Experimenting with Ash: The Trade-Effects of Airspace Closures in the Aftermath of Eyjafjallajökull

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Abstract

This paper attempts to quantify the effects of a temporary disruption to air transportation on trade using the natural experiment that forced cancellations to roughly one half of all flights originating and/or terminating in Europe between April 15 and April 22. The immediate impact of the disruption to flights was to cause a relatively small (8%) decline in US-bound air freight from Europe. The corresponding elasticity of air freight with respect to flight cancellations was about -0.55. Over the long-term, however, the impact may have been larger due to the persistence of trade, moreover some of the effects of flight cancellations spilled over by affecting air freight volumes between the US and its non-European trading partners. Partially offsetting these effects however were positive impacts on trading relationships, as US importers sourced alternative sources to countries to make up for the loss in European supply.

JEL classification:

Key words: Trade; disruptions; natural experiment; mode of transportation.

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1. Introduction

In 2012, the value of worldwide merchandise exports was roughly $18.5 trillion (WDI, 2014). In other words, nearly a quarter of the world's GDP is trade in goods that is physically transported across international borders. Shocks to transportation networks which deliver the goods can therefore pose significant risks to economies. In recent years a number of natural disasters, terrorist attacks, labor disputes, and other disruptions have caught the attention of a catastrophe-oriented media. There the focus is often on the human or the economic cost of these events on local communities, rather than the impact on trade. However, with increasing trade integration, complexity in supply chain logistics, as well as the adoption of leaner practices such as "just-in-time" inventory management, the flow of goods across borders is the primary conduit for scaling up these shocks so they have global impact. Yet, while the case-study evidence is deceptively convincing,[1] there is little systematic analysis quantifying the effects of disruptions to goods flow. Hendricks and Singhal (2005) is one of a few examples, though there the focus is on the microeconomic impacts of isolated disruptions to supply-chains, rather than the broader macroeconomic effect of a disruption to one or more nodes in the transportation network. To our knowledge, there has been no attempt to empirically assess the "pure" effect of such disruptions. This paper is an attempt to provide some focused answers to two specific questions: what does our recent experience with disruptions to the transportation network tell us about their trade impact? Further, what do these events tell us about the ability of affected parties to react to mitigate the impact of these shocks?

Our attention centers in particular on air transportation and the impact of a disruption to that network on goods trade. Although air freight is only a small fraction of the total tonnage of goods that move across international borders, when the unit of "account" is money, this fraction is much higher. The International Civil Aviation Organization (ICAO) estimates that about 35 percent of the total value of world trade is moved by air. This matches the fraction of goods moved by air in our data set as well. Thus, disruptions to the air transportation network could, in theory, pose very significant risks to countries. Though anticipating our findings, the punchline is quite different—air-based goods trade is surprisingly robust to even large-scale, though temporary, disruptions to major hubs. This could reflect a number of

[1] A classic case study in the literature is the Ericsson case (see Latour, 2001; Sheffi, 2005; Mukherjee, 2008). In 2000, a small fire at a Phillips microchip plant that supplied components to Ericsson, was the proximate trigger that culminated in Ericsson's merger with Sony and its withdrawal from the mobile handset market.

factors, such as increased reliance on other transportation modes or the exploitation of redundancies in transportations networks. One other factor that we suggest as potentially important for mitigating the global impact of these shocks lies in the ability of affected parties to exploit *ex ante,* or *ex post*, diversity in global supply chains.

The literature on transportation has taken a number of different approaches to quantify impacts of disruptions to the transportation network. Of these, simulation methods, such as input-output analysis (I/O) (Gordon et. al., 1998; Okuyama, 2004; Hallegatte, 2008) and computed general equilibrium (CGE) models (Rose et. al., 1997; Rose and Liao, 2005; Tsuchiya et. al., 2007), have received the most attention. Their popularity lies, presumably, in their flexibility in allowing researchers to simulate shocks, though their realism and relevance is often subject to debate.[2] An alternative approach is to utilize data from natural experiments as the basis for estimating the impact of various disruptions. Often the natural experiment utilized is some kind of natural disaster, which is then used to evaluate the impact on trade (e.g. Bluedorn, 2005, Volpe Martinicus and Blyde, 2013; Volpe Martincus, et. al., 2014), as well as other macroeconomic variables (e.g. Horwich, 2000; Kahn, 2005; Barro, 2006; 2009; Raddatz, 2007; Hochrainer, 2009; Noy, 2009).

Unlike simulation-evidence, natural experiments are based on what actually happened, not what could happen in a model economy. As such impact-estimates are often more convincing, aided in no small part by the relative certainty about the *direction* of causality. This is the case even though natural experiments do not offer researchers experimental control over treatment effects, because the treatment itself is plausibly random. However, natural experiments are open to the important criticism that there are often a myriad of conflating influences at play. For instance if our goal is to make inferences about the link between transportation and trade, natural disasters typically do not offer ideal experimental conditions, since they are accompanied by widespread infrastructure damage and dislocation which can affect trade through other channels. Hurricane Katrina is a case in point. Although the storm provided an exogenous shock to the transportation network, the physical damage was not so confined. As a result production (and trade) fell independently of any effects that were a direct consequence of the shock to transportation.[3]

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[2] The I/O approach for instance, is often criticized for being too rigid, in not allowing for optimal supply (or even demand-side) responses to a shock. Moreover, since all changes are real, there is no role for price relations in the economy. By contrast, CGE models which do allow for optimal responses to shocks, are highly dependent on what parameter-values are assigned to key variables.

[3] The devastation caused to the Port of New Orleans, which was closed for seven months, as well as bridges, roads, and other transportation undoubtedly impacted the flow of trade through the Gulf states. However, the post-Katrina decline in trade was not

Unfortunately, measuring and controlling for these confounding influences is difficult. Thus the usefulness of a natural experiment is negatively correlated to the prevalence of these confounding factors, with the ideal case being one where they are absent altogether. Natural experiments fitting these criteria are very difficult to find, though the eruption of the Icelandic volcano Eyjafjallajökull to borrow the idiomatic expression, may just be the hen that had the teeth.

In 2010 the eruption of Eyjafjallajökull caused intermittent disruptions to air traffic for a two month period. This event has a number of characteristics which when combined form the basis for a "clean" natural experiment. First, the event was not associated with physical infrastructure damage or other confounding influences evident in many disaster-centric studies. Second, the scope of the disruption to air traffic was several orders of magnitude greater than any other volcanic eruption during the jet-engine era. During its most disruptive phase, from April 15 to April 22, volcanic ash from Eyjafjallajökull forced closures of much of European airspace, resulting in 107,000 flight-cancellations affecting 10 million passengers (Bye, 2011). Third, like most volcanic eruptions, the eruption of Eyjafjallajökull was largely unpredictable, leaving little time for advanced planning. In fact, the first reference to the eruption in the *New York Times*, for example, appeared on March 26, at which time there was no mention of the potential disruption to air traffic.[4] The first article discussing consequences for air travel appeared on April 15, after the closures of European airspace were already in effect.[5]

Although the punctuation to air traffic was short-lived, the eruption of Eyjafjallajökull provides a unique opportunity to assess the impact of a disruption to air transportation on goods-flow. We use the percent decrease in scheduled flights to recover estimates of the elasticity of imports with respect to these flight cancellations.[6] Our priors were that these estimates would be in the neighborhood of one, i.e., a 100% reduction in air traffic would be mirrored in a 100% reduction in imports originating in Europe. In the absence of close substitutes for moving freight long distances in a timely fashion, this seemed like a reasonable guess. However, our estimates revealed the relationship

wholly, or even necessarily primarily, the result of the diminished transportation infrastructure. Output losses, stemming from the temporary stops in the production and refinement of petroleum, as well as other disruptions, affected the volume of exports and imports of oil and other internationally-traded commodities and goods and services.

[4] Robert MacKey (March 26, 2010). "One Word: Eyjafjallajokull." *New York Times*. Retrieved January 19, 2015.

[5] Nicola Clark and Liz Robbins (April 15, 2010). "Volcanic Ash to Curtail Air Traffic into Midday Friday." *New York Times*. Retrieved January 19, 2015.

[6] We focus specifically on the impact on imports entering the United State. This reflects two considerations. First, Eyjafjallajökull sits below most air corridors between the US and Europe and second information on the mode of transportation are readily available for US data, even when those data are reported at highly disaggregated levels.

between flight cancellations and goods with European provenance to be less responsive. Despite the largest air-traffic shutdown since World War II, over 92% of air freight reached the US market in April 2010. Thus, a roughly 13% decline in flights in April resulted in roughly an 8% decrease in the value of U.S. imports from the affected region. This less than unitary elastic response of European exports to the US market may reflect the temporary and partial nature of the disruption,[7] which allowed cargo to percolate through during the week of flight restrictions as well as provide ample opportunities for airlines to clear the backlog after the restrictions were lifted. Thus, even though the decline in European exports was economically significant, the percent decline in flights during the month of the disruption outstripped the percent decline in European air freight.

Perhaps the more interesting finding, however, has to do with spillovers that affected the matrix of bilateral trading relationships more broadly than those "within the European sub-array". The role played by European airports in facilitating global connectivity meant that the disruption to European airspace had far-reaching effects that affected inter-regional travel between non-European destinations. As a consequence many bilateral trading relationships without direct European ties were also negatively impacted by the volcano. For instance, US-African air freight volumes, though a relatively minor component of US air freight, declined by over 60% in April 2010. Other bilateral trading relationships however benefited from the disruption. In fact, our results suggest that buyers demonstrated downstream flexibility in supply chains by switching to suppliers located in countries unaffected by the volcanic ash cloud. For instance, during the month of the disruption US trading relationships with partners in East Asia and the Pacific strengthened significantly, particularly in those goods for which strong US-European relationships already existed.

The remainder of this paper proceeds as follows. In section 2, we discuss the timeline of the eruption of Eyjafjallajökull, as well as its impact on European airspace. In section 3 we describe our data. Section 4 discusses our empirical approach. In section 5, we present our results. We end, in section 6, with some concluding remarks.

2. Eyjafjallajökull: It's Impact on European Airspace

On March 20, 2010, the Eyjafjallajökull volcano, located on the southern tip of Iceland's eastern volcanic zone, erupted. Over a period of roughly six months, the eruption would progress through a number of stages. The first stage, between

[7] For the region as a whole, the fraction of flights cancelled in April 2010, was close to 13%.

March 20 and April 13 was characterized by a gentle outpouring of lava and the relative absence of explosive activity (Sigmundsson, 2013).[8] Lava reached the surface via a number of fissures on the flanks of the volcano, in the relatively ice-free Fimmvörðuháls pass. This absence of ice and water and the effusive nature of the eruption, ensured that the fallout from the volcano was confined to a relatively small area—about 1.3 km^2 (British Geological Survey, 2010). In fact, during this stage of its eruption, Eyjafjallajökull's footprint was so small, it was known locally as the tourist volcano (Jenkins, 2010).[9]

Following a brief hiatus, the eruption entered its second stage on April 14, with sustained activity until May 22 (Sigmundsson, 2013). This time the eruption occurred at the center of the Eyjafjallajökull glacier, at the caldera. The presence of water vapor in the magma provided the impetus for an explosion that was roughly 20 to 30 times more powerful than its predecessor three weeks earlier. The eruption generated an ash cloud that reached heights of 10 km (Gudmundsson et.al., 2012; Sigmundsson, 2013). Although half of the tephra—fragmental material ejected by a volcano during an eruption—fell over Iceland, the remainder was distributed over a 7 million km^2 area spanning much of Europe and the North Atlantic (Gudmundsson et.al., 2012), resulting in the closure of much of Europe's airspace for a period of eight days and a cancellation of some 107,000 flights.

The eruption of Eyjafjallajökull was certainly not the only incident of volcanic activity to disrupt air traffic. The eruption of Grímsvötn on Iceland on May 21, 2011, sent a plume of tephra 20km into the atmosphere, which resulted in the cancellation of 900 flights between May 23 and May 25 (Learmount, 2011). Later that same year, an ash cloud from the Puyehue-Cordón Caulle volcanic complex in Chile led to airport closures in Argentina and as far afield as Australia and New Zealand (Critchlow and Craymer, 2011). More recently, at the end of May 2014 an eruption of Indonesia's Sangeang Api volcano prompted closure of Darwin's airport in Australia as well as cancellation of a number of flights between Australia and Indonesia, while four Indonesian airports were closed for several days in July 2015 due to an eruption of Mount Raung at the eastern end of the Island of Java. While the ash cloud following each of these

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[8] On the volcanic explosivity index (VEI), the Eyjafjallajökull eruption on March 20 was estimated to be no more than 1 (Jenkins, 2010). The VEI is logarithmic, varies between 0 and 8, and assesses the explosivity by the volume of tephra ejected.
[9] An April 1, 2010 story in The Times of London described the Eyjafjallajökull volcano as a daredevil tourist attraction (Trippier, Edward (2010), "Freezeframe in Iceland," *The Times*, accessed on May 4, 2014, http://www.thetimes.co.uk/tto/travel/images/article2468977.ece).

events often impacted very large geographic areas, the disruption to air traffic was relatively small as most of them occur in sparsely traveled areas. For instance the 900 flights cancelled following the eruption of Grímsvötn represented one percent of total European traffic. By contrast, the interruption of commercial aviation following the eruption of Eyjafjallajökull was orders of magnitude greater. This was not because this eruption was particularly powerful. It was of modest size, as its "explosivity" during phase two measured between 3 and 4 out of 8 on the volcanic explosivity index (Gudmundsson et.al., 2012). However, a number of factors combined to magnify the scope of the disruption to air traffic. These included the fine-grained nature of the ash, which was particularly dangerous to jet engines; the positioning of Eyjafjallajökull directly under an unusually stable south-easterly jet stream, which helped spread the tephra over large areas of North and Central Europe; as well as a zero-ash tolerance policy implemented by the International Civil Aviation Organization after multiple incidents when volcanic ash interacted with jet turbines (Guffanti et al., 2010; Dunn, 2012).

The initial interruption to air traffic lasted eight days beginning on April 15, when roughly 27% of flights were cancelled (Eurocontrol, 2010), and the airspace over Norway was completely shut down (Bye, 2011). The next day the number of cancellations had increased to 60% and the day after the number of cancellations reached 78%. On April 18, the disruption to air traffic reached its peak, with over 84% of flights cancelled. Between April 17 and April 19, 1.2 million passengers were affected each day (Bye, 2011). Over the eight-day interruption to air traffic, about 107,000 flights were cancelled, affecting over 10 million passengers, which represented about 48% of total air traffic during that period. Restrictions were lifted on April 22 after the introduction of new guidelines that raised the safe level of volcanic ash density to 2000 micrograms of ash per cubic meter.

Besides Iceland, three countries were particularly severely affected by air traffic disruptions. Finland was the worst affected followed by Ireland and the UK. In each of these countries over 90% of flights were cancelled over five consecutive days (Eurocontrol, 2010). After the initial eight-day shutdown between April 15 and April 22, some intermittent closures of the European airspace followed as the volcanic ash density exceeded new safety thresholds. Between May 4 and 5 and May 16 and 17 some restrictions were imposed on the airspace over the British Isles. Additionally on May 9, there were partial closures of airports in Austria, Germany, Italy, Portugal and Spain. These closures led to flight cancellations, but not on the scale observed during the first week of closures in April. In total there were about 7000 flight cancellations in May (Eurocontrol, 2010), about 15 times fewer than in April.

By May 22 the eruption of Eyjafjallajökull had entered its third and final phase, which was marked by a steady decline in eruption intensity, interrupted by only a minor explosive event between June 4 and 8 (Sigmundsson et. al., 2011). No more flight cancellations resulted from this eruption.

3. Data Description

3.1. Monthly Trade Data

In our analysis below, the dependent variable is bilateral product-level import data for the US, observed monthly. We use relatively high frequency data, since the disruption to air traffic caused by the eruption of Eyjafjallajökull was short-lived, and its impact is difficult to isolate in annual time series. At the same time, focusing on import-data makes sense, since one of the primary drivers of imports is the level of economic activity in the destination (rather than source) country. Thus, import dynamics are similar whether a product originates in Europe (the treatment group) or elsewhere (the control group). This simplifies the identification problem, but it also means our analysis is silent on the impact of the disruption on US exports to Europe. Our focus on the US can be justified for at least two reasons. First, for the US, information on the mode of transport is available. Second, the US shared strong trade links with Europe. In March 2010, the US was the leading destination for EU's non-European exports, accounting for 24% of all EU exports.

Table 1 - Share of U.S. Import Value and Weight Arriving by Air

Region	Value	Value
Europe affected by the eruption	52.6%	1.5%
Africa	9.9%	0.0%
Middle East	56.2%	0.4%
Central Asia	29.4%	2.0%
East Asia and Pacific	30.1%	1.6%
Americas	44.0%	0.1%

Our data, sourced from the US Census Bureau,[10] are organized according to the 10-digit Harmonized System

[10] These data are available on monthly CDs/DVDs the Census Bureau makes available.

(HS), an internationally standardized system for classifying traded products. HS codes are arranged into 96 2-digit codes or chapters,[11] which are then grouped into 21 sections. We base much of our analysis on the 10-digit classification system. Our sample begins 15 months prior to the eruption of Eyjafjallajökull, in January 2009, just after the dramatic collapse in trade brought on by the onset of the credit-crunch, and ends in December 2011, 18 months after the primary eruption. Crucially, for our purposes, our data specify mode of transportation. In rare cases, when this information was unavailable, the data were dropped. The method of transport is grouped into three categories—air, sea and other. The third category, which refers to goods carried by road and rail, was not available for European imports, hence these data were omitted from our sample. While some 35% of U.S. imports arrives by air, this fraction varies widely by the source of those imports, as is indicated by Table 1, which shows the fraction of U.S. air imports in 2009 by source countries grouped into several regions.

We use the detailed trade data to generate a balanced panel of all country-product relationships that were active in at least one month over our 36-month sample window. Given the level of product detail, the number of observations is large. The data on air freight has nearly 300,000 cross-sectional units, with 9,830,952 observations in total. However, the vast majority of these, about 73%, are zeros. The proliferation of zero observations, reflects the ephemeral nature of trading relationships. In our data, 40% of these relationships were active for less than three months; only 6% were active during the entirety of the 36-month window. This is consistent with an earlier literature on the duration of trade, which shows that the vast majority of trade relationships are short-lived.[12]

Unfortunately, the large numbers of zeros in our data, are for the most part noise. Intermittent trading relationships that were not active during the month of the airspace closures are not informative about the extent to which this disruption impacted trade. Hence attenuation bias in coefficient estimates may be a significant problem, due to the high noise-to-signal ratio. Below we discuss a simple approach for mitigating this issue.

3.2. Flight Cancellations Data

Although the airspace closures from Eyjafjallajökull affected much of Europe, not every country was equally affected.

[11] There are in fact 99 chapters, however chapters 77, 98 and 99, are for special use

[12] For instance Besedeš and Prusa (2013) show that the median duration of a US import relationship is one quarter.

Countries in Southern Europe were impacted to a lesser extent by the airspace closures. Portugal and Spain, for instance operated at least a third of their scheduled flights, even during the height of the disruption. By contrast, a number of countries in Northern Europe were forced to ground all instrument flight rules (IFR) traffic when the disruption was at its peak. Curiously, Iceland was not among the most severely affected countries, having experienced 17% of all flights cancelled in April 2010, less than the 23% experienced by Finland, the most severely affected country. This occurred primarily because Iceland was able to maintain some of its flights to North America. Iceland did experience the longest disruption, however, lasting thirteen days as compared to eight days for all other countries. Given this cross-country variation in the intensity of the disruption to air traffic, a more graded measure, rather than a one-zero indicator differentiating treatment and control countries, is the appropriate RHS variable in this case. Here, we use data on flight cancellations to measure this cross-country variation in the intensity of the disruption. These data were obtained on a country-by-country basis from *Eurocontrol*—the European organization responsible for air traffic management (Eurocontrol, 2010). These data, which are estimates of the number of flights cancelled relative to the number of flights scheduled, are reported on a daily frequency over the eight-day long interruption beginning on April 15 and continuing into April 22. However, for our purposes we use the average of the fraction of flight cancellations over this eight-day period normalized by 3.75 to express the intensity of the disruption relative to the monthly "quota" of flights to match the frequency of our trade flow data.

It is important to note these data do not provide separate numbers for cancellations of outgoing vs incoming flights or overfly flights. The data report the fraction of all flights cancelled, irrespective of the nature of the cancelled flight or its operator. This should not be a problem for our identification purposes as the airspace closure affected all flights, both commercial passenger flights as well as commercial cargo flights. Additionally, there are no data, at least on a country-by-country basis, specifically on the number of transatlantic or US-bound flight cancellations. Our more aggregate measure of the fraction of flight cancellations is therefore an approximation of the intensity of the disruption, as it would have impacted US-European trading relationships.

4. Results and Methodology

4.1. Methodology

Central to our research design is the eruption of Eyjafjallajökull, which provided a large and exogenous shock to the air transportation network. Specifically, we calculate the difference-in-differences in import valuations between treatment and control groups prior to and in the aftermath of the volcanic eruption. Formally, our empirical strategy is organized around variations of the following two-way fixed-effects model:

$$m_{i,j,k,t} = \mu_{i,j,k} + \tau_{i,t} + \beta I_{k,t} + \varepsilon_{i,j,k,t} \qquad (1)$$

Here $m_{i,j,k,t}$ is the log of the volume of imports of products in HS category i, from country j, shipped by mode of transport k, at time t; $\mu_{i,j,k}$ is a product-country-transport mode fixed-effect; $\tau_{i,t}$ is a product-specific time effect; and $I_{k,t}$ is an indicator variable that assumes the value one, if the method of transport, k, is air and t is equal to April 2010. Note that the indicator $I_{k,t}$ identifies the treatment group, and the coefficient, β, quantifies the impact of the treatment on that group.

In the absence of a randomized control group, unbiased estimation of β hinges on how well the control group "reconstructs" a counterfactual in which the airspace restrictions never happened and goods, between Europe and the US, flowed normally. Although we cannot observe this counterfactual, we can form a best guess for the hypothetical variation in air freight absent the disruption. One way to accomplish this would be to use data for countries whose air routes were unaffected by airspace restrictions. Unfortunately, it is difficult to find countries that were completely unaffected by the disruption to the European hub. In part this stems from the important role that European airports play as international gateways for non-European traffic. Thus for instance, Heathrow is Mumbai's primary gateway to the world; when it closed, the effective distance between Mumbai and airports located all over the world increased. In particular distances to North America increased by about 40% (Woolley-Meza et. al., 2013), possibly affecting the cost of airfreight between India and the US. But even where Europe did not serve as a transit point for North American traffic, air freight to the North America continent may have been impacted—if not negatively, possibly positively. The possibility of these types of effects is discussed in section 4.4.

Here instead, we use data on the volume of maritime-based trade to build a control for European air freight in the post-intervention period. In doing so, implicitly we are making two assumptions. First, that sea freight was unaffected by the disruption to air traffic, i.e., sea freight was "untreated," and second, that the first difference in the volume of air freight absent the treatment and the first difference in the volume of sea freight are equivalent.

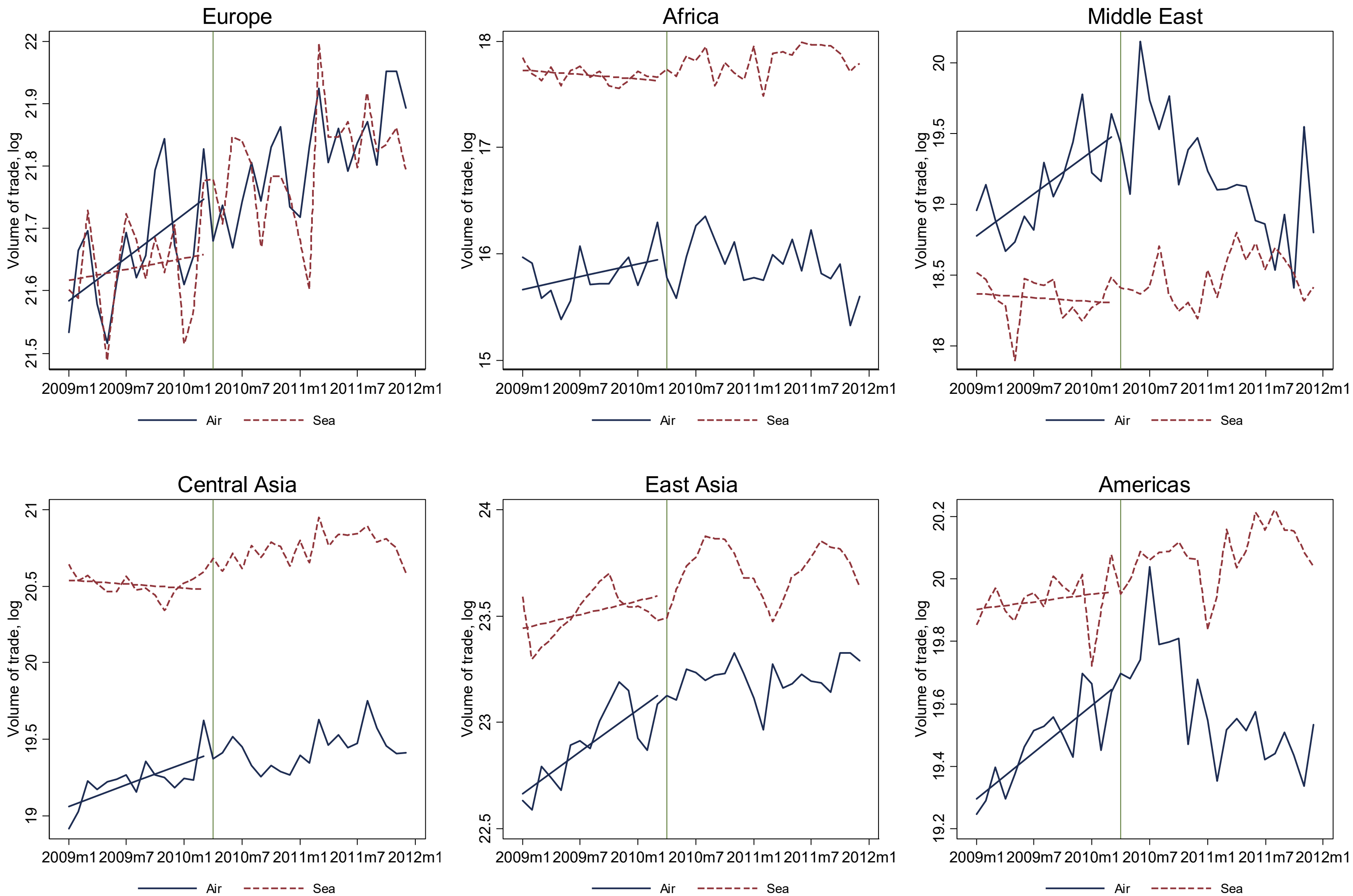
Unfortunately, there is no way to test either of these assumptions. Without observing the counterfactual we cannot know for sure whether sea freight was affected by the disruption to air traffic. It is conceivable that distributors re-routed air cargo by sea, however this seems unlikely given the ephemeral nature of the disruption. At the same time, it is impossible to know for sure if the trend in sea freight post April, 2010, identifies the hypothetical variation in airfreight, absent the volcanic eruption. We can, however, compare air- and sea-freight volumes in the months prior to the eruption, and in the event that the variation in sea freight is found to mirror the variation in air freight, we would certainly be more confident in our assumption. In fact, Figure 1, which plots the monthly totals of US imports originating from affected European countries for each mode of transportation, suggests a strong correspondence between control and treatment groups during the pre-eruption phase, giving credence to the choice of sea freight as the control group.

Below we consider two specific strategies for constructing our controls. The first, utilizes data on changes in the volume of sea freight, for any given product-country pair, to proxy for the counterfactual variation in the corresponding volume of air freight. This approach is simple, but it attaches no weight to sea-based imports from other countries when developing these counterfactuals.

Our second approach, does utilize these data. Specifically, for every product-country pair, we construct a control group as a weighted average of sea freight from all countries for which data are available in the months preceding the disruption. This approach is similar to the synthetic control method developed in Abadie and Gardzeabal (2003) and Abadie et. al. (2010). There are however some methodological differences with the approaches outlined there. In Abadie and Gardzeabal (2003) and Abadie et. al. (2010), a synthetic control is constructed by comparing the characteristics of a treated unit, with the characteristics of untreated units in the pre-treatment period. These characteristics are predictors of the outcome variable that are orthogonal to the intervention. An analogous approach would entail "comparing" data on a vector of predictors for the volume of air freight across countries and constructing an optimally weighted average of air freight in unaffected countries to develop a synthetic match. This is simply not feasible for a number of reasons. First, given the highly disaggregated nature of our LHS variable, data limitations are quickly a binding constraint. In fact, the only predictor of air freight for which data are available across a large number of country-product pairs is the volume of sea freight. Second, and perhaps more importantly, for reasons that we made clear above, the assumption that air freight was unaffected, even in countries outside the geographic footprint of the ash cloud, is simply a bad assumption.

Here we take a different approach. For each product-country pair $(i, \bar{j})$ in our affected sample, we take the weighted average of shipments by sea from all countries with positive shipments of product i to the US in every single

Figure 1 - Parallel Paths Assumption in U.S. Imports by Region and Mode of Transportation



month between January 2008 and December 2011, including shipments from country $\bar{J}$.[13] Thus data on maritime shipments serve as both the predictors of air freight and the controls on which we construct our weighted synthetic. These weights are chosen so that the synthetic control matches pre-intervention air freight data from the treated country, $\bar{J}$, as closely as possible, ie., we choose the weights so as to minimize the following quadratic:[14]

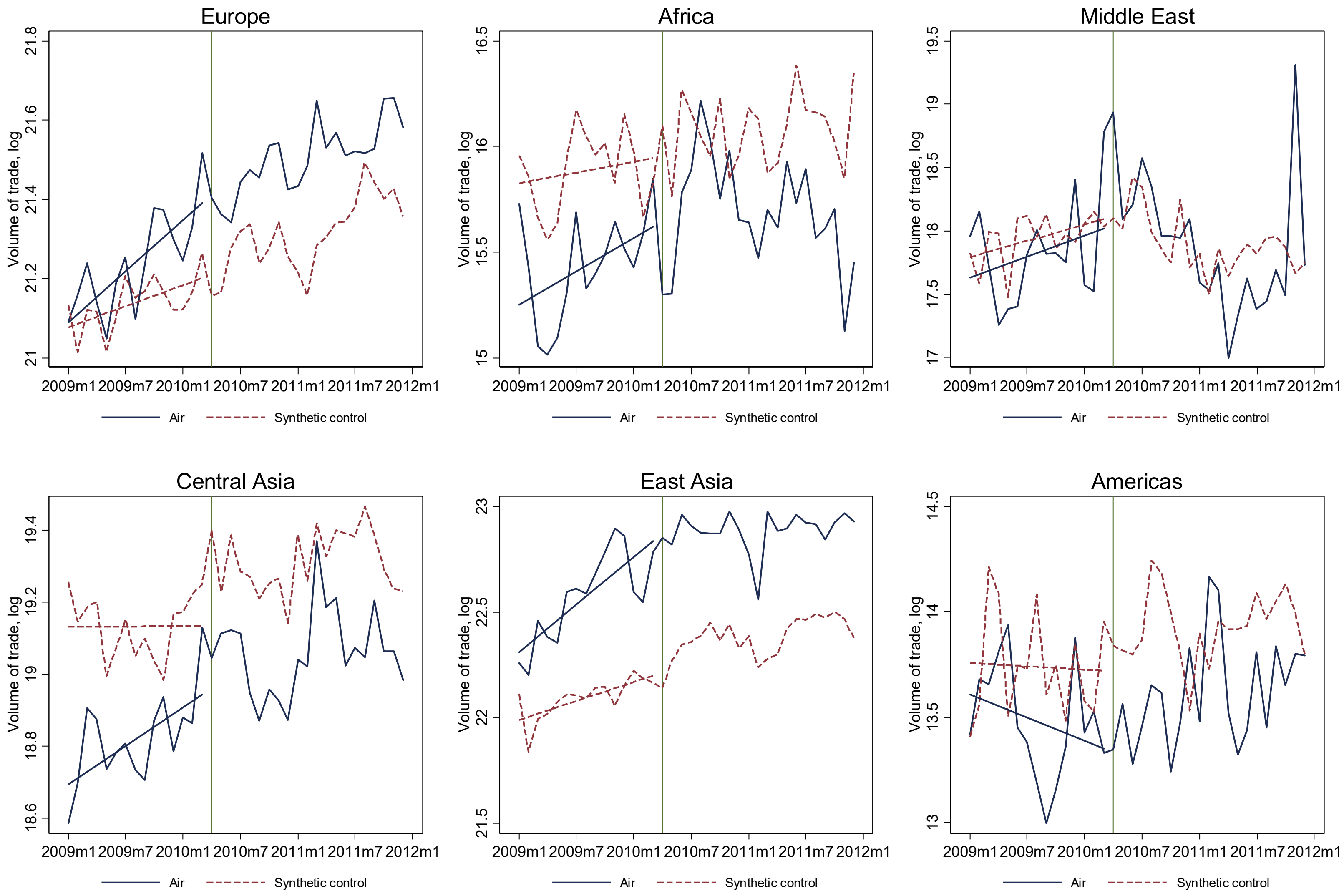
$$\sum_{t<t_0}\left(m_{i,j,\text{air},t}-\sum_{j}\omega_j m_{i,j,\text{sea},t}\right)^2$$

Here $m_{i,\bar{J},\text{air},t}$ is the log of the volume of imports of products in HS category i, from country $\bar{J}$, transported by air, at time t; $m_{i,\tilde{k},\text{sea},t}$ are (the log of) maritime-based trade flows of the same product from each country, j, with positive shipments, including the treated country, $\bar{J}$; ω_j are non-zero weights that sum to one; and t_0 corresponds to the date of the treatment. Figure 2 displays the total air imports by region and the total synthetic control imports across the regions computed by this method.

Before proceeding to a discussion of the results, we will make some remarks on the estimation procedure, which are merited. Although in theory estimating equation (1) is straightforward, in practice its estimation can pose computational challenges, when the number of panel units is large. For instance, when imports are measured at the 10-digit HS product level, there are, in some specifications, close to 46,000 product-country-mode fixed effects, $\mu_{i,j,k}$, in our air freight data. The number of product-specific time effects, $\tau_{i,t}$, is similarly large. In the European sample alone, the number of dummies needed to incorporate a *product-specific* time effect is close to 500,000. Although a simple transformation can purge the $\mu_{i,j,k}$'s (or $\tau_{i,t}$'s) from the data, the memory requirements necessary to handle the other time- (or fixed-) effect dummies can be daunting.

[13] We need to extend the time window for this calculation as we will be using AR lagged terms of the volume of imports in 2009 necessitating that we compute the synthetic control volume of imports in 2008 as well. Since the synthetic control can only be computed for a positive observation of the treated group, we apply the same condition on the source of synthetic control group requiring that a country's sea exports to the U.S. can be a part of the synthetic control only if it exports the product in question by both air and sea in every single month between January 2008 and December 2011.
[14] Thus in effect we are regressing air freight against sea freight data in a number of countries, including, most importantly, the affected country.

Figure 2 - Parallel Paths Assumption in U.S. Imports by Region, for Treated and Synthetic Control Groups



Fortunately, in recent years a number of advances in the estimation of high-dimensional two-way fixed-effects models have reduced these memory requirements considerably (see McCaffrey et. al., 2012, for a review). One simple, but elegant, approach to this problem (which can be extended to three-way fixed effect models), proposed in Carneiro et al. (2012), entails initially sweeping away one of the fixed-effects (by removing the group means) from the data and then iteratively refining estimates of the model parameters (both the fixed-effects as well as the β's). This latter step is accomplished by regressing import volumes, $m_{i,j,t}$, (as well as a certain transformation of these data) on the slope variable, $I_{k,t}$, and as result is not impacted by the dimensionality of the matrix of dummies. This approach, which we adopt, imposes minimal memory requirements (for more details see Carneiro et. al., 2012).

4.2. *Initial Results: Air-Based Exports Remain Robust Despite the Shock to Air Traffic Network*

We begin by presenting baseline estimates of the effects of the volcano on trade flows. At this stage, we focus only on the impact on exports (to the United States) of countries that instituted restrictions to their airspace, and/or countries for whom data on flight cancellations were available. This included much, though not all, of Europe. Most notably absent from our sample is Russia. Though the ash cloud did reach parts of Russia, Russian airports did not cease operations, despite numerous delays and flight cancellations.[15] Unfortunately, accurate data on these cancellations over the eight-day period were unavailable, hence Russia was excluded from our analyses. In addition to restricting our sample to affected countries, we impose the mild restriction that trading relationships were active in both modes of transportation—air and sea—for at least one month in the 15 months prior to the eruption of Eyjafjallajökull.[16] The resulting sample is composed of over 1.65 million observations.

On the basis of these data, we find that, in April 2010, the volume of US-bound air freight, from the affected region, declined by less than 5% [Table 2, column (1)]. This effect seems surprisingly small, though the coefficient is nonetheless estimated reasonably precisely—at about 5.3% significance. This initial figure however may under-estimate the impact of the disruption; of the over 1.65 million observations in our sample, the bulk (over 92%), are zeros—months when no shipments took place. Unfortunately, these zero-observations do not provide any

[15] "Developments in Volcanic Ash Affecting Air Travel," CNN, April 20, 2010.
[16] Since our research design utilizes the trend in maritime-based trade to identify the counterfactual change in air freight, only products that were shipped using *both* modes—air and sea—were included in our sample.

Table 2 - Decline in Air Freight, April 2010

Dependent Variable: Value of freight	(1)	(2)	(3)	(4)	(5)
April 2010 air imports	-0.0491*	-0.0785**			
	(0.0254)	(0.0346)			
Fraction of flights, cancelled			-0.444**	-0.549***	-0.449***
			(0.214)	(0.212)	(0.113)
lag 1				0.184***	0.201***
				(0.00749)	(0.00674)
lag 2				0.111***	0.114***
				(0.00624)	(0.00544)
lag 3				0.0810***	0.0639***
				(0.00591)	(0.00523)
lag 4				0.0409***	0.0396***
				(0.00598)	(0.00482)
lag 5				0.0346***	0.0262***
				(0.00546)	(0.00486)
lag 6				0.0166***	-0.00570
				(0.00567)	(0.00489)
lag 7				0.0153***	0.000364
				(0.00519)	(0.00495)
lag 8				0.00447	-0.00861*
				(0.00481)	(0.00493)
lag 9				0.000214	-0.000963
				(0.00429)	(0.00459)
lag 10				-0.00485	-0.0184***
				(0.00448)	(0.00502)
lag 11				-0.00125	-0.00615
				(0.00395)	(0.00456)
lag 12				0.00966**	0.0275***
				(0.00424)	(0.00510)
Constant	0.625***	11.95***	11.95***	6.077***	7.083***
	(0.0004)	(0.0005)	(0.0005)	(0.2570)	(0.172)
Observations	1,655,424	199,080	199,080	199,080	122,616
R-square	0.347	0.822	0.822	0.838	0.917
Number of countries in sample	38	25	25	25	24
Number of products	13,116	1,339	1,339	1,339	751
Number of products by both air and sea from at least one country	2,194	1,339	1,339	1,339	751

Notes: Statistical significance at 10, 5 and 1 percent marked with *, **, ***, respectively. The dependent variable in columns (1) to (5) is the volume (dollar value) of freight, by either air or sea. Column (1) utilizes the universe of all air-based merchandize trading relationships. In columns (2) to (5) only data on continuously positive trading relationships between January 2009 and March 2010 are utilized. Each specification controls for product-level fixed effects and product-specific time-effects.

information—contributing to noise rather than signal. This tends to attenuate our estimates of the effect of the volcano.

One way to address this source of bias, is to base our analysis on trading relationships that were continually active in the 15 months prior to the eruption (column 2). Stated differently, we would re-estimate the regression in column (1) using only those data for which positive shipments were observed (for both modes of transportation) in every month, in the 15-month window, from January 2009—the start date of our data—to March 2010—a month prior to the eruption. The resulting sample has 595,080 observations or just 3.3% of all our observations. However, these observations account for 38.6% of the total value of U.S. imports in the three-year period we investigate.[17] This restriction all but eliminates zeros from our sample, and therefore goes a long way to reducing the noise component embedded in our data.[18] The estimate in column (2) suggests that the decline in air freight between Europe and the US was closer to 8%; a little larger than our initial estimate, but small nonetheless, even when gauged in relation to the fraction of flights that were cancelled. Based on Eurocontrol data, in April 2010, 49.8% of North Atlantic flights scheduled to operate between April 15 and April 22, were cancelled. Scaled in relation to monthly flight totals, this amounts to a 13.3% decline in the number of scheduled flights. Thus the relationship between monthly air freight and monthly flight cancellations was apparently inelastic with an elasticity of around -0.6, i.e., the percent decline in the number of flight cancellations exceeded the percent decline in air freight.

Importantly however these initial estimates do not account for the differential impact of the ash cloud across Europe.[19] Ideally we would allow for this cross-country variation by interacting the fraction of US-bound flights departing country j, f_j, with the indicator, $I_{j,t}$, from equation (1). Unfortunately, Eurocontrol (2010) data do not provide a level of detail necessary to accomplish this. We can however approximate f_j using the average number of flight cancellations affecting country j, i.e., all flights departing from or arriving in country j to and from all destinations. In such a specification, β can be interpreted as the elasticity of air-based trade flows with respect to the number of flight

[17] Broken down by mode of transportation, this subsample accounts for 35.8% of imports by air and 44.2% of imports by sea,
[18] To be precise, this eliminates any zeros prior to April 2010, but preserves those occurring after April 2010. Our results are qualitatively and quantitatively similar if we eliminate all zeros in the 36 month period under study. It should be noted however that imposing this selection rule drops nearly 90% of the observations from our previous sample, bringing the number of observations down to 199,080.
[19] The impact of the volcano was greatest in Finland, where over 80% of flights scheduled to operate between April 15 and April 22, were cancelled. Other countries in Northern Europe, such as Denmark, Ireland, Sweden and the UK, had over 70% of flights cancelled. By contrast, flight cancellations averaged 30% in Spain and only 19% in Greece.

cancellations rather than the percent decline in air freight.[20] Modifying the specification in this way, yields an even lower estimate of the elasticity of air freight with respect to flight cancellations, about -0.4 (column 3), which compares to our previous estimate of -0.6 [=8% (decline in air freight) / 13% (decline in the number of flights)] implied by our result in column (2). Calibrating this elasticity estimate using average flight cancellation numbers for Europe as a whole, suggests that the volcano lowered the volume of air freight in April 2010 by 5.9%. Although this average figure masks some heterogeneity across countries, the magnitudes of these declines are far from catastrophic. In Finland, for instance, over 90% of its US-bound air freight made it to its destination, even though 4,682 of 5,782 flights were cancelled between April 15 and April 22. For the region as a whole, the monetary impact of the loss in exports to the US-market was about $2.9 Billion. Though nothing to scoff at, this decline in trade-flow was consistent with the normal variation experienced on account of month-to-month fluctuations. For instance between December 2009 and January of 2010, the decline in air freight was $1.8 billion. This compares to a $2.7 billion decrease in April 2010.

All of our impact assessments however assume that the effects of the disruption were limited to April, which is unlikely since trade flows are, on average, highly persistent. In Table 2, column (4), we estimate a dynamic trade equation to account for the persistence and seasonality of trade data. Our model allows for 12 lags in the dependent variable.[21] The coefficient on the treatment effect is slightly larger, in an absolute sense, in this dynamic specification relative to our earlier estimate (Table 2, column 3), corresponding to a higher elasticity estimate (-0.55), and a higher short-run impact of the volcano—a 7.3% decline in import volumes. The more interesting, and sizeable, difference however is the difference between the short-run and long-run impacts of the disruption. The positive dynamics in our trade data imply that the effects of the disruption persisted for months after flights had returned to normal. We estimate the long-run elasticity of air-based trade with respect to the flight cancellations to be about -1.08. This corresponds to a cumulative decline in air freight of 14.4%, most of which took place within a year of the intervention.

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[20] Strictly, since the dependent variable, $m_{i,j,t}$, is measured in logs and the RHS variable, $I_{j,t}f_j$, is not, β is a semi-elasticity, i.e., for small absolute changes in f_j (with $I_{j,t} = 1$), β measures the percent decline in imports. However, in this case, since f_j is the *fraction* of flights cancelled, an absolute increase in f_j corresponds to a *percent* decrease in the number of scheduled flights, so in effect we can interpret β as an elasticity.

[21] We also considered ARDL specification with an additional lag in the treatment dummy, however the coefficient on lagged explanatory term was statistically insignificant. Since the predicted results from that model are largely similar to those presented for model (4), we omit those results from this presentation.

As an additional robustness exercise, in column (5), we base our estimate of the impact of the volcano on a synthetic control for air freight constructed using a weighted average of sea freight data from the donor pool. Specifically, for every product-country combination, this pool includes all countries for which sea freight volumes are observed in each of the 48 months between January 2008 and December 2011, including the treated country. Since our synthetic control sample requires positive sea flows in additional countries the sample shrinks further in these regressions.

The synthetic control method is particularly useful when there are a number of potential candidate controls of which no one candidate is obviously more suited than the others. This is not the case here. For any given product-country pair, the natural control for air freight volumes are the corresponding sea freight data from the same product-country pair. Even so, the synthetic control approach utilizes the available data more fully by drawing on sea freight volumes from other candidate donor countries to reconstruct the counterfactuals. Our estimates for the elasticity of air freight with respect to flight cancellations are slightly smaller (-0.45 in the short run and -0.81 in the long-run) when measured relative to the synthetic control, but are still nonetheless comparable to the simpler difference-in-differences approach utilized thus far.

In each of the model-variations considered, static vs dynamics, difference-in-differences vs. synthetic control, our estimates suggest that air freight remained robust even despite a large scale disruption to the European hubs of the air traffic network. The inelastic response of air freight to the decrease in flights, at least in the short-run, may reflect a number of factors. First, the disruption was incomplete. Even in Northern Europe some flights were able to take off and land. For instance, about 1100 flights were able to operate routes to and from Finland between April 15 and April 22. For the affected region as whole, over 100,000 flights were able to operate during that period. Nevertheless over 13% of flights on routes over the North Atlantic were cancelled, though freight volumes did not fall by a comparable amount. Part of the explanation may have to do with freighters operating at closer to capacity as well as increased reliance on belly space on passenger flights. Second, the restrictions over European airspace were short-lived, which gave the airlines the opportunity to clear the backlog after the resumption of flights in the last week of April. Accordingly the decline in trade may appear less significant in monthly trade data than it would in a daily or weekly series.

Third, even as the disruption to flights was appexing in Northern Europe, freight forwarders, airlines and other intermediaries established work-arounds that utilized capacity in transportation infrastructure less impacted by the new airspace regulations. European hubs for air traffic, for instance, shifted southward to airports in Spain, Italy, and Greece. By April 20, the largest airports in Spain and Italy—Madrid Barajas and Rome Fiumicino—were operating normally and other airports, such as Palma De Mallorca—Spain's third largest airport—and Lisboa in Portugal—laid on additional flights, by as much as 30% (Eurocontrol, 2010). The German logistics company DHL, took advantage of the unregulated airspace over Southern Europe, by rerouting flights scheduled for its hub in Leipzig/Halle to Rome, Bergamo and Vittoria, while shipments scheduled to be flown from Leipzig were transported by ground.

4.3. Impact Outside Europe

Thus far our analysis of European-US trade, suggests that air freight remained relatively robust despite over 100,000 flight cancellations affecting the European Union. This focus on European-US trade however ignores the greater scope of the impact of the volcano on world-wide trade flows. Although airspace closures were limited to Europe, the implication is not that only trade with European partners was impacted. In fact, many bilateral trading relationships between countries outside the geographic footprint of the ash cloud also have been negatively affected. This is because European airports play a critically important role as international gateways for non-European traffic.[22] The disruption caused by Eyjafjallajökull likely not only affected US-European trade, but also trade with other countries that use Europe as a transit point for their exports to the US. Offsetting these effects however are bilateral trading relationships that may, in theory, have benefited from the disruption to Europe, as importers sought alternative suppliers.

To examine these effects—both negative and positive—we estimate the impact of the volcano on US trading relationships on a region-by-region basis. Our results are arranged across two panels in Table 3. The top panel, Panel A, reports our difference-in-differences estimates when using the corresponding sea freight data as the control for each product-country pair. The lower panel, Panel B, report results from a robustness exercise where we use a synthetic control, i.e., a weighted average of the sea freight data from all other countries with active relationships with the US. Our results are based on the dynamic specification utilized in Table 2, columns (4) and (5).

[22] For instance, Heathrow is Mumbai's primary gateway to the world. Thus when it closed, the effective distance between Mumbai and airports located all over the world increased. In particular distances to North America increased by about 40% (Woolley-Meza et. al., 2013), possibly affecting the cost of airfreight between India and the US.

Five regions are distinguished—Africa, the Middle East, Central and South Asia, East Asia and the Pacific, North and South America. Since data on flight cancellations are not available outside the affected region, the explanatory variable in our regressions is now simply an indicator, $I_{k,t}$, identifying the treatment group, i.e., air freight in the affected month. Hence the slope coefficient should be interpreted as the percent decline in the volume of imports. Of the five regions examined, two—Africa and Central Asia—experienced some adverse effects from the fallout of Eyjafjallajökull (Table 3, columns 1 and 3). Africa was the most impacted. For the continent as a whole, air-based trade fell by between 51% (synthetic) and 64% (standard DiD) (Table 3, column 2), though admittedly this estimate is based on a rather small sample as African economies export very few products on a consistent monthly basis to the U.S. via both air and sea. This figure makes some sense as US-Africa jet routes rely on European overfly, and a large fraction US-Africa air freight is composed of perishable items. Even so, it is interesting to note that the relative impact on (air-based) US-African trade was an order of magnitude greater than US-European trade.

Table 3 - The Impact on Air Freight: Region by Region

Panel A: Control is Sea Freight Data for Corresponding Country-Product Pair					
	(1)	(2)	(3)	(4)	(5)
Dependent Variable: Value of freight	Region 1 - Africa	Region 2 - Middle East	Region 3 - Central Asia	Region 4 - East Asia	Region 5 - Americas
April 2010 air imports	-0.642**	-0.0940	-0.174***	0.220***	0.110
	(0.300)	(0.249)	(0.0661)	(0.0208)	(0.0876)
Observations	2,808	4,968	38,592	325,152	21,168
R-square	0.816	0.832	0.882	0.888	0.843
Panel B: Syntehtic Control					
April 2010 air imports	-0.512**	-0.106	-0.107**	0.149***	-0.246
	(0.235)	(0.126)	(0.0469)	(0.0152)	(0.234)
Observations	1,080	2,160	26,064	194,976	288
R-square	0.803	0.928	0.899	0.919	0.865

Notes: Statistical significance at 10, 5 and 1 percent marked with *, **, ***, respectively. Due to space considerations, dynamic terms are not reported. The dependent variable in each case utilizes both air and sea freight data as the LHS variable. For any given region and any given country-product pair the control group is the corresponding volume of sea freight for that pair. In all cases, data on continuously positive trading relationships between January 2009 and March 2010 are utilized.

Central Asia also experienced some connectivity issues with the US during the crisis period (Woolley-Meza et. al., 2013) and accordingly imports from that region fell by between 11 and 17 percent. The largest exporter to the

US from that region is India. US imports from India did experience a sharp contraction, in part because India exports a number of high-value, as well as perishable, products by air; these include gems and jewelry as well as pharmaceuticals, which together account for 35% of Indian exports to the US. Though some of the impact of the disruption to European airspace may have been cushioned as some of this freight was re-routed. Air India for instance continued to operate its Delhi/Mumbai-New York flights by taking the more direct, polar, route, while *Jet Airways* was able to operate some of its trans-Atlantic routes, by re-routing these flights though Athens, as opposed to Brussels.[23]

Another region to experience a loss in connectivity with the US was the Middle East. Woolley-Meza et. al. (2013) find that the median change in distance from all airports in the Middle East to all airports in North America was about 20%. Even so the impact on US-bound air freight from that region is uncertain in our data. The explanation for this could be related to the composition of Mid-East exports to the US, which is concentrated more in products that are shipped by sea, such as petroleum and petroleum based products (Table 3, column 3). Accordingly products shipped by air may have been less affected.

Outside of these three regions the impact of the volcanic disruption on US imports varied between negligible and positive. Exports of air freight between the US and countries in North, South and Central America were essentially unaffected by the European closures (column 6), but this imprecision in our estimates could reflect the particularly small sample number of products satisfying our selection criteria. This could be because land-based transportation modes play a more important role in connecting the US to that region—Canada and Mexico in particular. In fact, we omit the synthetic results altogether for the Americas, as it is based on too small a sample (288 observations) to draw any meaningful inferences.

By contrast, East Asia and the Pacific, a region that includes the US's second largest trading partner, increased its air-based exports to the US by between 15 and 22 percent (column 5). Importantly, this spike in air freight was probably not on account of the seasonal upswing in trade with East Asia that coincides with the Lunar year celebrations. In fact, in 2010, the new (Lunar) year began a full two months prior to eruption of Eyjafjallajökull. It seems

[23] "AI, Jet, Kingfisher cancel flights to Europe." *The Hindu*, April 19, 2010.

more plausible that East Asia strengthened its trading linkages with the US, in response to the interruption in supply from European sources.

4.4. *Alternative Sourcing: Supply Chain Flexibility*

Our results from the previous section seem to imply that US importers drew from two alternative sources when supply from Northern Europe, and possibly other regions, was disrupted. This could explain why imports from some regions were boosted by the volcano. There is certainly some anecdotal evidence to suggest that impacted parties were able to react to the disruption to supply by sourcing elsewhere. Consider the retail seafood industry in the US, which relies heavily on imports. Over 90% of salmon, for instance, is imported, and a large fraction of this is supplied by fisheries in Ireland, Norway, and the UK. Importantly however the disruption to European supply was not mirrored by declines in salmon supplies in US supermarkets proportionate to the market share of European fisheries. In large part, this is because US retailers "pulled" from other sources, such as Canadian and Chilean fisheries.[24] Chilean exports of Atlantic salmon to the US were 35% higher in April 2010 relative to the corresponding month a year later. Similarly the disruption to European supply proved fortuitous for the aquaculture industry in New Zealand, which experienced a sharp increase in demand.

To get a better handle on whether such substitutions were at play, we re-estimate our regional regressions but impose a more focused sampling technique. As before, we draw only those data for which we observe continuous trading using both modes of transportation over the 15-month pre-eruption window. However, now we impose an additional restriction: for an HS-10 product code to be included in our sample, active trade linkages with the US must be present both for the region on which we are focused and for countries from the affected areas in Europe. By restricting attention to a common set of products, we are trying to see if US importers switched from their European suppliers to suppliers from a region outside the direct footprint of the ash cloud. Note that this approach focuses only on expansions in trade linkages along the intensive margin that may have occurred when the European hub was disrupted. It ignores growth along the extensive margin of trade, which, in any case, was quite unlikely, both because

[24] "Flights, Deliveries to Europe Resume." Seafood Source, April 22, 2010.

of the sunk (and time) costs associated with forming new trading relationships and the temporary nature of the disruption.

The results from this exercise (Table 4) suggest a number of conclusions. European airfreight typically declined, irrespective of the sample of HS codes on which we base our regression. Though, in one case, specifically products that the US sourced from both Europe and Africa, the estimated coefficient was not statistically different from zero. Additionally, when we focused on the intersection of products shipped from Europe and the Middle East, the

Table 4 - Substitution Effects: Evidence on Multi-Sourcing

Panel A: Control is Sea Freight Data for Corresponding Country-Product Pair					
	(1)	(2)	(3)	(4)	(5)
Dependent Variable: Value of freight	Region 1 - Africa	Region 2 - Middle East	Region 3 - Central Asia	Region 4 - East Asia	Region 5 - Americas
April 2010 air imports from Europe	-0.0974	-0.00911	-0.113***	-0.0783***	-0.125***
	(0.0902)	(0.0832)	(0.0395)	(0.0263)	(0.0466)
April 2010 air imports outside Europe	0.118	0.137*	0.122***	0.126***	0.133***
	(0.0808)	(0.0756)	(0.0357)	(0.0238)	(0.0376)
Observations	26,208	49,104	144,576	363,672	104,112
R-square	0.831	0.830	0.852	0.848	0.845
Panel B: Synthetic Control					
April 2010 air imports from Europe	-0.137	-0.0950	-0.150***	-0.0837***	-0.215**
	(0.0909)	(0.0593)	(0.0312)	(0.0170)	(0.104)
April 2010 air imports outside Europe	-0.0510	-0.167	-0.0998**	0.138***	-0.110
	(0.131)	(0.146)	(0.0500)	(0.0180)	(0.0979)
Observations	3,600	9,864	50,400	225,936	2,520
R-square	0.905	0.943	0.920	0.905	0.905

Notes: Statistical significance at 10, 5 and 1 percent marked with *, **, ***, respectively. Due to space considerations, dynamic terms are not reported. The dependent variable in each case utilizes both air and sea freight data as the LHS variable. For any given region and any given country-product pair the control group is the corresponding volume of sea freight for that pair. In all cases, data on continuously positive trading relationships between January 2009 and March 2010 are utilized. To be included in the sample, active trade linkages with the US must be present both for the region on which we are focused and for countries from the affected areas in Europe.

estimated impact on European air freight was insignificant when using the standard control, i.e., corresponding sea-freight data for each country-product pair. In the synthetic sample however the coefficient was borderline significant at 10%. In all other samples we find that European air freight to the US fell by between 7.8% and 12.5%. Our results based on the synthetic controls, suggest possibly even higher declines, perhaps as high as a 21.5% reduction in the case of products exported by both Europe and the Americas, though the sample size may be too small to draw any reasonable conclusions in this case. Second, as European air freight declined, the rest of the world picked up the slack. Our results however are not significant at the conventional 5% level, when we focus on exports common to both Europe and Africa and Europe and the Middle East, and in fact are negative and insignificant when using the synthetic control data [Panel B, columns (1) and (2)]. In each case, this lack of significance may reflect the relatively small sample sizes, although it may also have to do with the proximity of Africa and the Mid-East to Europe, and the impact that the disruption to European airspace had on connectivity to the US.

Central Asia by contrast had more mixed fortunes. Though some flights, particularly those directed over the Atlantic, were affected by the ash cloud, other flights transiting over the Pacific or taking the Polar route were less impacted. Our results for Central Asia are in fact mixed. When we use the standard control, our results suggest that Central Asia may have picked up some of the slack when European exports were disrupted. However, when using the synthetic control, we arrive at the opposite conclusion. The two regions for which we find more convincing evidence of an increase in air-exports to the US, are East Asia and the Pacific and the American Continent. Neither region experienced any significant effects on their US-bound flights, and so should have been able to respond more easily to increased demand from the US market, as our results clearly indicate.

4.5. Channeling the Effects of the Disruption

Prior to concluding, we can examine the channels through which the disruption affected the value of U.S. imports. We can usually think of the imported value being affected through two channels: price and quantity of imports. Unfortunately, while U.S. import data are highly disaggregated, they do not report the quantity shipped by mode of transportation. However, data do report the weight of imports traveling by air and by sea. This then allows us to examine whether the observed increases and decreases in U.S. imports across the various sources were driven by changes in the weight of shipments and/or average-prices-charged-per-unit-of-weight. A negative change in the former is the straightforward effect we should expect to observe. However, the effect on the price is not as obvious. For example, consider the strategy an alternative supplier from East Asia could pursue. The inability of European suppliers to export their goods to the U.S. reduces the competition in the marketplace. Active East Asian suppliers may then be in a position to, at least temporarily, take advantage of their increased market power and charge higher prices. On the other hand, taking a longer view, they may be more strategic in their intentions and supply cheaper products with the intent on supplanting the European suppliers once the shock dissipates by charging lower prices.

In Table 5 we examine these two channels using the same specification and samples as Table 4 and only using the difference-in-differences approach. We do not use the synthetic control approach as that would necessitate that we create a synthetic control for observed weight and average-prices-per-unit-of-weight, which would likely result in the breaking of the multiplicative relationship between the two which results in the total value of imports. We group our results in six panels, the top left examining the relationship between U.S. imports sourced from European countries which closed their airspace for some period of time during April 2010 and the rest of the world. Remaining panels examine the relationship between imports sourced from Europe and each of the five regions separately, similar to Table 4. Focusing on the top left panel, indicates that the estimated 9% reduction in imports sourced from Europe was driven solely by the reduction in the imported weight, while the change in price was not significant. This is in contrast to what we find for the rest of the world. While imports sourced from the rest of the world increase by 16%, the imported weight increases by 18%, while the average-price-per-unit-of-weight decreases by 3%. Thus, some of the increase in imports from the rest of the world are due to them being cheaper, potentially indicating that those exporters may have attempted to establish themselves in the U.S. by using this disruption as an opportunity to offer cheaper products.[25]

Examining the remaining panels we can see that in products exported by both European and Central Asian countries, the reduction in imports from Europe was driven by both a reduction in weight as well as price, potentially indicating that some expensive products were affected more severely. There is similar, though somewhat weaker, evidence for the Americas as well. Much of the reduction in the price of imports from the rest of the world is driven by

[25] This observation raises the possibility of an induced change along the extensive margin as some European exporters are replaced by exporters from other regions. We have attempted to identify possible changes along the extensive margin in several ways, but were unable to identify any significant changes. Thus, either these replacement attempts failed, or were not successful on a large basis whereby a European country would cease to export a product to the U.S. altogether.

cheaper imports from East Asia, the only region of the world showing a significant evidence of lower prices, an unsurprising results given the China is a major exporter in that region.

Table 5 - Value, Weight, and Price Results

	All regions			Central Asia		
Dependent Variable:	Value	Weight	Weight unit price	Value	Weight	Weight unit price
April 2010 air imports from Europe	-0.0925***	-0.0497**	-0.0151	-0.130***	-0.0919**	-0.0476**
	(0.0262)	(0.0196)	(0.0117)	(0.0480)	(0.0403)	(0.0221)
April 2010 air imports outside Europe	0.161***	0.184***	-0.0261***	-0.0537	-0.0426	-0.0242
	(0.0192)	(0.0148)	(0.00788)	(0.0780)	(0.0536)	(0.0271)
Observations	595,080	561,372	561,372	76,536	72,554	72,554
R-square	0.851	0.904	0.883	0.844	0.878	0.858

	Africa			East Asia		
Dependent Variable:	Value	Weight	Weight unit price	Value	Weight	Weight unit price
April 2010 air imports from Europe	-0.00324	0.0329	-0.0793	-0.0717***	-0.0433**	-0.0194
	(0.155)	(0.118)	(0.0589)	(0.0270)	(0.0208)	(0.0127)
April 2010 air imports outside Europe	-0.221	-0.0382	0.0863	0.165***	0.174***	-0.0351***
	(0.346)	(0.253)	(0.0772)	(0.0258)	(0.0213)	(0.0123)
Observations	8,784	8,382	8,382	324,936	309,381	309,381
R-square	0.790	0.862	0.834	0.856	0.897	0.862

	Middle East			Americas		
Dependent Variable:	Value	Weight	Weight unit price	Value	Weight	Weight unit price
April 2010 air imports from Europe	0.125	-0.0139	-0.0594	-0.110*	-0.0352	-0.0648**
	(0.123)	(0.0679)	(0.0396)	(0.0580)	(0.0460)	(0.0270)
April 2010 air imports outside Europe	0.243	-0.0738	0.0834	0.202***	0.109	-0.0180
	(0.243)	(0.125)	(0.0729)	(0.0782)	(0.0671)	(0.0363)
Observations	23,904	22,202	22,202	51,984	49,001	49,001
R-square	0.775	0.857	0.863	0.824	0.868	0.826

Notes: Statistical significance at 10, 5 and 1 percent marked with *, **, ***, respectively. Due to space considerations, dynamic terms are not reported. For any given region and any given country-product pair the control group is the corresponding volume of sea freight for that pair. In all cases, data on continuously positive trading relationships between January 2009 and March 2010 are utilized. To be included in the sample, active trade linkages with the US must be present both for the region on which we are focused and for countries from the affected areas in Europe.

5. Discussion

Our results indicate that U.S. imports declined in the wake of the disruption due to the eruption of Eyjafjallajökull. In addition, our results suggest that some of the reduced imports from Europe were made up for by the increase in imports from East Asia and the Americas. We are now confronted with an obvious question: how plausible are our substitution results? In other words, is it plausible to expect that global supply chains and firms that set them up are sufficiently flexible that they can quickly find alternative sources of the goods they require? Prior to addressing this question we note that our results are likely an underestimate of the reduction. European airspace closures were over on April 22. Starting with April 23 air traffic over Europe was able to return to its per-disruption equilibrium. Even with some equipment out of place, it would take the airlines (both commercial and cargo) a day or two at most to get their planes where they needed them the most. Thus, there were at least six remaining days of normal air operations in April during which airlines could ferry passengers and cargo stuck in Europe to their respective destinations. Given the monthly frequency of our data, our results identify the net reduction in U.S. imports, a combination of the total reduction due to airspace closure and the recovery that occurred in the last week or so of April. Were daily or weekly data available, we would be able to more precisely estimate the effect of the disruption. Unfortunately, such data are not readily available.

Returning to the question we just raised, is it plausible that East Asian producers could quickly serve as a substitute for the suddenly unavailable European suppliers? At first blush it may appear that our data are too aggregated to answer this question. After all we do not observe imports at the firm level, which would make it easy to ascertain whether specific importers are substituting European goods with East Asian (or Americas') goods. However, we can evaluate the plausibility of this scenario which rests on two issues: are the products which are being substituted the kind of products that can be easily produced by multiple producers, and is the global air transportation network sufficiently flexible to accommodate additional freight that needs to be flown?

Without more detailed data it is difficult to determine whether the products which are being substituted are the kinds of products that are easily substitutable. However, we can provide a broad description of the 1,339 10-digit HS products codes continuously exported by European affected countries prior to the disruption. The vast majority of these products are differentiated, with some 92% belonging to the differentiated product category according to the Rauch

(1999) classification. The also span the entire range of the SITC classification with 42% of observations being classified as Machinery and transport equipment (SITC 7), 29% as Miscellaneous manufactured articles (SITC 8), 19% as Manufactured goods classified chiefly by material (SITC 6), 9% as Chemicals and related products (SITC 5), and the remainder sprinkled between Food and live animals (SITC 0), Beverages and tobacco (SITC 1), and Crude materials, inedible, except fuels (SITC 2). These products are also characterized by a broad range of the elasticity of substitution as estimated by Soderbery (2015). The average elasticity of substitution is 4.2, with the median of 1.7, and 90th percentile of 5.7. Finally, these product also display a wide range of relationship-specific investment costs according to the Nunn (2007) with an average value of 0.62 and a median of 0.66. The multitude of product-level fixed effects we include in our regressions preclude us from using any of these variables in our regressions and estimating our main specifications on subsets of the already small subsample strikes us as demanding too much from the data. However, it does appear that the range of products in this subsample is wide enough to allow for quick substitution of the supplier when the disruption due to Eyjafjallajökull occurs.

The second issue pertaining to the plausibility of substitution of suppliers is whether the global air transportation network is either flexible enough to accommodate the need for increase payload capacity on the routes utilized by substitution. This can happen in one of two ways: either airlines, both commercial and freight, can shift equipment to routes where they are suddenly needed, or they have excess payload capacity on existing routes which would make it easy to accommodate increased freight. Since we do not have data on actual flights flown, we cannot determine whether additional flights were added to accommodate the substitution patterns we identify. However, we can examine whether existing flights have available payload capacity to accommodate additional goods that were exported from East Asian countries. To that effect we use the U.S. Department of Transportation's T-100 International Market data. This data set reports, on a monthly basis, detailed information on U.S. inbound and outbound flights for each active route. Data of particular interest to us are the number of available passenger seats, the number of passengers, the available payload capacity, and the amount of freight carried. We can use this data to calculate the extent to which both the passenger seat capacity and the payload capacity are utilized on U.S. inbound flights from countries in our 15-month sample. Table 6 summarizes used capacity for each of the regions in our sample during the 2009-2011 period.

Table 6 - Used Aircraft Capacity

	All flights		Passenger flights		Cargo flights	
Region	Seats	Payload	Seats	Payload	Seats	Payload
Affected Europe	81.2%	22.5%	81.2%	16.0%	0.0%	64.6%
Africa	75.8%	6.8%	75.9%	6.4%	0.0%	27.1%
Middle East	80.1%	16.0%	80.1%	14.7%	0.0%	47.9%
Central Asia	81.2%	12.4%	81.2%	12.5%	0.0%	11.3%
East Asia	80.3%	45.8%	80.3%	16.9%	0.0%	80.3%
Americas	74.9%	14.2%	75.0%	3.7%	0.0%	58.1%
Total	77.9%	24.3%	77.9%	10.7%	0.0%	69.7%

As data in Table 6 indicate, there is a fair amount of flexibility in the global air transportation network to facilitate at least some substitution without the need to add additional flights. On average, only 24.3% of payload is used to ferry cargo, with much of that excess capacity existing on commercial passenger flights, where only 10.7% of available freight space is used for freight. On average slightly more than two thirds of freight space on cargo flights is used. Flights from East Asia utilize their payload capacity the most, with 80% of payload on cargo flights used. Taken together, commercial passenger and cargo flights from East Asia have more than half the available capacity not being used on a regular basis, indicating that it there is sufficient capacity to double the amount of U.S. imports from that region which arrives by air. Our substitution results (see Table 4) indicate that East Asian exports to the U.S. of the same products exported by directly affected European countries increased by less than 15%. Thus, the global air network had more than the necessary excess capacity to accommodate the temporary increase in imports.

6. Conclusion

Increased globalization in trade, outsourcing and the advent of leaner global supply chains, have made economies more susceptible to disruptions to the normal flow of goods. These disruptions can, and often do, entail shocks to international transportation networks. In recent years, a number of high impact events have functioned as natural experiments for understanding the role that transportation and infrastructure play in trade and production (e.g., Volpe

Martincus and Blyde, 2013; Volpe Martincus, et. al., 2014). Unfortunately, due to the myriad of conflating influences at play, more often than not these "natural experiments" are blunt instruments and cannot isolate the role of transportation or infrastructure more generally on trade or other macroeconomic variables. Here we have used the eruption of the Icelandic volcano—Eyjafjallajökull—as a natural experiment to estimate the impact of a disruption to air traffic on air freight. Like many other naturally occurring events that impacted transportation networks, the eruption of Eyjafjallajökull was sufficiently unpredictable to have altered importer-exporter behavior in advance of the event. However, unlike other natural disasters, the eruption of Eyjafjallajökull was relatively free of confounding factors, making this an unusually clean experiment with which to isolate the role of transportation in intercontinental goods flow.

Given the absence of close substitutes for air transportation, particularly where intercontinental shipments are concerned, it was perhaps reasonable to expect a unitary or greater than unitary elastic response of air cargo to flight cancellations. Yet, our findings suggest a far more inelastic relationship; using data on flight cancellations, we estimate this elasticity to be approximately -0.6. Overall, we find that European air freight volumes (to the US) declined by about 7% in April 2010, as a result of the week-long disruption, though the effect may have been larger over the long-term. The somewhat inelastic response of air cargo could reflect both the short duration of airspace closures as well as their partial nature, but also the flexibility of the airlines and freight forwarders in accommodating backlogs and using capacity in parts of the infrastructure un-impacted by airspace regulations. Moreover, as supply to US market from European sources decreased, the rest of the world picked up some of the slack. Thus, even while ash cloud disrupted trade outside Europe, industries that supplied the US market in competition with European firms were able to increase shipments to the US market.

In light of recent disruptions to global supply chains, the view that optimized lean practices, such as just-in-time inventory management and low-cost offshoring expose industries to too much risk, has received a stronger voice (Bloomberg, 2010). In the aftermath of the eruption of Eyjafjallajőkull, Bloomberg Businessweek cited the need for supply chain flexibility through multiple sourcing and logistics networks capable of alternative routing. Yet, perhaps surprisingly, our evidence suggest that, in this instance at least, some of those mechanisms may already have been in operation.

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