Advanced Physics-AI Models for Rain Enhancement in Arid Regions in Current and Future Climate States

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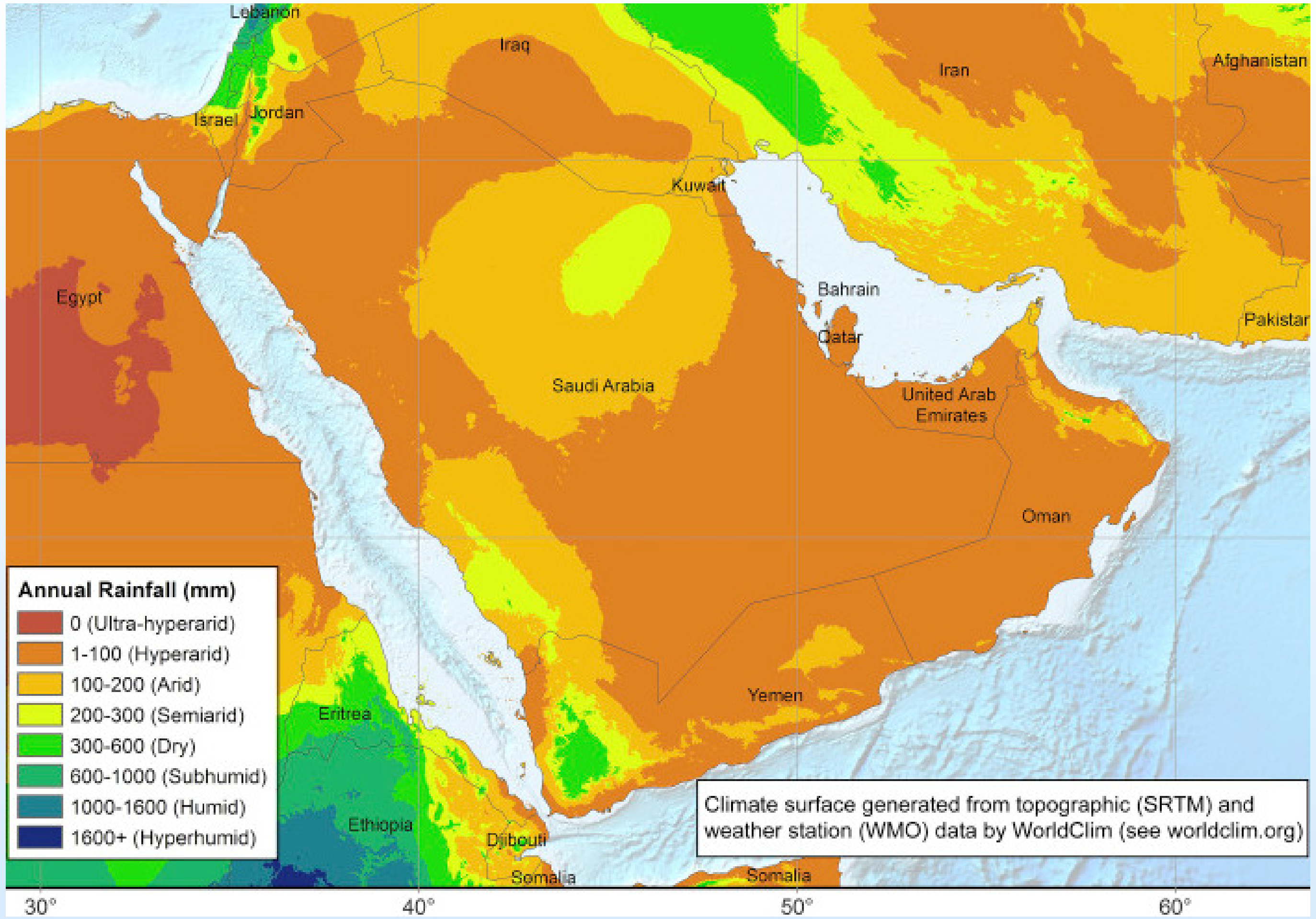
- Background
- Challenges
- Approach
- Future work

Background

- **Despite advances in numerical weather prediction, the morphology of significant precipitation events are poorly captured in arid regions, especially those with large, growing urban centers**
- **Further, weather modification efforts such as cloud seeding are currently underway or being planned in many such regions**
- **As the climate warms along with expanding urbanization and increasingly dry soil conditions, it is expected that the current stress on the availability of water will be exacerbated**
- **Hence, understanding these limitations is critical to the success of weather modification efforts**

Motivation -- Example

- **Consider the Arabian Peninsula, where typical annual precipitation is under 100mm, and has growing urban centers**
- **Yet, MCSs lead to a significant fraction of observed rainfall, which usually occur during the winter and spring, can result in more than 200mm, and flash floods.**
- **Several numerical studies (e.g., Francis et al, 2020; Branch et al, 2020) discuss poor reproduction of these MCSs due to misrepresentation of soil moisture, sea breezes, etc.**



Present day rainfall levels of the Arabian Peninsula
[Jennings et al, 2015, https://doi.org/10.1016/j.quaint.2015.01.006]

- **Hence, Fonseca et al, 2022 and Gopalakrishnan et al, 2023 illustrated the need for improved model fidelity at higher resolution for planning of cloud seeding**

Motivation – Additional Issues

- The role of dust as cloud condensation nuclei (CCN) in polluted desert environments with diverse aerosol physio-chemistry is poorly understood
- Chen et al, 2020 showed non-linear responses of precipitation to dust when it serves as both CCN and ice-nucleating particles (INPs)
- Urbanization can also be a major source of convection and potentially of microphysics activation and invigoration in the nuclei that are available naturally and/or from anthropogenic sources
- Understanding such events and their representation in models are critical to the success of current and planned weather modification efforts in both today's and possible future climate states

Challenges in Arid Regions with Large, Coastal Urban Centers

- **Some issues could be addressed by the community atmospheric model, Weather Research and Forecasting with Chemistry (WRF-Chem), since it represents coupled cloud and aerosol properties**
- **However, we assert that urbanization is a major source of convection and potentially of microphysics activation and invigoration in the nuclei**
- **Past WRF-Chem studies, have shown that the default configurations for aerosol specifications may not accurately represent the diversity, including dust, urban pollution and marine salt that can also affect cloud condensation and ice nucleation, for example**
  - **Fountoukis et al, 2022 with a focus on air quality in Qatar, used high-quality, local emissions inventory and urban land use to improve model fidelity**
  - **Noyola Poblete and García Reynoso, 2022 with a focus on air quality in Mexico City, used high-resolution with the BEP UCM to improve model fidelity**

Challenges -> Two-Part Approach

To address some issues, the development of a novel hybrid (physics and AI) modeling framework is required to help understand, predict, and improve the effectiveness of weather modification experiments, which will be need to be properly validated with both numerical experiments and field campaigns

I. (Physics) Standard WRF-Chem and WRF-Urban are too limited to predict strong precipitation events and assess areas for potential cloud seeding experiments in arid regions with large, coastal urban centers

II. (AI) Even with improvements in I., too much uncertainty about aerosol characteristics from numerical models will remain

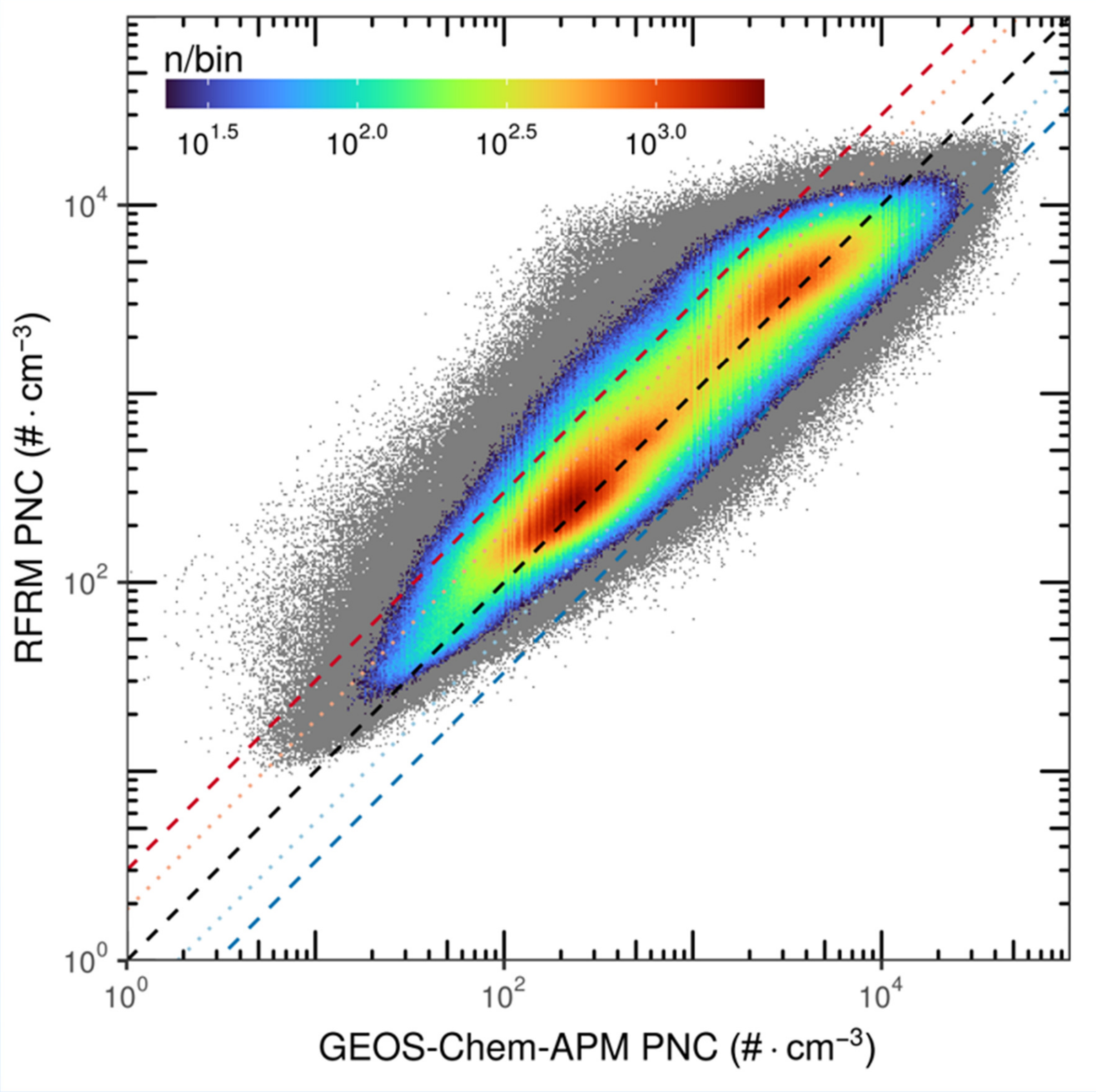
Approach – Numerical Models (Part I.)

We are enhancing and applying two community modelling systems for atmospheric physics and chemistry for aerosols

1. A version of WRF-Chem that is tailored for the region(s) of interest and includes urban processes
2. For cost-effective execution at the required high resolution, deployment is in a Cloud computing environment supporting parallelized workloads
3. The community Model for Prediction Across Scales Atmosphere (MPAS-A) is used to improve the fidelity of the forcing data and eliminate telescoping outer nests and compensating for their artifacts
   - The model uses an unstructured computational mesh to enable a smooth and consistent transition from global to local scales
   - To further reduce the computational cost, we will leverage the future MPAS-A support for hybrid CPU/GPU-based clusters

Approach – Machine Learning Models (Part II.)

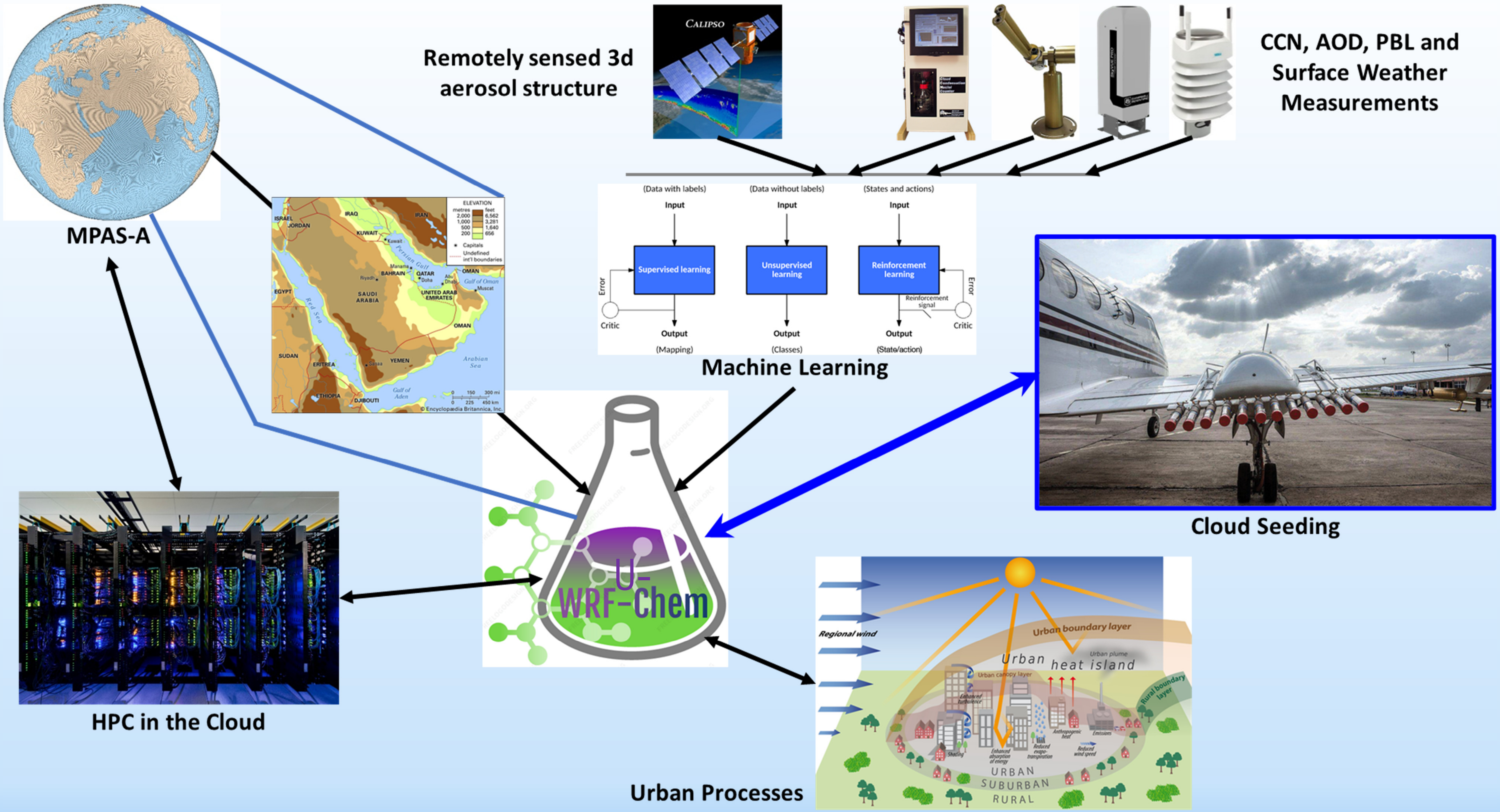
- To reduce the uncertainty in the aerosol estimates from the urbanized WRF-Chem, machine learning algorithms will be used
- For example, Yu et al, 2022, used outputs from a detailed aerosol microphysics model to train a random forest (RF) regression model to more accurately predict particle number concentration (PNC) in a global climate model (GCM)
- Similar methods were also used to estimate aerosol CCN and size from composition data
- These techniques will be extended to INPs and used with uWRF-Chem output
- Results will be validated with observations of aerosol composition, number and size that lead to condensation in clouds



ML vs. Simulated PNC (> 7.3M points)

[Yu et al, 2022, https://doi.org/10.1029/2022GL09855106]

Approach: Hybrid (Physics and AI) Modeling Framework



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Next Steps

- This approach is in its early development
- Some of the components have already been addressed independently
  - Urbanized WRF-Chem (but not yet for coastal, arid urban centers)
  - MPAS->WRF coupling (but not yet for urbanized WRF-Chem nor in coastal areas)
  - Machine learned aerosol characteristics (but not yet to urbanized WRF-Chem)
- The components need to be applied to relevant regions, and then integrated and tested
- The results could then lead to improved representations of aerosols and clouds with the potential to enhance operational support of cloud-seeding exercises
- Validation will likely require deploying observational field campaigns using ground-based remote sensing