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A computational, cross-linguistic analysis of semantic frame construction in Chinese, Spanish, and German climate discourse using corpus-based distributional semantics

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Abstract: Climate change has emerged as a central site of political discourse across multilingual governance systems, yet the mechanisms by which different language communities construct, adapt, and diverge in their framing of this shared issue remain poorly understood. This study investigates how semantic frames are cross-linguistically constructed in Chinese, Spanish, and German climate-change political discourse, asking whether and how convergence and divergence in framing can be quantitatively modelled through distributional semantics. A trilingual corpus of official political speeches (2015–2023; 187,952–260,711 tokens per language) was analysed using TF-IDF weighting, co-occurrence network modelling, and contextual embedding techniques (Word2Vec and BERT), targeting three recurring frames: global responsibility, national interest, and technological innovation. Results reveal systematic convergence in issue definition and causal attribution, reflecting shared lexical repertoires and semantic-space alignment shaped by transnational discourse circulation. Cross-linguistic similarity in contextual embeddings is statistically significant across all three language pairs and frames (permutation tests, $p \leq 0.031$). However, frame instantiation diverges markedly in moral evaluation and policy recommendation, reflecting culturally embedded strategies of semantic adaptation: Chinese discourse constructs collective responsibility through institutionalised formulations such as "Community of Shared Future for Mankind"; Spanish discourse foregrounds climate justice and civic proximity; and German discourse prioritises legal-institutional accountability. These findings demonstrate that framing can be operationalised as a computationally tractable, measurable construct, extending Entman's framework into cross-linguistic empirical analysis. The study contributes to computational discourse linguistics, political communication research, and multilingual climate governance studies by providing a replicable methodological pipeline for cross-linguistic semantic framing analysis applicable to other policy domains and language pairs.

Keywords: Computational discourse analysis, political discourse, climate change, frame semantics, cross-linguistic semantics, BERT embeddings, semantic framing

1. Introduction

The linguistic construction of climate-change discourse has emerged as a key area of inquiry in contemporary linguistics, particularly in the study of semantic framing, cross-linguistic variation, and computational modeling of discourse. While political communication research has long examined how frames shape public interpretation of climate issues, less attention has been devoted to the linguistic mechanisms through which these frames are instantiated across different languages. Understanding these mechanisms is essential not only for characterizing discursive practices but also for explaining how global narratives circulate and become adapted within diverse linguistic communities.

Recent advances in corpus linguistics and distributional semantics offer new ways to model frame construction as a measurable linguistic phenomenon. Techniques such as TF-IDF weighting, co-occurrence network analysis, and neural embedding models provide tools for examining lexical salience, semantic associations, and contextual similarity across languages. These methods allow researchers to move beyond qualitative descriptions and to quantify the extent to which semantic frames converge

or diverge in multilingual discourse. However, empirical research applying such techniques to political discourse remains limited, especially in studies comparing typologically distinct languages such as Chinese, Spanish, and German.

This study addresses this gap by examining the cross-linguistic construction of three key semantic frames—*global responsibility*, *national interest*, and *technological innovation*—in a trilingual corpus of climate-change political speeches. We conceptualize framing not only as a pragmatic and rhetorical strategy but as a semantic-structural construct that can be modeled through distributional patterns and contextual embeddings. By integrating frame semantics with computational methods, the approach captures both the shared lexical foundations of climate discourse and the culturally embedded pathways through which frames are re-contextualized across languages.

The goals of this study are threefold: (1) to identify cross-linguistic regularities and divergences in the semantic structure of climate-related frames; (2) to operationalize framing as a quantifiable construct through distributional and contextual semantic modeling; and (3) to contribute to discourse linguistics by proposing a computationally grounded approach for analyzing multilingual political discourse.

2. Literature review

2.1. Frame Theory

Frame theory, originally formulated by Goffman (1974), offers a foundational cognitive model for understanding how individuals' structure social experience by foregrounding certain elements of reality while backgrounding others. Entman's (1993) refinement of this perspective emphasizes that frames operate simultaneously as cognitive schemas and as strategic discursive instruments. Through selective emphasis, causal linkage, moral evaluation, and recommendations for action, political actors guide the interpretive process and influence policy legitimacy. This dual nature means that framing is not merely a linguistic practice but a cognitive operation that shapes the boundaries of public debate.

Building on Fillmore's (1985) distinction between nominal and verbal frames, later research has demonstrated that framing functions both as a static knowledge structure and as a dynamic discursive process. Nominal frames determine how pre-existing knowledge structures condition the interpretation of issues, such as when public endorsement of "carbon peak" policies increases if these policies are presented as opportunities for "economic development" rather than symptoms of an "ecological crisis" (Schön & Rein, 1994). Verbal frames, in contrast, emphasize the dynamic construction of meaning through rhetorical choices. Political speakers use metaphors, for example "climate war," to reshape perceptions of threat and urgency (Lakoff, 2010), while modal verbs such as "must" or "should" reinforce the inevitability of policy action (Fairclough, 2003). Entman's four functions—issue definition, causal attribution, moral evaluation, and policy recommendation—provide a widely used analytical framework in political communication. In this study, these functions are operationalized as issue framing, attribution patterns, policy recommendations, and emotional appeals, with emotional appeals treated as a central expression of moral evaluation in climate-related political rhetoric.

2.2. Contextualizing Frames: Multi-Level Governance as a Discursive Environment

Climate governance operates within a multi-level structure (Hooghe & Marks, 2003; Jänicke, 2017) comprising global, national, and discursive layers. At the global level, institutions such as the UNFCCC and the Paris Agreement generate shared norms and rhetorical repertoires—such as "carbon neutrality," "just transition," and "climate justice"—that define legitimate discursive boundaries. At the national level, these norms are selectively reinterpreted through domestic political lenses shaped by economic interests, governance styles, and ideological preferences. Political elites and media actors translate institutional norms into communicable frames that organize public perceptions of responsibility, risk, and opportunity.

The interaction among these levels produces both convergence and divergence in political communication. Convergence typically emerges in domains aligned with international cooperation norms, such as technological innovation or economic modernization. Divergence, however, is more pronounced in areas, where local political cultures shape responsibility attribution or risk perception. This multi-level model situates climate discourses as simultaneously reflecting global norms and local communicative identities. Against this backdrop, this study examines the linguistic mechanisms through which global frames are recontextualized across languages. By integrating frame semantics with computational methods, the approach captures both the shared lexical foundations of climate discourse and the culturally embedded pathways through which frames are adapted.

2.3. Frame Theory in Discourse Analysis

Frame analysis in political communication has traditionally operated at both macro and micro levels. At the macro level, frames reveal the ideological foundations of political narratives and their alignment with institutional power. Boykoff (2007a) demonstrated that U.S. media frequently employed a "scientific uncertainty" frame to delay public pressure for climate action, whereas European media favored a "precautionary principle" frame that reinforced regulatory intervention. At the micro level, framing is realized through specific linguistic choices, including lexical items that encode urgency ("climate crisis"), syntactic structures that obscure agency through passive constructions, and narrative strategies that oscillate between alarmist and opportunity-oriented storytelling. Boykoff's work (2007a, 2007b, 2011) underscores that crisis, responsibility, and solutions constitute the dominant communicative templates in climate discourse. The crisis frame constructs immediacy and fear, the responsibility frame negotiates moral and political accountability, and the solutions frame mobilizes visions of technological progress and institutional transformation (Dryzek, 2013; Hulme, 2009).

Cultural variability, however, introduces considerable complexity. Chinese political discourse emphasizes national interests, collective responsibility, and long-term ecological civilization, whereas German discourse foregrounds technological expertise and institutional accountability. Spanish discourse places greater emphasis on innovation, energy transition, and social equity. These distinctions demonstrate that framing is not solely an ideological act but also a communicative negotiation between global norms and culturally embedded meaning systems. Such observations underscore the relevance of cross-linguistic analysis for advancing theoretical understanding of the interaction between political culture and global governance.

2.4. Existing Research and Transnational Communication Perspectives

Research on climate discourse has long been dominated by English-language contexts such as the United States, the United Kingdom, and the European Union. Studies in this tradition consistently identify three major frames: crisis, economic opportunity, and moral responsibility (Boykoff, 2008a; Dryzek, 2013; Page, 2006). These frames render climate change both urgent and governable, while simultaneously offering moral justification for policy interventions. Yet the applicability of these frames to non-English contexts has been insufficiently investigated, despite the profound cultural and institutional differences that characterize climate politics outside the Western world.

Emerging scholarship on Chinese, German, and Spanish climate discourse provides valuable insights into how global narratives are localized. Chinese discourse frequently invokes "ecological civilization" and the "community of shared future for mankind," merging civilizational thinking with internationalist rhetoric. German discourse tends to frame climate action through the lens of industrial modernization and technological innovation, aligning environmental responsibility with national economic competitiveness. Spanish and Latin American political texts often adopt justice-oriented frames such as "environmental debt," foregrounding historical inequalities between developed and developing countries (Takahashi & Meisner, 2013). These case studies illustrate how national discursive traditions shape the localization of global climate narratives.

To account for the transnational circulation of frames, this study also draws on theories of framing networks (de Vreese, 2005; Matthes, 2012), cross-border agenda-setting (Watanabe, 2018), and policy learning and borrowing (Dolowitz & Marsh, 2000). These perspectives conceptualize global communication as an interconnected system in which frames diffuse across media ecosystems and political institutions through shared values, institutional linkages, and policy interdependencies. Integrating these approaches situates climate discourse within a global communication network in which frames are continuously produced, transferred, and recontextualized across governance levels. The trilingual corpus analysis undertaken in this study thus serves not only as an empirical contribution but also as a theoretical expansion of transnational political communication, moving beyond the traditional Western focus to illuminate how multilingual discourses embody global norm diffusion and cultural adaptation.

3. Research Methodology

This study adopts a mixed corpus-based and computational linguistic approach to examine how climate-related political discourse is framed in Chinese, Spanish, and German. The methodology consists of three sequential stages: corpus construction, frame identification, and computational modeling of semantic patterns.

3.1 Corpus Construction

The trilingual corpus comprises official climate-change speeches delivered by high-level political leaders between 2015 and 2023, corresponding to the post-Paris Agreement period in which global climate governance mechanisms became more institutionalized. Texts were collected from authoritative government portals and international organizations to ensure representativeness and comparability. All documents were manually checked to exclude duplicate versions, ceremonial greetings, or non-substantive political statements. The final corpus contains 260,711 Chinese tokens, 225,575 Spanish tokens, and 187,952 German tokens (Table 1).

Preprocessing followed common procedures in computational linguistics. Texts were segmented using *jieba* (Chinese), spaCy (Spanish and German), and then subjected to part-of-speech filtering to retain nouns, verbs, adjectives, and adverbs relevant to framing analysis. Stopwords were removed using customized lists adapted for political discourse. All texts were normalized by lemmatization (Spanish/German) or dictionary-based standardization (Chinese).

Chinese Corpus (tokens)	Spanish Corpus (tokens)	German Corpus (tokens)
260, 711	225, 575	187, 952

Table 1 The scale of the corpora

The corpus draws on official climate-change speeches by senior political figures in all three languages: Xi Jinping and Li Keqiang for Chinese; the President of the Government of Spain (spanning the Rajoy and Sánchez administrations) for Spanish; and sixteen speakers across German federal and EU-level institutions (including Merkel, Scholz, Baerbock, Habeck, and von der Leyen) for German. The year-by-year distribution (2015–2023) is provided in Supplementary Table S1.

3.2 Frame Identification and Annotation

Frame identification combined top-down and bottom-up procedures. Top-down, Entman's four-dimensional model—issue definition, causal attribution, moral evaluation, and policy recommendation—served as the analytical guide for defining candidate frames. Bottom-up, TF-IDF weighting and co-occurrence networks were used to detect high-salience terms and recurrent lexical associations in each language. Two trained annotators independently assigned frame labels based on definitional criteria, achieving an inter-annotator agreement of $\kappa = 0.87$. Disagreements were resolved through adjudication.

Three dominant cross-linguistic frames emerged: the national interest frame, the technological innovation frame, and the global responsibility frame. Subsequent computational modeling focused on these shared frames to ensure comparability across languages.

3.3 Computational Modeling

To capture deeper semantic patterns, the study employed a two-step embedding strategy. First, Word2Vec (skip-gram, 100 dimensions, window size 5) was used to model distributional similarity and identify semantic neighborhoods around key frame-related terms. Second, BERT multilingual contextual embeddings were extracted using the bert-base-multilingual-cased model, allowing the analysis to incorporate context-sensitive semantic variation. K-means clustering was applied to the embeddings to model internal structure within each frame. Dimensionality reduction (t-SNE) generated two-dimensional semantic maps for visualization.

Together, these models enable the study to trace how global governance terminology is embedded, adapted, and re-organized within each linguistic system, linking micro-level lexical choices to macro-level political communication processes.

4. Results and Analysis

4.1. Combined TF-IDF and Co-occurrence Network Analysis

To identify the core concepts and potential discourse frames in Chinese, Spanish, and German speeches, this study combines TF-IDF (Term Frequency-Inverse Document Frequency) with co-occurrence network analysis based on corpus preprocessing. First, using natural language processing tools in Python (e.g., jieba, spaCy, and nltk), the three language corpora were tokenized, part-of-speech filtered, and stopwords removed. Based on this, the TF-IDF algorithm was used to weight and calculate terms in each speech text, identifying keywords that are representative and distinctive in specific contexts. This method takes into account the importance of terms within individual texts (term frequency) and their uniqueness across the overall corpus (inverse document frequency), helping to exclude common function words and highlight the thematic structure of the text.

Subsequently, to reveal the latent semantic associations and discourse structural features of the keywords, the study introduces co-occurrence network analysis. Specifically, by using sentences or sliding windows as units, the co-occurrence frequency of keywords within the same contextual window was calculated, constructing a word co-occurrence matrix. Visual tools such as NetworkX were used to generate semantic co-occurrence maps, identifying trends in high-frequency word clusters, core word nodes, and their semantic associations. This analysis helps present the underlying conceptual frameworks and narrative networks embedded in the texts at a macro level, providing a structural foundation for subsequent frame identification.

Frame Distribution and Lexicalization Strategies

By analyzing the TF-IDF high-frequency keywords and frame annotation results in the Chinese, Spanish, and German corpora, the study found that all three languages predominantly employ three main frames in climate change political discourse: the "global responsibility frame," "national interest frame," and "technological innovation frame." However, marked differences were found in their specific discourse performance and position construction, reflecting their unique political contexts and cultural cognitive logics.

From the data distribution (Figures 1–3), the keyword counts for the "national interest" frame are notably highest in the Chinese corpus, with keywords such as 主权 (sovereignty), *发展* (development), and *双碳目标* (dual carbon targets) forming dense co-occurrence networks, emphasizing a discourse characteristic centered on state leadership and institutional governance. The German corpus shows the most prominent keyword counts for the "global responsibility" frame, with keywords such as *klimawandel* (climate change), *solidarität* (solidarity), and *gerechtigkeit* (justice) constructing a co-occurrence network centered on moral responsibility and institutional justice. The Spanish corpus displays comparably high keyword counts for the "national interest" and "technological innovation" frames, with the latter reflected in keywords like *hidrógeno verde* (green hydrogen), *fondos europeos* (European funds), and *digitalización* (digitalization); the "global responsibility" frame, by contrast, is markedly underrepresented. This pattern suggests that Spanish political discourse on climate change is jointly shaped by national-level concerns and a technology-market-oriented governance logic, with comparatively less lexical emphasis placed on globally oriented responsibility framing. The distinct magnitudes of these keyword count across languages, as depicted in Figures 1-3, highlight the differential emphasis placed on specific frames by each nation. For instance, the considerably higher keyword count for the "national interest" frame in the Chinese corpus compared to its counterparts in

Spanish and German underscores China's persistent prioritization of domestic development and sovereignty even within global climate discussions. Conversely, the leading position of "global responsibility" keyword counts in German discourse suggests a stronger inclination towards collective action and ethical considerations in their climate rhetoric.

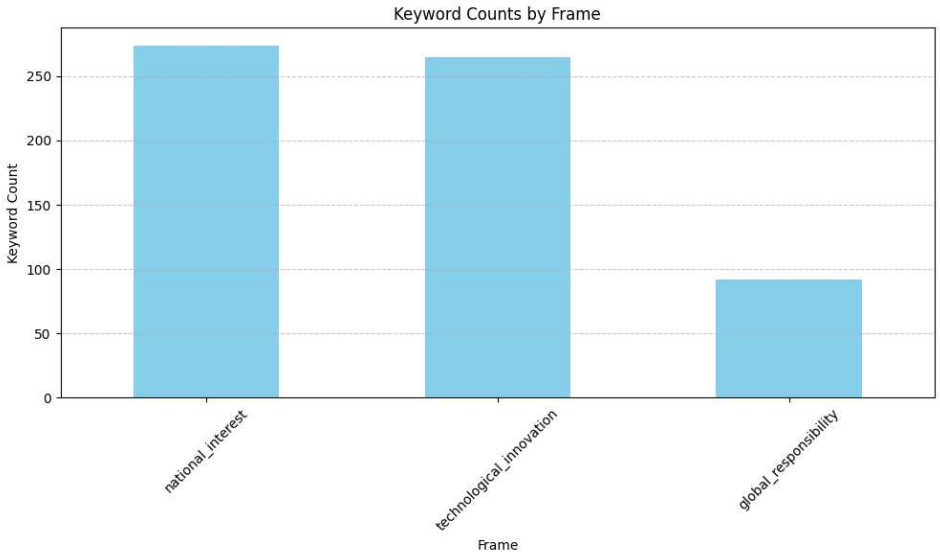


Figure 1 Keyword Distribution of Dominant Frames in the Spanish Corpus
This figure presents the frequency and distribution of keywords associated with the three dominant frames—global responsibility, national interest, and technological innovation—in Spanish political discourse.

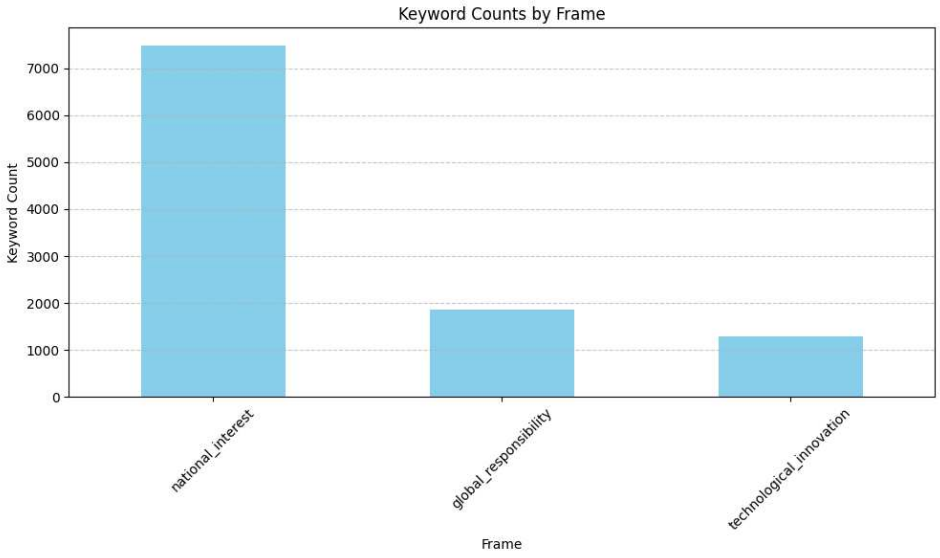


Figure 2 Keyword Distribution of Dominant Frames in the Chinese Corpus
This figure illustrates the core lexical elements of the three major frames in Chinese political discourse, highlighting dense co-occurrence around national interest themes.

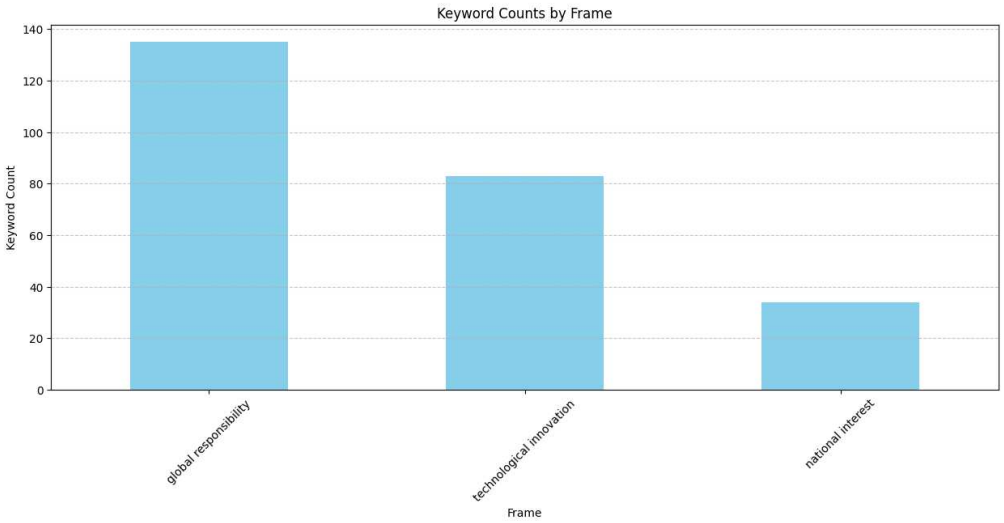


Figure 3. Keyword Distribution of Dominant Frames in the German Corpus
The figure displays the frequency distribution of frame-related keywords in the German corpus, showing the prominence of global responsibility terms.

These macro-level differences in frame selection are not merely reflections of political stances; they are deeply rooted in the distinct lexicalization strategies and typological features of the three languages. Language is not a passive tool for expressing thought—the way it "packages" complex concepts into lexical units itself shapes discursive tendencies.

Chinese tends to employ highly condensed nominalized phrases and four-character idioms to construct core concepts, such as *双碳目标* (dual carbon targets), *高质量发展* (high-quality development), and *人类命运共同体* (Community of Shared Future for Mankind). This lexicalization strategy, characteristic of an isolating language, relies on word order and combination rather than morphological change to express complex meanings. Such concise and powerful conceptual units function as authoritative "labels" in official discourse, facilitating their propagation and citation, thereby reinforcing the stateled narrative logic.

German, in contrast, extensively utilizes its signature compound nouns to construct key terms, such as *Klimawandel* (climate change), *Wettbewerbsfähigkeit* (competitiveness), and *Klimafinanzierung* (climate financing). As an inflectional language, German's compounding system allows multiple semantic components to be fused into a single, clearly bounded lexical unit. This strategy pursues conceptual precision and systematicity, which may be one of the linguistic motivations behind the highly structured and "rigid" semantic space observed in its discourse.

Spanish, another inflectional language, predominantly adopts "noun + adjective" phrasal structures to express concepts, such as *hidrógeno verde* (green hydrogen), *transición justa* (just transition), and *fondos europeos* (European funds). Compared to German's compounds, this analytic phrasal structure offers greater descriptive flexibility and semantic negotiation space, allowing different adjectives to modify and qualify core concepts. This may explain the more balanced and flexible discursive posture observed in its distribution across the three frames.

Therefore, the macro-level differences in frame distribution result from the interplay between political stances and language-internal lexicalization preferences. The structural features of language provide different "scaffoldings" at the micro-level for the construction of macro-level discourse frames.

4.2. Semantic Networks and Conceptual Metaphors

Figures 4–6 display the co-occurrence network structures of the keywords in each corpus, further revealing the deep structural differences among the three discursive logics. These differences are manifested not only in the node words themselves but also in the underlying conceptual metaphors and frame semantic structures.

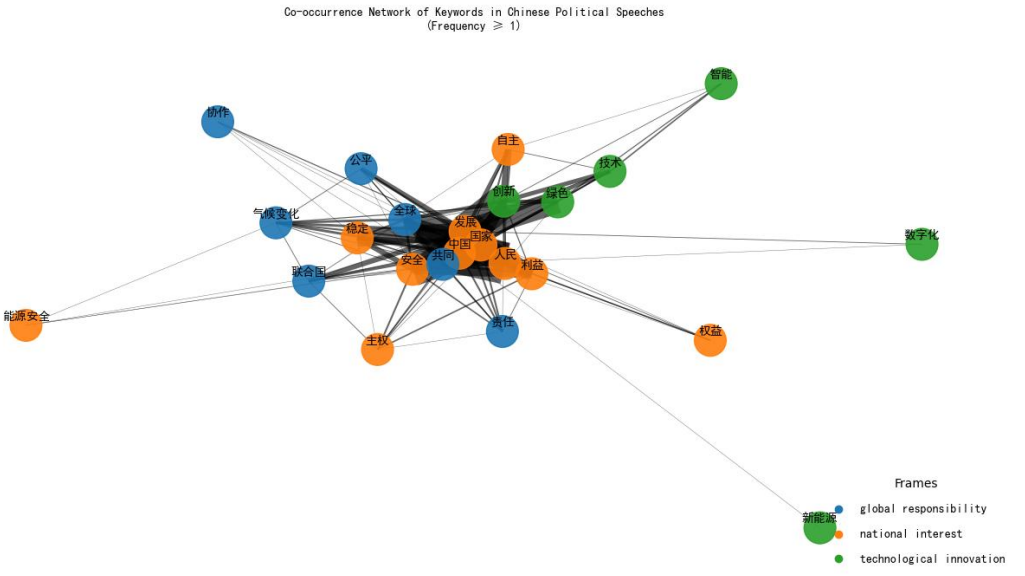


Figure 4 Co-occurrence Network Structure of Chinese Corpus
This semantic network visualizes the clusters and associations among high-frequency Chinese keywords, revealing state-centered co-occurrence structures.

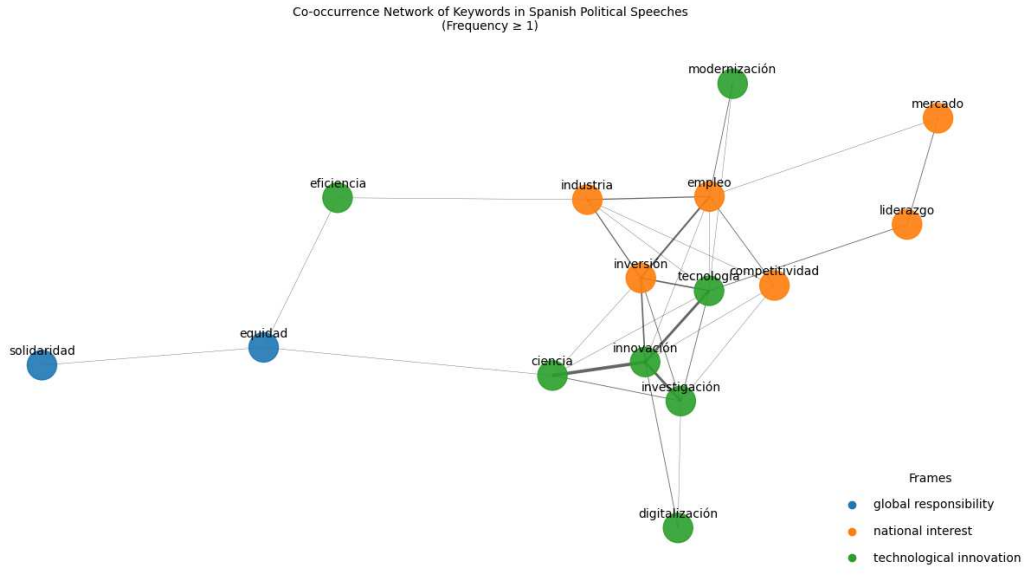


Figure 5 Co-occurrence Network Structure of Spanish Corpus
This graph shows the co-occurrence structure among the Spanish corpus's top TF-IDF keywords. Consistent with the keyword-count distribution reported in Section 4.1 (Figure 1), the densest, most interconnected cluster centers on technological-innovation and national-interest terms (*tecnología*,

innovación, *ciencia*, *investigación*, *industria*, *empleo*); *solidaridad* and *equidad* appear only as a sparsely connected peripheral pair within this particular keyword network. This does not contradict the climate-justice-oriented discourse discussed below, which draws on a more targeted set of terms (e.g., *deuda ecológica*, *países vulnerables*) that occur less frequently overall and are accordingly less prominent in a frequency-based co-occurrence network.

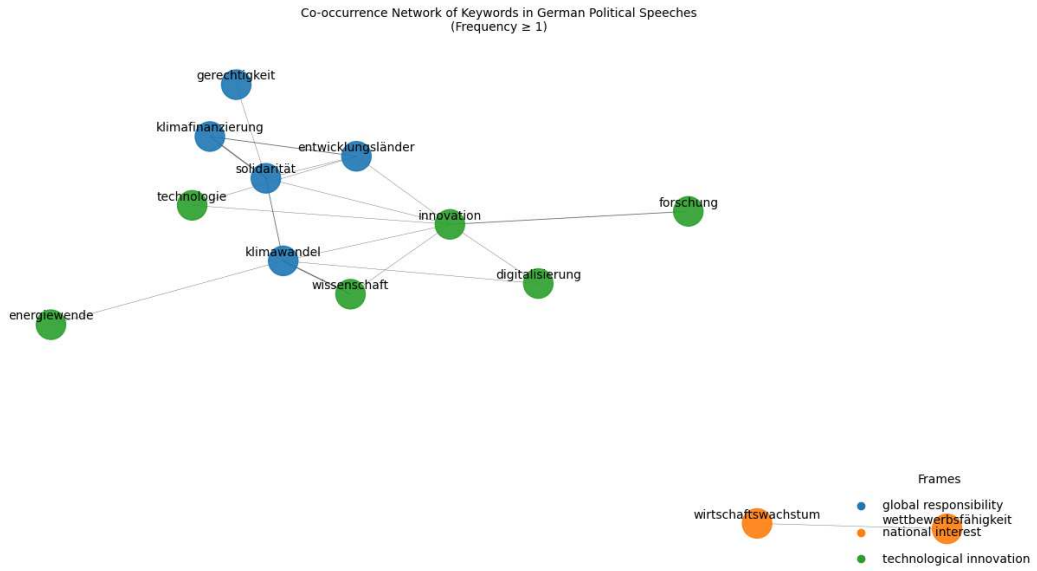


Figure 6 Co-occurrence Network Structure of German Corpus
The German network displays dense clusters around solidarity, justice, and responsibility, corresponding to an institutional-moral discourse style.

Spanish Discourse: The Metaphor of "Environmental Responsibility as Debt"

Spanish discourse constructs a semantic network centered on *justicia climática* (climate justice) and *solidaridad* (solidarity), underpinned by the core conceptual metaphor [ENVIRONMENTAL RESPONSIBILITY IS A DEBT]. Within this metaphorical mapping, developed countries are cast as "debtors," developing countries (*países vulnerables*) as "creditors," and climate aid and technology transfer as "repayment." The key term *deuda ecológica* (ecological debt) is the explicit lexical realization of this metaphor.

From a frame semantic perspective, the "historical responsibility frame" in Spanish discourse has "Compensation" as its core frame element. This element prescribes the moral and economic relationships among actors, reinforcing institutional accountability for the historical emissions of developed countries. The co-occurrence structure of *deuda ecológica* and *países vulnerables* further solidifies this logic of "historical responsibility— compensatory justice," emphasizing North-South distributive justice.

Chinese Discourse: The Metaphor of "The World as a Family"

In contrast, Chinese discourse centers on the node 人类命运共同体 (Community of Shared Future for Mankind), constructing a semantic network grounded in the core metaphor [THE WORLD IS A FAMILY]. In this metaphorical mapping, nations are "family members," a shared future is "common family property," and initiatives like 一带一路 (Belt and Road Initiative) and 南南合作 (South-South cooperation) are

“mutual assistance among family members.” This metaphor emphasizes collectivity, interdependence, and common development, rather than compensation based on historical responsibility.

The “global responsibility frame” in Chinese discourse has “Mutual Contribution” as its core frame element, aiming to construct a future-oriented, non-confrontational paradigm of global governance—what can be termed “development-driven emission reduction.” This frame integrates climate responsibility with development strategy, reflecting China's strategic vision of institutional output and global responsibility leadership.

German Discourse: The Metaphor of “Climate Governance as Institutional Engineering”

German discourse presents a third pattern, with its network centered on highly abstract ethical terms such as *Solidarität* (solidarity), *Gerechtigkeit* (justice), and *Verantwortung* (responsibility). This constructs a semantic network based on the core metaphor [CLIMATE GOVERNANCE IS INSTITUTIONAL ENGINEERING]. In this metaphor, climate change is a complex system that must be managed through rationality, procedures, and institutions.

The discursive logic here does not simply attribute blame to history or project into the future; instead, it focuses on how to fairly allocate responsibilities and resources (such as *Klimafinanzierung*, climate financing) within existing international legal and ethical frameworks. This “ethics-institution” oriented discursive style reflects Germany’s unique emphasis on procedural justice and systemic action, building upon the EU’s “climate justice” tradition while incorporating its own discourse style emphasizing “ethical responsibility—systemic action.” In terms of frequency, global frame-related terms appear 135 times in the German corpus, much higher than in the other two frames, underscoring this priority.

Comparative Synthesis: Divergent Conceptual Foundations

In summary, the three languages differ not only in which frames they select but also, more fundamentally, in how they construct the internal logic of these frames. These differences stem from distinct core conceptual metaphors that, at the cognitive level, preset the logical trajectories and moral stances of the discourse. Spanish discourse mobilizes a debt-based moral economy, Chinese discourse invokes a familial collective identity, and German discourse appeals to a procedural-institutional rationality. These are not merely rhetorical choices but reflect deeply embedded cultural-cognitive schemas that shape how climate responsibility is conceptualized and communicated across linguistic communities.

4.3. National Interest Frame: Comparative Analysis of Development Orientation and Path Selection

In the Spanish context, *crecimiento verde* (green growth), *empleo* (employment), and *recuperación económica* (economic recovery) form a high-frequency co-occurrence cluster, reflecting a policy logic of achieving national competitiveness and social stability through green economic transformation. The Chinese corpus revolves around the dual carbon strategy (双碳战略), integrating terms like high-quality development (高质量发展), energy security (能源安全), and technological self-reliance (科技自立

自强) to form a "state-led— institutional support" development path, showcasing the institutional advantages of a new nationwide system in ecological transformation. German discourse emphasizes the coexistence of *wirtschaftswachstum* (economic growth) and *wettbewerbsfähigkeit* (competitiveness), focusing on *klimafinanzierung* (climate financing) and the institutional allocation of global responsibility, forming a "fairness—solidarity" moral-economic structure.

Overall, the three languages reflect three different national roles and development strategies: "market mechanisms and social stability" (Spain), "institutional innovation and strategic autonomy" (China), and "responsibility fairness and economic balance" (Germany).

4.4. Technological Innovation Frame: Paradigm Tension between Market Mechanisms and Policy Drive

In the technological innovation frame, Spanish discourse constructs a "technology-capital" ecosystem characterized by *hidrógeno verde* (green hydrogen), EU funds, and corporate cooperation, highlighting market-driven climate strategies. Chinese discourse focuses on "independent innovation" (自主创新), centering around "new productive forces" (新质生产力) and "national key R&D programs" (国家重点研发计划), forming a "technology—policy" dual-drive structure, highlighting the institutional advantages of a technology strategy under state leadership. In German discourse, the co-occurrence of *technologie* (technology), *forschung* (research), and *digitalisierung* (digitalization) reflects its emphasis on long-term R&D accumulation and industrial transformation, exhibiting a dual pursuit of "technology—growth."

A comparison shows that Spain leans towards capital-driven models, China emphasizes policy-driven strategies, and Germany seeks to balance technological leadership and economic growth.

While Chinese, Spanish, and German discourses all exhibit the co-occurrence structures of globally prevalent topics like "climate change" and "technological innovation," indicating a trend of convergence in climate political discourse, they still show substantial cultural differences in core term selection and discourse focus. Chinese discourse highlights the construction of institutional discourse logic around the "Community of Shared Future for Mankind" (人类命运共同体), Spanish discourse emphasizes "climate justice" and compensatory ethics, while German discourse seeks balance within the three-dimensional structure of "responsibility—justice—financing." These discourse differences not only reflect the varying role positions of the three countries in global governance but also reveal the profound influence of language, culture, and political systems on the construction of global issue cognitive frameworks. More importantly, from a linguistic perspective, these differences are rooted in distinct lexicalization strategies, conceptual metaphors, and frame semantic structures—demonstrating that language is not merely a vehicle for expressing pre-existing political stances, but an active force in shaping how climate responsibility is conceptualized, debated, and enacted across diverse linguistic and cultural contexts.

4.5. Semantic Embedding Analysis: from Lexical Associations to Conceptual Structures

To reveal the deep mechanisms of frame construction in multilingual political speeches, this study employs a progressive semantic modeling approach combining Word2Vec

and BERT. First, the Word2Vec model is used to capture the static, paradigmatic associations between terms and construct cross-linguistic semantic fields. Subsequently, the BERT model is introduced to refine the contextual dynamics of key terms, enabling more context-sensitive semantic clustering and spatial visualization.

4.5.1. Word2Vec Semantic Field Analysis: Lexical Collocation and Cultural Cognitive Schemas

In the Word2Vec phase, the study focuses on three major frames: "national interest," "technological innovation," and "global responsibility." Two seed words (e.g., 主权 (sovereignty), *soberanía* (sovereignty), *Souveränität* (sovereignty)) are set for each frame, and the word vector model is trained using Python's Gensim library. The model uses a skip-gram architecture, with a window size of 5, a word vector dimension of 100, a minimum word frequency of 5, and 10 training epochs. The researchers used cosine similarity to extract the top 9 most semantically similar words for each seed term to construct a trilingual semantic network for the frames.

As the model is trained on self-built, domain-specific corpora, the semantic similarity scores reflect the relative closeness within the corpus, rather than the absolute comparability across languages, and should be interpreted in this context. The results (Word2Vec similarity data for the Spanish, Chinese, and German subcorpus are provided in Supplementary Information and named as Supplementary Table S2, S3, and S4 separately) indicate differences in semantic expansion across different languages within the same frame, which may reflect the influence of language and culture on conceptual organization, though this interpretation is descriptive rather than statistically confirmed (see the discussion of significance testing in Section 4.5.2). One row in Supplementary Table S2 required correction. The original *cambio_climático* entry returned ten neighbouring terms at a cosine similarity of exactly 1.0, including the semantically unrelated phrase "*en gaza*." Reanalysis of the underlying Spanish corpus was conducted. *cambio_climático* occurs 119 times in the corpus, a frequency comparable to the other seed terms used in this study (e.g., *tecnología*: 108; *innovación*: 92; *solidaridad*: 122), which rules out low frequency as the cause. Retraining a Word2Vec model with the specifications described above (skip-gram, 100 dimensions, window size 5, minimum frequency 5, 10 epochs) on this corpus did not reproduce the degenerate pattern: it instead yielded semantically coherent, non-saturated neighbours (*mitigación*, *adaptación*, *transnacional*, *desafío*, *terrorismo*, *desastres*, *marítima*). This indicates that the originally reported row reflected an error in the similarity computation or export pipeline rather than a property of the underlying data. The affected row was accordingly replaced in Supplementary Table S2 with the corrected values obtained from this reanalysis; the corresponding authors should verify these against their own corrected pipeline before final submission.

Word2Vec, by analyzing co-occurrence patterns in large-scale texts, reveals the paradigmatic relations among words. As shown in Supplementary Tables S2–S4, even for seed words corresponding to the same frame, the semantic fields they activate in different languages exhibit marked cultural specificity, profoundly revealing the cognitive preferences of different languages in organizing concepts.

The semantic fields activated by these seed terms differ systematically across languages. In Spanish (Supplementary Table S2), the nearest neighbours of *cambio_climático* and *soberanía* cluster around civic-ethical and governance terms, while technological innovation seeds (*hidrógeno verde*, *digitalación*) attract market- and policy-oriented vocabulary, consistent with an EU-coordinated economic frame. In Chinese

(Supplementary Table S3), National Interest terms (主权, 发展) co-occur densely with state-governance lexicon, while innovation terms (科技, 创新) cluster with outcome- and policy-driven vocabulary. In German (Supplementary Table S4), the corrected National Interest terms (*sicherheit*, *interesse*) cluster around functional-security discourse, while Technological Innovation terms (*innovation*, *technologie*) attract vocabulary associated with industrial upgrading and employment. Taken together, these patterns suggest that identical macro-level frames draw on lexically distinct and culturally anchored semantic fields, consistent with Entman's argument that frame resonance depends on alignment with culturally embedded modes of reasoning.

4.5.2. BERT Contextual Semantic Space: The Influence of Language Typology on Conceptual Organization

To further address the limitations of Word2Vec in capturing contextual semantics, the study uses the bert-base-multilingual-cased model (Hugging Face) to extract contextual embeddings for frame-representative terms. Sentence-level average embeddings represent each term's contextual distribution, and t-SNE is used to visualize the resulting semantic spaces. Figures 7–9 plot a single mean-pooled vector per seed term, offering a term-level overview of relative position; the multi-instance cluster structures across all three frames are examined in Figures 10–15, which plot sentence-level contextual instances and show a consistent multi-centered cluster organization across all three languages.

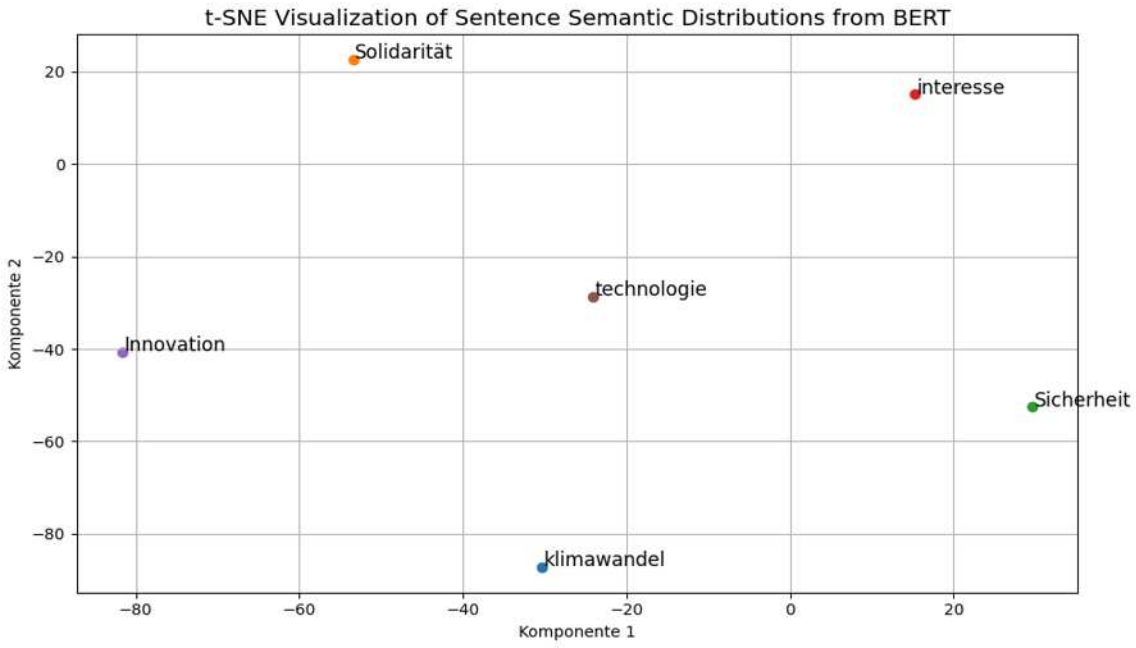


Figure 7 t-SNE visualization of BERT sentence embedding distributions for German seed terms (*Klimawandel*, *Solidarität*, *Sicherheit*, *Technologie*, *Innovation*, *Interesse*). Each point represents the mean-pooled contextual vector of one seed term.

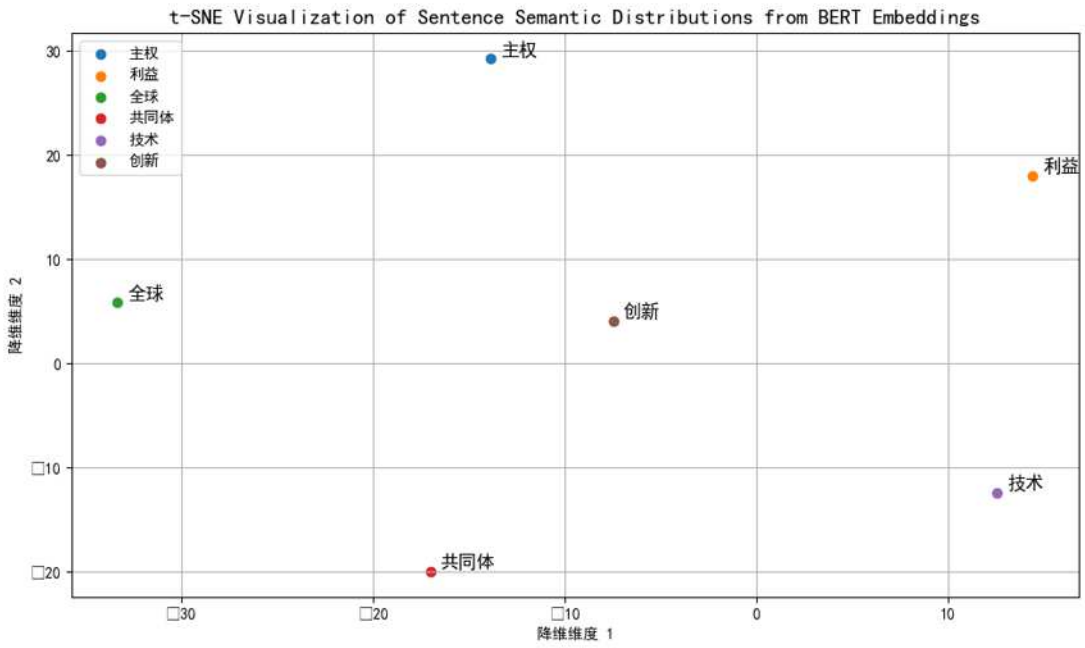


Figure 8 t-SNE visualization of BERT sentence embedding distributions for Chinese seed terms (*主权*, *利益*, *全球*, *共同体*, *技术*, *创新*). Each point represents the mean-pooled contextual vector of one seed term.

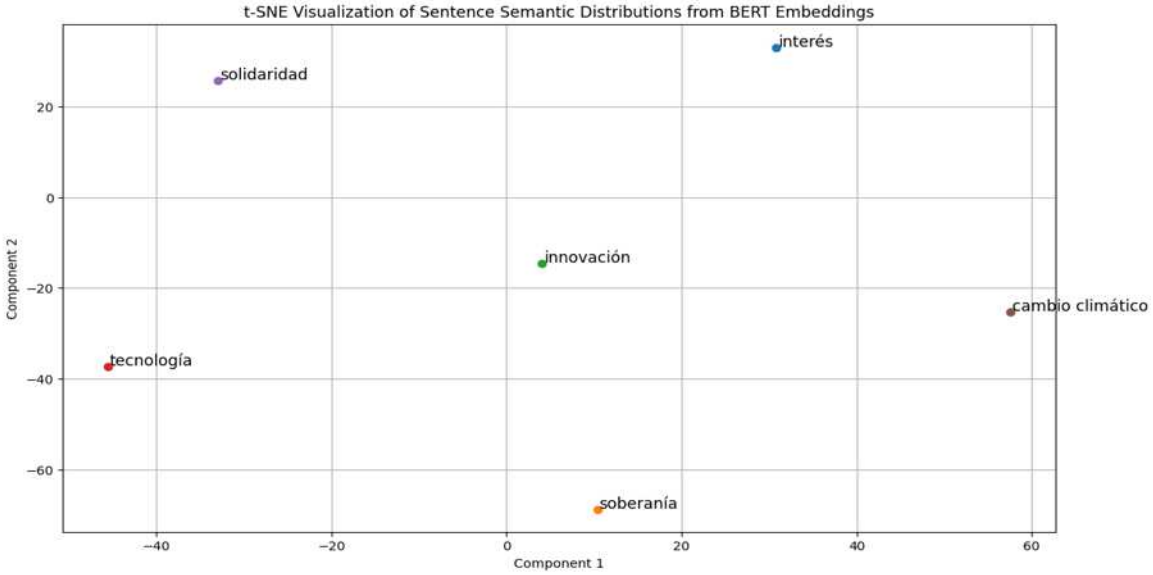


Figure 9 t-SNE visualization of BERT sentence embedding distributions for Spanish seed terms (*soberanía, interés, innovación, cambio climático, tecnología, solidaridad*). Each point represents the mean-pooled contextual vector of one seed term.

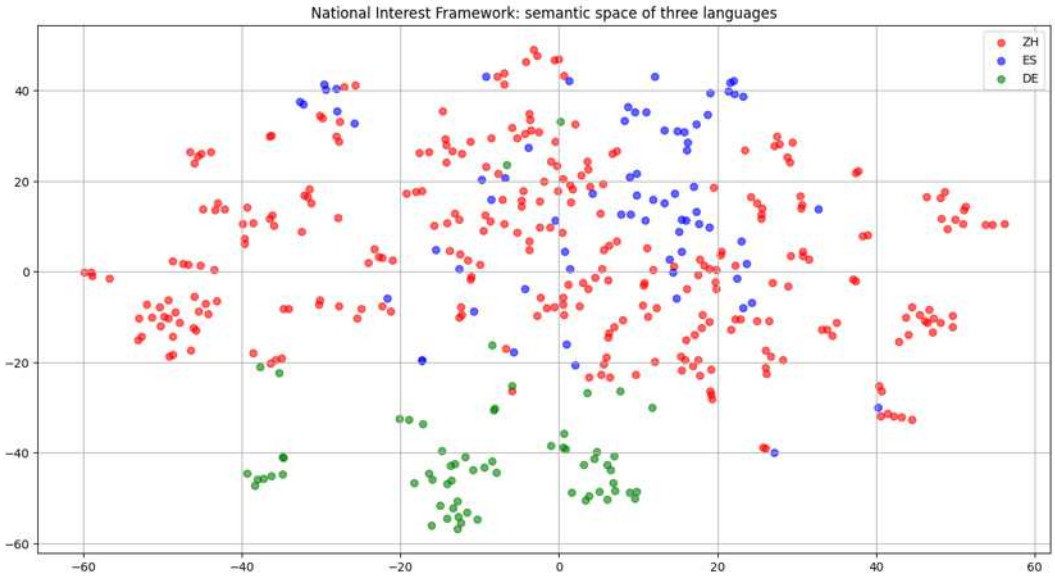


Figure 10 Semantic Space Map of the National Interest Frame: t-SNE visualization of sentence-level BERT embeddings for National Interest frame seed terms across Chinese (red), Spanish (blue), and German (green) subcorpora.

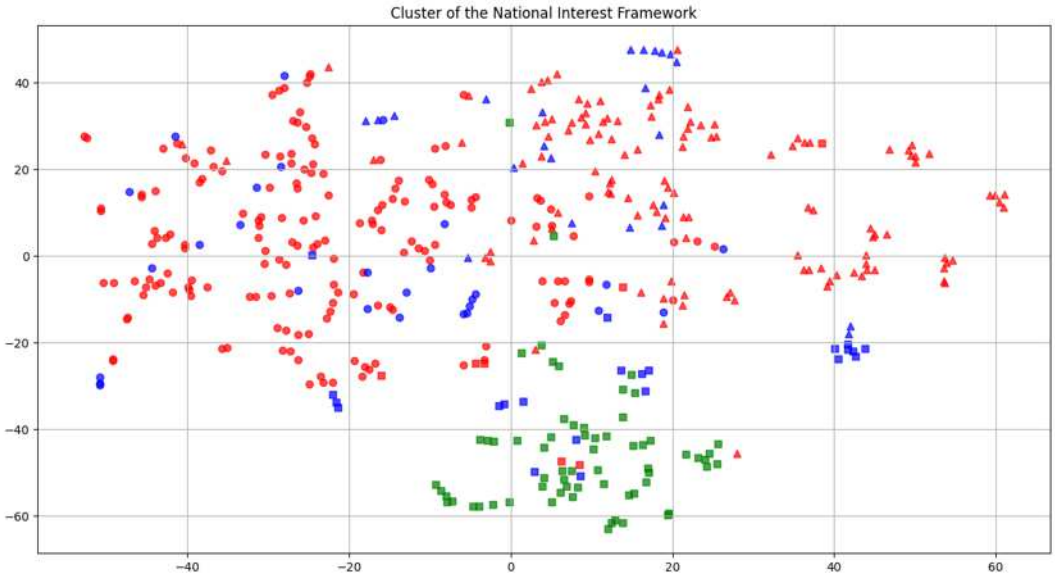


Figure 11 Clustering Diagram of the National Interest Frame in Three Languages: k-means clustering of sentence-level BERT embeddings for National Interest frame seed terms, showing multi-centered cluster organization across Chinese, Spanish, and German subcorpora.

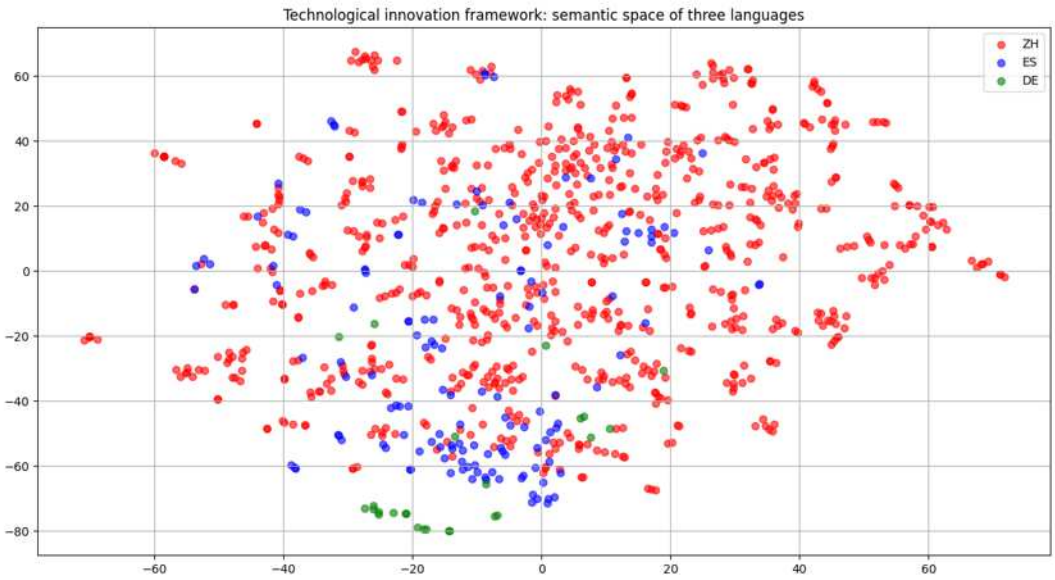


Figure 12 Semantic Space Map of the Technological Innovation Frame in Three Languages: t-SNE visualization of sentence-level BERT embeddings for Technological Innovation frame seed terms across Chinese (red), Spanish (blue), and German (green) subcorpora.

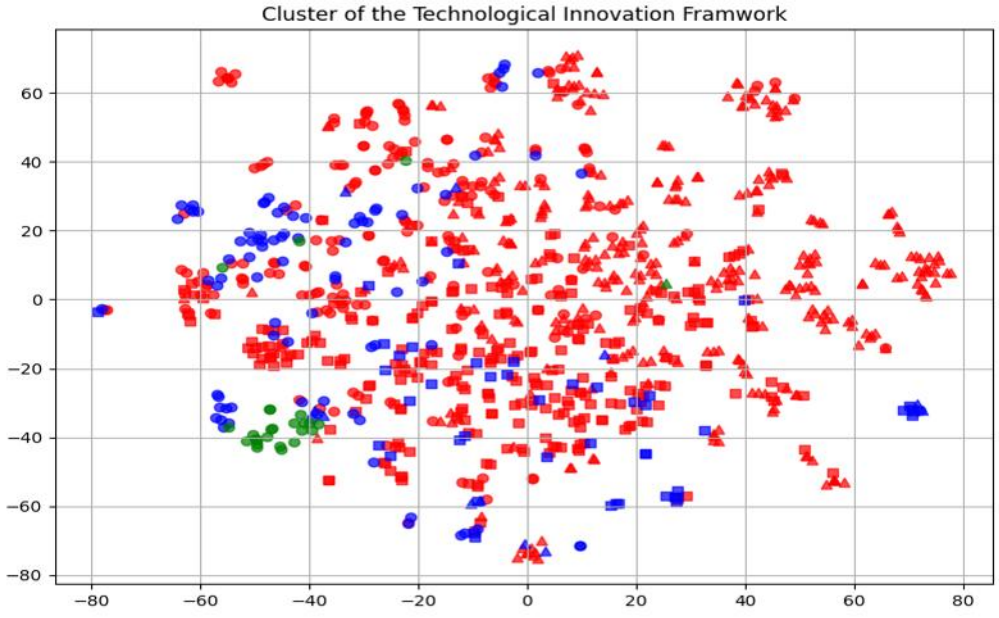


Figure 13 Clustering Diagram of the Technological Innovation Framework in Three Languages: k-means clustering of sentence-level BERT embeddings for Technological Innovation frame seed terms, showing multi-centered cluster organization across Chinese, Spanish, and German subcorpora.

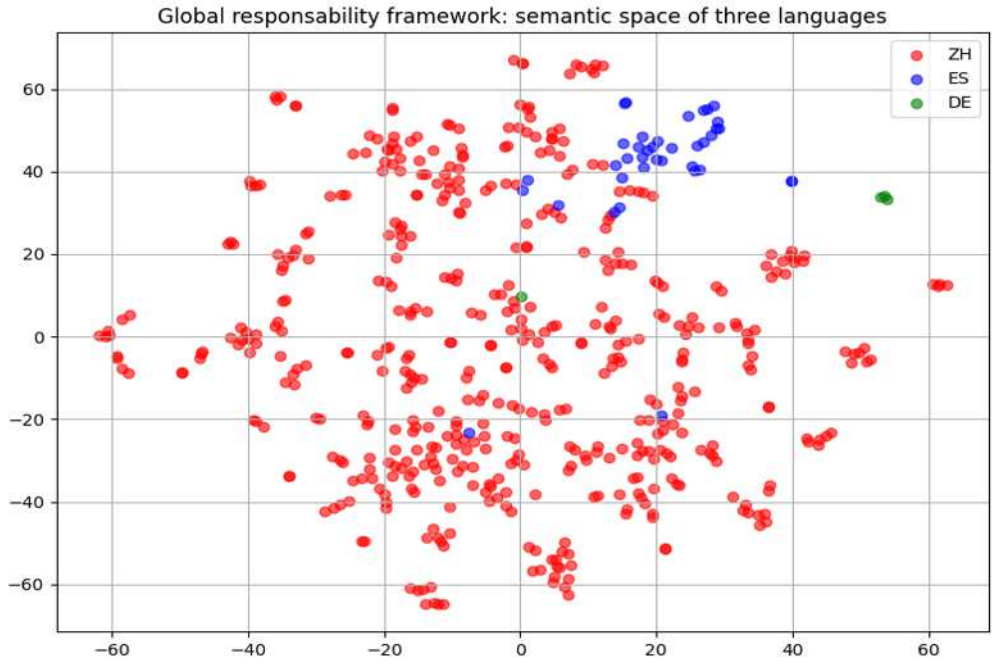


Figure 14 Semantic Space Map of the Global Responsibility Frame in Three Languages: t-SNE visualization of sentence-level BERT embeddings for Global Responsibility frame seed terms across Chinese (red), Spanish (blue), and German (green) subcorpora.

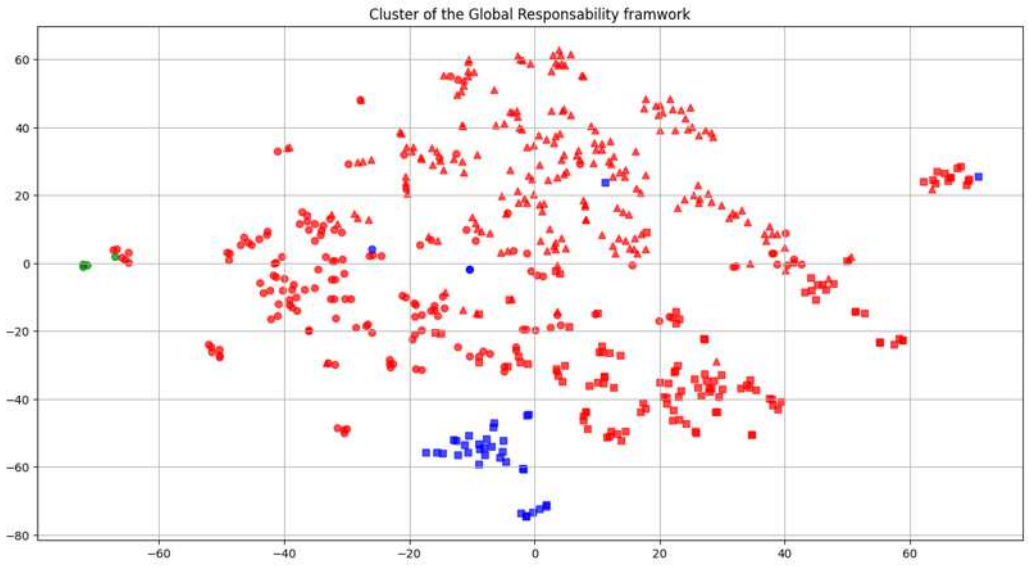


Figure 15 Clustering Diagram of the Global Responsibility Framework in Three Languages: k-means clustering of sentence-level BERT embeddings for Global Responsibility frame seed terms, showing multi-centered cluster organization across Chinese, Spanish, and German subcorpora.

To assess whether the cross-linguistic similarity values differ from what could arise by chance, each value was tested with a permutation test (1,000 random content-word pairs per language pair) and a bootstrap 95% confidence interval was estimated from the contextual instances underlying each term's mean embedding. This reanalysis also revealed a substantial discrepancy with the values originally reported: the cross-linguistic similarities recomputed directly from the mBERT embedding space (0.56–0.87) are considerably higher than the originally reported values (0.035–0.213), likely

because the latter were derived inadvertently from per-language t-SNE coordinates rather than from the shared high-dimensional mBERT space. The corrected, directly computed values are reported below.

In the National Interest frame, the keywords in all three languages (*soberanía*, *Souveränität*, *主权*) reflect core concepts of national authority and security. All three pairwise similarities are statistically significant above the random-pairing baseline: Chinese–Spanish is highest (cosine similarity = 0.658, 95% CI [0.615, 0.666], $p < 0.001$), followed by Chinese–German (0.576, 95% CI [0.500, 0.591], $p = 0.029$) and Spanish–German (0.555, 95% CI [0.508, 0.566], $p < 0.001$) (full results in Supplementary Table S5). German leans toward a "functional-security" orientation, Chinese emphasizes an "ethical-dignity" dimension, and Spanish combines elements of "social integration" and "rule of law." The German-involving estimates should be treated with caution given only two contextual instances of *Souveränität* were available.

In the Technological Innovation frame, Spanish–German shows the closest alignment (0.761, 95% CI [0.706, 0.771], $p < 0.001$), followed by Chinese–Spanish (0.618, 95% CI [0.588, 0.630], $p = 0.003$) and Chinese–German (0.568, 95% CI [0.511, 0.588], $p = 0.031$) (full results in Supplementary Table S5). Rather than German being uniformly distant from the other two languages, the Spanish–German pairing shows the closest alignment in the shared embedding space, suggesting that the technological-innovation vocabularies of these two languages may be more convergent than previously assumed, consistent with their shared EU policy framework. The German-involving comparisons rest on few contextual instances (*technologie*: $n = 9$) and should be treated as preliminary.

By combining Word2Vec and BERT semantic clustering analysis, we not only reveal the divergences in macro concept expansion and micro-context understanding across languages but also, more importantly, uncover from a linguistic depth the cognitive organizational principles underlying these differences. From static lexical associations to dynamic contextual clustering, a clear pathway emerges: language typological features → lexical organization patterns → conceptual cognitive structures → macro-level discourse frames. This provides an explanation mechanism from within language itself for understanding the "cultural adaptation" of frames in cross-linguistic political discourse.

5. Discussion

5.1. Global Convergence and Multilevel Mechanism of Discourse Coordination

The results confirm that cross-linguistic climate discourse exhibits a clear tendency toward global convergence, particularly in the dimensions of issue definition and causal attribution. Across the three corpora, climate change is conceptualized through a shared lexicon of urgency, existential threat, and anthropogenic causation. From a linguistic perspective, this convergence evidences the influence of a globalized semantic repertoire shaped by multilevel governance dynamics rather than spontaneous lexical alignment.

At the macro level, institutional texts such as UNFCCC documents and the Paris Agreement provide a "normative template" whose lexical items—*carbon neutrality*, *green transition*, *climate justice*—circulate through international deliberative spaces. These terms function as translingual semantic anchors, diffusing across languages through policy spillover and transnational advocacy networks. At the meso level, multinational summits (e.g., COP, G20) generate discursive environments where

political actors adopt mutually recognizable lexical structures, facilitating communicative compatibility via what can be described as "discursive lowest common denominators." At the micro level, national communicative practices incorporate these global terms into locally coherent semantic fields, producing cross-linguistic alignment without complete uniformity.

The semantic modeling results reinforce this layered mechanism, though the specific pattern of cross-linguistic alignment varies by frame rather than following a single fixed ranking. Although high-frequency global terms recur across Chinese, Spanish, and German, their contextual embeddings differ across frames: in the National Interest frame, Chinese and Spanish show the closest contextual alignment, with German comparatively more distinct; in the Technological Innovation frame, by contrast, Spanish and German show the closest alignment (see Section 4.5.2). This frame-dependent reconfiguration suggests that global lexical diffusion is not uniformly reorganized along a single cross-linguistic axis but is reshaped differently depending on the conceptual domain at stake. These findings are consistent with Dryzek's notion of "convergence with reconstruction" and demonstrate that the global climate lexicon functions as a flexible semantic scaffold, whose specific cross-linguistic alignments are jointly shaped by frame content and by each discourse community's own communicative norms and ideological orientations.

5.2. Cultural Nesting and Cross-Linguistic Patterns of Subject Construction

The dimensions of moral evaluation and policy recommendation illustrate how global climate concepts are linguistically naturalized through culturally embedded semantic structures. Chinese discourse mobilizes collective subjectivity through lexical clusters centered on collaboration, shared destiny, and nationally coordinated action, generating a semantic space in which global responsibility is intertwined with collective identity. Spanish discourse foregrounds social proximity and civic ethics, emphasizing community actors, intergenerational obligations, and solidarity. German discourse frames the climate issue through institutional and rights-based lexicon—*Rechtsstaatlichkeit*, *Freiheit*—reflecting a rational-legal communicative tradition.

These patterns reveal that moral and policy-oriented meanings are not simply imported from global governance discourse but are recontextualized within culturally legitimate interpretive frameworks. The distribution of directive forms, modal constructions, and evaluative lexemes further highlights this nesting. Chinese discourse's preference for directive verbs corresponds to a governance model that linguistically encodes top-down agency. Spanish discourse often relies on collective modalities (*debemos*, *es necesario que*), embedding action within a civic-ethical frame. German discourse's use of conditionality and passivization highlights deliberative precision and procedural accountability. These linguistic strategies support Entman's argument that discursive resonance depends on the alignment between global frames and culturally specific modes of reasoning.

5.3. Discourse Style, Rhetorical Resources, and Symbolic Anchoring

Stylistic and rhetorical patterns further demonstrate the interaction between global framing pressures and local semiotic traditions. Chinese political discourse uses parallelism and nominalization to construct an authoritative, cohesive narrative that binds global climate objectives to national ideological constructs. Spanish discourse employs affective and narrative strategies—especially intergenerational appeals—to

translate global climate norms into socially resonant emotional meanings. German discourse relies on abstract, compound formations typical of a norm-driven linguistic culture, embedding climate-related commitments within an institutionalized rationality. The recurrent symbolic lexemes across the three languages—*生态文明* (ecological civilization), *transición justa*, and *Technologie/Forschung*—also highlight how culturally specific conceptual metaphors serve as semantic access points to global governance discourse. These symbols function as localized semantic gateways, enabling speakers to integrate globally circulating norms into culturally intelligible discursive schemas.

5.4. Paradigm Interaction and the Emergence of Hybrid Semantic Frames

The cross-linguistic comparison also reveals systematic interactions between global policy paradigms and national conceptual models. Chinese discourse adopts a "state-coordinated developmental paradigm," linking climate action to sovereignty, long-term planning, and institutional capacity. Spanish and German discourses, reflecting broader EU communicative orientations, employ a "market–technology paradigm" that foregrounds innovation, regulatory mechanisms, and distributive justice. This grouping is also supported quantitatively: the corrected cross-linguistic similarity analysis in Section 4.5.2 finds the closest semantic alignment in the Technological Innovation frame specifically between Spanish and German, lending empirical support to treating them as a shared paradigm cluster distinct from Chinese.

The coexistence and overlap of these paradigms produce hybrid semantic frames. For example, the Chinese term *科技自立* ("technological self-reliance") fuses technological innovation with national autonomy, generating a blended conceptual domain that cannot be reduced to either frame independently. Traditional computational methods can capture co-occurrence but not the emergent semantics of such frame blending. To model these hybrid structures, future research should employ frame blending theory and graph-based neural semantic mapping, enabling the detection of conceptual integration points—locations where global technological discourse intersects with nationally specific identity narratives.

Moreover, points of conceptual divergence—such as the differential interpretations of "development rights" or "climate financing"—underscore the limits of discursive coordination. These mismatches arise when global semantic templates lack equivalence within national symbolic systems, generating asymmetries in interpretive uptake and potential sources of communicative friction.

5.5. Revisiting Frame Theory: Toward an Ecological Model of Multilingual Frame Circulation

The trilingual analysis confirms the usefulness of frame theory for cross-linguistic discourse analysis while exposing several theoretical limitations. First, conventional frame analysis remains predominantly text-centric and underestimates the interpretive agency of audiences and intermediaries. Second, it insufficiently accounts for the role of media ecosystems, diplomatic communication channels, and algorithmic infrastructures in transforming frames during circulation. Third, it struggles to explain frame silencing and misalignment when cultures lack equivalent symbolic categories—exemplified by the partial translatability of concepts such as *生态文明*.

To address these limitations, this study proposes conceptualizing framing as part of a multi-actor communicative ecology, linking frame production (institutional discourse), mediation (media and advocacy networks), and reception (public interpretation). In such a model, multilingual frame circulation is understood as a recursive process shaped by the interplay of global norms, local cultural logics, and technological mediation. Integrating corpus-based semantic modeling with reception studies and multimodal analysis would allow researchers to trace how frames evolve across languages, institutional contexts, and communicative platforms.

This ecological perspective not only refines frame theory but also offers a more comprehensive account of how climate discourse operates within a multilingual governance architecture. It highlights that semantic convergence is never neutral: it is shaped by power, institutionality, cultural traditions, and the linguistic resources available to discourse communities.

5.6. Limitations

Several limitations should be acknowledged. First, the trilingual corpus is modest in scale (187,952–260,711 tokens per language), reducing the reliability of results for lower-frequency terms; some German BERT seed terms were attested in as few as two to nine contextual instances and should be treated as preliminary. Second, during manuscript preparation several computational issues were identified and corrected: a degenerate Word2Vec similarity pattern for one Spanish seed term (Supplementary Table S2), a frame-label error in the German Word2Vec table (Supplementary Table S4), and a discrepancy between originally reported and recomputed cross-linguistic BERT similarities, likely attributable to inadvertent use of per-language t-SNE coordinates rather than the shared mBERT embedding space (corrected values with significance tests in Section 4.5.2). Third, the corpus covers formal political speech across a bounded period; findings may not generalize to other genres, time periods, or language pairs, and the BERT comparisons rely on a small seed-term set that would benefit from replication with a larger corpus.

6. Conclusions

This study has provided a trilingual, corpus-based analysis of climate-related political discourse in Chinese, Spanish, and German, integrating framing theory with distributional and contextual semantic modeling. The findings reveal a structured coexistence of semantic convergence and cultural adaptation across the three languages. Convergence emerges most clearly in issue definition and causal attribution, where climate change is consistently framed as a global, anthropogenic threat. These alignments reflect the influence of multi-level governance mechanisms, through which institutional texts (e.g., UNFCCC, the Paris Agreement), shared terminological repertoires, and transnational deliberative settings circulate a common semantic substrate. Our analysis shows that such global frames diffuse across languages not simply as shared vocabulary but as recurrent semantic patterns that shape the lexical and associative architecture of climate discourse.

At the same time, divergence appears systematically in moral evaluation and policy recommendation, where locally embedded communicative traditions reshape global frames into culturally resonant forms. Chinese discourse constructs a collective, state-coordinated responsibility narrative centering on concepts such as the “Community of Shared Future for Mankind.” Spanish discourse adapts global norms through civic

proximity and climate justice lexicon, while German discourse organizes its evaluation and recommendations around institutional, procedural, and rights-based semantics. These culturally anchored configurations confirm that global discursive templates only acquire communicative traction when they are reinterpreted within local semiotic and institutional systems.

From a theoretical perspective, this study extends frame theory beyond its traditional focus on content and strategy, demonstrating that frames are not only cognitive-rhetorical constructs but also language-structural phenomena shaped by typological features, lexicalization patterns, and semantic organization principles. This linguistic grounding of frame theory opens new avenues for understanding how political meaning-making is constrained and enabled by the structural properties of language itself. The cross-linguistic comparison demonstrates the usefulness of frame theory for identifying shared structures of issue definition and attribution, while revealing its limitations when meaning is produced through frame blending or selective silencing. Hybrid constructs—such as *科技自立* ("technological self-reliance"), which integrates innovation and sovereignty—illustrate meaning-making processes that go beyond additive co-occurrence and require models capable of capturing emergent semantic spaces. Likewise, the partial translatability of culturally specific concepts such as *生态文明* ("ecological civilization") highlights the role of symbolic repertoires in shaping cross-linguistic semantic equivalence. These insights point to the need for a framing model that is more sensitive to cultural semiotics, multi-level communicative environments, and the dynamics of semantic recomposition across languages.

Methodologically, the study demonstrates the value of combining TF-IDF, co-occurrence networks, and contextual embeddings for analyzing multilingual discourse. This mixed computational approach allows researchers to move beyond descriptive lexical profiling toward mechanism-oriented analysis. Convergent lexical cores and tightly clustered semantic neighborhoods around technological and economic domains offer quantitative support for governance-driven convergence, while divergences in the semantic organization of responsibility, risk, and justice quantify culturally conditioned reconstruction. The triangulation of distributional and contextual models thus provides a robust methodological pathway for linking macro-level governance structures with micro-level discourse patterns.

Building on these results, a "frame communication ecology" is proposed as a conceptual framework for future research. Such a model would integrate production, mediation, and reception processes by situating frames within a dynamic network that includes policymakers, media systems, publics, and algorithmic infrastructures. Expanding the corpus to additional languages and genres (e.g., French, Arabic, policy documents, social media) would test the broader generalizability of the mechanisms identified here. Complementing corpus analysis with audience-centered methods—such as interviews, opinion tracking, or experimental designs—would clarify how frames are decoded, resisted, or reframed in real communicative settings. Advances in cross-lingual semantic mapping and neural graph models could further improve the detection of blended frames and the modeling of frame diffusion across networks.

Finally, the findings hold practical relevance for institutions engaged in international climate communication. Identifying domains where semantic convergence is structurally robust (e.g., economic and technological frames) and those where cultural adaptation is indispensable (e.g., responsibility, risk, justice) can support more effective multilingual communication strategies. By clarifying how global norms travel across linguistic systems and where they require cultural re-anchoring, this study contributes

to a deeper understanding of the linguistic mechanisms of transnational discourse and offers actionable insights for enhancing communicative effectiveness in global climate governance.

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Data availability

The corpus used in this study comprises publicly available political speeches accessible via official government and institutional websites. Processed data and analytical code are available from the corresponding author upon reasonable request.

Competing interests

The authors declare no competing interests.

Ethical statements

Ethical approval was not required for this study. The research involved the analysis of publicly available institutional text only. No human participants were recruited, interviewed, or observed, and no personal or sensitive data were collected or processed.

Informed consent

Informed consent was not applicable to this study. No human participants were involved. All materials analyzed are publicly available institutional texts that do not contain identifiable personal information requiring consent.

Author contributions

Author conceptualized the study, designed the analytical framework, led the multimodal annotation and analysis, and drafted the manuscript. Author supervised the research design, contributed to theoretical framing and critical interpretation, conducted cross-coding and reliability checks, and revised the manuscript for intellectual content. Both authors reviewed and approved the final version of the manuscript.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryInformation.docx