Opportunities and uncertainties in the EMEP-WRF model

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UKRI GCRF South Asian Nitrogen Hub

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NATIONAL CAPABILITY FOR GLOBAL CHALLENGES
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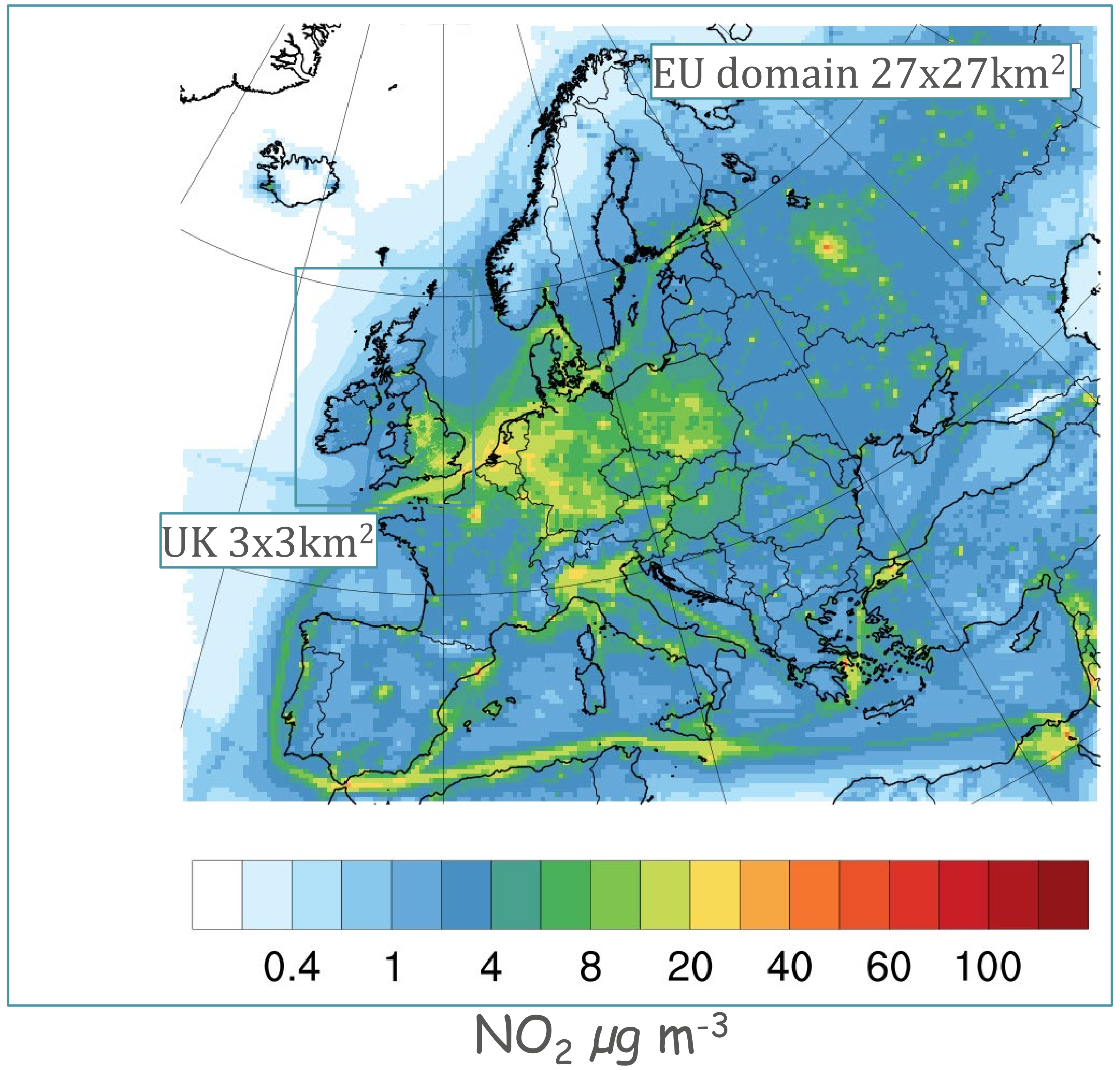
The EMEP-WRF model



- EMEP-WRF in an atmospheric chemistry transport model and it is based/identical on the EMEP MSC-W model (www.emep.int – Norwegian Meteorological office)
- Meteorology driver is the Weather Research & Forecasting model (www.wrf-model.org)
- The typical vertical domain from the surface (~45 m) up to 100hPa (~16 km)
- Globally at 1°×1° degree and with nested domains at 0.1°×0.1°
- The emissions are derived from NAEI (UK), EMEP (EU), EDGAR (global), and HTAP (Global)
- Chemistry transformation, removal processes (dry and wet) are implemented

EMEP4UK specific papers
ACP Vieno et. al, 2010, 2014, 2016, ERL Vieno et. al, 2016, GMD Ge et. al, 2021, ACP Ge et. 2022, Science Gu et al. 2021

EMEP MSC-W model
(ACP Simpson et al., 2012) and EMEP 2023 report

WRF
(Skamarock, W. C. wt al., 2019)

EMEP MSC-W model
www.emep.int - https://github.com/metno/emep-ctm

EMEP4UK model
www.emep4uk.ceh.ac.uk

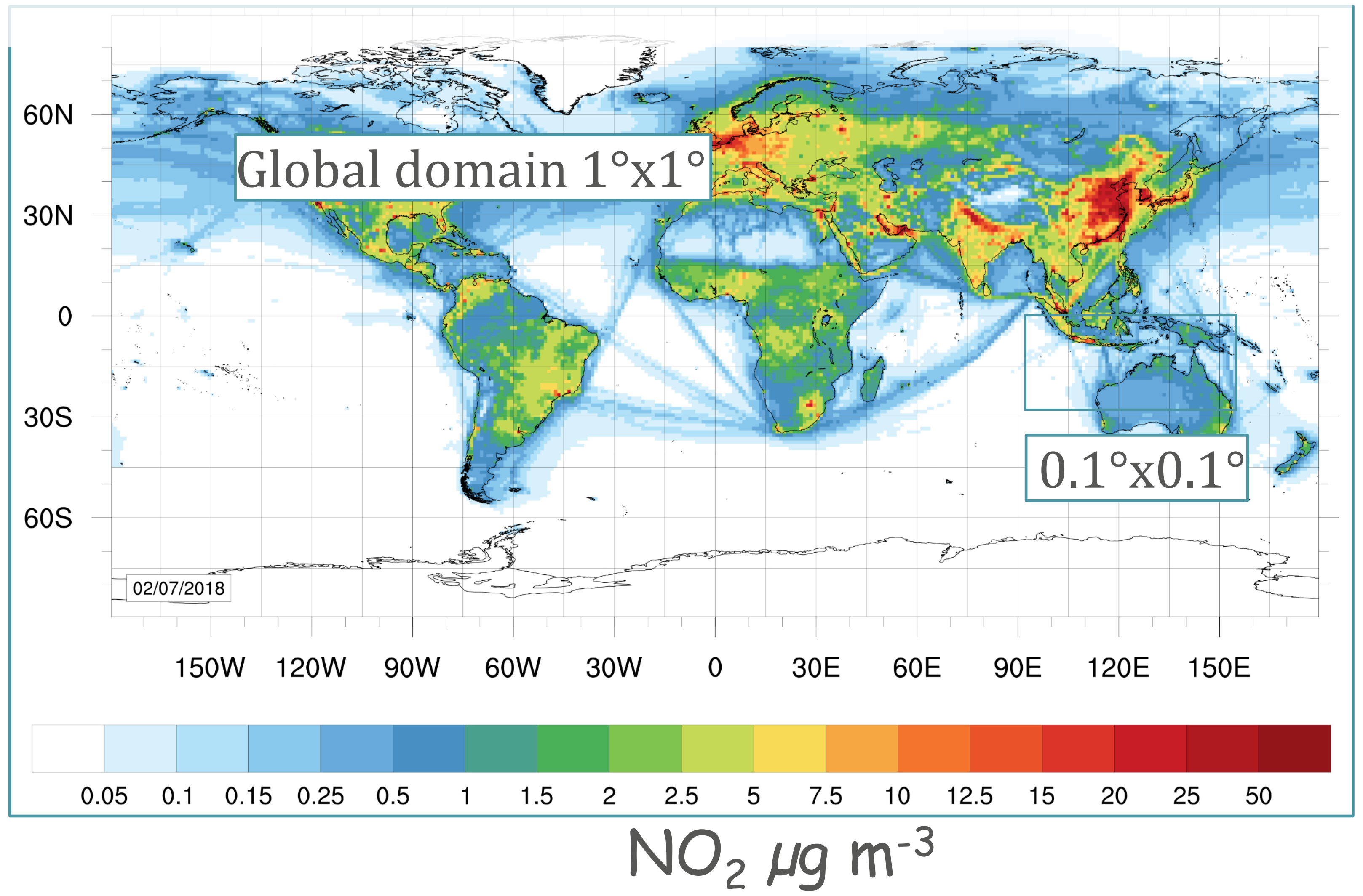
NAEI emissions:
https://naei.beis.gov.uk/data/mapping

EMEP emissions:
https://www.ceip.at/webdab-emission-database/emissions-as-used-in-emep-models

EDGAR emissions:
https://edgar.jrc.ec.europa.eu/emissions_data_and_maps

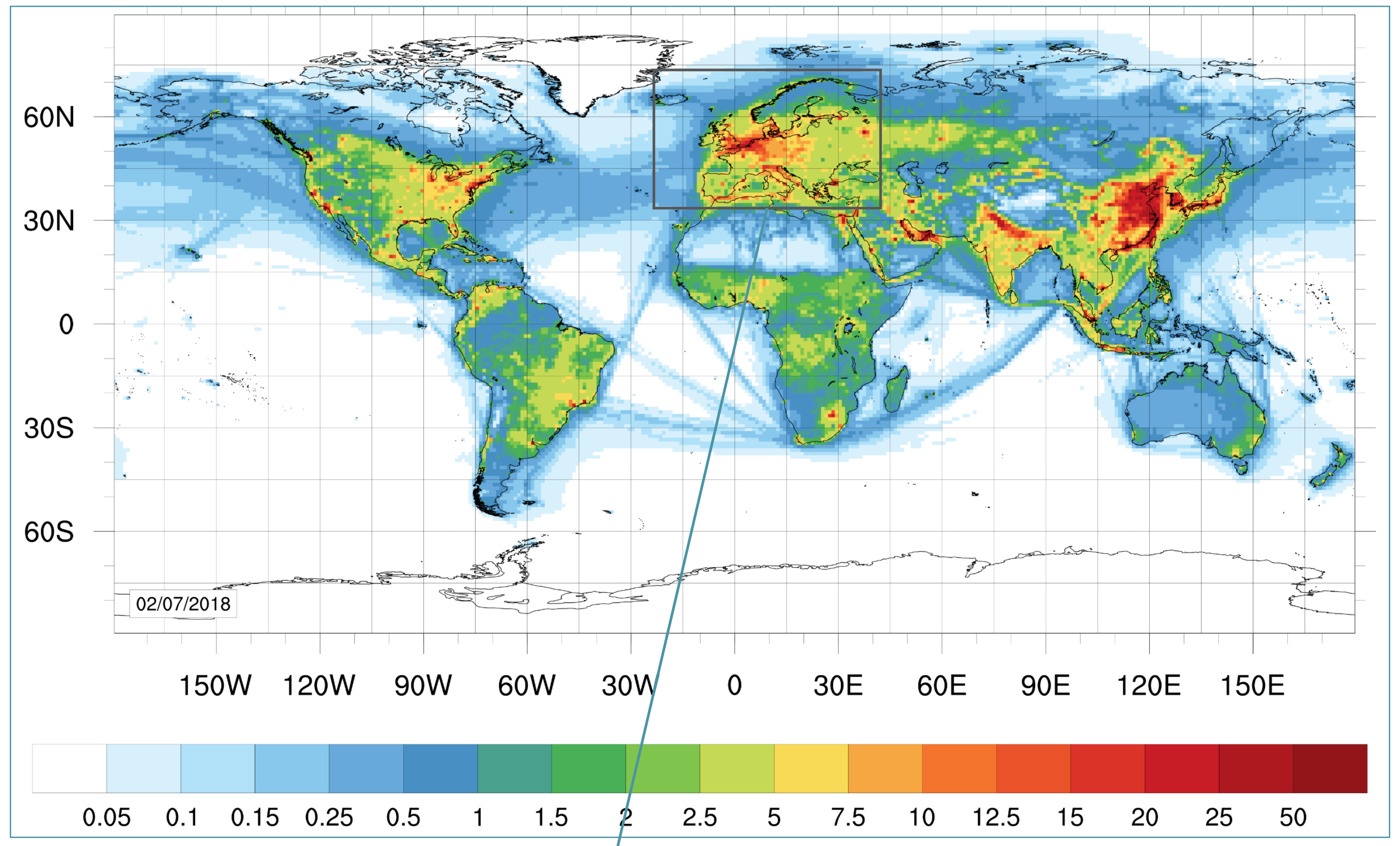
HTAP emissions:
https://edgar.jrc.ec.europa.eu/dataset_htap_v3

WRF model:
https://www2.mmm.ucar.edu/wrf/users/

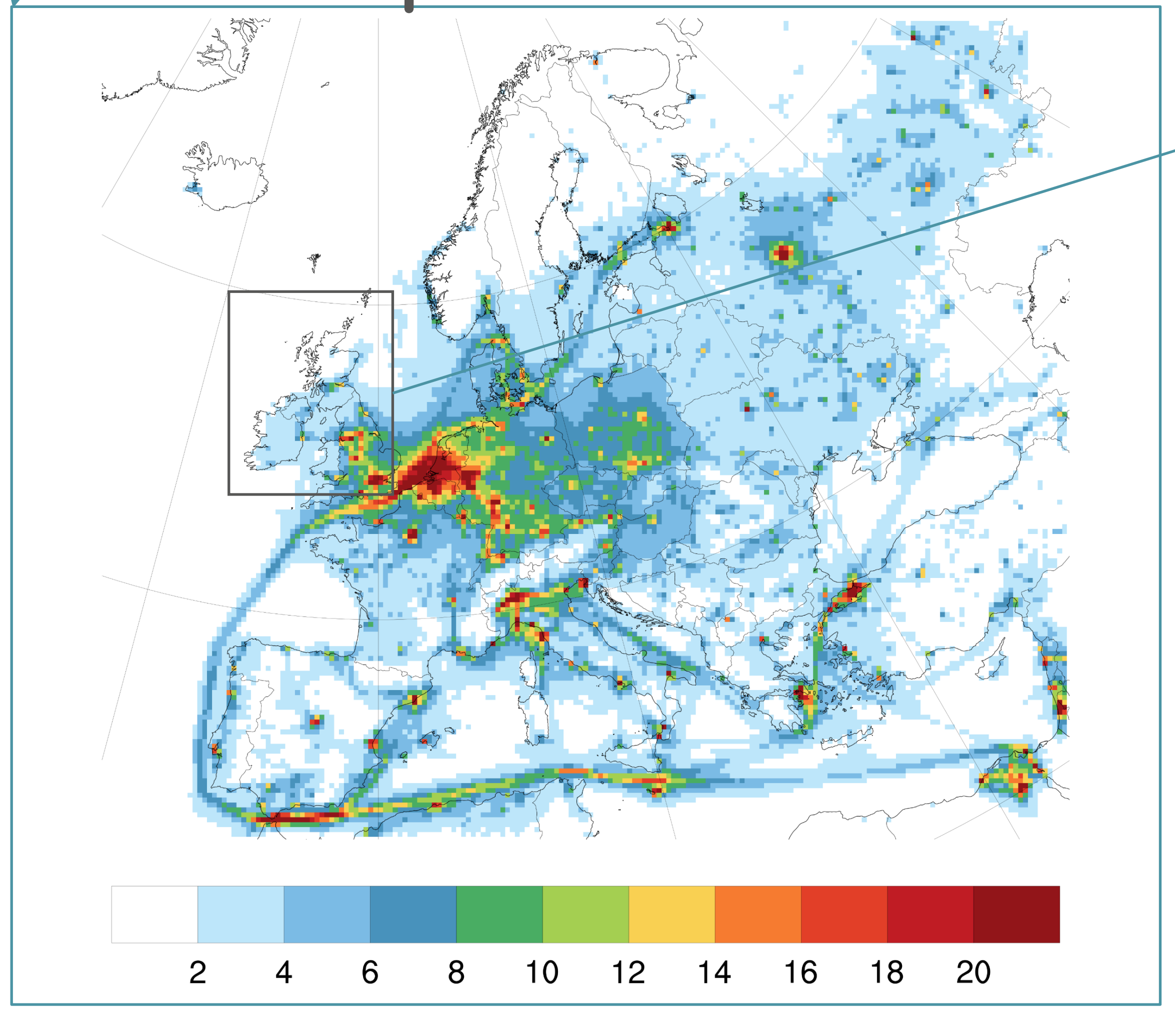


From global to urban scale modelling with the EMEP-WRF model

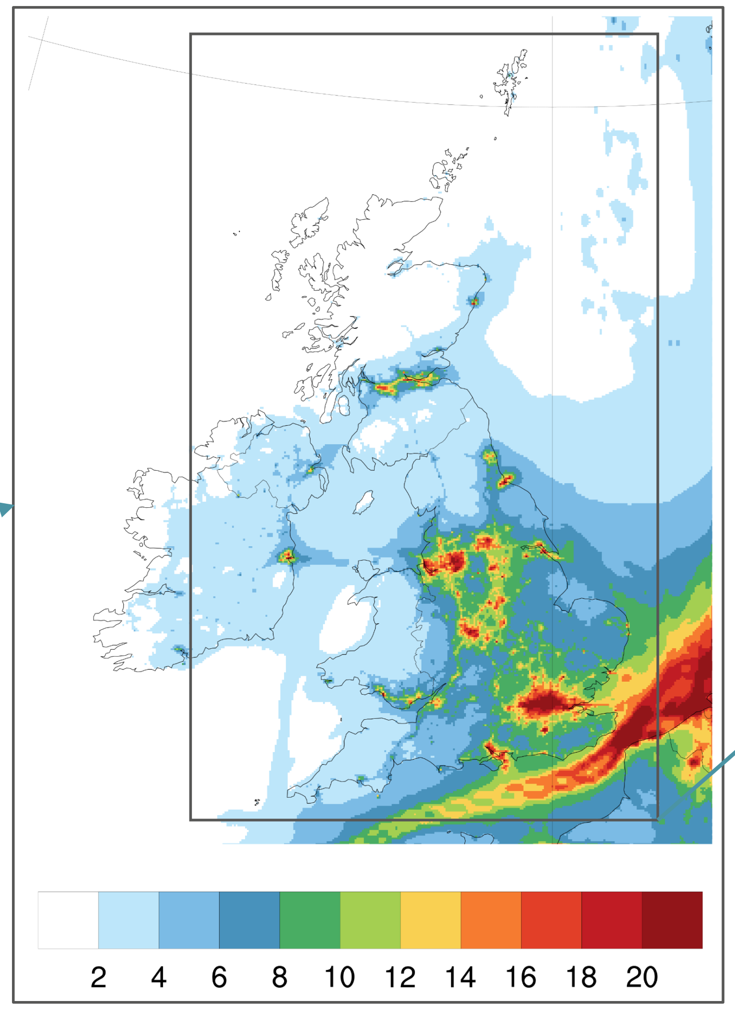
Global 1°x1°



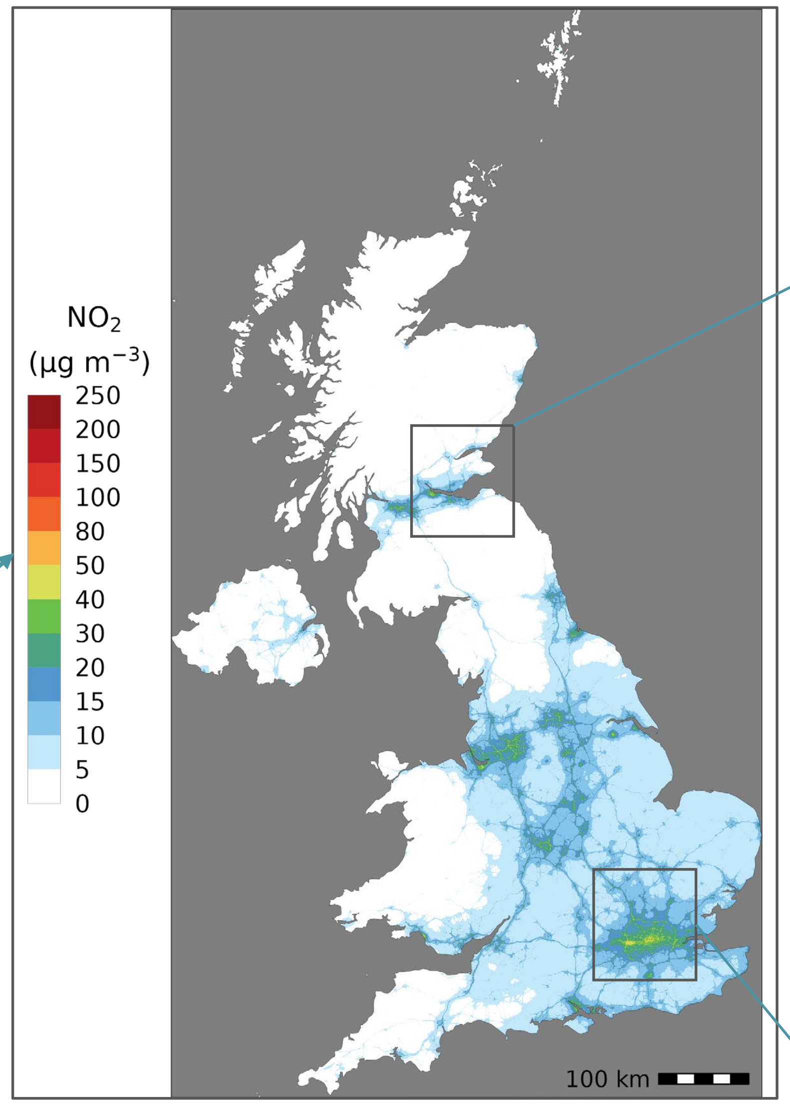
Europe 27x27km^2



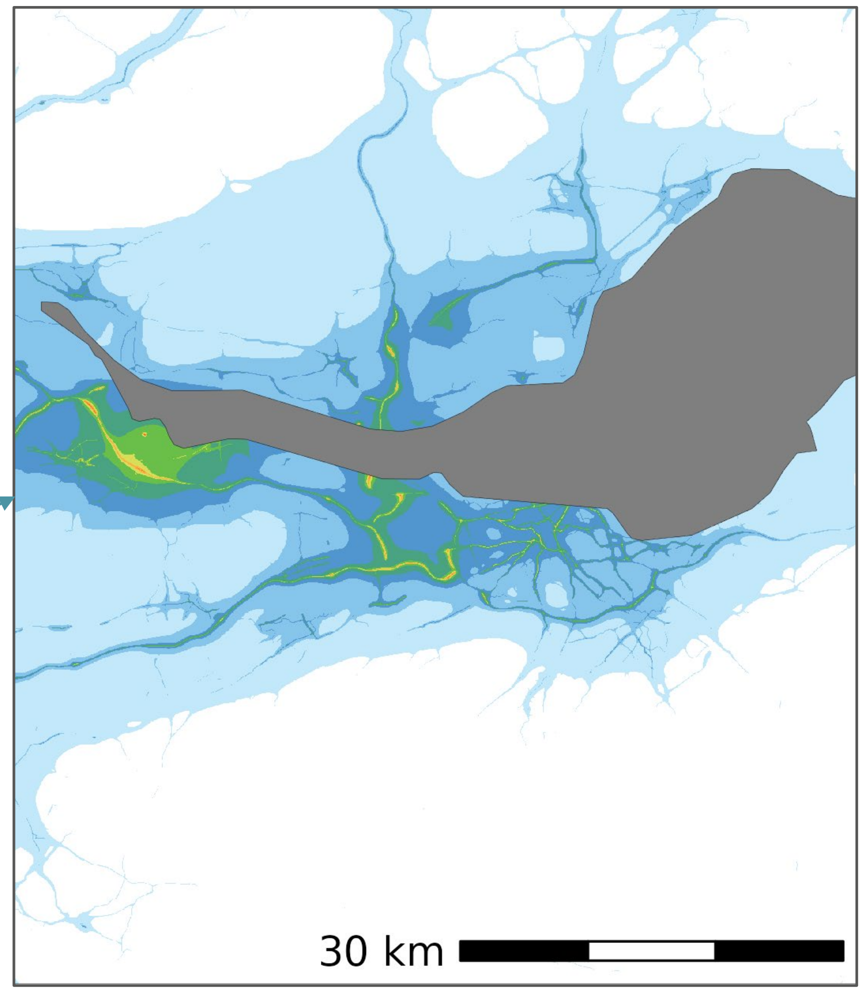
UK 3x3km^2



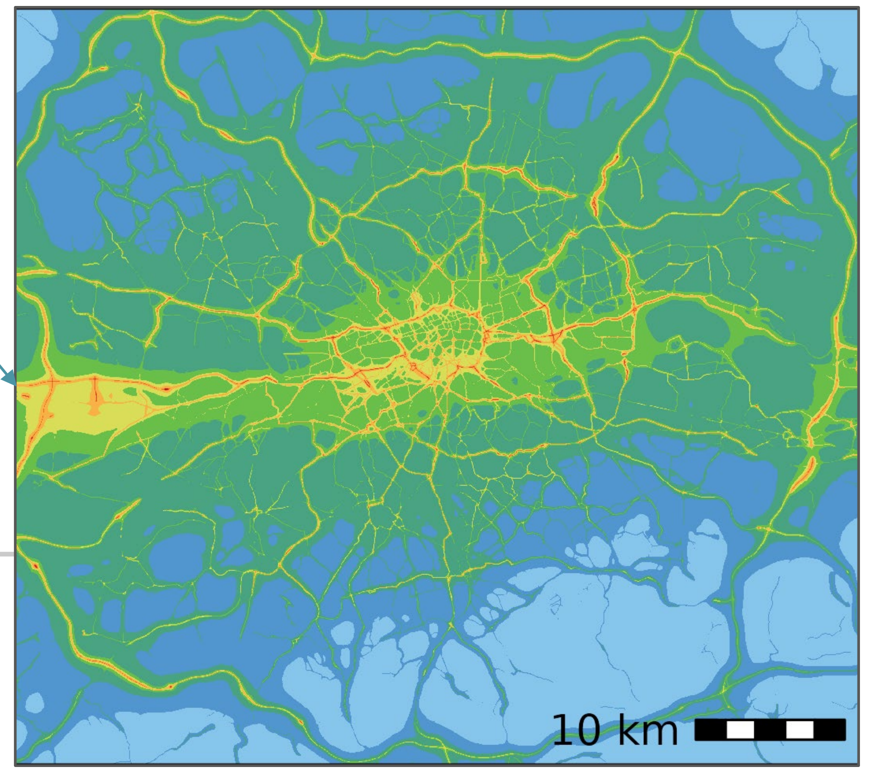
UK 50x50m^2



Edinburgh 50x50m^2



London 50x50m^2



All figures shows NO_2 $\mu g\ m^{-3}$ – different colour scale

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Ecology & Hydrology

Mu, Q., Denby, B. R., Wærsted, E. G., and Fagerli, H.: Downscaling of air pollutants in Europe using uEMEP_v6, Geosci. Model Dev., 15, 449–465, https://doi.org/10.5194/gmd-15-449-2022, 2022

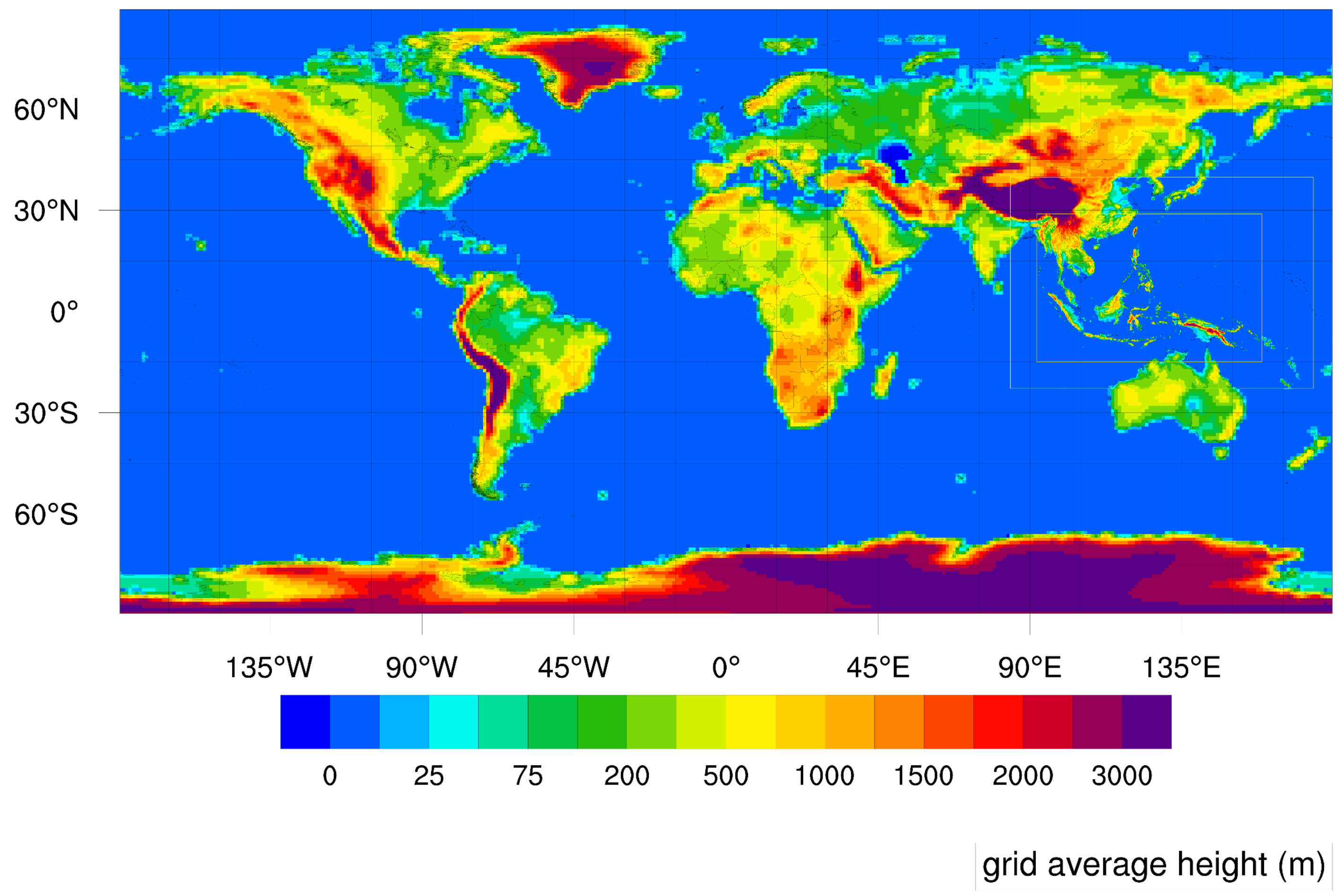
Denby, B. R., Gauss, M., Wind, P., Mu, Q., Grøtting Wærsted, E., Fagerli, H., Valdebenito, A., and Klein, H.: Description of the uEMEP_v5 downscaling approach for the EMEP MSC-W chemistry transport model, Geosci. Model Dev., 13, 6303–6323, https://doi.org/10.5194/gmd-13-6303-2020, 2020

ACTM across scales and domains

Currently, it is remarkably easy to apply a complex ACTM (EMEP, WRF-Chem, GEOS-Chem, CMAQ, etc)

- Anywhere in the world
- From historical years (e.g. ERA5 1940 up to present days) to forecast (GFS and ERA5)
- Emissions are available at remarkably spatial high res for the entire planet (EDGAR, HTAP, ECLIPSE, etc..)

But it is very difficult to assess the uncertainties in the model results



https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5
https://edgar.jrc.ec.europa.eu/dataset_htap_v3
https://www.emep.int

Some challenges…

- Evaluation of the WRF meteorology (we use the NOAA website)
- Which micro physics options to use in WRF, or aerosols scheme in EMEP?
- Emissions: both anthropogenic and biogenic
- Evaluation for concentrations outside the US, Europe, and perhaps China… is very difficult
- Dry deposition is difficult to evaluate for N_r compounds (and other chemical compounds)
- Ad-hoc measurement/campaigns done across the world are also a hard to gather
- In the UK, the R package OpenAir did simplify the availability of the AURN

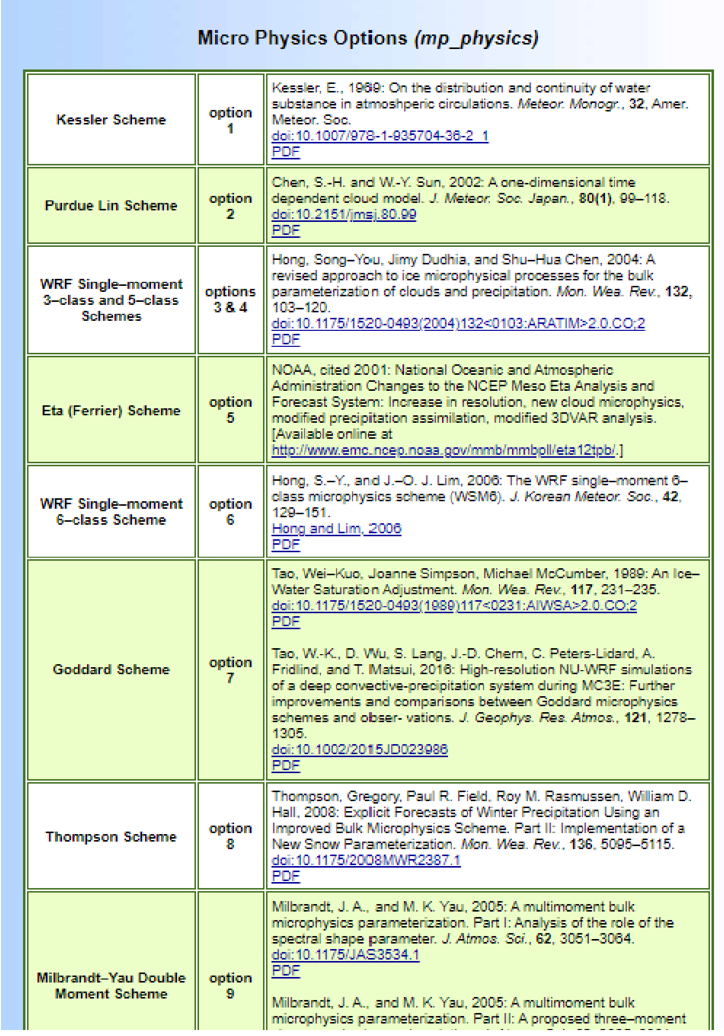
https://uk-air.defra.gov.uk/networks/network-info?view=aurn
https://www2.mmm.ucar.edu/wrf/users/physics/phys_references.html

What are the largest sources of uncertainties in ACTMs?

A personal and very incomplete list (not in any order)

- 3D (+time) meteorology (wind, rainfall, temperature, etc.)
- 3D (+time) emissions (anthropogenic and biogenic)
- Missing sources
- Human errors
- Chemical complexity (MCM, CRI vs simplified EMEP)
- Removal processes
- Model vs observations (apple and pears)
- Model resolution for specific pollutants (very important for NO_x not as much for $PM_{2.5}$)

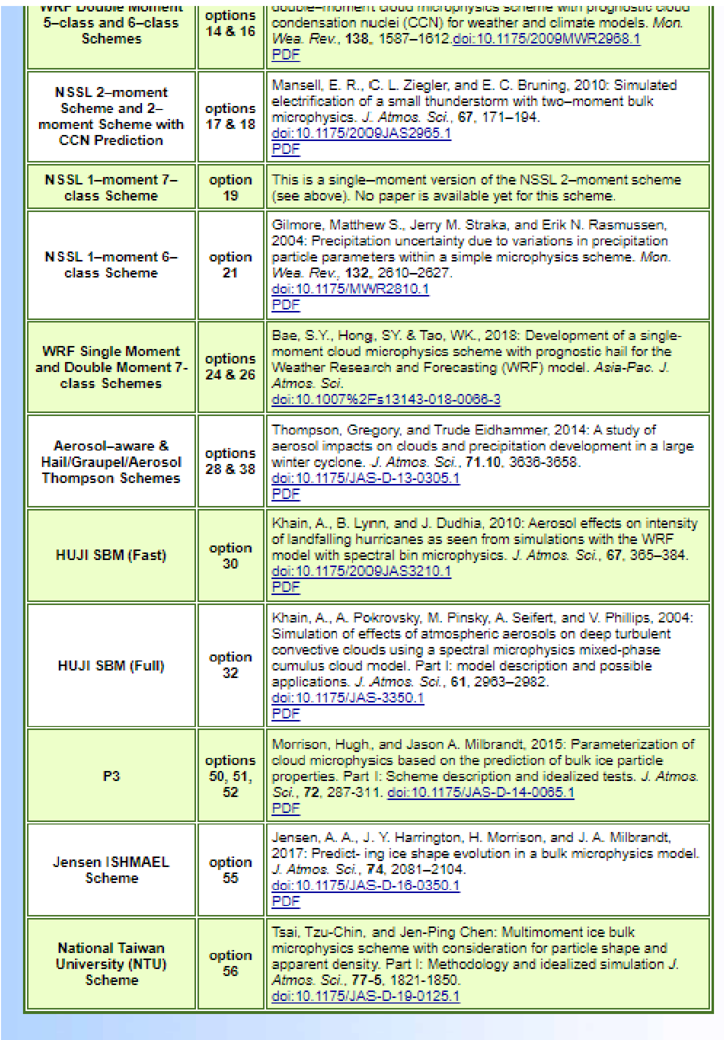
WRF calculated meteorology



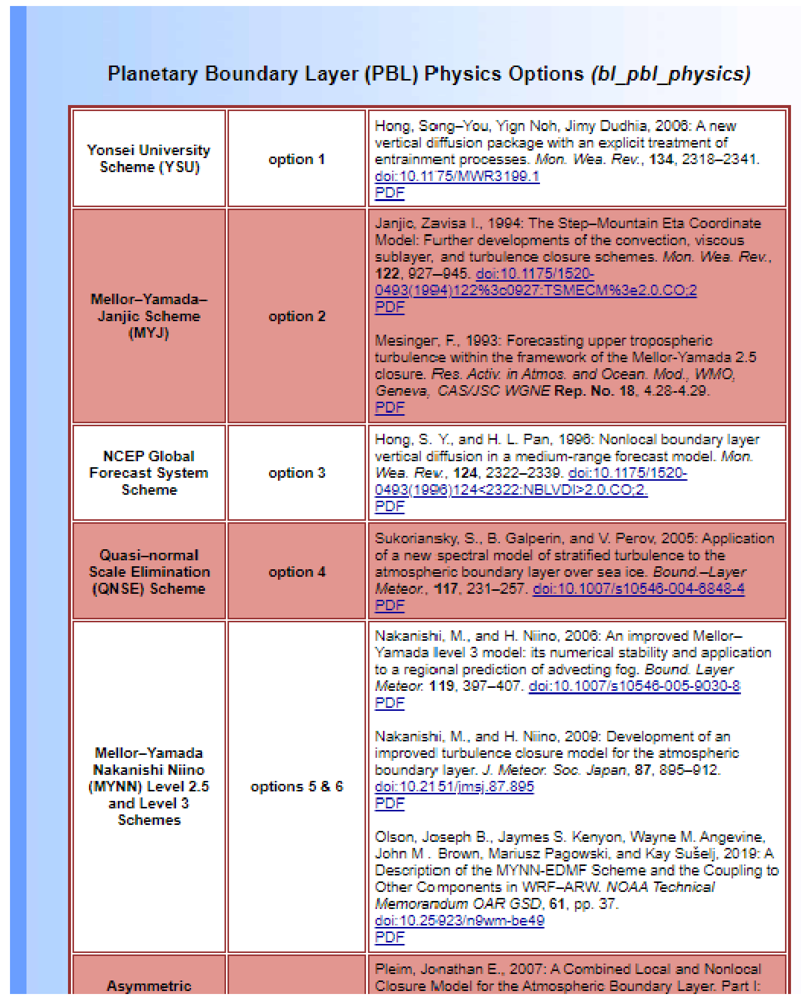
Micro Physics Options *(mp_physics)*

Kessler Scheme	**option 1**	Kessler, E., 1969: On the distribution and continuity of water substance in atmoshperic circulations. *Meteor. Monogr.*, **32**, Amer. Meteor. Soc. doi:10.1007/978-1-935704-36-2_1 PDF
Purdue Lin Scheme	**option 2**	Chen, S.-H. and W.-Y. Sun, 2002: A one-dimensional time dependent cloud model. *J. Meteor. Soc. Japan.*, **80(1)**, 99–118. doi:10.2151/jmsj.80.99 PDF
WRF Single–moment 3–class and 5–class Schemes	**options 3 & 4**	Hong, Song–You, Jimy Dudhia, and Shu–Hua Chen, 2004: A revised approach to ice microphysical processes for the bulk parameterization of clouds and precipitation. *Mon. Wea. Rev.*, **132**, 103–120. doi:10.1175/1520-0493(2004)132<0103:ARATIM>2.0.CO;2 PDF
Eta (Ferrier) Scheme	**option 5**	NOAA, cited 2001: National Oceanic and Atmospheric Administration Changes to the NCEP Meso Eta Analysis and Forecast System: Increase in resolution, new cloud microphysics, modified precipitation assimilation, modified 3DVAR analysis. [Available online at http://www.emc.ncep.noaa.gov/mmb/mmbpll/eta12tpb/.]
WRF Single–moment 6–class Scheme	**option 6**	Hong, S.–Y., and J.–O. J. Lim, 2006: The WRF single–moment 6–class microphysics scheme (WSM6). *J. Korean Meteor. Soc.*, **42**, 129–151. Hong and Lim, 2006 PDF
Goddard Scheme	**option 7**	Tao, Wei–Kuo, Joanne Simpson, Michael McCumber, 1989: An Ice–Water Saturation Adjustment. *Mon. Wea. Rev.*, **117**, 231–235. doi:10.1175/1520-0493(1989)117<0231:AIWSA>2.0.CO;2 PDF Tao, W.-K., D. Wu, S. Lang, J.-D. Chem, C. Peters-Lidard, A. Fridlind, and T. Matsui, 2016: High-resolution NU-WRF simulations of a deep convective-precipitation system during MC3E: Further improvements and comparisons between Goddard microphysics schemes and obser- vations. *J. Geophys. Res. Atmos.*, **121**, 1278–1305. doi:10.1002/2015JD023986 PDF
Thompson Scheme	**option 8**	Thompson, Gregory, Paul R. Field, Roy M. Rasmussen, William D. Hall, 2008: Explicit Forecasts of Winter Precipitation Using an Improved Bulk Microphysics Scheme. Part II: Implementation of a New Snow Parameterization. *Mon. Wea. Rev.*, **136**, 5095–5115. doi:10.1175/2008MWR2387.1 PDF
Milbrandt–Yau Double Moment Scheme	**option 9**	Milbrandt, J. A., and M. K. Yau, 2005: A multimoment bulk microphysics parameterization. Part I: Analysis of the role of the spectral shape parameter. *J. Atmos. Sci.*, **62**, 3051–3064. doi:10.1175/JAS3534.1 PDF Milbrandt, J. A., and M. K. Yau, 2005: A multimoment bulk microphysics parameterization. Part II: A proposed three–moment

Micro physics



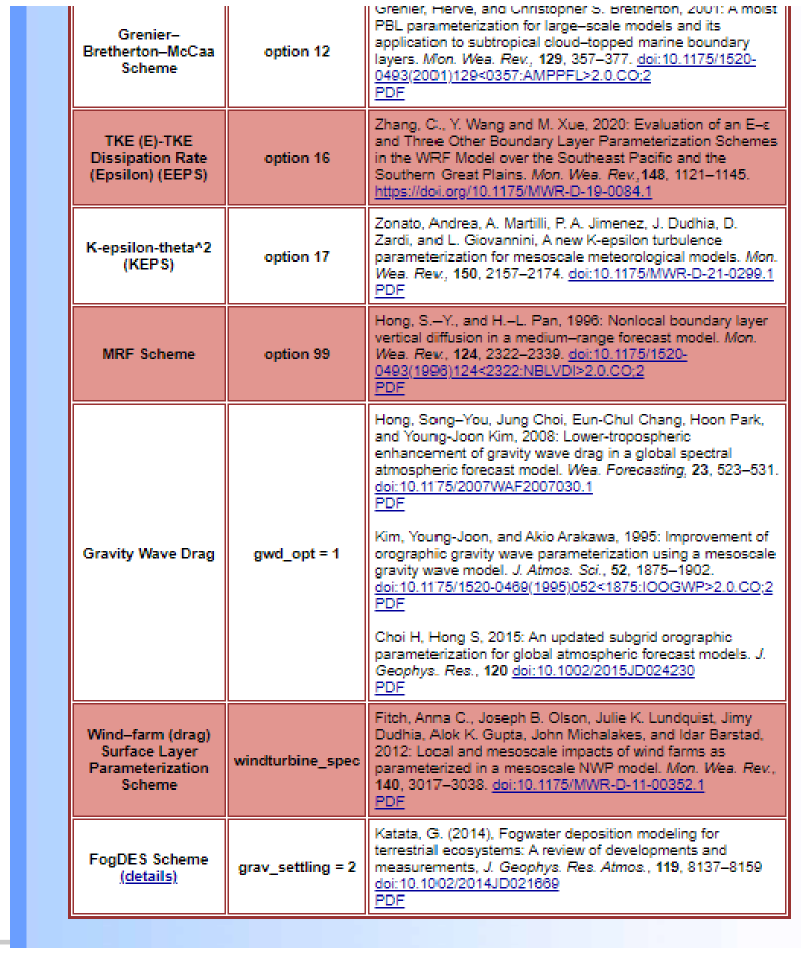
WRF Double Moment 5–class and 6–class Schemes	**options 14 & 16**	double–moment cloud microphysics scheme with prognostic cloud condensation nuclei (CCN) for weather and climate models. *Mon. Wea. Rev.*, **138**, 1587–1612.doi:10.1175/2009MWR2968.1 PDF
NSSL 2–moment Scheme and 2–moment Scheme with CCN Prediction	**options 17 & 18**	Mansell, E. R., C. L. Ziegler, and E. C. Bruning, 2010: Simulated electrification of a small thunderstorm with two–moment bulk microphysics. *J. Atmos. Sci.*, **67**, 171–194. doi:10.1175/2009JAS2965.1 PDF
NSSL 1–moment 7–class Scheme	**option 19**	This is a single–moment version of the NSSL 2–moment scheme (see above). No paper is available yet for this scheme.
NSSL 1–moment 6–class Scheme	**option 21**	Gilmore, Matthew S., Jerry M. Straka, and Erik N. Rasmussen, 2004: Precipitation uncertainty due to variations in precipitation particle parameters within a simple microphysics scheme. *Mon. Wea. Rev.*, **132**, 2610–2627. doi:10.1175/MWR2810.1 PDF
WRF Single Moment and Double Moment 7-class Schemes	**options 24 & 26**	Bae, S.Y., Hong, SY. & Tao, WK., 2018: Development of a single-moment cloud microphysics scheme with prognostic hail for the Weather Research and Forecasting (WRF) model. *Asia-Pac. J. Atmos. Sci.* doi:10.1007%2Fs13143-018-0066-3
Aerosol–aware & Hail/Graupel/Aerosol Thompson Schemes	**options 28 & 38**	Thompson, Gregory, and Trude Eidhammer, 2014: A study of aerosol impacts on clouds and precipitation development in a large winter cyclone. *J. Atmos. Sci.*, **71.10**, 3636-3658. doi:10.1175/JAS-D-13-0305.1 PDF
HUJI SBM (Fast)	**option 30**	Khain, A., B. Lynn, and J. Dudhia, 2010: Aerosol effects on intensity of landfalling hurricanes as seen from simulations with the WRF model with spectral bin microphysics. *J. Atmos. Sci.*, **67**, 365–384. doi:10.1175/2009JAS3210.1 PDF
HUJI SBM (Full)	**option 32**	Khain, A., A. Pokrovsky, M. Pinsky, A. Seifert, and V. Phillips, 2004: Simulation of effects of atmospheric aerosols on deep turbulent convective clouds using a spectral microphysics mixed-phase cumulus cloud model. Part I: model description and possible applications. *J. Atmos. Sci.*, **61**, 2963–2982. doi:10.1175/JAS-3350.1 PDF
P3	**options 50, 51, 52**	Morrison, Hugh, and Jason A. Milbrandt, 2015: Parameterization of cloud microphysics based on the prediction of bulk ice particle properties. Part I: Scheme description and idealized tests. *J. Atmos. Sci.*, **72**, 287-311. doi:10.1175/JAS-D-14-0065.1 PDF
Jensen ISHMAEL Scheme	**option 55**	Jensen, A. A., J. Y. Harrington, H. Morrison, and J. A. Milbrandt, 2017: Predict- ing ice shape evolution in a bulk microphysics model. *J. Atmos. Sci.*, **74**, 2081–2104. doi:10.1175/JAS-D-16-0350.1 PDF
National Taiwan University (NTU) Scheme	**option 56**	Tsai, Tzu-Chin, and Jen-Ping Chen: Multimoment ice bulk microphysics scheme with consideration for particle shape and apparent density. Part I: Methodology and idealized simulation *J. Atmos. Sci.*, **77-5**, 1821-1850. doi:10.1175/JAS-D-19-0125.1



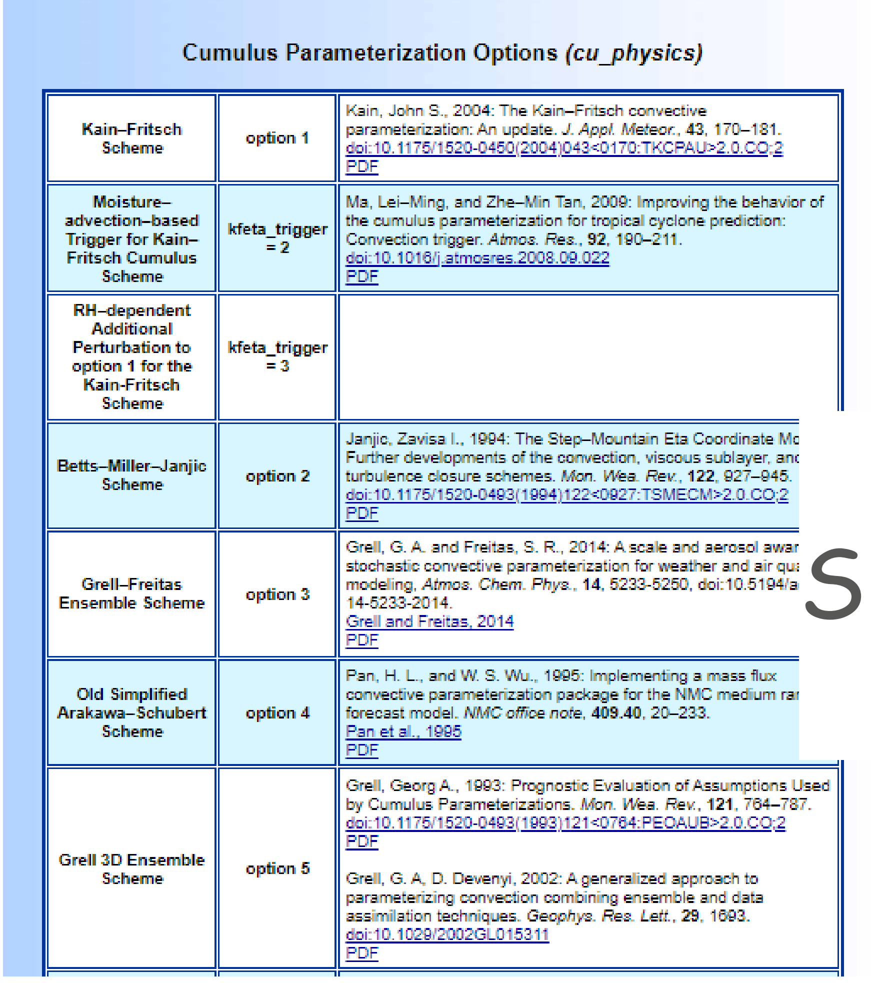
Planetary Boundary Layer (PBL) Physics Options *(bl_pbl_physics)*

Yonsei University Scheme (YSU)	**option 1**	Hong, Song–You, Yign Noh, Jimy Dudhia, 2006: A new vertical diffusion package with an explicit treatment of entrainment processes. *Mon. Wea. Rev.*, **134**, 2318–2341. doi:10.1175/MWR3199.1 PDF
Mellor–Yamada–Janjic Scheme (MYJ)	**option 2**	Janjic, Zavisa I., 1994: The Step–Mountain Eta Coordinate Model: Further developments of the convection, viscous sublayer, and turbulence closure schemes. *Mon. Wea. Rev.*, **122**, 927–945. doi:10.1175/1520-0493(1994)122%3c0927:TSMECM%3e2.0.CO;2 PDF Mesinger, F., 1993: Forecasting upper tropospheric turbulence within the framework of the Mellor-Yamada 2.5 closure. *Res. Activ. in Atmos. and Ocean. Mod., WMO, Geneva, CAS/JSC WGNE* **Rep. No. 18**, 4.28-4.29. PDF
NCEP Global Forecast System Scheme	**option 3**	Hong, S. Y., and H. L. Pan, 1996: Nonlocal boundary layer vertical diffusion in a medium-range forecast model. *Mon. Wea. Rev.*, **124**, 2322–2339. doi:10.1175/1520-0493(1996)124<2322:NBLVDI>2.0.CO;2. PDF
Quasi–normal Scale Elimination (QNSE) Scheme	**option 4**	Sukoriansky, S., B. Galperin, and V. Perov, 2005: Application of a new spectral model of stratified turbulence to the atmospheric boundary layer over sea ice. *Bound.–Layer Meteor.*, **117**, 231–257. doi:10.1007/s10546-004-6848-4 PDF
Mellor–Yamada Nakanishi Niino (MYNN) Level 2.5 and Level 3 Schemes	**options 5 & 6**	Nakanishi, M., and H. Niino, 2006: An improved Mellor–Yamada level 3 model: its numerical stability and application to a regional prediction of advecting fog. *Bound. Layer Meteor.* **119**, 397–407. doi:10.1007/s10546-005-9030-8 PDF Nakanishi, M., and H. Niino, 2009: Development of an improved turbulence closure model for the atmospheric boundary layer. *J. Meteor. Soc. Japan*, **87**, 895–912. doi:10.2151/jmsj.87.895 PDF Olson, Joseph B., Jaymes S. Kenyon, Wayne M. Angevine, John M . Brown, Mariusz Pagowski, and Kay Sušelj, 2019: A Description of the MYNN-EDMF Scheme and the Coupling to Other Components in WRF–ARW. *NOAA Technical Memorandum OAR GSD*, **61**, pp. 37. doi:10.25923/n9wm-be49 PDF
Asymmetric		Pleim, Jonathan E., 2007: A Combined Local and Nonlocal Closure Model for the Atmospheric Boundary Layer. Part I:

Planetary boundary layers



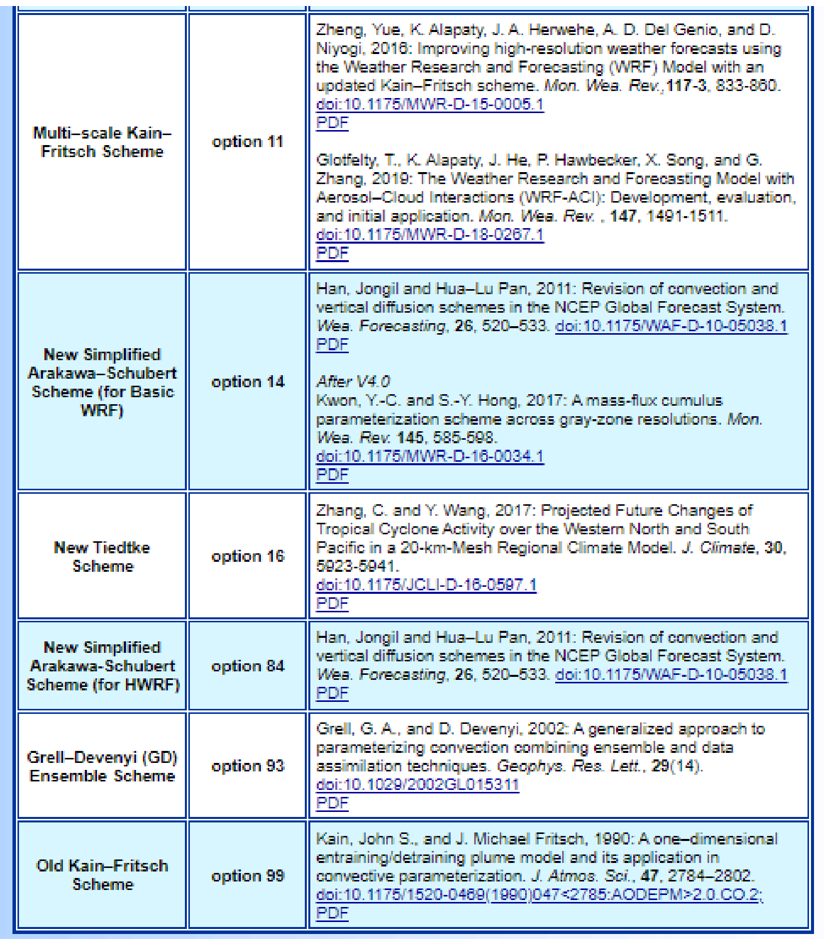
Grenier–Bretherton–McCaa Scheme	**option 12**	Grenier, Herve, and Christopher S. Bretherton, 2001: A moist PBL parameterization for large–scale models and its application to subtropical cloud–topped marine boundary layers. *Mon. Wea. Rev.*, **129**, 357–377. doi:10.1175/1520-0493(2001)129<0357:AMPPFL>2.0.CO;2 PDF
TKE (E)-TKE Dissipation Rate (Epsilon) (EEPS)	**option 16**	Zhang, C., Y. Wang and M. Xue, 2020: Evaluation of an E–ε and Three Other Boundary Layer Parameterization Schemes in the WRF Model over the Southeast Pacific and the Southern Great Plains. *Mon. Wea. Rev.*,**148**, 1121–1145. https://doi.org/10.1175/MWR-D-19-0084.1
K-epsilon-theta^2 (KEPS)	**option 17**	Zonato, Andrea, A. Martilli, P. A. Jimenez, J. Dudhia, D. Zardi, and L. Giovannini, A new K-epsilon turbulence parameterization for mesoscale meteorological models. *Mon. Wea. Rev.*, **150**, 2157–2174. doi:10.1175/MWR-D-21-0299.1 PDF
MRF Scheme	**option 99**	Hong, S.–Y., and H.–L. Pan, 1996: Nonlocal boundary layer vertical diffusion in a medium–range forecast model. *Mon. Wea. Rev.*, **124**, 2322–2339. doi:10.1175/1520-0493(1996)124<2322:NBLVDI>2.0.CO;2 PDF
Gravity Wave Drag	**gwd_opt = 1**	Hong, Song–You, Jung Choi, Eun-Chul Chang, Hoon Park, and Young-Joon Kim, 2008: Lower-tropospheric enhancement of gravity wave drag in a global spectral atmospheric forecast model. *Wea. Forecasting*, **23**, 523–531. doi:10.1175/2007WAF2007030.1 PDF Kim, Young-Joon, and Akio Arakawa, 1995: Improvement of orographic gravity wave parameterization using a mesoscale gravity wave model. *J. Atmos. Sci.*, **52**, 1875–1902. doi:10.1175/1520-0469(1995)052<1875:IOOGWP>2.0.CO;2 PDF Choi H, Hong S, 2015: An updated subgrid orographic parameterization for global atmospheric forecast models. *J. Geophys. Res.*, **120** doi:10.1002/2015JD024230 PDF
Wind–farm (drag) Surface Layer Parameterization Scheme	**windturbine_spec**	Fitch, Anna C., Joseph B. Olson, Julie K. Lundquist, Jimy Dudhia, Alok K. Gupta, John Michalakes, and Idar Barstad, 2012: Local and mesoscale impacts of wind farms as parameterized in a mesoscale NWP model. *Mon. Wea. Rev.*, **140**, 3017–3038. doi:10.1175/MWR-D-11-00352.1 PDF
FogDES Scheme (details)	**grav_settling = 2**	Katata, G. (2014), Fogwater deposition modeling for terrestrial ecosystems: A review of developments and measurements, *J. Geophys. Res. Atmos.*, **119**, 8137–8159 doi:10.1002/2014JD021669 PDF



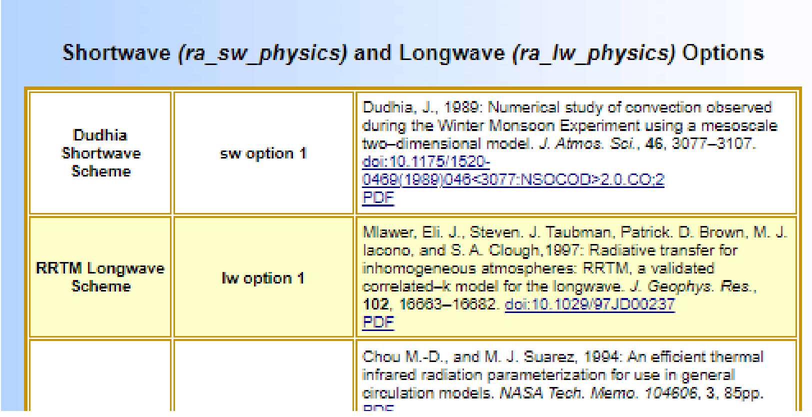
Cumulus Parameterization Options *(cu_physics)*

Kain–Fritsch Scheme	**option 1**	Kain, John S., 2004: The Kain–Fritsch convective parameterization: An update. *J. Appl. Meteor.*, **43**, 170–181. doi:10.1175/1520-0450(2004)043<0170:TKCPAU>2.0.CO;2 PDF
Moisture–advection–based Trigger for Kain–Fritsch Cumulus Scheme	**kfeta_trigger = 2**	Ma, Lei–Ming, and Zhe–Min Tan, 2009: Improving the behavior of the cumulus parameterization for tropical cyclone prediction: Convection trigger. *Atmos. Res.*, **92**, 190–211. doi:10.1016/j.atmosres.2008.09.022 PDF
RH–dependent Additional Perturbation to option 1 for the Kain-Fritsch Scheme	**kfeta_trigger = 3**	
Betts–Miller–Janjic Scheme	**option 2**	Janjic, Zavisa I., 1994: The Step–Mountain Eta Coordinate Mo Further developments of the convection, viscous sublayer, and turbulence closure schemes. *Mon. Wea. Rev.*, **122**, 927–945. doi:10.1175/1520-0493(1994)122<0927:TSMECM>2.0.CO;2 PDF
Grell–Freitas Ensemble Scheme	**option 3**	Grell, G. A. and Freitas, S. R., 2014: A scale and aerosol awar stochastic convective parameterization for weather and air qu modeling, *Atmos. Chem. Phys.*, **14**, 5233-5250, doi:10.5194/a 14-5233-2014. Grell and Freitas, 2014 PDF
Old Simplified Arakawa–Schubert Scheme	**option 4**	Pan, H. L., and W. S. Wu., 1995: Implementing a mass flux convective parameterization package for the NMC medium ra forecast model. *NMC office note*, **409.40**, 20–233. Pan et al., 1995 PDF
Grell 3D Ensemble Scheme	**option 5**	Grell, Georg A., 1993: Prognostic Evaluation of Assumptions Used by Cumulus Parameterizations. *Mon. Wea. Rev.*, **121**, 764–787. doi:10.1175/1520-0493(1993)121<0764:PEOAUB>2.0.CO;2 PDF Grell, G. A, D. Devenyi, 2002: A generalized approach to parameterizing convection combining ensemble and data assimilation techniques. *Geophys. Res. Lett.*, **29**, 1693. doi:10.1029/2002GL015311 PDF

Cumulus Parameterizations



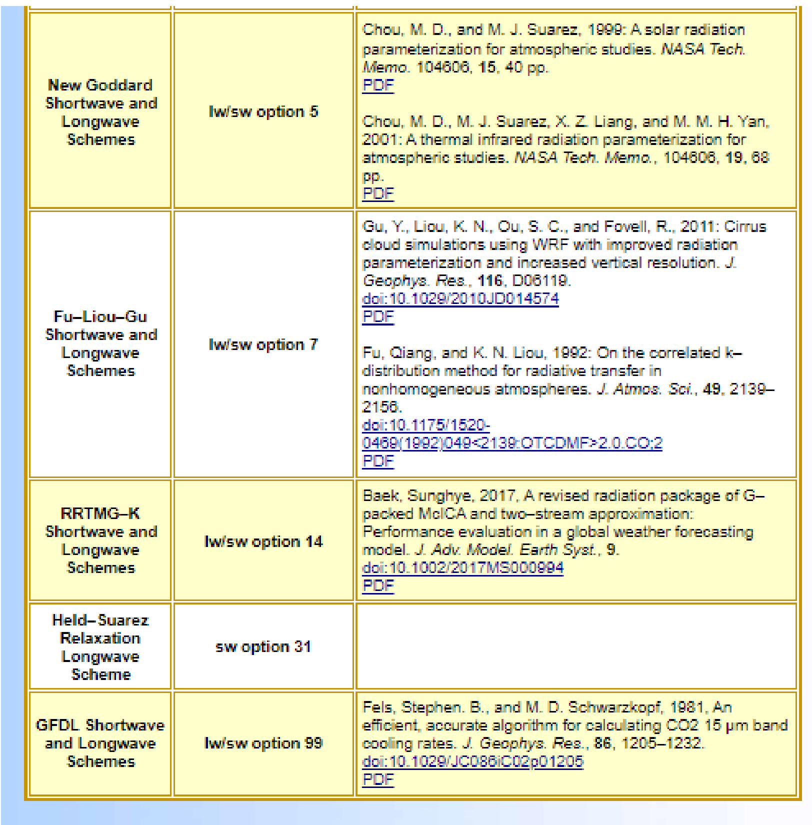
Multi–scale Kain–Fritsch Scheme	**option 11**	Zheng, Yue, K. Alapaty, J. A. Herwehe, A. D. Del Genio, and D. Niyogi, 2016: Improving high-resolution weather forecasts using the Weather Research and Forecasting (WRF) Model with an updated Kain–Fritsch scheme. *Mon. Wea. Rev.*,**117-3**, 833-860. doi:10.1175/MWR-D-15-0005.1 PDF Glotfelty, T., K. Alapaty, J. He, P. Hawbecker, X. Song, and G. Zhang, 2019: The Weather Research and Forecasting Model with Aerosol–Cloud Interactions (WRF-ACI): Development, evaluation, and initial application. *Mon. Wea. Rev.* , **147**, 1491-1511. doi:10.1175/MWR-D-18-0267.1 PDF
New Simplified Arakawa–Schubert Scheme (for Basic WRF)	**option 14**	Han, Jongil and Hua–Lu Pan, 2011: Revision of convection and vertical diffusion schemes in the NCEP Global Forecast System. *Wea. Forecasting*, **26**, 520–533. doi:10.1175/WAF-D-10-05038.1 PDF *After V4.0* Kwon, Y.-C. and S.-Y. Hong, 2017: A mass-flux cumulus parameterization scheme across gray-zone resolutions. *Mon. Wea. Rev.* **145**, 585-598. doi:10.1175/MWR-D-16-0034.1 PDF
New Tiedtke Scheme	**option 16**	Zhang, C. and Y. Wang, 2017: Projected Future Changes of Tropical Cyclone Activity over the Western North and South Pacific in a 20-km-Mesh Regional Climate Model. *J. Climate*, **30**, 5923-5941. doi:10.1175/JCLI-D-16-0597.1 PDF
New Simplified Arakawa-Schubert Scheme (for HWRF)	**option 84**	Han, Jongil and Hua–Lu Pan, 2011: Revision of convection and vertical diffusion schemes in the NCEP Global Forecast System. *Wea. Forecasting*, **26**, 520–533. doi:10.1175/WAF-D-10-05038.1 PDF
Grell–Devenyi (GD) Ensemble Scheme	**option 93**	Grell, G. A., and D. Devenyi, 2002: A generalized approach to parameterizing convection combining ensemble and data assimilation techniques. *Geophys. Res. Lett.*, **29**(14). doi:10.1029/2002GL015311 PDF
Old Kain–Fritsch Scheme	**option 99**	Kain, John S., and J. Michael Fritsch, 1990: A one–dimensional entraining/detraining plume model and its application in convective parameterization. *J. Atmos. Sci.*, **47**, 2784–2802. doi:10.1175/1520-0469(1990)047<2785:AODEPM>2.0.CO.2; PDF



Shortwave *(ra_sw_physics)* and Longwave *(ra_lw_physics)* Options

Dudhia Shortwave Scheme	**sw option 1**	Dudhia, J., 1989: Numerical study of convection observed during the Winter Monsoon Experiment using a mesoscale two–dimensional model. *J. Atmos. Sci.*, **46**, 3077–3107. doi:10.1175/1520-0469(1989)046<3077:NSOCOD>2.0.CO;2 PDF
RRTM Longwave Scheme	**lw option 1**	Mlawer, Eli. J., Steven. J. Taubman, Patrick. D. Brown, M. J. Iacono, and S. A. Clough,1997: Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated–k model for the longwave. *J. Geophys. Res.*, **102**, 16663–16682. doi:10.1029/97JD00237 PDF
		Chou M.-D., and M. J. Suarez, 1994: An efficient thermal infrared radiation parameterization for use in general circulation models. *NASA Tech. Memo. 104606*, 3, 85pp.

Shortwave and Longwave



New Goddard Shortwave and Longwave Schemes	**lw/sw option 5**	Chou, M. D., and M. J. Suarez, 1999: A solar radiation parameterization for atmospheric studies. *NASA Tech. Memo.* 104606, **15**, 40 pp. PDF Chou, M. D., M. J. Suarez, X. Z. Liang, and M. M. H. Yan, 2001: A thermal infrared radiation parameterization for atmospheric studies. *NASA Tech. Memo.*, 104606, **19**, 68 pp. PDF
Fu–Liou–Gu Shortwave and Longwave Schemes	**lw/sw option 7**	Gu, Y., Liou, K. N., Ou, S. C., and Fovell, R., 2011: Cirrus cloud simulations using WRF with improved radiation parameterization and increased vertical resolution. *J. Geophys. Res.*, **116**, D06119. doi:10.1029/2010JD014574 PDF Fu, Qiang, and K. N. Liou, 1992: On the correlated k–distribution method for radiative transfer in nonhomogeneous atmospheres. *J. Atmos. Sci.*, **49**, 2139–2156. doi:10.1175/1520-0469(1992)049<2139:OTCDMF>2.0.CO;2 PDF
RRTMG–K Shortwave and Longwave Schemes	**lw/sw option 14**	Baek, Sunghye, 2017, A revised radiation package of G–packed McICA and two–stream approximation: Performance evaluation in a global weather forecasting model. *J. Adv. Model. Earth Syst.*, **9**. doi:10.1002/2017MS000994 PDF
Held–Suarez Relaxation Longwave Scheme	**sw option 31**	
GFDL Shortwave and Longwave Schemes	**lw/sw option 99**	Fels, Stephen. B., and M. D. Schwarzkopf, 1981, An efficient, accurate algorithm for calculating CO2 15 µm band cooling rates. *J. Geophys. Res.*, **86**, 1205–1232. doi:10.1029/JC086iC02p01205 PDF

and more….

WRF model available options,

for microphysics, PBL, Cumulus, shortwave, …

WRF Physics Suites may be the way forward…?

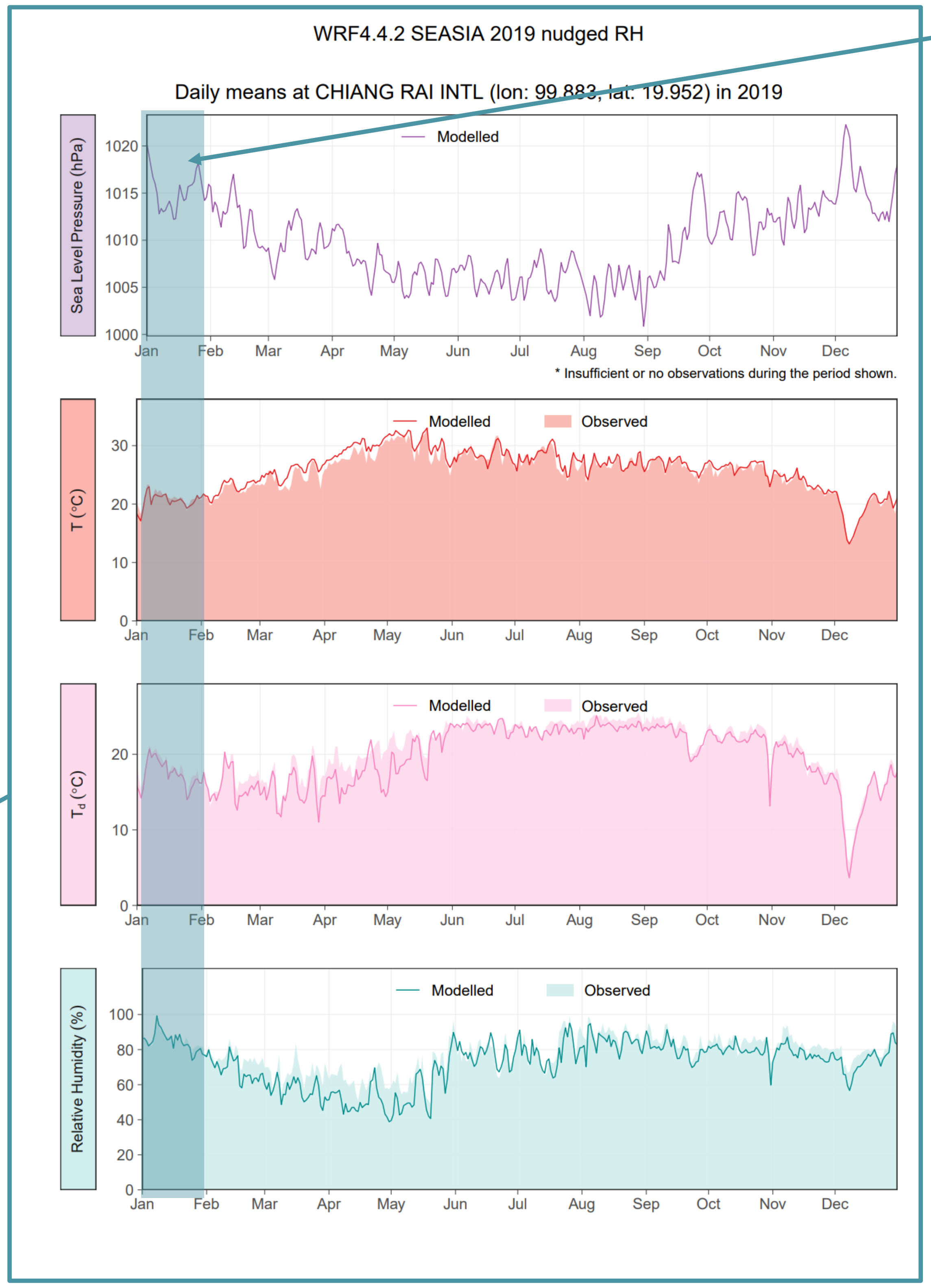
Nudging, if so what to nudge, or full data assimilation 4DVAR?

Meteorology – ERA5 downscaled with the WRF model in southeast Asia

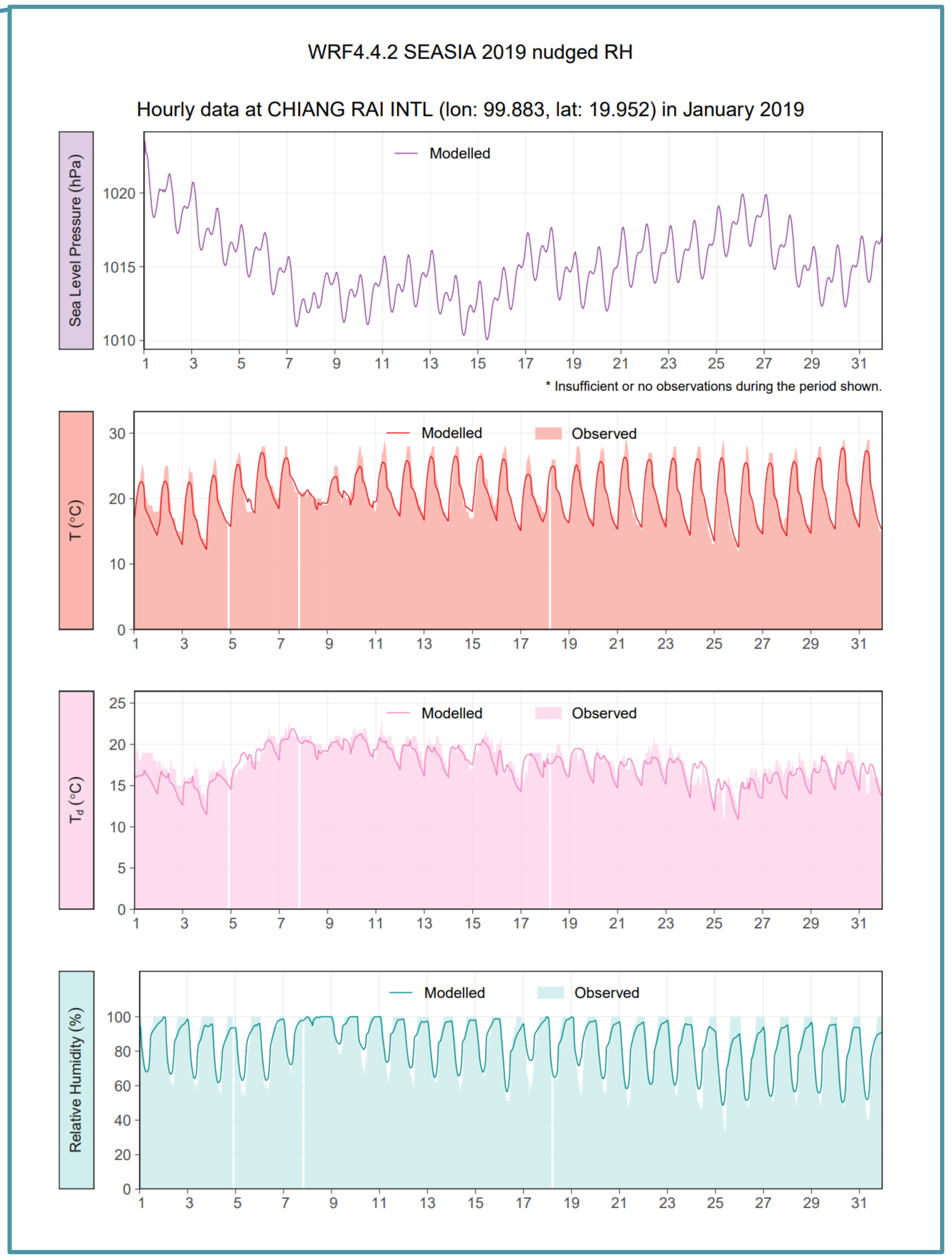
The WRF model is used here to downscale the ERA5 reanalysis to the required resolution (in this case 0.11° × 0.11°)

We are currently evaluating if nudging the relative humidity is beneficial or not to our WRF model results

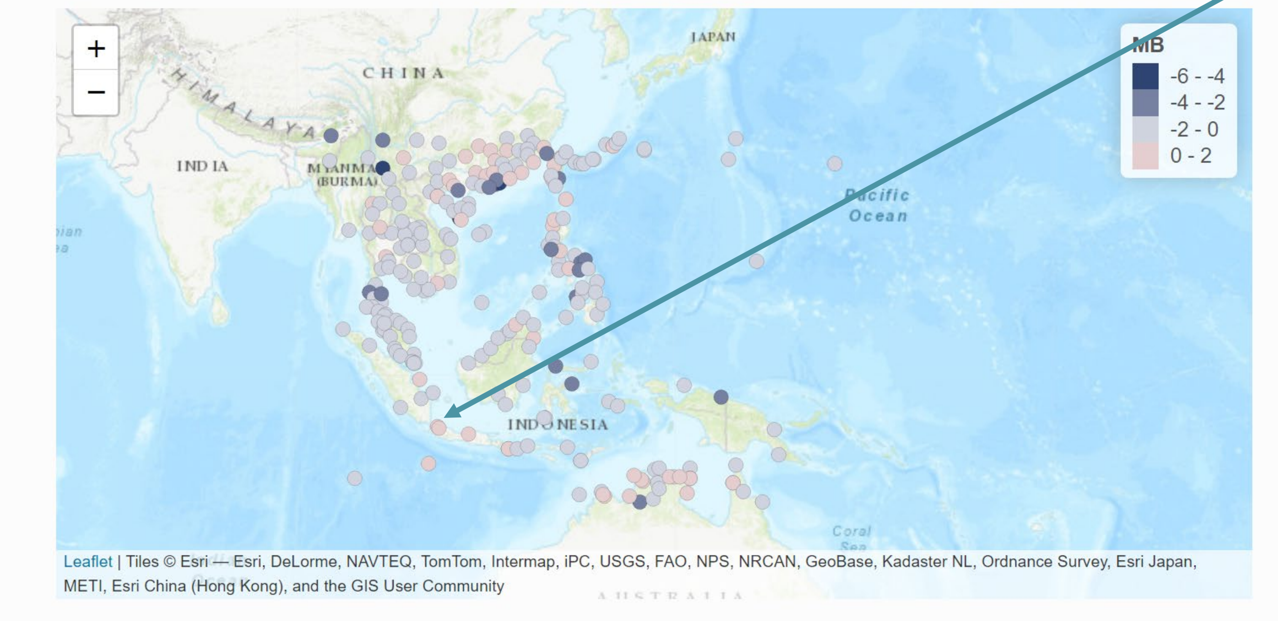
Singapore 2019 daily mean



hourly values for January



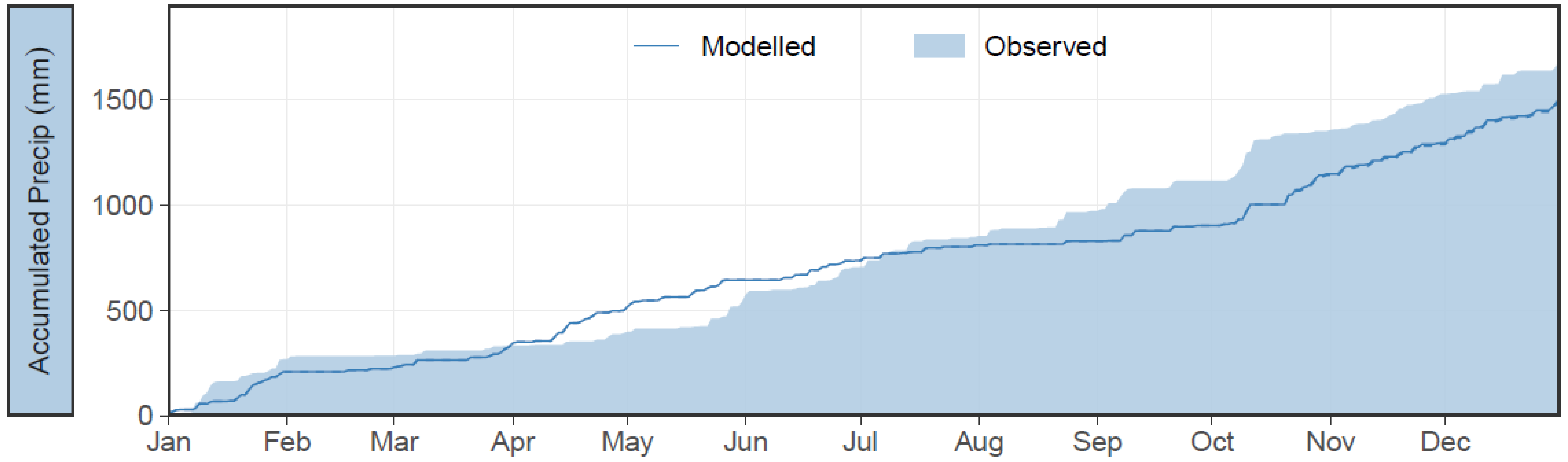
Summary plot for mean bias for the 2m T - SEA WRF domain



Variable	n	FAC2	MB	NMB	RMSE	r
air temperature (K)	251	1	-0.4	0	1.1	0.94
dew point temperature (K)	249	1	-0.5	0	1.1	0.96
relative humidity (%)	249	1	0.3	0	4.9	0.79
sea level pressure (hPa)	154	1	0.3	0	0.7	0.92
accumulated precip (mm)	156	0.68	-204.2	-0.13	919.4	0.56
wind speed (m s^{-1})	251	0.96	0.2	0.05	1	0.72

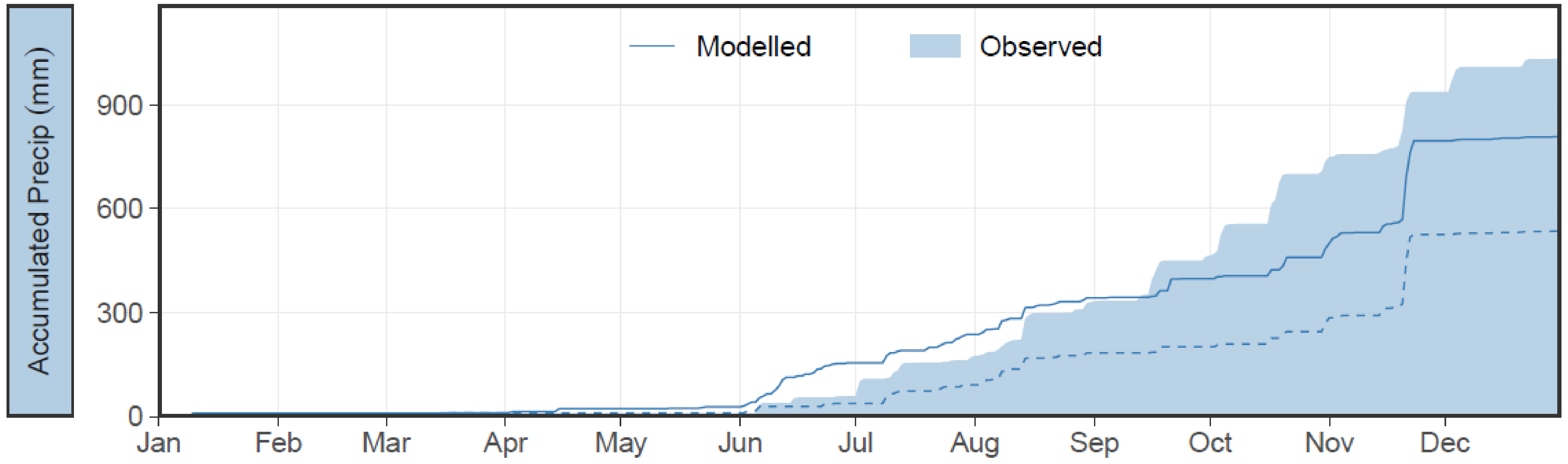
Meteorology – What about Rainfall?

SINGAPORE CHANGI INTL (lon: 103.994, lat: 1.35) in 2018



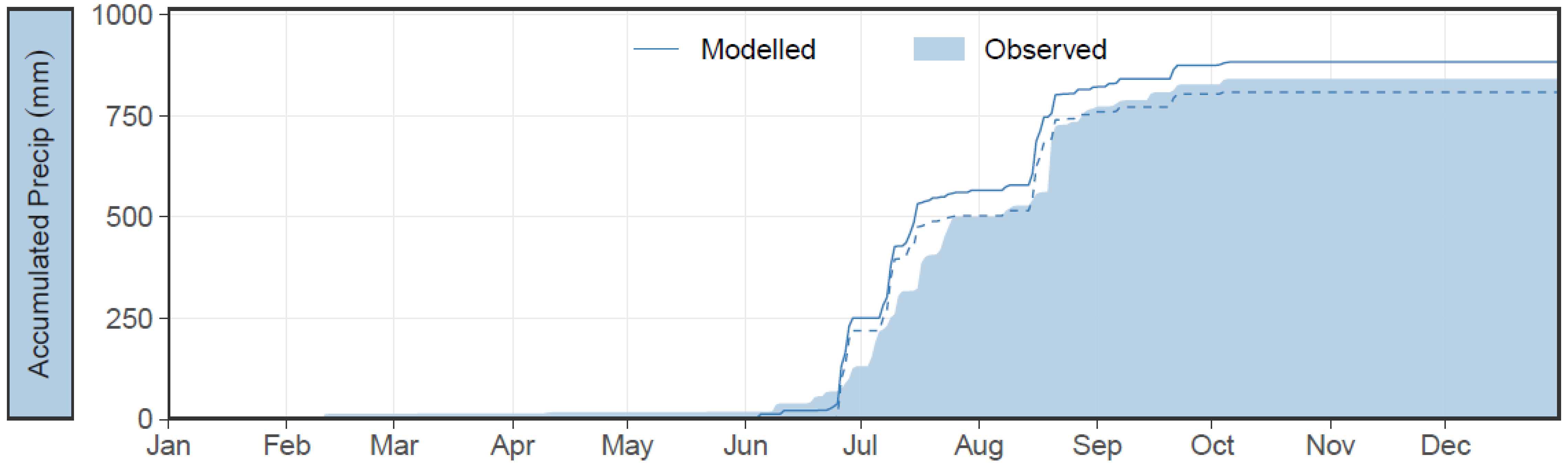
* Dashed line shows modelled data when observations exist. Data shown are a cummulative sum.

CHENNAI INTL (lon: 80.181, lat: 12.994) in 2018



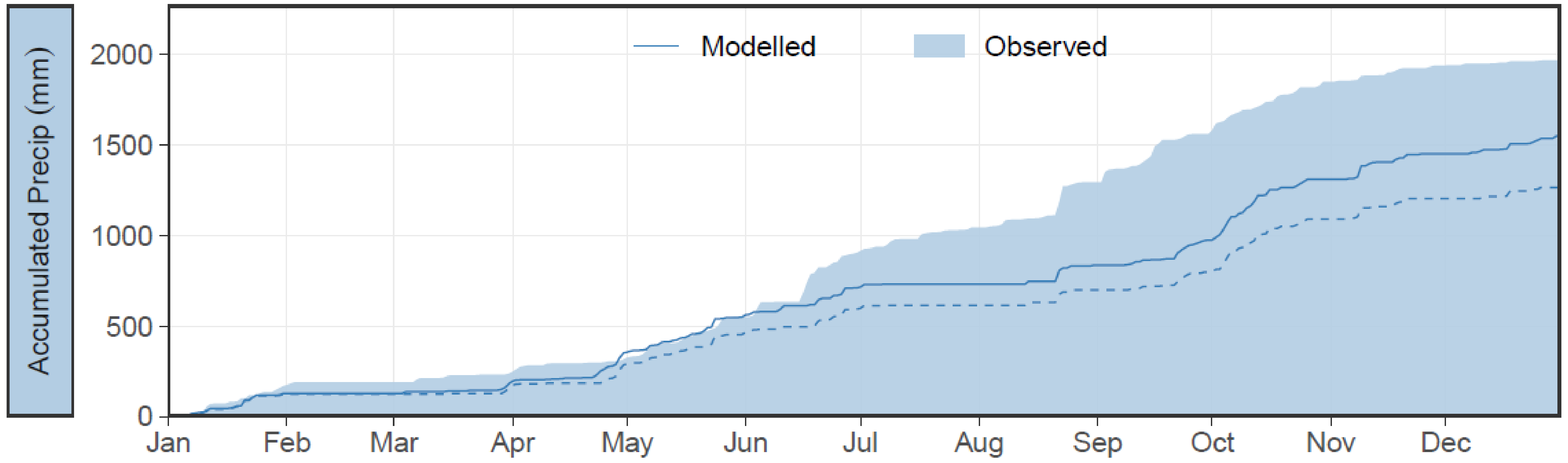
* Dashed line shows modelled data when observations exist. Data shown are a cummulative sum.

BHOPAL (lon: 77.337, lat: 23.287) in 2018



* Dashed line shows modelled data when observations exist. Data shown are a cummulative sum.

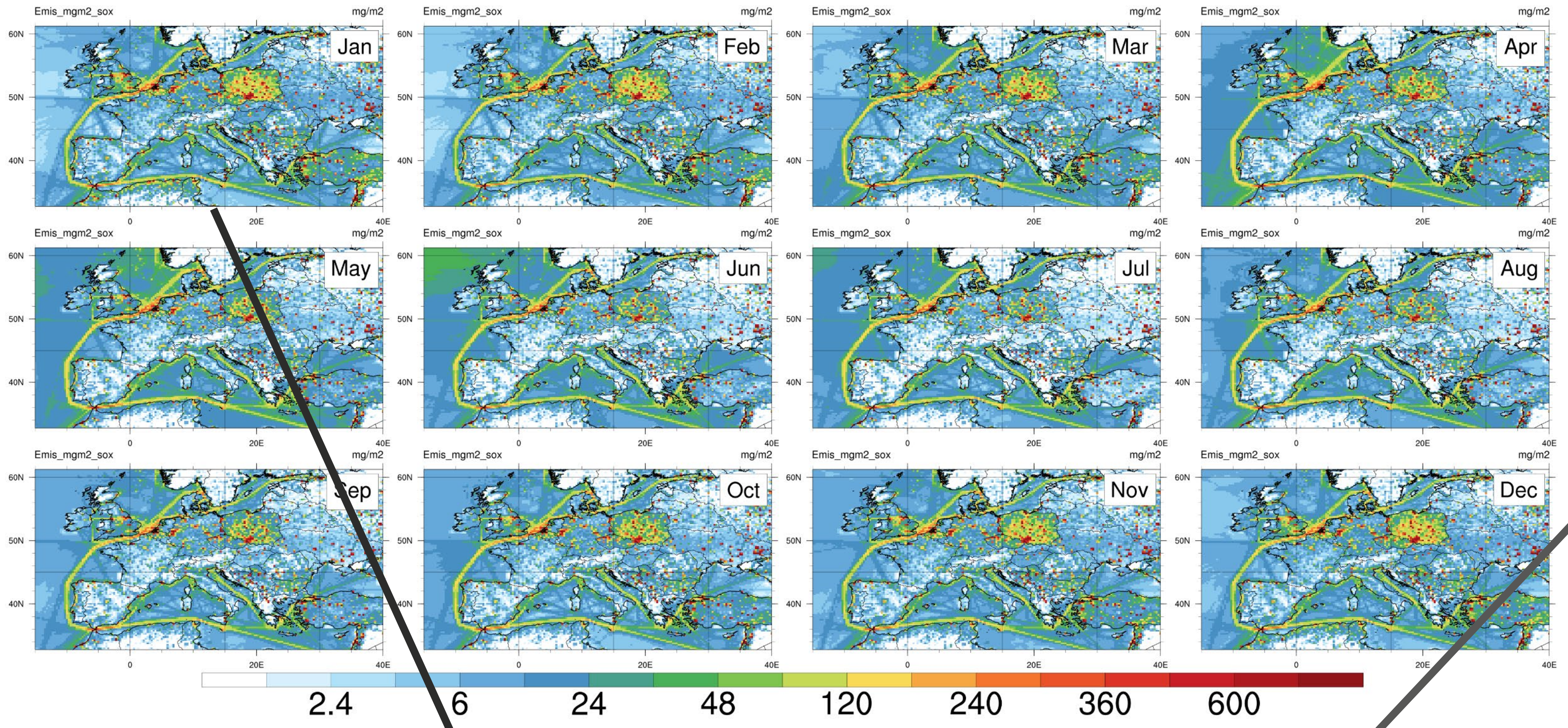
PHUKET (lon: 98.4, lat: 7.883) in 2018



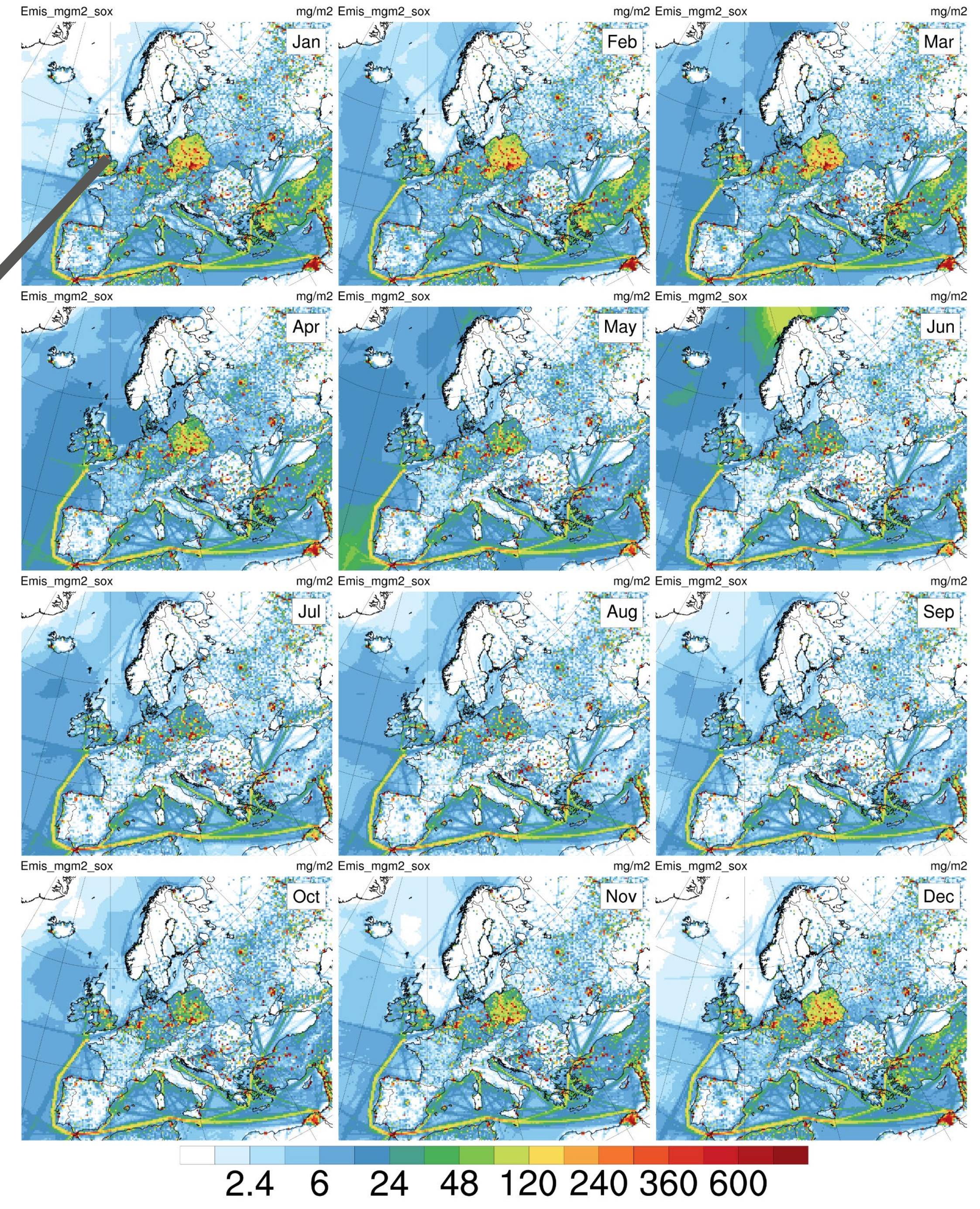
* Dashed line shows modelled data when observations exist. Data shown are a cummulative sum.

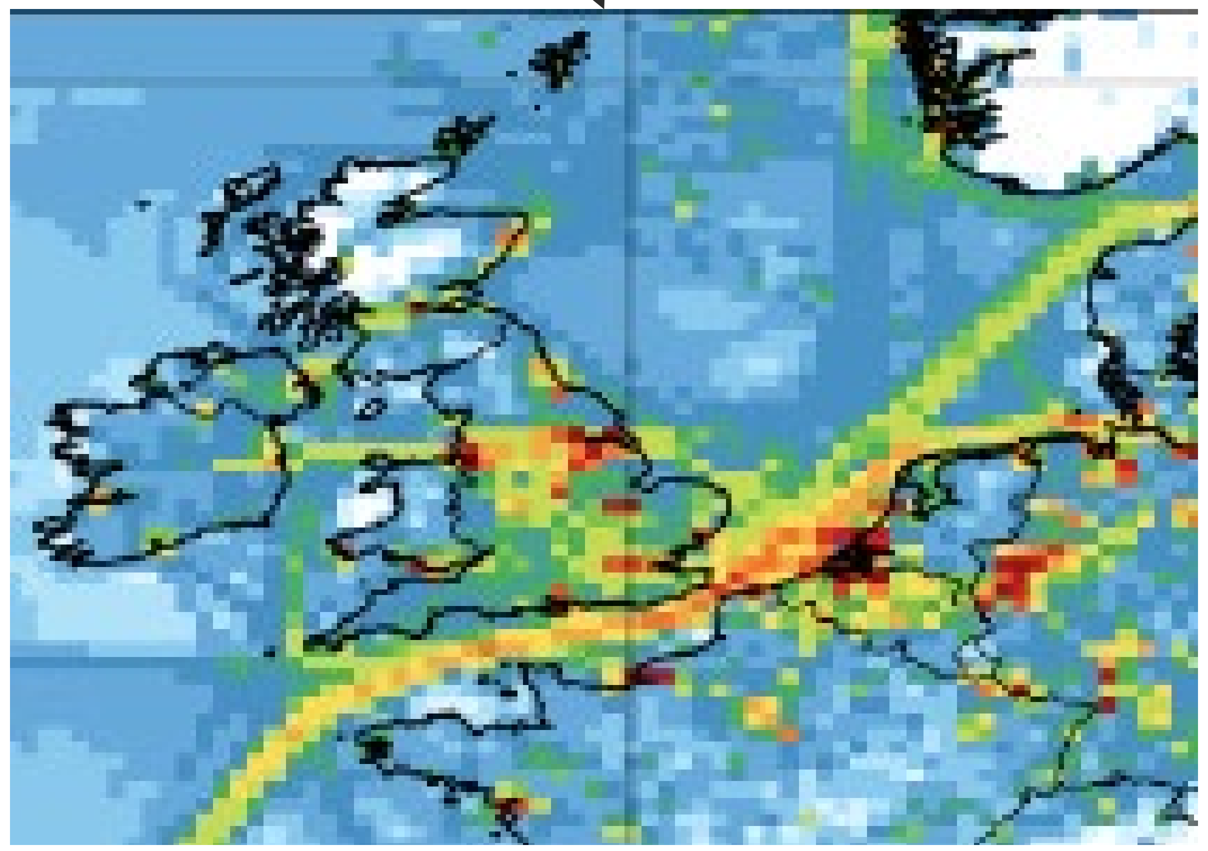
Emissions input

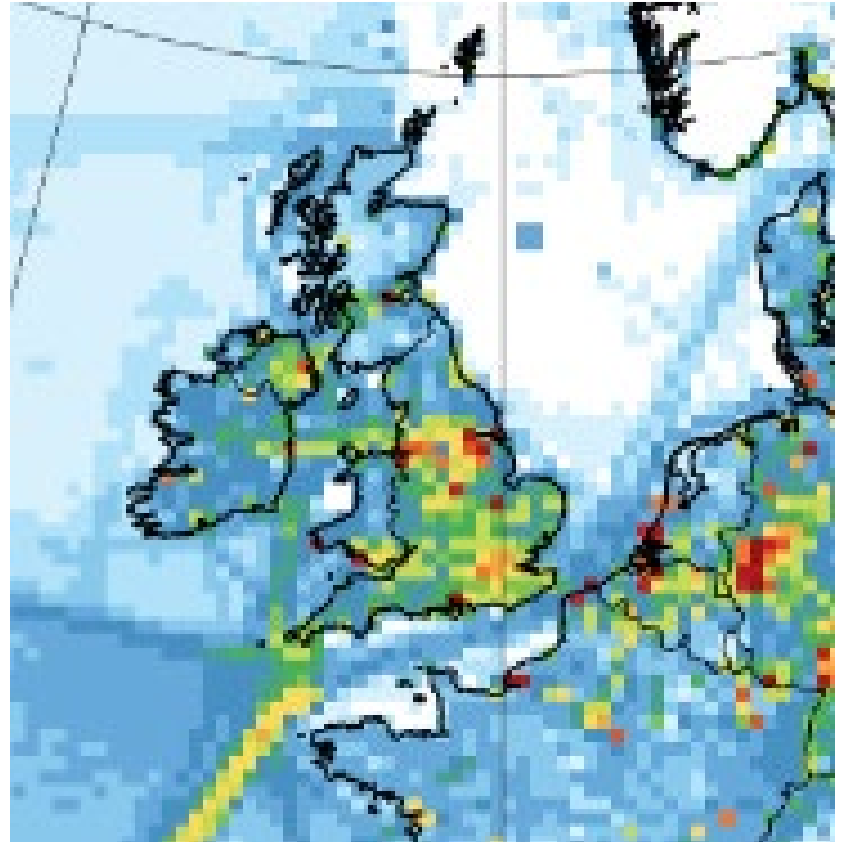
2018 SO$_x$ monthly emission from HTAPv3 (mgm^{-2})



2018 SO$_x$ monthly emission from the EMEP website (mgm^{-2})







"Ships trading in designated emission control areas will have to use on board fuel oil with a sulphur content of no more than 0.10% from 1 January 2015, against the limit of 1.00% in effect up until 31 December 2014"

This is an example of uncertainties/representativity of anthropogenic emissions sources.

Biogenic emissions; calculated online in ACTM (e.g. isoprene from vegetation, sea salt, dust, etc..), or as an input from satellite derived product (forest fires), do all participate in the overall uncertainties

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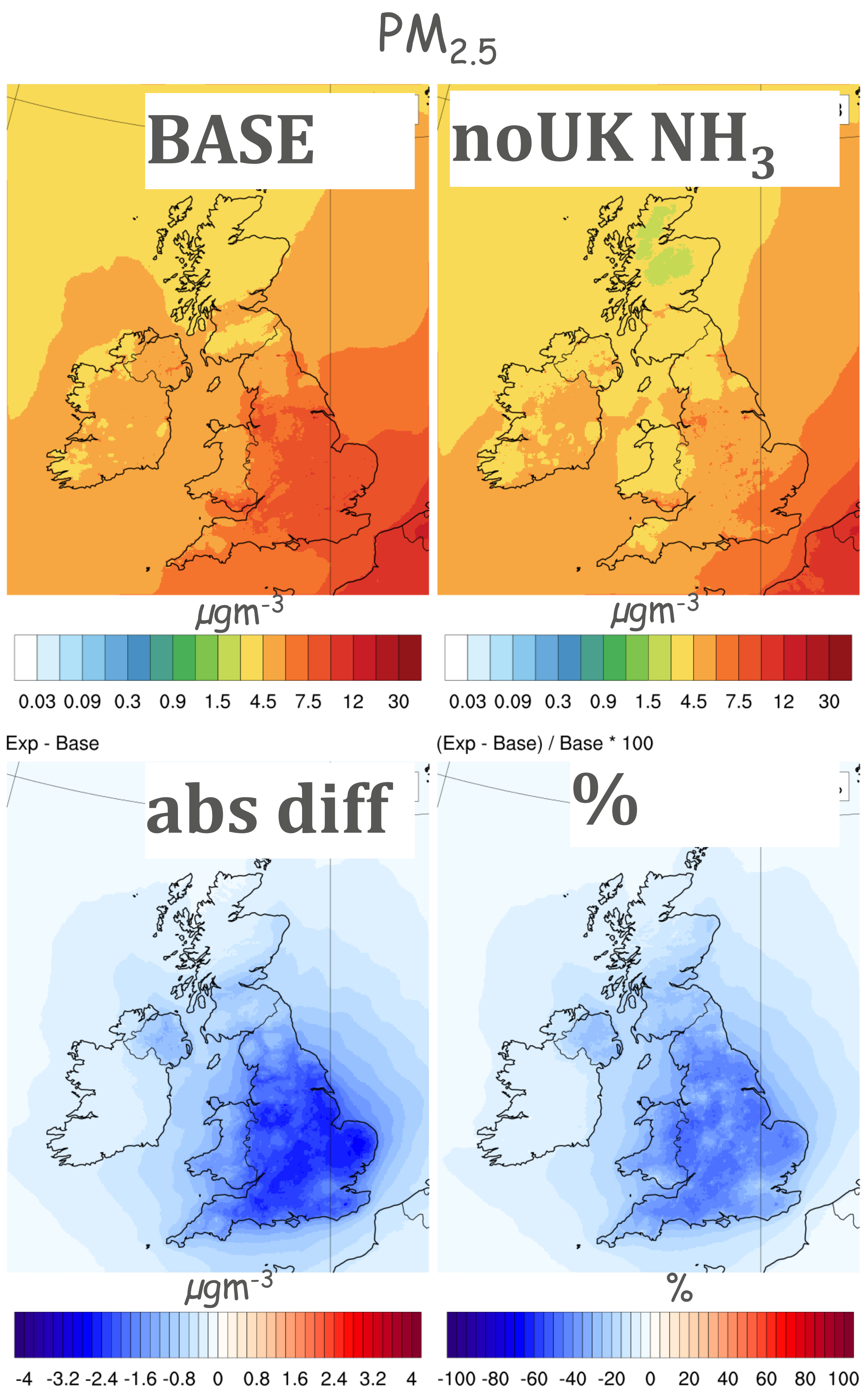
https://edgar.jrc.ec.europa.eu/dataset_htap_v3
https://www.ceip.at/webdab-emission-database/emissions-as-used-in-emep-models
https://www.imo.org/en/MediaCentre/PressBriefings/Pages/44-ECA-sulphur.aspx

EMEP-WRF applications

What is the effect of removing all UK NH_3 emissions



- A 100% reduction of UK anthropogenic NH_3 emissions is associated with up to 50% of $PM_{2.5}$ reductions. This broadly agrees with other studies (ACP Vieno et al 2016, Kelly et al 2023).
- However, this may be misleading as without HNO_3 and H_2SO_4 there will not be much NH_4^+ around in Europe.
- In other parts of the world (for example South Asia) this may not be the case as HCl emissions are very substantial and NH_4Cl is a significant fraction of the total $PM_{2.5}$

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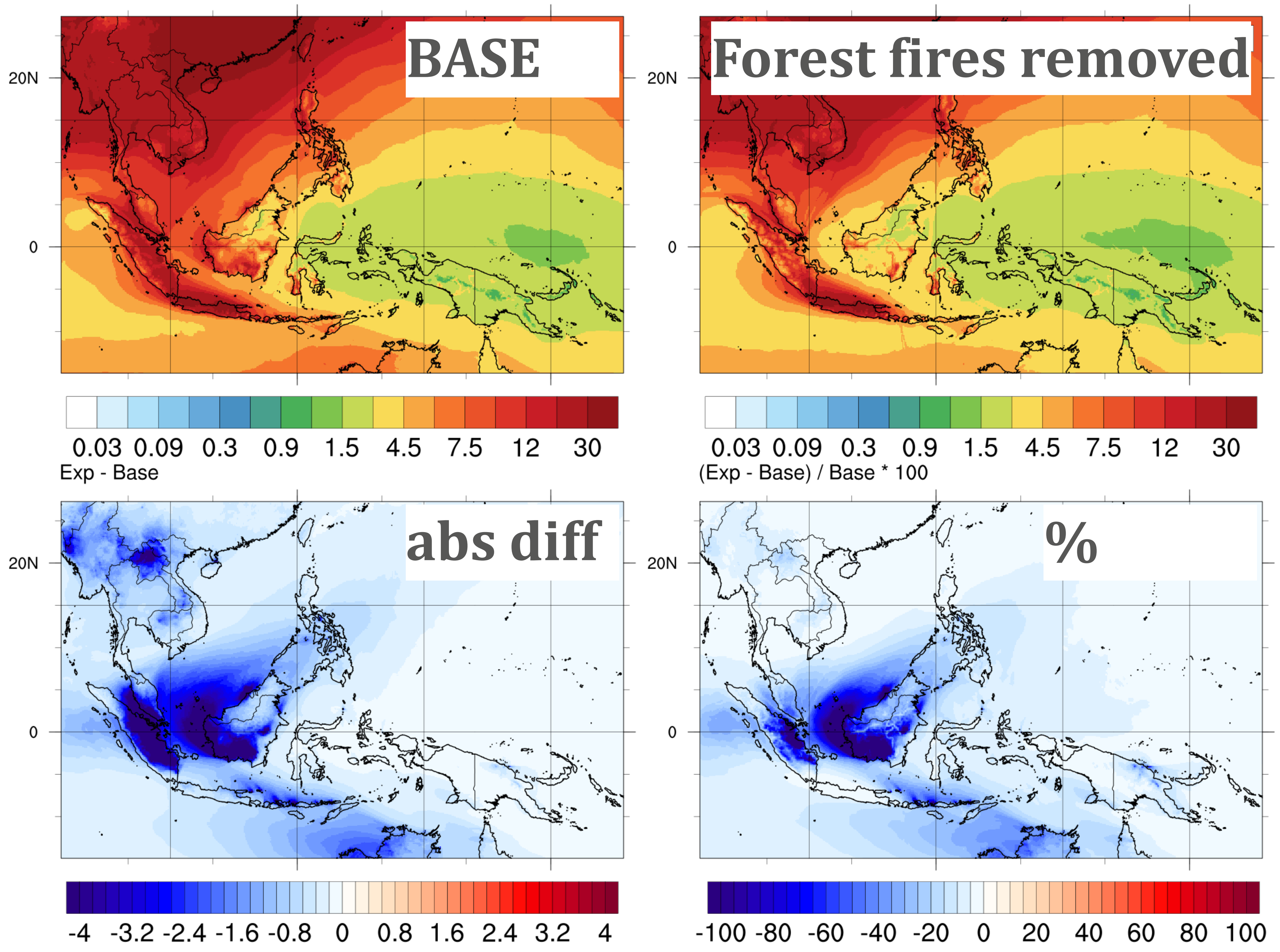
Kelly, J. M., Marais, E. A., Lu, G., Obszynska, J., Mace, M., White, J., and Leigh, R. J.: Diagnosing domestic and transboundary sources of fine particulate matter (PM2.5) in UK cities using GEOS-Chem, City and Environment Interactions, 18, 100100, https://doi.org/10.1016/j.cacint.2023.100100, 2023.

Vieno, M., Heal, M. R., Williams, M. L., Carnell, E. J., Nemitz, E., Stedman, J. R., and Reis, S.: The sensitivities of emissions reductions for the mitigation of UK PM2.5, Atmos. Chem. Phys., 16, 265-276, 10.5194/acp-16-265-2016, 2016

What is the effect of biomass burning in Southeast Asia



Surface $PM_{2.5}$ (μgm^{-3})

- The simulation was done for the year 2019
- The figures show the annual mean (from hourly values)
- HTAPv3 emissions
- Daily Forest fires derived from the Global Fire Assimilation System (GFAS)

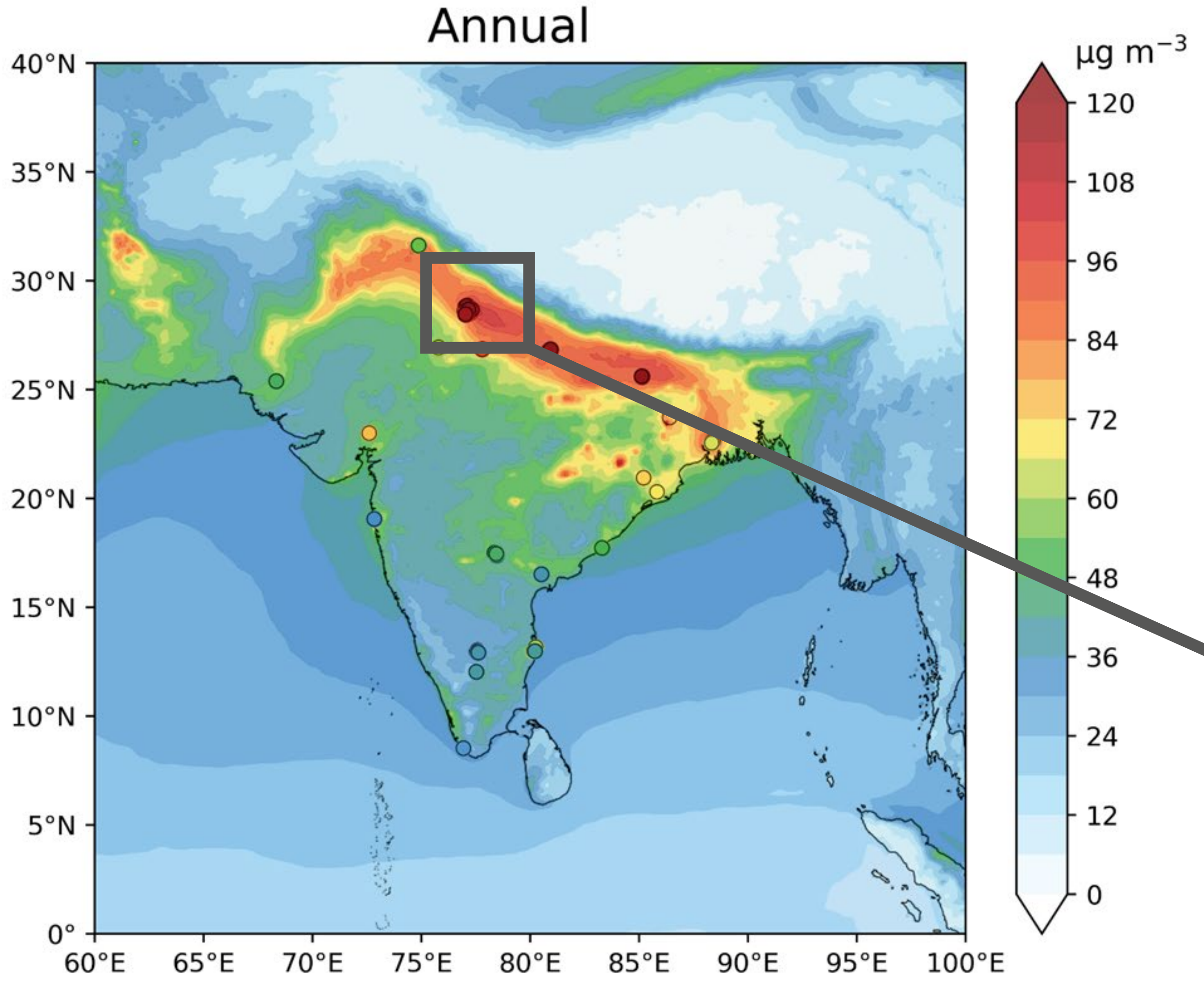
GFAS dataset:
Generated using Copernicus Atmosphere Monitoring Service Information [2024]

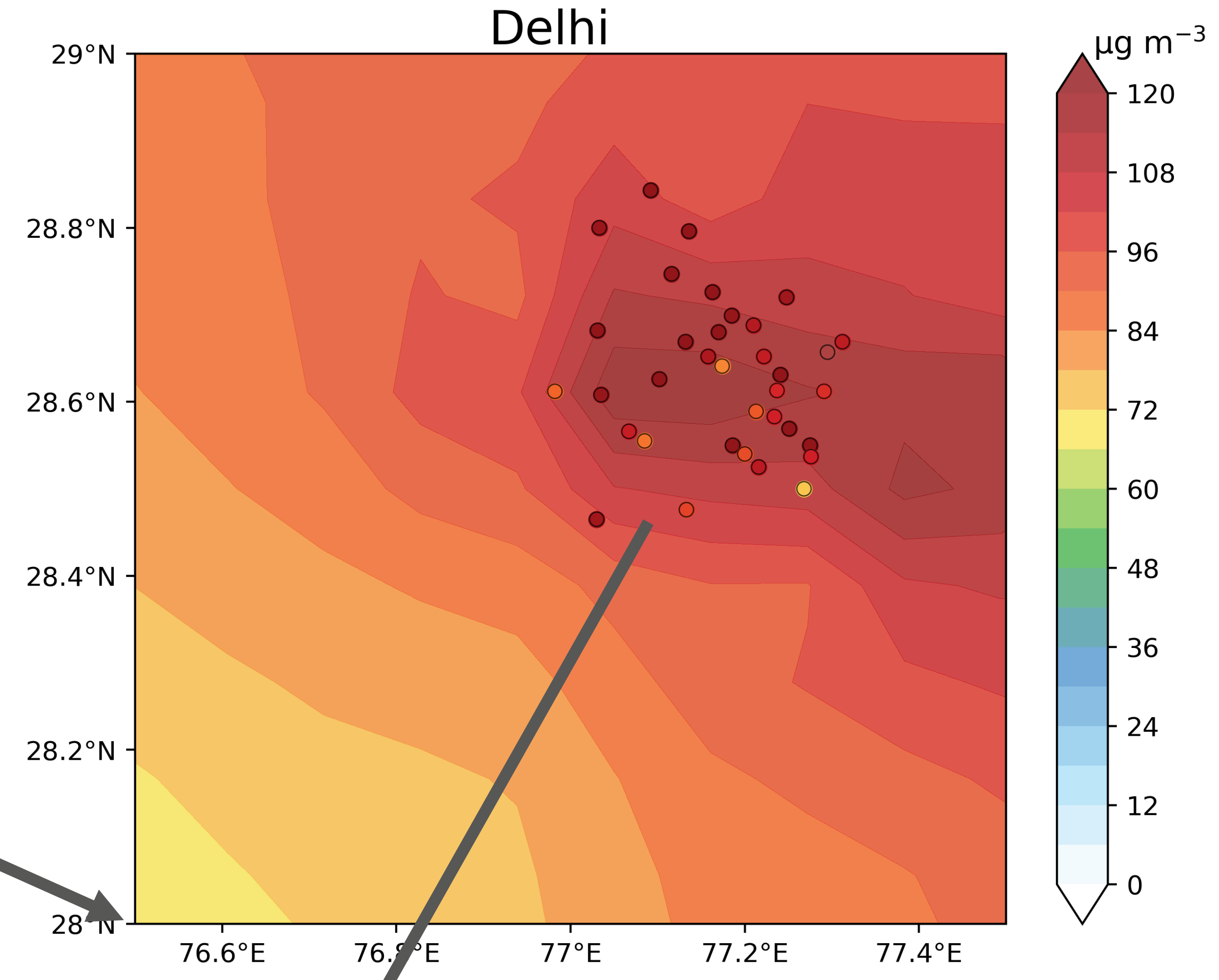
HTAPv3:
Huang, G., Brook, R., Crippa, M., Janssens-Maenhout, G., Schieberle, C., Dore, C., Guizzardi, D., Muntean, M., Schaaf, E., and Friedrich, R.: Speciation of anthropogenic emissions of non-methane volatile organic compounds: a global gridded data set for 1970–2012, Atmos. Chem. Phys., 17, 7683–7701, doi:10.5194/acp-17-7683-2017, 2017

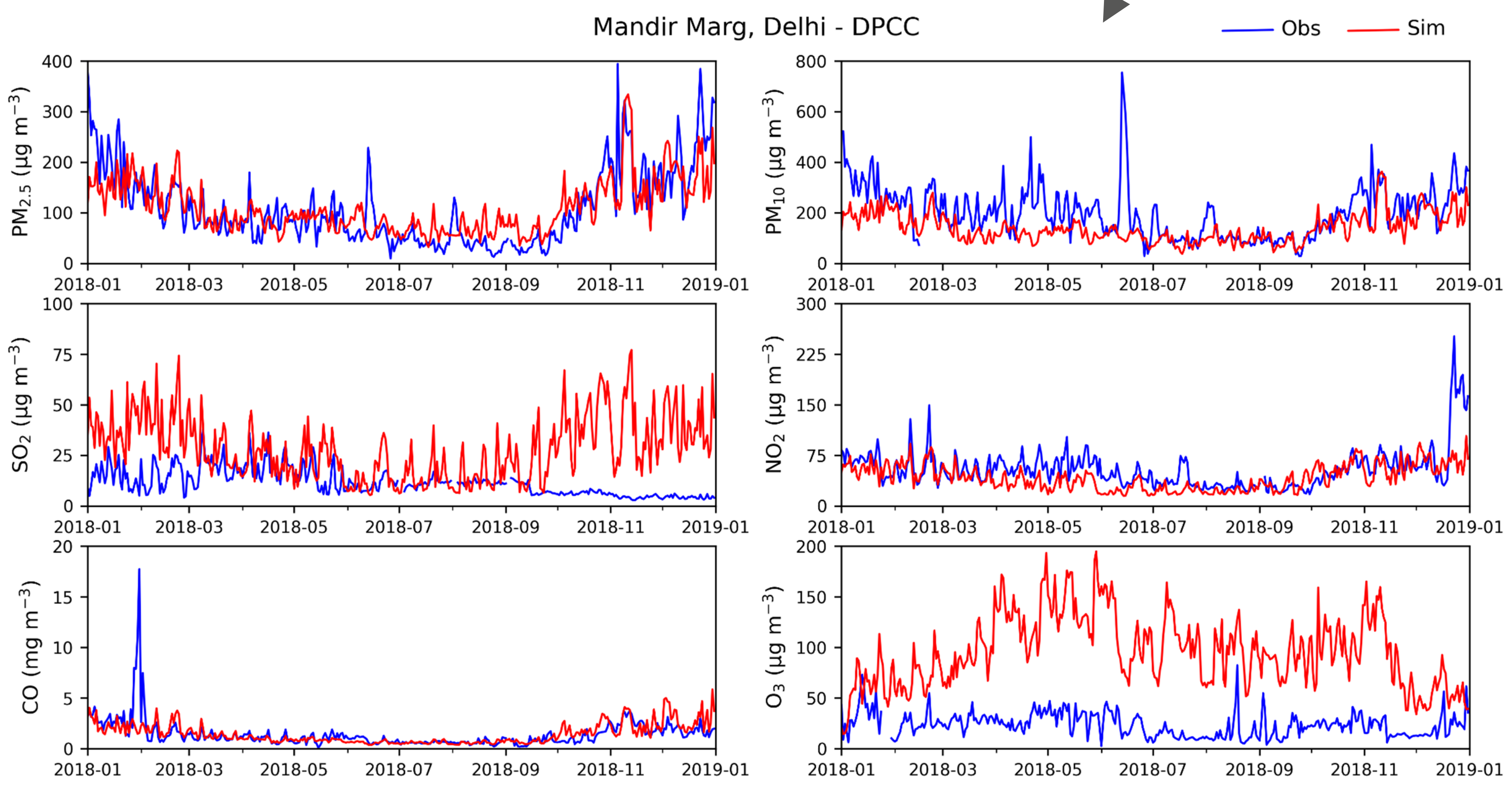
EMEP-WRF, evaluation, missing processes, missed rain event, and observations…

South Asia 2018 daily mean $PM_{2.5}$

- The model shows similar patterns for $PM_{2.5}$ at several Indian sites
- Other pollutants such as ozone are not what we expected, but when compared with measurement campaign, the model better captures ozone concentrations
- Sulphur dioxide also shows some “uncharacteristic” patterns in the observations







Central Pollution Control Board
Ministry of Environment, Forest and Climate Change
Government of India

https://cpcb.nic.in/

Data uploaded using **MOHAMED SHIRAZ notebook**
India's Air Quality: EDA and Prediction | Kaggle
Python · geojson, Air Quality Data in India (2015 - 2020)

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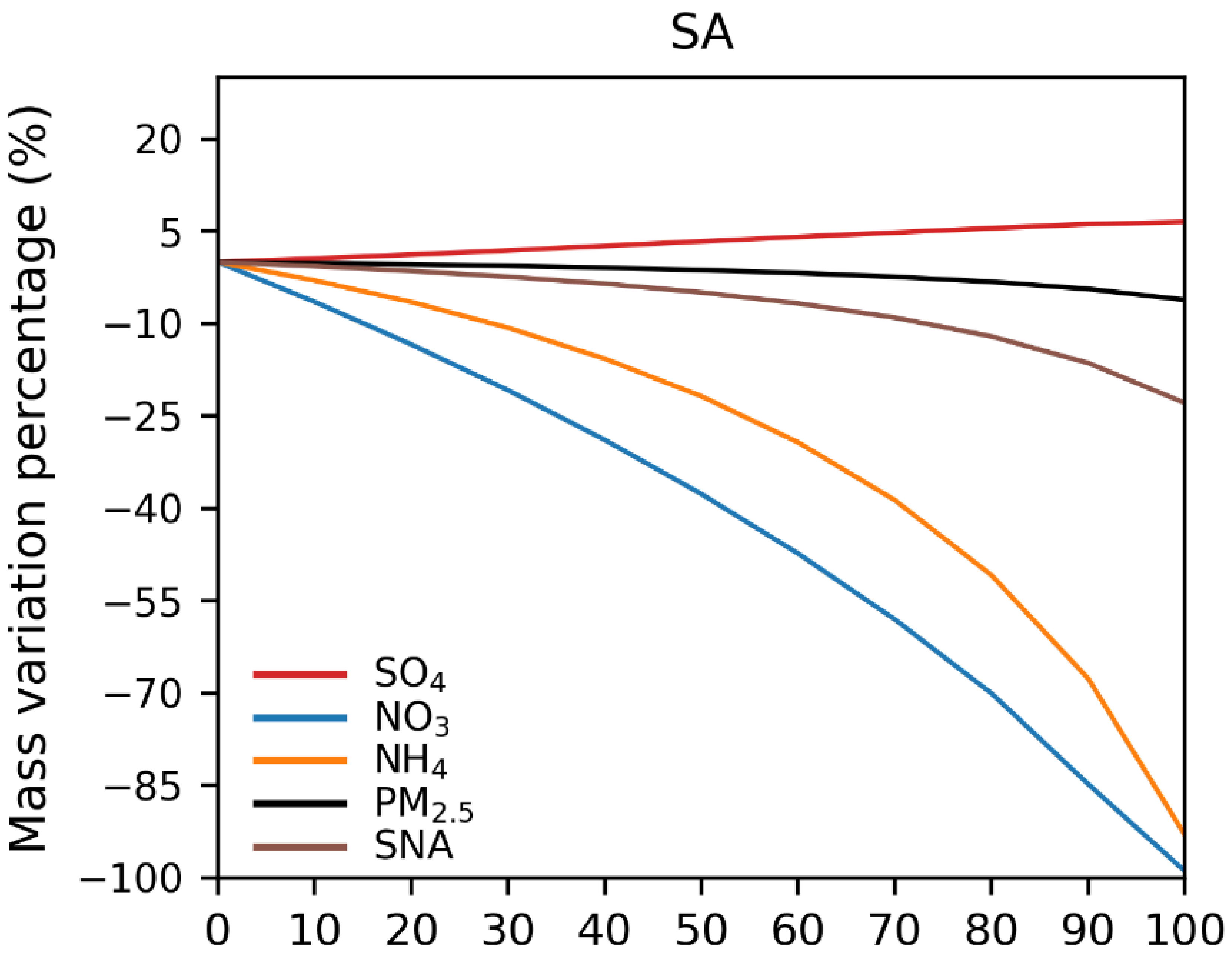
Deposition velocity and non-linearity

$PM_{2.5}$ sensitivity to a reduction of NH_3 emissions - 10%, 20%, … , 100% NH_3 reduction

Sensitivity of SO_4^{2-}, NO_3^-, NH_4^+ and $PM_{2.5}$ to ammonia reductions in South Asia



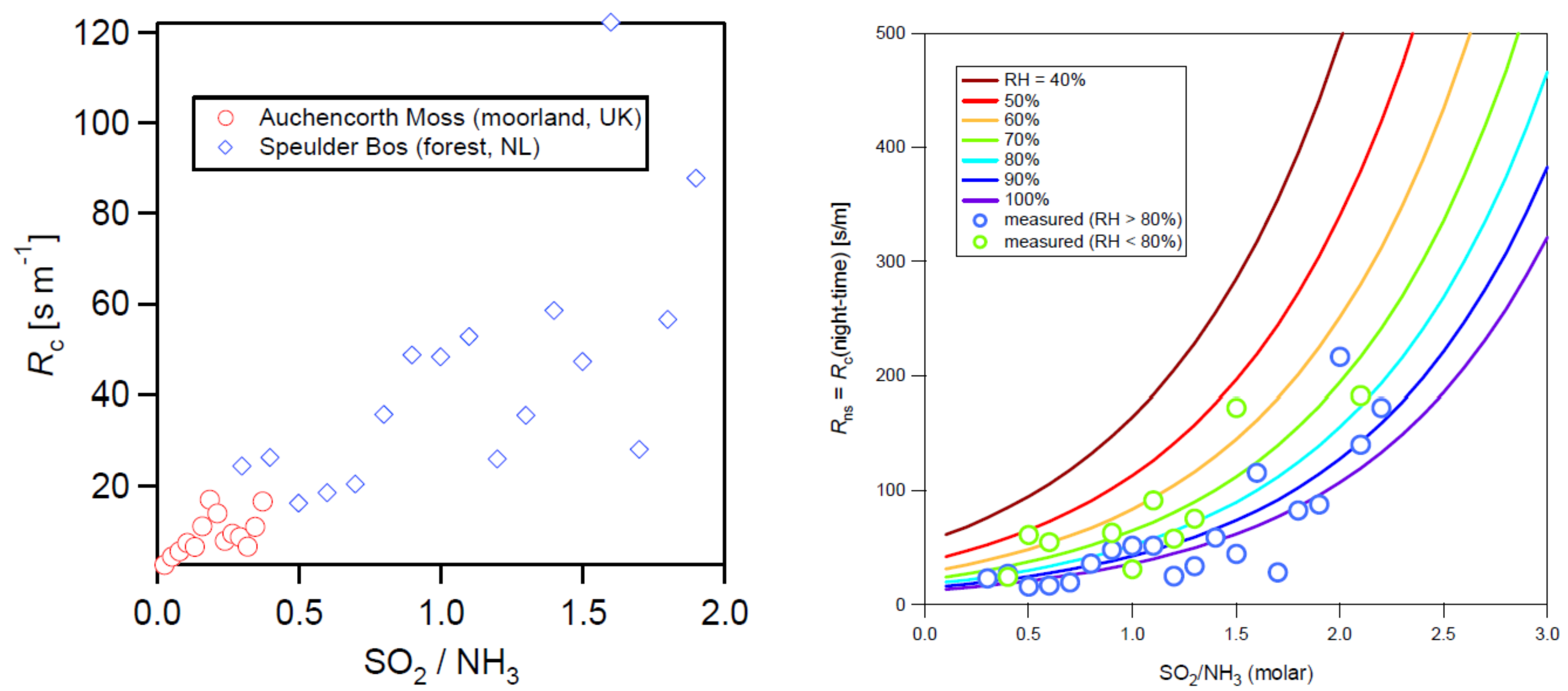


Figure 1.9. Dependence of the SO_2 canopy resistance on the ratio of the SO_2 and NH_3 air concentration of the previous 24 hours, combining data from two different field sites: (a) measurements and (b) parameterisation.

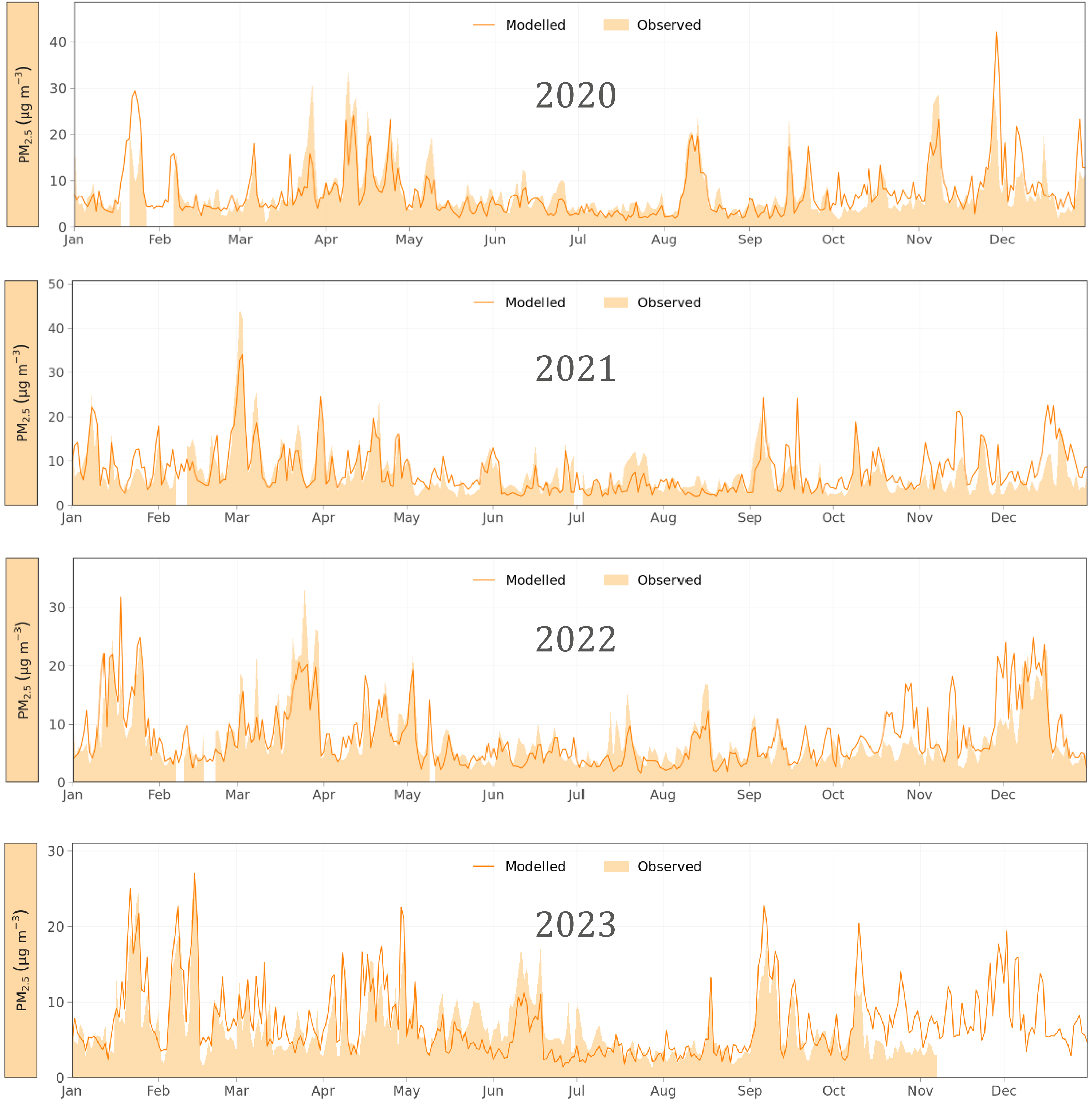
In the EMEP model the deposition velocity of SO_2 is a function of the SO_2/NH_3 ratio

Fowler, D., Pilegaard, K., Sutton, M. A., Ambus, P., Raivonen, M., Duyzer, J., Simpson, D., Fagerli, H., Fuzzi, S., . . . Erisman, J. W.: Atmospheric composition change: Ecosystems-Atmosphere interactions, Atmospheric Environment, 43, 5193-5267, DOI 10.1016/j.atmosenv.2009.07.068, 2009.

Conclusions

- ACTMs have been made easily accessible to all researchers' community
- Uncertainty analysis is still an issue?
- Model evaluation is relatively easy in some parts of the world (e.g. US, China, and the EU)
- Model accuracy is also difficult to assess
- Ensembles of air quality models may provide a better understanding of uncertainties

HOWEVER,…



EMEP4UK daily average at the AURN Chilbolton observatory site

The model captures the timing and magnitude of the elevated PM$_{2.5}$

Other models may do even better which suggests that the uncertainties/errors are not too large…

In 1976, a British statistician named George Box wrote the famous line, "All models are wrong, some are useful"

I prefer to say, "All models are an incomplete representation of reality", but not necessarily wrong.

Thank You

For more information
please contact:

mvi@ceh.ac.uk

Ge, Y. et al., A new assessment of global and regional budgets, fluxes, and lifetimes of atmospheric reactive N and S gases and aerosols, ACP, 10.5194/acp-22-8343-2022, 2022.
Gu, B., et al.,, Abating ammonia is more cost-effective than nitrogen oxides for mitigating PM(2.5) air pollution, Science, 374, 758-762, 10.1126/science.abf8623, 2021.
Simpson, D. et al.,: The EMEP MSC-W chemical transport model - technical description, Atmos. Chem. Phys., 12, 7825-7865, 10.5194/acp-12-7825-2012, 2012
Vieno, M. et al.,: The sensitivities of emissions reductions for the mitigation of UK PM2.5, Atmos. Chem. Phys., 16, 265-276, 10.5194/acp-16-265-2016, 2016a.
Vieno, M. et al.,: The UK particulate matter air pollution episode of March–April 2014: more than Saharan dust, Environmental Research Letters, 11, 044004, 2016b

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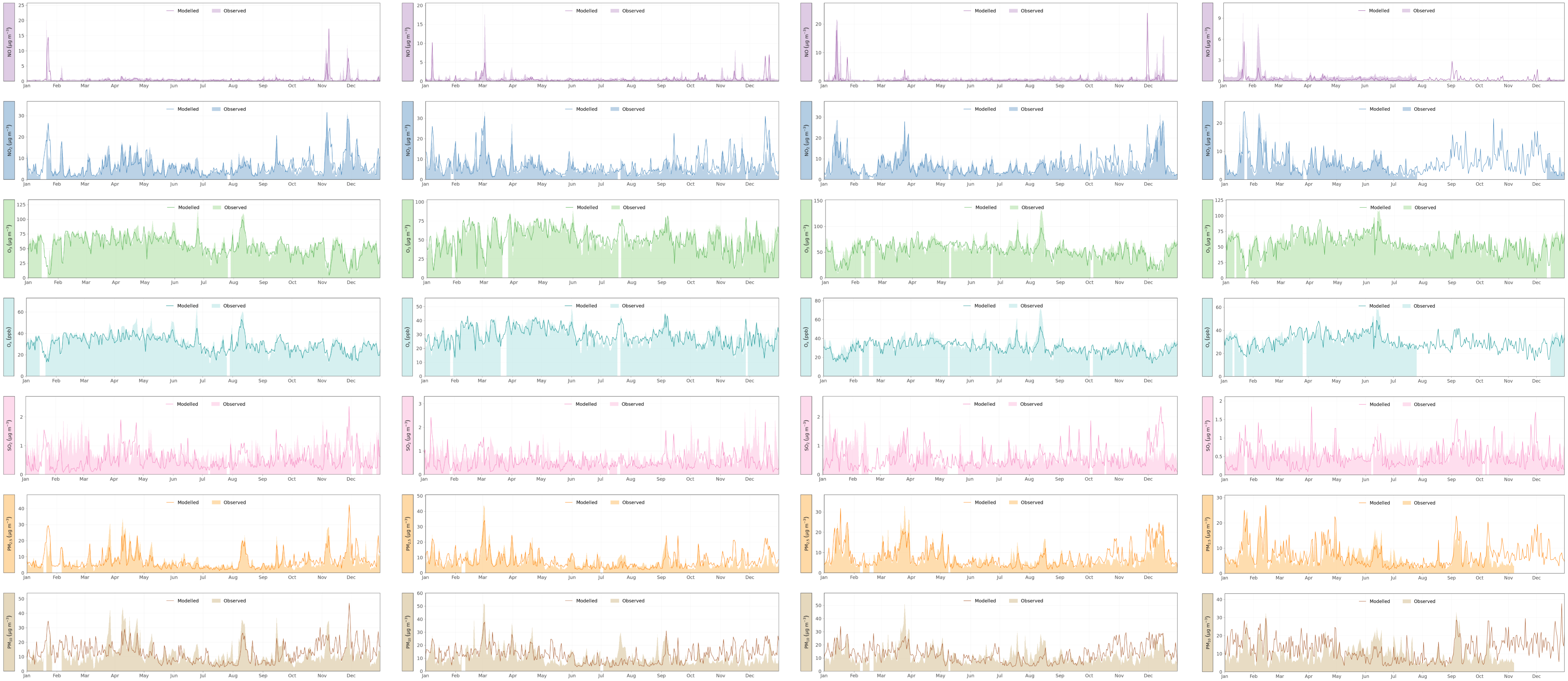
FOR GLOBAL CHALLENGES
International science for net zero plus

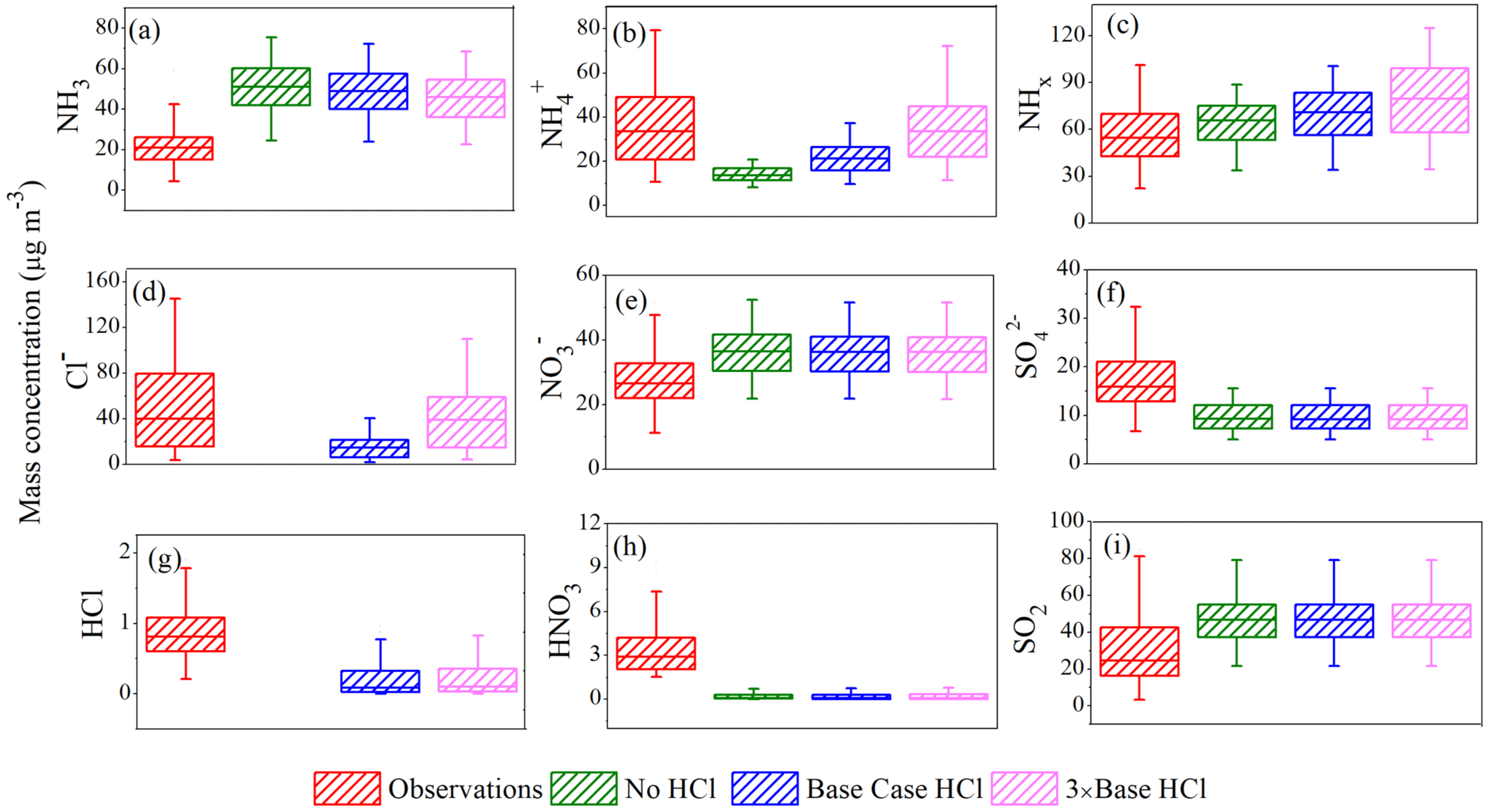
EMEP4UK daily average at the Chilbolton observatory



2020 2021 2022 2023

…recent studies shows the importance of HCl emissions in Delhi

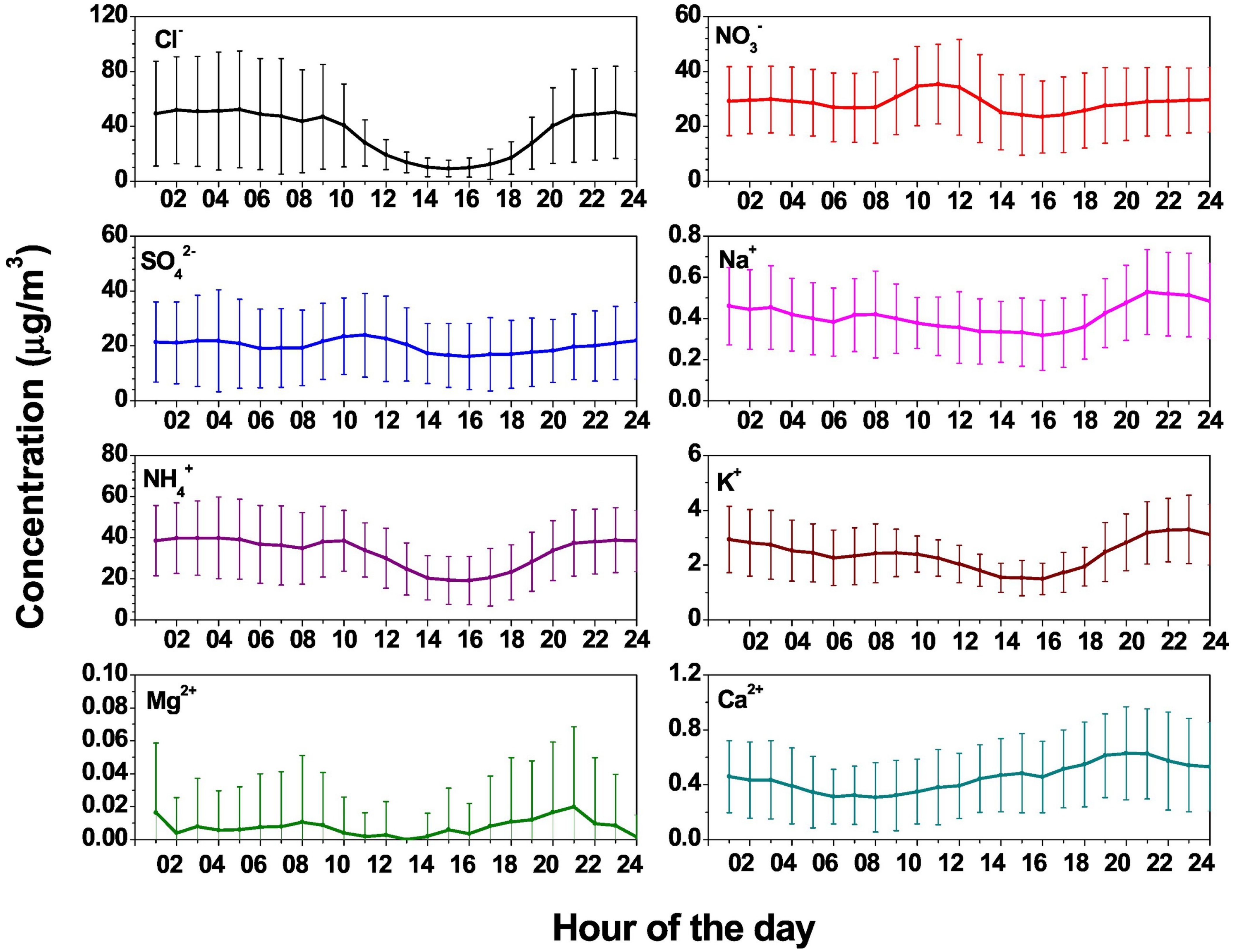
Pawar et al. shows that adding HCl emissions over Delhi the results agree better with the observed $PM_{2.5}$



Box-and-whisker plot for trace gases and secondary inorganic aerosols from the observations (MARGA) and simulated in sensitivity test with changes in HCl emissions in no HCl (0 mol km^{-2} h^{-1}), base case HCl (24.8 mol km^{-2} h^{-1}), and 3 × base HCl (74 mol km^{-2} h^{-1}) runs at IGIA, Delhi.

Pawar, P. V., Ghude, S. D., Govardhan, G., Acharja, P., Kulkarni, R., Kumar, R., Sinha, B., Sinha, V., Jena, C., Gunwani, P., Adhya, T. K., Nemitz, E., and Sutton, M. A.: Chloride (HCl ⁄ Cl−) dominates inorganic aerosol formation from ammonia in the Indo-Gangetic Plain during winter: modeling and comparison with observations, Atmos. Chem. Phys., 23, 41–59, https://doi.org/10.5194/acp-23-41-2023, 2023.

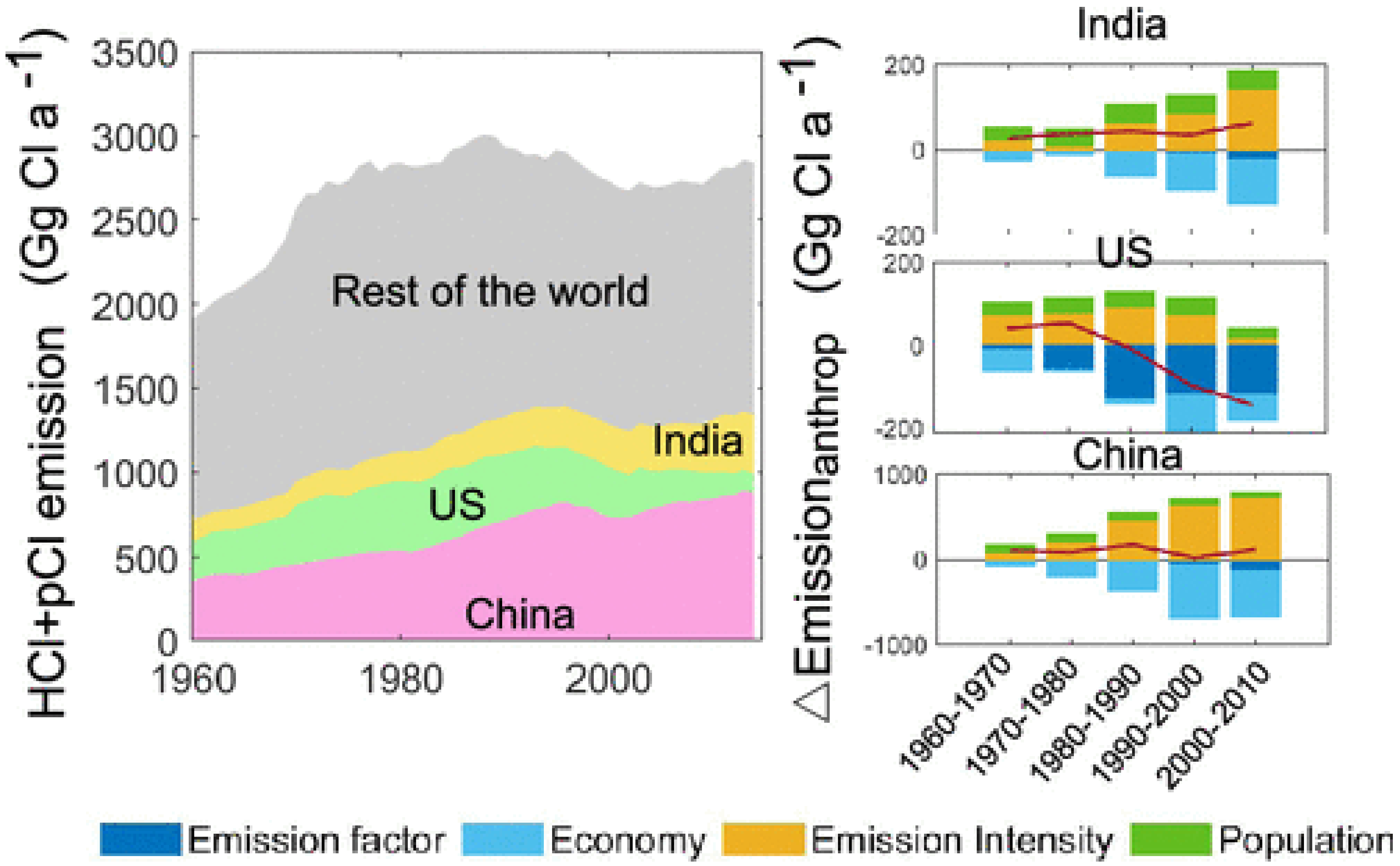
MARGA dataset at the Dheli airport



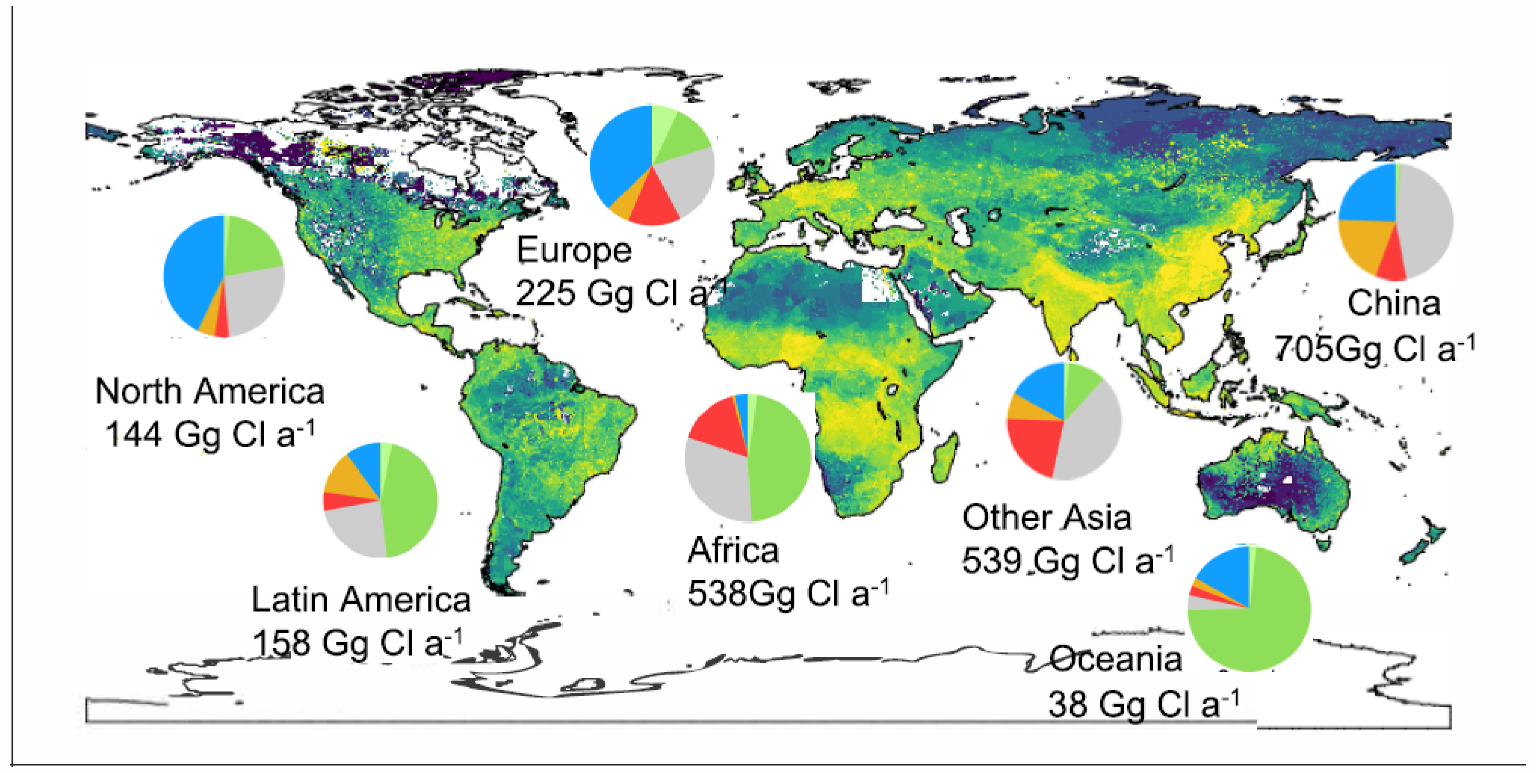
Acharja, P., Ali, K., Trivedi, D.K., Safai, P.D., Ghude, S., Prabhakaran, T., Rajeevan, M. (2020) Characterization of atmospheric trace gases and water soluble inorganic chemical ions of PM1 and PM2.5 at Indira Gandhi International Airport, New Delhi during 2017–18 winter. Science of the Total Environment 729, 138800.

EMEP rv4.45 and HCl extension

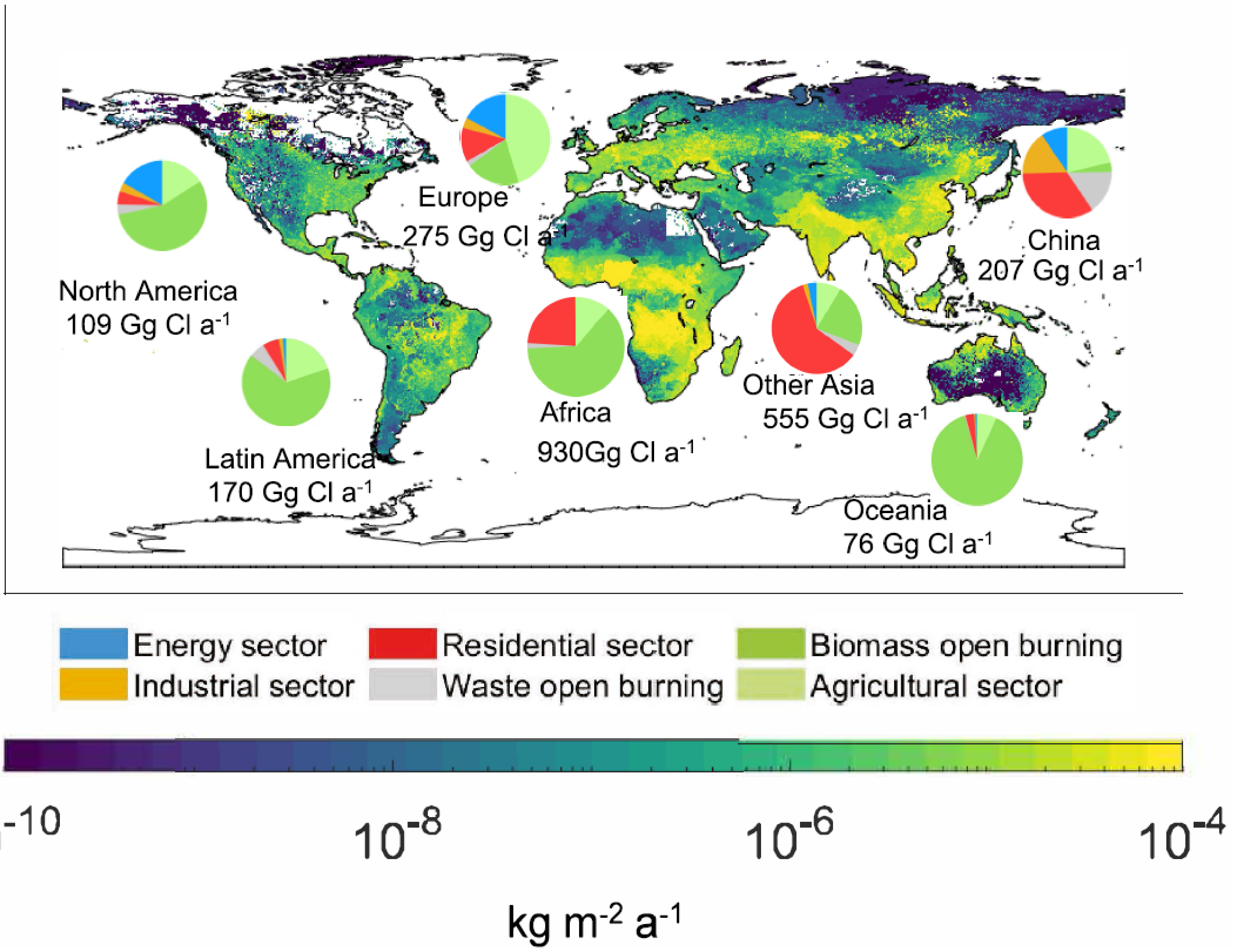
We used a global HCl and primary pCl emissions at 0.1 x 0.1 degrees (Zhang et al., 2022)



(a) HCl emission



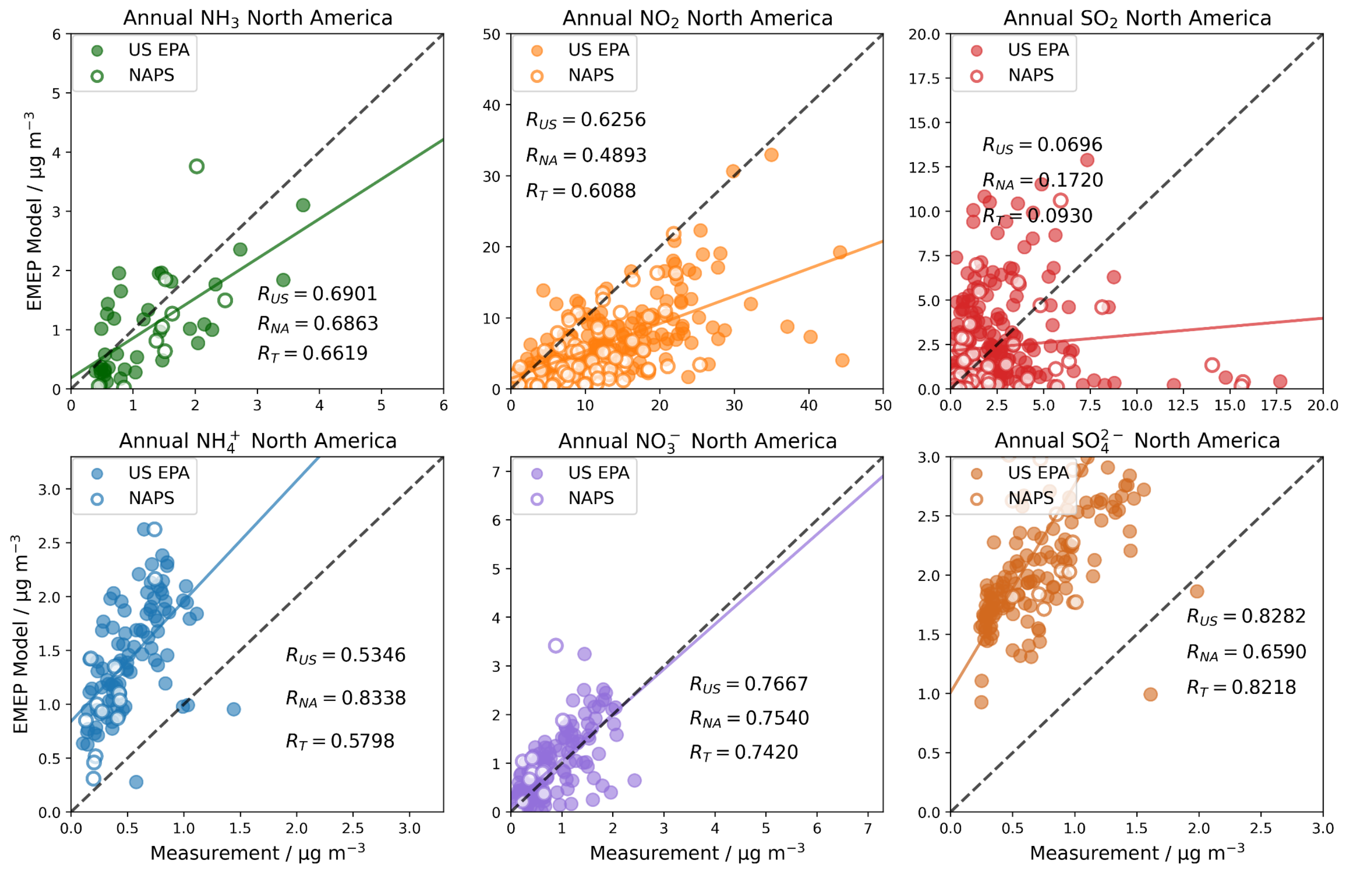
(b) pCl emission



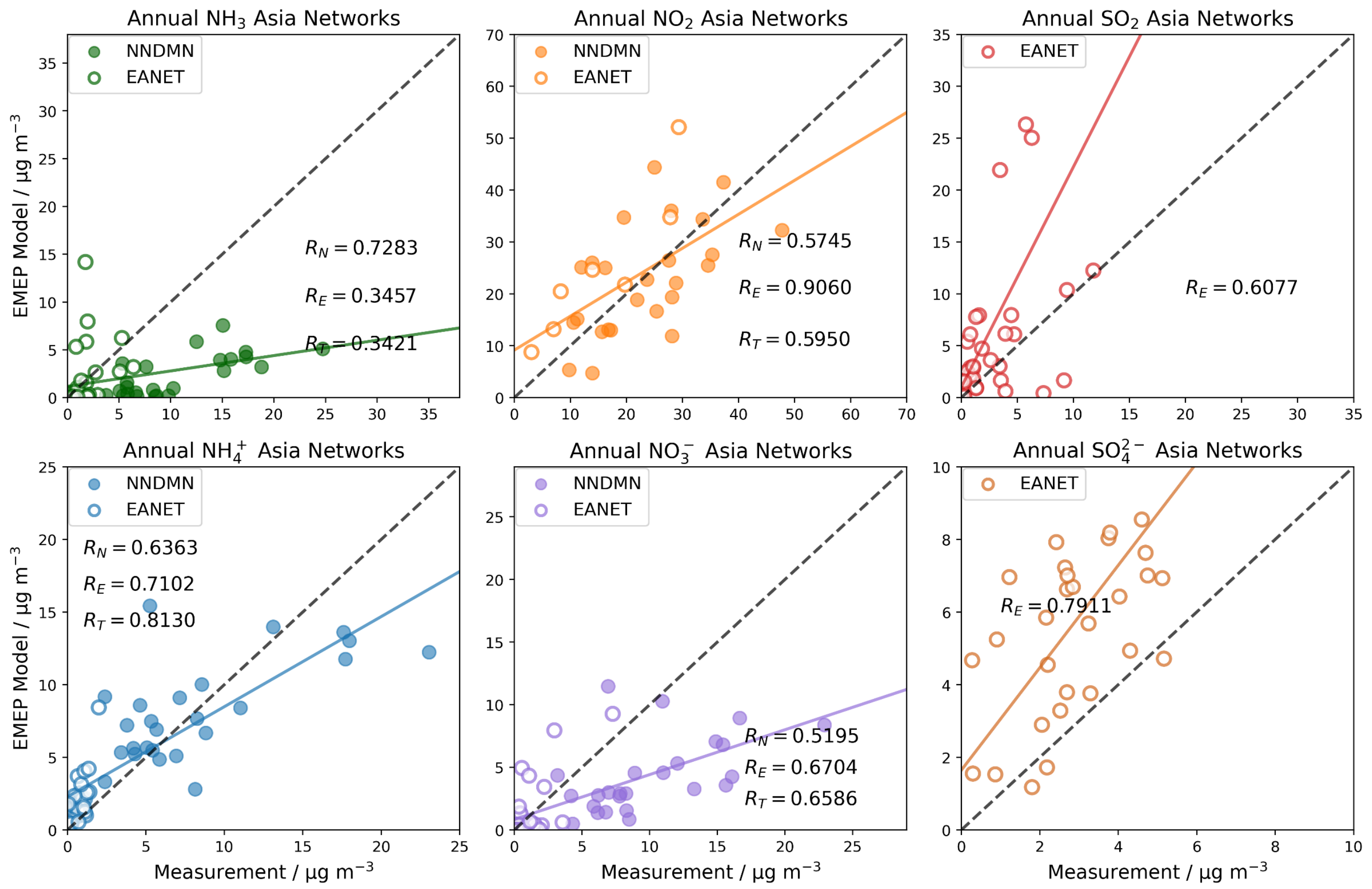
Zhang, B., Shen, H., Yun, X., Zhong, Q., Henderson, B.H., Wang, X., Shi, L., Gunthe, S.S., Huey, L.G., Tao, S., Russell, A.G., Liu, P. (2022) Global Emissions of Hydrogen Chloride and Particulate Chloride from Continental Sources. Environmental Science & Technology 56, 3894-3904

EMEP-WRF global 2015 evaluation

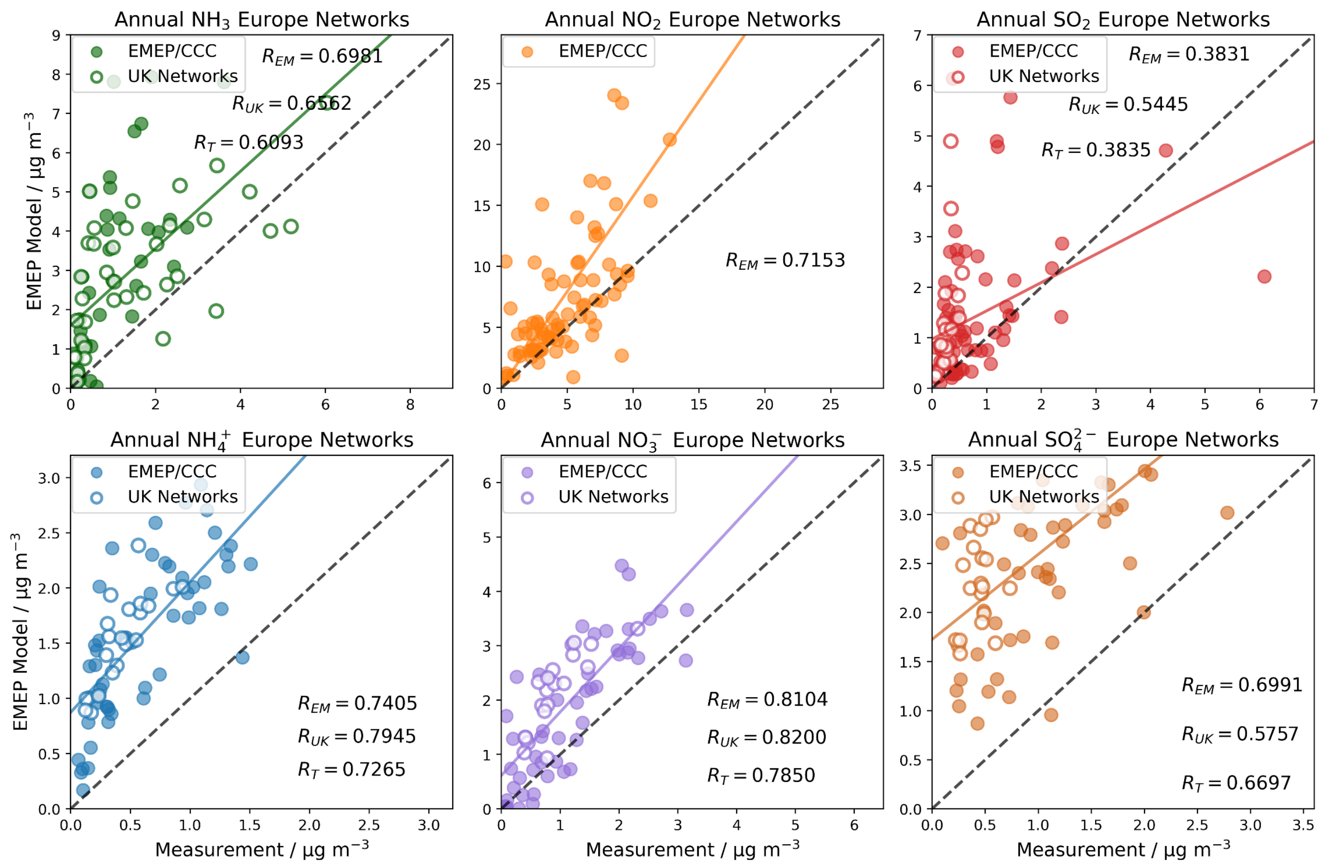
North America



Asia



Europe

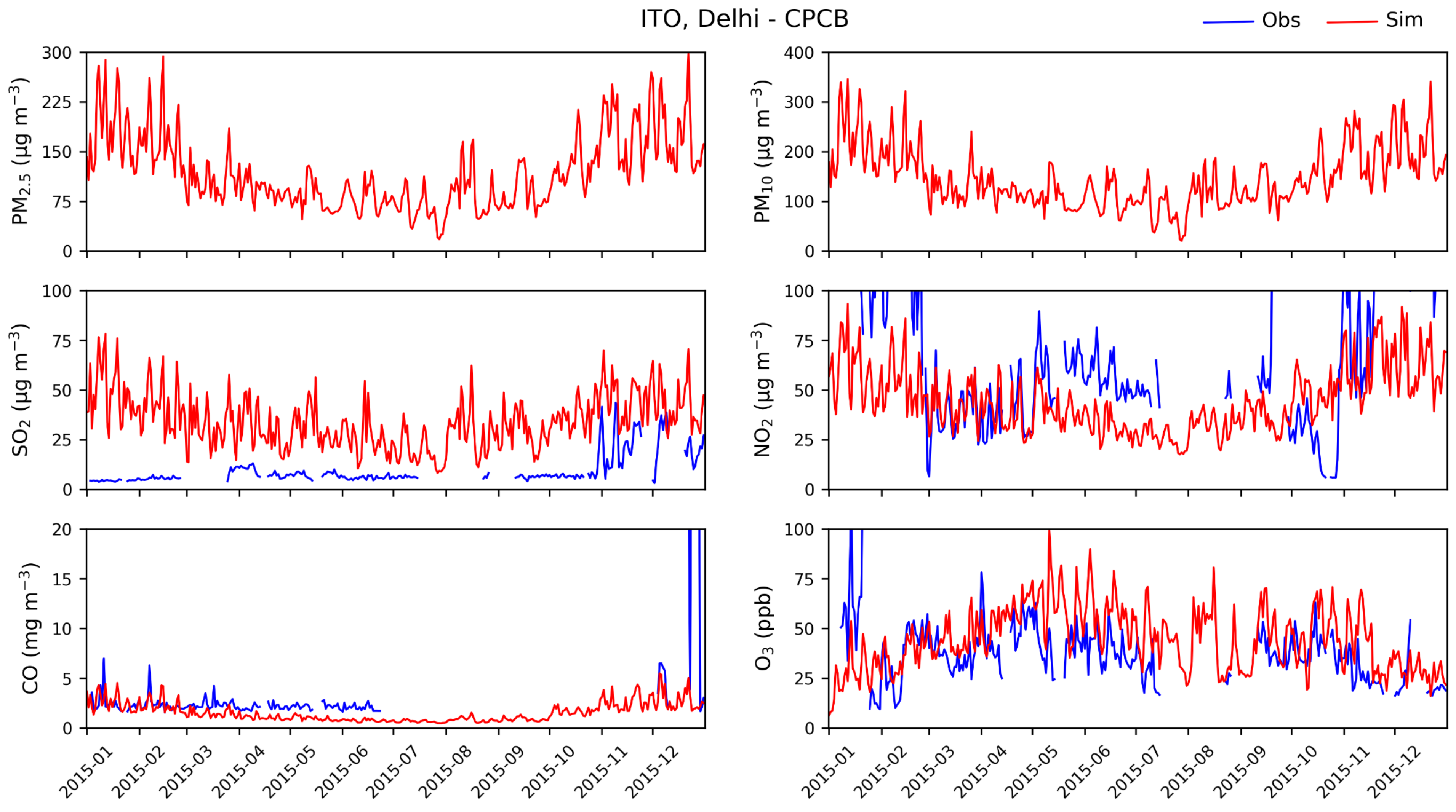


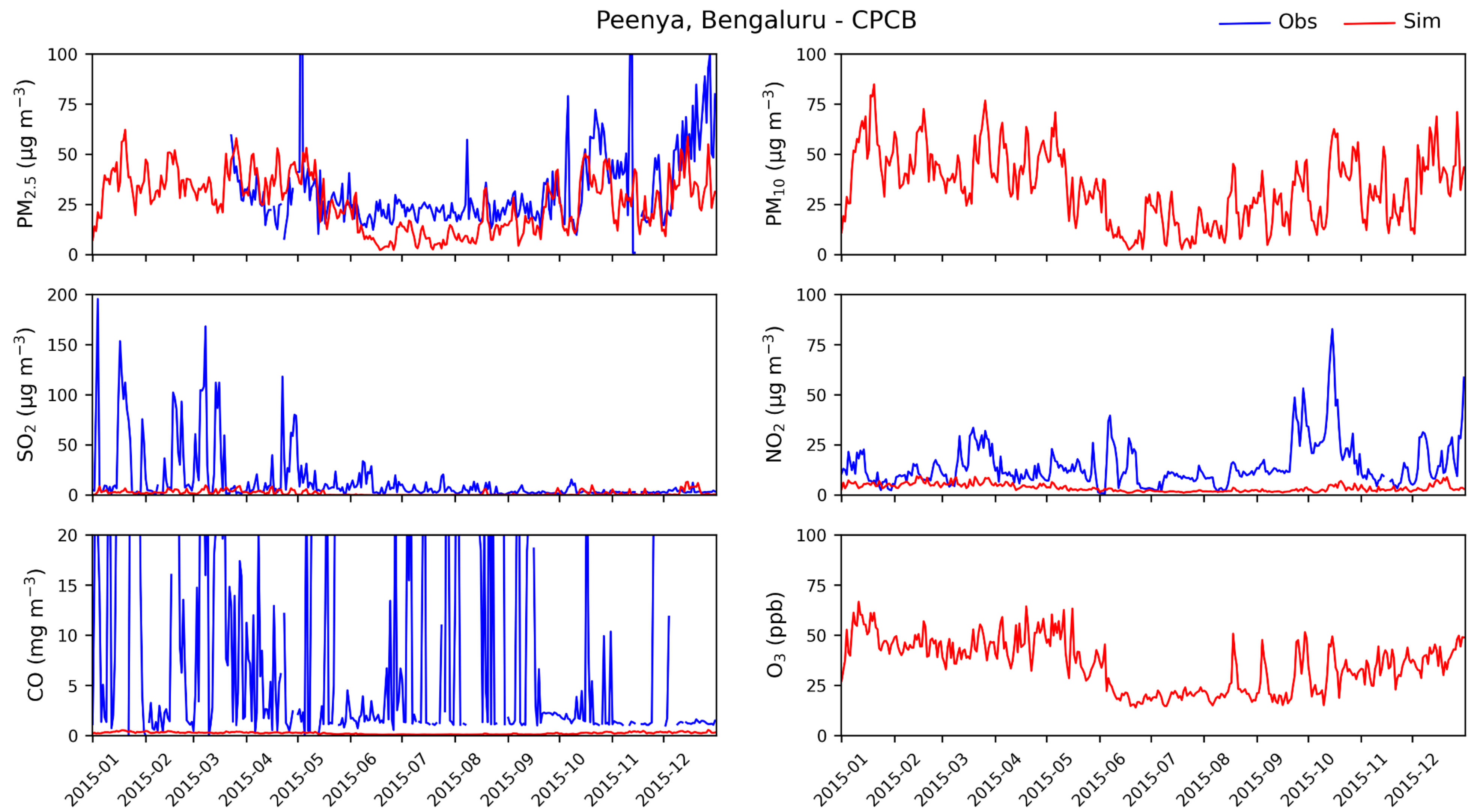
Based on Ge et al. 2021 but for the SANH 2015 BASE run

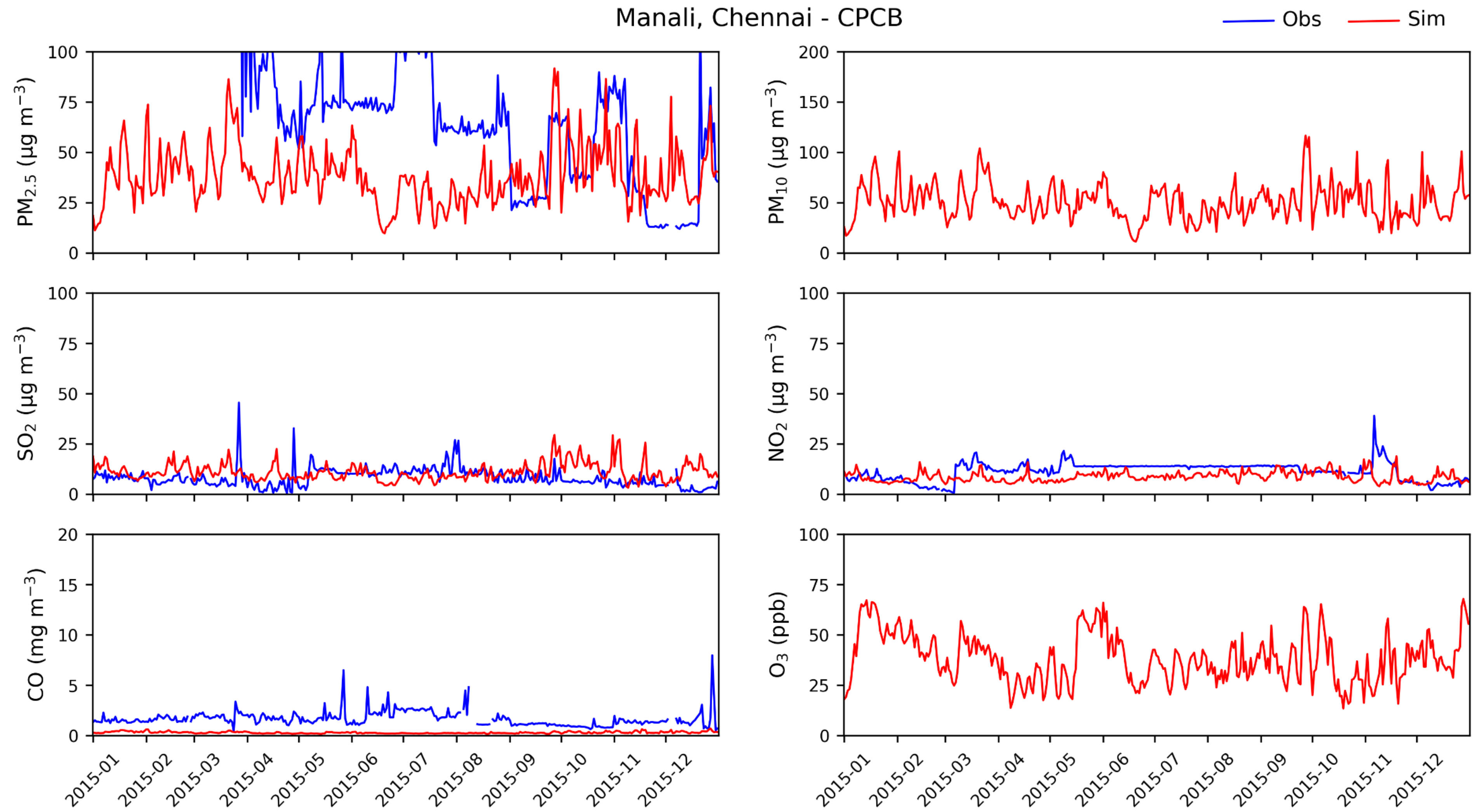
Ge, Y., Heal, M. R., Stevenson, D. S., Wind, P., and Vieno, M.: Evaluation of global EMEP MSC-W (rv4.34) WRF (v3.9.1.1) model surface concentrations and wet deposition of reactive N and S with measurements, Geosci. Model Dev., 14, 7021–7046, https://doi.org/10.5194/gmd-14-7021-2021, 2021

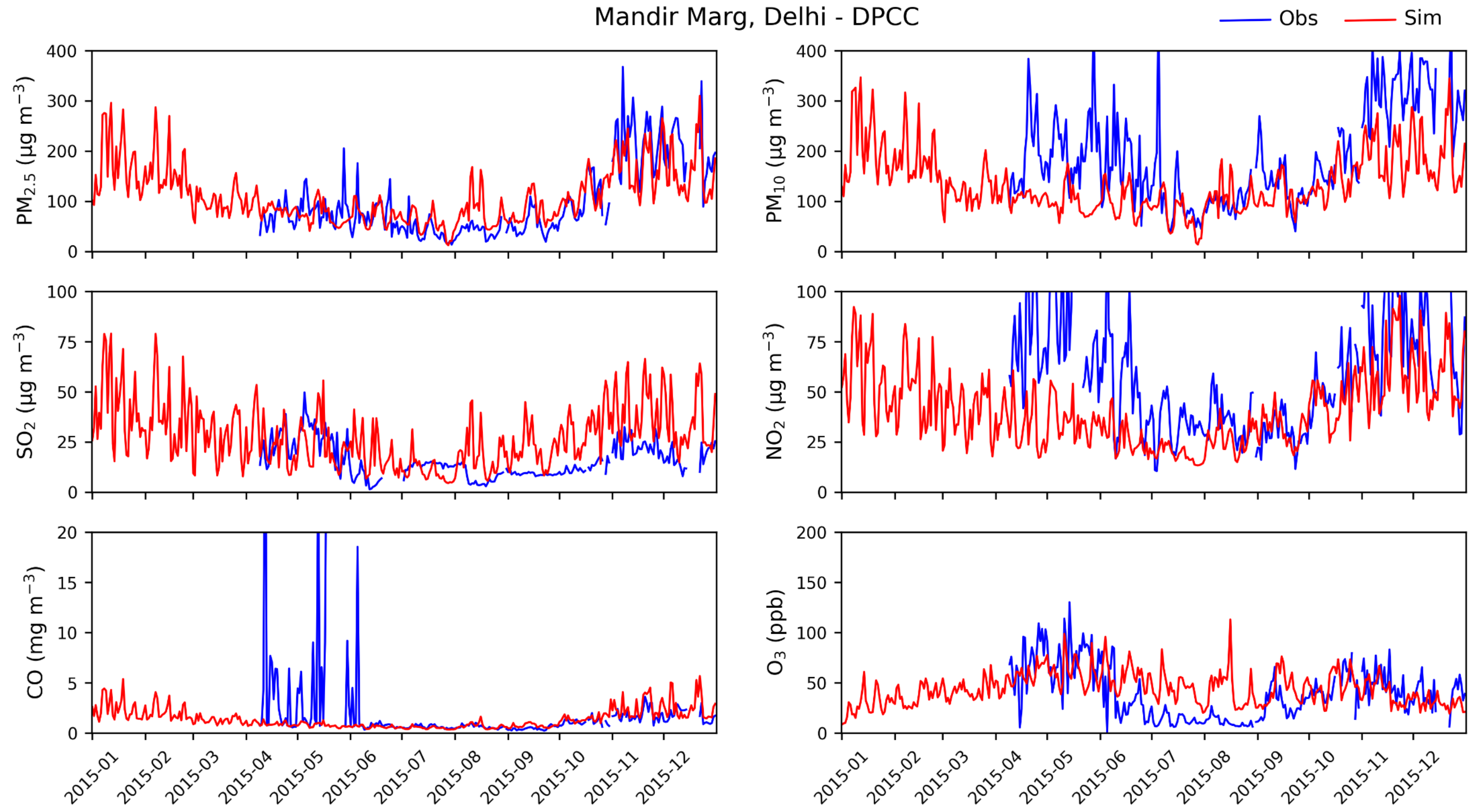
Lloyd's (2012) ECA Calculator—Helping you plan your compliance with MARPOL Annex VI, Regulation 14

EMEP-WRF BASE run vs. observations at some sites (daily average for 2015) - Yuanlin Wang


ITO, Delhi - CPCB


Peenya, Bengaluru - CPCB


Manali, Chennai - CPCB


Mandir Marg, Delhi - DPCC