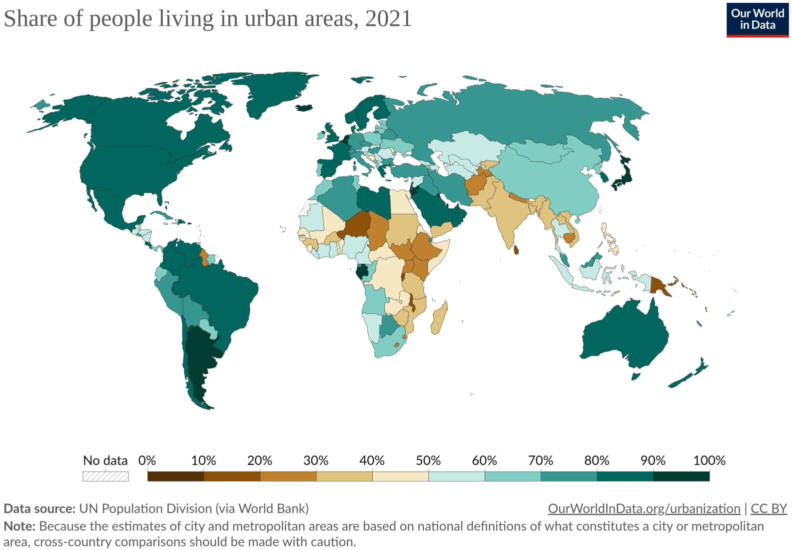
Urbanization and climate change

Machine learning for climate action
CS-E407519 Lecture 6

We will talk about ...

- Urbanization today
- Cities and climate action
- Classification of Local Climate Zones (LCZs)
- The World Urban Database and Portal Tool (WUDAPT)
- The urban morphology of our planet – Global perspectives from space (paper)

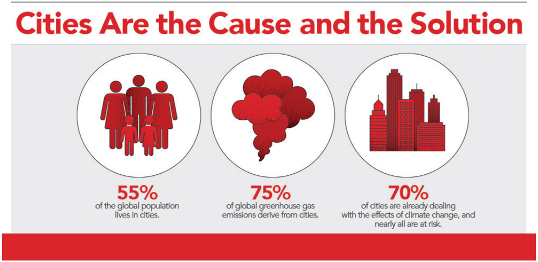
Big picture: urbanization today



Big picture: urbanization today

Emissions from energy, industry, transport and buildings all come together in urban areas.

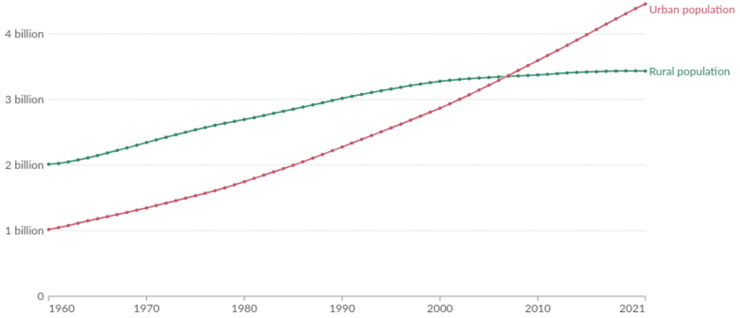
- Carbon emissions from **cities represent the single largest human contribution to climate change**. They represent 2/3 of global greenhouse gas emissions.
- Cities also contribute to climate change through changes in land use and the heat island effect.
- **Climate change impacts cities**, making them more vulnerable to extreme weather events, rising sea levels, etc.



Big picture: urbanization today

- Today, more than half of the world's population live in urban areas.
- By 2050, more than two-thirds of the world will live in urban areas. Nearly 90% of the growth in urban population expected in Asia and Africa.
- **UN Global Goal 11:** Sustainable cities and communities. Make cities and human settlements inclusive, safe, **resilient and sustainable**.
- If our aim is to develop resource-efficient and inclusive cities, understanding their structure, morphology and how many people they must provide for is essential for urban planning.

Big picture: urbanization today



Number of people living in urban and rural areas, World. Data source: World Bank based on data from the UN Population Division

Climate action for cities

- In 2014, for the first time, the IPCC report included a specific chapter on urban areas.
- IPCC report emphasizes that **cities** of sufficient density and dimensions can **influence their local micro-climate**. This highlights the importance of cities to climate action.
- Despite recognition, there is a significant lack of detailed, localized climate data for many urban areas.
- Urgen need for clear, actionable strategies that align urban development with climate goals.
- Understanding urban morphology is essential to bridge these gaps, offering data and insights for tailored urban climate action.

Climate action for cities

Climate action for urbanization involves strategies for reducing greenhouse gas emissions, enhancing resilience to climate impacts, and ensuring sustainable development of urban areas.

- **Green infrastructure:** Urban forests, green roofs, etc. to combat heat island effect and enhance air quality.
- **Sustainable transportation:** Expand public transport, encourage cycling and walking, develop electric vehicle infrastructure.
- **Renewable energy:** More solar panels and wind energy. Promote energy efficiency in buildings.
- **Urban planning:** Adopt energy-efficient building planning and integrate natural spaces.
- **Water management:** Rainwater harvesting, improve sewage treatment, manage water resources sustainably.
- **Waste management:** Recycling, waste-to-energy technologies, circular economy principles.
- **Community engagement**
- **Climate resilience**

Poll: How would you create comprehensive and detailed maps of an urban areas at large scale?

Local Climate Zones (LCZs)

Local climate zones (LCZs) describe landscapes in terms of their thermal impact on the near surface atmosphere.

LCZs were introduced in 2012 in connection to urban heat island studies. Soon they also showed potential in urban morphology mapping.

The LCZ scheme distinguishes between 17 basic types.

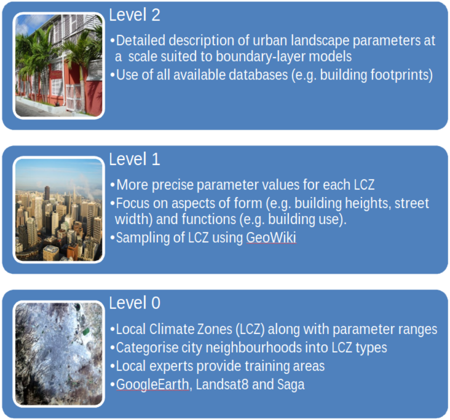
Local Climate Zones (LCZs)

LCZs are critical for urban planning and environmental scientists to tackle climate change impacts, enhance sustainability, and improve livability in cities.

- **Heat island mitigation:** Guide the design of cooler urban environments through strategic green spaces and reflective materials.
- **Energy conservation:** Energy-efficient building design and urban distribution based on thermal characteristics.
- **Flood prevention:** Utilize surface characteristics and topography data to implement effective water management and reduce flood risks.
- **Biodiversity support:** Aid in integrating natural habitats into urban settings.
- **Sustainable growth:** Informed and climate-resilient urban development and expansion strategies.

The World Urban Database and Portal Tool (WUDAPT)

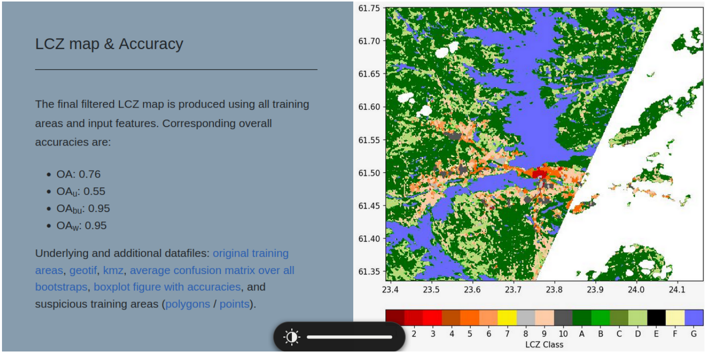
The **World Urban Database and Portal Tool (WUDAPT)** is an international collaborative project for the acquisition, storage and dissemination of climate relevant data on the physical geography of cities worldwide.



WUDAPT's data hierarchy

WUDAPT's data. Level 0

- L0 data are derived using Landsat data, image software, and the knowledge of urban experts
- Check how level 0 data is created in one example here (minute 7'45")
- Check the **Global LCZ map**.
- You can collaborate in the **LCZ generator**.



WUDAP's data. Level 1

Each category of LCZ is associated with a range of parameter values that measure aspects of urban form and function such as the built density, the typical building hights and materials, etc.

An urban map of LCZs is also a map showing the **city's internal geography**, and this is very useful for climate studies.

Urban Parameters

LCZ Type	SVF	Canyon Aspect Ratio (H/W)	Mean Height (m)	Terrain Roughness Class	Building Surface Fraction	Impervious Surface Fraction	Pervious Surface Fraction	Surface Albedo	QF (Wm^{-2})
1	0.2- 0.4	>2	>25	8	40-60%	40-60%	<10%	0.10-0.20	50-300
2	0.3-0.6	0.75-2	10-25	6-7	40-70%	30-50%	<20%	0.10-0.20	<75
3	0.2-0.6	0.75-1.5	3-10	6	40-70%	20-50%	<30%	0.10-0.20	<75
4	0.5-0.7	0.75-1.25	>25	7-8	20-40%	30-40%	30-40%	0.12-0.25	<50
5	0.5-0.8	0.3-0.75	10-25	5-6	20-40%	30-50%	20-40%	0.12-0.25	<25
6	0.6-0.9	0.3-0.75	3-10	5-6	20-40%	20-50%	30-60%	0.12-0.25	<25
7	0.2-0.5	1-2	2-4	4-5	60-90%	<20%	<30%	0.15-0.35	<35
8	>0.7	0.1-0.3	3-10	5	30-50%	40-50%	<20%	0.15-0.25	<50
9	>0.8	0.1-0.25	3-10	5-6	10-20%	<20%	60-80%	0.12-0.25	<10
10	0.6-0.9	0.2-0.5	5-15	5-6	20-30%	20-40%	40-50%	0.12-0.20	>300
A	<0.4	>1	3-30	8	<10%	<10%	>90%	0.10-0.20	0
B	0.5-0.8	0.25-0.75	3-15	5-6	<10%	<10%	>90%	0.15-0.25	0
C	0.7-0.9	0.25-1	<2	4-5	<10%	<10%	>90%	0.15-0.30	0
D	>0.9	<0.1	1	3-4	<10%	<10%	>90%	0.15-0.25	0
E	>0.9	<0.1	<0.25	1-2	<10%	>90%	<10%	0.15-0.30	0
F	>0.9	<0.1	<0.25	1-2	<10%	<10%	>90%	0.20-0.35	0
G	>0.9	<0.1	N/A	1	<10%	<10%	>90%	0.02-0.10	0

Urban parameters associated to an urban map.

Poll: What limitations does the WUDAPT classification system encounter in its current implementation? Select all that apply.

Paper: The urban morphology on our planet – Global perspectives from space

Paper: The urban morphology on our planet – Global perspectives from space [1]

Steps:

1. Need for reliable, detailed and high resolution urban maps.
2. Review of LCZs classification methods
3. New approach for LCZ classification
4. Data from Sentinel-1 and Sentinel-2
5. Hand labelling for benchmark dataset
6. Model: modified ResNet
7. Global analysis

Dataset available HERE.

[1]Xiao Xiang Zhu, Chunping Qiu, Jingliang Hu, Yilei Shi, Yuanyuan Wang, Michael Schmitt, Hannes Taubenböck, The urban morphology on our planet – Global perspectives from space, Remote Sensing of Environment, Volume 269, 2022. `https://doi.org/10.1016/j.rse.2021.112794`

Motivation

- Many international proposals addressing issues of urbanization, such as the UN call for **Sustainable Cities and Communities**, are based on accurate measurements of urban morphological and demographic data.
- Urban geographic information has improved a lot in recent decades. However the required geo-information is still not available in many countries.
- World Urban Database provides intra-urban local climate zone classification maps. However only for about 100 metropolises and to a best resolution of a few hundred meters.
- Global urban mapping approaches still lag behind. Consistent and resilient global spatial data in high geometric, thematic and temporal resolutions necessary to address the challenges described above is still nonexistent. This is mainly due to the lack of high resolution global satellite data and computationally and methodologically efficient algorithms.

Motivation

- Earth observation (EO) has arrived at a golden era of big data. Game changer: European Copernicus programme providing continuous, reliable, quality controlled big EO data, free and open.
- To effectively retrieve global urban geo-information from such a massive data source requires **new technological approaches** to manage large amounts of data and also **new analysis methods**.
- **Machine learning has become indispensable.**

Review of LCZs classification

Current situation:

- Main existing development of LCZ classification is community-based large-scale LCZ mapping using freely available Landsat data and softwares, the **World Urban Database and Portal (WUDAPT)**.
- **Problem 1:**The quality of maps is heavily dependent on individual producers.
- **Problem 2:** Standard WUDAPT mapping approach cannot fulfill quality demands of practical usage.
- Therefore, there's a (parallel) need to improve the classification methodologies.

Review of LCZs classification

What can be improved?

- **Additional data sources:** Synthetic aperture radar (SAR), geographic information system (GIS).
- **Classification algorithms:** Random forests are used as main method in many classification studies due to its easy implementation and robust performance.
- Recently: CNN outperform random forests on LCZ classification.

New approach in LCZ classification

In the paper, they propose a new approach for LCZ classification:

- Novel deep learning and big data analytics approach.
- Data fusion: SAR from Sentinel-1 and optical imagery from Sentinel-2.

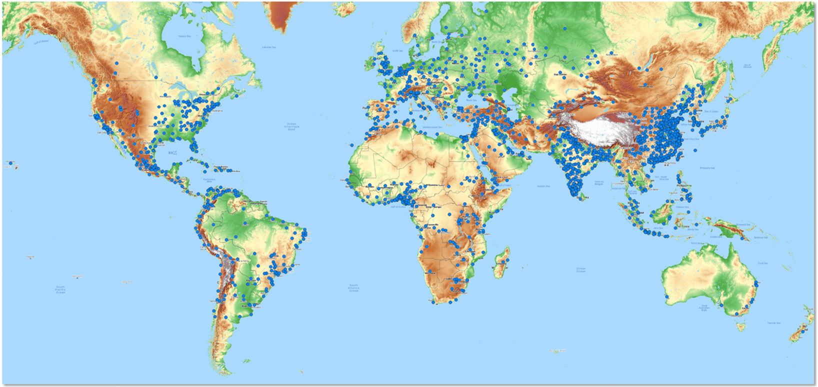
Results:

- First-ever global and quality controlled urban LCZs classification covering all cities with a population greater than 300 000, 1692 cities in total.
- Approach validated on 52 urban sites across all five inhabited continents.
- Dataset So2Sat Global Urban LCZ (So2Sat GUL) available here.

Study area

According to the UN, 1/3 of the world population will live in cities of at least 500 000 inhabitants in 2030.

The study focuses on producing maps of urban morphology for 1692 cities whose population is greater than 300 000.



1692 cities whose population is greater than 300 000.

Data sources: Sentinel-1 and Sentinel-2

- **Sentinel-1 level-1 SAR data** of 2017 summer were collected for the 1692 cities. After processing, 7 bands are contained in the Sentinel-1 analysis-ready data.
- **Sentinel-2 L1C data** were collected. The preprocessing Sentinel-2 images is less demanding than that of Sentinel-1.
- **Main challenge:** creating cloud-free images. This whas achieved by pixel-wise cloud detection and combination of multi-temporal images within short time periods.
- In the Sentinel-2 analysis-ready data, 10 out of the 13 bands used.
- Since seasonal variation in optical images is larger compared to SAR, they divide the set of Sentinel-2 images in four seasons.
- Note: some of the cities in the study areas do not have four seasonal data due to an excessive amount of cloud or data corruption. For those cities, they only include seasons that have data available.

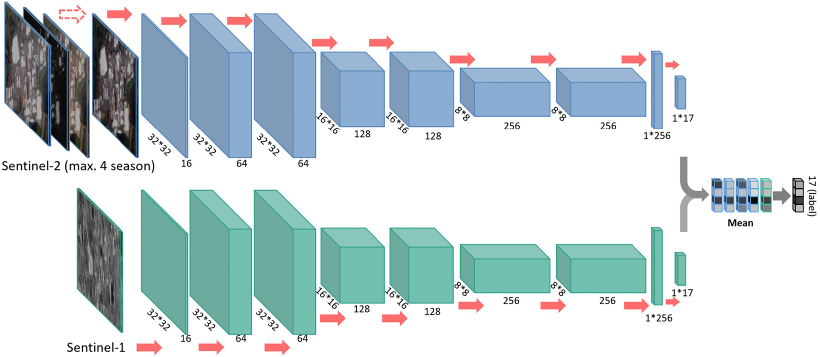
Benchmark dataset So2Sat LCZ42 (data labelling)

Benchmark dataset: So2Sat LCZ42. They were extremely thorough:

- Over one month: 15 domain experts designed the labeling workflow, error mitigation strategy, validation methods, and then conducted the data labeling.
- Dataset: manually assigned LCZ labels of 400 673 Sentinel-1 and Sentinel-2 image pairs. Distributed in 42 urban areas plus 10 additional smaller areas. Covering all the inhabited continents and 10 different cultural zones.
- Rigorous quantitative evaluation of 10 cities in the dataset. A group of remote sensing experts cast 10 independent votes on each labeled polygon, in order to identify possible errors and assess the human labeling accuracy.
- In general, human labels achieved 85% confidence. This confidence number can serve as a reference accuracy for the machine learning models trained on this dataset.

Method: modified ResNet

Base model: modified residual neural network (ResNet).



Architecture of the ResNet

Model training

Implementation of the network in Keras.

Three training-testing splits: *random-split*, *block-split* and *cultural-10*.

Together, these three evaluation scenarios give a solid impression of the quality of the global LCZ maps produced through this approach.

- **Random-split** serves as the upper bound of achievable classification accuracy.
- **Block-split** is a deterministic data split, i.e., the data from each city is separated into non-overlapping east-west blocks and the accuracy is evaluated on unseen blocks. It gives a representative measure of accuracy for unseen cities whose data distribution is similar to the training cities.
- **Cultural-10** defines the lower bound of the achievable accuracy by evaluating completely held-out data in a cross-validation scheme. This provides a completely unbiased view of the accuracy achievable on absolutely unseen data.

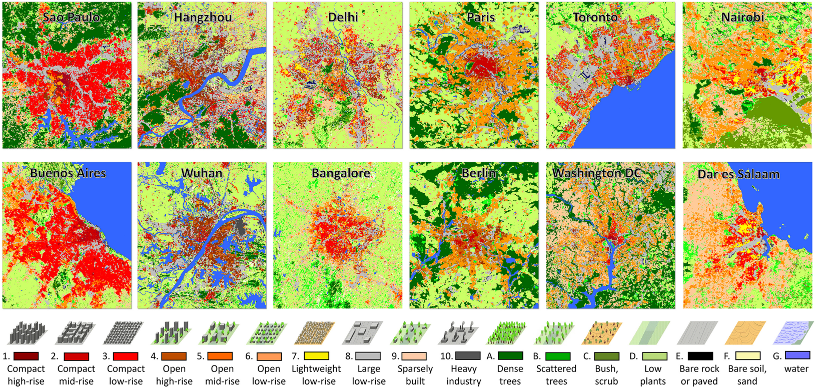
Model evaluation

- Evaluation of the model is done on the three data splits mentioned before.
- Fusion of SAR and optical data consistently leads to the best results.
- Although the improvement is not significant, the inclusion of Sentinel-1 image plays an important role in large scale or global scale inference, in particular for cloudy areas such as western Africa and Amazon forest. It is estimated that 60–70% of the global Sentinel-2 images are cloudy.

	Random	**Block**	**Culture-10**
Sentinel-1	64.2%	51.6%	34.0%
Sentinel-2 (4 seasons)	82.2%	75.7%	51.0%
Sentinel-1 + Sentinel-2 (4 seasons)	83.4%	76.8%	51.3%

Averaged accuracy of Sentinel-1 and Sentinel-2 data, and fused results, from three types of assessment: random-split, block-split, and held-out cultural-10 split.

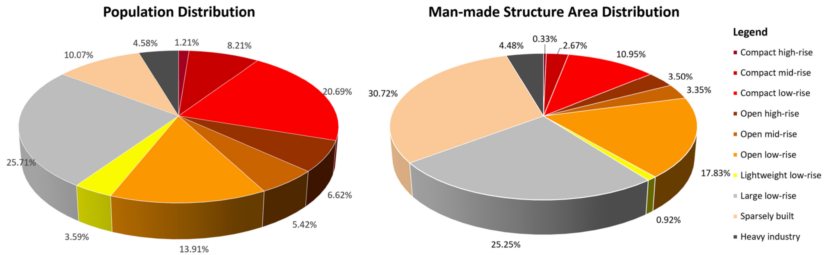
Application: global analysis



Examples of the global urban morphological maps.

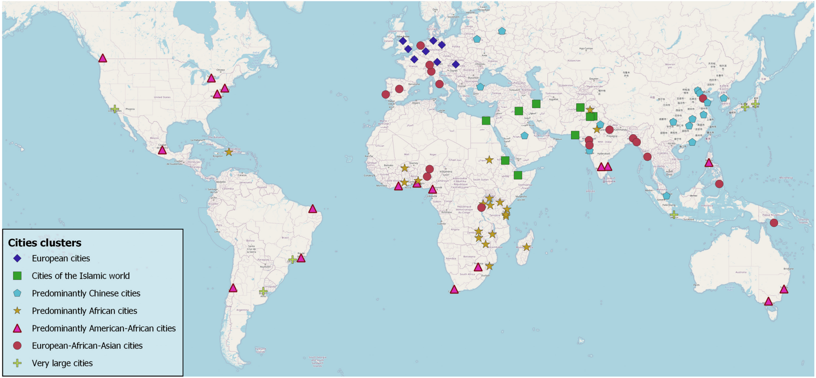
Example: Delhi LCZ map shows there is no large compact high rise district. Dense areas are scattered across the city. Large areas of large low-rise buildings could be related to informal settlements. Water resources and vegetation are also clearly mapped. This is important information that can aid decision making on urban development.

Application: global analysis



The proportions of population (left) and area (right) of the ten LCZ built up classes (classes 1–10) in the 1692 cities.

Application: LCZ patterns vs culture



Seven resulting clusters of morphological city pattern types. Findings are based on the k-means algorithm using an 18-dimensional feature space (consisting of 17 LCZs as well as city size as features) at the spatial unit of the morphological urban areas.

Some conclusions

- The way we physically build our cities defines our life patterns, our mobility, the quality of life, the resilience of our cities, and much more.
- Across the globe, there are no two identical urban configurations and yet there are many groups of cities that are similar in their morphological characteristics.
- The measured differences in land consumption per person testify to the variability of cities worldwide and are an expression of inequality.
- A uniform and consistent classification is the basis for better understandings of the status quo and for improving urban planning.
- Basis for different applications: understanding the urban thermal environment to mitigate urban heat islands, assessing population distributions, analyzing urban morphological configurations, etc.

Poll: What uses could LCZ database have for climate action?

More on the topic...

- Dataset So2Sat Global Urban LCZ data and demo in GitHub
- Benchmark dataset So2Sat LCZ42 available on Tensorflow
- Follow-up paper: So2Sat POP - A Curated Benchmark Data Set for Population Estimation from Space on a Continental Scale and corresponding dataset
- TED talk here

Quick recap

Summary of the course

You are now familiar with **satellite data**:

- SAR data from Sentinel-1
- optical imagery from Sentinel-2
- atmospheric trace gases from Sentinel-5P

You know **different databases** that can be used for a wide range of applications (and those are just examples, there are many more you can explore):

- ships database
- weather data from ground weather stations
- LCZs and World Urban Database and Portal Tool (WUDAPT)

Summary of the course

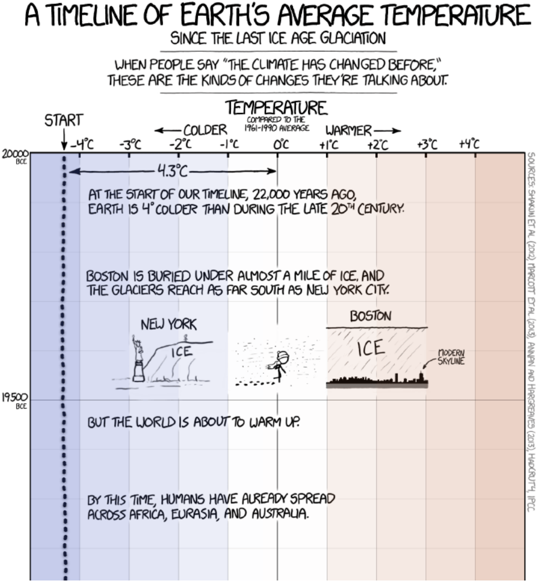
You have experience with Copernicus Dataspace. There are more **satellite data providers** that you can explore:

- Copernicus Dataspace
- WEkEO
- EuroDataCube

You have some hands-on experience with **machine learning applications to tackle climate change**

- preparing a dataset of NO_2 plumes
- CNN to detect NO_2 plumes
- SVM to classify methane plumes
- CNN for ship detection
- time series forecast of temperature with Prophet

Now go and take climate action!



From xkcd. It continues ...