Using Radio Occultation to Detect Clouds in the Middle and Upper Troposphere

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(In review at JTech)

Research Objectives:

Develop an RO-based cloud detection (ROCD) algorithm that analyzes radio occultation measurables, along with collocated NOAA GFS forecasts, to first predict if atmospheric layers are either cloudy or clear.

Then validate the predictions using a truth dataset created from the imagery of the GOES-16 Advanced Baseline Imager (ABI) instrument and GFS three-dimensional analysis of cloud state conditions.

Use confusion matrices and receiver operating characteristic (ROC) curves to analyze how well the algorithm performed.

Confusion Matrix Background

		Actual: Cloudy	Actual: Clear
Prediction	Cloudy	TP	FP
	Clear	FN	TN

True Positive (TP) = prediction is cloudy and actual is cloudy

False Positive (FP) = prediction is cloudy but actual is clear

True Negative (TN) = prediction is clear and actual is clear

False Negative (FN) = prediction is clear but actual is cloudy

TP + TN = total correct decisions made; **accuracy**

FP + FN = total wrong decisions made

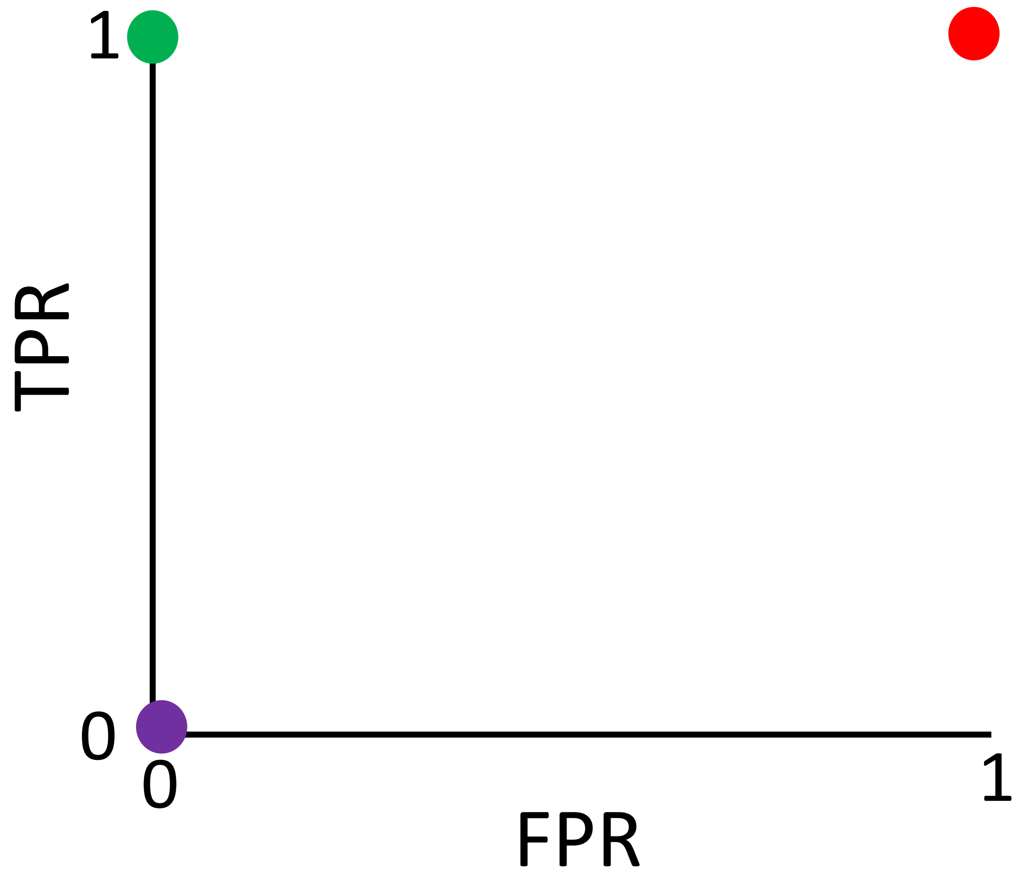
ROC Graph Background

An ROC graph depicts relative tradeoffs between benefits (TP) and costs (FP).

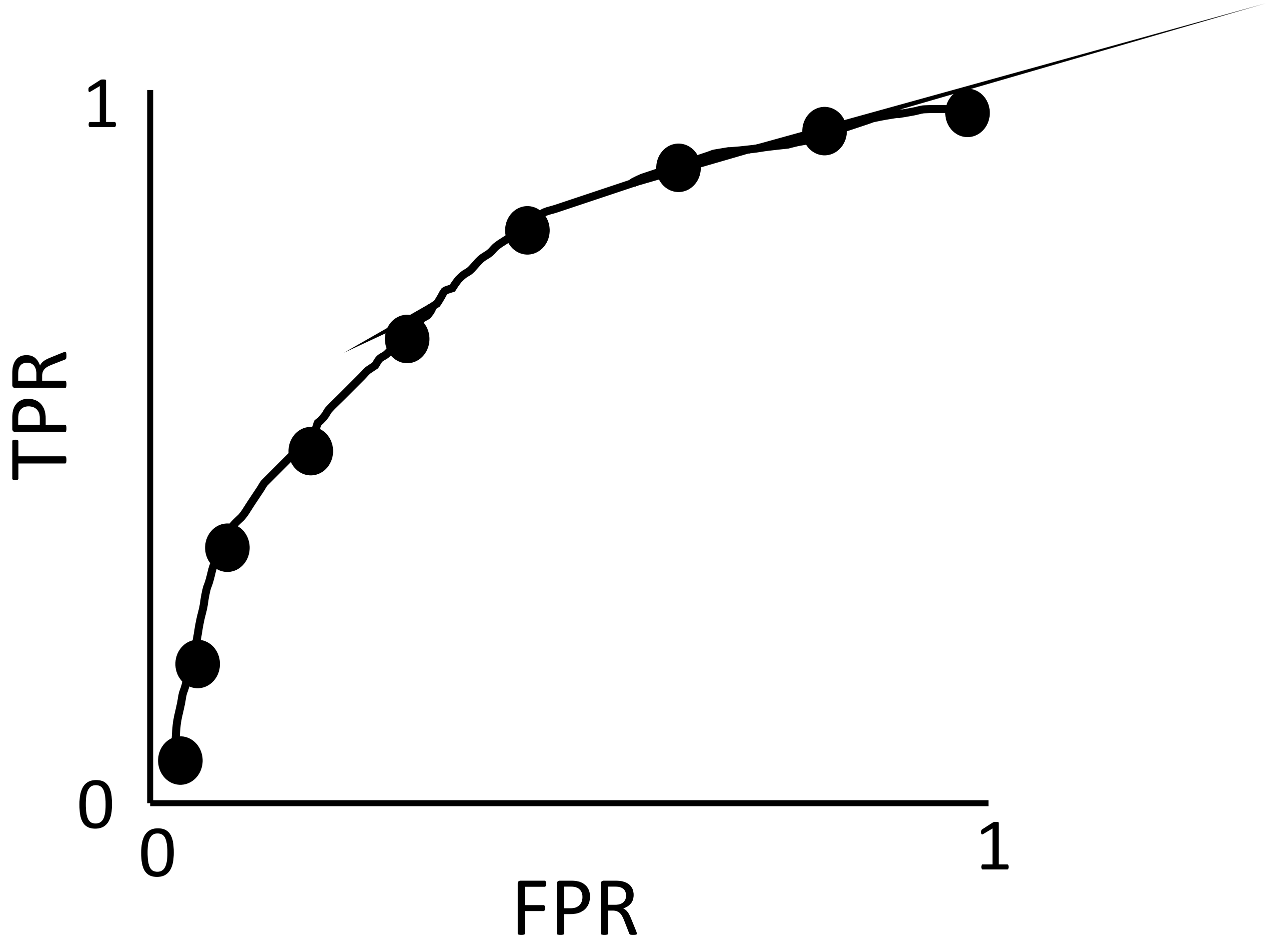
True Positive Rate (TPR) False Positive Rate (FPR)

$$\mathrm{TPR} = \frac{\mathrm{TP}}{\mathrm{TP} + \mathrm{FN}} \qquad \mathrm{FPR} = \frac{\mathrm{FP}}{\mathrm{FP} + \mathrm{TN}}$$

- (purple) = strategy of never issuing a positive classifier, classifier commits no FP errors but also gains no TP
- (red) = unconditionally issues both positive and negative classifications
- (green) = perfect classification by the algorithm, commits no FP errors – **this classifier is most accurate!**

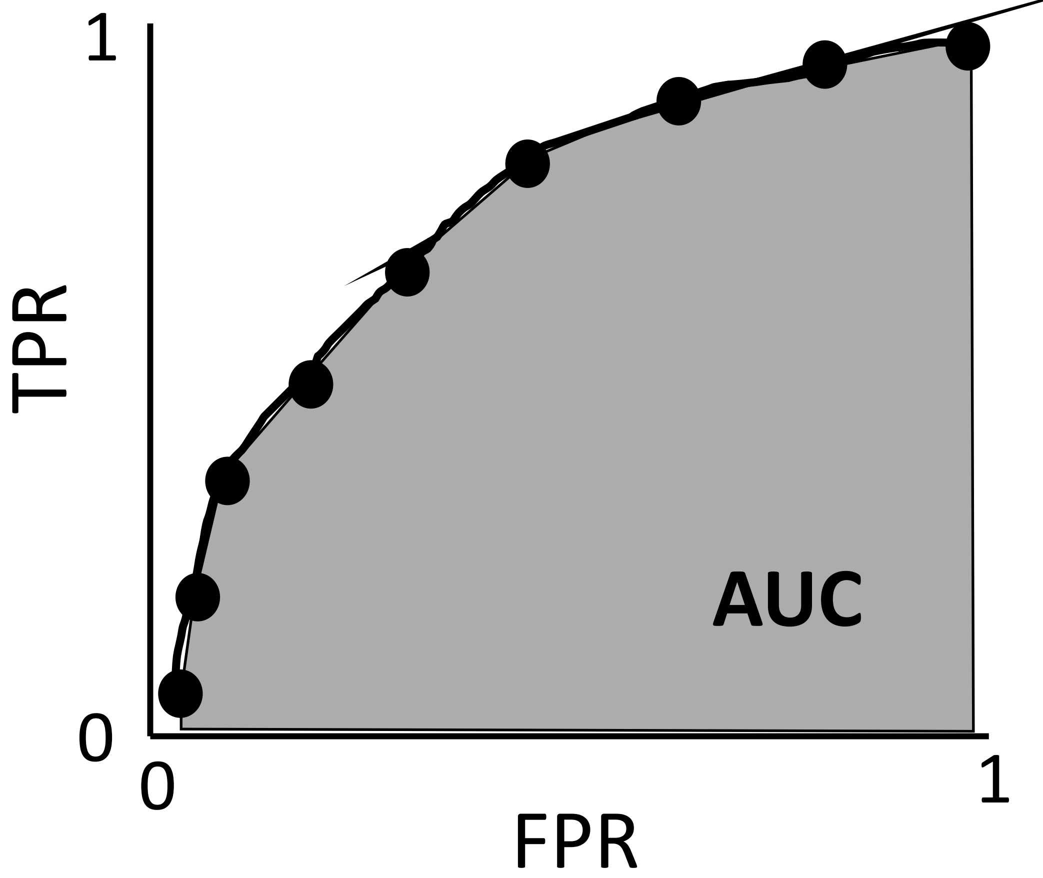


ROC Curve Background



A group of classifiers can create an ROC curve.

ROC Curve Background



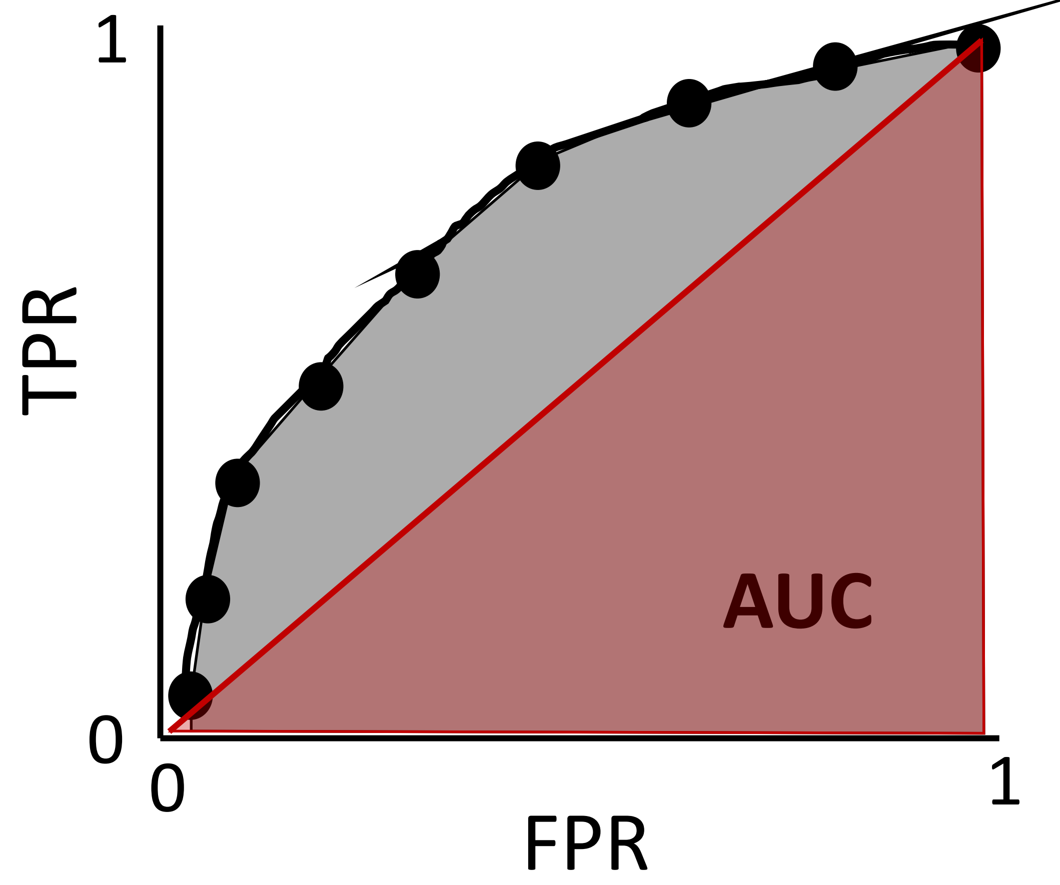
A group of classifiers can create an ROC curve.

Area Under the Curve (**AUC**): calculated to determine overall accuracy of ROC curve, and to compare different ROC curves

$$0 < AUC < 1$$

1 = perfect classification

ROC Curve Background



A group of classifiers can create an ROC curve.

Area Under the Curve (**AUC**): calculated to determine overall accuracy of ROC curve, and to compare different ROC curves

$$0 < AUC < 1$$

1 = perfect classification

Random guessing: AUC = 0.5

□ **any AUC less than 0.5 is unrealistic**

Data

COSMIC-2 radio occultations:

- Quality control checks based on average bending angle differences
- Limited to spatial region of 40°N and S, and 30° and 120°W
- Limited to between 6-12 km at geopotential height

NOAA GFS Forecasts:

- 6-hr product forecasts – pressure, temperature, and relative humidity
- 5x5 grid (horizontal resolution of 1.25°x1.25°) centered around average latitude/longitude location of RO profile between 6-12 km

GOES-16 ABI imagery:

- Highest horizontal resolution of 0.5 km/pixel
- Captures images every 10 minutes

Data

Divided each collocated RO-GFS-ABI profile into 500-m layers, so each layer would have a predicted value and a truth value.

Created a database of 10 days worth of collocated RO, GFS and ABI data to use in our ROCD algorithm

January 21	April 15
February 5	May 4
February 16	June 1
March 15	July 1
March 28	July 20

10 days span over seven months in 2020 to capture some seasonal variability

Total profiles = 9035 □ Total 500-m atmospheric layers = 108,420

RO-Based Cloud Detection (ROCD) Algorithms

ROCD-P

(Previously proposed by Peng et al. 2006)

Three distinct tests – pass these then "cloudy" is predicted:

1. Logarithmic refractivity lapse rate > 45
2. Temperature lapse rate > 0
3. RO-inferred RH (AER RH) > 100%

If at least one of these is not passed, then "clear" is predicted.

ROCD-M

One test – only looking at an RH threshold

- If the RH of a layer is greater than some threshold, then the layer is predicted as "cloudy".

Used 3 separate RH databases – GFS only RH, AER RH, and RO-inferred RH calculated by PlanetiQ (PiQ RH)

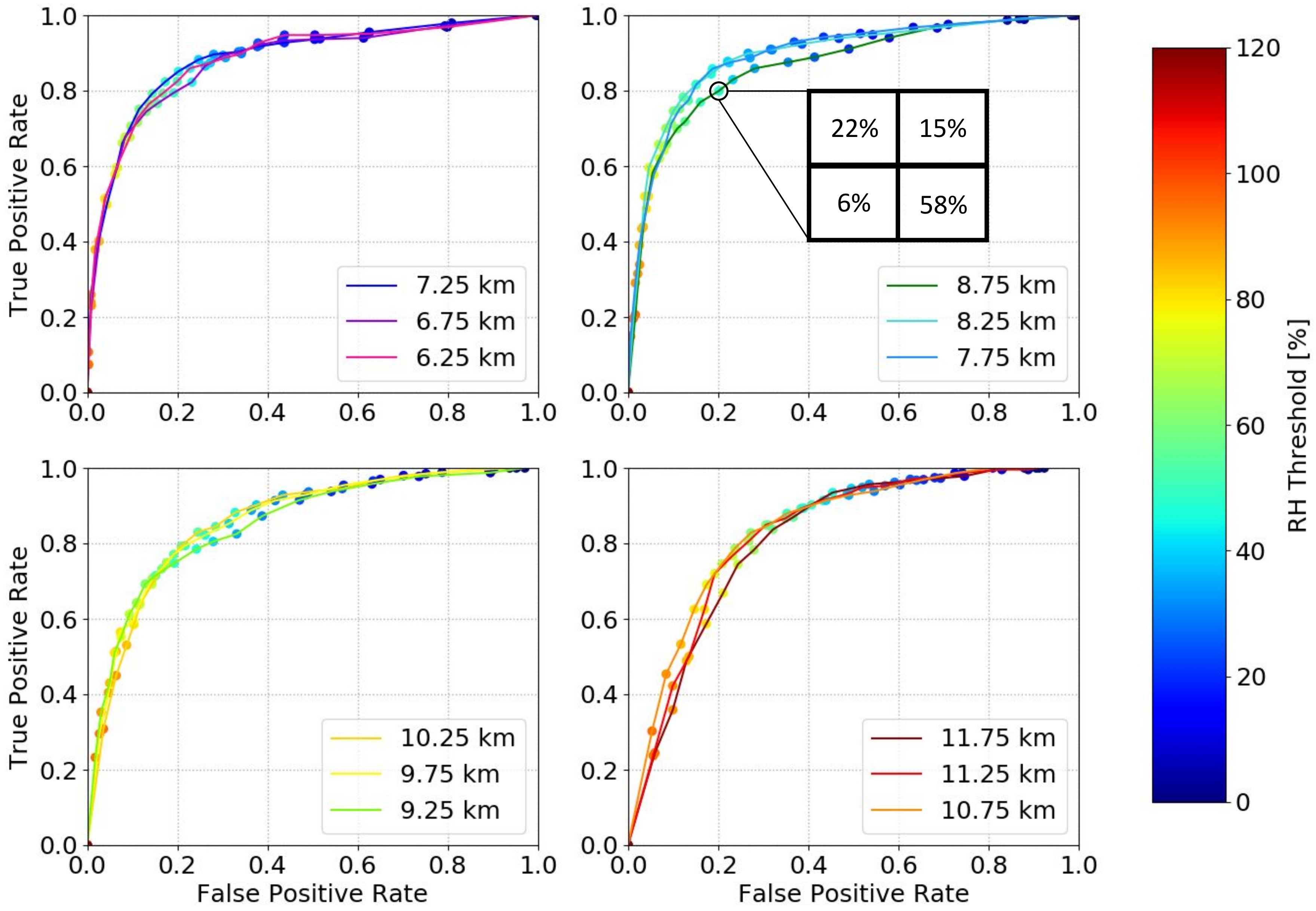
Defined truth cloudy (clear) when atmospheric extinction > (<) 0.1

ROCD-M

ROC curves for **GFS RH**

Key points:

- All AUCs > 0.5
- AUCs vary by altitude of atmospheric layer
  – AUCs increase as altitude decreases
- Accuracy of specific classifier varies by RH threshold

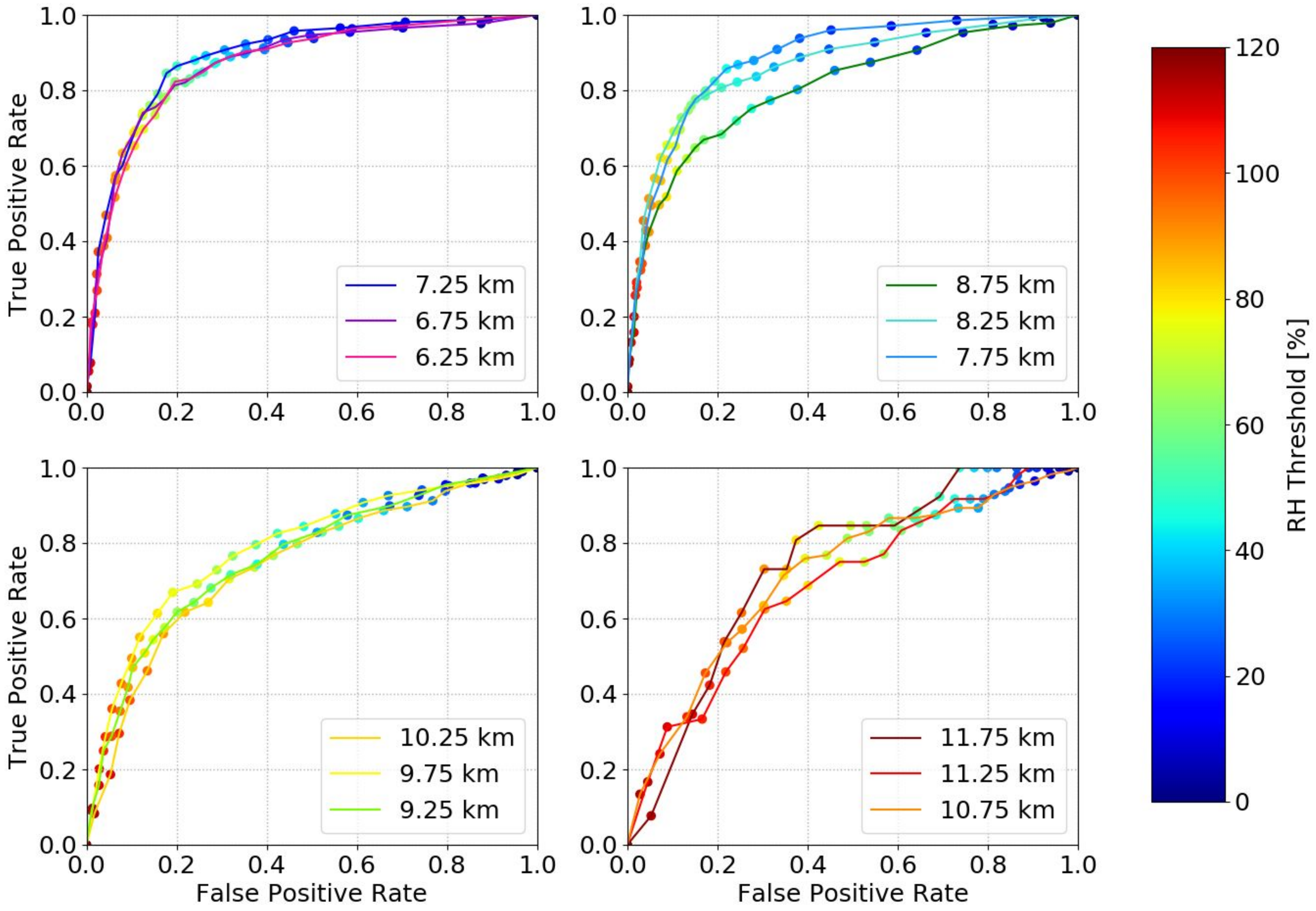


ROCD-M

ROC curves for **AER RH**

Key points:

- All AUCs > 0.5; **higher altitudes worse than GFS**
- AUCs vary by altitude of atmospheric layer – AUCs increase as altitude decreases
- Accuracy of specific classifier varies by RH threshold

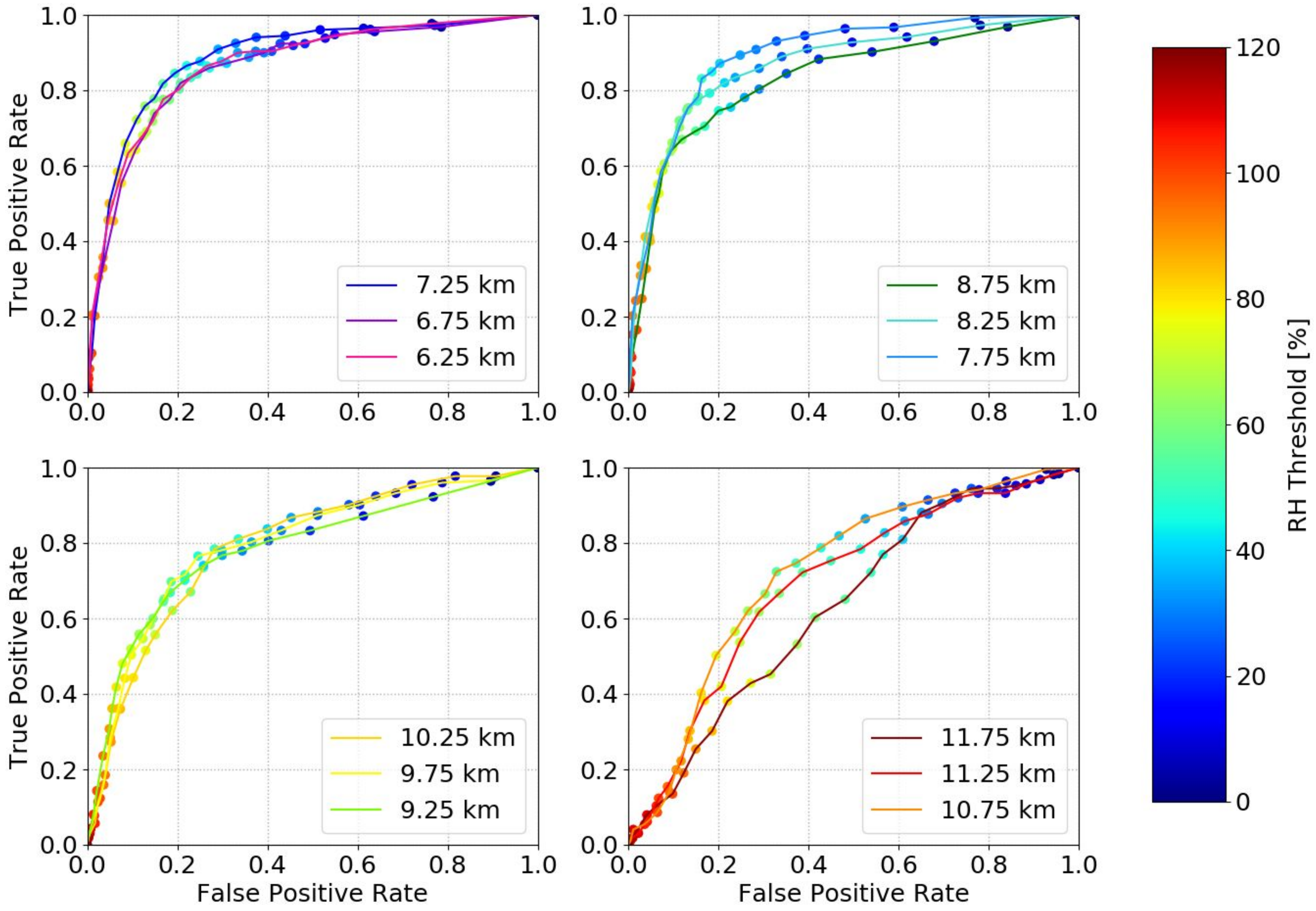


ROCD-M

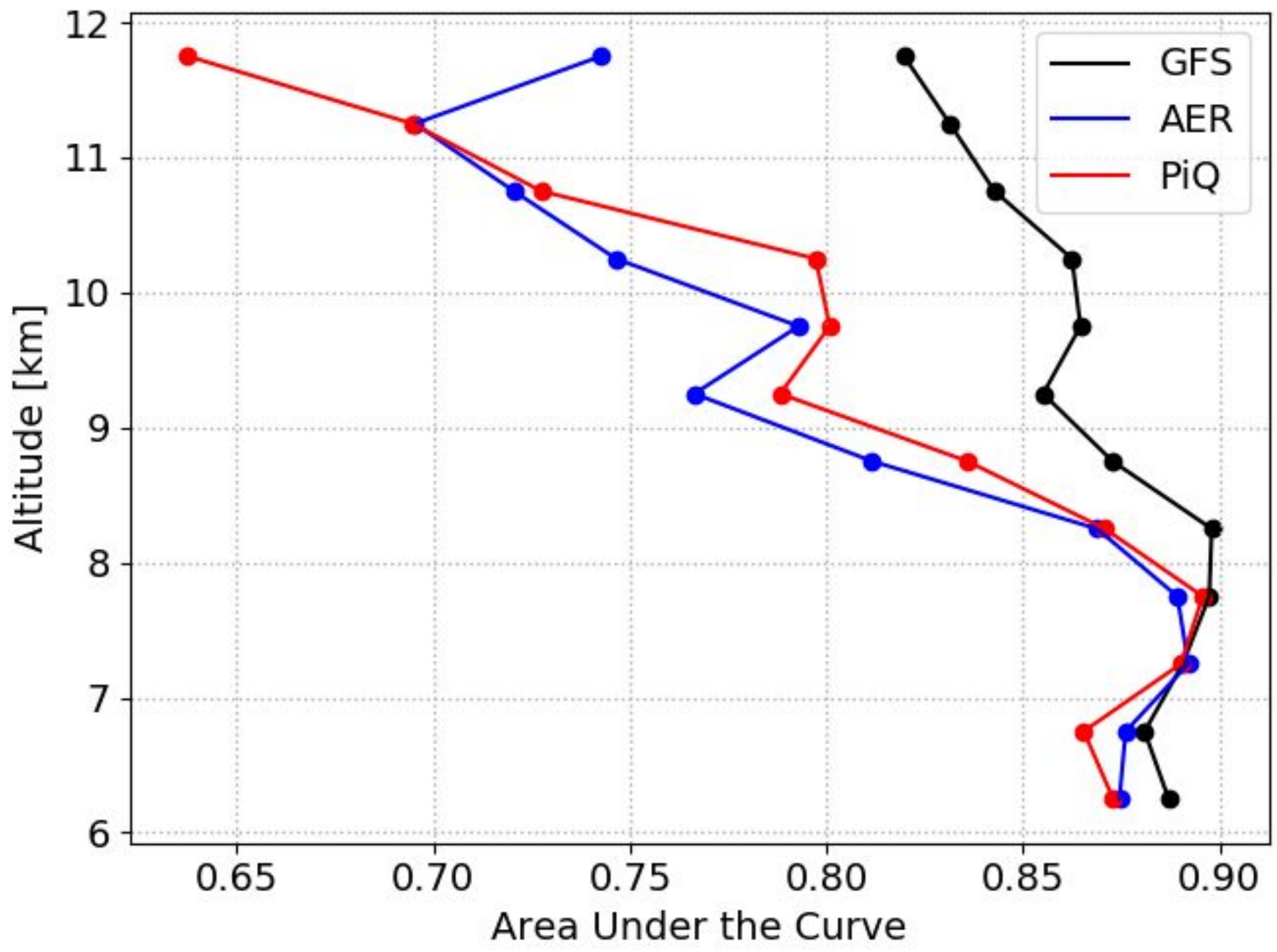
ROC curves for **PiQ RH**

Key points:

- All AUCs > 0.5; **higher altitudes worse than other datasets**
- AUCs vary by altitude of atmospheric layer – AUCs increase as altitude decreases
- Accuracy of specific classifier varies by RH threshold



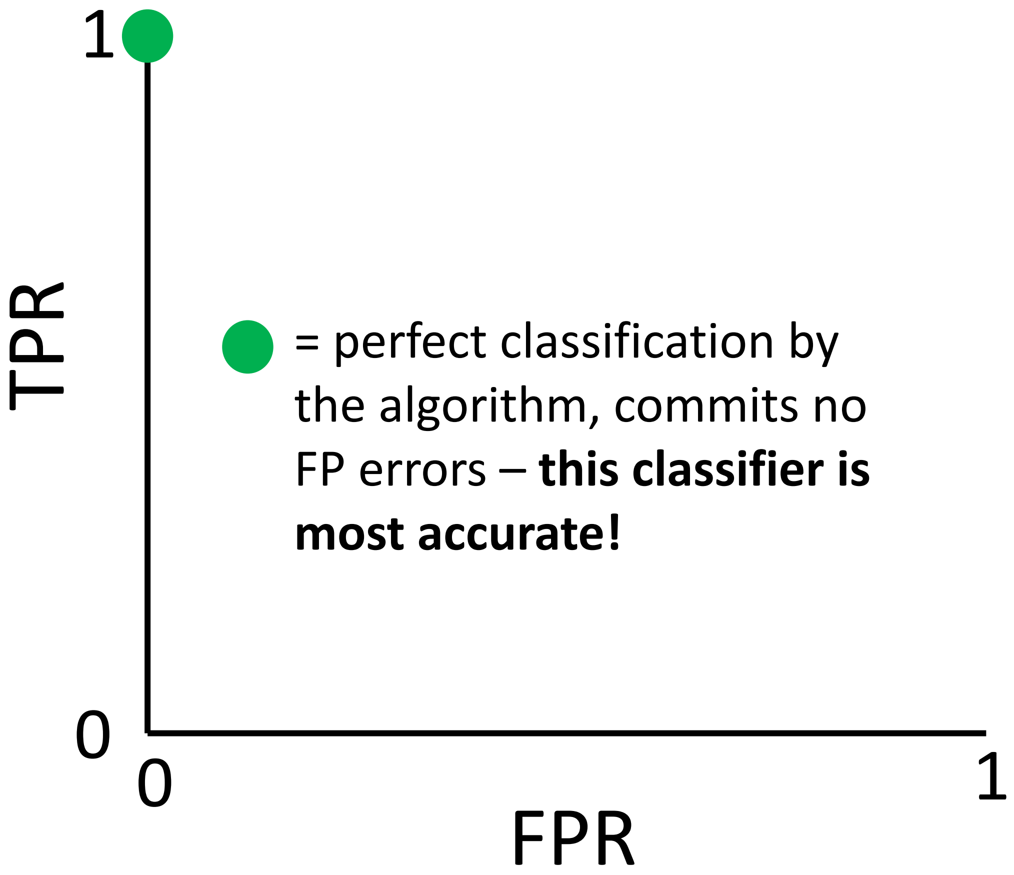
ROCD-M – AUC for all RH Datasets vs Altitude



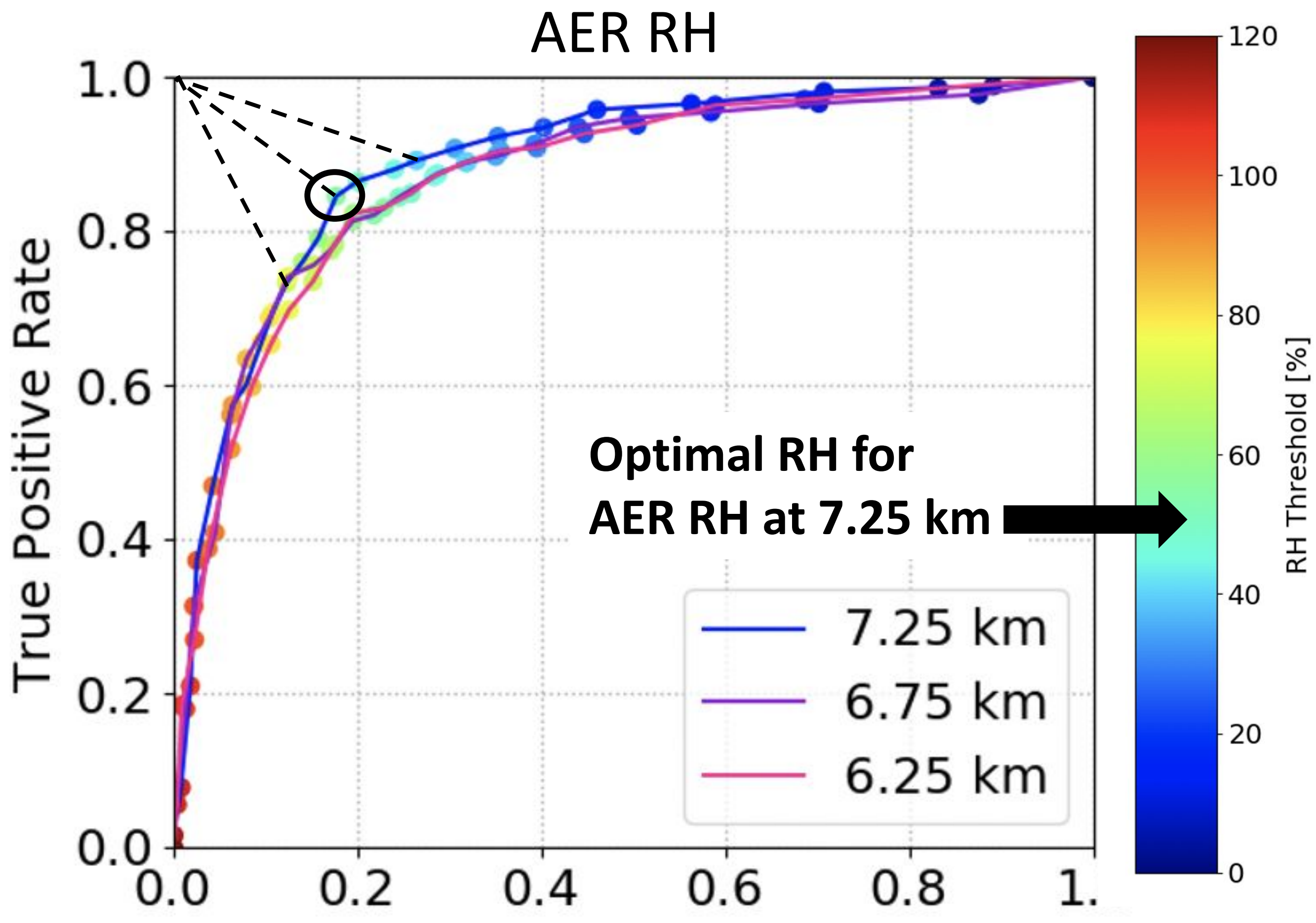
Key points:

- All AUCs > 0.5 □ **for ROCD-M all datasets produce useful information in cloud detection**
- AUCs below 8 km are relatively similar between RH datasets
- Large decrease in AUC above 8 km for AER and PiQ RH is expected since the uncertainties of the retrieved RHs increases above 8 km
- The PiQ dataset performs a bit better than AER, at all layers except for between 6 and 7 km and above 11.5 km

ROCD-M – Determining Optimal RH Threshold



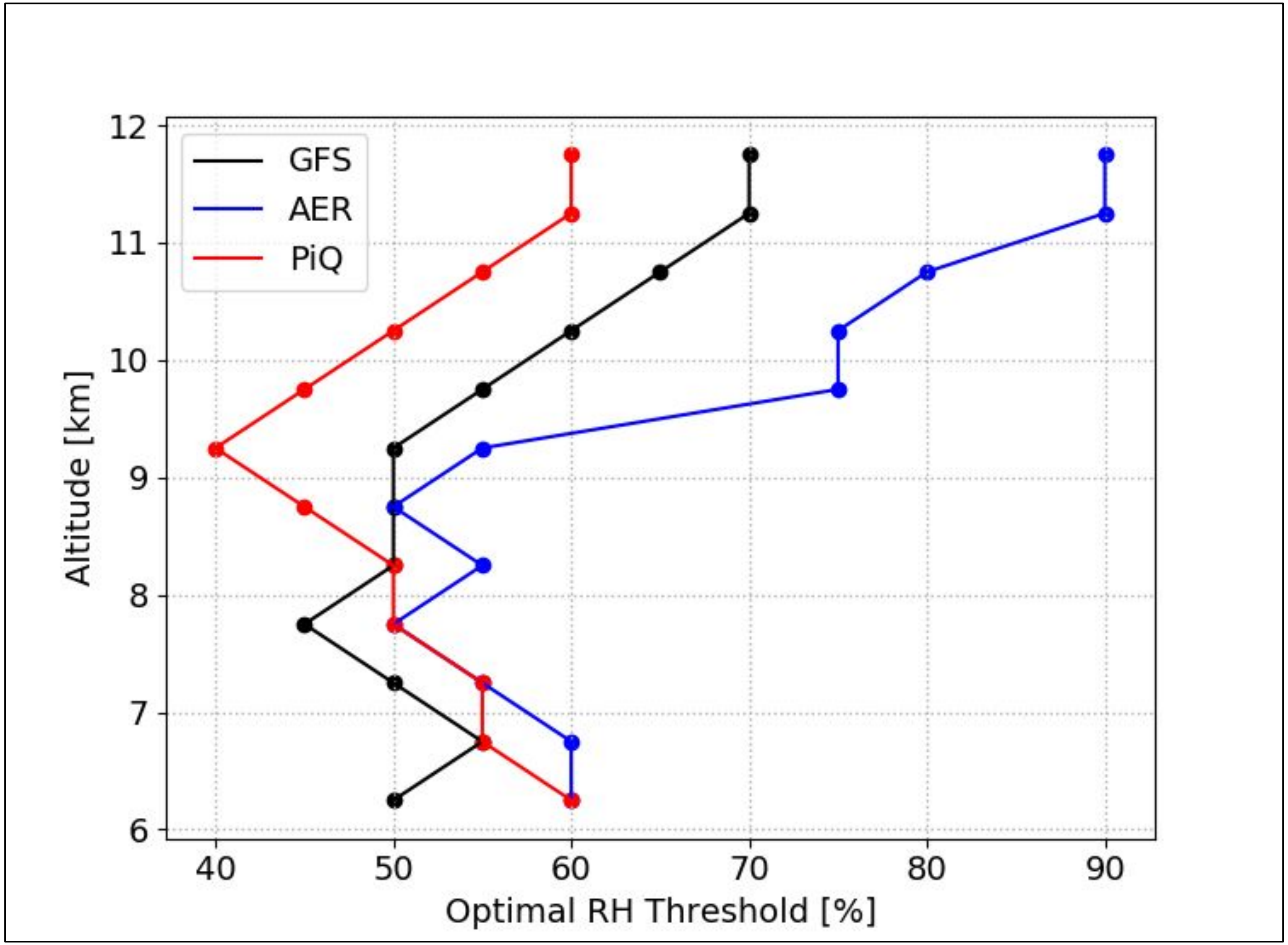
= perfect classification by the algorithm, commits no FP errors – **this classifier is most accurate!**



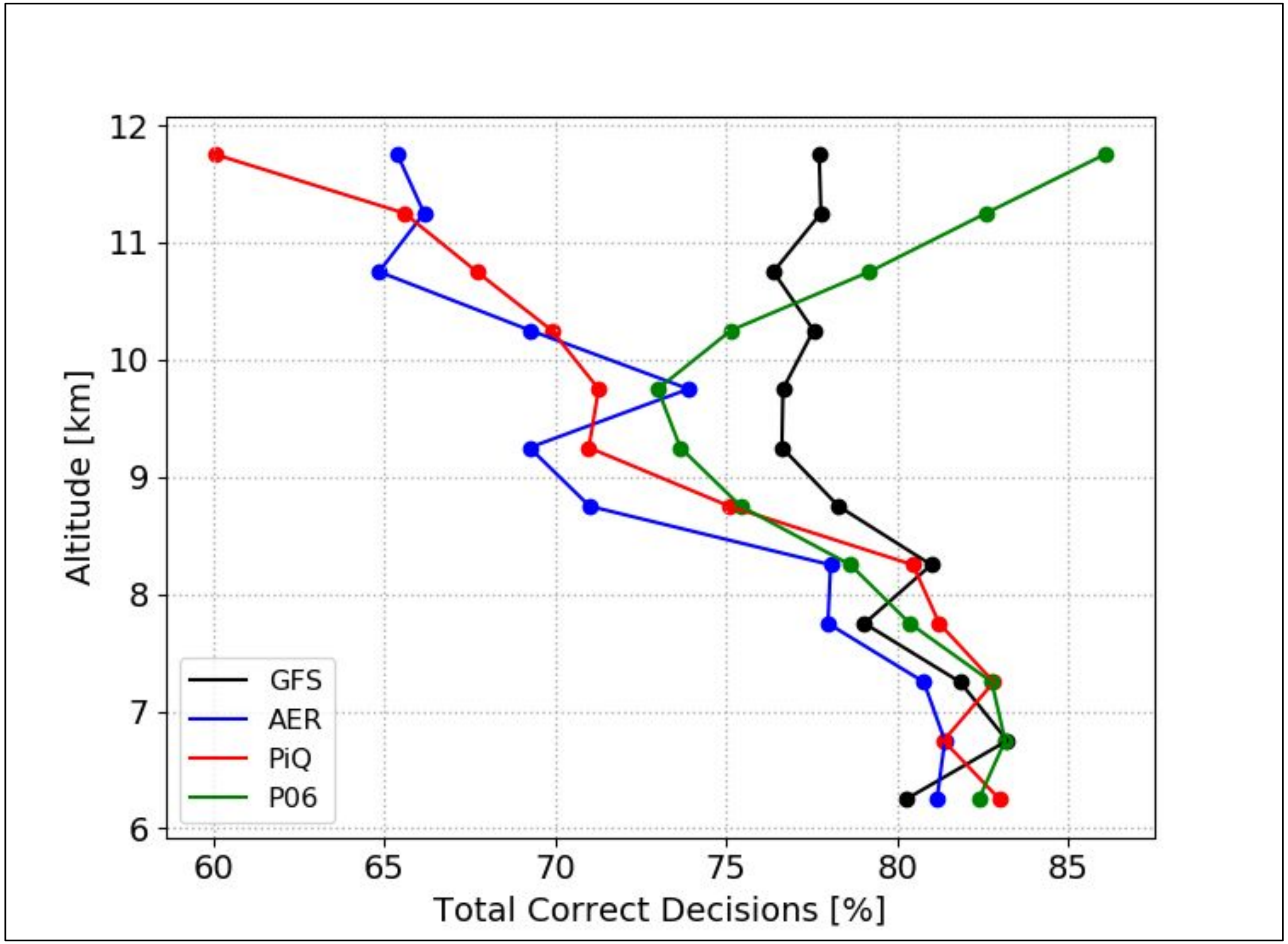
ROCD-M – Determined Optimal RH Thresholds

Key points:

- For most atmospheric layers, regardless of RH dataset, **a layer is most accurately predicted as cloudy, if the observed RH is between 40 and 60%**
- ROCD-P only predicts a layer to be cloudy if the observed RH > 100% -- the only layers for ROCD-M that got close to this were altitudes greater than 11 km for the PiQ RH



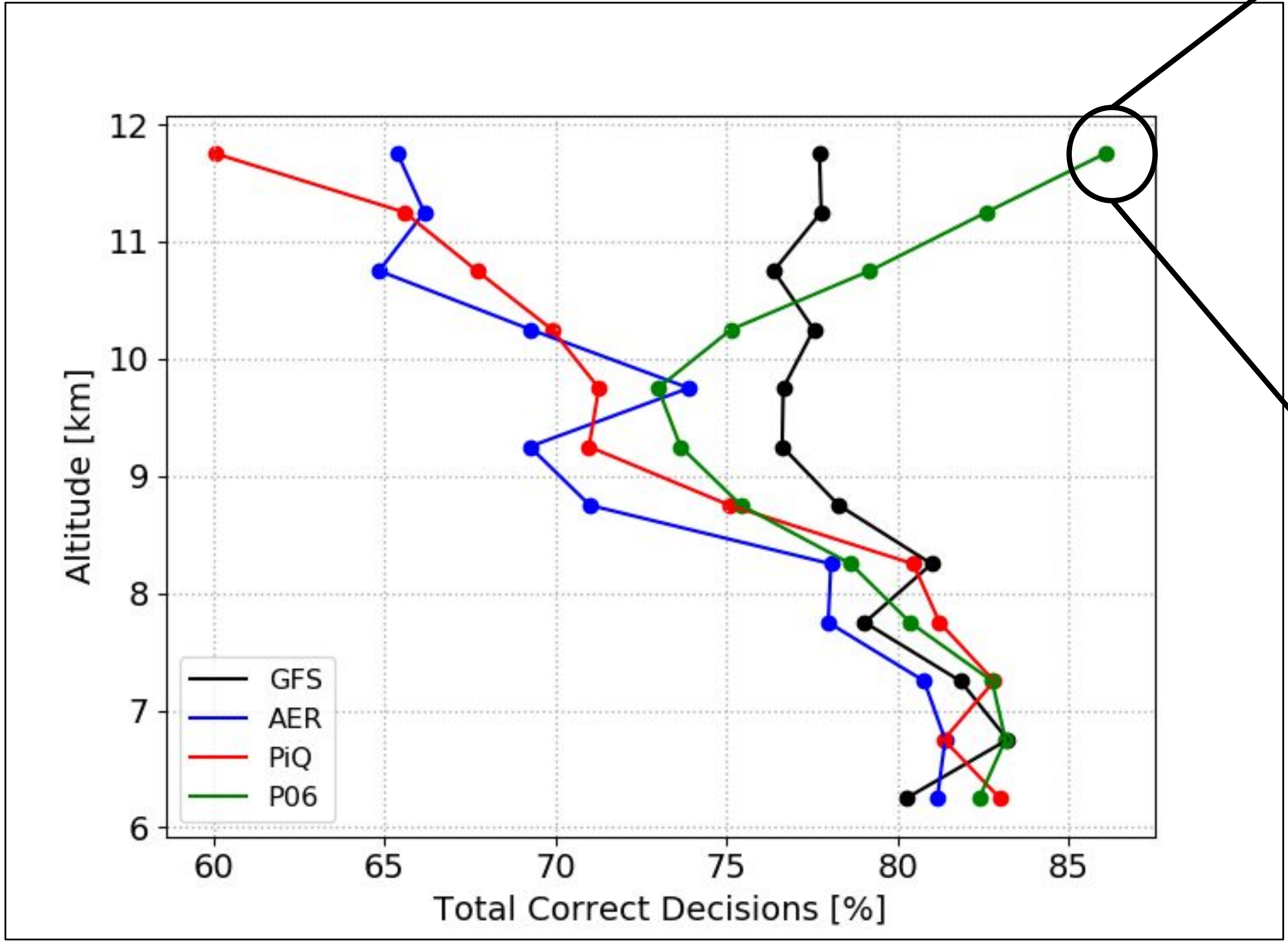
Accuracy of Both Algorithms



Key points:

- The PiQ dataset has highest accuracy for all layers below 8 km (except for one layer) – **use of RO observables in cloud detection provides benefits over only using forecast products**
- The ROCD-P and ROCD-M are comparable in accuracy despite algorithm testing differences
- The ROCD-P outperforms all RH datasets via ROCD-M above 10.5 km

Accuracy of Both Algorithms



		Actual: Cloudy	Actual: Clear
Prediction	Cloudy	0 %	0 %
	Clear	14 %	86 %

This classifier never predicted the layer was cloudy.
But because the truth dataset labeled this layer as clear 86% of the time, the accuracy was then 86%.

Conclusions:

- Using the ROCD-M algorithm, a layer is most accurately predicted as cloudy if the observed RH is 40-60% -- in comparison the RH threshold for ROCD-P is 100%
- The overall accuracy of ROCD-M is 60-85%, with accuracy decreasing with altitude
- The overall accuracy of ROCD-P is 73-86%, where accuracy decreases up to 10 km and then increases
- The large accuracy of ROCD-P at 12 km is because the truth dataset labeled this layer clear 86% of the time and the algorithm never predicted cloudy at this layer