Desert Dust Storms: Insurability and Financial Solutions

Andreas Milidonis[1], Marina Solomou[1], Panayiotis Kouis[2], Petros Mouzourides[3], and Marina Neophytou[3]

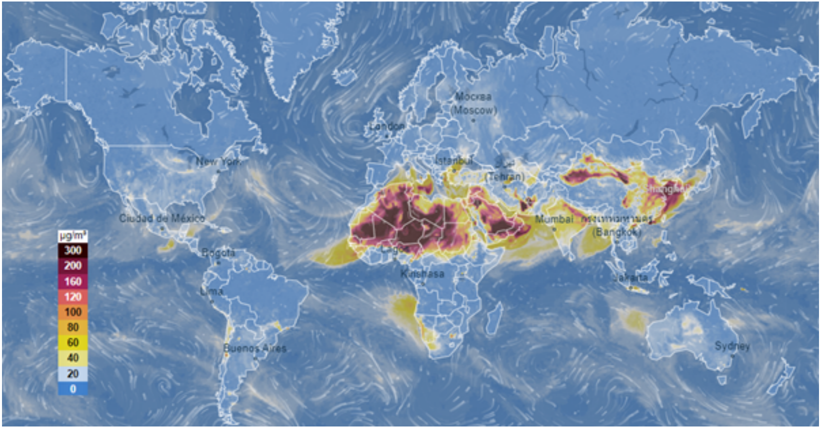
[1]Department of Accounting and Finance, School of Economics and Management,

[2]Respiratory Physiology Laboratory, Medical School,

[3]Environmental Fluid Mechanics Laboratory,
University of Cyprus

Chapter 1

PM_{10} Global Distribution



Source: *https://www.ventusky.com*

PM_{10} Definition and Sources

PM_{10} ***Definition:*** Particulate Matter with an aerodynamic diameter of 10 micrometers (µm) or less. These particles are composed of a variety of materials, such as dust, smoke, pollen, and liquid droplets.

PM_{10} ***Emission Sources:***

Anthropogenic Sources:

- Industrial activity
- Vehicle emissions
- Combustion of fossil fuels
- Construction activities
- Agricultural activities

Natural Sources:

- Desert Dust Storms
- Volcanic eruptions
- Wildfires
- Pollen

PM_{10} Related Risks

Health Risks:

- PM_{10} exposure is one of the five most severe health risks globally (WHO; US EPA)
- Europe's most crucial environmental health risk.
- 96% of EU population exposed to levels above US thresholds.
- Respiratory and Cardiovascular problems
- 330 million people affected in over 150 countries (WMO, 2025).

Economic Risks:

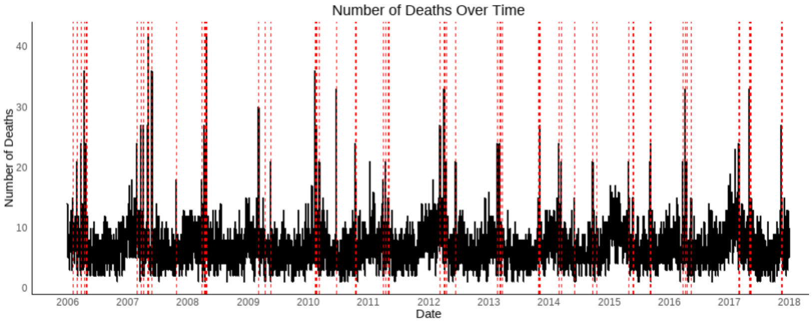
- Agricultural and infrastructure damage.
- Loss of productivity (workplace absenteeism, halted operations).
- Increased healthcare costs.
- Increased Economic distribution, 2.5% of regional GDP in MENA region and US$154 billion in 2017.

Motivation: Descriptive Statistics

According to the World Meteorological Organization (https://wmo.int/):

1. Only 25% of the global dust from Anthropogenic Emissions.
2. About 80% of Global Dust from North Africa and Middle East Deserts.
3. 330 million people are impacted.
4. About 2000 million tons of sand and dust per year.

DDS vs. Daily Number of Deaths



Research Questions

Question 1: What is the impact of DDS on daily mortality and morbidity?

Question 2: Can this natural hazard be transferred to financial markets?

→ We argue that DDS events are insurable and propose some stylized insurance and financial instruments for their mitigation.

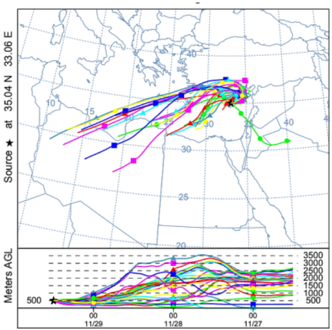
Conditions for Insurability (Kousky, 2019)

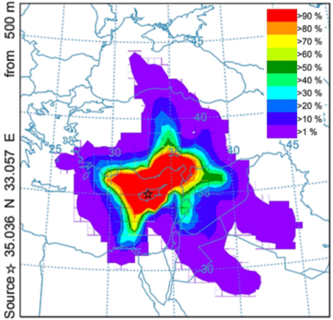
Main Conditions for a Risk to be Insurable:

1. Identifiable and Definable
2. Randomness and Independence (Risk Pooling)
3. Quantifiable (Tail) Probability
4. Minimal Moral Hazard
5. Minimal Adverse Selection

Source: Kousky, C. (2019). Managing Climate Risk in the U.S. Insurance Sector. Environmental Law Reporter, 49(3), 10220-10231.

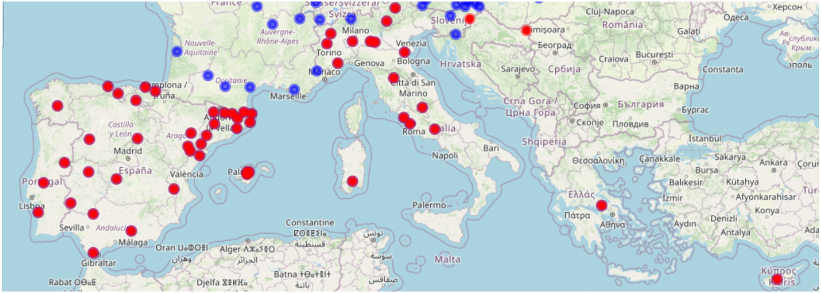
DDS Identification (Cyprus)





- We adopt the DDS methodology proposed by Achilleos et al. (2020).
- Intigrade ground observations, satellite images and satellite Aerosol Optical Depth (AOD) data to identify DDS events, verified using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT).
- A Classification and Regression Tree (CART) logic is applied for the optimization of DDS classification rules based on meteorological data.

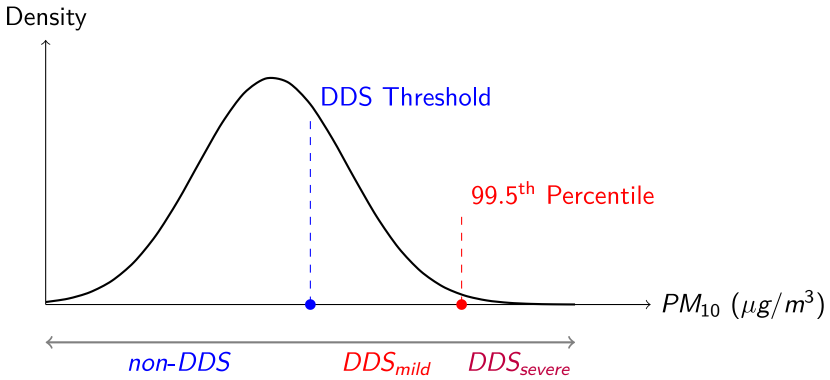
DDS Identification (Southern EU) and RBSs



- **Rural Background Stations (RBSs)**
- **Rural** stations are situated away from urban areas so that PM_{10} measures are not contaminated by anthropogenic components.
- **Background** stations measure the background levels of PM_{10} thus keeping anthropogenic PM_{10} activity to very low levels.

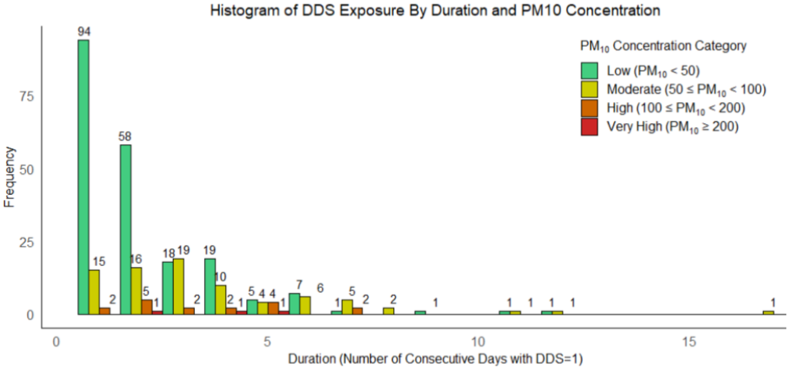
Classification of DDS Events: DDS_{mild} and DDS_{severe}

Definition Based on PM_{10} Concentrations



DDS_{mild}: DDS Threshold $\leq PM_{10} < 99.5^{th}$ percentile.
DDS_{severe}: $PM_{10} > 99.5^{th}$ percentile.

Cyprus: DDS Frequency by PM_{10} level and duration



Cyprus: "DDS day" Indicator by year.

Year	Total Days with DDS=1	Total Average PM10 con. ($\mu g/m^3$)	Average PM10 con. for DDS=1 ($\mu g/m^3$)	Average PM10 con. for DDS=0 ($\mu g/m^3$)	P-value
2007	94	28.082	51.606	19.764	<0.001
2008	134	35.426	60.296	21.061	<0.001
2009	62	27.051	63.218	19.576	<0.001
2010	118	33.486	59.972	20.684	<0.001
2011	38	21.469	49.055	18.204	<0.001
2012	31	19.543	48.551	16.810	<0.001
2013	53	24.776	66.410	17.704	<0.001
2014	49	22.750	53.833	17.884	<0.001
2015	48	22.984	60.665	17.186	<0.001
2016	35	20.140	47.168	17.238	<0.001
2017	48	21.892	56.868	16.405	<0.001

Cyprus: Deaths, Hospitalizations and PM_{10}

	N	*Min.*	*Max.*	*Mean*	*Median*	*Q1*	*Q3*	*Std. Dev*
Dependent								
Total Deaths	3960	0.00	23.00	6.64	6.00	5.00	8.00	2.90
Deaths. I	3960	0.00	18.00	5.44	5.00	4.00	7.00	2.53
Deaths. J	3960	0.00	12.00	1.20	1.00	0.00	2.00	1.18
Total Hospit.	3960	5.00	88.00	33.42	32.00	23.00	42.00	13.60
Hospit. I	3960	0.00	43.00	17.82	17.00	12.00	23.00	7.42
Hospit. J	3960	0.00	61.00	15.60	14.00	9.00	20.00	8.09
Independent								
PM_{10}	3960	2.43	455.78	25.09	20.10	13.69	28.65	25.08
Rel.Hum	3960	14.08	91.56	53.45	55.25	42.83	64.59	14.47
Temp	3960	0.77	35.60	19.77	19.80	13.67	25.89	7.15
DDS	3960	0.00	1.00	0.18	0.00	0.00	0.00	0.38

Generalized Additive Model (GAM)

The impact of DDS on daily deaths and hospital admissions is estimated using the methodology of Liu et al., 2019.

- Applied to model the relationship between DDS and daily counts of deaths and hospital admissions.
- Quasi-Poisson regression used to fit the model.

$$ln(\mu_t) = \alpha_0 + \sum_{i=1}^{p} f_i(X_{t,i}) + \beta DDS_t + \sum_{d=1}^{6} Dow_d + \sum_{s=1}^{3} Season_s$$

- μ_t: Daily count of health outcomes (deaths, hospital admissions).
- β: Effect of DDS on health outcomes.
- Dow_d: Indicator capturing the day of the week.
- $Season$: Indicator capturing season.
- $X_{t,i}$: Meteorological variables (temperature, humidity).

Results for Cyprus

Impact of DDS on daily number of deaths for Cyprus.

Panel A

	Total Daily Deaths		Respiratory		Cardiovascular	
	Estimate	*p*-value	Estimate	*p*-value	Estimate	*p*-value
Parametric Coefficients						
Intercept	-4.438	0.281	-93.513	< .01 ***	14.714	0.001 ***
DDS	0.037	0.036 **	0.105	0.010 **	0.020	0.297
Smooth Terms						
s(RelHum_lag1)	1.001	< .01 ***	1.001	0.251	1.001	< .01 ***
s(Temp_lag1)	5.656	< .01 ***	3.577	< .01 ***	6.427	< .01 ***
Model Fit Statistics						
Adjusted R^2	0.144		0.081		0.110	
Deviance Explained	14.2%		7.18%		10.7%	
n	3820		3820		3820	

Results for Cyprus

Impact of DDS on daily number of hospitalizations for Cyprus.

Panel A

	Total Daily Hospitalizations		Respiratory		Cardiovascular	
	Estimate	p-value	Estimate	p-value	Estimate	p-value
Parametric Coefficients						
Intercept	-57.57	$< .01$ ***	-51.84	$< .01$ ***	-63.81	$< .01$ ***
DDS	0.066	$< .01$ ***	0.087	$< .01$ ***	0.049	$< .01$ ***
Smooth Terms						
s(RelHum_lag1)	6.714	$< .01$ ***	7.776	$< .01$ ***	3.188	$< .01$ ***
s(Temp_lag1)	8.290	$< .01$ ***	7.881	$< .01$ ***	7.863	$< .01$ ***
Model Fit Statistics						
Adjusted R^2	0.462		0.463		0.344	
Deviance Explained	47%		48.7%		33.8%	
n	3820		3820		3820	

Results for Cyprus

Impact of DDS_{mild} and DDS_{severe} on daily number of deaths for Cyprus.

Panel B

	Total Daily Deaths		Respiratory		Cardiovascular	
	Estimate	*p*-value	Estimate	*p*-value	Estimate	*p*-value
Parametric Coefficients						
Intercept	-4.400	0.285	-93.512	< .01 ***	14.782	0.001 ***
DDS_{mild}	0.032	0.073 *	0.105	0.011 **	0.014	0.472
DDS_{severe}	0.161	0.034 **	0.112	0.544	0.173	0.037 **
Smooth Terms						
s(RelHum_lag1)	1.001	< .01 ***	1.001	0.251	1.001	< .01 ***
s(Temp_lag1)	5.837	< .01 ***	3.577	< .01 ***	6.576	< .01 ***
Model Fit Statistics						
Adjusted R^2	0.145		0.081		0.110	
Deviance Explained	14.3%		7.18%		10.8%	
n	3820		3820		3820	

Results for Cyprus

Impact of DDS_{mild} and DDS_{severe} on daily number of hospitalizations for Cyprus.

Panel B						
	Total Daily Hospitalizations		Respiratory		Cardiovascular	
	Estimate	*p*-value	Estimate	*p*-value	Estimate	*p*-value
Parametric Coefficients						
Intercept	-57.56	< .01 ***	-51.79	< .01 ***	-63.84	< .01 ***
DDS_{mild}	0.066	< .01 ***	0.085	< .01 ***	0.051	< .01 ***
DDS_{severe}	0.078	0.030 **	0.155	< .01 ***	-0.000	0.994
Smooth Terms						
s(RelHum_lag1)	6.701	< .01 ***	7.734	< .01 ***	3.190	< .01 ***
s(Temp_lag1)	8.290	< .01 ***	7.888	< .01 ***	7.859	< .01 ***
Model Fit Statistics						
Adjusted R^2	0.462		0.463		0.344	
Deviance Explained	47%		48.7%		33.8%	
n	3820		3820		3820	

Expanding Analysis to Italy

- Coordinates of RBSs were matched with corresponding NUTS-2 codes.
- Only stations with the most populated PM_{10} hourly observations were retained.
- Historical weather data for each NUTS-2 code were obtained via NOAA's API.

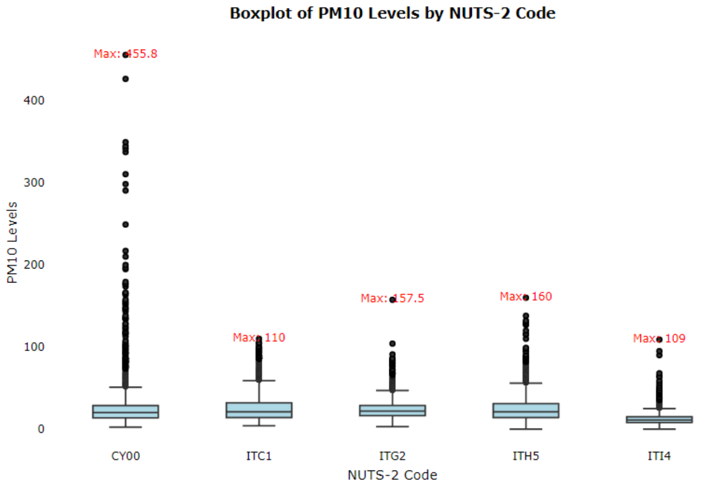
→ Final Sample includes ITG2 (Sardegna), ITH5 (Emilia-Romagna), ITI4 (Lazio) and ITC1 (Piemonte).

→ Captures one quarter of Southern Europe population living in close proximity to RB stations.

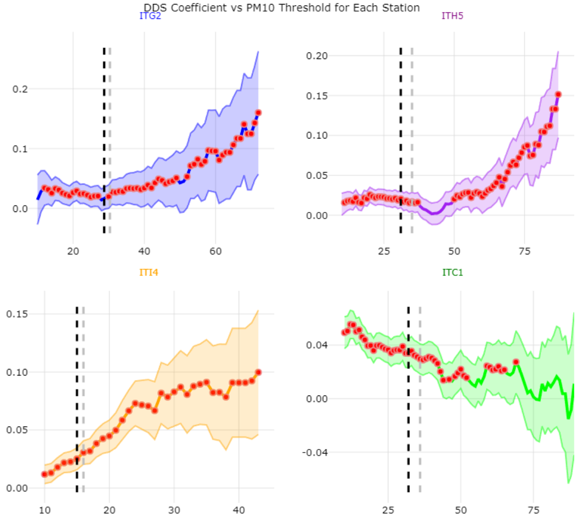
Expanding Analysis to Italy

NUTS-2 Code	Region Name	Population
CY00	Cyprus	875,899
ITC1	Piemonte	4,328,565
ITI4	Lazio	5,773,076
ITG2	Sardegna	1,622,257
ITH5	Emilia-Romagna	4,459,453
Total Sample Population		**17,059,250**

PM_{10} Descriptive Statistics - RBS Box-plots



Results for Italy: Threshold Analysis



Results for Italy

Impact of DDS-proxy on daily number of deaths for Italy.

	ITG2		ITH5		ITI4		ITC1	
	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value
Parametric Coefficients								
(Intercept)	-6.147	0.00550 **	2.595	0.0717 *	-17.84	< 0.001 ***	-5.468	< 0.001 ***
DDS proxy	0.021	0.0390 **	0.017	0.005 ***	0.031	< 0.001 ***	0.030	< 0.001 ***
Smooth Terms								
s(temp_lag1)	8.104	< 0.001 ***	6.548	< 0.001 ***	8.457	< 0.001 ***	7.632	< 0.001 ***
s(RH_lag1)	2.466	0.523	4.508	< 0.001 ***	5.738	0.00607 **	7.140	< 0.001 ***
Model Fit Statistics								
Adjusted R^2	0.262		0.386		0.460		0.408	
Deviance Explained	26.6%		39.4%		47.1%		41.9%	
n	3882		3818		3913		4215	

Results for Italy

Impact of *DDS_{mild}* and *DDS_{severe}* on daily deaths for Italy.

	ITG2		ITH5		ITI4		ITC1	
	Estimate	*p*-value	Estimate	*p*-value	Estimate	*p*-value	Estimate	*p*-value
Parametric Coefficients								
(Intercept)	-5.957	0.007 ***	2.565	0.075 *	-17.83	< 0.001 ***	-5.510	< 0.001 ***
DDS_{Severe}	0.150	0.003 ***	0.139	< 0.001 ***	0.105	< 0.001 ***	0.031	0.265
DDS_{Mild}	0.017	0.098 *	0.014	0.022 **	0.028	< 0.001 ***	0.030	< 0.001 ***
Smooth Terms								
s(temp_lag1)	7.947	< 0.001 ***	6.497	< 0.001 ***	8.426	< 0.001 ***	7.612	< 0.001 ***
s(RH_lag1)	3.495	0.222	4.548	< 0.001 ***	5.497	0.0109 **	7.172	< 0.001 ***
Model Fit Statistics								
Adjusted R^2	0.266		0.390		0.460		0.407	
Deviance Explained	26.9%		39.7%		47.1%		41.8%	
n	3881		3817		3912		4215	

DDS CAT Bond Proposal: Overview & Value Proposition

Proposal: A jointly issued CAT bond by Southern European countries (EuroMed 9), EU climate fund, World Bank, covering all NUTS-2 regions with RB stations.

Value Proposition

- Access to capital market funding for DDS-related health impacts $\rightarrow$ enhances resilience.
- DDS is a diversifying peril for investors—uncorrelated with earthquakes/hurricanes.
- Geographic diversification benefit (Southern Europe) may reduce risk premiums.

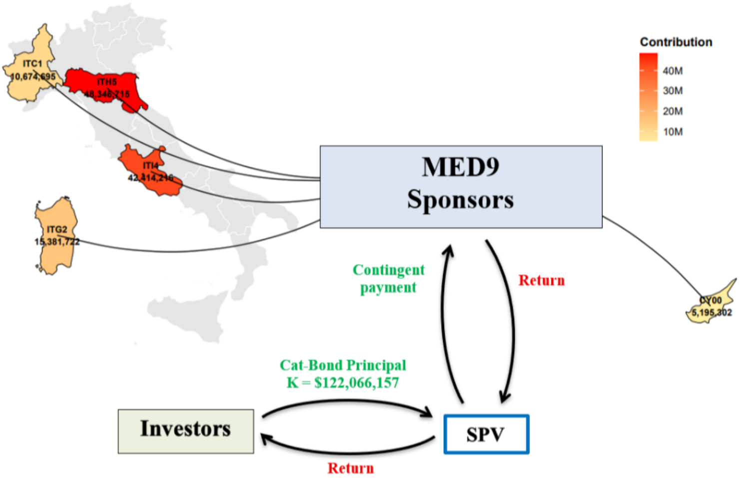
Proposal for a DDS CAT Bond

- **CAT Bond Structure:**
  - Regional CAT bond covering multiple NUTS-2 regions in Southern Europe.
  - Triggered when PM10 $\geq$ 99.5th percentile in any region during a DDS event.
  - Payout linked to economic loss from excess deaths: $\text{Loss}_i = \text{VSL}_i \cdot C_{dds,i} \cdot \bar{d}_i$
- **Principal at $t = 0$:**

$$K = \alpha \sum_i \text{VSL}_i \cdot C_{dds,i} \cdot \bar{d}_i$$

- **Trigger Process:**

$$Y(t) = \frac{\sum_i \text{VSL}_i \cdot C_{dds,i} \cdot \bar{d}_i \cdot \mathbb{1}(PM10_{i,t} \geq \text{PM10}_{99.5,i})}{K}$$


ITC1
10,674,695
ITH5
48,346,715
ITI4
42,414,216
ITG2
15,381,722
CY00
5,195,302
Contribution
40M
30M
20M
10M
MED9
Sponsors
Contingent
payment
Return
Cat-Bond Principal
K = $122,066,157
Investors
SPV
Return

DDS CAT Bond – Payoff and Risk Adjustment

- **Payoff Function:**

$$\Pi(Y_t) = \max\{1 - Y_t, 0\}$$

- **CAT Bond Price (Zero Coupon):** Hybrid framework (Tang Yuan (2019)) with independent financial (Q_1) and DDS risk (Q_2).

$$P_t = \mathbb{E}^{\mathbb{Q}_2}\left[D(t,\tau)\cdot\vartheta\cdot\nVdash_{\{\tau\leq T\}} + D(t,T)\cdot\Pi(Y_T)\cdot\nVdash_{\{\tau>T\}}\right]$$

- **Wang Transform (Market Price of Risk κ):**

$$\tilde{p} = \Phi\left(\Phi^{-1}(p) + \kappa\right)$$

where Φ is the standard normal CDF and p is the natural trigger probability.

DDS CAT Bond: Simulation Steps

- **Step 1:** Estimate regional DDS intensity λ_i and trigger probability p_i
- **Step 2:** Simulate compound Poisson DDS event paths for 365 days across 10,000 paths
- **Step 3:** Apply Wang-transformed trigger probabilities for various $\kappa \in [0, 1]$
- **Step 4:** Compute daily losses per region and subtract from principal
- **Step 5:** Estimate bond price as the expected remaining principal
- **Step 6:** Compute optimal bond return R under risk neutrality:

$$P_0 = \frac{K}{(1+R)^T} \Rightarrow R = \left(\frac{K}{\mathbb{E}[\text{Remaining Principal}]}\right)^{1/T} - 1$$

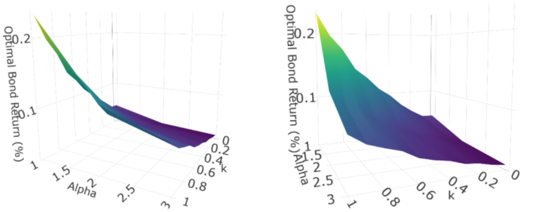


Figure 10 (a):Graphical illustration between the relation of Optimal Bond Return R with $Alpha$ and κ values.

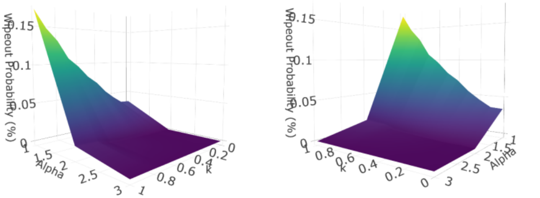


Figure 10 (b): Graphical illustration between the relation of Wipe out Probability R with $Alpha$ and κ values.

Simulation & Return Optimization

Key Results:

- Optimal return $R \approx 17.5\%$ for $\kappa = 0.8$, $\alpha = 1$
- Wipe-out probability: $\approx 13.2\%$

Diversification: DDS CAT bond offers unique risk-return profile with regional and peril diversification benefits.

Conclusion: Key Insights

- **Desert Dust Storms (DDS)** pose a significant risk to public health.
- Findings support the case for **DDS insurability**, as DDS risks quantifiable, identifiable, and diversifiable.
- Propose and price solutions for risk mitigation.
- Price a DDS CAT-bond, across Southern Europe.
- Public policy implications: Current European PM10 air-quality standards may not adequately protect public health during DDS events.

Thank You. Paper below: