Evaluation and improvement of inverse modeling systems with ACT-America

Ken Davis and colleagues, Penn State
Department of Meteorology
and the ACT-America science team.

NASA CMS Flux Inversion working group

20 January, 2016

ACT-America

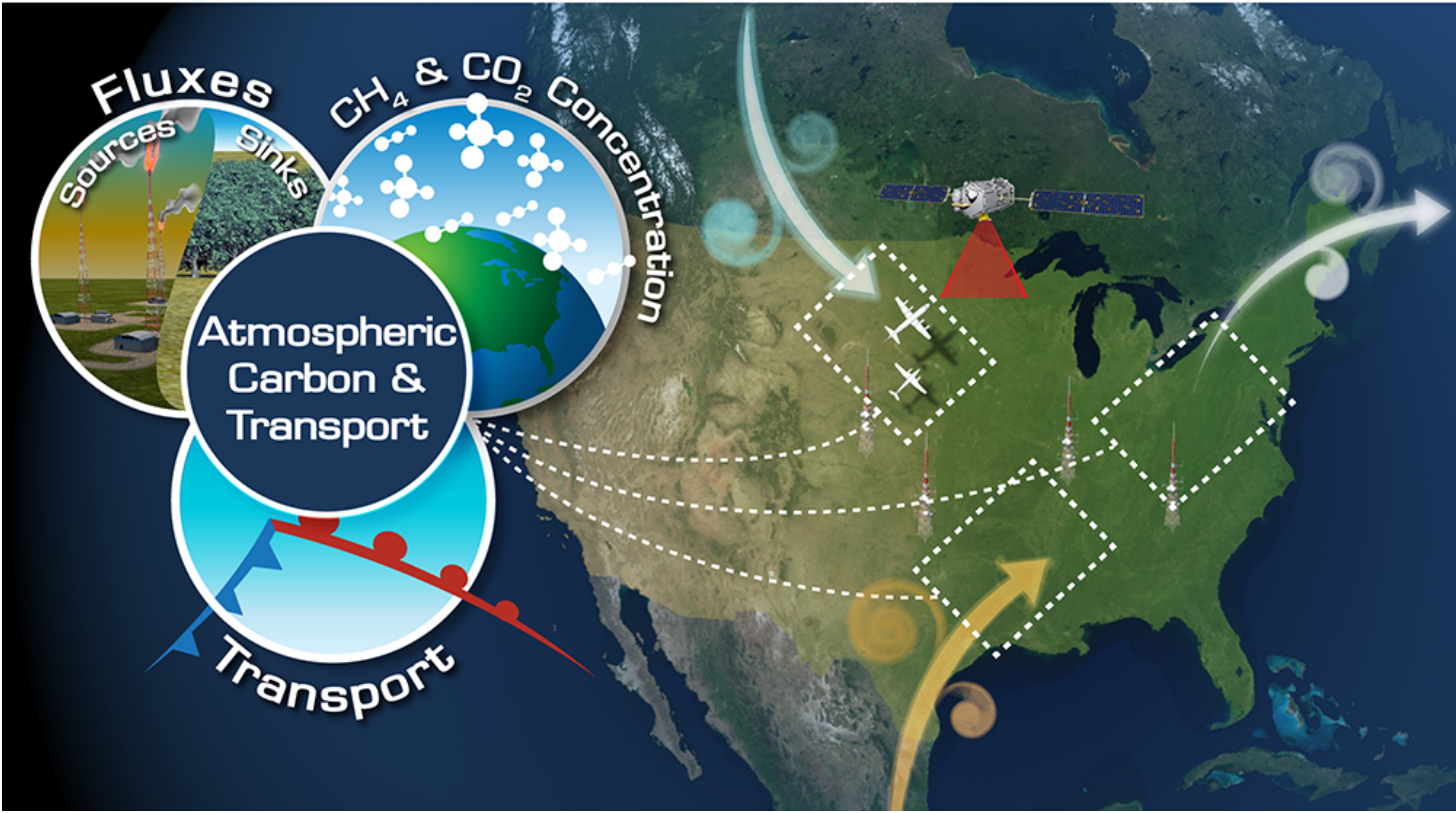

Image credit: Tim Marvel / NASA Langley

Atmospheric Carbon and Transport – America

A new NASA Earth Venture mission dedicated to improving the accuracy, precision and resolution of atmospheric inverse estimates of CO_2 and CH_4 sources and sinks

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overview

- Atmospheric Carbon and Transport (ACT)-America
  - new NASA Earth Venture Suborbital project.
  - Airborne study including in situ and remote GHG observations, 2016-2018, eastern U.S.
  - Primary objective – quantify and reduce transport uncertainty in regional to continental scale atmospheric inversions.
- Potential links to current NASA CMS call for proposals? We are happy to collaborate.

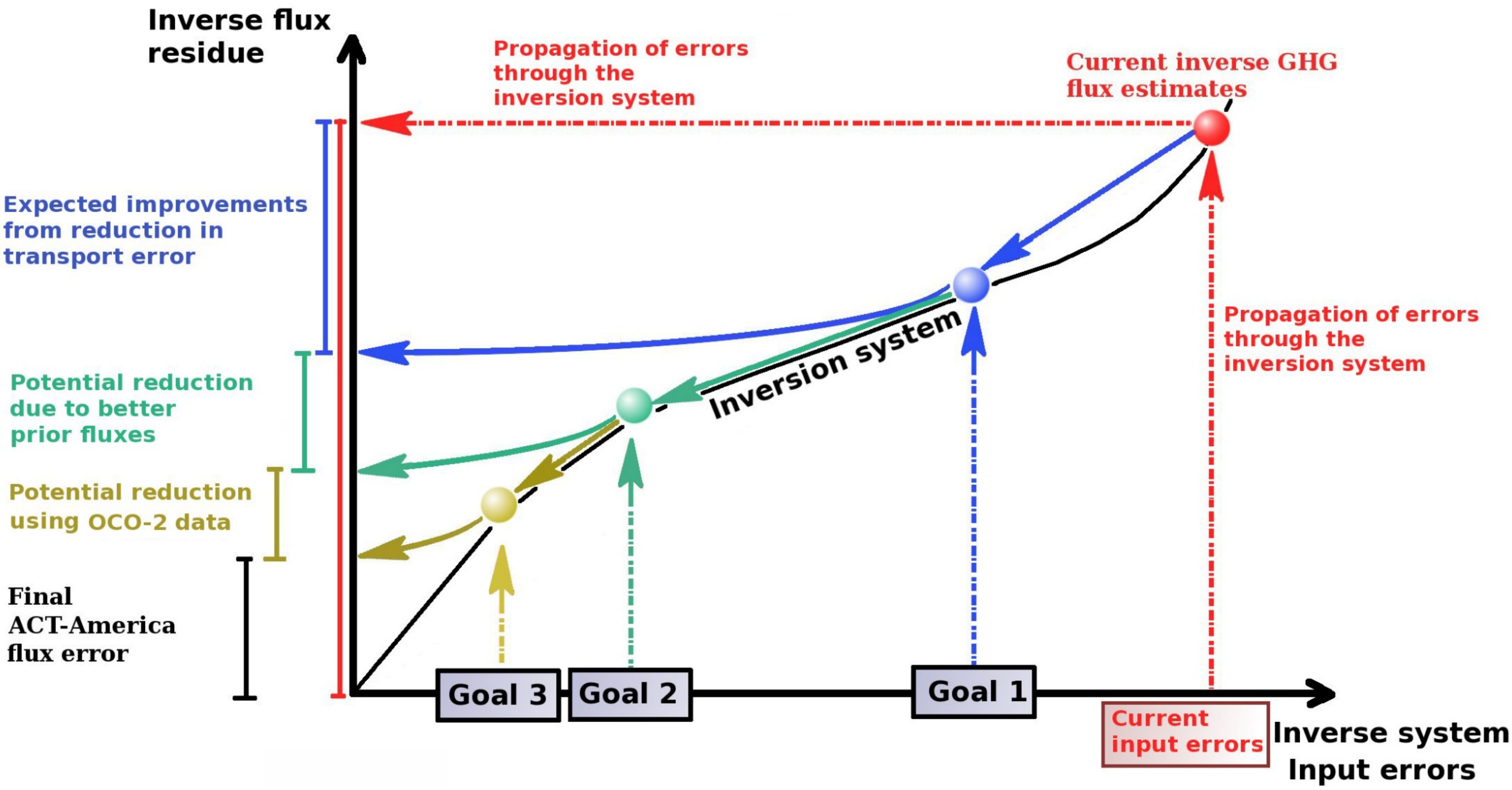
Overarching Goal

- The Atmospheric Carbon and Transport-America (ACT-America) mission will enable and demonstrate a new generation of atmospheric inversion systems for quantifying CO_2 and CH_4 sources and sinks at regional scales.
- These inversion systems will be able to:
  - Evaluate and improve terrestrial carbon cycle models, and
  - Monitor carbon fluxes to support climate-change mitigation efforts.

Mission Goals

1. Quantify and reduce atmospheric transport uncertainties (prune transport ensemble / reduce spread / quantify error)
2. Improve regional-scale, seasonal estimates of CO_2 and CH_4 fluxes (prune prior fluxes / reduce spread / quantify error)
3. Evaluate the sensitivity of Orbiting Carbon Observatory-2 (OCO-2) column CO_2 measurements to regional variability in tropospheric CO_2 (improve utility of OCO-2 data for regional inverse flux estimates)

Envisioned impact of mission on regional atmospheric inversions



Experimental Design

- Atmospheric transport of C at mid- and high-latitudes is dominated by synoptic-scale weather – the periodic passage of low-pressure systems (mid-latitude cyclones) and intervening periods of high-pressure, fair-weather conditions.
- The current CO_2 and CH_4 observational networks (including OCO-2) are too sparse to resolve synoptic-scale atmospheric transport.
- The high density and resolution, and large spatial domain offered by intensive airborne campaign data will provide the observational constraint required to prune both flux and transport ensembles.

Experimental Design

- Sustained airborne observations will bridge the gap from case studies to general understanding.
- By improving our ability to simulate accurately and precisely the GHG transport in high- and low-pressure systems in the mid-latitudes, we will improve our ability to construct accurate and precise atmospheric inverse estimates of C sources and sinks.

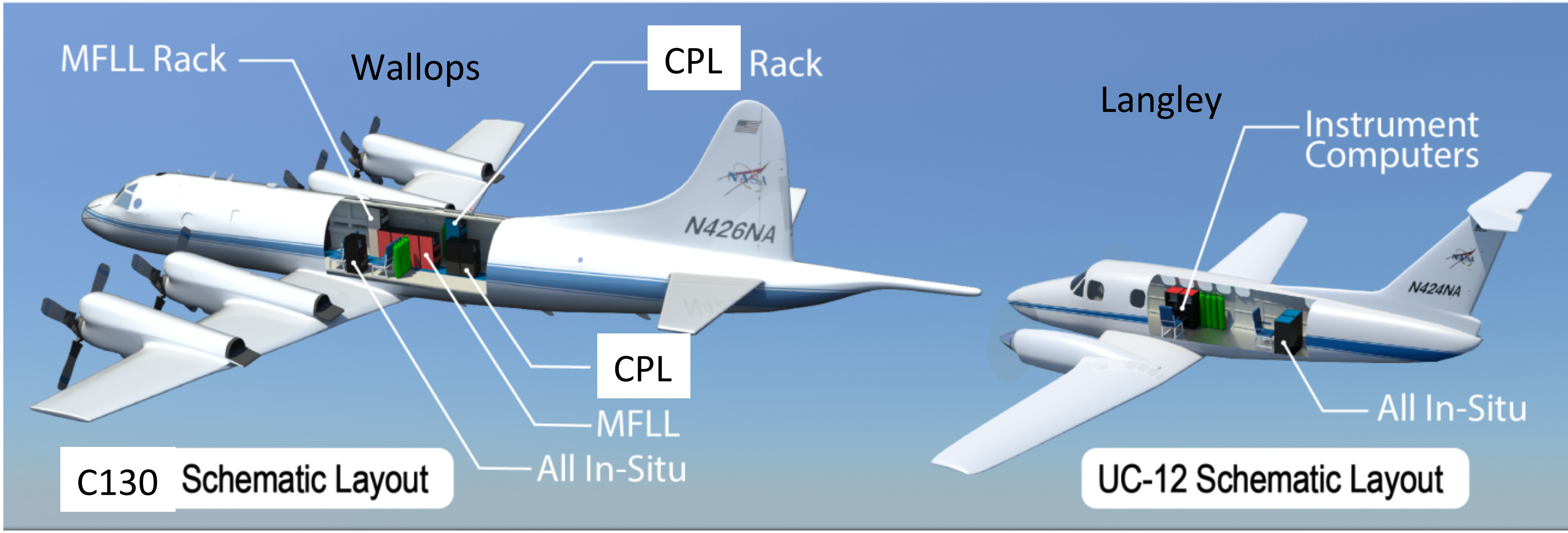
aspiration

The carbon flux and atmospheric transport processes we study will be common across the mid-latitudes, and the OCO-2 evaluation will apply globally, thus the results of the study will improve atmospheric inverse flux estimates around the globe and over decades.

Instruments and platforms

Aircraft

REPLACE THIS SCHEMATIC! C-130.



C-130 has a lot of room and endurance. We can accommodate more instruments than proposed. C-130 we have has not yet been used for science. Modifications underway.

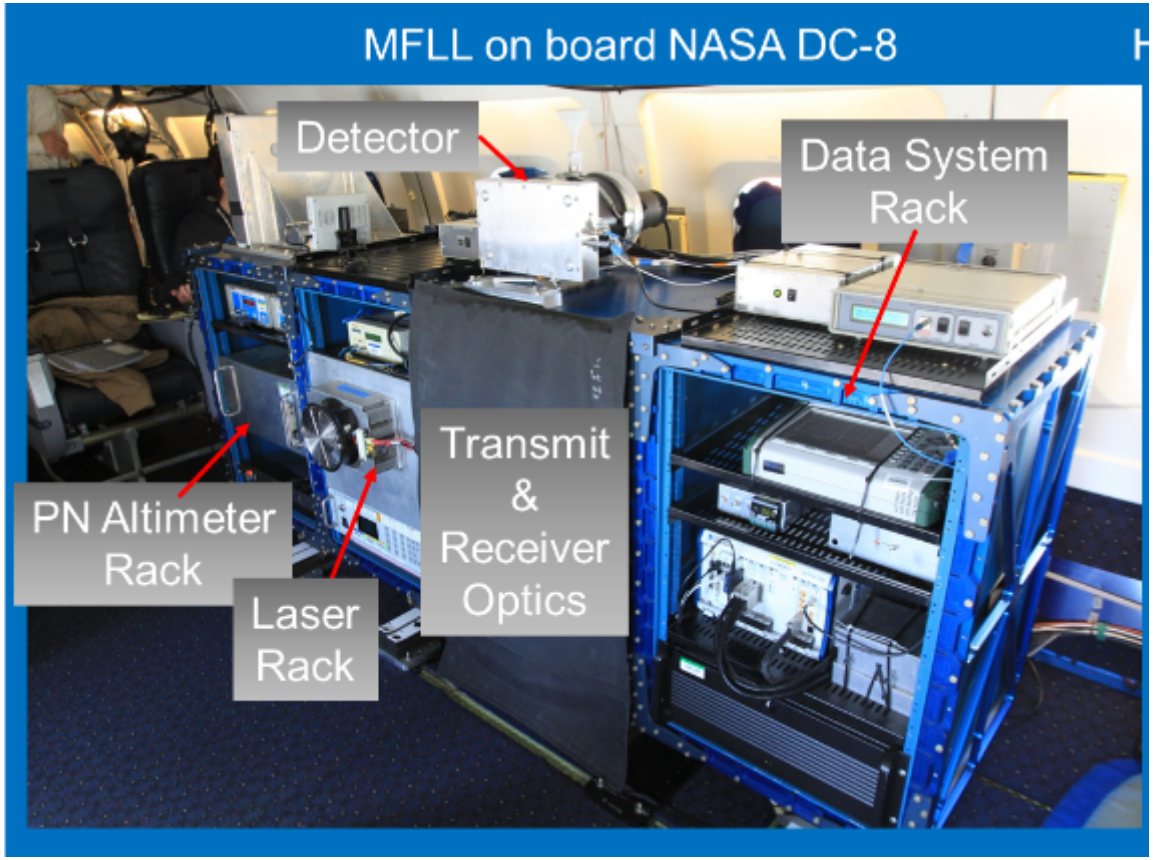
Measurements and STM Requirements

Instrument	Platform	Technique	TRL	Species/ Parameter	Instrument Precision (Averaging Time)	STM Precision Requirement [over 20 km unless otherwise noted]
MFLL	C-130	LAS[1]	8	CO_2 Column Density[4]	≤0.08% (10 sec) ≤0.25% (1 sec)	0.1% 1% (0.2 km)
		Pseudorandom Number Altimetry		Range to ground	< 1m (0.1 sec)	5 m (0.2 km)
CPL	C-130	Pulsed Lidar	9	ABL Height[5]	≤ 100 m (10 sec)	100 m
Picarro G2401-m	C-130, B-200	CRDS[2]	9	CO_2	≤ 0.15 ppm (5 sec)	1 ppm
				CH_4	≤ 1 ppb (5 sec)	4 ppb
				CO	≤ 30 ppb (5 sec)	15 ppb
				H_2O	≤ 0.12 g/kg (5 sec)	0.5 g/kg
2B Tech Model 205	C-130, B-200	Laser Spectrometer	9	O_3	1 ppb (10 sec)	8 ppb
Picarro G2301	Tower	CRDS[2]	9	CO_2	≤ 0.07 ppm (5 sec)	1 ppm hourly
				CH_4	≤ 0.5 ppb (5 sec)	4 ppb hourly
Flasks	C-130 B-200	GC/ MS[3]	9	CO_2, CH_4, CO, $^{14}CO_2$, COS	0.2 ppm CO_2;1 ppb CH_4; 2 per mil $^{14}CO_2$;2 ppt COS; (all 10 sec)	1 ppm CO_2; 4 ppb hourly CH_4; 2 per mil $^{14}CO_2$; 10 ppt COS
Environmental Parameters Suite	C-130	INS[3]	9	Wind Speed and Direction	1 m/s; +/- 5 degrees (0.1 sec)	1 m/s; 5 degrees
	C-130 B-200	Various		Pressure	0.25 mbar (0.015 sec)	0.5 mbar
				Temperature	0.2 deg C (0.15 sec)	0.5 degrees Celsius

Instruments and objectives

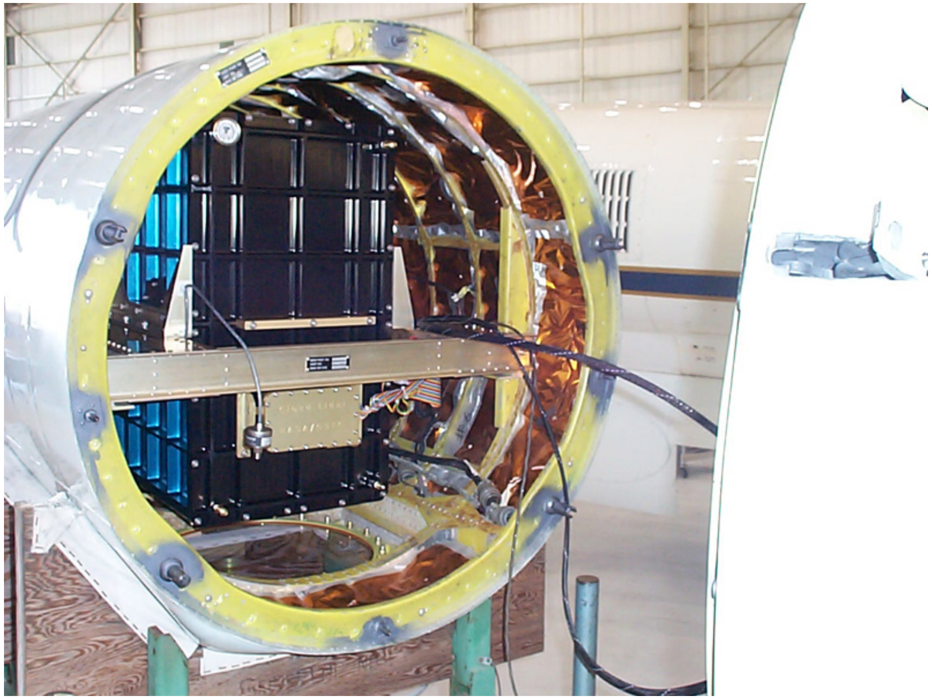
Instrument (Platform)	Variables Measured	Sampling Frequency	Data Latency (Archiving)	Purpose of measurement
MFLL (C-130)	Column CO_2 number density, altimetry, surface reflectance	10 Hz	1 day (≤6 months)	Core GHG CO_2 measurement & ranging capability
CPL (C-130)	ABL height, aerosol distribution	2 Hz, 30m vertical resolution	1 day (≤4 months)	Transport model constraint, OCO-2 validation
Picarro Air (C-130 & B-200)	CO_2, CH_4, CO, H_2O mole fraction	1 Hz	1 day (≤4 months)	Core GHG measurements, combustion & airmass tracer
2-B Tech. (C-130 & B-200)	O_3 mole fraction	1 Hz	1 day (≤4months)	Airmass tracer
Atm. state and nav. (C-130)	GPS Lat.-Lon, Wind speed, direction, Pressure, Temp.	1 Hz or higher	1 day (≤6 months)	Evaluate atmospheric transport models
Atm. State and nav. (B-200)	GPS Lat. and Lon., Pressure, Temperature	1 Hz or higher	1 day (≤6 months)	Evaluate atmospheric transport models
Flasks (C-130 & B-200)	Multiple trace gases. See table 3-2	12 flasks / aircraft / flight	1 month (≤6 months)	Core GHG measurements, GHG source tracers.
Picarro Ground	CO_2, CH_4, H_2O mole fraction	1 Hz	1 day (≤6 months)	Core GHG measurements.

Remote sensors (lidars)



The Harris Corporation MFLL instrument, shown here as a full system integrated on the NASA DC-8 aircraft, remotely measures column densities of CO_2 and path length between the C-130 aircraft and the ground or cloud surface.

Remote sensors (lidars)



The NASA Goddard Cloud Physics Lidar (CPL), shown here being integrated onto the NASA ER-2 aircraft, has extensive flight heritage and will provide atmospheric boundary layer depth measurements.

Both remote sensors have been flight-proven through multiple aircraft missions and will be integrated on the NASA C-130 aircraft for ACT-America.

In situ instrumentation

CO_2, CH_4, CO, O_3, H_2O, and flask sampling – DiGangi, Sweeney et al

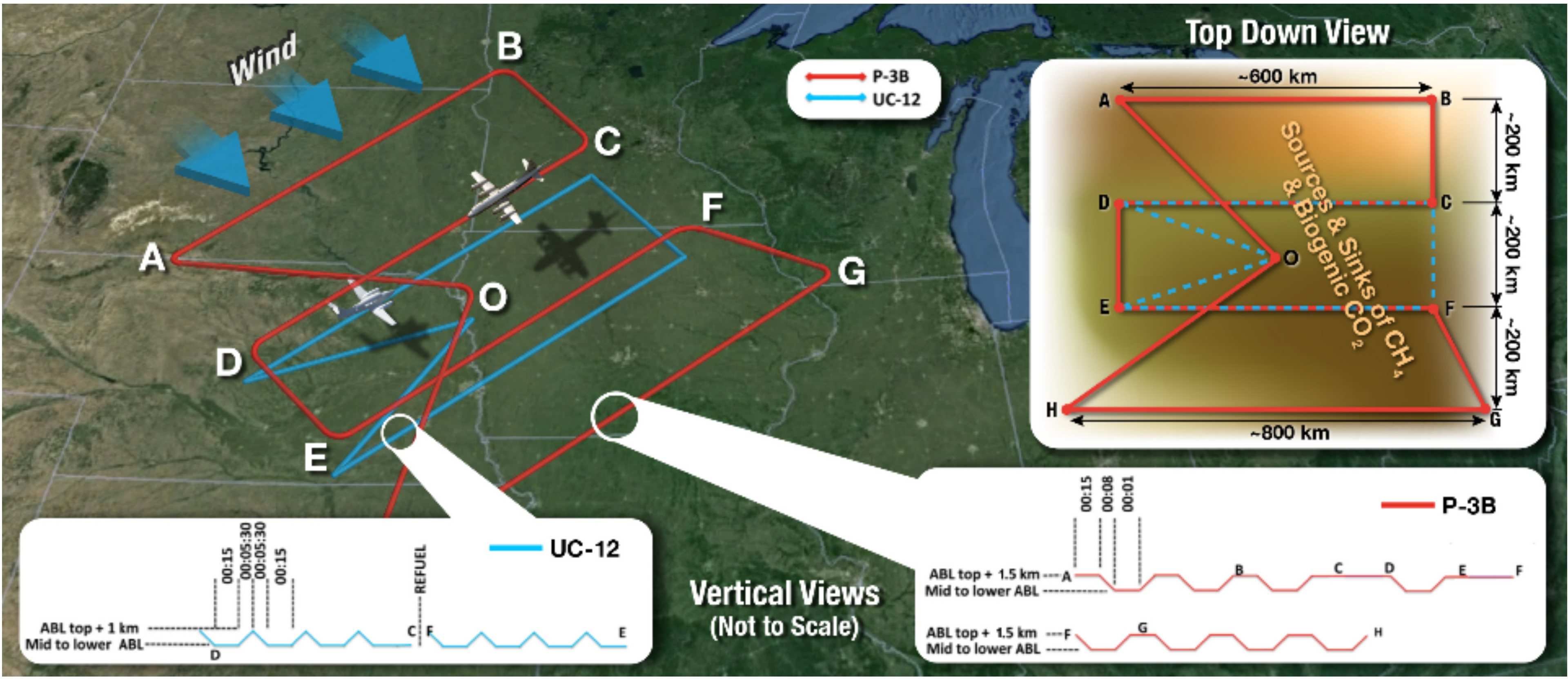
Additions

- Ethane on the B-200. Maybe also on the C-130 in future campaigns.
- Searching for remote instrumentation interested in utilizing the third optical port on the C-130. Options include:
  - Redundant CO_2 lidar
  - Solar induced fluorescence instrument
  - Passive CO_2/CO/CH_4 instrument
  - CH_4 lidar

Flight plans

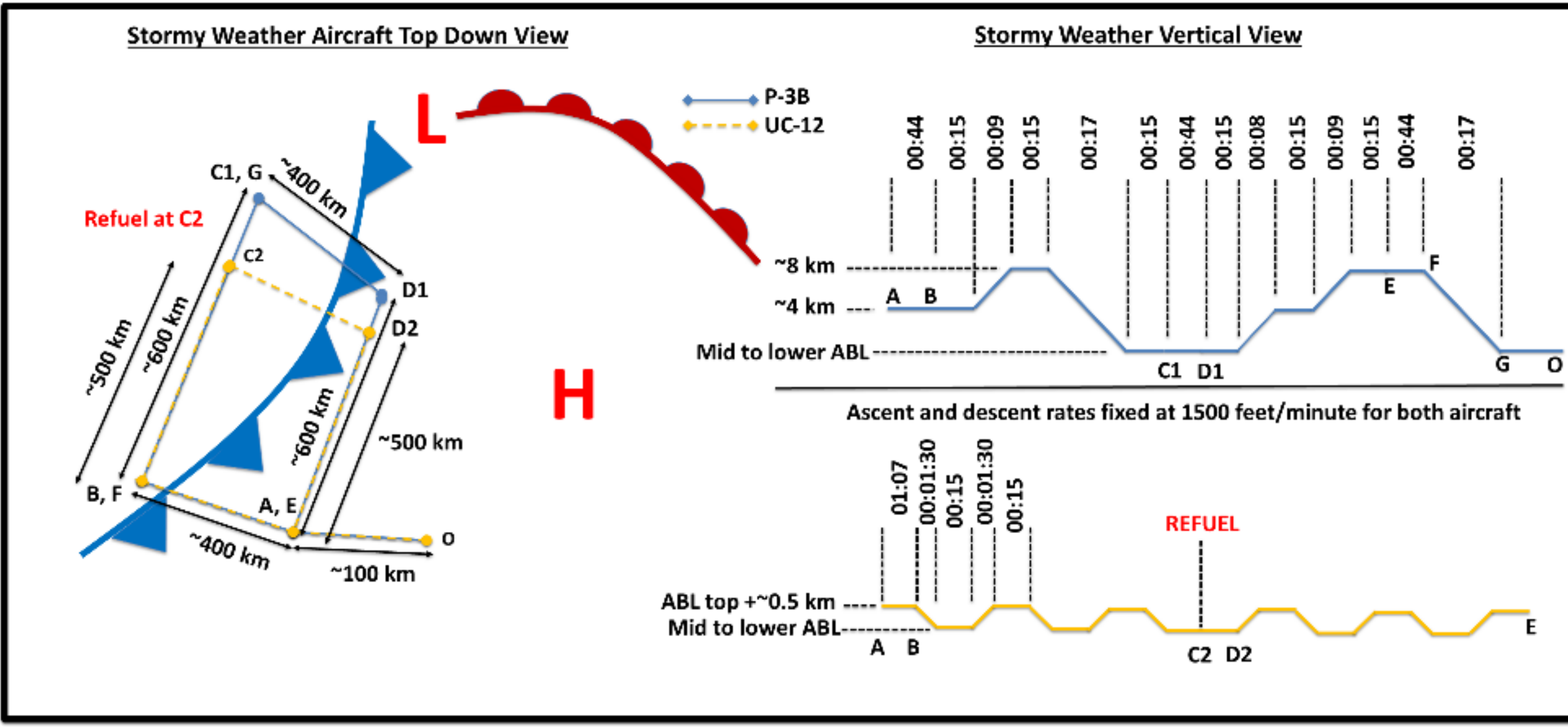
Fair-weather (flux-dominated) flight plan (goals 1 and 2)

Tim Marvel, NASA Langley



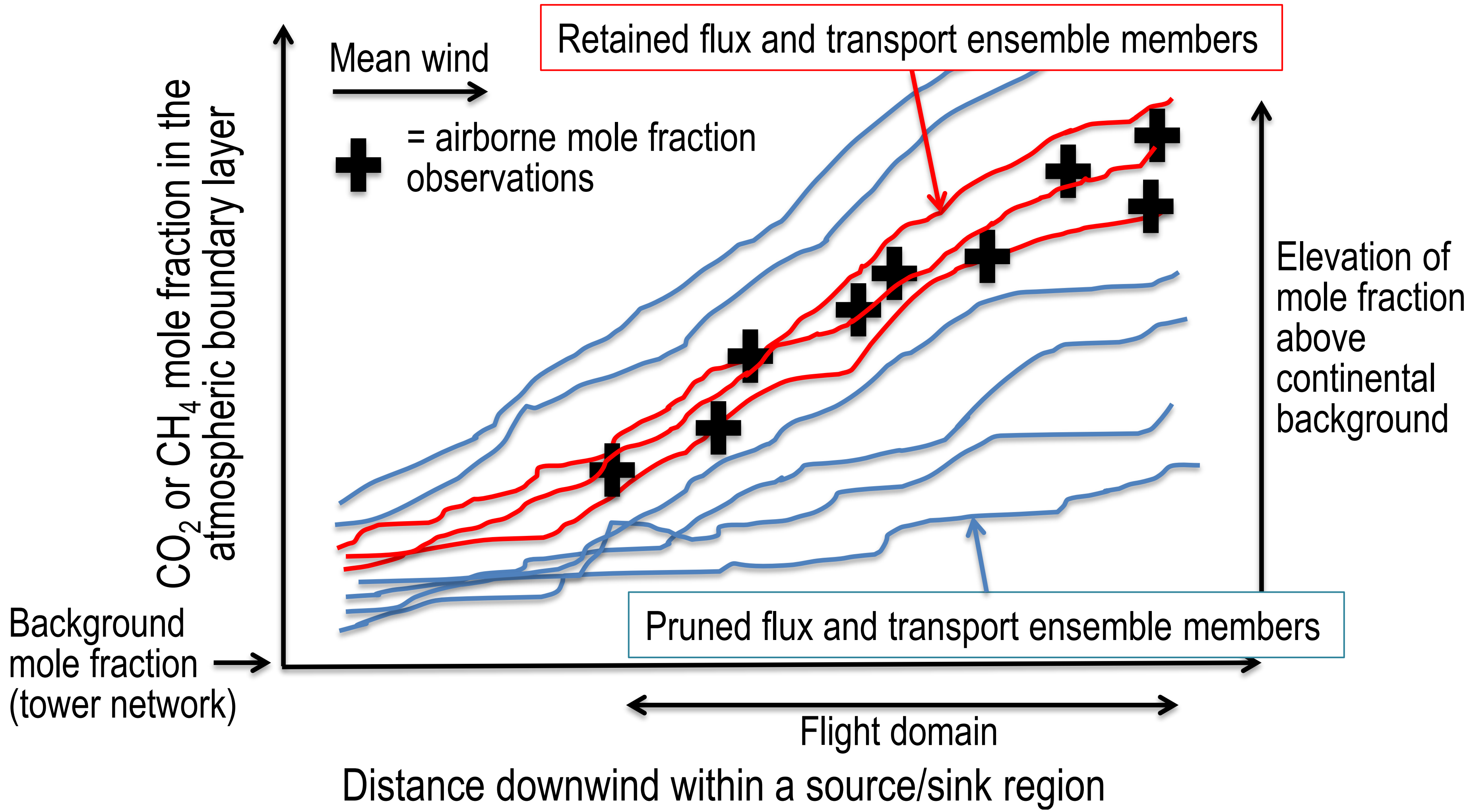
- Measure winds, ABL depth, CO_2, CH_4 and tracers (CO, $^{14}CO_2$, O_3) across 100's of km.
- Solve for regional fluxes for the days of flights directly – prune prior flux estimates.
- Evaluate fair weather meteorology in atmospheric transport ensemble.

Stormy-weather (transport-dominated) flight plans (goal 1)



- Measure atmospheric state, CO_2, CH_4 and tracers (CO, $^{14}CO_2$, O_3) across and around frontal systems.
- Evaluate atmospheric transport in our model ensemble. Prune transport ensemble.

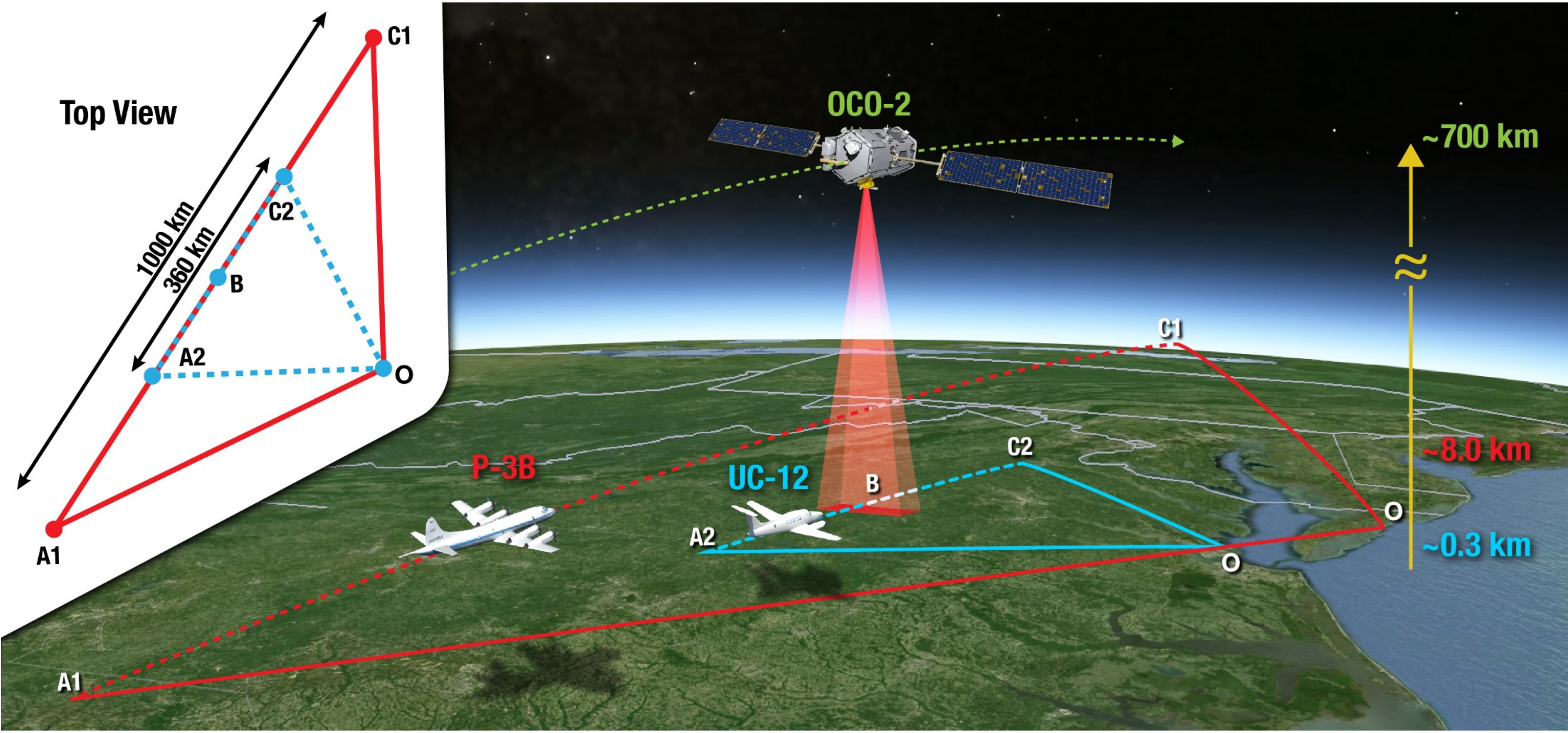
Simplified vision of model (flux and transport) ensemble pruning using airborne observations



Pruned ensembles lead to more accurate and precise flux inversions using long-term GHG data (towers, flasks, satellite, long-term airborne profiling).

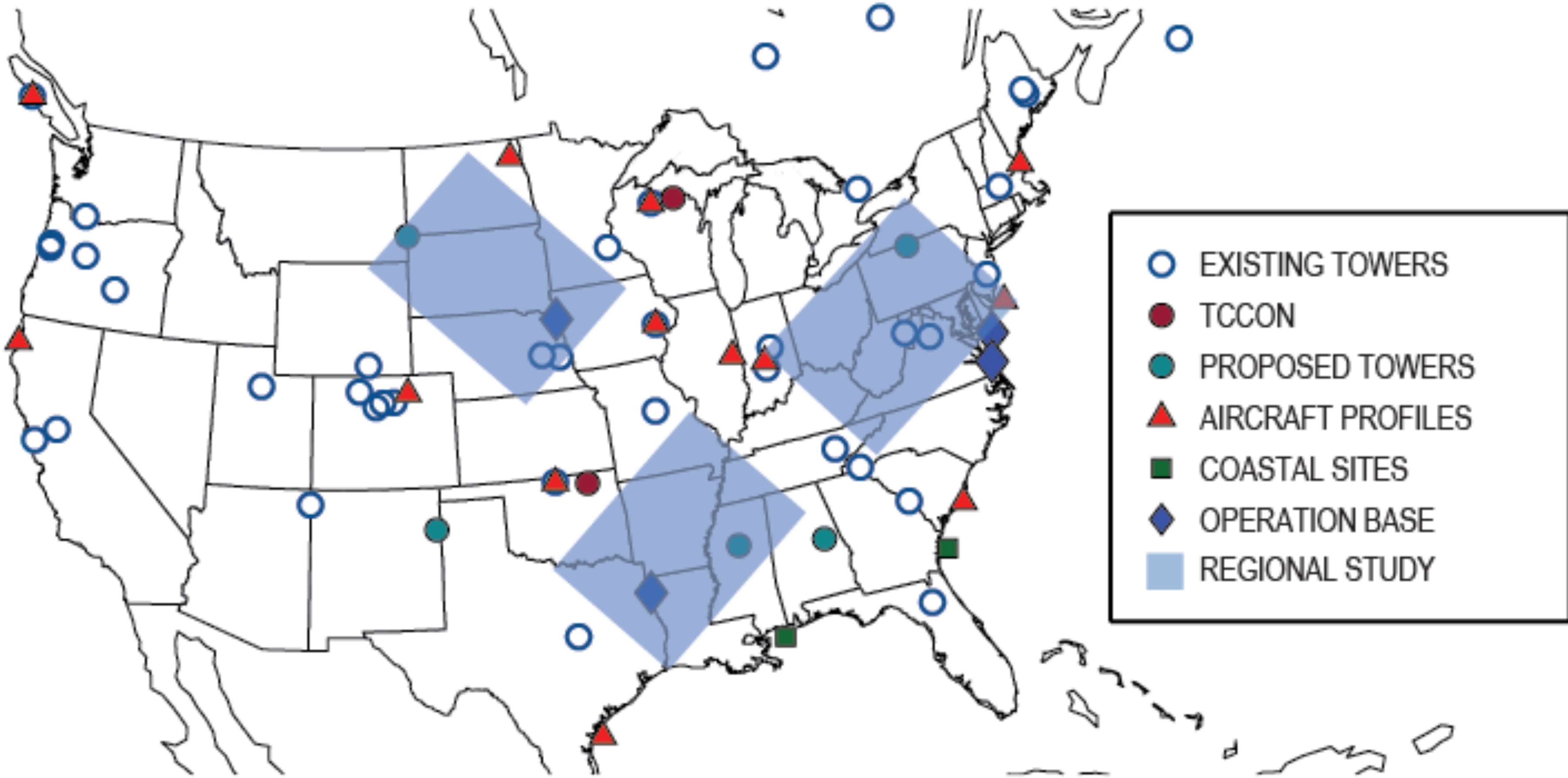
OCO-2 under-flights (goal 3)

Tim Marvel, NASA Langley



- Measure much of the atmospheric CO_2 column at < 20km horizontal resolution across 100's of km below OCO-2. Also measure aerosols, clouds with lidar.
- Compare spatial variability in airborne CO_2 to OCO-2 CO_2. Evaluate OCO-2 ability to capture tropospheric CO_2 variability along-track.
- One mid-flight vertical sounding (point B).

Where?



The eastern half of the United States, a region that includes a highly productive biosphere, vigorous agricultural activity, extensive gas and oil extraction, dynamic, seasonally varying weather patterns and the most extensive GHG and meteorological observing networks on Earth.

Blue boxes are approximate study domains. Sizes are roughly equal to a fair weather flight plan.

Flight Campaign Schedules: Baseline

Season/ Year	Spr 2016	Sum 2016	Fall 2016	Win 2017	Spr 2017	Sum 2017	Fall 2017	Win 2018	Spr 2018	Sum 2018	Fall 2018
Baseline Schedule		X		X		X	X		X		

Year 1 (2015): Instrument aircraft, integrate modeling systems, perform flight design simulations. Work with existing aircraft data sets.
Years 2-4 (2016-18): Flight campaigns and analyses. Goals 1-3.
Year 5 (2019): Wrap up goals 1-3. Apply findings to a multi-year reanalysis of N. American C fluxes using long-term observational assets (i.e., demonstrate new atmospheric inversion system).
End date: Jan, 2020.

What's one campaign?

- 6 week campaign.
- 2 weeks in each region (NE, MW, SE).
- 4 flights per region (both aircraft in each flight)
- 2 OCO-2 validation flights per campaign
- Try for at least one fair and stormy weather flight in each region, for each campaign. Total of ~6 storm and ~6 fair weather flights per campaign.

Science team, management structure

Management structure

Principal Investigator: Ken Davis, Penn State
Deputy-PI (goals 1 and 2): Thomas Lauvaux, Penn State
Deputy-PI (goal 3): Chris O'Dell, Colorado State
Project Scientist: Bing Lin, NASA LaRC
Project Manager: Mike Obland, NASA LaRC
Instrument and Aircraft Logistics: Byron Meadows, NASA LaRC
Instrument Science: Amin Nehrir, NASA LaRC
Program Scientist: Ken Jucks, NASA HQ

Science team "functional categories"

- Global atmospheric and inverse modeling
  - Jacobson, Bruhwiler, Baker/Schuh, Pawson/Ott/Chatterjee, Bowman/Liu, Denning
- Regional atmospheric and inverse modeling
  - Lauvaux, Moore
- Ecosystem carbon cycle modeling
- Satellite CO_2 data evaluation
- Aircraft observational studies
- Data and model management
- Instrument scientists
- Statistical and ensemble methods
  - Zhang, Keller, Michalak, Lauvaux

summary

- 60, 2-aircraft science flights over the eastern U.S. in the next 3 years, targeting reducing uncertainties in transport and prior fluxes using in atmospheric inversions
- 10, 2-aircraft OCO-2 underflights.
- Data will be public.
- We invite:
  - Collaborators who'd like to work with us (modeling, observational, analysis).
  - Proposals (e.g. NASA CMS) that could leverage this project.

If time allows, a quick review of transport model evaluation work underway at Penn State.

Applications of Meteorological Observations in Atmospheric Transport Modeling

- Evaluation of atmospheric model performance.
  - How well does it work? Bias, random error. ABL depth, ABL wind speed, ABL wind direction. How good is good enough? *Essential*
- Improvement of the atmospheric modeling system.
  - Are some modeling systems superior? When and where, and for what components of the model? Why? Can we construct better modeling systems? *Long-term investment*
- Meteorological data assimilation.
  - Use meteorological observations to kick the model transport fields in the right direction. *Very useful*

Work underway on transport uncertainty assessment

All unpublished work. (in prep). Please treat gently.

Liza Diaz – midcontinent intensive

- 45 member WRF-Chem physics ensemble
- Rawinsonde and flux tower model evaluation
- Focus on ABL depth, wind speed, wind direction
- Evaluation of impact of parameterizations on CO2
- Progress towards a calibrated transport ensemble

Urban scale: INFLUX, Indianapolis
Daniel Sarmiento

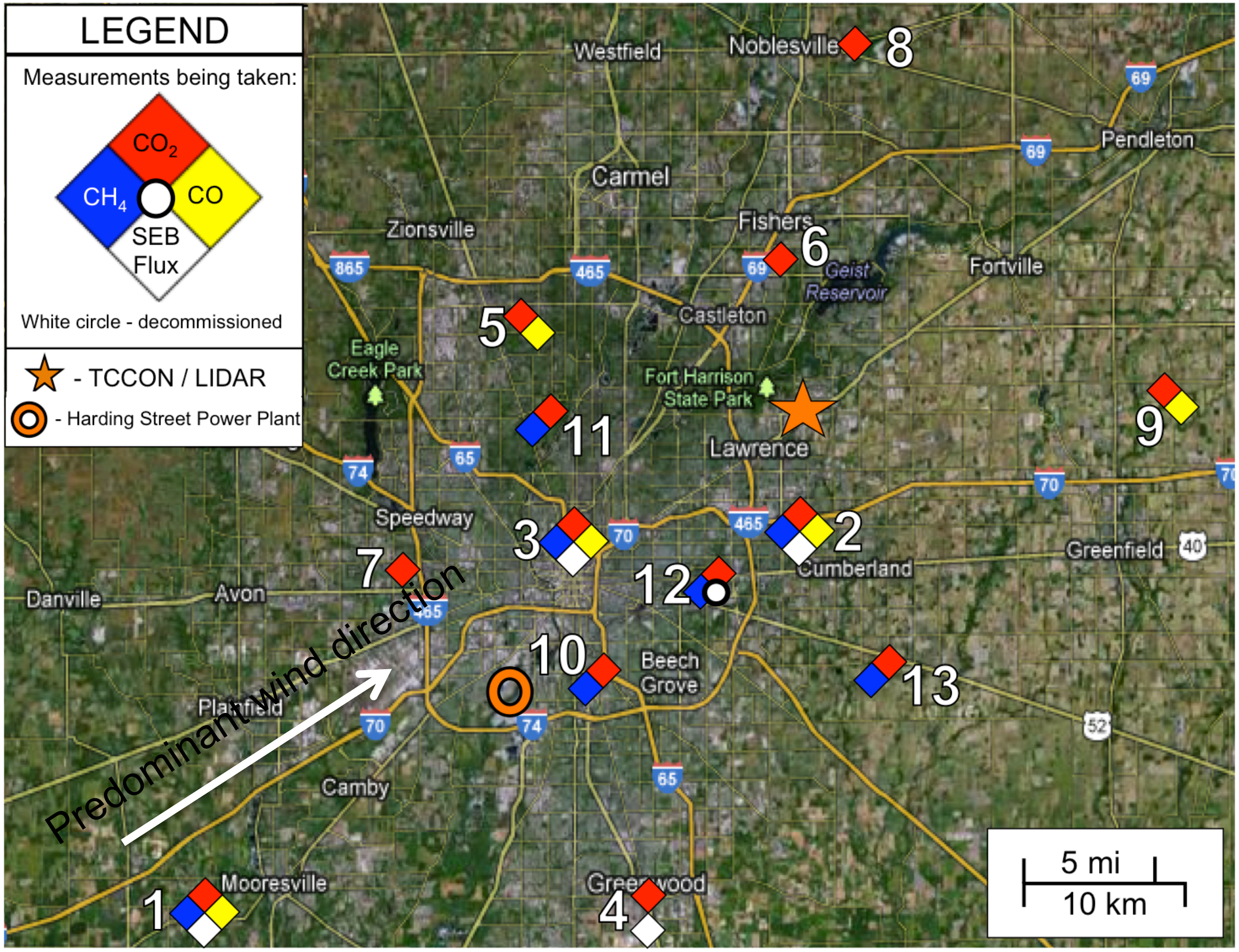
- ABL and Land surface model ensemble, land cover data upgrade
- Evaluation of ensemble vs. flux tower, ABL wind and depth observations (lidar, aircraft)
- Identification of best LSM/ABL systems for the urban environment

AJ Deng - Impact of meteorological data assimilation on urban transport modeling. Lidar, aircraft, surface data.

Summary: PSU transport modeling results

- WRF ABL depth, wind speed, wind direction
  - can be significantly biased for given locations and times. But averaged over time and sites, we often find small aggregate bias, especially with careful choice of physical parameterizations.
  - Random errors (hourly) are "pretty large."
- Significant internal errors can exist (e.g. incoming solar radiation, land surface fluxes) but the transport metrics can still be pretty good. Compensating errors?
- ABL parameterization scheme, land surface flux parameterization, cumulus microphysics, and meteorological boundary conditions can all have large impacts on the model performance
- Meteorological data assimilation, especially ABL wind profiles, significantly improves model performance

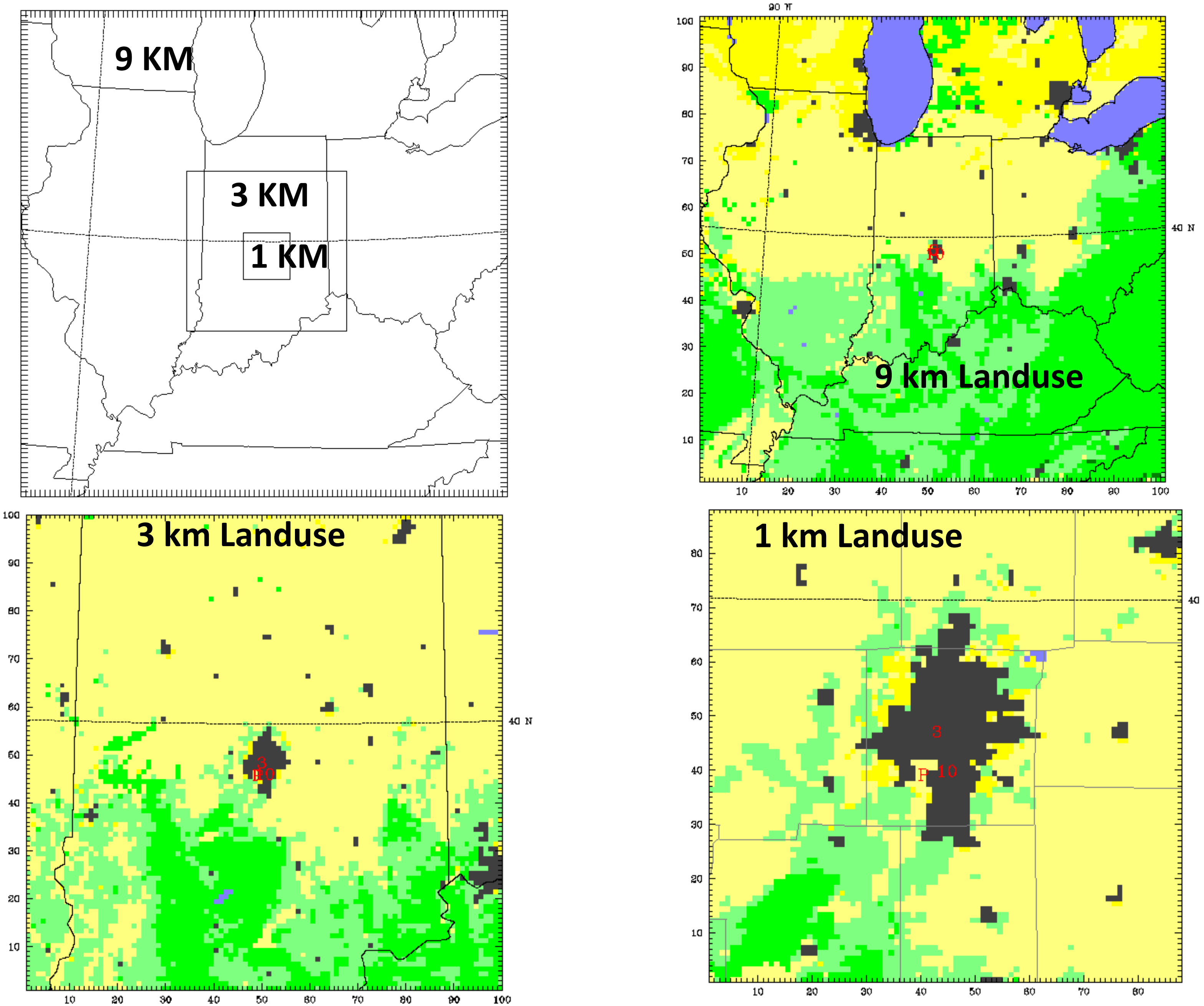
INFLUX GROUND-BASED NETWORK

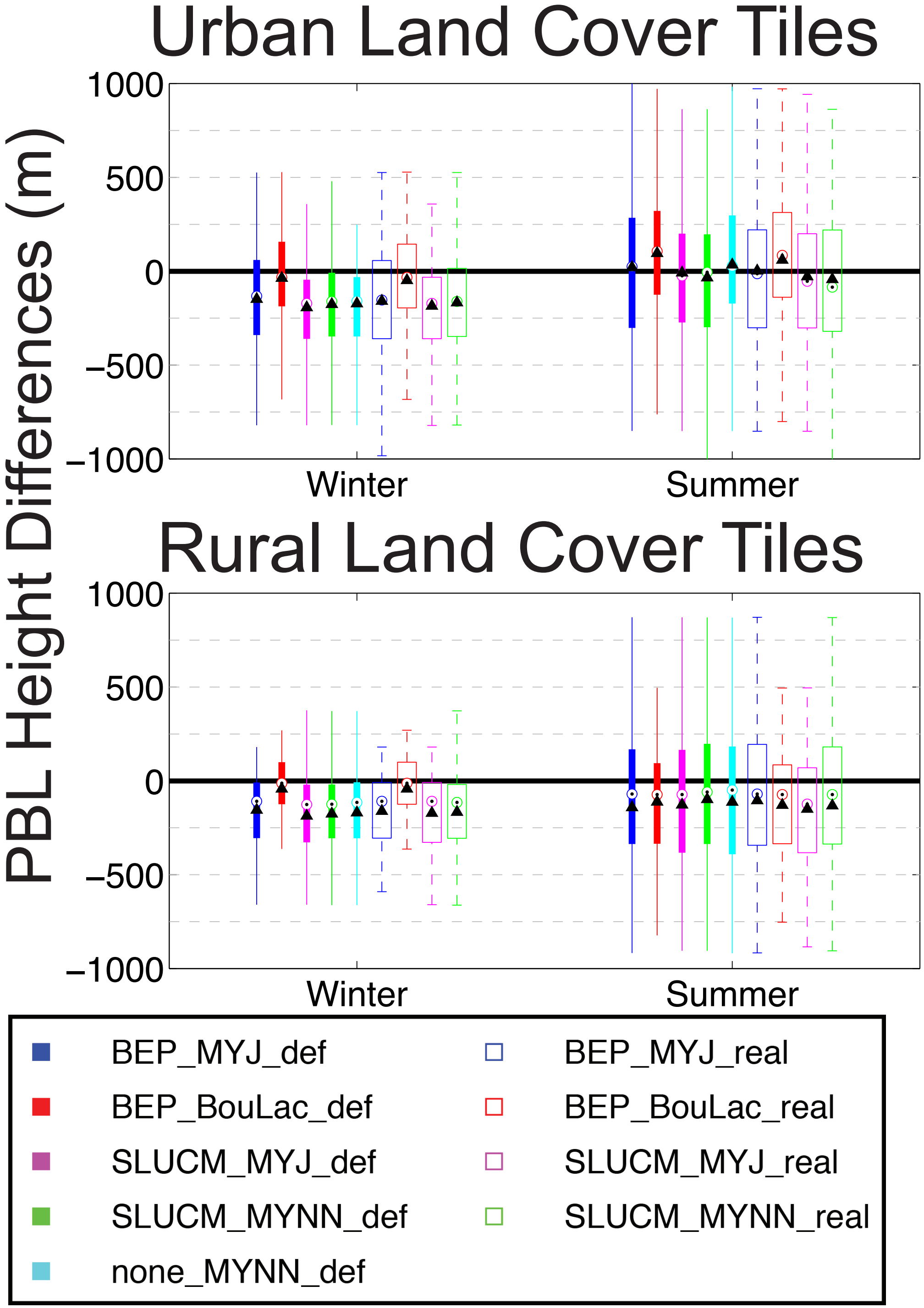


- Communications towers ~100 m AGL
- Picarro, CRDS sensors
- 12 measuring CO2, 5 with CH4, and 5 with CO

- NOAA automated flask samplers
- NOAA LIDAR
- Eddy flux at 4 towers

INFLUX WRF Grids and Landuse

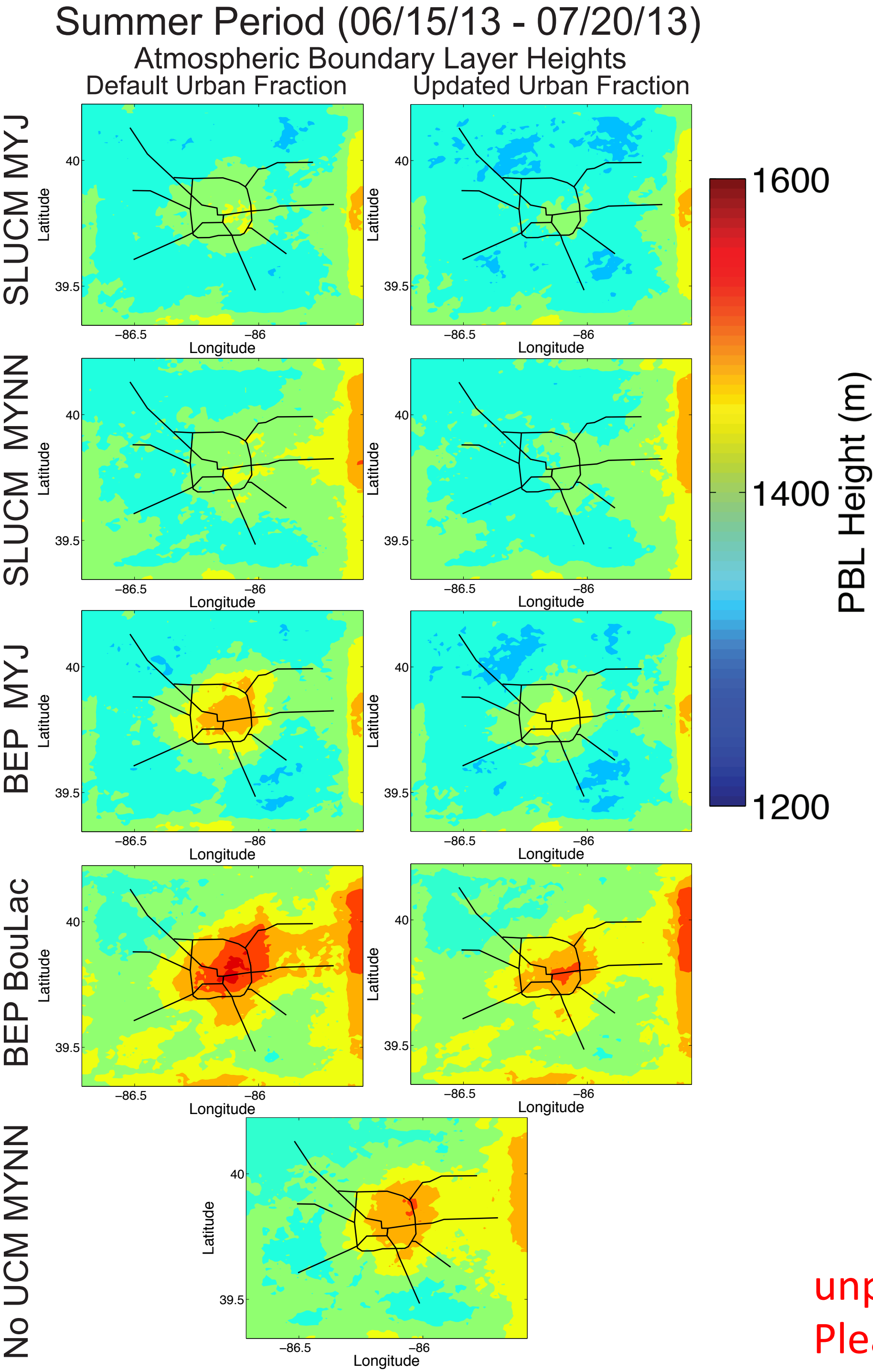




- The distributions of hourly modeled daytime errors (11am – 4pm LST) for the ABL are shown (Triangles represent the mean of the errors and the circle represents the median of the distribution). Observations were gathered using the MADIS ACARS aircraft data.
- During the winter, the BEP BouLac runs had the most accurate representation of the ABL depth when compared to other model configurations.
- There is a smaller bias in the summertime runs across all model configurations, but the spread of errors is much larger during these summertime runs.

unpublished work. (in prep).
Please treat gently.

Sarmiento



- The average daytime (11am – 4pm LST) ABL across the 1 km^2 domain.
- All runs create an urban enhanced ABL feature during the daytime hours in the summertime runs, which was not true for the wintertime runs.
- The BEP UCM enhances the urban heat island effect in the summer.

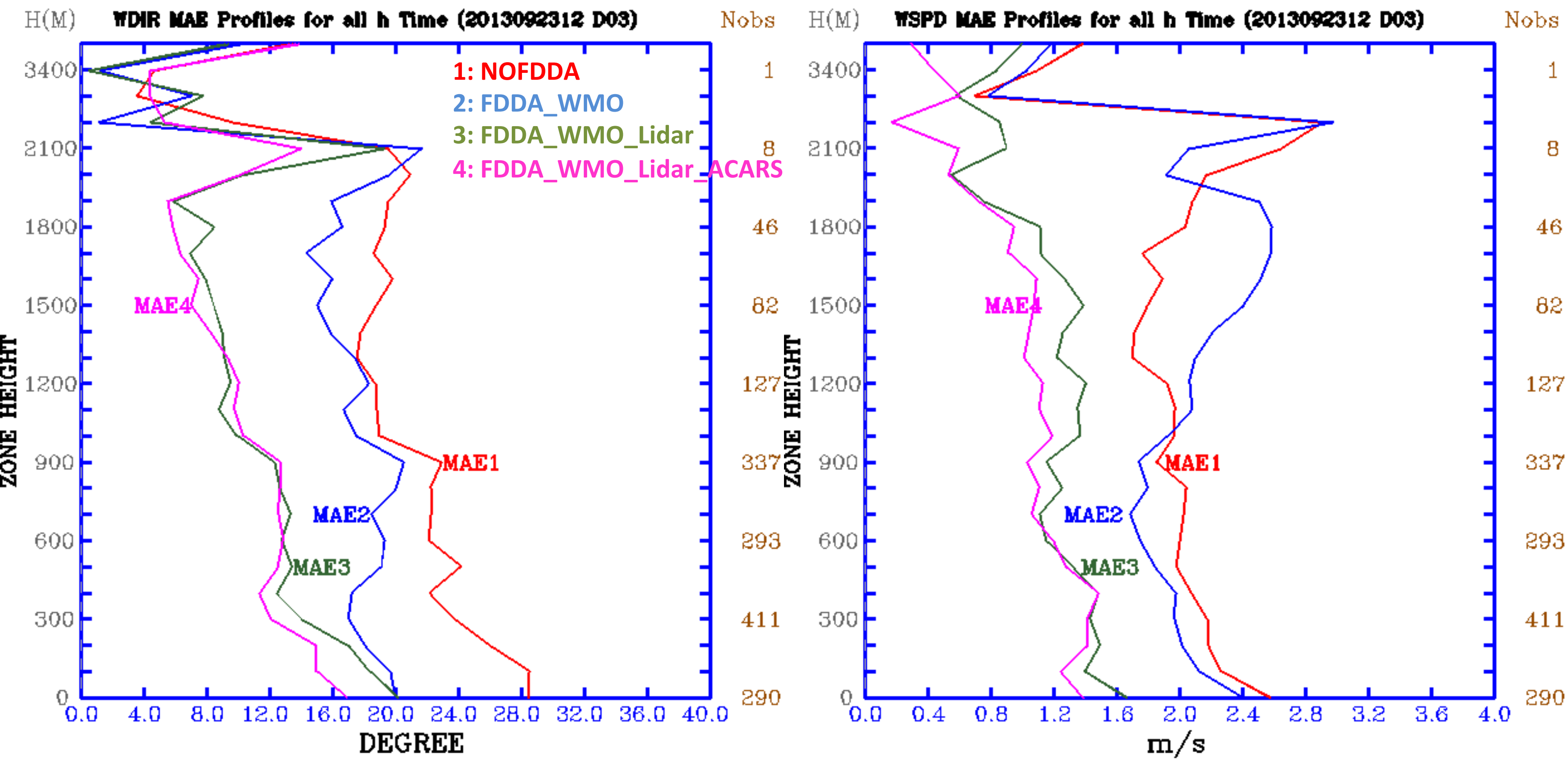
unpublished work. (in prep).
Please treat gently.

Sarmiento

WRF MAE Vertical Distribution Averaged Over the 5-day Period Ending at 12 UTC 23 Sep. 2013 on the 1-km Grid

Wind Direction MAE

Wind Speed MAE



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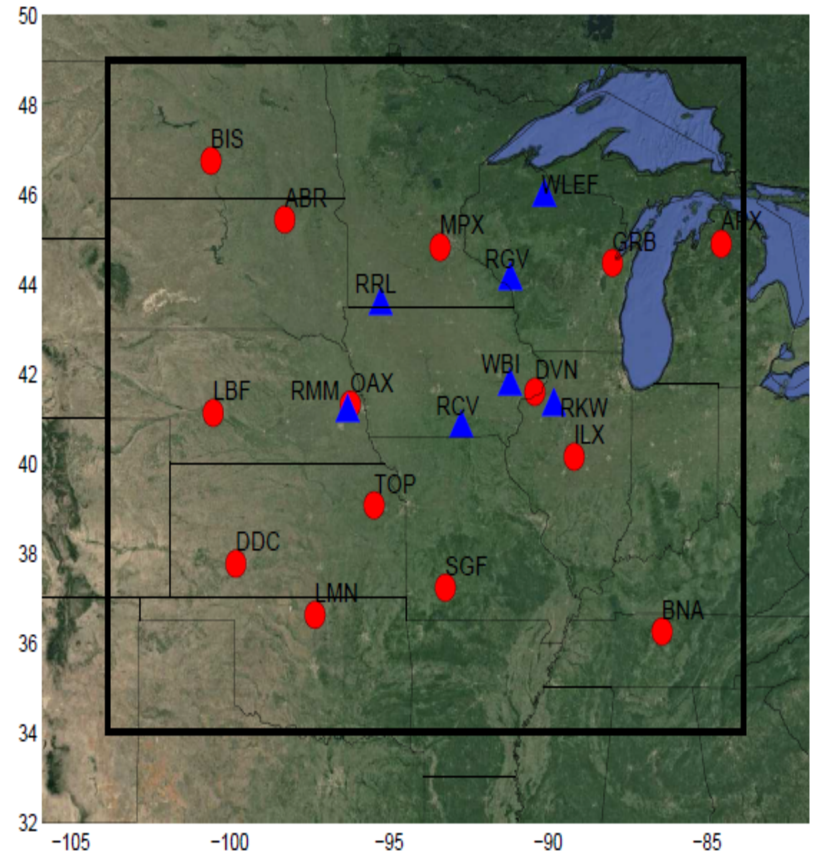
Deng

Transport Evaluation

<u>Observations:</u>

- Over the region there is a total of 14 rawinsondes (red circles).
- Some of the data that will be evaluated from these measurements are:
  1. Wind Speed (300m AGL)
  2. Wind Direction (300m AGL)
  3. PBL Depth (virtual potential temperature gradient ($\nabla\theta_v$) ≥ 0.2 K/m.)
- Rawinsondes data was evaluated at 0000UTC.
- In-situ CO_2 mixing ratio measurements (blue triangles) were evaluated from 1800 to 2200



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Diaz-Isaac

Impact of Physics Parameterization on Transport Errors

	RMSE			
	Schemes	WSPD	WDI	PBLH
LSM	Noah	3.48	53.77	821.68
	RUC	3.61	57.14	936.72
	SLAB	3.36	54.82	753.62
PBL	YSU	3.46	53.52	901.09
	MYJ	3.53	57.23	777.65
	MYNN 2.5	3.39	53.59	774.43
Cumulus	Kain-Fritsch	3.5	54.95	804.99
	Grell-3D	3.36	56.16	818.74
	No Cumulus	3.46	54.65	916.04
Micro	WSM-5class	3.44	55.03	806.93
	Thompson	3.54	55.33	810.08
Rean.	NARR	3.45	53.49	755.89
	GFS	3.41	51.56	703.14

	Bias			
	Schemes	WSPD	WDI	PBLH
LSM	Noah	0.81	-1.62	108.39
	RUC	0.71	0.01	219.4
	SLAB	0.38	1.97	96.72
PBL	YSU	0.84	1.29	381.44
	MYJ	0.54	-1.94	-67.49
	MYNN 2.5	0.51	-0.02	56.21
Cumulus	Kain-Fritsch	0.71	-0.55	86.3
	Grell-3D	0.35	-0.24	132.51
	No Cumulus	0.67	0.99	250.6
Micro	WSM-5class	0.68	-0.95	89.8
	Thompson	0.72	-0.39	104.15
Rean.	NARR	0.69	-0.78	49.37
	GFS	0.7	-1.2	12.98

- In these table we show the average of the RMSE and bias for each of the physics parameterization used to build the ensemble.
- The different selection of physics parameterization do no show any major impact in the wind speed and wind direction.
- The different land surface models (LSMs), PBL schemes and cumulus parameterizations (CPs) the we choose can have an impact of about 100 m or more in the PBL height.

unpublished work. (in prep). Please treat gently.

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