



RESOURCES
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The Societal Value of the HYSPLIT Air Dispersion Model

Final Report to the NOAA Air Resources Laboratory

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Abstract

The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model, which was developed by NOAA's Air Resources Lab (ARL), is used in a wide variety of applications to estimate the forward and back trajectories of pollutants. Because HYSPLIT is available for free, its societal value is not easily measured. This study describes its many types of applications and provides a literature review that highlights how the benefits of these uses could theoretically be quantified. However, the heart of the report is quantifying in monetary terms the social value of information that the HYSPLIT model provides to its users and society at large. Both case studies highlight instances in which consulting HYSPLIT led to better information and more informed decisionmaking, with measurable benefits to society. The first case explores the state of Maine's citing HYSPLIT to prove to the Environmental Protection Agency (EPA) that certain counties were not contributing to ozone exceedances in the state and to petition for those areas to be removed from the ozone transport region, a designation that imposes stricter environmental regulations on polluters. The second case explores the benefits of using HYSPLIT to better inform the evacuation zone following a fire at the Husky Refinery in Duluth, MN. The combined case study values more than exceed the annual cost of maintaining the HYSPLIT model.

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Introduction

Government-run programs are increasingly under scrutiny to prove their value to justify their funding. Since such programs provide resources and tools that are public goods and are generally available for free, they typically lack traditional methods for assessing product value used by private companies, such as a price on the product. Instead, one way to estimate the value of a government program is to assess the value of information (VOI) it provides. Such an assessment requires knowledge of the uses to which it is put, the benefit of those uses, and the counterfactual: what would happen to the activities if the program in question were no longer available.

The National Oceanic and Atmospheric Administration (NOAA) Air Resources Lab (ARL) developed the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model to simulate dispersion and forward and back trajectories of pollutants in the atmosphere. HYSPLIT is widely used for a variety of reasons, such as modeling smoke from wildfires, tracing the source of radionuclides, and informing aircraft rerouting in the event of volcanic eruptions. HYSPLIT is distinguished because it is free, accessible, supported, and frequently updated. Additionally, it can run faster than similar models, and the website provides curated meteorological data to drive the model for use and/or download.

HYSPLIT's uses and corresponding benefits are vast and can be difficult to assess because it is available for free to the public. Without a price tag, the user's willingness to pay (WTP) for such a product is not directly known. However, it is possible to assign a monetary value to many of HYSPLIT's benefits through techniques developed in the VOI literature, as discussed in section 4, which will help decisionmakers measure this value against the program's cost and assess its overall net societal value.

This report examines those net benefits to society by making monetary estimates where possible. Section 1 covers the concept of value, which defines what we mean by VOI and how we would begin to quantify it. Section 2 categorizes HYSPLIT by use, source, and the corresponding possible benefits from that use, which includes human health, environmental health, property, and administrative benefits, such as time saved and mitigation costs avoided. Section 3 describes the two case studies performed as part of this project, along with the methods and the results. The first study estimates the benefits of Maine's citing HYSPLIT to prove that parts of the state could be excluded from the ozone transport region (OTR), which imposed additional regulations on facilities that emit volatile organic compounds (VOCs) in those areas. The second case study explores the use of HYSPLIT in an emergency to help inform an evacuation zone following an explosion at the Husky Refinery in Duluth, MN. Section 4 examines the literature relevant to each benefit category and, where possible, the economic valuation literature as it relates to the uses of HYSPLIT. Section 5 concludes.

1. The VOI

In this study, we use an economic valuation technique referred to as the “VOI.” This method relies on an understanding of what constitutes “value.”

“Value,” in economic terms, refers to things that benefit the user in some way. In a market, the value of a product is typically considered to be its price—for example, a sandwich that costs \$10 is worth at least \$10 to the person who chooses to purchase it. Thus, the price of the good or service typically serves as a simple way to assess its value.

While the value of market goods is easily understood, the value for nonmarket goods or those that do not have a price but provide users with benefits is not as easily determined. However, economists have various techniques to assign value to nonmarket goods, which is typically expressed in monetary terms as a way to make clear comparisons between products and with product costs.

One example of a nonmarket good is information. Government agencies, such as the NOAA, operate a variety of tools that are used by local governments, universities, and even other government agencies, such as NASA, that provide users with information.

The HYSPLIT model offers information on the dispersion of various particles, both naturally occurring and anthropogenic. By itself, information is not considered “valuable” by these standards. If, however, information leads to a change in decisionmaking that results in better outcomes for people and the environment, then that information *is* considered valuable.

Having reliable and readily available information can be valuable in many contexts, such as for decisions aided by HYSPLIT, including contexts as diverse as emergency planning, nonattainment designations, and aircraft rerouting. These uses can lead to a variety of benefits, including reduced property damage and loss of life in an emergency. Measuring the magnitude of these improvements to societal outcomes—lives saved, for example—is one way that governments can understand and communicate the benefits of their work.

There are many benefits of the information provided by models such as HYSPLIT. Most cases involve improvements in the decisionmaking process, such as reducing the time to come to a decision because a particular model is so familiar and easy to use or its frequent updating gives the decisionmaker more confidence about whether the information underlying a decision is credible and correct.

Additionally, information provided by government programs can still be useful and valuable (if hard to quantify), particularly for research purposes, even if it does not lead to a change in decisions.

1.1. How to Assess the VOI

Measuring the impacts of the VOI is termed an “impact assessment.” These are quantitative studies that investigate how people use improved information to make decisions and quantify how these decisions improve socioeconomically meaningful outcomes, such as lives saved or resources conserved. The ones that pertain to or are directly about HYSPLIT are reviewed in the next section.

The VOI methodology¹ compares outcomes in two different states of the world: one in which action is taken based on one set of information and a different state in which action is taken using better information. Uncertainty is present in the possible outcomes. The difference in socioeconomically meaningful outcomes between the two states represents the value of the information.

For example, remotely sensed data may provide water resource managers with hydrologic data at finer spatial and temporal resolutions, allowing them to implement more elaborate water allocation strategies that increase benefits to users and also maintain aquatic species habitats. In some contexts, the gains of improved information to decisionmakers may be realized in reduced damages. For example, farmers may be able to rely on detailed field-level estimates of crop evapotranspiration requirements derived from satellites to fine-tune irrigation schedules with the goal of minimizing negative impacts of an ongoing drought on crop yields.

Note that the VOI approach relies partly on the premise that information can influence decisionmaking; information is meaningful in the presence of uncertainty and valuable when something is at stake in a decision. It is also important to note that additional or better information may be valuable even if it does not lead to a different choice on the part of a decisionmaker. This is especially true if the decisionmaker exhibits risk aversion; that is, a reluctance to accept a set of choices with an uncertain payoff rather than another set of choices with a more certain but possibly lower expected payoff. If a decisionmaker is risk averse, they will have an ex ante WTP for information to reduce the uncertainty associated with the decision.

The impact assessment process adopted here is based on a “theory of change” approach, which describes the causal logic of how and why a particular project will reach its intended outcomes. For a HYSPLIT project, describing a theory of change involves identifying how the availability of project outputs (for example, data products, models, information systems, decision-support tools) may change the actions taken by a decisionmaker who uses those project outputs relative to the case in which the project outputs are not available or are available with greater uncertainty (Figure 1).

1 This concept of VOI can be traced historically to the classical expositions by Hirshleifer and Riley (1979) and McCall (1982).

Figure 1. Impact Assessment Visual Map of the Components Involved in Conducting an Impact Assessment Using a Theory of Change Approach

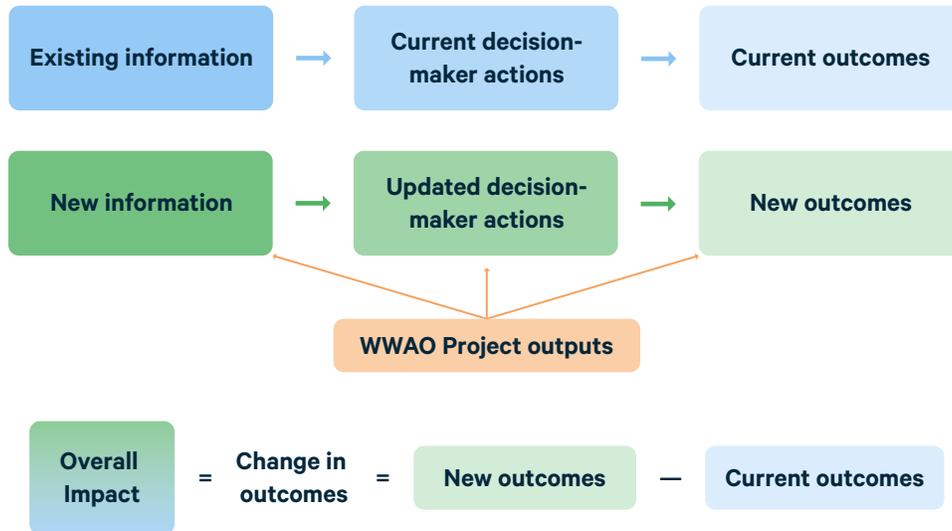
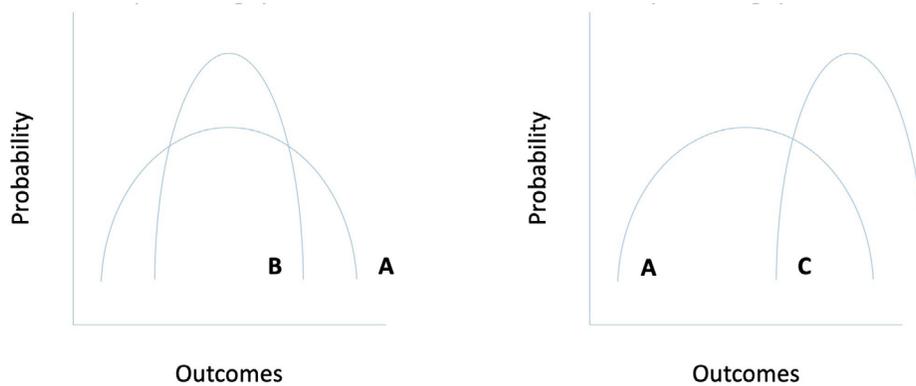


Figure 1 illustrates the basic logic behind a theory of change associated with the impacts of a project. The blue boxes represent a scenario in which the decisionmaker relies on existing information—the information available in the absence of the HYSPLIT model outputs—to take an action, and this action leads to a certain set of outcomes for people and the environment. The green boxes represent the scenario in which the decisionmaker has access to new information provided by the model, and the decisionmaker’s actions lead to (potentially different) outcomes for people and the environment. The impact of HYSPLIT is defined as the difference between the outcomes that arise from actions based on HYSPLIT information and the outcomes of actions taken in the absence of this information—with the next best alternative, termed the “counterfactual.”

Sometimes, as in Figure 1, the counterfactual is how things are done now or would be done without the information from HYSPLIT. In this case, we observe the counterfactual but must estimate or guess at the value of, say, applying HYSPLIT instead of whatever else is providing necessary inputs to the decisionmaker. In other cases, however, HYSPLIT use and outcomes are what is observed, and the counterfactual is what would have happened if HYSPLIT were not available. This is tricky to estimate. With the latter type of counterfactual, there can be many choices. In terms of this report, one must ask, if HYSPLIT were not available, what information would be provided without it? One option is that another model, similar to HYSPLIT, would serve instead. Perhaps the alternative model would have less spatial or temporal granularity than HYSPLIT, leading to poorer decisions. Another option is that no model is possible, and much more crude rules of thumb or historical information are used instead. In general, the more crude the counterfactual approach, the greater the benefit of HYSPLIT.

A final important concept is mean-preserving spread and non-mean-preserving spread. These are ways of describing the effect of better information on probabilistic outcomes. Figure 2, curve A, shows the possible outcomes with existing information, and curve B shows the distribution of outcomes with better information. Better information is that which reduces uncertainties about outputs from a decision. In the first panel (2.1), this better information reduces the spread of uncertainty—curve B is less spread out than curve A—but the means of both distributions are the same—termed a “mean-preserving change in spread.” In the second panel, curve C is again providing greater certainty about outcomes than curve A, but the outcome distribution has shifted so the mean outcomes also differ across the curves, indicating that the information has not only reduced uncertainty but also improved the mean outcome. Both panels are relevant for thinking about the VOI associated with using HYSPLIT.

Figure 2. Reducing Uncertainty of the Distribution of Possible Outcomes via HYSPLIT (shown as moving from curve A to B and A to C)



2. Categorization of HYSPLIT Uses

Table 1 summarizes HYSPLIT's applications and categorize their benefits and costs to society. The source material is an analysis of documents describing HYSPLIT's uses and their impacts. The first column covers the ways in which HYSPLIT is consulted, from emergency planning to forensic analysis associated with a nuclear test, for example. The second column lists for each use the pollutants or other substances (including lake-effect snow) whose transport has been modeled. The third column indicates the source of the substances or their cause, ranging from natural causes to terrorist releases. The remaining columns show the various benefits and costs to society that result from these applications. We use "X" to indicate that tracking a substance for a given application can lead to the benefit or cost listed at the top.

Some clarification of some of these various categories is provided next. Back trajectories are typically related to nonroutine or accidental releases, whereas routine releases refer to routine or scheduled events, either natural or not. These can have different societal impacts despite tracing the same substances. Planned releases for smoke, for instance, can have human health and property benefits if the timing of prescribed burns is done to avoid smoke plumes moving to populated areas. Back trajectories to determine the origin of a wildfire could be beneficial for saving time and reducing mitigation costs but may not provide any benefits to human health or property if the wildfire has already spread. In essence, modeling a particular substance, such as smoke, will have different benefits and costs depending on its origin and the consequent application of HYSPLIT.

We designated academic research as a category of use because many graduate students use HYSPLIT in their dissertations and other academics rely on it routinely in their research. Also, academic research is distinguished from the other use categories in the list because it is heterogeneous and not necessarily tied to specific, real-world applications. For example, Deka et al. (2015) used HYSPLIT back trajectories to determine how transported pollutants affect phosphorus in lakes. They found that waste burning associated with agriculture significantly contributed to phosphorus levels in lake sediment, which would have implications for environmental health. Wentworth et al. (2018) used HYSPLIT to investigate how wildfires affect concentrations of VOCs and ozone, which can have human health impacts. Such research may ultimately have a societal impact, but it is indirect at best.

In contrast, the other categories cover real-world applications, such as emergency planning or altering aircraft flight plans to avoid volcanic ash plumes. Attainment designation is a specific use category where HYSPLIT has provided rationales for state-proposed nonattainment designations under the Clean Air Act (CAA). Planned releases of conventional pollutants and greenhouse gases associated with prescribed burns involve using HYSPLIT to address the timing of the deliberate setting of forest fires or agricultural land burning to help fight fires or reduce future fire risk and to clear fields for new plantings, respectively. One of HYSPLIT's most interesting applications is discovering where a particular substance was emitted, which we label "forensics," by using the back-trajectory feature, which develops probability distributions for the location and timing of a given release based on observed concentrations downwind.

The benefit/cost categories cover time and out-of-pocket cost-savings and various health and environmental externalities reduced through the application of HYSPLIT. We allow for the possibility that benefits could be negative by terming the category “Societal Benefits/Costs.” The term “societal” is applied in the sense that economists use it in cost–benefit analyses of regulations, denoting the welfare effects to society of various activities or policies or, in this case, information provision. Information provision can save time and money, which is broadly captured in market behavior, and also includes the nonmarket or “extramarket” benefits. For instance, where probabilities of death are reduced, the expected fewer deaths from using HYSPLIT projections would typically be multiplied by a value of statistical life (VSL)² to arrive at the social benefit to that risk reduction.

Benefits (and costs) are always measured against a counterfactual, which we discuss briefly. Depending on the counterfactual, HYSPLIT may lead to outcomes that would be mean preserving relative to the next best alternative (the counterfactual) or not mean preserving, as explained earlier.

We use the aircraft rerouting example to explain the counterfactual thinking and how it impacts the benefit categories. The airline industry (Stein et al., 2015) consults HYSPLIT to forecast the plume direction and locations of ash after a volcano erupts, which can enable planes to be efficiently rerouted to avoid the plume. If the counterfactual assumes mean preservation and no alternative or a poorer alternative model, then planes would be rerouted less efficiently, meaning they would take a wider berth around the plume. In this case, HYSPLIT results in fuel cost-savings and shorter flights (time savings) relative to the counterfactual, but we assume that crash risks and plane damage risks are the same between HYSPLIT and the counterfactual (mean preservation). By contrast, if we do not assume mean preservation and HYSPLIT reduces overall average crash risks and property damage (a shift in the outcomes distribution), then it would deliver health and property benefits compared to the counterfactual.

We can apply the same way of thinking to determine the benefits of using HYSPLIT for prescribed burns. HYSPLIT forecasts are used to time the burn to reduce the probability that a smoke plume would intersect populated areas. Here, the counterfactual might be no model, as HYSPLIT is free and very popular for this purpose, and therefore HYSPLIT would not likely be mean preserving. Using this counterfactual, the burn would occur when convenient to the farmer or forest manager, which could result in greater damages and risks to human health. Therefore, HYSPLIT provides benefits to health and possibly property from lower smoke exposure. However, as shown in Figure 1, the benefits are dependent on the information that would be available without the HYPPLIT model, which could be information from another model. Thus, if the counterfactual is an alternative model for the same application, then the benefits of HYSPLIT to human health and property would be the

2 The VSL is defined as the WTP to reduce one’s risk of death divided by the amount of the risk reduction. So, if WTP is \$1,000 for a 1 in 1,000 reduction in risk, the VSL = \$1 million. The WTP number is typically derived by survey answers to hypothetical questions or analysis of real-world data, such as wage disparities across jobs with different death risks. VSLs used by the EPA are in the \$9 million range.

benefits of HYSPLIT (new information) minus the benefits of the alternative model (older or alternative information), which would likely be much smaller than if another model were not available.

Additionally, HYSPLIT could actually have *negative* societal benefits if, in fact, an alternative model would provide a more accurate result. In this specific example, however, risk-averse forest managers may well value reductions in the uncertainties surrounding their decision about the timing of the burn—hence, HYSPLIT would still have value even if an alternative model could provide similar information but with less certainty. Without further study, there is no presumption that ecological impacts would be more or less with HYSPLIT relative to the counterfactual, as there would be a plume under any circumstance. Potentially, residents of populated areas would save money by not having to take steps to avoid the smoke. To the extent they do so, they substitute avoidance costs for health costs—generally a welfare-improving strategy.

A similar example is for emergency planning for the accidental release of hazardous chemicals. A likely counterfactual may be a different publicly available dispersion model, such as FLEXPART or STILT (FLEXPART.EU, 2019; STILT Information Page, n.d.). Even if these models perform similar functions, HYSPLIT may still be easier to understand and use or more familiar, which would provide time savings as a benefit. HYSPLIT may also provide more accurate estimates relative to these other models, which could offer benefits to human health and lower mitigation costs if certain areas are able to better prepare for chemical emergencies through evacuations, etc. For example, if FLEXPART’s trajectories or downwind concentrations are not as accurate as HYSPLIT’s following the release of a chemical, then perhaps communities that are inaccurately shown by FLEXPART as being in danger may overprepare, which could lead to unnecessary mitigation costs, whereas communities that are in harm’s way but not flagged in the model could face human health consequences.

Note that this discussion assumes that HYSPLIT is superior, which is not necessarily the case. Hegarty et al. (2013) showed that HYSPLIT is roughly equal in performance to STILT or FLEXPART; similarly, Pagano (2010) found that both HYSPLIT and FLEXPART are roughly comparable, though FLEXPART may have more accurate results. If HYSPLIT is in fact inferior to the counterfactual model in its forecasting but is easier to use and understand, then it leads to mitigation cost and time savings but possibly greater costs to environmental or human health. Pagano (2010) did note that forecasting a plume with both models also has great value to enable decisionmakers to reduce their uncertainty in forecasts.

Notably, however, HYSPLIT’s wide usage in many different applications provides evidence of a revealed preference for the model versus other alternative models. This preference may be due to the model’s functionality or its “nontechnical” benefits, such as ease of access, being free, available trainings, user support, integration with other datasets (e.g., for meteorology), historical inertia and familiarity, and even regulatory mandates for its use (see our Maine case study). A VOI study to monetize some or all of these benefits would require a user survey, to determine which attributes are most salient to users and their WTP for those attributes. Such a survey, however, would be awkward at best, because there are no plans to charge for HYSPLIT and users might fear their responses could justify charging.

Thus, in our case studies, we developed specific counterfactuals by interviewing HYSPLIT users to understand what they would have done without it, which enabled us to better estimate the benefits that it provides in those specific circumstances. In both cases, it was reasonable to assume that an alternative model was not available for those specific purposes. In the Maine case, the rules for redesignating an area under the CAA require HYSPLIT. In the Husky case, the regional NOAA offices in Duluth have staff ready in real time to support the emergency response effort with HYSPLIT runs. Thus, the benefits of the information provided by the HYSPLIT model were fully attributable to it without having to subtract out the potential benefits of an alternative model.

Developing the appropriate counterfactual for each scenario requires extensive research and understanding. In Table 1, we assume that the counterfactual for each scenario is no alternative model and that outcomes are worse (not mean preserving) without HYSPLIT. In practice, the “true” counterfactuals might vary, which would change the “X’s” as listed.

Table 1. Uses of HYSPLIT Data and Societal Benefits and Costs

Use of HYSPLIT*	Substance	Sources or Causes	Mitigation and Avoidance Costs Saved	Time Saved	Human Health, Discomfort	Property	Environmental Health	Climate
Aircraft Operations	Ash	Volcanic Eruptions	x	x	x	x		
Attainment Designation^a (Back Trajectories)	PM2.5 and PM10	Industry, Wildfires, Agricultural Burning	x		(x)		(x)	
Emergency Planning and Response	Radionuclides, Hazardous Materials/ Chemicals, Biological Agents	Accidental Release, Terror	x	x	x		x	
	Smoke ^b	Wildfire			x			

^a States use HYSPLIT to prove that an exceptional event beyond their control (such as a wildfire) caused an increase in pollutants, which allows them to stay in compliance with the NAAQS. If HYSPLIT did not exist, these states would have to take measures to achieve attainment, which would have health and environmental benefits, hence why these categories are negative.

^b HYSPLIT is used in emergency response to track the dispersion of smoke from wildfires. This can have health benefits through evacuation but likely has no impact on property or environmental health (it cannot change the direction of the smoke).

Table 1. Uses of HYSPLIT Data and Societal Benefits and Costs Cont.

Use of HYSPLIT*	Substance	Sources or Causes	Mitigation and Avoidance Costs Saved	Time Saved	Human Health, Discomfort	Property	Environmental Health	Climate
Environmental Impact Statements^c	Radiological and Non-Radiological Substances	NASA Space Launches			x			
	Allergens	Natural			x			
Routine Releases (Natural)	Particulates	Natural			x	x		
	Hurricanes	Natural			x	x		
	Lake-Effect Snow	Natural			x	x		
Routine Releases (Anthropogenic)	Hazardous Materials, or Chemicals	Industry			x		x	
	Conventional Air Pollutants ^d	Timed Prescribed Burns		(x)	x	x	x	
Forensics (Back Trajectories)	Greenhouse gases ^e	Urban Areas		x				x
	Mercury	Power Plants and Industry, Incineration		x	x		x	
	Particulate Matter	Industry		x	x		x	

^c NASA has relied on HYSPLIT to determine the impacts of space launches. This can improve human health by understanding the impacts of the launches and where they will be most impactful.

^d Time prescribed burns could take more planning efforts relative to the counterfactual, so time savings is a negative here.

^e HYSPLIT is currently used to model back trajectories for greenhouse gases in urban areas. This provides climate benefits and time savings associated with finding a source (as is the case with all back trajectories).

Table 1. Uses of HYSPLIT Data and Societal Benefits and Costs Cont.

Use of HYSPLIT*	Substance	Sources or Causes	Mitigation and Avoidance Costs Saved	Time Saved	Human Health, Discomfort	Property	Environmental Health	Climate
Forensics (Back Trajectories) Cont.	Radionuclides	Accidental Release		x	x		x	
	Radionuclides ^f	Nuclear Testing		x				
Academic Research	Allergens	Natural		x				
	Dust	Natural		x				
	Hazardous Materials, or Chemicals	Accidental Release, Terror		x				
	Particulate Matter	Industry, Wildfires		x				
	Radionuclides	Accidental Release, Nuclear Testing, Terror		x				
	Smoke	Wildfires		x				

^f HYSPLIT can provide time savings when searching for the source of radionuclides from nuclear testing but likely will not change the outcome of the dispersion. This could have geopolitical benefits down the line that are not explored here.

2.1. Summary of Recent HYSPLIT Uses

HYSPLIT is used hundreds of times per year for the categories specified in Table 1. The ARL documents many of these uses by event type and frequency; a summary of the documented runs for 2018 and 2019 is included.

As shown in Table 2, HYSPLIT is often run multiple times for a single event, thus resulting in nearly double the number of simulations per number of events for both 2018 and 2019.

HYSPLIT is run for a variety of purposes, which include emergency preparation for a variety of high-profile events. The “Special Event” category includes strategic placement of emergency equipment for crowded events. In 2018, for example, it included emergency preparation for Fourth of July fireworks, New Year’s Eve events, a presidential visit, Barbara Bush’s funeral, and the National Collegiate Athletic Association (NCAA) Final Four games.

Table 2. Summary of HYSPLIT Runs in 2018 and 2019

Event Type	Number of Simulations (2018)	Number of Events (2018)	Number of Simulations (2019)	Number of Events (2019)
Hazmat Industrial	95	55	302	100
Hazmat Transportation	63	23	71	38
Wildfire	84	54	32	21
Prescribed Burn	134	93	318	228
Unspecified Burn	0	0	52	43
Special Event	79	26	46	27
Volcanic Eruption	8	3	0	0
Total	464	254	821	457

2.2. References

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3. Case Studies

This section of the report presents two case studies of the value of HYSPLIT—to support reclassifying Maine counties out of the OTR and to help determine the evacuation zone from the explosion, fire, and smoke event at the Husky refinery near Duluth, MN.

These cases were chosen after an exhaustive search of possible cases based on NOAA's press releases, which often mention when HYSPLIT is applied in an official capacity, and guidance from the office that developed and maintains the model—NOAA's ARL. We were looking for uses that were important to society, reasonably routine (so illustrative of how the model can improve decisionmaking), and doable (all the necessary steps for a VOI analysis, as outlined earlier, could be taken, and we had a willing local contact to help develop the case).

Both of our cases fit these criteria. The Maine case demonstrates an important use of HYSPLIT in providing more efficient air quality area designations under the CAA. Specifically, HYSPLIT helped to show that the added expense of being in the OTR did not make economic or environmental sense for counties not contributing to air quality violations. It is illustrative because HYSPLIT is required to be used in similar air quality redesignation cases, such as by counties or larger areas that want to redesignate from nonattainment of standards to attainment or to exclude extraordinary events (such as days of high concentrations of particulate matter that is 2.5 micrometers or less in diameter [PM_{2.5}] from nearby wildfires) from their air quality performance calculations. We were able to work directly with local contacts from Maine's Bureau of Air Quality, who helped enormously in preparing the case study.

We had originally planned to do an extraordinary event exclusion case in Washington, in the middle of the state. However, the stakes for whether the exclusion was permitted or not were low, so we decided against pursuing it. Instead, details of how HYSPLIT is used for exceptional events are included in the Literature Review section.

The Husky case similarly demonstrates an important use of HYSPLIT because the decision to evacuate an area after a major disaster or other event is expensive and controversial and could significantly affect public health if the decision is wrong. It is illustrative of the application of HYSPLIT because many events, such as the Husky explosion, lead to evacuation and have major impacts. As in the Maine case, we chose this one partly because we were able to work closely with a contact in the National Weather Service office in Duluth, MN. The last subsection comments on how the Husky case results could be extrapolated, at least qualitatively.

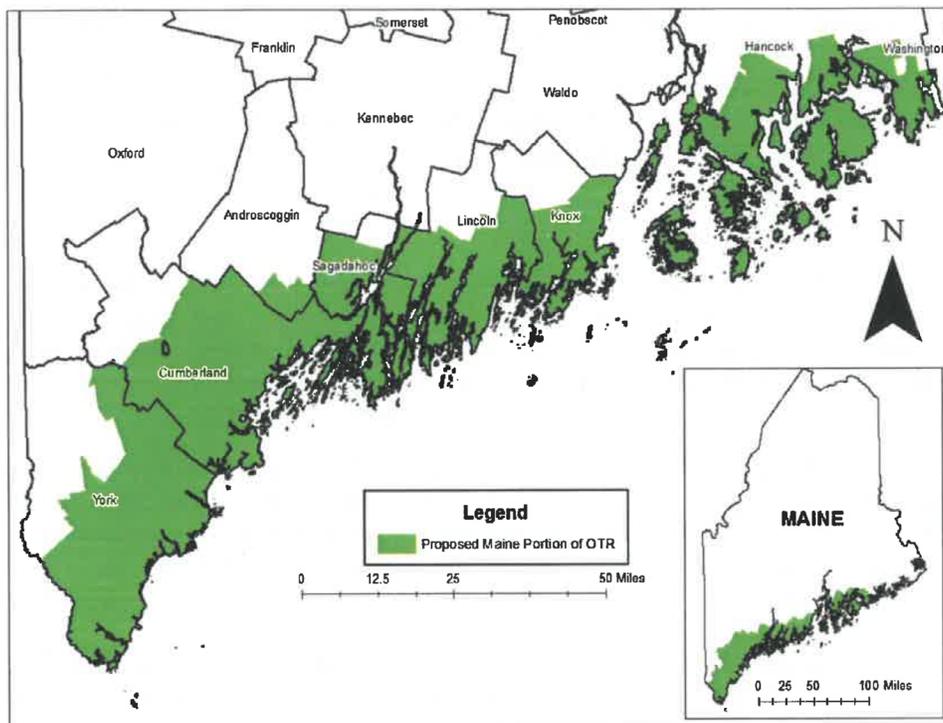
3.1. Maine Attainment Designation Case Study

3.1.1. Background and Use of HYSPLIT

All of Maine is part of the OTR pursuant to the CAA § 184(a) (42 US Code § 7511c). The OTR is a region subject to “moderate nonattainment” requirements under the CAA for emissions of ozone precursor pollutants—oxides of nitrogen (NO_x) and VOCs, to address regional ozone transport across state boundaries. These requirements apply to both existing and new sources and are more stringent than those for regions in attainment with ozone national ambient air quality standards (NAAQS) outside the OTR. Although all of Maine has been formally designated in attainment with ozone NAAQS since 2007, the state remains part of the OTR. This keeps applicable Maine facilities subject to control and operational requirements that are more stringent and more costly than they would otherwise be.

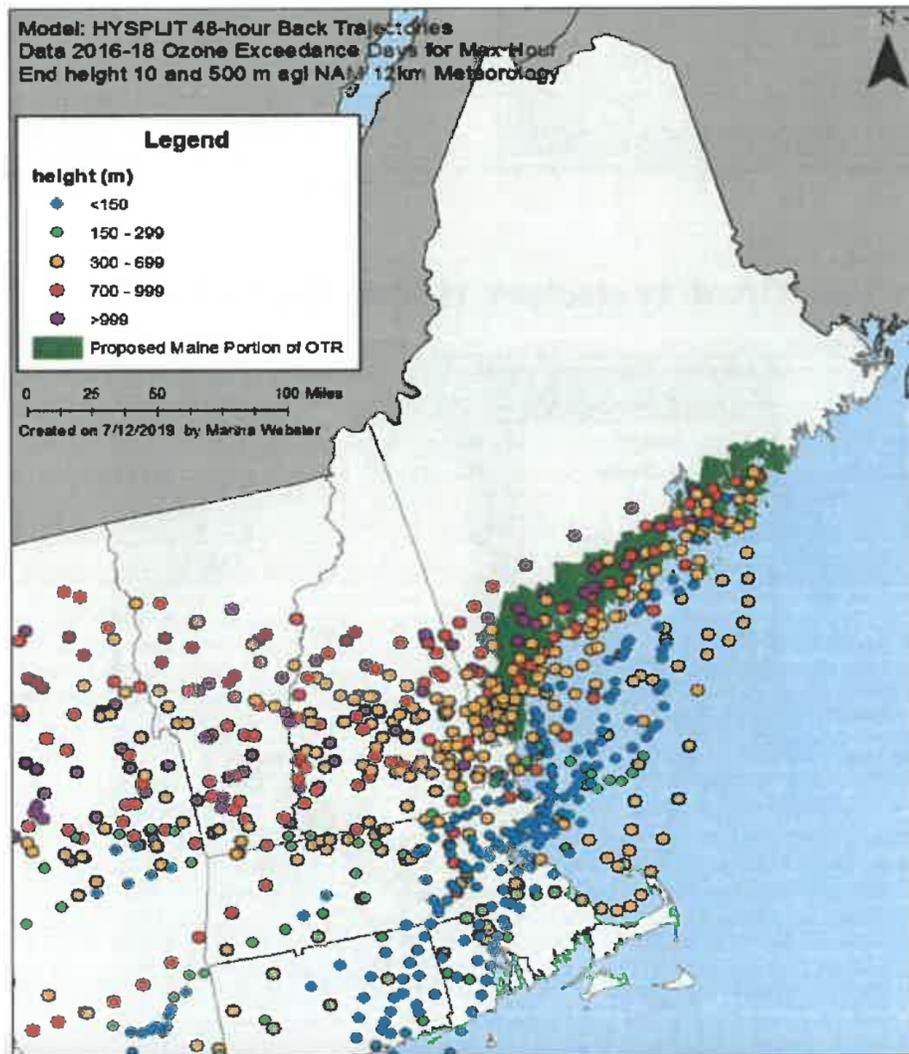
On February 6, 2020, the governor, Janet T. Mills, submitted a letter and petition to the US Environmental Protection Agency (EPA) requesting the “removal of the majority of Maine from the OTR,” with the exception of the communities shown in Figure 3, based on use of the HYSPLIT model runs to show this classification change will not significantly impact the ability of any other state in the OTR (or the part of Maine remaining in the OTR) to attain the ozone standard.

Figure 3. Maine Municipalities to Remain in the OTR



The petition shows that HYSPLIT back trajectories for 2016–2018 for monitor locations in the OTR recording ozone exceedances during that period were not attributable to ozone precursor emissions from Maine facilities. Multiple HYSPLIT runs were done to demonstrate that most of Maine was not causing ozone exceedances; a summary of such runs appear in Figure 4, which shows that Maine is not responsible for the ozone exceedances in the southern part of the state. Those were caused by emissions from south and west of the coast of Maine.

Figure 4. HYSPLIT model 48-hour Back Trajectories of Ozone Exceedance Days from 2016-2018 in Portland and Mid-Coast Ozone Maintenance Areas



Note, in Figure 4 above, each circle represents where frequent transport flows of particles found their way to the southern coast of Maine, differentiated by height in the atmosphere. Combining the proximity of points and their respective colors provides a sense of the path that a pollutant plume takes through time and elevation to arrive in Maine.

Maine requested that all the state be removed from the OTR, except 111 towns and cities in the Portland and mid-coast ozone maintenance areas that include select towns and cities in the following counties: Androscoggin, Cumberland, Hancock, Knox, Lincoln, Sagadahoc, Waldo, and York. Several towns within these specified counties were also petitioned for removal. The report included a variety of measures the state would take to ensure that removal would not adversely affect air quality in the future. As of this writing, Maine is still awaiting the EPA administrator's response.

For the purposes of this analysis, we assume that the decision to ultimately remove these parts of Maine from the OTR is attributable to the HYSPLIT back trajectories. We also assume that the petition will be granted. The expected benefits of HYSPLIT in this case (successful petition) are compared to the counterfactual case of what would have occurred if HYSPLIT were not available (no basis for the petition in the first place, so all of Maine would remain in the OTR).

3.1.2. Counterfactual Scenario

As noted, the counterfactual is what would have occurred if HYSPLIT had not served as evidence that Maine facilities were not causing exceedances and, consequently, they had not been removed from the OTR.

Despite uncertainty regarding what would occur in the future in both the change and the counterfactual scenarios, the counterfactual can be based on the historical record during the time that all of Maine was in the OTR. The entire state is subject to rules that apply in an ozone nonattainment area even though the state is formally classified as being in attainment with the ozone NAAQS ambient air quality standard. Maine has been subject to the following restrictions:

1. Enhanced vehicle inspection program
2. Stage II vehicle vapor recovery program
3. Reasonably available control technology (RACT) applied to all sources of VOCs
4. RACT for major sources of VOCs and NO_x
5. Nonattainment New Source Review (NSR)

Interviews with officials of the Maine air program revealed that the only requirement that would be alleviated if portions of Maine were removed from the OTR would be the NSR program requirements specific to areas in the OTR. Other OTR requirements that might otherwise have become inapplicable are being retained voluntarily as State Implementation Plan (SIP) strengthening measures.

NSR for major new or modified stationary sources in ozone nonattainment areas requires the use of technologies and/or controls to attain the lowest achievable emissions rate (LAER) for each ozone precursor pollutant (NO_x and VOC) whose emissions (new) or emissions increases (modified) are above threshold levels defined in the CAA. LAER is guided by EPA and defined in state plans, which prescribe the process to identify it. For residual emissions that cannot be controlled by LAER

technologies, sources in ozone nonattainment areas are also required to purchase emission reduction credits to offset the expected emissions increase at a rate greater than 1:1 (the ratio depends on the level of nonattainment).

For Maine, for an area designated as within an OTR, the regulations for NSR are stricter for major new sources of VOCs, which is a precursor to the formation of ambient ozone. A “major stationary source” for VOCs within an OTR region is defined as one with the ability to emit more than 50 tons of VOCs annually (40 CFR § 51.165). By contrast, a “major stationary source” for VOCs within an area of attainment can emit 100 tons per year. Thus, the counties under the OTR are currently subject to a standard for VOCs that is twice as stringent as it would be if they were not included in the OTR.

For this case, the focus is narrowed to exclusively consider the threshold for VOC emissions for a minor source becoming a major source. We do not focus on major modifications to existing major sources because the thresholds for determining a “major modification” are the same for VOCs in areas of attainment and those located within the OTR. Similarly, the focus is not on other NSR pollutants because VOCs are the only pollutant with a different threshold for becoming a major source in Maine within the OTR versus excluded from it. For NO_x emissions, for example, the threshold for a minor source becoming a major source for most major pollutants (such as power plants, oil refineries, and cement plants) is 100 tons per year regardless of whether the region is in an OTR.

The requirements for major sources for NO_x do change with respect to the control technology required. However, for this study, it is assumed that major sources in Maine that have already applied more stringent control technologies for NO_x will not dismantle them if taken out of the OTR.

There are a variety of sources in Maine with licensed VOC emissions limits close to the threshold that would classify them as major sources of VOCs. We do not observe actual emissions of minor pollutant sources in Maine but, with guidance from Maine’s Bureau of Air Quality, we assume that facilities operate close to or at their licensed limit at least some of the time. This tendency of facilities to near but not exceed 50 tons per year of VOC emissions suggests that these sources are constrained at their respective emissions limits because they are operating within the OTR region and elect to avoid being a “major stationary source” and subject to more stringent requirements. It is assumed that these sources would increase production capacity but do not because that would subject them to nonattainment NSR requirements. For major sources in the state that have already applied LAER and purchased offsets, it is assumed that that will not change their behavior, because of antibacksliding provisions.

Table 3. Facilities to be taken out of the OTR with Licensed Emissions Close to 50 tons/year

Facility Type	Location	Licensed VOC (tons/year)
Lumber Mill	Bethel, ME (Oxford County)	49.50
Bulk Petroleum Storage and Distribution	Bucksport, ME (Hancock County)	49.90
Petroleum Storage	Bangor, ME (Penobscot County)	49.90
Processing of Wood for Golf Equipment	Burnham, ME (Waldo County)	46.50
Bulk Petroleum Storage and Distribution	Searsport, ME (Waldo County)	49.90
Bulk Gasoline and Fuel Oil Terminals	Hampden, ME (Penobscot County)	49.90
Lumber Mill	Dover-Foxcroft, ME (Piscataquis County)	49.40
Electric Power Station (Cogeneration, Natural Gas and Oil)	Jay, ME (Franklin County)	49.90
Metal Fabrication and Coating	Pittsfield, ME (Somerset County)	49.90
Industrial Paper and Polyethylene Packaging Producer	Presque Isle, ME (Aroostook County)	49.90
Wood Pellet Manufacture	Corinth, ME (Penobscot County)	49.90
Wood Store Display Manufacturing	Milo, ME (Piscataquis County)	49.10
Aircraft Maintenance and Repairs	Bangor, ME (Penobscot County)	47.90
Railcar Cleaning and Repairs	Milo, ME (Piscataquis County)	49.90

3.1.3. The Change Scenario

The change scenario will eventually be observed, but this analysis is *prospective*, so assumptions are made about what will happen when most of Maine leaves the OTR. In fact, we assume that the facilities in Table 3 will double in production capacity and corresponding emissions. Comparing the change scenario to the counterfactual scenario, the benefits of leaving the OTR are the costs of nonattainment NSR that could be avoided if the plants choose to expand.³

The facilities considered in this study are listed in Table 3.

3.1.4. Attribution

A key element in the calculation of the benefits of HYSPLIT is attribution: how much of the benefits of removal from the OTR are attributable to HYSPLIT and how much to other factors. If multiple factors are involved, the benefits attributable to HYSPLIT would be reduced to account for the other factors that aided the decision.

We assume that the benefits of removal from the OTR can be attributed entirely to HYSPLIT because using HYSPLIT to prove that the change in status will not worsen air quality in other areas in the OTR is a necessary condition for obtaining EPA approval. Thus, without HYSPLIT, redesignation would not be possible, and those benefits (cost-savings) would not be realized. Of course, HYSPLIT back trajectories alone are not sufficient to obtain approval, as the area itself must also demonstrate that its ozone concentrations are below the ozone standard. However, this condition was met in 2004 onwards and resulted in all of Maine being designated as in attainment in 2007.

Another relevant basis for full attribution to HYSPLIT is the letter written by the Ozone Transport Commission to Congress testifying on behalf of the HYSPLIT team on how important HYSPLIT was to the OTR. Specifically, the Commission said that “the activities of the Air Resources Laboratory (ARL) [which supports HYSPLIT as its *raison d’être*] are enormously valuable to us for research into the atmospheric chemistry, air quality and mesoscale meteorology that is necessary to solve the problem of unhealthy air quality in the Eastern United States.”

Finally, there is no basis for choosing a degree of attribution to HYSPLIT other than 100 percent. Thus, for the purpose of this case study, it is stipulated that all the benefits of removal of the majority of the state of Maine from the OTR can be attributed to evidence from the HYSPLIT model.

To determine the value of HYSPLIT in this and similar settings, it is assumed that, as HYSPLIT is the EPA-mandated model for this setting, if it were not available, the

³ This is a simplification. Presumably, the plant would expand to increase profits. We can assume that the plant did not expand with the OTR in place because the added costs of NSR would exceed the increased profits. Without the NSR restriction, we assume that the cost-savings is a minimum estimate of the benefit to the plant, as profitability would also increase.

redesignation would not be approved and the state and its affected municipalities would not realize the expected economic benefits. There is reason to believe this assumption is reasonable based on conversations with officials in Maine.

3.1.5. The Benefits of Reclassification

A reasonable estimate of the benefits of reclassification is a comparison of the costs that emitting sources in these areas would incur under the counterfactual scenario versus the change scenario. Since the counterfactual scenario presents additional costs to these sources, the benefits would be the costs avoided by removal from the OTR. Following the judgment by Maine Bureau of Air Quality officials, the primary material impact of OTR removal is the lifting of nonattainment NSR restrictions. The benefits of lifting these restrictions for major stationary sources can be substantial. For this case, we focus on the benefits of less-stringent requirements on certain facilities' ability to expand operations.

For these areas in Maine, these benefits are primarily avoiding restrictions on development from the nonattainment NSR program or, alternatively, the cost of compliance with the nonattainment NSR requirements over and above the costs of emissions controls that would be required if not part of the OTR.⁴ These additional costs are the costs from requiring LAER for VOC for all major new and modified sources (as defined by the NSR program—VOC emissions above 50 tons per year for new sources and VOC emissions increases above 40 tons per year for major modifications) minus the costs of Best Available Abatement Technology (BACT) requirements. Because the nonattainment NSR program requires offsets (at a ratio of at least 1.15 tons of VOCs reduced for any “new” ton of VOCs emitted after LAER is applied), avoiding having to purchase offsets is another, potentially major, benefit of the attainment redesignation.

Formally, then, the benefits of removal from the OTR are (1) the difference in the present discounted costs of LAER versus BACT technologies for all eligible sources making major modifications (or minor sources that become major sources); (2) the same for all eligible new sources to the area; (3) the costs of purchasing offsets for VOC emissions from each of these sources; and (4) any related economic growth that would not have occurred without eliminating the nonattainment NSR requirements.

Estimating (2) and (4) is difficult, as they involve hypotheticals about the development of new facilities in the area and other changes due to economic growth; they are not considered here. For (1), we know of at least a handful of facilities in the petitioned area that are licensed just under the VOC major source threshold and can be assumed to expand further through lower abatement and zero offset costs ((1) and (3)).

4 We assume that NSR costs are modest enough that the economic growth would have occurred even with having to meet NSR requirements. It is possible that these NSR requirements are so onerous that potential new major sources and modifications to existing sources for VOCs are discouraged from locating in the counties in question, in which case, our calculations underestimate costs because they exclude forgone growth of local industry.

Sources

Air emission licenses were examined for sources that might be expected to expand operations if nonattainment NSR requirements were lifted, and 14 facilities were found that are licensed to emit VOC up to 49.9 tons per year—just below the cutoff for “major stationary source” requirements. It was assumed that these facilities are emitting at or near this level at least some of the time and would double their operations if nonattainment NSR requirements were lifted. This is admittedly a strong assumption, but accurately forecasting facility decisions is impossible. A doubling is a reasonable assumption because it is expected that it would be profitable for these sources to expand their operations up until the point that they are considered a “major” source, which, if taken out of the OTR, increases from 50 to 100 tons per year for VOC emissions. Table 4 lists the emissions information of these sources.

Presumably, these sources meet BACT requirements that result in licensed emissions in Table 3. If LAER were required for these sources, it would be expected to result in lower emissions totals and reduce the number of emissions offsets required to be purchased. If LAER were defined to be the same as BACT technology, then doubling the facility production would result in twice the emissions.

A newly designated major source within an OTR has three options to comply with NSR: complete control of residual emissions by LAER technology, partial control from LAER technology supplemented by offsets, or complete coverage by emission offsets in the absence of clearly identifiable LAER technology.

Our research has revealed no identifiable LAER control technologies for any of the 14 identified sources. Therefore, it is assumed that if the sources were to each double in size under the counterfactual scenario and be subject to nonattainment NSR, their only additional costs would be the purchase of offsets.

A simple example will clarify. Suppose a plant is currently emitting 45 tons of VOCs per year (currently a minor VOC source). If taken out of the OTR, the plant would presumably double in size and expand to below the new major source threshold of 100 tons per year, emitting 90 tons of VOCs per year (and still be a minor VOC source). If the plant within the OTR were to expand in this way, then the NSR threshold for VOCs would still be 50 tons per year, and thus the plant would be required to be licensed as a major source under Title V (minor modification making the facility a major source) in the state and control their 40 tons per year of VOC emissions beyond the minor source threshold.

Table 4. Estimated Offset Costs

Licensed VOC (tons/year)	Residual Emissions (Above 50 tons per year) After Doubling	Offset Requirements (TPY, 1.15 x Residual Emissions)	Total Offset Cost (Range, Thousand\$)
49.50	49	56.35	\$169.05–394.45
49.90	49.8	57.27	\$171.81–400.89
49.90	49.8	57.27	\$171.81–400.89
46.50	43	49.45	\$148.35–346.15
49.90	49.8	57.27	\$171.81–400.89
49.90	49.8	57.27	\$171.81–400.89
49.40	48.8	56.12	\$168.36–392.84
49.90	49.8	57.27	\$171.81–400.89
49.90	49.8	57.27	\$171.81–400.89
49.90	49.8	57.27	\$171.81–400.89
49.90	49.8	57.27	\$171.81–400.89
49.90	49.8	57.27	\$171.81–400.89
49.10	48.2	55.43	\$166.29–388.01
47.90	45.8	52.67	\$158.01–368.69
49.90	49.8	57.27	\$171.81–400.89
Total			\$2,356.35–5,498.15

Offset Prices

Offsets would need to be purchased either from sources in the coastal Maine counties remaining in the OTR or from Massachusetts, which has an offset agreement with Maine. Unlike California and Houston where transparent offset markets exist and prices are published, in New England, offsets are obtained from brokers who facilitate buying and selling them (emissions reduction credits) and do not publish price information. Prices for VOC offset transactions through these private brokerages are currently \$3,000–7,000 per ton/year,⁵ depending on whether the offset is sourced from within Maine or from a fellow OTR state. Table 4 lists the offset costs of the facilities expanding in size.

3.1.6. Results and Conclusion

For these 14 facilities currently located within the OTR, the estimated associated cost-savings for removal—and the associated value of the HYSPLIT model for this specific application—is roughly \$2.3–\$5.5 million per year in avoided costs for offsets associated with expanding these facilities. With a budget of \$2 million annually for HYSPLIT upkeep and improvement, this one application provides benefits exceeding the budget every year.

Of course, there are many caveats. First, the change in OTR status is still awaiting EPA approval, although such approval is expected. Second, although demonstrating no impact of removal from the OTR is a necessary condition for approving Maine's petition and the HYSPLIT runs were highlighted by Maine officials as crucial to this demonstration, attributing 100 percent of saved costs to HYSPLIT is a strong assumption. Third, we assumed that nonattainment NSR requirements for plant expansions within the OTR would be covered entirely by offset purchases, rather than a combination of greater treatment stringency (LAER rather than BACT) and offset purchases. This assumption was based on the difficulty of defining LAER technologies for controlling VOC emissions beyond the BACT technology already in use. Fourth, it was assumed that the 14 plants with licensed emissions limits at or near the 50 tons VOCs per year threshold for major sources have emissions up to their permitted amount at least some of the time. Lastly, we assumed that plants freed up from nonattainment NSR requirements would double in size, which may not be reasonable or precise. It is expected that the 14 plants would likely expand if not for nonattainment NSR requirements, but how much cannot be predicted. Some plants could expand in this way or grow even larger, whereas others would be unable to expand their footprint to this degree. In any event, the benefits of HYSPLIT scale directly with this assumption. So, if the expansion were 50 percent of existing operations, the benefits as quantified would be half as large. Note, however, that the additional profit from expansion is not being counted. So, given the assumptions, these benefits are underestimates because the additional profit was not taken into account.

5 Email communication with John McDougal, vice president of Environmental Products, Elemental Markets (elementalmarkets.com).

3.2. Husky Refinery Case Study

3.2.1. Background and Use of HYSPLIT

On April 26, 2018, a large plume of black smoke was seen coming from an explosion that occurred at 10:06 AM at the Husky Energy oil refinery in Superior, Wisconsin within the fluid catalytic cracking unit. Debris from the explosion punctured the nearby asphalt storage tank, causing it to leak. Emergency responders and firefighters put out the fire at 11:00 a.m. However, the asphalt continued to leak over at least a 10,000 m² area. At 12:15 p.m., a large black plume was seen going hundreds of feet into the air, which was the result of the asphalt catching fire (Figure 5). In addition to smoke from the burning asphalt, up to 6,800 kg of highly toxic hydrofluoric acid (HF) might have also been released (this concern was later determined to be unfounded), and other units at the refinery were placed in danger.

Figure 5. Second Plume at the Husky Refinery



An evacuation notice was ordered at 12:43 p.m. for all persons within 3 miles east and west of the refinery, 10 miles south, and 1 mile in all other directions (Figure 6). Approximately 6,000 people live within this boundary. The northern extent of the evacuation zone was communicated in contradictory ways: sometimes 3 miles and sometimes 1 mile. The county eventually published a graphic showing the northern extent to be a 1-mile-radius half circle with a cautionary notice for those living in a 2-mile-radius half circle north of the fire. Reviews of the event recognize the conflicting evacuation orders but identify the official evacuation zone to be a 1-mile-radius half circle to the north plus the 6x10 mile rectangle to the south of the facility. Because of the broadcasting confusion over the northern boundary, we include all three possible

distances in our analysis to account for scenarios in which people may have evacuated within all three zones. Thus, the evacuation order covered a maximum of 74 square miles and a minimum of 62 square miles. The second fire was put out around 6:30–6:45 p.m., and the evacuation order ended at 6:00 a.m. the next day, a little more than 17 hours after the initial evacuation notice was issued.

Figure 6. Evacuation Zones for the Husky Fire

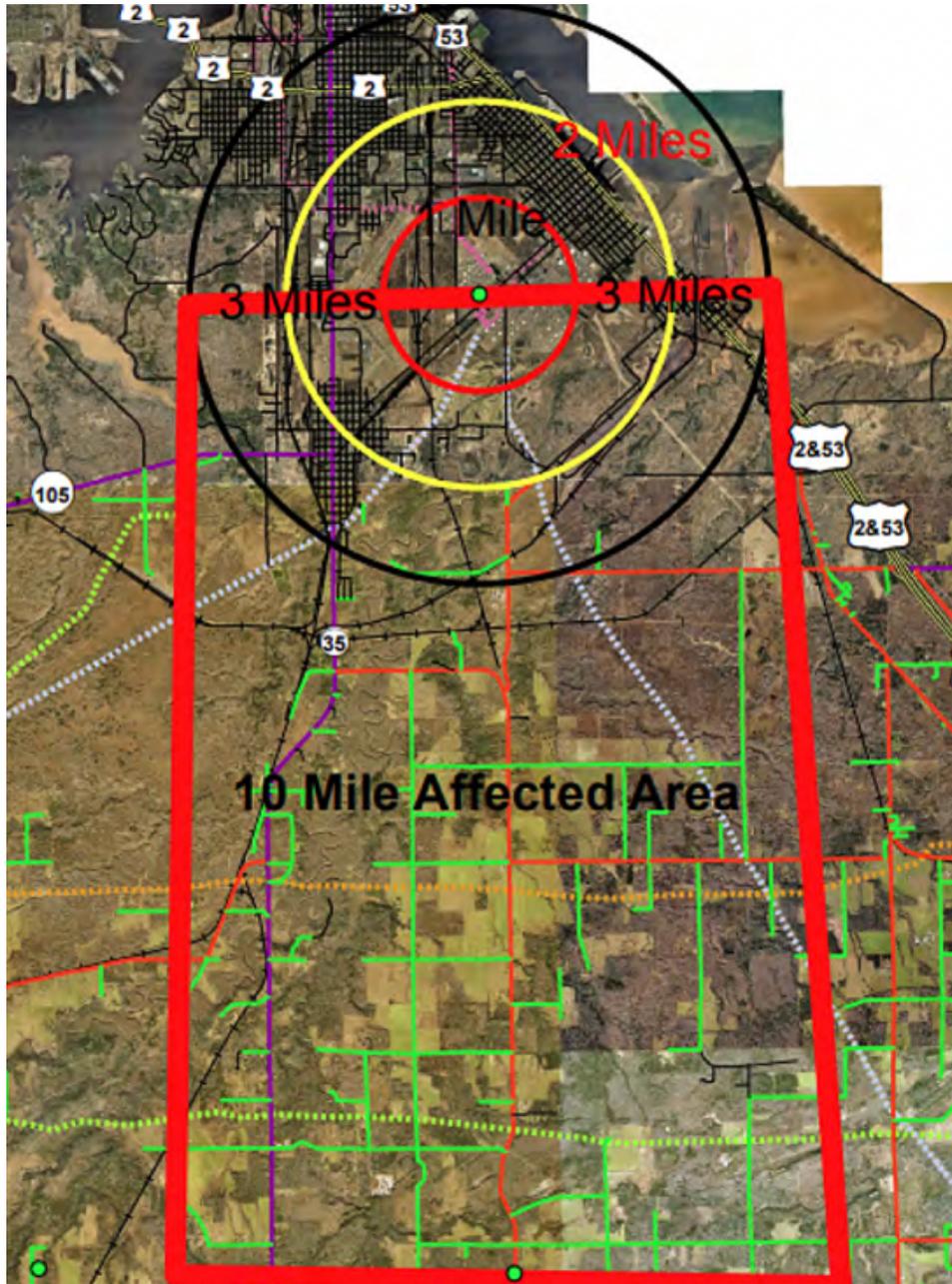


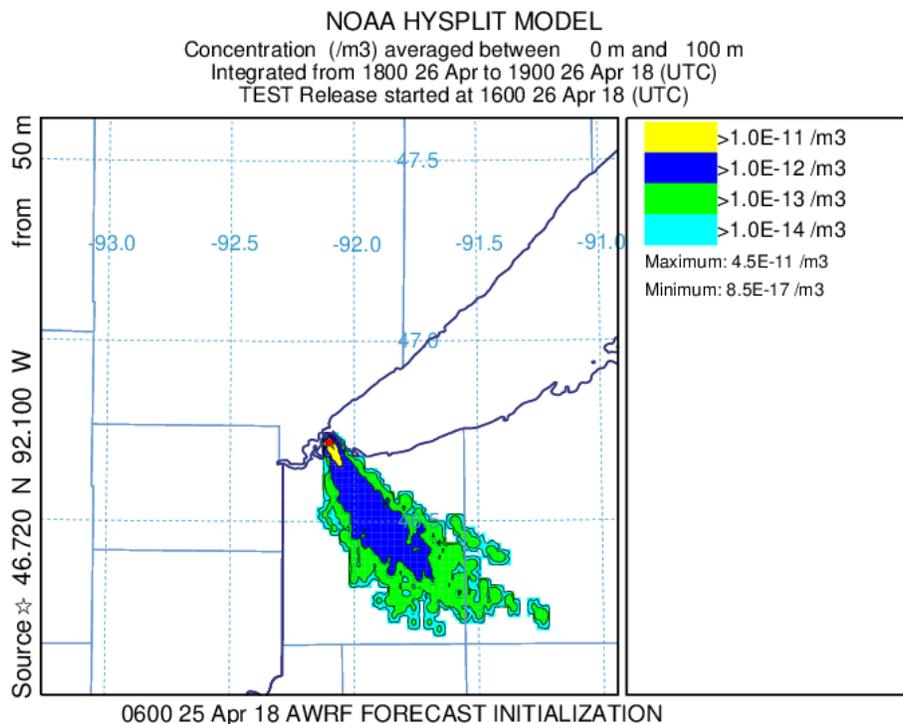
Table 5. Log of HYSPLIT Runs for Husky Refinery Event

Date (Local)	Job ID #	Time (UTC)	Time (Local)
4/26/2018	22,974	22:46	16:46
4/26/2018	22,976	17:46	11:46
4/26/2018	22,981	23:49	17:49
4/26/2018	22,982	18:49	12:49
4/26/2018	22,983	2:09 ⁺¹	20:09
4/26/2018	22,988	21:09	15:09
4/26/2018	22,989	2:31 ⁺¹	20:31
4/26/2018	22,991	21:31	15:31
4/26/2018	22,992	3:14 ⁺¹	21:14
4/26/2018	22,993	5:46 ⁺¹	23:46
4/26/2018	22,995	0:46 ⁺¹	18:46
4/26/2018	22,996	6:08	0:08
4/26/2018	22,997	1:08 ⁺¹	19:08
4/26/2018	22,998	6:47	0:47
4/27/2018	23,000	1:47 ⁺¹	19:47
4/27/2018	23,001	6:48	0:48
4/27/2018	23,002	1:48 ⁺¹	19:48
4/27/2018	23,003	7:17	1:17

HYSPLIT runs were performed almost immediately following the first explosion to estimate where the smoke plume would travel, and runs were performed continuously throughout the day and night. Figure 7 is an example of a plume forecast from a HYSPLIT run. In all, 19 official runs were made (Table 5). All but four runs were on the day of the fire, with one run after the first explosion and the next logged in a half hour after the second plume was observed. Curiously, the last run (3:11 a.m. the next day) and another run five hours earlier are labeled as runs for hydrogen fluoride (HF; that is, hydrofluoric acid), even though the model does not generate unique results for this substance. The fact that these runs came after the event was over suggests they were to intended for emergency response on the twenty-seventh, at least until it was determined whether the HF tanks actually ruptured (they had not). Usefully, the emissions quantity modeled (6,804 kg) was indicated in the HYSPLIT run log, along with the designation that this substance and, perhaps, emissions rate, made it an Acute Exposure Guideline Levels for Airborne Chemicals (AEGL) event. We say more about this later.

Based on conversations with the team in Duluth, MN and documents from the event, we assume that the early HYSPLIT forecasts for the smoke plume were critical in defining the evacuation zone. Due to confidentiality concerns, it has not been possible to determine from the event management team how they set the evacuation zone. However, the HYSPLIT team in nearby Duluth was in constant contact with the event managers and sent them HYSPLIT runs continuously during the event, which gives us confidence that HYSPLIT was essential in setting the evacuation zone.

Figure 7. A Recreation of a HYSPLIT Plume Unit Emissions Concentration Simulation for the Huskv Fire



3.2.2. The Counterfactuals

The most difficult and speculative part of a VOI analysis is often the counterfactual scenario: in this case, what the evacuation zone would have been if HYSPLIT results were not immediately available. We can imagine that decisionmakers would have consulted the weather forecast showing winds from north-northwest to south-southeast and determined that Duluth to the north would not have to be evacuated. Beyond that, it is unclear. One option would be to follow standard procedure. The Center for Disease Control (CDC) has evacuation guidelines available. Another option is to follow Husky Energy's evacuation guidance for potential disasters (Husky Energy, 2019). A third option is to set an evacuation zone that is broad enough to encompass all the conceivable geographic area that could be affected by the plume. The first two options would have resulted in a smaller area for the evacuation zone, as it turns out. The third option would, by definition, have resulted in a far larger area. We model all three, terming the third the "risk avoidance scenario." Each evacuation scenario considered in our analysis is outlined in Table 6.

CDC Guidance

For this scenario, we assume that in the absence of HYSPLIT modeling, the evacuation zone would have been set according to response guidance available for the chemical components of asphalt. While asphalt fumes contain many chemical compounds, such as PAHs and PACs, we found limited guidance by major US disaster response agencies for the specific chemical makeup of asphalt. Ultimately, we use CDC evacuation recommendations for benzene, considering it a suitable representative for the hydrocarbons in asphalt fumes (Butler, 2000). The CDC recommendation is for evacuation in a 0.5-mile zone in all directions from the source of a tank fire (CDC, 2011). Because of the expansive size of the Husky facility and the location of the fire (close to the center of the plant), we have added an additional 1 mile to the baseline evacuation radius to compensate for potential differences in interpreting the CDC standard. The 0.5-mile CDC-informed zone constitutes an extension beyond the perimeter of the plant, producing a 1.5-mile radius evacuation zone that we use as this counterfactual evacuation order; this would have evacuated 4,000 people.

The estimated benefits of HYSPLIT in this scenario will be relative to this counterfactual, in which only about 7 square miles are evacuated. Compared to the 62–74 square miles actually evacuated, depending on which of the contradictory notices about the zone determined evacuation behavior, this counterfactual results in far fewer people being evacuated than were under the HYSPLIT scenarios.

Husky Refinery

For this scenario, we assume decisionmakers would have followed Husky Energy's evacuation plan. We do not know the precise boundary for this zone, but a local news article cites the refinery's plan as having identified 7,000 people in the surrounding area who would be at risk in the event of a serious disaster (Johnson, 2018), so we assume that local officials would have responded to the Husky fire by evacuating

the nearest 7,000 people to the refinery. Our estimates suggest this would require an approximate 2-mile radius evacuation in all directions, or about 13 square miles. As in the CDC scenario, this results in fewer people being evacuated than actually were.

Risk Avoidance

For this scenario, we assume that a larger evacuation zone than the one provided by HYSPLIT would have been set. Specifically, we assume that the eastern, western, and southern borders of the evacuation zone would have been extended 3 miles. All in all, this assumption adds 78 square miles to the evacuation zone and 3,250 people to the evacuation.

Table 6. Evacuation Scenarios

Scenario Name	Scenario Description
CDC Counterfactual	1.5-mile-radius circle evacuation zone; 4,149 people evacuated
Husky Counterfactual	2-mile-radius circle evacuation zone; 7,000 people evacuated
1-Mile North Radius HYSPLIT	Evacuation zone of 1-mile-radius half circle to the north, 3 miles east and west, and 10 miles south; 6,064 people evacuated
2-Mile North Radius HYSPLIT	Evacuation zone of 3-mile-radius half circle to the north, 3 miles east and west, and 10 miles to the south; 26,336 people evacuated
3-Mile North Radius HYSPLIT	Evacuation of an additional 3 miles in each direction west, east, and south beyond the rectangular portion of the HYSPLIT zone
Risk Avoidance	Evacuation of an additional 3 miles in each direction west, east, and south beyond the rectangular portion of the HYSPLIT zone

3.2.3. The Benefits of HYSPLIT

Given the difference in the evacuation zones associated with the HYSPLIT reference case (what actually happened) and the counterfactuals, benefits come in two possible classes. The first can be termed a type I error, which is a false positive: assuming that

the HYSPLIT-derived evacuation zone is the appropriate zone, the CDC or Husky zones would have been used instead. Under either counterfactual, many people who should have been evacuated would not have been, so there would have been health effects from exposure to the smoke. Consequently, the benefits of HYSPLIT under a type I error would be the avoided health costs that would have occurred under the counterfactual scenario.

Weighed against this benefit are the costs of the evacuation itself. Husky Energy agreed to pay all claims for evacuation costs, and thus the evacuees would be made whole. However, the costs to Husky do count as social costs and therefore must be included in the analysis. The evacuation costs of the HYSPLIT zone minus the costs of only the 1.5-mile radius zone (in the CDC case) would be subtracted from the health benefits to provide an estimate of the benefits to HYSPLIT in this case.

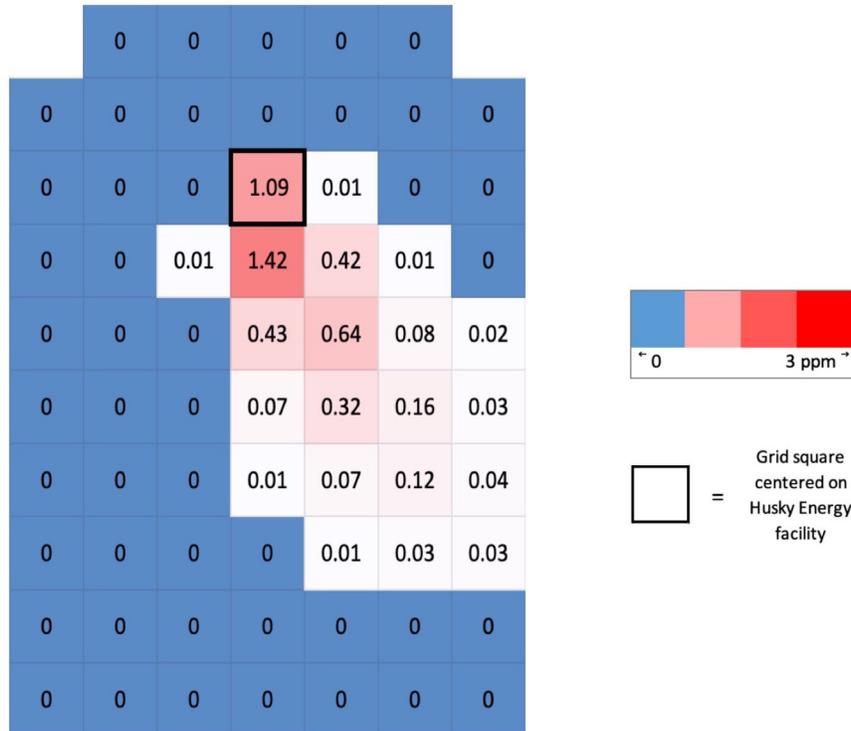
The second benefit class is the avoidance of a false negative, or Type II error, which would be the costs of evacuating people unnecessarily. As the CDC and Husky zones are embedded in the HYSPLIT zone, no one fits this second class for those counterfactuals. However, in the risk avoidance counterfactual, more than 3,000 additional people would have been evacuated. Weighed against this benefit are the health damages, if any, from these people not evacuating under the HYSPLIT scenario.

Before getting into the details, we note a few issues. First, there may have been property damages in addition to health effects from the plume, but these were unavoidable with any evacuation plan and therefore do not count in a VOI analysis.

Second is the issue with HF. The HYSPLIT team was working with decisionmakers to address plume direction and dispersion, but the plume constituents were uncertain. The burning asphalt contained very high levels of fine particulates, some of which were carcinogenic. But a bigger concern was the HF, which is highly toxic and life threatening at 22,000 ug/m³ for eight hours (AEGL-3) and has action levels at 1,000 ug/m³, or 1 ppm (AEGL-1, eight hours or less) (US EPA, 2020b).

Thus, the HYSPLIT team did two runs for the amount of HF stored at the refinery that could have been in the plume. Because NOAA only archives complete HYSPLIT run results for 90 days, ARL staff reran HYSPLIT for the atmospheric conditions on the day of the event to reproduce calculations similar to those that the team would have generated at the time. As we see in Figure 8, even in the final hour of the fire where a release would result in the greatest downstream concentrations, only people living in a 4 km² radius would experience HF levels at or over the AEGL-1 threshold of 1 ppm, and this would be for only a single hour as opposed to the eight-hour time frame established by AEGL-1. We assume that the HYSPLIT team observed this limited risk and quelled emergency response officials' concerns about a devastating HF release.

Figure 8. HYSPLIT Simulation Results for a Complete Hydrogen Fluoride Release from 6:15–7:15 p.m., with ppm Concentrations per 2 km Grid Square

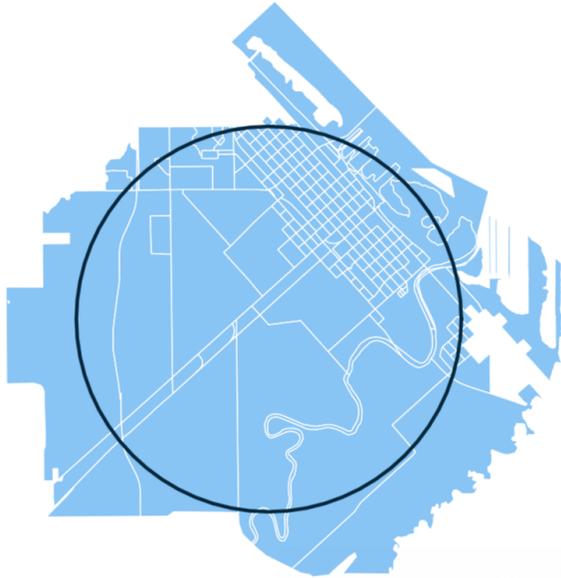


3.2.4. Methods and Components of Estimating Health Benefits

The health benefits from avoiding what we shall see were very high PM_{2.5} concentrations are not easy to estimate. The standard epidemiology models used to estimate health benefits from tighter ambient air quality standards do not examine events as extreme as the Husky fire. Rather, they are derived from pairing relatively small ambient differences in air quality over time and space with observed health impacts of many types. Although we use this approach in one of our cases, it provides very small benefits. Another approach is to assume, as is logical given the high concentrations of PM_{2.5} observed for a short period, that anyone not evacuated in the HYSPLIT zone could have experienced some health impacts, depending on how high the PM_{2.5} concentrations were. We take this approach below, as well.

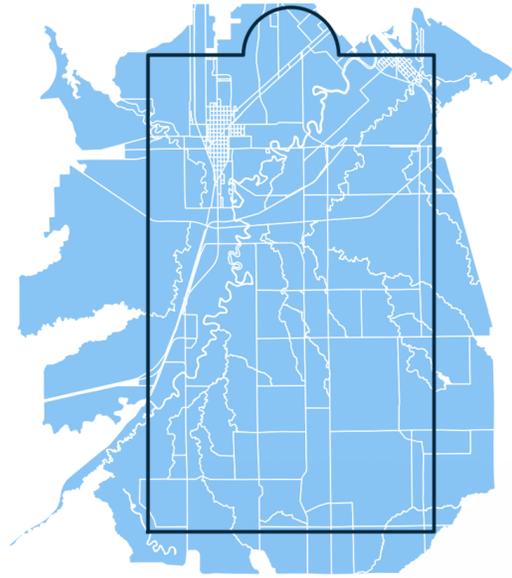
We can monetize health benefits of avoided exposure using either of these two approaches. A third approach is to examine how many people would have been exposed to concentrations above critical levels had they not been evacuated. We use two critical levels for PM_{2.5}—250 $\mu\text{g}/\text{m}^3$, noted by EPA as hazardous and threatening death, and 150 $\mu\text{g}/\text{m}^3$, labeled as very unhealthy. For HF exposure, as noted, the action level is 1,000 $\mu\text{g}/\text{m}^3$ (1 ppm). Several steps are needed to estimate the health benefits.

Figure 9. Census Tract Population Plots

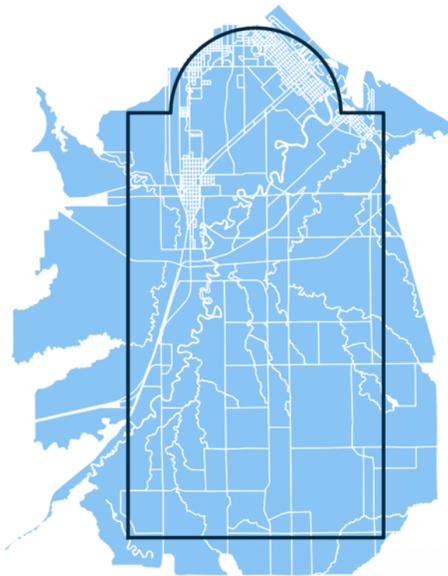


CDC Counterfactual Census Tracts

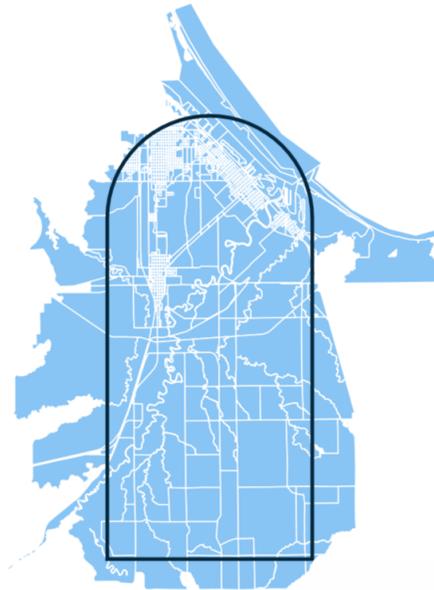
Population: 4,149 People



1-Mile North Radius
HYSPLIT Census Tracts
Population: 6,064 People



2-Mile North Radius HYSPLIT
Census Tracts
Population: 14,764 People



3-Mile North Radius
HYSPLIT Census Tracts
People: 26,336 People

Population Data

First, we need the population evacuating according to the evacuation zone defined by the team and the population that would have been evacuated in the counterfactual cases. We used census tract population data from the Bureau of the Census to estimate the population that would have experienced health effects were it not for use of HYSPLIT in setting the proper evacuation zone. Figure 9 presents plots to visualize the census tracts included in each evacuation group and the total populations calculated to be in each zone. The axes are latitude and longitude. These plots demonstrate that the number of people affected by the evacuation zone choice is largely dependent on the extent of the half circle border extending northward from Husky Energy, with the 3-mile-radius zone containing more than 20,000 more people than the smaller 1-mile-radius zone.

Pollution Concentrations

The second step is to figure out the incremental pollution concentration exposure for this population were it not for the HYSPLIT determination of the evacuation zone. Which pollutants are relevant? Clearly, these include HF and the smoke itself, which primarily consists of PM2.5 and a variety of VOCs, PACs, and PAHs. Research shows that exposure to PM2.5 is directly linked to negative health effects, but this is inconclusive for many VOCs. Benzene is one example of the hydrocarbons present in asphalt and is a known carcinogen, but the one day of exposure would not result in any measurable damages. Hence, we focus only on health impacts from PM2.5 concentrations.

We need a baseline concentration from before the event and concentrations associated with the event. The easiest approach would be to consult ground-based monitors. There is an Air Quality Index measurement for the day before from monitors in Duluth, and the air quality was quite good, in the range of 5 ug/m³ PM2.5. Unfortunately, no permanent PM2.5 monitors were located in the immediate path of the smoke plume or in the evacuation zone during the event. The closest permanent PM2.5 monitors in the direction that the plume traveled were more than 100 miles southeast of the facility. After the first fire was extinguished, Husky Energy deployed four monitors to track residual emissions. Unfortunately, the larger second explosion and fire rendered all four monitors inaccessible and resulted in the loss of all telemetry from the pre-established equipment. EPA response efforts resulted in the only usable air quality monitoring information immediately following the event from ground-level monitors: one monitor in the hot zone, intended to protect first responders, and a system of fence-line monitors and neighborhood-based mobile monitoring, intended to protect the community from residual effects of the fire's emissions. The EPA data are useful largely for recording PM2.5 concentrations in the days immediately after the fire, though concentrations data are lacking for the day of the event.

With this paucity of information on event-day concentrations, we considered several options. We could use satellite data or actually rely on HYSPLIT to run scenarios, given the meteorological conditions from the period of the event, or both. We rejected satellite data for several reasons. The data relevant for PM2.5 concentrations would

come from the MODIS satellite, which measures aerosol optical depth (AOD) that is then converted to PM_{2.5} concentrations (NASA, 2020). One issue is that only one satellite reading exists on the day when the plume was active—at 1:30 p.m. Thus we have no idea how the concentration changed over time. Second, it is assumed in the AOD calculation (which measures optical depth near the ground and very high in the atmosphere) that the ground level and lower atmosphere have good mixing (i.e., homogeneity of AOD with altitude). Clearly, this was not the case, as the plume stood out. Third, converting AOD to PM_{2.5} is not straightforward and becomes more problematic for smaller areas. Fourth, pressing ahead on all of these issues yielded an increase of PM_{2.5} concentrations that was *at most* (over the 3 km grid squares for 1:30 p.m.) 12 ug/m³ above the background (5 ug/m³), meaning that the satellite approach yielded an overall highest reading of 17 ug/m³. With the PM_{2.5} 24-hour standard of 35 ug/m³ as protective of public health, and given the dark smoke cloud produced by the Husky fire, this low concentration is implausible.

HYSPLIT Modeling

The second approach is to use new HYSPLIT runs (model version 1345) directly to simulate the event average and hour by hour PM_{2.5} and HF concentrations. Using NOAA HRRR meteorological data with a 3 km resolution and 36 vertical levels from the event day and an emissions rate of 1 gm/hour, concentrations were simulated over grid squares of 2 km on a side. These were then multiplied by assumed emissions rates to arrive at concentrations. The model treats particulate and HF emission diffusion and dispersion identically.

The assumed emissions rate of PM_{2.5} is based on reviews of the event stating that 15,000–17,000 barrels of asphalt, some 2.7–3.1 million kg, leaked from the punctured storage tank. Our calculations are based on 15,000 barrels of spilled asphalt. The amount of spillage recovered and disposed of after the fire was extinguished is unknown, as is the amount burned. In our calculations, we assumed that 50 percent of the leaked asphalt was burned over the seven-hour incident. Dividing the amount of burned asphalt by seven hours and assuming that 75 percent of particulates generated by the burn were PM_{2.5}, the modeled emissions rate was 1.5E+08 gm/hr of PM_{2.5}.

We choose this percentage for several reasons. A study of emissions rates from burning oil spills in Alaska implied that an oil spill covering 930 m² resulted in a burn rate of around 2E+07 gm/hour (Cohen, 2019; McGrattan, Putorti, Twilley, & Evans, 1993). Applying that rate to the Husky case implies around 5 percent of the asphalt spilled would have burned. Because asphalt is thicker than oil, perhaps less of it would burn per unit of time. On the other hand, examination of the burn area in satellite and drone photos and in visual simulations from the Chemical Safety Board suggests that the burn area was larger, perhaps more than 10 times larger (CSB, 2019). With the burn rate in the Alaska study being approximately proportional to area burned, this implies that 50 percent of the asphalt actually burned. We believe this estimate is probably on the high side. However, as Figure 10 shows, even assuming 50 percent of the leaked asphalt burned, health benefits estimated from standard epidemiological studies are very small and exceedances of critical concentration levels are also low.

The last step to estimating concentrations is to multiply the concentrations associated with the 1 gm/hour emissions rate (Figures 10 and 11) by the assumed gm/hr of PM2.5 actually emitted (1.5E+08 gm/hr), which gives us the change in PM2.5 resulting from the event.

Figure 12 shows the event average concentrations for each grid square in the evacuation zone for the 50 percent burn scenario, assuming a constant rate of hourly burn over the duration of the event, as well as average concentrations for the 5:15–6:15 p.m. hour when the wind direction and force changed. The highest concentrations are observed in the grid square containing the emissions source, and the next highest grid squares are directly downwind of the source. Also, observe that the concentration gradient falls off rapidly with distance downwind and with lateral distance outside the central plume trajectory. These observations are important to determining health effects. Both concentration maps illustrate the extreme levels of PM extending southeastward, deep into the area evacuated because of HYSPLIT.

Figure 10. Modeled Ground-Level (0–100m) Hourly Concentration Averages (pg/m³) for 12:15 p.m. to 7:15 p.m

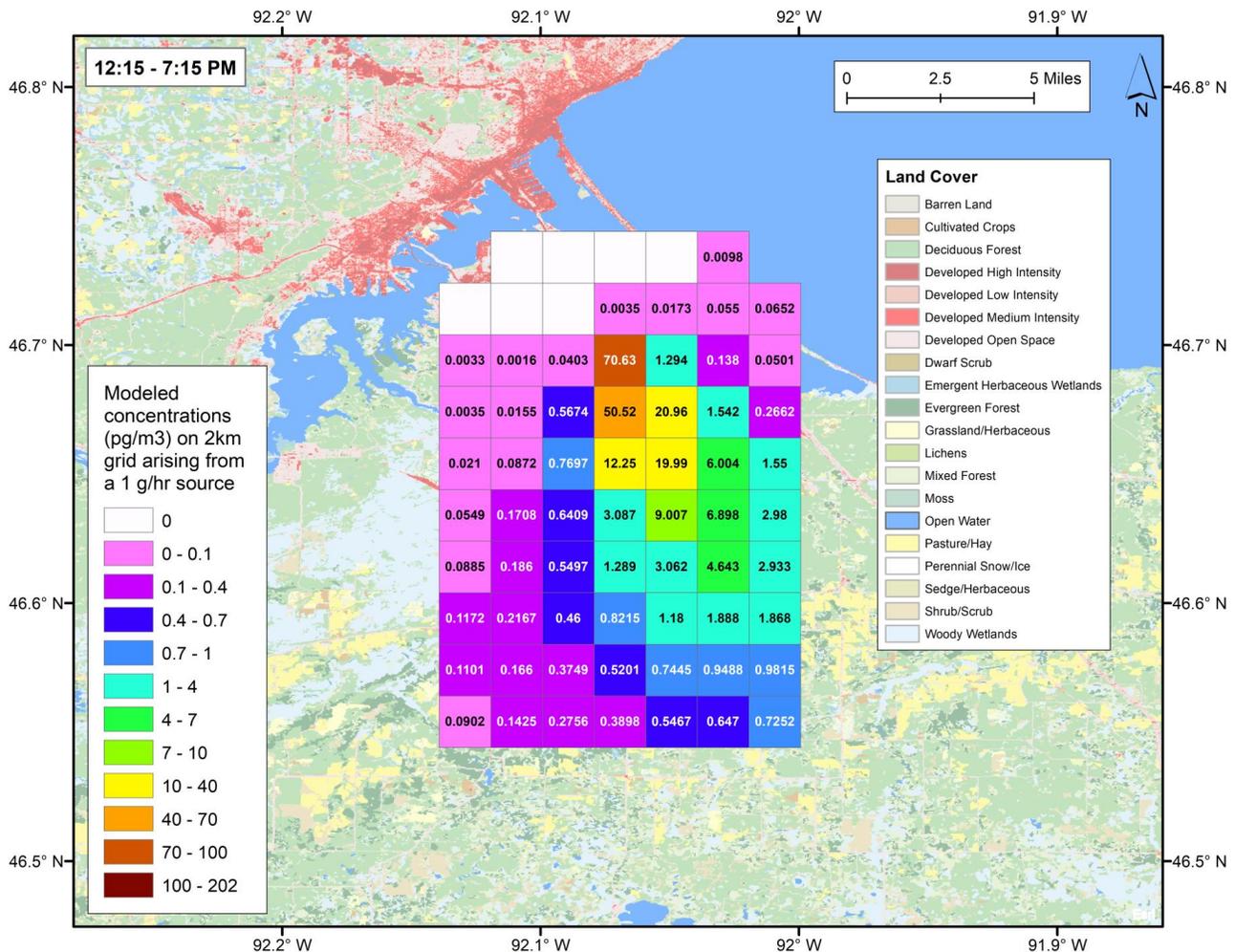
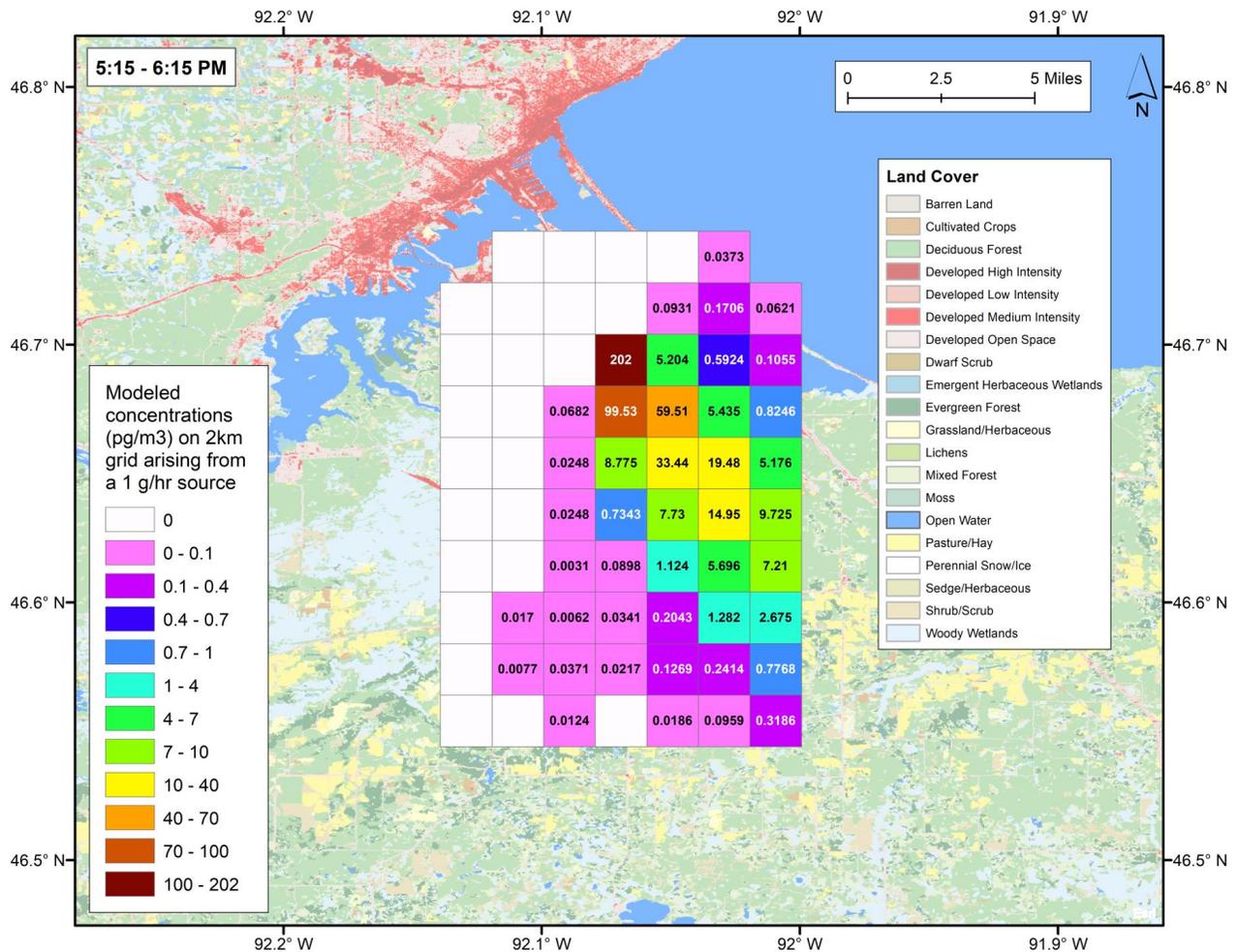


Figure 11. Modeled Ground-Level (0–100m) Hourly Concentration Averages (pg/m³) for 5:15 p.m. to 6:15 p.m



We followed the same procedure for HF. We assumed first that all the 6,800 kg of HF would be burned and evenly over the event period, which provides an emissions rate of 971 kg/hr. An alternative estimate is that it would all burn in one explosion (in a single hour), with the rate of 6,800 kg/hr.

After generating PM_{2.5} levels for each grid square, we then calculated the population-weighted average PM_{2.5} concentrations for each of the evacuation zones considered. The result is a measure of hourly PM_{2.5} exposure over the full duration of the fire for the residents of each zone (Table 7).

Figure 12. Modeled Ground-Level (0–100m) Hourly PM2.5 Concentration Averages (ug/m³) per 2 km Block by Simulation Period Arising from a 1.5E+08 gm/hr Source

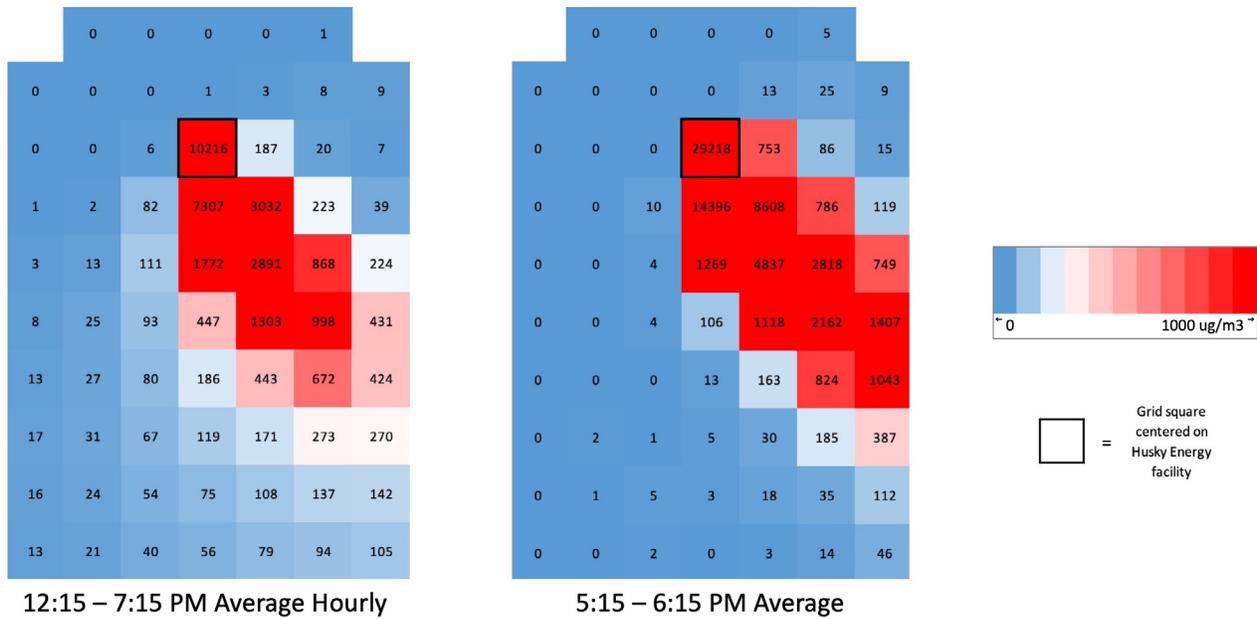


Table 7. Population-Weighted Average Hourly PM2.5 Concentrations

Evacuation Scenario	Population-Weighted Average Hourly PM2.5 Concentration (ug/m ³)
CDC Counterfactual	253
Husky Counterfactual	179
1-Mile North Radius HYSPLIT	302
2-Mile North Radius HYSPLIT	137
3-Mile North Radius HYSPLIT	87

PM2.5 and Health – Standard Approach

The next step is to feed the PM2.5 concentration change into PM2.5-health concentration-response (C-R) functions. With only one day of exposure avoided, only short-term exposure concentration-response functions are relevant. These were obtained from the US EPA's Co-Benefits Risk Assessment (COBRA) health impacts screening and mapping tool, an EPA air quality benefits program used by state and local governments to analyze both the health and economic effects of changes in air pollution (US EPA, 2020a). COBRA provides a curated list of concentration-response functions from a broad air pollution health impact estimation literature and the associated incidence data for each condition necessary to complete any calculations. Table 8 lists the health endpoints of relevance. Many of these functions require a baseline estimate of the presence of these health effects at low PM2.5 concentrations, which COBRA also provides. The C-R functions are used to estimate the expected change in endpoint incidence over the baseline population incidence.⁶ This estimate is then multiplied by the relevant population in the evaluation area to get an estimate of aggregate health effects. The population age groups are also listed in Table 8. Note also that COBRA contains C-R functions from more than one study for several endpoints, in which case, estimates are pooled using standard COBRA methodology, and not all endpoints are strictly additive to others. These issues are addressed with weighting factors contained in the model. Lastly, for the asthma symptom endpoints, the functions only address childhood asthma. Adult asthma incidence is about the same, but we ignored it in the calculations because we lack a concentration-response function for this group.

Monetization

The last step is to value these avoided health effects in monetary terms. Again, we rely on the US EPA's COBRA tool for its list of unit values relevant to each health endpoint (these values are from the economics literature). Within each health endpoint, these unit values can vary significantly depending on age, and our analysis accounts for this before determining total values for each endpoint. Summing over the value of each of the avoided health effects provides an estimate for the expected cost of illness for those in the counterfactual who would not have been evacuated during the fire. Summing over the monetized values of each unit of avoided health endpoint incidence provides an estimate for the health benefits of evacuating a given zone. The net benefits of HYSPLIT in this application are thus estimated as the difference in health benefit estimates between each of the HYSPLIT-informed evacuation zones and the counterfactual zones, which equates to the avoided health damages that would have been incurred if the standard CDC chemical fire guidance or Husky response plan were used instead of HYSPLIT.

6 Some of the C-R functions are nonlinear in concentrations. We tested this and determined that the nonlinearity was insignificant, permitting us to simplify the calculations by using the population-weighted concentrations across the relevant grid squares.

Table 8. C-R Function Health Endpoints

Health Endpoint	Age Range
Acute myocardial infarction, nonfatal (high)	18-99
Acute myocardial infarction, nonfatal (low)	18-99
Asthma exacerbation, cough	6-18
Asthma exacerbation, shortness of breath	6-18
Asthma exacerbation, wheeze	6-18
Emergency room visits, asthma	0-99
HA, all cardiovascular (less myocardial infarctions)	18-99
Hospital admissions (HA), asthma	0-17
HA, chronic lung disease	18-64
HA, all respiratory	65-99
Lower respiratory symptoms	7-14
Upper respiratory symptoms	9-11
Minor restricted activity days	18-64

3.2.5. Health Benefits

PM2.5-related Health Benefits from HYSPLIT Simulations – Standard Approach

Table 9 presents calculations of health impacts in each of our five evacuation zones and the additional health benefits generated by using HYSPLIT instead of the counterfactual to determine the evacuation zone.

These calculations show a net health benefit of the HYSPLIT-determined evacuation zones of \$629–\$1,786 more. In context, these benefits are quite small, largely because

the wind directed the fire plume to one of the most sparsely populated areas of Superior, WI, and thus it did not impact many residents. Had the wind pushed the smoke to the north or had a similar fire happened in a more densely populated city, we would expect the benefits of a HYSPLIT-informed evacuation to be orders of magnitude greater. Regardless, we find that using HYSPLIT to set the evacuation zone reduced the health impacts of the Husky fire by half by evacuating a larger population than would have been evacuated under CDC guidelines.

Our analysis does not include several health impacts that EPA uses in their regulatory analysis of air quality regulations (such as widespread eye irritation and asthma attacks in adult asthmatics), as well as the carcinogenic effects of exposure to various VOCs, including benzene.

Table 9. Estimated PM2.5-Related Health Benefits

Evacuation Scenario	Health Benefits of Evacuation	Health Benefits Relative to CDC Counterfactual	Health Benefits Relative to Husky Counterfactual
CDC Counterfactual	\$1,294	-	-
Husky Counterfactual	\$1,585	-	-
1-Mile North Radius HYSPLIT	\$2,214	\$920	\$629
2-Mile North Radius HYSPLIT	\$2,607	\$1,313	\$1022
3-Mile North Radius HYSPLIT	\$3,080	\$1,786	\$1,495

PM2.5-related Health Benefits from HYSPLIT – Alternative Approach

The standard epidemiological literature drawn upon to estimate the health benefits in section 3.2.5 is not entirely appropriate for use in extreme pollution situations, being calibrated primarily for mild to moderate change over larger geographic areas and longer periods of time. Thus on reflection, it is not surprising that the health benefits are so small. In this section, we assume that anyone not evacuating would experience some health impact. We first considered each of the health impacts in the COBRA

model plus eye irritation, which is an impact estimated in many EPA Regulatory Impact Analyses, but absent from COBRA. We then assigned an effects threshold to each of the health endpoints based on the US EPA PM_{2.5} exposure index (Figure 13)—the more severe the health impact the higher our assigned threshold.

The US Environmental Protection Agency (US EPA) guidance for short-term exposure to PM_{2.5} is found in its documentation for the Air Quality Index, which is published in many outlets around the US to help citizens and officials gauge their response to bad air pollution days (Stone et al. 2019). Figure 13 explains this index and provides the severity cut-points for various concentrations of PM_{2.5}. In our analysis we map the set of health endpoints to these cut-points and establish concentration thresholds over

Figure 13. US EPA Recommended Actions for the Consideration of Public Health Official (Stone et al. 2019)

AQI Category (AQI Values)	PM _{2.5} ¹ µg/m ³ 24-hr avg	Recommended Actions for Consideration
Good (0–50)	0–12	If smoke event forecast, implement communication plan.
Moderate (51–100)	12.1–35.4	Prepare for full implementation of School Activity Guidelines (https://www3.epa.gov/airnow/flag/school-chart-2014.pdf). Issue public service announcements (PSAs) advising public about health effects, symptoms, and ways to reduce exposure. Distribute information about exposure avoidance.
Unhealthy for Sensitive Groups (101–150)	35.5–55.4	Evaluate implementation of School Activity Guidelines If smoke event projected to be prolonged, evaluate and notify about possible sites for cleaner air shelters. If smoke event projected to be prolonged, prepare evacuation plans for at-risk populations.
Unhealthy (151–200)	55.5–150.4	Full implementation of School Activity Guidelines Consider canceling outdoor events (e.g., concerts and competitive sports), based on public health and travel considerations.
Very Unhealthy (201–300)	150.5–250.4	Move all school activities indoors or reschedule them to another day. Cancel school physical activities (e.g., physical education, athletic practice) unless the school is able to provide cleaner indoor air for the students. Consider closing some or all schools Cancel outdoor events involving activity (e.g., competitive sports). Consider canceling outdoor events that do not involve activity (e.g. concerts).
Hazardous (> 300)	250.5 > 500	Consider closing schools ² . Cancel outdoor events (e.g., concerts and competitive sports). Consider air quality in indoor workplaces and take measures to protect workers as needed ³ Consider curtailment of outdoor work activities unless the workers have a fully implemented respirator plan in place and clean air respite breaks. If PM levels are projected to remain high for a prolonged time, consider evacuation of at-risk populations.

which we expect the sensitive populations to experience each health effect (Table 10).

Table 10. Alternative Approach Health Impact PM2.5 Thresholds

Health Endpoint	PM2.5 Exposure Threshold (ug/m³)
Acute myocardial infarction (AMI), nonfatal	250
Asthma exacerbation	35
Emergency room visits, asthma	55
Hospital admissions (HA), asthma	150
HA, chronic lung disease	150
Lower respiratory symptoms	12
Upper respiratory symptoms	12
Minor restricted activity days (MRADs)	12
Eye Irritation	12

In determining the number of people affected by a given health effect, we assumed that the prevalence of a given health effect in the population determines the percent of the population in a grid cell that would experience the health effect as a result of PM2.5 exposure. For example, we applied an asthmatic prevalence rate of 10.7% to the total population of each grid cell with PM2.5 concentrations over the asthma thresholds in Table 10. Where possible we used age discriminant prevalence data, such as in the case of AMI, where annual prevalence can range from 0.9% for the 25-44 age group to 9.1% for those 65 years of age and older (Center for Disease Control (CDC) 2020). For the least severe endpoints—lower respiratory, MRADs and eye irritation—we assumed 100% population-wide impacts at or above their respective PM2.5 concentration thresholds. Then, as in section 3.2.5, health effects were monetized. As for the value of avoiding eye irritation, a meta-analysis by Vassanadumrongdee et al. (2004) estimates WTP for avoiding a single day of itchy eyes of approximately \$45 (\$2017; inflation adjusted) in developed countries. Table 11 presents the resulting estimates of cases and valuations from these calculations.

Table 11. Alternative Approach – PM2.5-Related Health Benefits of Evacuation

Health Endpoint	Health Benefits Relative to CDC Counterfactual		
	1-Mile North Radius HYSPLIT	2-Mile North Radius HYSPLIT	3-Mile North Radius HYSPLIT
Acute myocardial infarction (AMI), nonfatal	\$101,900	\$101,900	\$101,900
Asthma exacerbation	\$1,600	\$2,300	\$2,300
Emergency room visits, asthma	\$57,900	\$92,500	\$92,500
Hospital admissions (HA), asthma	\$92,000	\$341,300	\$341,300
HA, chronic lung disease	\$165,000	\$612,400	\$612,400
Lower respiratory symptoms	\$6,900	\$9,100	\$9,800
Upper respiratory symptoms	\$400	\$600	\$600
Minor restricted activity days (MRADs)	\$150,000	\$197,800	\$213,600
Eye Irritation	\$143,900	\$189,500	\$204,700
Net Costs of Evacuation Relative to CDC Counterfactual	\$7,564	\$25,507	\$49,376

Note that we do not add benefits over endpoints, but rather leaving the estimates disaggregated. This is because they effects are not necessarily additive. For example, US EPA MRADs unit values include eye irritation, and as such these endpoints should not be considered in combination. Further note that the estimates for evacuation costs in the final row of Table 11 come from Table 12 and are discussed in sections 3.2.6 and 3.2.7.

This alternative estimation strategy yields substantially greater benefits of evacuation compared to the C-R function estimates, depending on the health effects of interest. Notably, under all three HYSPLIT evacuation zones asthma related health benefits exceed \$150,000 over the counterfactual zoning. Even the relatively mild PM2.5 exposure endpoints of MRADS or eye irritation reflect substantial health benefits from the HYSPLIT evacuations. These AMI figures over \$100,000 relative to the counterfactual capture the extreme PM2.5 concentrations, in many grid squares well over 250 ug/m3, that residents may have been exposed to and adversely affected by under an evacuation strategy not informed by HYSPLIT projections.

3.2.6. Evacuation Costs

This section presents our approach to estimating evacuation costs and the results against the two counterfactual cases: CDC and Husky.

Evacuation is a costly and disruptive activity. We searched for estimates of the WTP to avoid evacuation but found none. Therefore, we limit the costs to travel expenses, valued at \$0.55 per mile—the standard value for business travel.

People located within the specified zone traveled to one of two shelters. The first was at the University of Wisconsin Superior (UWS-Superior), which is about 3 miles north of the Husky fire. The second shelter was at the Four Corner Elementary School, which is about 12 miles south of the Husky site.

For this case, we assume in the counterfactual scenarios that all evacuated people go to the UWS - Superior site because it is the closest. For the HYSPLIT scenario, we assume that half of the evacuated population goes to the UWS site and the other half to the elementary school.

Further, it was necessary to identify points of origin from which the average evacuee of each group would travel from to their respective shelter. The counterfactual population and the half of each HYSPLIT population evacuating to the UWS shelter are assumed to start travel from the center of the circle or half circle of each respective evacuation zone. We use the resulting distance between each point and the UWS shelter, approximately 2.6 miles in both cases, as the expected distance of travel for the average evacuee going to UWS. For the second half of the HYSPLIT evacuation zone population, we chose to use the center of the rectangle portion of the evacuation zone that is common to the three HYSPLIT zone options. The distance from this point to the Four Corner Elementary School shelter amounts to 6.4 miles of travel for the average evacuee from this group. Both travel figures must then be doubled to reflect a round-trip distance, from residence to shelter and then back to residence.

Lastly, we use information on average household size and assume a uniform cost of travel. Census Bureau projections suggest an average of 2.4 persons per household in Wisconsin in 2018, which implies up to 10,800 households. We assume each has a vehicle to drive to the evacuation location.

The product of the number of households, the round-trip distance of travel, and the cost per mile of travel generates a cost for the evacuation of each zone. Special care is given in the case of the HYSPLIT zones, with evacuation costs being the sum of two separate products for the two separate groups and shelter locations we consider. Our calculations for each zone are reported in Table 12, along with the difference in evacuation travel costs between each HYSPLIT zone and the counterfactual.

The short distance between the counterfactual zones and the UWS shelter to the north unsurprisingly results in small evacuation costs for these two scenarios. Inversely, households located in the southern portion of the HYSPLIT zones occupy a much more rural area and must travel a longer distance to arrive at the Four Corner Elementary School shelter. This difference in travel distance to shelters is reflected in higher evacuation costs for each of the HYSPLIT scenarios relative to the counterfactuals, resulting in net costs for evacuation of the HYSPLIT zones.

In addition to the CDC and Husky counterfactuals, we specified a third counterfactual—termed “risk avoidance”—that extends the evacuation zone beyond the HYSPLIT zone. The additional evacuation costs are small because the population is so low and we assumed only a 3-mile round trip.

Table 12. Evacuation Costs from Ground Travel to Shelters

Evacuation Scenario	Gross Cost of Evacuation Travel	Net Costs of Evacuation Relative to CDC Counterfactual	Net Costs of Evacuation Relative to Husky Counterfactual
CDC Counterfactual	\$4,945	-	-
Husky Counterfactual	\$8,343	-	-
1-Mile North Radius HYSPLIT	\$12,509	\$7,564	\$4,166
2-Mile North Radius HYSPLIT	\$30,452	\$25,507	\$22,109
3-Mile North Radius HYSPLIT	\$54,321	\$49,376	\$45,978
Risk Avoidance	\$2,236	-	-

3.2.7. Net Benefits

Net Benefits of Evacuation – Standard Approach

The final step in our cost-benefit analysis is to calculate the net benefits for each of the cases. Table 12 presents the results, taking the difference between the health benefits and evacuation costs arising from each evacuation. The net benefits relative to the counterfactual scenarios are also provided.

It is immediately apparent that evacuation costs greatly exceed the estimated health benefits for all but one scenario, resulting in largely negative net benefits. While evacuating even the counterfactual zone is found to generate negative net benefits, the change scenario evacuation zones that we consider show incrementally larger negative benefit as populations affected increase. We attempt to address the apparent inadequacy of applying conventional C-R functions to the event studied here through a consideration of more widespread health effects in the following section.

Finally, we note that the net benefits from the risk avoidance counterfactual case are the evacuation costs avoided by the HYSPLIT zone rather than the larger evacuation zone we assumed. We also assumed no health effects to anyone outside the HYSPLIT zone. Thus, the net benefits remain the additional evacuation avoidance costs of \$2,236 (not in Table 13).

Table 13. Net Benefits of Husky Refinery Fire – Standard Approach

Evacuation Scenario	Net Benefits of Evacuation	Net Benefits Relative to CDC Counterfactual	Net Benefits Relative to Husky Counterfactual
CDC Counterfactual	-\$3,651	-	-
Husky Counterfactual	-\$6,758	-	-
1-Mile North Radius HYSPLIT	-\$10,295	-\$6,644	-\$3,537
2-Mile North Radius HYSPLIT	-\$27,845	-\$24,194	-\$21,087
3-Mile North Radius HYSPLIT	-\$51,241	-\$47,590	-\$44,483

Net Benefits of Evacuation – Alternative Approach

Here we calculate net benefits from our alternative health impact estimates referred to in Table 11. The net benefits of evacuation for each zone and each health endpoint in this alternative approach are calculated through the same procedure as in the standard approach, taking the difference in net health benefits from net evacuation costs relative to the counterfactual.

It is important to emphasize that the alternative health impact value estimates cannot be aggregated by evacuation zone because of indiscernible health effect interactions and overlap that would be expected among the populations affected by each health endpoint. We opt to avoid any combination of health endpoint groups that may not be independent and would therefore not sum without the risk of double counting.

We will use the eye irritation and chronic lung disease health endpoints to exemplify the magnitude of net benefits estimated by this approach. To calculate the net benefits of a HYSPLIT evacuation zone for a single health endpoint in Table 11, we subtract the evacuation costs at the bottom of the same zone column from the health benefit estimate of the endpoint. For example, we calculate the net benefits of the 2-mile north radius HYSPLIT evacuation zone from avoided eye irritation by subtracting the evacuation costs of approximately \$25,500 from the health benefits of approximately \$189,500 to yield \$164,000. Completing this calculation for all HYSPLIT zones, net benefits of evacuation from avoided population-wide eye irritation are estimated to be \$136,300, \$164,000, and \$155,300 for the 1-mile, 2-mile, and 3-mile north radius HYSPLIT evacuation zones, respectively.

Evacuation generates the largest benefit through avoided chronic lung disease incidence, with net benefits estimated at \$157,400, \$586,900, and \$563,000 for the 1-mile, 2-mile, and 3-mile north radius HYSPLIT zones. These figures indicate the potential for high net benefits in instances where large numbers of people are afflicted with even a minor health condition, with even greater net benefits from avoiding major health effects.

3.2.8. Revealed Preference Estimates

Looking at the picture of the thick black plume from the explosion, it is obvious that people needed to be evacuated. To fail to do so would have opened up the company and the government bodies making the decision to huge political problems and liability claims, not to mention genuine health effects, both immediate and longer term. We cannot quantify the political and legal ramifications, and we used the best tools available to us to quantify and value the health effects. Unfortunately, these tools are not up to the task. They are designed to estimate impacts from routine, systemic air pollution rather than extreme events. Thus, the relatively small change in air pollution over a short duration results in predictably small estimates of health damages, except when we depart from the specific functions for minor restricted activity days (MRADs) in COBRA and assume the entire exposed population would have had eye irritation.

Fortunately, we have another way of looking at benefits, the “revealed preference approach.” In short, the decisionmakers, knowing the evacuation and disruption costs would be tens of thousands of dollars, decided that the evacuation was worth at least as much as the costs. Thus, in ordering the evacuation, they revealed their preferences, or their social WTP, to be greater than the costs.

Using this approach, we can reasonably say that the benefits of the evacuation were greater than the costs (\$13,000–54,000). Since the evacuation costs we estimated were only those for travel, rather than the public’s WTP to not be evacuated (i.e., for the event not to have happened, not counting health effects), even these benefits are likely an underestimate of the true value of the evacuation.

Using the revealed preference approach, which is the *difference* in evacuation costs between the change and counterfactual scenarios, we estimate the benefits of using HYSPLIT to be \$4,000 to \$49,000. Thus, we can say that the benefits of the HYSPLIT-determined evacuation zone relative to the smaller counterfactual zones exceed the net evacuation costs.

3.2.9. Exceedances

An alternative way to look at health benefits is to focus on the number of people who were moved out of harm’s way by the HYSPLIT evacuation zone versus the counterfactual zones. Harm can be defined in a variety of ways. We use EPA guidelines for PM_{2.5} and for HF and compare those to our HYSPLIT-simulated concentrations and the population by grid square versus the same for the counterfactuals to make that determination.

PM_{2.5} Exceedances

Exceedances cutpoints were taken from the US Environmental Protection Agency (US EPA) guidance for short-term PM_{2.5} exposure as shown in Figure 13. Concentrations over a 24-hour or shorter period that are more than 250 ug/m³ are labeled “hazardous,” and those more than 150 ug/m³ are “very unhealthy.” We compare these cutpoints to each grid square concentration for a given HYSPLIT scenario (plus background PM_{2.5} of 5 ug/m³) and add the populations in each square exceeding the cutpoint. We do the same for the counterfactual evacuation zone. Subtracting the latter from the former yields the benefit in terms of population exceedances avoided of the HYSPLIT evacuation zone.

Table 14 shows that the HYSPLIT evacuation zone resulted in 295 people avoiding exposure to 250ug/m³ or more of average hourly PM_{2.5} than the CDC counterfactual and 632 people experiencing between 150 ug/m³ and 250 ug/m³ average hourly concentrations compared to the CDC counterfactual. For the Husky counterfactual, the corresponding numbers are 262 and 181 people.

Table 14. Populations Evacuated from Areas Exceeding EPA PM2.5 Exposure Recommendation

Health Endpoint	Exceedance Threshold (ug/m ³)	Population Evacuated
CDC Counterfactual	250	137
	150-250	903
Husky Counterfactual	250	170
	150-250	1,354
HYSPLIT Zones	250	432
	150-250	1,535
HYSPLIT Zones Minus CDC/Husky	250	295 / 262
	150-250	632 / 181

Making the same calculations for each individual hour, HYSPLIT zones spared 748 people from the 250 ug/m³ exceedance level compared to the CDC counterfactual and 461 people compared to the Husky counterfactual in the worst hour of exposure for each counterfactual zone.

HF Exceedances

The approach for HF exceedances is identical to that for PM2.5 exceedances (except we assume background concentrations of HF are zero). The US EPA sets guidelines (by AEGL) and cutpoints for dangerous levels of short-term exposure to HF (US EPA, 2020b). The lowest level (AEGL-1) for any exposure lasting 8 hours or less is 1 ppm. According to the EPA,

AEGL-1 is the airborne concentration (expressed as ppm [parts per million] or mg/m³ [milligrams per cubic meter]) of a substance above which it is predicted that the general population, including susceptible individuals, could experience notable discomfort, irritation, or certain asymptomatic nonsensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure. (National Research Council, 2004)

AEGL-2 and AEGL-3 levels range from 12 to 170 ppm and are much larger than our simulated results. In only the final two hours that the fire was active would a complete release of the onsite HF have resulted in concentrations greater than 1 ppm, and only between 6:15 and 7:15 p.m. would a complete release have resulted in a greater area being affected than the immediate two square km surrounding the Husky facility. Ultimately the HYSPLIT evacuation zones would not have prevented exposure to the public beyond those already evacuated from the counterfactual zones.

3.2.10. Final Results and Case Study Conclusions

As estimated from PM_{2.5} concentration-response functions, the health benefits of using the HYSPLIT model to determine the evacuation zone rather than the standard evacuation radius are small when measured by conventional air pollution concentration-response functions. They are reduced further (indeed, made negative) by the added costs of evacuating the larger area identified by HYSPLIT relative to the standard area. This finding reflects the limitations in standard methods when applied to a major smoke event.

Using alternative methodologies or adjusting certain assumptions results in positive net benefits. Assuming more wide-spread health impacts than predicted with the standard C-R function approach or taking a revealed preference approach, we find that HYSPLIT has a positive net benefit in the Husky case. With the former approach, the net benefits contributed by HYSPLIT can reach \$587,000. With the latter approach, we can put a floor on the benefits to society as decisionmakers saw them at the time (\$13,000–54,000), with the benefits to HYSPLIT being at least \$4,000–49,000. While we found that the HYSPLIT zone relative to the counterfactuals did not result in fewer people experiencing exceedances of HF action levels, the HYSPLIT zone reduced exceedances above the very unhealthy PM_{2.5} action level (compared to CDC) for more than 1,000 people.

Some additional caveats are in order. First, the assumption of the fraction of asphalt burned may be wrong, although even correcting a very large error would not change the results qualitatively. Second, the fine particulate fraction of the plume may be wrong, again without a huge effect on the results. Third, the HYSPLIT model itself may generate simulations at variance with reality to an unknown degree. Fourth, certain health effects or certain groups having a given health effect were missing from the COBRA model, resulting in an underestimate of damages. Finally, we assumed that the larger evacuation zone was developed because of the HYSPLIT runs and so attribute all the costs and benefits to HYSPLIT. This is an oversimplification even if HYSPLIT played a major role in forecasting the plume's path and dispersion. To the extent that other factors mattered, the health benefits and evacuation costs attributable to HYSPLIT would be reduced.

Finally, with a \$2 million per year budget for HYSPLIT upkeep and improvement, it is unlikely that this one event can justify the budget. However, in any given year, HYSPLIT is applied for other events like this. In addition, HYSPLIT is consulted in so many settings, as detailed in sections 2 and 4 and for the Maine case study, that we have little doubt that its benefits far exceed its costs.

3.3. Case Study Extrapolation

As noted in Table 2, the ARL keeps track of all official uses of HYSPLIT, classifying these into several categories, including “hazmat industrial” (the Husky event), but excluding the use for reclassification of attainment status under the CAA (our Maine case study). We know of several instances of the latter use, but lack of a database precludes any hope of extrapolating the Maine results.

Turning to the hazmat industrial category, the data are complete only for 2018 and 2019. The industrial category was 22 percent of all recorded events in each year using HYSPLIT, second only to prescribed burns and tied with wildfires in 2018. The industrial events nearly doubled between 2018 and 2019. In 2020, there were 36 events as of 8/20/20.

To extrapolate our results, we first must get a sense of how many of these events were similar to the Husky fire. Of the variables listed, possible indicators of similarity include the number of HYSPLIT runs, type of substance that leaked/burned, quantity leaked/burned, and level of concern. The database is not complete in its reporting (all fields are not filled in for every event). For instance, the Husky listing has the quantity and level of concern associated with the HF but not the PM release. The database also does not include some desirable information for extrapolation, such as the population in the vicinity and whether it was evacuated. These would be useful additions to the database.

There is also the issue of what could be extrapolated, such as the total health benefits, evacuation costs, or net benefits. As we do not know the particulars of the events in the database—such as whether evacuation occurred and how many people were affected—to confidently extrapolate would require a level of information virtually equivalent to that collected for the Husky case study, which is far beyond the available resources for this study.

To give some indication of how representative the Husky event is, we offer the following statistics for 2019 (which had 100 industrial events using HYSPLIT). Ten exceeded the 6,800 kg HF entry, although for other substances, and 24 were below, with the rest lacking a value. Only one event was designated AEGL-3, one AEGL-2, and three AEGL-1 (counting only the highest designation for each event), with the remainder lacking a designation (three events with an N/A, five “none,” and one preferred action criteria-1 designation). Thus, the Husky event appears to be at the higher end of severity relative to other events, but it was not the worst.

3.4. References

40 CFR § 51.165

42 US Code § 7511c

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4. Literature Review Applicable to HYSPLIT Benefits

The literature review addresses the literature applicable to the benefits associated with the uses of HYSPLIT included in our benefits categorization scheme. The major uses of HYSPLIT, as summarized in Table 1, are academic research, aircraft operations, attainment designation, emergency planning and response, environmental impact statements, routine releases (natural and anthropogenic), and forensics. Each potentially has quantifiable benefits that include mitigation and avoidance costs saved, time saved, human health, property, environmental health, and impacts on climate. Some of these benefit categories are cross-cutting, such as health effects, environmental effects, and climate change, and they will be discussed under a cross-cutting category (subsection 4.6). An alternative approach to valuing HYSPLIT benefits is option value theory, which is discussed in subsection 4.7.

For each topic, our write-up includes a brief summary of how HYSPLIT applies for that purpose and a presentation and summary of valuation studies of the benefits of those uses. We searched for studies that quantify the costs and benefits of the potential impacts of HYSPLIT's uses in monetary units and sources that help contextualize our review. We included the published and "grey" literature and government reports. We searched in journals where finding such studies was likely, such as the *Journal of Environmental Economics and Management* and the *Journal of Political Economy*. We also searched Google Scholar using phrases commonly used in studies that quantify effects in monetary units, such as "cost," "WTP," "monetary benefits," "economic impacts," "value," and "savings," along with the specific societal benefits of each use identified in Table 1.

This section includes subsections for attainment designation, emergency planning, academic research, cross-cutting impacts, and option value.

4.1. Attainment Classification: Documenting Exceptional Events

HYSPLIT can demonstrate an exceptional event for the purpose of complying with the NAAQS. The "Exceptional Events Rule" allows states to prove that violation of the NAAQS is due to an exceptional event outside of the state's control, such as a wildfire that causes air quality in a city to be out of compliance with NAAQS for a brief period. States are able to (and often do) demonstrate that increases in PM within their borders are due to an exceptional event through HYSPLIT's back trajectories, which can trace the pollutants back to their source.

Being in violation of the NAAQS could have costly consequences, including being required to update SIPs to achieve attainment via air emissions controls on sources in the state (US EPA, 2016). Doing so can be costly and even unnecessary if the region

would be in attainment without the exceptional event. For example, Becker (2005) found that for sources with high emissions of particulates, those in nonattainment counties had additional capital expenditures of more than \$147,000 (1988\$) relative to similar plants with high emissions of particulates in attainment counties. Nonattainment status can also reduce economic activity in an area significantly; Greenstone (2002) found that from 1972 to 1987, nonattainment counties lost about 590,000 jobs and \$37 billion in capital stock relative to attainment counties.

If counties are already in attainment when an exceptional event occurs that causes a reassignment to nonattainment, this could be negligible for health effects but costly for a county, as noted. Thus, using HYSPLIT to avoid a nonattainment designation is likely to have large positive socioeconomic benefits.

Many states have used HYSPLIT to file exceptional events reports to receive attainment designation. For example, in May 2017, the Oregon Department of Environmental Quality submitted an exceptional event Concurrence Request to EPA that argued that Klamath Falls was impacted by wildfires for one day in 2014 and three days in 2015 that caused the town to be in violation of NAAQS for PM2.5. The filing included HYSPLIT runs showing the link between wildfires in other areas of Oregon causing the monitors to pick up high ratings for PM2.5. In November 2017, the Washington State Department of Ecology similarly filed an exceptional event demonstration for Kennewick with EPA using back trajectories from HYSPLIT runs. The file shows that PM10 exceedance during one day in 2015 was caused by a dust storm from high winds (Washington State Department of Ecology, 2017).

In each case, HYSPLIT provided important evidence that the NAAQS violations were caused by natural events, thus allowing these communities to avoid penalties associated with nonattainment.

Without HYSPLIT, it is possible that these counties would have had to face costs of nonattainment. Thus, the benefits of HYSPLIT in these cases would be the avoided costs of nonattainment.

4.1.1. References

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4.2. Tracking Anthropogenic Sources

4.2.1. Heavy Metals

HYSPLIT is used for both forecasting mercury transport and dispersion from a given source and developing back trajectories to determine the source of mercury impacting a certain region. For example, Han et al. (2005) used back trajectories to estimate the source of reactive gaseous mercury at sites in New York State in 2002–2003. The likely sources were coal-fired power plants in New York and Pennsylvania, a copper smelter in Quebec, and mining areas in the Great Lakes.

Using HYSPLIT to identify sources that are depositing mercury in a region could be valuable if it helps address the problem and reduce mercury transport to that area. Mercury is toxic to both humans and animals. In humans, exposure is associated with IQ losses, particularly for fetuses in the womb. Transande et al. (2005) found that 316,588–637,233 children in the US have elevated blood mercury levels due to mercury exposure, and the associated negative impacts on IQ amount to about \$8.7 billion annually from lost productivity. A literature review by Sundseth et al. (2010) found that economic damages from the loss of one IQ point due to mercury exposure are \$4,500–\$22,000 per person.

Using HYSPLIT for mercury back trajectories or forecasting could have significant public health benefits and thus cost-savings to the extent that these results lead to changes in mercury dispersion from these sources. Information on which sources are causing mercury deposits in certain regions could lead to stricter regulations at the plant level, ultimately reducing mercury deposition and associated damages. In that case, the societal benefits of HYSPLIT for this purpose would be the avoided health effects and/or environmental effects associated with mercury exposure. Health effects in this case are easier to quantify than the environmental effects because more research has been done in this area.

HYSPLIT has also been used to track dispersion of other heavy metals from industrial facilities, such as chromium, cobalt, nickel, lanthanum, and molybdenum, as in Chen et al. (2013). These elements similarly have negative environmental and human health effects.

4.2.2. Radionuclides

HYSPLIT has been used frequently to model the transport and dispersion of radionuclides from nuclear testing and nuclear accidents. For example, HYSPLIT modeled the dispersion of radiation from damage to the Fukushima nuclear power plant in Japan in 2011 (Draxler et al., 2015; Kinoshita et al., 2011).

Information on the fallout from nuclear accidents is extremely useful for determining the associated risks. Exposure to radiation can be very detrimental to human health, depending on the dose. Ten Hoeve and Jacobson (2012) estimate that human

exposure to radiation after the Fukushima accident, through inhalation, external exposure, and ingestion, will result in about 130 cancer-related deaths and 180 cancer morbidities worldwide. They also cite other major health impacts as long-term psychological effects, such as depression and anxiety. Von Hippel (2011) similarly found an increased risk for cancer (0.1 percent) in the aftermath of Fukushima for people living in areas with more than 1 curie per km² of Cs-137.

If tracing radionuclides leads to necessary evacuations, then the benefits of HYSPLIT for this purpose would be the avoided damages from exposure to radionuclides for evacuated populations. Such a case would be structured similar to the Husky fire case, albeit with different expected health impacts.

HYSPLIT is also used to both track the dispersion of radionuclides from a nuclear test and determine the origin of a nuclear test (as in Becker et al., 2007). These uses are incredibly important for national intelligence and security and preparation for potential disasters. Their benefits are not easy to monetize, however.

Moroz, Beck, Bouville, and Simon (2010) evaluated HYSPLIT's accuracy for fallout from nuclear tests in the Marshall Islands and found that it is reasonably accurate in predicting both fallout times and deposition patterns of radionuclides.

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4.3. Tracking Natural Sources of Pollution

4.3.1. Volcanic Ash

Volcanic ash is defined as particles less than 2–4 mm in diameter of volcanic rock pushed into the atmosphere by an eruption (US Geological Survey, 2015a, 2015b). The International Civil Aviation Organization's US Volcanic Ash Advisory Centers (VAACs) models volcanic ash dispersion with HYSPLIT (Air Resources Laboratory, n.d.) and prevents interactions between aircraft and volcanic ash. The potential benefits of HYSPLIT to inform air travel decisions include reduced exposure of aircraft to volcanic ash clouds, which has direct savings from lower aircraft repair costs and a lower risk of compromised flights or harm to passengers' health. When provided more accurate volcanic ash forecasts, airline operators observe less uncertainty, which translates into more precise flight boundaries that can lead to both increased aircraft safety and fewer flight cancellations (Mulder et al., 2017).

Volcanic ash can damage aircraft operations in two ways. First, physical abrasion to engines, external sensors, and windscreens can lead to dangerous flight control limitations, including complete engine failure, radio communication interference, and windows being worn to the point of opaqueness (US Geological Survey, 2015b). Second, volcanic ash can delay or cancel flights, which directly costs airlines and passengers and can cause economic losses in the hospitality sector and lost productivity from stranded workers (Oxford Economics, 2010). Passengers may also lose trust in the airline, which can reduce future demand for air transport (Ball et al., 2010; McCarty & Cohn, 2018).

Studies have attempted to quantify the economic damages from volcanic ash on aircraft operations. Kite-Powell (2001) estimates that the total annual cost of volcanic ash encounters with the commercial air transport industry total \$70 million, which consists of the probability that a passenger jet is lost and the associated damages from a value for the lives of all passengers and the price of the aircraft. Kim et al. (2019) evaluated the impact of a simulated eruption of Mt. Paektu along the Chinese-Korean border on international Asia-Pacific air travel and found that the economic damages, consisting of airline and passenger costs from flight cancellations, would range from \$68 million in the most lenient scenario to as much as \$231 million in a hypothetical six-day scenario (Kim et al., 2019).

Not including cancelled flights and rebooking, diversion costs for airlines can range from \$15,000 for a narrow-body domestic flight to \$100,000 for a wide-body international flight, depending on the size of the aircraft and the diversion route (Passur Aerospace, n.d.; UK Civil Aviation Authority, 2018).

HYSPLIT provides vital information in volcanic ash dispersion to air traffic controllers, which potentially reduces route closures and diversions if it shrinks ash no-fly zones, which in turn reduces forgone airline operations. Alternatively, using HYSPLIT can avoid aircraft damage if it finds that volcanic ash poses a greater danger along a route than previously expected. Both cases capture the economic benefits that reduced uncertainty in volcanic ash dispersion model estimates can provide to air travel.

Depending on volcanic ash exposure tolerance along any given flight path affected by an eruption, it was found that economic costs could be as high as \$68 million per day (Kim et al., 2019). This study highlights the importance of detailed and precise forecasting for improving economic outcomes because of the possibility of flight paths being closed due to volcanic ash presence.

Given the sheer magnitude of costs associated with disruptions in air operations, even modest improvements in outcomes as a result of HYSPLIT forecasts can create significant benefit through avoided costs to the aviation industry.

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4.4. Emergency Planning

Emergency responses to natural disasters and atmospheric releases of wildfire smoke, radionuclides, biological agents, and similar hazards to human health can be improved via HYSPLIT forecasting. HYSPLIT's tracking and forecasting is used for emergency planning immediately in response to a variety of intentional and unintentional disasters. In this application, HYSPLIT could improve health outcomes, mitigate costs, and reduce response planning time.

A good example of emergency planning is HYSPLIT runs before and during the Super Bowl to predict wind direction and dispersal of toxic substances from a terrorist attack and place emergency equipment in the most advantageous position to minimize impacts. Here, as is the case for other uses of HYSPLIT for emergency response, HYSPLIT forecasts enable planners to be better prepared for an emergency, which can then reduce impacts to health and even death. In economic terms, avoided health impacts (depending on the kind) and avoided death are valuable. For example, the VSL in economics literature can be as high as more than \$18 million per life lost (Viscusi & Masterman, 2017).

Thus, emergency planning that can reduce lives lost is extremely valuable. A paper by Al Kazimi and MacKenzie (2016) cites Kristalina Georgieva of the European Commissioner for Humanitarian Aid and Crisis Response, who said that every dollar put into natural disaster preparation yields \$4 in avoided damages and that, despite this return on investment, only about 4 percent of the money put toward natural disasters is spent on preparations; the majority goes to recovery efforts.

A newly expanded area for HYSPLIT is forecasting locust swarm movements (NOAA, 2020). A new HYSPLIT-based web application to forecast the movements of desert locust swarms has been developed, in a collaboration between the United Nations Food and Agriculture Organization (FAO) and the NOAA, in response to the unusually large and destructive swarms appearing over East Africa, the Arabian Peninsula, and into the Indian Subcontinent in late 2019 and into 2020. FAO's Desert Locust Information Service provides global forecasts and early warnings to facilitate countermeasures in protecting the food supply in vulnerable regions. During emergencies, FAO coordinates response activities in affected countries to lessen the devastating impacts of locusts on food security and livelihoods. It is too early to estimate the added value of HYSPLIT in preventing adverse health and economic costs due to locusts, but we mention this application because it could be quite significant.

4.4.1. Fire

HYSPLIT, along with other models, is used to provide dispersion forecasts of smoke (as PM_{2.5}) in the United States from wildfires (Ni'am et al., 2017; Rolph et al., 2009) and anthropogenic sources (as seen in the case study on the Husky fire in Section 3)

during emergencies, as well as during nonemergency times, such as controlled burns (Vasys, 2010).

Fires release toxic compounds into the atmosphere that are dangerous to humans. Smoke from wildfires contains PM and nitrogen oxides, which affect human health and the environment. Smoke from anthropogenic sources typically contains even more toxic substances, depending on the source.

The impacts of PM on human health are well understood and researched. Exposure to PM causes respiratory problems and can lead to difficulty breathing, aggravated asthma, and premature death due to heart attack, all of which are worse for people with underlying health conditions, such as heart disease or lung disease (EPA, n.d). Economists value loss of life or illness using economic valuation methods that are explained more in the cross-cutting impacts subsection of the literature review and referenced in the Husky fire case study.

Consulting HYSPLIT for information either in response to an emergency, such as a wildfire or anthropogenic fire, or as preparation for prescribed burns is extremely valuable for human health if this information allows for evacuating people from certain areas or warning them to take extra precautions, such as staying indoors or wearing face masks to avoid smoke inhalation. As illustrated in our Husky fire case study, without the vital information from HYSPLIT during emergency situations, more people would likely be exposed to dangerous toxins from smoke and face health consequences. Thus, HYSPLIT in this context likely has benefits for human health in avoided health costs.

HYSPLIT's ability to provide scheduling guidance for prescribed (planned and controlled) burns to minimize impacts to humans is also valuable. HYSPLIT could be used to plan for where emergency fire equipment should be located to help bring a fire under control. Out-of-control fires are extremely costly. Nisengard et al. (2002) estimated the total cost associated with Arizona's Cerro Grande Fire in 2000, which began as a controlled burn but became a 150-thousand-acre fire that destroyed hundreds of homes, concluding that it had generated \$1 billion in total damages, a rare (but expensive) example of accidental costs that can arise from poor emergency planning. With better forecasting wind conditions, it is likely that fire damages could have been partially or completely avoided (Nisengard et al., 2017).

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4.5. Academic Research

HYSPLIT has been and will continue to be a valuable resource to researchers in a variety of academic fields and with a plethora of atmospheric modeling needs. A review of HYSPLIT's uses (Stein et al., 2015) is one of the most widely cited papers in the academic field of geosciences. Many other papers have been published with HYSPLIT as a resource.

The value of academic research itself is not entirely clear. As Bornmann (2013) recognizes in his literature survey on the topic, valuing academic research is difficult; one significant issue is that the relevance and value (or the absence thereof) of research depends largely on whom you ask and the realization of benefits can be years or even decades after the research is completed. Further, attribution to HYSPLIT would be extremely problematic even if these other issues could be addressed.

The studies reviewed by Bornmann (2013) on estimating the value of academic research applied different approaches, primarily econometric studies, surveys, and case studies; different indicators are considered and used as metrics for the usefulness of research, including citations, patents, long-term health outcomes, and environmental impacts. However, as Ravenscroft, Liakata, Clare, and Duma (2017) found, metrics such as citations are not foolproof because they “represent the dissemination of knowledge among scientists rather than the impact of the research on the wider world” (1). Ravenscroft et al. (2017) argued that a more comprehensive quantification of nonacademic impacts of research would require data mining information from, for example, social media posts and news articles.

4.5.1. Allergens

HYSPLIT, for example, has been used in various studies to show that the model can reasonably predict trajectories of allergens (Efstathiou, Isukapalli, S., & Georgopoulos,

2011; Pasken & Pietrowicz, 2005), though this has not yet been done in application. In the future, the benefits of HYSPLIT for such a purpose could be substantial.

Allergens can cause moderate to severe human health impacts, depending on the individual. Exposure to allergens can cause inflammation in the upper respiratory tract and result in symptoms such as sneezing, nasal congestion, and eye irritation (Ozdoganoglu, Songu, & Inancli, 2012). Moderate and severe allergies can also cause generalized symptoms, such as fatigue, sleep disturbances, and impaired cognitive function (Ozdoganoglu et al., 2012). Over-the-counter allergy treatments tend to have a sedating effect, which can further reduce productivity (Crystal-Peters, Crown, Goetzel, & Schutt, 2000). Avoiding exposure altogether is the best way to minimize health impacts associated with allergens.

In addition to human health costs, allergies can lead to additional societal costs by negatively affecting work and school attendance and reducing worker productivity (Crystal-Peters et al., 2000; Kim et al., 2010; Vandenplas et al., 2018). For example, Crystal-Peters et al. (2000) estimate that the economic costs of allergic rhinitis due to reduced worker productivity are \$2.4–\$4.6 billion annually. HYSPLIT and similar programs are used to model the levels and dispersion of pollen (Efstathiou et al., 2011; Pasken & Pietrowicz, 2005), providing sensitive individuals with the information necessary to reduce their exposure during peak periods (Efstathiou et al., 2011).

HYSPLIT's ability to forecast pollen could lead to societal benefits in practice. Pollen forecasting enables people to reduce their exposure through information on allergen levels in the area and could decrease the mitigation costs of allergies if it reduced the need for treatment through medication, which is a likely alternative. Since medication can cause drowsiness and thus decreased productivity, limiting outdoor exposure instead can have economic benefits. In addition to providing health benefits, HYSPLIT's pollen forecasts may also save time that would have been lost to decreased productivity.

Thus, pollen forecasting with HYSPLIT would likely result in benefits for human health and society more generally through avoided sick days and decreased productivity. The methods for quantifying such benefits are available in economic literature.

Currently, 10–30 percent of the population suffers from allergies (World Allergy Organization, 2013), meaning the health benefits of HYSPLIT for this purpose are likely very large. Climate change is expected to cause longer pollen seasons and increase atmospheric pollen levels. These changes can increase the population with sensitivity to pollen, extend the duration of allergy symptoms, and increase the severity of allergy symptoms (Settipane & Schwindt, 2013; Schmidt, 2016; Ziska et al., 2011), so pollen forecasts will become more important in the future.

Research on this topic cannot be quantified until it goes into practice. However, the potential for HYSPLIT to provide enormous societal benefits by tracking allergens is high.

4.5.2. Dust

Studies have similarly shown that HYSPLIT can be used to track dust storms (Ashrafi, Shafiepour-Motlagh, Aslemand, & Ghader, 2014; Wang, Stein, Draxler, Jesús, & Zhang, 2011). Dust contains PM that is harmful to human health, as discussed in the section on fire. Although only academic studies have thus far consulted HYSPLIT to track dust, this application could be extremely valuable in practice. It would enable governments to warn nearby inhabitants to evacuate, thus allowing people to avoid dust exposure and benefit from improved health outcomes. This research has provided important guidance for government officials in this respect, which could lead to future benefits.

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4.6. Cross-Cutting Impacts

4.6.1. Health

Many of the uses of HYSPLIT affect public health through injury prevention, prevention of symptoms of acute and chronic effects (such as those from exposing the lungs to toxic substance), and even reducing the risk of premature death, whether from exposure or injury.

Impacts to health can be quantified using medical costs (both out of pocket and what the service and drugs actually cost without insurance) as a metric. However, medical costs alone as a proxy for valuing impacts to health are insufficient because they do not include the costs of premature death (where medical costs could be zero). Thus, economists use a WTP approach to capture the full costs of health impacts. WTP encapsulates a person's aversion to being affected by a given health impact, producing a monetary estimate for the amount they would pay to avoid the condition. This approach relies on two methods: revealed preference—using market behavior to estimate WTP—and stated preference—using survey responses designed to derive monetary values for WTP (Stavins, 2019).

For many of the relevant health impact categories, WTP estimates are reasonably well established; some of the best sources are Regulatory Impact Analyses, which are cost-benefit analyses that government agencies use to tally the benefits of environmental and other types of regulations affecting health and injuries. These studies have identified the VSL (the WTP for reducing death risk divided by the death risk reduction) to be around \$9 million for rules affecting exposure to pollution, which would be multiplied by the expected deaths avoided by a use of HYSPLIT to calculate the benefits of HYSPLIT in this health category (US EPA, 2015). The Department of Transportation uses a VSL for reducing death risks from injuries of \$4 million (Federal Highway Administration, 2018). The agency has a long list of values of avoiding a statistical injury (VSI) by injury type. There are also values for avoiding an expected case of respiratory disease or respiratory symptoms (US EPA, 2015). The literature on avoiding more exotic health effects of pollution exposure (e.g., dementia, IQ loss,

reduced fertility, poor birth outcomes) is less well developed but growing.

4.6.2. Environmental Impacts

HYSPLIT tracks many toxic sources, such as mercury, using back trajectories to determine their origin. HYSPLIT can also quantitatively estimate source-attribution information for atmospheric deposition of toxic pollutants (e.g., mercury) arising from emissions (Cohen et al., 2016). These sources have toxic impacts on the environment, and information on which sources cause deposition of these substances in certain areas could have environmental benefits, if it leads to emissions reductions.

Many HYSPLIT applications can have positive environmental outcomes for plant and animal populations and reduce damages to habitats. For example, HYSPLIT is often used to track dispersion of sand and dust during dust storms (Wang, Stein, Draxler, Jesús, & Zhang, 2011; Escudero et al., 2011; Alam, Qureshi, & Blaschke, 2011). Improved understanding of where dust, which is composed of PM, is located can improve environmental outcomes in those areas.

While studies are thin on the actual environmental benefits of using HYSPLIT, people give preference to a healthy environment, which can be captured in monetary value. There is a deep valuation literature using mostly stated preference approaches to provide monetary values for these endpoints, with particular emphasis on valuing avoiding damages to endangered species and water quality, among several categories (Bateman et al., 2002). For example, Sundseth et al. (2010) combine assumptions from three studies to estimate that American households' WTP to reduce mercury deposits in the environment by 50 percent is about \$6 (2005\$) annually.

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4.7. Option Value

An alternative method of valuing the reduction in predictive uncertainty provided by HYSPLIT is option value theory. There is a small literature on this topic. We review one of the papers by our team members, Roger Cooke and Sasha Golub.

Cooke and Golub (2019) lay out the theory and conduct a notional case study with new methods of option value to value the reduction in uncertainty associated with using satellite data versus traditional methods to predict soil moisture, in the context of agricultural productivity. The futures market for soybeans and corn incorporates beliefs about future soil moisture and its effect on crop yields. Futures prices for crops also depend on future demand and a host of other factors. The options value approach decomposes futures price variation into market and weather components and computes the value of reducing the weather uncertainty by using satellite data. The overall price uncertainty (the standard deviation of corn prices, for example), which is measured by price volatility, costs US consumers about \$5.25 billion per year. Reducing weather-related uncertainty by 30 percent was found to generate yearly increases in consumer surplus (through better future price predictions and the effects on yields this would entail) for corn by around \$0.9 billion. Adding in benefits for soybeans brings the total benefit to \$1.44 billion (relative to a total annual market value of \$95 billion for both crops combined).

This approach could be applied to any markets affected by uncertainties that would be reduced by HYSPLIT relative to a counterfactual, such as markets that insure properties against forest fire damage.

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5. Conclusion

In this study, we used a VOI approach to discuss and estimate the benefits that the HYSPLIT air dispersion and transformation model provides to society at large. HYSPLIT, developed by the NOAA's ARL, is a government resource provided to government agencies, researchers, and the public for free. Because users do not have to pay, alternative methods are needed to assess its value. A VOI approach estimates the value by comparing the benefits of two outcomes under scenarios in which users rely on information provided by HYSPLIT to make informed decisions and one in which they do not do so. With the available resources, we make a reasonable assumption about the information that would have been available without HYSPLIT (deemed the counterfactual). We compare the expected outcomes under the HYSPLIT and counterfactual cases to determine the expected benefits of HYSPLIT. Then, through analysis informed by literature, we attempt to quantify those benefits in monetary terms.

In the second section, we present a taxonomy of the many uses of HYSPLIT and expected benefits from them. Many of these can have substantial benefits, such as using HYSPLIT's back trajectories to determine the violation of nuclear treaties. However, we were unable to perform a case study on such examples due to the difficulty in monetizing such benefits. Consequently, our analysis does not include some of the likely most beneficial uses of HYSPLIT from society's perspective. Nonetheless, we were able to focus on a few select case studies that were important, illustrative, and doable.

The cases we highlight use HYSPLIT to make better-informed decisions than would be possible without it. The case studies presented here in combination with the literature review exemplify the extensive benefits that HYSPLIT provides to its users and society at large. The uses of HYSPLIT are wide-ranging, as are the projected benefits. HYSPLIT serves many different purposes, and it would be nearly impossible to capture all of these benefits in monetary terms. Thus, we use case studies to highlight specific uses of HYSPLIT for which we are able to use economic valuation methods to quantify the benefits to provide an informed estimate of HYSPLIT's value.

HYSPLIT can lead to more efficient environmental regulation. In the Maine example (section 3), HYSPLIT back trajectories showed that including the majority of Maine's counties in the OTR was unnecessary because those areas did not contribute significantly to ozone concentrations in the OTR. While the fate of Maine's petition to be removed from the OTR remains to be determined, its success could enable previously restricted facilities to expand their business operations. We estimate that removal from the OTR could lead to benefits of \$2.3–\$5.5 million in annual avoided costs resulting from strict environmental regulations under the NSR regulations for facilities located within the OTR that we expect would expand if not subject to these regulations.

The Husky fire case is an example of how complex it can be to estimate the value of information and, with standard methodologies, how small the VOI can be. Taking two

other approaches to estimating benefits, however, the VOI for HYSPLIT is positive and reasonably large.

Given that HYSPLIT's budget is \$2 million per year, our estimates of net benefits from the case studies offer ample evidence that the program's benefits to society outweigh its costs; the projected benefits from the Maine case study alone exceed that annual budget. However, these results should be interpreted cautiously, as they contain a fair amount of uncertainty due to various assumptions made during the analysis. These benefits depend on how we define the counterfactual and how much we attribute the decision to HYSPLIT. In both cases, it is nearly impossible to accurately predict both factors.

For the many uses we could not quantify, the literature review in section 4 offers a large number of uses that can easily generate benefits in the millions of dollars. For example, using HYSPLIT to prove an exceptional event has occurred to avoid nonattainment status saves states thousands of dollars in compliance and protects valuable industry and jobs in those areas. Similarly, the use of HYSPLIT to track toxic pollutants, such as mercury, can have enormous societal benefits in improved public health and environmental outcomes. Together, the case studies and literature review provide good evidence of the high value of the information that HYSPLIT provides to its users.

