



1 **Dilemmas and Actions for Tropical Cyclone Risk Insurance under**
2 **Climate Change: Governmental Bodies, Market Entities, and**
3 **Scientific Communities**

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6 **Abstract:** Faced with the increased frequency of tropical cyclones (TCs) amid
7 climate change, insurance is becoming increasingly critical in disaster response and
8 adaptation. Current research on TC risk insurance exhibits a trend of multidisciplinary
9 integration and multi-stakeholder participation. Using a large language model, this
10 paper systematically reviews 890 TC risk insurance publications. Spatio-temporal
11 distribution analysis reveals growing research attention yet persistent spatial
12 imbalances. Co-authorship network analysis uncovers varying but still insufficient
13 degrees of collaboration among three stakeholder groups: governmental bodies,
14 market entities, and scientific communities. Generally, the literature mainly converges
15 on four interlocking dilemmas that constrain the current insurance system: Can TC
16 risk remain insurable under climate change? Is insurance comprehensive enough? Is
17 insurance accessible to those who need it most? Will people purchase insurance even
18 when it is available? In response, the paper proposes a dilemma-aligned tripartite
19 collaboration framework that specifies joint actions for the three stakeholder groups.
20 This framework aims to strengthen cooperation and innovation, advancing the TC risk
21 insurance system toward greater fairness, efficiency, and resilience in a changing
22 climate.

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26 **Keywords:** Tropical cyclone; Insurance system; Large language model; Cooperation;
27 Climate change

28



29 **1. Introduction**

30 Tropical cyclone (TC, also known as hurricane or typhoon in different regions) is a kind of
31 highly destructive natural disasters that poses severe threats to lives and property in coastal areas.
32 With the intensification of climate change, factors such as the decline of El Niño and the
33 development of La Niña in autumn and winter have contributed to an increase in both the
34 frequency and severity of TC. According to the *2024 Global Natural Disaster Assessment Report*,
35 storms primarily classified as TCs occurred 87 times worldwide, resulting in 2,582 fatalities,
36 affecting approximately 47,924 million people, and causing direct economic losses amounting to
37 172,591 billion dollars (ADREM et al., 2025). As global connectivity continues to intensify, the
38 impacts of typhoons have transcended geographic boundaries, leading to cross-regional and
39 cross-sectoral economic repercussions (Zhang et al., 2019).

40 Human society has actively engaged in responding to TC disasters. As a financial tool for risk
41 mitigation, insurance plays a significant role in addressing the impact of TC. With the continuous
42 development of society, insurance systems have been increasingly refined, and TC risk insurance
43 services have gradually gained greater public attention. Existing TC risk insurance systems can be
44 categorized into three models: the government-led model, the public-private partnership (PPP)
45 model and the market-led model. The government-led model gives the state a dominant role in
46 underwriting or reinsuring TC risks. The United States exemplifies this through the Florida
47 Hurricane Catastrophe Fund (FHCF) established in 1993, with the state government acting as a
48 reinsurer to assume catastrophic risks (Pacini and Marlett, 2001). The public-private partnership
49 (PPP) model combines market-based front-end operations with government-backed mechanisms.
50 China introduced typhoon-specific insurance in 2016, known as the typhoon catastrophe index
51 insurance (Jing et al., 2024), and Australia brought into effect the Cyclone Reinsurance Pool (CRP)
52 in 2022 (Jarzabkowski et al., 2022). The Japanese insurance sector placed particular emphasis on
53 the development of typhoon simulation models to better assess insurance loss (Okazaki et al.,
54 2022). The market-led model relies primarily on private insurers. The UK has a developed
55 insurance and reinsurance system, making purely commercial operation of risks possible. Overall,
56 as an effective mechanism for addressing impacts of TCs, the significance of insurance continues
57 to grow against the backdrop of economic development and intensifying climate change.



58 In existing academic research, scholars from diverse backgrounds, including insurance
59 practitioners, government officials, and scientists, have conducted studies on TC risk insurance,
60 such as operational models and loss assessment frameworks, thereby contributing to the
61 advancement of insurance systems. Against the current backdrop of climate change, which
62 continues to amplify the impacts of TC disasters, it is necessary to systematically review these
63 studies, summarize innovative perspectives and methods proposed by different stakeholders, and
64 examine the status and patterns of collaboration among them. Such a synthesis holds significant
65 implications for the practical implementation and market promotion of TC risk insurance
66 mechanisms. Furthermore, by identifying the challenges and gaps in current research, this effort
67 can provide clear guidance for the future development and enhancement of TC risk insurance,
68 ultimately strengthening the role of insurance in mitigating and responding to TCs.

69 There are currently few literature review articles focusing on TC risk insurance (Nobanee and
70 Nghiem, 2024; McAneney et al., 2016; Jain et al., 2022). These studies still rely on traditional
71 expert-based methods, such as literature reviews and meta-analyses, which are often constrained
72 to a limited number of publications, making it difficult to comprehensively reflect the overall
73 landscape of research in this field. In response, this research will employ an artificial intelligence
74 (AI)-based approach, the Large Language Model (LLM), to conduct a systematic analysis of over
75 eight hundred relevant publications. Compared to the traditional review articles, the innovations of
76 this study are as follows:

77 • Leveraging the long-text analysis capability of LLM, this study overcomes the limitations of
78 traditional reviews in terms of literature volume, significantly expanding the scale of the reviewed
79 publications. It comprehensively presents the overall landscape of current TC risk insurance
80 research through the dual dimensions of temporal dynamics and spatial distribution patterns.

81 • Utilizing the semantic comprehension capabilities of LLM, the research literature is further
82 refined and analyzed. The study identifies four core dilemmas that cut across stakeholder
83 perspectives: Can TC risk remain insurable under climate change? Is insurance comprehensive
84 enough? Is insurance accessible to those who need it most? Will people purchase insurance even
85 when it is available? It then systematically organizes innovative achievements for each dilemma,
86 providing stakeholders with a concise, indexed reference.

87 • From a collaboration perspective, the study examines the cooperation among governmental



bodies, market entities, and scientific communities in the research literature. Based on the analysis of four core dilemmas, it proposes a dilemma-aligned tripartite collaboration framework that specifies joint actions for each stakeholder, thereby advancing multi-stakeholder cooperation to improve the TC risk insurance system.

In the subsequent sections, Part 2 introduces the method adopted in this study and the sources of the literature. Part 3 presents the spatiotemporal distribution and collaboration networks, and then elaborates the four core dilemmas together with stakeholder-specific innovations. Part 4 discusses the research results and proposes a tripartite cooperation framework for TC risk insurance. The final section concludes the paper.

2. Data and Method

Data

We conducted a thorough search of the Web of Science (WoS) core collection bibliographic database to obtain the research documents on TC risk insurance. The details of searching and query results are demonstrated as below:

1. Temporal range: 1900-31st Dec. 2025

2. Strategy: To ensure a comprehensive and thorough literature review, we performed a topic search (TS) combining the themes of TC (hurricane or typhoon) and insurance (or premium, or reinsurance). The search string used was: TS=((typhoon OR hurricane OR “tropical cyclone”) AND (insuran* OR premium OR reinsuran*)).

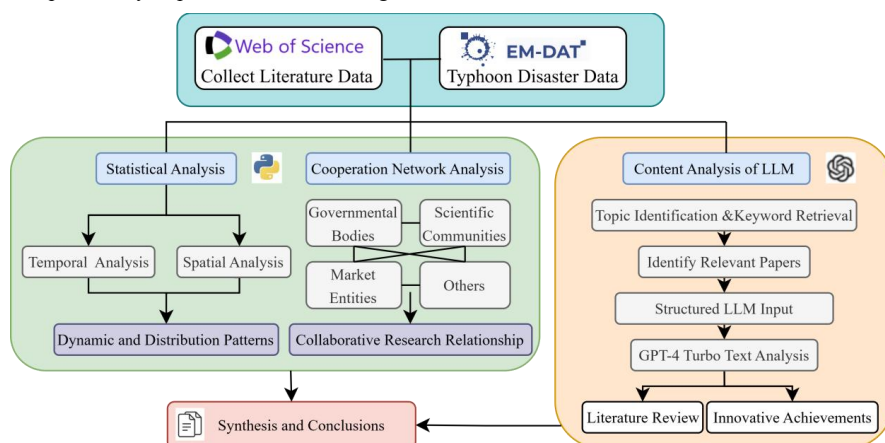
Finally, a total of 890 peer-reviewed papers and conference reports were selected from the query after duplicates were removed.

Additionally, we collected statistical data related to TC disasters. The empirical data were sourced from the authoritative EM-DAT international disaster database, which compiles records of more than 26,000 major disaster events globally between 1900 and 2025 (EM-DAT, 2025; Delforge et al., 2025). TC-related entries were subsequently extracted, encompassing critical information such as disaster timing, geographical location, trajectory, and the resulting casualties and economic losses. These data furnish a comprehensive empirical foundation for analyzing the historical impact of typhoon risk.



116 Method

117 The application of large language models (LLMs) in academic research has expanded rapidly in
 118 recent years, especially in literature review and knowledge synthesis (Alberts et al., 2023; Rane et
 119 al., 2023). Artificial intelligence (AI)-based tools facilitate content interpretation, topic extraction,
 120 and result summarization, improving the efficiency of comprehensive literature analysis.
 121 Therefore, this study adopts GPT-4 Turbo as the core intelligent analytical tool to investigate TC
 122 risk insurance research. The methodology involves three steps. First, a spatiotemporal statistical
 123 analysis of the collected literature is conducted to identify evolving trends and spatial patterns in
 124 TC risk insurance research. Second, collaborative relationships among stakeholders, categorized
 125 as governmental bodies, market entities and scientific communities, are examined. Third,
 126 leveraging the LLM's textual analysis capabilities, the study identifies four core dilemmas that cut
 127 across stakeholder perspectives: Can TC risk remain insurable under climate change? Is insurance
 128 comprehensive enough? Is insurance accessible to those who need it most? Will people purchase
 129 insurance even when it is available? For each dilemma, the LLM is employed to synthesize the
 130 innovative achievements of different stakeholder groups as reflected in the literature. The
 131 complete analysis process is shown in Figure 1.



132
 133 **Figure 1.** The complete literature review process of TC risk insurance with AI-based tools
 134 (GPT-4 Turbo).

135 To ensure the accuracy and relevance of the information extracted, a structured prompting
 136 approach was employed to guide the model in executing the content analysis task. The prompts
 137 were designed as follows :



138 **[Prompt 1 (Role and Task Setting)]** . I am a scholar in the field of natural disaster research,
139 currently working on tropical cyclone (TC) risk insurance. Please thoroughly review the content of
140 these relevant papers and then specify core research themes. Finally, produce a literature review
141 organized by these themes. For each theme, you should summarize the main research directions
142 and key findings from the perspective of three stakeholder groups: governmental bodies, market
143 entities, and scientific communities.]

144 **[Prompt 2 (Specific Instruction for Any Given Theme)]**. The current research question is:
145 insert specific theme. Based on the literature, please write one general paragraph that summarizes
146 the core academic debate or key conclusions for this theme. Then write one paragraph for each of
147 the following three stakeholder perspectives: governmental bodies, market entities, scientific
148 communities.]

149 **3. Results**

150 ***Chronological distribution of documents***

151 Based on the publication years, the dynamic changes in the number of research papers on TC
152 risk insurance are summarized in Figure 2. Among the retrieved studies, the earliest research can
153 be traced back to 1977 (Shows, 1977). Over the past two decades, the volume of literature has
154 increased significantly. Figure 2 also illustrates the year-by-year trend of economic losses caused
155 by TCs and the rising economic losses have, to some extent, driven the public to seek insurance as
156 a means of transferring and mitigating risks. Among the TC disaster names identified in the
157 literature, Hurricane Katrina (2005) emerges as the most frequently mentioned through word
158 frequency statistics, underscoring its profound significance to TC risk insurance research. Notably,
159 following Hurricane Katrina, the successive occurrence of TC disasters (e.g., Typhoon Mangkhut,
160 Yagi; Hurricane Sandy, Harvey) has spurred a steady growth in TC risk insurance research. This
161 trend reflects that insurance, as a financial instrument for risk management, is increasingly
162 recognized in academia as an effective complement to technological approaches.

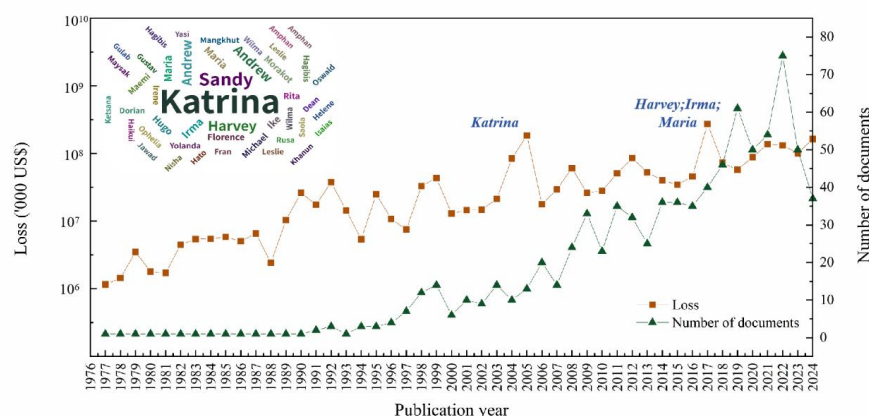


Figure 2. Chronological Distribution of publications and economic losses of TCs. The Squares and triangles represent the “publications” and “economic losses”.

Spatial distribution of documents

Based on the address information of the authors’ affiliated institutions, the spatial distribution of TC risk insurance publications is analyzed, as presented in Figure 3. TCs primarily affect countries and regions along the western Pacific, Atlantic, northeastern Pacific, as well as the Indian Ocean and South Pacific. Accordingly, the majority of current research originates from these areas.

Among these countries, China and the United States account for the vast majority of publications (more than 62%), while island nations with relatively smaller land areas and comprehensive national strength contribute significantly less research output. This reflects an uneven distribution in typhoon insurance research, highlighting the need to strengthen broader collaboration across different regions.

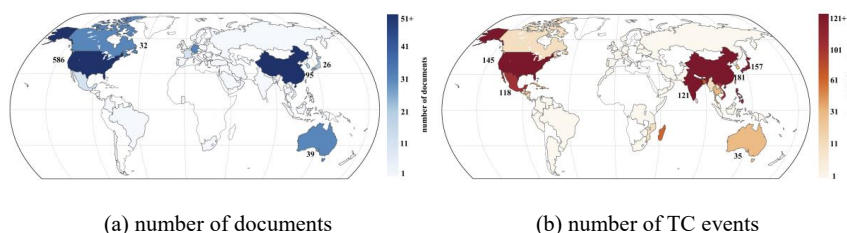
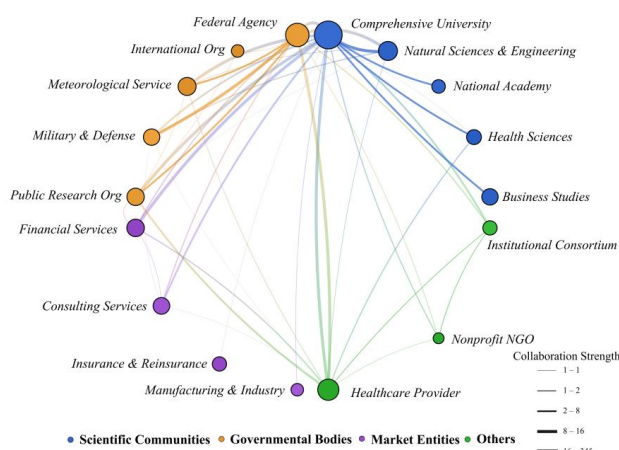


Figure 3. Spatial Distribution of publications on TC risk insurance. Compiled based on the address information of authors, and in cases where the authors are affiliated with multiple countries, each affiliation has been counted.



182 *Collaboration among multi-stakeholder researchers and across nations*

183 The development of TC risk insurance system necessitates participation from multiple
 184 stakeholders, including government bodies, market entities, and scientific communities. In fact,
 185 much of the existing research has been conducted through collaborative efforts. The study
 186 categorized the authors of the collected papers into three main groups: governmental bodies,
 187 market entities, and scientific communities, further subdivided into 17 specific categories.
 188 Statistical analysis of collaborative relationships within each category was conducted, and the
 189 results are presented in Figure 4. The findings reveal that authors from different backgrounds have
 190 engaged in varying degrees of collaboration in TC risk insurance research. However, the intensity
 191 of such collaboration remains insufficient and requires further enhancement.

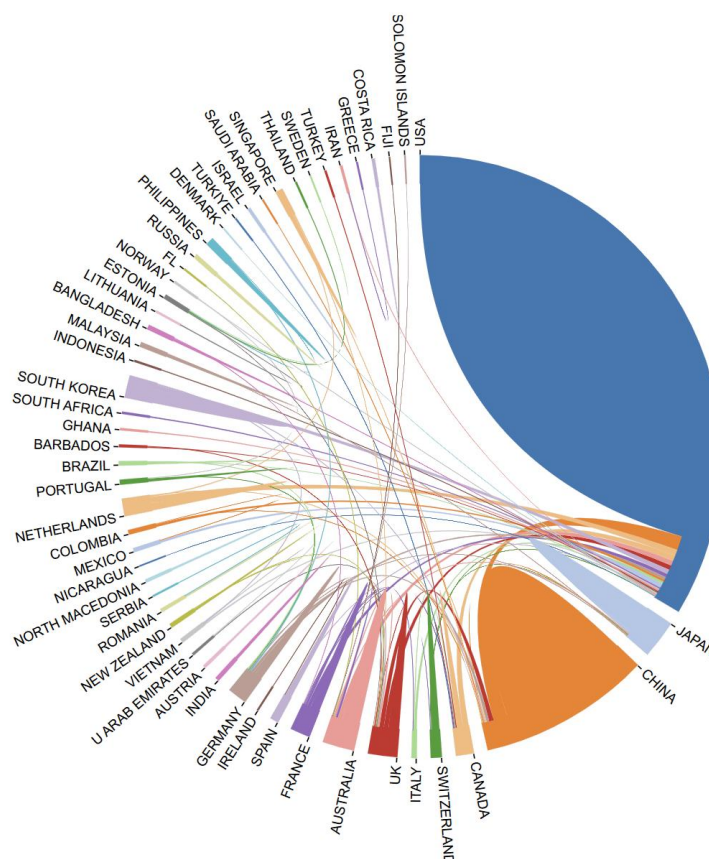


192
 193 **Figure 4.** Research Institution Collaboration Network. Node size: number of publications
 194 (larger nodes indicate more papers); Line thickness: collaboration intensity (thicker lines indicate
 195 more co-authored papers)

196 Based on the nationalities of the authors, an international collaboration network for TC risk
 197 insurance research was constructed, as shown in Figure 5. The figure indicates that although a
 198 collaborative network has been established among different countries and regions, the linkages
 199 remain relatively weak in terms of frequency. Most research collaborations are confined to
 200 scholars within the same country, particularly in the United States and China. This pattern
 201 suggests that TC risk insurance research remains largely nationally oriented, potentially limiting
 202 the cross-fertilization of ideas and methodologies across different institutional and cultural



203 contexts. Future research is expected to see an increase in international collaborative efforts,
204 which could enhance the global relevance and applicability of findings in this field.



205
206 **Figure 5.** International Collaboration Network. Line thickness: number of collaborative papers
207 (thicker lines indicate more collaborations)

208 **Key Concerns of Stakeholders**

209 To systematically synthesize the diverse research findings across stakeholders, we employ
210 GPT-4 Turbo to conduct an in-depth analysis of the collected literature and use it to analyze the
211 content of the retrieved articles and summarize their innovative achievements. The large language
212 model-assisted analysis reveals that, regardless of whether the research originates from
213 governmental bodies, market entities, or scientific communities, the vast majority of TC risk
214 insurance studies converge around four core dilemmas: Can TC risk remain insurable under
215 climate change? Is insurance comprehensive enough? Is insurance accessible to those who need it



216 most? Will people purchase insurance even when it is available? These dilemmas not only
 217 represent the key research frontiers but also provide a unifying framework for understanding the
 218 different roles and innovations of each stakeholder. Accordingly, the following subsections
 219 elaborate each dilemma in turn, and within each, the study presents the innovative achievements
 220 of the three stakeholder groups as reflected in the literature. A summary of stakeholder-specific
 221 key concerns and the corresponding keywords used for literature retrieval is provided in Table 1.

222 **Table 1** Key concerns of each stakeholder and relevant keywords.

core dilemma	stakeholder	key concerns	keywords
Can TC risk remain insurable under climate change?	governmental bodies	insurance system design and legislation	law; regulation
		financial support	finance; fiscal
	market entities	insurance pricing	price
		insurance product design	product
Is insurance comprehensive enough?	scientific communities	risk diversification	diversification; reinsurance
		insurability of TC risk	insurability
	governmental bodies	risk forecast	forecast; prediction
		insurance system design and legislation	law; regulation;
	market entities	insurance market supervision	supervision; management; governance
		risk management	risk management
	scientific communities	insurance product design	product
		vulnerability assessment	vulnerability; vulnerable
Is insurance accessible to those who need it most?	governmental bodies	risk regionalization	regionalization; area; zonal-based
		database design and development	database; platform; dataset
	market entities	financial support	finance; fiscal
		social equity	equity; fairness; justice
	scientific communities	insurance pricing	price
		risk diversification	diversification; reinsurance
	governmental bodies	risk regionalization	regionalization; area; zonal-based
		vulnerability assessment	vulnerability; vulnerable
Will people purchase even when it is available?	governmental bodies	insurance market supervision	supervision; management; governance
		social stability	stable
	market entities	insurance product design	product
		vulnerability assessment	vulnerability; vulnerable



market entities	insurance pricing	price
	risk management	risk management
scientific	risk forecast	forecast; prediction
communities	database design and development	database; platform; dataset
	vulnerability assessment	vulnerability; vulnerable

223 ***Can TC risk remain insurable under climate change?***

224 Climate change poses fundamental challenges to the insurability of TC risk. Under climate
 225 change, the insurability of large-scale natural disasters faces multiple impediments: potentially
 226 unbounded loss magnitudes that could render premiums prohibitive, strong spatial correlation that
 227 frustrates conventional diversification and demands substantial capital buffers, and heightened
 228 climate uncertainty that complicates actuarial pricing (Charpentier, 2008; Kunreuther, 2007).
 229 Addressing whether TC risk can remain insurable under climate change requires examining the
 230 roles of governments, market entities, and scientific communities in overcoming or mitigating
 231 these barriers.

232 Governmental bodies act as ultimate risk bearers when TC-induced losses may substantially
 233 exceed the underwriting capacity of private insurers. Consequently, the government must
 234 participate directly or indirectly in risk sharing through instruments such as catastrophe insurance
 235 funds and catastrophe bonds (Zhou and Tu, 2016). In the United States, the NFIP (National Flood
 236 Insurance Programme) has long been a focus of debate among regulators and academics due to its
 237 fiscal deficits and pricing mechanisms. Evaluations indicate that the programme continues to face
 238 persistent challenges, including funding shortfalls, affordability of premiums, and the validity of
 239 flood insurance rate maps, necessitating urgent reform (Grigg, 2019). While governments can
 240 temporarily fill insurability gaps, their interventions also carry structural weaknesses that threaten
 241 long-term viability under climate change.

242 Market entities confront the insurability question directly through pricing and risk
 243 diversification. The pricing of TC risk insurance presents insurers with a fundamental commercial
 244 dilemma: Setting premiums too high leads to underinsurance, exposing households and regional
 245 economies to risks that have not been adequately mitigated. Conversely, setting premiums too low
 246 threatens the insurers' solvency (Liu, 2025). Pricing accuracy is further influenced by factors such
 247 as climate change, interest rate volatility and environmental uncertainty. For example, there is a



248 significant correlation between climate indices and catastrophe bond premiums (Feng and Zeng,
249 2025; Chang et al., 2018). To enhance insurability, insurers use catastrophe models to estimate
250 expected losses (Hu et al., 2024; Lai, 2016), design parametric insurance to minimize basis risk
251 (Franco et al., 2024), and achieve risk diversification through reinsurance and alternative risk
252 transfer such as CAT bonds and insurance-linked securities (Csiszar, 2007). However, evidence
253 suggests that while insurers adjust loss expectations following disaster notification, systematic
254 underestimation persists (Feria-DomÃ - niguez, et al. 2017; Yamasaki, 2016). Thus, whether
255 insurers can maintain solvency while offering affordable coverage under climate change remains
256 an open question.

257 Scientific communities have addressed insurability as a foundational theoretical challenge.
258 Strategies such as premium adjustments, coverage limitations, and the expansion of risk transfer to
259 reinsurers and capital markets through securitisation or catastrophe options can help maintain the
260 affordability and accessibility of insurance in an era of escalating disaster risks (Charpentier, 2008;
261 Sturm and Oh, 2010; Kunreuther et al., 2013). However, the scientific community's persistent
262 questioning of insurance accessibility raises fundamental questions about the long-term viability
263 of the insurance system, upon which numerous societies globally rely on insurance as their
264 principal risk governance mechanism (Phelan et al., 2011). Therefore, while technical innovations
265 may partially address insurability, whether TC risk can be reliably insured under climate change
266 ultimately hinges on the pace of climate change itself and collective willingness of all parties to
267 mitigate losses.

268 ***Is insurance comprehensive enough?***

269 Existing TC risk insurance systems have shortcomings in terms of the comprehensiveness of its
270 coverage. Governments, market entities, and scientific communities have sought to expand
271 coverage through legislation, product innovation, and risk diversification, but legal loopholes,
272 product design limitations, insufficient coverage breadth, and weak data infrastructure leave many
273 risks inadequately covered. Overall, there is an urgent need to significantly improve the
274 comprehensiveness of TC risk insurance.

275 Governmental bodies have exposed structural deficiencies in insurance system design and
276 legislation. The United States has established a complex multi-level legal framework, which



277 played a significant role in regulating post-disaster reconstruction (Dehring and Halek, 2013; Platt
278 et al., 2002). Nevertheless, legal loopholes in the United States such as the anti-concurrent
279 causation (ACC) clauses may expose disaster victims to substantial coverage risks (Young, 2010;
280 Zink, 2014). Existing insurance systems have also revealed certain structural deficiencies:
281 insurance mechanisms themselves face theoretical dilemmas concerning the definition of risk and
282 insurability, and there is an urgent need to clarify the boundaries of risk through legislation (Roth,
283 1997). In addition, catastrophe models are not purely scientific tools but carry certain political
284 inclinations. The interplay between regulators and the industry jointly determines how “risk reality”
285 is quantified and priced (Weinkle and Pielke, 2017; Weinkle, 2020). These factors collectively
286 limit the comprehensiveness and fairness of the insurance system.

287 Market entities continuously continue to enhance coverage through product design and risk
288 management. To address affordability limitations, novel product architectures integrate
289 government subsidies, mutual insurance arrangements, and layered risk transfer structures.
290 However, insurers confront persistent operational challenges in claims settlement, including
291 regional inconsistencies in claims policies and exposure to opportunistic fraud (Tonn and
292 Czajkowski, 2022; Tonn and Czajkowski, 2022; Pao et al., 2014). Technological advancements
293 such as drones, remote sensing satellites, and AI-driven image recognition have substantially
294 improved the efficiency of claims processing (Guan et al., 2022; Böge et al., 2019), and research
295 has been conducted on the use of satellite imagery and remote sensing data for automated damage
296 assessment (e.g., the severity of crop lodging and building collapse) (Miura et al., 2022; Guo et al.,
297 2023; Thomas et al., 2013; Fryda et al. 2024). Social media analytics and search intensity metrics
298 have also been employed for rapid hurricane damage assessment and claims forecasting (Yuan and
299 Liu, 2020; Aaronson et al., 2022; Yuan and Liu, 2018). Nevertheless, these innovations cannot
300 fully replace comprehensive on-side inspection. Thus, existing insurance products still have gaps
301 in coverage breadth, pricing accuracy, and claims comprehensiveness.

302 Scientific communities have identified the technical foundations required to achieve
303 comprehensive insurance coverage. Vulnerability assessment provides a scientific foundation for
304 for insurance systems, addressing both social systems (income, insurance penetration, social
305 networks, educational attainment) and physical infrastructure (building type-specific vulnerability
306 functions constructed using stochastic finite element modeling combined with insurance loss data)



(Wang et al., 2012; Jaimes and Niño., 2018; Yum et al., 2021). Risk regionalization refers to the division of regions based on the spatial distribution of disaster risks. Researchers have conducted risk regionalization studies by integrating meteorological, physiographic, and socio-economic factors, encompassing hazard intensity, environmental exposure and vulnerability indices, to inform differentiated insurance premiums (Hu et al., 2024; PC et al., 2023; Chaojia et al., 2022; Chen et al., 2021; Mahendra et al., 2010; Rey et al. 2019; Arun and Kunte, 2012; Prakash et al., 2023). In terms of database design, several key datasets have been established, such as HURDAT2, the typhoon database for southern and eastern Chinese coastal regions (SECCR), and Taiwan's Central Weather Bureau tropical cyclone database (Delgado et al., 2018; Yap et al., 2015; Jian et al., 2022). However, numerous challenges persist in data acquisition and management, including the quality of disaster loss records, the complexity of economic impact indicators, spatial and temporal mismatches across datasets, data incompleteness, and the demand for rapid processing capabilities. All of these remain central research priorities (Wirtz et al., 2014; Zhang and Li, 2025; Pinelli et al., 2020). The lack of comprehensive, standardized foundational data directly constrains the comprehensiveness of insurance product design and accurate pricing.

Is insurance accessible to those who need it most?

Even when TC risk insurance exists in principle, it is not equally accessible to all populations. Marginalized residents such as residents of color, disabled residents, elderly residents, and residents occupying low-income housing may not afford the insurance premiums (Grinton and Paige, 2022; Baker and McElrath, 1996; Yu et al., 2025; Noser et al., 2021). They receive no financial compensation following a TC disaster, which further deteriorates their already fragile living conditions. A cross-national study has identified four mechanisms of inequity in disaster recovery: enclosure, exclusion, encroachment, and entrenchment (Sovacool et al., 2018). These mechanisms have been documented in major disasters such as Hurricane Katrina, the 2004 Indian Ocean tsunami, and typhoons in the Philippines, indicating that poorly designed recovery policies often further marginalize the most vulnerable populations. Thus, whether insurance is accessible to those who need it most depends on how governments, market entities, and scientific communities address affordability, social equity, and institutional design.

Governmental bodies have confronted the issue of social equity in disaster insurance provision.



336 Issues such as racism, classism and sexism can lead to social inequities. Governments have
337 adopted institutional innovations including risk-pooling insurance, the principle of informed
338 consent, and environmental penalty bonds to ensure that insurance systems and post-disaster aid
339 achieve genuine fairness and inclusivity (Gould, 2018). Moreover, governments have adopted
340 compensatory policies to support insurance market development. For instance, the Philippine
341 government provides insurance purchasers with facilitating access to credit, while the U.S.
342 government offers tax-deferred loss reserves for insurance companies (Goodwin et al., 2022;
343 Milidonis and Grace, 2008; Josephson and Marshall, 2016). However, federal disaster assistance
344 has been found to exert a “crowding-out effect” on private insurance uptake (Davlasheridze and
345 Miao, 2019). These findings suggest that government interventions can either enhance or
346 undermine accessibility for the most vulnerable.

347 Market entities address accessibility primarily through product design and pricing strategies that
348 aim to improve affordability. To address affordability limitations, novel product architectures
349 integrate government subsidies, mutual insurance arrangements, and layered risk transfer
350 structures (Hu et al., 2024). Pricing TC risk insurance poses a fundamental dilemma: premiums set
351 too high result in underinsurance, exposing households and regional economies to unmitigated
352 risk, while premiums set too low threaten insurer solvency (Liu et al., 2025). In response, market
353 entities advocate for flexible pricing frameworks incorporating ambiguity loading, multi-year
354 fixed-price contracting, and government subsidies to enhance affordability (Dietz and Walker,
355 2019). Nevertheless, evidence suggests that erosion of competitiveness may intensify risk
356 concentration (Aseervatham et al., 2017) in high-risk zones and geographical pooling does not
357 necessarily impose implicit subsidies on high-risk areas (Dumm et al., 2015). Therefore, while
358 market mechanisms offer tools to enhance accessibility, they require deliberate design to ensure
359 that those who need insurance most are not priced out.

360 Scientific communities have provided critical insights into the socioeconomic determinants of
361 access to insurance. Vulnerability assessment research addresses both social systems and physical
362 infrastructure. Socially, analyses of socioeconomic determinants such as income, insurance
363 penetration, social networks, and educational attainment delineate population-level vulnerability
364 profiles (Wang et al., 2012; Jaimes and Niño, 2018). These factors directly influence whether
365 individuals can afford and access insurance. In the context of insurability, scholars have noted that



under climate change, potentially unbounded loss magnitudes could render premiums prohibitive, thereby excluding low-income populations (Charpentier, 2008; Kunreuther and Michel-Kerjan, 2007). Strategies to sustain affordability include premium adjustments, coverage limitations, and expanded risk transfer (Sturm and Oh, 2010; Kunreuther et al., 2013). In risk regionalization, researchers have integrated hazard intensity, environmental exposure, and vulnerability indices to inform differentiated premiums (PC et al., 2023; Chaojia et al., 2022; Chen et al., 2021; Mahendra et al., 2010; Rey et al. 2019; Arun and Kunte, 2012; Prakash et al., 2023). However, this predominantly technocratic approach has drawn critique, with some scholars contending that social factors should also be integrated into risk zoning frameworks, particularly racial and economic inequality (Monk, 2020; Weinkle and Pielke, 2017). Such integration would help ensure that insurance accessibility is not undermined by zoning practices that inadvertently exclude disadvantaged communities. Thus, scientific research underscores that accessibility is not merely a matter of pricing but is deeply embedded in social vulnerability and institutional design.

Will people purchase insurance even when it is available?

Even when TC risk insurance is available in the market, whether people actually purchase it depends on multiple factors, including premium levels, risk perception, the substitution effect of government disaster assistance, and community stability. Research indicates that fluctuations in TC risk insurance participation rates directly affect housing market pricing signals and community cohesion. Periods of highly unstable policy enrollment are often accompanied by declining housing prices and residential out-migration behavior (Poudel et al., 2023). Therefore, understanding whether people will buy insurance requires analyzing how government policies, market strategies, and scientific research jointly shape purchasing incentives.

Governmental bodies significantly influence people's purchase decisions through their policy choices. Federal disaster assistance has been found to exert a "crowding-out effect" on private insurance uptake: the more aid provided, the lower the insurance take-up rates, a phenomenon that has prompted regulatory reflection on the "hidden costs" of such assistance (Davlasheridze and Miao, 2019). To maintain long-term stability, it is essential to adopt long-term risk forecasting, no-regret decision-making frameworks, and negotiated social acceptance thresholds (Tian et al., 2025). In insurance market supervision, governments affect purchase willingness by regulating



395 catastrophe models, premium rates, and market conduct. For instance, Florida has developed
396 publicly accessible hurricane loss models to enhance rate-setting transparency and provide an
397 independent basis for premium approval (Tao et al., 2022). However, if government-provided free
398 disaster assistance is too generous, people may rationally choose not to buy insurance and instead
399 rely on post-disaster relief. Conversely, when governments support the insurance market through
400 facilitating access to credit (as in the Philippines) or tax-deferred loss reserves (as in the United
401 States) (Goodwin et al., 2022; Milidonis and Grace, 2008; Josephson and Marshall, 2016), they
402 may incentivize purchase. Thus, the trade-off governments make between social equity and
403 stability directly determines residents' purchasing behavior.

404 Market entities influence residents' purchase decisions through product design, pricing
405 strategies, and risk management. Residents, as boundedly rational consumers, are often sensitive
406 to low initial premiums, which may lead to adverse selection. Market entities advocate for flexible
407 pricing frameworks incorporating ambiguity loading, multi-year fixed-price contracting, and
408 government subsidies to enhance affordability, thereby increasing take-up rates (Dietz and Walker,
409 2019; Kunreuther and Michel-Kerjan, 2015; Liu et al., 2025). Moreover, insurers offer premium
410 discounts for clients implementing protective measures (Stricker et al., 2025; Wang et al., 2025;
411 Jin et al., 2008; Chen et al., 2013; Liu et al., 2018; Qin and Stewart, 2021) and enhance public risk
412 awareness through education and training, both of which help promote purchase decisions.
413 However, if insurers exit high-risk areas due to excessive risk, or if claims processes are complex
414 and unfair, people will lose access or willingness to buy.

415 Scientific communities have revealed deeper factors affecting purchase behavior. From a
416 multi-stakeholder coordination perspective, scholars have employed game theory and system
417 dynamics models to explore equilibrium states among governments, insurance companies, and
418 residents. The findings suggest that when all three parties act in a self-interested manner, the
419 outcome tends to be an unstable equilibrium: residents gravitate toward the lowest-premium
420 products, insurers engage in price wars or exit the market, and governments are compelled to
421 assume an increasing burden of free disaster assistance (Eid et al., 2015). This finding explains
422 why low take-up rates may persist even when insurance is available. To maintain long-term
423 stability, it is essential to adopt long-term risk forecasting, no-regret decision-making frameworks,
424 and negotiated social acceptance thresholds (Tian et al., 2025). Furthermore, vulnerability



425 assessment research indicates that socioeconomic determinants such as income, insurance
426 penetration, social networks, and educational attainment delineate population-level vulnerability
427 profiles (Wang et al., 2012; Jaimes and Niño, 2018), which directly affect whether people can
428 afford and are willing to take out insurance. In the post-disaster context, the coordinated recovery
429 of social service systems including healthcare, housing, and information is equally critical;
430 establishing systematic community-based care modeled on the “medical home” approach can help
431 prevent secondary social risks and resource depletion following disasters (Kanter et al., 2015).
432 These studies suggest that without addressing underlying vulnerabilities and disruptions in social
433 support systems, even if insurance is available in the market, those who need it most may not or
434 cannot purchase it.

435 **4. Discussion**

436 *Research overview*

437 Based on the statistical analysis of TC risk insurance research, it is evident that over the past
438 two decades, TC risk insurance has garnered increasing attention. In the context of climate change
439 and socioeconomic development, the impact of TCs remains significant, and insurance will
440 continue to play a crucial role. It is foreseeable that more studies will focus on TC risk insurance,
441 contributing to the continuous improvement of the TC risk insurance system.

442 However, from the perspective of spatial distribution, the imbalance in insurance development
443 is pronounced. Currently, research from China and the United States dominates the field. This can
444 be attributed to the extensive coastal areas in both countries, their high exposure to TC risk, and
445 consequently, greater attention to disaster insurance. Nevertheless, it must be acknowledged that
446 economic and research capacity, as well as national system and policy orientation, also contribute
447 to this disparity. Some island nations, although frequently affected by TCs and in need of robust
448 insurance systems, lack insurance companies with sufficient risk-bearing capacity, resulting in
449 limited research output in these regions. Bridging this gap requires not only strengthened
450 cross-regional cooperation but also the prudent adaptation of knowledge and tools to local
451 institutional contexts.

452 The existing literature converges on four interlocking dilemmas, and they interact with each



other. A central tension runs between accessibility and insurability: government subsidies can lower premiums and make insurance cheaper, but they may also dampen private demand and distort risk signals, thereby threatening insurers' solvency. Conversely, pricing based on actuarial fairness can ensure solvency but makes premiums unaffordable for low-income households, excluding them from coverage. This trade-off is essentially political in nature, and neither side can resolve it unilaterally. A vicious cycle links the insurability crisis with low take-up rates. When climate change makes tropical cyclone risk fundamentally harder to insure, market entities signal this via non-renewals or steep price hikes, lowering residents' perceived value of insurance. At the same time, generous government post-disaster assistance encourages rational non-purchase: Why pay premiums when aid is available? This behavioral response worsens adverse selection, prompting further market withdrawal, which in turn increases the government's relief burden. Without coordinated intervention, the system drifts toward an unstable equilibrium where all three stakeholders lose. Overall, a comprehensive approach that integrates governmental bodies, market entities and scientific communities is required to transform what were previously conflicting trade-offs into mutually reinforcing solutions.

Potential issues

As demonstrated by the preceding analysis, the literature converges on four interlocking dilemmas. These dilemmas map directly onto the institutional challenges faced by governmental bodies, market entities, and scientific communities, and they demand coordinated, dilemma-specific responses.

While existing studies have yielded valuable theoretical insights and practical innovations across three stakeholder groups, the persistence of these four gaps indicates that piecemeal advances are insufficient. Closing the protection gap and strengthening systemic resilience will require each actor to assume a complementary role within an integrated governance framework. Accordingly, the following priorities are identified as critical for future research and practice:

- Governmental bodies: To address the accessibility and behavioral-failure dilemmas, the government's core responsibility is to ensure that all citizens, particularly vulnerable groups, have access to basic support in the face of TCs. On the one hand, it involves implementing targeted fiscal subsidies and incentives to allocate limited financial resources to the populations and



482 regions most in need, effectively addressing issues such as “insurance gaps” and “affordability”.
483 On the other hand, it requires enhancing public risk awareness and insurance literacy through
484 education, adopting effective risk communication and public education strategies, such as
485 risk-map-based communication and community education, to increase public participation in
486 insurance schemes, improve disaster preparedness, and promote proactive disaster prevention and
487 mitigation actions.

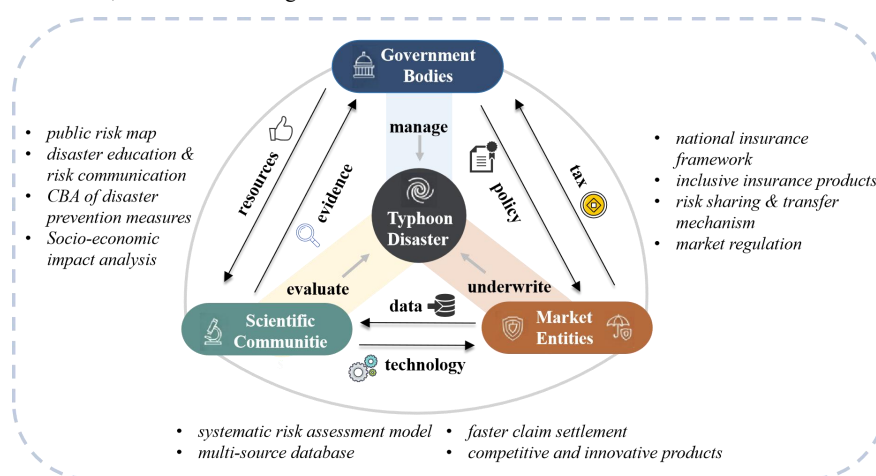
488 • Market entities: To resolve the insurability and comprehensiveness dilemmas, insurance
489 enterprises need to establish a more resilient and innovative multi-layered financial protection
490 system in the future. In terms of risk underwriting, it is essential to integrate advanced
491 technologies, such as climate scenario analysis and remote sensing imagery, to enable
492 forward-looking and precise risk assessment of insured subjects, thereby scientifically guiding
493 long-term strategies and reserve allocations. Regarding insurance claims settlement, technology
494 can also be leveraged to significantly reduce claim costs and time, achieving optimal operational
495 efficiency and cost control. As for risk transfer, beyond existing instruments like catastrophe
496 bonds, the development of other types of risk transfer tools should be continuously pursued to
497 adequately transfer and diversify excess loss risks, enhance capital efficiency, and ensure
498 sustainable profitability and growth.

499 • Scientific communities: To tackle the systemic-risk and data-gap dilemmas that
500 undermine both comprehensiveness and accessibility, scientists should focus on the systemic risks
501 associated with TC disasters in future research. Here, “systemic” refers to the compound and
502 structural nature of TC disasters. TCs not only cause direct casualties and property damage but
503 also lead to indirect and interconnected consequences. For example, TCs can trigger extreme
504 rainfall, which in turn causes urban flooding and landslides, further threatening social stability.
505 This chain of risk propagation requires in-depth study to reveal the compound effects and
506 cascading amplification mechanisms. By integrating interdisciplinary approaches, deeply
507 combining research paradigms from natural sciences, engineering, data science, economics,
508 finance, sociology, and political science, systematic solutions can be developed to address these
509 complex challenges.

510 ***Cooperation framework***



511 A comprehensive and stable TC risk insurance system requires the joint efforts and
512 collaboration of governmental bodies, market entities, and scientific communities, rather than
513 relying solely on any single party. As demonstrated by the current collaborative landscape,
514 preliminary cooperation has already been initiated among these stakeholders, with each
515 increasingly recognizing the importance of such partnerships. Building upon existing research
516 foundations and future research directions, we propose a feasible tripartite collaboration
517 framework, as illustrated in Figure 6.



518

519 **Figure 6.** A tripartite collaboration framework for TCs insurance system.

520 Within this framework, the governments can provide favorable policies for the development of
521 insurance companies, including financial support and effective regulation, while also offering
522 resources such as research funds and application scenarios for scientists. Correspondingly, the
523 sustainable development of market entities generates tax revenue for governments, which can
524 subsequently be used to support both insurers and scientists. Additionally, market entities provide
525 critical business data, such as claims information, to scientists. In turn, scientific communities can
526 develop innovative technologies for insurers to reduce costs and enhance profitability, while also
527 offering theoretical analysis and benefit evaluations for government decision-making, thereby
528 serving as evidence for policy implementation.

529 The content within the blocks in the diagram reflects areas where further collaboration can be
530 deepened. Through cooperation and innovation in these areas, a more powerful driving force can
531 be formed, propelling the entire TC risk insurance system toward greater fairness and efficiency,



532 thereby enhancing societal resilience under climate change scenarios.

533 It is important to note that there are developmental disparities among regions affected by TCs,
534 resulting in varying capacities to respond to TCs. From the perspective of a community with a
535 shared future for humankind, the collaboration among governmental bodies, market entities, and
536 scientific communities across different countries and regions should be strengthened. The
537 cooperative model among the stakeholders depicted in the diagram is not limited to local or
538 national levels but should also extend globally, encompassing international cooperation.

539 While the tripartite framework illustrated in Figure 6 provides a normative architecture for
540 collaboration, its practical viability hinges on how the three stakeholders align their incentives and
541 adapt the model to local institutional contexts. Rather than treating the framework as a
542 one-size-fits-all blueprint, we argue that its implementation must be calibrated to the three
543 archetypal insurance models identified in the Introduction: government-led, public-private
544 partnership (PPP), and market-led. Each model implies distinct roles for information sharing,
545 risk-knowledge translation, and resource mobilization.

546 • Government-led model: The state is the primary risk bearer and knowledge demander.
547 Governmental bodies should mandate independent scientific committees to conduct peer reviews
548 of catastrophe model outputs and exposure databases before they are used to set premium caps or
549 subsidy budgets, thereby preventing regulatory capture (Weinkle and Pielke, 2017).

550 • Market-led model: Underwriting standards are shaped by rating agencies and
551 industry-wide model accreditation boards. In this model, the governmental bodies act as the
552 meta-regulator. It certifies open-access hazard datasets and mandates disclosure of model
553 assumptions, thereby reducing information asymmetry without stifling innovation (Tao et al.,
554 2022).

555 • Public-private partnership (PPP) model: Governmental bodies, market entities, and
556 scientific communities co-invest in a shared data infrastructure. A neutral data trust which
557 governed by pre-agreed protocols on privacy and intellectual property rights can overcome the
558 reluctance to share proprietary data while preventing discriminatory pricing.

559 However, regardless of which model is adopted, information asymmetry remains a persistent
560 core obstacle. A feasible approach is to establish a tiered disclosure mechanism: Tier 1 involves
561 aggregated, sector-level loss data released to scientific consortia for model calibration. Tier 2



562 involves anonymized, geocoded policy and claims data shared with regulators via secure enclaves
563 for solvency monitoring. Tier 3 involves open publication of hazard-layer data by government
564 agencies (Tao et al., 2022).

565 However, the effective operation of the above-mentioned tiered disclosure mechanism relies on
566 strong scientific research and data infrastructure, which is not easy for many regions to achieve.
567 For regions with limited research capacity, a fully autonomous tripartite loop is often infeasible.
568 Regional risk pools, such as the Caribbean Catastrophe Risk Insurance Facility (CCRIF) and the
569 Pacific Catastrophe Risk Assessment and Financing Initiative (PCRAFI), offer a scaled-up
570 alternative: donor agencies and international scientific bodies provide hazard modeling,
571 participating governments provide sovereign guarantees and international reinsurance markets
572 absorb peak risks (Jain et al., 2022).

573 Incentive compatibility and enforcement are critical for stability. Governments should credibly
574 commit not to retroactively expand post-disaster relief in ways that crowd out private insurance
575 demand (Davlasheridze and Miao, 2019). Insurers should commit to remaining in high-risk
576 markets in exchange for regulatory clarity on capital requirements and the right to use risk-based
577 pricing. Scientists should commit to transparency in model uncertainty and conflict-of-interest
578 disclosure. Formalizing these mutual commitments through multi-year framework agreements
579 rather than ad-hoc project contracts can mitigate the “unstable equilibrium” identified in the
580 literature, wherein self-interested behavior by each party erodes system resilience (Eid et al.,
581 2015).

582 In sum, aligning the four core dilemmas with the three institutional models through
583 context-specific, incentive-compatible cooperation mechanisms offers a robust pathway to close
584 the protection gap.

585 **5. Conclusions**

586 In the context of climate change leading to an increasing destructiveness of TCs, improving the
587 TC risk insurance system is a pressing task. In this paper, a large language model (GPT-4 Turbo) is
588 employed to conduct a systematic analysis of existing research, revealing the developmental
589 trajectory of TC risk insurance studies and four interlocking dilemmas: Can TC risk remain
590 insurable under climate change? Is insurance comprehensive enough? Is insurance accessible to



591 those who need it most? Will people purchase insurance even when it is available? These
592 dilemmas constrain the current system. From the perspective of collaboration among
593 governmental bodies, market entities, and scientific communities, and taking into account the
594 heterogeneity of government-led, public-private partnership, and market-led models, a cooperative
595 framework is proposed, aiming to promote a more scientific, equitable, and efficient TC risk
596 insurance system.

597 The extent and focus of tripartite cooperation are also constrained by regional socioeconomic
598 conditions, policy frameworks, and other factors. Across different developmental stages and
599 institutional models, the emphasis of such collaboration may vary and should be adjusted
600 according to practical circumstances. However, from the perspective of promoting balanced global
601 development, broader international cooperation remains highly advisable. Ultimately, aligning the
602 three institutional models with the four core dilemmas through sustained tripartite collaboration is
603 essential to close the protection gap and enhance societal resilience in an era of accelerating
604 climate change.

605

Code and data availability. Portions of the data and code that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of interest. The authors declare no conflicts of interests.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process During the preparation of this work, the author(s) used GPT-4 Turbo (OpenAI) for literature content analysis and thematic synthesis. The author(s) reviewed and edited the output as needed and take full responsibility for the content of the published article.

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