Emissions from transportation and ship detection

Machine learning for climate action
CS-E407519 Lecture 4

We will talk about ...

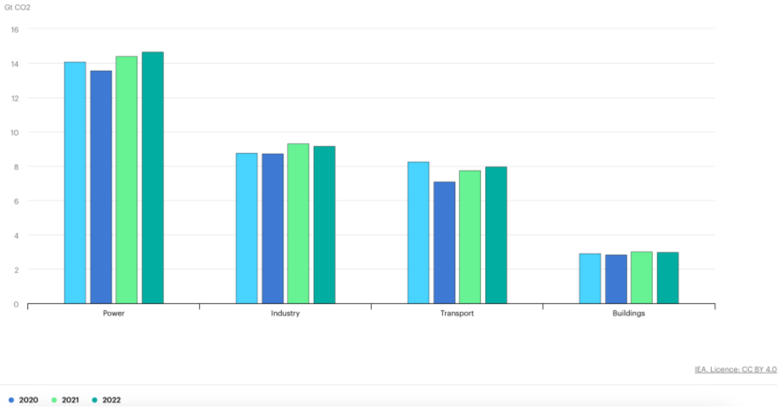
- Transport sector emissions
- Shipping emissions
- Satellite data and machine learning to monitor industrial activity at sea (paper)
- Methodology: combination of different data sources and ML methods

What are transport emissions?

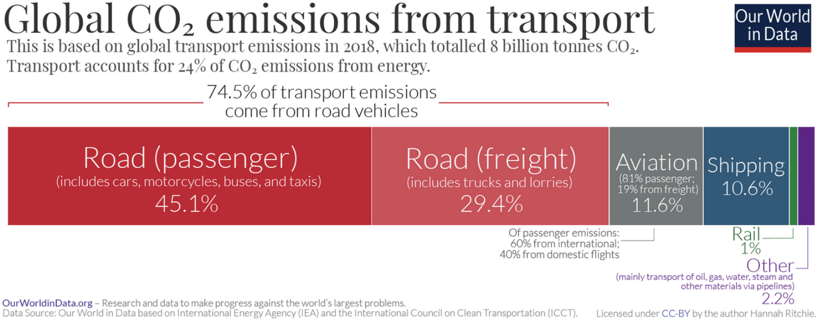
Transport emissions refer to **greenhouse gases released during transportation**. Main transport means are road vehicles, airplanes, ships, and trains. **Road transport is the largest emitter**.

- **Significant contributor**: Transport accounts for around one-fifth of global CO_2 emissions (24% if we only consider CO_2 emissions from energy).
- **Environmental impact**: Transportation emissions significantly contribute to climate change, air quality and public health.
- **Future perspectives:** Transport demand is expected to grow across the world in the coming decades as the global population increases, incomes rise, and more people can afford cars, trains and flights. IEA expects global transport to double, car ownership rates to increase by 60%, and demand for passenger and freight aviation to triple by 2070.

Global emissions by sector



Emissions from transportation



Main strategies to decarbonize transport sector (UNEP)

- Switch fleets to electric vehicles.
- Incentivize a transition to zero-emission transportation, including for cars, taxis, buses, trucks and trains.
- More bicyle lanes or walking paths.
- Promote related public health benefits.
- Switch to rail for the transportation of raw materials.
- Remote work, video conferencing for meetings and conferences.

Challenges to decarbonize transport sector

In this Science paper from Steven David et al., the authors examined strategies for achieving net-zero emissions across various sectors. They identified **long-distance road freight, aviation, and shipping as especially challenging to decarbonize**. Why?

- The size and weight of batteries or hydrogen tanks needed for these applications would significantly exceed those of current combustion engines.
- To reach net-zero for the energy sector as a whole, these emissions would have to be offset by *negative emissions* (e.g. the capture and storage of carbon from bioenergy or direct air capture) from other parts of the energy system.
- In the IEA's net-zero scenario, nearly two-thirds of the emissions reductions come from technologies that are not yet commercially available. **Reducing CO_2 emissions in the transport sector over the next half-century will be a formidable task**.

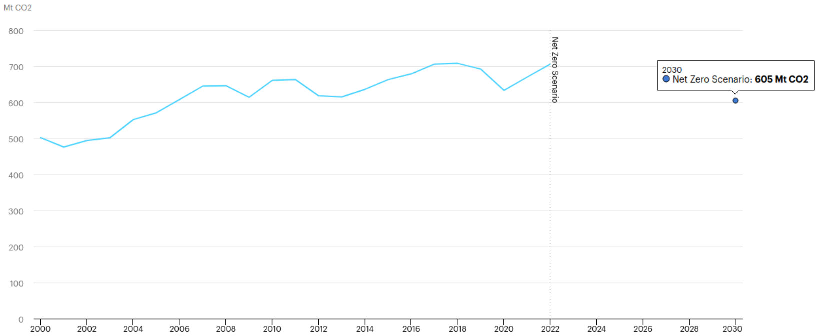
Poll: How many standard cargo containers can the largest container ship transport?

Emissions from maritime transport

- Maritime transport plays an essential role in the global economy.
- It is **one of the most energy-efficient modes of transport**.
- It is a **large and growing source** of greenhouse gas emissions.
- In 2018, global shipping emissions represented 1 076 million tonnes of CO_2, and were responsible for around 2.9% of global anthropogenic emissions.

Largest container ship: MSC Irina (China, December 2023). Dimensions: 400 m long, 61.3 m high. Maximum number of standard cargo containers (6.1 m long): 24 346. Those would need at least a 150 km long train.

CO_2 emissions from maritime transport

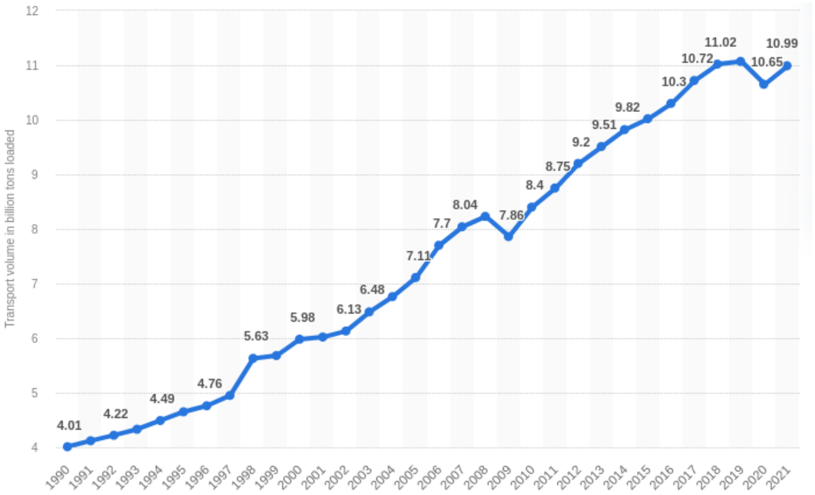


Evolution of CO_2 emissions from maritime transport and Net Zero scenario.

Why is shipping important?

- **Global trade engine**: Shipping is the backbone of global trade. It is estimated that over 80% of the world's goods are transported by ships.
- **Cost-effectiveness**: Shipping is the most cost-effective method to transport vast quantities of goods over long distances, facilitating international trade and economic globalization.
- **Economic growth**: Shipping directly contributes to the economies of maritime nations and the global economy (shipping, ports, and related industries).
- **Market accessibility**: Provides critical access to international markets, especially for developing countries, enhancing their economic development and integration into the global economy.

Why is shipping important?



Transport volume of seaborne trade from 1990 to 2021 (`https://www.statista.com/statistics/264117/tonnage-of-worldwide-maritime-trade-since-1990/`).

Some random facts about cargo ships

- A large cargo ship uses 150–250 tons of fuel per day and requires as much fuel as 3 770 cars per kilometre.
- 97% of all shipping containers are built in China.
- At least 20 million containers are currently travelling across the oceans at this moment in time.
- **Shipping is cheap:** It is cheaper for Scottish cod to be shipped to China (16 000 km away), filleted and returned to Scotland, than it is to pay Scottish workers to do the same job. It is cheaper to ship New Zealand tuna in Thailand and ship it back to New Zealand than it is to have the processing completed in New Zealand.
- Ships are high-value assets (larger high-tech vessels can cost more than 200 million dollar to build).
- **Slow but steady:** A general cargo ship has typically a maximum speed of about 25 knots (46 km/h) covers a distance from UK to Shanghai (China) in about 49 days.

Paper: Satellite mapping reveals extensive industrial activity at sea

Paper: Satellite mapping reveals extensive industrial activity at sea [1]

Steps:

1. Synthetic Aperture Radar (SAR) data from Sentinel-1
2. Visible and near infrared (NIR) imagery from Sentinel-2
3. Automated Identification System (AIS)
4. Other environmental data sources
5. Strategy: Detection and classification of vessels and infrastructure
6. Main methods: constant false alarm rate (CFAR) and convolutional neural networks (CNN or ConvNet)
7. Model evaluation and results

Code available HERE.

[1] Paolo, F., Kroodsma, D., Raynor, J. et al. Satellite mapping reveals extensive industrial activity at sea. Nature 625, 85–91 (2024). https://doi.org/10.1038/s41586-023-06825-8

Activities in the ocean

Fact: During 2017–2021, about **63 300 vessel** occurrences were **detected at any given moment** on average.

Industrial fishing (43–49% of 23.1 million vessel detections)

- Where? 86% in waters less than 200 m deep.
- Main region? 71% in Asia.
- Not officially tracked: 72–76%.

Other activity (transport, energy)

- Where? 75% in waters less than 200 m deep.
- Main region? 65% in Asia.
- Not officially tracked: 21–30%.

Check this.
Their method revealed high densities of vessel activity in large areas of the ocean that previously showed little to no vessel activity by public tracking systems. Check this, this and this.

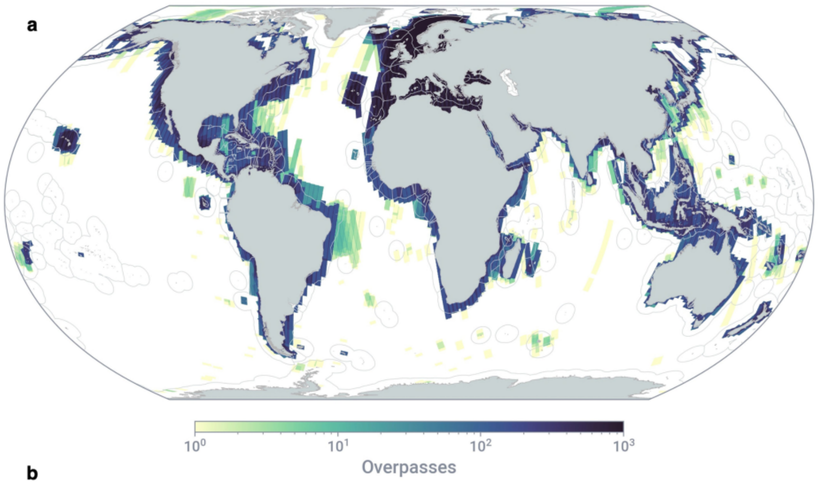
Poll: Do you believe the shipping industry can achieve net-zero emissions by 2050?

Copernicus Sentinel-1 mission

- **Sentinel-1 is an imaging radar mission** providing continuous all-weather, day-and-night imagery at C-band.
- **Use:** monitoring sea ice, oil spills, and maritime surveillance; mapping for forest, water, and soil management; and assisting in humanitarian aid and natural disaster scenarios.
- The mission consisted of two satellites (Sentinel-1A and Sentinel-1B) that orbited 180° out of phase in a polar, sun-synchronous orbit. Sentinel-1B stopped operating in December 2021 due to an anomaly in the instrument electronics. Plans are in force to launch Sentinel-1C asap (planned for 2024).
- **Imaging frequency:** Combined 6-day global mapping cycle for a while, 12-day cycle per satellite.

Check these examples.

Copernicus Sentinel-1 mission



The Sentinel-1 SAR imagery (IW GRD product) covers most coastal waters but does not sample most of the open ocean. The extent and frequency of SAR acquisitions is determined by the mission priorities.

Data source 1: SAR imagery

- **Synthetic Aperture Radar (SAR) imagery** refers to a type of high-resolution satellite or aircraft-based radar imaging.
- Unlike traditional optical imaging, SAR uses **radar waves** to capture images.
- Capable of **high-resolution** remote sensing.
- Independent of flight altitude.
- **All-weather capability:** can select frequencies to avoid weather-caused signal attenuation.
- SAR has **day and night** imaging capability.
- **Surface texture and structure information:** sensitive to the structural characteristics of surfaces, including texture, roughness, and patterns. This makes it useful for applications like land cover classification, deforestation monitoring, and urban development analysis.

In particular: **SAR imaging systems are the most consistent option for detecting vessels at sea.**

Data source 1: SAR imagery

Some technical aspects:

- The number of images per location varies greatly depending on mission priorities, latitude and degree of overlap between adjacent satellite passes.
- They use the Ground Range Detected (GRD) Level-1 product provided by Google Earth Engine here. Some data pre-processing is done.
- Data from October 2016 to February 2022, comprising 753 030 images of $29\,400 \times 24\,400$ pixels each on average.

Copernicus Sentinel-2 mission

- **Sentinel-2 is a multispectral imaging mission** primarily designed for land monitoring, offering detailed, high-resolution optical images in the visible and near-infrared part of the spectrum.
- **Use:** monitoring land changes, agriculture, and forestry; assessing vegetation health; and measuring and monitoring environmental pollution. It also plays a crucial role in disaster control, humanitarian tasks and security.
- The mission consists of two twin satellites, Sentinel-2A and Sentinel-2B, which orbit in the same sun-synchronous orbit, phased at 180° to each other. This configuration optimizes global coverage and data delivery.
- **Imaging frequency:** Together, they provide a 5-day revisit time at the equator, with the revisit frequency being higher at higher latitudes due to the overlapping swaths.

Check Sentinel-2 coverage here.

Data source 2: Visible and NIR imagery

Some technical aspects:

- They used RGB (red-green-blue) and NIR (near infrared) bands from the Level-1C product provided by Google Earth Engine here. **Pre-processing:** excluded images with more than 20% cloud coverage using the QA60 bitmask band with cloud mask information.
- Data from October 2016 to February 2022, comprising 2 494 370 images of $10\,980 \times 10\,980$ pixels on average.

Automated Identification System (AIS)

- The **Automatic Identification System (AIS)** is a global tracking system primarily used in the maritime domain for the automatic tracking and identification of ships. Key component of marine navigation safety and traffic management.
- AIS allows vessels and maritime authorities to exchange data such as vessel identity, position, course, speed, ... This system enhances navigational safety by enabling ships to see each other and be seen by shore-based tracking systems, even in poor visibility conditions.
- The system is mandated for all international voyaging ships with a gross tonnage of more than 300 and all passenger ships, regardless of size.
- AIS works by transmitting data at regular intervals via VHF radio frequencies. This information can be received by AIS transceivers on other ships and by terrestrial and satellite AIS receivers.

Vessels that are not visible on publicly accessible AIS data are called **not publicly tracked**. Also known as **dark vessels**.

Data source 3: AIS data from ORBCOMM and Spire

- **Orbcomm** is a family of low Earth orbit communications satellites, operated by the US satellite communications company Orbcomm. More than 50 satellites (Wikipedia).
- **Spire** is a space-to-cloud data and analytics company that specializes in the tracking of global data sets powered by a large constellation of nanosatellites, such as the tracking of maritime, aviation and weather patterns (Wikipedia). Check this.
- 53 billion AIS messages processed. Data extracted: locations, lengths and identities of all AIS devices that operated near the SAR scenes around the time the images were taken.

Poll: What other data sources would you use in this study?

Data sources 4–9: Environmental and physical data

Different data over the ocean at 1-km resolution:

- **Chlorophyll data** from the NASA Ocean Biology Processing Group (OBPG).
- **Sea-surface temperature and currents** from the Copernicus Global Ocean Analysis and Forecast System.
- **Distance to shore** from NASA OPG and Pacific Islands Ocean Observing System (PacIOOS).
- **Distance to port** from Global Fishing Watch.
- **Bathymetry** from General Bathymetric Chart of the Oceans (GEBCO)
- **Exclusive economic zone (EEZ)** [2] from Marine Regions.

[2] An **exclusive economic zone (EEZ)**, as prescribed by the 1982 United Nations Convention on the Law of the Sea, is an area of the sea in which a sovereign state has exclusive rights regarding the exploration and use of marine resources, including energy production from water and wind boundaries

Strategy

1. Vessel detection. Data: SAR. Method: CFAR.
2. Vessel presence and length estimation. Data: SAR, AIS. Method: CNN.
3. Infrastructure detection. Data: SAR. Method: CFAR.
4. Infrastructure classification. Data: SAR, RGB imagery. Method: CNN.
5. Fishing and non-fishing vessel classification. Data: SAR, environmental data, AIS. Method: CNN.

Introduction to the CFAR method

- **Purpose of CFAR**: Constant False Alarm Rate (CFAR) is a **statistical method** used in radar systems to detect targets against a background of noise or clutter.
- **Working principle**: CFAR adjusts the threshold dynamically based on the level of surrounding noise, ensuring a constant rate of false alarms.
- **Application in radar systems**: Widely used in radar signal processing to distinguish between true targets (like ships or aircraft) and false signals from environmental factors.
- **Key advantage**: Offers robust detection performance even in varying or uncertain noise environments, crucial for reliable radar operation.

Step 1: CFAR for vessel detection

- **Method:** Based on CFAR algorithm, an adaptive threshold method for anomaly detection in radar imagery.
- CFAR detects unusually bright pixel values (vessels) against the surrounding sea clutter. Sets a threshold based on local background statistics, using sliding windows (In this case inner: 200×200 pixels, outer: 600×600 pixels).
- **Adaptation: Modified two-parameter CFAR** algorithm accounts for mean and standard deviation of backscatter values.
- Time-dependent thresholds adjusted for changing SAR image properties from Sentinel-1 satellites. Five time intervals calibrated for consistent small vessel detection (15–20m length).
- **Outcome:** 60% detection rate for smaller vessels across the Sentinel-1 data.
- **Implementation:** Algorithm implemented using Google Earth Engine's Python API, leveraging Google's cloud infrastructure for big data processing, analysis, and distribution.

Step 2: CNN for vessel presence and length estimation

- **Method:** Convolutional neural network (CNN) based on residual networks (ResNet) [3] architecture for analyzing dual-band SAR image tiles (80$\times$80 pixels).
- CNN for binary classification (object presence) and a regression (object length estimation).
- **Data preparation:** Over 62 million image tiles with detected objects centered.
- **Data fusion:** SAR detections combined with AIS data, covering diverse scenarios (icy, rocky, vessel-dense areas, etc.).
- Integrating SAR and AIS data is challenging due to misaligned timestamps and potential mismatches between SAR detections and AIS vessel positions. The integration process involves a probability raster approach based on AIS data, which estimates vessel positions at different times and speeds for various vessel classes.

[3] **ResNet**, short for residual networks, is a type of NN architecture that was designed to make training of deep networks more effective.

Step 2: CNN for vessel presence and length estimation

- **Data labeling:** High-confidence annotations for training data provided by domain experts. Labelled dataset of 12 000 high-quality samples, divided into 80% training and 20% testing sets. Check this.
- **Training:** Fivefold cross-validation scheme for model learning and selection. Performance metrics averaged across folds, with final evaluation on a holdout test set.
- **Model evaluation:** Classification: F1 score of 0.97 and accuracy of 97.5%. Length estimation: R2 score of 0.84 and RMSE of 21.9m (approx. 1 pixel).

Step 3: CFAR for infrastructure detection

- **Method:** Adapted the two-parameter CFAR algorithm used for vessel detection to identify offshore infrastructure.
- **Modification 1:** Median composites of SAR images within a 6-month window were used to eliminate non-stationary objects (mostly vessels), retaining only stationary objects like infrastructure.
- **Modification 2:** Empirically adjusted detection window sizes to account for dense clusters of structures, like wind farms, and smaller objects like weather masts.
- **Outcome:** This modified approach enhances signal coherence from stationary structures while reducing background noise, effectively identifying infrastructure in high-density areas.

Step 4: CNN for infrastructure classification

- **Method:** CNN based on the ConvNeXt [4] architecture for classifying detected offshore structures.
- CNN with multi-input and single-output structure. The CNN processes two multiband image tiles (100×100 pixels) from SAR and optical imagery, through independent convolutional layers, then concatenates feature maps for final classification. 4 classes: wind infrastructure, oil infrastructure, other infrastructure, and noise.
- **Data fusion:** Combination of SAR imagery from Sentinel-1 with optical imagery from Sentinel-2.
- **Data labeling:** Integrated ground truth data from multiple sources for labeling over 47 000 samples (oil, wind, noise, other). Used 80% for training and 20% for testing with fivefold cross-validation.
- **Model evaluation:** Class-weighted average F1 score of 0.99 and accuracy of 98.9% on the test set for the multiclass classification task.

[4] **ConvNeXt** is a modern NN architecture that represents an evolution in the design of CNNs.

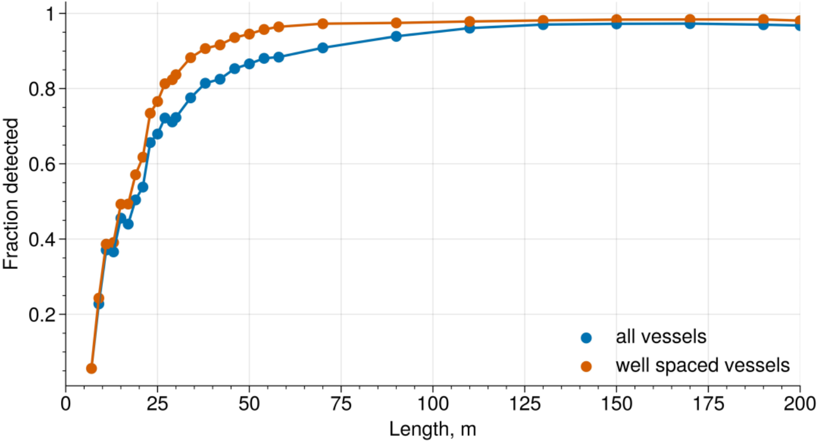
Step 5: Fishing and non-fishing classification

- **Method:** ConvNeXt architecture for binary classification of vessels as fishing or non-fishing, using vessel length and environmental data.
- CNN with multi-input and single-output structure. It combines estimated vessel length from SAR and an 11-band raster stack (100×100 pixels) representing environmental context variables like bathymetry, temperature, chlorophyll levels, and vessel activities. Final result is a binary classification: fishing or non-fishing vessel.
- **Data labeling:** The fishing and non-fishing labels are obtained from AIS vessel identities.
- **Data preparation:** 120 000 tiles split into training (80%) and test (20%) sets; test set of 14,100 tiles. Inference on over 52 million tiles.
- **Training:** Two separate models trained on alternating 'even' and 'odd' latitude and longitude grid cells to avoid spatial overlap and ensure comprehensive coverage.
- **Model evaluation:** Calibrated model output scores for balanced detection; performed sensitivity analysis for varying fishing/non-fishing ratios. Achieved a test set F1 score of 0.91 and accuracy of 90.5%.

On model evaluation: false positives and recall

- **Challenge in estimating false positives (FP)**: Due to the absence of ground-truth data on non-vessel areas, determining the global FP rate is complex.
- **FP density metric**: Analyzed 150 million km^2 of imagery in low AIS-density regions, estimating an upper limit of false positives at 5.4 detections per 10 000 km^2. This suggests a potential false-positive rate of about 2%, likely lower as some detections are real.
- **Recall estimation method**: Recall (correctly identified true positives) was estimated by comparing AIS data with SAR detections. Detected AIS-equipped vessels that were close in time to SAR image acquisition indicate recall.
- **Recall results**: Over 95% detection rate for vessels over 50m in length, about 80% for 25m–50m vessels, with lower detection for smaller vessels. Detection rate decreases for closely spaced vessels ($<$ 1km apart).

On model evaluation: false positives and recall

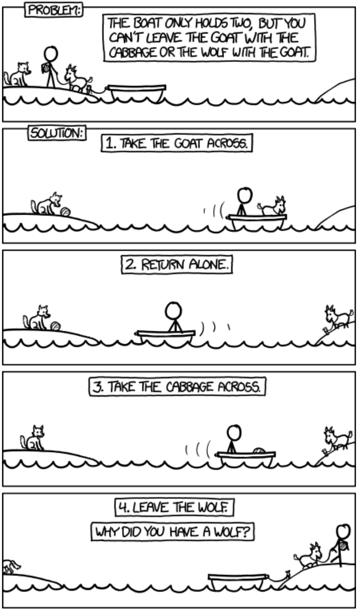


Recall

Limitations of the study

- **Sampling**: Sentinel-1 does not cover most of the open ocean, but industrial activity is predominantly near shore, where AIS use is higher.
- **Classification exclusions**: Objects within 1km of shore and in polar regions with sea ice are not classified due to ambiguities and false positives.
- **Resolution**: Sentinel-1 resolution (20m) limits detection of vessels smaller than 15m, influenced by factors like wind speed, sea surface state, and radar incidence angle.
- **Length estimate accuracy**: Vessel length estimates depend on AIS data quality; some inaccuracies exist due to incorrect AIS length reporting.
- **Fishing classification challenges**: Accuracy may be lower near cities or in regions with untracked activities; small industrial fishing vessels are often missed.
- **Regional underestimation**: Likely underestimates fishing activity in Asian waters and misses small artisanal fishing vessels less likely to carry AIS.

Logic boat (XKCD)



Or a cabbage, for that matter. The goat makes sense. Goats are fine.