BEARS | Berkeley Education Alliance for Research in Singapore

SinBerBEST | Singapore-Berkeley Building Efficiency and Sustainability in the Tropics

Human-Building Interactions and the Environment: Status Report

William W Nazaroff, UC Berkeley
Wei-Chung (Victor) Chang, NTU
SinBerBEST Seminar
9 January 2013

NANYANG TECHNOLOGICAL UNIVERSITY

NUS National University of Singapore

SinBerBEST Thrust 4: Mission

To acquire information, create knowledge, and convey understanding to ensure that indoor environmental quality provided for building occupants is maintained or improved while energy efficiency gains are achieved.

Singapore (2012)

Thrust 4: Areas of Emphasis

The 2012 list …

WP 4.1 — Heating, ventilating, and air-conditioning system hygiene

WP 4.2 — Human factors for thermal comfort

WP 4.3 — Bioaerosols in tropical buildings

WP 4.4 — Temperature & humidity effects on indoor pollutant dynamics

WP 4.5 — Critical reviews

WP 4.6 — Coordination with other SinBerBEST thrusts

A proposed addition for 2013 …

WP 4.7 — Ventilation and indoor environmental quality

SinBerBEST Thrust 4: Staff

Faculty


Bill NAZAROFF (UCB)


Victor CHANG (NTU)


Man Pun WAN (NTU)


Kwok Wai THAM (NUS)


Chandra SEKHAR (NUS)


David CHEONG (NUS)


Stefano Schiavon (UCB)

- Two postdoctoral fellows recruited (starting early 2013); two positions open.
- Two PhD students are employed; two positions open.

Postdoctoral fellows


Benjamin Bin YANG


Donghyun RIM

PhD students


Matt VANNUCCI (UCB)


Irvan LUHUNG (NTU)

Postdoctoral fellow and PhD student recruiting

- Original concept: WPs led separately by faculty PIs, staffed by postdoctoral fellows and PhD students.
- Current concept: Confederation of post-docs, mentored by faculty; PhD students work on projects directly guided by faculty.
- Postdoctoral fellows and PhD students to have some latitude in designing research projects that are responsive to the mission and that meaningfully address one or more research themes.
- Ongoing challenge: recruit top quality postdoctoral fellows & PhD students.
- International recruitment efforts (~ 200 emails; conferences; ads next).
- Completion of staffing process is a priority for 2013.

Postdoctoral fellows

Benjamin Bin YANG

- Benjamin Bin YANG (WP 4.2; to start March 2013)
  - joint PhD (2009) Technical University of Denmark, NUS
  - Associate Professor, Hebei University of Technology
  - Several first-authored articles in top quality journals
  - Expertise: air conditioning and air distribution; thermal comfort; ventilation strategies; building energy analysis

Donghyun RIM

- Donghyun RIM (WP 4.4; to start February 2013)
  - PhD (2009) University of Texas at Austin
  - Guest researcher, NIST, USA
  - Eight first-authored articles in top quality journals
  - Expertise: building ventilation; airflow distribution; measurement and modeling of indoor contaminant transport; human exposure; energy-efficient buildings

PhD students


Irvan LUHUNG (NTU)

- Irvan Luhong (WP 4.3; started Fall 2012)
  - PhD student in Civil & Environmental Engineering at NTU
  - Holds MS degree in CEE from NTU
  - Research supervised by Prof. Victor Chang
  - Research emphasis: bioaerosols in tropical buildings


Matt VANNUCCI (UCB)

- Matthew Vannucci (WP 4.4; started Summer 2012)
  - PhD student in Civil & Environmental Engineering, UCB
  - Holds MS degree in CEE from UCB
  - Research supervised by Prof. William Nazaroff
  - Research emphasis: temperature and humidity effects on indoor pollutant dynamics

Equipment and laboratory facilities

- Major equipment needs refined (DNA analysis, aerosol, chemical sampling)
- Met with instrumentation representatives during summer 2012:
    - Life Technologies
    - Roche
    - TSI
- Purchase order requests pending completion of institutional arrangements
- Some instrumentation requires wet-lab facilities anticipated to become available during 2013.

Interactions (examples)

- Environmental Health Institute of National Environment Agency regarding baseline survey of indoor air quality in Singapore (June 2012).
- Consulted with Singapore Centre on Environmental Life Sciences Engineering (SCELSE): Staffan Kjelleberg (director) and Cao Bin (PI) regarding microbiology analysis (WP 4.3)
- Consultation with Prof Lin Zhang regarding air quality sensing instruments for test bed at UC Berkeley (WP 4.6).

National Environment Agency

Our Environment - Sustain and Enjoy

SCELSE

Singapore Centre on Environmental Life Sciences Engineering

Shinyei Aerosol Sensor AES-4

Bioaerosols in tropical buildings (WP4 .3)

- Bioaerosols are an important aspect of indoor environmental quality:
  - Allergies and asthma
  - Sick-building syndrome symptoms
  - Communicable and infectious diseases

• Mold in air handling systems
• Damp/humid surfaces (visible and hidden)
→ potential microbial growth

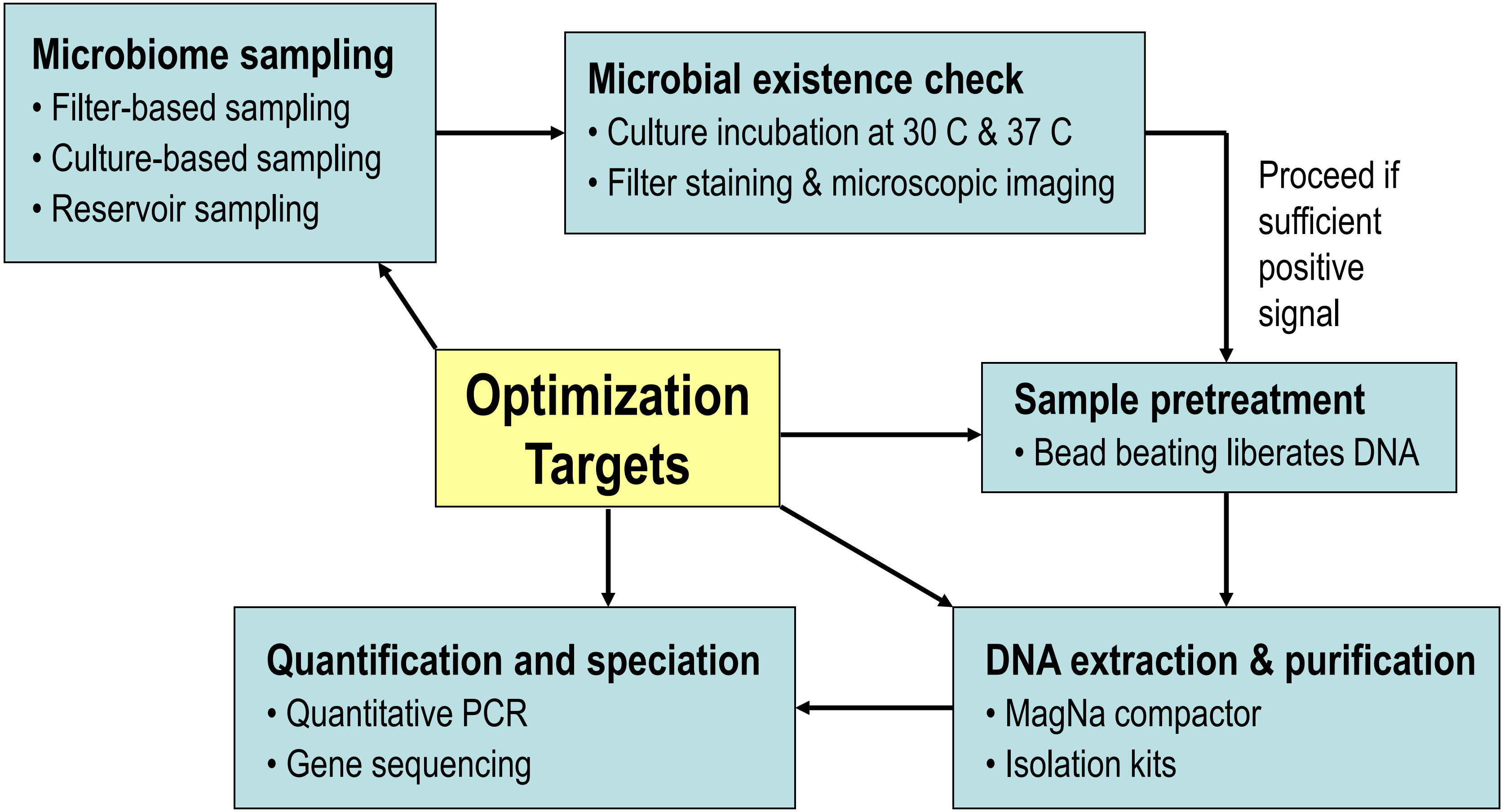
• Microbial material aerosolized and transported into indoor environment
→ potential adverse health effects

Bioaerosol measurement

- Traditional culture-based methods have severe limitations
- DNA-based analysis methods are revolutionizing bioaerosol studies
- Major concerns remain in bioaerosol analysis
    - No reliable detection protocol is proven for warm and humid environments
    - Sampling and analysis are vulnerable to contamination and Inhibition errors
    - Low airborne concentrations mean that good sensitivity is required

Protocol optimization for bioaerosol analysis

Overview of bioaerosol methods (WP 4.3)



Microbiome sampling
- Filter-based sampling
- Culture-based sampling
- Reservoir sampling

Microbial existence check
- Culture incubation at 30 C & 37 C
- Filter staining & microscopic imaging

Proceed if sufficient positive signal

Optimization Targets

Sample pretreatment
- Bead beating liberates DNA

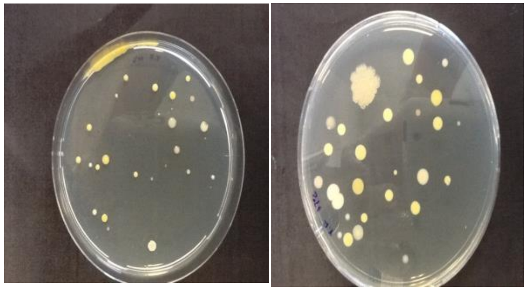
Quantification and speciation
- Quantitative PCR
- Gene sequencing

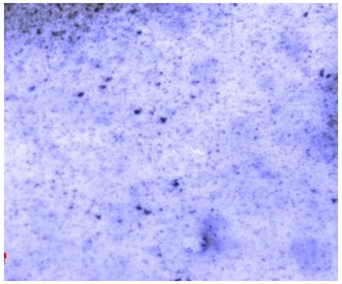
DNA extraction & purification
- MagNa compactor
- Isolation kits

Status and future plans (WP 4.3)


MagNa compactor


Quantitative PCR analyzer


Stained cultures: 30 ^{o}C (L), 37 ^{o}C (R)


Microscopic image of sampled filter

Early results:

- Confirmed presence of substantial indoor bioaerosols in local environments, and in excess of outdoor levels
- qPCR quantification thus far producing unsatisfactory results, possibly owing to inhibition

Future plans:

- Sampling optimization (DNA/RNA retention, filter material, sampling protocol, sample extraction)
- DNA purification optimization (various commercial approaches)
- qPCR protocol optimization (various probe and primer sets for higher efficiency and different target species)
- Develop capabilities for bioaerosol identification (e.g., pyrosequencing)
- Application to field campaign investigating indoor microbiome dynamics in commercial building(s)

Building ventilation: An energy-IEQ challenge

- Ventilation is an important contributor to building energy use.
  - Energy needed to adjust air temperature (sensible heat, c_p = 1.005 kJ kg_{air}^{-1} K^{-1})
  - Energy needed to adjust moisture content of air (latent heat, h_f = 2257 kJ kg_{H2O}^{-1})
  - Energy used by fans to move air in mechanically ventilated buildings
- Tempting to save energy by providing less ventilation.
- Ventilation strongly influences indoor environmental quality (IEQ).
- Generally, higher rates of ventilation yield better IEQ.

Basis for building ventilation rates

- In practice, standards are set largely to limit human bioeffluents so as to establish "acceptable" indoor air quality.
- Carbon dioxide is the common marker compound for human bioeffluents.
- Conceptual approach is old; rates and rules have varied over time.

Max von Pettenkofer (1818-1901)

We deteriorate the air of a closed space inevitably by using it for the maintenance of our respiration and perspiration. … I started from the excretion of carbonic acid [CO_2], as it takes place from the living human body… I will not say that I consider the detected carbonic acid as the principal drawback to such air; it is, in my mind, the measure only for all the other alterations which take place in the air simultaneously and proportionately, in consequence of respiration and perspiration. … A series of examinations resulted in the conviction that one volume of carbonic acid in 1000 volumes of room air indicates the limits, which divide good from bad air. … On an average, in spaces in which the air kept good, there existed a ventilation of more than 2100 cubic feet per head and hour [= 16.5 L/s per person]. — M von Pettenkofer, 1873

CP Yaglou (1897-1960)

Relationship of building ventilation to health

- Multidisciplinary review of literature through 2005.
- 27 papers provide sufficient information to inform the relationship.
- Consistency found: different epidemiologic designs and populations.
- Association is biologically plausible.
- Higher ventilation rates in offices, up to ~ 25 l/s per person, are associated with reduced prevalence of sick building syndrome symptoms.
- Limited data suggest that inflammation, respiratory infections, asthma symptoms and short-term sick leave increase with lower ventilation rates.
- Literature focuses on conditions in N Europe and N America.

Source: J Sundell et al., Ventilation rates and health: Multidisciplinary review of the scientific literature, *Indoor Air* **21**, 191-204, 2011.

Indoor pollutant levels vary with ventilation rates

- Basic relationship for (i) steady-state, (ii) well-mixed conditions, (iii) in a single-zone environment and (iv) for a pollutant with simple behavior

$$C \sim \frac{pQC_{out}+E}{Q+kV} \qquad \begin{array}{l} \longleftarrow \text{sources} \\[2ex] \longleftarrow \text{removal} \end{array}$$

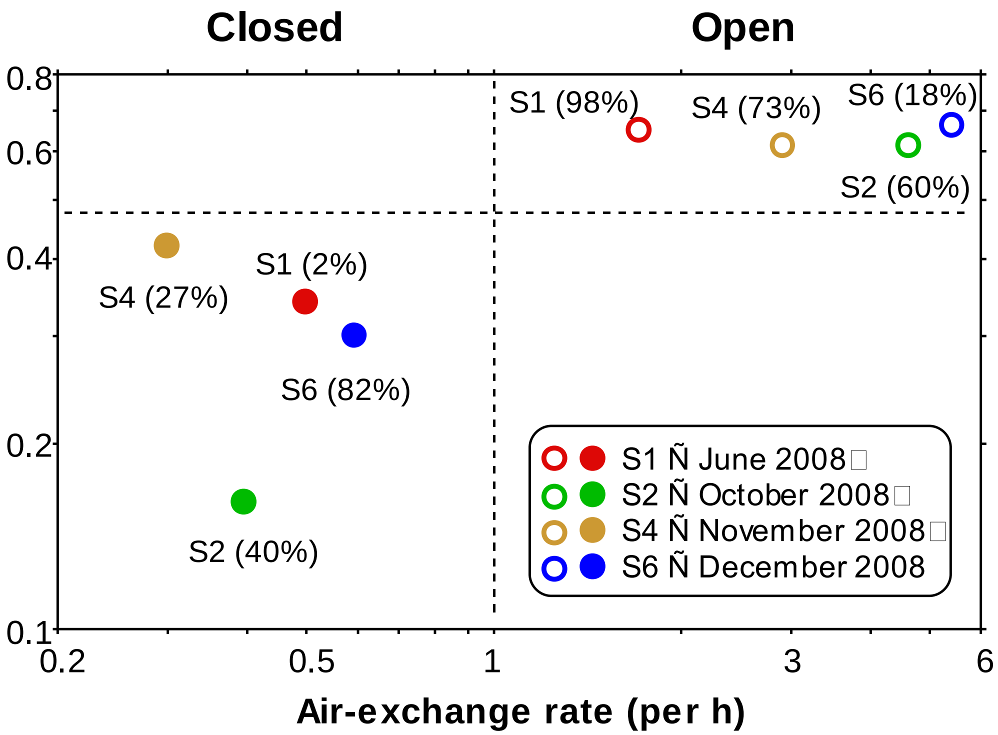
This equation is derived from material balance applied to the indoor contaminant and to the indoor air volume.

C — indoor pollutant concentration; p — penetration factor; C_{out} — outdoor pollutant concentration; E — emission rate from indoor sources; Q — ventilation rate; k — loss-rate coefficient (excl. ventilation); V — interior volume.

- For a pollutant with both indoor source (E) and outdoor presence (C_{out}):
  - high value of $Q \Rightarrow C \sim p\, C_{out}$ (indoors like outdoors modified by p)
  - low value of Q decouples the indoor air from outdoor conditions
- Relaxing any of the four key assumptions produces rich complexity.
- Multiple species influence indoor environmental quality.

Particles and CO_2 in schools: A balancing act

- Field study of ultrafine particles in 6 N California classrooms
- Outdoor air was main particle source
- Four classrooms were naturally ventilated



Occupied period with elevated CO_2 levels

(% time ΔCO_2 > 700 ppm)

S1 — 3%

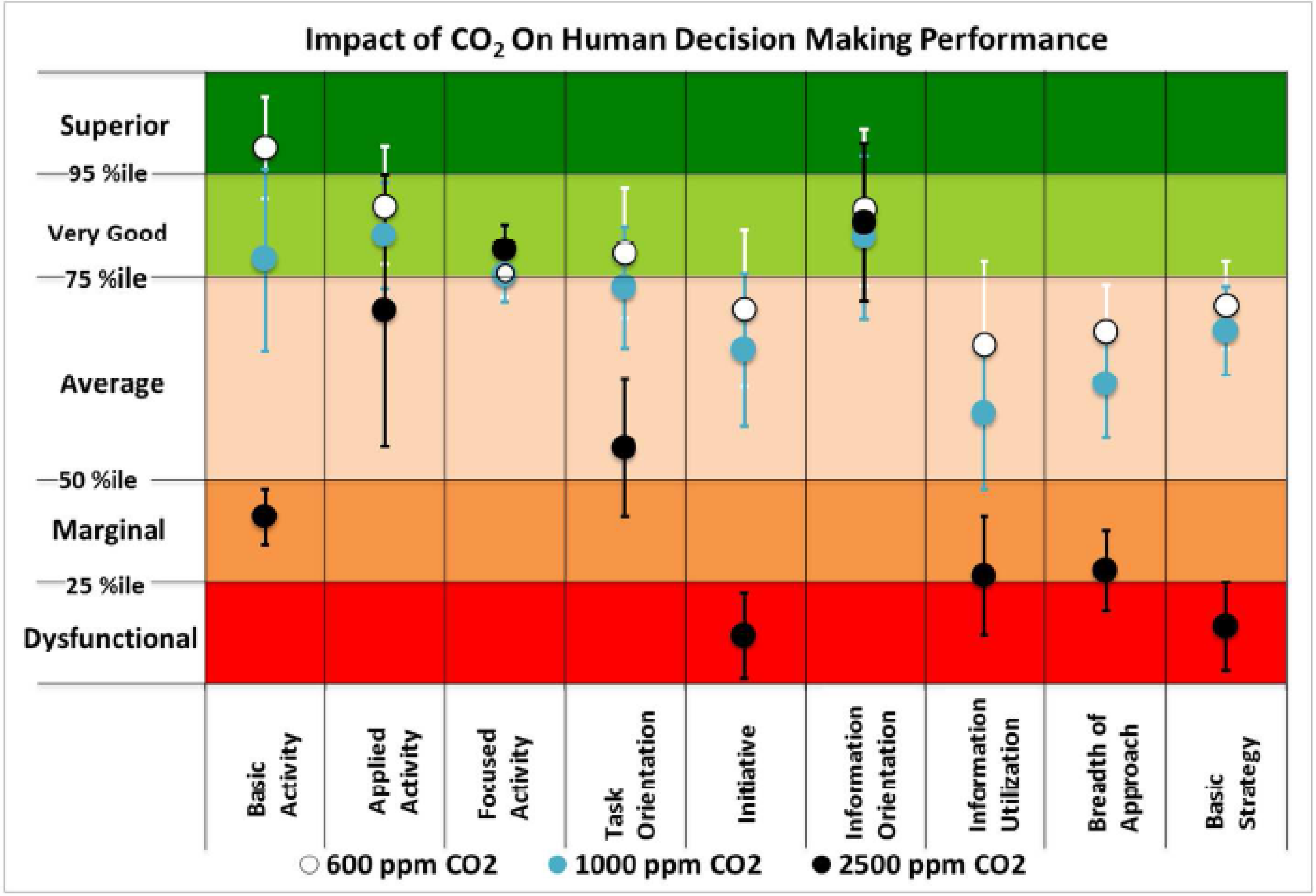
S2 — 5%

S4 — 56%

S6 — 33%

Source: NA Mullen et al., *Indoor Air* **21**, 77, 2011; Funded by California Air Resources Board

New evidence: Is CO_2 itself a pollutant?



Source: U Satish et al., Is CO_2 an indoor pollutant? Direct effects of low-to-moderate CO_2 concentrations on human decision-making performance, *Environmental Health Perspectives* **120**, 1671, 2012.

Ventilation: Simple in concept; hard in reality

- How much? Meet occupant needs and don’t waste energy
- Efficiency: Deliver to people; remove concentrated pollutants
- MV —Hygienic delivery system (filters, coils, ducts) + good controls
- Opportunity and need for critical review on ventilation-IEQ relationships

Priorities for 2013

- Complete hiring of postdoctoral researchers (2) and PhD students (2)
- Establish laboratory at CREATE campus with new equipment:
    - real-time aerosol monitoring
    - bioaerosol sampling and analysis
    - chemical analysis for organic species
- Progress on bioaerosol sampling, analysis and application (WP 4.1, WP 4.3)
- Screening experiments on ozone + personal care products (WP 4.4)
- Study energy saving potential of increased air movement (WP 4.2)
- Critical review: ventilation influence on indoor air pollutants (WP 4.5, WP 4.7)
- Seek synergistic opportunities with other thrusts and agencies (WP 4.6)

Summary

- High-performance buildings must have good IEQ to achieve purpose
- Energy efficiency + good IEQ requires improved understanding of key issues
- IEQ knowledge gaps in tropical climates include HVAC hygiene, thermal comfort, bioaerosols, T/RH effects on pollutants, and role of ventilation rates
- Thrust 4 aims to add knowledge that will advance IEQ science and improve building practice