Diagnosing the Role of Retrieved Cloud Properties in IR-Only Rain Detection and QPE from Himawari

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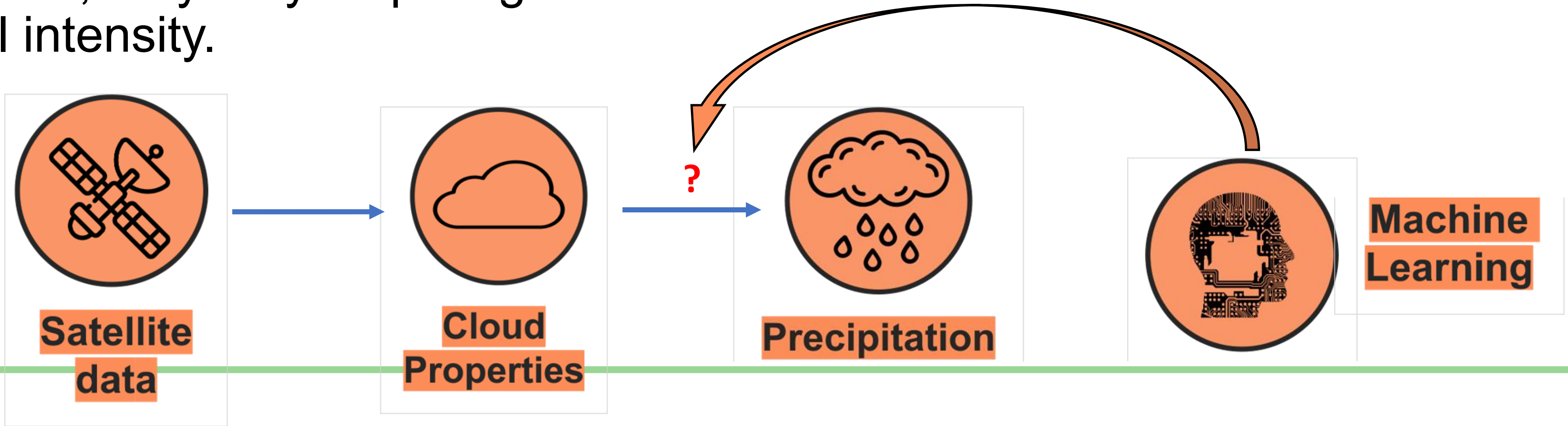
12th IPWG Workshop

Date: 2026/07/07 17:00 – 17:15

Motivation: Diagnosing the Cloud–Precipitation Relationship

Can AI models help us identify which cloud states are physically linked to surface rainfall?

- Passive microwave observations are more directly related to precipitation, but are temporally sparse.
- Geostationary satellites observe cloud-top radiative signals frequently.
- However, brightness temperature (**BT**) is a radiative quantity, not a direct physical description of cloud structure.
- Retrieved cloud properties (**CP**) provide more interpretable cloud-state variables, such as cloud-top height (CTH), optical thickness (COT), and cloud water path (CWP).
- Therefore, they may help diagnose how cloud structure relates to rain occurrence and rainfall intensity.

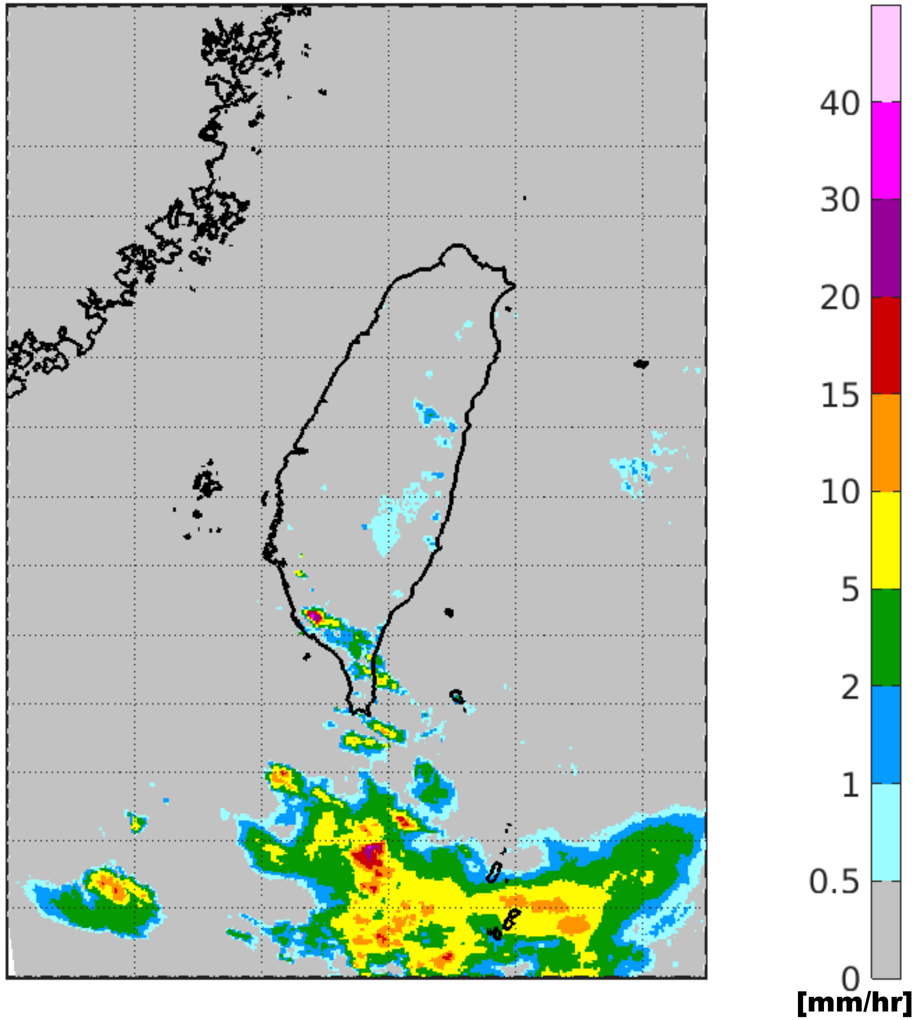


From Radiance Observation to Retrieved Cloud Properties (CP)

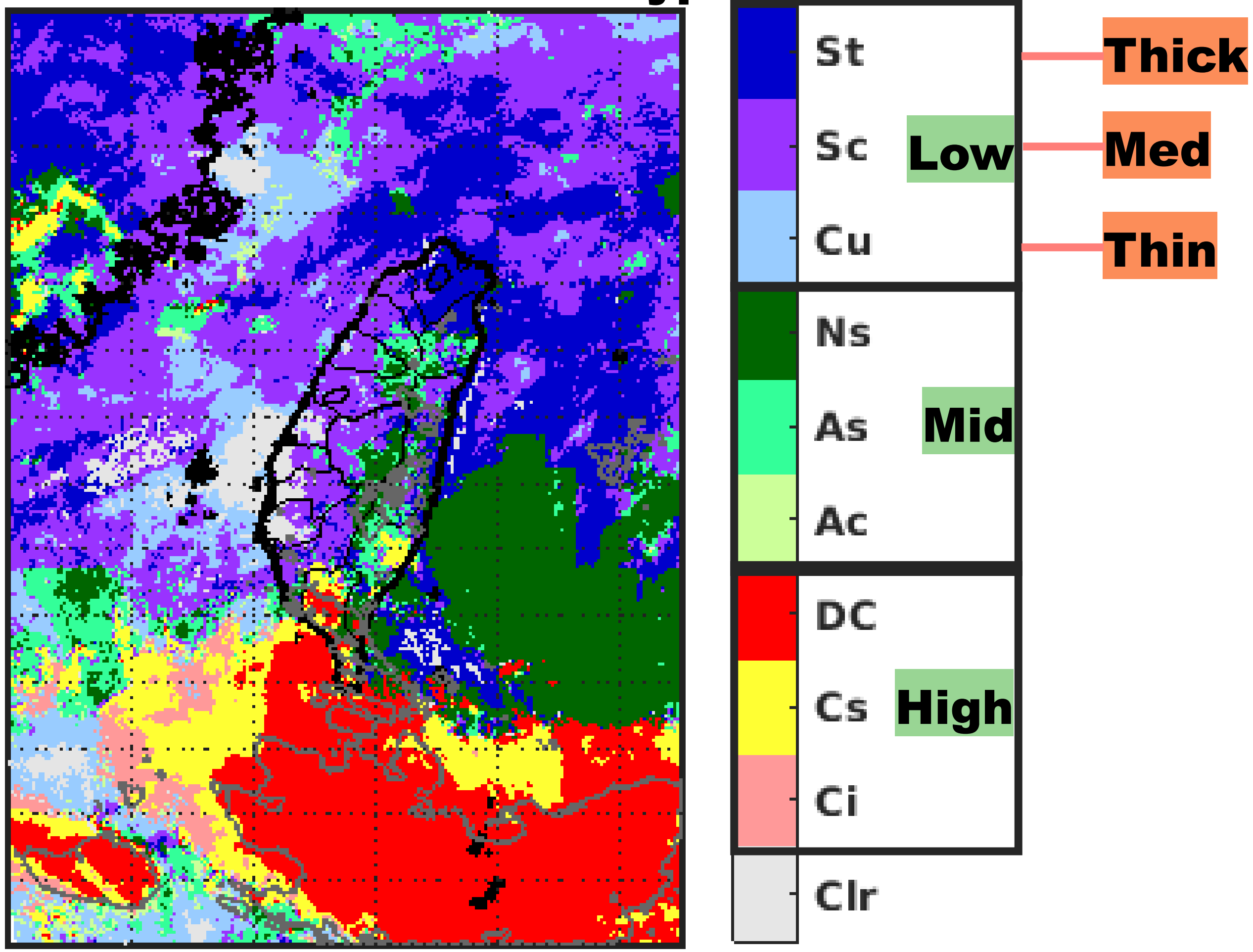
- Previous studies: Spectral Parameters as cloud proxies
  - BT differences and spectral combinations are often used to represent cloud-top height, phase, optical thickness, and moisture conditions.
  - These parameters are physically motivated, but they are still **radiance-derived proxies**.
- This study: retrieved cloud properties as physical cloud-state variables
  - Retrieved CPs provide explicit cloud-state descriptors, such as CTH, CTP, COT, CER, and cloud water path.
  - Even if CPs are not fully independent from radiances, they provide a more physically interpretable coordinate system.
- Take-home message
  - CPs are used not only as additional predictors, but as physical coordinates for diagnosing cloud–rainfall relationships.

From Radiance Signals to Cloud-State Interpretation

Radar Precipitation (QPESUMS from CWA Taiwan)



Satellite-derived Cloud Types

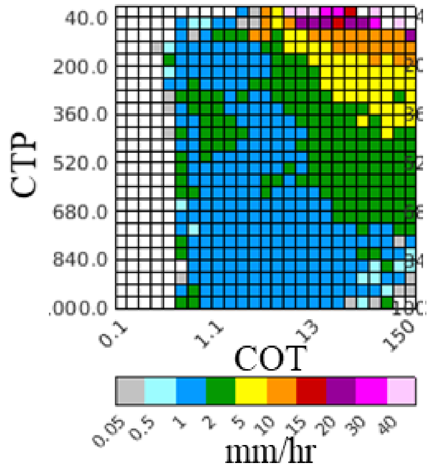


2023/05/23 – 04 UTC

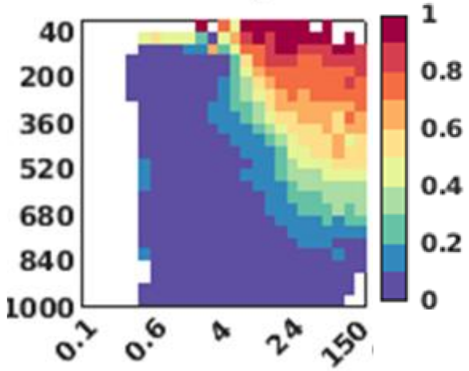
Cloud Properties Show Clear but Nonlinear Rainfall Relationships

CTP-COT histogram (Precipitation from radar)

Rain rate (avg.)

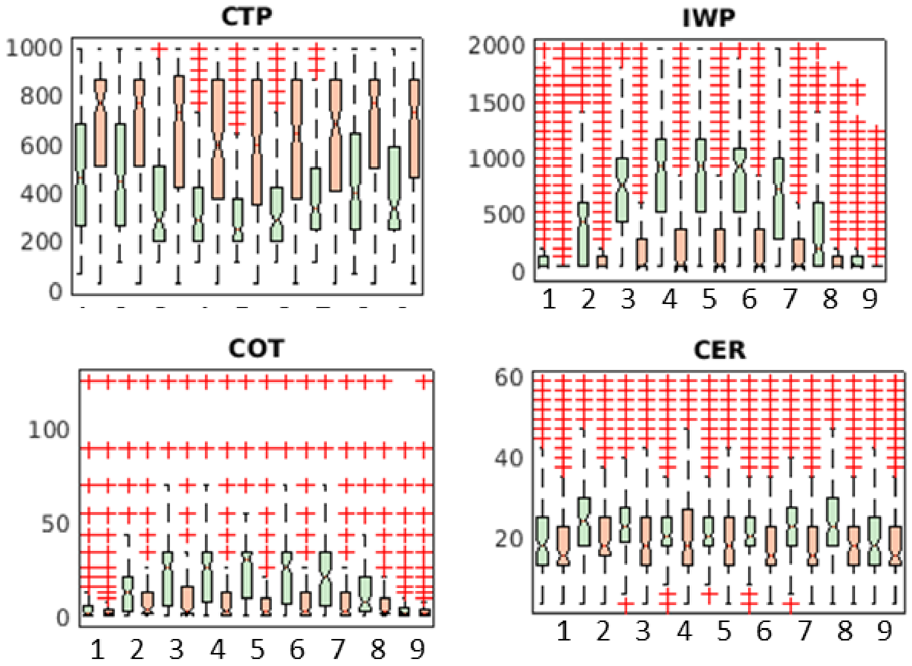


Rain Prob.



$$\text{Prob(rain)} = \frac{N_{rainy}}{N_{rainy} + N_{no-rainy}}$$

Cloud Properties Distribution (Rain VS. No-rain)



Rain

non Rain

Statistical period : 2023

- Deep, optically thick clouds are more likely to rain
- High cloud-top, large optical thickness, and large IWP are associated with stronger rainfall signals
- But rainfall contribution and rainfall confidence are not exactly the same

- Rain and non-rain distributions are distinguishable for some CPs
- CTP / IWP show clearer contrasts
- CER is weaker and less systematic

Using CPs to Guide and Diagnose AI Learning

- Challenge:
  - AI may detect rainfall patterns from BTs, but we do not know what physical features it actually learned.
- Role of CPs:
  - **Training constraint:** provide explicit cloud-state variables to guide the model toward physical features.
  - **Post-hoc diagnosis:** analyze model outputs by CP regimes to examine whether the learned behavior is physically consistent.
- Key message:
  - CPs are used not only to improve prediction, but to guide and verify the physical meaning of what the AI model learns.

BT-only AI
↓
Learns rainfall-related patterns
↓
But what did it learn?
Radiative correlation?
Cloud physical state?

BT + CP AI
↓
Explicit cloud-state variables
CTH / CTP / COT / IWP / CER
↓
More physically constrained learning

Post-hoc CP diagnosis
Model confidence / errors / rain rate
↓
Are outputs consistent with cloud regimes?

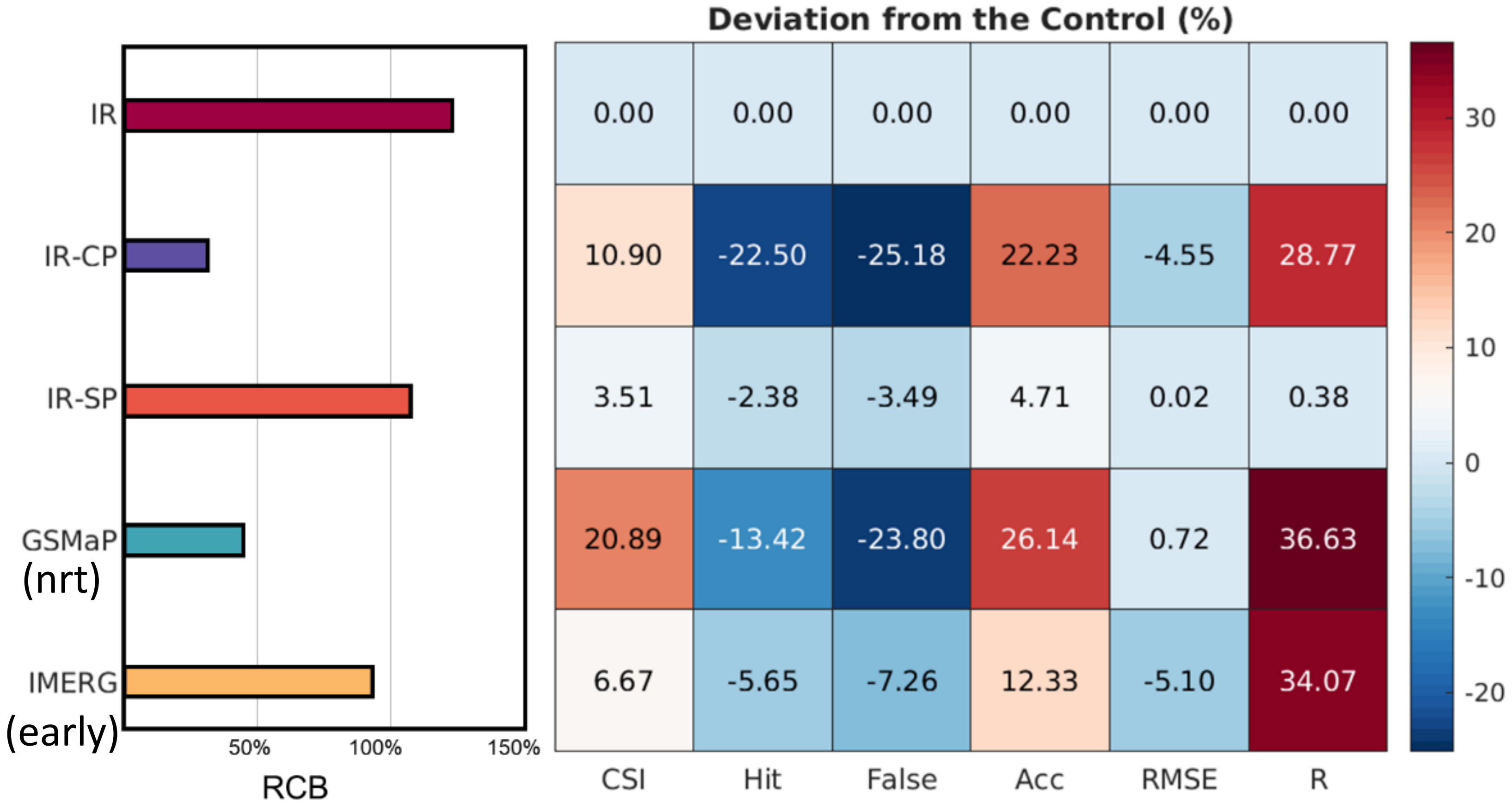
Controlled Feature Experiments for Physical Diagnosis

- Experimental logic:
  - **Keep the AI framework** comparable to focus on feature-group effects
  - **Fixed 3-layer MLP:** used to compare feature-group effects, not to optimize architecture
  - Change the input feature groups
  - Interpret performance changes as feature-diagnostic evidence
- Feature-group comparison:

Experiment	Input meaning	Diagnostic purpose
IR	Raw radiative signal	Baseline cloud–rainfall learning
+ SP	Radiance-derived cloud proxies	Test proxy-based cloud information
+ CP	Retrieved cloud-state variables	Test physical cloud-state constraints

- Evaluation:
  - Detection behavior: **HIT / FAR / CSI**
  - QPE behavior: **rain-rate structure / spatial pattern**
  - Physical consistency: **CP-regime diagnostics**
- Key message:
  - The main focus is not architecture optimization, but how different cloud representations change model behavior.

CPs Shift Model Behavior Toward Lower False Alarms



- IR and IR+SP:
  high detection sensitivity, but broader false-rain areas
- IR+CP:
  lower FAR and RCB, but lower HIT at the default threshold
- CPs shift the model to a more conservative operating point

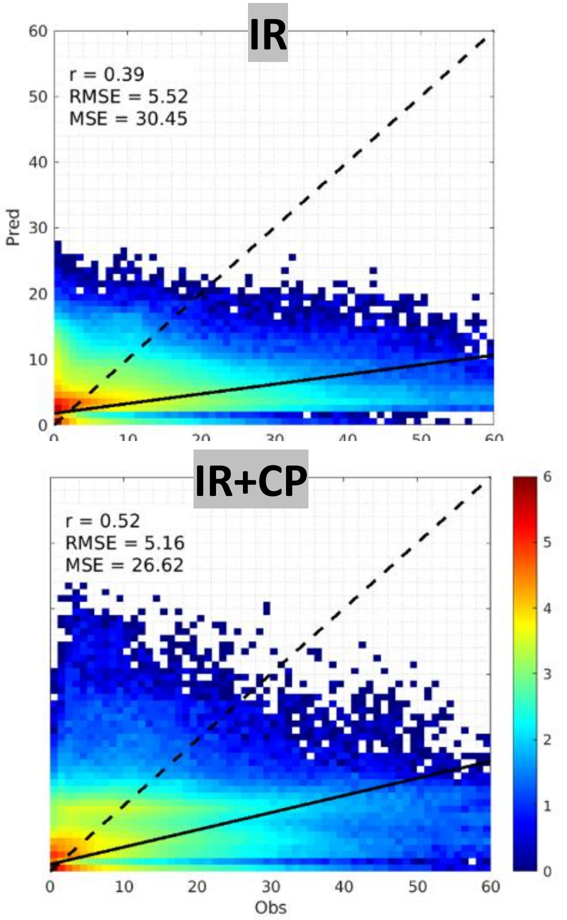
Key message:

- CPs do not simply increase scores; they constrain the model toward fewer false alarms and a cleaner rain-area footprint.

RCB: predicted rain-area bias; closer to 0% is better

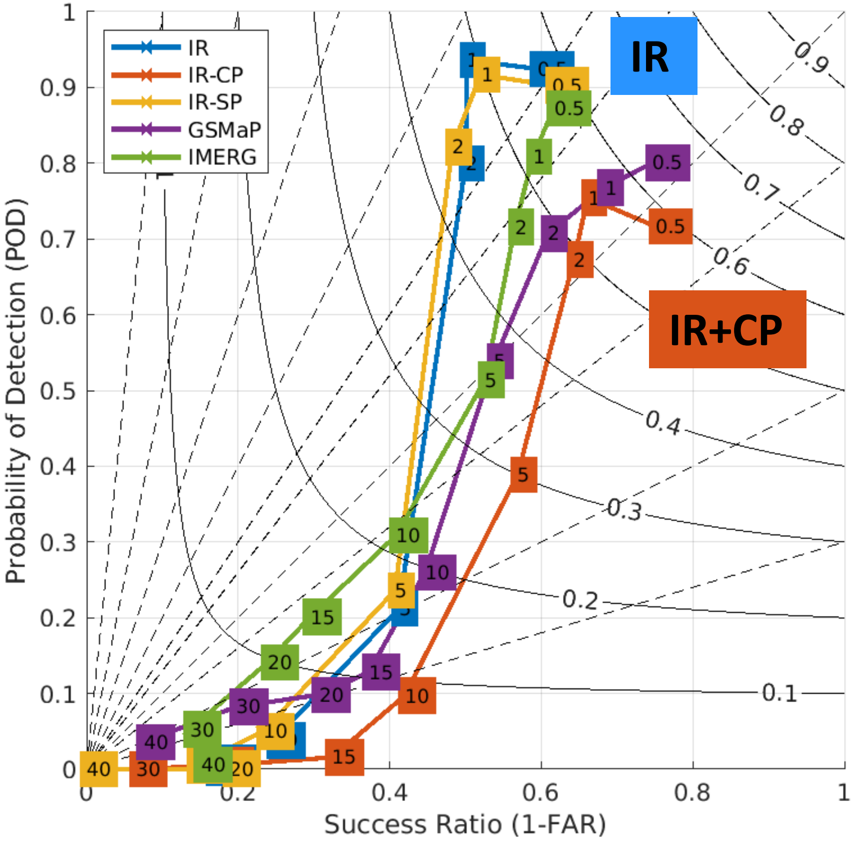
QPE Behavior: CPs Improve Rain-Rate and Regime Consistency

Scatter-density plot

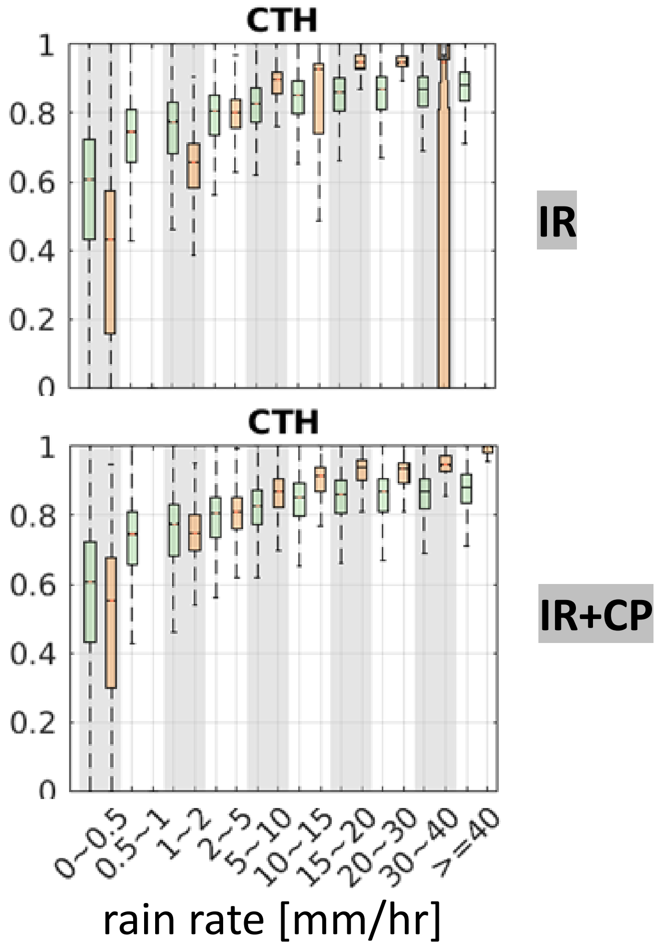


Performance diagram

box number: rainfall threshold
Upper-right = better

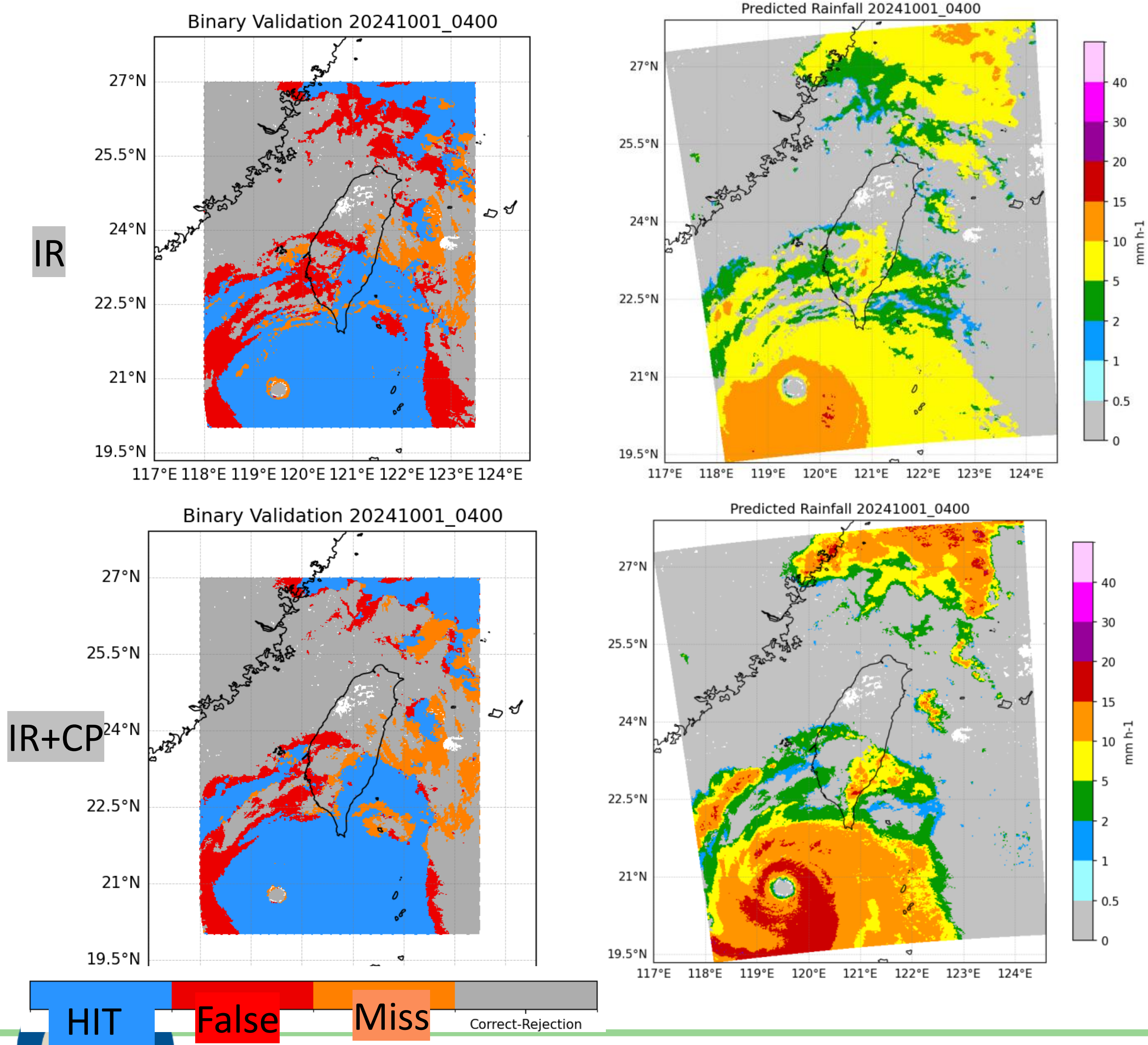


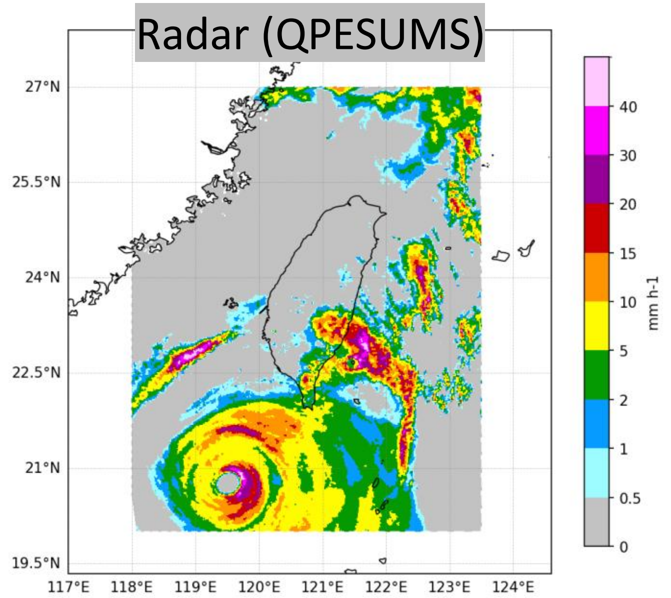
CP vs. Rain rate



- **IR / IR+SP:** rainfall intensity tends to be compressed
- **IR+CP:** better upper-range estimates and slower skill degradation at higher thresholds
- **Post-hoc diagnosis:** do predicted rain-rate bins correspond to physically reasonable cloud regimes?

Typhoon Case: CPs Reduce False Rain Areas and Improve Rainfall Structure





- **Binary validation:** IR+CP reduces false rain areas compared with IR
- **Rainfall amount:** IR+CP produces stronger and more organized rainband structure
- **Interpretation:** CPs constrain the spatial rainfall footprint, but intensity and location errors remain

Key message:

- The spatial case confirms the behavioral shift: CPs reduce spurious rain areas and produce a more radar-consistent rainfall pattern.

Conclusions

- Cloud properties (CPs) provide physical coordinates for cloud–rainfall diagnosis

  CPs are not just additional predictors; they translate radiative signals into interpretable cloud-state variables.

- CPs change model behavior

  They reduce false alarms and produce more conservative rain-area footprints.

- CPs improve QPE consistency, but missing physics remain

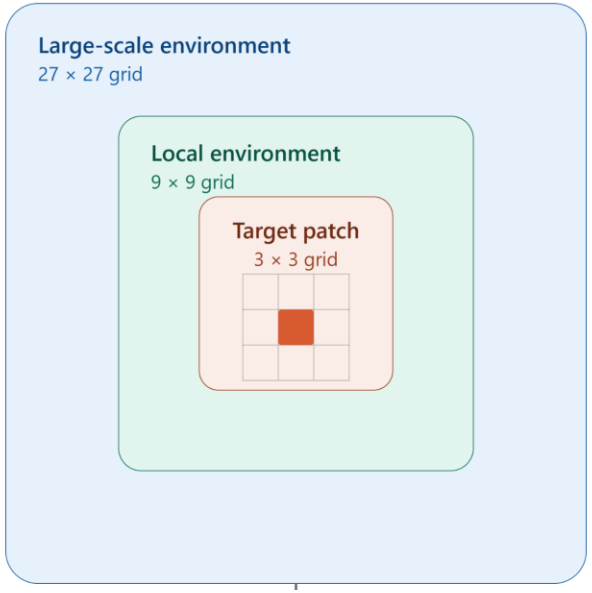
  Heavy-rain underestimation and spatial errors indicate the need for spatial, temporal, and terrain–flow information.

- Main takeaway:

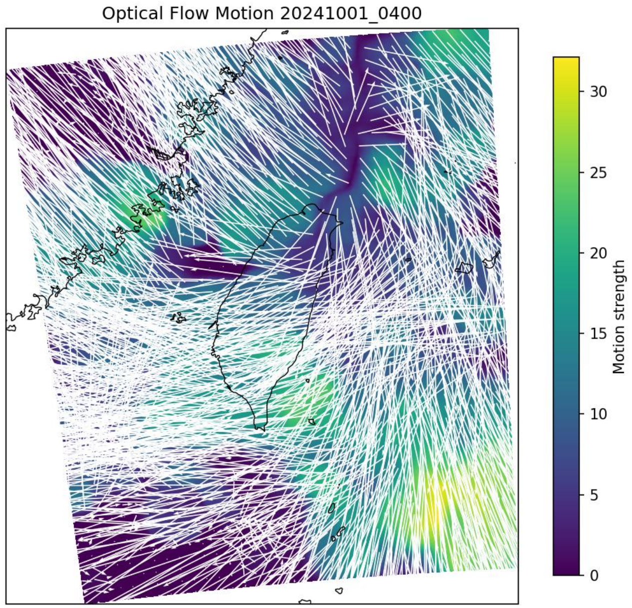
  The value of CPs is not simply higher model scores, but more physically interpretable model behavior.

Current work: Toward Physically Informed Model Design

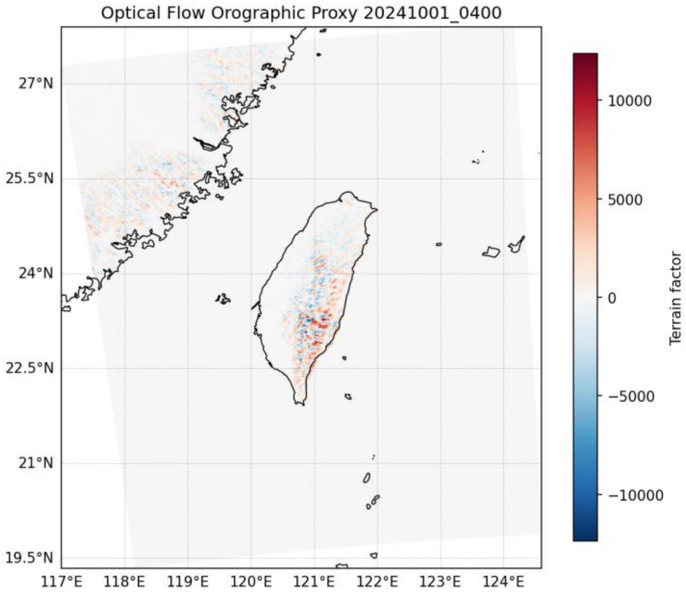
Spatial context: nested CNN



Temporal dynamics: LSTM / sequence branch



Terrain–flow interaction



Thank you for Listening!
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