Caught in the Loop: Climate Change and Computing Infrastructure

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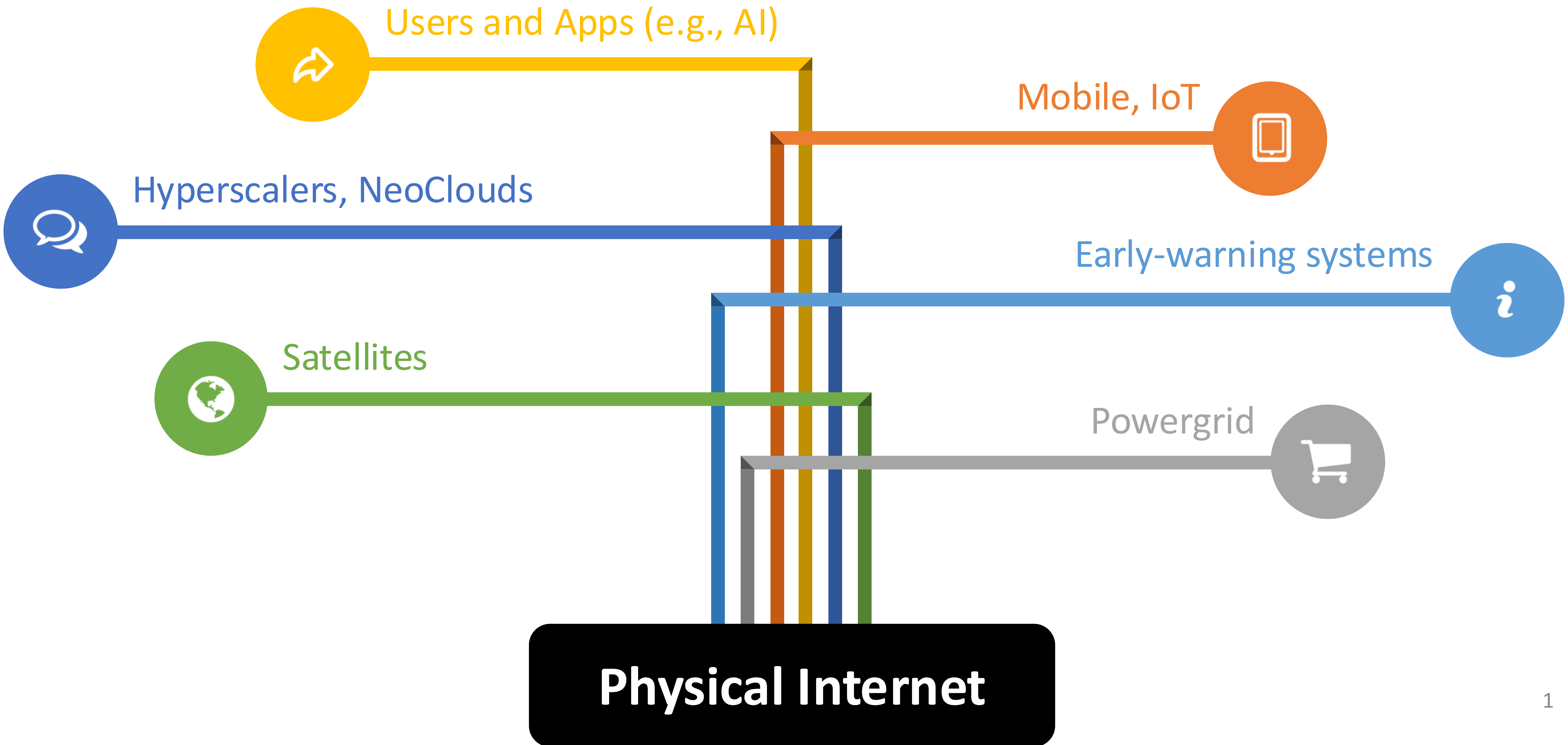
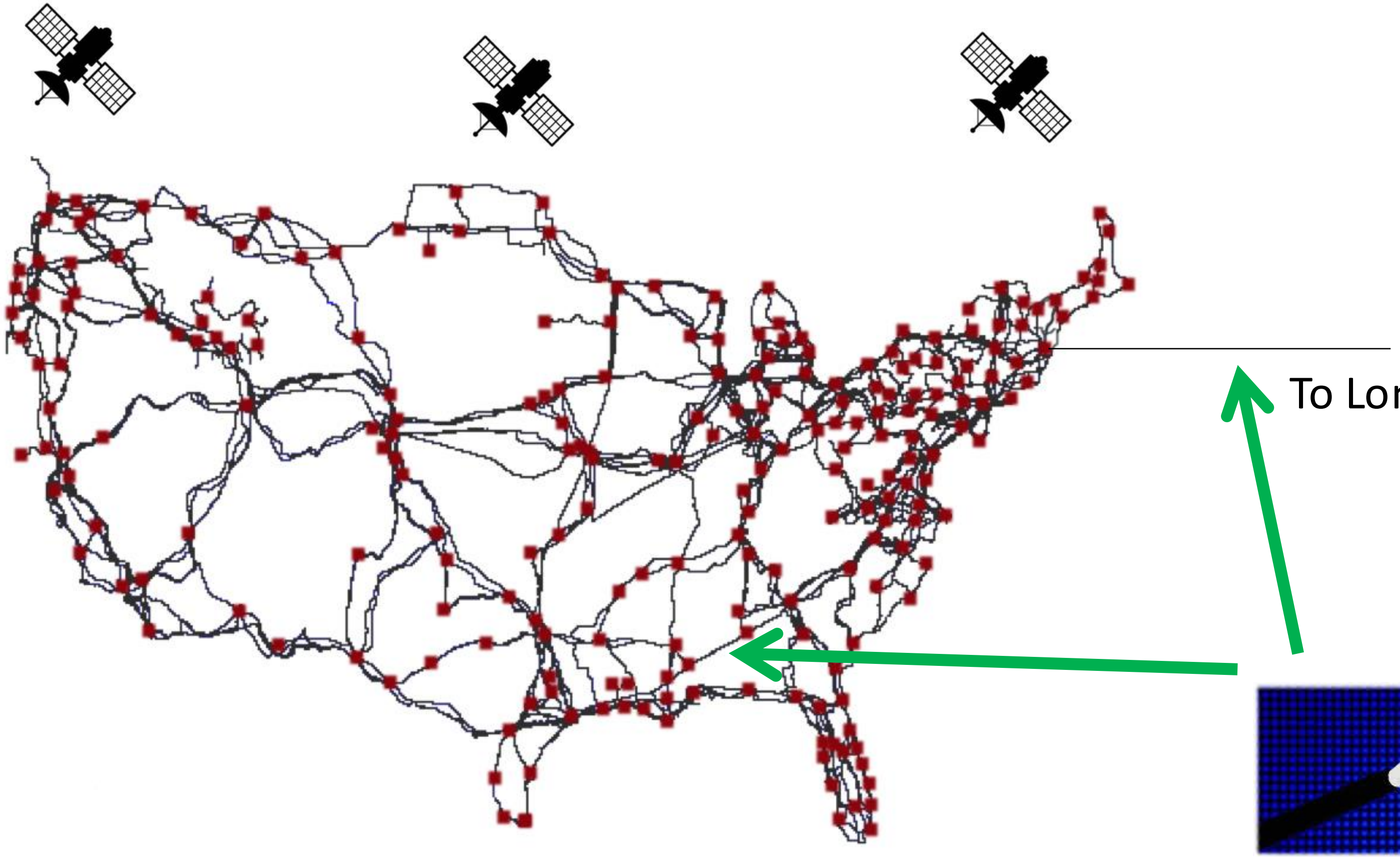
(This is not a talk on AI. In fact, this talk is about the boring part of AI.)

The *invisible* infrastructure we depend on



The physical Internet

Data center
Colocation facility or POP
Submarine cable landing station
Satellite ground station



Durairajan *et al.*, SIGCOMM '15

Fiber optics link
Submarine cable

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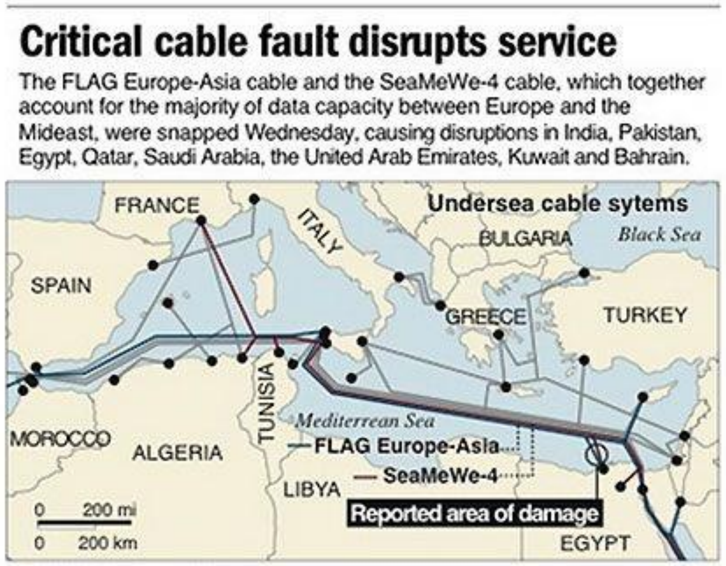
Internet outage causes

Outage

Why?

Accidents and geopolitics



Critical cable fault disrupts service

The FLAG Europe-Asia cable and the SeaMeWe-4 cable, which together account for the majority of data capacity between Europe and the Mideast, were snapped Wednesday, causing disruptions in India, Pakistan, Egypt, Qatar, Saudi Arabia, the United Arab Emirates, Kuwait and Bahrain.

http://www.ap.org/

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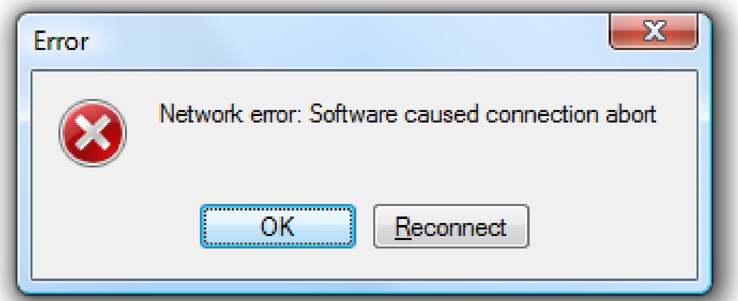
Internet outage causes

Outage

Why?

Bug in deployed software



Crowdstrike ‘24, AWS ‘25

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Internet outage causes

Climate change and natural disasters

Outage

Why?

Cause?

Multi-hazards
(Stevens, PAM' 24)

Earthquakes
(Mayer, PAM' 21)

Sea-level rise
(Durairajan, ANRW' 18)

Hurricanes
(Eriksson, CoNEXT' 13)

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Outline

- Climate change as a threat to computing infrastructure
- Computing as an environmental challenge
- How to build digital infrastructure while being mindful of these two issues?

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Climate change as a threat to computing infrastructure

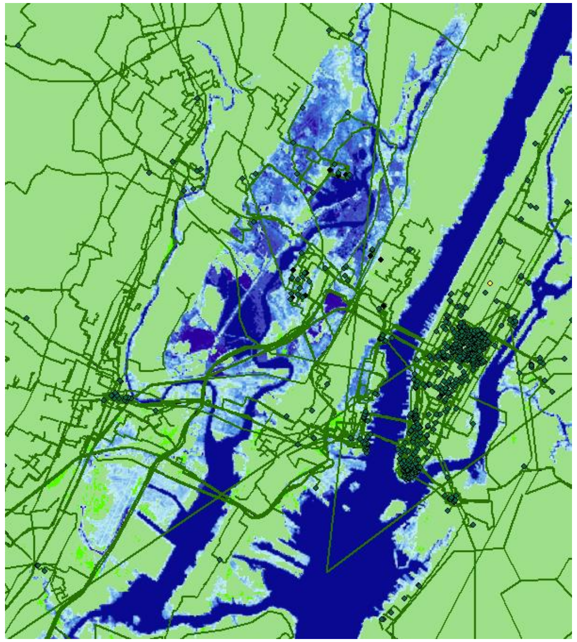
- Sea-level and coastal inundation
- Extreme weather (e.g., storms, floods, hurricanes, wildfires)
- Earthquakes
- Multi-hazard risks (e.g., earthquake -> tsunami; wildfire -> landslide)

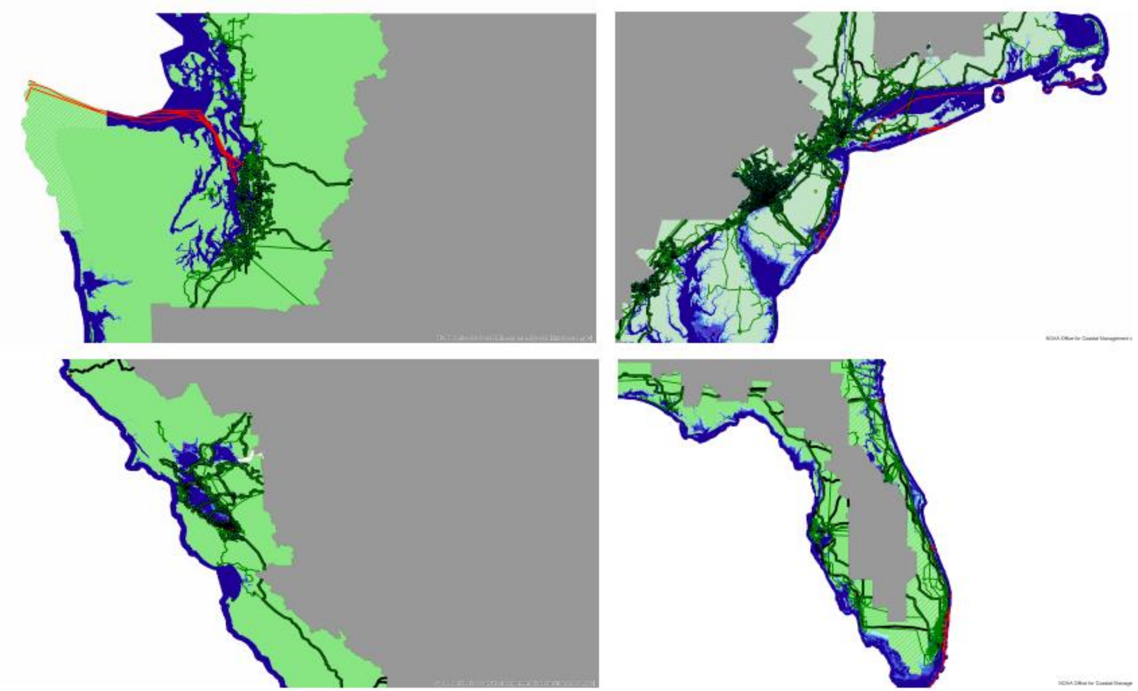
Rising seas and coastal inundation

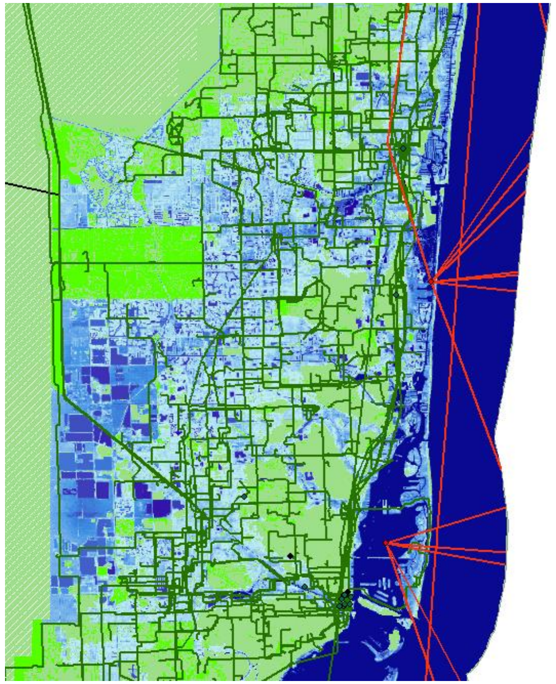
Greater Internet is resilient; localized effects on users and businesses!

Large-scale Disaster Event

Climate change induced sea-level rise poses serious risks to infrastructures in coastal coastal communities







Ramakrishnan Durairajan, Carol Barford, and Paul Barford, “Lights Out: Climate Change Risk to Internet Infrastructure” in ACM/IRFT/ISOC ANRW 2018.

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Rising seas and coastal inundation

City (POPs)	City (Data centers)	City (IXPs)	City (Landing Stations)
New York, NY (46)	New York, NY (43)	New York, NY (8)	Manasquan, NJ (2)
Miami, FL (31)	Newark, NJ (21)	Miami, FL (4)	Miami, FL (2)
Seattle, WA (28)	Seattle, WA (16)	San Francisco, CA (4)	Pacific City, OR (2)
Houston, TX (26)	Miami, FL (15)	Seattle, WA (4)	Tuckerton, NJ (2)
Washington, D.C. (23)	Palo Alto, CA (8)	Houston, TX (3)	Bandon, OR (1)

City (Long-haul)	City (Metro)
Los Angeles, CA (89, 14.54%)	New York, NY (337, 19.8%)
New York, NY (79, 32%)	Seattle, WA (236, 23.6%)
Miami, FL (62, 5.3%)	San Francisco, CA (158, 9.43%)
New Orleans, LA (43, 22.51%)	Miami, FL (149, 13.27%)
San Francisco, CA (31, 7.4%)	Los Angeles, CA (138, 20.14%)

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Extreme weather

Greater Internet is resilient; localized effects on users and businesses!

Small-scale Disaster Event

Hurricanes, wildfires pose serious threats to Internet infrastructures and early warning systems

Hurricane Tornado Storm Wildfire Damaging Wind

Brian Eriksson, Ramakrishnan Durairajan, and Paul Barford, “RiskRoute: A Framework for Mitigating Network Outage Threats” in ACM CoNEXT 2013.

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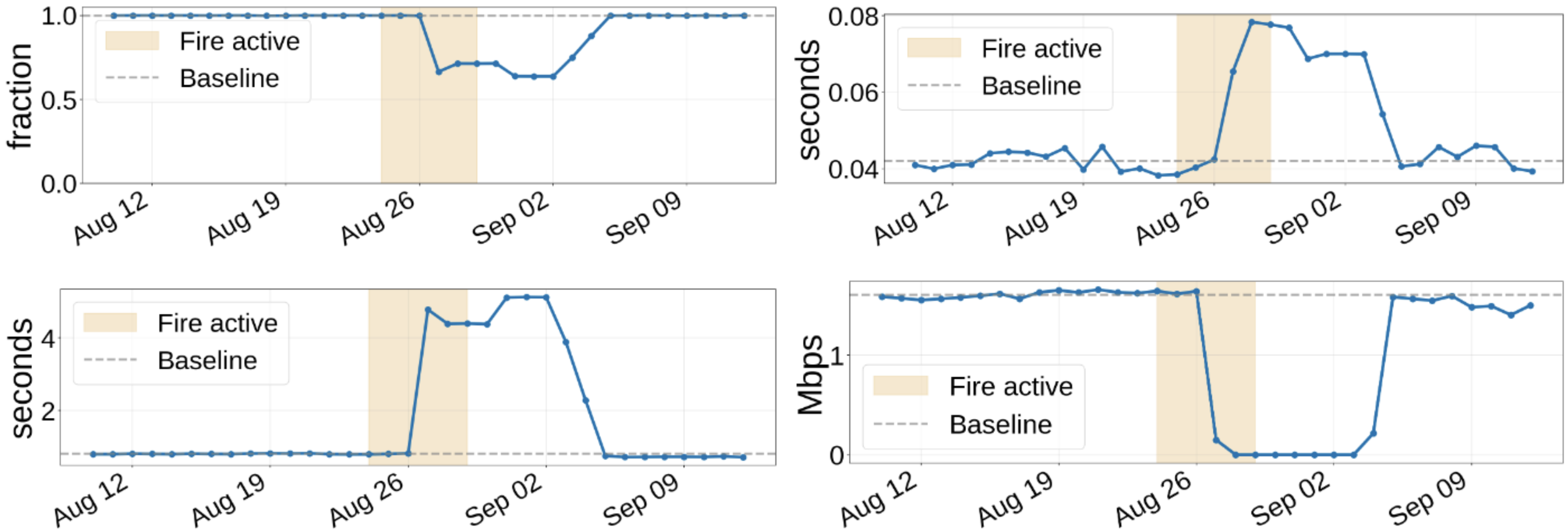
Effect of wildfires on network infrastructure

Probe Success

ICMP RTT

Scrape Duration

tput



River Bartz and Ramakrishnan Durairajan, "Network Performance Under Fire: Measuring Wildfire Hazard Networks in the Pacific Northwest" in submission.

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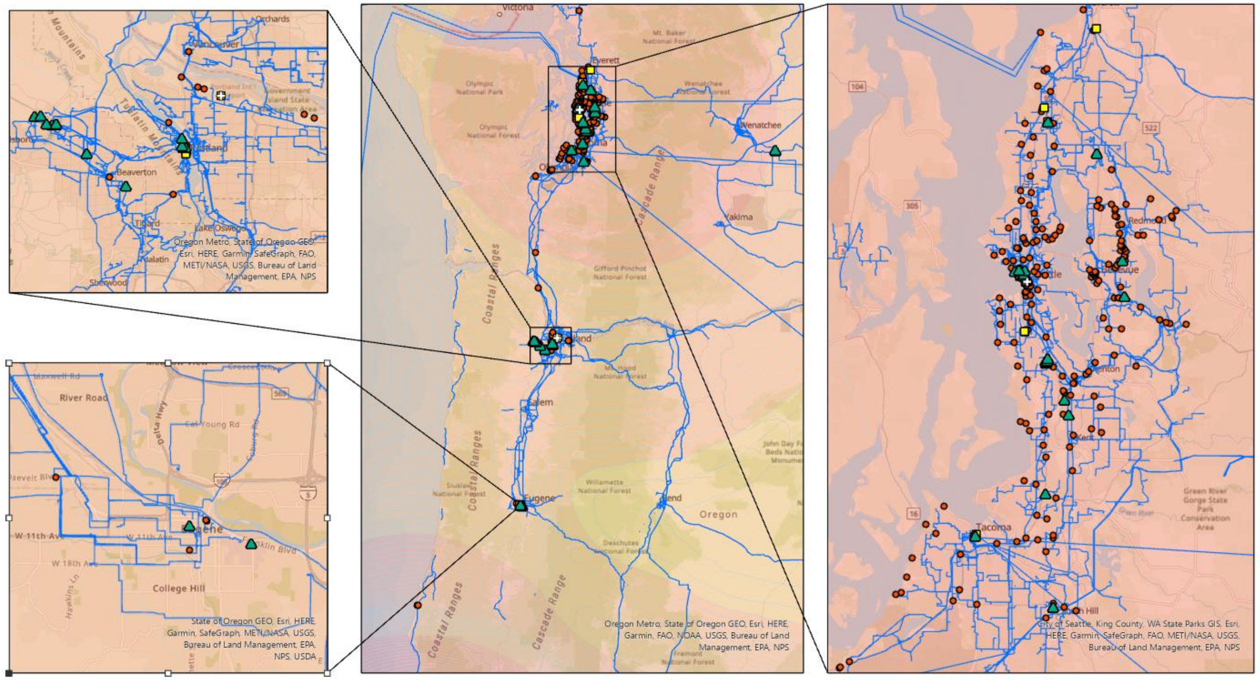
Earthquakes

Greater Internet is resilient; localized effects on users and businesses!

Medium-scale Disaster Event

Cascadia **M**9 earthquake poses serious risks to infrastructures in PNW



Juno Mayer, Valerie Sahakian, Emilie Hooft, Douglas Toomey and Ramakrishnan Durairajan, “On the Resilience of Internet Infrastructures in Pacific Northwest to Earthquakes” in PAM 2021.

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Assessment of shaking-induced damages

- We assess the extent of damages in two steps
  - Step 1: assess infrastructure risks
    - Contour the areas based on PGA values
    - Place infrastructures into contours
    - Count infrastructures

PGA (g)	MMI	Colos	POPs	Data centers
0.092 < x <= 0.18	Strong	20 (34%)	51 (12%)	2 (6%)
0.18 < x <= 0.34	Very Strong	27782 (65%)	11246 (26%)	29 (94%)

Count of nodes that are prone to shaking for PGAs with 10% prob. of exceedance.

PGA (g)	MMI	Colos	POPs	Data centers
0.18 < x <= 0.34	Very Strong	20 (34%)	51 (12%)	2 (6%)
0.34 < x <= 0.65	Severe	27782 (65%)	11246 (26%)	29 (94%)

Count of nodes that are prone to shaking for PGAs with 2% prob. of exceedance.

Assessment of shaking-induced damages

- We assess the extent of damages in two steps
  - Step 1: assess infrastructure risks
  - Step 2: augment risks with metropolitan statistical areas (MSAs)
    - *Summarize Within* tool to count the quantity of infrastructure per MSA

Fiber	DCs/IXPs/Colos/POPs	Cell Towers
Seattle-Tacoma-Bellevue	Seattle-Tacoma-Bellevue	Seattle-Tacoma-Bellevue
Portland-Vancouver-Hillsboro	Portland-Vancouver-Hillsboro	Portland-Vancouver-Hillsboro
Wenatchee	Eugene	Salem

Top 3 MSAs with infrastructures ranked based on high earthquake risks.

Future hardening or diversification of infrastructure efforts should consider these MSAs

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Multi-hazard risks

- Climate change-induced and naturally occurring multi-hazard risks are some of the biggest threats facing humanity
  - Multi-hazard risks occur in a cascading manner over time
  - E.g., earthquake (OR) -> tsunami (Japan), tsunami (OR) -> landslide (CA), etc.

- Multi-hazard risks have devasting impacts on different aspects of our lives
  - Societal impacts (e.g., increase in freq. and number of hazards)
  - Economical impacts (e.g., the cost of 18 hazards in 2024 was $165B)
  - Impacts on the network infrastructures (e.g., significant loss of connectivity)

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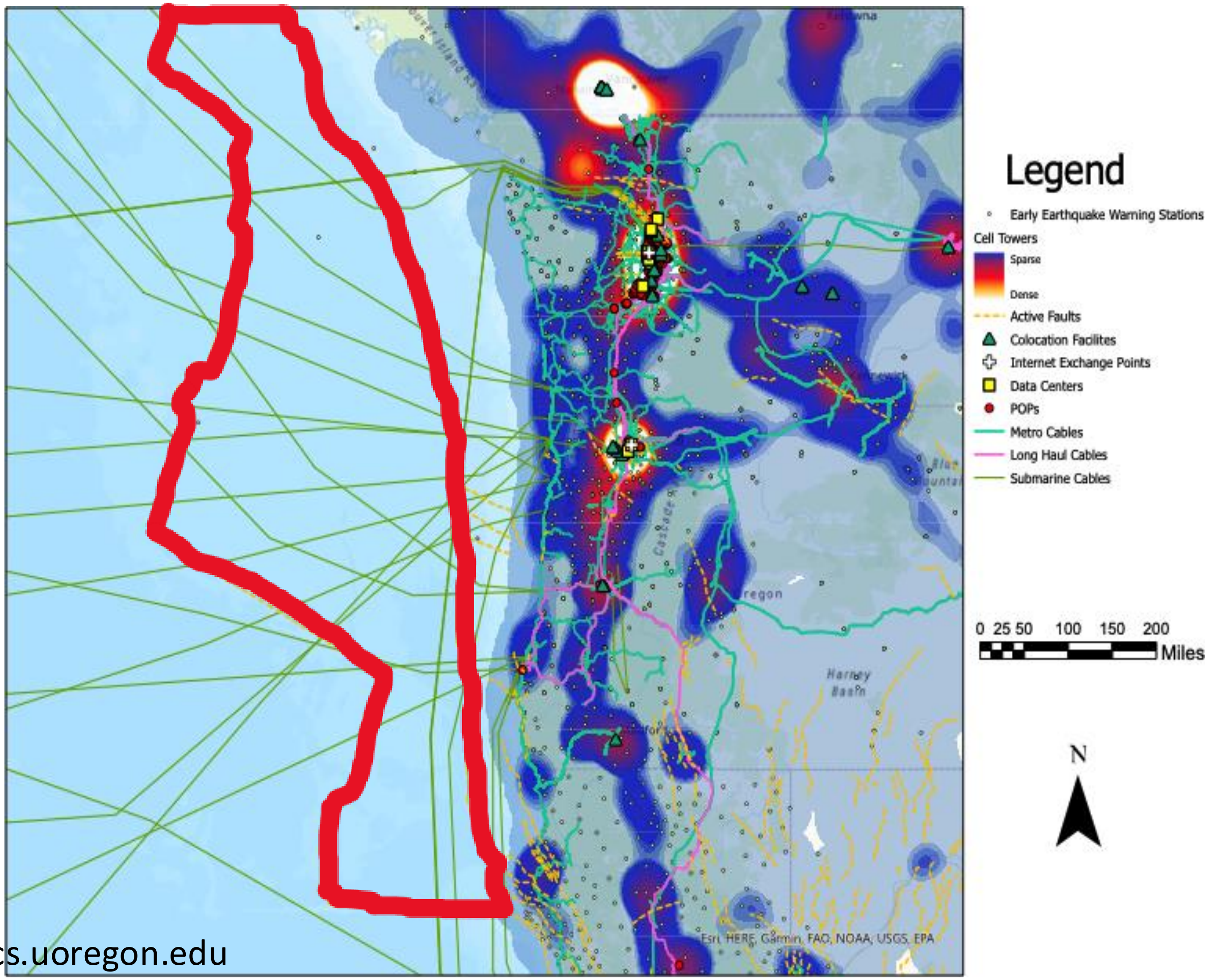
An Illustrative example

- PNW is a multi-billion dollar infrastructure hub
  - Networks (e.g., Submarine cables, colos, etc.)
  - Early warning systems (e.g., ShakeAlert, AlertWildfire)

- Cascadia M9 earthquake followed by a tsunami in PNW
  - ArcGIS to combine infrastructure maps, NOAA tsunami models, and PNSN earthquake hazards



An Illustrative example

- Count of infrastructures that are prone to damage during a multi-hazard risk in PNW

Fiber (km)	Cell Towers	PoPs	Data Centers	Colos
32,057	204,585	422	32	59

- Population affected by infrastructure damage in PNW

	Total Population	Emergency Responders
OR	3,879,430	6,681
WA	6,901,149	18,189

Aleksandr Stevens, Blaise Iradukunda, Brad Bailey and Ramakrishnan Durairajan, “Can LEO Satellites Enhance the Resilience of Internet to Multi-Hazard Risks?” in PAM 2024.

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Survivability against outages

- A key takeaway: physical redundancy matters!

- Goal: tolerate up to “k” failures
  - More submarine cables (e.g., ~60 new cables in 2027)
  - More satellites (e.g., megaconstellations)
  - More datacenters (e.g., rise of neoclouds)

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survivability

Climate change

infrastructure

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survivability

Climate change $\xrightarrow{}$ infrastructure

But: is it *sustainable*?

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Outline

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Computing as an environmental challenge

- Rise of datacenters leads to power-system strain and water strain
- Satellite megaconstellations lead to environmental hazards

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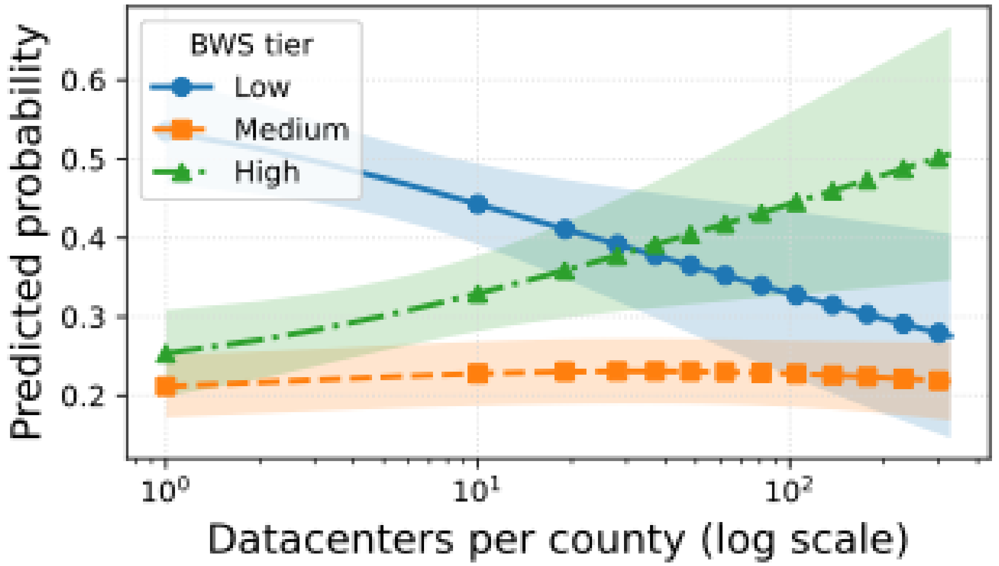
Rise of datacenters

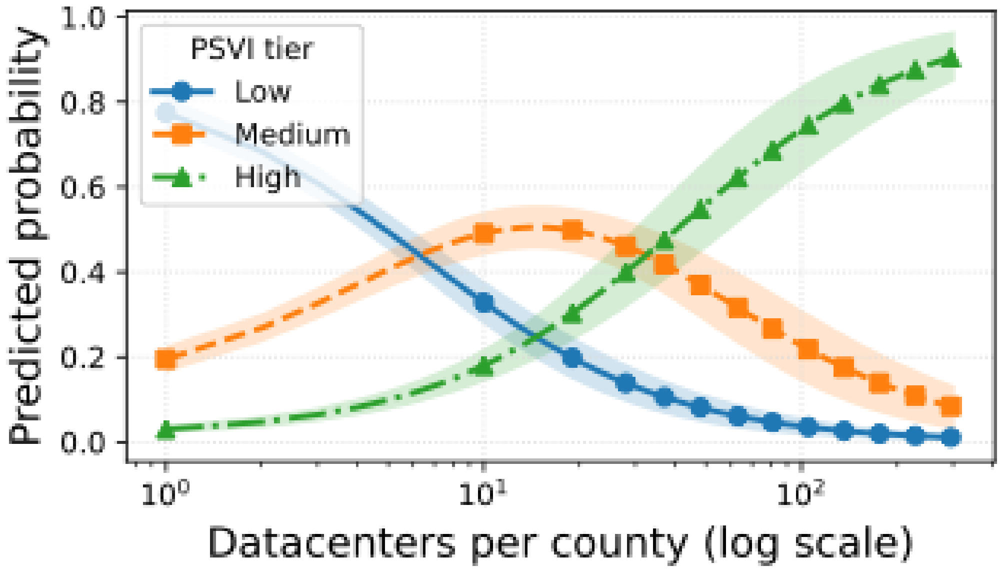
... leads to private WANS and NeoClouds!

Rise of datacenters

Overlap of baseline water stress (BWS) and datacenter locations in the US.



Overlap of Power System Vulnerability Index (PSVI) and datacenter locations in the US.



Datacenter density increases the probability of a county being in a high power-system vulnerability and BWS tiers!

Caleb Wang, Fabian Bustamante and Ramakrishnan Durairajan, “Deliberately Distributed: Rethinking Compute Siting at the Ocean’s Edge” in submission.

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"AI IS CAUSING CLIMATE CHANGE AND DESTROYING WATER..."
"WAIT A SECOND. THAT MEANS IT'S TAKING CARE OF THE RISING SEA LEVELS!"
imgflip.com


SPACEX
EVOLVING AI
ELON MUSK'S SPACEX ACQUIRES XAI AS HE PLANS MASSIVE SPACE-BASED DATA CENTERS TO POWER AI
SWIPE FOR MORE

Satellite megaconstellations

- LEO satellites have short operational lifespans (e.g., 5 to 7 years)
    - Atmospheric drag, solar storms, collisions, etc.

- This *impermanence* introduces a replacement requirement: launch new satellites to maintain network connectivity (i.e., by replacing those that deorbit)

- A 250-kg satellite can generate ~30 kg of aluminum oxide (AlO) particles
    - May endure for decades in the atmosphere

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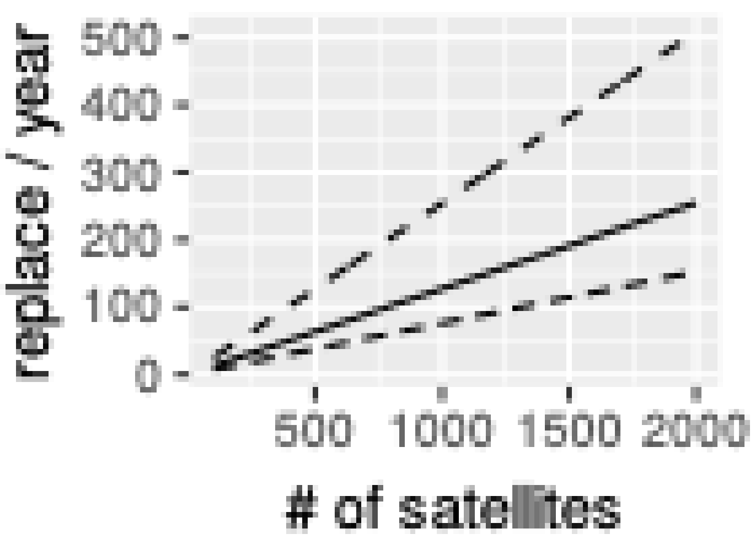
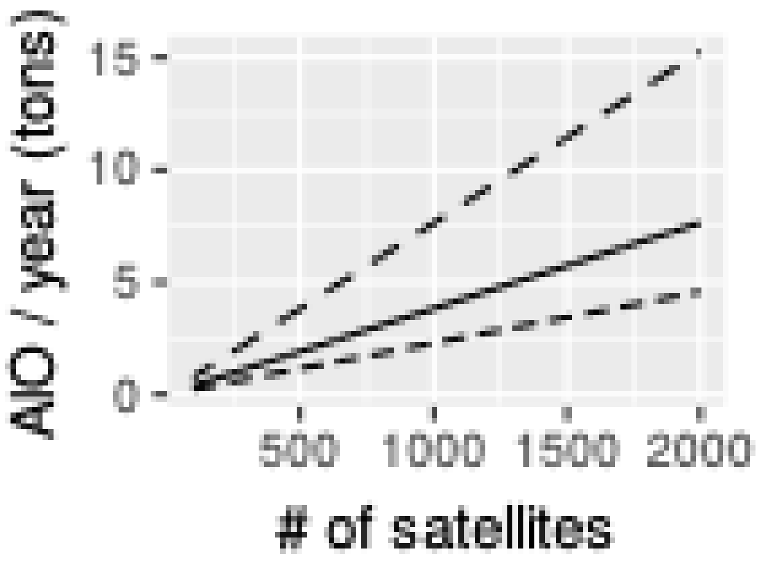
Satellite megaconstellations

No. of replacement events/year required to maintain a steady-state no. of satellites (x-axis).



Corresponding amount of AlO deposited in the mesosphere by re-entries (based on Ferreira et al., 2024)



Chris Misa and Ramakrishnan Durairajan, “The Internet from Space, Reimagined: Leveraging Altitude for Efficient Global Coverage” in ACM SIGCOMM LEO-NET 2025.

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Sustainability of infrastructure

- A key takeaway: more infrastructure is not merrier

- Goal: greenest way is often the infra. you do not need to deploy
  - Less submarine cables
  - Less satellites
  - Less datacenters

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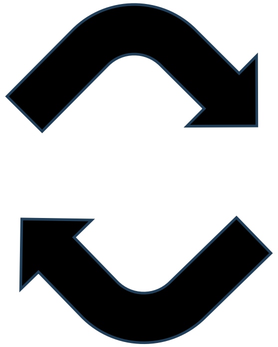
Caught in the loop

survivability

Climate change



infrastructure

sustainability

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Outline

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Survivability or sustainability: how do we eliminate the need to choose?

- Hurricanes
- Earthquakes
- Multi-hazards
- Submerged Compute

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Hurricanes

- All survivability efforts assume events have happened
  - For example, outage has happened -> provision *more* infrastructure, reactively run optimization and re-allocate traffic
- Insight: risk-aware routing
  - You can predict the course of an event (e.g., NOAA's APIs)
  - Use that prediction intelligently and move traffic *without* more infrastructure

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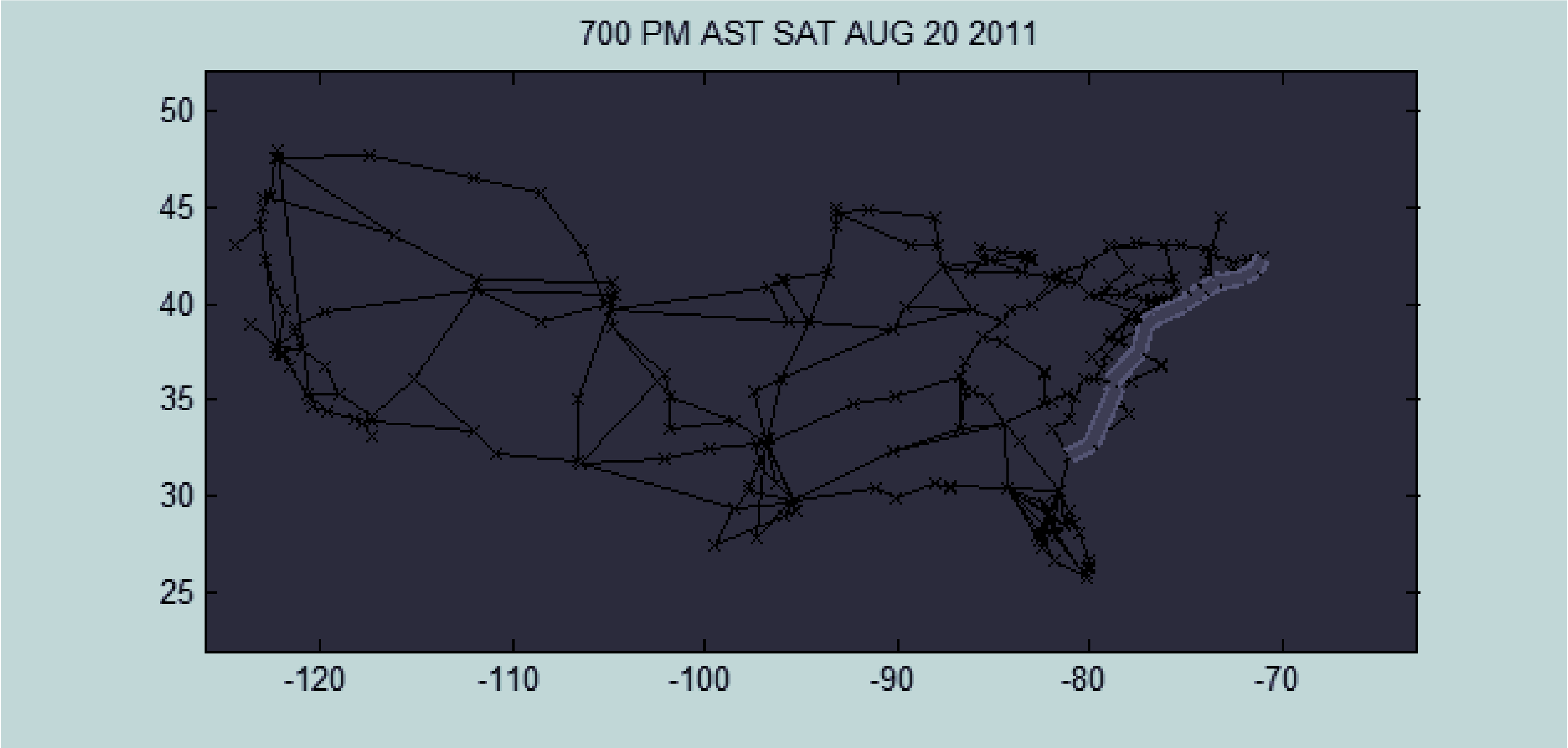
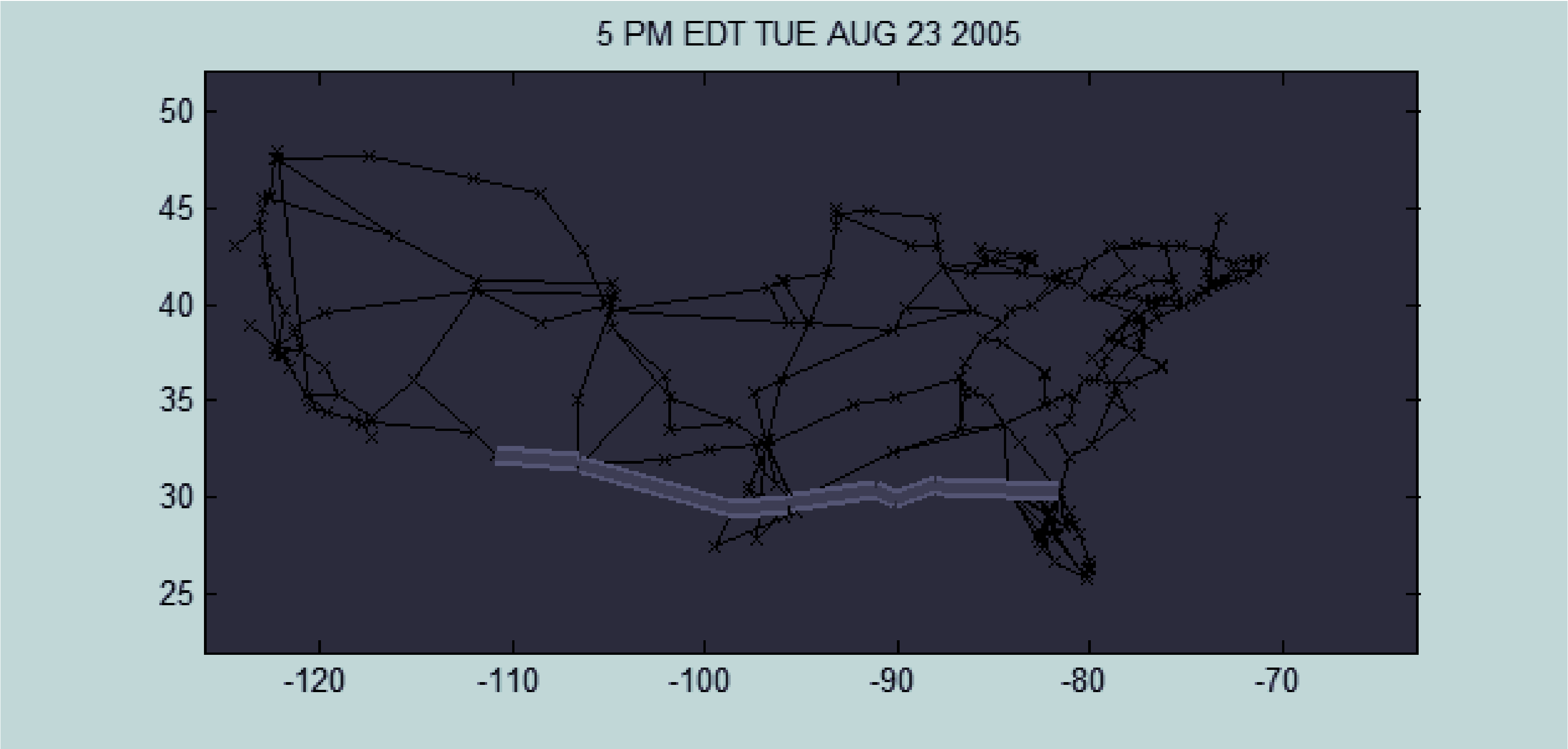
Hurricane Irene and Level3 - illustration



Hurricane Katrina and Level3 - illustration



Earthquake

- All survivability efforts assume events have happened
  - For example, outage has happened -> provision *more* infrastructure, reactively run optimization, and re-allocate traffic
- All survivability efforts assume “all MMIs have the same effect”
  - BUT: severe shaking has more impact on infra. than strong shaking?
- Insight: risk-aware + shaking-informed routing (core of ShakeNet)
  - You can predict the course + severity of an event (e.g., ShakeAlert)
  - Use that prediction intelligently and move traffic *without* more infrastructure

geographically longer fiber routes but are less susceptible to shaking

vs.

existing routes that are more prone to earthquake-induced shaking

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Mitigation of infrastructure risks

Routes	Latency	Avg – 10%	Avg – 2%
Baseline (along I-5)	~3ms	0.24	0.36
Yakima - Kennewick	~6ms	0.2	0.32
Spokane - Boise	~18ms	0.18	0.28

Comparison of PGA values and latencies for the shortest path from Seattle to Portland vs. other alternate paths.

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Multi-hazard risks

- All survivability efforts assume isolated events
- Risk-aware mitigation strategies route traffic *around* failures using geographically longer backup routes
  - For example: what if the primary and backup terrestrial routes are affected by earthquakes and landslides respectively?
- Insight: repurpose infrastructures that are not affected
  - E.g., terrestrial events (e.g., earthquakes) do not affect satellites
  - Opportunistically offload to/reroute via *unused* satellites

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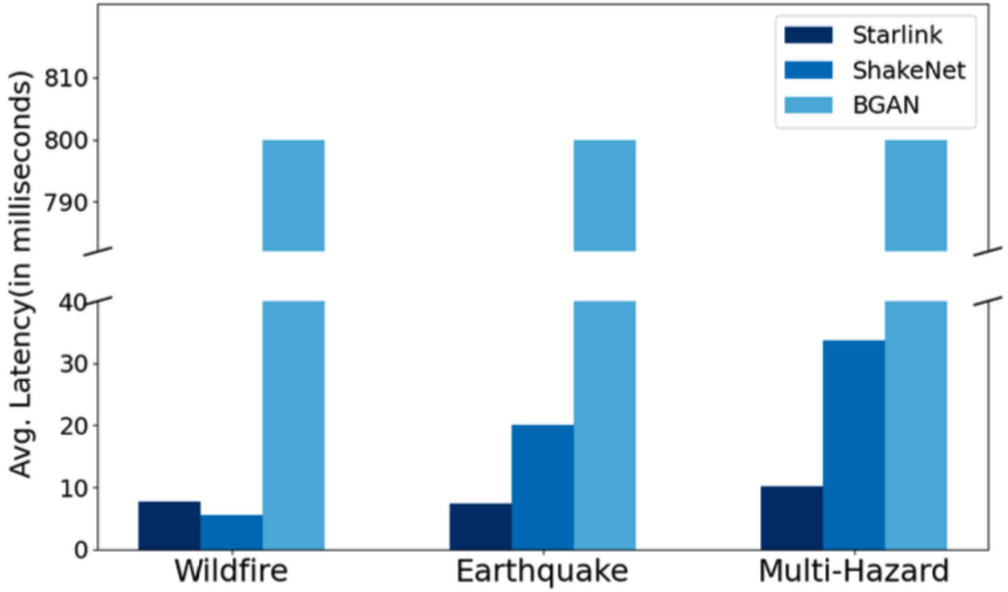
Opportunistic re-purposing is very effective!

- Comparison of emergency communication strategies for the three risk models



	Hardware	Network Plan	Total Cost
Starlink Wildfire	\$389,350	\$660	\$390,010
BGAN Wildfire	\$3,246,750	\$301,040	\$3,547,790
Starlink Earthquake	\$2,755,400	\$4,400	\$2,759,800
BGAN Earthquake	\$22,977,000	\$2,124,320	\$25,101,320
Starlink Multi-Hazard	\$6,235,590	\$9,900	\$6,245,490
BGAN Multi-Hazard	\$51,997,950	\$4,808,120	\$56,806,070

We also find that LEO-based backup provides 100% service to first responders with <0.01% of the current allocated budget for disaster response.

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Submerged compute

- Datacenters today
  - Siting = inland
  - Foci = cooling, fiber availability, power, etc.
  - Because siting is inland, onus is squarely on cooling and power
- Insight: datacenters should be a natural extension of submarine infra.
  - What if we submerge datacenters under water? (Microsoft's Project Natick, https://www.theguardian.com/world/2026/jun/09/worlds-first-wind-powered-underwater-datacentre-starts-operating-in-china)
    - Provides natural cooling
  - Co-locate with submarine cable infrastructure
    - Cables are already vetted for resiliency requirements
    - Opens up an alternate source of power: hydro, wind, etc.

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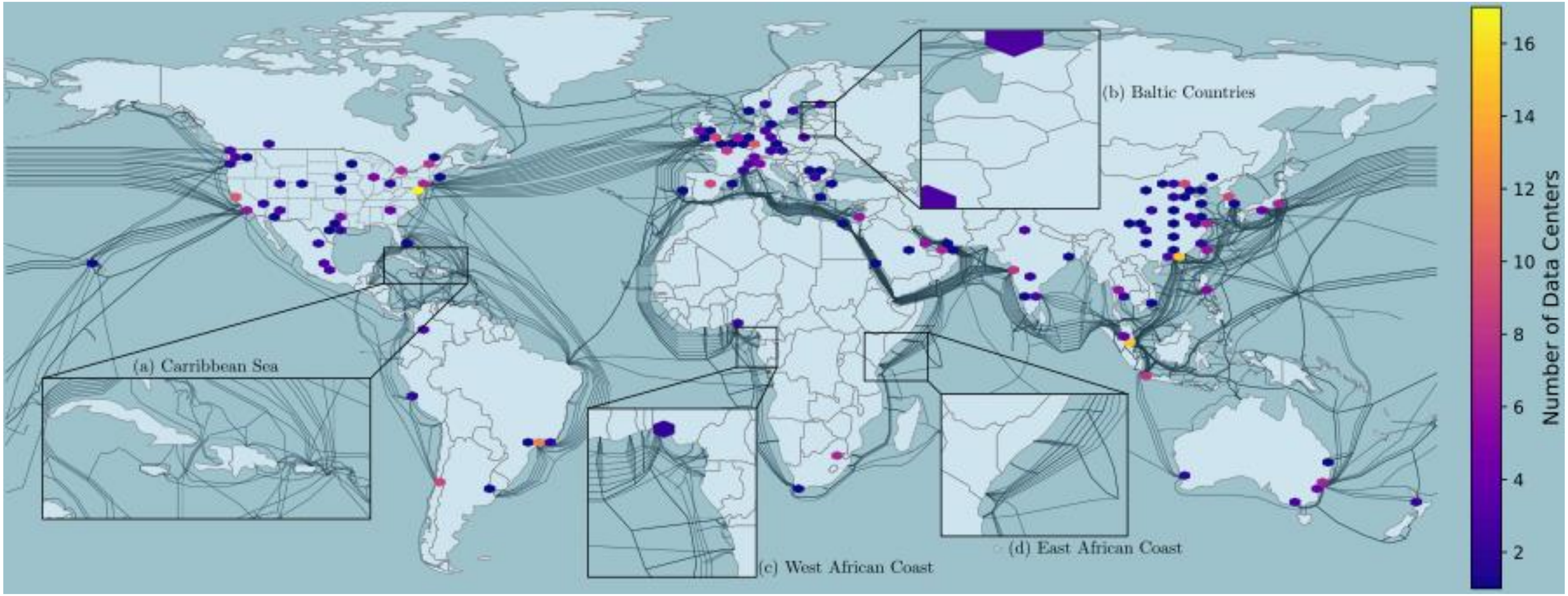
There are 100s of locations around the world…



Geographic distribution of datacenters and submarine cable landing points. Regions with high population density and strong cable connectivity but lacking nearby datacenters are highlighted as potential sites for submerged datacenters.

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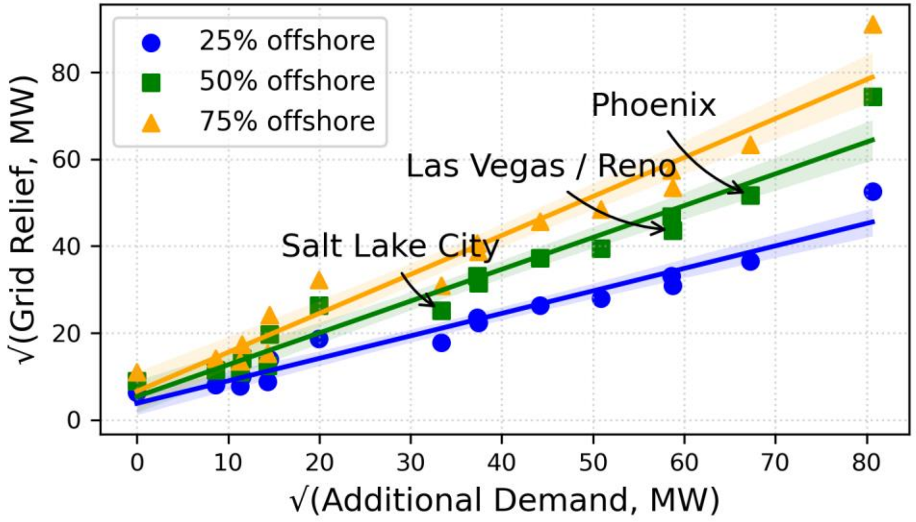
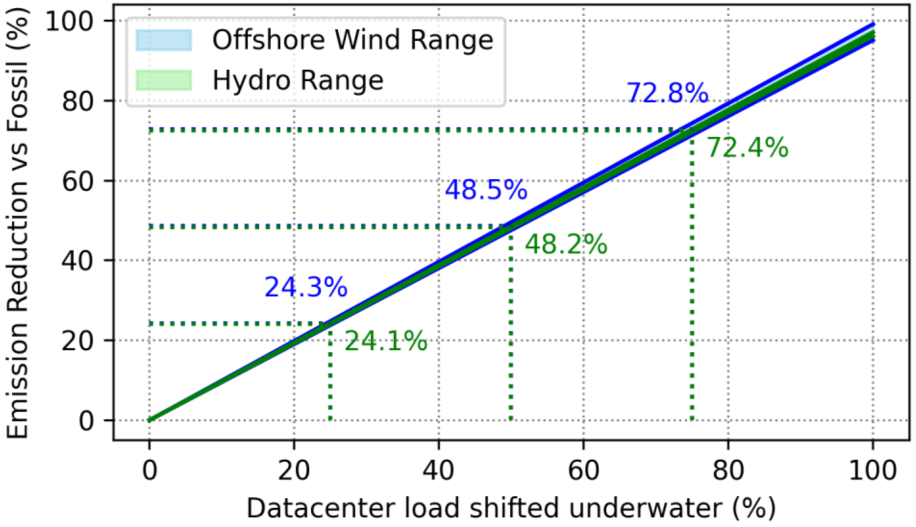
Submerged compute unlocks a new dimension of sustainability and survivability!



metros with the highest incremental demand reap the largest relief when workloads move offshore



proximity to renewables enables roughly 24%, 49%, and 73% emissions reductions at 25/50/75% shift, whether the modules are powered by offshore wind (Atlantic, Pacific, Gulf) or by hydro-rich corridors (Pacific Northwest, New England)

In the U.S., shifting even half of AI workloads offshore relieves the most stressed metros while cutting emissions

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Outlook

- Next decade will be defined by three constraints
  - ⚡ **Power:** AI growth increasingly limited by electricity availability, not chips alone.
  - 💧 **Water:** Cooling infrastructure will compete with growing environmental and societal demands.
  - 🌍 **Climate Resilience:** Data centers, networks, and power systems must operate under more frequent extreme events.

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Outlook

- Aligning sustainability and resiliency
  - Historically, resiliency = uptime and sustainability = env. impact
  - Now they are starting to overlap
    - Renewable energy improves resilience
    - Submerged systems reduce costs and emissions

The next era of computing should be measured not only in FLOPS, but in survivability and sustainability.

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Thank you!

survivability

Climate change

infrastructure

sustainability

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