Welcome to the

CDC's Model Aquatic Health Code Network Webinar

Indoor Air Quality in Swimming Facilities: Dynamics of Gas-Phase Trichloramine

2/23/23

2:00 PM ET

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NACCHO

National Association of County & City Health Officials

Webinar Agenda

NACCHO
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- CDC Announcements
- Indoor Air Quality in Swimming Facilities: Dynamics of Gas-Phase Trichloramine
- **Questions & Answers**

CDC Announcements

CDR Joe Laco, MSEH, REHS/RS, CPO
Environmental Health Scientist, National Center for Environmental Health
Centers for Disease Control and Prevention (CDC)

Today's Presenter

NACCHO
National Association of County & City Health Officials

Ernest R. Blatchley III, Ph.D, P.E., BCEE, F. ASCE

Lee A. Rieth Professor in Environmental Engineering
Lyles School of Civil Engineering and Division of Environmental & Ecological Engineering, Purdue University

Dynamics of Gas-Phase NCl_3 in Indoor Pool Facilities

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Presented to: Model Aquatic Health Code Webinar
23 February 2023

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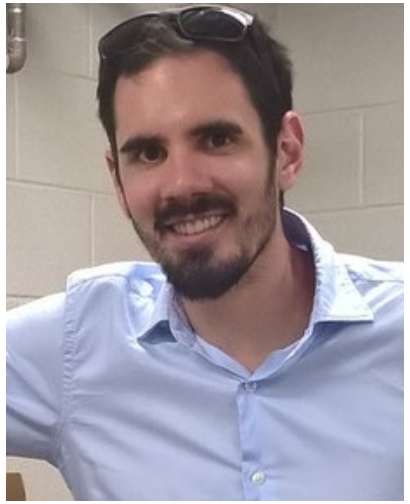
LYLES SCHOOL OF CIVIL ENGINEERING

PURDUE UNIVERSITY
Environmental and Ecological Engineering

Collaborators

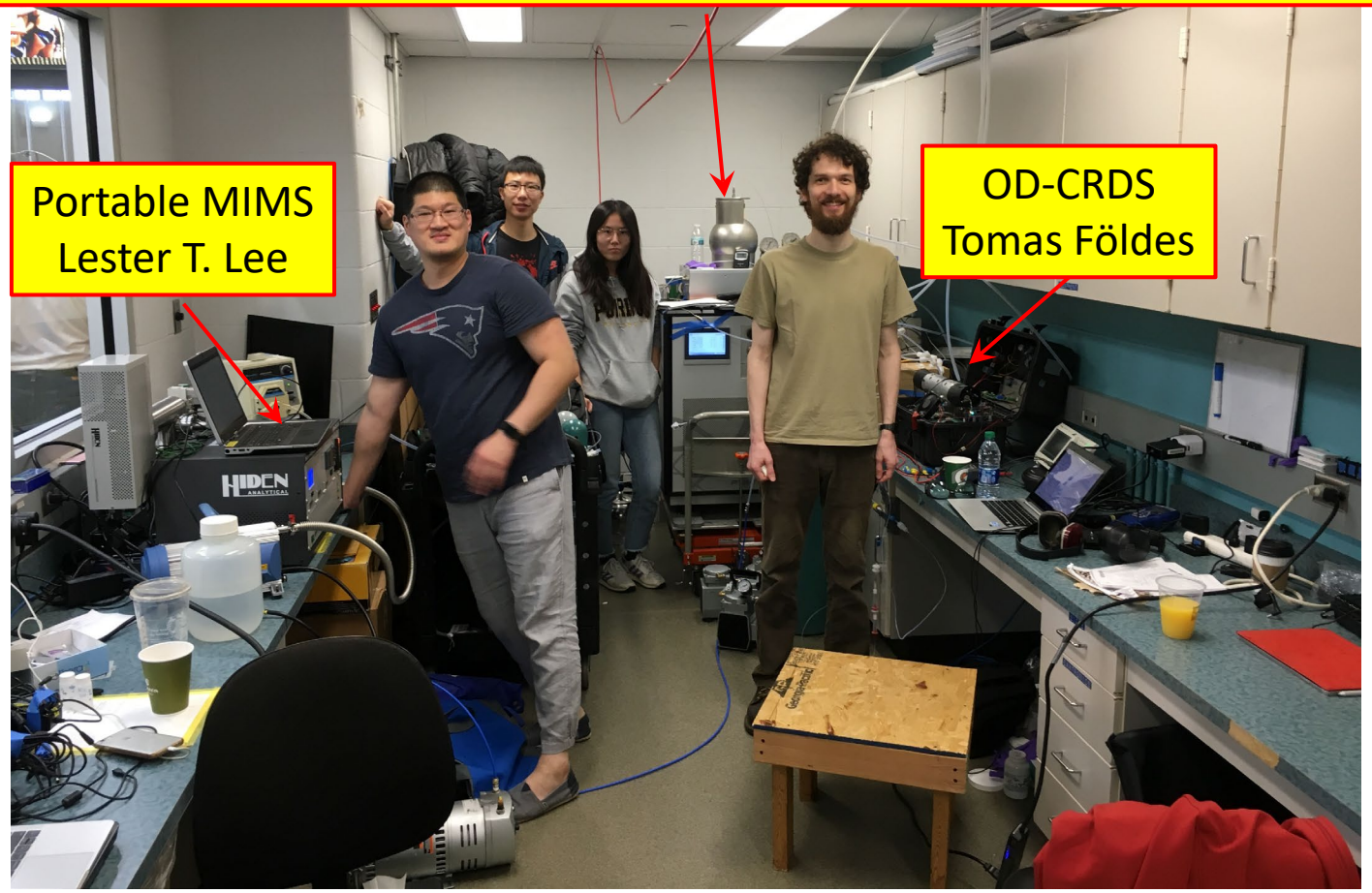


Brandon E. Boor

Danielle N. Wagner

Antonios Tasoglou

Proton Transfer Reaction Time-of-Flight Mass Spectrometer (PTR-TOF-MS)
Tianren Wu and Jinglin Jiang



NCl_3 and its Roles

- Sentinel compound for IAQ in indoor pools
- Produced by reactions between free chlorine and reduced-N
  - Urea
  - Uric acid
  - Creatinine
  - Amino acids
- 'Chlorine' odor (along with CH_3NCl_2)
- Irritation of human tissues
  - Respiratory system
  - Eyes
  - Skin
- Corrosion

From: http://lovelandpolitics.com/chloramineillness.html

Photo From PoolPak

From: http://www.wbur.org/onpoint/2016/10/18/new-science-on-gut-bacteria-and-allergies

Volatile Compounds in Pools

- Volatility = ability to transfer from liquid phase to gas phase
- Volatile compounds in water will affect indoor air quality (IAQ)
- Henry's law constant (H) is a measure of volatility
  - Highly volatile compounds have a large value of H
  - Less volatile compounds have smaller values of H
- For compounds with large H ($H \gtrsim 10 - 50\ atm$), the physics of liquid $\rightarrow$ gas transfer are essentially identical
  - Largely governed by mixing of water in near-surface areas

Compound	Chemical Formula	H (atm)
Trichloramine	NCl_3	552
Chloroform	$CHCl_3$	218
Dichloromethylamine	CH_3NCl_2	166
Cyanogen Chloride	CNCl	46
Cyanogen (?)	NCCN	303
Hypochlorous Acid	HOCl	0.060
Hypochlorite Ion	OCl^-	~ 0
Carbon Dioxide	CO_2	1655

Henry's Law Constants from:
http://satellite.mpic.de/henry/convert.html?csrfmiddlewaretoken=BFrDtNYbMhYrOnM9JtuMC80xQA7GhuSk4cssqTxIxrkVBHbeoGoatpMjdEYNptDn&x=0&y=0&Hval=.00033&Htype=HcpSI

Central Hypothesis

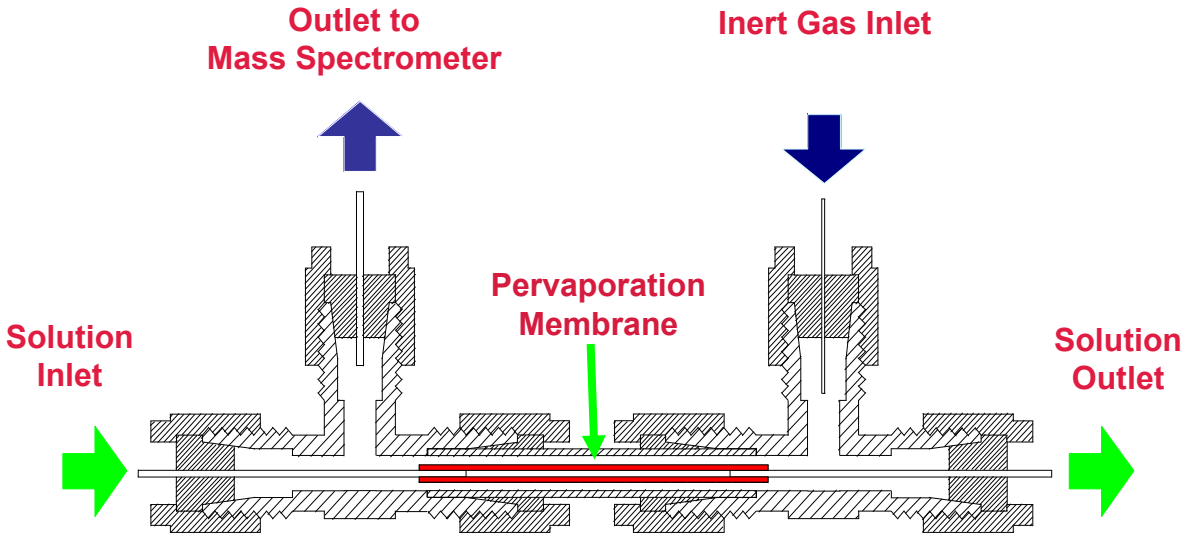
With all other conditions being constant, the worst air quality in an indoor pool facility will occur during times of heaviest bather loading.

- Experiments
  - Measure water chemistry, air chemistry before, during, after periods of normal use, heavy use (lap swimming, competition pools)
  - Quantify other factors that affect IAQ (e.g., HVAC system characteristics, pool operations, number of swimmers, etc.)
- Numerical Simulations
  - Mass-balance approach
  - Two-film theory used to account for liquid $\rightarrow$ gas transfer
  - Used to simulate (predict) IAQ dynamics
- Three-Phase Project
  - Phases I and II: Competition pools in upper-Midwest of US (complete)
  - Phase III: Other geographic areas, other facility types (planned)

- Methods and materials
  - MIMS ($NCl_{3\,(aq)}$ and other volatile DBPs)*
  - Alkalinity and pH → $CO_{2\,(aq)}$
  - NEMo
    - $NCl_{3\,(g)}$
    - RH
    - $CO_{2\,(g)}$
  - OD-CRDS ($NCl_{3\,(g)}$)
  - PTR-TOF-MS
  - LiCor LI-830 ($CO_{2\,(g)}$)

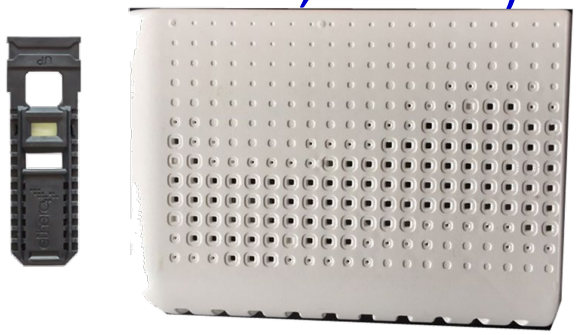
    Available for only one experiment
  - Number of swimmers
  - number of other pool patrons
  - Air flow (HVAC)
- Focus on NCl_3 and CO_2
- Venues
  - Indiana and Michigan
    - 5 experiments at a university pool in Indiana
    - 1 experiment at a HS pool in Indiana
    - 2 experiments at university pools in Michigan
  - Lap pools
  - Before, during, after heavy use (competition)

Membrane Introduction Mass Spectrometry (MIMS)



Liquid-Phase Volatile DBPs (grab samples)

NEMo (Ethera Labs Crolles, France)

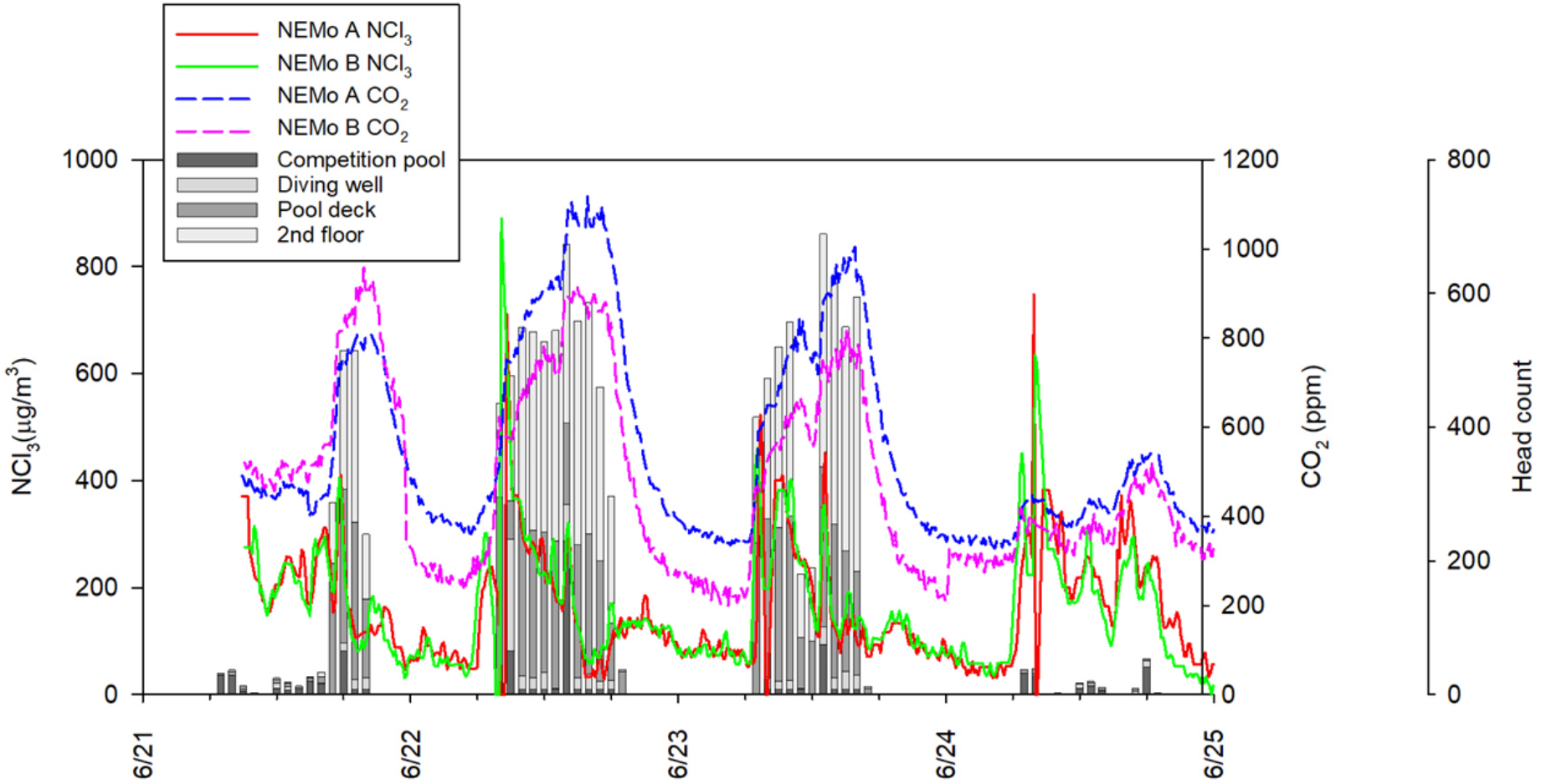


Gas-Phase NCl_3 (real time)

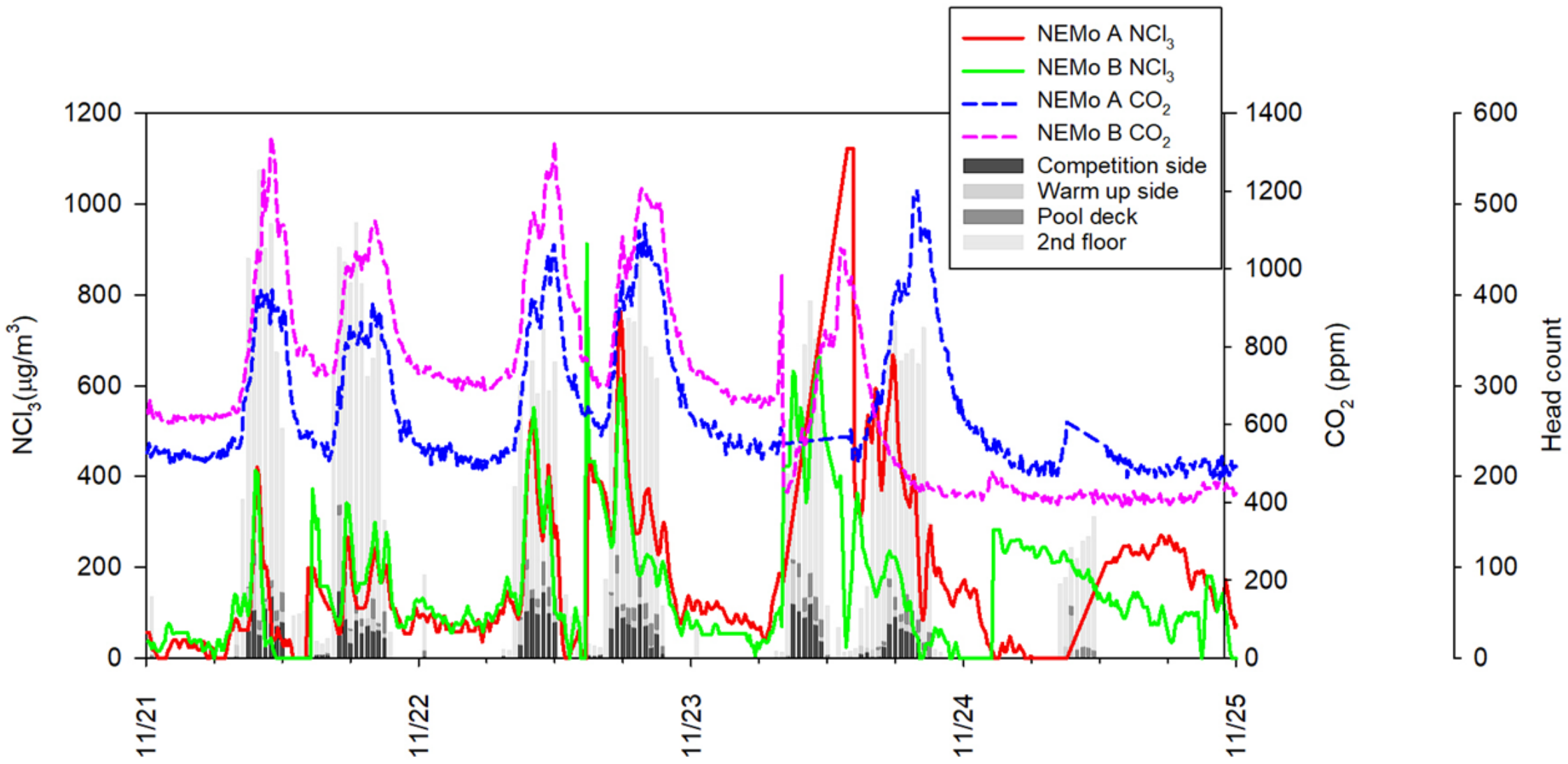
Li-COR LI-830 Lincoln, NE

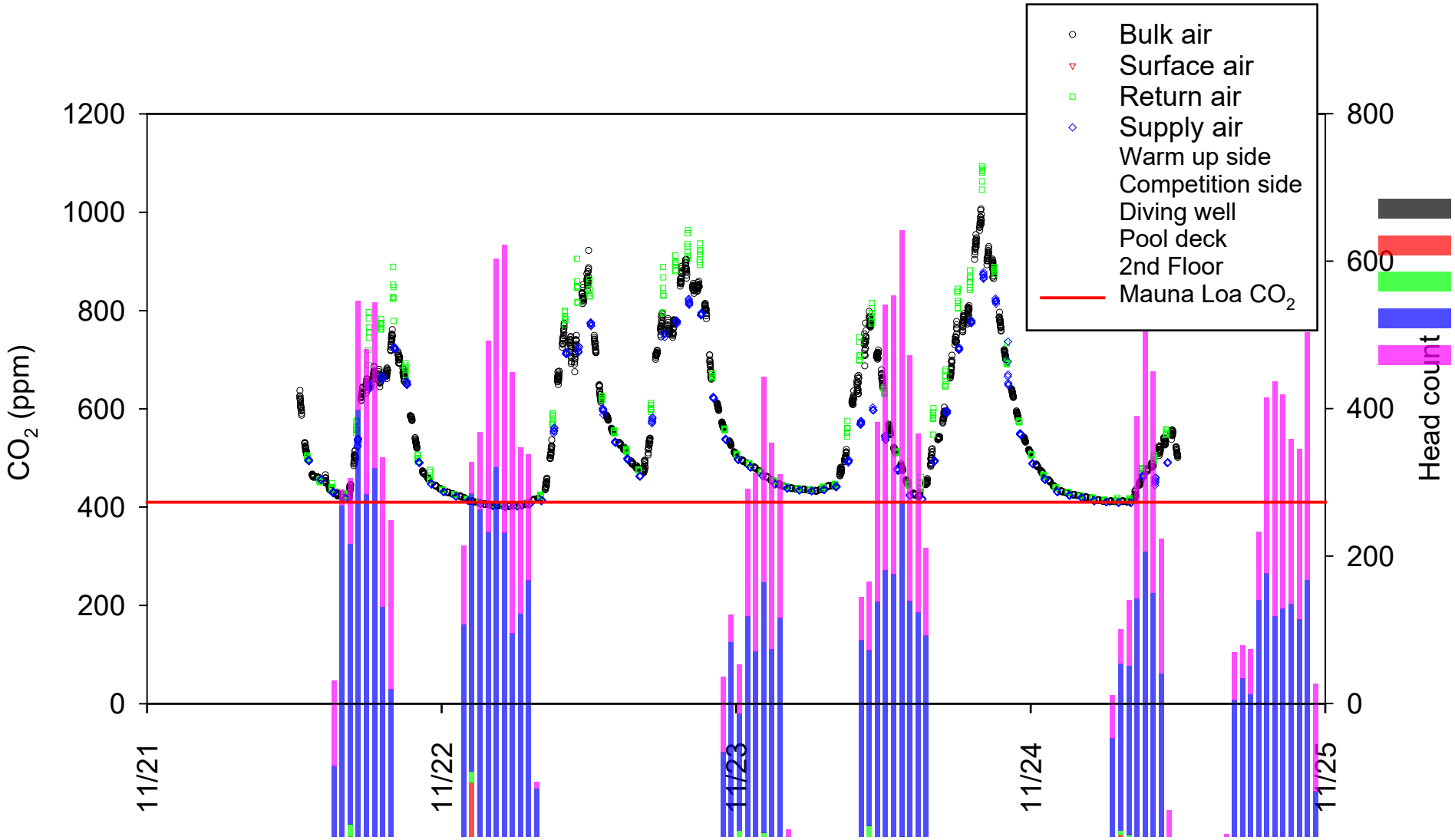
Gas-phase CO_2 (real time)

Facility/Trial	Number of pools in facility	Pool dimensions	Chlorination method	UV	pH control	Types of swimmers	Age groups of swimmers
B Feb	2	50 meter × 25 yard (Competition & warm-up) 25 yard × 20 yard (Diving well and warm-up)	Calcium hypochlorite	Y	CO_2 or Muriatic acid (HCl)	Swimming meet	14 and under (no swimmer counts)*
B Mar						daily lap swimmers and swim team practice	Adults and College students
B April						daily lap swimmers and swim team practice	Adults and College students
B June						Swimming meet	8 and under
B Nov						Swimming meet	Adults and College students
C	1	50 meter × 25 yard	Sodium hypochlorite	Y	Muriatic acid (HCl)	Swimming meet	13 to 18
D	1	50 meter × 25 yard	Sodium hypochlorite	Y	Sodium bisulfate	Swimming meet	14 and under
E	1	15 yard × 40 yard	Calcium hypochlorite	Y	CO_2	daily lap swimmers, swim team practice, and swimming meet	Adults and College students

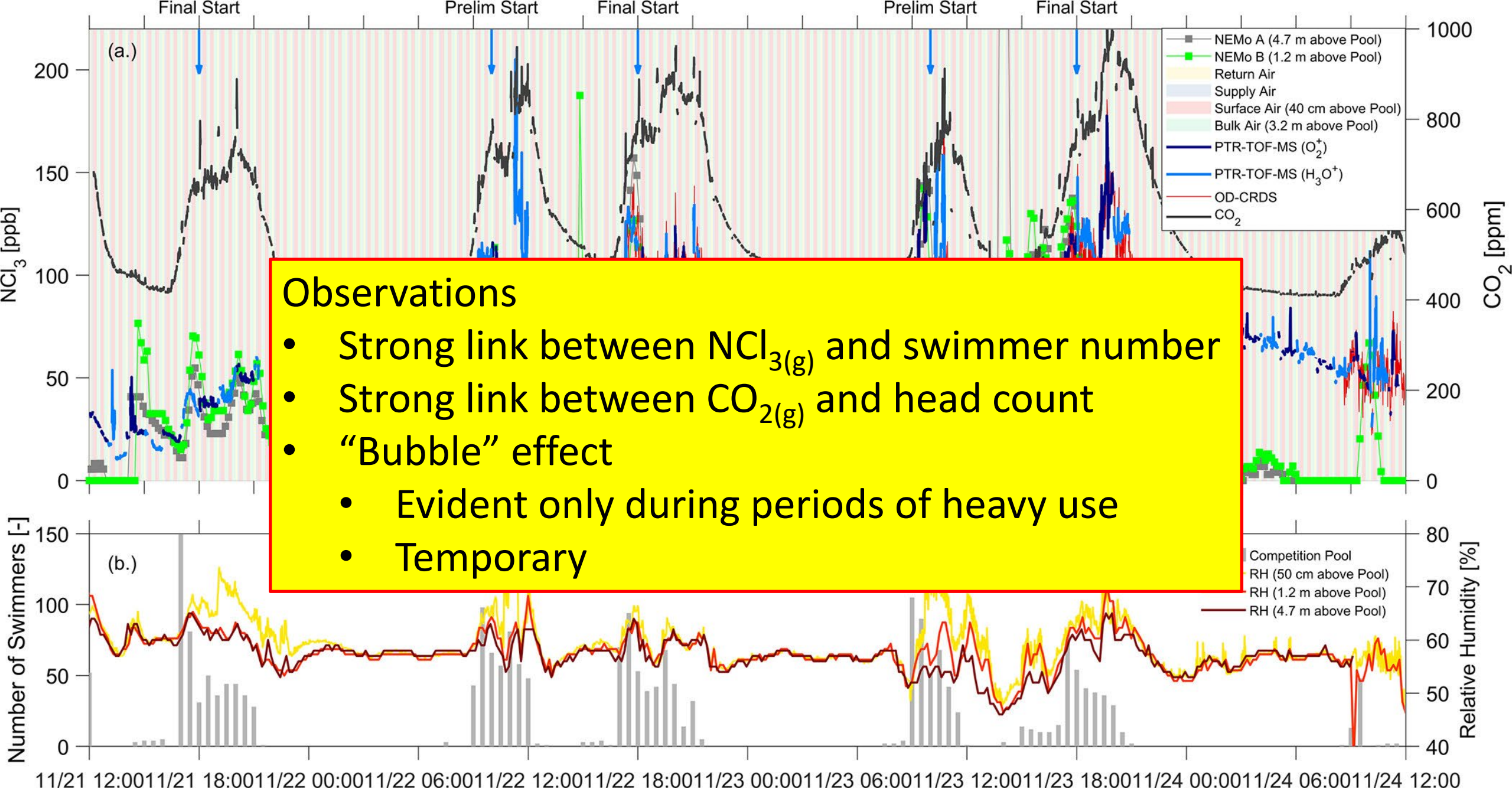


- Facility B, 8-under swimming meet (~350 swimmers)
- Time-course patterns of $NCl_{3(g)}$ and $CO_{2(g)}$ are similar
- Both linked to swimmer count
- $CO_{2(g)}$ as high as ~1100 ppm_v; probably influenced by swimmers and non-swimmers
- $CO_{2(g)}$ returned to ambient concentration during idle times
- NEMo B out of calibration, but qualitatively consistent with NEMo A


NEMo A NCl3
NEMo B NCl3
NEMo A CO2
NEMo B CO2
Competition side
Warm up side
Pool deck
2nd floor
NCl3(μg/m3)
CO2 (ppm)
Head count
1200
1000
800
600
400
200
0
1400
1200
1000
800
600
400
200
0
600
500
400
300
200
100
0
11/21
11/22
11/23
11/24
11/25

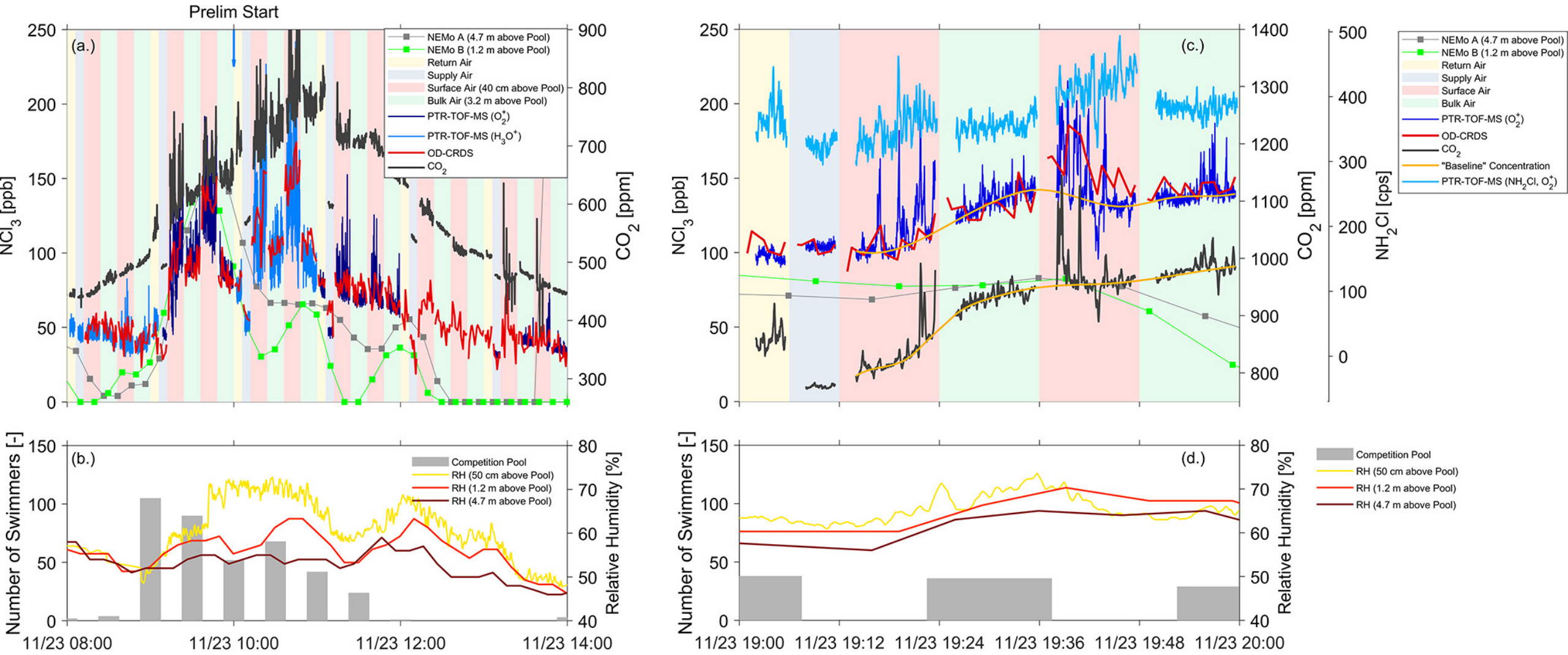


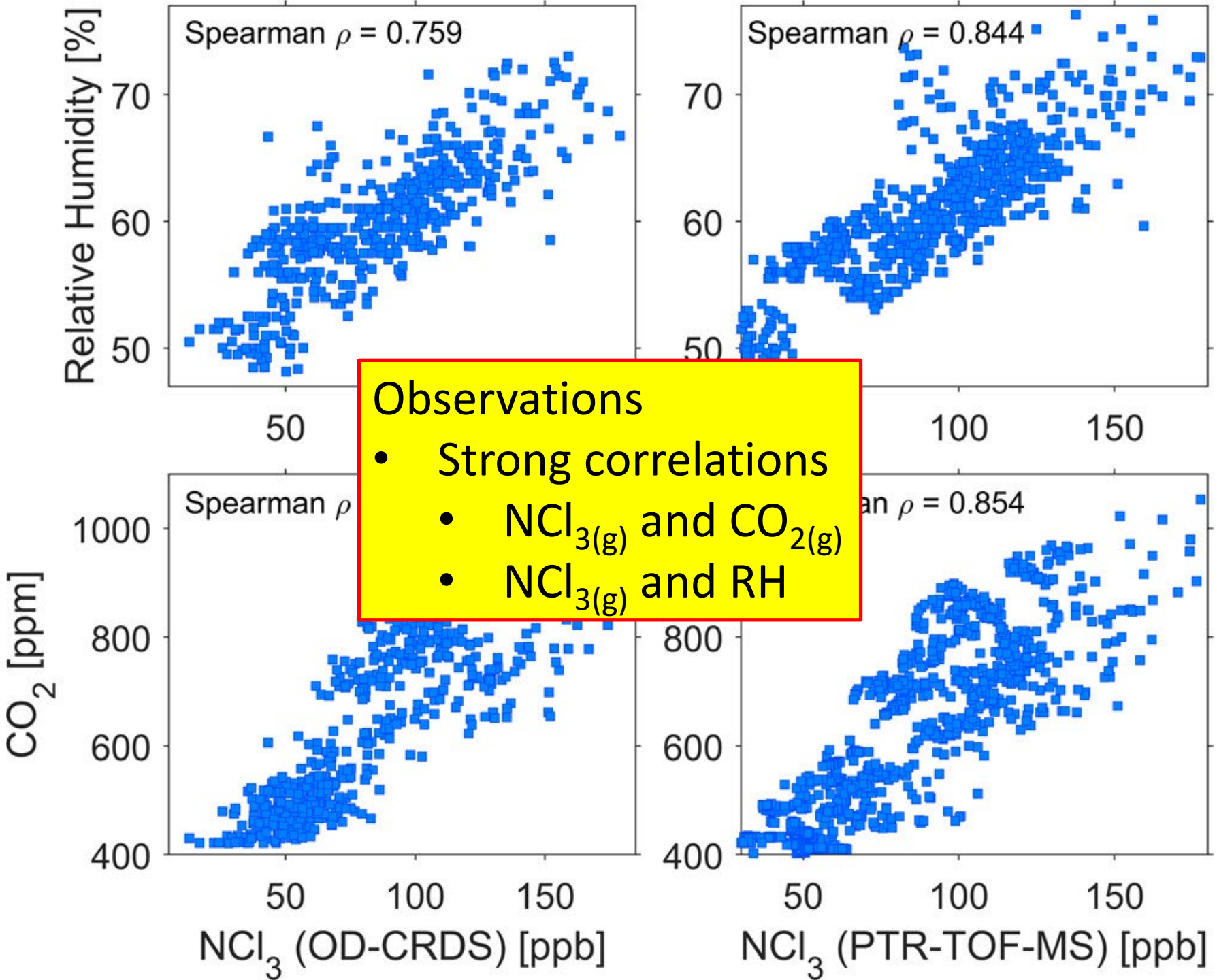
This analyzer was coupled with an automated switching valve system that connected Teflon tubing to 4 sampling locations including bulk air, surface air, supply air, and return air. Samples of Bulk air were collected from 3.2 meters above the pool deck and 0.5 meters away from pool surface. Samples of surface air were collected from 0.4 meters above pool deck and 0.5 meters away from pool surface. Samples of supply air were collected from one HVAC unit. Samples of return air were measured from a return air grille.



Observations

- Strong link between $NCl_{3(g)}$ and swimmer number
- Strong link between $CO_{2(g)}$ and head count
- "Bubble" effect
  - Evident only during periods of heavy use
  - Temporary


Prelim Start
(a.)
NEMo A (4.7 m above Pool)
NEMo B (1.2 m above Pool)
Return Air
Supply Air
Surface Air (40 cm above Pool)
Bulk Air (3.2 m above Pool)
PTR-TOF-MS (O_2^+)
PTR-TOF-MS (H_3O^+)
OD-CRDS
CO_2
NCl_3 [ppb]
CO_2 [ppm]
(b.)
Competition Pool
RH (50 cm above Pool)
RH (1.2 m above Pool)
RH (4.7 m above Pool)
Number of Swimmers [-]
Relative Humidity [%]
11/23 08:00
11/23 10:00
11/23 12:00
11/23 14:00
(c.)
Surface Air
OD-CRDS
"Baseline" Concentration
PTR-TOF-MS (NH_2Cl, O_2^+)
NH_2Cl [cps]
(d.)
11/23 19:00
11/23 19:12
11/23 19:24
11/23 19:36
11/23 19:48
11/23 20:00



Observations

- Strong correlations
  - $NCl_{3(g)}$ and $CO_{2(g)}$
  - $NCl_{3(g)}$ and RH

Lessons Learned From Field Experiments

- IAQ in indoor swimming facilities is affected by:
  - Water chemistry (swimmer hygiene, water treatment, pH, alkalinity)
  - Swimmer number, activity
  - HVAC system characteristics
- Strong link between swimmer number and IAQ
  - Gas-phase NCl_3 concentration is strongly influenced by swimmer activity
  - Physics responsible for NCl_3 transfer are essentially identical to those responsible for other volatile compounds (DBPs, CO_2)
  - CO_2 may represent a viable surrogate for NCl_3
  - CO_2 dynamics are influenced by
    - Respiratory activity of swimmers and non-swimmers
    - Concentration in ambient air (Mauna Loa or local CO_2 monitoring)

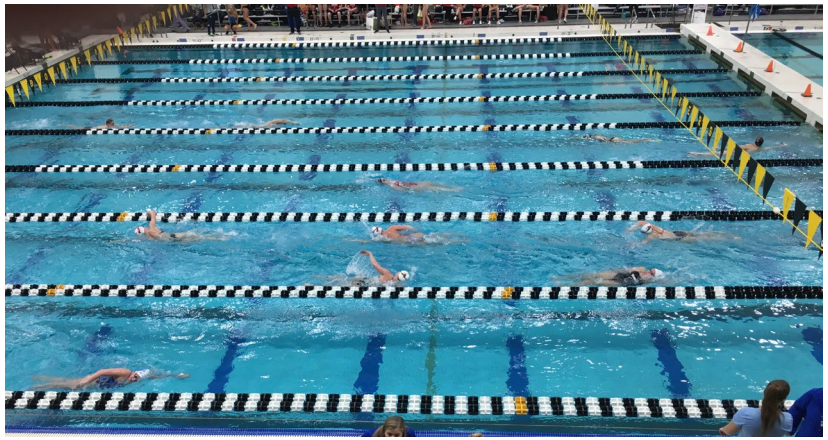
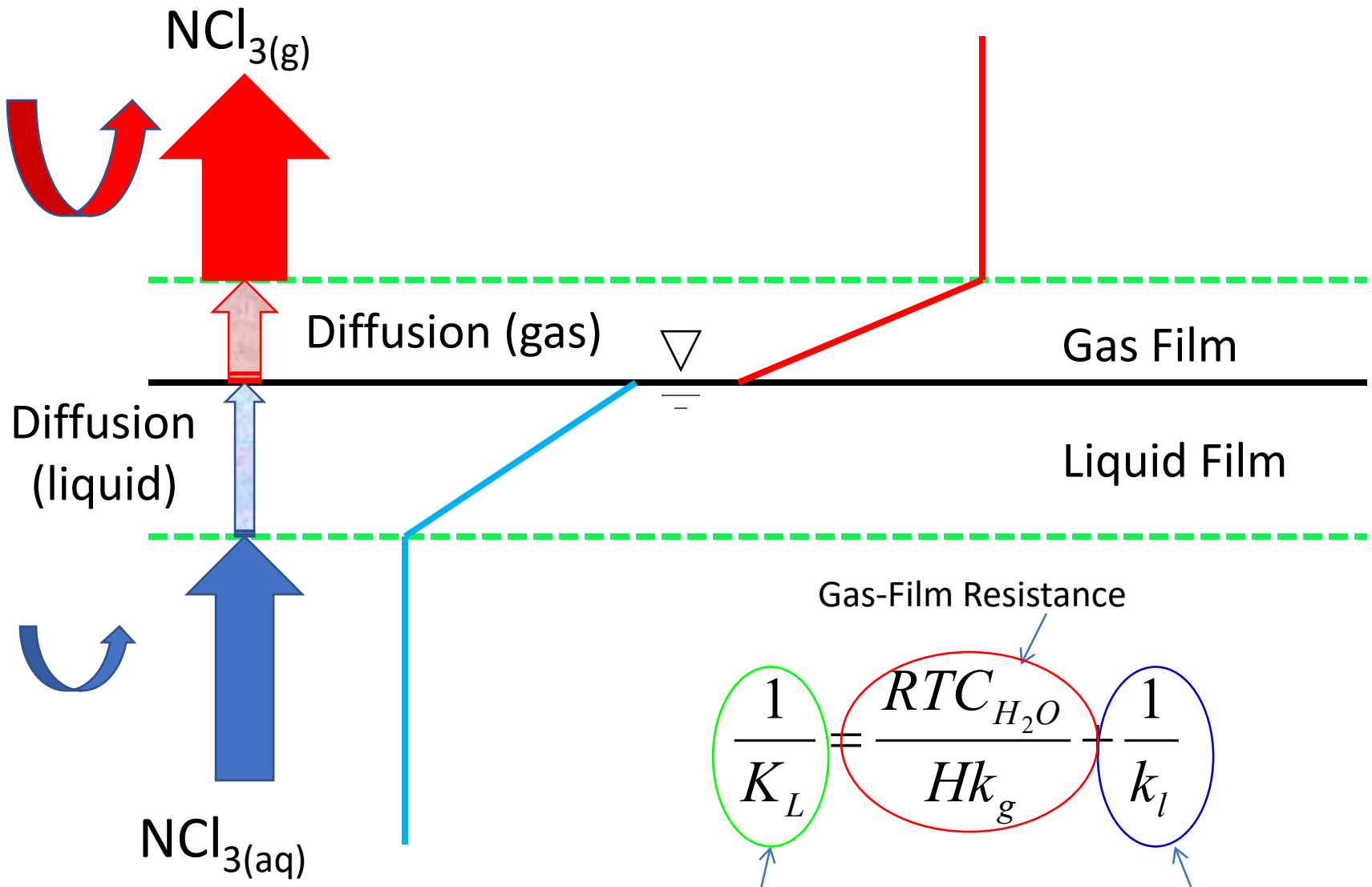


Image from: https://mommypoppins.com/houston-kids/best-indoor-waterparks-in-texas

Image from: https://research.noaa.gov/article/ArtMID/587/ArticleID/1502/Carbon-Dioxide-at-NOAA%E2%80%99s-Mauna-Loa-Observatory-reaches-new-milestone-Tops-400-ppm

Gas-Liquid Transfer: Two-Film Model



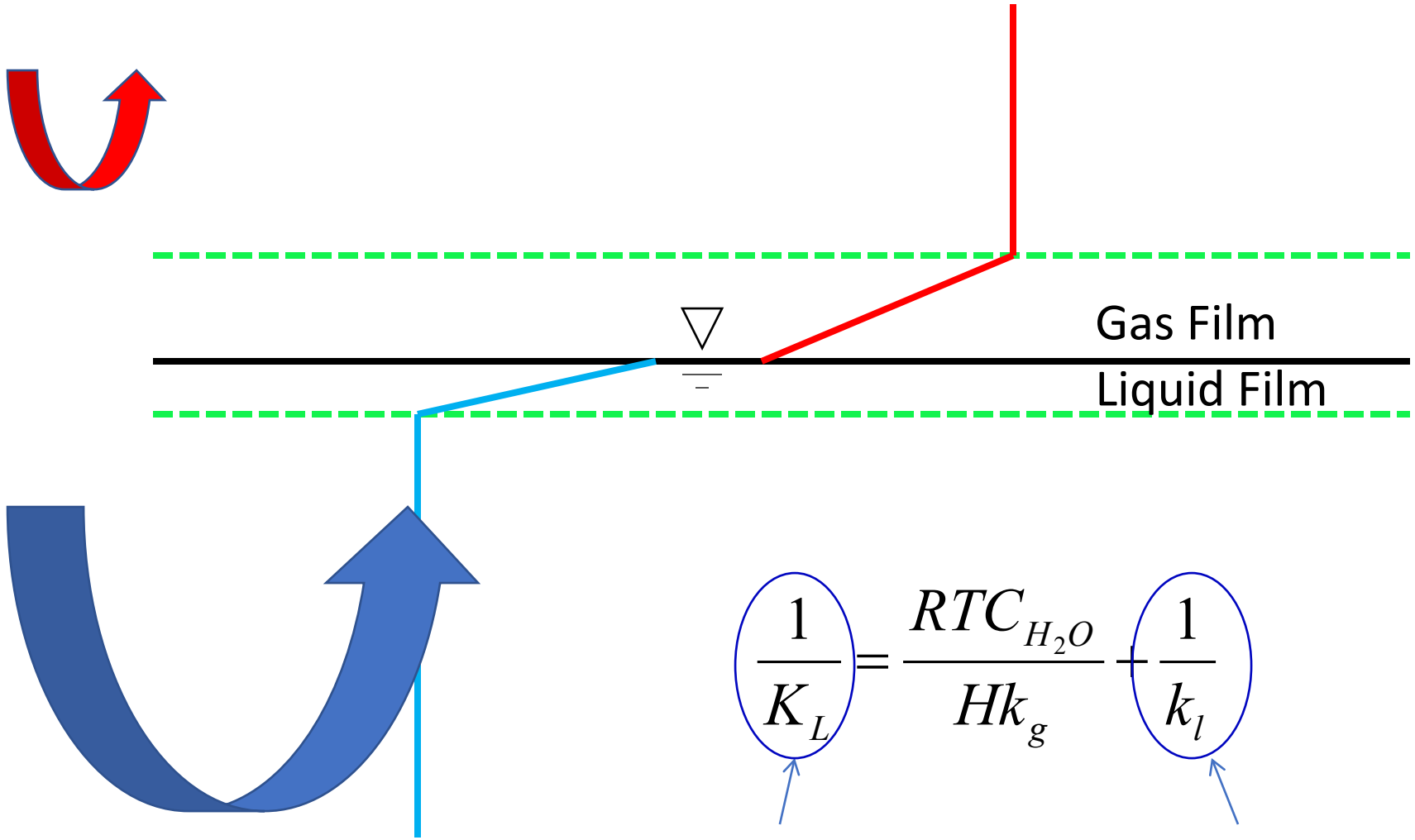
Gas-Film Resistance

$$\frac{1}{K_L} = \frac{RTC_{H_2O}}{Hk_g} + \frac{1}{k_l}$$

Overall Resistance

Liquid-Film Resistance

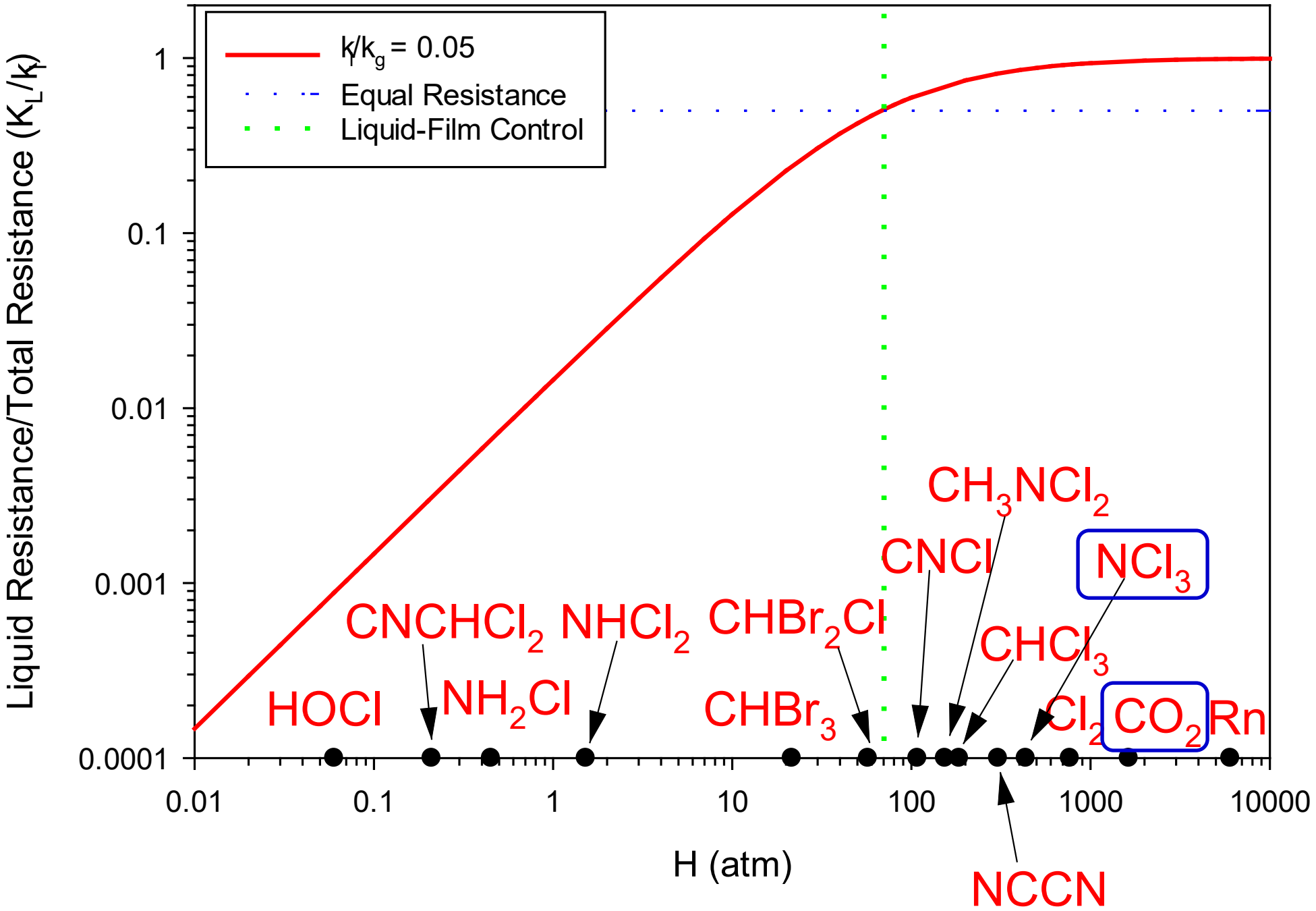
Gas-Liquid Transfer: Two-Film Model



$$\frac{1}{K_L} = \frac{RTC_{H_2O}}{Hk_g} + \frac{1}{k_l}$$

Overall Resistance

Liquid-Film Resistance

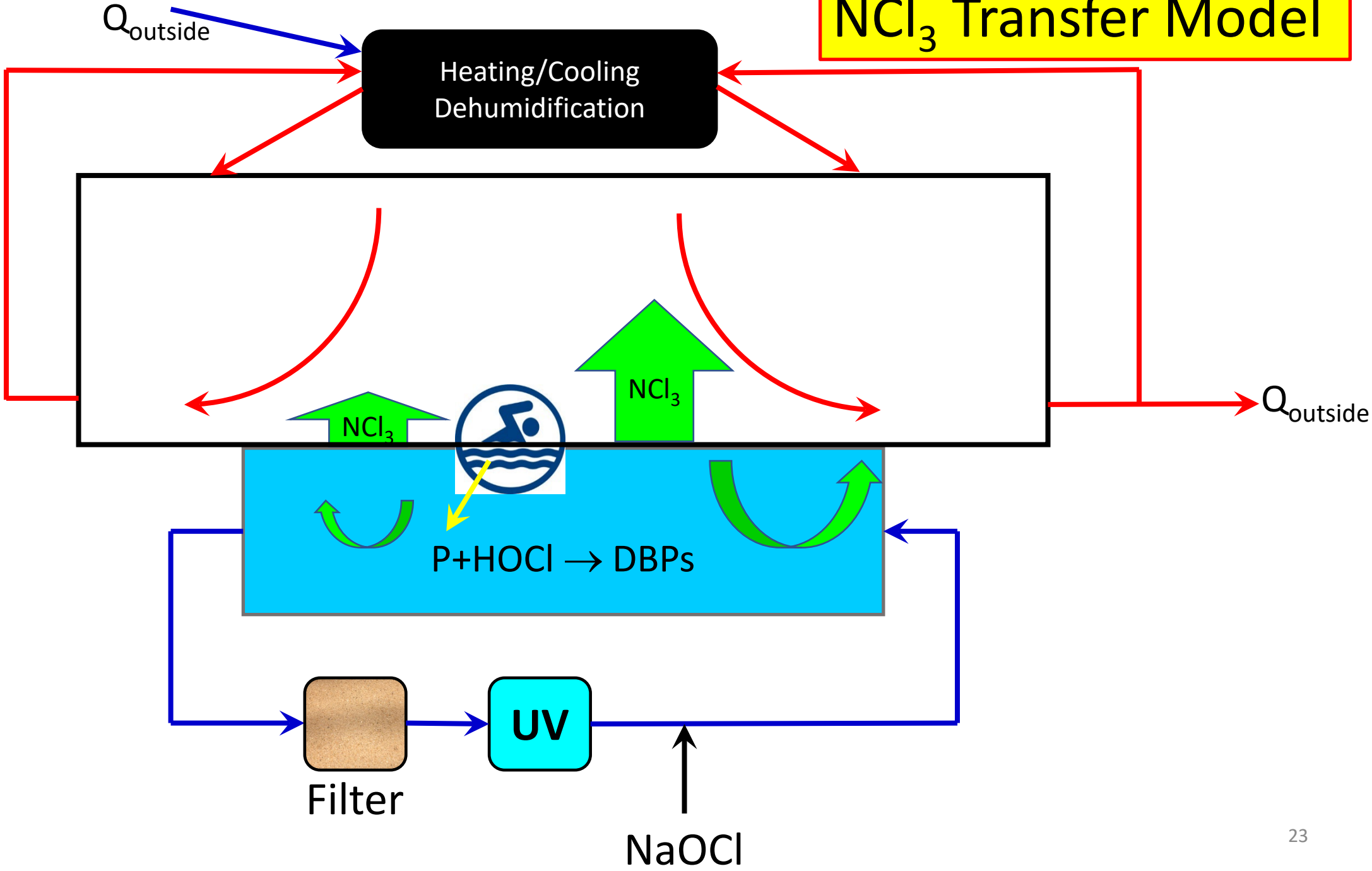

k_l/k_g = 0.05
Equal Resistance
Liquid-Film Control
Liquid Resistance/Total Resistance (K_L/k_l)
1
0.1
0.01
0.001
0.0001
0.01
0.1
1
10
100
1000
10000
H (atm)
HOCl
$CNCHCl_2$
NH_2Cl
$NHCl_2$
$CHBr_3$
$CHBr_2Cl$
CNCl
CH_3NCl_2
$CHCl_3$
NCl_3
Cl_2
CO_2
Rn
NCCN

Compound	Typical Liquid-Phase Concentration (mg/L)	Henry's Law Constant (atm)	Equilibrium Gas-Phase Concentration (mg/m³)	Reported Gas-Phase Concentration (mg/m³)
HOCl	1.2	0.060	0.053	N.A
Cl_2	0.000012	767	0.0067	N.A
NH_2Cl	0.30	0.45	0.10	N.A
$NHCl_2$	0.10	1.52	0.11	N.A
NCl_3	0.10	435	23	0.1-1.0
$CHCl_3$	0.080	185	11	0.009-0.058
$CHBr_2Cl$	0.0040	57.3	0.17	0.002-0.003
$CHBr_3$	0.0010	21.5	0.016	0.0008
CNCl	0.0030	108	0.24	N.A
$CNCHCl_2$	0.00080	0.21	0.00013	N.A
CH_3NCl_2	0.020	154	2.3	0.016-0.07

Observations

- Several DBPs have large values of H
- Physics of liquid→gas DBP transfer will be similar
- Observed gas-phase concentration ~1% of equilibrium value
- Air never approaches equilibrium with water for DBPs

NCl_3 Transfer Model



IAQ Model: NCl_3

$$\forall_g \frac{dC_g}{dt} = Q_g \cancelto{0}{C_{g,in}} - Q_g C_g + \Phi_B + \sum_{i=1}^{n} \Phi_{S,i}$$

- $\forall_g$ = volume of gas phase (air volume in indoor pool facility)
- C_g = concentration of contaminant (NCl_3) in air space, and leaving air space
- t = time
- Q_g = volumetric flow rate of air into (and out of) the air space
- $C_{g,in}$ = concentration of contaminant (NCl_3) in outside air entering the air space (assumed to be zero)
- Φ_B = (net) rate of mass transfer of contaminant (NCl_3) from liquid→gas under baseline conditions
- $\Phi_{S,i}$ = (net) rate of mass transfer of contaminant (NCl_3) from liquid→gas attributable to i^{th} swimmer
- n = number of swimmers

Φ_B and $\Phi_{s,i}$: NCl_3

Φ_B = (net) rate of mass transfer of contaminant (NCl_3) from liquid→gas under baseline conditions

- Two-film theory:

$$\Phi_B = K_l A(C_l - C_l^*)$$

- Where:

K_l = mass transfer coefficient (based on liquid-phase concentration)

A = pool surface area

C_l = liquid-phase concentration

C_l^* = liquid-phase concentration that would be in equilibrium with air

- But $C_l \gg C_l^*$
- Therefore:

$$\Phi_B \approx K_l A C_l$$

$\Phi_{S,i}$ = (net) rate of mass transfer of contaminant (NCl_3) from liquid→gas attributable to ith swimmer

- Two-film theory:

$$\Phi_{S,i} = K_{l,i} A_i (C_l - C_l^*)$$

- Where:

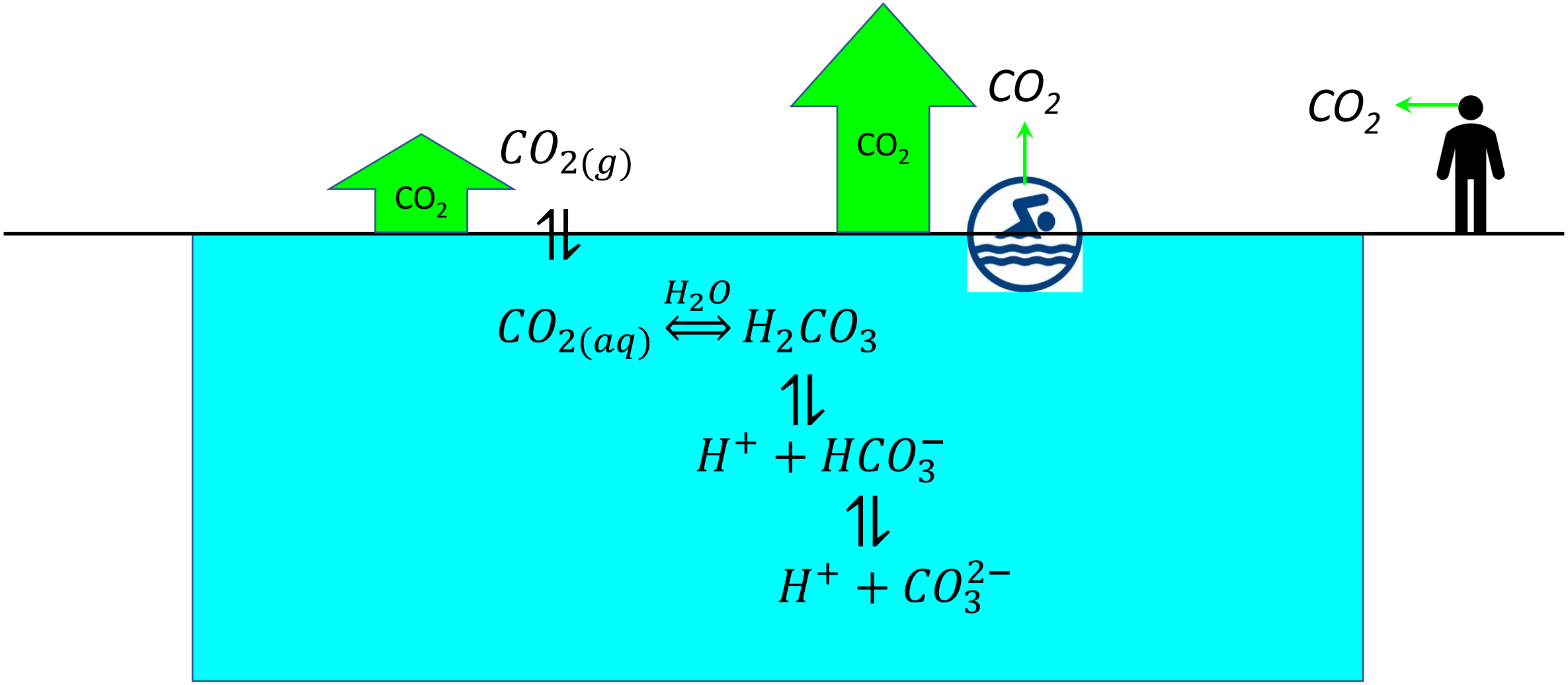
$K_{l,i}$ = overall mass-transfer coefficient based on liquid phase measurements for the ith swimmer

A_i = area disturbed by the ith swimmer

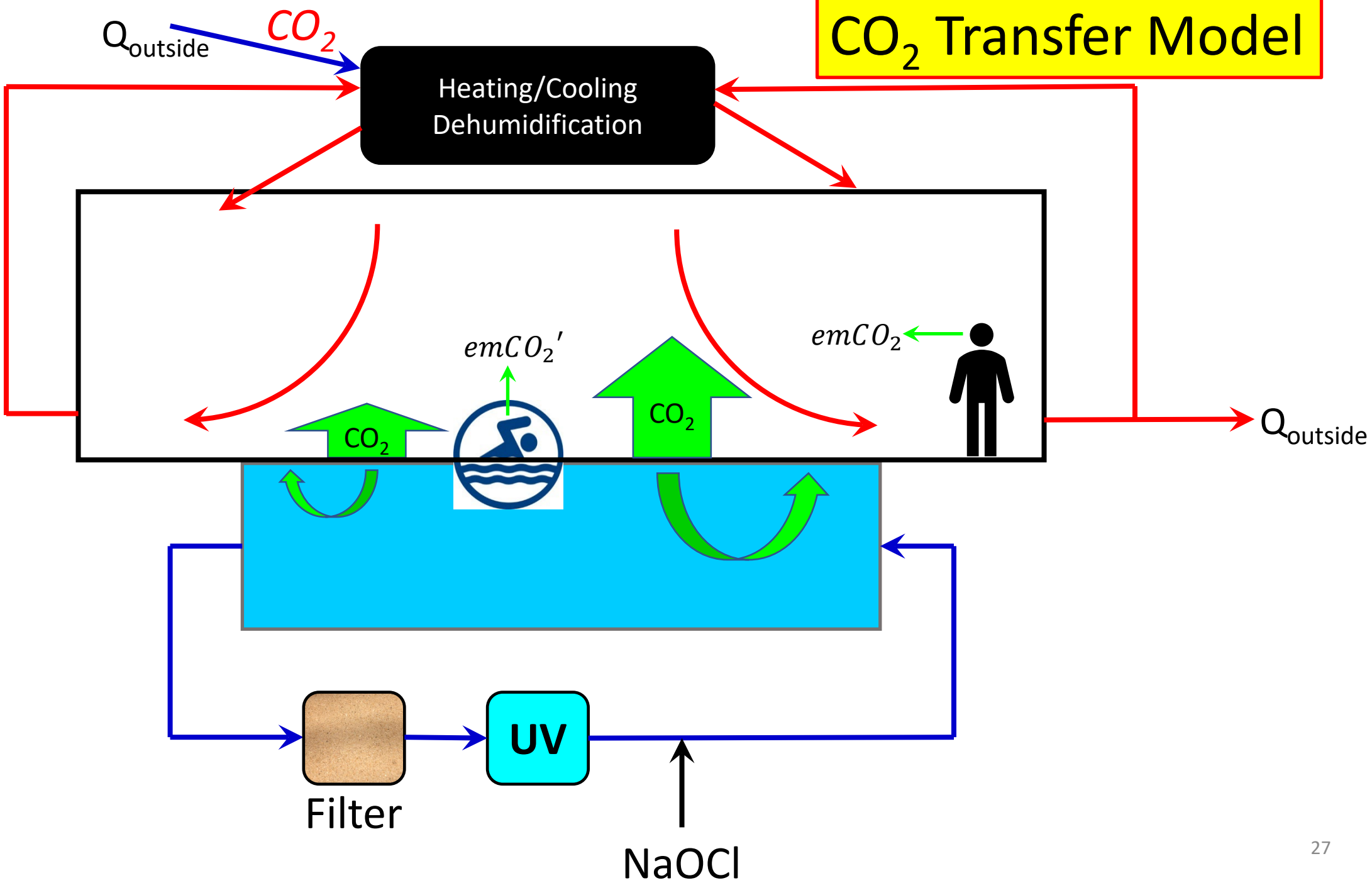
- But $C_l \gg C_l^*$ and $K_{l,i}$, A_i are difficult to measure independently
- Therefore:

$$\Phi_S = \sum_{i=1}^{n} K_{l,i} A_i C_l = n K_l' C_l$$

CO_2 Transfer Model, Aquatic Chemistry



CO_2 Transfer Model



IAQ Model: CO_2

$$\forall_g \frac{dC_g}{dt} = Q_g C_{g,in} - Q_g C_g + \Phi_B + \sum_{i=1}^{n} \Phi_{S,i} + nemCO_2{}' + NemCO_2$$

- $\forall_g$ = volume of gas phase (air volume in indoor pool facility)
- C_g = concentration of CO_2 in air space, and leaving air space
- t = time
- Q_g = volumetric flow rate of air into (and out of) the air space
- $C_{g,in}$ = concentration of CO_2 in outside air entering the air space (not zero!)
- Φ_B = (net) rate of mass transfer of CO_2 from liquid→gas under baseline conditions
- $\Phi_{S,i}$ = (net) rate of mass transfer of (CO_2) from liquid→gas attributable to i^{th} swimmer
- n = number of swimmers
- $emCO_2{}'$ = CO_2 mass emission rate per swimmer
- N = number of non-swimmers
- $emCO_2$ = CO_2 mass emission rate per non-swimmer

CO_2 Mass Emission Estimates for Swimmers, Non-Swimmers

Swimmers

$$emCO_2' = 2.00\,\frac{L}{breath} \cdot 48\,\frac{breath}{person \cdot min} \cdot 0.081\,\frac{g\ CO_2}{L} \cdot \frac{60\ min}{hr} \cdot \frac{1000\ mg\ CO_2}{g\ CO_2} = 470{,}000\,\frac{mg\ CO_2}{person \cdot hr}$$

Tidal Volume

Breathing Frequency

$CO_{2(g)}$ Concentration

14X Difference!

$$emCO_2 = 0.45\,\frac{L}{breath} \cdot 15\,\frac{breath}{person \cdot min} \cdot 0.081\,\frac{g\ CO_2}{L} \cdot \frac{60\ min}{hr} \cdot \frac{1000\ mg\ CO_2}{g\ CO_2} = 33{,}000\,\frac{mg\ CO_2}{person \cdot hr}$$

Non-Swimmers

Φ_B and $\Phi_{s,i}$: CO_2

Φ_B = (net) rate of mass transfer of CO_2 from liquid→gas under baseline conditions

- Two-film theory:

$$\Phi_B = K_l A(C_l - C_l^*)$$

- Where:

K_l = mass transfer coefficient (based on liquid-phase concentration)
A = pool surface area
C_l = liquid-phase concentration
C_l^* = liquid-phase concentration that would be in equilibrium with air (cannot be neglected)

$\Phi_{S,i}$ = (net) rate of mass transfer of CO_2 from liquid→gas attributable to ith swimmer

- Two-film theory:

$$\Phi_{S,i} = K_{l,i} A_i (C_l - C_l^*)$$

- Where:

$K_{l,i}$ = overall mass-transfer coefficient based on liquid phase measurements for the ith swimmer
A_i = area disturbed by the ith swimmer

- But $K_{l,i}$, A_i are difficult to measure independently
- Therefore:

$$\Phi_S = \sum_{i=1}^{n} K_{l,i} A_i (C_l - C_l^*) = nK'(C_l - C_l^*)$$

Final IAQ Models for $NCl_{3(g)}$, $CO_{2(g)}$

$NCl_{3(g)}$

$$\forall_g \frac{dC_g}{dt} = -Q_g C_g + K_l A C_l + n \cdot K' C_l$$

Air Volume In Pool Area

C_g as a Function of time

Outside Air Ventilation rate

C_l as a Function of time

Number of swimmers

Number of non-swimmers

$CO_{2(g)}$

$$\forall_g \frac{dC_g}{dt} = Q_g C_{g,in} - Q_g C_g + K_l A (C_l - C_l^*) + n \cdot K' (C_l - C_l^*) + n \cdot emCO_2' + N \cdot emCO_2$$

CO_2 Concentration in Ambient Air

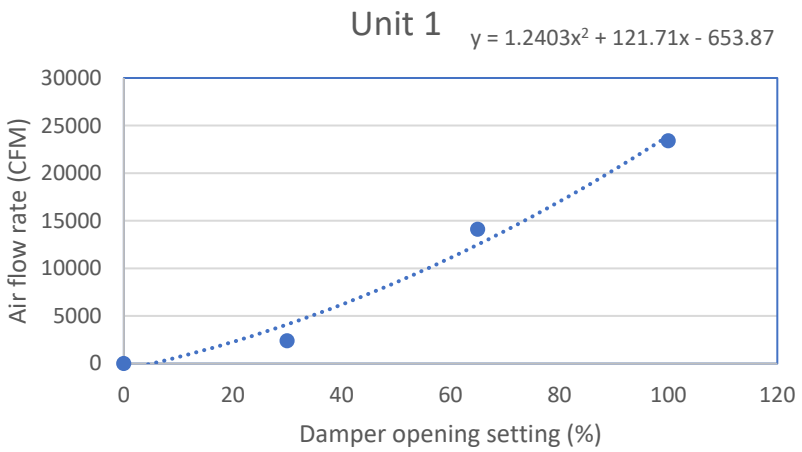
Mass Transfer Coeff Baseline Conditions

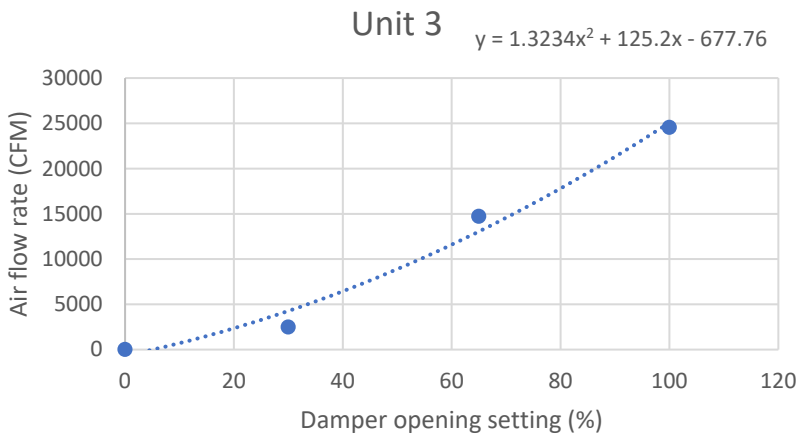
Mass Transfer Coeff For Swimmers

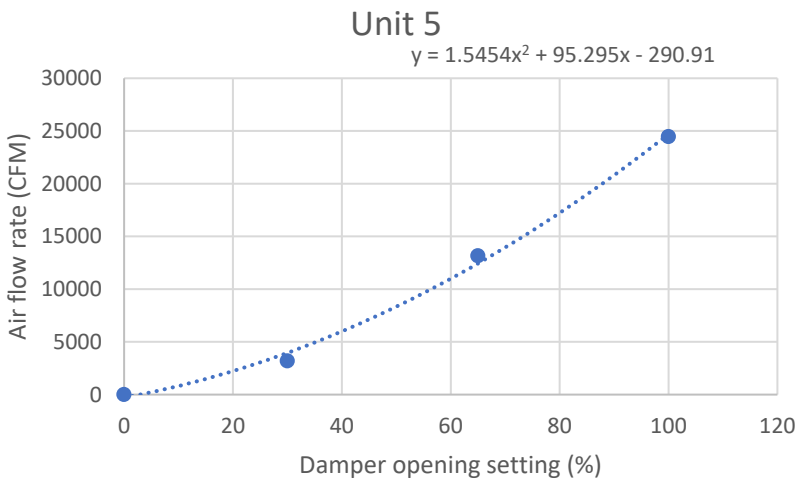
Measurements of Outdoor Air Flow Rate

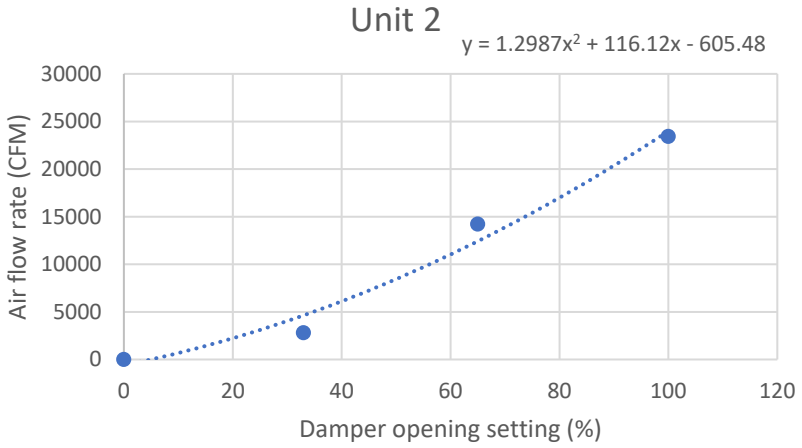
- Five air handling units
- Each air handling unit operates independently
- Damper settings control flow rate of outdoor air; settings are based on indoor relative humidity
- Outdoor air flow rates were measured at 3 damper opening settings for each air handling unit (30%, 65%, and 100%)

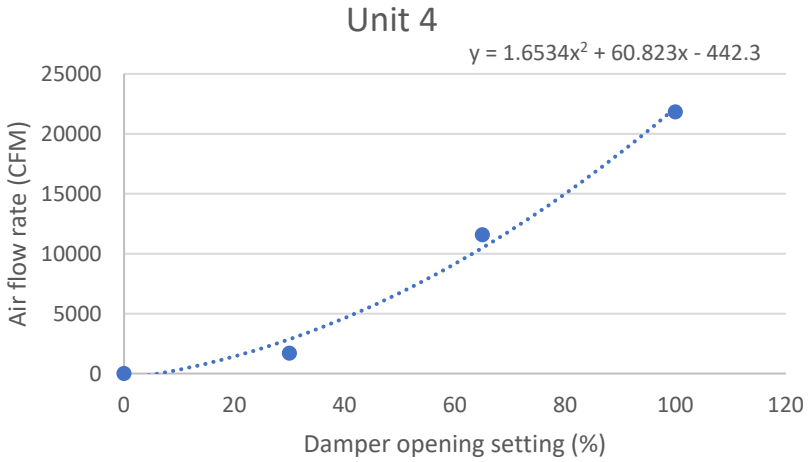
Outdoor Air Flow Rate vs. Damper Setting



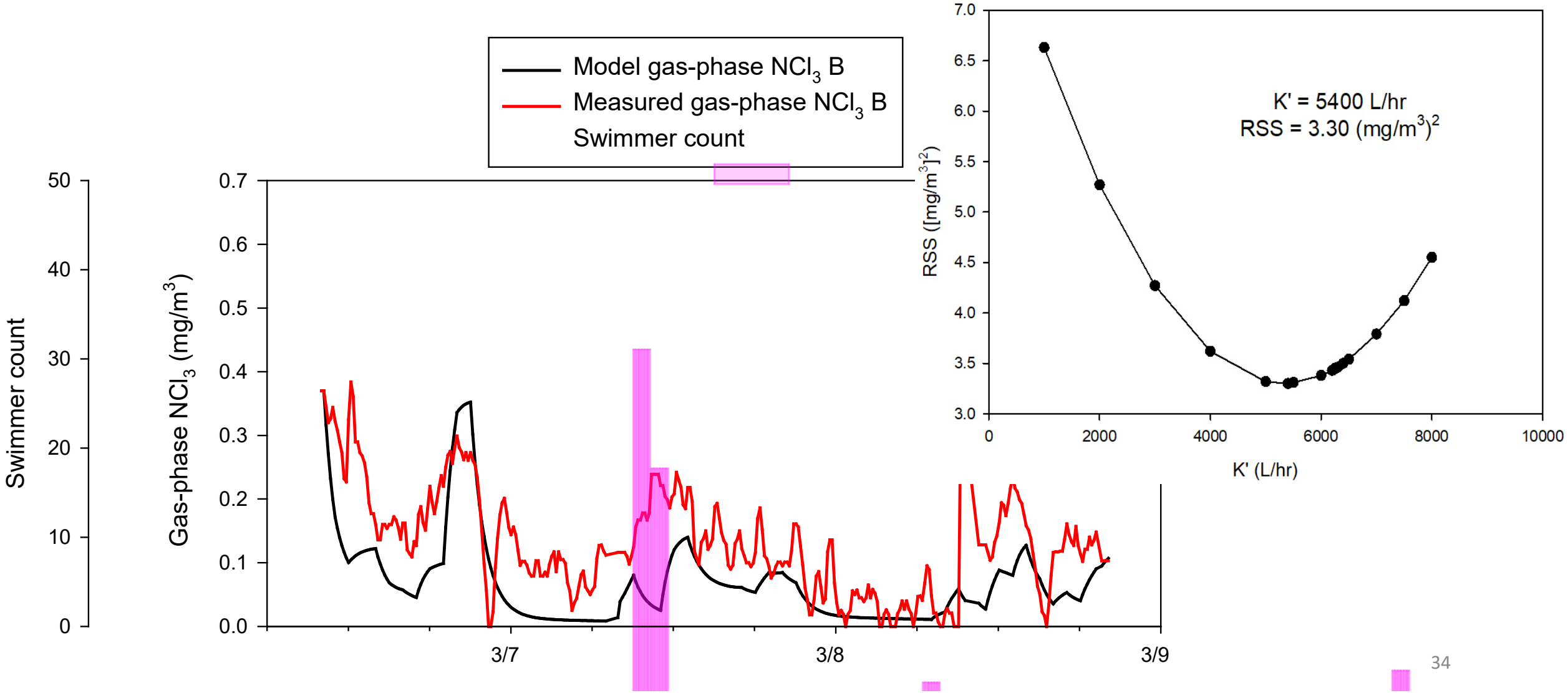


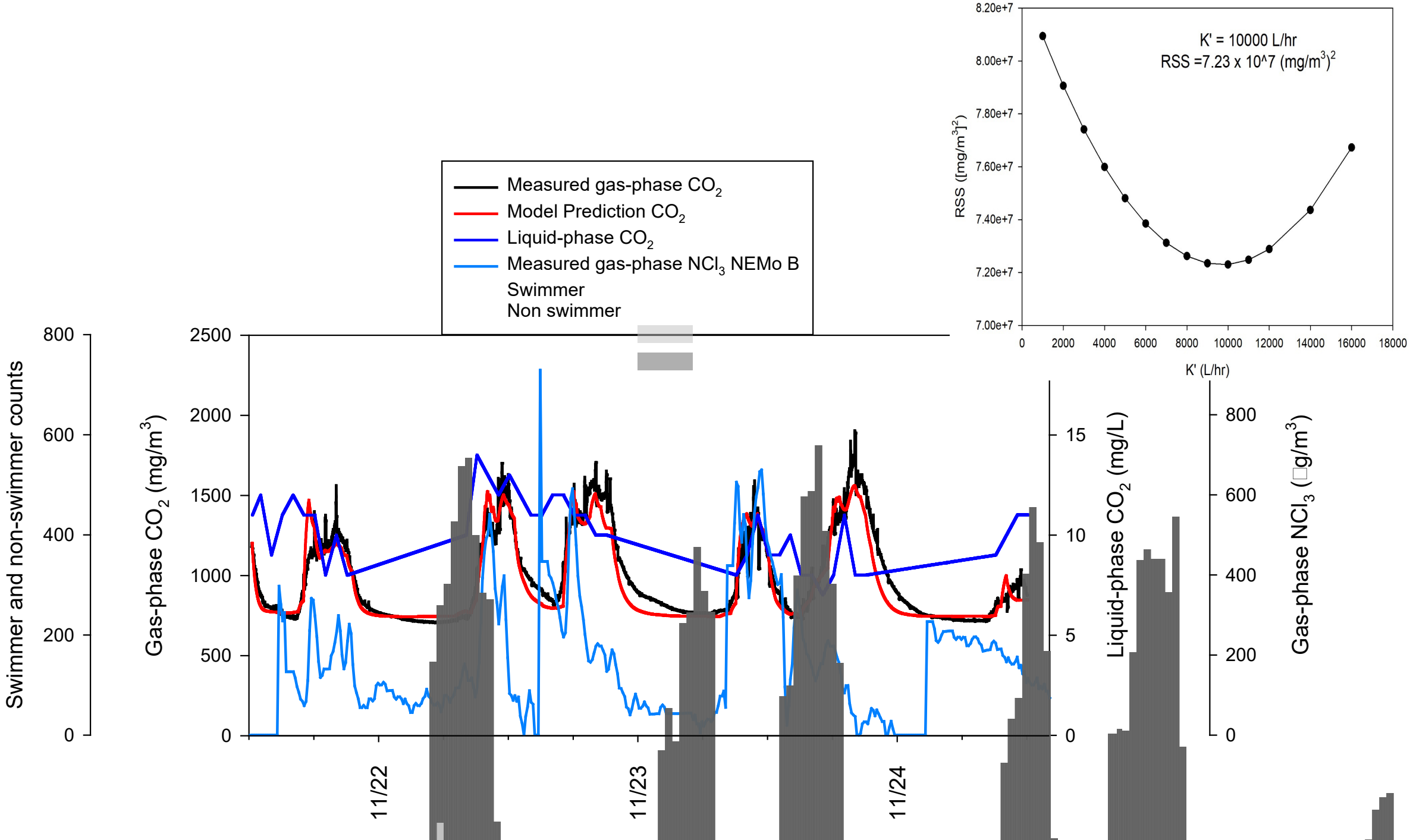


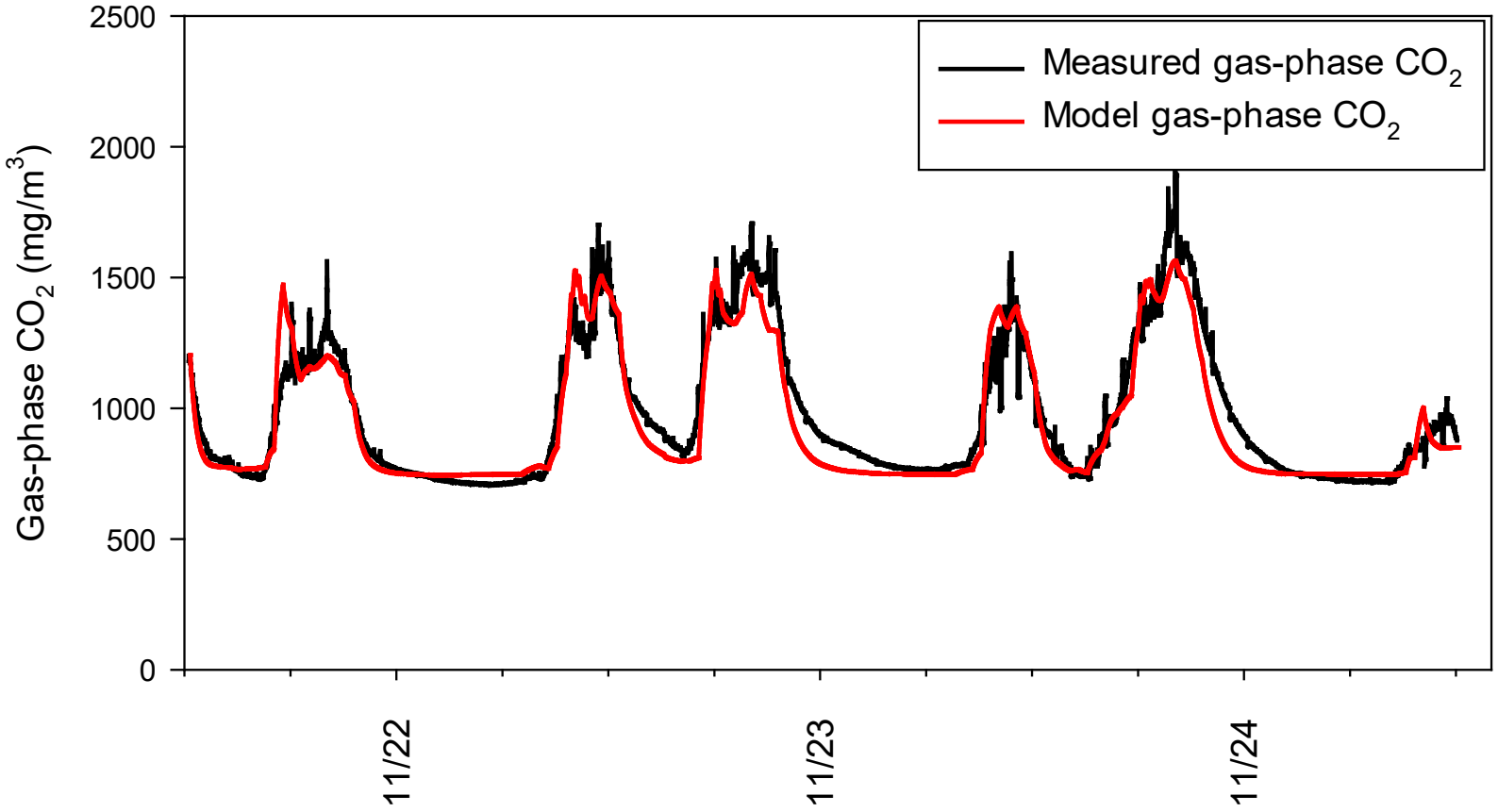




6-8 March 2019 Experiment: Adult Lap Swimmers + Collegiate Swimming Practice




K' = 10000 L/hr
RSS =7.23 x 10^7 (mg/m3)2
RSS ([mg/m3]2)
K' (L/hr)
8.20e+7
8.00e+7
7.80e+7
7.60e+7
7.40e+7
7.20e+7
7.00e+7
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
Measured gas-phase CO2
Model Prediction CO2
Liquid-phase CO2
Measured gas-phase NCl3 NEMo B
Swimmer
Non swimmer
Swimmer and non-swimmer counts
Gas-phase CO2 (mg/m3)
Liquid-phase CO2 (mg/L)
Gas-phase NCl3 (□g/m3)
11/22
11/23
11/24


Measured gas-phase CO_2
Model gas-phase CO_2
Gas-phase CO_2 (mg/m^3)
2500
2000
1500
1000
500
0
11/22
11/23
11/24

IAQ Model Parameters

Compound	Instrument	Swimmer Type	Swimmer Age	K_l (m/hour)	$K_l A$ (m^3/hour)	K' (m^3/hour)
NCl_3	NEMo	Adult Lap Collegiate Team	Adults College Students	0.0024	4.07	5.40
				0.0022	3.64	5.00
				0.0023	3.86	5.00
	NEMo	Adult Lap Collegiate Team	Adults College Students	0.0077	11.5	7.00
				0.0069	12.9	5.00
	NEMo	Age Group Swimmers	8 and Under	0.0022	3.67	0.80
				0.0017	2.76	0.90
CO_2	NEMo	Age Group Swimmers	8 and Under	0.045	75.2	0
	LiCor	Elite	Collegiate and Adult	0.051	85.2	10

Model Applications

- Prediction of IAQ (NCl_3 and CO_2) in indoor pool facilities
  - Links between swimmer number, swimmer type, IAQ
  - Anticipate problems before they occur
- Evaluation of IAQ control measures
  - Increased ventilation (ach)
  - Air stripping
  - Other?

Image from: https://facilityexecutive.com/2018/05/keep-swimming-pools-clean-this-season/

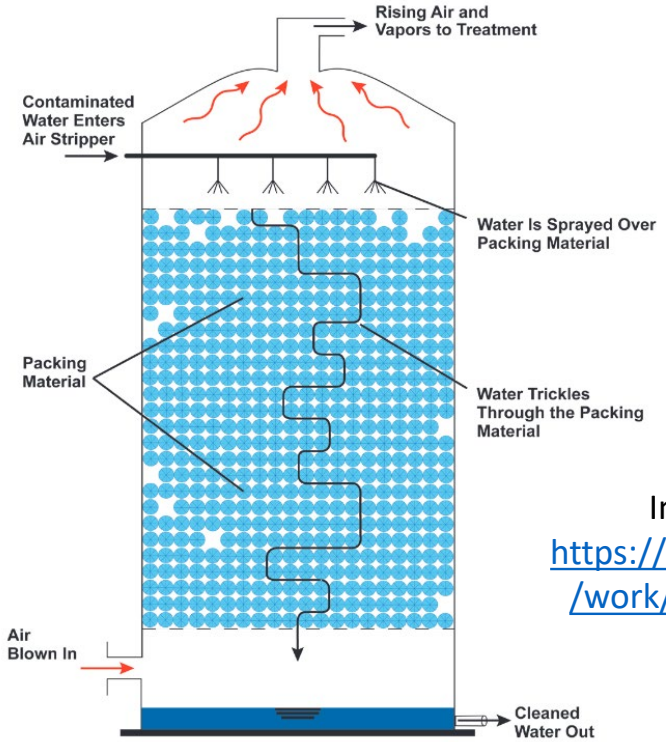
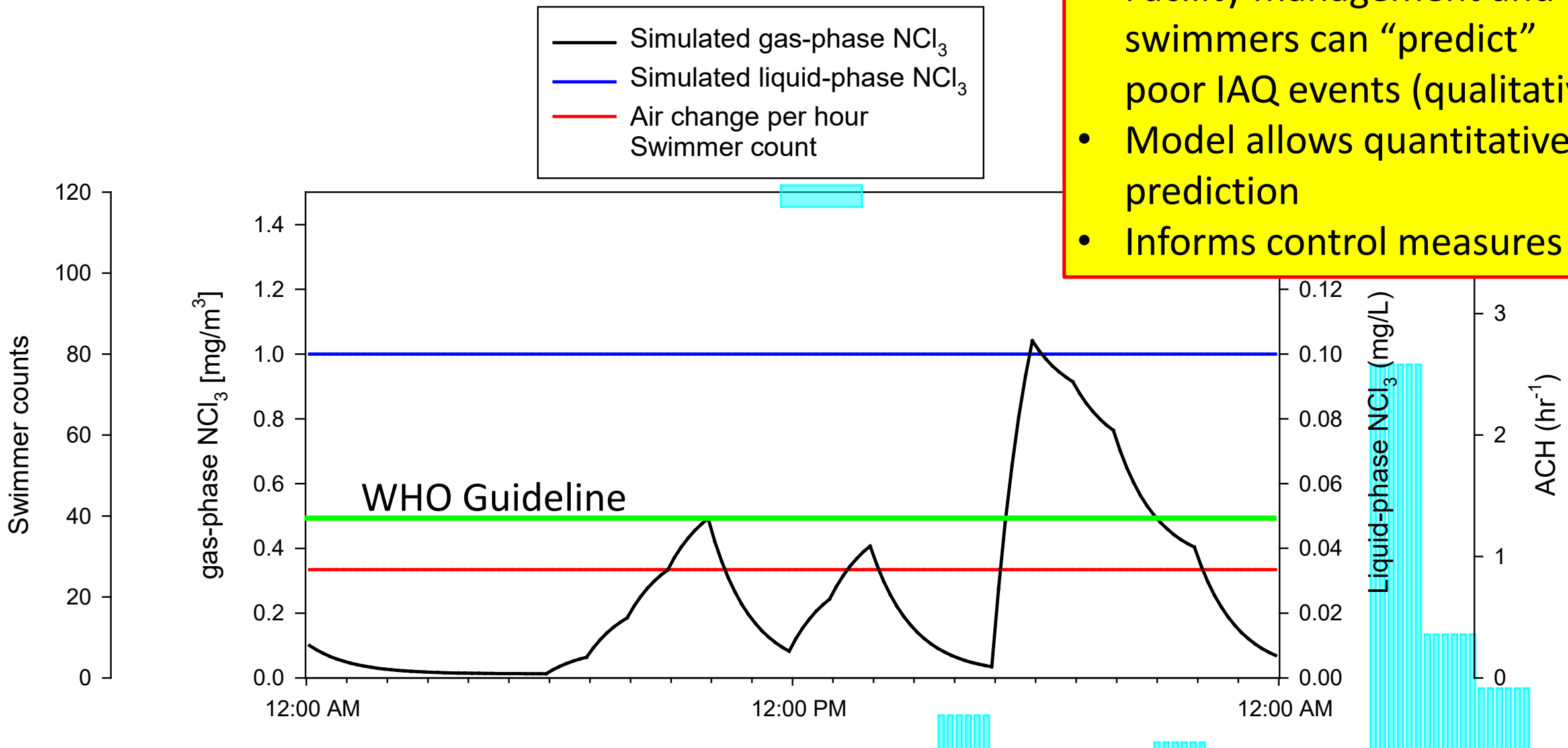


Image from: https://semspub.epa.gov/work/HQ/401577.pdf

Model Predictions: "Normal" Operating Conditions

Observations

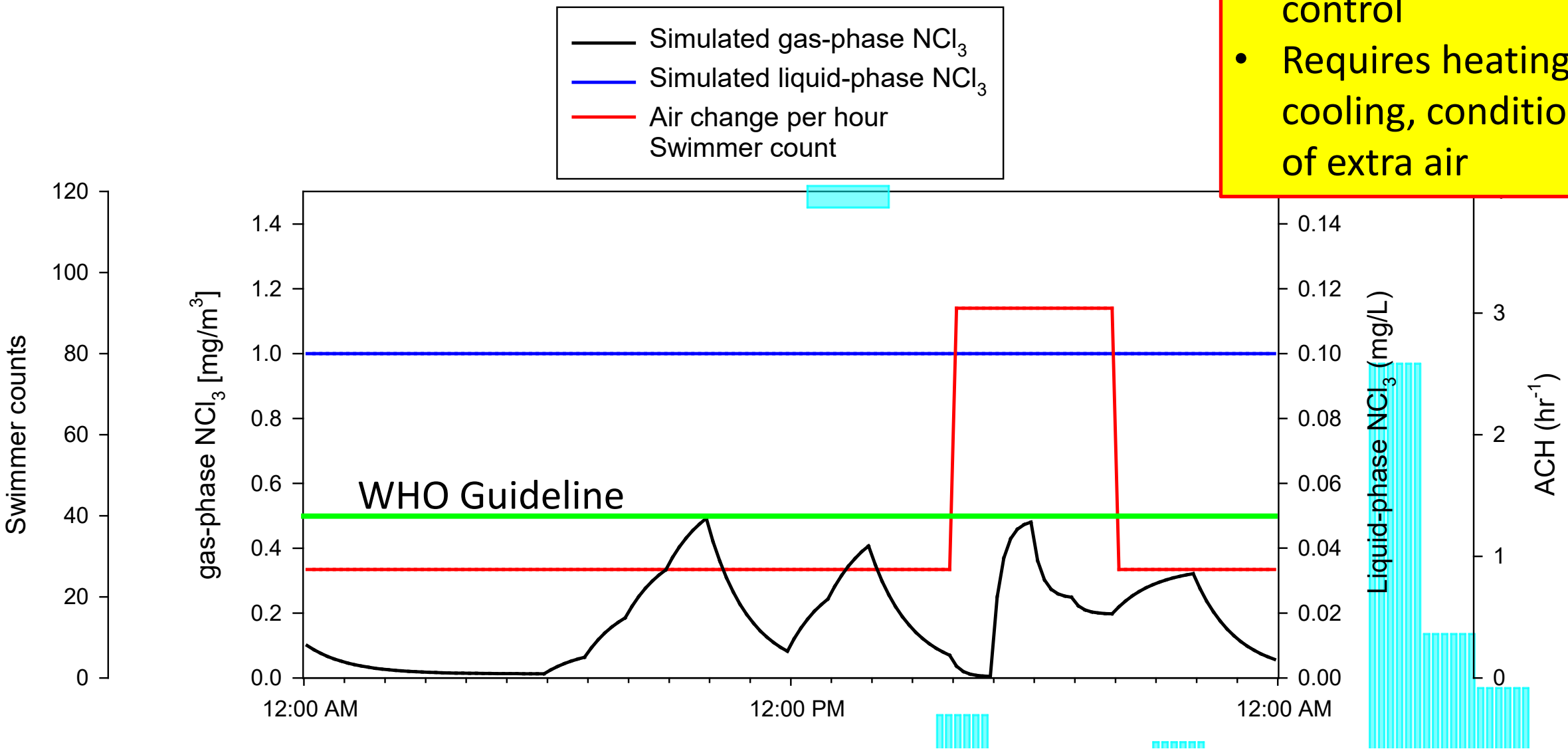
- Increases of $NCl_{3(g)}$ are related to swimmer number
- Facility management and swimmers can "predict" poor IAQ events (qualitative)
- Model allows quantitative prediction
- Informs control measures



Model Predictions: Increased Air Exchange

Observations

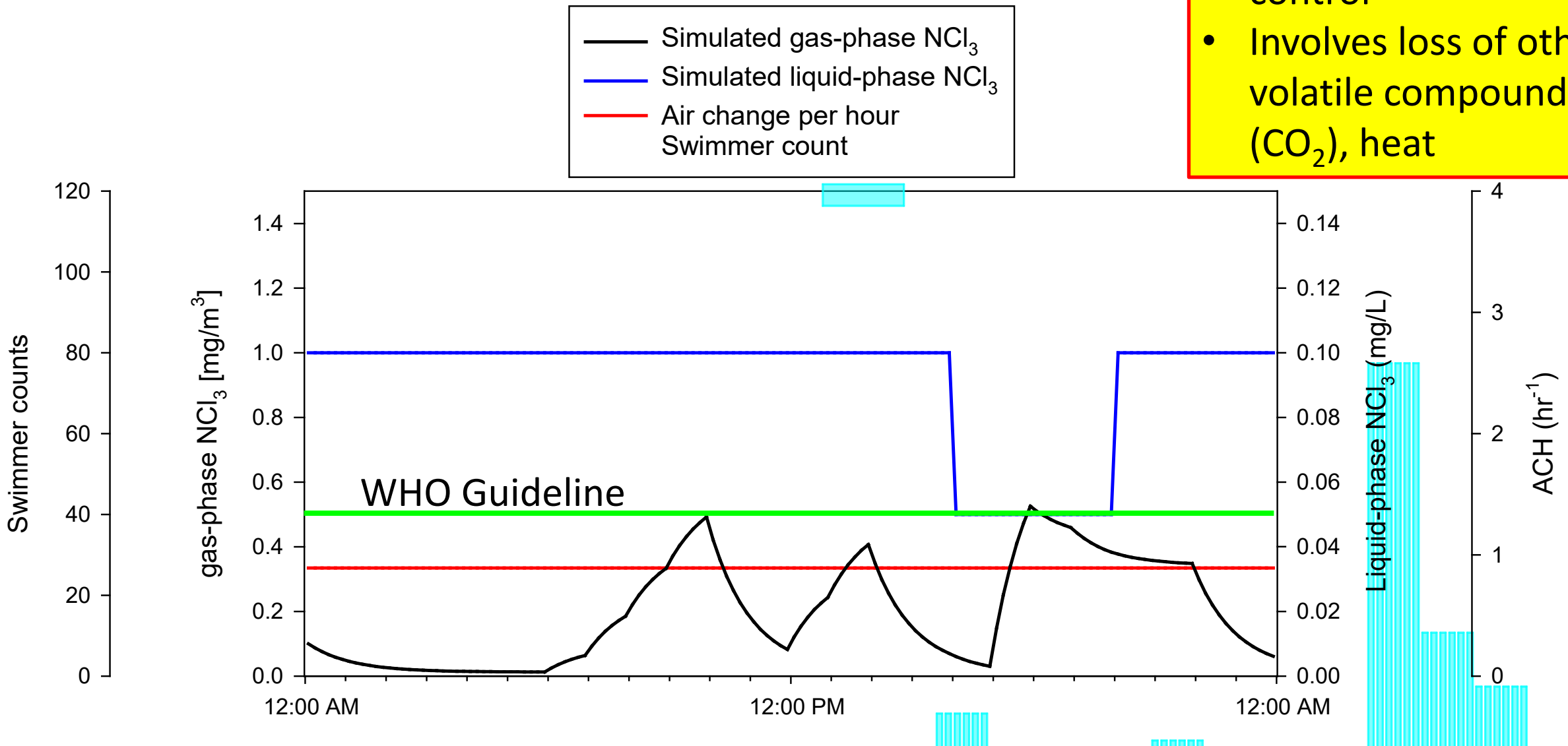
- Increased ach can be effective for IAQ control
- Requires heating, cooling, conditioning of extra air



Model Predictions: Inclusion of Air Stripping

Observations

- Air stripping can be effective for IAQ control
- Involves loss of other volatile compounds (CO_2), heat



Model Limitations

- All models are simplifications of reality
- It is a responsibility of the user to know and understand the limitations, sources of error that are inherent in a model
- All models have error, often associated with assumptions, input data (measurements)
- Known sources of error in this model (partial list)
  - Well-mixed assumptions (water and air)
  - Measurements of liquid-phase concentrations
    - Single location in pool
    - Intermittent sample collection and analysis
  - Analytical error
  - Assumption of same mass transfer coefficient (K') for all members of a population
  - Swimmer counts on an hourly schedule

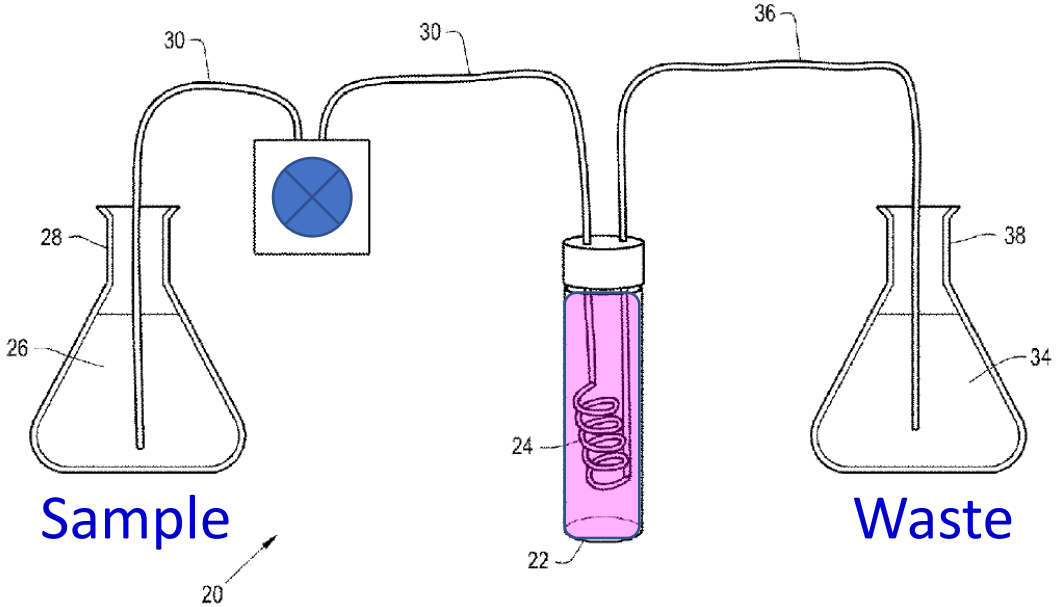
Plans for Phase III

- Measurements of IAQ dynamics at additional facilities
  - Other geographic locations
  - Indoor splash parks
  - Therapy pools
- Requirements
  - Ability to quantify outdoor air exchange rate in real time
  - Real-time measurements of gas-phase compounds (NCl_3, CO_2, others?)
  - Real-time measurements of liquid-phase composition (NCl_3, CO_2, others?)
  - Ability to quantify swimmer, non-swimmer numbers
  - Ability to quantify operational characteristics of water features
- Extension of model to other facilities, use types
  - Mass transfer coefficients for other swimmer types
  - Mass transfer coefficients for water features
- Development of user interface
- Application of model for real-time control of IAQ

Next Steps (Phase III)

- Extension of sampling program
  - Other venue types
    - Indoor splash parks
    - Therapy pools
  - Other geographic locations
- Extension of model
  - Prediction of IAQ dynamics in a wide range of facility types
  - Model becomes a tool to optimize IAQ in indoor pools
- Measurements of aqueous NCl_3
  - Membrane-based wet chemistry method
  - Simple, rapid method based on DPD/KI
  - Color development depends on NCl_3 concentration and pumping time
  - Effective, accurate for quantification of $NCl_{3(aq)}$

Image from: https://www.travelchannel.com/interests/amusement-parks/photos/most-incredible-indoor-water-parks



(12) **United States Patent**
Blatchley, III

(10) **Patent No.: US 11,084,738 B2**
(45) **Date of Patent: Aug. 10, 2021**

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- Melissa Millerick-May and Anthony Oliveri (Michigan State University)
- Participating Pools, Pool Staffs

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Article

Long-Term Monitoring of Water and Air Quality at an Indoor Pool Facility during Modifications of Water Treatment

Lester T. Lee [1] and Ernest R. Blatchley III [1,2,*]

[1] Lyles School of Civil Engineering, Purdue
[2] Division of Environmental and Ecologica
* Correspondence: blatch@purdue.edu

Abstract: Previous research has shown
affect the human respiratory system. A
play important roles in governing wate
air quality in a swimming pool facility
components of water treatment. This stu
air quality that are associated with chan
pool facility. Reductions in aqueous trich
use of secondary oxidizer with its activat
concentrations of cyanogen chloride (Cl
that is common in swimming pools and
as well as a marker compound for the in
after the addition of the activator. Cor
treatment processes were changed. The
also allowed for an assessment of the eff
concentrations of urea (an NCl_3 precur
during periods of high swimmer numbe

check for updates

Environmental Science & Technology

pubs.acs.org/est Article

Real-Time Measurements of Gas-Phase Trichloramine (NCl_3) in an Indoor Aquatic Center

Tianren Wu, Tomas Földes, Lester T. Lee, Danielle N. Wagner, Jinglin Jiang, Antonios Tasoglou, Brandon E. Boor,* and Ernest R. Blatchley III*

Cite This: *Environ. Sci. Technol.* 2021, 55, 8097–8107 Read

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ABSTRACT: NCl_3 is formed as a disinfection byproduct in chlorinated swimming pools and can partition between the liquid and gas phases. Exposure to gas-phase NCl_3 has been linked to asthma and can irritate the eyes and respiratory airways, thereby affecting the health and athletic performance of swimmers. This study involved an investigation of the spatiotemporal dynamics of gas-phase NCl_3 in an aquatic center during a collegiate swim meet. Real-time (up to 1 Hz) measurements of gas-phase NCl_3 were made via a novel on-line derivatization cavity ring-down spectrometer and a proton transfer reaction time-of-flight mass spectrometer. Significant temporal variations in gas-phase NCl_3 and CO_2 concentrations were observed across varying time scales, from seconds to hours. Gas-phase NCl_3 concentrations increased with the number of active swimmers due to swimming-enhanced liquid-to-gas transfer of NCl_3, with peak concentrations between 116 and 226 ppb. Strong cor with concentrations of CO_2 and water (relative humidity) were found and attri processes in pool air. A vertical gradient in gas-phase NCl_3 concentrations w demonstrating that swimmers can be exposed to elevated levels of NCl_3 beyon

KEYWORDS: *indoor air quality, swimming pool chemistry, volatile disinfection by proton transfer reaction time-of-flight mass spectrometry*

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Dynamic behavior of gas-phase NCl_3 and CO_2 in indoor pool facilities

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ARTICLE INFO

Keywords:
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Volatile disinfection byproducts
Trichloramine
Two-film theory

ABSTRACT

The presence of gas-phase trichloramine (NCl_3) in indoor swimming pool facilities is associated with adverse health outcomes among swimmers and other pool users, as well as degradation of pool infrastructure. Given their similarities in terms of volatility (*i.e.*, Henry's law constant), the dynamic behaviors of NCl_3 and carbon dioxide (CO_2) in the air above indoor pools were postulated to be similar. Experiments were conducted to characterize and quantify the dynamic behavior of gas-phase NCl_3 and CO_2 in a mechanically ventilated swimming pool facility. The results of these time-course measurements allowed for examination of the effects of background water circulation and swimmer-induced mixing on the dynamics of both compounds in the air space above an indoor swimming pool. Measured gas-phase NCl_3 concentrations exceeded the suggested guideline values of 300 $\mu g/m^3$ or 500 $\mu g/m^3$ during periods of heavy use. Measured gas-phase CO_2 concentration followed a similar dynamic pattern as gas-phase NCl_3; gas-phase CO_2 concentrations often exceeded 1000 ppm_v during swimming meets. Mass balance models for gas-phase NCl_3 and CO_2 were developed to relate the characteristics of the indoor pool environment to their dynamics. The results of these modeling efforts indicated that the similarity of CO_2 transfer behavior to NCl_3 may allow the use of CO_2, which can be measured with low-cost infrared gas sensors, as a control parameter for NCl_3. Moreover, the models that were developed to describe the dynamic behaviors of these volatile compounds may serve as tools for pool design, optimization of pool operations, and control of their mechanical ventilation systems.

Thank You For Your Attention!

Please Send Questions and Comments to:

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