socio-economic – in comparison with both neighboring countries (Southeast Asian economies) and developed (OECD) economies. For that matter, we use an original AFD framework (Exposure to Structural Transition in an Ecological-Economic Model – ESTEEM) to analyze countries' dependence on sunset and climate-impacted industries based on hybrid multi-region input-output (MRIO) matrices. The method consists in evaluating the direct and indirect importance of these industries to raise foreign currency and fiscal revenues and generate jobs and pay wages, which allows an international comparison.

In addition to this analysis is an assessment of Viet Nam's relative opportunities to promote green industries, using an economic complexity approach [Hausmann *et al.*, 2014; Mealy & Teytelboym, 2020] that compares green products in terms of their technological sophistication. Products for which Viet Nam already has a comparative advantage and high proximity are considered as green competitive strength, while products for which the country has a high proximity but a low comparative advantage are considered as mere green opportunities. The idea behind this approach is that Viet Nam can, through appropriate industrial policies, shift its production structure towards these specific industries.

In the face of potential climate scenarios, all countries must both decarbonize massively and adapt to potentially heavy impacts. The low-carbon transition is a unique type of structural change, where low-emission industries grow and high-emission industries decline. The process is led by deliberate policies, changes in preferences and technological changes [Semieniuk *et al.*, 2021]. Countries are impacted differently according to their

[Box 2/1]

Methodology / Measuring exposure through multi-region input-output matrices (MRIO)

Espagne *et al.* (2021b) developed a methodology to analyze the dependence of countries on declining industries, taking into account not only their direct impact, but also their productive interrelationship, based on the EORA multi-region input-output database [Lanzen *et al.*, 2013]. Firstly, sunset industries were defined based on total sectoral emission-intensity, which accounts for direct emissions, and those embodied in inputs. The hypothetical extraction technique [Dietzenbacher & Lahr, 2013] is then applied to identify the importance of the sunset industries for the economy. Essentially, one simulates total demand in the absence of these industries both as final demanders (household and government consumption, investment and exports) and providers of inputs. Because these industries are extracted from the input-output system, those impacted are not only the industries themselves, but also their suppliers and value chain.. In the case of the rise of foreign currency, which measures the external exposure, total exports discounted by the imported inputs necessary to produce them are accounted for. With regard to fiscal revenues, employment and wages, one considers that sectoral technical coefficients remain the same, which means that the more the economy depends on sunset industries and their value chain to raise fiscal revenues, generate employment and pay wages, the more it becomes exposed in the fiscal and socio-economic dimensions.

structure of production, trade and finance. Changes in world demand due to this transition also tend to impact more significantly those countries which depend on sunset industries for raising foreign currency and fiscal revenues, as well as for generating employment that pays high wages.

Developing countries where sunset industries play an important role on exports are especially affected because these industries are important to raise foreign currency and avoid balance-of-payment constraints. The low-carbon transition will demand many imported capital goods and inputs, and a drop in export revenues either from a decline in prices or in volume reduces the capacity of these economies to import, and, consequently, the capacity to move the transition forward. The transition will also demand a significant increase in public investment. A new infrastructure system needs to be built for increasing the capacities necessary to foster green industries.

Moreover, re-training workers and investing in a social protection system that can guarantee that workers displaced by such structural change will be less impacted is essential to promote a just transition. However, a high dependence on sunset industries to raise fiscal revenues might constrain both economic growth and the transition itself once fiscal imbalances reduce the capacity of governments to invest in the transition needs. Finally, guaranteeing employment, with special attention to those that pays high wages, is essential to ensuring a just transition. However, although the net impact of the transition may be positive worldwide, the impact is not homogeneous across countries. Economies that depend more on sunset industries to generate employment and pay wages will be negatively impacted by the transition, and they need to find solutions to avoid socio-economic downsides.

Countries thus have to develop a modernization and industrialization strategy that fully incorporate their climate constraints, vulnerabilities and opportunities. The next sections will analyze the different aspects of how this can be tailored in the context of Viet Nam and its net zero commitment.

This framework allows us to identify the countries most exposed to the low-carbon transition as well as those most impacted by climate change in different dimensions, due to the relative importance of their impacted industries. It is also possible to analyze which countries are the most vulnerable according to their ability to switch from declining industries to industries considered as green.

Following the framework of Espagne *et al.* (2021b), three different dimensions are considered in the analysis: external, fiscal and socio-economic. To assess the external exposure, the net foreign exchange income induced by the declining industries (exports adjusted for imported direct and indirect inputs used in production) is calculated. For the estimation of fiscal and socio-economic dependencies, both direct and indirect impacts are considered by estimating the total output by sector that is directly and indirectly related to declining industries. Whereupon, based on taxation, wages, and employment by sector, a calculation of the share of each of the variables related to declining industries is undertaken.

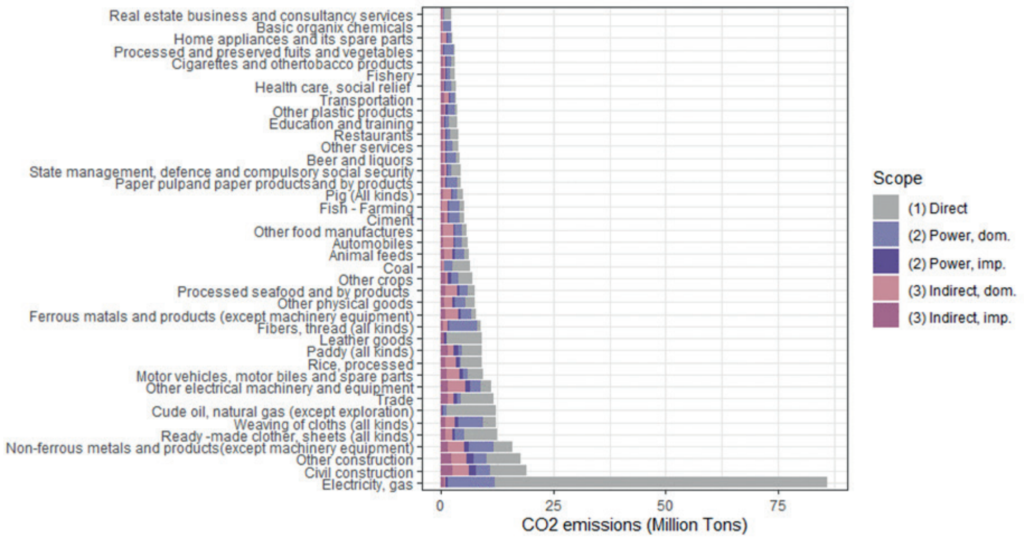
2. Exposure to a net zero transition

2.1 Definition of sunset industries

In 2021, a macroeconomic framework [Espagne *et al.*, 2021b] was used to analyze the dependence of countries on the sunset industries. Based on hybrid multi-regional input-output (MRIO) matrices, the analysis first identified the sectors with the highest upstream and downstream carbon emissions per unit of production, and then estimated the direct and indirect dependence of these sectors for 189 countries for 2015, including Viet Nam, in the EORA-26 database [Lenzen *et al.*, 2013]. Even though the level of aggregation of EORA-26 does not allow us to identify exactly the sunset industries, based on sectoral carbon-emission intensity, it finds that they are mainly within the following four sectors: mining and quarrying; petroleum, chemical and non-metallic mineral products; metal products; and electricity, gas and water.

Once the sectors were identified, the countries' exposure in the three dimensions (external, fiscal and socio-economic) is analyzed. External exposure is measured according to the net rise in foreign currency (exports discounted by imported inputs embodied in exports) due to the most emitting industries; fiscal exposure according to the net rise of fiscal revenues (tax directly paid by sunset industries and by industries that supply for sunset industries); and socio-economic exposure according to the employment and wages (including industries that supply for sunset industries). The analysis of countries' exposure must also consider the current emission-intensity of the

[Figure 2.1]
Total emissions per sector, by scope and origin, for Viet Nam



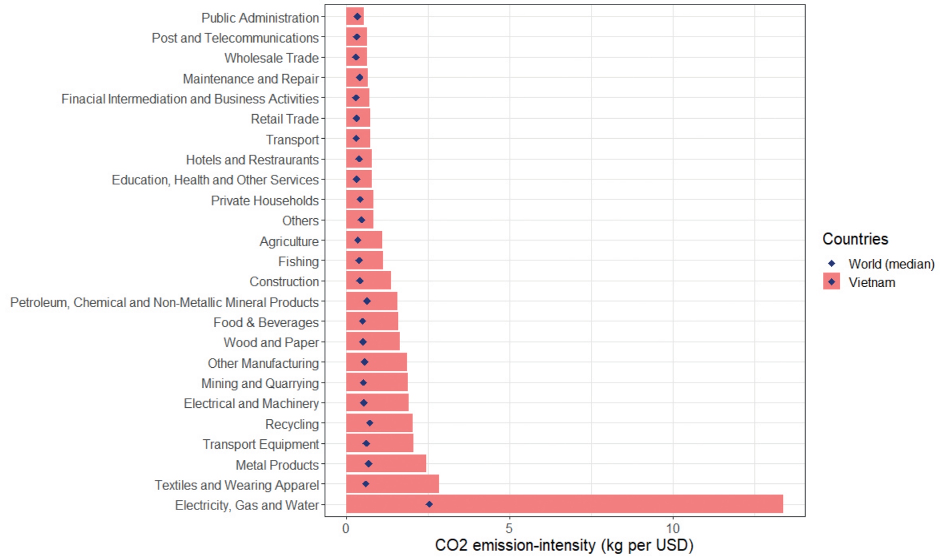
industries. Some countries may be dependent on these industries but, because they produce cutting-edge technology in terms of emissions, they will be less impacted by transition policies. On the other hand, the impact and the transition costs will be much higher if the production within these industries has a high emission intensity, even if the country is not very dependent on these industries.

Considering the emissions embodied in inputs, the most important industry for the aggregate emissions in Viet Nam is electricity and gas, followed by construction (civil and other), as shown in Figure 2.1. Total emissions can be split into: Scope 1, or direct emissions; Scope 2, which are those embodied in purchased power (they can be imported or domestically produced); and Scope 3, which are emissions embodied in other inputs, (they can also be imported or domestically produced). For electricity and gas, Scopes 1 and 2 are the most important ones, since the process of producing them is emission-intensive. In the construction sector, the most important sources of emissions are indirect emissions embodied either in inputs or in power, which is also the case in non-ferrous metals, the fourth most emitting industry in the country.

The analysis of other high emitting industries, such as power, helps explain this finding. In Viet Nam, power is also emission-intensive because fossil fuels are still relevant for the Vietnamese industry. Construction materials, such as prefabricated concrete, is also important in terms of emissions because the technology used to produce them is not updated from an ecological point of view. Finally, other industries, such as non-ferrous metals, textiles and extraction of crude oil and gas, are also vitally important in terms of emissions in the country.

Figure 2.2 presents an emission intensity comparison across countries for the sectors in the EORA-26 database, considering direct and indirect emissions. Despite an aggrega-

[Figure 2.2]
Comparison of emission intensity across sectors (Viet Nam and World)



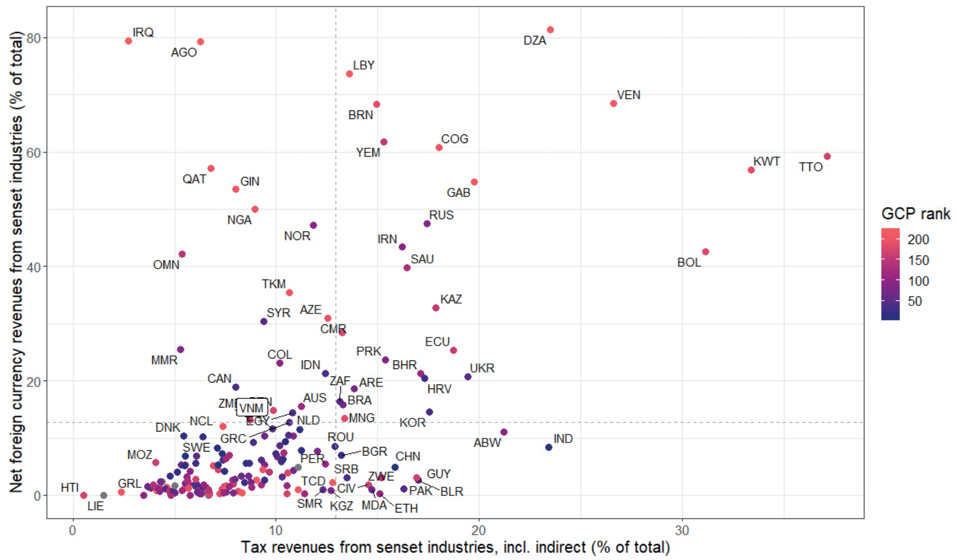
tion at the sectoral level, the database allows us to compare with a great number of economies, as data is available for almost 200 countries. As it is shown, Viet Nam is an economy with a significantly high emission intensity when compared with the world median. For example, in the electricity, gas and water sector, while the world emits less than 2.5 kg of CO_2 per US dollar, Viet Nam emits almost 15 kg of CO_2 per US dollar. The same pattern is verified in other industries. In the textiles and wearing apparel, as well as in metal products, Viet Nam emits about 2.5 kg of CO_2 per US dollar, while the world median is inferior to 1 kg per US dollar.

2.2 External and fiscal exposure

Since COP26, Viet Nam has been promoting ambitious efforts for a green transition. Vietnamese Prime Minister Phạm Minh Chính announced a net zero objective for the Vietnamese economy in 2050. It is already clear that this ambitious announcement of GHG emission reductions, combined with the prospective climate impacts that the country also face, will necessitate strong structural change in the country's process of industrialization and modernization. Despite not being among the most exposed countries in some dimensions, its dependence on sunset industries is still very significant.

Figure 2.3 presents external and fiscal exposure of the countries which depend the most on sunset industries, highlighting the Vietnamese macroeconomic exposure in these dimensions. Viet Nam (referred to as VNM in the figure) is not among the most exposed countries both from an external and a fiscal perspective. The dashed lines separate the first quintile of countries (top 20%) from the rest, and in spite of being next to this position, Viet Nam remains below the quintile. In fact, sunset industries account for about 10%

[Figure 2.3]
Fiscal and external exposure, all countries



Dashed lines indicates the first quintile; GCP: Green Complexity Potential.

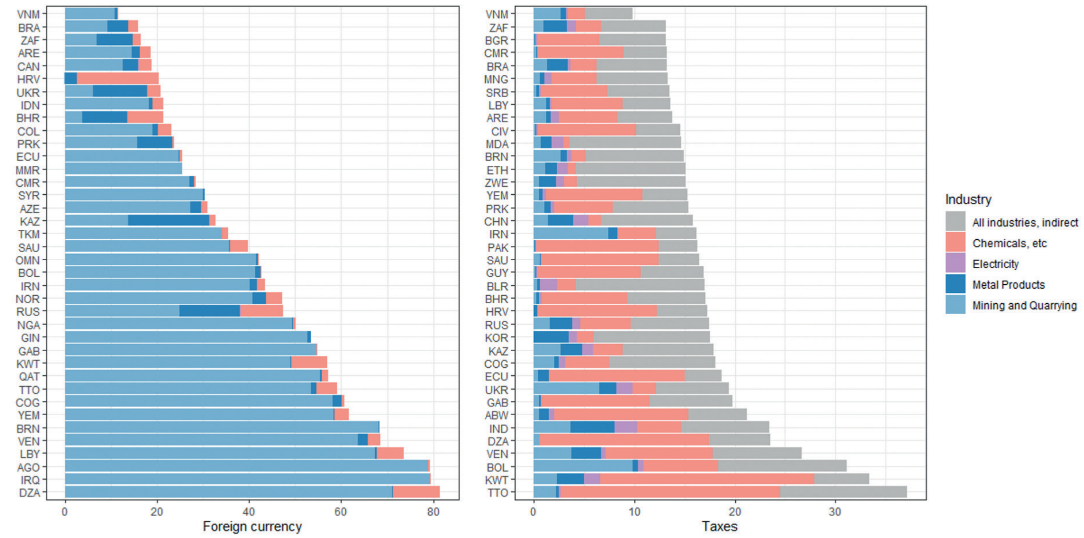
of the foreign currency raised by the country, as well as fiscal revenues, if we consider the indirect revenues obtained from sectors that provide inputs for sunset industries. It indicates that Viet Nam is relatively dependent on sunset industries, but this dependence is not as high as other economies, such as Trinidad and Tobago (TTO), Venezuela (VEN), Kuwait (KWT), Bolivia (BOL) and Algeria (DZA).

Although Viet Nam presents a relatively high external and fiscal dependences, the country is not among the most vulnerable to the low-carbon transition in these dimensions. In addition, it presents a high Green Complexity Potential (GCP), which means that it has the capabilities necessary to migrate the industrial structure towards green industries. As discussed in Section 5, Viet Nam is a country that has better conditions to set forth a structural change towards industries that will allow the country to move away from sunset industries.

In terms of the external exposure, the dependence on sunset industries for most countries is explained by the prominence of high-emitting industries in mining and quarrying. As shown in the left side of Figure 2.4, except some countries such as Russia and Kazakhstan, mining and quarrying is the main determinant of the external exposure, on which Viet Nam is not dependent to raise foreign currency.

Figure 2.4 shows, for the quintile of most exposed countries and Viet Nam, dependence on such industries to raise foreign currency (left side of the figure), and dependence on fiscal revenues (right side of the figure). The sectors that explain countries' fiscal exposure, on the other hand, are much more heterogeneous. Although mining and quarrying is still relevant, the other sectors and the indirect impacts also play an important role. In the case of Viet Nam, metal products and the indirect impacts are the main ones responsible for the fiscal exposure, but other industries, especially petroleum, chemicals and non-metal minerals, also play an important role.

[Figure 2.4]
Share of foreign currency and tax revenues from sunset industries



Only countries in the first quintile in terms of exposure, and Viet Nam, are presented; Chemicals, etc.: Petroleum, Chemicals and Non-mineral metals; Electricity: Electricity, Gas and Water.

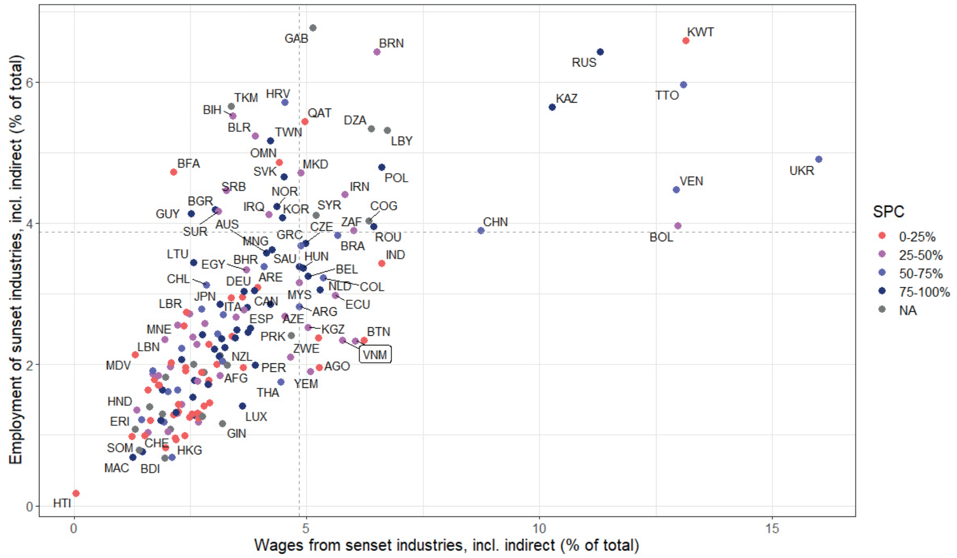
2.3 Socio-economic exposure

While the low-carbon transition will destroy many jobs in highly carbonized industries, such as fossil fuel electricity and extraction, it can generate many others in low carbon activities, such as renewable energy, agriculture and plant-based production. Although the worldwide net impact is considered to be positive, countries where sunset industries are responsible (directly and indirectly) for generating most of the jobs and paying large share of wages are those with the highest exposure to the low-carbon transition in the socio-economic dimension.

Figure 2.5 presents countries' direct and indirect dependence on sunset industries to generate employment in the vertical axis (y) and wages in the horizontal axis (x). The social protection coverage (SPC) is presented as the point color. Countries in the upper right part of the graph are those that depend on sunset industries for both employment generation and wages; those in the bottom left pay low wages in these industries, but sunset industries are not responsible for generating a large number of employment.

In contrast with the findings of the analysis of external and fiscal exposure, the socio-economic exposure of Viet Nam is higher compared to other countries because it is more dependent on sunset industries to generate well-paid jobs. Even though the country is not among the top fifth quintile of countries in terms of employment generation (represen-

[Figure 2.5]
Socio-economic exposure, all countries



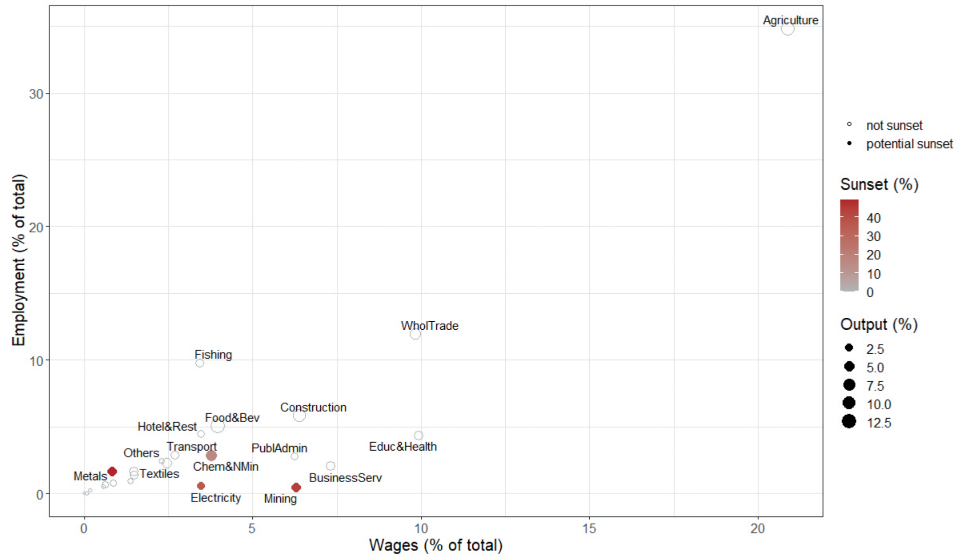
Dashed lines indicate the first quintile; SPC: Social Protection Coverage.

ting less than 2.5% of total employment), these industries are considerably relevant in terms of wage income, as they represent about 7% of the wage bill. Therefore, from a socio-economic perspective, one can say that Viet Nam is exposed to the low-carbon transition, as it depends (directly and indirectly) on these industries, and their decline might destroy employment opportunities that receive relatively high wages.

High exposure, however, does not necessarily mean high vulnerability. Countries with high socio-economic exposure to the low-carbon transition that also present high inequality, with a large share of the population below the poverty line and low levels of social protection, are much more vulnerable than countries where sunset industries are relevant but where population is relatively well protected against job losses. The International Labour Organization compiles data on SPC for most of the countries under consideration here. The share of the population covered by at least one social protection benefit provides synthetic information on the resilience of countries' most impacted population. This is, however, a main issue for Viet Nam in the socio-economic dimension. As Figure 2.5 shows, the SPC in Viet Nam is low, indicating that the country needs to improve its social security system to reduce the potential social impact of the transition on the population that may lose jobs.

The sectoral analysis of the socio-economic exposure, presented in Figure 2.6, shows the direct and indirect importance of each sector to generate employment (y axis) and to pay wages (x axis). Moreover, the color of the circle indicates the share of sunset industries within each sector and the size the sectoral share on total output.

[Figure 2.6]
Sectoral contribution for employment and wage income



While agriculture, wholesale trade and fishing are the most important industries that generate employment in the Vietnamese economy, education and health is essential in terms of the country's wage bill. More than 35% of employment is generated directly or indirectly by agriculture, and about 10% by wholesale trade and fishing. In terms of the wage income, agriculture contributes directly and indirectly, with more than 20%, and wholesale trade and education and health contribute another 10% each.

In terms of employment, sunset industries play a minor role, as they are not responsible for generating a substantial volume of jobs neither directly nor indirectly. In terms of wages, these industries are much more relevant. The mining and quarrying sector represents more than 5% of wage income, and sunset industries are about 45% of the sector. Electricity is also an important industry, as it is responsible for about 3% of wages (one-third is from fossil fuels). Petroleum, chemicals and non-metal minerals, as well as metal products, are less relevant. The former represents about 3% of wages, but only 15% is sunset industries, while the latter represents about 1%, one-half of which actually stem from sunset industries.

All these findings are important to understand both advantages and challenges that the Vietnamese economy may face in a net zero scenario. It is clear that the country has a relatively high exposure to the low-carbon transition because of its dependence on sunset industries, albeit mainly in socio-economic terms. At the same time, it indicates that it should promote a structural change towards green industries to reduce dependence and minimize the future negative impacts the low-carbon transition may have.

Despite having technological and productive capabilities to promote structural change, the country will face two important issues during the transition process. Firstly, many jobs, especially the well-paid ones, are at risk and a relevant share of the labor force is not covered by social protection. Moreover, because of high levels of emissions within industries there, the impact of the transition will be more prominent in Viet Nam than in other developing countries, demanding more investments in green technologies.

The next section addresses the other important exposure Viet Nam may face during a net zero transition, which is the exposure to the inevitable impacts of climate change.

3. Exposure to climate change damage

3.1 Building a global sector-by-country damage function

IPCC's sixth assessment report (AR6), the latest in a series of reports that assess the science of climate change, indicates that global average temperature is expected to reach 1.5°C as early as 2030. Logically, the average annual temperature has increased over most of the Asia region over the past century. That trend is expected to continue until 2050 unless GHG emissions are eliminated.

Climate change will result in more frequent extreme events and more significant associated risks to the ocean and terrestrial ecosystems. Some common regional changes are also expected for Southeast Asia in terms of heat extremes, increased rainfall, floods and cyclones.

The cumulative impacts of climate change, land subsidence, as well as more local human activities, will mean higher flood levels and prolonged inundation, for example, in the Mekong Delta region; rainfall for the northern part of Southeast Asia will increase, while it will decrease in maritime Southeast Asia. In the second half of the 20th century, the Southeast Asian monsoon weakened due to anthropogenic aerosol forcing. In the near term, such precipitation will be dominated by the effects of internal variability and tends to increase at the end of the 21st century.

Besides changes in national and global emissions following the alignment of climate policies with the Paris Agreement, countries will also be impacted by climate change. Countries which export natural resource-based products or which depend on their production might be impacted due to the lower availability of these resources. Moreover, climate change will also impact labour productivity according to countries' dependence on activities, which in turn will be impacted by the increase in solar radiation. The definition and the evaluation of the impacted sectors discussed in this section are based on recent international publications.

We consider here three sectors that will be deeply impacted by climate change: cereal production, fishing, and electricity from hydropower. We further add the specific impacts that climate change incurs on tourism demand, as well as sea-level rise.

With regard to cereal production, potential impacts will be due to a reduction in plantable yields if no adaptation measures are taken. In the case of fishing, changes in water temperature, for example, may reduce the supply of fish and other sea animals. Finally, in the case of electricity from hydropower, even though the impact might be positive in general, changes in water regimes may have some negative impacts, especially in regions that depend on it to produce low-emitting electricity such as Latin America.

Cereal production

The Fifth IPCC Assessment Report (2014) estimated a global reduction of about 1% in crop yield per decade due to climate change. The AR6 (2022) reports that 44 additional research confirm that it will disproportionately affect crop yields among regions, with more negative than positive effects expected in most areas. Even with the CO_2 fertilization effects, in the 21st century the overall median per decade yield change without adaptation is projected to be -2.3% for maize, -3.3% for soybean, -0.7% for rice, and -1.3% for wheat. The effects vary within each crop, timeframe, RCP (Representative Concentration Pathway) and region. The differences are related to the current temperature level and degree of warming. Climate change impacts appear to be positive where current annual mean temperatures are below 10°C and become increasingly negative where they are above 15°C [IPCC, 2022].

In this analysis, the climate change damage functions for the agricultural sector were built based on a dataset by Hasegawa *et al.* (2022), constructed through a systematic literature review on simulated crop yield change of four major crops (maize, rice, soybean and wheat). The database was developed for the use of IPCC and covers all the relevant studies published covering all six cycles of the IPCC assessment. More specifically, it builds on 8,703 simulations from 202 studies published between 1984 and 2020. The 91 countries in the study account for 95% of the world's production of each commodity as of 2010. In addition to projected yields under different emission scenarios for the 21st century, it also includes information on the climate and crop models used, geographical coordinates, the consideration of adaptation measures, and current and projected temperature and precipitation levels. Most studies do not consider technological advances, yet they provide useful insights into time-, scenario-, and warming degree-dependent impacts of climate change.

To get a directly interpretable quantitative assessment of the impact of climate change on agriculture, we shall focus on the relationship between local temperature increase and the change in relative yield from 2005. Analyzing crops in different countries separately allows us to control the divergent magnitude of the impact attributed to the variation in current mean temperatures. Results from studies referring to scenarios belonging to simulations previous to the Fifth Coupled Model Intercomparison Project (CMIP5) were not considered in this analysis. For each crop type, a Bayesian meta-analysis was performed for each country, which Hasegawa *et al.* (2022) presents in a dataset of results from more than one study. The individual studies were considered only if they published at least two observations per crop. To capture the impact of local temperature change on crop yield, for each study, we estimate a simple linear regression model with the following equation:

$$\Delta Y = \beta 0 + \beta 1 \ \Delta T + \varepsilon$$

where ΔY and ΔT represent the projected change in crop yield and local temperature change respectively. $\beta 0$ is the constant term of the model for the country-crop combination and $\beta 1$ is the slope of the linear model. The slope can be interpreted as the impact on crop yield change of an additional 1°C of warming of the local mean annual temperatures. This coefficient will be the effect size on which the meta-analysis focuses.

The random-effects Bayesian hierarchical model is applied to perform a meta-analysis for each crop in each country. The result is an estimate of the crop-country effect size. Results from the estimation of regression model (1) are pooled together in a Bayesian framework. This methodology takes into account the standard error of each study's estimated effect size; therefore, studies with higher precision are given a greater weight when computing the estimated value of the crop-country effect size. Moreover, the model we used is a random-effects model that allows for the estimation of heterogeneity among studies and takes it into account when pooling studies' results. The estimated crop-country effect size is a weighted sum of studies' effect estimated values where the study's weight depends now of its own precision and of heterogeneity among studies.

Fisheries

The Food and Agriculture Organization of the United Nations [FAO, 2020] highlights the growing role of fisheries and aquaculture in providing food, nutrition and employment across the world. Climate change is affecting marine biodiversity and the productivity and distribution of marine fish stocks mainly through two primary mechanisms: i) rising water temperatures; and ii) acidification. The magnitude of these changes is of crucial importance for societies who depend on marine fisheries for their livelihoods. The climate change risk score constructed by FAO takes into account the projected impact on marine capture fisheries and the country's vulnerability (based on nutritional dependence, economic dependence and development score). The countries identified as the most exposed to the risk coming from projected changes in catch potential are mostly located in the tropical coastal regions of sub-Saharan Africa and Small Islands in the Pacific.

The estimation of the impact of climate change on the fishing sector in the countries included in the model relies on the study by Lam *et al.* (2016), which analyzes how climate change will impact fisheries revenue at a global level by the 2050s under two scenarios, RCP2.6 and RCP8.5. First, it simulates future species distribution and maximum catch potential (MCP) under climate change using a Dynamic Bioclimate Envelope Model (DBEM). Projected changes in ocean conditions, such as for example sea surface temperature, sea bottom temperature, and salinity, were based on outputs from three Earth System Models. For the RCP8.5 scenario, the projected changes were based on the outputs of GFDL-ESM2M, IPSL-CM5-MR, and MPI-ESM. For the RCP2.6, the changes were based on GFDL-ESM2M only, as the outputs from the model are in the middle of the range projected with the other two models. The annual MCP change is subsequently projected for all species caught in each exclusive economic zone (EEZ) in the 2050s (average between 2041–2060) relative to the current status (2000s, or the average between 1991–2010) using an empirical model by Cheung *et al.* (2009). Finally, projected revenue is computed as the product of species-country real ex-vessel price (assumed to be constant throughout the study) and the projected MCP of each species.

Assuming constant price, under the RCP8.5 scenario, global MCP is projected to decrease by 7.7% by 2050 relative to 2000. Global fisheries revenue (or landed value at MRP) is projected to decrease about 35% more than the impact on MCP.

To have estimates of the projections of the change of fisheries revenue at a country level, we took the mean percentage change in fisheries MRP due to climate change in different fishing countries by latitudinal zonal average [Lam *et al.*, 2016]. The median percentage change in fisheries MRP under RCP8.5 and RCP2.6 is then attributed to the main fishing countries based on their average latitude, rounded to the nearest tenth.

For each fishing country[1] we extracted the average local temperature changes in 2041–2060 from the baseline years 1991–2005[2] in the three models used in the Lam *et al.* (2016) paper (GFDL-ESM2M, IPSL-CM5-MR and MPI-ESM). The result was a correspondence between the local temperature change and the maximum revenue potential (MRP) percentage change in the two RCPs considered. In order to get a quantitative assessment of the temperature-output damage function, we assume that the underlying relationship is linear. Under this assumption, we compute the slope $\beta 1$ of the linear model, where
(MRP change %) = $\beta 0 + \beta 1$ *(local temperature change).

The trivial slope that we obtain can be interpreted as the impact on the median maximum potential percentage change of an additional 1°C of the average temperature of a country. With the exception of New Zealand, all of the countries considered in the analysis performed exhibit a negative impact on the maximum revenue potential. In 2018, Viet Nam was the 7th major country for marine capture production, making up 4% of the global production.

1. For some of the non-landlocked countries, we do not have information on the temperature as the area covered by them is too small to be included in the climate models' projections. Due to this, we are unable to include them in the analysis.

2. The baseline years in Lam *et al.* (2016) are 1991–2010.

Energy

Climate change is believed to have an impact on both the supply and the demand side of energy systems. For example, energy demand is expected to vary as a result of an alteration in heating and cooling requirements patterns across the globe. On the supply side, temperature changes can affect cooling systems and turbine efficiency of thermal power plants. Additionally, changes in precipitation, temperature, wind speed, runoff, solar irradiation and other parameters alter the production capacity of various renewable energy sources to different extents. This section will focus mainly on climate change's impact on renewables.

Few studies in the literature published investigate global warming's impact on the whole energy system, and most of the studies on the supply side focus on the impact on hydropower production only. The meta-analysis by Yalew *et al.* (2020) presents results from 220 studies on the impact of climate change on energy systems. The supply-side impacts are classified into bioenergy, hydropower, solar, wind, and thermal power sources. The regional analysis from the reviewed papers shows large territorial differences across almost all energy technologies. A significant reduction in hydropower potential is projected for Latin America and South Asia, and a smaller one in the Middle East, North Africa, and Western Europe, The results are mixed for bioenergy, solar and wind power potentials, for which the authors report a significant lack of information. To obtain a regional-level assessment of the correlation between the local increase in temperature due to climate change and the renewable energy supply, our meta-analysis relies on the results from the studies by Gernaat *et al.* (2021) and Turner *et al.* (2021). The former provides a systematic energy-system-wide evaluation of climate change impact on the most relevant renewables known today, while the latter focuses on hydropower only.

The renewable sources investigated by Gernaat *et al.* (2021) include solar (utility-scale photovoltaic (PV), rooftop PV and concentrated solar power), wind (offshore and onshore), bioenergy (first-generation from sugars and vegetable oils and second-generation from lignocellulosic crops), and hydropower. To simulate the impact of climate change, the authors use outputs from four global climate models (GCMs) – GFLD-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, and MIROC5 – for relevant climate variables, such as solar irradiance, temperature, sugar cane, maize and lignocellulosic crop yields, wind speed, and runoff. The different technologies are affected by different groups of climate variables. For instance, wind energy is impacted by wind speed, and concentrating solar power (CSP) is impacted by temperature and solar irradiance. For each of these parameters, model means are computed from the historical period (1971–2001) and future (2070–2100) under the SSP2-RCP2.6 and the SSP2-RCP6.0 scenarios. The data are then used to calculate the relative impact of climate on technical potentials. Finally, the global energy system model TIMER (targets image energy regional model) is employed to simulate the long-term trends in primary energy supply in each IMAGE (integrated model to assess the global environment) region. Under RCP6.0, the results show a global increase of 4–6% in renewable use. This is a consequence of the increase of 10–20% in the use of bioenergy in most model regions. However, the impact on this renewable source depends on the CO_2 fertilization effect, the strength of which is still undetermined by the scientific community. Under the RCP2.6 scenario, the impact on energy potentials are limited, but since the renewables in this scenario account for a larger share in the total energy system, the effects on the energy system are comparable to those under RCP6.0.

Turner *et al.* (2017) explore the impact of climate change on hydropower generation in 32 world regions and the subsequent effects on the technological composition of the power sector, carbon emissions, and investment costs of new capacity. To do so, the authors use the 16 GCMs gridded climate projections for RCP8.5 and RCP4.5 scenarios as inputs for a coupled global hydrological and hydropower dam model. Then, the resulting hydropower projections are employed into an integrated assessment model to investigate how these changes would impact the power sector regionally. Globally, it is projected that by the end of the century, net global hydropower production will change between -8% and 5% under RCP8.5 and between -4% and 4% under RCP4.5 depending on the GCM.

To have a correspondence between the regional temperature change and the impact on energy supply, the average regional temperature changes are extracted from the climate models used in the studies by Geernat *et al.* (2020) and Turner *et al.* (2017) for the correspondent RCP and year spans. To obtain a quantitative assessment of the temperature-output damage function, the underlying relationship is assumed to be linear, *i.e.*

$$\Delta Y = \beta 0 + \beta 1 \; \Delta T + \varepsilon$$

where ΔY describes the energy supply change due to climate change and ΔT the corresponding change in regional temperature. An additional step is taken for the hydropower sector, for which we rely on two different sources and are therefore able to perform a small-scale meta-analysis. To do so, the hierarchical bayesian meta-analysis methodology is applied, which is described in more detail in Section Agriculture. For each global macro region, we obtain a measure of the impact of an additional 1°C in air temperature in the region on the supply or production of energy coming from the renewable energy sources considered.

Tourism

Academic works offering a quantitative analysis of the impact of climate change on international tourism flows at a global level are rare. Almost all refer to a paper published by Hamilton *et al.* (2005) 17 years ago. To bridge this gap, we used econometric tools to obtain a model allowing to fill missing observations on arrivals for some countries. The model that best fits the data regress total arrivals in a destination country (expressed in logarithm) on the area of a country (in km^2), the annual temperature for the period 1961–1990 (in degrees Celsius) averaged for the whole country, the length of coastline (in kilometres), and per capita income (expressed in logarithm). The squared temperature is added to the previous regressors to capture nonlinearity in the relationship between arrivals and temperature. Table 2.1 summarizes the estimation results.

The average temperature, the length of coastline and per capita income exhibit positive impacts on arrivals, while no significant effect is identified for country area. The arrivals-temperature relationship does not appear as nonlinear. Therefore, estimation results do not allow to compute a temperature level from which arrivals begin to decrease.

Roson and Sartori (2016) combined this estimated relationship with another one for departures to compute a first estimate of change in net foreign currency inflow. This obtained by the difference between variations in arrivals due to variations in temperature minus corresponding variations in departures multiplied by per capita tourist expenditure. Values for Viet Nam are reported in Table 2.2.

Once these forecasts of monetary inflows have been obtained, it is interesting to disaggregate them among the different economic sectors involved in tourism activity. Tourism Satellite Accounts (TSA) have been proposed by the United Nations as a tool to measure the relative size and importance of the tourism industry, along with its contribution to the

[Table 2.1]
Estimated regression model for arrivals

	Constant	Area	Temperature	Temperature^2	Coastline length	Per capita income (log)
Arrivals (log)	5.97 (0.97)	0.205x10^{-5} (0.96)	0.22 (0.07)	-0.00791 (2.21)	0.0000715 (3.03)	0.80 (0.09)

Number of countries = 139, year = 1995. Quality of fit: R^2_{adj} = 54%
Note: subscripted numbers are standard deviations. Source: Hamilton *et al.* (2005).

[Table 2.2]

Change in net foreign currency inflows (relative to 2011 GDP)

Temperature variation	1°C	2°C	3°C	4°C	5°C
Net foreign currency inflows	-0.82%	-1.55%	-2.19%	-2.77%	-3.29%

■ Source: Roson & Sartori (2016).

country's GDP (for a presentation of TSA, see OECD, 2010). TSA have now become an international standard in the evaluation of tourism activities, and they are freely available in about 60 countries. TSA has recently shown their usefulness in evaluating and disaggregating the carbon footprint of global tourism [Lenzen *et al.*, 2018]. Although very committed to the production of such data, Viet Nam does not yet have these accounts.

Sea-level rise/floods due to typhoons

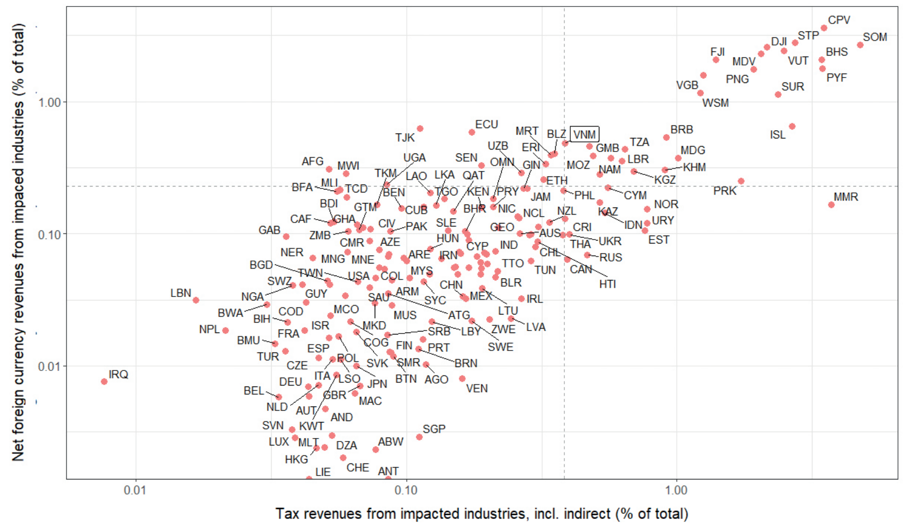
Estimations on the potential economic impact of sea level rise are based on Hinkel *et al.* (2014) and Lincke and Hinkel (2018). The authors estimate country-level impacts of floods on assets and the adaptation costs using different socio-economic and climate scenarios. These estimates consider that the coastal floodplain population is closely related to economic activity, and hence the higher the population living in these areas, the higher will be the economic impact of the increase in the water level of oceans. Essentially, they apply sub-national per capita GDP rates to the population data, multiplied by empirically estimated assets to GDP ratio of 2.8. For assets, the damage also depends on the depth by which the asset is submerged. They assume a logistic depth-damage function (giving the fraction of assets damaged for a given flood depth) with a 1-meter flood destroying 50% of the assets. Depth-damage functions have a declining slope, reflecting that additional damage declines with additional water depth. The selection of a 1-meter depth is a good indicative value based on the available information.

The damage to assets done by a flood of height x is computed by integrating from elevation level 0 to x over the product of the depth-damage function applied to the water depth, and the derivative of the cumulative exposure function applied to the elevation level y. If there are dikes, the damage is 0 for floods with a height below the top of the dike. The flood cost is computed as a mathematical expectation of the people and assets damage functions.

Aside from the above estimates, instead of estimating damage functions, we consider the scenarios given, and we use the flood costs directly to analyze the potential impacts on output, exports, employment, and wages. In the RCP 8.5 scenario, a 2°C increase in temperature is reached in 2040, and assuming the SSP5 scenario, the impact on assets is given by Lincke and Hinkel (2018). Once sea-level rise does not impact any specific sector, but the economy as a whole, we distribute these impacts proportionally to the output to account for the exposure in different dimensions.

[Figure 2.7]

External and fiscal exposure to climate change



■ Dashed lines indicates the first quintile.

4. Countries' exposure to climate change

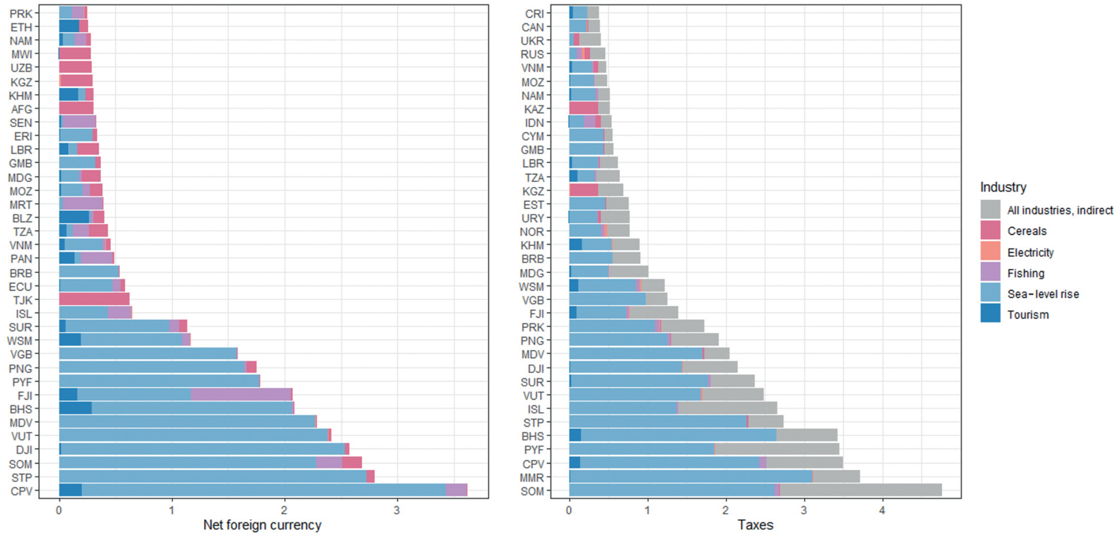
4.1 Fiscal and external exposure to climate change

Countries' external and fiscal exposure to climate change (in the 2°C scenario) is presented in Figure 2.7 (dashed lines indicate the first quintile, or the 20% most exposed countries). In general, small islands and countries with large costs, such as Somalia (referred to as SOM in the figure), are the most exposed countries in the fiscal and external dimensions. It means that climate damages due to temperature increase may reduce the capacity of key sectors to raise foreign currency and generate fiscal revenues. Southeast Asian countries are also among the most exposed economies. Myanmar (MMR), for example, is highly exposed in the fiscal dimension, but not as much in the external dimension, meaning that climate change tends to impact mainly the sectors important in raising fiscal revenues, but not so much the sectors important in raising foreign currency. Conversely, countries in the top left area of Figure 2.7, such as Ecuador (ECU) and Tajikistan (TJK), are exposed mainly in the external dimension, but not as much in the fiscal one.

Viet Nam (referred to as VNM in the figure, in a rectangle) is among the group of countries with a higher exposure in both dimensions. The country depends on the most impacted industries both to raise foreign currency and to generate fiscal revenues. Especially in the external dimension, the relative position of Viet Nam is not very comfortable: it is among the top 10% most exposed economies.

The high exposure of the country indicates that it should reduce the dependence on these industries to avoid both fiscal and ba-

[Figure 2.8]
External and fiscal exposure to climate change by sector, most exposed countries



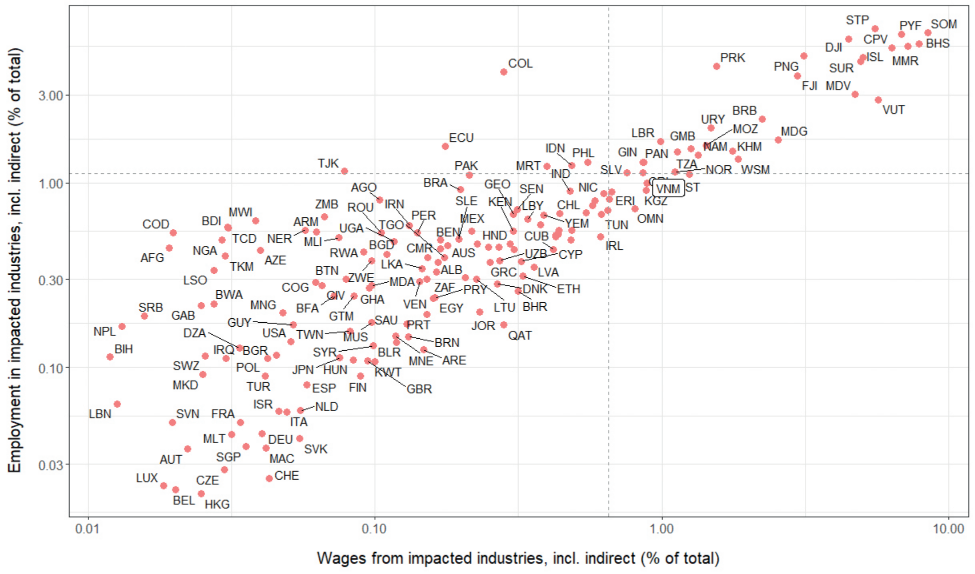
Only countries in the first quintile are present; share of net foreign currency and taxes from potentially impacted industries, including indirect impact (%).

lance-of-payment constraints. The reduction of available resources in a 2°C scenario might imply either lower production in the country or the need for investments in adaptation measures to compensate for these losses. In the first hypothetical case, if the country does not move towards less vulnerable activities, there will be a drop in the fiscal and foreign currency revenues, which may lead to an increase in domestic and external debt. In the latter scenario, costs of production will increase, possibly leading to competitiveness losses in these industries, and also imply some costs from fiscal and external perspectives.

Besides being different from one country to another, climate change has specific impacts when we account for each one of the dimensions. Countries' exposure is mainly explained by sea-level rise, as presented in Figure 2.8, because it impacts different sectors in the economy. This is especially relevant for small islands and countries with large costs. Nevertheless, potential reduction in, for example, cereal production caused by reduction in plantable yields is the main driver of the external exposure in some countries because many of them depend on this industry to raise foreign currency. Central Asia countries, such asUzbekistan (UZB), Kyrgyzstan (KGR), Afghanistan (AFG), and Tajikistan (TJK). In Viet Nam, sea-level rise is the main driver of the country's exposure in both dimensions, but other potential impacts, such as in tourism and cereals, also play an important role in explaining the high exposure of the country.

In the case of taxes, the results are slightly different since backward indirect impacts are also taken into account. Even though sea-level rise predominates in most of the countries, total indirect impacts also explain a relevant share of the fiscal dependence on impacted industries. The higher the dependence of industries that provide inputs to impacted sectors, the higher the backward indirect impacts are, and Viet Nam is among the most exposed countries in fiscal terms, due to potential drop in tourism, cereal production, as well as by the indirect impacts the drop in production may cause in other industries.

[Figure 2.9]
Socio-economic exposure to climate change



Dashed lines indicates the first quintile; SPC: Social Protection Coverage.

4.2 Socio-economic exposure to climate change

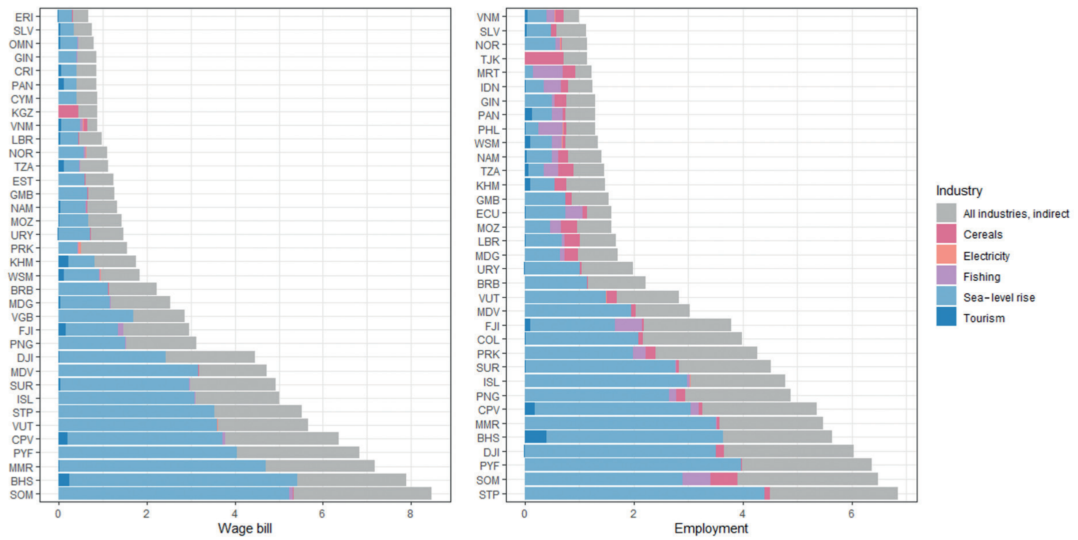
Besides being exposed to climate change in the fiscal and external dimensions, Viet Nam is also very exposed in socio-economic terms. As presented in Figure 2.9, the country is among the ones which depend the most on directly and indirectly impacted industries to generate employment and, mainly, wage income. Somalia (SOM) is the most exposed country, with almost 10% of employment and wages exposed to climate change. Apart from small islands, another extremely exposed country is Myanmar (MMR) with more than 5% of wages and employment exposed to climate change impacts. It means that with no adaptation or mitigation measures, a relevant share of employment and wages are at risk.

Viet Nam (VNM), on the other hand, is among the top 20% most exposed countries in terms of wage income, and close to this group in terms of employment. Around 1% of the wage bill and employment comes from the potentially impacted industries. The fact that potentially impacted industries are responsible for generating employment and paying wages in Viet Nam does not mean, however, that the country will be impacted in the same way. In fact, depending on its capacity to migrate to other industries and to adapt, the damage can be mitigated. Nevertheless, if the country is not capable of doing this, the damage can be amplified by the loss of competitiveness and supply constraints in value chains.

Figure 2.10 presents the source and sectoral distribution of the socio-economic exposure for the top 20% potentially most impacted countries as well as for Viet Nam. Sea-level rise is again the main source of damage in the economy for most of the countries both in terms of wages and employment. Nevertheless, because agriculture and fishing tend to be more labor-intensive than other sectors, jobs that depend on potentially impacted industries are not as concentrated as wages. In the case of employment, the impact of fishing, for example, is the main source of exposure in the Philippines (PHL), while the production of cereals is more relevant in many countries.

In the case of Viet Nam (VNM), sea-level rise is the main cause for the exposure of wages, but fishing and cereals are also very important in terms of employment. This means that jobs in the country may be impacted from different sources, and thus may require different types of adaptation measures to avoid the socio-economic impacts of climate change damage.

[Figure 2.10]
Socio-economic exposure to climate change by sector, most exposed countries



Only countries in the first quintile are present; share of wages and employment of potentially impacted industries, including indirect impact (%).

5. Green industrial and technological opportunities

5.1 Green complexity and industrial strategy

This section addresses the industrial opportunities of a low-carbon transition for Viet Nam. The promotion of green industries is a fundamental tool to ensure that the demand for products that reduce environmental impacts will be absorbed in large areas domestically. Resource-efficient technologies, renewable energy, pollution management tools, and many other green industries will become increasingly important in the coming years and decades as a result of the green transition. Countries capable of producing these goods will face fewer economic constraints during the transition period and will also be able to supply such goods to other economies, thus ensuring inclusion in both emerging and developed country markets.

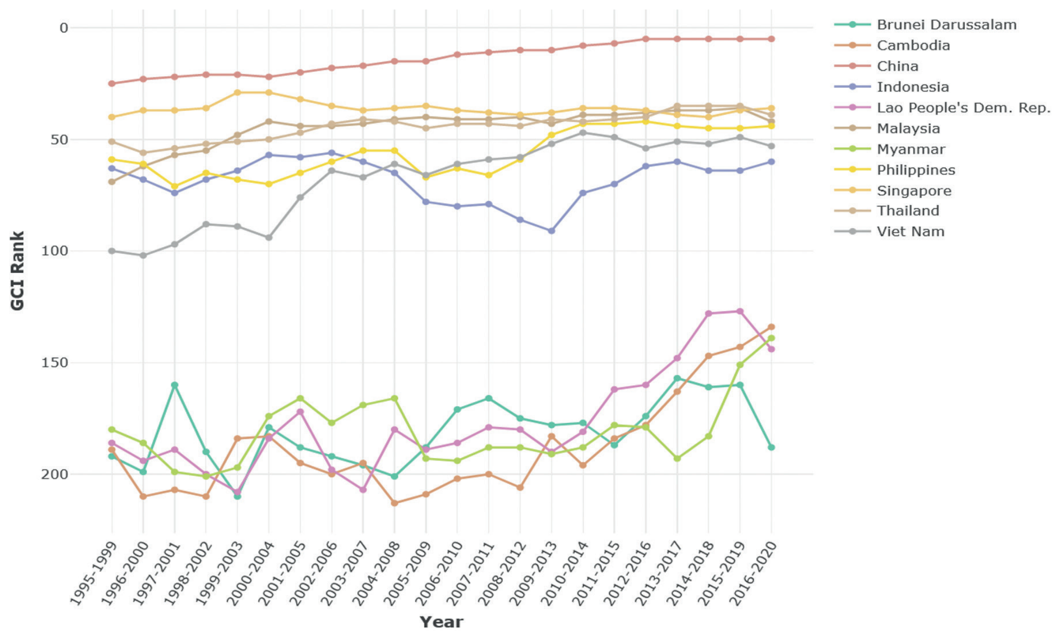
Yet, green products vary considerably in terms of technological sophistication. The production of more sophisticated goods requires specific capabilities that only a few countries possess. Conversely, the production of less sophisticated goods is easier, but less profitable from the perspective of firms and countries. The economic complexity approach suggested by Hausmann *et al.* (2014) compares products in terms of technological sophistication and, based on trade data, assesses which countries have the greatest capacity to produce these goods. Essentially, based on the group of products for which countries have revealed comparative advantages, the authors identify the products in order of complexity as well as new products that are closest in terms of the capabilities available in the country. They calculate an index of product complexity and the distance of a country from each product based on the products for which the country has a revealed comparative advantage. Mealy and Teytelboym (2020) used this method to identify countries' opportunities to promote green industries, where they calculated the complexity index of a list of products considered necessary for the green transition along with the proximity of all countries to these products.

Products for which the country already has a comparative advantage and high proximity are considered green competitive assets, while products for which countries have high proximity but low comparative advantage are considered mere green opportunities. The idea behind this approach is that countries with high proximity have the capacity to produce goods, and thus the capability, through appropriate industrial policies, to shift their production structure towards these industries.

5.2 Southeast Asia and Viet Nam in the green product space

Among the ASEAN countries and China, Viet Nam has experienced one of the most striking increases in its Green Complexity Index (GCI), reaching the 50th position at the world level in the late 2010. It now comes almost at the same level as Malaysia, the Philippines, Singapore, and Thailand, and higher than Indonesia. The group of Brunei, Cambodia, Lao PDR and Myanmar is far-removed from the rest of Southeast Asian countries, at around the 150th position, although we

[Figure 2.11]
Green complexity index of ASEAN countries and China, 1995–2020



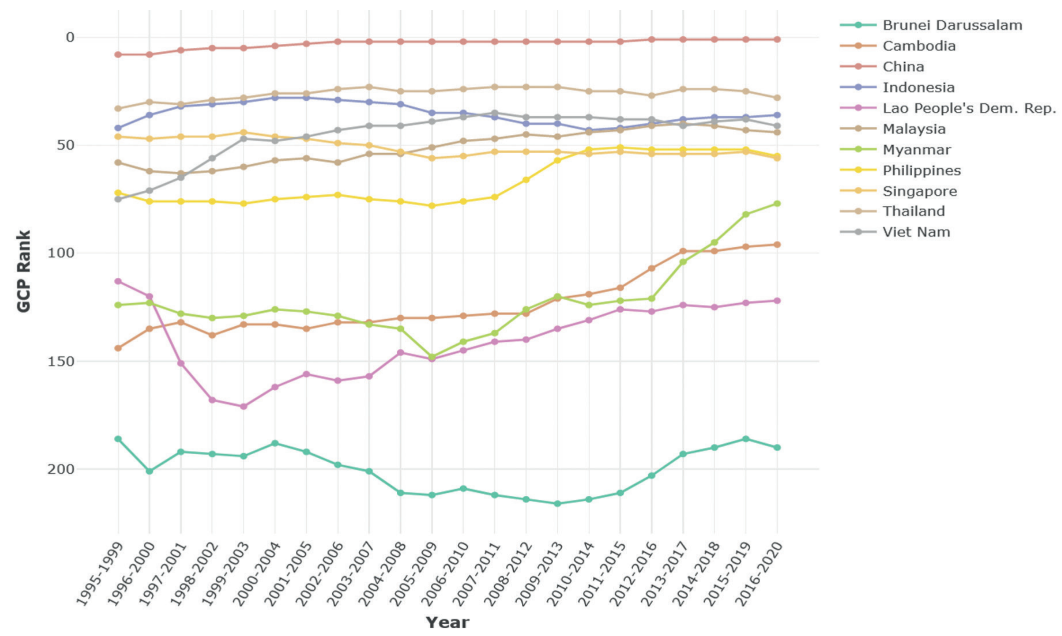
can observe a very rapid increase in GCI rank for Myanmar in recent years.

The picture in terms of GCP shows Viet Nam in a more stationary position, starting from a higher rank than its GCI rank, but progressing also slower. Apart from Brunei and Cambodia, the dynamics of ASEAN countries show a convergence in their GCP, which implies a potentially increased competition between ASEAN countries on their capacity to develop green products.

Within Southeast Asia, two groups of countries emerge depending on their green complexity index. One group, which includes Viet Nam, benefits from a combination of natural resources, an increasingly educated workforce, established regional supply chains, and low-cost manufacturing capabilities that have already started to pivot towards clean technologies. The other group includes countries which have not yet engaged in the process of complexification of products. Although they clearly lag behind in terms of their current GCI, the second group of countries still show a promising progress with respect to their green complexity potential. Cambodia and Myanmar even appear to catch up with the first group on this green complexity potential index.

In this new 'green race', many developing Asian countries thus already demonstrate clear latent opportunities for clean technologies and industries that can sustain and accelerate their development as the world moves to decarbonise. Viet Nam is well positioned in this group, with a strong dynamic progression in recent years on the two indicators considered here.

[Figure 2.12]
Green complexity potential of ASEAN countries and China, 1995–2020



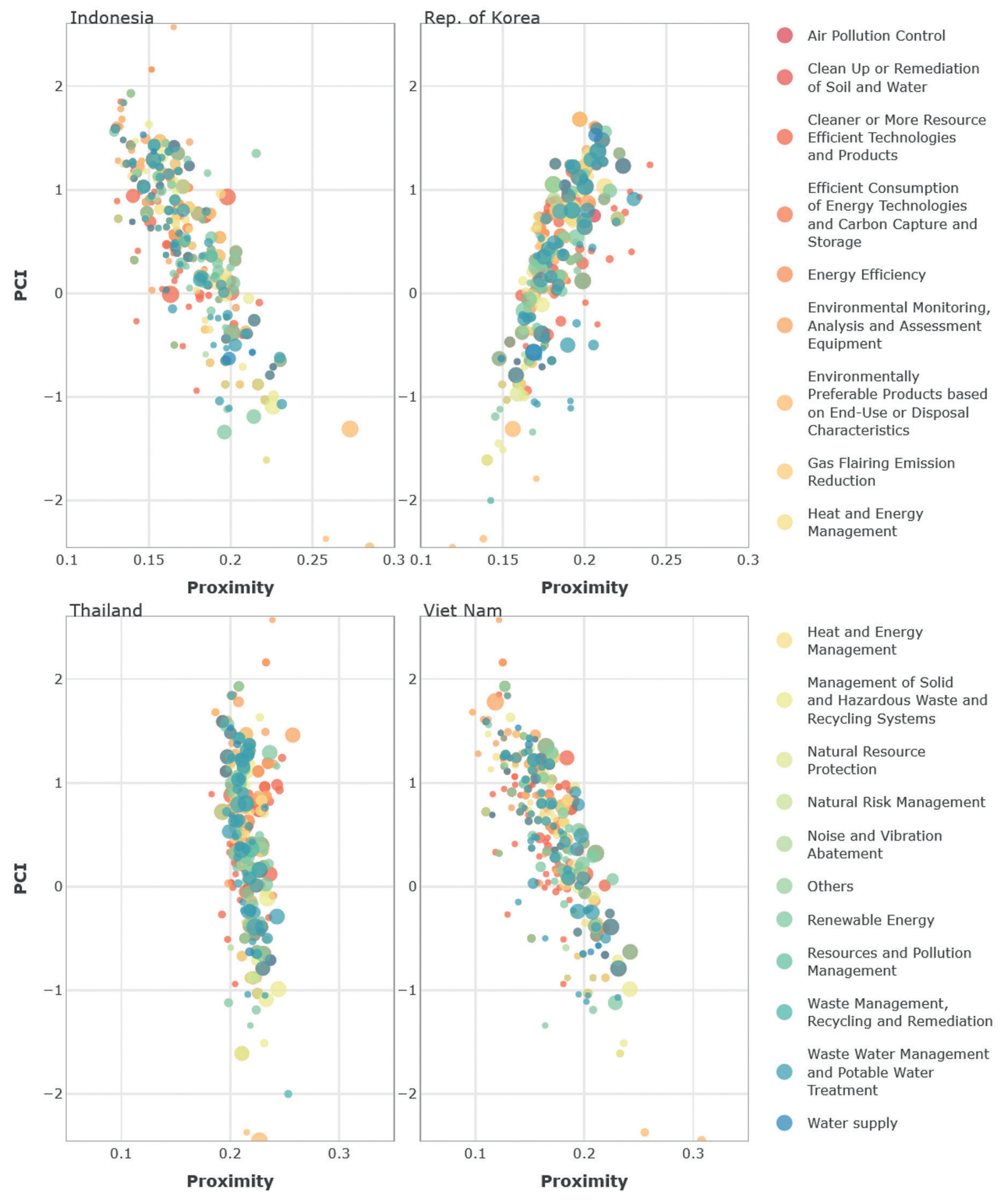
5.3 Complexity and proximity of green opportunities

We further look at the green opportunities for Korea, Indonesia Thailand and Viet Nam in the period 1996–2020. These graphs show the more or less complex nature of green products (product complexity index (PCI) on the ***y*** axis) and their relative proximity to the current productive structure of the country (proximity index on the ***x*** axis). The higher the PCI, the more technically complex the product; the higher the proximity, the higher the probability of developing future competitiveness in each specific product.

A comparison of the four countries shows an intermediary position of Viet Nam regarding its green opportunities, most of which (high proximity) are for relatively low-complexity products. In this respect, the profile is relatively similar to that of Indonesia. On the other hand, Thailand has a more equal distribution of its green opportunities between complex and low complexity products. Finally, Korea is not well-positioned in low-complexity products and its position on high-complexity green opportunities is also not better than Thailand's.

Due to global decarbonisation efforts, low-carbon technologies are poised to grow faster than many high carbon alternatives. As low-carbon hubs are emerging regionally (China for solar PV, Japan for electric vehicles, South Korea for energy storage), if Viet Nam manages to invest in targeted industrial and innovation policies in the areas where it has a potential high complexity green

[Figure 2.13]
Green opportunities of Korea, Indonesia, Thailand and Viet Nam over the period 2016–2020 in terms of product complexity (PCI) and proximity (similarity to the country's productive capacity)



opportunities,[3] it may succeed in combining an ambitious net zero strategy together with new competitive industrial development path.

6. Conclusion

Net zero objectives today cover most of the world, including the major developed and emerging economies, as well as many developing nations. This new reality ensures that demand for low-carbon products will grow fast in the coming decades. As the zero carbon paradigm spreads globally, development and industrial strategies need to turn into green development and green industrial strategies. Countries which will strategically position themselves in this new 'green race' will reap most of the benefits of these promising opportunities. Viet Nam's industrial and development strategy in the face of climate change will have to navigate between macro-financial constraints, multi-dimensional vulnerabilities due to inevitable impacts, current high emission path dependency, and its highly strong technological perspectives in green industries.

When Viet Nam positioned itself at the forefront at COP26, it ushered an era of rapid structural change for the country.. As the world economy transitions towards cleaner and less carbon-intensive forms of development, the ambitious COP26 announcement of a net zero horizon in 2050 by Vietnamese Prime Minister Phạm Minh Chính comes at a strategic moment. Viet Nam starts its journey from a position of high-emission intensity compared to the rest of the world. The country emits almost 15 kg of CO_2 per US dollar in the electricity, gas and water sector, while the world emits less than 2.5 kg of CO_2 per US dollar. The same pattern is verified in other industries. In the textiles and wearing apparel, as well as in metal products, Viet Nam emits about 2.5 kg of CO_2 per US dollar, while the world median is inferior to 1 kg per US dollar. The country also has a relatively high exposure to sunset industries in terms of external, fiscal and socio-economic constraints. A low social protection coverage adds to the potential social impact of a rapid transition.

At the same time, Viet Nam belongs to the most exposed countries to climate impacts confirming its own specific interest to lead the global 'green race'. The GEMMES Viet Nam COP26 special assessment report [Espagne *et al.*, 2021], as well as the latest IPCC report [IPCC, 2022], tend to confirm this picture. Beyond the now well-known impacts on individual economic sectors, a cross-sectoral exposure analysis shows some significant potential impacts of a 2°C world in terms of external, fiscal and socio-economic effects. Viet Nam is among the most exposed countries to climate impacts in fiscal terms, as well as in terms of wage income and employment.

However, Viet Nam also shows a truly promising industrial and technological opportunities in a 'green race' scenario. When compared to other Southeast Asian nations, or even to developed Asian economies, such as Korea, Viet Nam shows not only remarkably important green opportunities in the less complex green products, but also some pro-

3. The detailed list of green opportunities for Viet Nam (according to this methodology) can be accessed online at: https://green-transition-navigator.org/. They are classified by environmental categories. To give the example of the 'energy efficiency' environmental category, Viet Nam has green opportunities in the following categories: "Chandeliers, other electric ceiling or wall lights"; "Electric table, desk, bedside and floor lamps";"Electric lamps, lighting fittings"; and "Air conditioners with reverse cycle refrigeration".

mising opportunities in more complex products, which usually bring with them the best job opportunities and technical capabilities.

In the recent decade, Viet Nam had the fastest increasing green complexity index among Southeast Asian economies, and one of the highest green complexity potential. Developing a robust green industrial and development strategy in the face of climate change requires deploying the right mix of policies to support diversification in those priority sectors.

The macro-financial effects of different net zero investment strategies need to be carefully assessed. A net zero transition could have different impacts on macroeconomic stability, depending on the country's capacity to support a competitive low-carbon industrial strategy and reduce technical dependency on the rest of the world (*i.e.* decrease the proportion of imported intermediate consumption). Depending on the transition trajectory and the financing option (public, private or PPP) for net zero, exchange rate, public debt, and foreign reserve dynamics might be substantially different.

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Part 3

An integrated prospective assessment of climate impacts, adaptation strategies, and net-zero strategy

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Abstract

The negative impacts of climate change on the economy could prevent Viet Nam from achieving its development targets of around 7% annual GDP growth until 2030, and becoming an industrialized country by 2045. Climate change has deeply impacted different economic sectors, including cereal production, fishing, and hydroelectric power. The Vietnamese economy is also exposed to the transversal impact of climate change on labor and capital, which are production factors. Using an integrated prospective assessment, we estimate the expected annual GDP loss, as a function of Viet Nam mean surface temperature (VNMST) change 2020–2099 relative to the pre-industrial period 1851–1900. We found that without adaptation, the average annual GDP loss is around 1.8% relative to the baseline scenario at 1°C of warming. This loss becomes 3.1% for a 1.5°C increase, 4.4% for a 2°C increase and up to 8.1% for a 3°C increase.

As a country that is vulnerable to climate change, climate responses are mainstreamed in the national strategy. Uncertainty can challenge policymakers and the private sector in adaptation investment decisions. Even though the adaptation costs are high, effective adaptation will contribute to reducing the negative impacts of climate change. Climate adaptation projects should target not only the reduction of hazard exposure through hard infrastructure, but also reduce social and economic vulnerability. Thus, we examine the adaptation challenges the country faces by taking the uncertainties about future climate scenarios and the availability of financing into account. The amount of adaptation investment is supposed to depend on expected climate damage and the future preference of each sector. Overall, with adaptation, the economic loss will be smaller compared to the scenario without adaptation. However, adaptation investment will adversely affect the financial situation of sectors in the economy, such as public debt. Climate finance – the financial aspect of climate change adaptation – plays an important role in achieving adaptation objectives. In addition, adaptation cannot replace mitigation. The greater the global warming, the more difficult adaptation would be.

Recently, Viet Nam has made an ambitious climate change commitment to net zero emissions by 2050. A net zero transition could have different impacts on macroeconomic stability, depending on the transition trajectory and the financing option. Our integrated prospective assessment framework has already shown its potential. It should also play a central role in the new reality of a net zero transformation, and a just transition ambition over the coming years. An analysis of the structural change of the economy toward greener growth should be considered. The macro-financial effects of different net zero investment strategies thus need to be carefully assessed.

Tóm tắt

Những tác động tiêu cực của biến đổi khí hậu đối với tổng thể nền kinh tế có thể khiến Việt Nam gặp khó khăn trong việc thực hiện mục tiêu phát triển với mức tăng trưởng GDP hàng năm khoảng 7% cho đến năm 2030 và trở thành một nước công nghiệp vào năm 2045. Biến đổi khí hậu đã tác động sâu sắc đến các ngành kinh tế khác nhau như sản xuất nông nghiệp, thủy điện. Nền kinh tế Việt Nam cũng chịu tác động của biến đổi khí hậu đối với lao động và vốn, là những yếu tố đầu vào cho quá trình sản xuất. Nghiên cứu này ước tính tổn thất GDP hàng năm theo sự thay đổi nhiệt độ bề mặt trung bình của Việt Nam (VNMST) trong giai đoạn 2020–2099 so với thời kỳ tiền công nghiệp 1851–1900 bằng cách sử dụng một khung đánh giá vĩ mô tích hợp. Kết quả cho thấy rằng nếu không có sự thích ứng, mức tổn thất GDP trung bình hàng năm vào khoảng 1.8% so với kịch bản cơ sở khi nhiệt độ tăng lên 1°C. Tổn thất này sẽ 3.1% khi nhiệt độ tăng 1.5°C, 4.4% khi nhiệt độ tăng 2°C và tổn thất có thể lên đến 8.1% khi nóng lên 3°C.

Là một quốc gia dễ bị tổn thương trước biến đổi khí hậu, ứng phó với biến đổi khí hậu đã được lồng ghép trong chiến lược quốc gia. Sự bất ổn về khí hậu có thể đạt ra nhiều thách thức các nhà hoạch định chính sách và khu vực tư nhân trong các quyết định đầu tư thích ứng. Mặc dù chi phí thích ứng cao, nhưng thích ứng hiệu quả sẽ góp phần làm giảm các tác động tiêu cực của biến đổi khí hậu. Các dự án thích ứng với khí hậu không chỉ nhằm mục tiêu giảm thiểu rủi ro thông qua đầu tư vào cơ sở hạ tầng mà còn giảm tính dễ bị tổn thương về kinh tế và xã hội. Do đó, nghiên cứu xem xét những thách thức thích ứng mà quốc gia phải đối mặt bằng cách tính đến những bất ổn về các kịch bản khí hậu trong tương lai và khả năng cung cấp tài chính. Số tiền đầu tư cho thích ứng được giả định là phụ thuộc vào thiệt hại dự kiến và sự ưu tiên cho tương lai của từng lĩnh vực. Nhìn chung, nếu có thích ứng, thiệt hại về kinh tế sẽ giảm đi so với kịch bản không có thích ứng. Tuy nhiên, đầu tư thích ứng sẽ ảnh hưởng đến tình hình tài chính của các lĩnh vực trong nền kinh tế, chẳng hạn như nợ công. Tài chính khí hậu – khía cạnh tài chính của thích ứng với biến đổi khí hậu – đóng một vai trò quan trọng trong việc đạt được các mục tiêu thích ứng. Ngoài ra, thích ứng không thể thay thế giảm nhẹ. Trái đất càng nóng lên thì việc thích ứng càng trở nên khó khăn.

Tại Hội nghị COP26, Việt Nam đã đưa ra tuyên bố mạnh mẽ về đạt mức phát thải ròng bằng "0" vào năm 2050. Quá trình chuyển đổi này có thể có những ảnh hưởng khác nhau đến sự ổn định kinh tế vĩ mô tùy thuộc vào lộ trình chuyển đổi năng lượng và các phương án tài chính. Khung đánh giá vĩ mô tích hợp của nghiên cứu này hoàn toàn phù hợp và có thể tiếp tục được sử dụng để nghiên cứu tác động của các chính sách trong thực tế mới của chuyển dịch năng lượng và chuyển dịch công bằng tại Việt Nam trong những năm tới. Chúng ta cần xem xét phân tích sự thay đổi cơ cấu của nền kinh tế theo hướng tăng trưởng xanh hơn. Các tác động tài chính vĩ mô của các chiến lược đầu tư để đạt phát thải ròng bằng 0 cần phải được đánh giá toàn diện.

Résumé

Les effets négatifs du changement climatique sur l'économie pourraient empêcher le Viet Nam d'atteindre son objectif de développement d'une croissance annuelle du PIB de 7% jusqu'en 2030 et de devenir un pays industrialisé d'ici 2045. Le changement climatique a profondément affecté les différents secteurs économiques, notamment la production céréalière, la pêche et l'énergie hydroélectrique. L'économie vietnamienne est également exposée à l'impact transversal du changement climatique sur le travail et le capital, qui sont des facteurs de production. Nous estimons les pertes annuelles du PIB en fonction du changement de la température moyenne de surface du Viet Nam (VNMST) 2020–2099 et par rapport à la période préindustrielle 1851–1900 en utilisant un cadre macroéconomique intégré. Nous constatons qu'en l'absence d'adaptation, la perte annuelle moyenne de PIB est d'environ 1.8% par rapport au scénario de référence pour un réchauffement de 1°C. Cette perte devient de 3.1% pour un scénario de réchauffement de 1.5°C, 4.4% pour une augmentation de 2°C et jusqu'à 8.1% pour une augmentation de 3°C.

Etant un pays vulnérable au changement climatique, les politiques de lutte contre le changement climatiques sont intégrées dans la stratégie nationale. L'incertitude peut interpeller les décideurs politiques et le secteur privé dans les décisions d'investissement d'adaptation. Même si les coûts d'adaptation sont élevés, l'adaptation contribuera à réduire les effets négatifs du changement climatique. Les projets d'adaptation au changement climatique doivent viser non seulement à réduire l'exposition aux risques par le biais d'infrastructures matérielles, mais aussi à réduire la vulnérabilité sociale et économique. Ainsi, nous examinons les défis d'adaptation auxquels le pays est confronté en prenant en compte les incertitudes sur les scénarios climatiques futurs et la disponibilité des financements. Le montant des investissements d'adaptation est censé dépendre des dommages climatiques attendus et de la préférence pour l'avenir de chaque secteur. En général, avec l'adaptation, la perte économique sera moindre fort par rapport au scénario sans adaptation. Cependant, l'investissement d'adaptation aura un effet négatif sur la situation financière des secteurs de l'économie, comme la dette publique. Le financement du climat – l'aspect financier de l'adaptation au changement climatique – joue un rôle important dans la réalisation des objectifs d'adaptation. En outre, l'adaptation ne peut pas remplacer l'atténuation. Plus le réchauffement est important, plus l'adaptation sera difficile.

Récemment, le Viet Nam a pris un engagement ambitieux en matière de changement climatique d'atteindre zéro émission nette d'ici à 2050. Une transition vers zéro émission nette pourrait avoir différents impacts sur la stabilité macroéconomique en fonction de la trajectoire de la transition et des options de financement. Notre cadre macroéconomique intégré a déjà montré son potentiel. Il devrait également jouer un rôle central dans la transition energétique et une ambition de transition juste dans les années à venir. Une analyse du changement structurel de l'économie vers une croissance verte devrait être envisagée. Les effets macro-financiers des différentes stratégies d'investissement pour atteindre zéro émission nette doivent donc être évalués.

1. Introduction

As shown in the previous parts of this report, Viet Nam is substantially exposed to both important climate impacts and a low-carbon transition. Being among the world's most vulnerable to climate change, Viet Nam was ranked 13th among countries the most directly affected by extreme events in the period 2000–2019. With a rapid economic growth over the last two decades and in the context of an increasingly carbon intensive energy system, Viet Nam is an increasing contributor to GHG emissions. In 2000, the greenhouse gas (GHG) emissions per capita were 0.6 metric tons. In 2019, it was around six times higher with 3.5 metric tons. The country is experiencing a rapid rising of GHG emissions greater than that observed in all regional countries, including the People's Republic of China, India, and the Republic of Korea. This increasing growth of emissions mainly comes from energy, particularly in the power sector, and other energy industries, manufacturing, transportation, as well as industrial processes.

Climate impacts could prevent Viet Nam from achieving her development target in becoming an industrialized country by 2045. Over the last two decades, Viet Nam has been marked as a development success story. It has rapidly transformed from one of the world's poorest nations into a lower middle-income country in 2010. This historical, long-term positive growth trend experienced in Viet Nam, where downward fluctuations are minimal and income per capita has been steadily rising, justifies the ambitious goal of the country. However, in order to help Viet Nam achieve its development goals while implementing its climate commitments, adaptation is essential to reduce climate impacts and pursue a growth strategy that reduces the carbon intensity.

Climate change responses are mainstreamed in the national strategy to ensure that they will be in line with the country's socio-economic and sustainable development plans. Viet Nam has adopted the National Adaptation Plan (NAP), representing a comprehensive and specific framework at the national level for planning, designing, and implementing climate adaptation measures. Recently, at the 26th United Nations Climate Change Conference of the Parties (COP26), held in Glasgow, Scotland, Viet Nam declared its commitment to achieving net zero by 2050 and to phasing out coal power between 2030 and 2040. This announcement by the Vietnamese Prime Minister Pham Minh Chinh has positively surprised the international community and spurred an intense debate within Viet Nam regarding the best options to make that structural shift.

An assessment of climate change impacts in the new reality of a net zero transformation is crucial for policy planning at the macroeconomic level. Existing literature mainly focused on specific sectors or specific regions. Sectoral impacts of climate change only give a partial view of potential impacts if cross-sectoral effects and feedback loops on the aggregate macroeconomic variables, mainly investment, consumption, exports, imports, and prices such as the exchange rate, are not accounted for. In addition, adaptation policies can help reduce the vulnerability of the country to climate change shocks. Adaptation includes all policies that reduce the economic and social impact of climate change.

The main objective of this part is to propose an integrated prospective economy-wide assessment to analyze the economic impacts of climate change and adaptation measures in the context of a greener industrialization process for Viet Nam. Such analysis allows an estimation of the risks posed by climate change and inform policy makers in decision-making and designing national strategies to adapt to climate change. A first systematic macroeconomic assessment was conducted in the COP26 special assessment report of the GEMMES Viet Nam project [Espagne *et al.*, 2021]. Damage functions were integrated to capture the impact of higher temperature in productive sectors and transversal aspects of the economy. Then, we extend this assessment by introducing the adaptation investment functions to capture how sectors decide to invest in adaptive capital which contribute to reducing the damage that might occur.

This part is organised as follows. Section 1 gives an overview of the socio-economic context of Viet Nam and current climate change challenges. Section 2 explains in detail our integrated framework that has been built within this project. Section 3 discusses the potential economic losses of climate change and adaptation measures on the economy. Finally, Section 4 concludes with policy-oriented recommendations and avenues for further research.

2. Climate change challenges and climate commitments

2.1 Remarkable economic development but vulnerable to climate change

Over the last three decades, Viet Nam has emerged as one of Asia's great success stories. At the 6th National Congress of the Communist Party of Viet Nam in December 1986, the government decided to abandon the central planning model to adopt the socialist-oriented market economy. Since then, Viet Nam has witnessed remarkable economic growth and has become a lower-middle-income country in 2010. Integration into the world economy and the financialization process have contributed to the Vietnamese economic outcomes. The economic performance can be captured by macroeconomic indicators: economic growth, employment, the balance of payments, and price stability (inflation) [Crockett & Goldstein, 1987]. Firstly, Viet Nam has experienced a remarkable achievement in the GDP growth rate with an average of 6–7% annually. Secondly, the stability of the unemployment rate remained at a moderate level of less than 3% is a considerable accomplishment for Viet Nam. Thirdly, price stability appears to be the most substantial preoccupation of the Vietnamese government. Inflation increased sharply in the global financial crisis of 2008 and the banking crisis of 2011. Since 2012, inflation has remained at a modest level. Finally, regarding the trade balance, the country registered a deficit in trade balance before 2012, which can be explained by the fast economic growth that domestic production has not fully satisfied.

However, since 2012, the country has run a positive balance on goods and services.

The process of industrialization contributes significantly to the economic growth, but it has consequently led to severe resource depletion and serious environmental damage. According to the Notre Dame University Global Adaptation Index (ND-GAIN), Viet Nam is ranked 126th out of 182 countries in terms of vulnerability score. Vulnerability measures a country's exposure, sensitivity, and ability to adapt to the negative impact of climate change. ND-GAIN measures the overall vulnerability by considering six life-supporting sectors – food, water, health, ecosystem service, human habitat, and infrastructure. According to the Global Climate Risk Index (CRI) published by Germanwatch (2021) who analyzes to what extent countries and regions have been affected by impacts of weather-related loss events (storms, floods, heat waves, etc.), Viet Nam is ranked 13th among countries the most directly affected in the period 2000–2019. While located at the end of several transboundary river basins, a low-lying coastline of 3,444 km exposes the country to rising sea levels. With the high population density and 70% of the population living in coastal areas and low-lying deltas, fast population growth and urbanization increase risks of socio-economic losses attributable to climate hazards. Climate change has deeply impacted different economic sectors, including cereal production, fishing, and hydroelectric power. The Vietnamese economy is also exposed to the transversal impact of climate change on labour and capital, which are production factors. In this context, climate change, therefore, sets out major challenges for the country, and the Vietnamese government is putting climate change and sustainable development at the heart of its development policy.

2.2 Climate policies toward a resilience and net-zero development pathway

Climate change responses are mainstreamed in the national strategy to ensure that they will align with the country's socio-economic and sustainable development plans. Being aware of the urgence of climate change responses, the Vietnamese authorities have started, as soon as 2008, to draw action plans and policies for climate change response. Climate policies aimed at mitigating global warming or adapting to its most detrimental effects are the dynamic result of complex processes involving scientific evidence and instruments' for social and economic feasibility that involve stakeholders with varying interests in taking action.

Climate change and its impacts are projected to intensify in Viet Nam, which urges the country to pay more attention to climate change adaptation strategy. Different official documents are dedicated to climate change adaptation, such as National Strategy on Climate Change (NSCC), National Action Plan to Respond to Climate Change (NAPRCC) and Law on Environmental Protection 2020. Climate change responses are mainstreamed in the national strategy to ensure that they will align with the country's socio-economic and sustainable development plans. In particular, Viet Nam has adopted the NAP, representing a comprehensive and specific framework at the national level for planning, designing, and implementing climate adaptation measures.

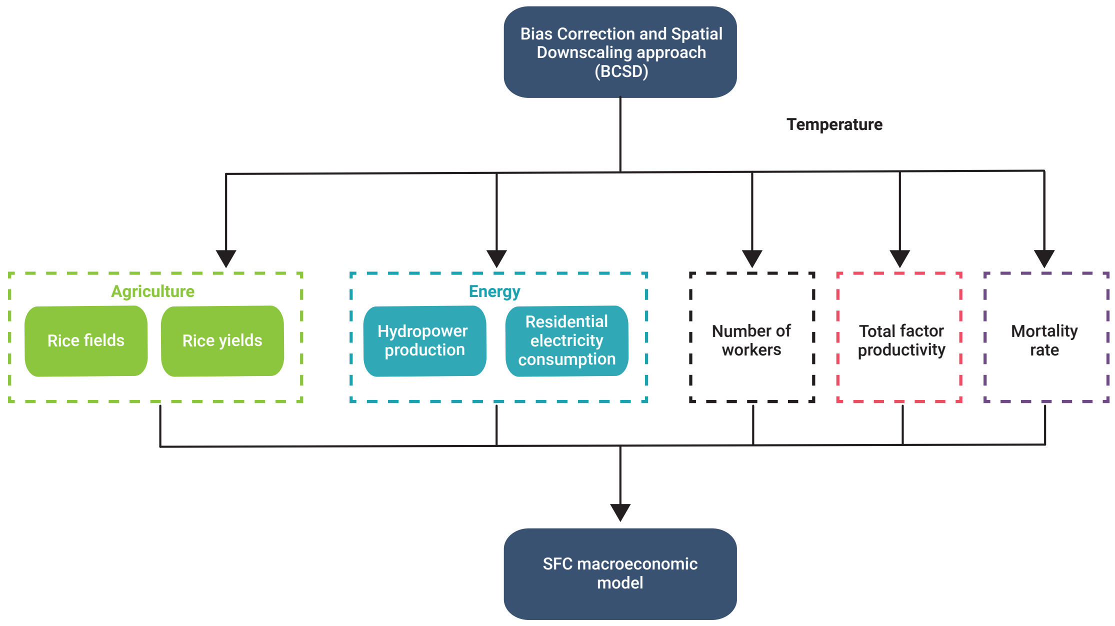
Adaptation interventions are classified into three categories corresponding to three main adaptation targets, including; **i)** strengthening resilience and enhancing adaptive capacity; **ii)** mitigating risk and damage from climate change-related disasters and enhancing preparedness to respond to extreme weather and natural disasters; and **iii)** strengthening national adaptive capacity through institutional improvement, capacity-building, securing resources, promoting international cooperation, and implementing international obligations. The NAP provides direction towards an effective and efficient allocation of resources, financial and technical management, and cross-sectoral and multilevel coordination. Following national adaptation policies, ministries and provincial authorities will develop their adaptation policies. Regarding budget, adaptation costs are mainstreaming in national budgets, and Viet Nam was the first among the Asia regions to prepare a Climate Change Public Expenditure and Institutional Reviews (CPEIRs).

A net zero transition could have different impacts on macroeconomic stability depending on the transition trajectory and the financing option. Following Viet Nam's commitment to net-zero at COP26, a National Steering Committee was established to direct programs, projects and prioritized tasks in response to climate change and to promote the energy transformation required to fulfill Viet Nam's commitments. The government focused on some areas of structural transformation, linked to: **i)** transitioning from fossil fuel to green/clean rene-wable energy sources; **ii)** reducing greenhouse gas GHG emissions (including methane in agriculture and waste management); **iii)** increasing the fleet of electric vehicles (EVs); **iv)** increasing trees to offset carbon emissions; **v)** suporting R&D for construction material usage and urban development; **vi)** increasing pu-blic and business awareness and support for the government's COP26 commitments and; **vii)** stepping up the development of a digital economy to address climate change. The current draft of the Power Development Plan VIII (PDP8) is expected to be significantly overhauled to create more space for renewable energy and sustainable energy solutions. Net zero emissions require profound structural change and will demand substantial new investments in green technologies, sustainable infrastructure and increased resource productivity. Given the high degree of openness of the Vietnamese economy, a net zero emissions target could lead the country to face a 'green transition trilemma' [Valdecantos, 2020]. External financial sustainability, internal economic development, and environmental sustainability can be antagonistic objectives unless specific macro financial conditions can be met. Thus, assessing climate change impacts and adaptation is crucial for policy planning at the macroeconomic level.

3. An integrated prospective assessment

We use an integrated prospective economy-wide assessment to analyze the economic impacts of climate change and adaptation measures in the context of a greener industrialization process for Viet Nam [Figure 3.1]. Existing studies on evaluating the impacts of climate change and adaptation in Viet Nam are usually focused on specific sectors or regions, as shown in the different meta-analysis and sectoral assessments in the COP26 assessment report of the GEMMES Viet Nam project. Few studies seek to assess the economy-wide effect of climate change.

[Figure 3.1]
An open integrated framework to assess climate damage in Viet Nam



Only countries in the first quintile in terms of exposure, and Viet Nam, are presented; Chemicals, etc.: Petroleum, The integrated framework used in this report allows for the measure of direct impacts on key socio-economic variables and their macroeconomic effect. It remains open to additional sectoral impacts, more detailed specifications of climate scenarios (including uncertain future tipping points), as well as probabilistic assessments considering different sources of uncertainties.
Source: Espagne *et al.* (2021).

Arndt *et al.* (2015) evaluated climate impacts on economic growth and welfare in a dynamic computable general equilibrium (CGE) model via three principal mechanisms: **i)** crop yields; **ii)** hydropower production, and; **iii)** regional road networks. This latest study provides insights into the potential macroeconomic effects of different climate scenarios from the previous IPCC report. World Bank (2022) assessed the potential economic losses associated with climate change in Viet Nam by using two complementary models. The first model is the World Bank's Mitigation, Adaptation and New Technologies Applied General Equilibrium (MANAGE) model that aims to capture the impacts of two of the main manifestations of climate change on future economic growth. The second model is a probabilistic catastrophe model to estimate the economic impacts associated with extreme events such as typhoons.

Comprehensive macroeconomic analysis and forecasts are crucial for policy-making decisions to contribute to Viet Nam's economic growth strategy and macroeconomic stability. Our methodological approach was built on the integrated assessment approach of Hsiang *et al.* (2017) who have attempted to assess the economic cost of climate change in the US via a combination of multiple climate scenarios, quantitative meta-analysis of sectoral and social impacts based on existing studies, and aggregation and integration within a macroeconomic model.

This integrated assessment framework involves three main steps:

i) Valuation of direct damage: in order to aggregate over each type of direct damage to obtain a total economic response to climate forcing, we first apply a monetary valuation to each individual sector, namely agriculture, energy, health, labor productivity. We use the key quantitative results from Espagne *et al.* (2021). The choice of studies as well as the valuation for specific sectors is discussed below. For all direct damage, values are presented as a proportion of Vietnamese Gross Domestic Product.

ii) Direct damage function calculation: constructing direct damage functions requires that losses in each sector be represented as conditional on Viet Nam mean surface temperature (VNMST) change. We estimate summaries of these relationships by regressing the impact value (for all realizations) on these temperatures. As in Hsiang *et al.* (2017), we consider that the results are not weighted, because the likelihood of states of the world is not relevant to the description of the damage function.

iii) Aggregate national-level damage function: Summing direct damage functions across the spectrum of possible temperature increases to obtain cumulative direct impacts; and applying the direct damage impacts to the stock-flow coherent macroeconomic model of Viet Nam, in order to assess the intersectoral and aggregate effects.

To assess the macroeconomic impacts of climate change, we integrate the climate damage functions into a macroeconomic model. We use an empirical stock-flow consistent model for the Vietnamese economy[1]. This macroeconomic model which was built on the science models is used for policy assessments of climate impacts and action [Stern, 2013]. It allows us to have some notion of what might happen and potential impacts of such policy measures. Contrary to standard CGE models, the stock-consistent model that we have specifically developed for the Vietnamese economy combines real side variables with financial balance sheet effects. Indeed, over the last three decades, the Vietnamese economy has been integrated into the world economy and undergone an important financialization process. Increased integration with other countries has contributed to income growth but raised the economic vulnerability of the country in the context of rising trade tensions. The global financial crisis of 2008, the ensuing Vietnamese banking crisis of 2011, and the recent COVID-19 pandemic – all mostly macroeconomic shocks coming from the financial side – have had significant impacts in real terms as well. They have thus revealed the critical need to pay more attention to the integration of the financial sector (*i.e.* money, debt, and assets/liabilities) and the real economy within a single framework to gain a proper understanding of the dynamics at hand. It is necessary for public policies, a sound development process and macroeconomic stability in the longer term. Stock-flow consistent models assume that financial and real variables should be put together and analysed in the same model and are therefore best suited to address the challenges posed by the

1. The detailed model is presented in the technical document for this report.

recent crisis. Beside some key macroeconomic features from the open-economy model of Godin and Yilmaz (2020) and more generic features from Godley and Lavoie (2007), the modelling procedure has sought to account for the structure of the Vietnamese economy, the availability of data, and the degree of stability of time-series estimates of parameters during the country's transition process. The present model seeks to provide a mechanism to link policies and an easy and adaptable means of simulating the interrelationships between macroeconomic variables. What is essential is that key features of the economic and financial process represented in the system allow characterizing the economy. The resulting system proposes a framework that links the financial and real sectors of the economy and an interpretation of the channel transmission through which economic policies can affect these transactions.

Stock-flow consistent macroeconomic models rely on some accounting principles [Zezza & Zezza, 2019]. These principles will be represented in two matrices: the balance sheet - stock matrix and the flow matrix. The balance sheet represents the financial structure of the economy by displaying the tangible stocks, financial stocks and financial liabilities of each institutional sector at the end of each period. The flow matrix demonstrates the real transactions and financial flows implied from stocks of financial assets and sectoral budget constraints. It combines the national income equations with the sectoral flow of funds accounting, meaning that each sector's net lending/borrowing position must correspond to the flows of investment and, hence, the stock (holdings) of net financial assets/liabilities. For most countries whose data are available, the balance sheet data are published in the financial accounts of institutional sectors. To the best of our knowledge, there are not yet institutional sector stock accounts or estimation of national wealth for the Vietnamese economy. Consequently, in this model, it relies on the international guidelines of system of national accounts (SNA) [UN, 2009] to collect the annual data for the period 1996–2019 from different sources to build the balance sheet and flow matrix.

Following a coherent way of thinking about macroeconomy in terms of both theory and economic policies [Arestis, 2013]**, the model will be divided into different blocks.**

– The production decision is based on adaptive expectations. Productive sectors decide their production level considering the sales expectations. However, given that they have a limited production capacity, there is a production constraint impacting their production decision. Climate change affects the agricultural and energy sectors via rice yields, electricity demand and the hydropower sector. It also affects these sectors in general via an impact on labor productivity. In addition, the aggregate mortality rate of the population can affect the labor supply of the economy.

– Firms have to decide how much to invest and how it will be financed. Firms' investment depends on the real lending rate representing the financial condition or cost of borrowing, the capacity utilisation rate of capital, profit rate, and financial profitability. Firms can finance their investment by using retained profits, borrowing from banks or abroad, and issuing equities. Firms finance all their remaining financing needs via foreign direct investment.

– Vietnamese households use their disposable income to consume, invest and accumulate financial assets in dong deposits, foreign deposits, government bonds, firm equities or other financial assets. Households can also borrow from commercial banks to meet their financing needs. Households will keep all remaining money once they have planned their consumption expenditures, investment, and other financial assets. Households will buy all remaining equities from firms and banks. Households are impacted by climate change through different channels: the number of working hours they can dedicate to firms; their labor productivity affects their received wages.

– The government collects taxes, receives other transfers or payments, and then consumes and invests. The government's current expenditures and public investment are exogenous as policy instruments. Public deficit can be financed by issuing bonds or borrowing from abroad. Climate change affects the economic activities and thus, the government's revenues. In addition, adaptation to climate change as well as net zero strategy require profound structural change and demand substantial investments. It will significantly increase public financing need and certainly public debt. The Vietnamese public domestic debt has sharply increased since the 2010s with the development of the domestic bond market, while the proportion of external debt gradually decreased. Before 2013, the government financed its deficit mainly by borrowing from abroad. There was considerable currency risk, which led to more prudent policies that reduce the external debt compared to domestic debt. Nowadays, domestic debt accounts for more than 60% of the public debt.

– The State Bank of Viet Nam (SBV), to achieve the objectives of price stability, determines the refinancing rate as a monetary policy tool, provides advances to the commercial banks. The central bank contributes to regulate the financial markets. We consider in our model that the central bank buys the bulk of remaining government bonds. We assume that all central bank's profits are transferred to the government. Following International Monetary Fund (IMF) (2019), we consider the dynamics of the exchange rate as the result of supply and demand of foreign exchange, with an active intervention of the central bank on the foreign exchange market through reserve management.

Given the high degree of openness of the Vietnamese economy, such as any climate policy could lead the country to face a 'Green transition trilemma' [Valdecantos, 2020] and affect the external financial sustainability of the country. Thus, it can impact the exchange rate and imply the intervention of the central bank to response to it.

– Commercial banks increase the deposits with respect to the demand for dong deposits of firms and households. Banks provide credits to firms and households, but they also impose credit rationing on firm and household loans, based on loan-to-value (LTV) and debt-to-income (DTI) respectively. They decide both the lending rate and the deposit rate based on a premium over the central bank's interest rate. Commercial banks also hold part of the government's bonds. Refinancing act as the residual buffer for banks.

– Exports and imports depend on demand, relative prices and other factors which are relevant for the Vietnamese economy. The rest of the world contributes to financing the domestic economy through foreign direct investment, portfolio investment. The rest of the world satisfies all foreign loans demanded by the domestic sectors. In addition, the change in other net financial assets is determined by the net borrowing/lending position.

– The general price is a cost-push function (wage and import price). Price is affected by the demand via the output gap which is represented as the ratio of actual output and potential output. The wage rate growth depends on the unemployment rate and the growth of the price of consumption and that of the labor productivity which is affected by the climate change. The impact of climate change on the economic activity will impact the wage. Other prices in the system mostly depend on this general price.

– Other blocks in the model will specify the determination of different interest rates, rates of return of different financial assets in the model and the labor market.

To simulate different climate change and adaptation scenarios, we create a baseline scenario broadly aligned with current Vietnamese greener industrialisation and modernisation strategies and the socio-economic development trends of Viet Nam and the world. Firstly, the agricultural contribution to GDP is projected to fall during the period 2020–2050. The population growth rate is taken from the United Nations population projections for Viet Nam. It represents a downward trend. The capital depreciation rates are projected to remain constant at their current value [ILO, 2018]. Due to the large share of informal and self-employment in the Vietnamese economy and the low level of unemployment in the past, we assume that the unemployment rate will remain constant at the 2019 value [IMF, 2018].

Secondly, several variables reflect the dynamics of the rest of the world. For the growth rate of world GDP, we take the quantitative projections of the so-called Shared Socio-economic Pathways to facilitate the integrated analysis of future policies. Trading partners' demand for real imports is based on the OECD's projections.

Thirdly, regarding the financial side of the model, we use the projection of the Federal Reserve's interest rate forecasts for the short term and the longer term.

Finally, net-zero emissions require profound structural change and will demand substantial new investments in green technologies, sustainable infrastructure, and increased resource productivity. Thus, it will raise the financing needs of the economy. A green industrial policy is represented in our model by a decreasing import proportion of intermediate consumption. It means that a green industrial policy is supposed to help substitute for green product inputs combined with different options of financing (private, public or public-private-partnership (PPP) investments). The size of investment is taken from the preliminary technical report of the updated National Climate Change Strategy of MoNRE, mentioning plans proposed to achieve net-zero emissions. This preliminary technical report suggests three plans to achieve net-zero emissions:

– Option 1 uses the TIMES model (optimising the simulation calculation system – the environment with the lowest cost).

– Option 2 uses the TIMES model combined with the LEAP model (a long-term alternative quantitative planning model system).

The main difference between Option 1 compared to Option 2 is that the proportion of renewable energy in 2050 in Option 1 (73%) is higher than in Option 2 (48.5%), in which the proportion of electricity fixed solar energy in Option 1 is about four to five times higher than that of Option 2. Option 2 has a higher proportion of fossil energy than Option 1, so prevention and landfilling measures must be applied.

– Option 3 is similar to Option 2 but with partially replaced electricity, applied for the period after 2035 when the level of safety and cost is appropriate.

[Table 3.1]
Main assumptions for exogenous variables

Variables	Projections
Imported intermediate consumption share	30%
Population in 2040	United Nation's population projections (downward trend)
Unemployment rate	2% (Value in 2019)
Capital depreciation	Value in 2019
Share of public expenditures	5.9% GDP
Share of public investment	6.8% GDP
Growth rate of world GDP	Shared Socio-economic Pathways (SSPs)
Demand for real imports of trading partners	OECD's projections
US interest rate	FED's forecasts for interest rate

4. Macroeconomic impacts and climate adaptation

4.1 Climate damage

Several productive sectors deeply are impacted by climate change and Viet Nam is exposed to the transversal impact of climate change on production factors. Climate change negatively affected the cereal production, fishing, and electricity from hydropower. Global warning also impacted the labour productivity, mortality and capital.

Agriculture

Climate change has important impacts on the agricultural sector via direct (temperature, precipitation, sea-level rise, etc.) and indirect mechanisms (water resource, saline intrusion, drought, floods, impacts on labour productivity, etc.). In our study, agricultural yield impacts are represented as changes in rice yields. We based our analysis purely on a meta-analysis of a set of key studies to develop the sector-specific damage functions for agriculture, namely: Li *et al.* (2017); Kontgis *et al.* (2018); Deb *et al.* (2015); and Shrestha *et al.* (2016).

Yu *et al.* (2010) first estimated the impacts of climate change on agricultural and water systems in Viet Nam based on crop simulation, hydrological simulation, and river basin models. Then, by using a multilevel mixed-effects model, they implemented a Cobb-Douglas yield function to model technology advances and policy interventions that mitigate the impact of climate change. The WOFOST model and the empirical hydro-crop model were used jointly to analyse the impacts of changes in rainfall and temperature on crop yields. As for the climate scenarios, in addition to the official MoNRE scenario [MoNRE, 2009].

The aim of Li *et al.* (2017) is to assess the impact of projected climate change on rice productivity in the Indochinese Peninsula and test whether adaptive measures, such as adjustment of planting dates, adoption of irrigation, and the use of heat-tolerant varieties, can counter any negative climate impacts. Large-scale climate variables from the General Circulation Model (GCM) HadGEM2-AO were dynamically downscaled with regional climate models, namely YSU-RSM, RegCM4, and HadGEM3-RA. The crop model chosen by the authors was the GLAM-Rice model. The paper finds that the rice yield losses due to climate change (including CO_2 gains) across all of Viet Nam are expected at 5-10% by 2040, with similar values under both RCPs 4.5 and 8.5.

In the study by Kontgis *et al.* (2019), the authors used management information from farmers and published information on soils collected in Can Tho, a province in the Mekong Delta. Then, with projected climate data for the RCP4.5 and RCP8.5 scenarios for 2040–2069, they simulated the CERES-Rice model and used the Decision Support System for Agrotechnology Transfer (DSSAT) platform to obtain future rice paddy yields. The study found that, when CO2 fertilization is not taken into account, yields decline by 5.5–8.5% annually on average for all three rice-growing seasons in Can Tho city and for both emissions scenarios.

The impacts of climate change on rice yield were investigated by Deb *et al.* (2015). Climatic variables were derived from six GCMs, which were further biased and corrected at Ca Mau city station for three future periods (2025s, 2055s, and 2085s). Using AquaCrop 4.0, the simulation results showed that prospective rice yield under climate change and different salinity levels in irrigation water decline from 1.60% to 23.69% and from 8.06% to 20.15% by 2085s relative to baseline climate A2 and B2 scenarios, respectively, in the case of the summer-autumn cropping season.

Shrestha *et al.* (2016) investigated the impact of climate change on winter and summer rice yield using the AquaCrop model. Future climate change scenarios for periods in the 2020s, 2050s, and 2080s were projected by downscaling the outputs of the GCM, Hadley Centre Coupled Model version 3 (HadCM3) A2 and B2 scenarios. Results show that climate change will reduce rice yield from 1.29% to 23.05% during the winter season for both scenarios and all periods. In contrast, an increase in yield by 2.07% to 6.66% is expected in the summer season for the 2020s and 2050s, relative to baseline yield.

In our study, we assume that a given change in rice output results in a proportional change in the value of that agricultural sector's gross output in the baseline scenario. Possible endogenous adaptation strategies at this stage were not taken into account. We estimate an upper threshold for the corresponding damage function. However, since non-linear tipping points of the climate system are not accounted for, we may also underestimate damage even if this assessment was completed by taking sea-level rise into account in the case of rice. With these limitations in mind, we performed a meta-analysis (random-effects model) of the regression results to derive an average estimate of the change in rice yield as a function of temperature change and then integrated it into the macroeconomic model.

Energy

The energy sector is a crucial component in any development dynamics but is affected by climate change both in terms of energy supply and demand [Auffhammer *et al.*, 2013; Yalew *et al.*, 2020]. The direct costs and benefits of climate-driven change in energy were assessed by including the forecasted development of the Viet Nam PDP8. On the supply side, changes in precipitation and temperature can affect energy production capacity, transmission systems or infrastructure itself [World Bank, 2011, Ciscar & Dowling, 2014]. In Viet Nam, hydropower has a dominant role in the country's total electricity production, amounting to 37.7% in 2019, in spite of a planned reduction of 18% by 2030 and 9% by 2045 (PDP8). Based on our study of the climate impact on hydropower production, projections indicate that the case of hydropower is more complex, as it induces an initial surplus of production (with a maximum of 1°C increase in temperature) because of increased precipitation. Beyond a 2°C increase, however, there is not much change compared to a baseline without further climate change.

On the demand side, the rising temperature and weather extremes in recent years have strongly affected residential electricity demand (27% of total end-use consumption in 2016). The main electricity used in households is for air conditioners, refrigerators, and electric fans. The response functions are derived from the outputs of LEAP in 2040 under a range of temperature scenarios. Beyond a 2°C increase in temperature, electricity demand could increase by as much as 12% and more than 20% above a 3°C increase.

Labor productivity

Several studies show that heat stress can have negative impacts on human health as well as worker productivity [Orlov *et al.*, 2020; ILO, 2019; ILO, 2016; Kjellstrom *et al.*, 2009]. Kjellstrom *et al.* (2012) describe how heat stress reduces work capacity, leading to lower economic output in the case of Southeast Asia. Hoa *et al.* (2013) found that in Da Nang, the temperature rise has particularly affected the working conditions of low-income outdoor workers. Opitz-Stapleton *et al.* (2016) demonstrates that heat stress-induced by climate change will increase the occupational heat exposure of workers. Kjellstrom *et al.* (2014) emphasises that in 2030, heat loss could represent 5.7% of Viet Nam's GDP. In our study, we considered the results of the GEMMES Viet Nam project to quantify an impact function in terms of working hours lost. A 1°C rise in temperature is associated with a decrease of 2.5% in working hours. The value of labor productivity impact is calculated by multiplying the equivalent number of workers, which is proportional to the working hours lost by GDP per worker.

Mortality

Most of the key studies showed negative impacts of climate change on health outcomes (*e.g.* physical health, mortality, infectious diseases, mental health, dietary outcomes) [Rocque *et al.*, 2021]. Regarding the effect on mortality, Gasparrini (2017) investigated the projections of temperature-related excess mortality under climate change scenarios, assuming no adaptation or population changes. The study shows the negative impacts of climate change, which potentially increases mortality in most regions. Guo *et al.* (2018) projected excess mortality about heatwaves in the future under each RCP scenario, with or without adaptation and with three population change scenarios (high variant, median variant, and low variant). They found that if there is no adaptation, heatwave-related excess mortality is expected to increase the most in tropical and subtropical countries/regions. Hales *et al.* (2014) showed climate change-attributable heat-related deaths by region in the world. The relative increase in excess deaths from 2030 to 2050 could be large in some regions, including Southeast Asia. In addition, countries with high populations and pre-existing disease burdens would be more vulnerable to the health impacts of climate change. Another study by Vicedo-Cabrera *et al.* (2018) suggested that the Paris Agreement's commitment to hold warming below 2°C could prevent an increase in temperature-related mortality. Based on these studies, we obtained the damage function of change in mortality related to the temperature change.

Several methods exist to value mortality damage in monetary terms, and we do not necessarily want to make a theoretical decision about them, as this should be the choice of policy makers. As a practical solution, despite the problems on both theoretical issues of interpretation and difficulties in the measurement of the Value of Statistical Life (VSL) [Ashenfelter, 2006], we used the VSL from a study by Ohno *et al.* (2012). VSL has been calculated to be US$65,726–209,660 for Viet Nam. Concerning the impact channel in the macroeconomic model, it is possible to consider an impact on population growth, which in turn affects aggregate demand, labour supply, and thus economic growth.

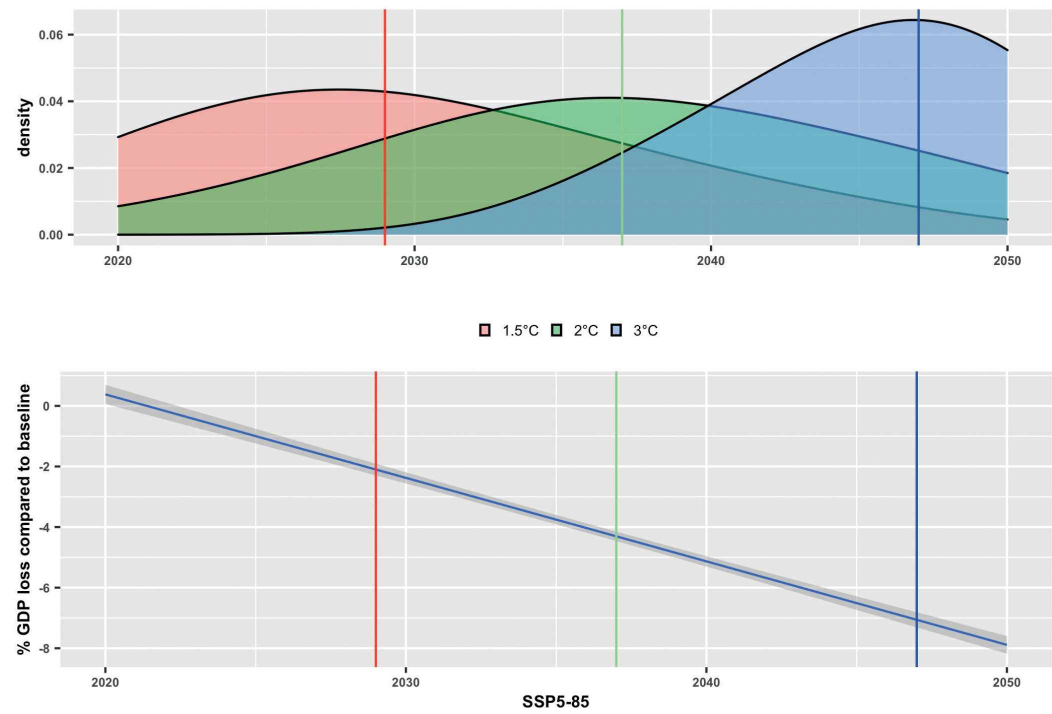
4.2 Macroeconomic impacts of climate change

The macroeconomic impacts of climate change are considered through integrating the damage functions into the macroeconomic model. It consists of the climate impacts on **i)** agriculture, **ii)** energy and transversal impacts on **iii)** labor productivity, and **iv)** mortality rate. In terms of modelling implications, we integrated the damage functions into the equations that determine agriculture production, energy production, final consumption of households, number of workers, and population growth.

We defined the effective agricultural production by the agricultural production of baseline scenario (without damage) and the production loss due to climate change. However, we only took the rice subsector from the agricultural sector. The damage function is the rice yield which depends on the changes in temperature.

The effective energy production is the difference between the hydropower production of the baseline scenario and the damage on the hydropower production. We consider a damage function of hydropower production as a function of temperature change. Regarding the damage on energy demand, the effective final consumption depends on the share of electricity consumption in the total consumption and the climate impact. The damage function shows how the temperature change affects the residential electricity consumption of households.

[Figure 3.2]
Macroeconomic damage as a percentage of GDP loss relative to baseline scenario under SSP5-8.5



The top graph is the distribution of 1.5°C, 2°C and 3°C VNMST change in SSP5-8.5 according to the different climate models. The bottom graph represents the average macroeconomic damage relative to the baseline scenario up to 2050 in SSP5-8.5. The red, green and blue lines indicate the median date when the GWL 1.5°C, 2°C and 3°C are reached respectively.

The labor productivity loss due to climate change is represented as the change in number of workers in relation to the change in temperature. The climate impact on the mortality rate equation is represented as a function of temperature change.

Quantitative estimates of the damage functions, which reflect how the level of damages would change under different climate change scenarios, are based on the findings of the COP26 assessment report [Espagne *et al.*, 2021] and Part 2 of this report.

Regarding the climate scenarios, low, intermediate, high and very high GHG emissions scenarios are considered (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5, respectively). According to the IPCC report (2022), under the four illustrative scenarios, in the near term (2021–2040), the 1.5°C global warming level is very likely to be exceeded under the extremely high GHG emissions scenario (SSP5-8.5). This will presumably be overtaken under the intermediate and high GHG emissions scenarios (SSP2-4.5 and SSP3-7.0), more likely than not to be exceeded under the low greenhouse gas emissions scenario (SSP1-2.6).

[Figure 3.3]
Impacts on public debt (without adaptation)

Boxes = interquartile range (25th (Q1) and 75th (Q3) percentile); Dark line = median value (maximum = Q3 + 1.5 * interquartile range (IQR: 25th to the 75th percentile), minimum = Q1 + 1.5 * interquartile range (IQR: 25th to the 75th percentile)).

A common set of reference years and time periods were adopted for assessing climate change impacts and potential impacts of adaptation measures: the reference periods 1980–2019 and 1850–1900 with approximate pre-industrial global surface temperature, while the future reference period covers 2020–2050. The changes in temperature of each year are the difference between the projected temperature of future reference period and the reference period 1980–2019. The climate data are taken from the Part 1 of this report.

Considering the uncertainty from the different climate scenarios (but not from the socio-economic side), the macroeconomic damage can reach up to a loss of 8.1% in annual GDP relative to the baseline scenario under SSP5-8.5. The model simulation will generate a baseline scenario, in which climate change impacts are ignored, and alternative scenarios in which climate change impacts are simulated. We considered the climate impacts when the global warming levels (GWLs) of 1.5°C, 2°C, and 3°C are reached for SSP5-8.5 in 2029, 2036 and 2047, respectively [Figure 3.2].

Temperature changes adversely affect the government budget and increase public debt. Figure 3.3 shows the impacts of temperature changes on the public debt over time. The average temperature can increase debt up to 3.7% annually in 2040–2050 under the assumption of a medium GHG emission scenario (SSP2-4.5) and up to 4.5% under the high GHG emission scenario (SSP5-8.5). The public financing need in the case of without adaptation measures can be explained by the loss in economic activity due to the climate change which can lead to loss in government revenues.

4.3 Efforts to adapt to climate change

The priority sectors for adaptation identified by the Vietnamese government include agriculture, transport, infrastructure and urbanisation, natural resources, industry and trade, public health, and tourism. These sectors are also the most affected by climate change, as shown in Part 2 of this report. Financial help for implementation shall be mobilized through different channels, including the state budget (central and local budgets), international funding (bilateral and multilateral partners), the private sector, and community contributions.

One of the key components of adaptation policies is investing in infrastructure resilience. It is also the costliest, which leads to a crucial question of the source of financing. IMF (2021) distinguish three types of adaptation investment: **i)** upgrading new projects to foster the resilience of capital stock against climate hazards over time; **ii)** retrofitting existing assets which aims to modify existing capital stock exposed to natural hazards to improve resilience, and; **iii)** developing coastal protection infrastructure such as dikes and storm surge barriers [Rozenberg & Fay, 2019]. Both public and private sectors can implement these adaptation investments, and it will raise their financing needs. In other words, the size of adaptation investment needs is critical for policy makers in designing an adaptation strategy.

The climate change public budget focused mainly on adaptation as mitigation is mainly in the private sector [UNDP, 2022]. At ministerial level, it accounted for between VND 8–13.5 trillion from 2016–2020, representing between 26% and 38% of the combined total budget of the six ministries. At provincial level, the climate change budget represented a relatively stable proportion of 16–21% of the total budget.

Even though the adaptation costs are high, effective adaptation will contribute to reducing negative impacts of climate change. Analysing the effects of adaptation with model-based simulations is still new in the literature. Our particular analysis is based on two main references related to the adaptation investment. The first one is a working paper of the World Bank (2021), entitled *Climate modelling for macroeconomic policy: A case study for Pakistan*. The paper describes the changes made to the World Bank's standard macro-structural model (MFMod) in integrated climate outcomes, climate policies, and the economic impacts of climate on Pakistan's economy. PAKMod represents the mechanism of the effects of adaptation investment to reduce the damages from climate events. The costs of adaptation investments will be assumed to be recorded in a budget tagging exercise. They do not consider private-sector adaptation. The effectiveness of adaptation is represented via a protection function. The approach here follows that of Bruin and Tol (2009) and Cian *et al.* (2016). Adaptation investment is adaptation capital that capital does not have a productive use. Adaptation capital works only to reduce damages. PAKMod considers adaptation public investment. The second study is the International Monetary Fund paper related to the fiscal policies to address climate change in Asia and the Pacific. They analyse how Asia and the Pacific adapt to climate change and the fiscal costs of adaptation measures. To assess the implications of adaptation investment, they consider an increase in public investment of 2% of GDP in years and compare it with the baseline scenario of no additional investment.

They analyse the effect of public investment efficiency, calibrated at 60% in the baseline, and 30% and 90% in low- and high-investment efficiency scenarios, respectively.

The economy-wide effects of adaptation investments depend mainly on the extent of the investments (their protection level) and the way they are financed. Following Lecocq and Shalizi (2007), Bruin and Tol (2009), Bosello *et al.* (2010), Millner and Dietz (2015), and World Bank (2021), adaptation is produced via an adaptation capital stock, or the accumulation of adaptation investment, which depreciates at the same rate as productive capital. The range of depreciation rates is taken from the 2019 IMF Investment and Capital Stock Dataset [IMF, 2019]. According to the Intergovernmental Panel on Climate Change (IPCC), in terms of human systems, adaptation seeks to moderate or avoid harm, or exploit beneficial opportunities. Different entities may have appropriate adaptation strategies to deal with climate change.

However, the national adaptation policies also define important principles that need to be applied, such as: an integrated and systems-based approach; take into account uncertainties; proactive strategies; address vulnerability and risk; mainstream adaptation into development planning and policies; actively mobilize and engage all relevant stakeholders; promote multi-benefit actions, soft measures, and ecosystem-based and community-based adaptation measures; and develop and implement a monitoring and evaluation system for climate change adaptation. These principles indicate the high quality of adaptation policies, which aim to promote integrated, holistic, and inclusive approaches, as well as account for the interrelationships between sectors and regions, short-term and long-term actions, and climate change uncertainties.

Adaptation can be private or public, anticipatory or reactive [Bruin & Tol, 2009] **and the choice of what should be invested depends on each society's preferences** [Bellon & Massetti, 2022]**.** Therefore, in our model, we consider both private and public adaptation investments. We suppose that each sector will decide their adaptation level by considering the expected damage. Firms and households will anticipate the direct damage on their activity sector and the government will anticipate the damage for the whole economy. Given that productive investment is expected to pay for adaptation investment, the productive capital stock and therefore potential supply of the economy will suffer. These effects are important drivers of the results in our model simulations. Thus, the level of adaptation investment of firms will depend on the opportunity cost of the money spent on the productive investments represented by the profit reduction related to this amount of investment and the effectiveness of different levels of protection. The reduction of profit related to the amount of adaptation investment will be proportional to the profit generated by the productive investment. However, given that the investment decision of adaptation can have an impact on the productive investment of firms, they have to dedicate a part of their total investment to adaptation, with the residual going to productive investment. The same formula is applied for households. The public adaptation investments could make the economy more resilient to climate events and damaging effects (lower productivity) of higher temperatures [World Bank, 2021]. The government will decide the level of adaptation investment only by considering their effectiveness to reduce the damage from climate change. The public adaptation investment can have positive externalities and address market imperfections.

The effectiveness of adaptation investment has been considered in the national strategy, especially the National Plan for Adaptation to climate change for the period 2021–2030, with a vision for 2050. The financing mechanism and resources mobilized for adaptation in countries have been evaluated by various international institutions. Climate finance readiness, proposed by the United Nations Development Programme (UNDP), was defined as *"the capacities of countries to plan, access, deliver, monitor, and report on climate finance, both international and domestic, in ways that are catalytic and fully integrated with national development priorities and the achievement of the Millennium Development Goals"* [UNDP, 2015, p. ii]. To support developing countries in strengthening their capacities in climate finance, the German Agency for International Cooperation (GIZ) has developed a "Ready for Climate Finance" approach which emphasizes the involvement of the private sector.

The effectiveness of adaptation is represented via a protection function [Bruin & Tol, 2009; Cian *et al.*, 2016]**.** It determines the residual damages and depends on the stock of adaptation capital and the changes in temperature. Firstly, in line with the literature [Bruin & Tol, 2009; World Bank, 2021], we assume a declining marginal increase in protection. Secondly, the more global warming, the less adaptation space we have. Therefore, the protection function is a negative function of global warming (increase in temperature). Assuming that the protection function is homogeneous for all sectoral damages, the residual damage is equal to the product of gross damage and the level of protection.

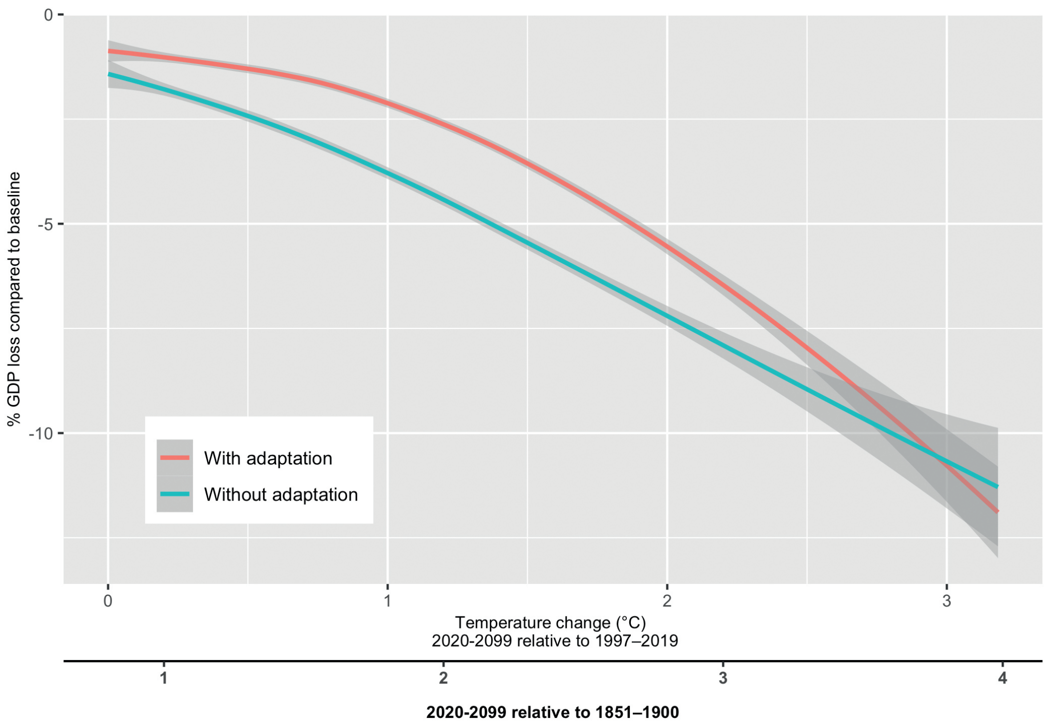
Even though the adaptation will be not considered as a productive capital, the adaptation investment must still be taken into account in the calculation of GDP, firms, and government expenses. Consequently, the economy-wide effects of adaptation investments will depend strongly on how each sector finances their adaptation investments. It will affect their debt structure and thus, imply important macro-financial impacts on the economy.

Uncertainty can pose challenges for policy makers and the private sector in adaptation investment decision. Climate projections remain uncertain, and thus, affect the magnitude of damage on which the adaptation decisions made will based. In other words, any projection of damages in the medium to long term will be uncertain [Markandya & González-Eguino, 2019]. However, Bruin *et al.* (2009) showed that uncertainty should not prevent investment in adaptation but choosing the adaptation level should be done with care.

With adaptation, the loss will be smaller relative to the scenario without adaptation. In other words, with adaptation investment, GDP losses could be reduced compared to the scenarios without adaptation investment. Figure 3.4 shows that remaining below a temperature increase of 2°C allows for a smaller loss of 2% of GDP on average compared to the scenario without adaptation.

Adaptation cannot replace mitigation. Adaptation investment seems to be effective when the changes in temperature remains below a certain threshold (3°C change of 2020–2099 relative to 1997–2019). The greater the global warming, the more difficult adaptation would be. In both cases of with or without adaptation, the impact will be higher in higher GHG

[Figure 3.4]
Impacts on real Gross Domestic Product



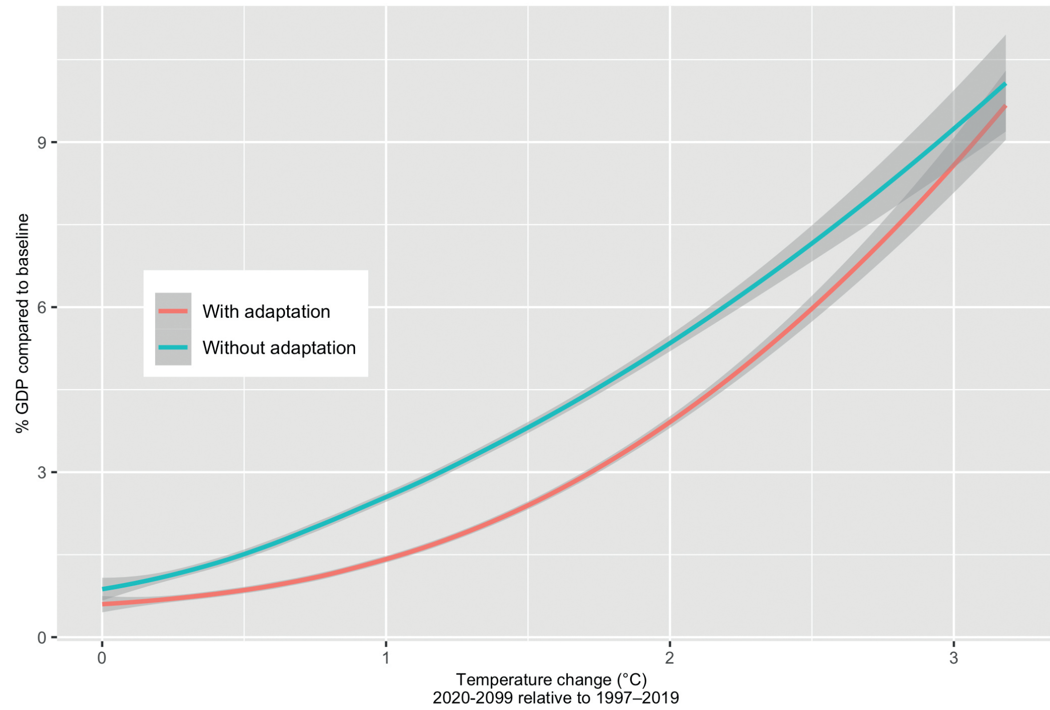
Macroeconomic damage to the Vietnamese economy as a function of VNMST change 2020–2099 relative to 1997–2019 (contemporary climate) and relative to 1851–1900 (pre-industrial climate). The temperature of the pre-industrial period is estimated from observation dataset and HadCRUT5 (with a coarse resolution of 5°x5°).

emissions scenarios. Mitigation efforts will contribute to stabilize global temperature, then adaptation would become not too expensive.

Adaptation can also be macro-critical because financial needs may be substantial, given the context of financial constraints, and thus raise the question about public debt sustainability. Figure 3.5 shows that public debt increases in general. The increase in public adaptation investment implies higher public debt, especially when a higher increase in temperature will reduce the level of efficiency of adaptation investment. Therefore, public debt strongly increases with a high temperature change. It implies that the adaptation decision must take into account budget constraints to obtain more efficient adaptation options. In addition, different options of financing by domestic or external debt can affect key macro-financial variables, such as the exchange rate, the current account, and international reserves management.

Private sectors will have an increase in their financing needs due to the additional adaptation investment, in particular in the initial

[Figure 3.5]
Impacts on public debt



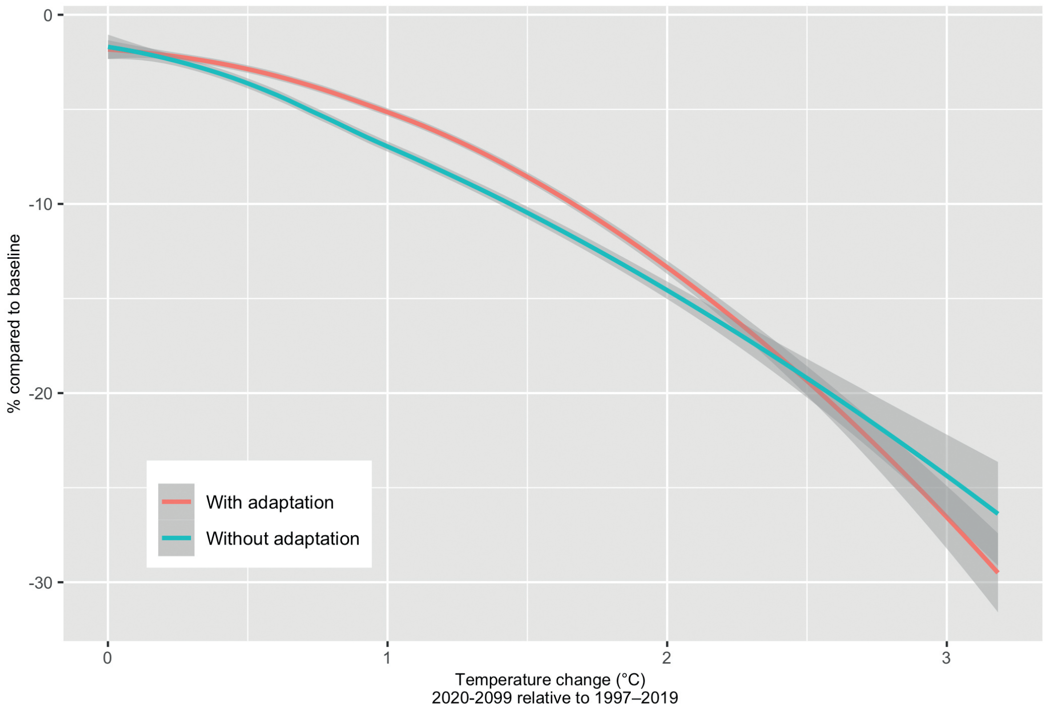
Impacts on public debt over the period 2020–2099 as a function of VNMST change 2020–2099 relative to 1997–2019 (contemporary climate).

years. However, as the adaptation capital accumulates over time, it will contribute to reducing losses due to climate damage and improving their activities in the long term. Above a certain level of temperature change, adaptation will be less protective and additional adaptation investments will worsen the financial situation of the business sector [Figure 3.6].

5. Conclusion and policy recommendations

This part provides an economy-wide assessment of the economic effects of climate change and potential effects of adaptation measures on the Vietnamese economy. It consists of an integrated macroeconomic framework and empirical analyses of climate impacts as well as available regional and global climate models. We integrate climate damage function

[Figure 3.6]
Impacts on private net financing needs



Impacts on private net financing needs over the period 2020–2099 as a function of VNMST change 2020–2099 relative to 1997–2019 (contemporary climate).

and adaptation strategy within the stock-flow consistent model of Viet Nam. Regarding the climate scenarios, from low to very high GHG emissions scenarios are considered, including SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5. Our approach allows for updates based on new econometric/sectoral modelling results or climate model projections.

Even if not all climate damage have been accounted for, the loss in Viet Nam could possibly reach up to about 8.1% GDP relative to the baseline scenario by 2050 under SSP5-8.5 without adaptation. Our results show that adaptation investments contribute to reduce the economic loss. However, adaptation cannot replace mitigation as global warming rises and adaptation becomes more difficult. Especially, adaptation investment will adversely affect the financial situation of sectors in the economy, such as the public debt, that possibly will have impacts on the macro-financial stability of the country.

The macroeconomic simulations results in this chapter highlight some policy recommendations for more effective adaptation. Adaptation strategies should be designed in a way that combines both bottom-up and top-down approaches. The bottom-up approach has been widely applied in Viet Nam and has helped to identify the climate change impacts on specific sectors or areas and then formulate the relevant adaptation activities accordingly. The top-down approach on the other hand will allow us to take into account the climate change aggregate effects of multi-sectors and help to prioritize resources for more effective adaptation strategies. Measuring aggregate impacts through an integrated modelling framework in this chapter is an example of such a combination approach and should be followed up and improved overtime.

Climate adaptation projects should not only target the reduction of hazard exposure through hard infrastructure but also reduce social and economic vulnerability. The government has to better harmonize development objectives with the adaptation agenda. Health and education sectors should be prioritized to increase the population's resilience to climate and environmental shocks. The fourth industrial revolution and the digitalization process will enhance the resilience and efficiency of adaptation investments.

Climate finance – the financial aspect of climate change adaptation – plays an important role in achieving the adaptation objectives. Viet Nam is facing challenges in effectively mobilizing and using resources for adaptation. The COP26 report of the GEMMES Viet Nam project indicates an important gap in tracking adaptation spending and measuring the impact of adaptation finance. A monitoring and evaluation system is therefore needed. The system needs to track not only formal financial flows, but also various resources that are often mobilized for adaptation at the local level. It also reveals a significant financial gap at the provincial, and especially at the community level. It calls for urgent national and international commitment to support local adaptation. The engagement of the private sector remains weak and should be pivotal in the next coming years. The government should play the role of support or engage with the private sector on adaptation investments. An orientation toward green finance and green financial products for the Viet Nam stock market will contribute to creating financial resources for investments that provide environmental benefits in the broader context of sustainable development.

Our integrated prospective assessment framework has already shown its potential and should also play a central role in the emerging debate on Viet Nam's net zero commitment and a just transition ambition in the coming years, as part of the second phase of the project. So far, the macroeconomic model is, by definition, a simplification and aggregates many additional details about the Vietnamese economy. There are likewise a number of areas where the analyses based on the model could be expanded as below. Notably, these future features of the model have been intended to provide a useful economic policy analysis taking into account the different economic and social development objectives of Viet Nam as follows.

An analysis of the structural change of the economy toward a greener growth should be considered. Given the strong interdependencies between industries, an input-output analysis is indispensable to analyze the transactions that take place within the production sectors in a complete system. The most emitting industries in Viet Nam include construction, electricity, gas and other sectors. These sectors also have a large share of imported intermediate consumption. In addition, the total intermediate imports tend to increase over time. On another hand, primary and low-tech manufacturing are classified as the most export-oriented sectors.

Given this current productive structure of the Vietnamese economy, the green transition strategy should take into account the potential problem of external sustainability.

The macro-financial effects of different net zero investment strategies thus need to be carefully assessed. As the world economy transitions towards cleaner and less carbon-intensive forms of development, the ambitious COP26 announcement of a net zero horizon in 2050 by Vietnamese Prime Minister Pham Minh Chinh comes at a crucial moment. Viet Nam starts its journey from a position of high-emission intensity compared to the rest of the world. It also has a relatively high exposure to sunset industries in terms of external, fiscal and socio-economic constraints. The net-zero objectives of Viet Nam ensures that demand for low-carbon products will grow fast in the coming decades. A net zero transition could have different impacts on macroeconomic stability, depending on the capacity to support a competitive low-carbon industrial strategy and reduce technical dependency on the rest of the world (*i.e.* decrease the proportion of imported intermediate consumption). Depending on the transition trajectory and the financing option (public, private, or PPP) for net zero, exchange rate, public debt and foreign reserve dynamics might be substantially different. Coupling between techno-economic models (such as the TIMES model or LEAP model) of the net zero transition of the energy sector in Viet Nam with the GEMMES Viet Nam macro-financial model would allow to simulate financing options as well as macro-financial impacts. Viet Nam's industrial and development strategy in the face of climate change will have to navigate between macro-financial constraints, multi-dimensional vulnerabilities due to inevitable impacts, current high emission path dependency, and its strong technological perspectives in green industries.

Viet Nam's COP26 climate targets are an opportunity to re-orient the nation's economy along a just and sustainable trajectory. A just energy transition must address inequality and protect the most vulnerable communities from potential adverse effects. Distribution of income is one of the core issues in economic policy analysis. An extension of our framework can be the integration of the personal income distribution, *i.e.* among the groups of the society. Simulation exercises on inequality can be conducted, which can potentially contribute to providing important policy recommendations with the long-term goal of reducing inequalities and improving well-being.

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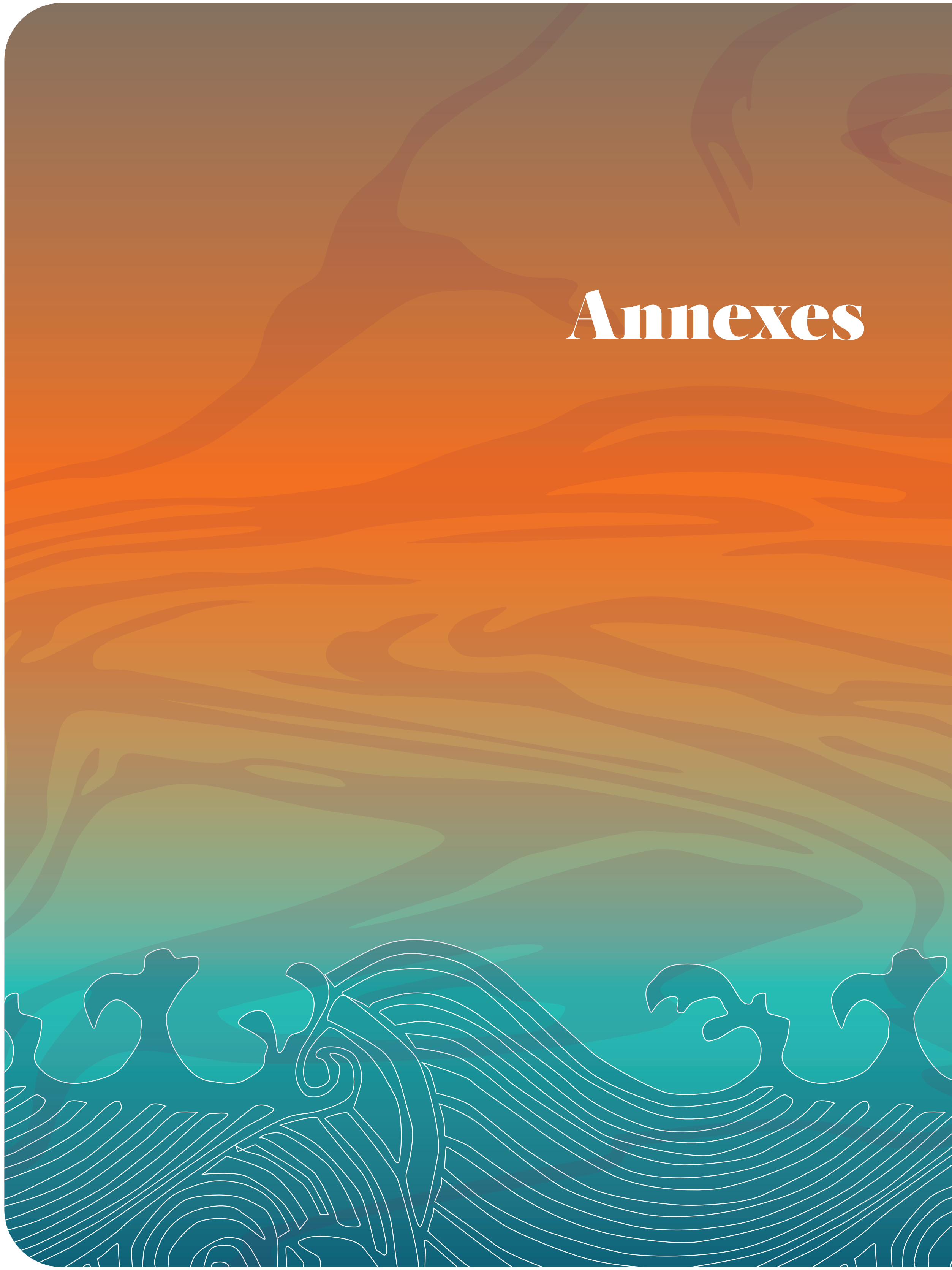
Annexes



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PART 2

PART 3

CONTENT TABLES

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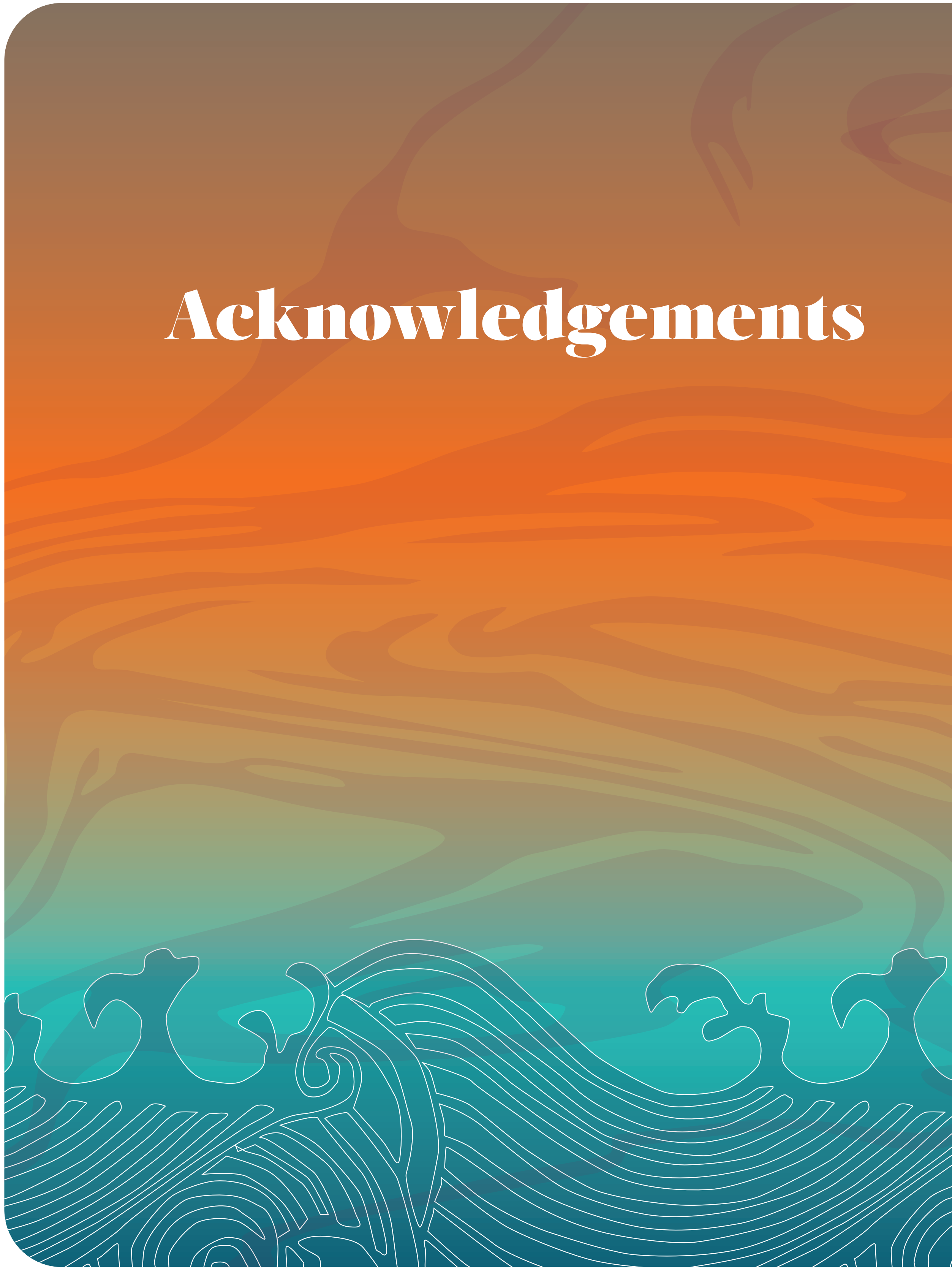
CONTENT BOXES

PART 2

ABBREVIATIONS

ASEAN	Association of Southeast Asian Nations
BC	Bias correction
BCSD	Bias Corrected Spatial Disaggregation
BIP	Bilinear interpolation method
BIP	Bilinear interpolation method
CDF	Cumulative distribution function
CGE	Computable general equilibrium
CEC	Central Economic Committee, Viet Nam Communist Party
CIEM	Central Institute for Economic Management
CMIP	Coupled Model Intercomparison Project Phase
CRI	Global Climate Risk Index
CSP	Concentrating solar power
DBEM	Dynamic Bioclimate Envelope Model
DCC	Department of Climate Change (MONRE)
DJF	December-January-February
ECS	Equilibrium Climate Sensitivity
EEZ	Exclusive economic zone
ESTEEM	Exposure to Structural Transition in an Ecological-Economic Model
GCI	Green Complexity Index
GCM	Global Climate Model
GCP	Green Complexity Potential
GHG	Greenhouse gas
IMAGE	Integrated model to assess the global environment
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
LASTA	Laboratoire d'Analyse des Sociétés Transformations Adaptations
MAGICC	Model for the Assessment of Greenhouse Gas Induced Climate Change
MAM	March-April-May
MAMJJA	March to July
MCP	Maximum catch potential
MONRE	Ministry of Natural Resources and Envi-ronment
MRIO	Multi-regional input-output
MRP	Maximum revenue potential
NAP	National Adaptation Plan
NAPRCC	National Action Plan to Respond to Climate Change
ND-GAIN	Notre Dame University Global Adaptation Index
NSCC	National Strategy on Climate Change
PCI	Product complexity index
PDF	Probability density function
PDP8	Power Development Plan VIII
QM	Quantile mapping
RCP	Representative Concentration Pathways
RMSE	Root mean square error
SCM	Simple Climate Model
SD	Spatial disaggregation
SMME	Surrogate/model mixed ensemble
SONDJF	September to February
SPC	Social protection coverage
SRES	Special Report on Emission Scenarios
SSP	Shared Socioeconomic Pathways
TF	Transfer function
TIMER	Targets image energy regional
TSA	Tourism Satellite Accounts
UEB	University of Economics and Business
UR	University of Rouen Normandy
VMHA	Viet Nam Meteorological and Hydrological Administration
VNMST	Viet Nam mean surface temperature
VNU	Viet Nam National University
VSL	Value of Statistical Life
WCRP	World Climate Research Programme
GWL	Global warming level



This COP27 Report of the GEMMES Viet Nam project was prepared by a team led by Senior Economists Etienne Espagne (AFD) and Guilherme Magacho (AFD), in close cooperation with the General Director of the Department of Climate Change of the Ministry of Natural Resources and the Environment The Cuong Tang .

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