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# The CONTRAIL commercial aircraft monitoring $CO_2$ emissions from cities


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CONTRAIL

Comprehensive Observation Network for Trace gases by Airliner

JAL FOUNDATION

# ← CONTRAIL Data Available (Now Including Meteolorogical Data) !!

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Atmospheric Chemistry and Physics
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## Seasonal evaluation of tropospheric $CO_2$ over the Asia-Pacific region observed by the CONTRAIL commercial airliner measurements

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**Abstract.** Measurement of atmospheric carbon dioxide ($CO_2$) is indispensable for top-down estimation of surface $CO_2$ sources/sinks by an atmospheric transport model. Despite the growing importance of Asia in the global carbon budget, the region has only been sparsely monitored for atmospheric $CO_2$ and our understanding of atmospheric $CO_2$ variations in the region (and thereby that of the regional carbon budget) is still limited. In this study, we present climatological $CO_2$ distributions over the Asia-Pacific region obtained from the CONTRAIL (Comprehensive Observation Network for TRace gases by AIrLiner) measurements. The high-frequency in-flight $CO_2$ measurements over 10 years reveal a clear seasonal variation in $CO_2$ in the upper troposphere (UT), with a maximum occurring in April–May and a minimum in August–September. The $CO_2$ mole fraction in the UT north of 40° N is low and highly variable in June–August due to the arrival of air parcels with seasonally low $CO_2$ caused by the summertime biospheric uptake in boreal Eurasia. For August–September in particular, the UT $CO_2$ is noticeably low within the Asian summer monsoon anticyclone associated with the convective transport of strong biospheric $CO_2$ uptake signal over South Asia. During September as the anticyclone decays, a spreading of this low-$CO_2$ area in the UT is observed in the vertical profiles of $CO_2$ over the Pacific Rim of continental East Asia. Simulation results identify the influence of anthropogenic and biospheric $CO_2$ fluxes in the seasonal evolution of the spatial $CO_2$ distribution over the Asia-Pacific region. It is inferred that a substantial contribution to the UT $CO_2$ over the northwestern Pacific comes from continental East Asian emissions in spring; but in the summer monsoon season, the prominent air mass origin switches to South Asia and/or Southeast Asia with a distinct imprint of the biospheric $CO_2$ uptake. The CONTRAIL $CO_2$ data provide useful constraints to model estimates of surface fluxes and to the evaluation of the satellite observations, in particular for the Asia-Pacific region.

### 1 Introduction

Actions for mitigating climate change require accurate knowledge of global budgets of greenhouse gases. It has been estimated that approximately one-half of $CO_2$ emissions had remained in the atmosphere during the period 1959–2010, with the rest taken up by land and ocean sinks (Ballantyne et al., 2012). With a rapidly growing economy in recent decades, Asia has become increasingly important in the global carbon budget. China is now the world's largest $CO_2$ emitter, and India, Japan, and the Republic of Korea are all in the world's top 10 emitting nations (Boden et al., 2016). At the same time, Asia has gone through significant land use and land cover changes, impacting the magnitude and the spatial distribution of terrestrial carbon fluxes (e.g., Calle et al., 2016; Cervarich et al., 2016). However, there are still large uncertainties in the estimates of every component of the Asian carbon budget.

To estimate surface $CO_2$ fluxes, atmospheric transport models have been conventionally constrained by various surface measurement networks (e.g., Gurney et al., 2002; Patra et al., 2008). But due to the sparseness of the surface

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## Statistical characterization of urban $CO_2$ emission signals observed by commercial airliner measurements

Taku Umezawa[1]✉, Hidekazu Matsueda[2], Tomohiro Oda[3,4], Kaz Higuchi[5], Yousuke Sawa[2,6], Toshinobu Machida[1], Yosuke Niwa[1,2] & Shamil Maksyutov[1]

**Cities are responsible for the largest anthropogenic $CO_2$ emissions and are key to effective emission reduction strategies. Urban $CO_2$ emissions estimated from vertical atmospheric measurements can contribute to an independent quantification of the reporting of national emissions and will thus have political implications. We analyzed vertical atmospheric $CO_2$ mole fraction data obtained onboard commercial aircraft in proximity to 36 airports worldwide, as part of the Comprehensive Observation Network for Trace gases by Airliners (CONTRAIL) program. At many airports, we observed significant flight-to-flight variations of $CO_2$ enhancements downwind of neighboring cities, providing advective fingerprints of city $CO_2$ emissions. Observed $CO_2$ variability increased with decreasing altitude, the magnitude of which varied from city to city. We found that the magnitude of $CO_2$ variability near the ground (~1 km altitude) at an airport was correlated with the intensity of $CO_2$ emissions from a nearby city. Our study has demonstrated the usefulness of commercial aircraft data for city-scale anthropogenic $CO_2$ emission studies.**

Climate change is considered to be one of the consequences of increased emissions of anthropogenic greenhouse gases during the industrial era, and carbon dioxide ($CO_2$) is the dominant contributor to the enhanced radiative forcing caused by anthropogenic long-lived greenhouse gases. Atmospheric $CO_2$ mole fraction has increased from ~280 ppm (parts per million) in 1750[1] to > 400 ppm in recent years[2] due to the rapid growth of human activities and population since the beginning of the industrial era. About half of the anthropogenic $CO_2$ emissions related to fossil fuel combustion and human driven land-use change is taken up by the ocean and the terrestrial biosphere[3,4]. In a top-down approach using atmospheric transport models, the global fossil fuel $CO_2$ emissions have often been presumed to provide good estimates of the strength of the land and ocean sinks[5]. But recent studies suggest that uncertainties in fossil fuel emission database could lead to significant biases in the optimized estimates of biospheric flux[6,7]. In fact, uncertainties of fossil fuel $CO_2$ emission estimates are growing because of increasing contributions from developing countries[3,4,8,9].

About 70% of the current anthropogenic $CO_2$ emissions is considered to come from urban areas that contain over 50% of the world population[10], and thus accurate quantification of $CO_2$ emissions from urban areas is of particular importance. The existing and projected rate of urbanization is different for different parts of the world; many cities in Asia and Africa are expected to continue to see rapid growths in population while cities in developed countries have basically already stabilized[11]. For effective mitigation actions against climate change, various independent approaches must be used to reduce the uncertainties associated with citywide greenhouse gas emissions estimates, and one of those approaches can be provided by atmospheric $CO_2$ observations[12]. For this purpose, atmospheric $CO_2$ measurements focusing on urban areas have been examined in recent years by means of citywide *in-situ* ground measurement networks[13–16] or satellite measurements[17,18]. The former methodology provides dense and accurate data and the latter broad spatial coverage, whilst both also have limitations.

Since 2000s, atmospheric observation instruments onboard commercial airliners have successfully acquired extensive number of trace gas (including $CO_2$) data[19–21]. The CONTRAIL (Comprehensive Observation Network for TRace gases by AIrLiners) program, an ongoing project that measures atmospheric $CO_2$ and other trace

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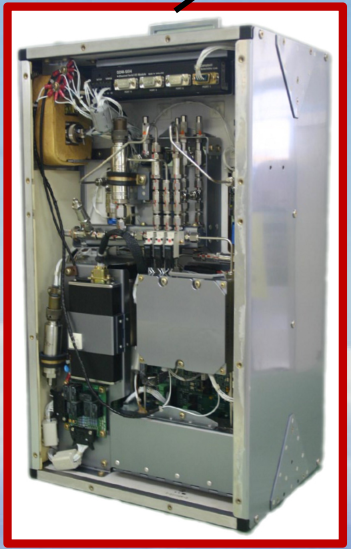
# CONTRAIL's Measurements

*Details in Machida et al. (2008, JAOT)*

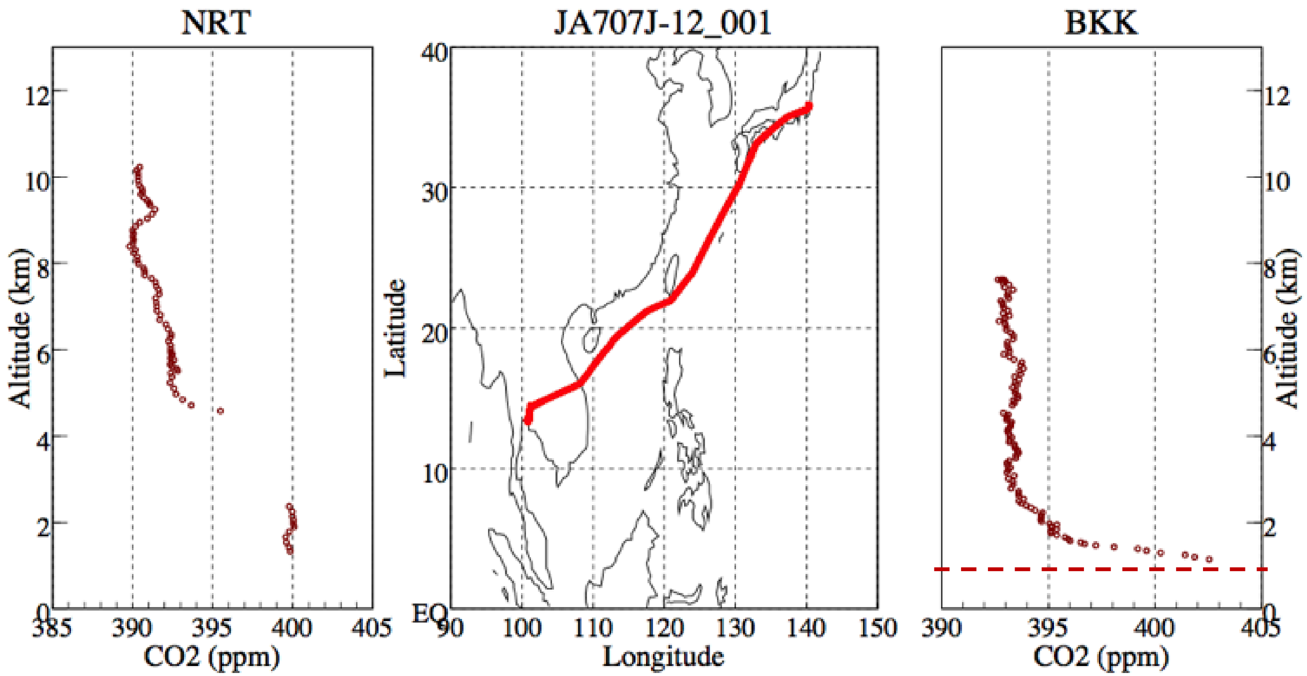

***MSE***
***(Manual air Sampling Equipment)***

***CME***
***(Continuous $CO_2$ Measuring Equipment)***

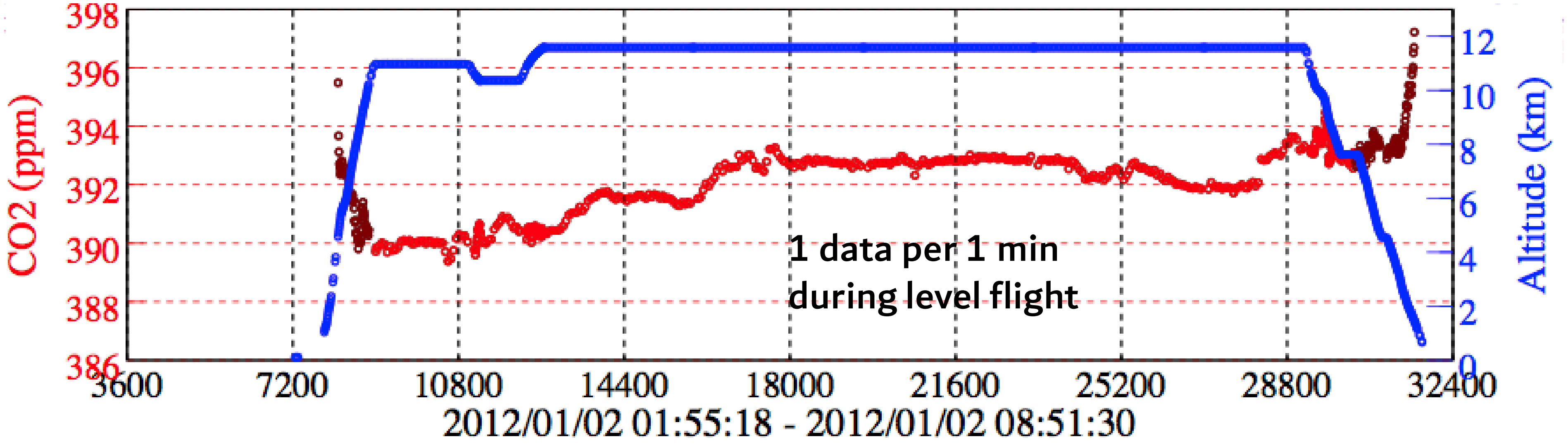
***ASE***
***(Automatic air Sampling Equipment)***

# An Example of CME Data




1 data per 10 sec during ascent/descent

CME can measure down to ~0.6 km

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CONTRAIL Comprehensive Observation Network for Trace gases by Airliner

# CONTRAIL CME Data Statistics (–2019)

http://www.cger.nies.go.jp/contrail/

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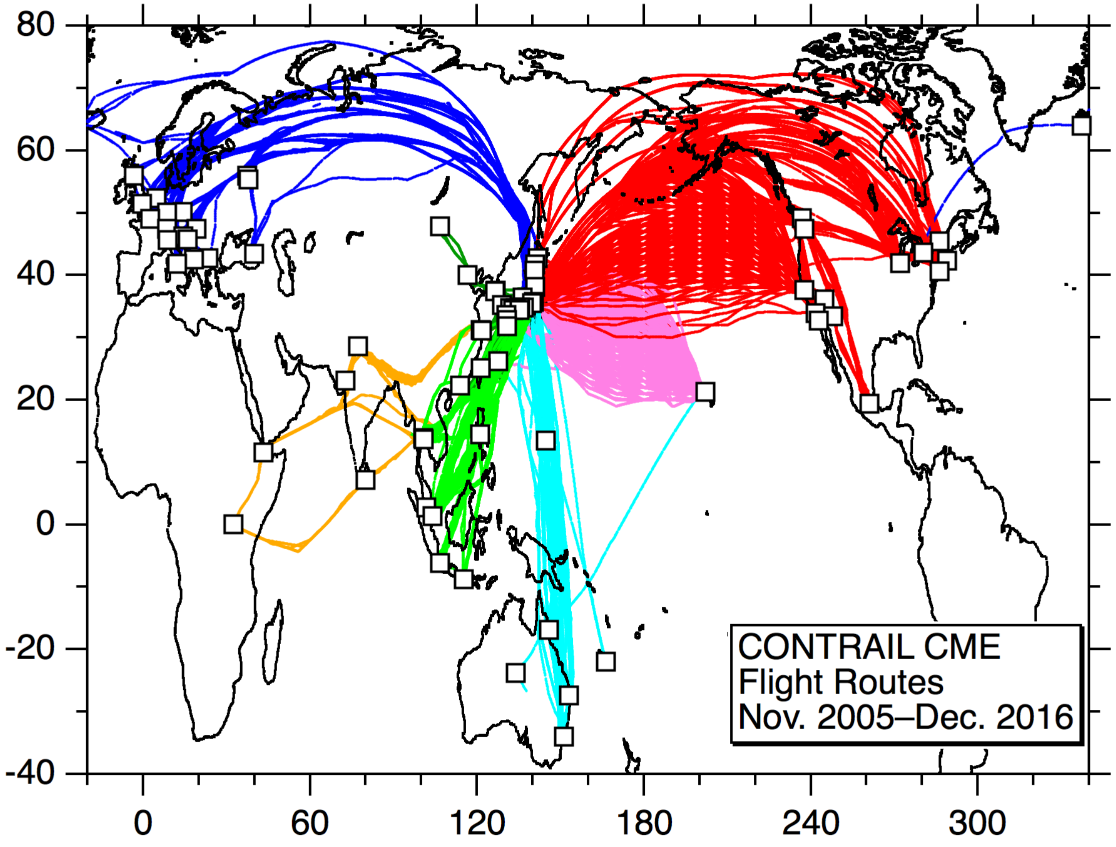
> *10 million $CO_2$ data points in total*
> *18,000 measurement flights*
> *35,000 vertical profiles worldwide*

- *Precision < 0.2 ppm*
- *All data quality checked consistently*
- *Data freely available*

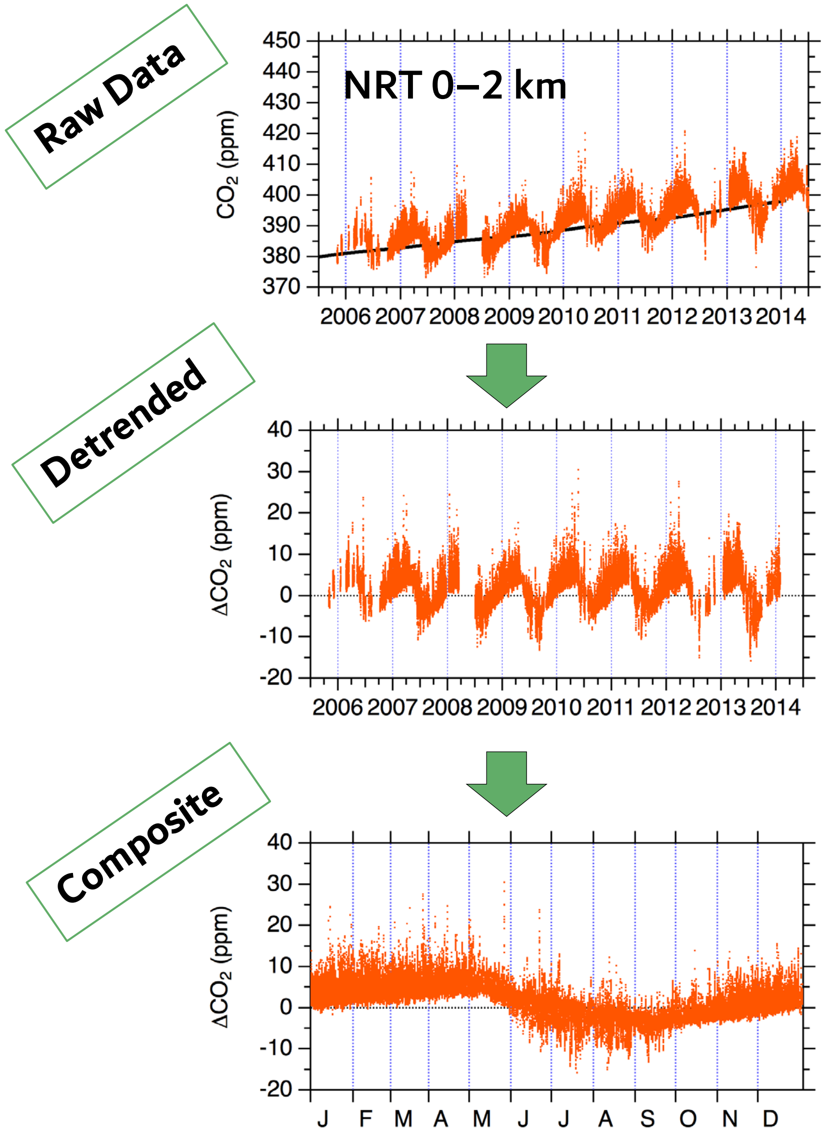


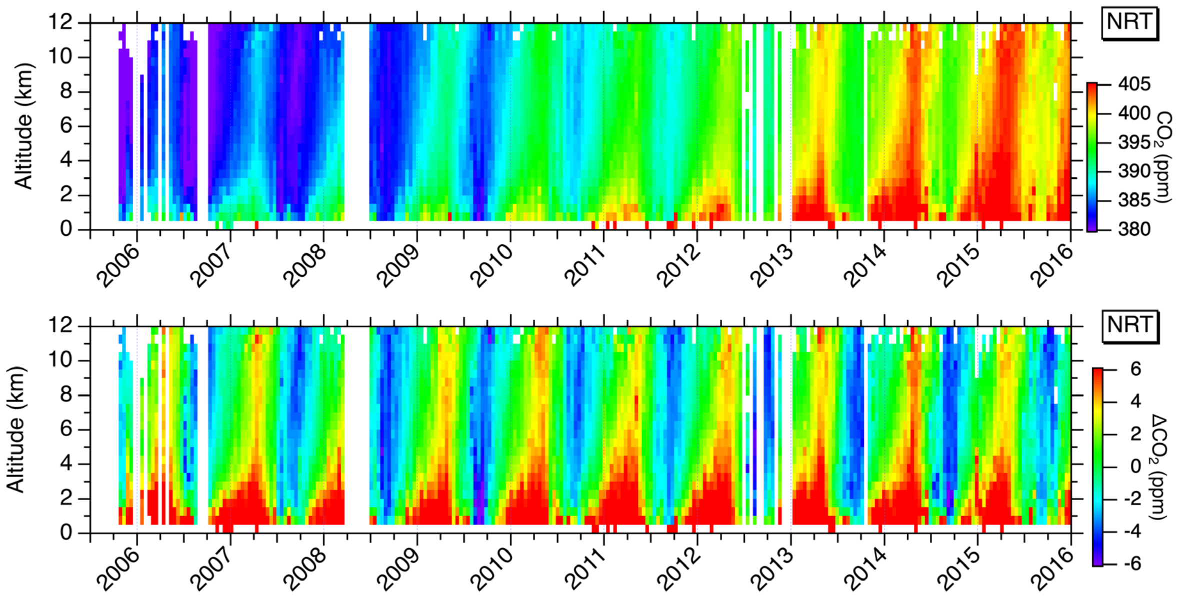

| Airport | *City* | # of Vertical Profiles (2005–2016) |
|---|---|---|
| NRT | *Tokyo* | 7692 |
| HND | *Tokyo* | 4462 |
| HNL | *Honolulu* | 2095 |
| BKK | *Bangkok* | 1670 |
| SYD | *Sydney* | 1568 |
| NGO | *Nagoya* | 999 |
| SIN | *Singapore* | 930 |
| KIX | *Osaka* | 824 |
| HKG | *Hong Kong* | 812 |
| DEL | *Delhi* | 739 |
| CDG | *Paris* | 661 |
| CGK | *Jakarta* | 493 |
| YVR | *Vancouver* | 431 |
| SFO | *San Francisco* | 378 |
| DME | *Moscow* | 374 |
| SHA | *Shanghai* | 332 |
| LHR | *London* | 264 |
| AMS | *Amsterdam* | 226 |
| ITM | *Osaka* | 202 |
| FUK | *Fukuoka* | 195 |
| ICN | *Incheon* | 191 |

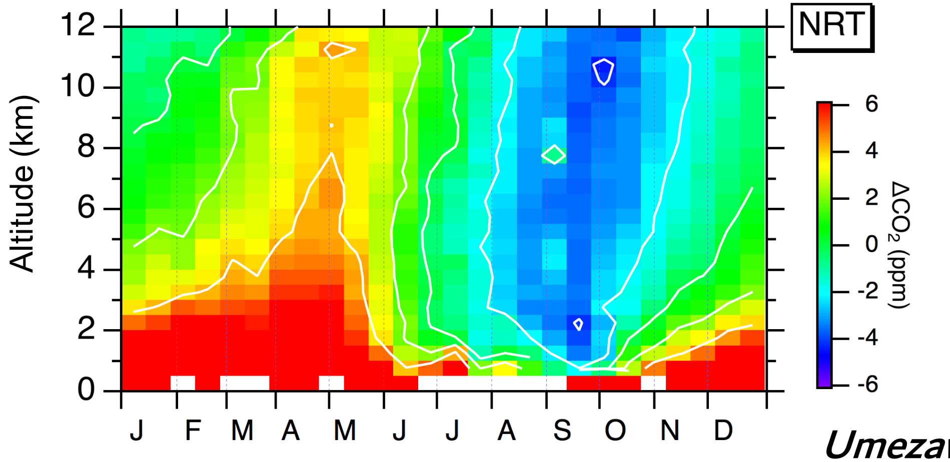
# CONTRAIL $CO_2$ Climatology

*$\Delta CO_2 = CO_2$ (observed) – $CO_2$ trend at MLO*

*$CO_2$ (observed)*
*= Long-term trend*
*+ (seasonal & shorter-term) variations*

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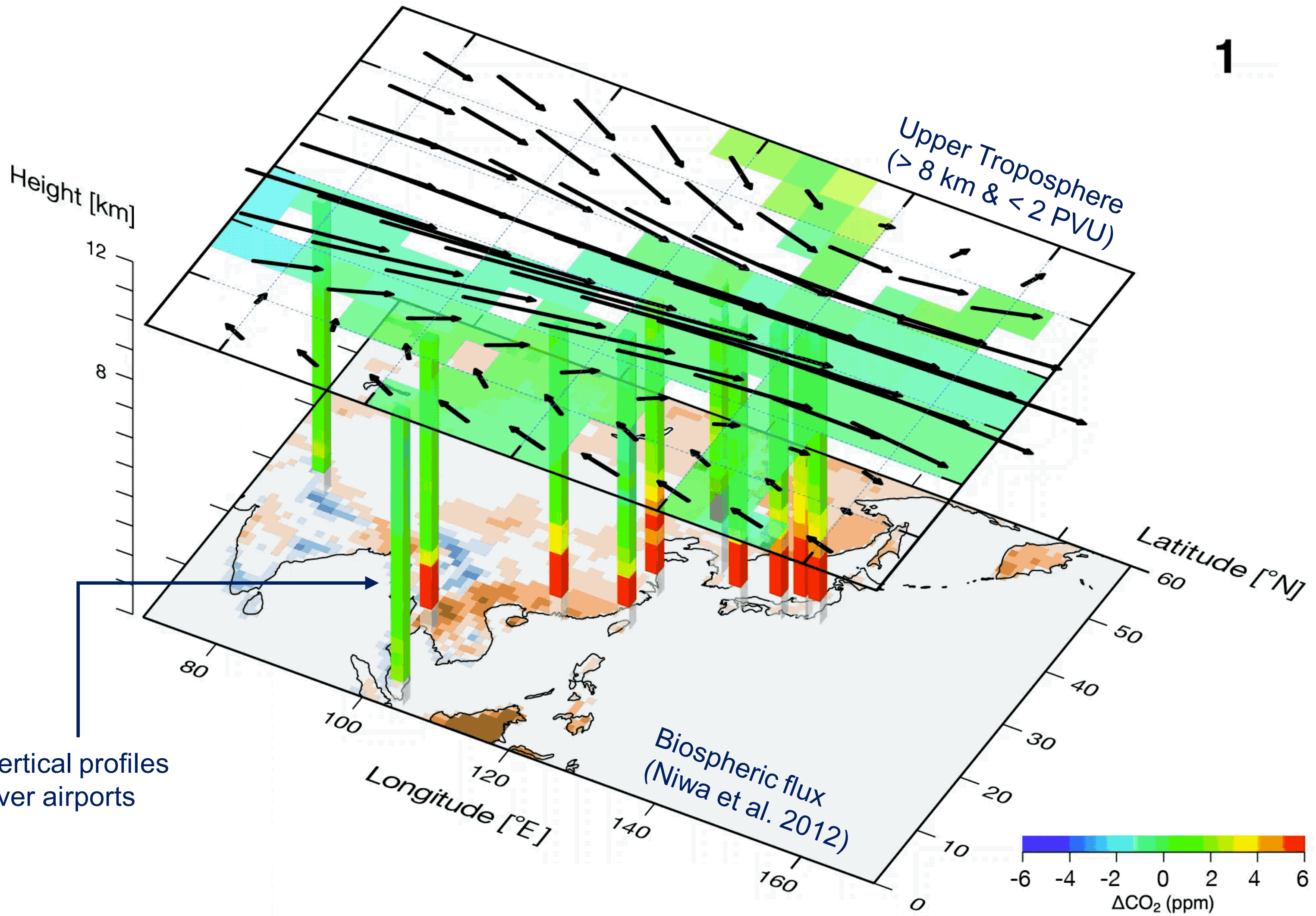
*Umezawa et al. (2018, ACP)*

# CONTRAIL $CO_2$ Climatology

http://www.cger.nies.go.jp/contrail/

Watch this movie on our website!

*Seasonal $CO_2$ variations over Asia*




*Produced from figures of Umezawa et al. (2018, AC*

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Comprehensive Observation Network for Trace gases by Airliner

# COTNRAIL Aircraft at Tokyo HND Airport


Major airports are located close to large cities

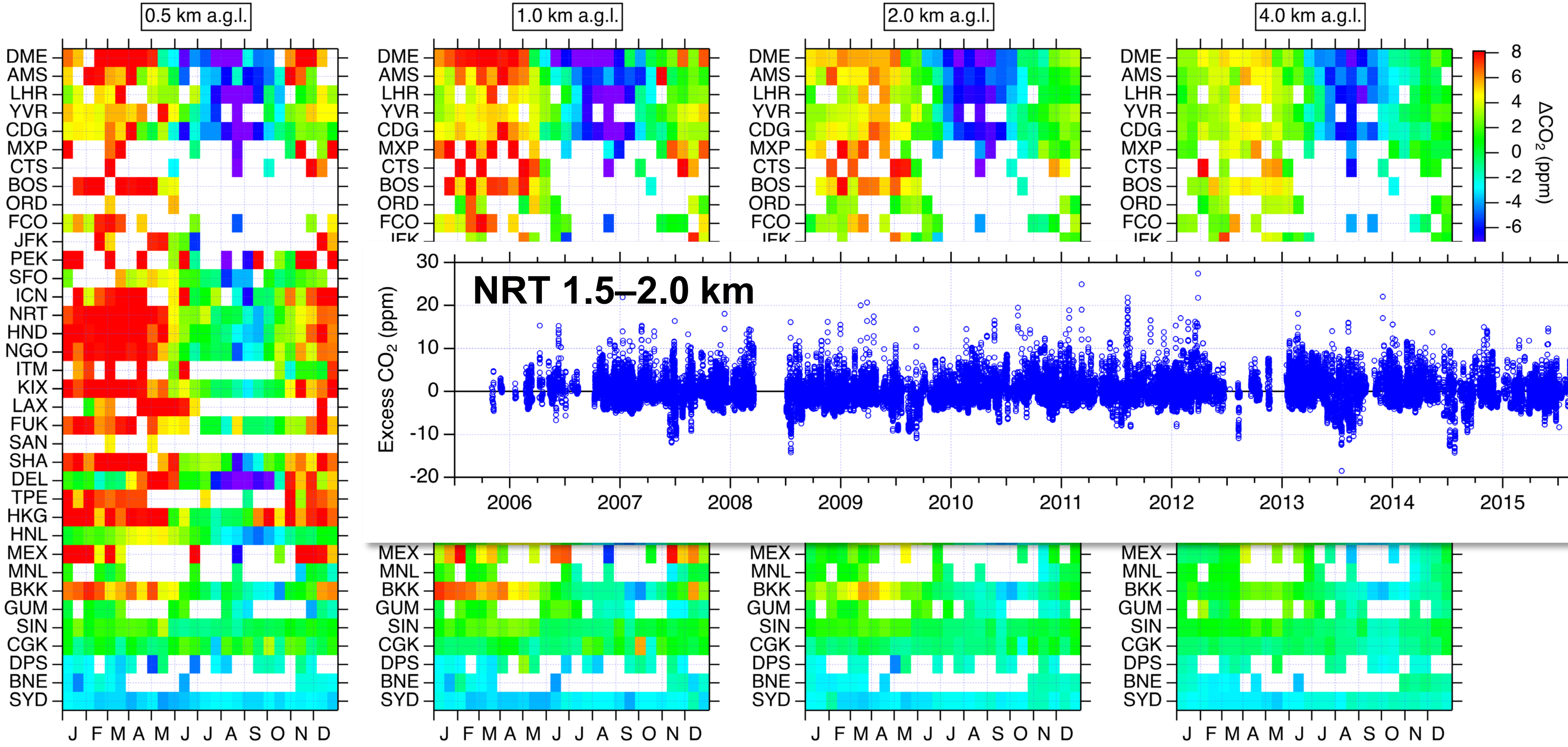
Airlines connect between large cities

Can commercail aircraft measurements see signals of $CO_2$ emissions from neaby cities?

# Analysis of Local Signals: "excess $CO_2$"

*excess $CO_2$ (lat, lon, alt, t)*
*= $\Delta CO_2$ (lat, lon, alt, t)*
*– median $\Delta CO_2$ (airport, alt-bin, t-bin)*

*$CO_2$ (observed)*
*= Long-term trend*
*+ (seasonal & shorter-term) variations*

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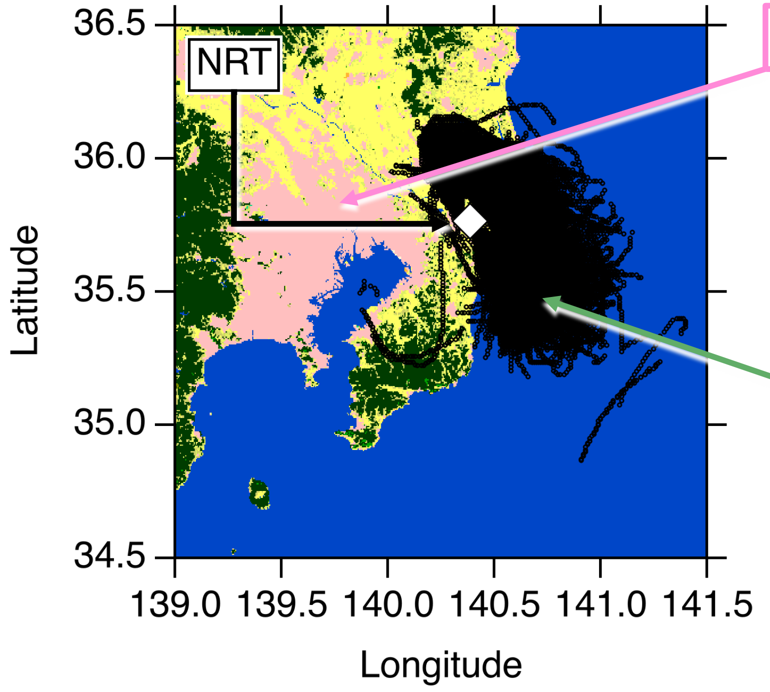
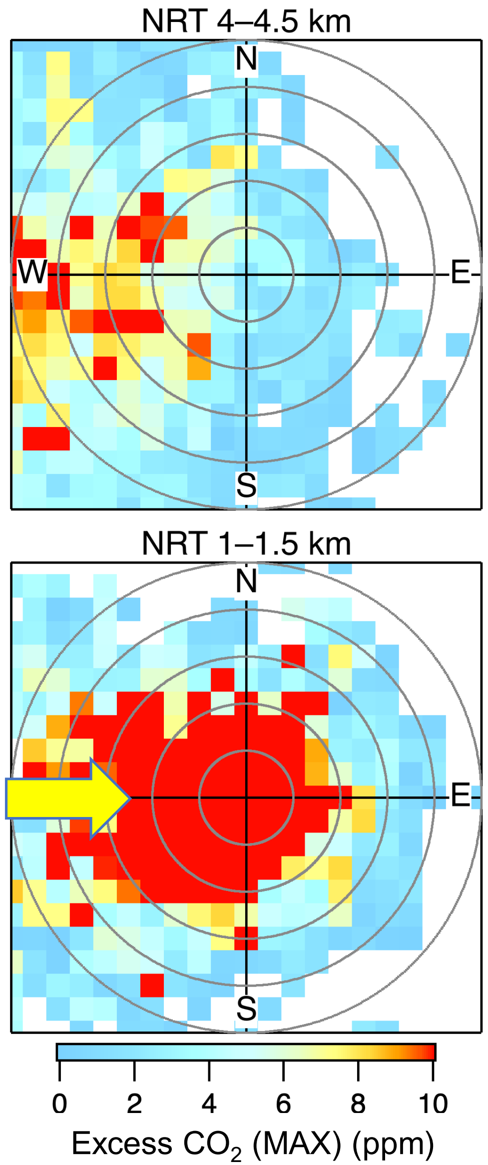
# Excess $CO_2$ Variations: Tokyo (NRT)

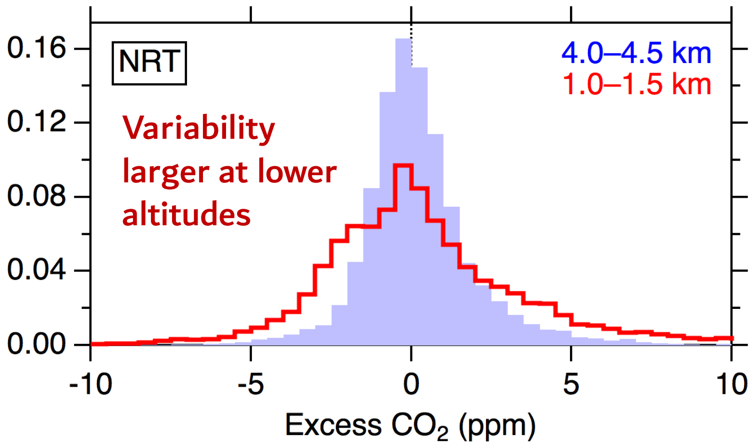
*7692 vertical profiles*



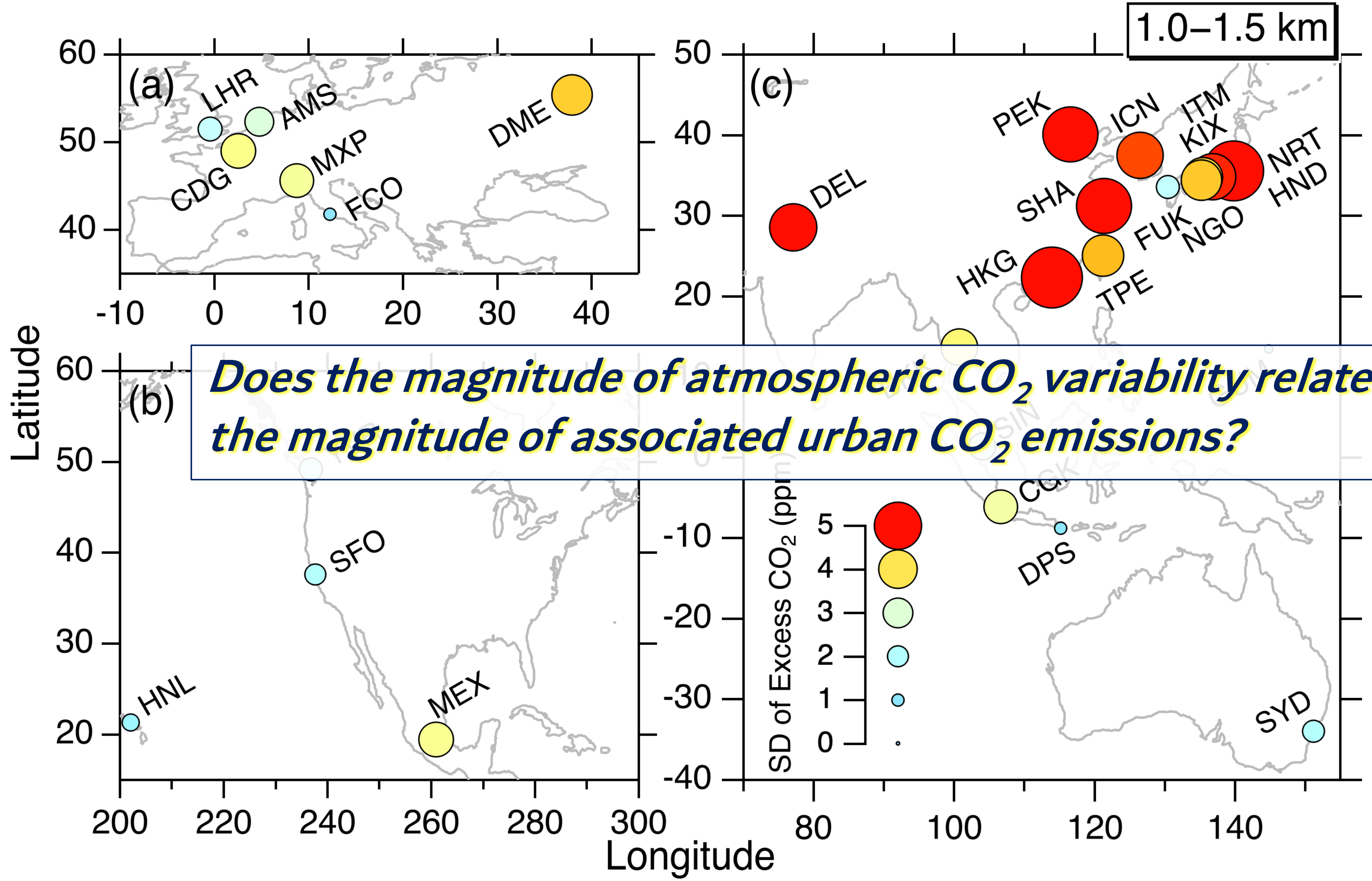

Aircraft Positions < 2km at the W edge of the Greater Tokyo Area


Height ~1 km: high $CO_2$ events with low wind speed in the W sector



# Where are $CO_2$ Variabilities large?

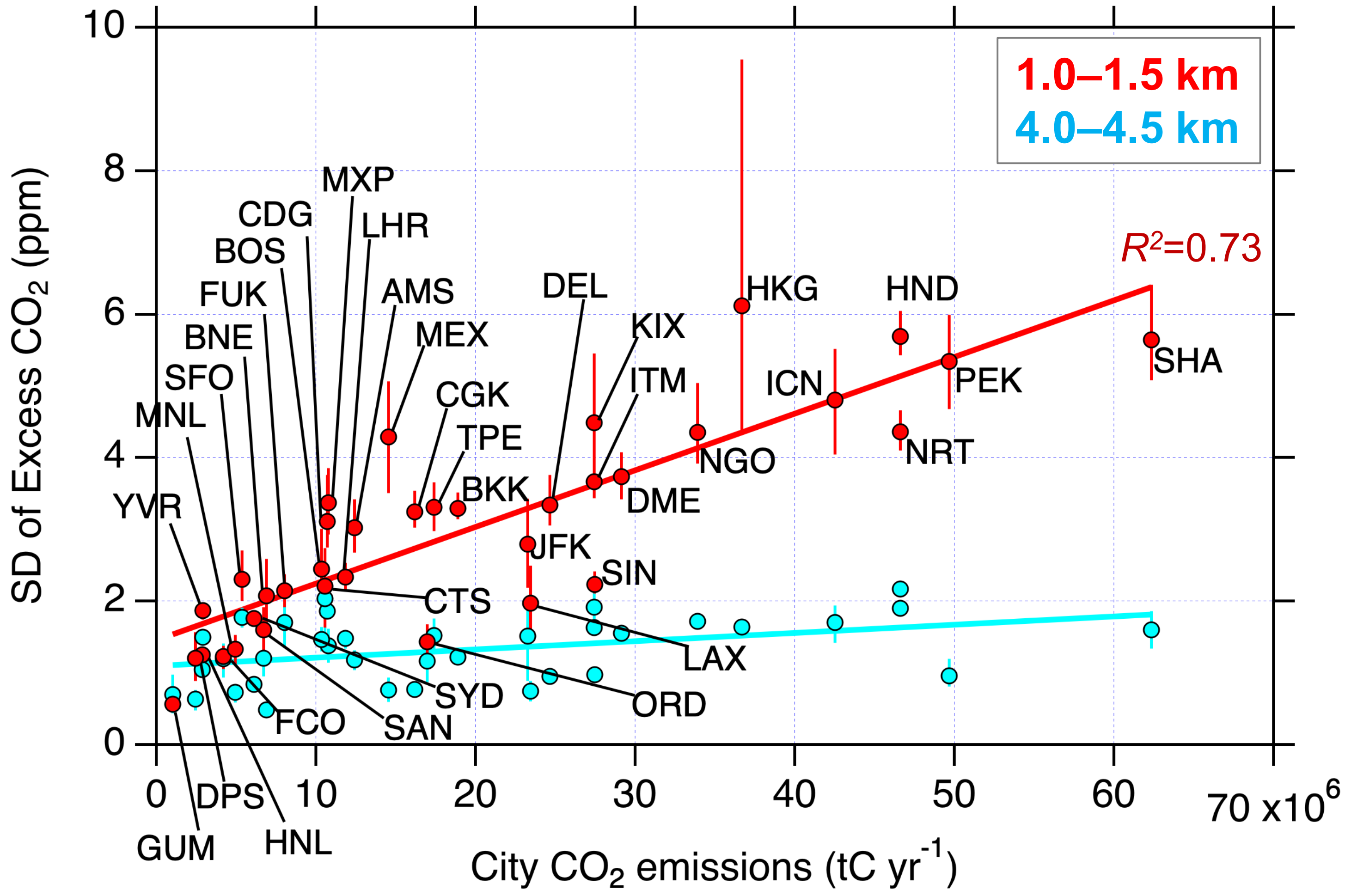



***Does the magnitude of atmospheric $CO_2$ variability relate to the magnitude of associated urban $CO_2$ emissions?***

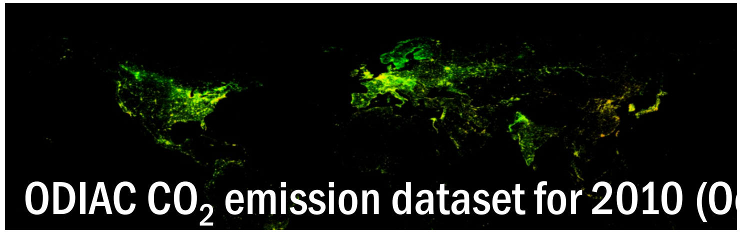
# $CO_2$ Variabilities vs City $CO_2$ Emissions

http://www.cger.nies.go.jp/contrail/

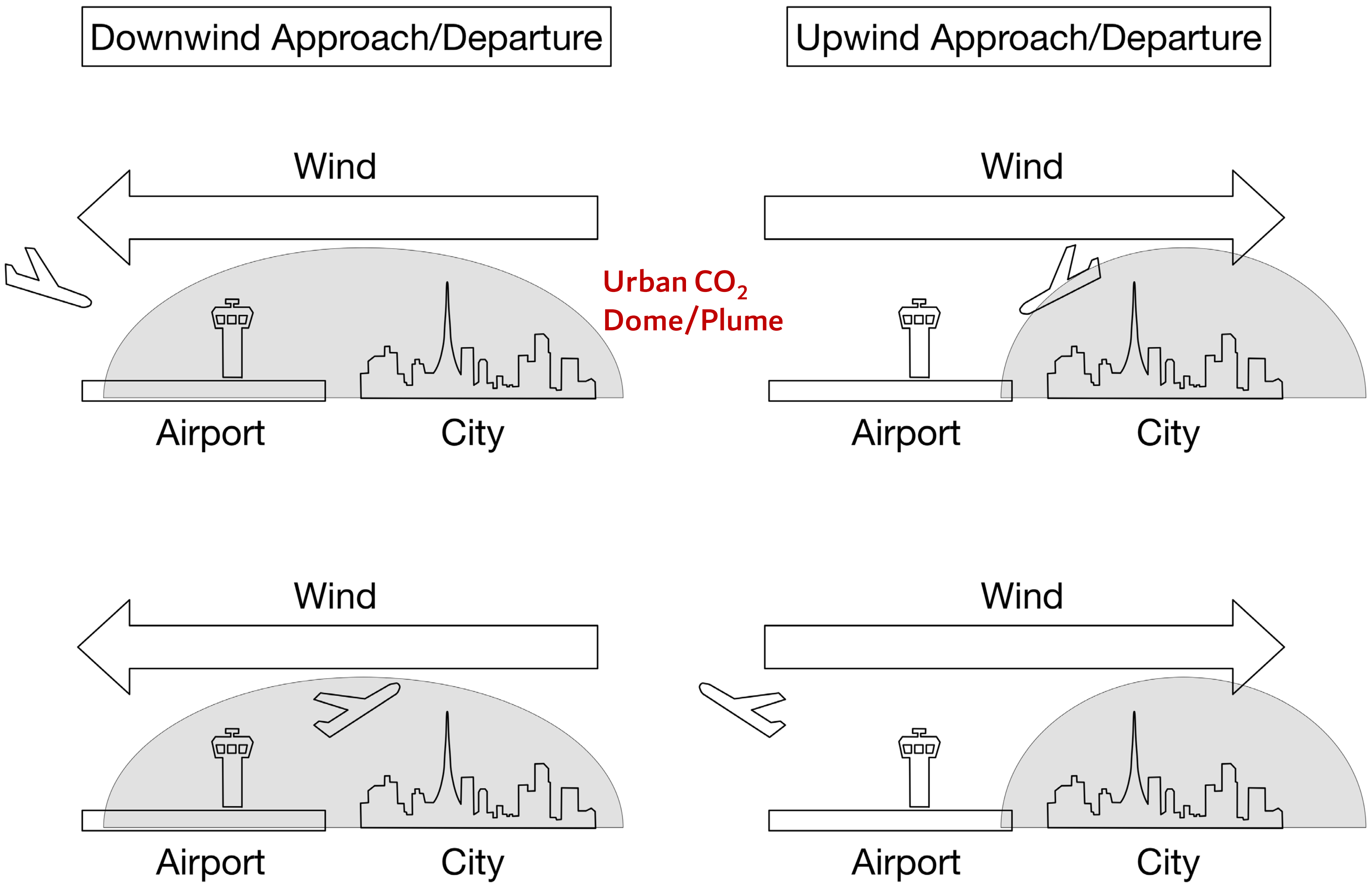





*The intensity of the nearby urban $CO_2$ emissions is the primary component of the magnitude of the observed $CO_2$ variability.*



# Measurement Flight & City $CO_2$ Emissions




- *Geographical airport-city location*
- *City $CO_2$ emissions*
- *Local meteorology*

  *Wind direction, Boundary layer, Local time…*

- *Upwind biospheric fluxes*

*One single profile data is not enough, we need some number of data for good statistical analysis !!*

# Summary


- CONTRAIL measures atmospheric trace gases using Japan Airlines aircraft
- The CMEs have collected large number of $CO_2$ data from cruising and ascending/descending measurement flights
- Significant $CO_2$ enhancements were observed in the lower troposphere downwind of neighboring cities over many airports
  - Advection of such high-$CO_2$ air masses causes flight-to-flight $CO_2$ variations
- The magnitude of $CO_2$ variability at ~1 km altitude over airports is correlated with $CO_2$ emissions from corresponding nearby cities
- The CONTRAIL data in airport proximity contain clear advective footprints of urban $CO_2$ emissions from major cities worldwide

http://www.cger.nies.go.jp/contrail/

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# How COVID-19 affected CONTRAIL?

http://www.cger.nies.go.jp/contrail/

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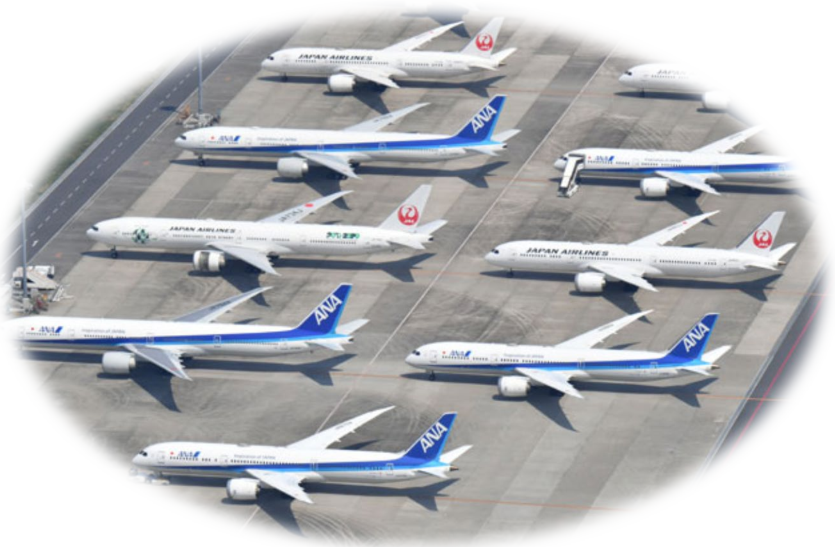
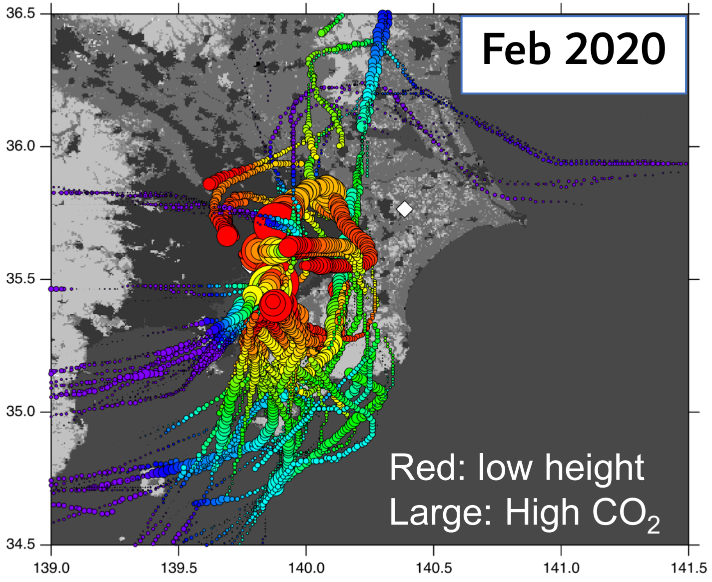
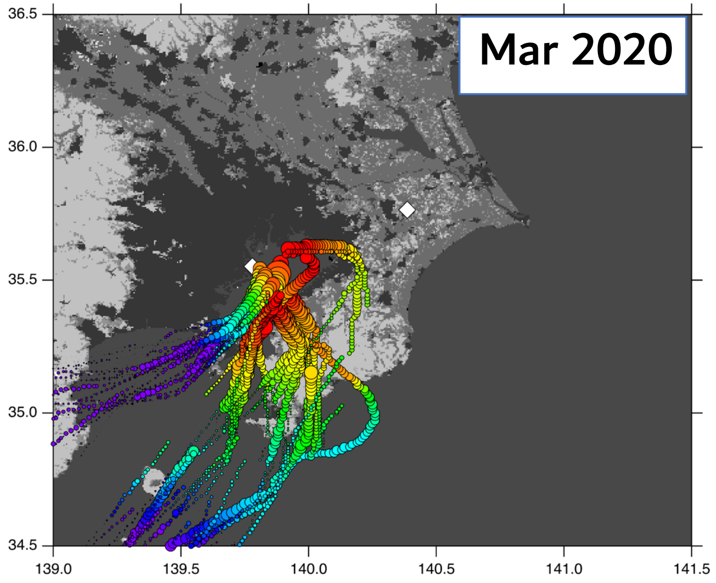
(Many) Aircraft at HND...

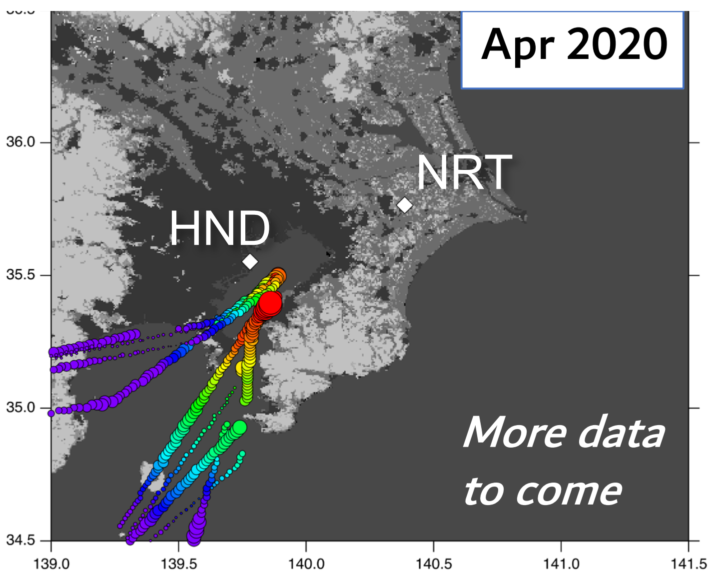




*https://www.aviationwire.jp/archives/200135*

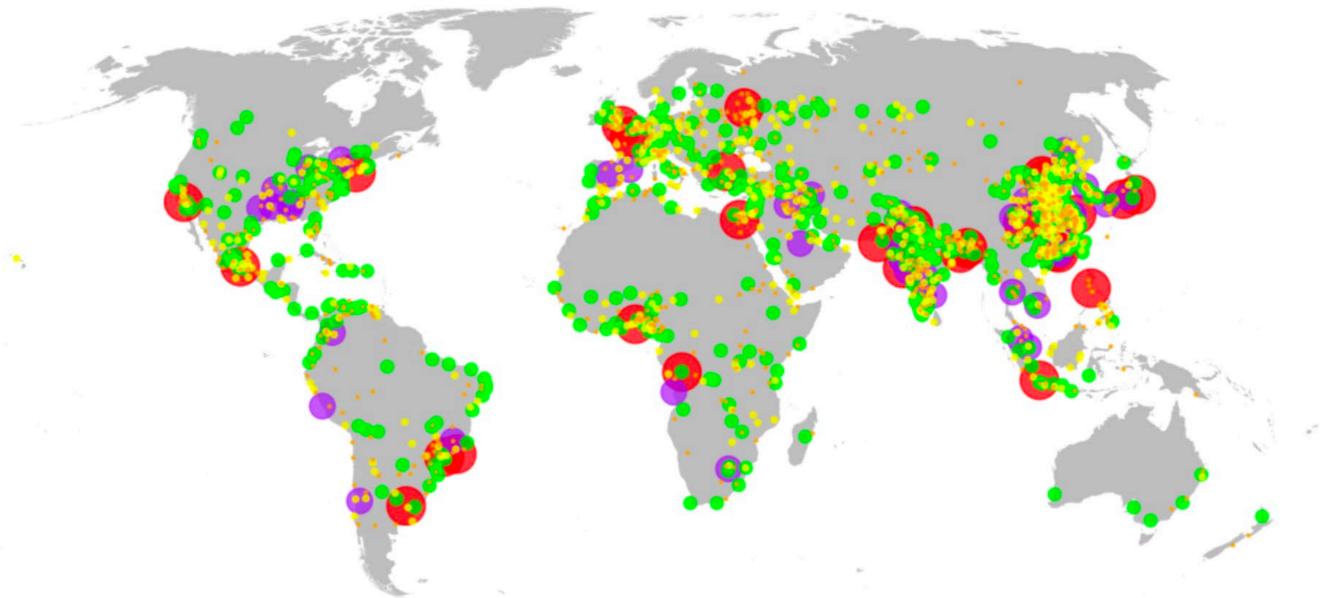


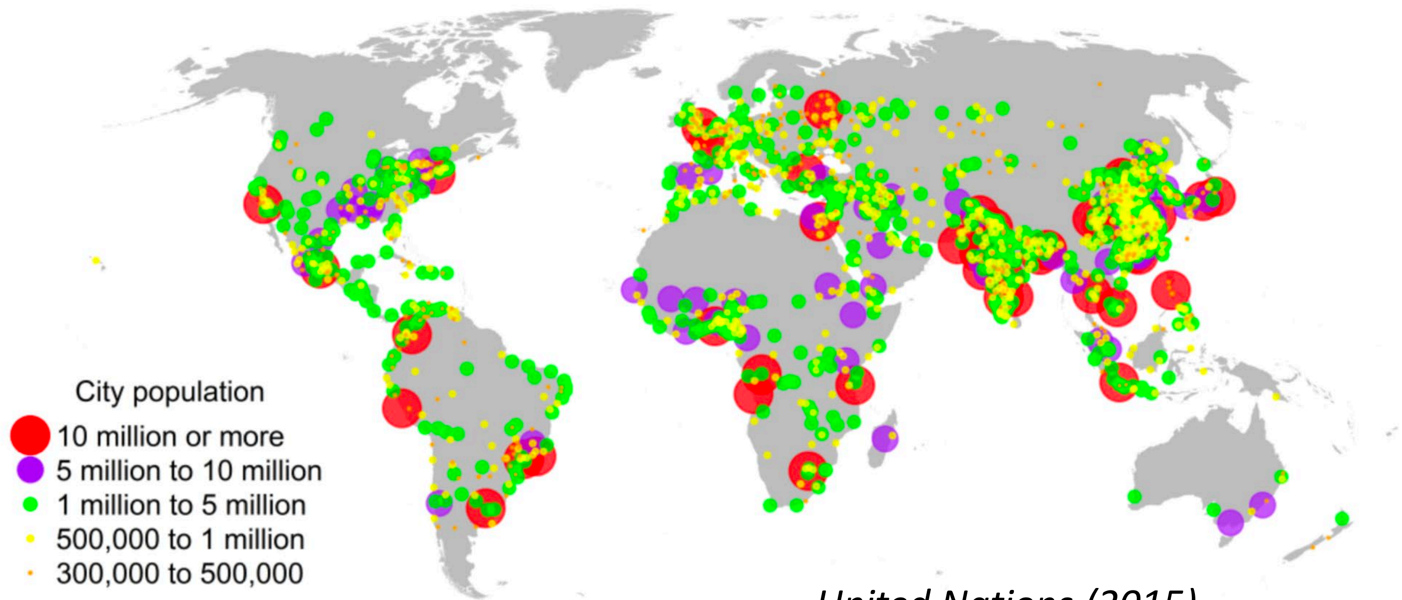

- We keep our instuments installed
- Measurements well achieved even during the lockdown period, though number of flights decreased
- We'll see and analyze the upcoming data

2014



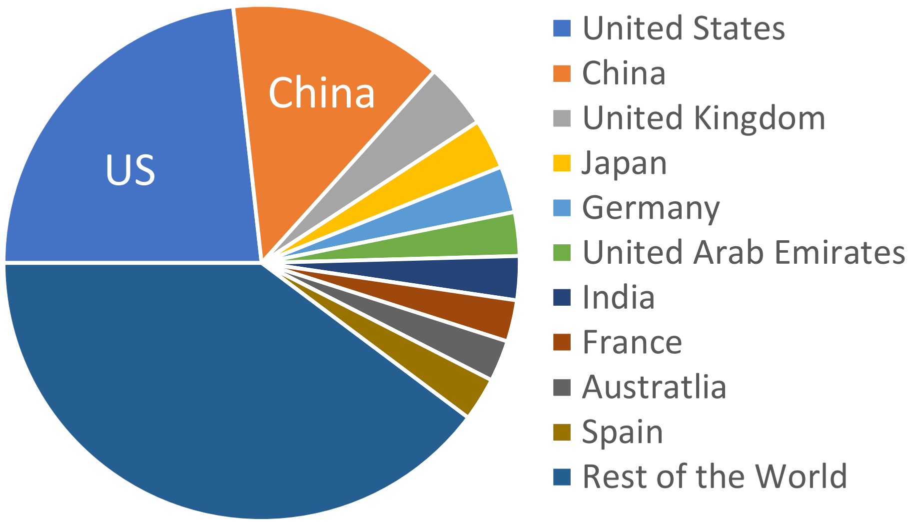
*Cities growing in the south!*

2030




*United Nations (2015)*


Revenue Passenger Kilometers
(Graver et al. 2019)




*JAL covers only small part of the global network!*