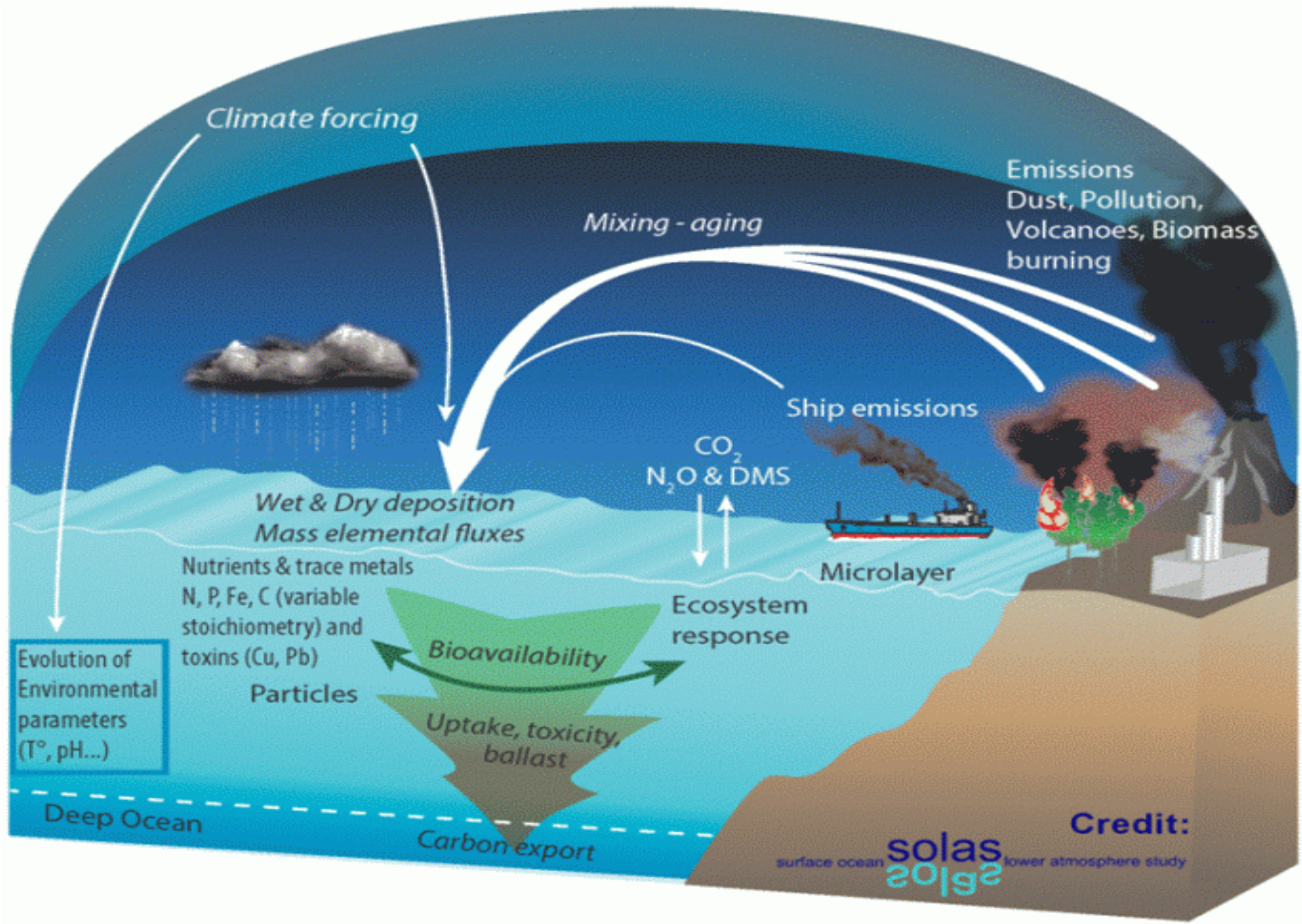
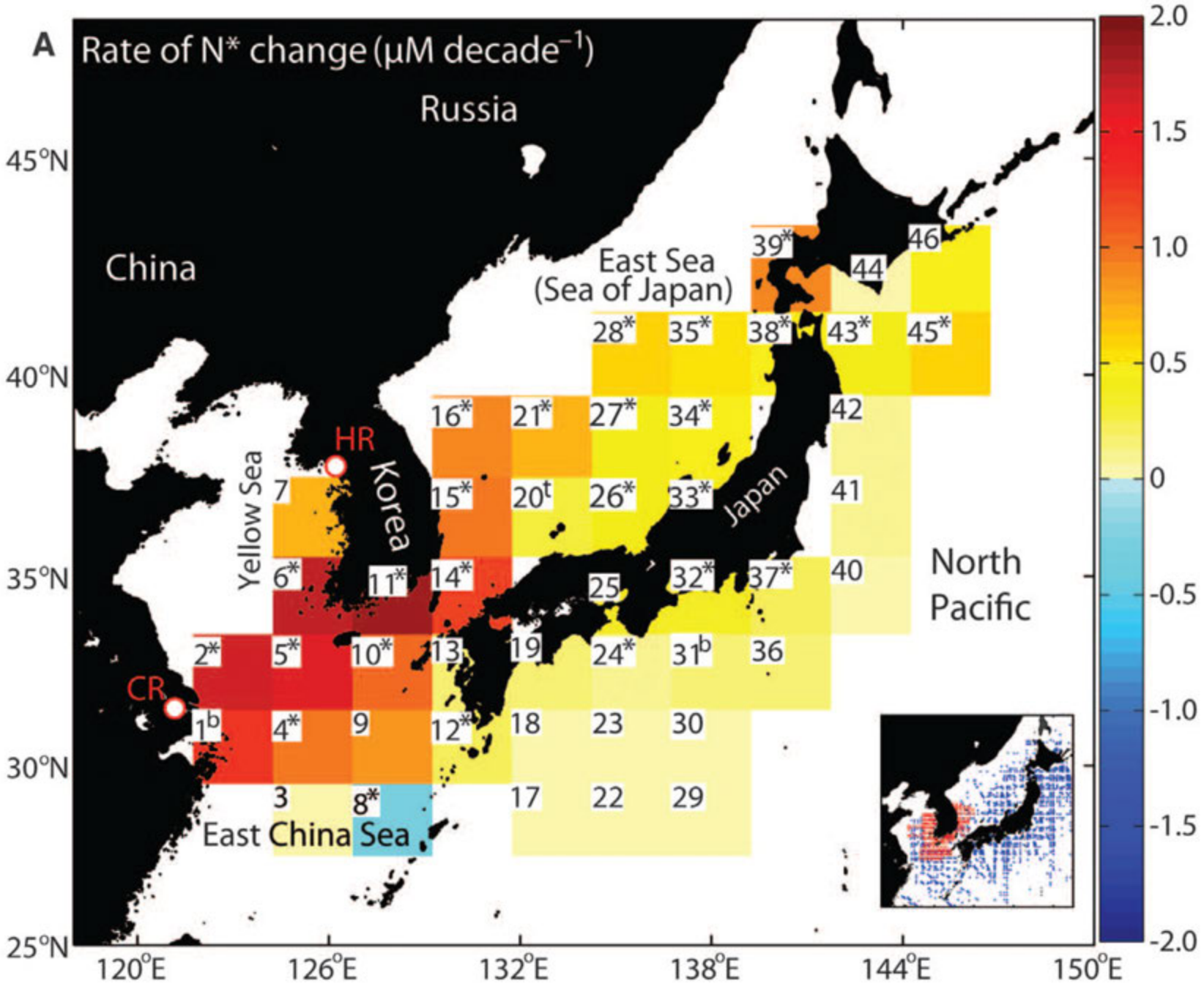
SOLAS Core Theme 3: Atmospheric Deposition and Ocean Biogeochemistry

Raymond Najjar
The Pennsylvania State University

OCB Ocean-Atmosphere Interaction: Scoping Directions for U.S Research Workshop
September 30 – October 3, 2019
Sterling, VA

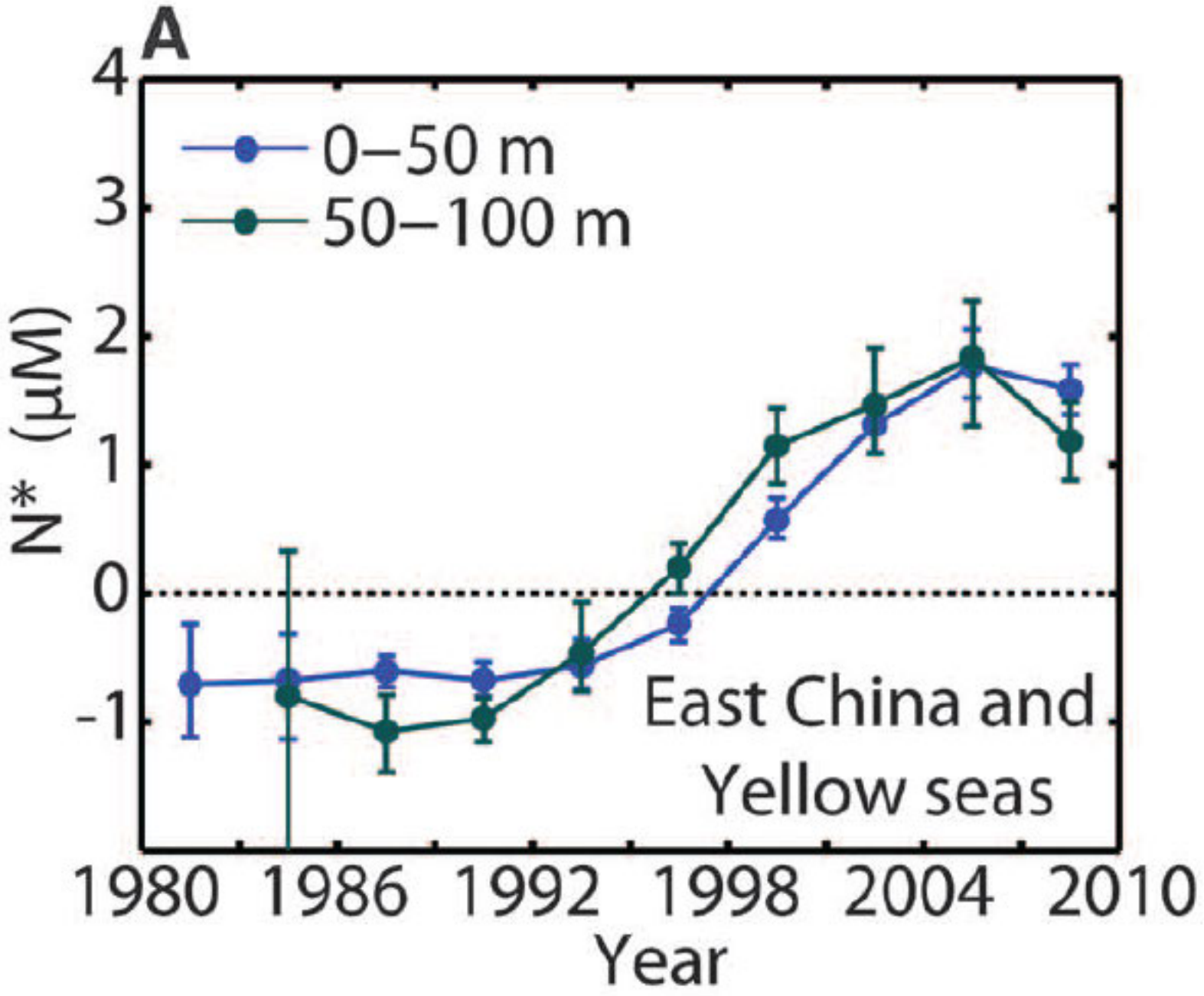

Climate forcing
Mixing - aging
Emissions
Dust, Pollution,
Volcanoes, Biomass
burning
Ship emissions
CO_2
N_2O & DMS
Wet & Dry deposition
Mass elemental fluxes
Nutrients & trace metals
N, P, Fe, C (variable
stoichiometry) and
toxins (Cu, Pb)
Particles
Microlayer
Ecosystem
response
Bioavailability
Uptake, toxicity,
ballast
Evolution of
Environmental
parameters
(T°, pH...)
Deep Ocean
Carbon export
Credit:
surface ocean solas lower atmosphere study

Increasing trend in N* (nitrate – 16*phosphate) in East Asian coastal waters



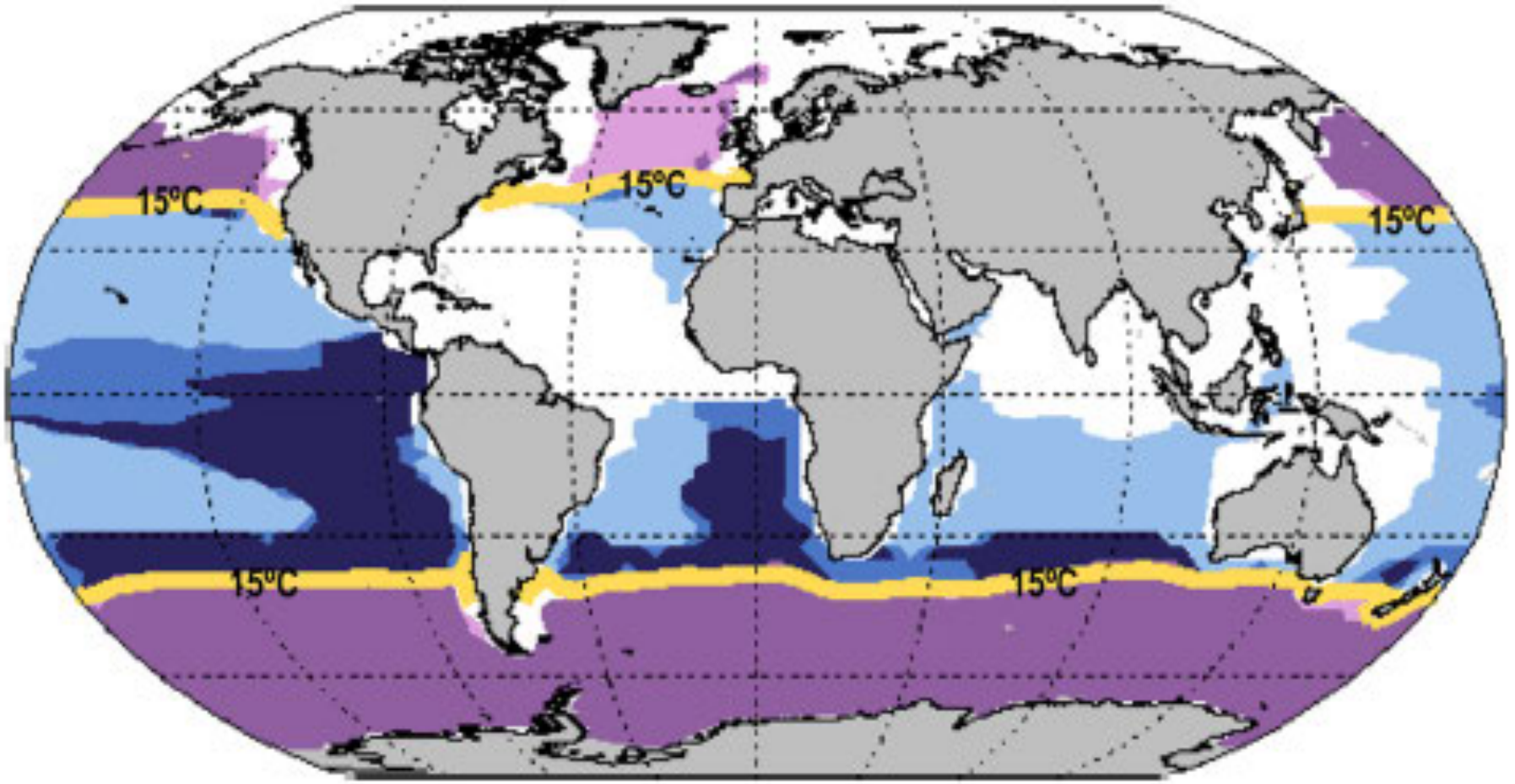
Kim et al. (2011)

Evidence for shift from N limitation to P limitation



Kim et al. (2011)

Ocean model simulation of iron limitation



Small phytoplankton only

Small phytoplankton and diatoms

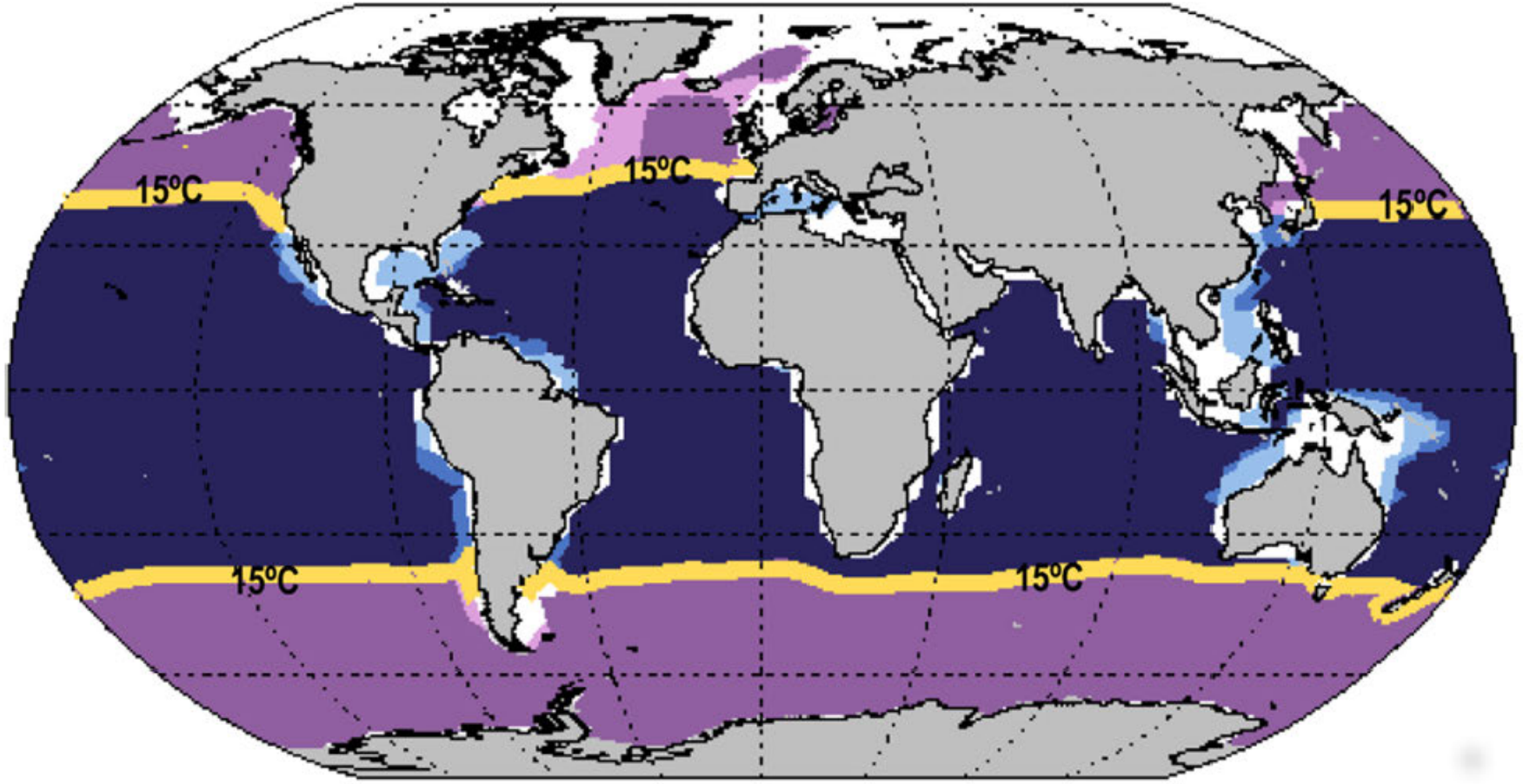
Small phytoplankton, diatoms and diazatrophs

Diazotrophs only

Diazotrophs and diatoms

Mahowald et al. (2018)

Ocean model simulation of iron limitation in absence of atmospheric deposition



Small phytoplankton only

Small phytoplankton and diatoms

Small phytoplankton, diatoms and diazatrophs

Diazotrophs only

Diazotrophs and diatoms

Mahowald et al. (2018)

Core Theme 3 questions
SOLAS 2015–2025 Science Plan and Organisation

How do biogeochemical and ecological processes interact in response to natural and anthropogenic material input from the atmosphere across different regions?

How do global warming and other anthropogenic stressors synergistically alter the uptake of atmospheric nutrients and metals by marine biota in different oceanic regions?

What are the large-scale impacts of atmospheric deposition to the ocean on global elemental cycles (e.g., C and N) and climate change feedbacks in major marine biomes?

1. Emissions
2. Transport and transformation
3. Deposition
4. Marine biogeochemical response

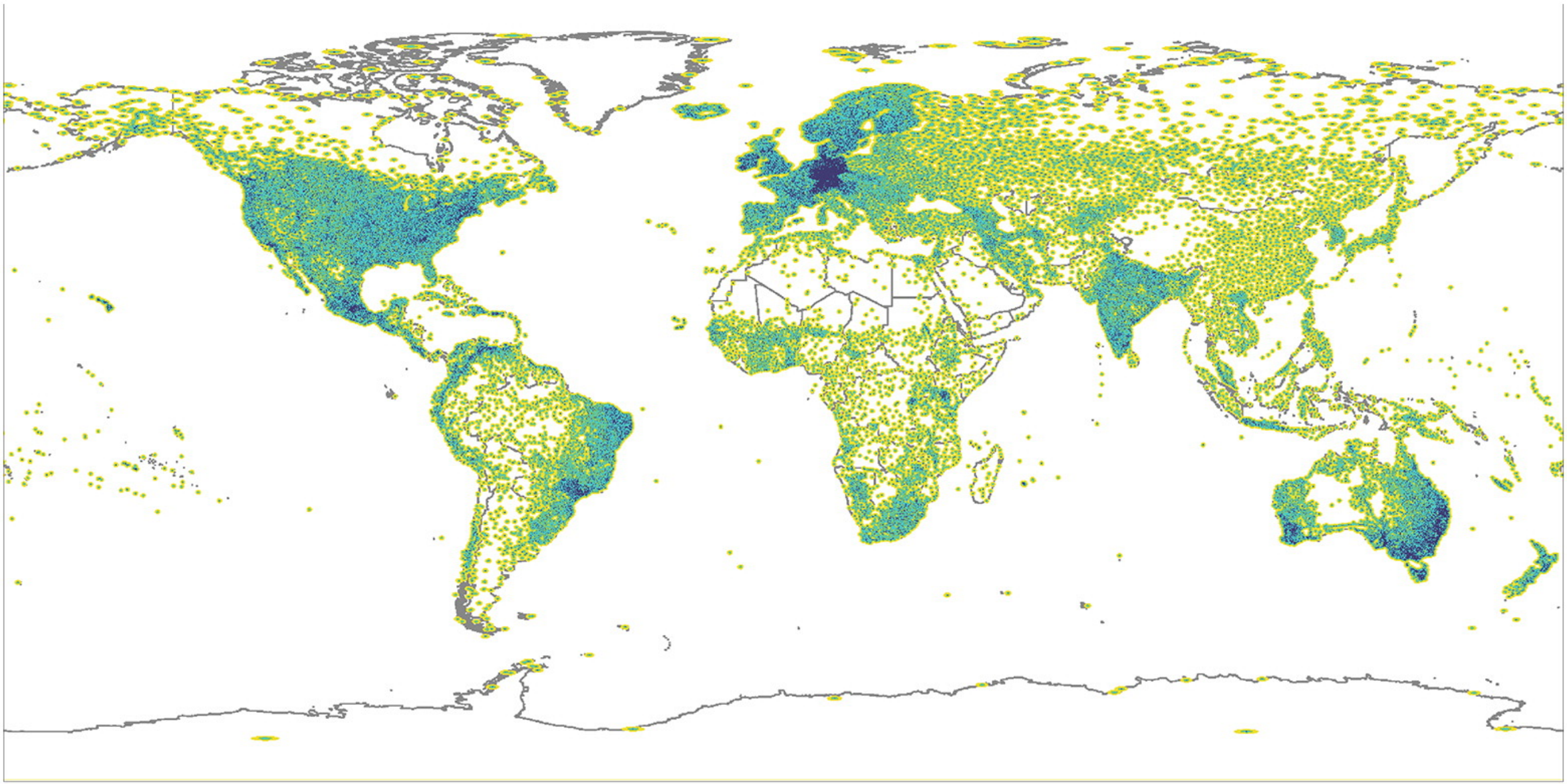
Deposition = Velocity × Concentration

Wet deposition	Velocity = precipitation rate Concentration = solute concentration
Dry deposition (gases)	Velocity = gas transfer velocity = f(turbulence) Concentration = gas concentration
Dry deposition (particles)	Velocity = deposition velocity = f(size, turbulence) Concentration = particle concentration

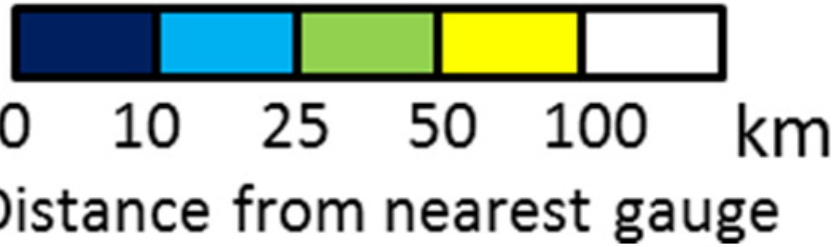
Outline

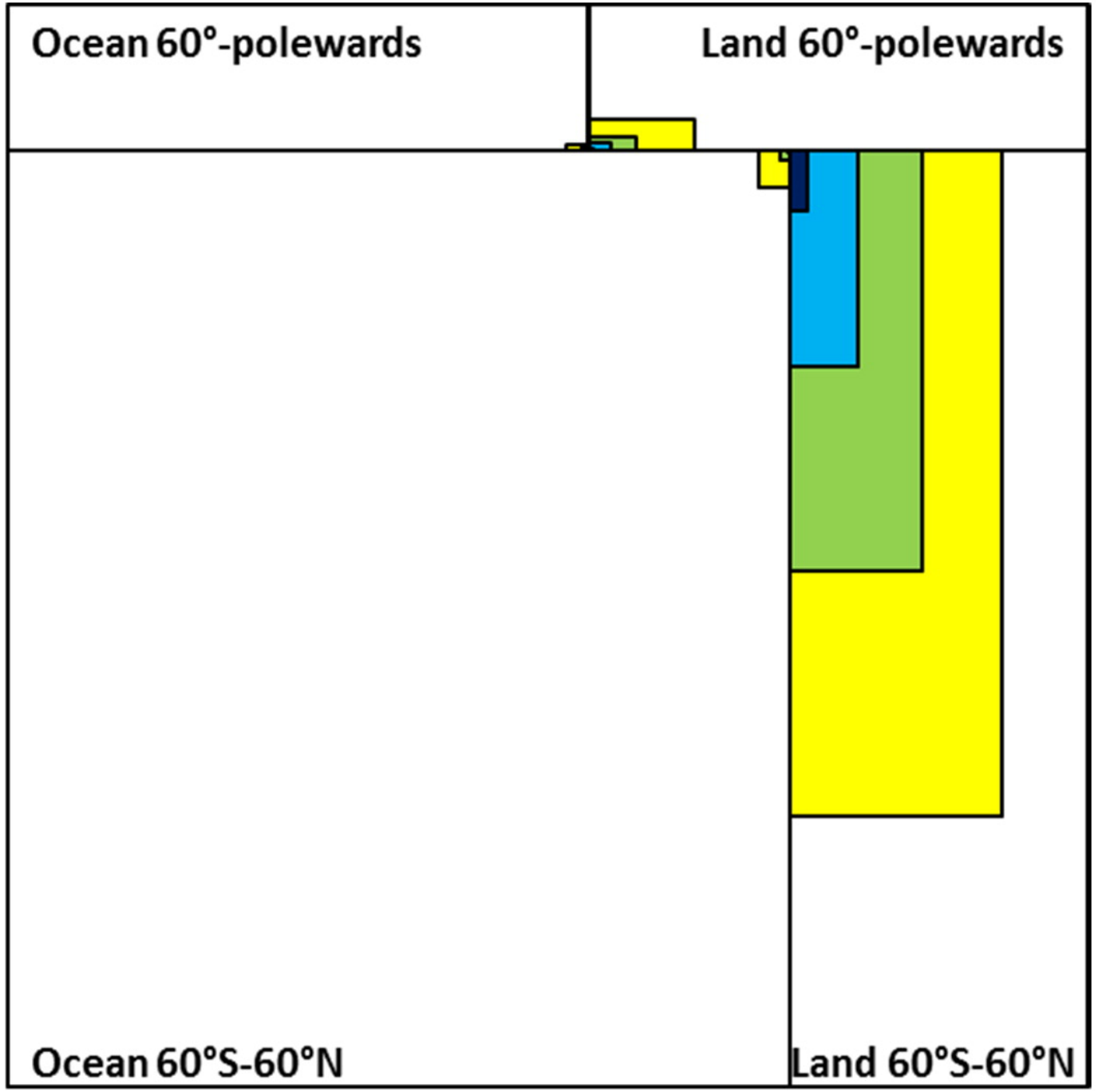
- Precipitation
- Wet deposition of N—observations and models
- Dry deposition of Fe—observations and models
- Example of impact of Fe deposition
- Recent developments in emissions sources
- Summary

Precipitation over the ocean



Kidd et al. (2017)





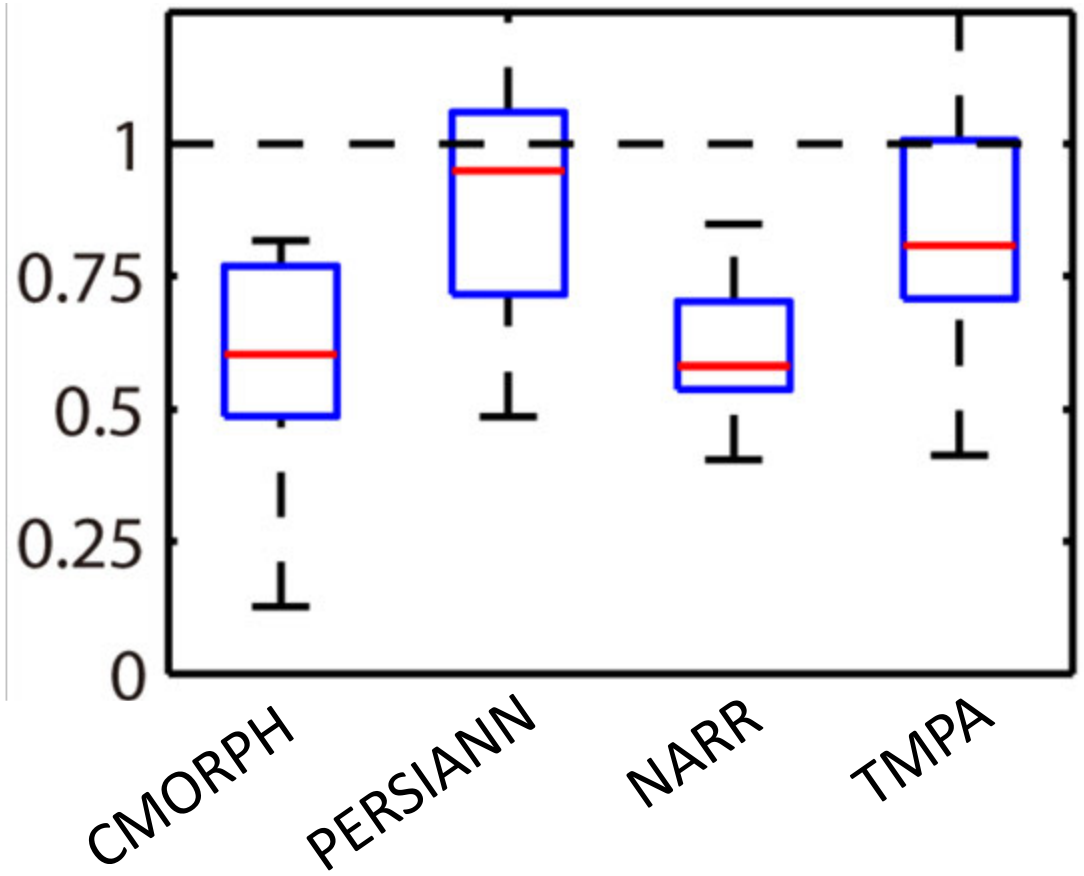
Kidd et al. (2017)

Filling the ocean precipitation gap

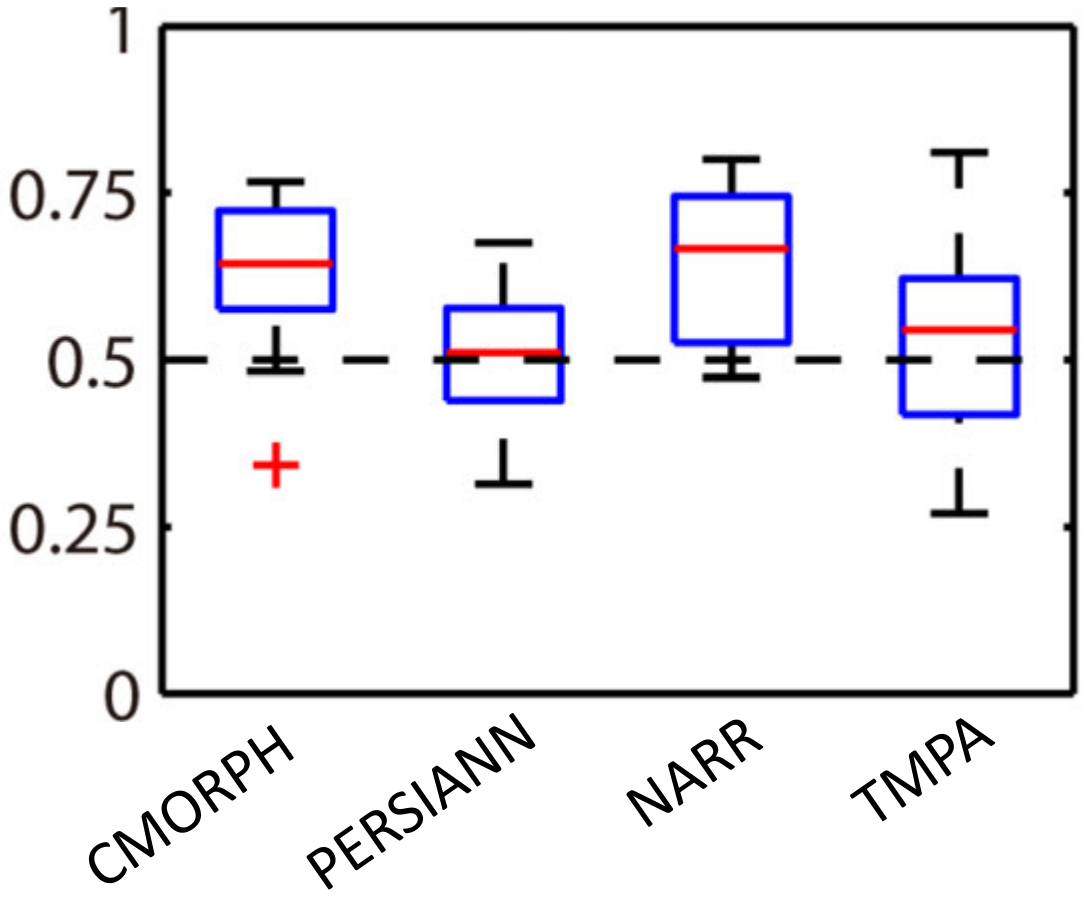
- Satellite sensors
- Numerical models
- Meteorological reanalysis products

Evaluation of four daily precipitation products (three satellite and one reanalysis) at 16 stations along the US east coast in spring

Fractional bias

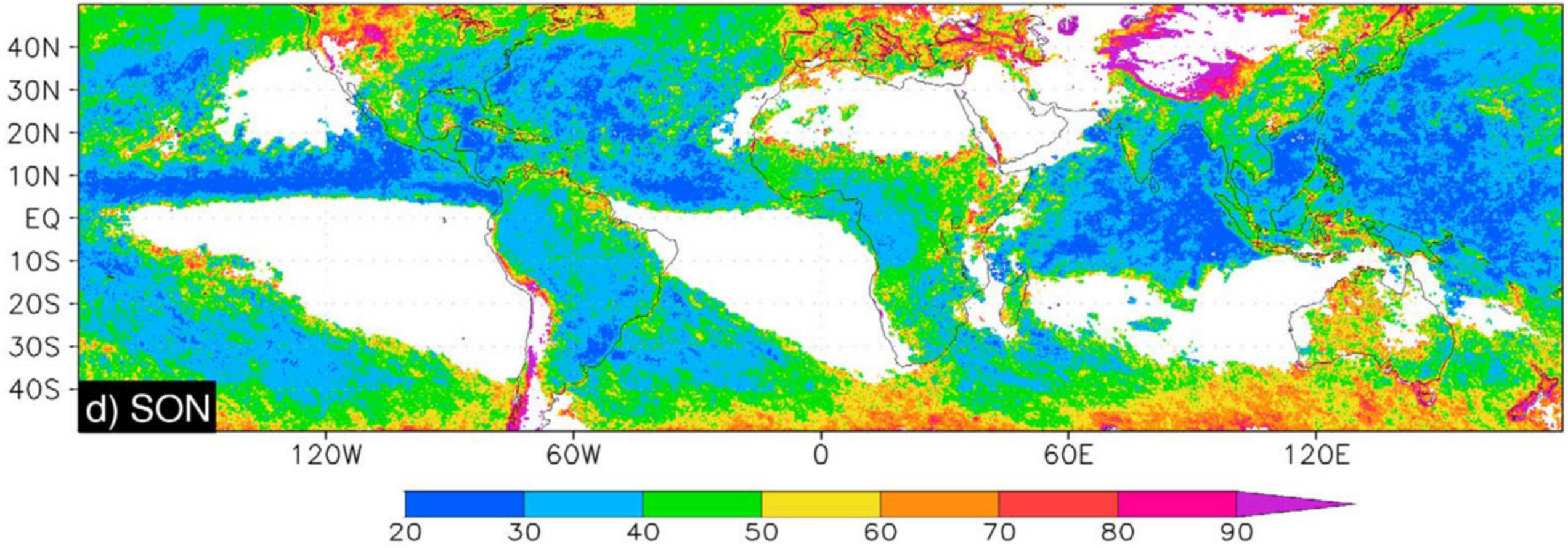


Correlation coefficient



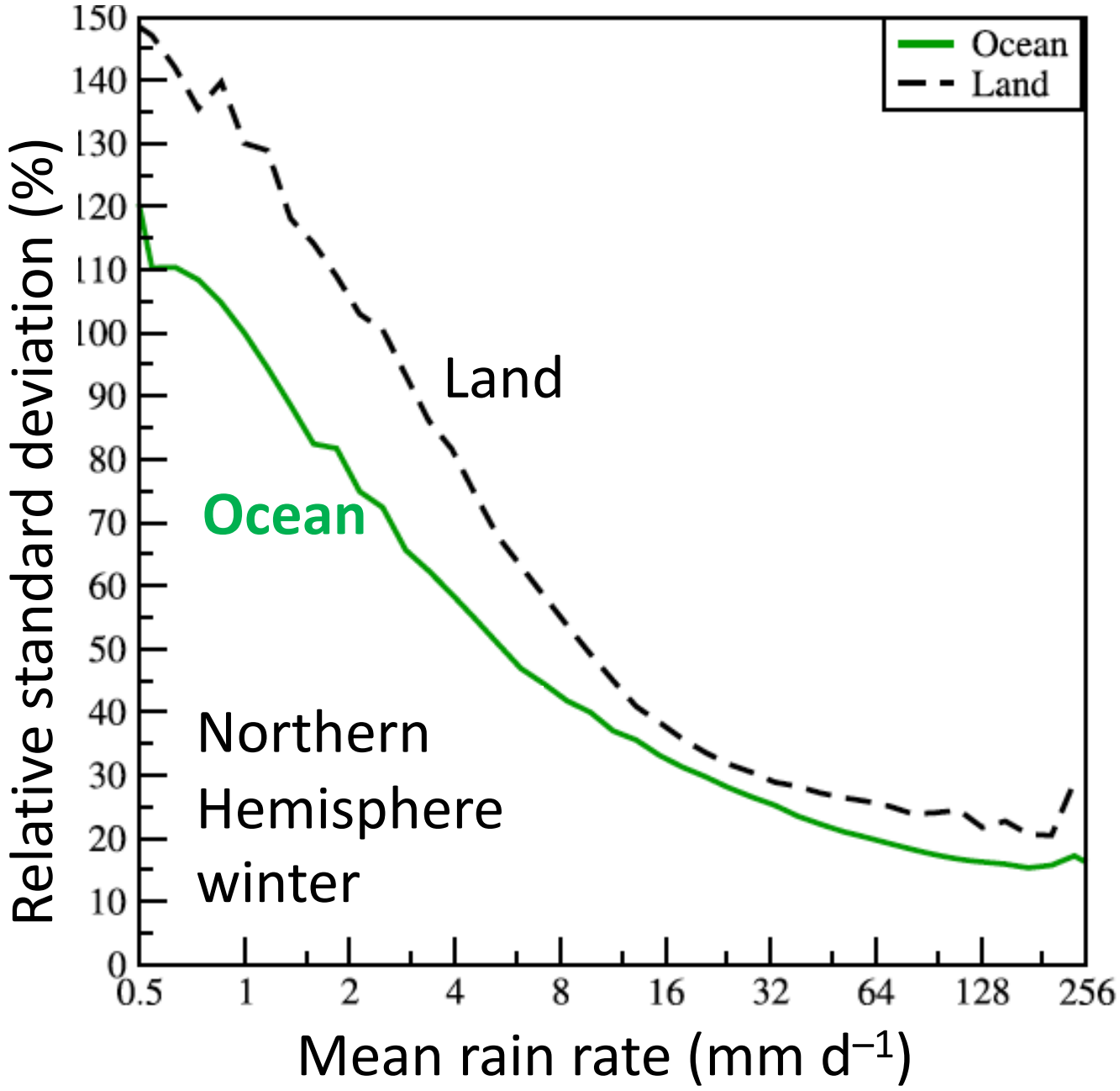
Kim et al. (2014)

Standard deviation from the ensemble mean of six satellite products as percentage of mean precipitation



Tian and Peters-Lidard (2010)

Differences among satellite precipitation products (n = 6) are greatest at low precipitation

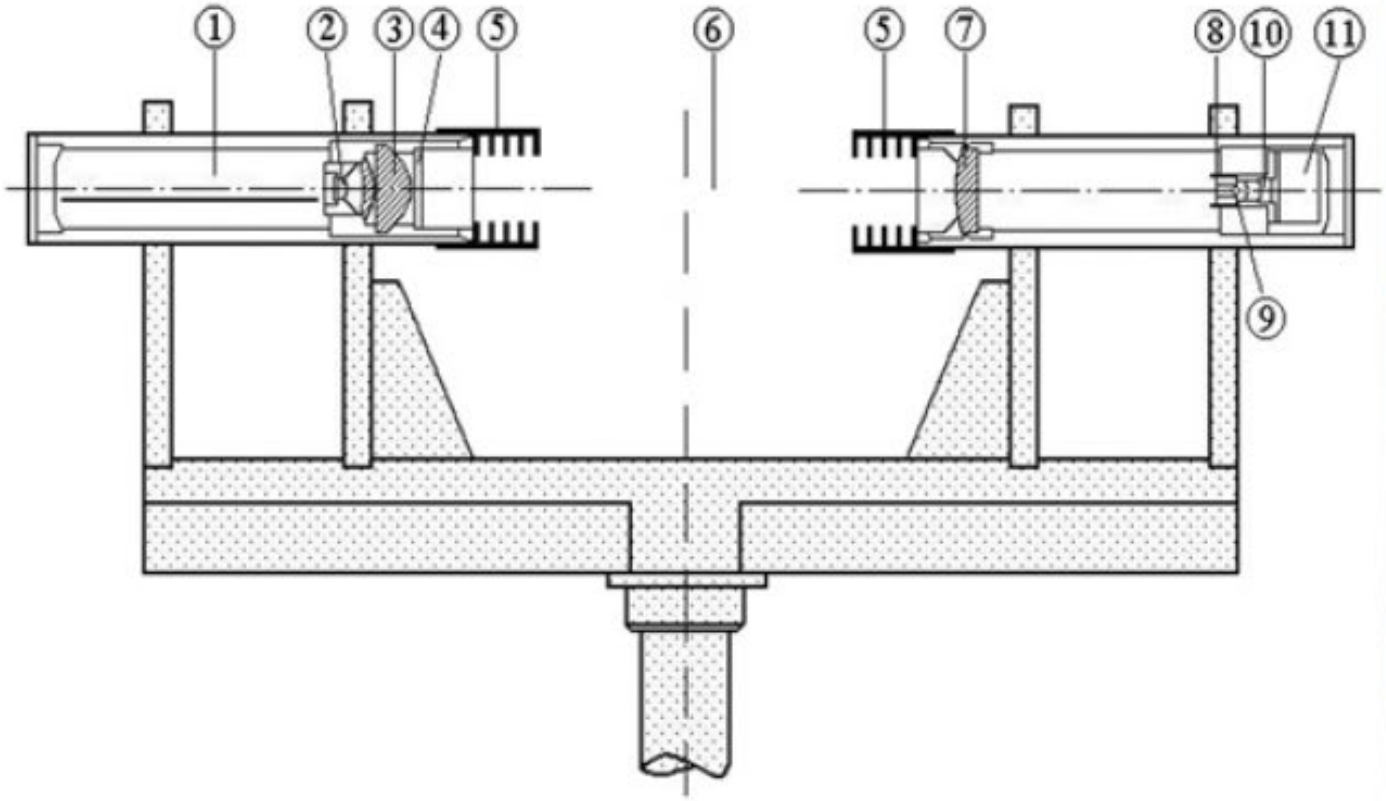


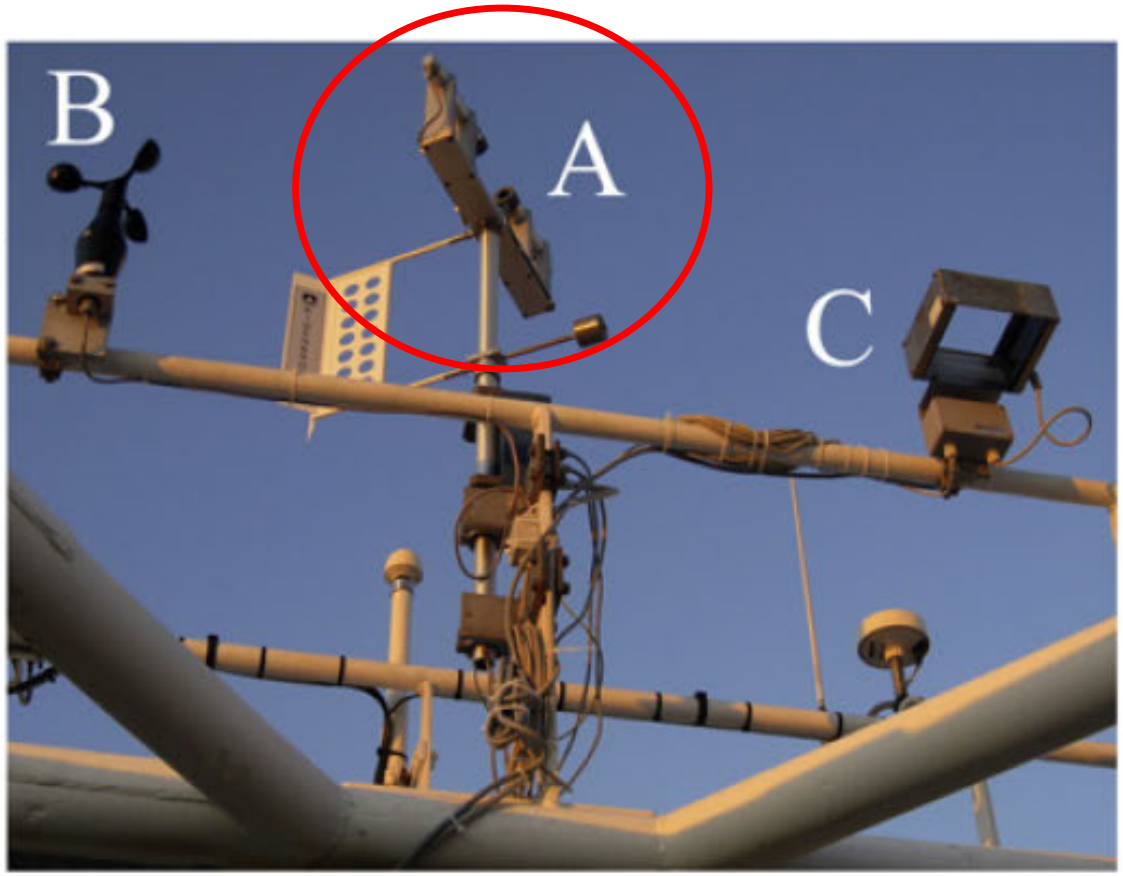
Tian and Peters-Lidard (2010)

Calibrating global ocean precipitation products with in situ sensors

- Ships
- Passive aquatic listeners
- Buoys

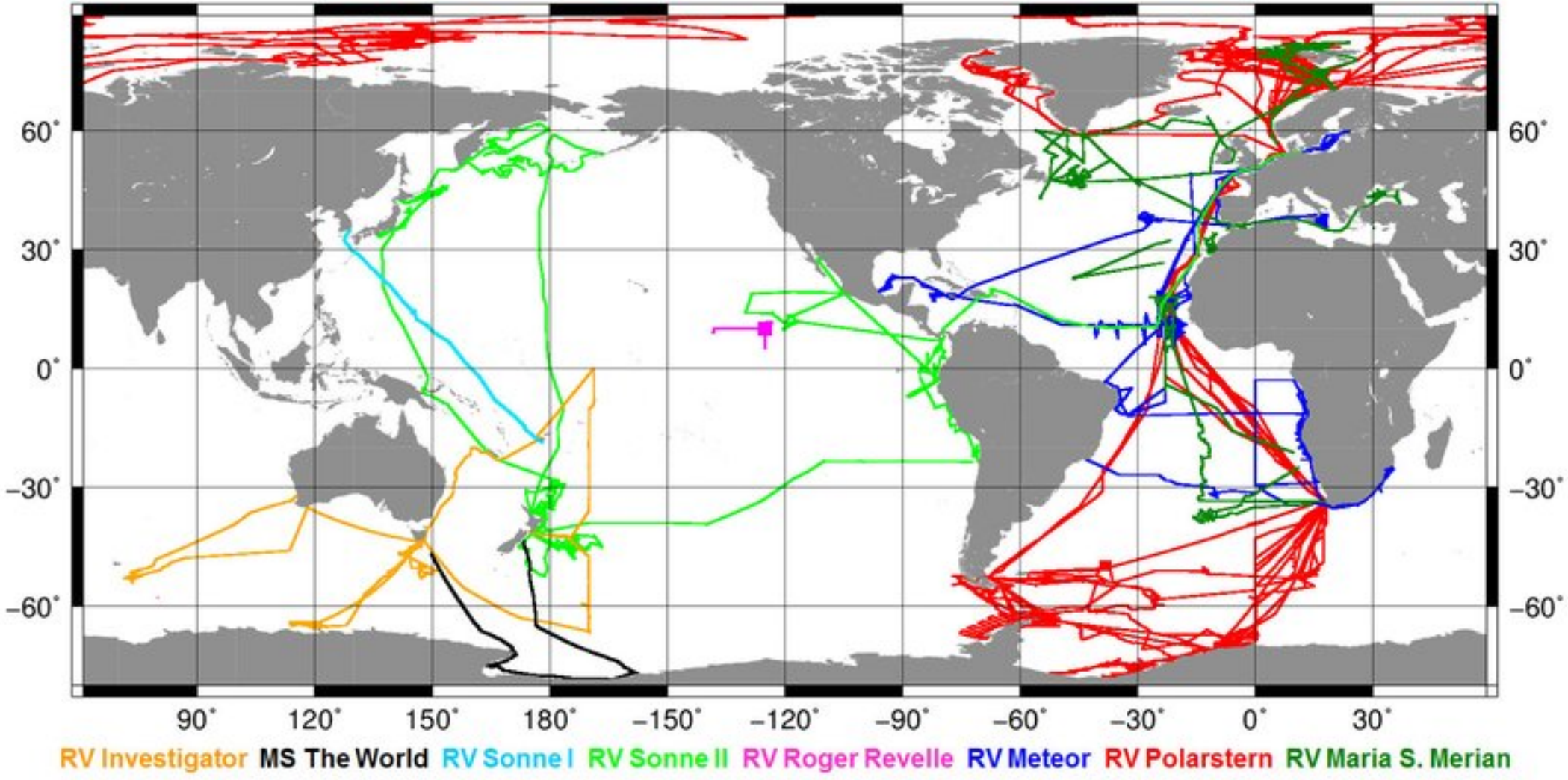
Disdrometer for ship-based precipitation measurement



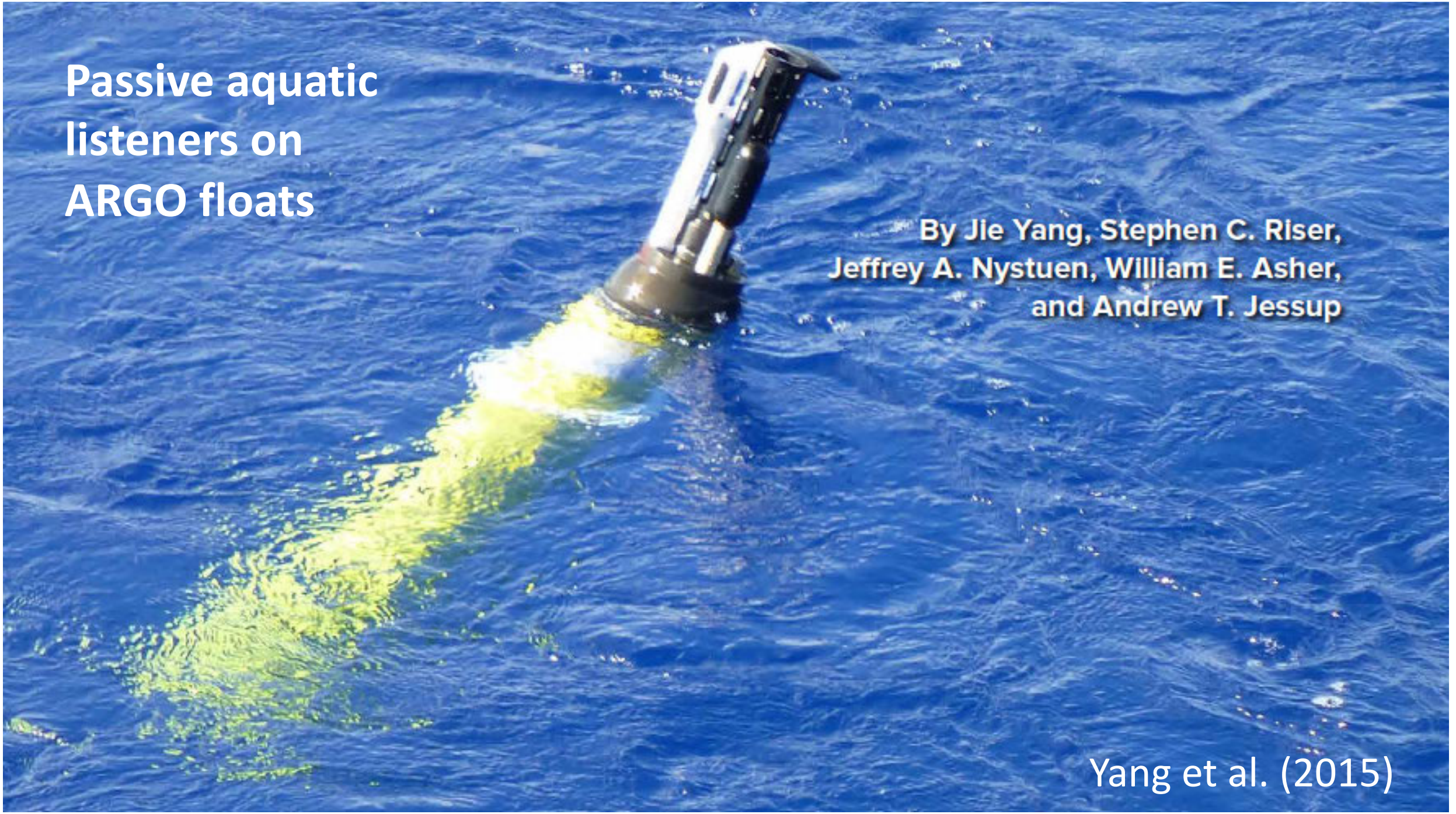


Klepp (2015)

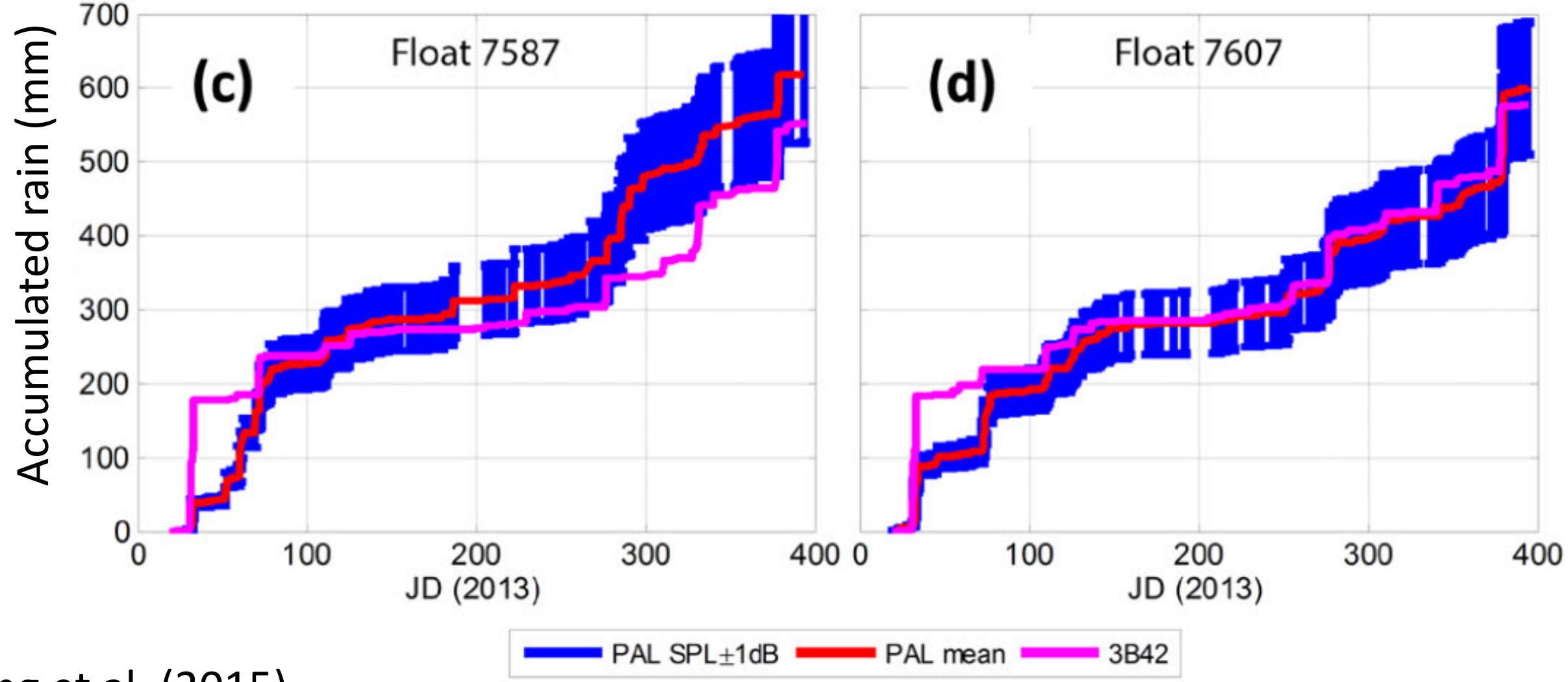
Research vessels participating in OceanRAIN—the Ocean Rainfall And Ice-phase precipitation measurement Network



Klepp et al. (2018)


Passive aquatic listeners on ARGO floats
By Jie Yang, Stephen C. Riser, Jeffrey A. Nystuen, William E. Asher, and Andrew T. Jessup
Yang et al. (2015)

Precipitation from acoustic sensors on floats and satellite sensors are in reasonably good agreement



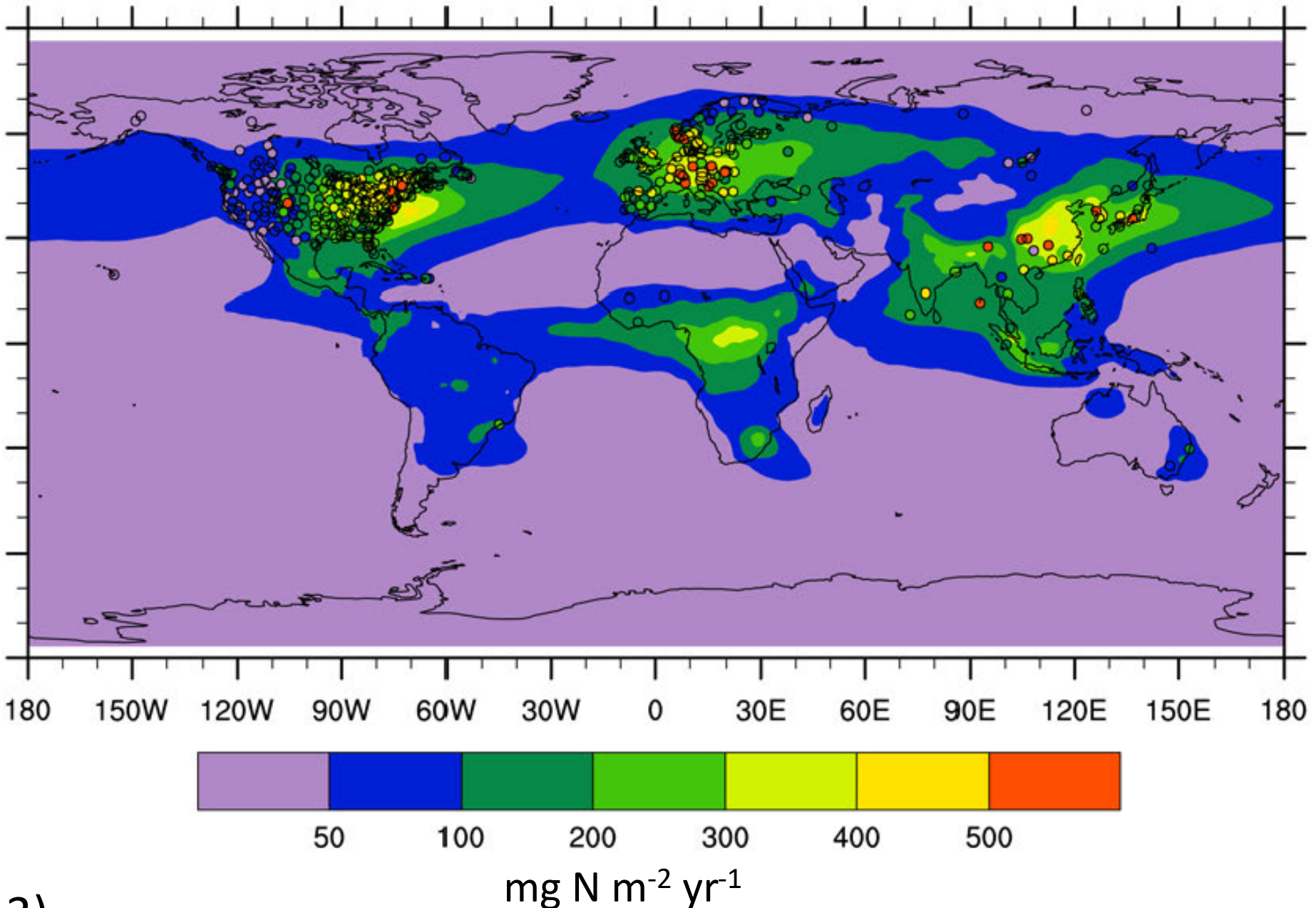
Yang et al. (2015)

Solute concentrations in precipitation

"Major regions of the world, including … all of the oceans, remain very poorly sampled for all of the major ions in precipitation."

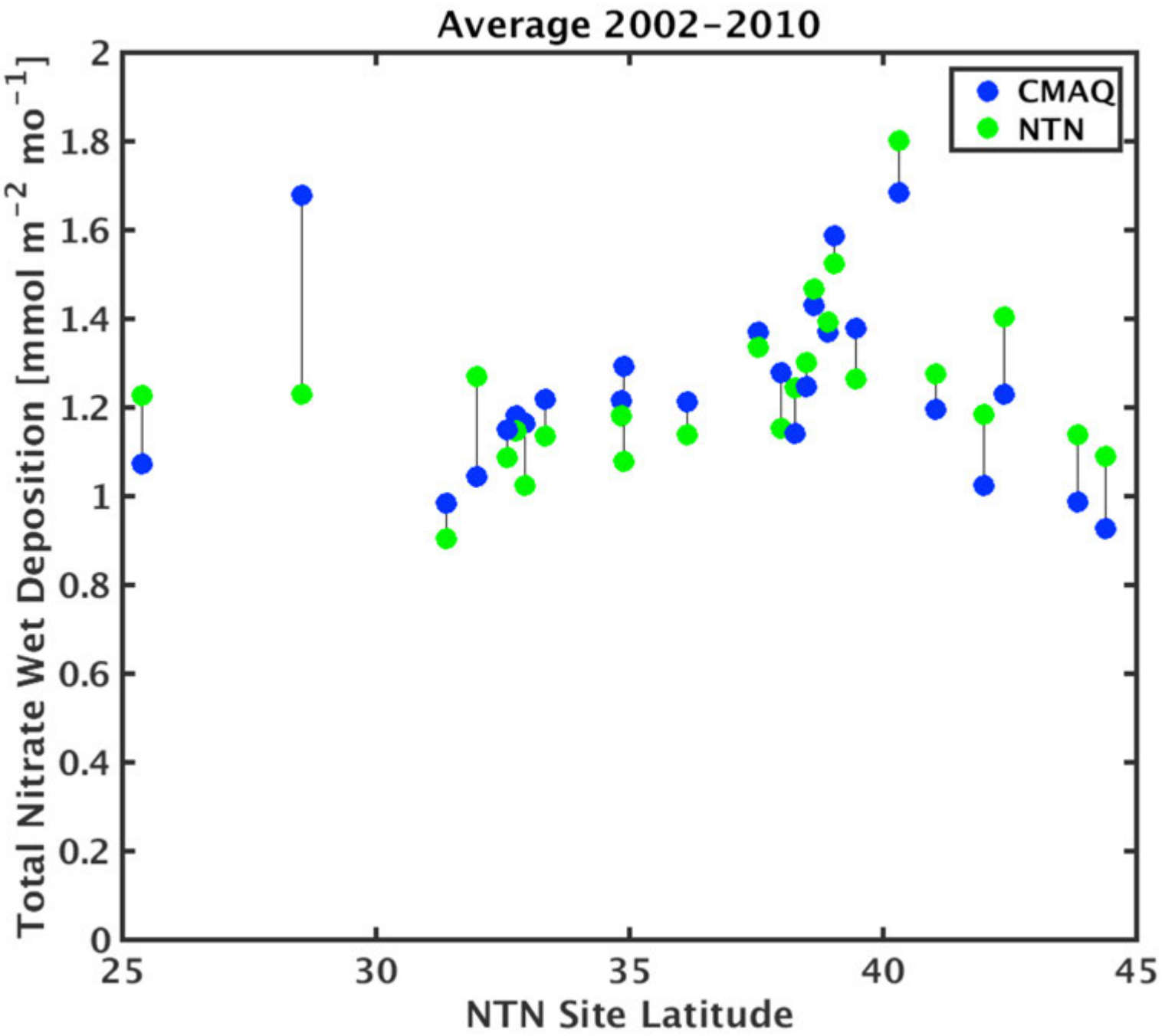
Vet et al. (2014)

Evaluation of nitrate wet deposition by multi-model mean (contours) with observations (circles)



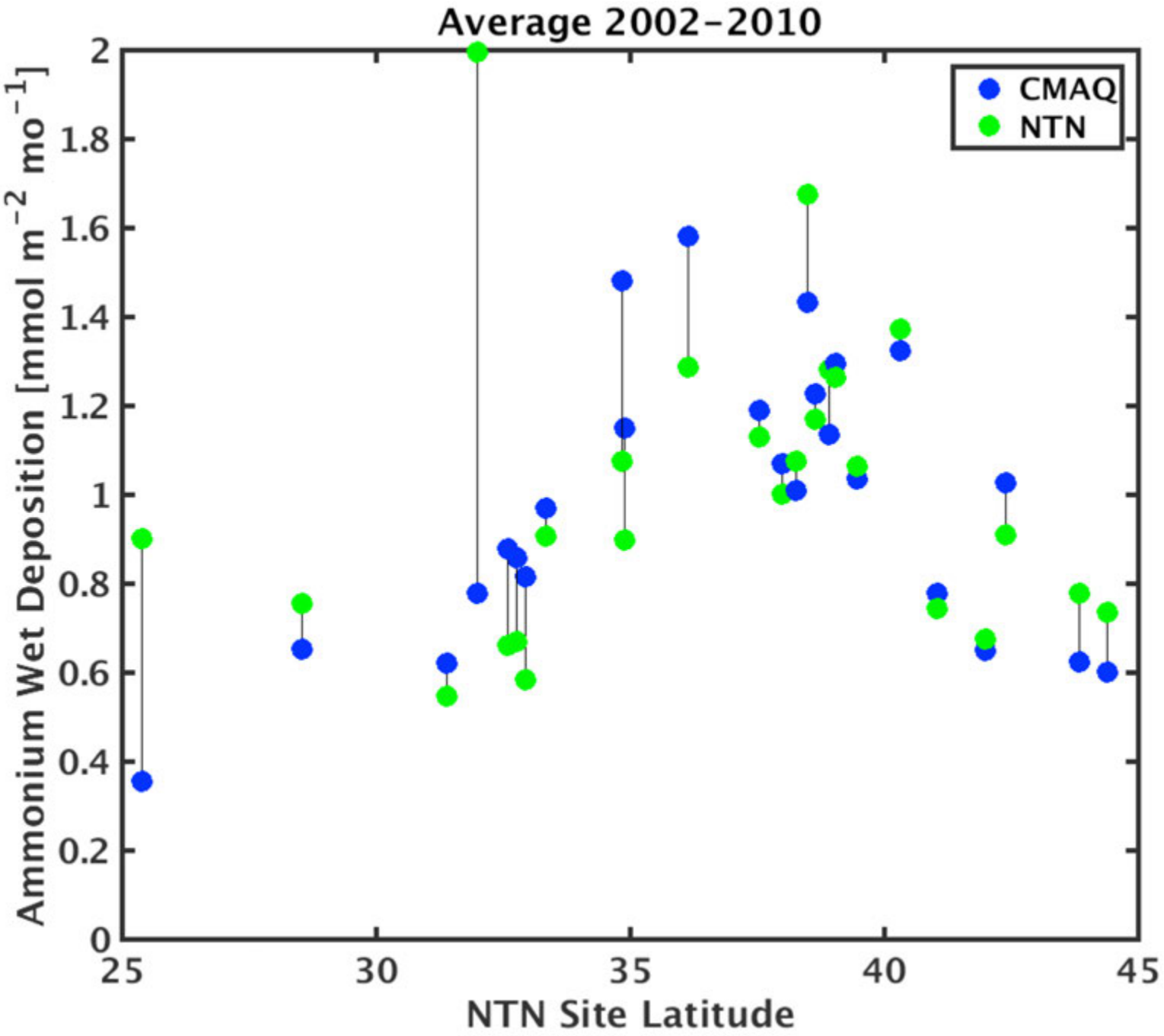
Lamarque et al. (2013)

Nitrate wet deposition along the US East Coast



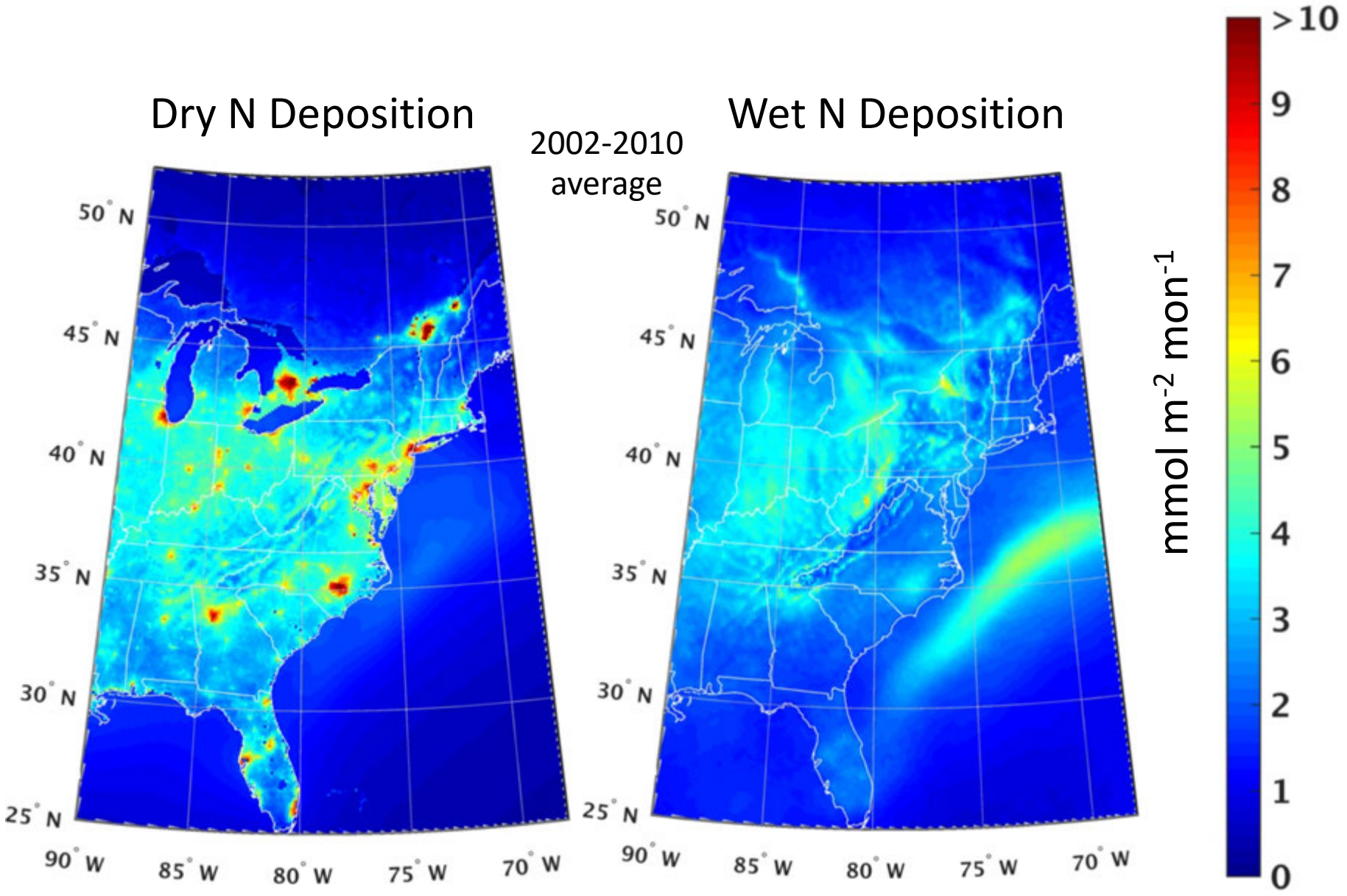
St-Laurent et al. (2017)

Ammonia wet deposition along the US East Coast

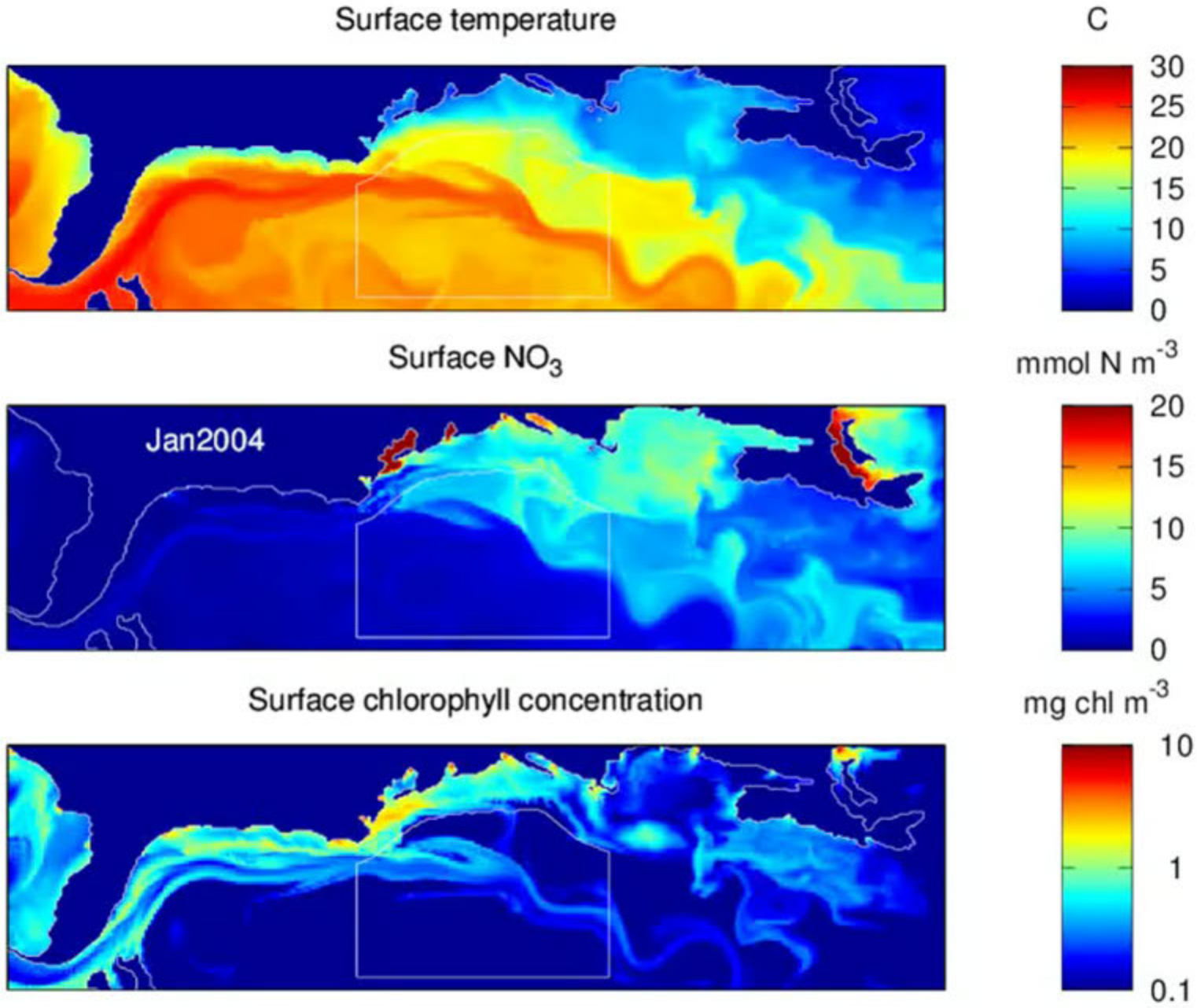


St-Laurent et al. (2017)

Community Multi-scale Air Quality Model (CMAQ)

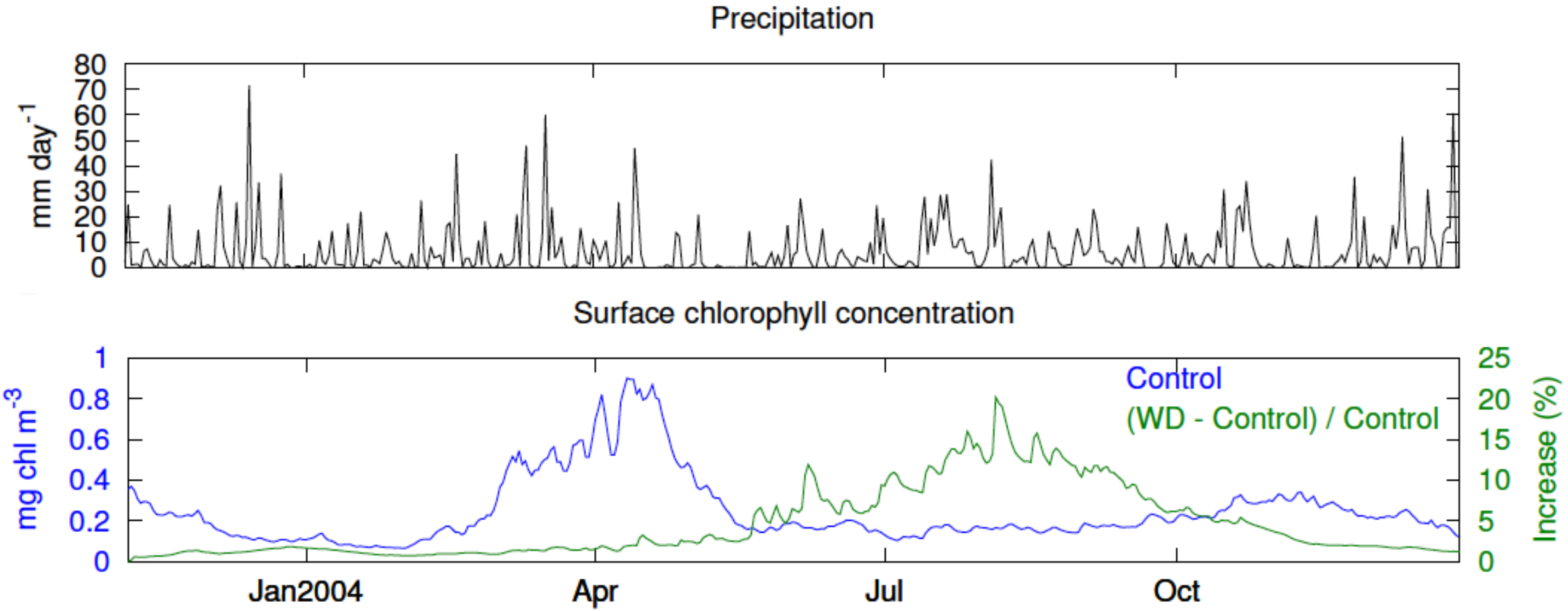


St-Laurent et al. (2017)



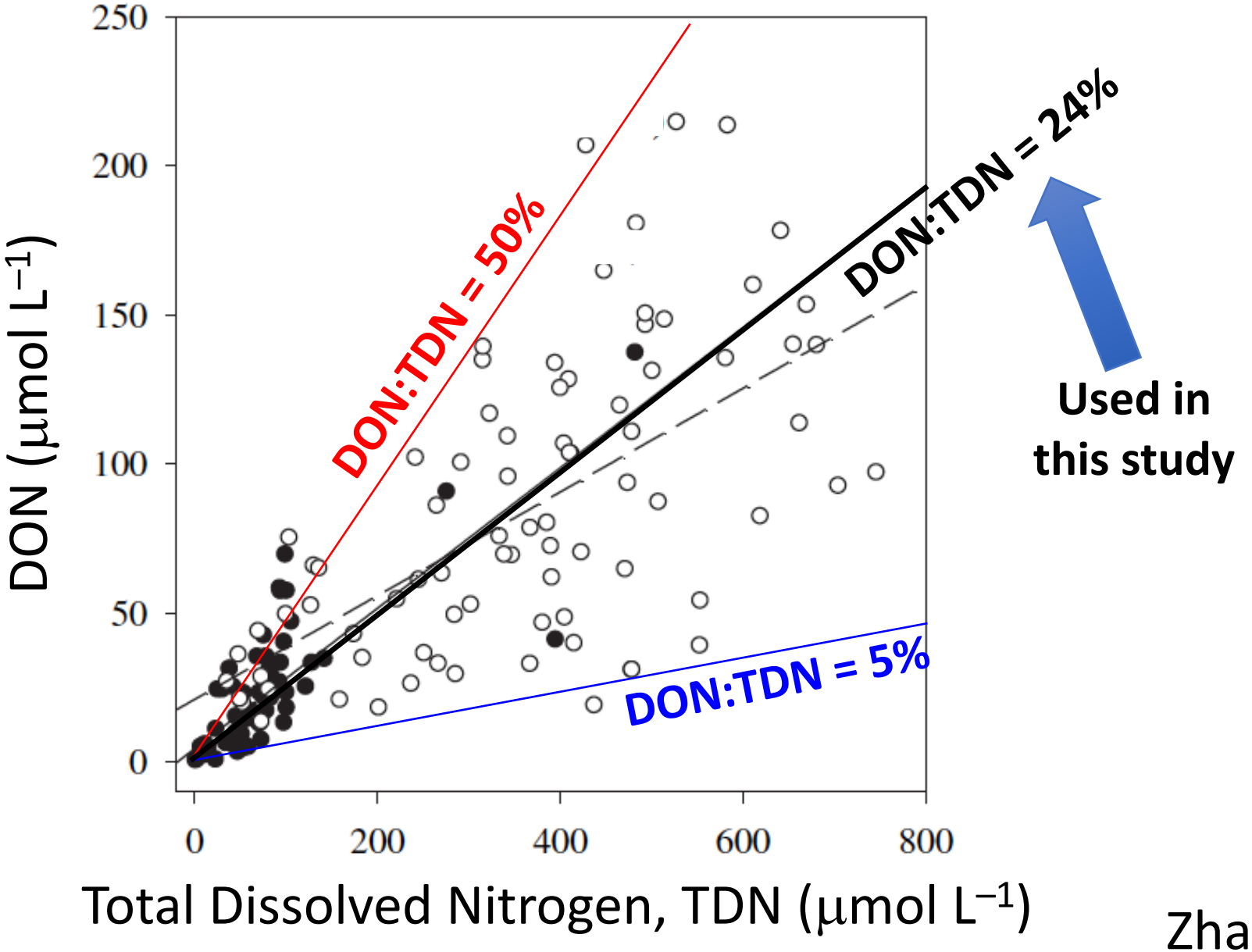
St-Laurent et al. (2017)

Impact of rain on chlorophyll in 2004



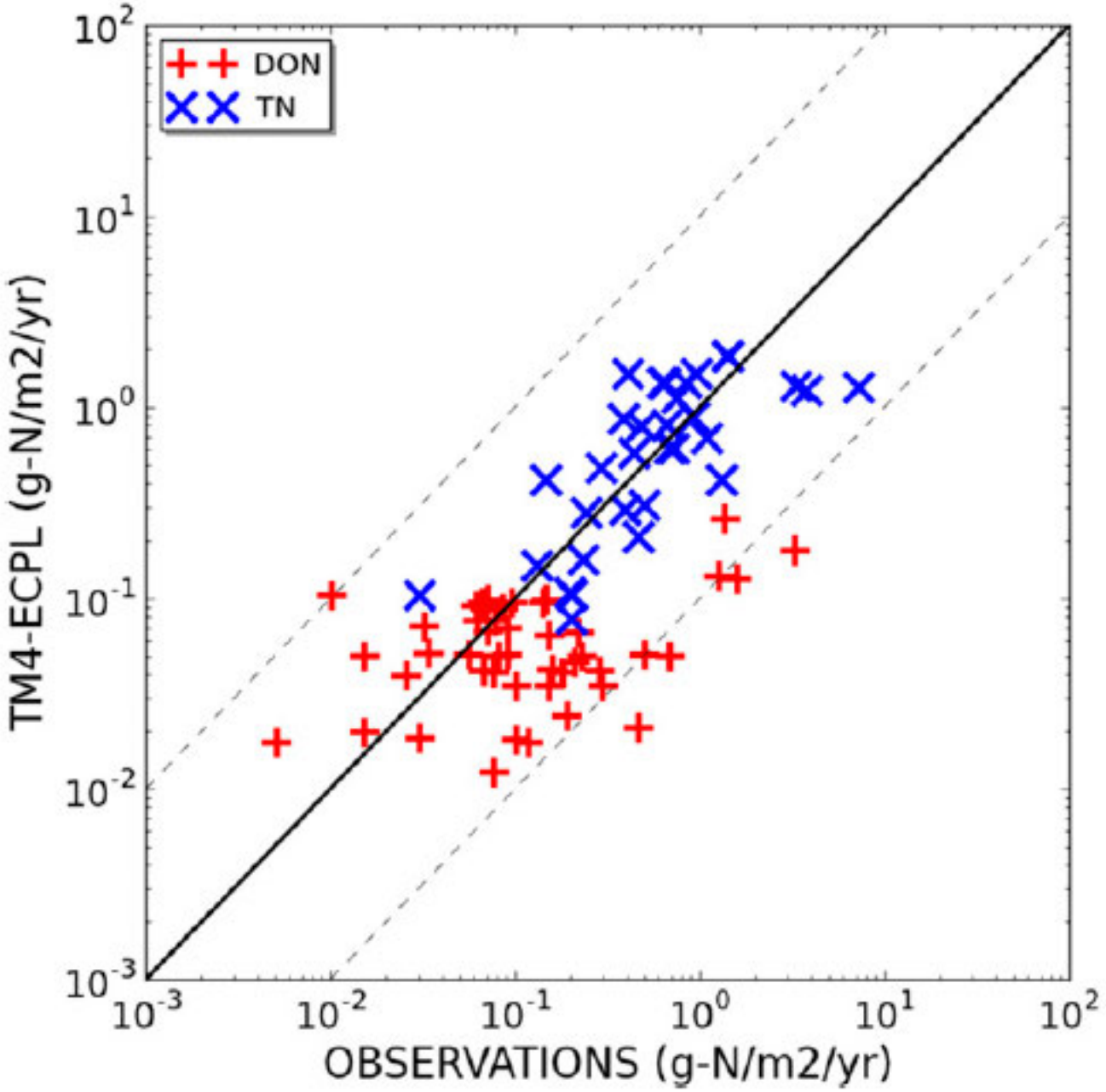
St-Laurent et al. (2017)

Literature summary of DON in rain



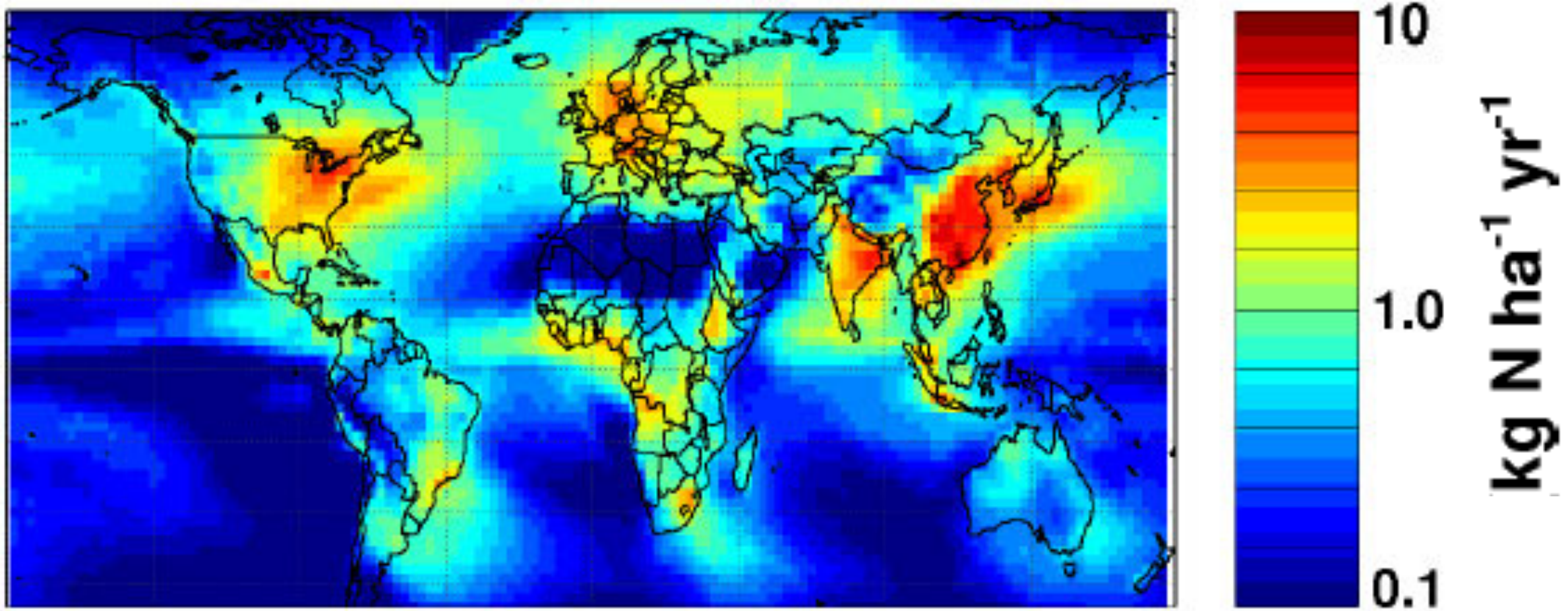
Zhang et al. (2012)

Evaluation of a new global atmospheric chemistry model that includes organic nitrogen linked to secondary organic aerosols



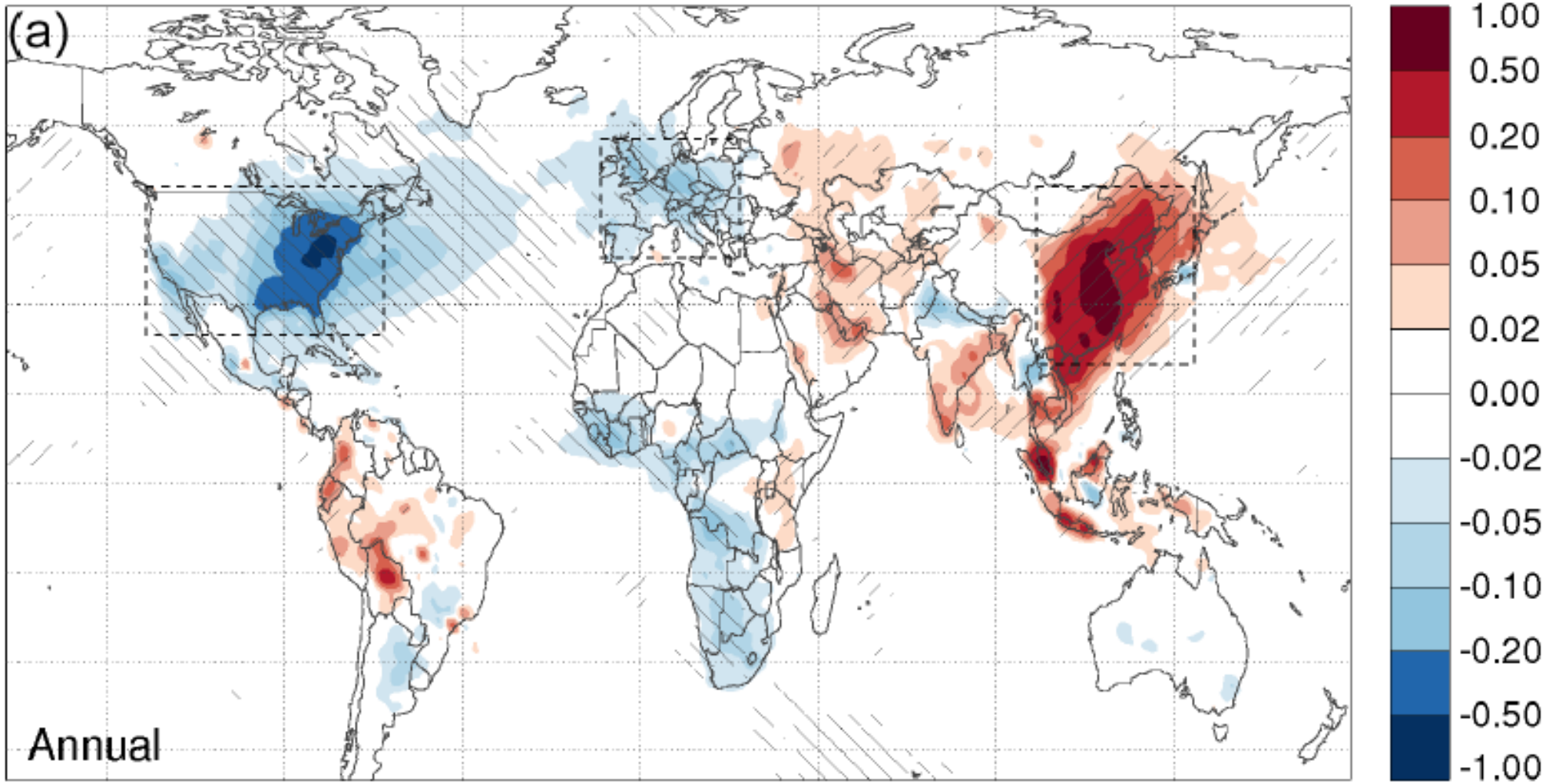
Kanakidou et al. (2016)

Wet nitrate deposition from model that assimilates satellite NO_2 column (2000–2002)



Geddes & Martin (2017)

Long-term trend (1996–2014) in the satellite-constrained simulation of NO_y deposition (kg N ha^{-1} yr^{-2})



Geddes & Martin (2017)

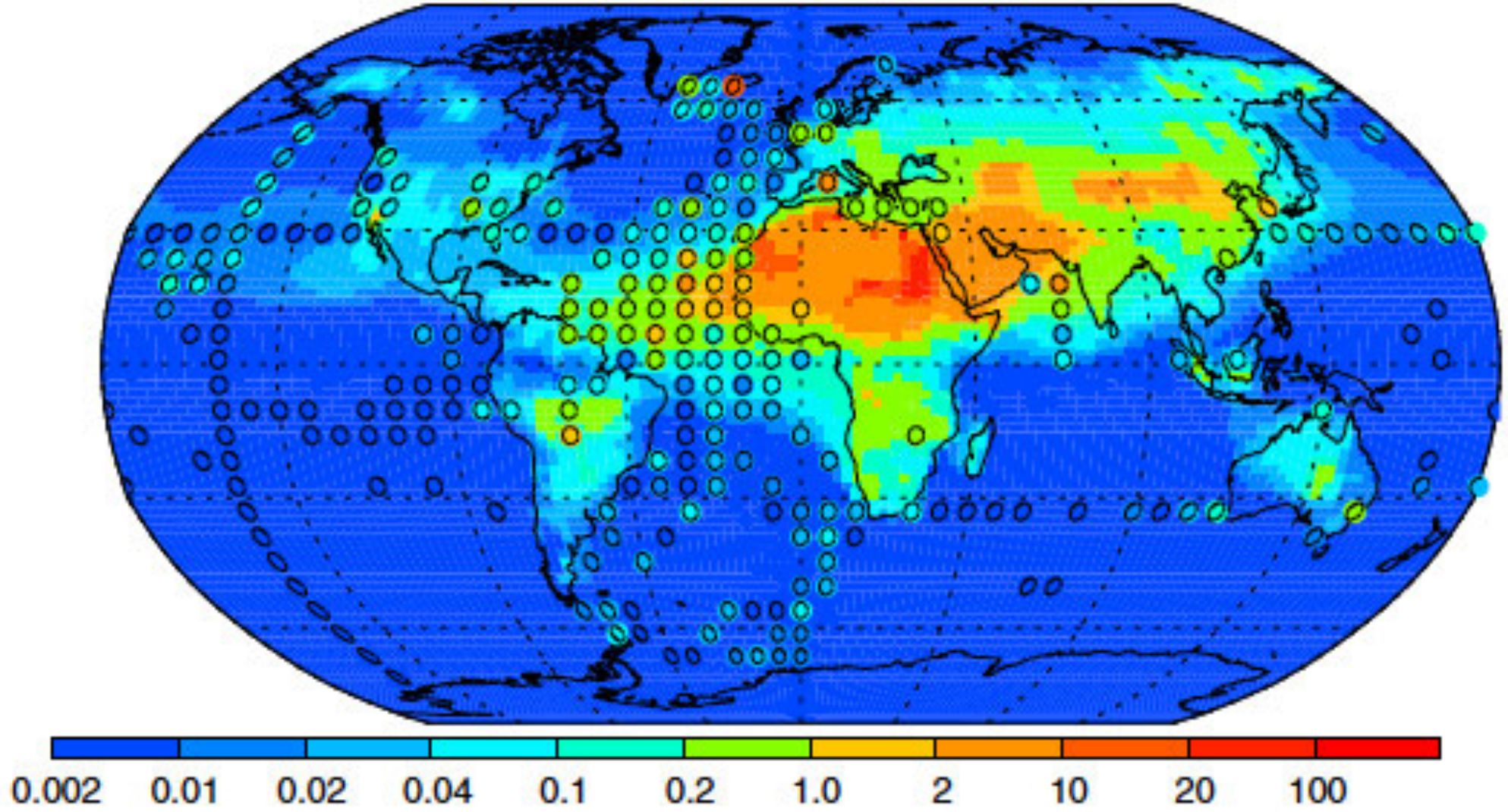
Hatching: $p < 0.01$

Deposition velocity

"The estimation of dry deposition remains highly uncertain because dry deposition velocities are not validated by direct flux measurements."

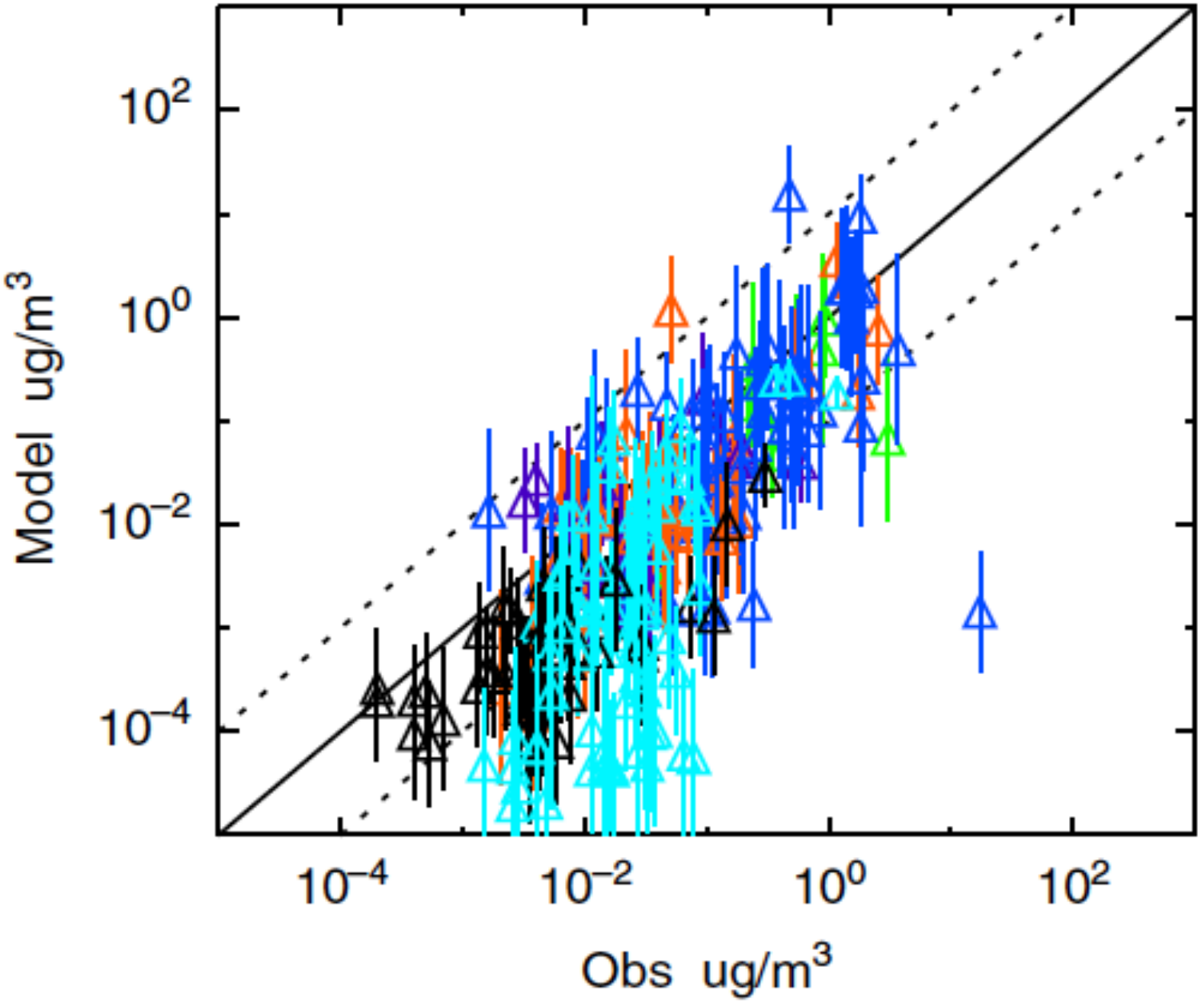
Vet et al. (2014)

Evaluation of surface iron concentration (μg m^{-3}) by atmospheric model (contours) with observations (circles)



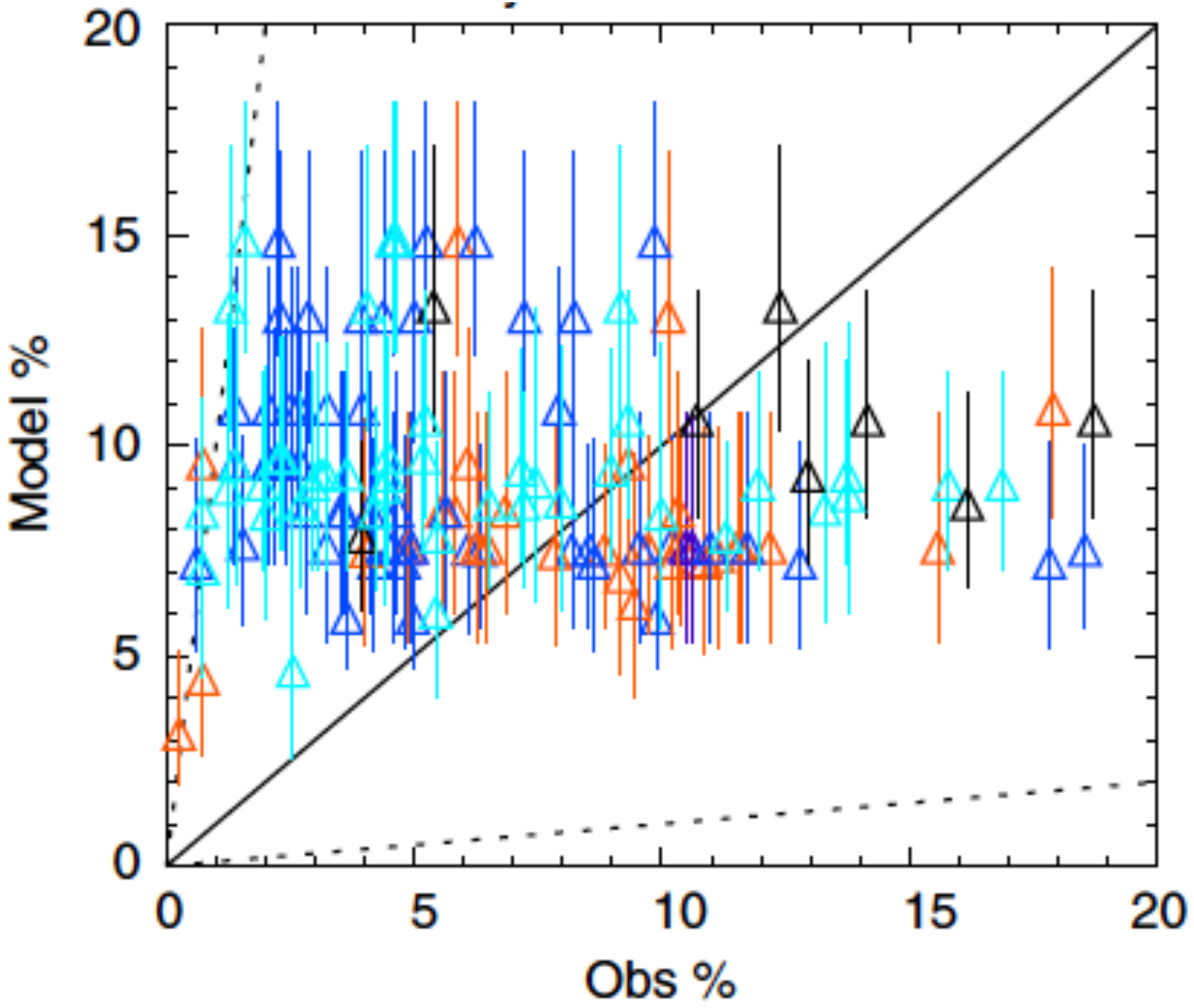
Mahowald et al. (2018)

Atmospheric model iron concentrations are correlated with observations but biased low



Mahowald et al. (2018)

Model is not able to capture variability in iron solubility



Mahowald et al. (2018)

Atmospheric iron model intercomparison

- Four models
- Flux into the global ocean 10–30 and 0.2–0.4 Tg Fe yr^{-1} for total and labile Fe, respectively
- Most models overestimate surface level Fe mass concentrations near dust source regions and tend to underestimate the low concentrations observed in remote ocean regions

Myriokefalitakis et al. (2018)

Ocean iron model intercomparison

- 12 models
- Mean (± 1 std. dev.) input flux (dust + sediment + rivers + hydrothermal) = 67 ± 67 Gmol yr^{-1}
- Mean (± 1 std. dev.) Fe concentration = 0.58 ± 0.14 nmol L^{-1}
- Mean (± 1 std. dev.) residence time = 145 ± 176 yr
- “Models struggle to reproduce many aspects of observed spatial pattern”
- “Models that reflect the emerging evidence for multiple iron sources or subtleties of its internal cycling perform much better”

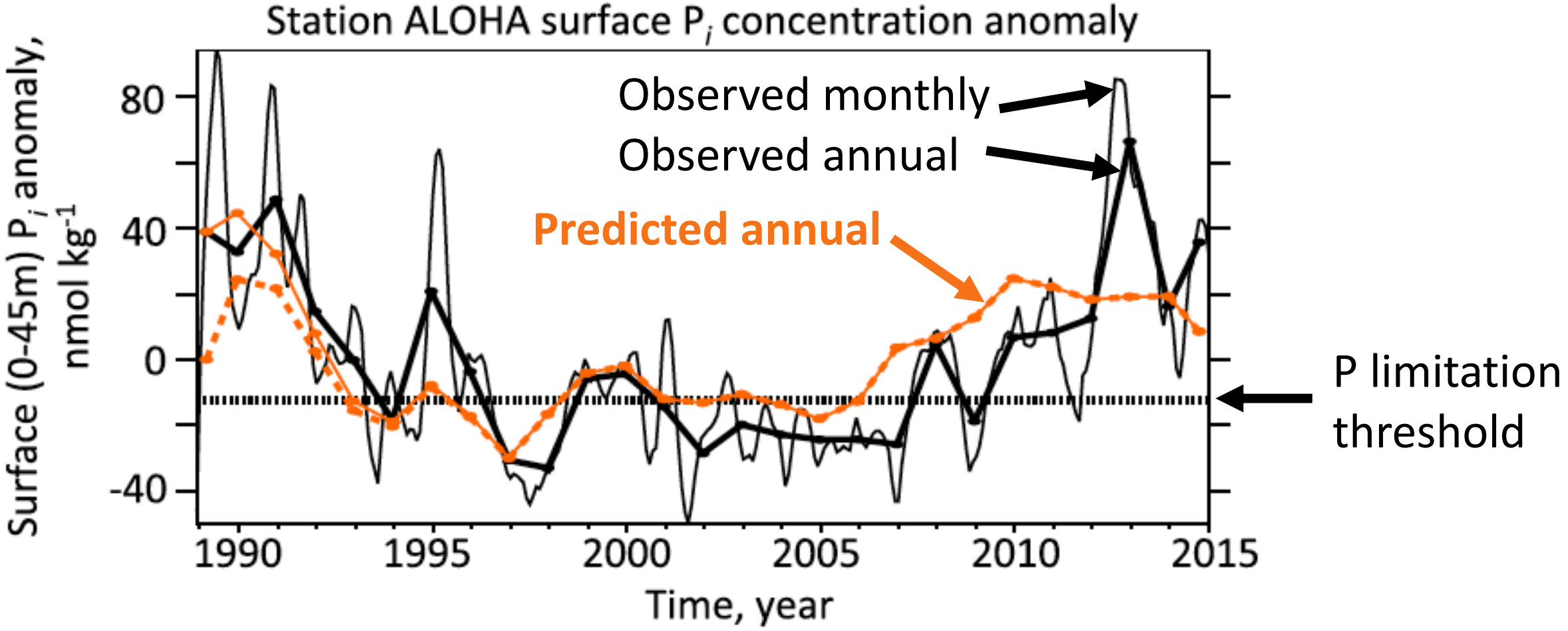
Tagliabue et al. (2016)

Essence of the iron ocean modeling problem

"Because the effective iron sources and sinks overlap, current dissolved Fe observations cannot constrain sources and sinks independently."

Frants et al. (2016)

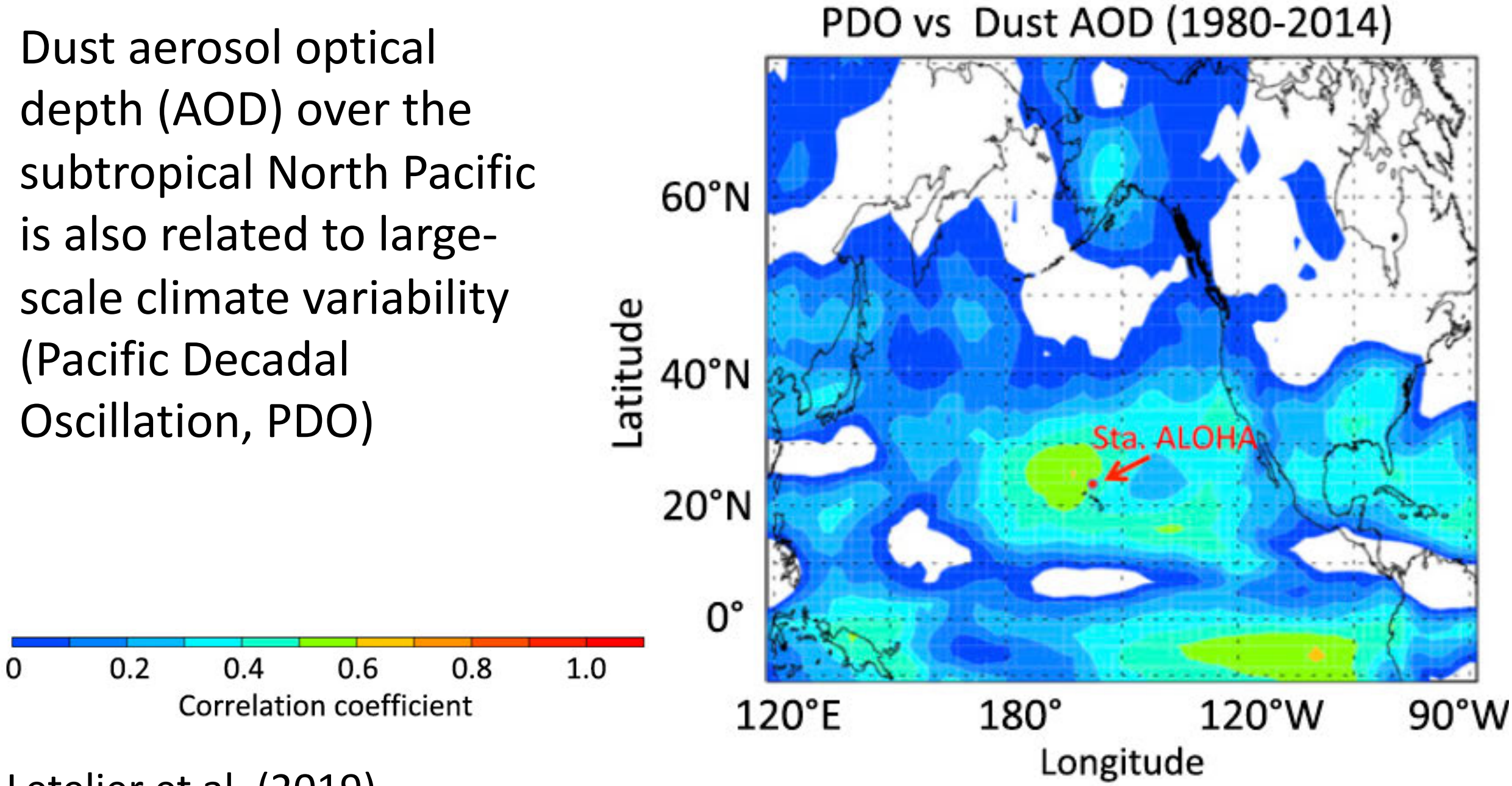
Temporal variability in inorganic phosphate (P_i) in the subtropical north Pacific is related to large-scale climate variability



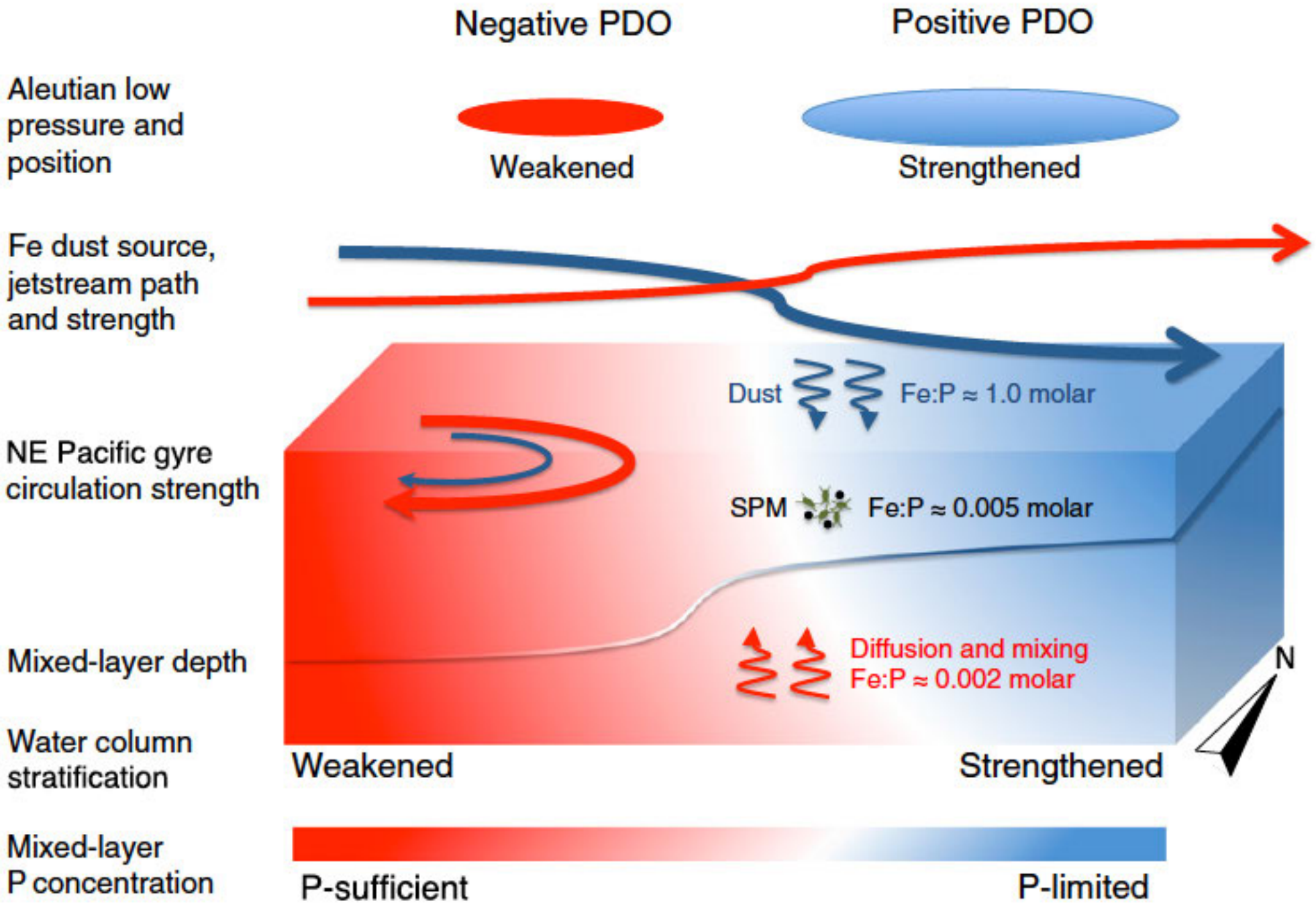
Autoregressive model based on Aleutian Low sea-level pressure (SLP): $P_i^{j+1} = aP_i^j + bSLP^j$

Letelier et al. (2019)

Dust aerosol optical depth (AOD) over the subtropical North Pacific is also related to large-scale climate variability (Pacific Decadal Oscillation, PDO)



Letelier et al. (2019)

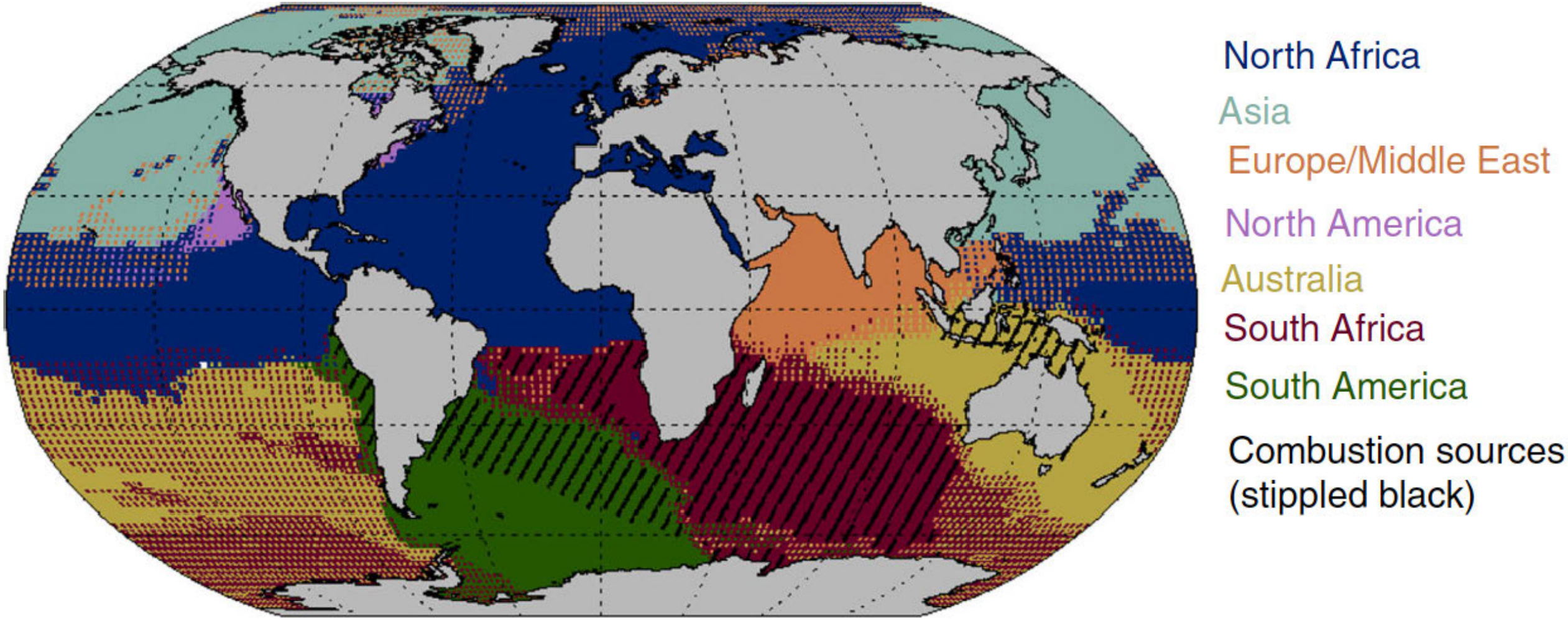


Letelier et al. (2019)

Recent developments in emissions sources

- **Volcanoes** fertilize the surface ocean by relieving iron stress but the response is complex (Hamme et al., 2010; Achterberg et al., 2013; Westberry et al., 2019)
- **Biomass burning** is an important and previously overlooked source of soluble P and Fe to the ocean (Barkley et al., 2019; Ito et al., 2019)

Model simulation of sources of soluble iron deposition



Mahowald et al. (2018)

What have we learned?

- Atmospheric deposition is a fundamental process in global biogeochemical cycles
- Atmospheric deposition has high spatial and temporal variability
- Atmospheric deposition has and will continue to undergo long-term changes

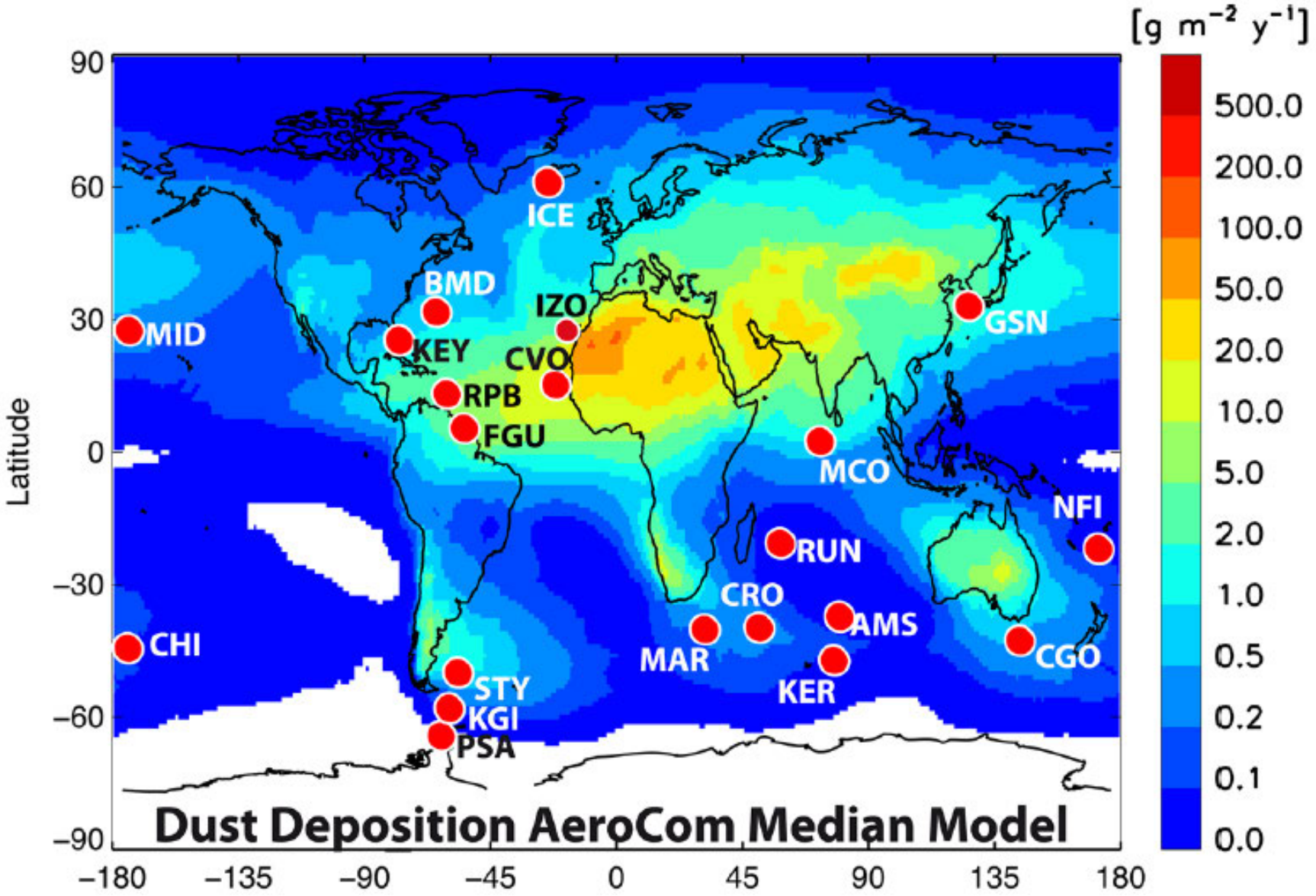
What are the challenges?

- Poor sampling of deposition
- Unreliable estimates of dry deposition
- Inadequate resolution of numerical models of deposition and its impacts
- Large divergence of models → processes not being adequately represented

How to move forward?

- Long-term deposition time series sites are needed
- Merging of in situ observations (ships, buoys, gliders, etc.), satellite data, and numerical models to make global-scale estimates of deposition fluxes and their impacts (data assimilation)

Sites for proposed long-term marine atmospheric measurement network

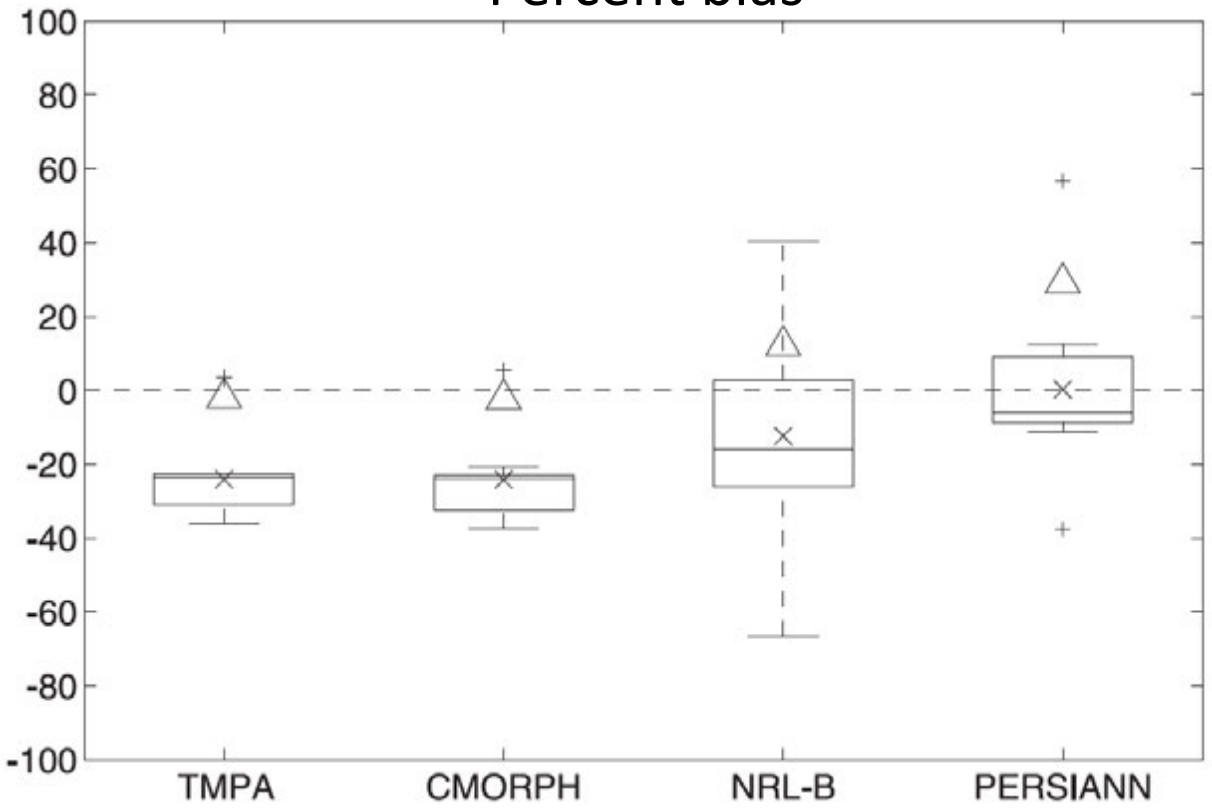


Schulz et al. (2012)

Extra slides

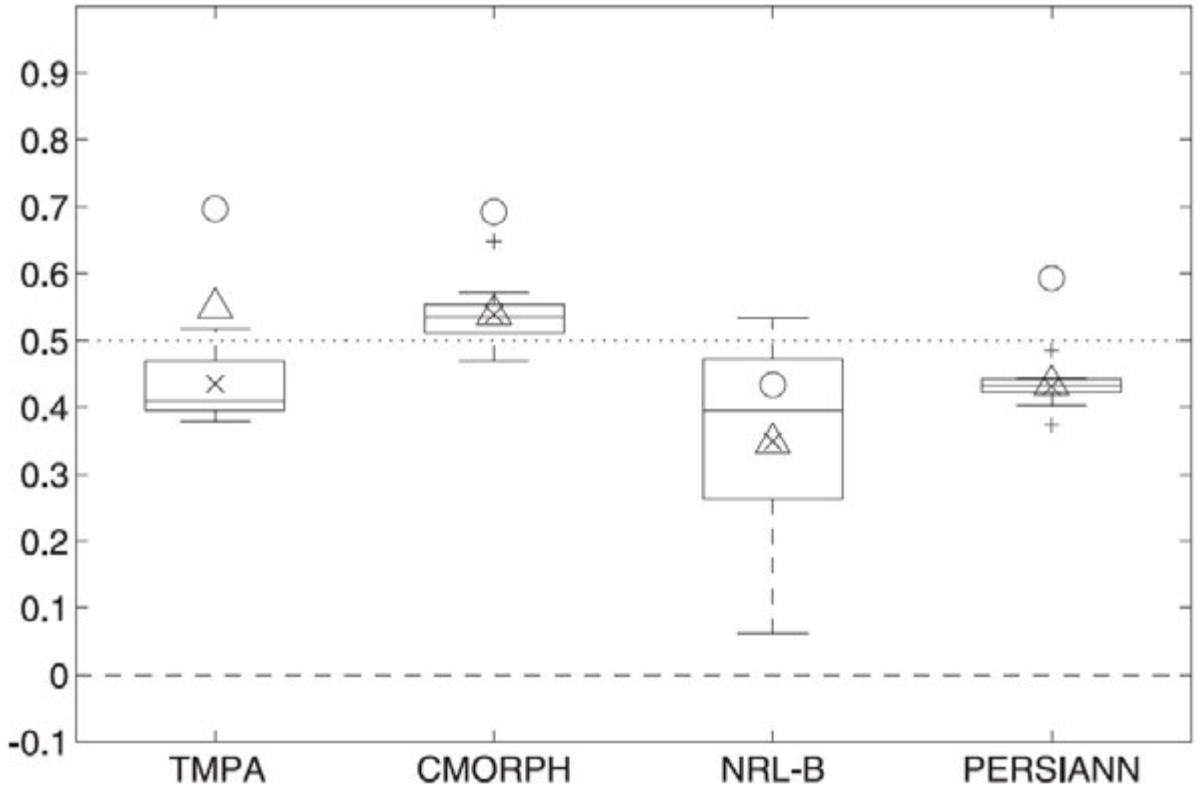
Evaluation of four 3-hourly satellite precipitation products at nine buoys in the western tropical Pacific Ocean

Percent bias



x = mean, Δ = mean with undercatch correction, + = outlier

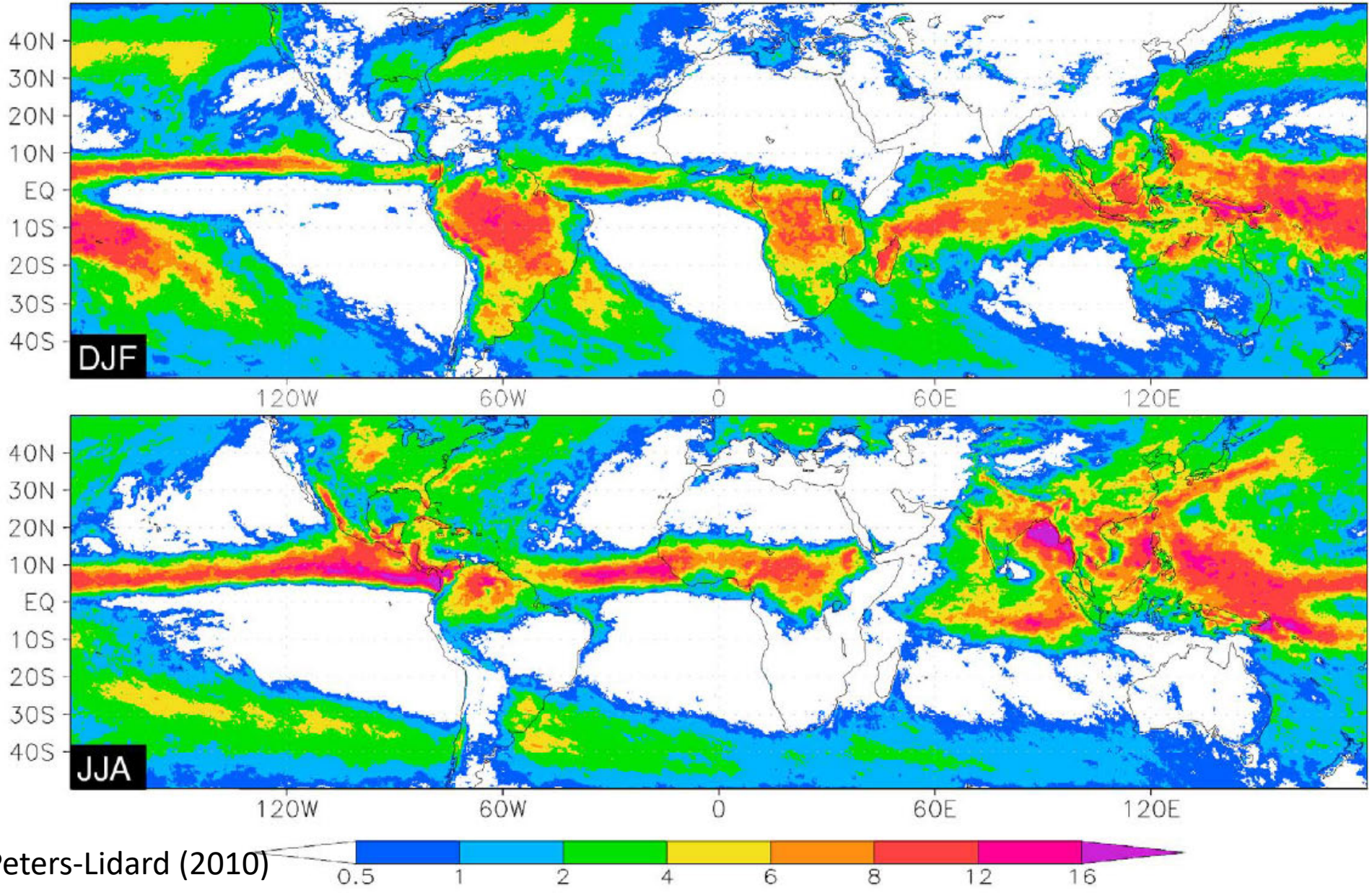
Correlation coefficient



o = correlations using daily averages

Sapiano and Arkin (2009)

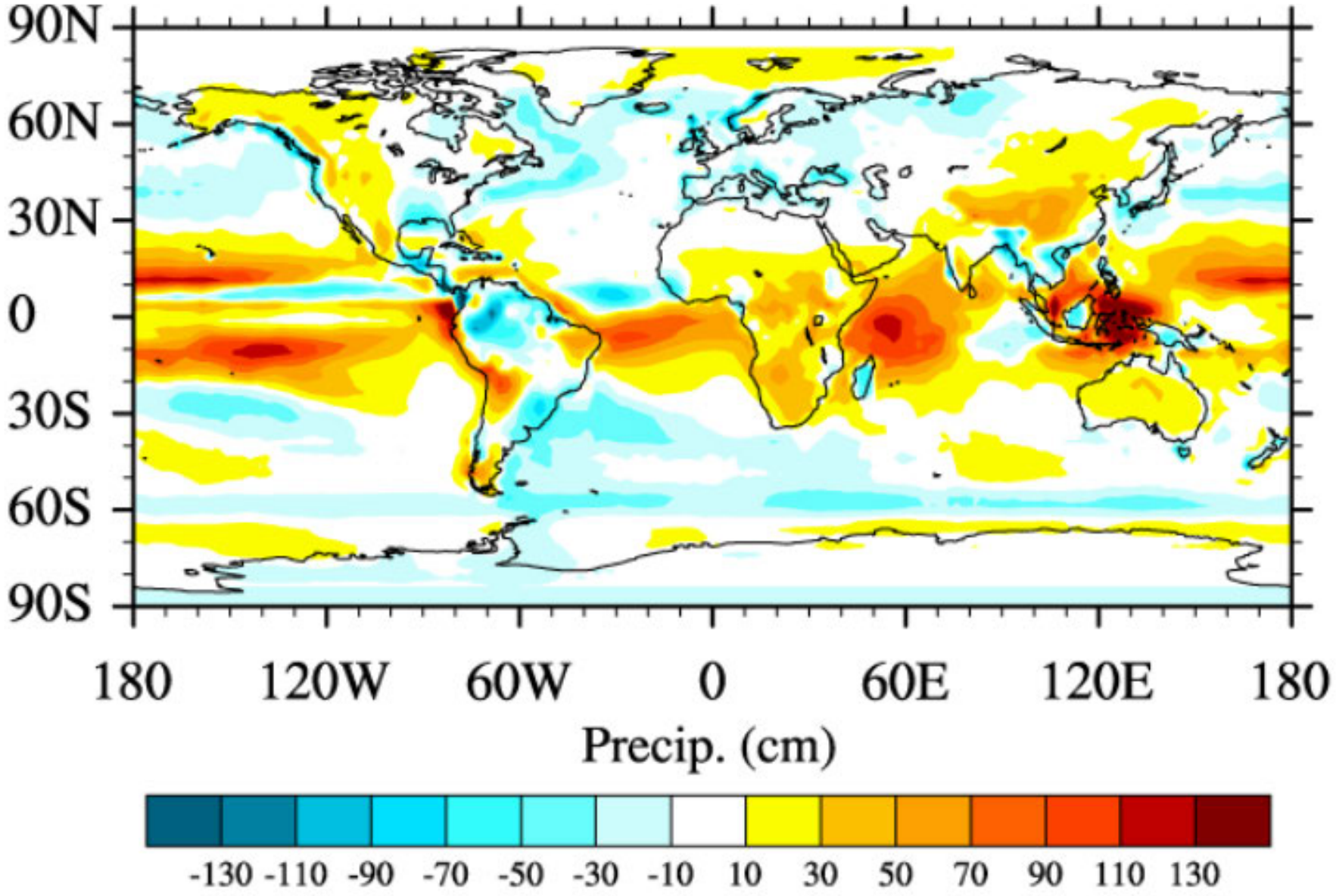
Ensemble mean (n = 6) precipitation (mm d^{-1})



Tian and Peters-Lidard (2010)

Climate models have substantial biases in precipitation, particularly over the tropical ocean

Multi-model mean minus observed*



*Observed is GPCP merged product (satellite and in situ)

Lamarque et al. (2013)

References

Achterberg, E.P., Moore, C.M., Henson, S.A., Steigenberger, S., Stohl, A., Eckhardt, S., Avendano, L.C., Cassidy, M., Hembury, D., Klar, J.K., Lucas, M.I., Macey, A.I., Marsay, C.M., Ryan-Keogh, T.J., 2013. Natural iron fertilization by the Eyjafjallajökull volcanic eruption. Geophysical Research Letters 40, 921-926.

Barkley, A.E., Prospero, J.M., Mahowald, N., Hamilton, D.S., Popendorf, K.J., Oehlert, A.M., Pourmand, A., Gatineau, A., Panechou-Pulcherie, K., Blackwelder, P., Gaston, C.J., 2019. African biomass burning is a substantial source of phosphorus deposition to the Amazon, Tropical Atlantic Ocean, and Southern Ocean. Proceedings of the National Academy of Sciences 116, 16216-16221.

Frants, M., Holzer, M., DeVries, T., Matear, R., 2016. Constraints on the global marine iron cycle from a simple inverse model. Journal of Geophysical Research: Biogeosciences 121, 28-51.

Geddes, J.A., Martin, R.V., 2017. Global deposition of total reactive nitrogen oxides from 1996 to 2014 constrained with satellite observations of NO 2 columns. Atmospheric Chemistry and Physics 17, 10071-10091.

Hamme, R.C., Webley, P.W., Crawford, W.R., Whitney, F.A., DeGrandpre, M.D., Emerson, S.R., Eriksen, C.C., Giesbrecht, K.E., Gower, J.F., Kavanaugh, M.T., 2010. Volcanic ash fuels anomalous plankton bloom in subarctic northeast Pacific. Geophysical Research Letters 37.

Ito, A., Myriokefalitakis, S., Kanakidou, M., Mahowald, N.M., Scanza, R.A., Hamilton, D.S., Baker, A.R., Jickells, T., Sarin, M., Bikkina, S., Gao, Y., Shelley, R.U., Buck, C.S., Landing, W.M., Bowie, A.R., Perron, M.M.G., Guieu, C., Meskhidze, N., Johnson, M.S., Feng, Y., Kok, J.F., Nenes, A., Duce, R.A., 2019. Pyrogenic iron: The missing link to high iron solubility in aerosols. Science Advances 5, eaau7671.

Kanakidou, M., Myriokefalitakis, S., Daskalakis, N., Fanourgakis, G., Nenes, A., Baker, A.R., Tsigaridis, K., Mihalopoulos, N., 2016. Past, Present, and Future Atmospheric Nitrogen Deposition. Journal of the Atmospheric Sciences 73, 2039-2047.

Kidd, C., Becker, A., Huffman, G.J., Muller, C.L., Joe, P., Skofronick-Jackson, G., Kirschbaum, D.B., 2017. So, how much of the Earth's surface is covered by rain gauges? Bulletin of the American Meteorological Society 98, 69-78.

Kim, T.-W., Lee, K., Najjar, R.G., Jeong, H.-D., Jeong, H.J., 2011. Increasing N abundance in the Northwestern Pacific Ocean due to atmospheric nitrogen deposition. Science 334, 505-509.

Kim, T.W., Najjar, R.G., Lee, K., 2014. Influence of precipitation events on phytoplankton biomass in coastal waters of the eastern United States. Global Biogeochemical Cycles 28, doi:10.1002/2013GB004712, 1-13.

Klepp, C., 2015. The oceanic shipboard precipitation measurement network for surface validation — OceanRAIN. Atmospheric Research 163, 74-90.

Klepp, C., Michel, S., Protat, A., Burdanowitz, J., Albern, N., Kähnert, M., Dahl, A., Louf, V., Bakan, S., Buehler, S.A., 2018. OceanRAIN, a new in-situ shipboard global ocean surface-reference dataset of all water cycle components. Scientific Data 5, 180122.

Lamarque, J.F., Shindell, D.T., Josse, B., Young, P.J., Cionni, I., Eyring, V., Bergmann, D., Cameron-Smith, P., Collins, W.J., Doherty, R., Dalsoren, S., Faluvegi, G., Folberth, G., Ghan, S.J., Horowitz, L.W., Lee, Y.H., MacKenzie, I.A., Nagashima, T., Naik, V., Plummer, D., Righi, M., Rumbold, S.T., Schulz, M., Skeie, R.B., Stevenson, D.S., Strode, S., Sudo, K., Szopa, S., Voulgarakis, A., Zeng, G., 2013. The Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP): overview and description of models, simulations and climate diagnostics. Geosci. Model Dev. 6, 179-206.

Lamarque, J.F., Dentener, F., McConnell, J., Ro, C.U., Shaw, M., Vet, R., Bergmann, D., Cameron-Smith, P., Dalsoren, S., Doherty, R., Faluvegi, G., Ghan, S.J., Josse, B., Lee, Y.H., MacKenzie, I.A., Plummer, D., Shindell, D.T., Skeie, R.B., Stevenson, D.S., Strode, S., Zeng, G., Curran, M., Dahl-Jensen, D., Das, S., Fritzsche, D., Nolan, M., 2013. Multi-model mean nitrogen and sulfur deposition from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP): evaluation of historical and projected future changes. Atmos. Chem. Phys. 13, 7997-8018.

Letelier, R.M., Björkman, K.M., Church, M.J., Hamilton, D.S., Mahowald, N.M., Scanza, R.A., Schneider, N., White, A.E., Karl, D.M., 2019. Climate-driven oscillation of phosphorus and iron limitation in the North Pacific Subtropical Gyre. Proceedings of the National Academy of Sciences 116, 12720-12728.

Mahowald, N.M., Hamilton, D.S., Mackey, K.R.M., Moore, J.K., Baker, A.R., Scanza, R.A., Zhang, Y., 2018. Aerosol trace metal leaching and impacts on marine microorganisms. Nature Communications 9, 2614.

Myriokefalitakis, S., Ito, A., Kanakidou, M., Nenes, A., Krol, M.C., Mahowald, N.M., Scanza, R.A., Hamilton, D.S., Johnson, M.S., Meskhidze, N., 2018. Reviews and syntheses: the GESAMP atmospheric iron deposition model intercomparison study. Biogeosciences 15, 6659-6684.

Sapiano, M.R.P., Arkin, P.A., 2009. An intercomparison and validation of high-resolution satellite precipitation estimates with 3-hourly gauge data. Journal of Hydrometeorology 10, 149-166.

Schulz, M., Prospero, J.M., Baker, A.R., Dentener, F., Ickes, L., Liss, P.S., Mahowald, N.M., Nickovic, S., García-Pando, C.P., Rodríguez, S., Sarin, M., Tegen, I., Duce, R.A., 2012. Atmospheric Transport and Deposition of Mineral Dust to the Ocean: Implications for Research Needs. Environmental Science & Technology 46, 10390-10404.

St-Laurent, P., Friedrichs, M.A.M., Najjar, R.G., Herrmann, M., Miller, S., Martins, D., Wilkin, J., 2017. Impacts of atmospheric nitrogen deposition on surface waters of the Western North Atlantic mitigated by multiple feedbacks. Journal of Geophysical Research: Oceans 122, 8406–8426.

Tagliabue, A., Aumont, O., DeAth, R., Dunne, J.P., Dutkiewicz, S., Galbraith, E., Misumi, K., Moore, J.K., Ridgwell, A., Sherman, E., Stock, C., Vichi, M., Völker, C., Yool, A., 2016. How well do global ocean biogeochemistry models simulate dissolved iron distributions? Global Biogeochemical Cycles 30, 149-174.

Tian, Y., Peters-Lidard, C.D., 2010. A global map of uncertainties in satellite-based precipitation measurements. Geophysical Research Letters 37, doi: 10.1029/2010gl046008.

Vet, R., Artz, R.S., Carou, S., Shaw, M., Ro, C.-U., Aas, W., Baker, A., Bowersox, V.C., Dentener, F., Galy-Lacaux, C., Hou, A., Pienaar, J.J., Gillett, R., Forti, M.C., Gromov, S., Hara, H., Khodzher, T., Mahowald, N.M., Nickovic, S., Rao, P.S.P., Reid, N.W., 2014. A global assessment of precipitation chemistry and deposition of sulfur, nitrogen, sea salt, base cations, organic acids, acidity and pH, and phosphorus. Atmospheric Environment 93, 3-100.

Yang, J., Riser, S.C., Nystuen, J.A., Asher, W.E., Jessup, A.T., 2015. Regional Rainfall Measurements: Using the Passive Aquatic Listener During the SPURS Field Campaign. Oceanography 28, 124-133.

Zhang, Y., Song, L., Liu, X., Li, W., Lü, S., Zheng, L., Bai, Z., Cai, G., Zhang, F., 2012. Atmospheric organic nitrogen deposition in China. Atmospheric Environment 46, 195-204.