摘要

随着气候变化影响的迅速增加，人们越来越关注所谓的“脆弱”国家。为了度量气候变化的影响，提出合理的国家干预措施，我们以国家脆弱性和气候变化理论为基础，建立了脆弱-气候变化耦合模型和其他模型。

在任务 1 中为了对气候变化的影响进行数值测量，我们引入了气象要素的异常和极端天气概率，它们构成了气候变化指数（CCI）。在此基础上，从三个方面初步选取了与气候变化密切相关的 12 个指标，并运用熵权法和变异系数法将指标综合到基于气候变化的脆弱性指标中。此外，利用模糊聚类分析（FCA）将国家分为四类：牢固、稳定、脆弱和极度脆弱。

在任务 2 中以索马里为研究对象，分析其 CCI 与脆弱国家指数（FSI）中 12 个指标的相关性，揭示气候变化的影响。结果表明，经济脆弱性对 CCI 较为敏感。同时，社会脆弱性对气候变化的反应较小，气候变化对政治具有潜在影响。

在任务 3 中利用卡方分析和拟合方法反映 FCI 与 CCI 之间的具体函数关系，建立脆弱-气候变化耦合模型。因此，我们认为，随着墨西哥气候变化的增加，脆弱性也相应上升。根据模糊聚类结果确定国家转折点，利用二次指数平滑法建立气候变化预测模型。结论是，当一个国家的 CCI 下降到 58.72 时，它就达到了临界点，很可能会落入脆弱国家。当其他指标达到自己的临界点时，它也应该保持警惕。

在任务 4 中基于脆弱性的三个视角，我们提出了一些针对十二项脆弱性指标的人为干预措施。加强基础设施建设，资源再利用，提高园艺覆盖率，退耕还水等。然后建立了由经济衰退干预成本、生态系统可持续性、社会可居住性和机会成本构成的干预成本预测模型。

在任务 5 中我们提出了一些修改以把我们的模型应用于更小或更大的状态。通过适当改变脆弱性和气候变化的指标，我们的模型具有较高的稳定性和广泛的适用性。

关键词气候变化，脆弱性，EWM，模糊聚类

Abstract

With the rapid increase of the climate change influence, considerab been attached to socalled 'fragile' country. In order to measure the im change and propose reasonable state interventions, we establish the] Change Coupling Model and other models based on the theory of country fragility and climate change.

In task 1, for the sake of numeric measurement of the climate change's influence, we introduce the anomaly of meteorological elements and the extreme weather probability, which make up the climate change index(CCI). Furthermore, 12 indicators closely related to the climate change from three aspects are selected primarily, and then entropy weight method (EWM) and coefficient of variation method(CVM) are applied to integrate the indexes into the fragility index based on the climate change(FCI). Moreover, fuzzy cluster analysis(FCA) is employed to clarify countries into four: impregnable, stable, vulnerable, and fragile.

In task 2, we select Somalia as a research object and analyze the correlation between its CCI and the 12 indexes in the fragile state index(FSI) to reveal the impact of climate change. The result indicates that the economic fragility is sensitive to CCI. Meanwhile, the social fragility has less reaction to climate change, and climate change has potential effect on politics.

In task 3, the Chi-square analysis and fitting method are employed to reflect the specific function relationship between FCI and CCI, by which we establish the Fragile-Climate Change Coupling Model. Thus, it comes to us that with the increase of climate change in Mexico, the fragility rises up correspondingly. We define the country tipping point in the light of the result of fuzzy cluster, and build up the climate change prediction model by utilizing the second exponential smoothing method. The conclusion is that a country reaches the tipping point when the CCI of the country drops down to 58.72, and it will probably fall into fragile country. When the other indexes reach their own critical points, it should also be vigilant.

In task 4, on the basis of three perspectives of fragility, we propose some human interventions aimed at the twelve fragility indicators. They are listed as follows: strengthen infrastructure construction, reuse of resources, improve the covering rate of gardening, return arable land to the water and so on. Then we establish the Intervention Cost Prediction Model, which is composed of the cost of intervention of economic recession, ecosystem sustainability, society habitability, and opportunity cost.

In task 5, we propose some modifications to apply our model into smaller or larger states. With the appropriate alteration of indicators of fragility and climate change, our models have high stability and extensive applicability..

Key Words: Climate change, Fragility, EWM, Fuzzy clustering

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1 介绍

1.1 背景

当谈到气候变化时，由于人们更加重视气候变化对环境、经济和社会的影响，因此可以参考许多研究.根据政府间气候变化专门委员会（IPCC）的第五次评估报告（AR5）[1]，气候变化指的是气候状态的变化。其原因可能是自然的内在过程或外在力量，如火山喷发或持续的人类活动，导致大气成分的变化。

此外，气候变化的影响可能加剧社会和政府结构的崩溃，从而导致脆弱的国家。脆弱性也在 AR5 中定义，它涉及各种概念和因素，包括对伤害的敏感性和缺乏反应或适应性。

作为一个脆弱的国家，其经济、社会和人口对极端气象灾害、海平面上升、全球气温上升、耕地减少等气候冲击更加敏感。与治理不善和社会分化有关，环境不稳定无疑会引发暴力冲突[2]。

1.2 我们的工作

为了找出气候变化对区域脆弱性的影响方式，需要建立确定一个国家脆弱性的评价指标模型。通过选择合适的评价指标，赋予指标权重，并将这些低指标进行组合，实现综合指标。随后，将建立的模型应用于各国以检验其适用性，并提出改进建议。

为了解决这些问题，我们将进行以下工作：

1. Introduction

1.1 Background

When it comes to climate change, many studies can be refe people think more highly of the impacts climate change exerts on environment, economic and society. According to the Fifth Assessment Report (AR5)[1] from the Intergovernmental Panel on Climate Change (IPCC), climate change refers to the changes in climate state. The reasons account for that may be natural internal processes or external forces, like volcano eruption, or continuous human activities which result in the composition changes of atmosphere.

Moreover, the effects of climate change are likely to aggravate the breakdown of social and governmental structures, leading to fragile states consequently. Fragility is also be defined in AR5, which involves with various concepts and factors including the sensitivity towards harm and the lack of response or adaptability.

As a fragile country, it’s economic, society and population will be more sensitive to the climate shocks such as extreme meteorological disaster, rising sea level, increasing global temperature and decreasing arable land. Correlating with poor governance and social fragmentation, environmental instability will trigger violent conflict undoubtedly[2].

1.2 Our work

In order to find out the way that climate change effects on regional fragility, we are required to establish an evaluation index model which determines a country’s fragility. By selecting appropriate evaluation indicators, we endow target weights and combine those low indicators to realize some comprehensive indexes. Subsequently, the established model will be applied to various countries to test its applicability and modifications will be proposed to improve it.

We will proceed as follows for the sake of tackling these problems:

- 状态假设和标记。忽略一些微不足道的影响，我们将缩小我们处理区域脆弱性和气候变化问题的方法的核心。然后，我们将列出一些符号，这些符号对于我们阐明我们的模型和确定它们的定义非常重要。
- 建立脆弱性评价指标模型，同时对气候变化的影响进行度量。我们将应用模糊聚类方法来阐述一个状态的脆弱性，如脆弱性、脆弱性或稳定性。气候变化如何影响脆弱性也是必要的。
- 将我们的模型应用于 10 种最脆弱状态之一和另一种非脆弱状态，并研究它们的实际影响因素。然后我们将定义一个临界点来判断一个国家何时达到这个临界点。
- 介绍人的干预。人类活动有助于防止一个国家变得更加脆弱，这可以从我们的模型的结果中预测。随后，我们提出了一些修改以将模型应用于一些较小或较大的状态。
- 敏感性分析和模型评价。利用前面定义的评价标准，对模型进行了可靠性评价和灵敏度分析。然后，我们将讨论我们的模型的优点和缺点。

整个建模过程可以如下所示：

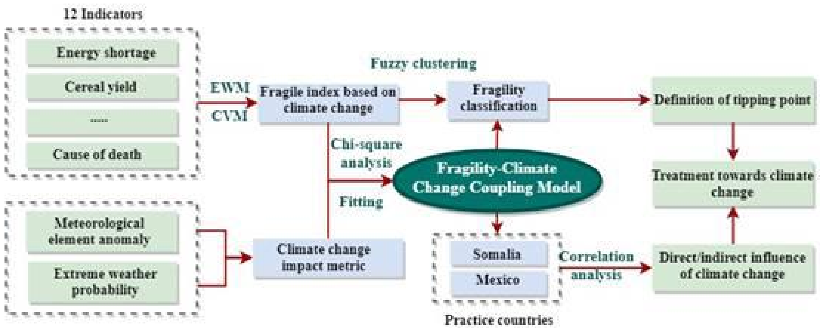


图 1 我们的论文创作的技术路线。

- State assumptions and make notations. Ignoring some insignificant impacts, we will narrow the core of our approaches towards regional fragility and climate change. Then we will list some notations which are important for us to clarify our model and determine their definitions.
- Establish an evaluation index model which illustrates the fragility and measures the effects of climate change simultaneously. We will apply the fuzzy clustering method to expound a state's fragility, like fragile, vulnerable, or stable. How the climate change affect fragility is also needed.
- Apply our model to one of the 10 most fragile states and another state not in that and investigate their actual influence factors. Then we will define a tipping point to judge when a country reaches it.
- Introduce the human intervention. Human activities can do a favor to prevent a country becoming more delicate, which can be predicted from the results of our model. Subsequently, we propose some modifications to apply our model to some smaller or larger states.
- Sensitivity analysis and model evaluation. With the evaluation criteria defined before, we evaluate the reliability of our model and do the sensitivity analysis.
  Then, we will discuss the strengths and weaknesses about our model.

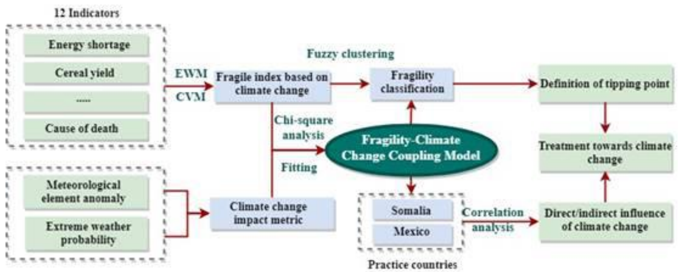


Fig.1 Technology route for the creation of our paper.

2 假设

为了简化给定的问题，并修改它更适合于模拟真实情况，我们作出以下基本假设，每个假设都适当地被证明。

我们假设国家是一个整体，没有考虑国内各地区的差异。这个假设是我们进行深入研究的前提。对于一些幅员辽阔的国家，气候条件在纬度上存在差异，不同地区的发展不平衡。

我们假设所有国家都积极应对气候变化，采取人为干预措施来降低本国的脆弱性，而忽视了被动国家。

3 符号

我们在表 1 中列出了本文中使用的符号和符号。

表 1 符号

符号	定义
ERI	经济衰退指数
ESI	生态系统可持续性指数
SHI	社会可居住性指数
FCI	基于气候变化的脆弱性指数
CCI	气候变化指数
C	皮尔森偶然系数
TC	人工干预总成本

2. Assumptions and Justification

To simplify the given problems and modify it more ap simulating real life conditions, we make the following basic hy of which is properly
justified.

- We assume the country as an overall unit without considering the differences
of regions within the country. The assumption is a prerequisite for us to do intensive study. For some countries with vast territory, the climatic conditions
vary in latitude and development of different regions is imbalanced.
- We assume that all the countries react positively to climate change and take
human interventions to decrease the fragility of their country, neglecting the passive countries

3. Notations

We list the symbols and notations used in this paper in Table 1

Table 1 Notations

Symbols	Definition
ERI	Economic recession index
ESI	Ecosystem sustainability index
SHI	Social habitability index
FCI	Fragility index based on the climate change
CCI	Climate change index
C	Pearson's contingency coefficient
TC	Total cost of human intervention

4 气候变化的脆弱性测度

经济合作与发展组织（OECD）认为，如果一个国家，在管理人口和领土等基本国家职能方面能力薄弱，缺乏发展建设性的相互加强关系的政治能力或政治意愿，社会，那么这个国家就被认为是一个脆弱的国家[3]。

国家政策和机构评估（CPA）是最广泛使用的评价体系之一，它包括经济管理、结构政策、社会包容和公平政策、公共部门管理和机构四大类。这四个集群允许进一步细化，并且可以扩展到 20 个标准（现在已经减少到 12 个标准）[4]。

4.1 气候变化指数（CCI）

近年来的研究表明，气候变化的核心影响主要集中在气温升高、降水异常、海平面上升、极端天气日数等方面。

4.1.1 温度、降水、海平面指示器

一个国家的气候，如温度、降水或海平面的特征因其经度、纬度和海拔而有很大差异。因此，我们定义了年际气温异常 d1、年降水异常 d2、年海平面异常 d3、气温年标准差σ1、降水量σ2、海平面σ3 等来描述气候变化。

回顾气象学的基本知识，狭隘的气候概念是指天气的平均状态。世界气象组织（WMO）规定了 30 年的统计平均值，气候因子的变异性可以代表本地气候的基本特征。

我们假设温度、降水和海平面指数服从分段分布。当一个国家的年度异常 di 超过 30 年的标准差σi 时，气候正在发生变化，其大小取决于其差异。因此，我们有

4. The Fragility Measurement on Climate C

The Organization for Economic Cooperation and Developr assumes that if a country, armed with the weak ability of mana state function like population and territory, lacks of political ability or political will to develop a constructive mutually reinforce relationship with the society, then the country is considered as a fragile country[3].

The Country Policy and Institutional Assessment (CPIA) is one of the most widely used evaluation systems, which is composed of four clusters: economic management, structural policies, policies for social inclusion and equity, and public sector management and institutions. These four clusters allow for further refinement and can be expanded to 20 criteria (now has been decreased to 12 criteria) [4]

4.1 Climate change index (CCI)

As the recent researches show[1], the core impact of the climate change mainly focused on the warming in temperature, the anomaly of precipitation, the rise of sea level, the number of days in extreme weather.

4.1.1 Temperature, precipitation, sea level indicator

The characteristics of a country's climate like temperature, precipitation or sea level differ a lot because of its longitude, latitude, and altitude. Therefore, we define annual temperature anomaly $d1$, annual precipitation anomaly $d2$, and annual sea level anomaly $d3$, annual standard deviation of temperature $\sigma 1$, precipitation $\sigma 2$, and sea level $\sigma 3$ to describe the climate change.

Recalling on the basic knowledge of meteorology, the narrow concept of climate is the mean state of weather. The World Meteorological Organization (WMO) stipulates 30 years' statistical mean and variability of climate factors can represent the basic characteristics of the native climate.

We assume that the temperature, precipitation, and sea level index obey segmented distribution. When the annual anomaly di of a country exceeds the 30years' standard deviation σi , climate is changing and the scale depends on their difference. Thus, we have

$$\varphi_i=\begin{cases} e^{a|d_i|}-1 & 0\le |d_i|<\sigma_i \\ b|d_i|+c & \sigma_i\le |d_i|<2\sigma_i \\ h\ln(|d_i|)+k & 2\sigma_i\le |d_i|<5\sigma_i \end{cases}$$

其中，φ1，φ2，φ3 分别表示温度 T、降水 P 和海平面 L 的指标。由于函数是连续的，所以相同临界点的值是等价的。因此，我们将给出边界条件。

$$\begin{cases} e^{a\sigma_i}-1=b\sigma_i+c=0.1 \\ 2b\sigma_i+c=h\ln(2\sigma_i)+k=0.5 \\ h\ln(5\sigma_i)+k=1 \end{cases}$$

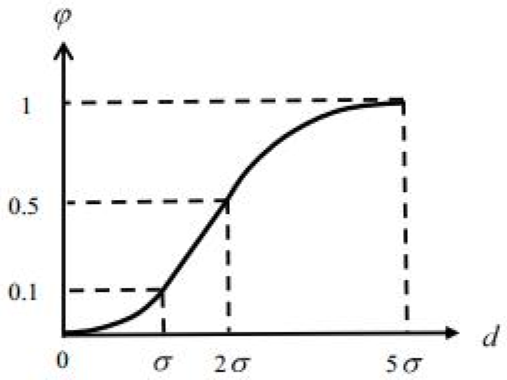


图 2 温度、降水量或海平面指数的曲线。

该指数模型包括指数分布、线性分布和对数分布三个部分，显示了三个指标异常对自然气候变化的影响。

如图 3 所示，年异常 *di* 在标准偏差σ*i* 内变化，由于微扰动的存在，是合理而常见的，因此该函数服从指数分布，并迅速趋向于气候变化，设定临界值φi=0.1。随着年异常值的增大，速度将逐渐减慢，从线性形状、设定临界值φi=0.5，到对数分布。然后我们有

$$\varphi_i=\begin{cases} e^{a|d_i|}-1 & 0\le |d_i|<\sigma_i \\ b|d_i|+c & \sigma_i\le |d_i|<2\sigma_i \\ h\ln(|d_i|)+k & 2\sigma_i\le |d_i|<5\sigma_i \end{cases}$$

Where φ1 , φ2 , and φ3 represent those index of temperature *T* , precipitation *P* , and sea level *L* respectively. Since the function is continuous, the values of same critical points are equivalent. Thus, we will give the boundary conditions.

$$\begin{cases} e^{a\sigma_i}-1=b\sigma_i+c=0.1 \\ 2b\sigma_i+c=h\ln(2\sigma_i)+k=0.5 \\ h\ln(5\sigma_i)+k=1 \end{cases}$$

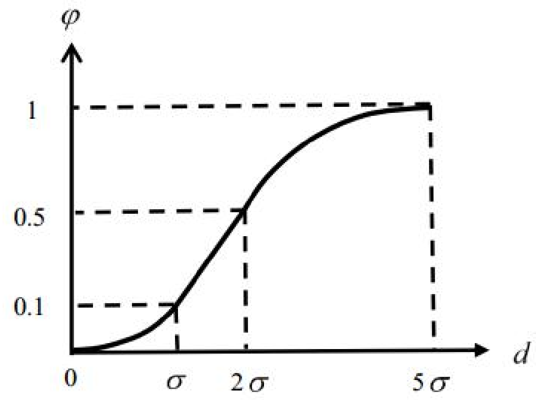


Fig.2 The curves of temperature, precipitation, or sea level index. The index model has three subsections: exponential, linear, and logarithmic distribution, showing the effects three indicators' anomalies have on native climate change.

As the Fig.3 shows, the annual anomaly *di* changing within a standard deviation σ*i* , it is reasonable and common because of the micro disturbance, thus this function obeys exponential distribution and tends to climate change rapidly, setting the critical value φ*i*=0.1. With the increasing value of annual anomaly, the speed will slow down gradually, from the linear shape, setting the critical value φ*i* =0.5 , to logarithmic distribution. Then we have

$$\varphi_i=\begin{cases} e^{\frac{\ln 1.1}{\sigma_i}|d_i|}-1 & 0\le |d_i|<\sigma_i \\ \frac{0.4}{\sigma_i}|d_i|-0.3 & \sigma_i\le |d_i|<2\sigma_i \\ \frac{0.5}{\ln 2.5}\ln(\frac{|d_i|}{5\sigma_i})+1 & 2\sigma_i\le |d_i|<5\sigma_i \end{cases}$$

4.1.2 极端天气指数

如图 4 所示，在全球变暖的背景下，极端天气灾害主要表现为高温和暴雨[6]。因此，结合气温和降水指数，可以构造极端天气指数 E。

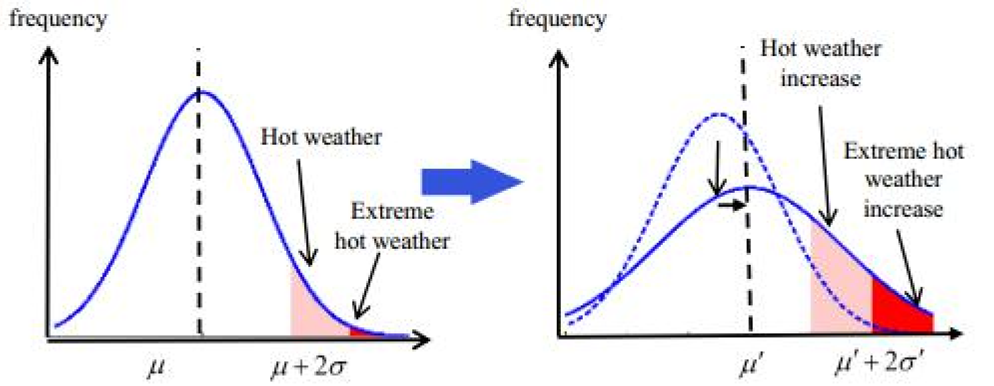


图 3 气候概率分布参数的示意图。

右边是平均温度的升高和标准偏差。浅红色表示炎热的天气，而红色表示极端炎热的天气。

我们假设一个国家一年内的温度和降水量具有正态分布，这将在以后得到证实。我们可以得出这样的结论

$$f(t)=\frac{1}{\sqrt{2\pi}\sigma_i}\exp(-\frac{(t-\mu_i)^2}{2\sigma_i^2})$$

其中 f(t)是温度的概率密度函数，t 是区域的日平均温度，μi 是年平均温度。

$$\varphi_i=\begin{cases} e^{\frac{\ln 1.1}{\sigma_i}|d_i|}-1 & 0\le |d_i|<\sigma_i \\ \frac{0.4}{\sigma_i}|d_i|-0.3 & \sigma_i\le |d_i|<2\sigma_i \\ \frac{0.5}{\ln 2.5}\ln(\frac{|d_i|}{5\sigma_i})+1 & 2\sigma_i\le |d_i|<5\sigma_i \end{cases}$$

4.1.2 Extreme weather indicator

As is vividly shown in Fig.4, in the context of global warming, the extreme weather disasters mainly embodies in high temperature and rainstorm[6]. Thus, combined with the temperature and precipitation index, we can construct the extreme weather index E.

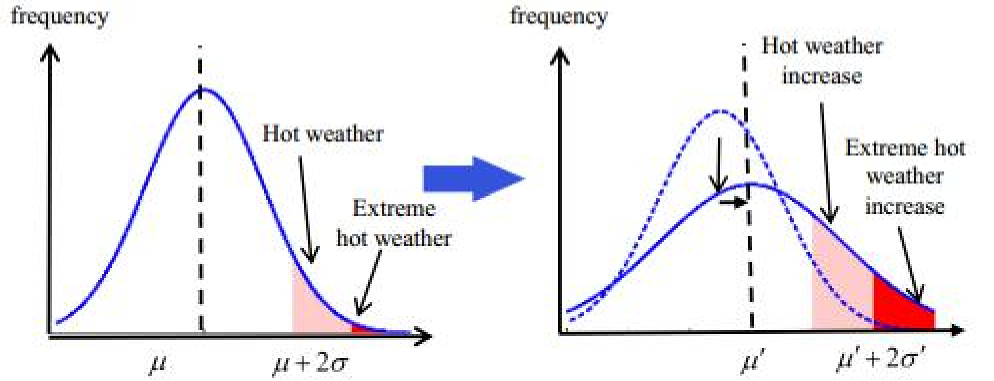


Fig.3 The schematic diagram of parameters of climate probability distribution. The right part shows the increase of average temperature and standard deviation. The shade of light red indicates the hot weather, while the red shade indicates the extreme hot weather.

We assume that the temperature and precipitation during one year of a country have a normal distribution, which will be confirmed later. We can derive that

$$f(t)=\frac{1}{\sqrt{2\pi}\sigma_i}\exp(-\frac{(t-\mu_i)^2}{2\sigma_i^2})$$

where $f(t)$ is the probability density function of the temperature, t is the daily average temperature of a region, and μi is the annual average temperature.

然后，我们定义当异常值超过标准差的两倍时，天气是异常的。从而得出温度异常概率 P(t)。同样地，降水具有 P(p)函数。

$$P(t)=\int_{\mu_t+2\sigma_t}^{\infty}f(t)dt, P(p)=\int_{\mu_p+2\sigma_t}^{\infty}f(p)dp$$

随后，我们可以计算极端天气指数 E。

$$E=P(t)+P(p)=\int_{\mu_t+2\sigma_t}^{\infty}f(t)dt+\int_{\mu_t+2\sigma_t}^{\infty}f(p)dp$$

因此，为了简化模型，同时提高模型的有效性，我们选择温度、降水、海平面和极端灾害日数等异常作为重点，分析气候变化的影响。随后，我们对这些指标进行加权，并集成到一个综合度量中，该度量被认为能够代表气候变化的程度。我们难以衡量这些因素的实际比例，因此我们假设它们彼此同样重要。

$$CCI=\frac{1}{m}(T+P+\lambda L+E)\times 100$$

其中 CCI 是气候变化影响度量，T、P、L、E 是温度、降水、海平面、极端天气等指标的评价值。

考虑到内陆国家不受海洋的影响，我们要求在内陆国家和沿海国家之间有所不同。因此，我们有

$$\begin{cases}\lambda=1, m=4 & coastal\ \ or\ \ island\ \ country\\ \lambda=0, m=3 & landlocked\ \ country\end{cases}$$

4.2 基于气候变化的脆弱性指数

4.2.1 主要指标体系

Then we define that when the value of anomalies beyond t as that of standard deviation, the weather is abnormal. Then we the probability of abnormal temperature $P(t)$. Similarly, precip function $P(p)$.

$$P(t)=\int_{\mu_t+2\sigma_t}^{\infty}f(t)dt, P(p)=\int_{\mu_p+2\sigma_t}^{\infty}f(p)dp$$

Subsequently, we can calculate the extreme weather index *E*.

$$E=P(t)+P(p)=\int_{\mu_t+2\sigma_t}^{\infty}f(t)dt+\int_{\mu_t+2\sigma_t}^{\infty}f(p)dp$$

Therefore, in order to simplify the model and simultaneously the effectiveness of our model, we select the anomaly of temperature, precipitation, sea level and the days of extreme disaster days as the points of focus for the sake of analyzing the influence of climate change. Subsequently, we weight the indexes and integrate into one comprehensive metric, which is considered to be able to represent the extent of climate change. It is difficult for us to measure the actual proportion of those factors, hence we assume that they are as crucial as each other.

$$CCI=\frac{1}{m}(T+P+\lambda L+E)\times 100$$

where CCI is the climate change impact metric, T, P, L, E are the evaluation indexes of temperature, precipitation, sea level, and extreme weather respectively.

Considering the landlocked countries without the effects of sea, we are required to make a difference between landlocked and coastal states. Thus, we have

$$\begin{cases}\lambda=1, m=4 & coastal\ \ or\ \ island\ \ country\\ \lambda=0, m=3 & landlocked\ \ country\end{cases}$$

4.2 Fragility index based on climate change

4.2.1 Primary indicator system

由于世界银行已经建立了自己的评价体系，他所选择的评价标准是从宏观和综合的角度出发的。为了在气候变化的影响与一个国家的脆弱性之间建立一种牢固的关系，在叙述环境压力与冲突之间联系的基础上[5]，我们从三个层次定义了脆弱性评价指标。

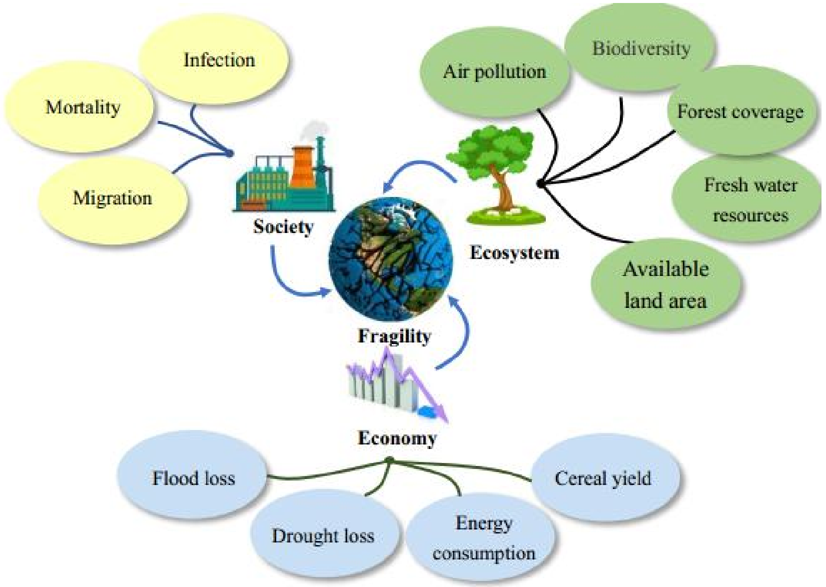


图 4 脆弱性评价标准。该模型从经济衰退、生态系统可持续性和社会适居性的角度出发，定义了 12 个指标，并将它们纳入基于气候变化的脆弱性指数。

（1）经济衰退

能源短缺记为 X1（人均千瓦时）。当一个国家遭受气候的影响，加上基础设施建设薄弱，国家对气候变化将更加敏感。因此，我们引入总电力与人口的比率来反映能源短缺。

谷物产量记为 X2（千克每公顷）。农业可能是对气候变化最敏感的部门之一。我们选择粮食生产来代表农业对气候变化的反应。该指标的值与脆弱性成反比。

Since the World Bank already has its evaluation system, t criteria he has chosen are from a macroscopic and comprehensi In order to develop a strong relationship between the impa change and a country's fragility, on the basis of a narrative ex links between environmental stress and conflict[5], we define fragility evaluation indexes from three levels.

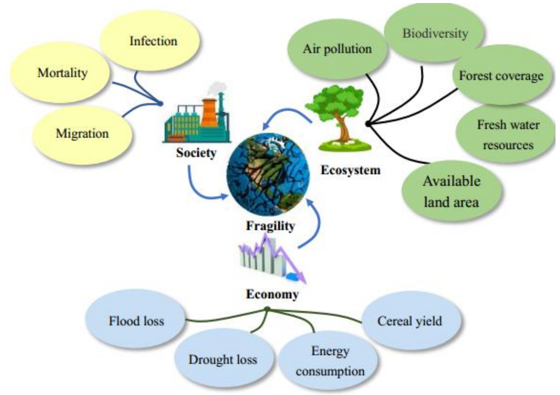


Fig.4 Process flow for the establishment of the fragility evaluation criteria. From the perspective of economic recession, ecosystem sustainability, and society habitability, the model defines twelve indicators and incorporated them into the fragility index based on climate change.

(1) **Economic recession**

- Energy shortage $X1$ (kwh per capita). When a country suffers from a climate shock, armed with the weak infrastructure construction, the country will be more sensitive to the climate change. Thus, we introduce the ratio of the total electricity to the population to reflect the energy shortage.
- Cereal yield $X2$ (kg per hectare). Agriculture may be one of the most sensitive departments to climate change. We choose food production to represent the agriculture's reflection on climate change. The value of this indicator is inversely proportional to the fragility.

洪灾经济损失记为 X3（占 GDP 的百分比）。全球变暖可能加强水文循环，平均降水量有增加的趋势。洪水灾害会导致山洪暴发、农田泛滥、基础设施破坏和人员伤亡。然后引入洪灾经济损失占 GDP 的比例来表示洪灾的影响。

干旱的经济损失记为 X4（占 GDP 的百分比）。虽然某些地区的降水量可能增加，但实际蒸发量将同时上升，这是由于世界平均气温上升造成的。因此，我们定义了干旱经济损失占 GDP 的比例，以象征干旱的压力。

（2）生态系统可持续性

森林面积 X5（占土地面积的百分比）。森林生产力是判断树木生长和生态系统功能的主要因素之一。气候变化对森林的影响主要表现在温度胁迫等方面。因此，我们引入森林面积占土地总面积的比例来表示一个国家的森林覆盖率。

年淡水 X6（人均立方米）。淡水资源是人类赖以生存的物质基础之一。气候变化可能导致地下水位下降，河流干涸。因此，每年人均淡水占有量的定义是为了说明气候变化的影响。

耕地 X7（人均公顷）。随着平均气温的显著上升，冰川无疑会融化，导致海平面上升。直观的结果是耕地减少。因此，我们引入人均耕地来描述其对气候冲击的反映。

温室气体排放量 X8（人均公吨）。众所周知，温室气体排放和气候变化是相互影响的。因此，我们把人均温室气体排放量确定为气候变化的影响之一。

原生生物多样性 X9。一些物种由于不能适应新的生活环境而濒临灭绝。因此，我们引入本地物种作为生物多样性反映气候变化的威胁。

- Economic loss in flood disaster $X3$ (% of GDP). Global war strengthen the hydrologic cycle and average precipitation tenc Flood disasters will cause the mountain torrents rushing dc farmland, destructions of infrastructures, and casualties. Then we introduce the ratio of economic loss in flood disaster to GDP to represent the disaster's impacts.
- Economic loss in drought $X4$ (% of GDP). Although the precipitation may increase in some regions, actual vaporization will rise simultaneously caused by the rising average world temperature. We hence define the ratio of economic loss in drought to GDP to symbolize drought's stress.

(2) Ecosystem sustainability

- Forest area $X5$ (% of land area). Forest productivity is one of the main factors to judge the tree growth and ecosystem functioning. The influences climate change exerts on forests major in temperature stress, etc. Thus, we introduce the ratio of the forest area to grossing land area to represent a country's forest cover rate.
- Annual fresh water $X6$ (cubic meters per capita). Fresh water resource is one of the material basis upon survival of mankind. Climate change may cause groundwater levels to decline and rivers to dry up. Consequently, annual fresh water occupation per capita is defined to illustrate the effects of climate change.
- Arable land $X7$ (hectares per person). With the average temperature rising noticeably, glaciers melt undoubtedly, leading to the rises in sea levels. The intuitionistic result is the reduction of arable land. We hence introduce the arable land per capita to describe its reflection to climate shock.
- Greenhouse gas emissions $X8$ (metric tons per capita). As we all know, greenhouse gas emissions and climate change are interacted with each other. Therefore, we determine greenhouse gas emissions per capita as one of the influence of climate change.
- Native biodiversity $X\,9$. Some species are in danger of extinction since they fail to adapt to the new living environment. Thus, we introduce the native species threatened as the biodiversity reflection to climate change.

（3）社会可居住性

净移民 X10。由于自然资源负担日益严重，气候变化的影响威胁到人类的自给自足能力。因此，我们将净迁移定义为评估指标。

因自然灾害死亡 X11（占总数的%）。极端天气如 EI Nino、沙尘暴和飓风等在气候变化后将增加频率和强度。因此，我们引入自然灾害死亡数与总数的比率。

疾病的流行率 X12。人们由于传播昆虫而死于传染病的风险很高。因此，我们选择感染的流行率来表示人类健康对气候变化的反映。

4.2.2 指标权重

a.熵权法

利用上述评价指标，我们进一步确定这些指标的权重，从而得到主要指标的组合。回顾熵权法（EWM），进行标准化处理，使交替后的各变量的最优值和最坏值分别是 1 和 0。评价指标为 X1,X2,X3,…,Xk，其中 X={xi1,xi2,…,xin}。其中，k 和 n 是确定的评估指标和世界上主权国家的数目，其中 k=12。

对于成本型指标，一个国家的脆弱性与指标的价值成正比。然而，就收益型指标而言，价值越高，国家就越不脆弱。因此，我们有

$$\begin{cases} y_{ij} = \dfrac{x_{ij} - \min(x_i)}{\max(x_i) - \min(x_i)} \\ y_{ij} = \dfrac{\max(x_i) - x_{ij}}{\max(x_i) - \min(x_i)} \end{cases} \qquad j = 1, 2, \dots, n$$

其中 yij 是各国各评价指标的标准值，max(xi)和 min(xj)是评价值 xi 的最大值和最小值。

(3) Society habitability

- Net migration $X10$. Due to the increasing severe burd resources, the impacts of climate change threaten the self-suffic human beings. We consequently define net migration as an evaluation indicator.
- Cause of death, by natural disasters $X11$(% of total). Extreme weather like EI Niño, sand storm and hurricane will increase in frequency and intensity after climate change. We hence introduce the ratio of death by natural disasters to total number.
- Prevalence of infection

$X12$. People are at high risk of dying from communicable diseases through the transmission of insects. So, we choose prevalence of infection to represent the reflection of human health to climate change.

4.2.2 Weight of indicators

a. Entropy weight method

With the evaluation indicators defined above, we further determine the weights of these indicators, resulting in the combination of primary indicators. Recalling on the Entropy Weight Method (EWM), we will carry out the standardized treatment, making the optimal and worst value of each variables after alternation be 1 and 0, respectively. The evaluation indexes are X_1 ,X_2 ,X_3,..., Xk , where Xi={ $xi1$,$xi2$,..., xin}. Among there, k and n are the number of defined evaluation indictors and sovereign countries throughout the world, where k=12 .

For the sake of the cost-type indicators, the fragility of a country is proportional to the value of the indicator. However, in terms of the gain-type indicators, the higher the value is, the less fragile the country will be. Thus, we have

$$\begin{cases} y_{ij} = \dfrac{x_{ij} - \min(x_i)}{\max(x_i) - \min(x_i)} \\ y_{ij} = \dfrac{\max(x_i) - x_{ij}}{\max(x_i) - \min(x_i)} \end{cases} \qquad j = 1, 2, \dots, n$$

Where yij is the standardized value of each evaluation indicator of each country, max(xi) and min(xi) are the maximum and minimum value of the evaluation indicator $X\,i$.

$$\max(x_i)=\max\{x_{i1},x_{i2},...,x_{in}\},\ \min(x_i)=\min\{x_{i1},x_{i2},...,x_{in}\}.$$

标准化后，我们成功地用 yij 代替 xij 来表示一个国家的脆弱性。然后我们得到

$$p_{ij}=y_{ij}/\sum_{j=1}^{n}y_{ij}$$

根据信息论中自信息和熵的概念，可以计算各评价指标的信息熵，从而得到各评价指标的信息熵 Ei，

$$E_i=-\ln(n)^{-1}\sum_{j=1}^{n}p_{ij}\ln(p_{ij})$$

在信息熵的基础上，进一步计算各个评价指标的权重。

$$w_i=\frac{1-E_i}{k-\sum_i E_i}\qquad i=1,2,...,k$$

随后，得出三个综合评价指标：经济衰退指数、生态系统可持续性指数和社会可居住性指数。此后，本文将分别缩写为 ERI，ESI 和 SHI。根据这些计算的重量，我们有

$$\begin{cases}ERI_j=w_1y_{1j}+w_2y_{2j}+w_3y_{3j}+w_4y_{4j}\\ESI_j=w_5y_{5j}+w_6y_{6j}+w_7y_{7j}+w_8y_{8j}+w_9y_{9j}\\SHI_j=w_{10}y_{10j}+w_{11}y_{11j}+w_{12}y_{12j}\end{cases}$$

b.变异系数法

此外，我们运用变异系数法对这三个指标进行加权，并将它们合并成一个综合度量。因此，我们将简要介绍变异系数法的应用。

变异系数法（CVM）利用各种指标的信息，通过计算得到各指标的权重，是一种客观赋权的方法。

$$\max(x_i)=\max\{x_{i1},x_{i2},...,x_{in}\},\ \min(x_i)=\min\{x_{i1},x_{i2},...,x_{in}\}.$$

After standardization, we succeed in substituting yij for xij to in fragility of a country. Then we introduce

$$p_{ij}=y_{ij}/\sum_{j=1}^{n}y_{ij}$$

According to the concepts of self-information and entropy in the information theory, we can calculate the information entropy Ei of each evaluation indicator, hence we can obtain

$$E_i=-\ln(n)^{-1}\sum_{j=1}^{n}p_{ij}\ln(p_{ij})$$

On the basis of the information entropy, we will further compute the weight of each evaluation indicator we defined before.

$$w_i=\frac{1-E_i}{k-\sum_i E_i}\qquad i=1,2,...,k$$

Subsequently, we can derive the three comprehensive evaluation indicators: economic recession index, ecosystem sustainability index, and social habitability. Hereafter this paper will be abbreviated as *ERI* , *ESI* , and *SHI* respectively. On the basis of those calculated weights, we have

$$\begin{cases}ERI_j=w_1y_{1j}+w_2y_{2j}+w_3y_{3j}+w_4y_{4j}\\ESI_j=w_5y_{5j}+w_6y_{6j}+w_7y_{7j}+w_8y_{8j}+w_9y_{9j}\\SHI_j=w_{10}y_{10j}+w_{11}y_{11j}+w_{12}y_{12j}\end{cases}$$

b. Coefficient of variation method

Furthermore, we apply coefficient of variation method to weight these three indices and merge them into a comprehensive metric. Therefore, we will introduce the application of coefficient of variation method briefly.

Coefficient of variation method (CVM) utilizes the information from various indexes and achieve the weight of each index through calculating, which shows to be an objective approach to give weight.

由于受不同维度的影响，很难直接对指标进行比较，因此需要各指标的变异系数来衡量各指标的差异程度。每个指标的公式可以表示为：

$$V_i = \frac{\theta_i}{\overline{z}_i} \qquad i = 1,2,3$$

其中，Vi 是指标 i 的变化系数，也可以称θ_i为标准偏差系数，而是指指标 i 的标准偏差。Z1、Z2、Z3 分别表示 ERI、ESI 和 SHI。然后可以得到每个指标的权重：

$$W_i = \frac{V_i}{\sum_{i=1}^{n} V_i} \qquad i = 1,2,3$$

通过这种方式，我们能够在没有任何主观印象的情况下实现每个指标的权重。最后，在得到权重后，可以推导出基于气候变化 FCI 的综合度量脆弱性指数。

$$FCI = (W_1 \times ERI + W_2 \times ESI + W_3 \times SHI) \times 100$$

4.2.3 模糊聚类分析

结合我们之前建立的综合脆弱性度量，我们将从世界银行输入各国的数据，并计算 FCI 值。然后，根据它们各自的得分，我们利用马氏距离将这些国家界定为：非常稳定、稳定、脆弱和极度脆弱。因此，我们可以从 FCI 中识别一个国家的脆弱性。由于它是一种传统的方法，我们忽略了它的计算过程。

Owing to the influence of different dimension, it is hard to comp directly, so it needs the coefficient of variation of each index t difference extent of them. The formula of each index can be exp

$$V_i = \frac{\theta_i}{\overline{z}_i} \qquad i = 1,2,3$$

Where Vi is the coefficient of variation of the index i , which can also be called as standard deviation coefficient, and θi means the standard deviation of the index i. And the $z1$, $z2$, $z3$ separately means ERI , ESI , and SHI . Then the weight of each index comes to us:

$$W_i = \frac{V_i}{\sum_{i=1}^{n} V_i} \qquad i = 1,2,3$$

By this way, we are able to achieve the weight of each index without any subjective impression. Finally, after getting the weight, we can derive the comprehensive metricfragility index based on the climate change FCI .

$$FCI = (W_1 \times ERI + W_2 \times ESI + W_3 \times SHI) \times 100$$

4.2.3 Fuzzy Cluster Analysis

Combined with the comprehensive fragility metric we established before, we will import data of various countries from the World Bank and calculate the values of FCI . Then according to their respective values, we use Mahalanobis distance to clarify these countries as: impregnable, stable, vulnerable, and fragile. Thus, we can identify a country's fragility from their FCI . Since it is a conventional method, we neglect the calculate process of it.

4.3 脆弱性鉴定

在建立脆弱性-气候变化耦合模型时，我们假设 n 是世界上主权国家的数目，执行起来太复杂。因此，我们从世界中选择 20 个地理位置、经济程度和气候特点不同的国家，这将在后面列出。

表 2 十二项评价指标和三项综合指标的权重值。

	指标	权重	指标	权重
脆弱性	经济衰退	0.1145	能源短缺	0.2912
			谷物产量	0.1227
			洪灾经济损失	0.1648
			旱灾经济损失	0.1971
	生态系统可持续性	0.6055	林区	0.2965
			一年生淡水	0.2083
			耕地	0.1122
			温室气体排放	0.1954
			原生生物多样性	0.1876
	社会可居住性	0.2800	净迁移	0.1986
			自然灾害死亡原因	0.5177
			感染流行率	0.2837

由于这些指标的具体值已在表 2 中给出，因此我们可以计算我们选定国家的 FCI，并应用模糊聚类方法将这些国家分为四类：非常稳定、稳定、脆弱和极度脆弱。值越高，国家就越脆弱。聚类结果如下所示。

4.3 Fragility identification

In the establishment of fragility-climate change coupling mod that *n* is the number of sovereign countries throughout the worl complicated to implement. Thus, we select 20 countries varying in geographical locations, economy degree, and climate features throughout the world, which will be listed later

Table 2 Weight values of the twelve evaluation indicators and three comprehensive indexes.

	Indicators	Weights	Indicators	Weights
Fragility	Economic recession	0.1145	Energy shortage	0.2912
			Cereal yield	0.1227
			Economic loss in flood disaster	0.1648
			Economic loss in drought	0.1971
	Ecosystem sustainability	0.6055	Forest area	0.2965
			Annual fresh water	0.2083
			Arable land	0.1122
			Greenhouse gas emissions	0.1954
			Native biodiversity	0.1876
	Society habitability	0.2800	Net migration	0.1986
			Cause of death, by natural disasters	0.5177
			Prevalence of infection	0.2837

Since the specific value of those indicators have been given in Table 2, hence we can calculate the *FCI* of our selected countries and apply fuzzy clustering method to clarify these countries into four groups: impregnable, stable, vulnerable, and fragile. The higher the value is, the more fragile the country is. The results of clustering are shown as follows.

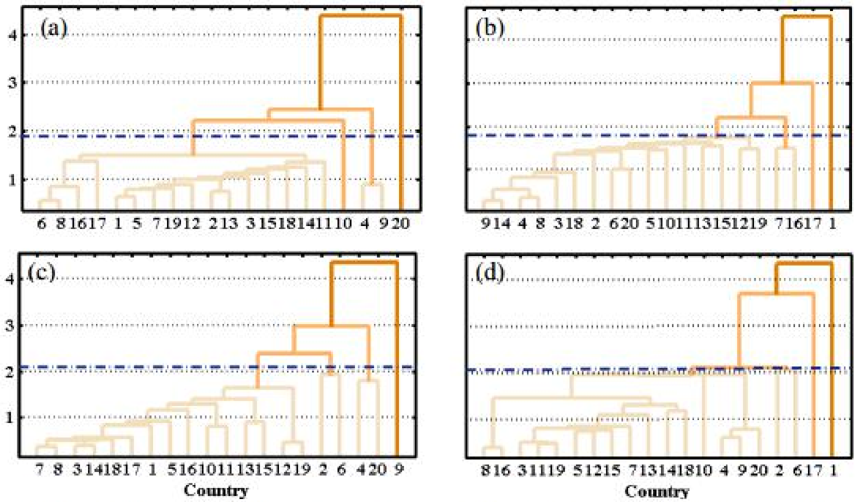


Fig.5 Clustering results of the four indicators. (a) economic recession; (b) society

图 5 聚类结果的四个指标。

(a)经济衰退；(b)社会可持续性；(c)生态系统可居住性；(d)脆弱性。沿横坐标轴的序列号代表该国：1 阿富汗；2 孟加拉国；3 巴巴多斯；4 加拿大；5 哥伦比亚；6 古巴；7 多米尼克；8 厄立特里亚；9 芬兰；10 法国；11 格鲁吉亚；12 伊朗；13 马里；14 毛里求斯；15 巴拉圭；16 塞内加尔；17 南苏丹；18 特立尼达和多巴哥；19 突尼斯；20 美国。

根据图 5，一旦确定了 ERI、ESI、SHI 和 FCI 的值，就可以确定一个国家脆弱性的分类标准。如图 6 所示，三个组合指标和综合指标的分类标准略有不同。由于它们关注的焦点：经济、生态系统、社会以及结合的重点放在一个国家的各种发展上，最终的脆弱性等级也会同时不同。

颜色越深，国家就越脆弱。根据分类标准，综合度量脆弱性等级表明稳定国家是压倒一切的国家，在引导可持续发展之间取得了平衡。

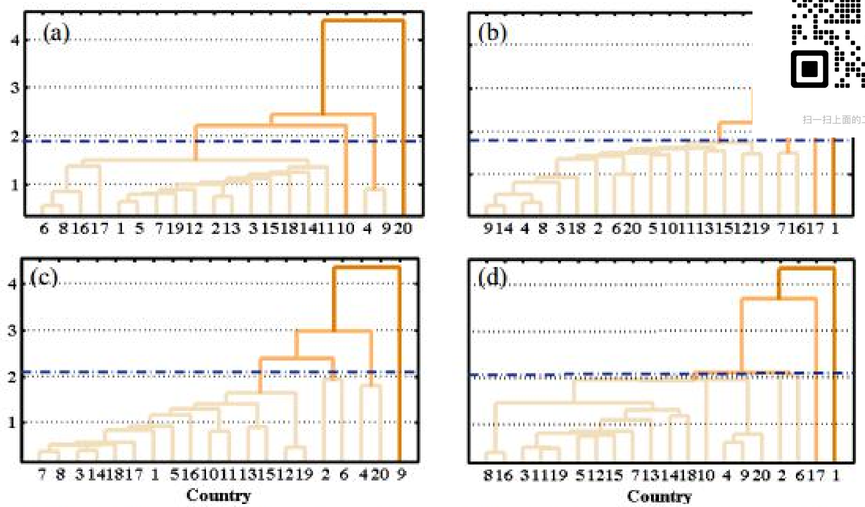


Fig.5 Clustering results of the four indicators. (a) economic recession; (b) society

Fig.5 Clustering results of the four indicators. (a) economic recession; (b) society sustainability; (c) ecosystem habitability; (d) fragility. The sequence number along the abscissa axis represents the country: 1 Afghanistan; 2 Bangladesh; 3 Barbados; 4 Canada; 5 Colombia; 6 Cuba; 7 Dominica; 8 Eritrea; 9 Finland; 10 France; 11 Georgia; 12 Iran; 13 Mali; 14 Mauritius; 15 Paraguay; 16 Senegal; 17 South Sudan; 18 Trinidad and Tobago; 19 Tunisia; 20 United States.

According to Fig.5 , we can determine the classification standards of a country's fragility, once the value of *ERI* , *ESI* , *SHI* , and *FCI* is figured out. As is shown in Fig.6, the classification standards of the three combined indicators and the comprehensive metric vary a little. Since their focus of attention: economy, ecosystem, society, and combination put the emphasis on the various development of a country, the ultimate ranks of fragility will be different simultaneously.

The deeper the color is, the more fragile the country will be. According to classification standards, the comprehensive metric-fragility rank indicates that stable country is the overwhelming country, succeeding in striking a balance between vectoring sustainable development.

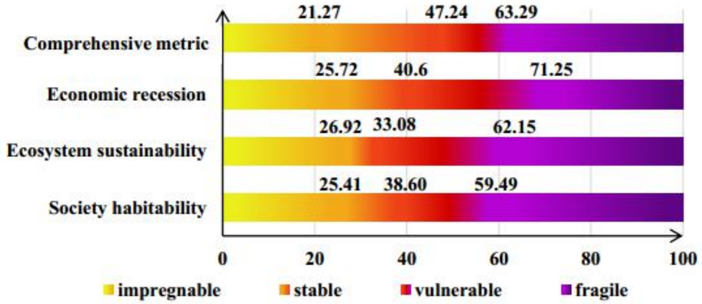


图 6 分类标准及其各自的关键点验证一个国家的脆弱性，这被分类为极其稳定、稳定、脆弱和非常脆弱。

如图 7 所示，脆弱性指数 2017（FSI）的原始脆弱性排名与我们建立的基于气候变化的脆弱性指数相匹配。我们选择六个国家为例。

例如，南苏丹实际上是世界上最脆弱的国家，因为它的贫穷，基础设施薄弱，以及相对基本的农业技术。同样，它对气候变化更加敏感，成为最脆弱的指标。谈到像美国这样的发达国家，它的全球超级大国、坚实的基础设施和先进的技术决定了它将更容易应对气候变化。因此，它被定义为坚不可摧的。

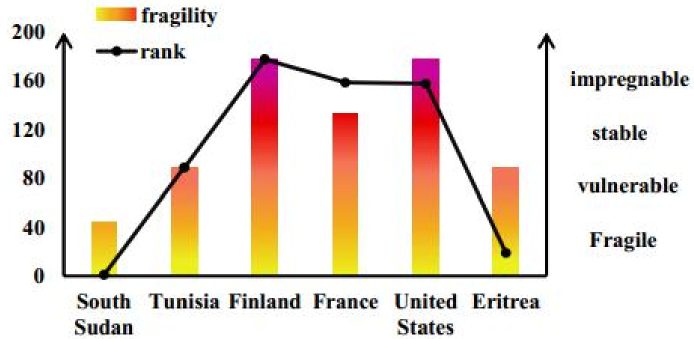


Fig.7 Comparison of original ranks from FSI and estimated fragility indexes from *FCI* .

图 7 对 FSI 原始等级和来自 FSI 的脆弱性评估指标的比较。

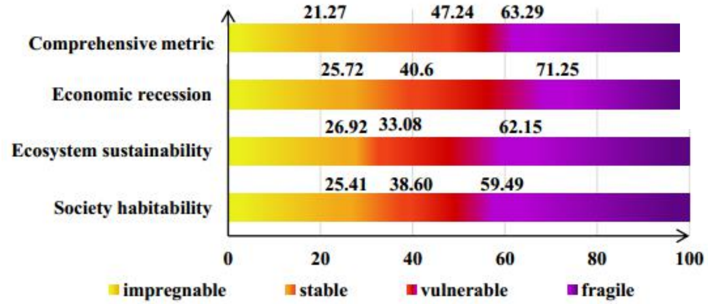


Fig.6 Classification standards and their respective critical points of verifying a country's fragility, which is classified as impregnable, stable, vulnerable, and fragile.

The original fragility ranks from Fragile States Index 2017 (FSI), as we can see in Fig.7, match the fragile index based on climate change *FCI* we established well. We choose six countries as an example.

For example, South Sudan is actually the most fragile country in the world because of its poverty, weak infrastructure, and relatively basic agriculture technologies. Similarly, it is more sensitive to climate change, making itself the most fragile index. When it comes to developed countries like United States, its global superpower, firm infrastructure, and advanced technology determine that it will be easier to deal with climate change. Thus, it is clarified as impregnable.

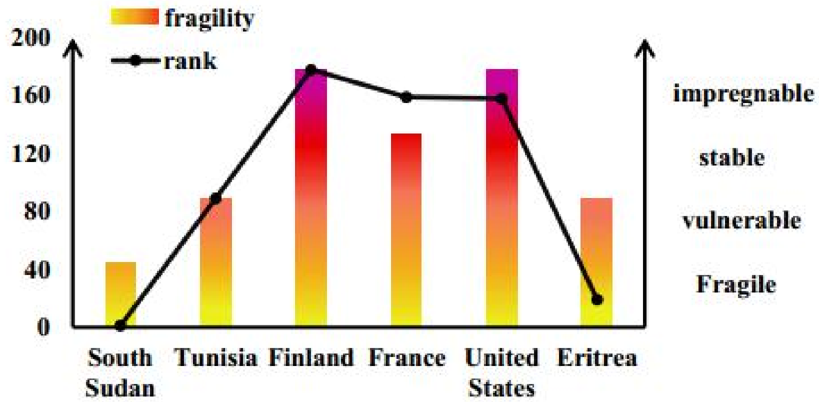


Fig.7 Comparison of original ranks from FSI and estimated fragility indexes from *FCI* .

5. 索马里脆弱性分析

5.1 气候特征

排名第二的索马里位于非洲大陆的索马里半岛，位于印度洋的边缘。它是世界上最不发达的国家之一，工业脆弱，粮食短缺，自然灾害。索马里大部分地区属于亚热带和热带沙漠气候。其典型特征是全年高温和干燥或无雨环境[7]。

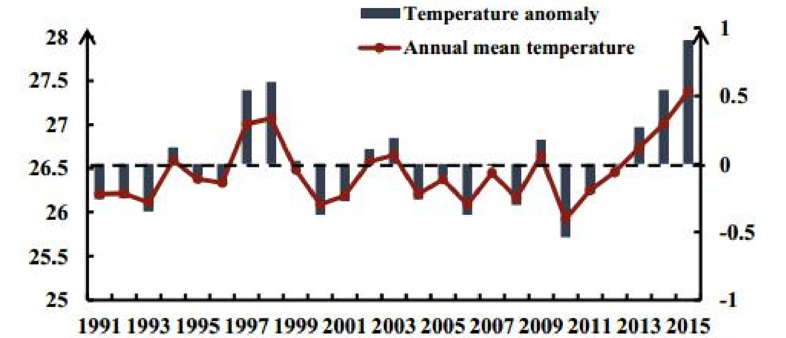


Fig.8 The annual mean temperature and temperature anomaly of Somalia from 1991 to 2015.

图 81991～2015 年索马里年平均气温和温度异常。

如图 8 所示，索马里 24 年的平均气温为 26.5，这很好地说明了它的高温。年气温变化很小，从-0.5 到 0.5。然后对温度和降水进行正态分布检验。

根据图 9，日平均气温和降水散点图与正态分布曲线拟合得很好。因此，我们在建立 CCI 中的假设是合理的和实用的。

5. Fragility Analysis of Somalia

5.1 Climate characteristics

Second-placed Somalia locates in Somali peninsula in the Afric on the verge of the India Ocean. It is one of the least developed nations throughout the world, with vulnerable industry, food shortage, and natural disasters. Most regions of Somalia belong to subtropical and tropical desert climate. The typical characteristics are high temperature throughout the year and dry or rainless environments[7].

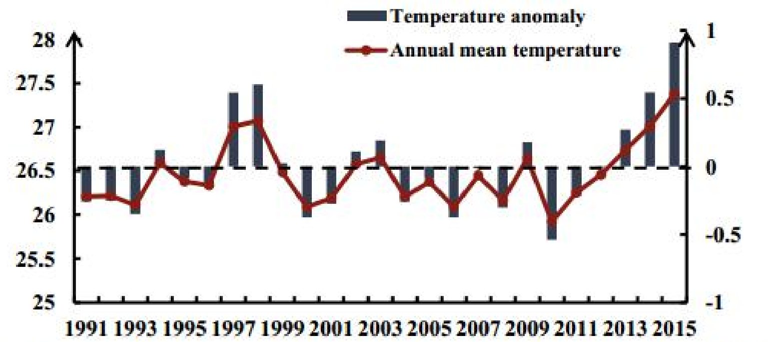


Fig.8 The annual mean temperature and temperature anomaly of Somalia from 1991 to 2015.

As is shown in Fig.8, the 24 years'average temperature of Somalia is 26.5 C , which illustrates its high temperature very well. The annual temperature fluctuates in a small scale: from -0.5 C to 0.5 C . Then we conduct the normal distribution verification of temperature and precipitation as follows.

According to Fig.9, the daily average temperature and precipitation scatterplots fit very well with the curves of normal distribution. Thus, our assumption used in the establishment of CCI is reasonable and practical.

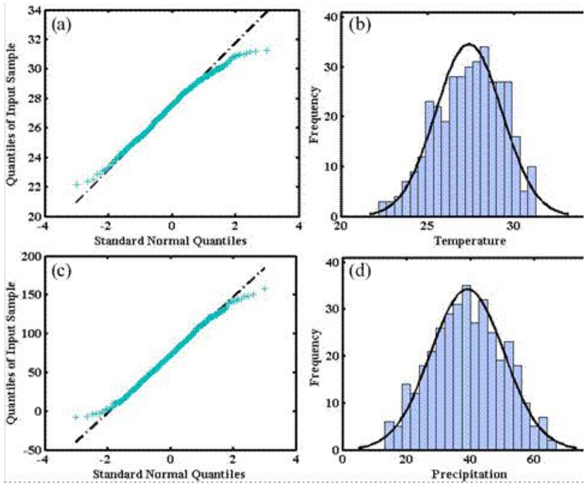


图 9 正态分布检验。（a）温度 Q-Q 图；（b）日平均温度的频率直方图；（c）降水的 Q-Q 图；（b）日平均降水频率直方图。

5.2 CCI 与 FSI 的相关性

为了进一步研究气候变化的影响，利用皮尔逊相关分析方法，研究了近 30 年来索马里气候变化与 FSI 指数的关系。相关系数如表 3 所示。

表 3 气候变化与 FSI 各指标的相关系数

指标	安全装置	宗派精英	群体不满	经济
系数	0.1327	0.0028	0.4007	0.6528
指标	经济不平等	人的迁移与人才流失	国家合法性	公共服务
系数	0.5431	0.3287	0.0028	0.2758
指标	人权	人口压力	难民和流离失所者	外部干预
系数	0.1279	0.5628	0.6526	0.0167

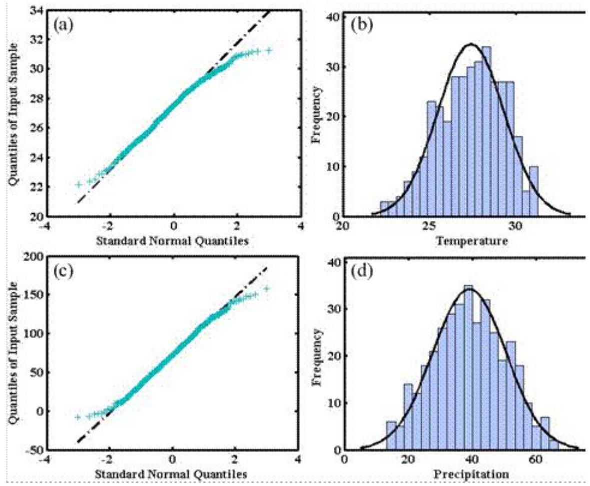


Fig.9 Verification of normal distribution. (a) q-q plot of the temperature; (b) frequency histogram of daily average temperature; (c) q-q plot of the precipitation; (b) frequency histogram of daily average precipitation.

5.2 Correlation between CCI and FSI

To research more deeply on the effect of climate change, we study the relationship among climate change and several indexes of FSI in Somalia for the last 30 years by method of Pearson correlation analysis. Correlation coefficients are shown in Table 3.

Table 3 Correlation coefficients of climate change and each index of FSI

Indictors	Security apparatus	Factionalized elites	Group grievance	Economy
Coefficients	0.1327	0.0028	0.4007	0.6528
Indicators	Economic inequality	Human flight and brain drain	State legitimacy	Public services
Coefficients	0.5431	0.3287	0.0028	0.2758
Indicators	Human rights	Demographic pressures	Refugees and IDPs	External intervention
Coefficients	0.1279	0.5628	0.6526	0.0167

在表 3 中，我们清楚地看到 CCI 和 FSI 具有很强的相关性。例如，CCI 与贫困和经济衰退、经济不平等有很高的相关系数，表明经济方面对气候变化很敏感。气候变化直接而有力地改变着一个国家的经济。例如，平均温度的升高会带来更多的干旱，这降低了粮食产量，不可避免地减少了收入。然而，最富有的人群仍然占据了这个国家的大部分财富，因此经济不平等不断加剧。

另一方面，公共服务、人才外流、人权等属于社会层面的系数小于经济层面的系数。这很容易理解。虽然气候变化对社会的影响是显著的，但其影响是缓慢而隐蔽的。因此，社会层面的影响需要时间来揭示。

然而，与派系化精英的系数，国家合法性，代表政治方面，是非常少。这意味着气候变化与政治之间的联系是有限的。究其原因，主要是因为政治是人类主观能动性的结果，与天气关系不大。然而，这并不意味着没有效果。气候变化仍然对政治有潜在的影响。例如，饥荒造成的贫困，其主要原因是干旱，可能引发一场政治革命。

6. 脆弱性气候变化耦合模型

6.1 墨西哥气候特征

由于高原和山区众多，墨西哥的气候复杂多样。在大多数地区，分为旱季和雨季。

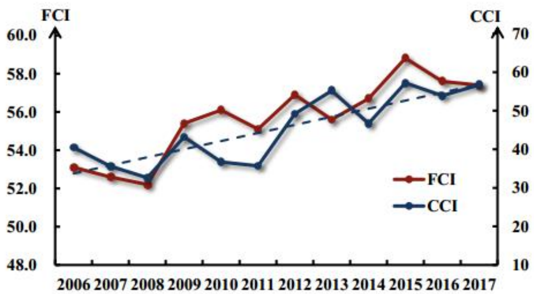


Fig.11 Comparison of Mexico FCI and CCI

图 11 墨西哥 FCI 与 CCI 的比较

In Table 3, it comes to us clearly that *CCI* and FSI show gr
For example, *CCI* has high coefficient with poverty and econ
economic inequality, which represent that the aspect of econon
to the change of climate. And the climate change directly an powerfully changes the economy of one country. For example, the increase of mean temperature would come more droughts, which decreases the grain yield and inevitably reduces the income. However, the richest crowd still take up most of the wealth in the country, so the economic inequality keeps increase.

On the other side, the coefficients with Public services, Human flight and brain drain, Human rights, which belong to the social aspect, are less than that of economy. It is easily to understand. Because, though the influence of climate change on the side of society is significant, the influence is slow and hidden. So the effect on the social aspect needs time to reveal.

Nevertheless, the coefficients with Factionalized elites, State legitimacy, which stand for the politics aspect, are very little. That means the connection between climate change and politics is limited. The main reason is that politics is the result of human subjective initiative, which has little relationship with weather. However, it doesn't mean there is no effect. The climate change still has potential influence on politics. For example, the poverty resulting from famine, whose critical reason is drought, may trigger a political revolution.

6. Fragility-Climate Change Coupling Model

6.1 Climate characteristics of Mexico

Because of the many plateau and mountainous areas, the climate of Mexico is complexed and various. The vertical climate is characterized. In most areas, they can be clarified as drought and rain seasons.

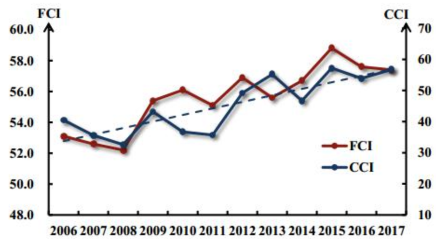


Fig.11 Comparison of Mexico FCI and CCI

如图 11 所示，肯尼亚的 FCI 在 2006-2008 年间迅速上升，随后又出现高水平波动。它以线性趋势线显示。*CCI* 虽然 CCI 水平没有持续上升，但总体趋势是上升，CCI 影响 FCI 指数的增加。

6.2 脆弱性气候变化相关

为了确认气候变化与国家脆弱性的相关性，我们将对 FCI 和 CCI 进行卡方分析。根据 FCI、CCI 的值，我们将得到基础矩阵 M

$$M=\begin{bmatrix} m_{11} & m_{12} & \cdots & m_{1n} \\ m_{21} & m_{21} & \cdots & m_{2n} \end{bmatrix}$$

其中 m_{1j} 表示 FCI $_j$，m_{2j} 表示 CCI $_j$。然后，我们可以计算 χ^2 的值：

$$\chi^2=g\left(\sum_{j=1}^{n}\sum_{i=1}^{2}\left(\frac{m_{ij}^2}{g_2 g_n}\right)-1\right)$$

其中 $g=\sum_{j=1}^{n}\sum_{i=1}^{2}m_{ij}$ ， $g_2=\sum_{i=1}^{2}m_{ij}$ ， $g_n=\sum_{j=1}^{n}m_{ij}$ 。然后得到皮尔逊系数 C

$$C=\sqrt{\chi^2/(g+\chi^2)}$$

C 值越高，气候变化效应与国家脆弱性的相关性越密切。

为了衡量气候变化对脆弱性的影响，我们假设没有气候变化的影响时国家的脆弱性很小。当它受到气候变化的冲击时，脆弱性将迅速增加，以指数形式形成，因此，我们有

$$FCI=r\times\exp(l*CCI+u)$$

其中，r,l,u 是从拟合曲线导出的回归系数。

As is illustrated in the Fig.11, the *FCI* of Kenya rise up rapidly and 2008, and then it fluctuates at a high level. It is displayed trend line of *CCI* that though the level of *CCI* doesn't keep i overall trend is to rise up, and the impact of the *CCI* is to impr *FCI* .

6.2 Fragility-climate change correlation

In order to confirm the correlation between climate change and fragility of the country, we will conduct Chi-square analysis between *FCI* and *CCI* . According to the values of *FCI* , *CCI* , we will have the basis matrix M

$$M=\begin{bmatrix} m_{11} & m_{12} & \cdots & m_{1n} \\ m_{21} & m_{21} & \cdots & m_{2n} \end{bmatrix}$$

Where m_{1j} represents FCI $_j$, m_{2j} represents CCI_j. Then, we can calculate chi-square value χ^2 :

$$\chi^2=g\left(\sum_{j=1}^{n}\sum_{i=1}^{2}\left(\frac{m_{ij}^2}{g_2 g_n}\right)-1\right)$$

Where $g=\sum_{j=1}^{n}\sum_{i=1}^{2}m_{ij}$ ， $g_2=\sum_{i=1}^{2}m_{ij}$ ， $g_n=\sum_{j=1}^{n}m_{ij}$

Then the Pearson's contingency coefficient C comes to us

$$C=\sqrt{\chi^2/(g+\chi^2)}$$

The higher the value of C , the more closely the correlation between climate change effects and fragility of the country.

In order to measure the effects of climate change on fragility, we assume that without the influence of climate change, the country's fragility is very small. When it is shocked by climate change, the fragility will increase rapidly, with the exponential formation, thus we have

$$FCI=r\times\exp(l*CCI+u)$$

where r ,l , u are the regression coefficients derived from the fitting curve.

如图 10 所示，通过分析索马里近 30 年来气候变化影响指数与国家脆弱性的关系，可以看出，当气候变化影响指数增大时，国家脆弱性近似呈现正指数函数关系。估计为：

$$FCI = 21.25 * \exp(0.0636CCI + 0.0014)$$

拟合模型的拟合优度为 0.5317。由于气候是随机的复杂性，结果并不完美，但我们的拟合模型仍然详细阐述了生命现象。那就是当气候变化非常剧烈的时候，这个国家相当脆弱。没有气候变化的影响，CCI 值为 0，FCI 是一个常数。这个国家的脆弱性将如此之小，以至于我们可以认定它稳定或坚不可摧。

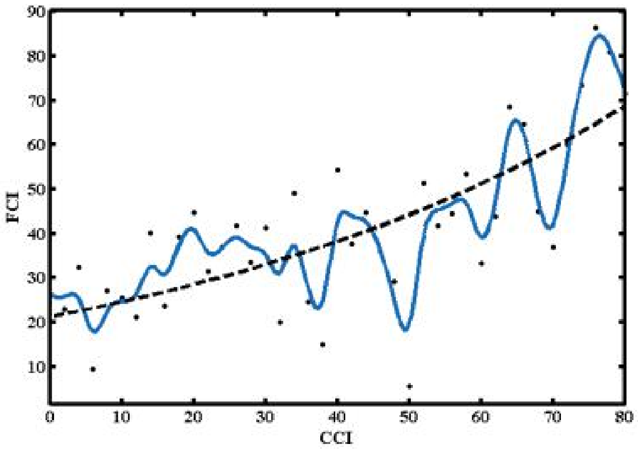


图 10 我们的耦合模型的曲线拟合。蓝线采用三次样条曲线法，黑点线为拟合曲线。

6.3 临界点的定义

气候变化总是存在的，每个国家都或多或少受到它的影响。但是，在气候变化的压力下，并非所有的国家都会沦为“脆弱的”国家。然而，它们中的一些不可避免地转变为脆弱的国家，每一个都经历了“稳定”和“脆弱”之间的转折点。在这一部分中，我们将基于脆弱性-气候变化耦合模型的结论，讨论临界点的定义。

As is shown in Fig.10, by analyzing the relationship bet change impact index and the national vulnerability in the last Somalia, we can see that when climate change impact ind national vulnerability approximately presents positive exponential function, which is estimated as:

$$FCI = 21.25 * \exp(0.0636CCI + 0.0014)$$

The good-of-fit test of our coupling model is 0.5317. The result is not perfect, because climate is random complexity, however, our fitting model still elaborate vital phenomenon. That is when climate change is very intense, the country is rather fragile. Without the effects of climate change, the value of *CCI* is 0 and *FCI* is a constant. The country’s fragility will be so small that we can identify it as stable or impregnable.

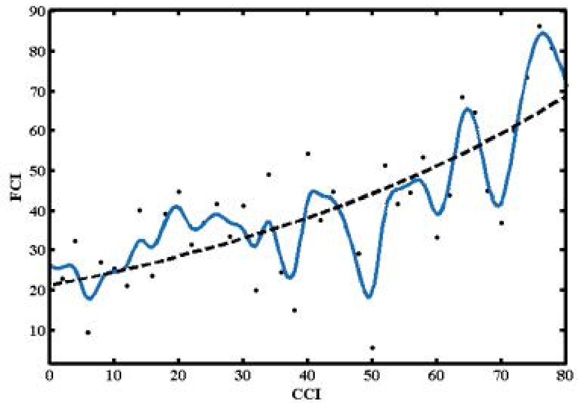


Fig.10 The curve fitting of our coupling model. The blue line is made by the method of cubic spline, and the black dotted line is a fitting curve.

6.3 Definition of tipping point

The climate change always exists and every country more or less is influenced by it. But not all of the country will fall into the ‘fragile’ country under the pressure of climate change. However, some of them inevitably change into fragile country, and each of them has gone through the tipping point between ‘stable’ and ‘fragile’. In this part we will discuss about the definition of tipping point based on the conclusion of Fragility-Climate Change Coupling Model.

首先，很难给出这个国家何时会陷入脆弱国家的确切时间点，但是我们可以了解这个国家即将成为脆弱国家的情况。我们需要做的是说明这个临界点，它由指标的值表示。通过以上讨论，我们可以很清楚地知道，当一个国家的 FCI 下降到 63.29 时，它就进入了脆弱的国家行列。然而，一个国家的关键点不应该仅仅是一个指数，因为当一个方面显示出对一个国家的脆弱性具有危险性时，它可能不会反映在综合指数中，但它确实需要引起注意。因此，我们在表 4 中列出了每个方面的提示点。

表 4 各方面的临界点

综合指标	ERI	*ESI*	SHI	*FCI*
值	71.25	62.15	59.49	63.29

当上述参数的值达到表中的水平时，国家应该对气候变化的影响保持警惕，气候变化的影响已经达到一个较高的水平，国家将进入脆弱国家的行列。

根据 IPCC 的研究，我们可以清楚地看到，世界正在不可逆转地变暖，各种天气灾害的发生更加频繁。基于脆弱性-气候变化耦合模型的结论，可以很容易地得到 CCI 与 FCI 之间的关系。将临界点值代入公式，得出当 CCI 达到 58.72 时，国家经历临界点，应引起高度重视。

利用第二种指数平滑方法建立气候变化预测模型。其公式可以表述为：

$$\begin{cases} S_t^{(1)} = \alpha y_t + (1-\alpha) S_{t-1}^{(1)} \\ S_t^{(2)} = \alpha S_t^{(1)} + (1-\alpha) S_{t-1}^{(2)} \end{cases}$$

其中 $S_t^{(1)}$ 是主指标的平滑值， $S_t^{(2)}$ 是第二指标的平滑值。当参数的趋势显示为直线时，可以采用直线模型：

To begin with, it's hard to give a precise point of time when w fall into fragile country, but we can learn the circumstance th will soon become fragile country. What we need to do is that critical point which is shown by the value of indexes. And fr discussed above, we can fairly know that when one country's FCI drop down to 63.29, it enters the fragile country rank. However, a country's critical point is ought not to be just one index, for when one aspect shows to be hazardous for one country's fragility, it may not be reflected in the comprehensive index, but it really need to be noticed. Therefore, we list the tipping point for each aspect in Table 4.

Table 4 Tipping point for each aspect

Aspect	*ERI*	*ESI*	*SHI*	*FCI*
Value	71.25	62.15	59.49	63.29

When the value of above parameters reach the level in the table, the country should keep vigilant against the influence of climate change, which already goes to a high level and the country would slid to the rank of fragile country. According to the research of IPCC, it comes to us clearly that the world is Irreversibly warming and different weather disasters take place more frequently. Based on the conclusion of Fragility-Climate Change Coupling Model, we can easily get the relationship between CCI and FCI . Substitute the value of tipping point into the formula, we will derive that when the CCI comes to 58.72, the country experiences the critical point, which should be attached close attention to.

We use the second exponential smoothing method to establish the Climate Change Prediction Model. Its formula could be expressed as:

$$\begin{cases} S_t^{(1)} = \alpha y_t + (1-\alpha) S_{t-1}^{(1)} \\ S_t^{(2)} = \alpha S_t^{(1)} + (1-\alpha) S_{t-1}^{(2)} \end{cases}$$

Where the $S_t^{(1)}$ is the smooth value of the primary index, $S_t^{(2)}$ is the smooth value of the second index. When the trend of parameter shows to be straight line, it could employ the straight line model:

$$M_{t+m} = a_t + b_t m \quad m = 1, 2\cdots$$

$$\begin{cases} a_t = 2S_t^{(1)} - S_t^{(2)} \\ b_t = \dfrac{\alpha}{1-\alpha}(S_t^{(1)} - S_t^{(2)}) \end{cases}$$

其中 M_{t+m} 表示 CCI 的值。基于该模型，我们可以预测气候变化的强度，结果显示到 2023 年，墨西哥的 CCI 将迅速增长并超过 58.72，这说明墨西哥已沦为脆弱国家。

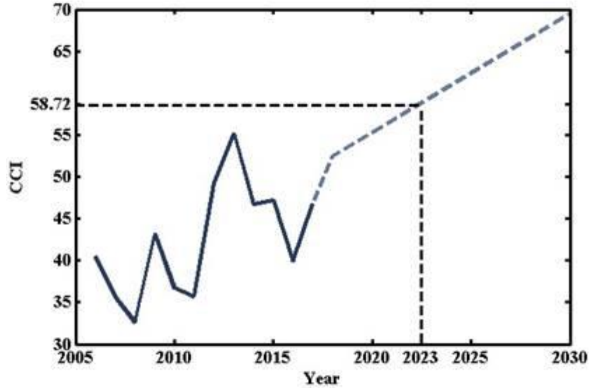


图 12 实际值（2006~2017）和 CCI 预测值（2017~2030）。

7. 人工干预与成本预测

我们的脆弱-气候变化耦合模型反映了气候变化与国家脆弱性的相互作用。如果一个国家稳定或坚不可摧，它就提高了对气候变化风险的抵抗力。这是一个正反馈系统。下一步，我们将提出一些国家驱动的干预措施，以提高应对气候变化的能力，并减轻气候变化的风险。

根据我们建立的 12 个脆弱性指标，我们从暴露、敏感性和适应能力的角度提出了一些干预措施[6]。暴露表明遭受气候变化的国家的压力。敏感性反映了内部系统对气候变化的敏感性。适应能力描述内部系统对气候变化的反应和适应。

$$M_{t+m} = a_t + b_t m \quad m = 1, 2\cdots$$

$$\begin{cases} a_t = 2S_t^{(1)} - S_t^{(2)} \\ b_t = \dfrac{\alpha}{1-\alpha}(S_t^{(1)} - S_t^{(2)}) \end{cases}$$

where the M_{t+m} means the value of CCI . Based on this model, we can predict the strength of climate change, and the result reflects that by 2023, Mexico's CCI will boom and exceed 58.72, which represents that it falls into fragile country.

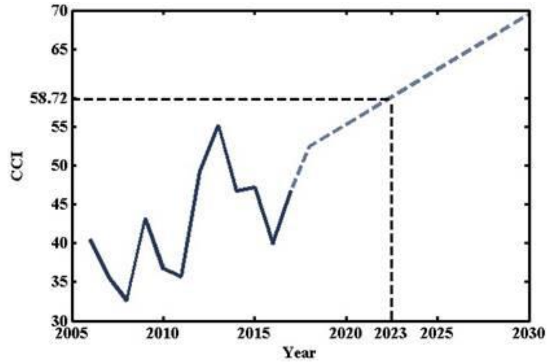


Fig.12 The practical value (2006~2017) and predictied value of CCI (2017~2030).

7. Human Intervention and Cost Prediction

Our fragile-climate change coupling model presents the interaction of climate change and national vulnerability. If a country is stable or impregnable, it raised the resistance of the risk of climate change. This is a positive feedback system. Next, we will propose some state driven interventions which could improve the ability to cope with climate change and mitigate the risk of climate change.

On the basis of our established twelve fragility indicators, we propose some interventions from the perspective of exposure, sensitivity, and adaptive capacity[6]. Exposure indicates the pressure of a country suffering from climate change. Sensitivity reflects the internal system's sensitivity to climate change. Adaptive capacity describes the internal system's response and adaptation to climate change.

（1）经济衰退

加强基础设施建设。水坝或排水系统等基础设施在洪水、暴雨等自然灾害中具有重要价值。这一措施将有效地减少经济损失和人员伤亡。

资源的再利用。发电消耗大量的燃料，导致温室气体排放。资源的再利用将大大减少空气污染，节约能源，减缓气候变化。

（2）生态系统可持续性

提高园艺覆盖率。造林和保护森林可以改善生态系统，抑制侵蚀，抵御沙尘暴的破坏。实施它可以降低对气候变化的脆弱敏感性。

退耕还林。这一措施不仅有利于防洪，而且保护了生态系统，从而提高了国家的生态系统稳定性。

（3）社会可居住性

提高社会保障效益。如果大多数人在受到气候灾害的冲击时都能享受到社会保障福利，国家就会更加稳定，人民之间一定能够和谐相处。

提高基层医疗机构的服务水平。当气候变化冲击时，感染的流行率将迅速增加。有了完善的医疗，我们可以把伤亡降到最低。

因此，我们可以开发干预成本预测模型：

$$TC = ERC + ESC + SHC + TC$$

其中，TC 是人类干预的总成本，ERC、ESC、SHC 是经济衰退、生态系统可持续性和社会可居住性干预的成本，TC 是机会成本。机会成本是我们为了减少国家的脆弱性而放弃的经济发展。

(1) Economic recession

- Strengthen infrastructure construction. Infrastructure like da drainage system values important faced with natural disasters lik rainstorm. This measure will reduce economic losses and casualties efficiently.
- Reuse of resources. Electricity generation consumes enormous fuel, leading to greenhouse gas emissions. The reuse of resources will reduce air pollution and save energy a lot, which slows down the climate change.

(2) Ecosystem sustainability

- Improve the covering rate of gardening. Afforestation and protection of forests can improve the ecosystem, curb erosion, and resist sandstorm damage. Implement of it can reduce the fragile sensitivity to climate change.
- Return arable land to the water. This measure is not only helpful to flood control, but also protect the ecosystem, thus increase the country’s ecosystem stability.

(3) Society habitability

- Improve social security benefits. If the majority of people have access to social security benefits when shocked by climate disasters, the country will be more stable and people get along certainly harmonious with each other.
- Increase the service level for elementary medical institutions. When the climate change shocks, the prevalence of infection will increase rapidly. With the perfect medical treatment, we can minimize casualties.

Thus, we can develop the intervention cost prediction model:

$$TC = ERC + ESC + SHC + TC$$

where TC is the total cost of human intervention, ERC , ESC , SHC are the cost of intervention of economic recession, ecosystem sustainability, and society habitability, TC is the opportunity cost. Opportunity cost is the economy development we give up in order to decrease the country’s fragility.

8. 模型的修正

为了让我们的模型在更小的“州”（如城市）或更大的“州”（如大陆）也可以工作，虽然预测精度将会降低。因此，我们必须提出一些修改来改进我们的模型。

8.1 较小国家

城市温室气体排放主要来源于化石燃料的消耗，化石燃料用于发电、交通、照明等。因此，必须调整模型的权重，以适应城市的实际情况。例如，温室气体排放的重量应该增加。

城市排水系统等基础设施在很大程度上决定了城市的脆弱性。因此，城市脆弱性的指标必须更加详细，如基础设施建设、可再生能源。此外，我们应该考虑国家的宏观调控政策。

8.2 较大国家

至于大陆，其辽阔的土地决定了气候变化将更加复杂多变。作为高纬度地区，预计将考虑融化的冰川和冻土。同时，诸如沃克环流、温盐环流和厄尔尼诺南方涛动（ENSO）等海洋之间的大规模环流是气候变化的主要问题。

非洲大陆的脆弱性也需要改变。由疾病爆发、饥荒或军事行动引起的难民的大规模迁徙可能对该大陆的脆弱性产生重大影响。这些指标的权重不可避免地发生变化。

9. 灵敏度分析

在现实生活中，统计数据常常是不准确的，我们的模型的输入可能存在一些偏差。这些偏差可能影响我们的模型的结果。为了检验模型的鲁棒性，在本节中，我们将分析任务 3 中的气候变化预测模型的敏感性。灵敏度分析结果表明，该模型具有良好的稳定性。

8. Modifications of our model

For the sake of smaller “states” (such as cities) or larger “st continents), our coupling model can also work, while pre prediction will decrease. Thus, we have to propose some modifications to improve our model.

8.1 Smaller states

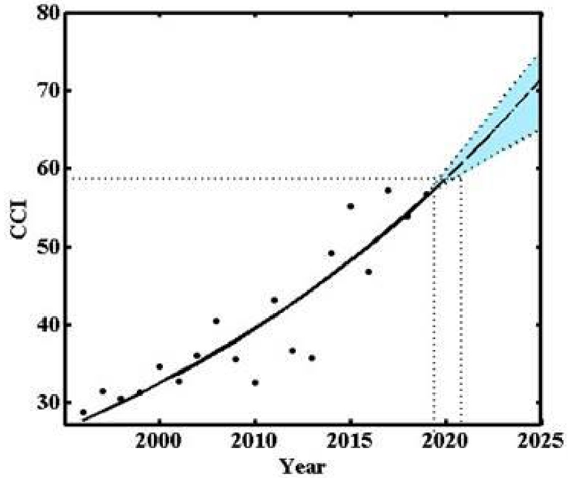
- The majority of greenhouse gas emissions comes from cities result from the consumption of fossil fuel, which used in electricity generation, transportation, lighting, etc. Thus, the weights of our model must be adjusted to adapt to the practical situation of the city. For example, the weight of greenhouse gas emissions should increase.
- The infrastructure like drainage system of a city determine its fragility to a great extent. Thus, the indicators of a city’s fragility must be more detailed, such as infrastructure construction, renewable energy. Moreover, we should take the country’s macro-control policies into consideration.

8.2 Larger states

- As for continents, its vast land determines that the climate change will be more complicated and changeable. As high-latitude areas, melting glaciers and frozen soil are expected to be considered. Meanwhile, large scale circulations between oceans like Walker Circulation, Thermohaline Circulation, and El Niño Southern Oscillation (ENSO) are the major concerns of climate change.
- The fragility of the continent also needs alteration. Mass migration of refugees caused by disease breaks, famine, or military action, may exert great influences on the fragility of the continent. The weights of those indicators change inevitably.

9. Sensitivity Analysis

In real life, statistical data are often inaccurate and there may be some deviations in the inputs of our model. These deviations may affect the results of our model. To test the robustness of our model, in this section, we will analyze the sensitivity of our Climate Change Prediction Model in task 3. The results of the sensitivity analysis explain that our model show a perfect stability.



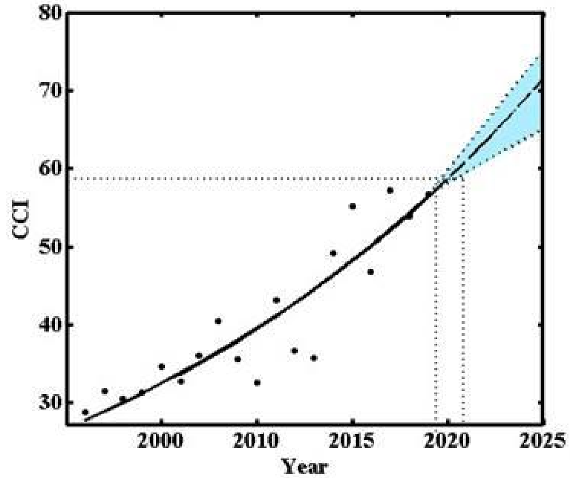


图 13 CCI 随时间的曲线拟合。黑线是拟合曲线，蓝影部分是未来预测的置信区间。

Fig.13 The curve fitting of CCI with time. The black line is a fitting curve and the blue shadow part is the confidence interval for future prediction.

在任务 3 中，我们用二次指数平滑法预测了 2023 年墨西哥的 CCI 将超过 58.72，这表明如果不采取措施应对气候变化，墨西哥将在 2023 年成为一个脆弱的国家。在本章中，我们用曲线拟合的方法对墨西哥的临界点进行了预测，拟合结果表明，在 2020 年，墨西哥的 CCI 超过了 58.72，接近于先前的结果。此外，通过改变 95%置信区间的曲线拟合参数，如蓝色阴影部分所示，我们发现我们的模型仍然稳定，临界点范围从 2019 年到 2021 年。与过去的结果相比，误差在 2-4 年左右，在可接受的范围内。这表明我们的模型的稳定性，可以解决现实生活中的实际问题。

In task 3, we predict in 2023 Mexico’s CCI will exceed 58.72 in the method of Second Exponential Smoothing, which indicate that it will fall into a fragile country in 2023, if not take actions to cope with climate change. In the section, we forecast the tipping point in Mexico by curve fitting, the fitting result show that in the year of 2020, the CCI excess 58.72 close to the previous result. Furthermore, by changing the parameters of curve fitting with 95% confidence bound, as is shown in the blue shadow part, we discover our model is still stable and the tipping point range from the year of 2019 to 2021. Compared with the past results, the error is about 2-4years, which is within acceptable limits. This shows the stability of our model, which can solve practical problems in real life.

10. 优势与劣势

10.1 优势

- 本文建立的脆弱性气候变化耦合模型是基于脆弱性理论和 IPCC 的研究成果，因此相对较严格。
- 基于气候变化的脆弱性指数的结果与 FSI 的选定国家相匹配，这表明我们的模型是合理的和有效的。
- 我们的评价指标是从经济衰退、生态系统可持续性和社会可居住性三个角度来确定的。描述一个国家的脆弱性是全面和客观的。

10.2 弱点

- 忽略全国气候分布的差异，采用全国平均水平描述国家的气候特征，可能降低模型的精度。
- 我们认为，各国对气候变化反应积极，忽视了反应消极的国家，这可能会影响我们的干预成本预测模型。

10. Strengths and Weaknesses

10.1 Strengths

- The fragility-climate change coupling model established i based on the fragility theory and research results of IPCC, thus it is relatively rigorous.
- The results of fragility index based on climate change matches the ranks of selected countries from FSI well, which indicates our model is reasonable and effective.
- Our evaluation indicators are determined from three perspectives: economic recession, ecosystem sustainability, and society habitability. It is comprehensive and objective to describe the fragility of a country.

10.2 Weaknesses

- Ignoring the difference of climate distribution throughout the country, we use the national average levels to describe the country’s climate characteristics, which may reduce the accuracy of our model.
- We argue that all the countries react positively to climate change, neglecting those passive countries, which may exert on our intervention cost prediction model.