

Modelling of greenhouse gases and related species in the Arctic environment

P. K. Patra¹, T. Saeki¹, K. Ishijima¹, K. Ravi Kumar², S. Taguchi³, D. Belikov⁴, S. Makyutov⁴, Y. Niwa⁵, T. Maki⁵,
D. Goto², Y. Tohjima⁴, S. Ishidoya³, S. Morimoto⁶, S. Aoki⁶, K. Takata²

¹Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Yokohama, Japan

²National Institute for Polar Research (NIPR), Tokyo, Japan

³National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Japan

⁴National Institute for Environmental Studies (NIES), Tsukuba, Japan

⁵Meteorological Research Institute (MRI), Tsukuba, Japan

⁶Tohoku University, Sendai, Japan

Numerical modelling of greenhouse gases (GHGs) has become an integral part for understanding amplitude and variability in their concentrations and sources/sinks, atmospheric transport and climate implication. Carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) are the three major species studied in the Arctic Green Network of Excellence (GRENE), a programme funded by the Ministry of Education, Culture, Sports, Science and Technology-Japan (MEXT). In addition some of the ozone depleting substances, e.g., methyl chloroform (CH₃CCl₃), have provided strong constrain on the global mean abundance of hydroxyl (OH) radical and its relative abundance in the northern and southern hemispheres (NH/SH OH ratio; Patra et al., 2014). Being the main destroyer of many of the GHGs (e.g., CH₄, hydrofluorocarbons), accurate quantification of OH was needed for estimation of CH₄ sink in the troposphere, and thus the sources on the Earth's surface by inverse modelling (Patra et al., 2016). OH is also contributes to chemical production of CO₂, up to ~50% of land/ocean sink. The modellers are also required to verify the accuracy of model transport using tracers of short (e.g., ²²²Rn with 3.8 days) and long (SF₆ with 3200 yrs) lifetimes. For understanding of the carbon cycle science, analyses of oxygen (O₂/N₂) variability are also conducted. List of chemistry-transport models (CTMs) participating in the Arctic GRENE programme are given Table 1.

Table 1. Summary of atmospheric models participated in the Arctic-GRENE project (✓denotes forward simulation of concentrations, and ☑ denotes both forward simulations and regional sources/sinks inverse modeling using the model).

Model Name*	Institution	Chemical species simulated for carbon, nitrogen cycle studies and atmospheric transport						
		CO ₂	O ₂ /N ₂	CH ₄	N ₂ O	SF ₆	CH ₃ CCl ₃	²²² Rn
ACTM	JAMSTEC	☑	✓	☑	☑	✓	✓	✓
JMA-CDTM	MRI/JMA	☑				✓		✓
NICAM-TM	MRI	☑		✓		✓		✓
NIES-TMi8	NIES	☑	✓	☑		✓		✓
STAG	AIST	☑	✓			✓		✓
MJ98-CDTM	MRI/JMA	☑				✓		✓

*Detailed description of models can be found in Patra et al. (2014) for ACTM, Maki et al. (2013) for JMA-CDTM, Niwa et al. (2012) for NICAM-TM, Belikov et al. (2013) for NIES-TMi8, Taguchi et al. (2013) for STAG, Deushi and Shibata for MJ98-CDTM.

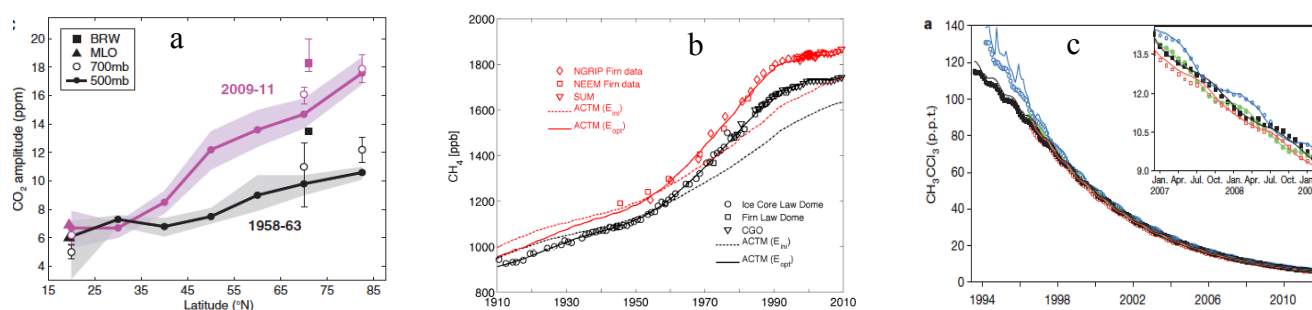


Figure 1. Examples of recent changes in GHGs and related species concentrations; left (a): observed CO₂ seasonal cycle amplitude change since the International Geophysical Year (from Graven et al., 2013; copyright Science), center (b): model - observation comparison of CH₄ over the past 100 years (Ghosh et al., 2015), right (c): simulation of observed CH₃CCl₃ decay for estimation OH in troposphere (Patra et al., 2014; copyright Nature). The detailed modelling capabilities of different participating groups are listed in Table 1.

Figure 1 shows examples of observed and model simulated concentrations of CO₂, CH₄ and CH₃CCl₃. Using the direct CO₂ measurements at the surface sites and aircrafts in the lower-middle troposphere during 1958 and 2011, an increase in seasonal amplitude of CO₂ throughout the troposphere is detected (Graven et al., 2013). The detection of longterm trends in GHGs is key to track the changes in

biospheric and anthropogenic activities on the Earth's surface, and it is suggested that the CO₂ seasonal amplitude increase with time is mainly caused by greater carbon assimilation in the summer months over the boreal latitudes. Using model simulations and analysis of ¹³C isotopic fractionation in atmospheric CH₄ over the past 100 years (Fig. 1b), the fastest increase rate during 1955-1990 is attributed to enhanced biomass burning (Ghosh et al., 2015). For modelling of atmospheric CH₄, the transport and chemistry in ACTM have been evaluated using SF₆ and CH₃CCl₃ (Patra et al., 2014). We are continuing to collaborate with various observational groups in Japan for further elucidating the variations in GHGs in the Arctic region, e.g., model results are being used for analysis of the observational data collected as a part of the Arctic GRENE project; e.g., O₂/N₂ (Goto et al.; Ishidoya et al., in prep.), CH₄ on the ship cruises (Tohjima et al., 2016).

Several inverse modeling schemes are also being developed using forward transport models developed in AIST, JAMSTEC, JMA, MRI and NIES. Figure 2b shows examples of CO₂ fluxes estimated for the arctic region in comparison with the global total fluxes for the land and ocean regions as estimated by ACTM in JAMSTEC. Analyses of CO₂ fluxes for different parts of the globe suggest that the difference between winter release and summer uptake is increasing in the boreal regions (Fig. 2c using NICAM-TM at MRI; Niwa et al., 2012, updated) and that the flux amplitude change is mainly governed by the summer uptake increase (Welp et al., 2016). A multi-model analysis of CO₂ inversion fluxes using the flux tower measurements at Yakutsk, in Siberia and biogeochemical cycle models is being conducted for understanding the trends in CO₂ fluxes due to climate variations (Takata et al., 2015, also in prep.).

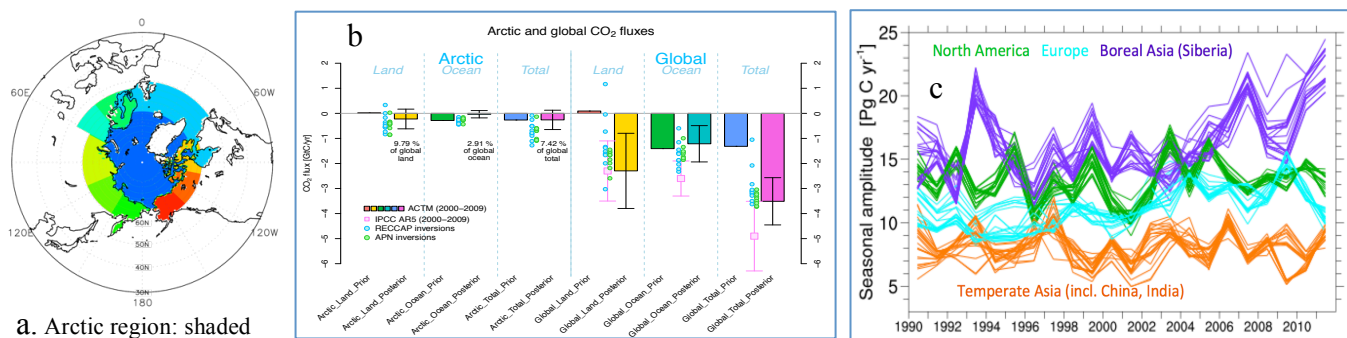


Figure 2. Distribution of CO₂ sources and sinks around the Arctic region (a) compared to the global totals as simulated by ACTM (b; middle panel), and CO₂ flux amplitude change for 4 major regions in the Northern Hemisphere by NICAM-TM (c: right panel).

References

- Belikov, D. A., S. Maksyutov, M. Krol, A. Fraser, M. Rigby, H. Bian, et al., Off-line algorithm for calculation of vertical tracer transport in the troposphere due to deep convection, *Atmos. Chem. Phys.*, 13, 1093-1114, 2013.
- Ghosh, A., P.K. Patra, K. Ishijima, T. Umezawa, A. Ito, D.M. Etheridge, S. Sugawara, K. Kawamura, et al., Variations in global methane sources and sinks during 1910-2010, *Atmos. Chem. Phys.*, 2595-2612, 2015.
- Graven, H.D., R.F. Keeling, S.C. Piper, P.K. Patra, B.B. Stephens, S.C. Wofsy, L.R. Welp, et al., Enhanced seasonal exchange of CO₂ by northern ecosystems since 1960, *Science*, 341, 1085-1089, 2013.
- Maki, T., M. Ikegami, T. Fujita, T. Hirahara, K. Yamada, et al., New technique to analyse global distributions of CO₂ concentrations and fluxes from non-processed observational data, *Tellus*, 62B, 797-809, 2010.
- Niwa, Y., T. Machida, Y. Sawa, H. Matsueda, T. J. Schuck, et al., Imposing strong constraints on tropical terrestrial CO₂ fluxes using passenger aircraft based measurements, *J. Geophys. Res.*, 117, D11303, 2012.
- Patra, P.K., M.C. Krol, S.A. Montzka, T. Arnold, E.L. Atlas, B.R. Lintner, B.B. Stephens, B. Xiang, et al., Observational evidence for interhemispheric hydroxyl parity, *Nature*, 513, 219-223, 2014.
- Patra, P.K., T. Saeki, E.J. Dlugokencky, K. Ishijima, T. Umezawa, A. Ito, S. Aoki, S. Morimoto, et al., Regional emission and loss budgets of atmospheric methane (2002-2012), *J. Meteorol. Soc. Jpn.*, 94, 83-105, 2016.
- Taguchi, S., A three-dimensional model of atmospheric CO₂ transport based on analyzed winds: Model description and simulation results for TRANSCOM. *J. Geophys. Res.*, 101, 15099-15110, 1996.
- Takata, K., P.K. Patra, A. Kotani, D. Belikov, J. Mori, et al., Comparison of carbon fluxes estimated by top-down and bottom-up methods - a case study at Yakutsk, Siberia, The 6th Symposium on Polar Science (IAP27), NIPR, Tokyo, Nov. 2015.
- Tohjima, Y., K. Katsumata, J. Matsushita, D. Sasano, N. Kosugi, S. Ishidoya, K. Ishijima and P.K. Patra, Atmospheric CH₄ distributions observed during Arctic cruises of R/V Mirai in 2012-2015, This meeting, NIPR, Tokyo, Mar. 2016.
- Welp, L.R., P.K. Patra, C. Rödenbeck, R. Nemani, J. Bi, S.C. Piper, and R.F. Keeling, Increasing summer net CO₂ uptake in high northern ecosystems inferred from atmospheric inversions and remote sensing, *Atmos. Chem. Phys. (Discuss)*, submitted, 2016.
- Deushi, M., and K. Shibata, Development of an MRI Chemistry-Climate Model ver. 2 for the Study of Tropospheric and Stratospheric Chemistry. *Pap. Meteor. Geophys.*, 64, 1-46, 2011.