Estimating the Damages of Mediterranean Hurricanes

Laura A. Bakkensen*

Abstract

Mediterranean hurricanes, or "medicanes," are powerful cyclonic disturbances that cause wind, flooding, and surge damages around the Mediterranean region. Recent advancements in the natural sciences have improved historical understanding of medicane characteristics. Yet a systematic analysis of the economic impacts of medicanes has not been carried out. In this paper, we analyze 62 years of newly re-analyzed historical medicane tracks to characterize landfalls across space and time. We match historical landfalls with local socioeconomic characteristics. Using a cyclone damages function, we estimate historical medicane losses. We find that Italy suffers the highest expected damages from medicanes at $33 million dollars annually. Scaling by location size, Mediterranean islands are most at risk. We also present findings on landfall characteristics and calculate the return rate for storm damages. These findings are important for policy, especially with regards to medicane warning systems and adaptation decisions for wind, surge, and inland flooding.

JEL Classifications: D81, N54, O1, Q54, R50
Keywords: Economic Damages, Impacts, Integrated Assessment Model, Mediterranean Hurricanes, Natural Disasters

---

*University of Arizona. E-mail: *laurabakkensen@email.arizona.edu.* The research leading to these results has received funding from the Italian Ministry of Education, University and Research and the Italian Ministry of Environment, Land and Sea under the GEMINA project, as well as the Yale Institute for Biospheric Studies. The author sincerely thanks Carlo Cararro, Antonio Navarra, Francesco Bosello, Robert Mendelsohn, Leone Cavicchia, Silvio Gualdi, Emanuele Massetti, and Hans von Storch for valuable assistance and comments. Additionally, the author warmly thanks the Fondazione Eni Enrico Mattei and the Euro-Mediterranean Center for Climate Change for hosting the author and providing technical support during the project.

1 Introduction

Mediterranean hurricanes, commonly known as medicanes, are strong cyclonic wind storms occurring in the Mediterranean Sea. While relatively infrequent, medicanes are destructive nonetheless as 18 countries with more than 126 million in coastal population from three continents boarder the Mediterranean Sea. Additionally, the Mediterranean Sea experiences high cyclogenetic activity, leading to the potential rapid formation of storms (Homar and Stensrud, 2003). However, despite the risks, a systematic analysis of economics damages from medicanes across space and time has not been attempted. Understanding the risks posed by medicanes is fundamental to create better policy and risk reduction strategies.

Medicanes, categorized as mesoscale cyclones, are physically very similar to tropical cyclones. Both types of storms gain strength through vertical heat transfer between the ocean and upper atmosphere. Thus, strong vertical temperature gradients are important (Cavicchia, 2013; Emanuel, 2005). In addition, both types of events produce cyclonic wind patters that, when fully developed, exhibits a well formed eye wall with turbulent wind and clouds rotating outwards in a spiral formation. Winds reaching hurricane force, in addition to storm surge and inland flooding from intense precipitation, can cause harmful destruction. However, given the smaller geographic extent and cooler water temperatures of the Mediterranean Sea relative to tropical waters, medicanes are, on average, shorter lived and smaller than tropical cyclones in other parts of the world.

Reporting in the popular press describes Medicane damages from strong winds, storm surge, and flooding (for example, Masters, 2013; Grieser, 2013). However, no research has systematically analyzed medicane losses across the ocean basin. In addition, as we will describe more fully in the paper (see Section 3.1), no comprehensive, publicly available reporting of historical medicane damages exists. Thus, a major contribution of this paper is to systematically estimate historical damages, thereby calculating relative risk rates across space and time throughout the Mediterranean region.

In this paper, we estimate historical damages to medicanes using a cyclone integrated assessment model. Starting with historical medicane tracks re-analyzed by Cavicchia, von Storch, and

Gualdi (2014), we find points of track landfall and match medicane characteristics at landfall with local socioeconomic characteristics. Using historical damage relationships observed in the tropical cyclone record, we estimate expected damages for medicanes. We are able to characterize historical damages across the Mediterranean region and calculate location specific damage return rates. We find that large wealthy countries suffer the most in terms of aggregate damages, but islands in the central Mediterranean experience the most landfalls once normalized by coastline length. The impact of climate change and sea level rise is left for future work (Romero and Emanuel, 2013; Cavicchia et al, 2014; Pycroft et al., 2015).

There are important policy implications of this work, including the need for real-time forecasts and public warnings of medicane flood and surge risks to better tailor evacuation plans and adaptation strategies. Second, transparent and publicly available data on disaster damages is a crucial next step to better understand these phenomena. While rich data exists to characterize the physical forces of medicanes, the lack of public data on impacts leaves individuals and governments in the dark when making important risk management decisions. Lastly, this work informs public adaptation projects and highlights the return rates of storm damages.

2 Theoretical Foundation

Growing literature exists on natural disaster impacts characterizing loss risks as well as evidence of adaptation to current climate risks (Cavallo and Noy, 2011; Kousky, 2014). Some work examines levels of damages across institutional quality and level of economic development, finding both lead to lower levels of damages, although the relationship is not necessarily monotonic (Toya and Skidmore, 2007; Kellenberg and Mobarak, 2007). Additional work also examines fatalities (Kahn, 2005; Sadowski and Sutter, 2005). More recent work has focused on evidence of adaptation to disasters, including cyclones (Seo, 2013; Fankhauser and McDermott, 2013; Neumayer and Plumber, 2014; and Schumacher and Strobl, 2011).

We base our theoretical foundation on insights from Mendelsohn and Saher (2011) which has been applied to global tropical cyclones (Mendelsohn, Emanuel, and Chonabayashi, 2011a). We extend the theory by applying it to the case of Mediterranean hurricanes (medicanes).

Let D_{ij} be the damages from medicane i in location j. These damages include direct losses to the physical capital and goods including losses to agricultural products and factory inventories, as well as infrastructural damages to buildings, roads, and other capital stock. Note that we do not include human impacts such as fatalities, injury, or psychological harm. We also include neither indirect damages or potential indirect benefits (Leiter et al., 2009), nor long-range impacts from the storm. For example, some storms may trigger unusually high tides in sensitive areas such as Venice, Italy (Camuffo et al., 2000; Robinson, Tomain, and Artegiani, 1973).

Storm damages are determined by both natural and human forces (Pielke, 2005; Pielke et al., 2008). Thus, we assume damages are explained by a vector of characteristics of medicane i at location j, X_{ij}, as well as a vector of local socioeconomic variables, Z_{ij}, in location j at the time medicane i makes landfall:

$$D_{ij} = D(X_{ij}, Z_{ij})$$

We assume damages are greater for a more intense storm, $\frac{dD}{dX} > 0$, (see Emanuel, 2005; Bell et al., 2000; Pielke and Landsea, 1999; Nordhaus, 2010; Mendelsohn el al. 2012). However, changes in socioeconomic characteristics have competing directions of influence on damages (see Bakkensen and Mendelsohn, 2015; Schumacher and Strobl, 2011; and Kellenberg and Mobarak, 2007). For example, increases in the capital stock due to increases in income or population density can increase damages because more is in harm's way. But, increases in the capital stock will increase the marginal benefit of adaptation as there will be higher damages avoided from the same amount of protection. Empirical evidence can show which direction dominates.

Medicane i makes landfall in location j with probability Π_{ij}:

$$\Pi_{ij} = \Pi(X_{ij}, C)$$

which is a function of the intensity of the storm, X_{ij}, as well as the climate, C. Consistent with empirical evidence, the landfall probability in a given location decreases as the strength of the storm increases, $\frac{d\Pi}{dX} < 0$. The impact of climate, C, on storm probability is left for future work.

Finally, we characterize annual damages. The expected annual damages, E[D], for a given region in a given year is the product of individual storm damages multiplied by the probability of landfall in a given area, summed across all storms in set I and sub-locations within region J:

$$E[D] = \sum_{i=1}^{I} \sum_{j=1}^{J} \Pi(X_{ij}, C) D(X_{ij}, Z_{ij})$$

This equation is the foundation for the empirical methodology and results below.

3 Methodology

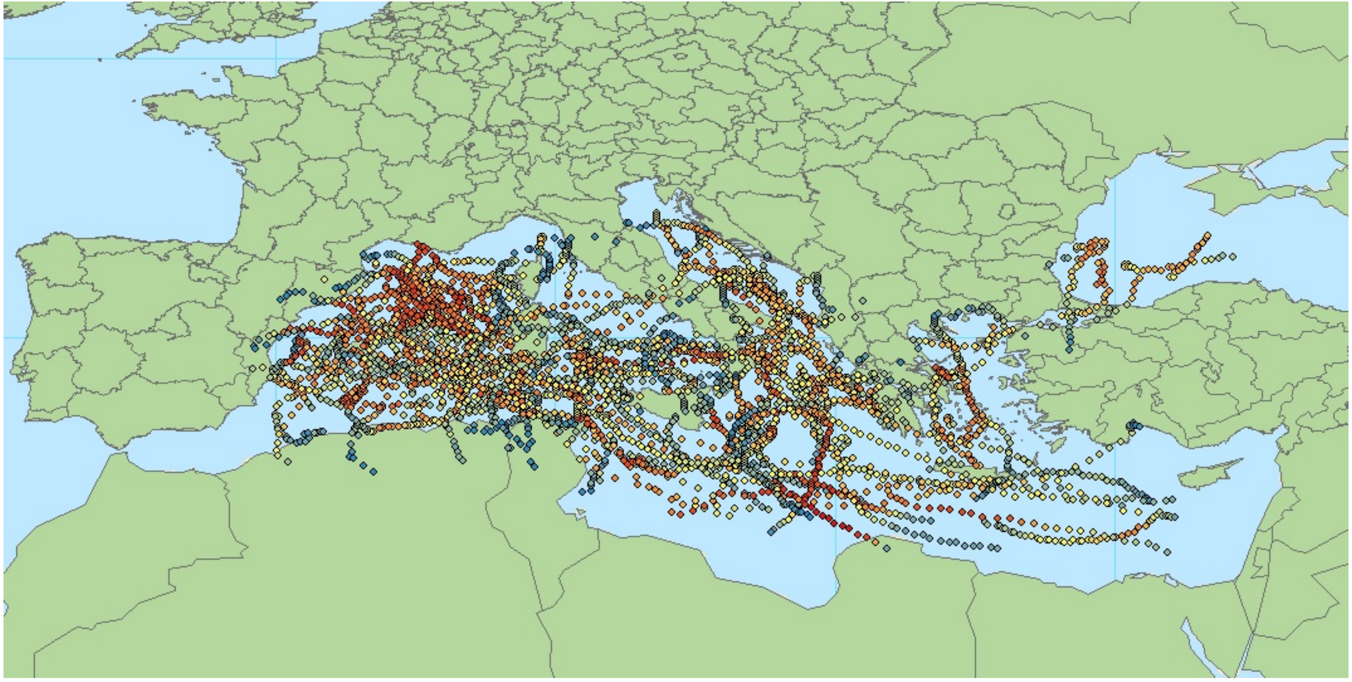
We estimate historical damages for Mediterranean hurricanes (medicanes) for storms from 1950 to 2011 and calculate expected damages for regions across the Mediterranean sea using a cyclone integrated assessment model. There are two parts to the analysis: 1) characterizing historical landfalls and matching them with socioeconomic characteristics, and 2) estimating damages.

First, we characterize historical medicane landfalls. In ArcGIS, we intersect historical medicane tracks from Cavicchia, von Storch, and Gualdi (2014) with coastlines to find points of landfall. See the tracks in Figure 1. The track points are colored by maximum wind speed with weaker wind speeds in blue and stronger wind speeds in red. We identify the points of first landfall of a given storm for each country. However, we allow storms that strike islands to continue on and make landfall on the mainland. Therefore, as is consistent with the real world, each medicane can make landfall multiple times. We also buffer islands with a 50 kilometer radius to catch near misses. After finding points of landfall, we match medicane characteristics at landfall with relevant local socioeconomic characteristics.

Second, we estimate damages for historical medicane landfalls. As no historical data on medicane damages are publicly available (see Section 3.1 below), we cannot estimate a historical damages function directly from medicane data. However, given the close physical similarities between medicanes and tropical cyclones, especially small tropical cyclones, we turn to a rich dataset on tropical cyclones to estimate a storm damages function. We use the following log-log functional form for our damages function:

$$ln\ D_{ij} = \beta_0 + \beta_1 ln\ I_{ij} + \beta_2 ln\ P_{ij} + \beta_3 ln\ X_{ij} + \beta_4 ln\ H_{ij} + u_{ij} \tag{1}$$

Figure 1: Historical Medicane Tracks



where damages from storm i in location j, D_{ij}, is explained by the per capita income of location j at the time of landfall i, I_{ij}, the population density of location j at the time of landfall of cyclone i, P_{ij}, and the intensity of storm i when it makes landfall at location j, X_{ij}. We also control for direct landfall of the storm, H_{ij}, which takes the value 1 if storm i makes direct landfall in location j, otherwise the variable is equal to the distance in kilometers of the storm i's closest approach to location j. Together, per capita income and population density models the capital stock at risk. The estimated coefficient on storm intensity reflects the fraction of the capital stock that is destroyed by changes in storm characteristics.

The damages function is thoroughly tested in Bakkensen and Mendelsohn (2015), using a variety of country and time fixed effects as well as sub-sample regressions for high- and low-income countries. In the end, the above specification was chosen for goodness of fit, parsimony, and applicability. We include two main specifications from Bakkensen and Mendelsohn (2015) in this analysis based on Equation 1. In Model 1, we run Equation 1 using minimum sea level pressure as our proxy for storm intensity (X_{ij}). In Model 2, we use maximum wind speed. We add to the analysis of Bakkensen and Mendelsohn by running two additional Models that focus only on tropical cyclones exhibiting wind speeds and minimum sea level pressures that are also observed across the range of values in our medicane sample, as medicanes are, on average, less intense than tropical cyclones. Therefore, in Model 3, we re-run Model 1 but only include cyclones with minimum sea level pressure above 980 mbar. In Model 4, we include only cyclones with maximum wind speed below 57 knots. Therefore, the damage regression results from Models 3 and 4 are original contributions of this study.

With the above damages function, we estimate damages from each medicane landfall in our sample, based on storm characteristics and local socioeconomic conditions at the time of landfall. We also calculate the expected annual damages for each sub-national region by averaging across landfall damages in our sample. This assumes that the climatology of medicanes was constant over our sample time frame.

3.1 Data

Two types of data are used for this analysis. First, we construct a historical dataset of Mediterranean hurricane (medicane) landfalls matched with local socioeconomic and cyclone control variables. Second, to value the landfalls, we use data on historical tropical cyclone damages matched with affiliated characteristics.

To create the historical medicane dataset, we utilize medicane tracks from Cavicchia, von Storch, and Gualdi (2014). Generated through high-resolution dynamic downscaling of global-scale NCEP/NCAR reanalysis results using the CCLM regional atmospheric model (Rockel, Will, and Hense; 2008), medicane tracks contain the storm latitude, longitude, wind speed, and minimum sea level pressure in 1-hour time steps. All together, there are 100 storm tracks from 1950 to 2011. Local socioeconomic data on per capita income and population density are taken from EuroStat, a product of the European Commission, at the NUTS 2 sub-national level. Complete records are not available in the early years of the sample, thus we assume that sub-national regions remain in the same income and population density positions relative to the EU-27 from 1995-2010. Sub-national population data are taken from the year 2008 from national census records from Algeria, Tunisia, and Libya. No reliable sub-national income records were located for these regions. Characteristics for Albania are left at the country level. We do not include data on Egypt and the Middle East as no landfalls occurred there during our sample. Country-level per capita income and population density records for 1950 to 2011 are from the Penn World Table v7.01. Summary statistics for the medicane landfalls and affiliated local socioeconomic data are presented in Table 2.

To estimate the damages function, we first search for sources of publicly available data on historical medicane damages. We examine EM-DAT, the Emergency Disasters Database. While no events are categorized as "medicane" or "Mediterranean hurricane", we search the database for storm and severe weather reports across the Mediterranean basin and cross-reference results with dates and locations of medicanes from our sample. However, no matches were found. Given that medicanes cause damage but no large losses of life, it is likely that no medicane events meet the database inclusion criterion, based on lives lost, number affected, and declaration of emergency or need for international aid (EMDAT, 2012). Next, we search international disaster event databases including UNISDR's DesInventar Disaster Information System, ReventionWeb's Disaster & Risk Profiles, and the Global Risk Information Platform's Disaster Databases list. We search for any events across the Mediterranean for which English websites are available, but find to event damages for medicanes. We also search online news articles. While fatalities and descriptions of damages are reported, no figures on total economic losses are available. Lastly, we examine replication data from Neumayer, Plumper, and Barthel (2014), who have access to cyclone loss data assembled by the re-insurance company Munich Re. However, no Mediterranean hurricanes are included. Therefore, we conclude that no systematic or comprehensive public data on historical medicane damages is currently available.

As a result, we turn to tropical cyclones and use a dataset created by Bakkensen and Mendelsohn (2015) to analyze adaptation to tropical cyclones. In their analysis, they do not consider medicanes. The database includes more than 1,400 historical storm landfalls between 1960 to 2010. In it, cyclone damage and fatality impacts from EM-DAT Emergency Disaster Database and Nordhaus (2010) are matched with cyclone characteristics from NOAA IBTrACS v03r03, U.S. Navy Tropical Cyclone Reports, and Nordhaus (2010), as well as country-level socioeconomic characteristics from the Penn World Table v7.01, USDA ERS International Macroeconomic Data, the CIA World Factbook, and Columbia CIESIN's Gridded Population of the World v3. Also included are county-level official census socioeconomic data for large countries often hit by cyclones including Australia, China, India, Japan, Philippines, and United States, with Mexico at the state-level. The unit of observation is a country-landfall and not the coarser country-year level as others have done (Neumayer and Plumber, 2014; Noy, 2009; Kahn, 2005). Nations that do not experience cyclone landfalls are omitted from the database, leaving 87 countries included. We present a summary of tropical cyclone landfall characteristics in Table 1. See Bakkensen and Mendelsohn (2015) for a more detailed discussion.

Table 1: Tropical Cyclone Landfall Summary Statistics

Variable	Observations	Mean	Standard Deviation	Minimum	Maximum
Damages (million $USD)	886	826	5,240	0.01	138,741
Income per capita (PPP $USD)	1410	$11,420	$11,994	$374	$67,723
Population density (ppl/km.sq.)	1410	448	1,526	0.01	33,922
Max. wind speed (kts)	1233	66	24	18	141
Min. sea-level pressure (mbar)	1354	972	24	885	1,012

4 Results and Discussion

4.1 Mediterranean Hurricane Characteristics

In this section, we begin by presenting our findings summarizing Mediterranean hurricane (medicane) characteristics at landfall. In the second part of the results section, we present the results of the economic valuation of medicane damages. All together, 86 storms make landfall during the 62-year sample reanalysis period from 1950-2011. A large percent of storms make landfall in at least one country (86%), while 33% of storms make landfall in 2 countries and 5% of storms make landfall in 3 countries.

Summary statistics for landfall characteristics are presented in Table 2. The median characteristics can be compared with those of tropical cyclones in Table 1 in the section above. On the whole, medicanes are weaker than tropical cyclones, as the average maximum wind speed and minimum sea level pressure of medicane landfalls is 36 knots and 1001 mbar, respectively, versus 66 knots and 972 mbar for tropical cyclones in other ocean basins. This is due to factors including cooler water temperatures and smaller surface area of water combined with more land masses in the Mediterranean Sea (Cavicchia, 2013). The relationship has been noted before for medicanes versus tropical cyclones in general and we confirm the relationship also for landfall characteristics. The maximum wind speed observed in this sample at landfall was 56 knots, just shy of Category 1 hurricane strength. We also find that the average per capita income is higher, and population density lower, in locations of medicane landfall versus cyclone landfalls, as Europe tends to have lower population growth and higher incomes than the rest of the world. Medicane landfalls in Africa are characterized by lower incomes and higher population densities, but correspond with a smaller proportion of the total landfall sample. These factors together will characterize medicane landfall damages below.

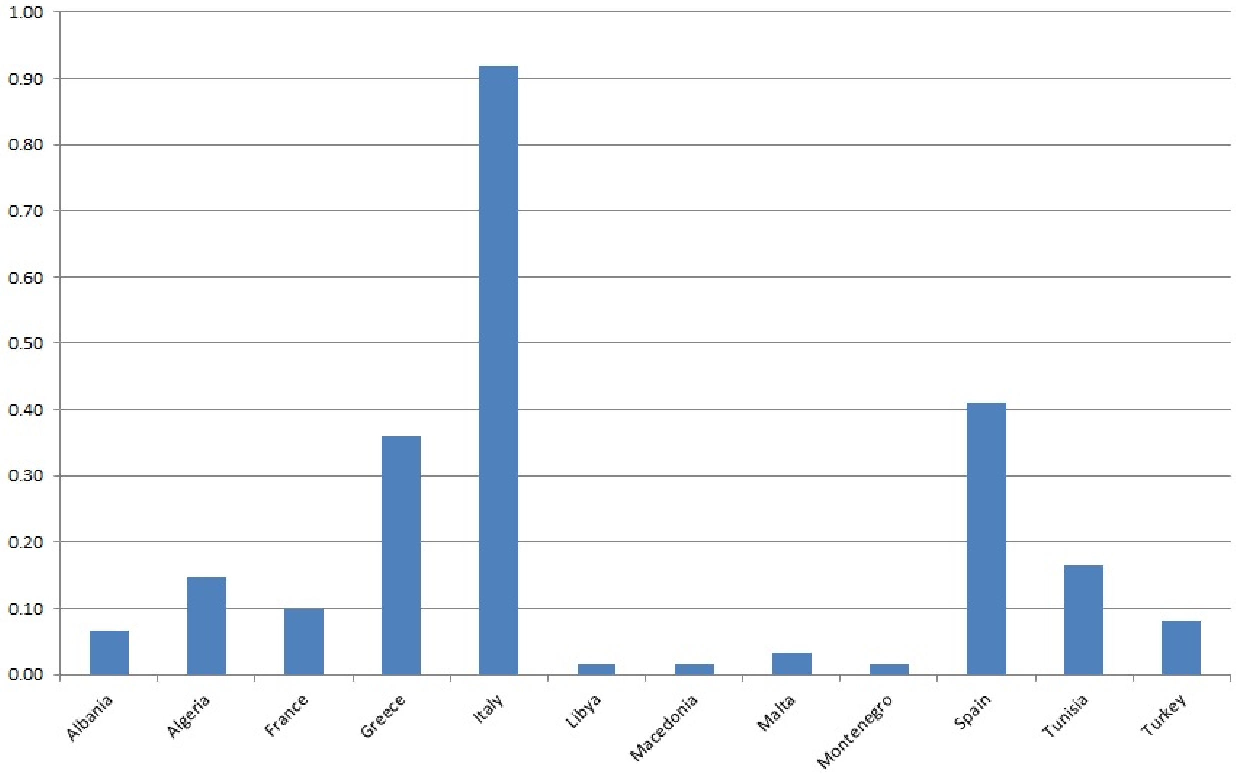
Table 2: Medicane Landfall Summary Statistics

Variable	Observations	Mean	Standard Deviation	Minimum	Maximum
Income per capita (PPP $USD)	142	$12,368.06	$8,667.03	$1,439.45	$36,820.48
Population density (ppl/km.sq.)	142	149.02	219.41	1.08	2016.60
Min. sea-level pressure (mbar)	142	1000.75	7.87	981.60	1023.30
Max. wind speed (kts)	142	36.33	7.93	16.42	56.17

We also consider the geographic distribution of medicane landfalls. Figure 2 tallies the expected number of annual landfalls per country. We see that Italy is hit more frequently, with an expected 0.92 landfalls per year. This is due in part to the fact that Italy has a large coastal surface area both in the Mediterranean and Ionian Seas, where medicanes are commonly found. Spain and Greece are second with approximately 0.41 and 0.37 expected landfalls per year, respectively. Overall, Africa receives only 14 percent of medicane landfalls, although much of the population and productive potential of Algeria, Tunisia, and Libya is centered around the Mediterranean coast. African coastal cities including Algiers, Tunis, and Benghazi remain at risk.

We also consider the sub-national medicane landfall frequencies and present the results in Figure 3. Recall that we allow storms to make landfall on islands and continue on to potentially make landfall on the mainland of the same country. Islands included are the Balearic Islands of Spain, Corsica in France, Crete in Greece, as well as Malta. We consider two Italian islands: Sicily and Sardinia. As we see in Figure 3, there is strong geographic heterogeneity to the distribution of landfalls. Locations hit most often are the Mediterranean islands listed, with approximately

Figure 2: Expected Number of Landfalls per Year



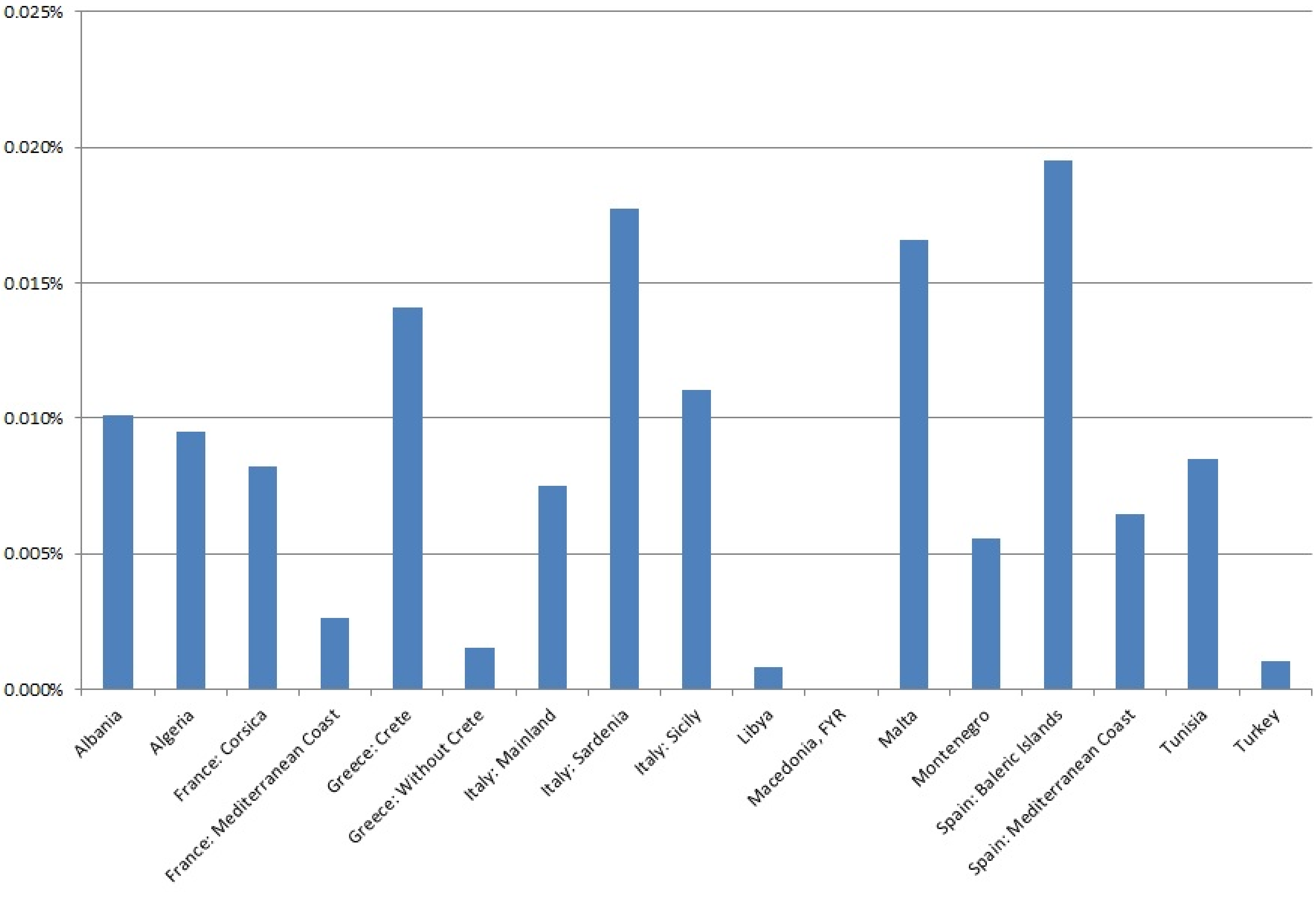
a 33 percent chance of landfall in Sardinia every year. In addition, Southern mainland Italy including Calabria and Apulia are hit approximately once every 6 to 7 years. Cyclones also form occasionally in the Black Sea, striking Istanbul and northwestern Turkey. Note also regions of low landfall activity, including Egypt and the Middle East.

We present annual frequency of landfall scaled by the coastline length in Figure 4. We include results for large islands separate from their mainland country counterparts, as risk rates vary greatly across space. Given this normalization, Mediterranean islands including Malta, Corsica, Crete, Sardinia, Sicily, and Spain's Balearic Islands are at high risk. Note that the probability for Macedonia is zero simply because it is a landlocked country, not because it is not hit. This also assumes that all coastline within a given country or island is hit by medicanes with the same probability. This will overestimate the risk in some areas, such as parts of France and Spain bordering the Atlantic Ocean, while underestimating the risks in other areas bearing more landfalls.

Lastly, we examine seasonality in medicane landfalls. While tropical cyclones are most active

Figure 3: Annual Landfall Frequency

Figure 4: Percent Chance of Annual Landfall per Coastline Kilometer



during periods of warm sea surface temperatures, including June through November in the North Atlantic Ocean, November through April in the Southern Hemisphere, and year-round in the warmer Western Pacific Ocean, medicane landfalls often occur in colder months. While the sea surface temperature is cooler, the vertical temperature gradient is greater in winter than in summer, when both water and air are warm, thereby better facilitating energy transfer from the sea to air typical of tropical cyclones (Cavicchia, 2013). Table 3 shows the seasonality of historical landfalls from 1950 to 2011. Locations more frequently hit also have longest seasons, from September to April in Greece, and September to May in Italy and Spain. Locations in the Adriatic Sea, such as Albania, Macedonia and Montenegro, see storms during the late winter to early spring. African landfalls occur during the fall and winter. No landfalls were observed during July and August.

Table 3: Seasonality of Medicate Landfalls by Country

Country	Landfall Season
Albania	January to March
Algeria	October to December
France	September to January
Greece	September to April
Italy	September to May
Libya	September
Macedonia	March
Malta	September to December
Montenegro	January
Spain	September to May
Tunisia	October to April
Turkey	October to June

4.2 Economic Losses from Mediterranean Hurricanes

Next, we turn to the results of our damages functions and estimated medicane landfall losses. First, we present the results of the damages function. Recall that we include two main damage function specifications from Bakkensen and Mendelsohn (2015). In Model 1, we run our base specification using minimum sea level pressure as our proxy for storm intensity (X_{ij}) and including all cyclones. In Model 2, we use maximum wind speed. We add to the analysis of Bakkensen and Mendelsohn by running two additional Models that focus only on tropical cyclones exhibiting wind speeds and minimum sea level pressures that are also observed across the range of values in our medicane sample, as medicanes are, on average, less intense than tropical cyclones. Therefore, in Model 3, we re-run Model 1 but only include cyclones with minimum sea level pressure above 980 mbar. In Model 4, we include only cyclones with maximum wind speed below 57 knots. Therefore, the damage regression results from Models 3 and 4 are original contributions of this study.

Table 4 displays the four damages functions used in this analysis. We use the Ordinary Least Squares estimator and regress damages on socioeconomic factors and cyclone characteristics. Columns 1 and 2 are regressions with the full sample of historical cyclones in our dataset from 1960 to 2010, with storm intensity proxied by minimum sea level pressure in Column 1 (Model 1) and by maximum wind speed in Column 2 (Model 2). Columns 3 and 4 are identical to Columns 1 and 2, except that since medicanes are physically more similar to tropical depressions, storms, and Category 1 tropical cyclones, we only include low intensity storms in the regression. In Column 3 (Model 3), we use minimum sea level pressure as our intensity proxy and include storms with pressure above 980 mbar, representing the strongest storm at landfall in our medicane sample. In Column 4 (Model 4), we use maximum wind speed in lieu of pressure and only include wind speeds below 57 knots, reflecting the intensity of the strongest storm in our sample based on wind speed. We also use a log-log functional form, so all estimated coefficients can be interpreted as elasticities, or the percent change in damage that would result from a one percent change in the explanatory variable.

We highlight results from the model and compare Models 1 and 2 regression results (from Bakkensen and Mendelsohn, 2015) with our new results from Models 3 and 4. The elasticity of socioeconomic characteristics is less than 1, and very stable across all four models, contrary to what was assumed by previous literature (Nordhaus, 2010; Pielke et al., 2008; Pielke and Landsea, 1998). We find that development and urban density helps to decrease damages through adaptation, since both variables have estimated coefficients of less than one. Similarly, we find statistical significance in the tropical cyclone characteristics, with coefficient signs in the expected direction that more intense storms, with higher winds and lower pressure, are more damaging.

Table 4: Damages Functions

	(1)	(2)	(3)	(4)
VARIABLES	Ln Damages	Ln Damages	Ln Damages	Ln Damages
Ln Income Per Capita	0.447***	0.394***	0.325**	0.285*
	(0.0737)	(0.0760)	(0.130)	(0.146)
Ln Population Density	0.0688	0.0112	-0.00321	0.0207
	(0.0539)	(0.0627)	(0.109)	(0.132)
Ln Min. Sea Level Pressure	-29.48***		-42.44**	
	(3.318)		(21.35)	
Ln Max. Wind Speed		1.808***		0.236
		(0.219)		(0.710)
Ln Landfall Distance	-0.396***	-0.363***	-0.283***	-0.300***
	(0.0373)	(0.0377)	(0.0673)	(0.0744)
Constant	216.7***	7.198***	307.3**	13.73***
	(22.83)	(1.136)	(147.4)	(2.839)
Sample	Full	Full	Pressure $>$ 980	Wind $<$ 57
Observations	856	843	296	269
R-squared	0.223	0.206	0.108	0.087

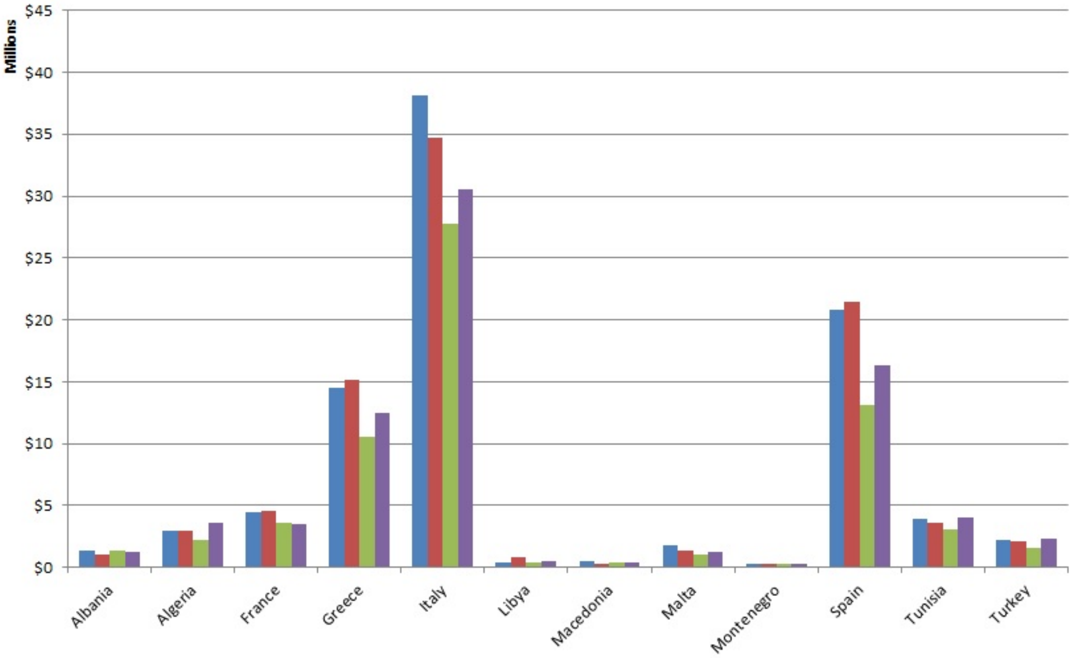
Table 5: Estimated Damages by Model

Model	Landfalls	Mean	Standard Deviation	Minimum	Maximum
Model 1	142	$39,300,000	$16,400,000	$14,400,000	$94,200,000
Model 2	142	$38,000,000	$20,200,000	$7,170,000	$106,000,000
Model 3	142	$28,200,000	$11,300,000	$9,196,000	$63,200,000
Model 4	142	$32,900,000	$7,580,000	$17,100,000	$50,800,000

Also, storms that do not make direct landfall are less damaging. Only the wind speed elasticity is insignificant in Model 4, indicating a weaker relationship between wind and damages at low intensities. Typical inference tests including the AIC, BIC, or Vuong test are not comparable because the underlying data are different across specifications. However, the Vuong test weakly prefers Models 1 and 3 to 2 and 4, respectively. Overall, we prefer Model 1 as our main specification, given the stronger statistical significance and larger sample size. However, Model 3 and 4 better represent cyclones similar to medicanes. We therefore present results across the four models.

Finally, we value all historical medicane landfalls using all four models. Results for the average landfall are presented in Table 5. We find close agreement between models, with the average landfall leading to expected losses of \$34.8 million dollars[1]. Model 2 shows the greatest spread in expected damages, with single landfalls ranging from around \$7 to \$106 million dollars, while Model 3 has the lowest estimated mean storm damages. This is because of the highly nonlinear relationship between pressure and damages coupled with the fact that medicanes have much lower average pressure readings than tropical cyclones, thereby driving down the estimated damages. Since medicanes are allowed to make landfall in both islands and mainlands separately, a single storm could cause higher damages with multiple landfalls.

Figure 5: Annual Expected Damages per Country



Note: Blue bars = Model 1, Red bars = Model 2, Green bars = Model 3, Purple bars = Model 4

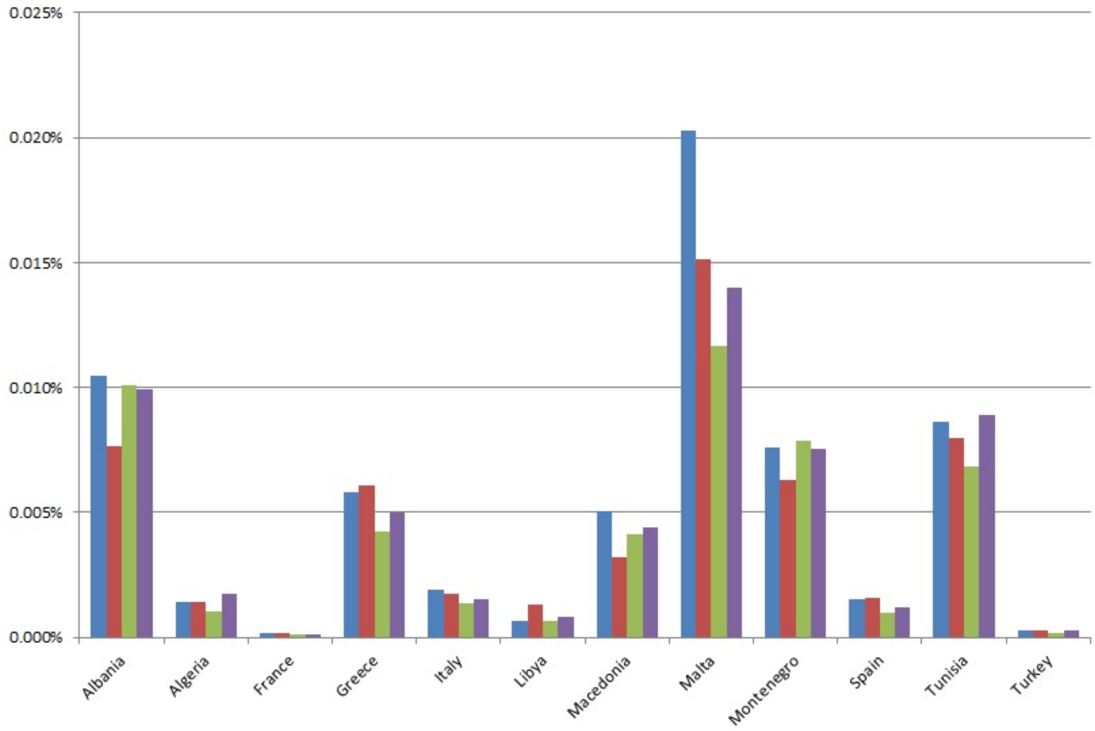
In Figure 5, we represent the average expected annual damages per country. We find that Italy suffers the greatest losses per year, with expected damages of almost \$33 million per year. Spain and Greece are second and third highest, with approximately \$18 and \$13 million per year in losses. These high losses reflect both a higher underlying frequency of landfalls as well as greater capital stock in coastal areas due to development. Much of Africa, as well as Eastern Europe receives relatively less damage due to a lower frequency of landfall and less capital stock in harm's way. Note, however, that medicanes are low probability events and occur with varying

---

[1] All dollar values in this study are real 2010 \$USD scaled by purchasing power parity.

frequency, so the right tail of the damages distribution is long. A single medicane in 2002 made landfall in Spain and Italy, leading to more than $280 million in estimated damages.

Figure 6: Annual Expected Damages as a Percent of Gross Domestic Product

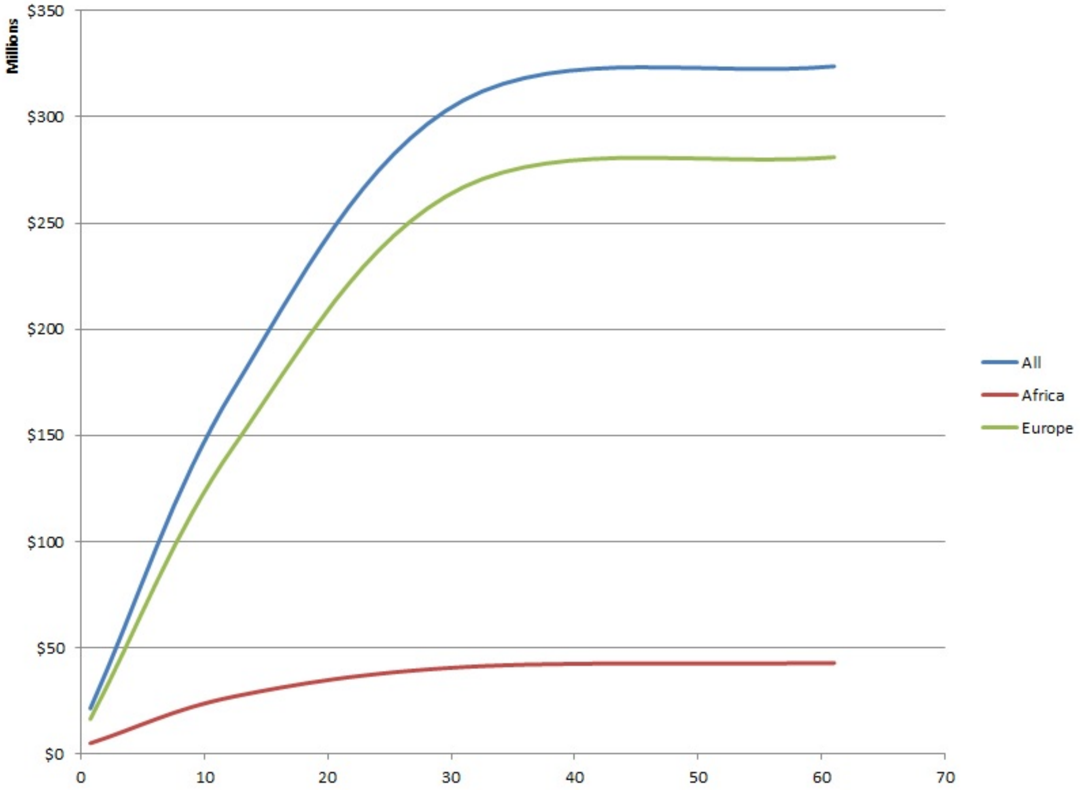


Note: Blue bars = Model 1, Red bars = Model 2, Green bars = Model 3, Purple bars = Model 4

In Figure 6, we scale damages by gross domestic product (GDP) to show the relative magnitudes of medicane losses. Overall, due to the fact that medicanes are relatively rare and low intensity, their losses represent a small fraction of GDP with no more than around 0.02% lost on average per year. But this normalization shows a different risk profile than Figure 5. We see that small and developing countries receive the most damages as a fraction of GDP. Malta losses the greatest fraction of GDP, at approximately 0.015% of GDP. Also at risk are Albania, Greece, Macedonia, Montenegro, and Tunisia. Highly developed European countries including France, Spain, and Italy are relatively less at risk for normalized losses due to their large economies.

Lastly, we calculate a return rate for medicane damages using estimated data from Model 1. Figure 7 shows the rate of return, or the average number of years that passes before a landfall of at least a certain damages level occurs. The red line is the return rate for Africa, the green line represents Europe, and the blue line represents all the Mediterranean basin. Similar to the

Figure 7: The Return Rate for Medicane Damages



previous evidence, we see that the European Mediterranean has a much shorter return rate for a given level of damages. Aggregate levels of damages in Africa are almost five times lower than in Europe due to socioeconomic differences. Also, storms making landfall are slightly weaker on average than in Europe, with a mean pressure of 1004 mbar for African landfalls versus 1000 mbar in Europe. Both these factors together lead to the longer return rate on African storms.

There are several key assumptions of this work that are important to note. First, we assume that the historical damage relationship is comparable between tropical cyclones and Mediterranean hurricanes. Therefore, this analysis is valid only if this assumption holds. Second, we only consider medicane damages from tropical cyclone-like Mediterranean hurricanes, and not extra tropical storm damages from extra tropical Mediterranean storms. While this distinction is important for meteorological purposes, it may be more arbitrary for impact purposes. Lastly, this analysis considers only direct economic damages in the locations surrounding the point of landfall. Given the relatively small size of the Mediterranean basin, longer range impacts from high tides can occur. For example, storms can lead to acqua alta, or high tide, events in Venice, Italy. Thus, these connectivities in long-range damages are not included and left for future work.

There are several important policy implications of this work. First, we call for better disaster records and a standardized accounting scheme to characterize disaster records. Second, given the risk characterization, public policies on medicane warning and evacuation plans are important. Improvements in storm forecasting, especially surge and freshwater flooding, are important. Given medicanes' relatively low intensity, precautionary measures to remove people and protect objects in harm's way can be quite effective. However, unlike tropical cyclones, medicanes occur and dissipate quickly, sometimes lasting only 24 to 48 hours. Therefore, policy decision must be made over short time frames. Lastly, public adaptation is important and complementarities between Mediterranean hurricane and other Mediterranean storms should be exploited to more efficiently prevent some level of damages and fatalities. It is also important for governments to efficiently reduce the negative externality of secondary damages through building codes and zoning regulations.

5 Conclusion

Mediterranean hurricanes, or medicanes, are damaging meteorological events across the Mediterranean Sea. Given recent advancements surrounding historical reanalysis coupled with climate models, we can better characterize current risk rates and expected damages from these storms. In this analysis, we present a systematic estimation of historical losses from medicanes. Taking 62 years of historical tracks, we record points of landfall and match them with spatially refined socioeconomic characteristics. Using knowledge from tropical cyclones, we estimate losses with a damages function. We present results both on the natural science and economic side, characterizing medicane landfalls and affiliated losses across space and time. We find that Italy remains at high risk in terms of aggregate damages, given its large economy and long coastline. Scaling by country size, we find that Mediterranean islands including Malta, Crete, Sardinia, Sicily, and the Balearic Islands sustain the highest frequency of landfalls. Lastly, we calculate a return rate for both Africa and Europe.

This area is ripe with future work. One priority is exploring the impacts of extratropical

Mediterranean storms and their connections with tropical-like medicanes. In addition, better data, both historical and current, can help create location and disaster specific damage functions. Another area of interest is the long-range connectivity in damages as well as a better understanding of the extent of medicane-like storms outside of the Mediterranean. Additionally, the impact of future climate and socioeconomic change is critical, as well as including the impacts of sea level rise. Finally, given that relative risks are characterized, optimal adaptation and risk management analysis remains.

References

Bakkensen, Laura and Robert Mendelsohn (Forthcoming), "Risk and adaptation: Evidence from global tropical cyclone damages and fatalities." *Journal of the Association of Environmental and Resource Economics.*

BBC (2013). Blog post entitled Sardinia hit by deadly Cyclone Cleopatra and floods, accessed on-line at *http : //www.bbc.co.uk/news/world – europe –* 24996292.

Bell, Gerald D, Michael S Halpert, Russell C Schnell, R Wayne Higgins, Jay Lawrimore, Vernon E Kousky, Richard Tinker, Wasila Thiaw, Muthuvel Chelliah, and Anthony Artusa (2000), "Climate assessment for 1999." *Bulletin of the American Meteorological Society*, 81, s1–s50.

Camuffo, Dario, Caterina Secco, Peter Brimblecombe, and Javier Martin-Vide (2000), "Sea storms in the adriatic sea and the western mediterranean during the last millennium." *Climatic Change*, 46, 209–223.

Cavallo, Eduardo and Ilan Noy (2011), "Natural disasters and the economy: a survey." *International Review of Environmental and Resource Economics*, 5, 63–102.

Cavicchia, Leone (2013). Interview on December 2 at the Euro-Mediterranean Center for Climate Change in Bologna, Italy.

Cavicchia, Leone, Hans von Storch, and Silvio Gualdi (2014a), "A long-term climatology of medicanes." *Climate dynamics*, 43, 1183–1195.

Cavicchia, Leone, Hans von Storch, and Silvio Gualdi (2014b), "Mediterranean tropical-like cyclones in present and future climate." *Journal of Climate*, 27, 7493–7501.

CRED, E. (2012), "Em-dat: The ofda/cred international disaster database, université catholique de louvain, brussels (belgium)."

Emanuel, K (2005a), "Genesis and maintenance of "mediterranean hurricanes"." *Advances in Geosciences*, 2, 217–220.

Emanuel, Kerry (2005b), "Increasing destructiveness of tropical cyclones over the past 30 years." *Nature*, 436, 686–688.

Grieser, Justin (2011). Blog post entitled Mediterranean storm brings heavy rain and flooding to Italy and France, accessed on-line at $http://www.washingtonpost.com/blogs/capital-weather-gang/post/mediterranean-storm-brings-heavy-rain-and-flooding-to-italy-and-france/2011/11/09/gIQAim3N5M_blog.html$.

Gualdi, Silvio (2013). Interview on December 2 at the Euro-Mediterranean Center for Climate Change in Bologna, Italy.

Heston, Alan, Robert Summers, and Bettina Aten (2012), "Penn world table version 7.1." *Center for International Comparisons of Production, Income and Prices at the University of Pennsylvania*.

Kahn, M. E. (2005), "The death toll from natural disasters: The role of income, geography, and institutions." *The Review of Economics and Statistics*, 87, 271–284.

Kellenberg, D. K. and A. M. Mobarak (2007), "Does rising income increase or decrease damages risk from natural disasters?" *Journal of Urban Economics*, 63, 788–802.

Kousky, Carolyn (2014), "Informing climate adaptation: A review of the economic costs of natural disasters." *Energy Economics*, 46, 576–592.

Leiter, Andrea M, Harald Oberhofer, and Paul A Raschky (2009), “Creative disasters? flooding effects on capital, labour and productivity within european firms.” *Environmental and Resource Economics*, 43, 333–350.

Masters, Jeff (2011). Blog post entitled Rare Mediterranean Hybrid, accessed on-line at *http : //www.wunderground.com/blog/JeffMasters/sean−rare−mediterranean−hybrid−and−ak − superstorm − forms − quakes − and − t*.

Mendelsohn, R., K. Emanuel, S. Chonabayashi, and L. Bakkensen (2012), “The impact of climate change on global tropical cyclone damage.” *Nature Climate Change*, 2, 205–209.

Mendelsohn, Robert, Kerry Emanuel, and Shun Chonabayashi (2011), *The impact of climate change on hurricane damages in the United States*. World Bank Washington, DC.

Mendelsohn, Robert and Gokay Saher (2011), *The global impact of climate change on extreme events*. World Bank Washington, DC.

Neumayer, Eric, Thomas Plümper, and Fabian Barthel (2014), “The political economy of natural disaster damage.” *Global Environmental Change*, 24, 8–19.

Nordhaus, W. (2010), “The economics of hurricanes and implications of global warming.” *Climate Change Economics*, 1, 1–20.

Noy, Ilan (2009), “The macroeconomic consequences of disasters.” *Journal of Development Economics*, 88, 221–231.

Pielke, R.A. (2005), “Meteorology: Are there trends in hurricane destruction?” *Nature*, 438, E11–E11.

Pielke Jr, R.A., J. Gratz, C.W. Landsea, D. Collins, M.A. Saunders, and R. Musulin (2008), “Normalized hurricane damage in the united states: 1900–2005.” *Natural Hazards Review*, 9, 29–42.

Pielke Jr, Roger A and Christopher N Landsea (1999), “La niña, el niño and atlantic hurricane damages in the united states.” *Bulletin of the American Meteorological Society*, 80, 2027–2033.

Pielke Jr, Roger A and Christopher W Landsea (1998), “Normalized hurricane damages in the united states: 1925-95.” *Weather and Forecasting*, 13, 621–631.

Pycroft, Jonathan, Jan Abrell, and Juan-Carlos Ciscar (2015), “The global impacts of extreme sea-level rise: A comprehensive economic assessment.” *Environmental and Resource Economics*, 1–29.

Robinson, AR, A Tomasin, and A Artegiani (1973), “Flooding of venice: Phenomenology and prediction of the adriatic storm surge.” *Quarterly Journal of the Royal Meteorological Society*, 99, 688–692.

Rockel, Burkhard, Andreas Will, and Andreas Hense (2008), “The regional climate model cosmo-clm (cclm).” *Meteorologische Zeitschrift*, 17, 347–348.

Romero, R and K Emanuel (2013), “Medicane risk in a changing climate.” *Journal of Geophysical Research: Atmospheres*, 118, 5992–6001.

Sadowski, N. C. and D. Sutter (2005), “Hurricane fatalities and hurricane damages: Are safer hurricanes more damaging?” *Southern Economic Journal*, 72, 422–432.

Schumacher, I. and E. Strobl (2011), “Economic development and losses due to natural disasters: The role of hazard exposure.” *Ecological Economics*, 72, 97–105.

Seo, S Niggol (2014), “Estimating tropical cyclone damages under climate change in the southern hemisphere using reported damages.” *Environmental and Resource Economics*, 58, 473–490.

Toya, H. and M. Skidmore (2007), “Economic development and the impacts of natural disasters.” *Economic Letters*, 94, 20–25.