

ภาคผนวก 7

➤ มาตรฐานคุณภาพสิ่งแวดล้อมที่เกี่ยวข้อง



มาตรฐานคุณภาพอากาศ



1) มาตรฐานคุณภาพอากาศในบรรยากาศโดยทั่วไป





ประกาศคณะกรรมการสิ่งแวดล้อมแห่งชาติ

ฉบับที่ ๑๐ (พ.ศ. ๒๕๓๘)

ออกตามความในพระราชบัญญัติส่งเสริมและรักษาคุณภาพสิ่งแวดล้อมแห่งชาติ

พ.ศ. ๒๕๓๕

เรื่อง กำหนดมาตรฐานคุณภาพอากาศในบรรยากาศโดยทั่วไป

อาศัยอำนาจตามความในมาตรา ๓๒ แห่งพระราชบัญญัติส่งเสริมและรักษาคุณภาพสิ่งแวดล้อมแห่งชาติ พ.ศ. ๒๕๓๕ คณะกรรมการสิ่งแวดล้อมแห่งชาติกำหนดมาตรฐานคุณภาพอากาศในบรรยากาศโดยทั่วไป ไว้ดังต่อไปนี้

ข้อ ๑ ในประกาศนี้

“เครื่องวัด ระบบนั้ดิสเพอร์ซีฟ อินฟราเรด ดีเทกชั่น (Non- dispersive Infrared Detection)” หมายความว่า เครื่องมือวัดค่าก๊าซคาร์บอนมอนอกไซด์โดยใช้รังสีอินฟราเรด

“เครื่องวัดระบบเคมีลูมิเนสเซน (Chemiluminescence)” หมายความว่า

(๑) เครื่องมือวัดค่าก๊าซไนโตรเจนไดออกไซด์โดยใช้ก๊าซโอโซนทำปฏิกิริยากับก๊าซไนตริกออกไซด์ ซึ่งถูกเปลี่ยนมาจากก๊าซไนโตรเจนไดออกไซด์แล้ววัดความเข้มของแสงซึ่งเกิดจากปฏิกิริยานั้น ณ ที่ความยาวคลื่นที่สูงกว่า ๖๐๐ นาโนเมตร (Nanometer) หรือ

(๒) เครื่องมือวัดค่าก๊าซโอโซนโดยใช้ก๊าซเอธิลีนทำปฏิกิริยากับก๊าซโอโซนแล้ววัดความเข้มของแสงซึ่งเกิดจากปฏิกิริยานั้น ณ ที่ความยาวคลื่นระหว่าง ๓๕๐ ถึง ๕๕๐ นาโนเมตร

“ระบบพาราโรซานิลีน (Pararosaniline)” หมายความว่า การวัดค่าก๊าซซัลเฟอร์ไดออกไซด์ โดยการดูดอากาศผ่านสารละลายโพตัสเซียม เตตราคลอโรเมอร์คิวเรต (Potassium Tetrachloromercurate) เกิดเป็นสารไดคลอโรซัลไฟโดเมอร์คิวเรต คอมเพลกซ์

(Dichlorosulfite Mercurate Complex) ทำปฏิกิริยากับสารพาราโรซานิลินและฟอร์มาลดีไฮด์ (Pararosaniline and Formaldehyde) เกิดเป็นสีของพาราโรซานิลินเมทิล ซัลฟอนิก แอซิด (Pararosaniline Methyl Sulfonic Acid) ซึ่งจะวัดความสามารถในการดูดซึมแสง ณ ที่ช่วงคลื่น ๕๔๘ นาโนเมตร

“เครื่องวัดระบบอะตอมมิก แอ็บซอร์ปชัน สเปกโตรมิเตอร์ (Atomic Absorption Spectrometer)” หมายความว่า เครื่องมือวัดปริมาณของตะกั่ว โดยใช้เปลวไฟอะเซทิลีน (Acetylene Flame) ที่ความยาวคลื่น ๒๘๓.๓ หรือ ๒๑๗ นาโนเมตร

“ระบบกราวิเมตริก (Gravimetric)” หมายความว่า การวัดค่าฝุ่นละออง โดยดูดอากาศผ่านแผ่นกรอง ซึ่งมีประสิทธิภาพในการกรองฝุ่นละอองขนาด ๐.๓ ไมครอน (Micron) ได้ร้อยละ ๙๙ แล้วหาน้ำหนักฝุ่นละอองจากแผ่นกรองนั้น

ข้อ ๒ ค่าก๊าซในบรรยากาศโดยทั่วไปในช่วงเวลาหนึ่งเวลาใดให้เป็นไปดังต่อไปนี้

(๑) ค่าเฉลี่ยของก๊าซคาร์บอนมอนอกไซด์ในเวลา ๑ ชั่วโมง จะต้องไม่เกิน ๓๐ ส่วนในล้านส่วน (ppm) หรือไม่เกิน ๓๔.๒ มิลลิกรัมต่อลูกบาศก์เมตรและในเวลา ๘ ชั่วโมง จะต้องไม่เกิน ๕ ส่วนในล้านส่วน หรือไม่เกิน ๑๐.๒๖ มิลลิกรัมต่อลูกบาศก์เมตร

(๒) ค่าเฉลี่ยของก๊าซไนโตรเจนไดออกไซด์ในเวลา ๑ ชั่วโมง จะต้องไม่เกิน ๐.๑๓ ส่วนในล้านส่วน หรือไม่เกิน ๐.๓๒ มิลลิกรัมต่อลูกบาศก์เมตร

(๓) ค่าเฉลี่ยของก๊าซโอโซนในเวลา ๑ ชั่วโมง จะต้องไม่เกิน ๐.๑๐ ส่วนในล้านส่วน หรือไม่เกิน ๐.๒๐ มิลลิกรัมต่อลูกบาศก์เมตร

(๔) ค่าเฉลี่ยของก๊าซซัลเฟอร์ไดออกไซด์ในเวลา ๒๔ ชั่วโมง จะต้องไม่เกิน ๐.๑๒ ส่วนในล้านส่วน หรือไม่เกิน ๐.๓๐ มิลลิกรัมต่อลูกบาศก์เมตร และค่ามัธยฐานเรขาคณิต (Geometric Mean) ในเวลา ๑ ปี จะต้องไม่เกิน ๐.๐๔ ส่วนในล้านส่วน หรือไม่เกิน ๐.๑๐ มิลลิกรัมต่อลูกบาศก์เมตร

ข้อ ๓ การคำนวณค่าความเข้มข้นของก๊าซแต่ละชนิดในบรรยากาศโดยทั่วไปให้คำนวณเทียบที่ความดัน ๑ บรรยากาศ และอุณหภูมิ ๒๕ องศาเซลเซียส

ข้อ ๔ ค่าสารในบรรยากาศโดยทั่วไป ในช่วงเวลาหนึ่งเวลาใดให้เป็นไปดังต่อไปนี้

(๑) ค่าเฉลี่ยของตะกั่วในเวลา ๑ เดือน จะต้องไม่เกิน ๑.๕ ไมโครกรัมต่อลูกบาศก์เมตร

(๒) ค่าเฉลี่ยของฝุ่นละอองขนาดไม่เกิน ๑๐ ไมครอน ในเวลา ๒๔ ชั่วโมง จะต้องไม่เกิน ๐.๑๒ มิลลิกรัมต่อลูกบาศก์เมตร และค่ามัธยฐานเรขาคณิตของสารดังกล่าวใน เวลา ๑ ปี จะต้องไม่เกิน ๐.๑๕ มิลลิกรัมต่อลูกบาศก์เมตร

(๓) ค่าเฉลี่ยของฝุ่นละอองรวมหรือฝุ่นละอองขนาดเล็กไม่เกิน ๑๐๐ ไมครอน ในเวลา ๒๔ ชั่วโมง จะต้องไม่เกิน ๐.๓๓ มิลลิกรัมต่อลูกบาศก์เมตร และค่ามัธยัมเรขาคณิตของสารดังกล่าวในเวลา ๑ ปี จะต้องไม่เกิน ๐.๑๐ มิลลิกรัมต่อลูกบาศก์เมตร

ข้อ ๕ การวัดค่าเฉลี่ยของก๊าซคาร์บอนมอนอกไซด์ในเวลา ๑ ชั่วโมงหรือในเวลา ๘ ชั่วโมง ให้ใช้เครื่องวัดระบบนันทิสเปอร์ซีฟ อินฟราเรด ดีเทกชั่น หรือระบบอื่นที่กรมควบคุมมลพิษให้ความเห็นชอบ

ข้อ ๖ การวัดค่าเฉลี่ยของก๊าซไนโตรเจนไดออกไซด์หรือก๊าซโอโซนในเวลา ๑ ชั่วโมง ให้ใช้เครื่องวัดระบบเคมีลูมินเนสเซน หรือระบบอื่นที่กรมควบคุมมลพิษให้ความเห็นชอบ

ข้อ ๗ การวัดค่าเฉลี่ยของก๊าซซัลเฟอร์ไดออกไซด์ในเวลา ๒๔ ชั่วโมง หรือในเวลา ๑ ปี ให้ใช้วิธีการวัดตามระบบพาราโรซานิลิน หรือระบบอื่นที่กรมควบคุมมลพิษให้ความเห็นชอบ

ข้อ ๘ การวัดค่าเฉลี่ยของตะกั่วในเวลา ๑ เดือน ให้เก็บอากาศผ่านแผ่นกรองในเครื่องเก็บตัวอย่างอากาศชนิดไฮโวลุ่ม (High Volume-Air Sampler) สกัดตะกั่วออกจากแผ่นกรองโดยใช้กรดดินประสิวและกรดเกลือ แล้วนำไปวัดค่าของตะกั่วโดยใช้เครื่องวัดระบบอะตอมมิก แอ็บซอร์ปชัน สเปกโตรมิเตอร์ หรือระบบอื่นที่กรมควบคุมมลพิษให้ความเห็นชอบ

ข้อ ๙ การวัดค่าเฉลี่ยของฝุ่นละอองรวมหรือฝุ่นละอองขนาดเล็กไม่เกิน ๑๐ ไมครอน ในเวลา ๒๔ ชั่วโมง หรือในเวลา ๑ ปี ให้ใช้วิธีการวัดตามระบบกราวิเมตริก หรือระบบอื่นที่กรมควบคุมมลพิษให้ความเห็นชอบ

ข้อ ๑๐ การวัดค่าเฉลี่ยของก๊าซหรือสารอย่างหนึ่งอย่างใดตามข้อ ๕ ถึงข้อ ๗ ให้ทำในบรรยากาศทั่วๆ ไป และต้องสูงจากพื้นดินอย่างน้อย ๓ เมตร แต่ไม่เกิน ๖ เมตร

การวัดค่าเฉลี่ยของตะกั่วและฝุ่นละอองตามข้อ ๘ และข้อ ๙ ให้ทำในบรรยากาศทั่วๆ ไป และต้องสูงจากพื้นดินอย่างน้อย ๑.๕๐ เมตร แต่ไม่เกิน ๖ เมตร

ประกาศ ณ วันที่ ๑๗ เมษายน พ.ศ. ๒๕๓๘

ชวน หลีกภัย

นายกรัฐมนตรี

ประธานคณะกรรมการสิ่งแวดล้อมแห่งชาติ

(ประกาศในราชกิจจานุเบกษา เล่ม ๑๑๒ ตอนที่ ๔๒ ง วันที่ ๒๕ พฤษภาคม ๒๕๓๘)

แก้คำผิด

ประกาศคณะกรรมการสิ่งแวดล้อมแห่งชาติ
ฉบับที่ ๑๐ (พ.ศ. ๒๕๓๘) ออกตามความในพระราชบัญญัติส่งเสริมและรักษา
คุณภาพสิ่งแวดล้อมแห่งชาติ พ.ศ. ๒๕๓๕

เรื่อง กำหนดมาตรฐานคุณภาพอากาศในบรรยากาศโดยทั่วไป
ซึ่งประกาศในราชกิจจานุเบกษา

ฉบับประกาศทั่วไป เล่ม ๑๑๒ ตอนที่ ๔๒ ง ลงวันที่ ๒๕ พฤษภาคม ๒๕๓๘

หน้า ๕๑ บรรทัดที่ ๑๕ คำว่า

“ไม่เกิน ๐.๑๕ มิลลิกรัม” ให้แก้เป็น

“ไม่เกิน ๐.๐๕ มิลลิกรัม”

(ประกาศในราชกิจจานุเบกษา เล่ม ๑๑๒ ตอนที่ ๗๑ ง วันที่ ๕ กันยายน ๒๕๓๘)

ประกาศคณะกรรมการสิ่งแวดล้อมแห่งชาติ

ฉบับที่ ๒๔ (พ.ศ. ๒๕๔๗)

เรื่อง กำหนดมาตรฐานคุณภาพอากาศในบรรยากาศโดยทั่วไป

อาศัยอำนาจตามความในมาตรา ๓๒ และมาตรา ๓๔ แห่งพระราชบัญญัติส่งเสริมและรักษาคุณภาพสิ่งแวดล้อมแห่งชาติ พ.ศ. ๒๕๓๕ อันเป็นพระราชบัญญัติที่มีบทบัญญัติบางประการเกี่ยวกับการจำกัดสิทธิและเสรีภาพของบุคคล ซึ่งมาตรา ๒๕ ประกอบกับมาตรา ๓๕ มาตรา ๔๘ มาตรา ๕๐ และมาตรา ๕๑ ของรัฐธรรมนูญแห่งราชอาณาจักรไทย บัญญัติให้กระทำได้โดยอาศัยอำนาจตามบทบัญญัติแห่งกฎหมาย คณะกรรมการสิ่งแวดล้อมแห่งชาติ จึงได้มีมติในคราวการประชุมครั้งที่ ๒/๒๕๔๗ เมื่อวันที่ ๒๔ กุมภาพันธ์ ๒๕๔๗ ให้ปรับปรุงแก้ไขมาตรฐานคุณภาพอากาศในบรรยากาศโดยทั่วไป ดังต่อไปนี้

ข้อ ๑ ให้ยกเลิกความใน (๔) ของข้อ ๒ แห่งประกาศคณะกรรมการสิ่งแวดล้อมแห่งชาติ ฉบับที่ ๑๐ (พ.ศ. ๒๕๓๘) ออกตามความในพระราชบัญญัติส่งเสริมและรักษาคุณภาพสิ่งแวดล้อมแห่งชาติ พ.ศ. ๒๕๓๕ เรื่อง กำหนดมาตรฐานคุณภาพอากาศในบรรยากาศโดยทั่วไป และให้ใช้ความต่อไปนี้แทน

“(๔) ค่าเฉลี่ยของก๊าซซัลเฟอร์ไดออกไซด์ ในเวลา ๒๔ ชั่วโมง จะต้องไม่เกิน ๐.๑๒ ส่วนในล้านส่วน หรือไม่เกิน ๐.๓๐ มิลลิกรัมต่อลูกบาศก์เมตร และค่ามัธยฐานเลขคณิต (Arithmetic Mean) ในเวลา ๑ ปี จะต้องไม่เกิน ๐.๐๔ ส่วนในล้านส่วน หรือไม่เกิน ๐.๑๐ มิลลิกรัมต่อลูกบาศก์เมตร”

ข้อ ๒ ให้ยกเลิกความใน (๒) และ (๓) ของข้อ ๔ แห่งประกาศคณะกรรมการสิ่งแวดล้อมแห่งชาติ ฉบับที่ ๑๐ (พ.ศ. ๒๕๓๘) ออกตามความในพระราชบัญญัติส่งเสริมและรักษาคุณภาพสิ่งแวดล้อมแห่งชาติ พ.ศ. ๒๕๓๕ เรื่อง กำหนดมาตรฐานคุณภาพอากาศในบรรยากาศโดยทั่วไปและให้ใช้ความต่อไปนี้แทน

“(๒) ค่าเฉลี่ยของฝุ่นละอองขนาดไม่เกิน ๑๐ ไมครอน ในเวลา ๒๔ ชั่วโมง จะต้องไม่เกิน ๐.๑๒ มิลลิกรัมต่อลูกบาศก์เมตร และค่ามัธยิมเลขคณิต (Arithmetic Mean) ในเวลา ๑ ปี จะต้องไม่เกิน ๐.๐๕ มิลลิกรัมต่อลูกบาศก์เมตร

(๓) ค่าเฉลี่ยของฝุ่นละอองรวมหรือฝุ่นละอองขนาดไม่เกิน ๑๐๐ ไมครอน ในเวลา ๒๔ ชั่วโมง จะต้องไม่เกิน ๐.๓๓ มิลลิกรัมต่อลูกบาศก์เมตร และค่ามัธยิมเลขคณิต (Arithmetic Mean) ในเวลา ๑ ปี จะต้องไม่เกิน ๐.๑๐ มิลลิกรัมต่อลูกบาศก์เมตร”

ประกาศ ณ วันที่ ๕ สิงหาคม พ.ศ. ๒๕๔๗

จาตุรนต์ ฉายแสง

รองนายกรัฐมนตรี

ปฏิบัติหน้าที่ประธานกรรมการสิ่งแวดล้อมแห่งชาติ

ประกาศคณะกรรมการสิ่งแวดล้อมแห่งชาติ

ฉบับที่ ๒๘ (พ.ศ. ๒๕๕๐)

เรื่อง กำหนดมาตรฐานคุณภาพอากาศในบรรยากาศโดยทั่วไป

โดยที่เป็นการสมควรปรับปรุงแก้ไขมาตรฐานคุณภาพอากาศในบรรยากาศโดยทั่วไปที่ได้กำหนดไว้แล้วให้เหมาะสมตามความก้าวหน้าในทางวิทยาศาสตร์ เทคโนโลยี และความเปลี่ยนแปลงทางเศรษฐกิจ และสังคมของประเทศ อาศัยอำนาจตามความในมาตรา ๓๔ แห่งพระราชบัญญัติส่งเสริมและรักษาคุณภาพสิ่งแวดล้อมแห่งชาติ พ.ศ. ๒๕๓๕ ประกอบกับคำสั่งสำนักนายกรัฐมนตรีที่ ๓๑/๒๕๕๐ ลงวันที่ ๑๒ มีนาคม ๒๕๕๐ และมีมติคณะกรรมการสิ่งแวดล้อมแห่งชาติในคราวการประชุมครั้งที่ ๒/๒๕๕๐ เมื่อวันที่ ๑๘ มกราคม พ.ศ. ๒๕๕๐ จึงปรับปรุงแก้ไขมาตรฐานคุณภาพอากาศในบรรยากาศโดยทั่วไป ไว้ดังต่อไปนี้

ข้อ ๑ ให้ยกเลิกความใน (๓) ของข้อ ๒ ของประกาศคณะกรรมการสิ่งแวดล้อมแห่งชาติ ฉบับที่ ๑๐ (พ.ศ. ๒๕๓๕) ออกตามความในพระราชบัญญัติส่งเสริมและรักษาคุณภาพสิ่งแวดล้อมแห่งชาติ พ.ศ. ๒๕๓๕ เรื่อง กำหนดมาตรฐานคุณภาพอากาศในบรรยากาศโดยทั่วไป ลงวันที่ ๑๓ เมษายน ๒๕๓๕ และให้ใช้ความต่อไปนี้แทน

“(๓) ค่าเฉลี่ยของก๊าซโอโซนในเวลา ๑ ชั่วโมง จะต้องไม่เกิน ๐.๑๐ ส่วนในล้านส่วน หรือไม่เกิน ๐.๒๐ มิลลิกรัมต่อลูกบาศก์เมตร และในเวลา ๘ ชั่วโมง จะต้องไม่เกิน ๐.๐๗ ส่วนในล้านส่วน หรือไม่เกิน ๐.๑๔ มิลลิกรัมต่อลูกบาศก์เมตร”

ข้อ ๒ ให้ยกเลิกความในข้อ ๖ ของประกาศคณะกรรมการสิ่งแวดล้อมแห่งชาติ ฉบับที่ ๑๐ (พ.ศ. ๒๕๓๕) ออกตามความในพระราชบัญญัติส่งเสริมและรักษาคุณภาพสิ่งแวดล้อมแห่งชาติ พ.ศ. ๒๕๓๕ เรื่อง กำหนดมาตรฐานคุณภาพอากาศในบรรยากาศโดยทั่วไป ลงวันที่ ๑๓ เมษายน ๒๕๓๕ และให้ใช้ความต่อไปนี้แทน

“ข้อ ๖ การวัดหาค่าเฉลี่ยของก๊าซในโตรเจนไดออกไซด์หรือก๊าซโอโซน ให้ดำเนินการดังนี้

(๑) การวัดหาค่าเฉลี่ยของก๊าซในโตรเจนไดออกไซด์ในเวลา ๑ ชั่วโมง ให้ใช้เครื่องวัดระบบเคมีลูมิเนสเซน หรือระบบอื่นที่กรมควบคุมมลพิษให้ความเห็นชอบ และ

(๒) การวัดค่าเฉลี่ยของก๊าซโอโซนในเวลา ๑ ชั่วโมง หรือในเวลา ๘ ชั่วโมง ให้ใช้
เครื่องวัดระบบเคมีลูมิเนสเซน หรือระบบอื่นที่กรมควบคุมมลพิษให้ความเห็นชอบ”

ประกาศ ณ วันที่ ๑๐ เมษายน พ.ศ. ๒๕๕๐

โสมสิต ปันเปี่ยมรัชฎ์

รองนายกรัฐมนตรี

ประธานกรรมการสิ่งแวดล้อมแห่งชาติ

ประกาศคณะกรรมการสิ่งแวดล้อมแห่งชาติ

ฉบับที่ ๓๓ (พ.ศ. ๒๕๕๒)

เรื่อง กำหนดมาตรฐานค่าก๊าซไนโตรเจนไดออกไซด์ในบรรยากาศโดยทั่วไป

โดยที่เป็นการสมควรกำหนดมาตรฐานค่าก๊าซไนโตรเจนไดออกไซด์ในบรรยากาศโดยทั่วไป เพื่อเป็นเกณฑ์ทั่วไปสำหรับการส่งเสริมและรักษาคุณภาพสิ่งแวดล้อมตามพระราชบัญญัติส่งเสริมและรักษาคุณภาพสิ่งแวดล้อมแห่งชาติ พ.ศ. ๒๕๓๕

อาศัยอำนาจตามความในมาตรา ๓๒ (๔) และมาตรา ๓๔ แห่งพระราชบัญญัติส่งเสริมและรักษาคุณภาพสิ่งแวดล้อมแห่งชาติ พ.ศ. ๒๕๓๕ อันเป็นพระราชบัญญัติที่มีบทบัญญัติบางประการเกี่ยวกับการจำกัดสิทธิและเสรีภาพของบุคคล ซึ่งมาตรา ๒๙ ประกอบกับมาตรา ๓๓ มาตรา ๓๔ มาตรา ๔๑ และมาตรา ๔๓ ของรัฐธรรมนูญแห่งราชอาณาจักรไทย บัญญัติให้กระทำได้ โดยอาศัยอำนาจตามบทบัญญัติแห่งกฎหมาย คณะกรรมการสิ่งแวดล้อมแห่งชาติจึงออกประกาศ กำหนดมาตรฐานค่าก๊าซไนโตรเจนไดออกไซด์ในบรรยากาศโดยทั่วไปไว้ ดังต่อไปนี้

ข้อ ๑ ในประกาศนี้

“เครื่องวัดระบบเคมีลูมิเนสเซน” (Chemiluminescence) หมายความว่า เครื่องมือวัดค่าก๊าซไนโตรเจนไดออกไซด์โดยใช้ก๊าซโอโซนทำปฏิกิริยากับก๊าซไนตริกออกไซด์ซึ่งถูกเปลี่ยนมาจากก๊าซไนโตรเจนไดออกไซด์แล้ววัดความเข้มของแสงซึ่งเกิดจากปฏิกิริยานั้น ณ ที่ความยาวคลื่นที่สูงกว่า ๖๐๐ นาโนเมตร (Nanometer)

ข้อ ๒ ให้ยกเลิก

(๑) ความใน (๒) ของข้อ ๒ แห่งประกาศคณะกรรมการสิ่งแวดล้อมแห่งชาติ ฉบับที่ ๑๐ (พ.ศ. ๒๕๓๘) ออกตามความในพระราชบัญญัติส่งเสริมและรักษาคุณภาพสิ่งแวดล้อมแห่งชาติ พ.ศ. ๒๕๓๕ เรื่อง กำหนดมาตรฐานคุณภาพอากาศในบรรยากาศโดยทั่วไป

(๒) ความใน (๑) ของข้อ ๖ แห่งประกาศคณะกรรมการสิ่งแวดล้อมแห่งชาติ ฉบับที่ ๑๐ (พ.ศ. ๒๕๓๘) ออกตามความในพระราชบัญญัติส่งเสริมและรักษาคุณภาพสิ่งแวดล้อมแห่งชาติ พ.ศ. ๒๕๓๕ เรื่อง กำหนดมาตรฐานคุณภาพอากาศในบรรยากาศโดยทั่วไป แก้ไขเพิ่มเติมโดย ประกาศคณะกรรมการสิ่งแวดล้อมแห่งชาติ ฉบับที่ ๒๘ (พ.ศ. ๒๕๕๐) เรื่อง กำหนดมาตรฐานคุณภาพอากาศในบรรยากาศโดยทั่วไป

ข้อ ๓ ให้กำหนดมาตรฐานค่าก๊าซไนโตรเจนไดออกไซด์ในบรรยากาศโดยทั่วไปไว้ดังต่อไปนี้

(๑) ค่าเฉลี่ยของก๊าซไนโตรเจนไดออกไซด์ในเวลา ๑ ชั่วโมง จะต้องไม่เกิน ๐.๑๗ ส่วนในล้านส่วนหรือไม่เกิน ๐.๓๒ มิลลิกรัมต่อลูกบาศก์เมตร

(๒) ค่ามัชฌิมเลขคณิต (Arithmetic Mean) ของก๊าซไนโตรเจนไดออกไซด์ในเวลา ๑ ปี จะต้องไม่เกิน ๐.๐๓ ส่วนในล้านส่วน หรือไม่เกิน ๐.๐๕๗ มิลลิกรัมต่อลูกบาศก์เมตร

ข้อ ๔ การคำนวณค่าความเข้มข้นของก๊าซไนโตรเจนไดออกไซด์ในบรรยากาศโดยทั่วไปให้คำนวณเทียบที่ความดัน ๑ บรรยากาศ และอุณหภูมิ ๒๕ องศาเซลเซียส

ข้อ ๕ การวัดค่าเฉลี่ยของก๊าซไนโตรเจนไดออกไซด์ในเวลา ๑ ชั่วโมง หรือค่ามัชฌิมเลขคณิต (Arithmetic Mean) ในเวลา ๑ ปี ให้ใช้เครื่องวัดระบบเคมีลูมิเนสเซน หรือระบบอื่นที่กรมควบคุมมลพิษให้ความเห็นชอบ

ประกาศ ณ วันที่ ๑๗ มิถุนายน พ.ศ. ๒๕๕๒

อภิสิทธิ์ เวชชาชีวะ

นายกรัฐมนตรี

ประธานกรรมการสิ่งแวดล้อมแห่งชาติ

ประกาศคณะกรรมการสิ่งแวดล้อมแห่งชาติ

ฉบับที่ ๓๖ (พ.ศ. ๒๕๕๓)

เรื่อง กำหนดมาตรฐานฝุ่นละอองขนาดไม่เกิน ๒.๕ ไมครอน ในบรรยากาศโดยทั่วไป

โดยที่เป็นการสมควรกำหนดมาตรฐานค่าฝุ่นละอองขนาดไม่เกิน ๒.๕ ไมครอน ในบรรยากาศโดยทั่วไป เพื่อเป็นเกณฑ์ทั่วไปสำหรับการส่งเสริม และรักษาคุณภาพสิ่งแวดล้อม ตามพระราชบัญญัติส่งเสริมและรักษาคุณภาพสิ่งแวดล้อมแห่งชาติ พ.ศ. ๒๕๓๕

อาศัยอำนาจตามความในมาตรา ๓๒ (๔) และมาตรา ๓๔ แห่งพระราชบัญญัติส่งเสริม และรักษาคุณภาพสิ่งแวดล้อมแห่งชาติ พ.ศ. ๒๕๓๕ อันเป็นพระราชบัญญัติที่มีบทบัญญัติ บางประการเกี่ยวกับการจำกัดสิทธิและเสรีภาพของบุคคล ซึ่งมาตรา ๒๙ ประกอบกับมาตรา ๓๓ มาตรา ๓๔ มาตรา ๔๑ และมาตรา ๔๓ ของรัฐธรรมนูญแห่งราชอาณาจักรไทย บัญญัติให้กระทำได้ โดยอาศัยอำนาจตามบทบัญญัติแห่งกฎหมาย คณะกรรมการสิ่งแวดล้อมแห่งชาติจึงออกประกาศ กำหนดมาตรฐานค่าฝุ่นละอองขนาดไม่เกิน ๒.๕ ไมครอน ในบรรยากาศโดยทั่วไปไว้ ดังต่อไปนี้

ข้อ ๑ กำหนดมาตรฐานฝุ่นละอองขนาดไม่เกิน ๒.๕ ไมครอน ในบรรยากาศโดยทั่วไป ค่าเฉลี่ยในเวลา ๒๔ ชั่วโมง จะต้องไม่เกิน ๐.๐๕ มิลลิกรัมต่อลูกบาศก์เมตร และค่ามัธยิมเลขคณิต (Arithmetic Mean) ในเวลา ๑ ปี จะต้องไม่เกิน ๐.๐๒๕ มิลลิกรัมต่อลูกบาศก์เมตร

ข้อ ๒ วิธีตรวจวัดค่าเฉลี่ยของฝุ่นละอองขนาดไม่เกิน ๒.๕ ไมครอน ตามข้อ ๑ ให้ใช้ วิธีตรวจวัดมาตรฐาน Federal Reference Method (FRM) ตามที่องค์การพิทักษ์สิ่งแวดล้อม แห่งประเทศสหรัฐอเมริกา (US EPA) กำหนดหรือวิธีอื่นที่กรมควบคุมมลพิษประกาศในราชกิจจานุเบกษา

ข้อ ๓ การตรวจวัดค่าเฉลี่ยของฝุ่นละอองขนาดไม่เกิน ๒.๕ ไมครอน ตามข้อ ๒ ให้ทำ ในบรรยากาศทั่วๆ ไป และต้องสูงจากพื้นดินอย่างน้อย ๑.๕๐ เมตร แต่ไม่เกิน ๖ เมตร

ประกาศ ณ วันที่ ๒๘ มกราคม พ.ศ. ๒๕๕๓

อภิสิทธิ์ เวชชาชีวะ

นายกรัฐมนตรี

ประธานกรรมการสิ่งแวดล้อมแห่งชาติ

2) เกณฑ์ความเข้มข้นก๊าซคาร์บอนไดออกไซด์ในเขตเมืองกรุงโรม
ประเทศอิตาลี โดย I. Pigliautile, et al.

Article

Investigation of CO₂ Variation and Mapping Through Wearable Sensing Techniques for Measuring Pedestrians' Exposure in Urban Areas

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Abstract: Citizens' wellbeing is mainly threatened by poor air quality and local overheating due to human-activity concentration and land-cover/surface modification in urban areas. Peculiar morphology and metabolism of urban areas lead to the well-known urban-heat-island effect, characterized by higher air temperature in cities than in their surroundings. The environmental mapping of the urban outdoors at the pedestrian height could be a key tool to identify risky areas for humans in terms of both poor-air-quality exposure and thermal comfort. This study proposes urban environment investigation through a wearable miniaturized weather station to get the spatial distribution of key parameters according to the citizens' perspective. The innovative system monitors and traces the field values of carbon dioxide (CO₂) concentration, such as air temperature and wind-speed values, which have been demonstrated to be related to outdoor wellbeing. The presented monitoring campaign focused on a two-way, two-lane road in Rome (Italy) during traffic rush hours on both working days and weekends. Collected data were analyzed with respect to timing and position, and possible correlations among different variables were examined. Results demonstrated the wearable system capability to catch pedestrian-exposure variability in terms of CO₂ concentration and local overheating due to urban structure, highlighting potentials in the citizens' involvement as observation vectors to extensively monitor urban environmental quality.

Keywords: microclimate; CO₂ monitoring; urban heat island; monitoring; wearable sensing; outdoor comfort

1. Introduction

World urban-population growth and urban built-up expansion are internationally recognized and consolidated trends [1], particularly intense in developing countries [2]. This demographic tendency means that an increasing number of people will live in urban areas where impervious surfaces generally replace natural ground, altering local energy balance [3,4]. Increasing concentration of anthropogenic actions and activities is further responsible for air-quality deterioration and contributes to local overheating [5,6]. In this view, in 2015, the Member States of the United Nations committed to implementing the 2030 Agenda for Sustainable Development [7], including the economic, social, and environmental fields of sustainable development. The Agenda is based on 17 universal Sustainable Development Goals (SDGs), aimed at reducing inequality and improving living standards all around the globe, and always keeping high attention on sustainability [8]. The urban sustainability concept is thus gaining increasing attention among the scientific community and urban planners, as reported by Shen et al. [9]. Within this framework, governments have to promote urgent actions to fight climate

change and its impact on humans' life quality and well-being, and the improvement of urban air quality is a key point in achieving the proposed SDGs [10–14].

Regarding the pollutant emissions, some research has underlined that transport (including the movement of people and goods by cars, trucks, trains, ships, airplanes, and other vehicles) is one of the main sectors for the emission of the Greenhouse Gases (GHGs) [15]. Garceau [16] demonstrated, through long-term monitoring of air pollutants, that introduction of roundabouts allowed decreasing PM_{2.5} concentrations up to 40% in the case study of Kneehill, New Hampshire (USA). The municipality of Potsdam (Germany) introduced specific traffic-reducing measures in 2017, and Schmitz et al. [17] investigated the public acceptance of the implemented actions by means of questionnaire submission. The study highlighted that individual awareness of the air-quality problem was the most important predictor of community support. Moreover, the European Commission has defined an important CO₂ vehicle-emission-reduction project, setting the limit value for the New European Driving Cycle (NEDC) of 95 g/km of CO₂ to be reached before 2021 [18].

Urban areas, and thus citizens, are particularly vulnerable to pollutant exposure since the urban form alters wind patterns, producing wind-calm or vortex zones [19], and pollutant sources are mainly concentrated in urbanized areas, such as vehicular traffic, industrial activities, heating systems, and commercial areas. Thanks to rising awareness and recent emission-reduction standards, important improvements have been achieved worldwide in terms of air quality, but pollutant-concentration limit values still exceed the Air-Quality Standards' threshold values in several cities [20–23]. These standards mainly focus on PM₁₀, PM_{2.5}, NO_x, and SO_x concentration monitoring, while CO₂ is not commonly mentioned as a pollutant since it is harmful to human beings only at very high concentration levels, that is, equal to or above 2%, as specified by Langford [24]. Nevertheless, high CO₂ emissions cause severe damage to human health [25–27], and variations of its concentration levels below the urban canopy could represent the existence of punctual anthropogenic sources which may be threatening the environmental quality of the outdoors. Accordingly, CO₂ concentration could be assumed as representative of the air quality [28].

Furthermore, cities are affected by the well-known phenomenon of the Urban Heat Island (UHI) [29,30] due to their morphological peculiarities, land surface cover and usage, and lack of greenery [31]. This specific microclimate characteristic mainly occurs in the higher air temperatures detected in the urban areas with respect to rural surroundings, but it also further deteriorates the air quality of urban spaces, altering city photochemistry [32] and affecting atmospheric circulation [33]. The relationship between microclimate features, such as air temperature, solar radiation, wind speed, air pollution, and urban morphology, can be understood through a detailed analysis of the temporal and spatial distribution of the Urban-Heat-Island Intensity (UHII) [34] which numerically expresses the impact on microclimate due to urban environment. High values of UHII compromise citizens' everyday commuting, open-air activities, and dwellers' well-being, in general [35,36].

Zhang et al. [37] considered a diagnostic methodology to evaluate the UHI effect in Xi'an, a Chinese city. They proposed a model to estimate the maximum UHI intensity on the basis of real meteorology data of a rural station, analyzing the link between UHI and the city morphology. Pakarnseree et al. [38] highlighted the importance of considering, in buildings, such physical features as the Water Surface Ratio (WSR), Street Surface Ratio (SSR), Park Surface Ratio (PSR), Building Coverage Ratio (BCR), and Floor Area Ratio (FAR) that strongly influence the presence of the UHI issue in the Bangkok area. Li et al. [39] underlined the interaction between the UHI and the Urban Pollution Island (UPI) by analyzing their effects on the environment during summer in Berlin, focusing on various risky aspects that made citizens more vulnerable during hotter seasons. Rizvi et al. [40] showed the existence of UHI in a city in the Pakistan zone and analyzed the effects of its interaction with Heat Waves (HWs) which are foreseen to be more intense and frequent in the next decades due to climate change [41]. The sensitivity of the existing synergy between HWs and UHI was investigated through climate modelling by Zhao et al. in [42], even in future climate scenarios. The relationship between microclimate parameters in urban zones and the effects of global warming were analyzed by Sun et al. [43]. Gu and

Li [44] evaluated the impact of precipitation on the intensity of UHI in the continental United States at microclimate scales. Jato-Espino [45] analyzed the impact of UHI in the Mediterranean area by means of statistical analysis, considering the value of the daily thermal fluctuations.

The common practice of urban environmental monitoring is conducted by means of fixed monitoring-station networks [46,47] properly designed in order to optimize monitoring costs, that is, the instruments, installation and maintenance, and spatial coverage [48]. Nevertheless, the high heterogeneity of city landscapes leads to highly granular microclimatic conditions which could not be detected by those networks due to their dimensions [49]. Furthermore, weather stations are generally located above roof levels, and such position does not allow to catch the pedestrians' perspective in the urban environment, losing information for an accurate evaluation of citizens' life quality and well-being. Spatial distribution of anthropogenic activities, which could be assumed as punctual or linear sources of pollutants, produces different air quality levels at the pedestrian height throughout cities [50] that could not be highlighted from common station networks either.

Therefore, experimental data collection below the urban canopy is fundamental to map the urban environment in terms of site-specific microclimate conditions and air-quality personal exposure. To guarantee citizens' health and security, the current challenge is to study more and more sophisticated monitoring systems and methods for real-time evaluation of the urban-microclimate spatial pattern.

Nowadays, the scientific community is moving in this direction, focusing on collecting environmental data at a high spatial resolution, taking advantage of advances in technology and communication sectors [51–53]. Dominguez et al. [54] developed a cloud platform to integrate different typologies of environmental-sensor networks with a sensor web providing urban air and noise pollution data to common citizens. Pedestrians can thus decide how to move around the city on the basis of pollutant spatial distribution, as proposed by Dhingra et al.'s IoT-Mobair application [55].

Considering this scenario, the current work moved from previous contributions of the authors [56–58] to further investigate monitoring potentials of an experimental innovative system in terms of urban CO₂-level mapping. In particular, CO₂ concentration was assumed as an indicator of existing anthropogenic activities in the investigated area [59] that may affect the environmental quality at the pedestrian height which cannot be highlighted by common fixed monitoring stations. Taking advantage of the improvements in wearable sensing techniques [60], pedestrians became predominant observational vectors allowing to accomplish a twofold aim: (i) to increase monitoring network coverage, and (ii) to focus data collection on humans exposed to urban environmental conditions. In particular, the developed system was a miniaturized weather station which could be settled on a common bike helmet due to its small size and light weight. The adoption of a wearable sensing technique also allowed to monitor the quality of the urban environment across areas which were not approachable by vehicles that were the most common observation vectors. Moreover, the monitoring perspective was that of the pedestrian, thus data collected through this method were strictly related to the real perception of dwellers living in the outdoor spaces of the city. As the key research progress with respect to previous works, here the focus was also on CO₂-concentration mapping through wearable sensing techniques, which are considered to be an innovative tool for identifying air quality as specifically perceived by pedestrians in dense and polluted urban areas [61]. In addition, CO₂ concentration, even at a very local scale, may be correlated to an increase in premature mortality. CO₂ local increase in concentration was indeed correlated to an increase in ozone concentration and particulate matter. In this view, even more importantly, specific granular, localized CO₂-concentration-mitigation strategies may also be helpful in reducing local air-pollution mortality, even if CO₂ is not specifically controlled in adjacent regions [62].

The experimental set-up with the basic information on the prototype design, embedded sensors accuracy and system recording mode, and a description of the planned monitoring for the CO₂ concentration analysis across the case study area are presented in Section 2. The monitoring system was tested by planning a monitoring campaign focused on the limited area of Rome (Italy) which is described in Section 3. Finally, the obtained monitoring results are discussed, showing detected CO₂

spatial distribution and pointing out correlations among the monitored gas particles, other collected environmental parameters, and site-specific characteristics.

2. Material and Methods

The experimental campaign focused on a heavy-traffic urban road which was monitored during peak rush hours, i.e., around 9:30 a.m. and 6:30 p.m., by means of a miniaturized weather station settled on a common bike helmet. The observer was always the same person throughout the whole monitoring campaign, thus the worn station was always at the same height, i.e., sensors platform was at about 180 cm in height, and the walking speed was kept constant as much as possible going along the selected road from A to B and backward. The designed monitoring system and the planned monitoring campaign are described in the following subsections.

2.1. Monitoring System

The monitoring system was a miniaturized weather station specifically designed in order to be worn by pedestrians or city bikers and thus to catch the perspective of these weak categories within the urban environment. The system monitored the main environmental parameters such as air temperature, relative humidity, wind speed and direction, solar radiation, illuminance level, and CO₂ concentration. Table 1 reports technical specifications of the embedded sensors in terms of data accuracy which was acceptable considering the small size of the whole system.

Table 1. Technical specifics of the embedded sensors.

Monitored Parameter	Technical Specifications
Air Temperature (Ta) [°C]	Operation range: $-40 < T_a < +85^{\circ}\text{C}$ Absolute accuracy: $\pm 0.5^{\circ}\text{C}$ at 25°C
Relative Humidity (RH) [%]	Absolute tolerance: $\pm 3\%$
Atmospheric Pressure (Pa) [hPa]	Operation range: $300 < P_a < 1100 \text{ hPa}$ Sensitivity error: $\pm 0.25\%$
Global Solar Radiation (SR) [W/m^2]	Spectral range: $360 < S_R < 1120 \text{ nm}$ Calibration uncertainty: $\pm 5\%$
Lighting (E) [lux]	Spectral error: 2.3%
Wind Speed (ws) [m/s]	Operational range: $0.25 < E < 40 \text{ m/s}$ Resolution: 0.1 m/s Sensitivity: 0.13 m/s
Wind Direction (wd) [deg]	Resolution: 1° Sensitivity: $\pm 1^{\circ}$
CO ₂ Concentration (CO ₂) [ppm]	Accuracy: $\pm 2\%$ full scale at 20°C and 1000 hPa

Data were collected every two seconds, and each observation was associated with GPS coordinates, i.e., latitude, longitude, elevation, and attitude (roll, pitch, and yaw). The GPS horizontal spatial accuracy was 2.5m. The operator communicated with the system through a Wi-Fi access point which was automatically generated by the system when it was switched on. The Wi-Fi connection allows to check data in real time and manage data-recording sessions from a smartphone or other portable device. The authors have already presented the monitoring system validation and its potentials in detecting critical conditions for citizens in terms of thermal comfort in [56,57].

2.2. Monitoring Campaign and Data Analysis

The monitoring campaign aimed to statistically characterize a heavy-traffic urban road in terms of CO₂ concentration according to the pedestrian perspective.

In this view, the designed campaign consisted of several repetitions of the same path in different days in order to compute means and fluctuations of the parameter in the specific area and thus to verify the monitoring system's capability in detecting CO₂ punctual or linear sources, most probably related to intense anthropogenic activities in urban contexts [58]. All the monitoring sessions were carried out

during the same month (March 2019) to avoid a significant effect of collected data fluctuation due to the seasonal cycle of the gas.

In particular, the observer covered the same path from point A to point B and backward along the selected road several times throughout the month, always during traffic rush hours, i.e., around 9:30 a.m. and 6:30 p.m. The presented monitoring campaign comprised 16 continuously monitored transects consisting of eight sessions at 9:30 a.m. and eight sessions at 6:30 p.m.; five out of the 16 conducted sessions concerned weekend days, as summarized in Table 2. In this way, a comparative assessment of the two traffic-dependent conditions was possible.

Table 2. Performed monitoring sessions.

Time	Number of Monitoring Sessions		
	9:30 a.m.	6:30 p.m.	
Weekdays	6	5	11
Weekend days	2	3	5
	8	8	Total: 16

The monitoring repetitions allowed to collect a significant amount of data and to analyze both the background level and the events-related spatial distributions of the analyzed gas. In particular, datasets collected during each monitoring session were analyzed in terms of detected minimum and maximum values, and the average and standard deviation of the data distribution. The same statistical analysis was performed on the whole collected population of data and two data partitions outlined following two different criteria: (i) morning and afternoon campaigns, and (ii) weekdays and weekends.

Finally, correlations between detected CO₂ concentration and other environmental parameters, i.e., air temperature and wind speed, were investigated since possible significant dependencies would support the analysis of the CO₂-level dispersion throughout the monitored area. All the presented data were simultaneously collected by the same wearable station described in the previous section.

3. Case Study

The case study was selected in order to be a relatively “short” transect of the city that could be (i) easily accessible by the researcher wearing the system and (ii) covered in a limited time span in order to avoid time-related fluctuations of the monitored parameters in each single monitoring session. Furthermore, the selected area had to present a clearly defined morphology, i.e., unique orientation and almost-constant aspect ratio, in order to avoid any possible fluctuations of the parameter which could be imputed to different configurations of the crossed area. All the observed variations were thus to be imputed to punctual sources existing in the area or to mutual dependencies among different environmental parameters.

Given the presented constraints, the specific case study was in a moderately polluted area, according to the reports of the Regional Environmental Protection Agency [63], connecting one of the two main railway stations in Rome to one of the functional hubs of the city.

The case study comprised two carriageways, both of two lanes covering a road of 450 meters in length in Rome (Italy) and connecting two squares which were generally congested during traffic rush hours, around 9:30 a.m. and 6:30 p.m. The monitoring path started and finished in the Southern square. The operator covered both the roadsides and a single monitoring session comprising forward and backward routes, i.e., total length of each session of about 900 meters. The walking average speed was 6 km/h, and it ensured a dataset of about 260 observations for each performed session. Figure 1a and b shows the monitored area scheme and the conducted monitoring campaign, respectively.

The monitored road intersected at two points by secondary roads. These were one-way, one-lane streets, and both intersections with the main road under study were regulated by traffic lights. Therefore, it was common to face frequent acceleration and deceleration of traffic speed along the selected road with a consequent increment of vehicle emissions in the area.

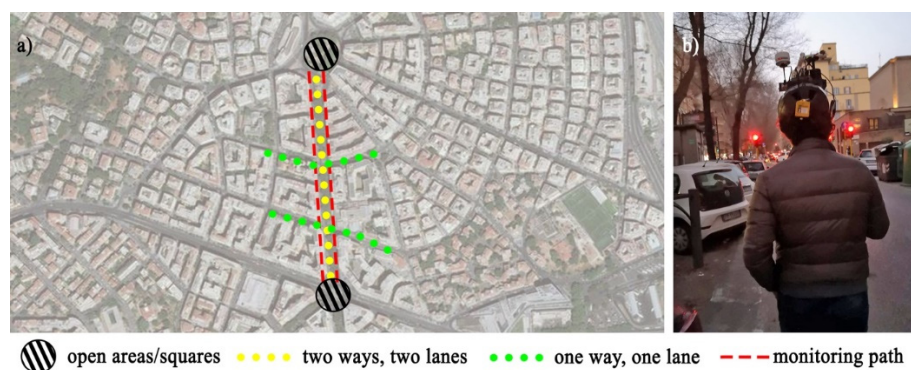


Figure 1. (a) Monitored area scheme; (b) conducted monitoring campaign.

4. Results and Discussion

Human exposure to varying carbon dioxide concentration was investigated in terms of CO₂ geospatial distribution and combining detected pollutant levels with air temperature and wind speed monitored data. In particular, CO₂ concentration analysis was correlated with each specific session of monitoring, day of the week (weekends and working days), timing during the course of the day, and position along the path, with particular attention to crossroads points, which have been demonstrated to exacerbate pedestrians' wellbeing, as showed in previous studies [64]. In detail, Figure 2 shows the spatial distribution of the collected CO₂ concentration along the monitored route for each monitoring session, both forward and backward. Evident massive variability of carbon-dioxide-concentration levels was visualized by means of the proposed techniques. Monitoring sessions 1 and 2 (both tests) and monitoring session 6 in the afternoon refer to weekends showing a relatively weaker anthropogenic pressure, compared to most weekdays. Non-negligible local increase of concentration was focused in specific spots with no clear instant correlation to crossroads (highlighted sections) and in specific peak times, even within the same monitoring round. Results demonstrated how highly detailed and granular data are required to be integrated into classic weather stations' data, since the variability of air-quality related parameters was strongly affected by the local and temporary phenomena, affecting pedestrians' wellbeing.

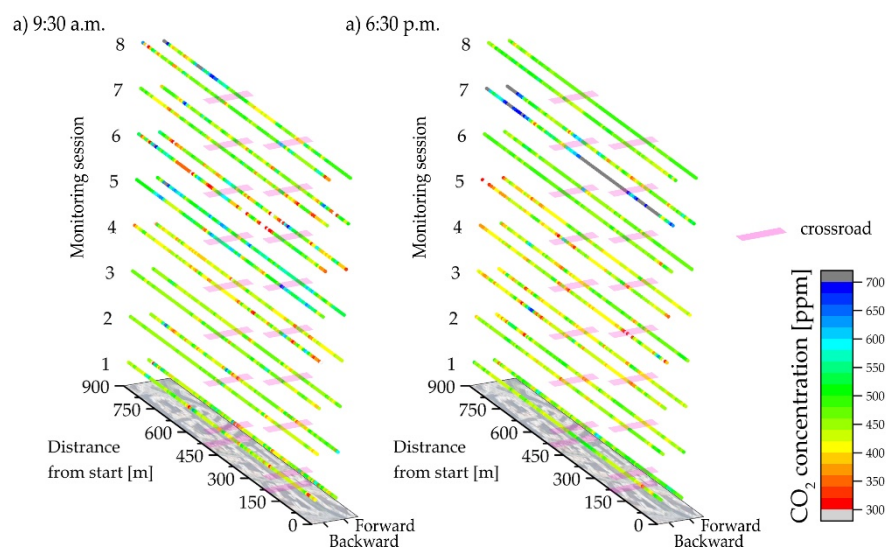


Figure 2. Spatial distribution of CO₂ concentration as collected during the performed monitoring sessions at (a) 9:30 a.m., and (b) 6:30 p.m.

Table 3 shows that the single-session averages throughout the several performed campaigns assumed similar values around 450 ppm, ranging in between a minimum of 419 ppm and a maximum of 592 ppm. Nevertheless, between the total 16 sessions, two of these (session 5 at 9:30 a.m. and session 7 at 6:30 p.m.) were clearly out of the common concentration profile, presenting higher CO₂ concentration baseline, i.e., an average value of 524 and 592 ppm, respectively. This fact can be explained considering that both sessions were monitored during working days when the maximum flux was concentrated at rush hour.

Table 3. Statistical descriptors of datasets collected in each monitoring session.

	Monitoring Session							
9.30 am	1	2	3	4	5	6	7	8
Min [ppm]	290	330	360	260	350	190	160	290
Max [ppm]	620	710	570	600	800	750	700	790
Ave [ppm]	441	445	448	419	524	441	449	479
St. Dev. [ppm]	49	44	27	44	65	95	60	78
6.30 pm	1	2	3	4	5	6	7	8
Min [ppm]	350	300	310	230	260	350	340	390
Max [ppm]	610	540	660	620	560	610	1340	550
Ave [ppm]	458	442	425	430	419	462	592	469
St. Dev. [ppm]	38	35	44	51	41	27	205	27

For a better understanding, correlation to other physical parameters is here discussed.

CO₂ variability (i) in space for the whole 9:30 a.m. and 6:30 p.m. monitoring sessions, and (ii) during every single session are expressed simultaneously by graphs in Figure 3 on the *xz* and *yz* planes, respectively. Moreover, each observation was associated with the collected air temperature (Figure 3a,b) and wind speed (Figure 3c,d) values by color plots. The space variation, along the *x*-axis, is expressed in terms of absolute distance between the specific observation location and the starting point of the monitoring path in meters. Locations of the two crossroads are highlighted on the *xz* planes of the graphs.

The highest peaks of CO₂ were observed during monitoring session 7 at 6:30 p.m. when the collected dataset standard deviation rose up to 205 ppm. The CO₂ peaks were detected in the proximity of the Northern crossroads and at the beginning of the monitoring path, i.e., when the operator was still in the Southern square. Moreover, such CO₂ peaks occurred almost simultaneously with the highest detected air temperatures and low values of wind speed, responsible for buoyancy and stagnation.

The same Figure 3a,b also shows interesting data in terms of air-temperature overheating. An increase in air temperature was registered during the afternoons when a more compact temperature distribution was monitored, imputable to local anthropogenic actions. In fact, morning air temperature was still dependent on weather conditions, which were relatively buffered in the afternoons due to UHI perceived at the pedestrian level. The only exception is the monitoring number 7, when both the morning and the afternoon sessions showed comparable values with an average temperature of 18.2 °C and 17.7 °C, respectively. This condition could be imputed to hotter conditions experienced during the day, able to dominate the local UHI effect.

Figure 4 shows the CO₂ concentration with respect to both air temperature (Figure 4a) and wind speed (Figure 4b), considering the whole collected data to better underline possible existing correlations among the presented data. The CO₂ dispersion fluctuated around the average value, i.e., 459 ppm, representative of the monitored area level of pollution. CO₂ values above 1000 ppm were observed only for air temperatures between 17.6 °C and 19.0 °C and wind speed below 1.3 m/s, suggesting the occurrence of air stagnation.

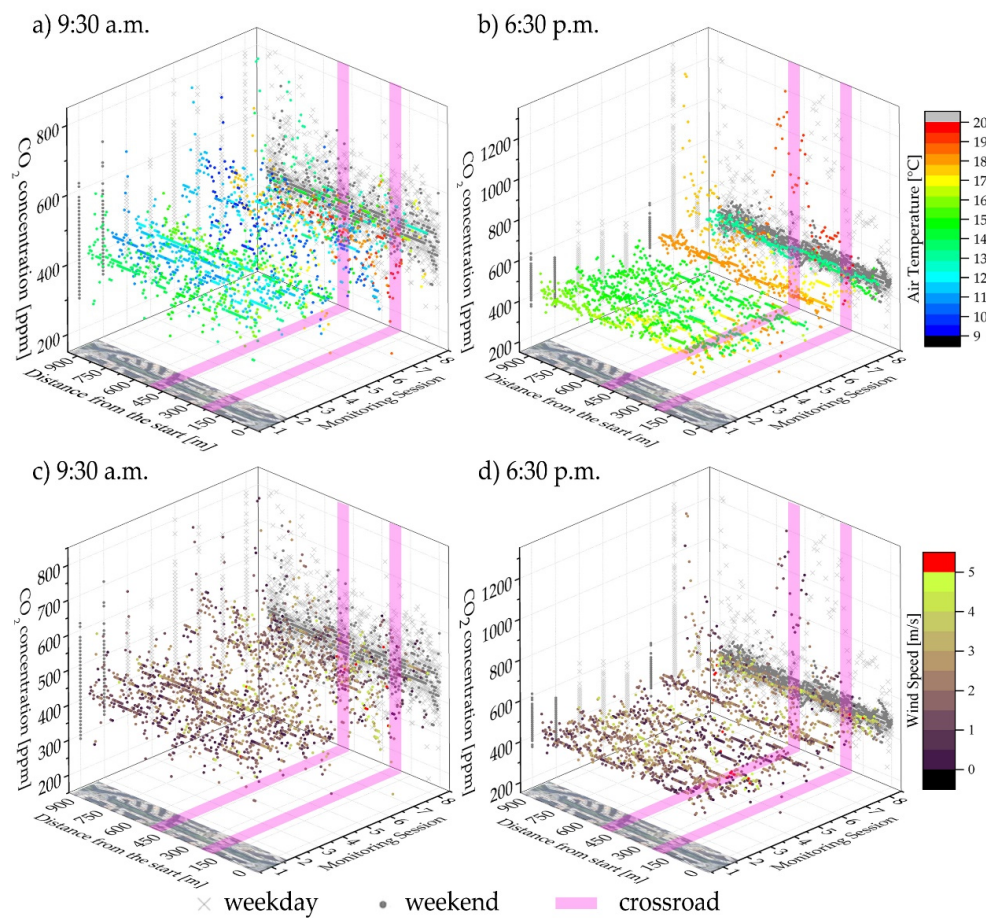


Figure 3. CO₂ concentration and air temperature with respect to the distance from the starting point for each session conducted at (a) 9.30 am and (b) 6.30 p.m.; CO₂ concentration and wind speed with respect to the distance from the starting point for each session conducted at (c) 9.30 a.m. and (d) 6.30 p.m.

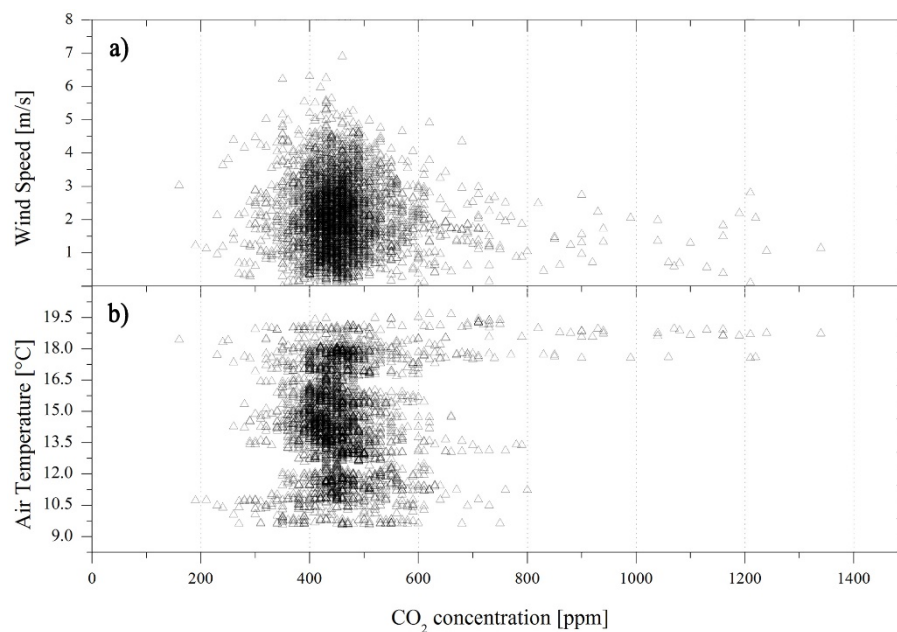


Figure 4. CO₂-concentration distribution with respect to (a) wind speed and (b) air temperature for the whole collected data.

The detected CO₂ dispersion across the monitored road is statistically analyzed in Figure 5, by taking into account the two day-time monitoring sessions, i.e., 9:30 a.m. and 6:30 p.m., and distinguishing between working days and weekends. The continuous horizontal lines in the graphs represent CO₂ data range out of what observations can be considered outliers. In particular, outliers were defined from the interquartile range (IQR), which is the difference between the third (Q₃) and the first (Q₁) quartile of the dataset, i.e., 75th and 25th percentiles, respectively, as reported in Figure 5.

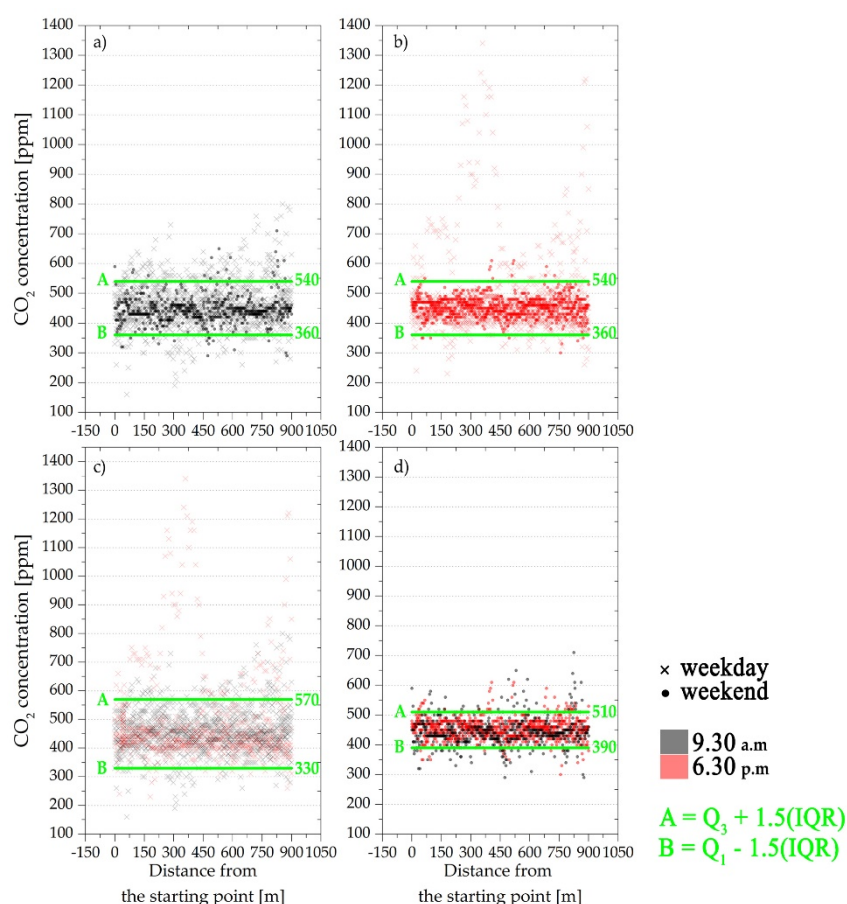


Figure 5. CO₂ distribution with respect to the latitude of the (a) 9:30 a.m., (b) 6:30 p.m., (c) weekdays, and (d) weekends monitoring sessions.

The monitoring sessions performed in the morning and in the afternoon did not show any significant differences in terms of the sample distribution. The upper and lower outlier limits were the same for both obtained datasets, i.e., 360 and 540 ppm, respectively. On the other hand, the collected CO₂ range seemed less disperse during the weekends with respect to weekdays. Therefore, the peak daily hours may be defined as having similar air quality conditions, even if they are characterized by different levels of UHI, as previously shown. These observations were in line with the choice of the monitoring times as the two traffic rush hours throughout a working day. In addition, the weekday traffic may be responsible for important peaks of CO₂-concentration increase, which were not visible during the weekends, where the anthropogenic action in terms of CO₂-concentration increase was more compact and narrowly distributed.

5. Conclusions

The study of physical environmental parameters influencing the pollutant dispersion in urban areas plays a key role in achieving the main sustainable goals that are fixed in the 2030 Agenda for

Sustainable Development. These variables are also important for determining population well-being in urban areas affected by anthropogenic actions, responsible for urban heat island and local climate change. In this view, this work presents the original results coming from the novel adoption of a wearable sensing device meant to map environmental parameters' (including CO₂ concentration) spatial distribution in the urban environment from the pedestrian perspective. Citizens have an active role in environmental mapping of the urban spaces. The above-mentioned device was placed on a common bike helmet and the environmental information collected by the system was linked to geographic coordinates by means of a GPS antenna embedded in the compact experimental apparatus. The performed monitoring campaign consisted of several repetitions of the same path at traffic rush hours on both working days and weekends. In particular, the selected case study was a two-way, two-lane road in Rome, and 16 monitoring sessions were performed in total throughout one month, that is, eight at 9:30 a.m. and eight at 6:30 p.m. Collected CO₂-concentration values were therefore correlated to timing, position, and other environmental parameters affecting pedestrians' well-being in the outdoors.

Data analysis showed that CO₂ concentration was generally around 450 ppm in the area. The pollutant dispersion was quite homogeneous along the road, while peaks were observed during only a few performed monitoring sessions. Rare concentration peaks, that is, up to 1340 ppm, meant the temporary presence of punctual sources of CO₂ or, referring to traffic flow, vehicle accelerations/congestions on working days. This assumption was confirmed by peak spatial distribution: they were located almost in proximity of the crossroads, regulated by both roundabouts and traffic lights. Therefore, the wearable monitoring system demonstrated the ability to catch pedestrian exposure variability to vehicle exhaust gases with a high spatial and temporal resolution. The same CO₂ concentration was also investigated in parallel to the air temperature analysis along the path, which showed to be influenced by emitted anthropogenic heat during the afternoons, combined with UHI intensity exacerbation.

The complexity of the monitoring system, indeed, allows to simultaneously collect several environmental parameters and experimentally investigate existing correlations. In this work, the CO₂ concentration was then analyzed with respect to air temperature and wind speed. None of the investigated correlations was found to be of statistical relevance, even if reasonable observations were carried out. For instance, CO₂ levels above 1000 ppm were observed only in relatively high air temperatures, that is, ranging between 17.6°C and 19.0°C, and low wind speed, that is, below 1.3 m/s, suggesting the occurrence of air stagnation. Finally, differences between weekday and weekend measures were analyzed. The dataset collected during weekends was more concentrated around the average, 450 ppm for both datasets. The monitored area was, indeed, less congested than during the weekends.

The experimental analysis and data assessment showed that the innovative methodology can provide further insight into people's well-being in an urban environment, where several variables affecting people's health and city livability may be correlated and need to be monitored at a specific pedestrian level in order to identify realistic risk and vulnerability maps. Therefore, further size reduction of the proposed tool and its diffusion among citizens may provide new opportunities and perspectives to extensively monitor and improve the life quality of pedestrians, influenced by poor air quality and local overheating, especially in a very dense and polluted city such as Rome.

As a future development to push forward effective exploitation of wearable monitoring systems, further monitoring campaigns will be planned in order to compare data collected in (i) different areas of the same city or (ii) the same types of outdoor spaces but located in different geographical areas. Final optimal configuration of combined monitoring strategies (e.g., weather stations, satellite measurements, and portable wearable instruments) for detecting microclimate granularity within the urban areas is the final ambition of this research.

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3) เกณฑ์ความเข้มข้น Total Non-methane Hydrocarbon
ในเมือง Nagpur ตอนกลางของประเทศอินเดีย
โดย D. Majumdar และ A. G. Gavane

Research Article

Diurnal-, Seasonal- and Site-Dependent Variability in Ground-level Total Non-Methane Hydrocarbon in Nagpur City of Central India

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ABSTRACT Temporal & spatial variations in ground-level total non-methane hydrocarbon (TNMHC) were studied in Nagpur urban agglomeration (UA) for a year over three seasons viz. post-monsoon (September–October), winter (January–February) and summer (May–June) in 2013–14. Ground-level TNMHC showed low to moderate spatial (over residential, commercial, traffic intersections, residential cum commercial sites) and temporal (at 7:00, 13:00; 18:00 and 23:00 h in all three seasons) variations. There was no specific increasing or decreasing trend with time, either within a day or a season. Daily mean concentration of TNMHC (averaged over concentrations at 7:00, 13:00; 18:00 and 23:00 h) ranged from 0.88–1.73 ppmV, 1.75–4.04 ppmV and 1.20–1.53 ppmV at residential sites; 2.99–6.47 ppmV, 1.52–7.38 ppmV and 0.98–1.63 ppmV at traffic site; 0.83–1.15 ppmV, 2.03–3.24 ppmV, 1.1–1.70 ppmV at residential cum commercial sites and 1.05–4.79 ppmV, 6.2–8.58 ppmV, 0.34–0.64 ppmV at the purely commercial site, during post-monsoon, winter and summer, respectively. Occasional spikes (TNMHC > 10 to < 13.6 ppmV) were observed on three occasions over two sites in winter but reasons thereof remained unidentified. During Diwali Festival (in post-monsoon) marked by large-scale firecrackers bursting, observed TNMHC concentrations hovered around 3–5 ppmV, which almost matched with 90th percentile of other post-monsoon concentrations. Highest mean seasonal TNMHC concentration was observed during winter, followed by means of post monsoon and summer seasons while mean ground-level TNMHC concentrations on weekdays were slightly higher (1.17–1.21 times) than weekends over all seasons.

KEY WORDS Air pollution, NMHC, Urban, VOC, Weekend

1. INTRODUCTION

Non-methane hydrocarbons (NMHCs) together comprise major group of organic pollutants (Caselli *et al.*, 2010; Xiao and Zhu, 2003) that are actively involved in atmospheric photochemical reactions (Mudliar *et al.*, 2010; Elbir *et al.*, 2007). The NMHCs are constituents of volatile organic compounds (VOC) that have short atmospheric lifetimes (fractions of a day to months) and have direct but small impacts on atmospheric radiative forcing (Intergovernmental Panel on Climate Change; <https://www.ipcc.ch/ipccreports/tar/wg1/140.htm>). NMHCs may also have serious health effects like neurosis and dementia among others (Kandiyala *et*

al., 2010; Filley *et al.*, 2004; Chen *et al.*, 1994). High reactivity of NMHCs enables them to produce tropospheric ozone (O_3) through reactions with nitrogen oxides (NO_x) and radicals. As NMHCs have certain influence on O_3 formation, controlling NMHC emissions assumes significance and has been imposed to attain O_3 standards (Batterman *et al.*, 2005). In rural areas, where NO_x concentration is generally low, O_3 generation is also less, but in polluted urban locales, presence of low ambient NMHCs might lead to substantial O_3 production under significant NO_x levels (Donahue and Prinn, 1990). NMHCs are thus well known agents of O_3 precursor through the involvement of OH radical and NO_x (Warne, 1988). World Meteorological Organization Global Atmospheric Watch (WMO/GAW) programme undertakes measurements on NMHCs and other reactive compounds in global network (WMO, 2007).

Gasoline filling stations, open-waste burning practices, LPG leakages, solvents and vehicular emissions are the primary anthropogenic sources of NMHCs in urban air (Duan *et al.*, 2008; Tang *et al.*, 2007). Also, power and petrochemical plants, refineries, chemical plants, painting operations, varnishes, coating operations, consumer products, cold clean degreasing, printing inks, dry-cleaning and solid waste disposal are other sources (Srivastava and Mazumdar, 2011; Barletta *et al.*, 2002; Arya, 1999). Vehicular emission is one of the major NMHC sources and their emissions from vehicles include refuelling losses, starting emissions, evaporative losses and tailpipe emissions (Batterman *et al.*, 2005). As per Tan *et al.* (2011), i-pentane, ethene, ethane, ethyne, toluene and propane were the primary hydrocarbons (HCs) in Foshan in China. Generally, most abundant HCs exhibited high concentration in morning, dipped to the lowest level in afternoon and increased to higher values in evening hours. But, i-pentane exhibited highest level in afternoon, indicating accelerated solvent evaporation in higher temperature. Vehicular emissions were the main source of propene, i-butene, isoprene, ethene, benzene and toluene and n-pentane, n-hexane, and n-heptane came from petrol evaporation. LPG leakage could have been the main source of propane, while leakage of natural gas was source of ethane in Foshan City (Tan *et al.*, 2011). Potential sources of greenhouse gases and air pollutants in Nagpur Urban Agglomeration (UA) has been discussed before (Majumdar *et al.*, 2013; Majumdar and Gajghate, 2012) and some of these sources are also potential emitters of NMHCs in Nagpur city.

Monitoring of total NMHC (also known as TNMHC) concentrations in ground-level air has been undertaken sparsely from a few Indian cities (Sharma *et al.*, 2016; Sarkar, 2015; Nishanth *et al.*, 2014) and there are some reports on ambient concentrations of select individual NMHCs and VOCs from a few Indian locations (Srivastava and Mazumdar, 2011; Purkait *et al.*, 2009; Sahu and Lal, 2006a, b). Knowledge on ground-level TNMHC concentrations could actually help formulate air quality management planning of a city. Indian cities could be potential hotbeds of NMHCs due to variety of NMHC sources like vehicular traffic consisting of sizeable fleet of old vehicles, fossil fuel burning in household and commercial sector, small manufacturing units, painting and varnishing workshops, petrol pumps, auto refinishing workshops etc. and therefore, it is important to assess ground-level TNMHC concentrations over Indian cities. This work was undertaken to measure TNMHC in ground-level air of Nagpur, one of the major and progressive cities of Central India over post-monsoon (September–October), winter (January–February) and summer (May–June) during 2013–2014 in a year-long study. Temporal (diurnal and seasonal) and spatial variation in TNMHC *vis a vis* the abundance of reported sources over the selected UA has been examined and reported. Also, mean TNMHC concentrations during weekdays and weekends over all the seasons were calculated, evaluated and compared.

2. RESEARCH METHODS

2.1 Background of Study Area and Potential Sources of NMHCs

The study was conducted in Nagpur city within Maharashtra State of India. As per Govt. of India's last Census data in 2011, Nagpur is an Urban Agglomeration (UA)/city with a Million Plus population (2,122,965). It is the largest UA/city in Central India and by population, 3rd largest in State of Maharashtra. Nagpur District has an area of about 9897 sq. km. while Nagpur UA/city encompasses about 217.65 sq. km. (Nagpur Municipal Corporation 2006). National highways NH-7 and NH-6 and Asian highways AH-43 and AH-46 pass through Nagpur (Bhonsle, 2010) and carry significant load of commercial and personal vehicles.

Nagpur has a variety of potential sources of NMHCs. A detail reconnaissance was conducted to make an inven-

tory of prominent sources of NMHCs (Table 1). Some of these sources like thermal power plants and industries could potentially contribute to TNMHC in ground-level air of Nagpur through local and regional dispersion, although some of the sources are located beyond 10 km of the nearest air quality monitoring sites. Prevailing season is also expected to have a direct role to play on relative predominance of specific sources by influencing activities like open burning, domestic heating/cooling, tourist influx and festivities.

Suitable sites for collection of ground-level air samples for estimations of NMHCs were scouted by a thorough analysis of city map followed by reconnaissance, delineating various residential, commercial, market areas and important traffic intersections and roads. Inventory was made on various potential sources of NMHCs during reconnaissance. It was observed that there was conspicuous overlapping of various important activities viz. vehicular movements, commercial activities, sporadic biomass combustion, residential activities, cooking by fossil fuels in restaurants and mobile streetside food stalls, operation of petrol pumps etc. at several sites that could affect diurnal and seasonal air quality in terms of NMHCs. There-

fore, selected sites could only be classified into (i) Residential (ii) Purely commercial (iii) Traffic intersections and (iv) Residential cum commercial, based on major activities in and around the sites. The sites in Nagpur study area is presented in Fig. 1.

2.2 Sampling and Analysis of TNMHC

Sampling for ground-level air was undertaken over 2 months during summer (May–June), post-monsoon (September–October) and winter (January–February) seasons in 2013–14. Ground-level city air at about 1.5 m above ground level was collected at different time periods of a day (08:00 h, 13:00 h; 18:00 h and 23:00 h) over about three weeks in each season to capture diurnal and spatial variations. The samples represented city's ground-level air which was influenced by direct emissions from an ensemble of abundantly available NMHC sources, most of the sites being active in-terms of anthropogenic activities like cooking in roadside eateries, movement of vehicles, presence of petrol pumps (in a few areas), environmental tobacco smoke in congested areas (especially in commercial and traffic intersections) etc. TNMHC was analyzed in the ground-level air samples collected in

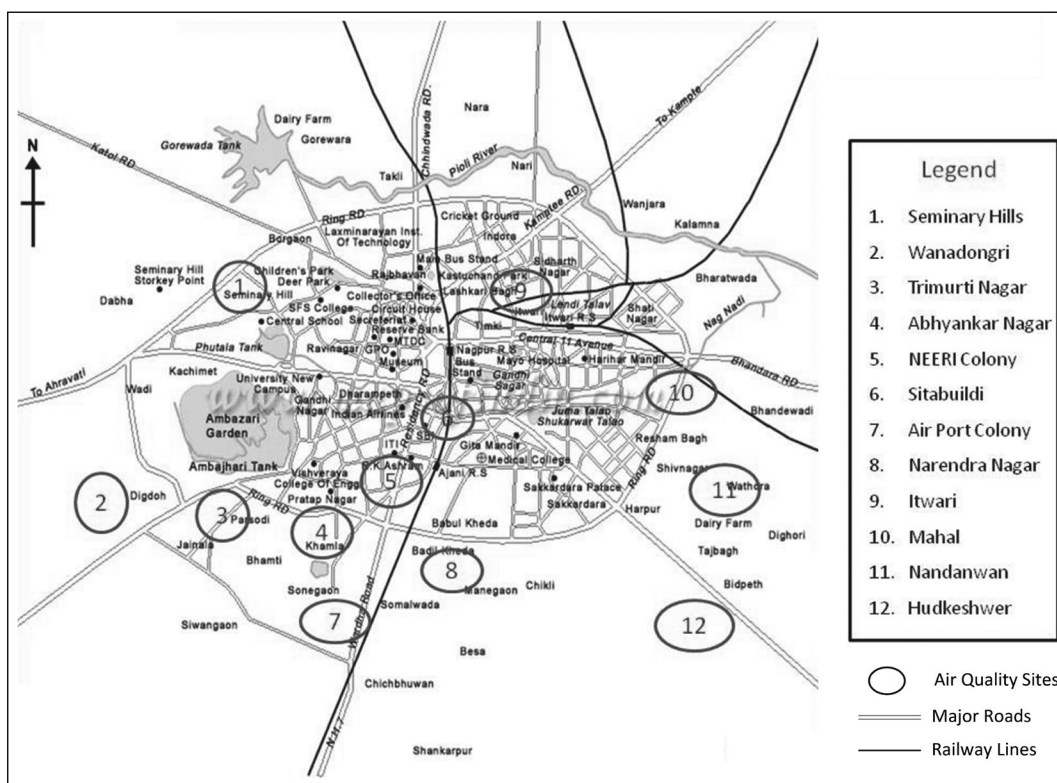


Fig. 1. Locations of the selected air quality monitoring sites in Nagpur city (Map Source: Compare Infobase Pvt. Ltd.).

Table 1. Inventory of potential sources of non-methane hydrocarbons (NMHCs) in Nagpur city.

Source	Predominant NMHCs sources in Nagpur	Sites affected
Industries	Nagpur city is fringed by Butibori Industrial Area and Hingna Industrial Estate, which have industries like chemicals, rubber, paints, polymer etc. These industries are potential emitters of NMHCs.	Wanadongri (Residential + Commercial)
Power plants	Two coal-fired super thermal power stations (STPS), namely the 840 MW Khaparkheda STPS and the 1080 MW Koradi STPS adjacent to Nagpur are potentially big emitters of NMHCs. The selected sites are far away from these plants, nearest one being about 12 km away (Itwari).	No air quality site was near (< 10 km) to this source
Vehicular traffic	Nagpur has National highways NH-7 and NH-6 passing through apart from two Asian Highways AH43 and AH46. Auto rickshaws running on mixtures of petrol and kerosene are the main form of hired transport within the city along with private vehicles and buses. About 4.6 lakh registered vehicles are there in Nagpur including 2-wheelers, 3-wheelers and 4-wheelers. Total length of city roads was 1907 km in 2002–2003 (Nagpur Municipal Corporation, 2006).	Itwari (Commercial), Sitabuldi (Traffic), Hudkeshwar Road and Wanadongri (Residential + Commercial)
Domestic cooking	Domestic sector in Nagpur consists of residential colonies, urban slums, semi urban and rural population. Apart from LPG, sizeable quantity of low-grade coal, kerosene and wood are used for domestic combustion due to their easy availability and low cost, significantly influencing NMHC emissions from Nagpur (Majumdar and Gajghate, 2011).	NEERI Colony, Abhyankar Nagar, Narendra Nagar, Trimurti Nagar, Nandanwan, Mahal (All Residential)
Commercial cooking	Apart from LPG being the primary fuel, low-grade coal, charcoal cow dung, fuelwood, coal balls etc. are used by the organized and unorganized restaurant sectors in Nagpur (Majumdar <i>et al.</i> , 2013) which all are potential sources of NMHCs.	Itwari (Commercial), Sitabuldi (Traffic), Hudkeshwar Road and Wanadongri (Residential + Commercial)
Sewage channels	Sewage channels and severely polluted Nag River running through Nagpur could be a potential source of NMHCs.	Nandanwan, Mahal, Hudkeshwar Road (Residential), Sitabuldi (Traffic)
Aircrafts	Dr. Babasaheb Ambedkar International Airport could be a significant source of NMHCs due to aviation fuel loading and storage activities. Over twenty passenger aircrafts operate from this airport everyday catering to about 4000 passengers per day (Nagpur Airport, http://www.nagpurairport.com/). Nagpur also has an Indian Airforce Maintenance Command.	Airport Colony (Residential)
Waste burning	Sporadic open burning, especially in winter to fight off cold, could be responsible for NMHC emissions in various parts of the city.	Difficult to designate, as this source is unregulated and sporadic
Waste dumps	Waste generation was estimated to be 650 tons per day (TPD) (http://www.cpcb.nic.in/divisionsofheadoffice/pcp/MSW_Report.pdf , accessed on 27.9.17) in Nagpur city during 2004-05. The city had a population of about 2,405,421 as per 2011 census (http://www.census2011.co.in/census/city/353-nagpur.html) signifying the likely extent of solid organic waste generation in future. Bhandewadi dump yard in Nagpur handles MSW in about 22 hectares land while about 20 hectare land is used for composting (Akolkar <i>et al.</i> , 2008).	No site is near (within 5 km) to this source except Nandanwan (Residential)
Petrol pumps	Nagpur city has about 38 auto petrol filling stations (http://automobiles.mapsofindia.com/petrol-stations/nagpur.htm , accessed on 27.9.17) that also are potential emitters of NMHCs.	Itwari (Commercial), Sitabuldi (Traffic), Hudkeshwar Road and Wanadongri (Residential + Commercial)

Tedlar bags (SKC Inc., USA) as specified by ASTM-D6345-98 by passive filling up for about 30 minutes. Some of the sites, as described above, were directly inside heavy traffic or commercial activities in the heart of the city and being just above ground level, were directly under the heavy influence of ground level NMHC emissions. TNMHC was determined by a Hydrocarbon Analyser (Model HC51M, Environment, SA) within 12 hours of sample collection. This analysis is based on flame ionization detection of hydrocarbons (0–1000 ppm). The analyzer was fitted with a FID housed in oven with a column that separated methane from TNMHC. The gas samples pass at 1.4 L/min flow rate through a specially layered packed column wherefrom CH₄ is fed first into the detector. Subsequently, the column is back-flushed and other hydrocarbons are passed into the detector, resulting in two quantifications, one of them being the TNMHC. Instrument calibration was undertaken by CH₄-free zero air for zeroing and a standard certified NIST traceable 10000 ppb hydrocarbon (as isobutylene) in Air balance (Chemtron Science Laboratory, Mumbai) with certification accuracy of $\pm 1\%$. Lowest detectable limit (LDL) of the instrument was 0.05 ppm HC while zero drift was 0.2 ppm and span drift was $< 1\%$ over 7 days. The uncertainty of the standard deviation of measurements, related to the dispersion of results (U_{disp}) was calculated by the following expression:

$$U_{\text{disp}} = s(q)/(n)^{1/2}$$

where $s(q)$ is the standard deviation and n is the number of readings (Madeira *et al.*, 2009). The U_{disp} for TNMHC measurement by the instrument was estimated to be 0.1257.

2.3 Meteorological Data

Temperature, relative humidity, wind direction and speed that govern ground-level concentrations, distribution and dispersion of NMHCs over the UA were collected to support air quality data on TNMHC. Nagpur's meteorological data was collected from online data archived at wunderground.com that uses meteorological data received from the meteorological station of Indian Meteorological Department (IMD) in Nagpur. World Meteorological Organisation's (WMO) global station data archive on vertical atmospheric temperature profile data reported by radiosondes was used to represent atmospheric temperature inversions in June, September and December.

2.4 Statistical Calculations

Measures on descriptive statistics (mean, median, mode, standard deviation, range, percentiles) were undertaken on season-wise dataset. Student's t-test was used to estimate statistical difference in seasonal mean concentrations of TNMHC. Kruskal-Wallis One Way Analysis of Variance on Ranks test was conducted to test the medians of site-wise TNMHC concentrations over all the seasons to test significant difference amongst sites. The TNMHC concentration dataset was subjected to cluster analysis for tree clustering of sites via Ward Method. Significant differences between values were calculated by Duncan's Multiple range Test (DMRT). Statistical analyses were carried out by Statistica (Dell Software, Version 13) and MSTAT C Software (Crop and Soil Science Division, Michigan State University, USA).

3. RESULTS AND DISCUSSION

3.1 Diurnal and Seasonal Variation of TNMHC

Ground-level TNMHC concentrations had low to moderate temporal variation diurnally (coefficient of variation or CV = 36–110%) as well as over post-monsoon, winter and summer seasons (CV = 52–122%) apart from also having low-moderate spatial variations over the selected sites (CV = 8–152%). There was also intra-site differences in TNMHC concentration amongst various chosen time periods viz. 8:00, 13:00, 18:00 and 23:00 hrs, only few of which were statistically significant (Table 2). Over the various time periods in a day (24-h), mean TNMHC concentrations ranged from 0.88–1.73 ppmV, 1.75–4.04 ppmV and 1.20–1.53 ppmV at residential sites; 2.99–6.47 ppmV, 1.52–7.38 ppmV and 0.98–1.63 ppmV at traffic site; 0.83–1.15 ppmV, 2.03–3.24 ppmV, 1.1–1.70 ppmV at residential cum commercial sites and 1.05–4.79 ppmV, 6.2–8.58 ppmV, 0.34–0.64 ppmV at purely commercial sites during post-monsoon, winter and summer, respectively. Occasional spikes in concentration (TNMHC > 10 to < 13.6 ppmV) were observed on three occasions at two sites on two winter days and considered in calculations, leading to high case-specific mean concentrations, but reasons thereof remained unidentified. In winter, the purely commercial site returned highest mean TNMHC values at all times of the day, followed by the traffic site. Overall, mean TNMHC values were highest in winter (mean TNMHC Conc.: 3.15 ppmV) that was > 2 times higher

Table 2. A summary of average TNMHC concentrations (ppm) at different times of day and sites over various seasons.

Time	Post-Monsoon				Winter				Summer			
	Residential	Traffic	Residential + commercial	Pure commercial	Residential	Traffic	Residential + commercial	Pure commercial	Residential	Traffic	Residential + commercial	Pure commercial
08:00	0.88 a	2.99 a	1.15 a	1.20 a	2.17 a	1.52 a	2.04 a	8.58 a	1.53 a	1.60 a	1.54 a	0.64 a
13:00	0.92 a	6.47 b	0.88 a	4.79 b	1.75 a	1.89 a	2.07 a	6.72 a	1.27 a	0.98 a	1.68 a	0.53 a
18:00	1.73 a	4.90 ab	1.08 a	1.05 a	4.04 a	7.38 b	3.24 a	6.81 a	1.21 a	1.14 a	1.15 a	0.34 a
23:00	1.34 a	5.06 b	0.83 a	4.04 ab	2.75 a	4.08 a	2.03 a	6.20 a	1.20 a	1.63 a	1.70 a	0.49 a

Values followed by same letters are not statistically different from each other at 5% level of significance as per DMRT.

over both post monsoon (mean TNMHC Conc.: 1.62 ppmV) and summer (mean TNMHC Conc.: 1.26 ppmV) concentrations. Weaker dispersion and ground-level subsidence of city air in winter could also have played the most significant role in causing TNMHC to scale highest values in winter. Near ground-level inversion was also prominent in winter, affecting elevated ground-level TNMHC concentrations, as discussed later in this section. Intra-season temporal variability in ground-level TNMHC concentrations was highest in post-monsoon (coefficient of variation, CV: 122%), followed by winter (CV: 80%) and summer (CV: 52%). Higher usage of biomass fuels for warming water and house warming in city slums could be one the major reasons behind highest mean TNMHC concentration in residential areas in this season. It has been estimated that about 4.9 Tg of Non-methane VOCs (NMVOCs) are generated annually in India from residential cooking (Pandey *et al.*, 2014). Fleming *et al.* (2018) have reported substantial VOC emissions from dung-fired cookstoves in Indian homes. Further, wanton open waste burning in practiced in various cities in India, leading to air pollution (Kumar *et al.*, 2018, 2015) and emissions of NMHCs (Sharma *et al.*, 2019; Chen *et al.*, 2017). In summer months, TNMHC concentrations were generally lower at all sites over all the time periods of the day which could have been influenced to a great extent by higher dispersion supported by low pressure, warmer conditions and higher wind speed (Fig. 2). Also, household fuel combustion and open waste burning towards heat generation could actually be lower in summer, leading to decline in NMHC generation. On the other hand, increasing levels of ground-level TNMHC was evident from October onwards when atmospheric temperature started to dip with approaching winter. The comparative scenario of ground-level TNMHC concentrations over the three seasons (Fig. 3) indicates some sporadic extreme and outlier values, possibly due to sampling very near to NMHC sources at ground level in congested and anthropogenically active areas. Highest mean seasonal TNMHC concentration was observed during winter due to lower dispersion followed by post-monsoon and summer. Also, the non-outlier range of TNMHC concentration was highest in winter. Summer had no outliers and range of TNMHC concentrations was low, probably due to apparent lack of commercial roadside cooking in summer when dining out declines and also, declining open burning activities for lack of need of warmth,

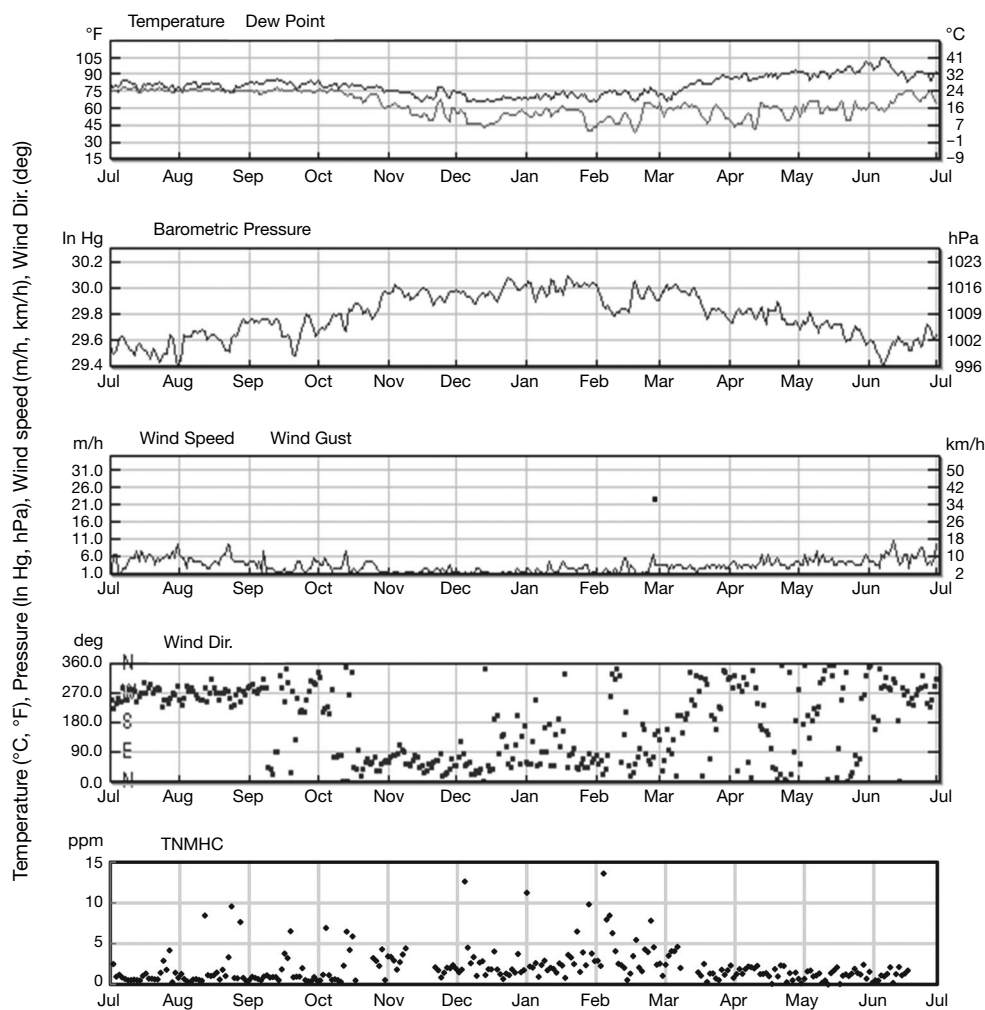


Fig. 2. Seasonal variation in atmospheric temperature, dew point temperature, barometric pressure, wind speed and gust, and wind direction in Nagpur city during the study.

accompanied by quick dispersal after generation.

All-season data in terms of daily time-dependent TNMHC concentrations reflected that concentrations at 8:00 and 23:00 h were frequently lower than 13:00 and 18:00 h (Fig. 4). Higher TNMHC concentrations at 13:00 and 18:00 h could be strongly influenced by *real time* vehicular movements and commercial activities that remain at their peaks during these hours in Nagpur. At Itwari (purely commercial site), a winter day witnessed a bout of relatively higher TNMHC concentrations, ranging from 7.8–12.6 ppmV while another winter day witnessed a concentration of 13.6 ppmV at 18:00 h in Mahal (a residential site). In terms of season-wise mean TNMHC concentrations, highest was observed during winter due to potentially lower dispersion of ground-level

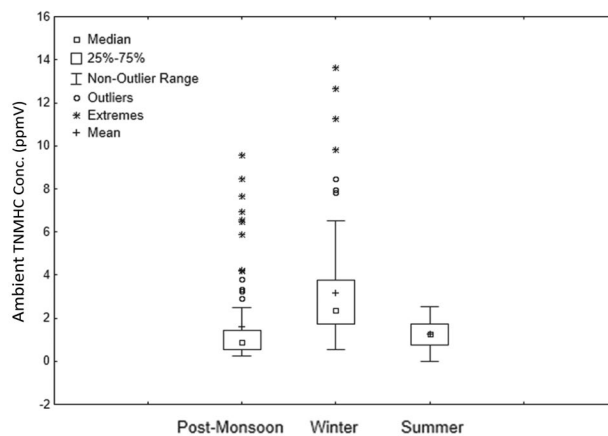


Fig. 3. Summary statistics of near-ground TNMHC concentrations in different seasons.

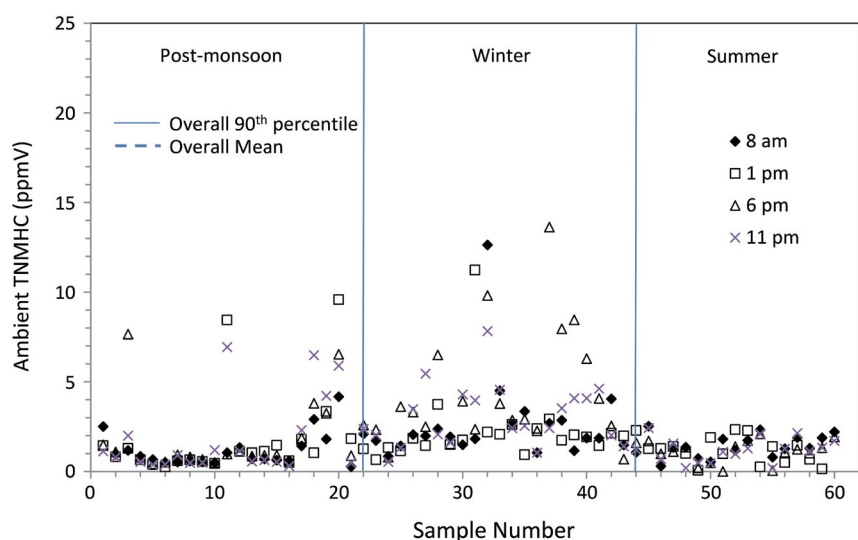


Fig. 4. Distribution of near-ground TNMHC concentrations over Nagpur city *vis a vis* different times of a day over all the selected seasons (post-monsoon, winter and summer).

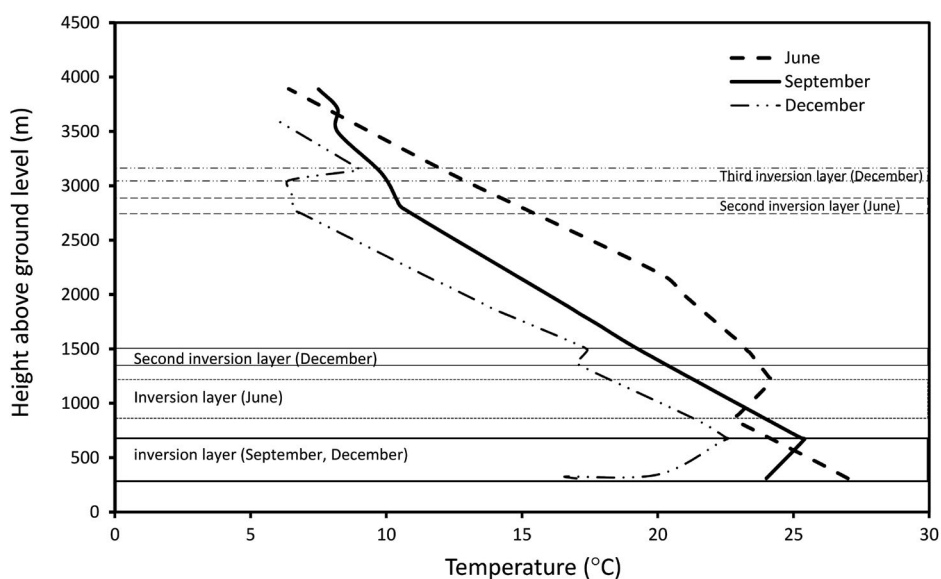


Fig. 5. Vertical temperature profile and inversion layers over Nagpur city in June, September and December months during the study.

el air, followed by post monsoon while summer concentrations were persistently the lowest. There was a presence of strong ground-level inversion in winter (in December) (approx $< 250\text{--}750\text{ m}$) revealed by Radiosonde data on vertical atmospheric temperature profile over Nagpur (Fig. 5), signifying increased chances of lower dispersion of pollutants at ground level. Also, a weaker inversion was observed in September (post-monsoon season), just before the winter set in. However, during

peak summer of June, near-ground inversion was absent and the inversion layer was detected above 750 m height above ground, indicating better chances of dispersion and dilution of air pollutants at ground level. Descriptive statistics of a season-wise database is presented in Table 3, which reflects stand-alone characteristics of winter TNMHC concentrations. The season-wise TNMHC database were found to be normally distributed.

TNMHC concentrations at some locations measured

during Diwali Festival (Festival of Lights which is characterized by large-scale firecrackers bursting and coinciding with late post-monsoon season), ground-level TNMHC concentrations hovered mostly around 3–4.4 ppmV, which almost matched with 90th percentile of post-monsoon concentrations excepting Diwali period. Although concentrations >4 ppm were obtained on 2 different occasions on Diwali day that were more than average summer concentration and also, post-monsoon concentrations on several days, no persistent increasing or decreasing trend in ground-level concentrations were observed over pre- or post-Diwali periods. Emissions from firecracker bursting is reportedly instrumental in elevating ambient concentrations of NMHCs (Chang *et al.*, 2011).

Table 3. Outcome of Descriptive statistical test on air quality data.

Parameter	Post-Monsoon	Winter	Summer
Sample number	83	84	72
Mean (ppm TNMHC)	1.61	3.15	1.26
Median (ppm TNMHC)	0.88	2.38	1.28
1 st quartile (ppm TNMHC)	0.56	1.76	0.78
3 rd quartile (ppm TNMHC)	1.44	3.75	1.72
Geometric mean (ppm TNMHC)	1.04	2.52	0.94
Interquartile range (ppm TNMHC)	0.88	1.99	0.94
Variance (ppm TNMHC)	3.91	6.42	4.34
Skewness	2.44	2.34	-9.56×10^{-2}
Kurtosis	5.46	5.94	-7.18×10^{-1}
Distribution (Anderson-Darling normality test)	Normal	Normal	Normal

3.2 Site-Specific Variability in Ground-level TNMHC

Site-specific TNMHC concentrations over all the seasons together (Fig. 6) revealed important observations in terms of influence of site-specific activities on ground-level TNMHC concentrations. Mean TNMHC concentrations were found to be highest at the commercial site (Itwari), closely followed by a residential cum commercial site (Wanadongri). While Itwari is known to have strong NMHC sources like vehicles, commercial cooking, petrol pumps and DG sets, the residential cum commercial areas also had some of the similar sources apart from various household ones. On the other hand, the traffic site had lower TNMHC concentrations than several primarily residential areas rather unexpectedly. But, it was noted that roadside eateries and biomass combustion activities were co-existent with other activities in many residential areas in this UA, making the latter potentially a strong TNMHC emission hub. Guo *et al.* (2004) reported that internal combustion engines, unburnt fuel, solvents including paints, liquefied petroleum gas (LPG) or natural gas leakages, solvents, fuel

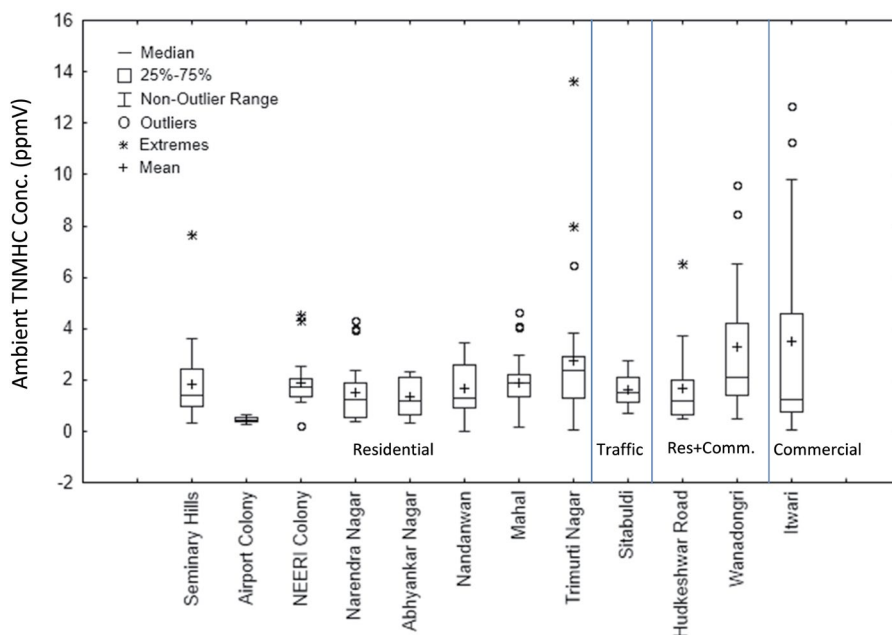


Fig. 6. Site-wise summary statistics of ambient TNMHC concentrations recorded over post-monsoon, winter and summer.

combustion, chemical factories and power plants were the major sources of NMHCs in Hong Kong. In Nagpur, a few of above sources could potentially get together to contribute to TNMHC present in ground-level air and might be one of the reasons for getting sporadic high concentrations in residential areas. As per Kruskal-Wallis One Way Analysis of Variance on Ranks test, the differences in the median values among the sites, in terms of TNMHC concentrations over all the seasons together, are greater than would be expected by chance and therefore, there was a statistically significant difference ($P \leq 0.001$).

Cluster analysis was performed and the branching dendrogram represented similarity or dissimilarity amongst various groups of sites in terms of ground-level TNMHC concentrations (Fig. 7). The site-groups of Airport Colony and Narendra Nagar; Nandanwan and Wanadongri were categorized as similar ones and were not very different from each other. The sites of Sitabuldi, Itwari and Seminary Hills, Mahal were outstanding in nature and were also much different from others, as revealed by height of their vertical lines that signified the degree of difference between branches i.e. longer the line, greater is the difference. Seminary Hills, Hudkeshwar and NEERI Colony could also be categorized as stand-alone sites in terms of ground-level TNMHC concentrations.

Ambient TNMHC concentrations reported by various researchers over the world are observed to be highly variable spatially and temporally. Zielinska *et al.* (2001) in a study conducted near California/Mexico border report-

ed concentration ranges of < 0.1 ppm to slightly greater than 0.2 ppm at Rosarito at 10:00 AM and 1:00 PM samples while another site Mexicali showed concentrations up to near about 2.4 ppm in 6:00 AM samples in the month of September. As per Nishanth *et al.* (2014), the annual maximum, minimum and average TNMHCs were 25.45, 13.84 and 19.23 ppbv, respectively, in a rural coastal location at Kannur, India during November 2009 to December 2011. Chen *et al.* (2014) reported TNMHC concentration distribution over 2007–2011 in Taiwan under two monitoring networks viz. air quality stations (AQS) of USEPA across Taiwan and Photochemical Assessment Monitoring Stations (PAMS) that generate hourly observations of 56 non-methane hydrocarbons (NMHCs). The time-series concentrations by both networks showed wide temporal variations but maximum TNMHC values reached were about 1.6 ppm under both networks while the lowest concentrations touched down to about 0.02 ppm in PAMS. Sharma *et al.* (2016) measured TNMHC at one site during the month of May in New Delhi, India and reported that TNMHC concentration varied from 0.22–0.25 ppm during day to night time. The low variation in this study obviously was a result of short duration of study and also, summer being chosen as the study time, when ground-level air is known to have good all-round dispersion and vertical mixing as well. In a study conducted in summer season at three locations in a zone of 5 km radius around Mathura Refinery in India, TNMHC was found in the range of 0.11–5.7 ppm while at two of the sites, concentration was frequently found

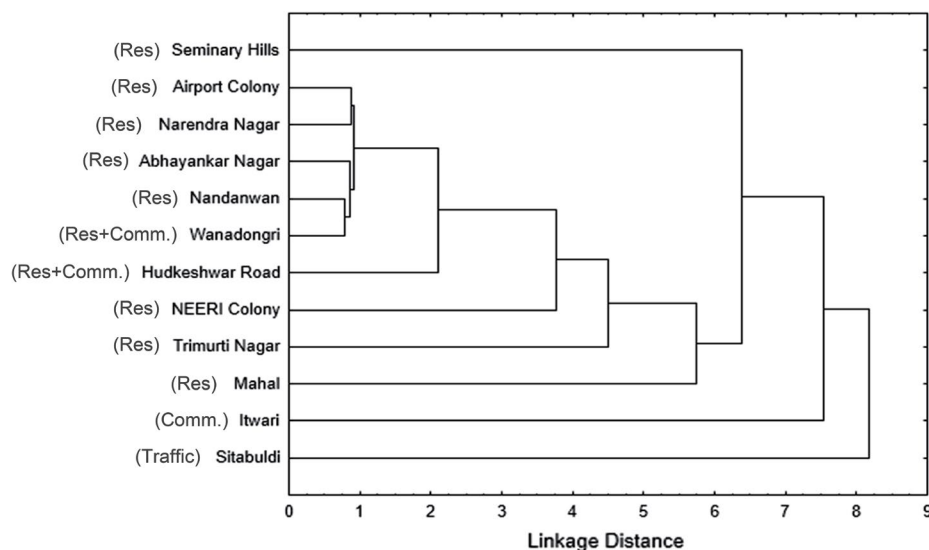


Fig. 7. Cluster pattern of selected sites in terms of ambient TNMHC mixing ratio recorded over all the seasons.

over 4 ppm and 2 ppm during the short study (EIL, 2015). Vehicular traffic emissions were found to be one of the predominant sources of hydrocarbons at these stations.

Considering year-round average (2.02 ppmV), 90th percentile (4.07 ppmV), several instances of high TNMHC concentrations in short-period samples of this study and also, in the light of average TNMHC concentrations reported at some other locations in the world, it is evident that a good number of short-term TNMHC concentrations encountered in this study were much higher than reported in most other studies. The reasons thereof could be: this study reports ground-level concentrations at the height of only about 1.5 m, which at times were directly sampled (i) near kerb sites severely affected by traffic emissions or nearby commercial activities like burning fossil fuels like biomass, charcoal, coal and LPG in closely located restaurants and mobile food vendors or (ii) just adjacent to streams of city crowd where influence of environmental tobacco smoke on TNMHC concentrations cannot be ruled out or (iii) within the influence zones of petrol pumps that are abundant and quite close to each other in this city. Even ground-level sampling in residential zones could be influenced by occasional traffic movements, especially of two-wheelers that are popular in this city.

3.3 Weekday-Weekend Variability in Ground-level TNMHC

There was subtle weekend effect on mean ground-level

TNMHC concentrations observed over all sites, time-periods and the seasons. A few of the higher TNMHC concentrations were recorded during winter weekdays while mean TNMHC concentrations on weekends (Sundays) in all the seasons were lower than weekdays. It may be noted from mean and 90th percentile values of TNMHC reported in Fig. 8 that the escalations registered in mean TNMHC concentrations on weekdays over weekends were low and statistically insignificant (1.17–1.21 times more on weekdays) but perceptible in all seasons. This probably hinted at a slim positive influence of larger on road vehicular fleet and escalated commercial activities of weekdays on ground-level NMHCs. Traffic-driven TNMHC emissions have been aptly reflected in the study of Liu *et al.* (2014), where TNMHC concentrations within a traffic tunnel was found to reach up to about 2.8 ppm when the traffic was slow-moving at about 45 km h⁻¹, which is similar to general traffic movement speed in most Indian cities. In another tunnel study in Taiwan (Chang *et al.*, 2008), where downslope entrance, downslope exit, upslope entrance and upslope exits were monitored, average TNMHC was observed to be 1.9, 3.5, 0.8 and 2.7 ppm.

4. CONCLUSIONS

Intra-season variability in ground level TNMHC in Nagpur were low to moderate. Concentrations in winter

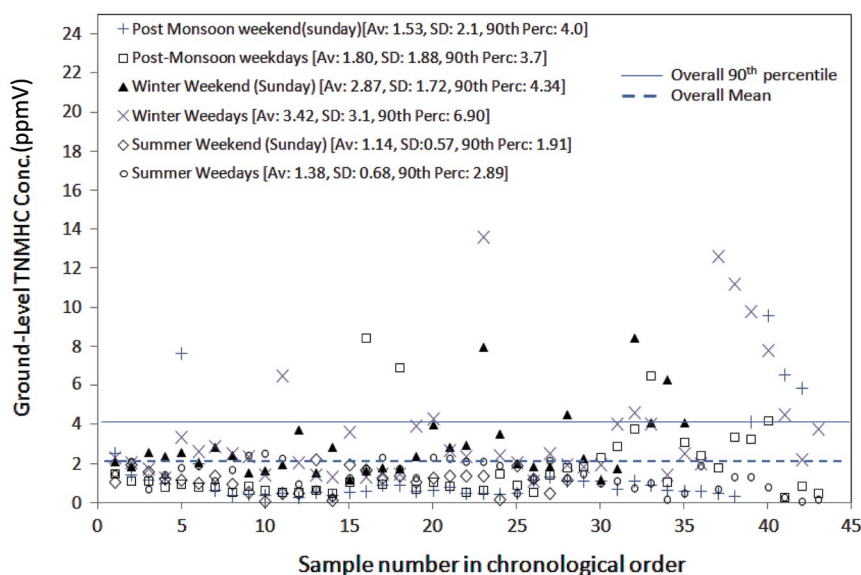


Fig. 8. Distribution and summary statistics of TNMHC concentrations during weekdays and weekends in different seasons.

were conspicuously higher over other seasons and concentrations in summer were lowest, evidently due to better dispersion. In spite of lower dispersion with dipping night-time temperature, TNMHC build-up was not found to be alarming at 23:00 h over day-time hours in any season and observed concentrations at 23:00 h were almost consistently lower than noon and evening-time concentrations when higher vehicle movements and operation of other sources might have played a major role in elevating ground-level TNMHC. At morning 8:00 h when atmospheric temperature remains lower than noon and evening, there was no substantial build-up of TNMHC, probably because winter is mild in Nagpur and by morning 8 o'clock, the city heats up substantially to allow good dispersion. Causes of spurts in ground-level TNMHC at some localities could not be identified.

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ศึกษาโดย

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