CO_2 flux estimation by top-down approach

Meteorological Research Institute
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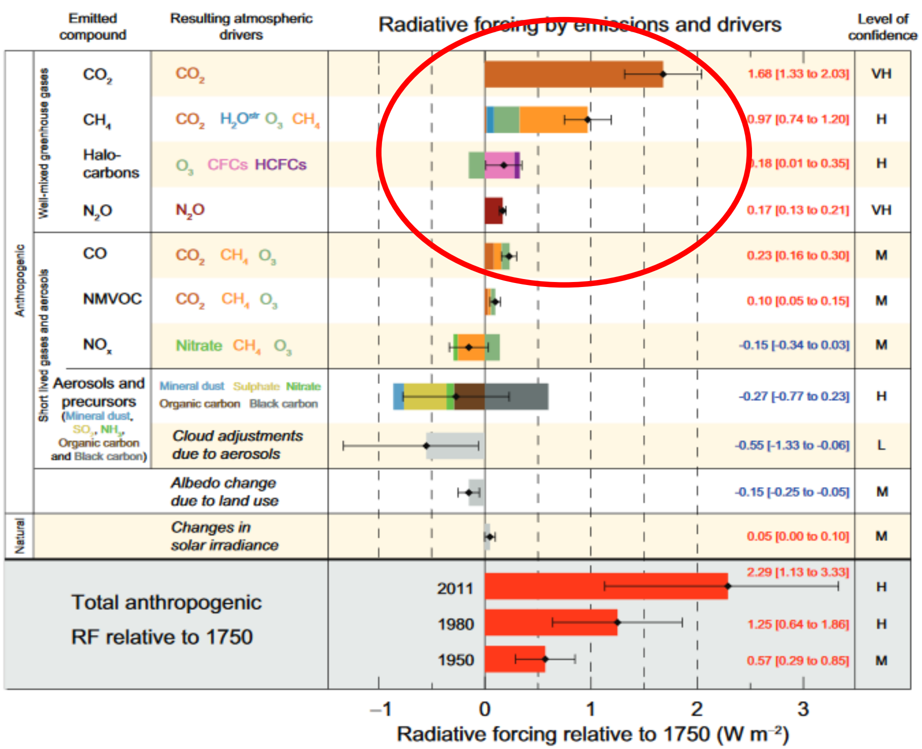
Data Assimilation Workshop, JAMSTEC, 30th Jan. 2020

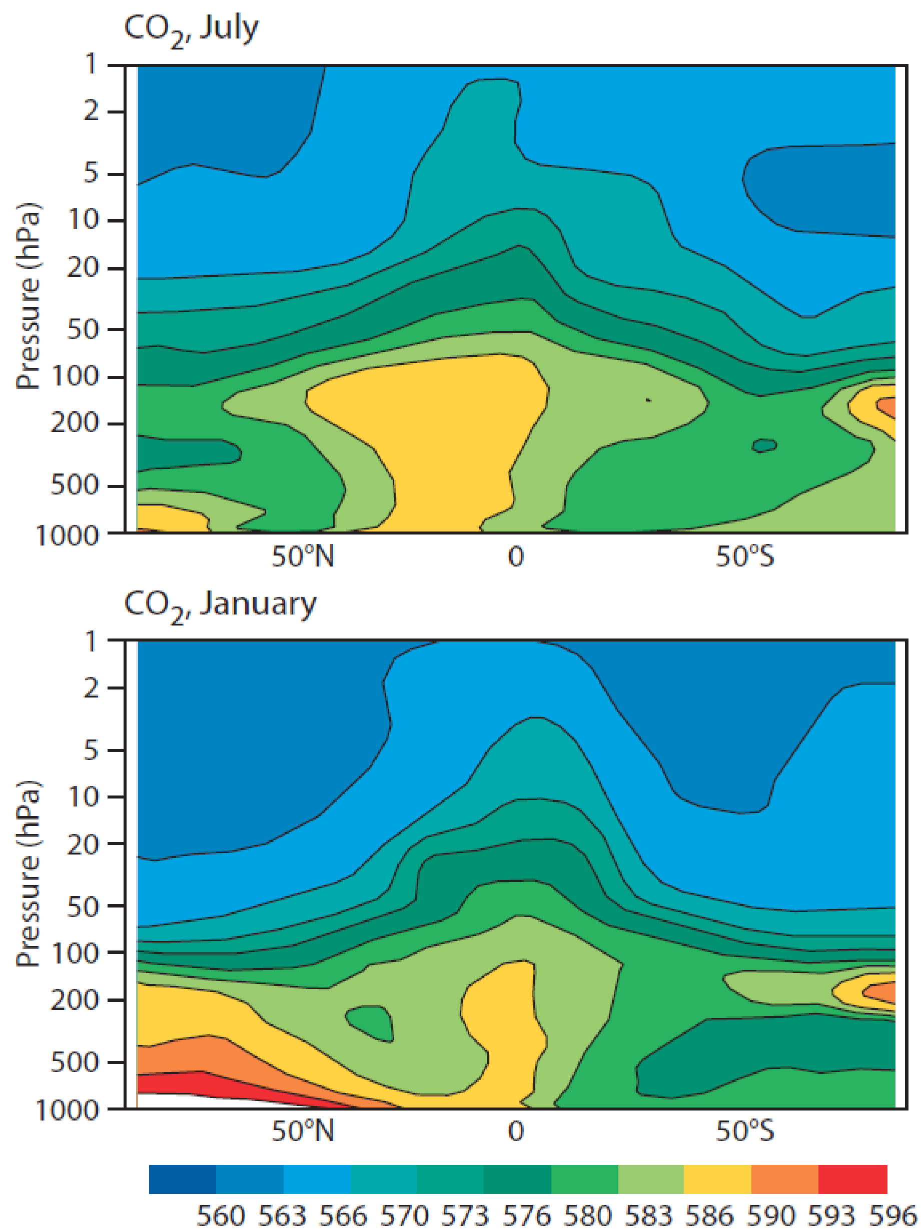
Today's presentation

1. Background
2. Bayesian synthesis Inversion
3. Making use of satellite data
4. Summary

Importance of Green House Gas



IPCC AR5 WG1



CO2, CH4, etc. are major substances in global warming. Its distribution in the atmosphere has been revealed by observation, but the geographical distribution of emission and absorption in particular is not well understood.

ECMWFはIFS Cycle 35r3（2009）➔CO2、CH4 monthly climatology（ECMWF newsletter）

Carbon cycle

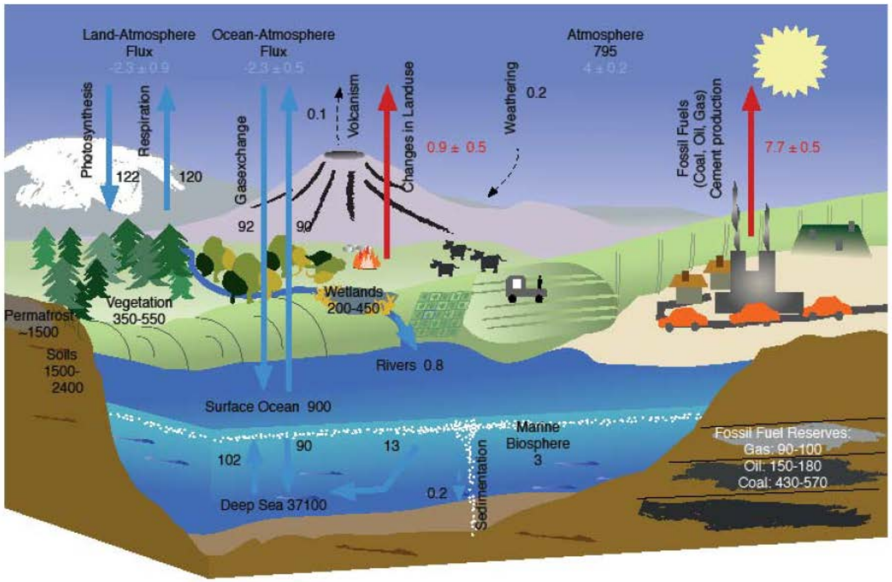
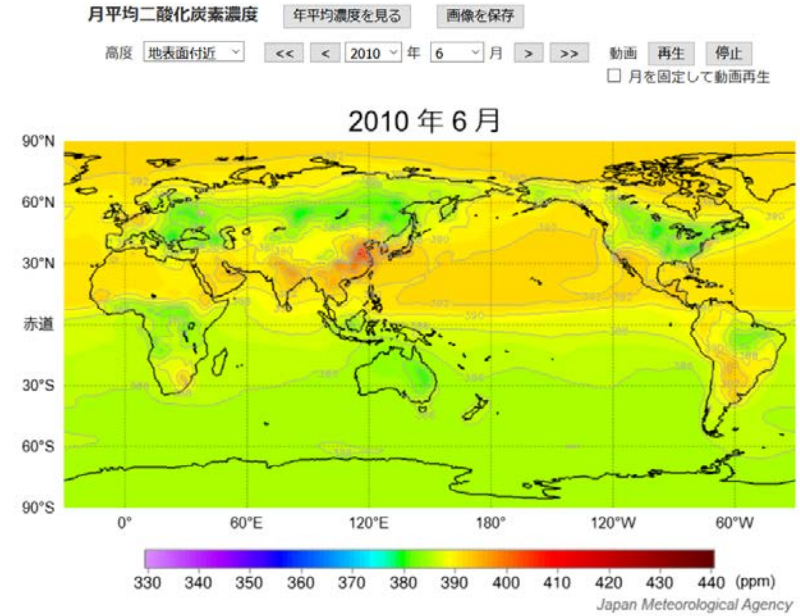
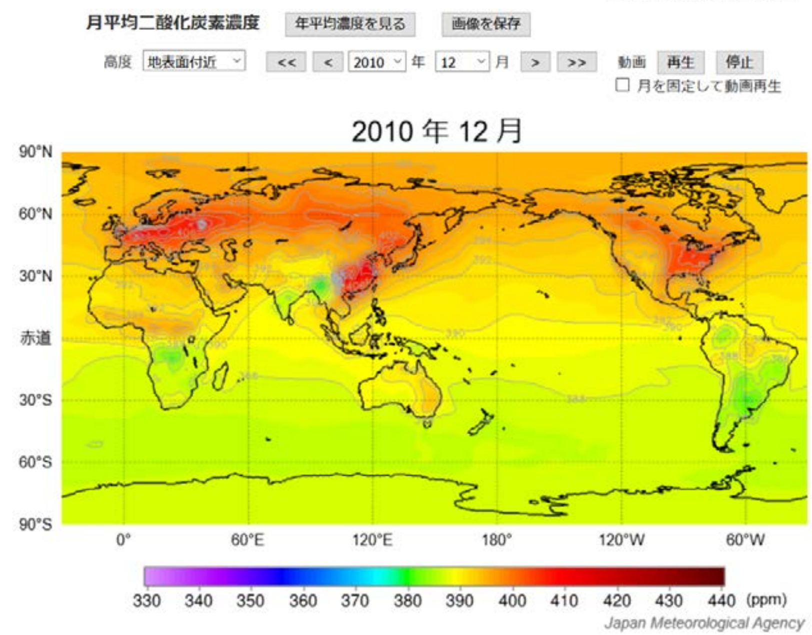


Figure 6.1: Simplified schematic of the global carbon cycle. Numbers represent reservoir sizes (in PgC), resp. carbon exchange fluxes (in PgC yr^{-1}), representing average conditions over the 2000–2009 time period.

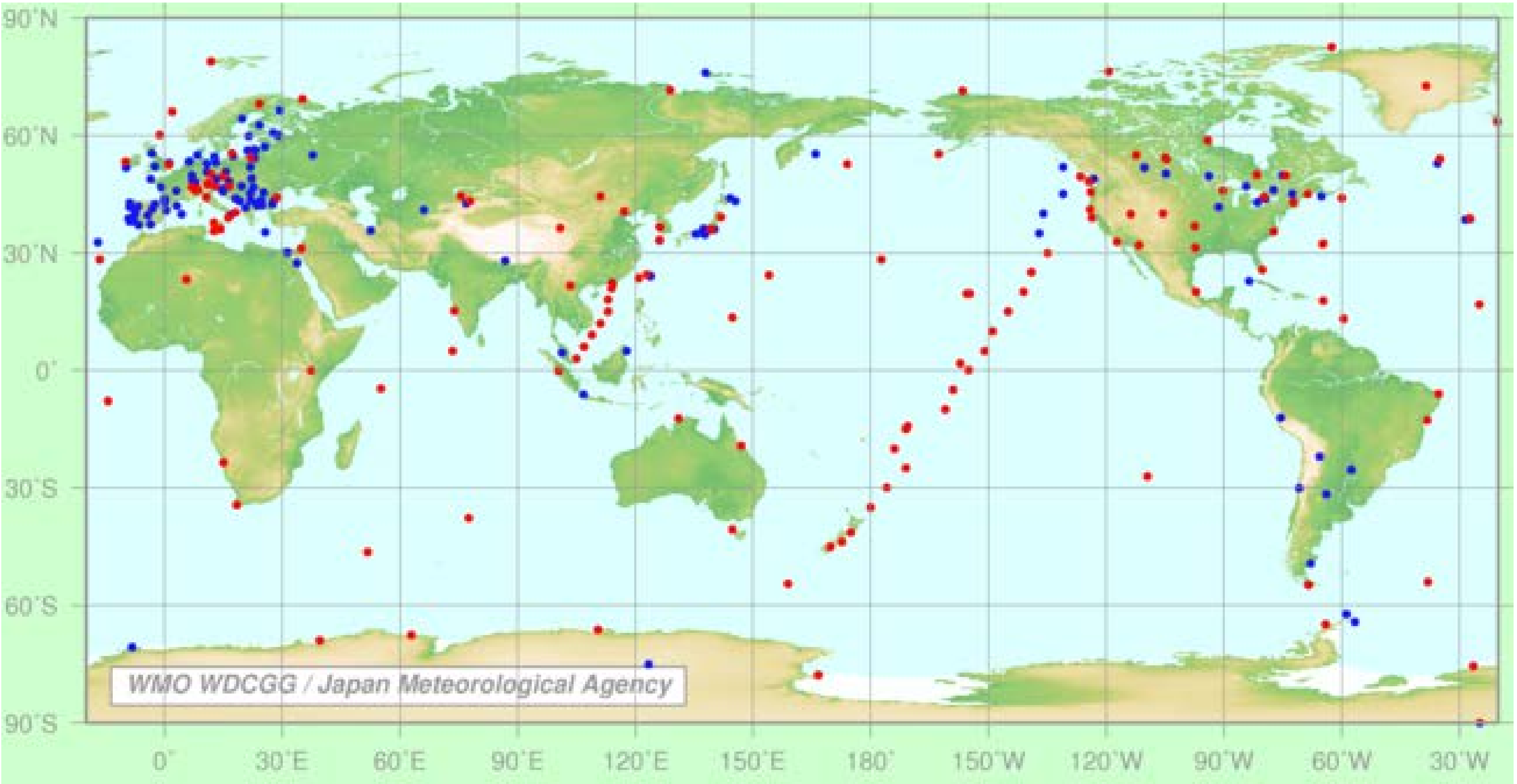




At present, 9 PgC / yr of CO2 is released into the atmosphere, about 2 PgC / yr is absorbed in the ocean and land, and the rest remains in the atmosphere.

The distribution of CO2 concentration is greatly affected by anthropogenic emissions and vegetation, and the seasonal change is severe especially in the Northern Hemisphere.

Global GHG observation network

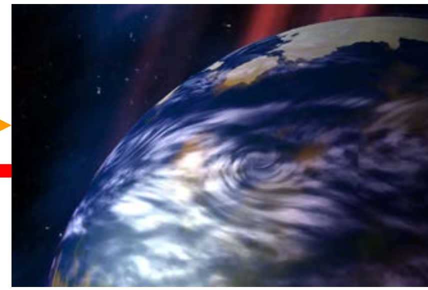


From WDCGG operated by JMA

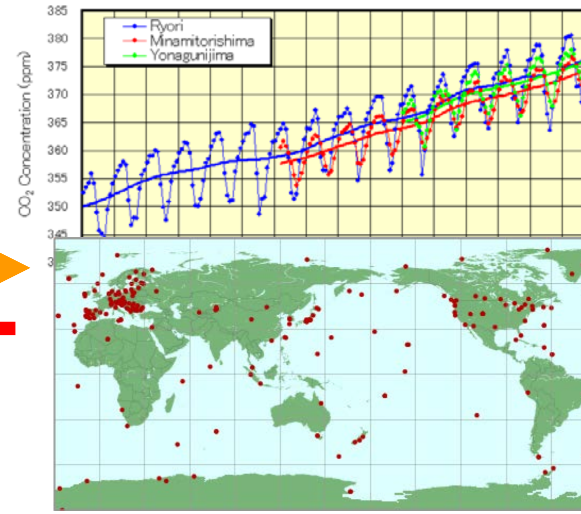
- Observed by ground, ship, aircraft, etc.
- Compared to meteorological observations, extremely small number (about 200 points globally) and unevenly distributed
- Observation accuracy is very high (± 0.1ppm or less).

What is an Inversion?

CO2 flux



Atmospheric transport



CO2 concentration

Finding results from causes is a forward analysis

Example: Numerical weather prediction (Bottom up approarch)

Estimating the cause from the results is an inverse analysis

Example: Data assimilation, Inverse model

Using the result (observed data) and the process (transportation model), the cause (carbon dioxide balance in this case) is estimated.

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Bayesian synthesis Inversion

$$J = (\mathbf{c}_{\mathrm{obs}} - \mathbf{c}_{\mathrm{fwd}} - \mathbf{Hx})^T \mathbf{R}^{-1} (\mathbf{c}_{\mathrm{obs}} - \mathbf{c}_{\mathrm{fwd}} - \mathbf{Hx}) + (\mathbf{x}_0 - \mathbf{x})^T \mathbf{P}_0^{-1} (\mathbf{x}_0 - \mathbf{x})$$

Find x that minimizes the evaluation function J in the above equation. Here, c_{obs} is the observed CO2 value, c_{fwd} is the CO2 concentration at the observation point calculated from the a priori information (CO2 flux), H is the contribution of the unit area flux to the observed value, x_0 is the a priori value of the area flux, R Indicates an observation error, and P_0 indicates an error of a priori value of the area flux.

$$\hat{\mathbf{x}} = (\mathbf{H}^T \mathbf{R}^{-1} \mathbf{H} + \mathbf{P}_0^{-1})^{-1} (\mathbf{H}^T \mathbf{R}^{-1} (\mathbf{c}_{\mathrm{obs}} - \mathbf{c}_{\mathrm{fwd}}) + \mathbf{P}_0^{-1} \mathbf{x}_0)$$

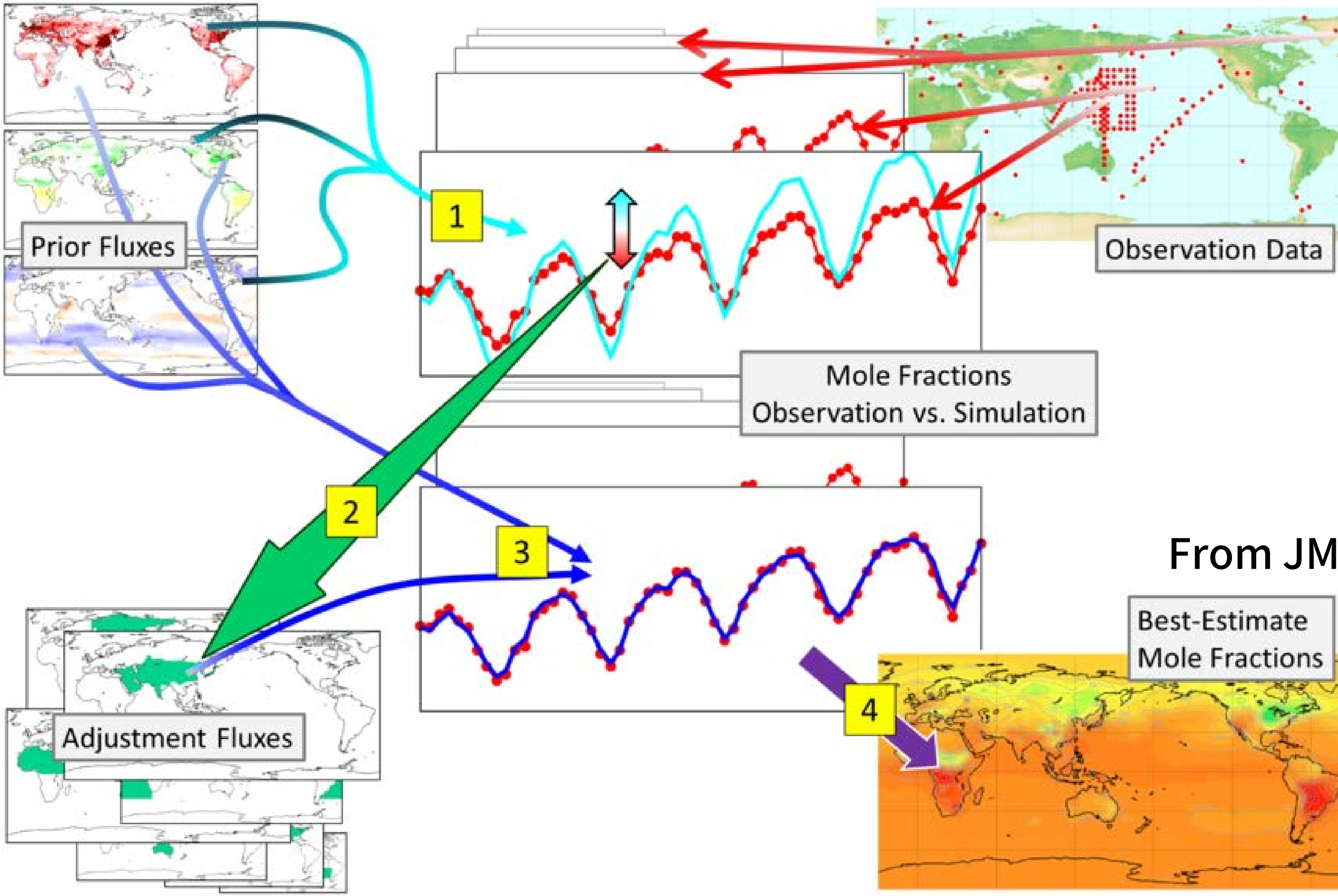
x that minimizes J is expressed by the above equation, and the uncertainty of the CO2 balance in each region is expressed by the following equation.

$$\mathbf{P} = (\mathbf{H}^T \mathbf{R}^{-1} \mathbf{H} + \mathbf{P}_0^{-1})^{-1}$$

In the Japan Meteorological Agency's CO2 budget analysis, the number of regions is 22, the analysis period is 384 from 1985 to 2018 (monthly average), and the number of observation data is about 150 in the globe, so the size of the matrix is about 10,000 × 60,000. Although the matrix operation library (LAPACK) is used, it is thought that in the future, with the increase of observation data and the number of regions, it will be necessary to devise ways such as using a parallel version.

In order to avoid this limitation, data assimilation methods (4D-Var, LETKF) have been developed recently.

Inversion analysis of GHG (CO2)



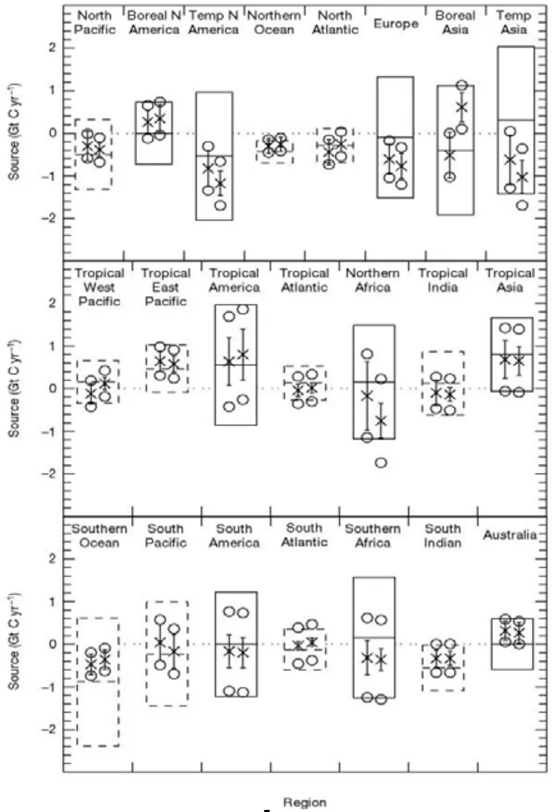
From JMA HP

- Analyze CO2 balance of each area using observation data and transport model and calculate concentration distribution
- Annually released as carbon dioxide distribution information

https://ds.data.jma.go.jp/ghg/kanshi/co2sphere/co2spherem.html

International activities

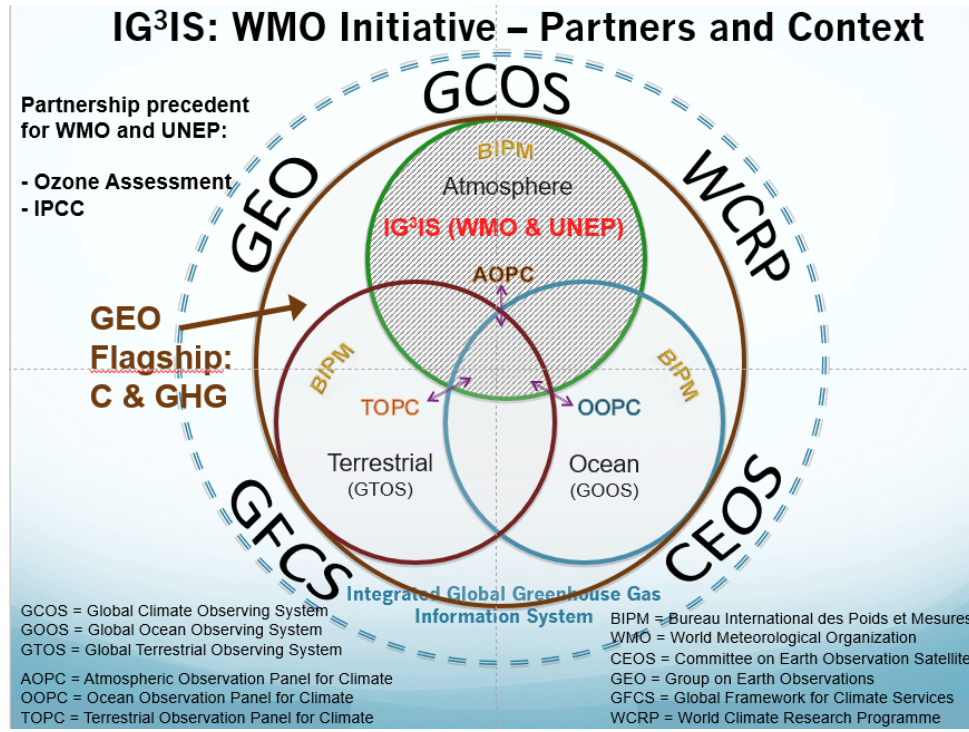
TransCom (Atmospheric Tracer Transport Model Inter-comparison)



Gurney, et al., 2002, nature

A project for estimating errors due to transport models when estimating carbon flux by inverse analysis, sponsored by IGBP/GAIM ➔ IG3IS.

IG3IS (Integrated Global Greenhouse Gas Information System)



by Dr. Decola

IG3IS will play an international coordination mechanism with WMO partners such as UNEP and GEO. It aims to reduce uncertainties in the national emission inventory, identify emission reduction opportunities, and provide monitoring information on natural emissions.

Making use of top down approach

IPCC AR5 (carbon cycle)

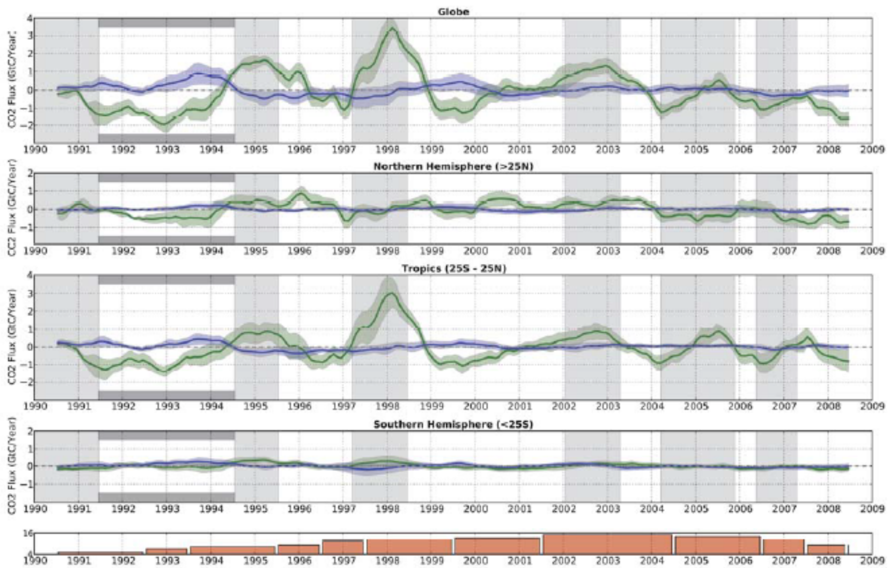


Figure 6.9: The interannual variability of surface CO_2 fluxes from inversions of the TRANSCOM project for the period of 1990–2008. The ensemble of inversion results contains up to 17-atmospheric inversion models. The ensemble mean is bounded by the 1 sigma inter-model spread in ocean-atmosphere (blue) and land-atmosphere (green) CO_2 fluxes (PgC yr^{-1}) grouped into large latitude bands, and over the globe. For each flux and each region, the CO_2 flux anomalies were obtained by subtracting the long term mean flux from each inversion and removing the seasonal signal. Grey shaded regions indicate El Niño episodes, and the back bars indicate the cooling period following the Mt. Pinatubo eruption. A positive flux means a larger than normal source of CO_2 to the atmosphere (or a smaller CO_2 sink).

IPCC AR5 (Climate model evaluation)

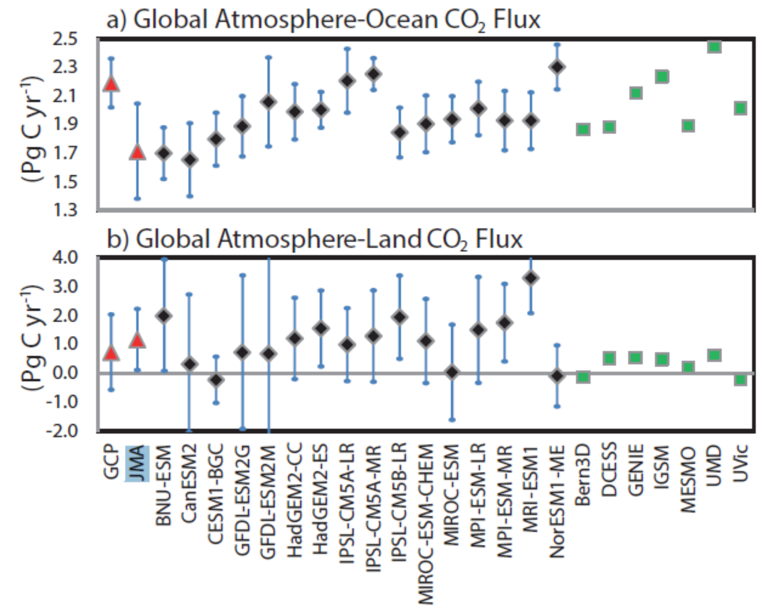


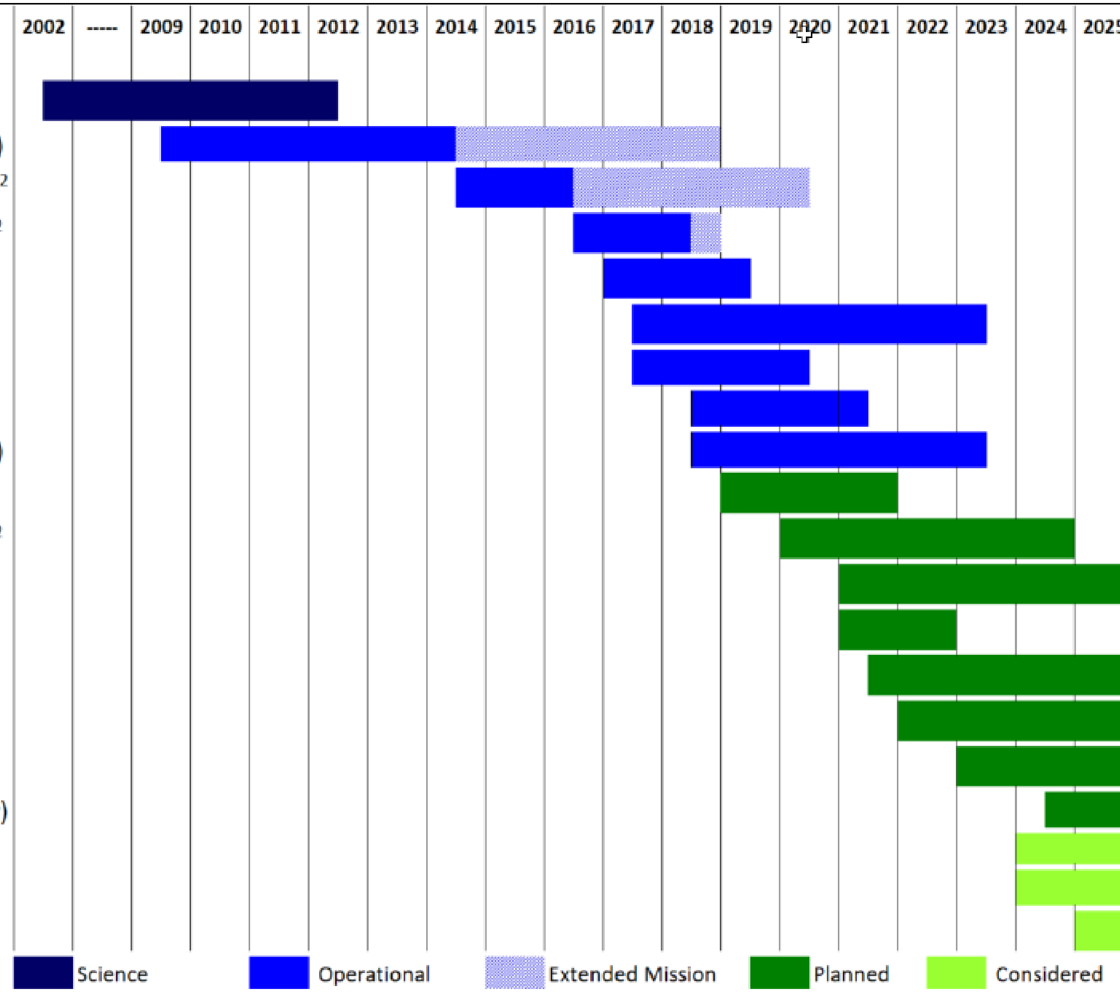
Figure 9.27 | Simulation of global mean (a) atmosphere–ocean CO_2 fluxes ('fgCO2') and (b) net atmosphere–land CO_2 fluxes ('NBP'), by ESMs (black diamonds) and EMICs (green boxes), for the period 1986–2005. For comparison, the observation-based estimates provided by Global Carbon Project (GCP; Le Quere et al., 2009), and the Japanese Meteorological Agency (JMA) atmospheric inversion (Gurney et al., 2003) are also shown as the red triangles. The error bars for the ESMs and observations represent interannual variability in the fluxes, calculated as the standard deviation of the annual means over the period 1986–2005.

In IPCC AR5, the results of the Japan Meteorological Agency inverse analysis are cited in Chapter 6 (carbon cycle) and Chapter 9 (climate model evaluation).

A DLR expert told ESMValTool that they would like to use the updated results of the Japan Meteorological Agency inverse analysis, and provided the latest analysis results (June 2019).

GHG satellite missions

Satellite, Instrument (Agencies)	CO_2	CH_4	Swath	Sample
ENVISAT SCIAMACHY (ESA)	●	●	960 km	30x60 km^2
GOSAT TANSO-FTS (JAXA-NIES-MOE)	●	●	3 pts	10.5 km (d)
OCO-2 (NASA)	●		10.6 km	1.3x2.3 km^2
GHGSat (Claire)		●	12 km	0.0004 km^2
TanSAT (CAS-MOST-CMA)	●		20 km	1x2 km^2
Sentinel 5P TROPOMI (ESA)		●	2600 km	7x7 km^2
Feng Yun 3D GAS (CMA)	●	●	7 pts	10 km (d)
GaoFen-5 GMI	●	●	5-9 pts	10 km (d)
GOSAT-2 TANSO-FTS (JAXA-MOE-NIES)	●	●	5 pts	10.5 km (d)
OCO-3 (NASA)	●		11 km	4 km^2
Bluefield Technologies		●	25x20 km	0.0004 km^2
MicroCarb (CNES)	●		13.5 km	40 km^2
MethaneSAT (EDF)		●	200 km	1 km^2
MetOp Sentinel-5 series (Copernicus)		●	2670 km	7x7 km^2
Feng Yun 3G (CMA)	●	●	100 km	< 3 km^2
GEOCARB (NASA)	●	●	2800 km	4x4 km^2
MERLIN (DLR-CNES)		●	100 m	0.14 km (w)
TanSat-2 Constellation	●	●	3x100 km	2x2 km^2
GOSAT-3 (JAXA-MOE-NIES)	●	●	TBD	TBD
CO2 Sentinel (Copernicus)	●	●	3x250 km	2x2 km^2



Dr. Crisp (IWGGMS15)

- Japan, US, Europe and China are expected to launch various greenhouse gas observation satellites in the future.
- Searching for synergy from other satellites (AMSR3 → GOSAT3, etc.)

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温室効果ガス衛星観測データの特徴

Merit

・Wide observation range can be observed with the same sensor

・Many observation data can be obtained

・Wide spatial representation and high affinity with the model

Issues

・Restriction of observable area due to cloud or solar zenith angle (sampling bias)

Except for thermal infrared (TIR) or active sensors (riders, etc.), it is difficult to observe at night.

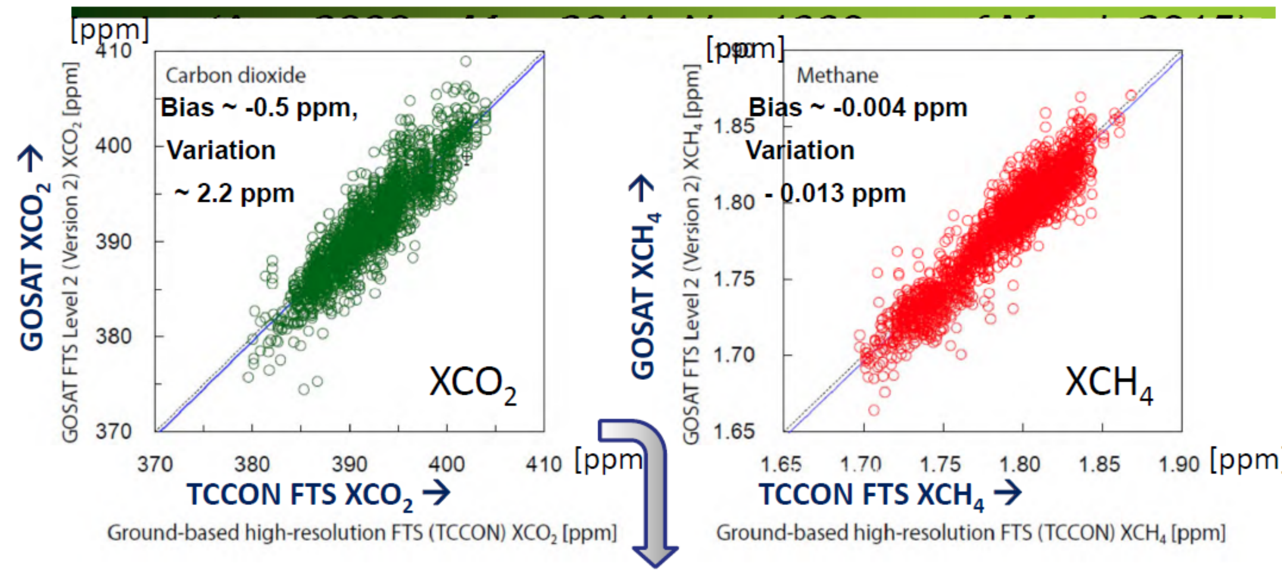
・There are errors due to retrieval, especially retrieval bias.

#During data assimilation and reverse analysis, bias has an adverse effect on analysis results

At present, regional CO_2 flux estimation using satellite observations cannot be said to be sufficiently successful.

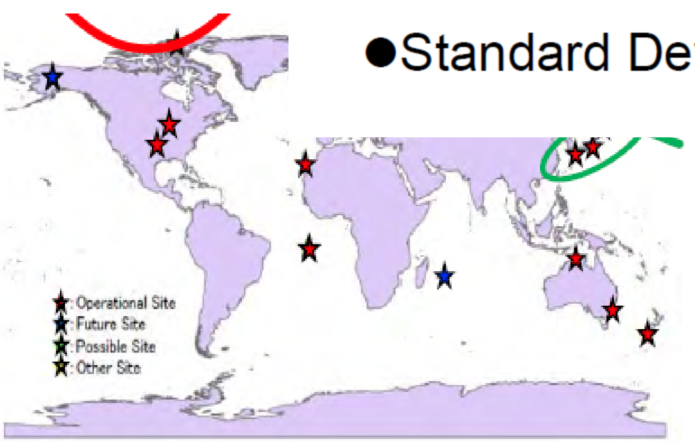
Validation of satellite observation data

Validation of GOSAT (TANSO-FTS SWIR) Level 2 Data with TCCON data（Ver.02.21）



- Slightly lower values (negative biases) of GOSAT
- Standard Deviation is lower than 1 %, respectively

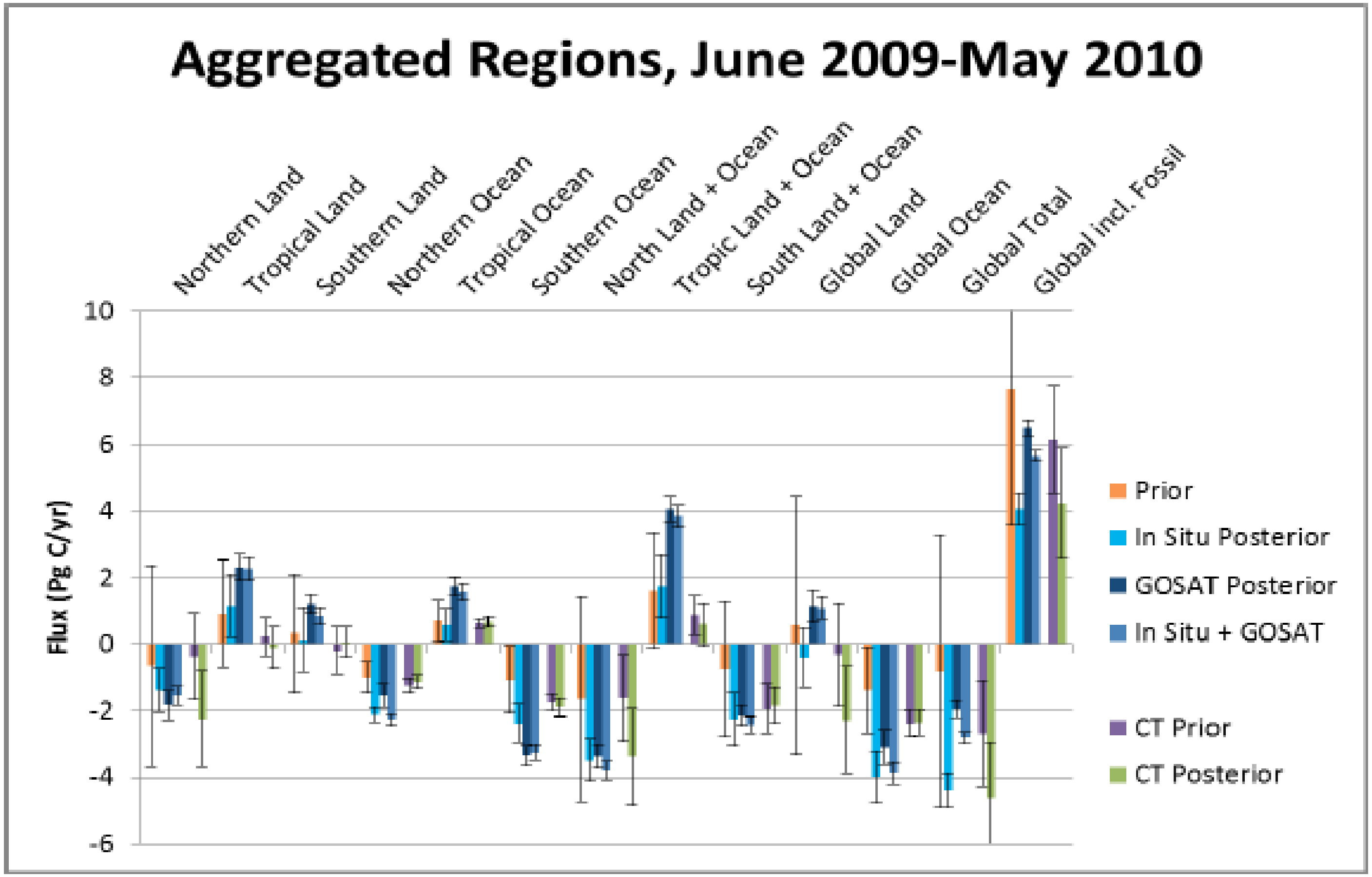
(by I. Morino & O. Uchino (NIES)) 13



A worldwide network of ground-based FTS（TCCON; over 20 sites in the world） 12

Dr. Yokota（IWGGMS12）

Impact of satellite data bias



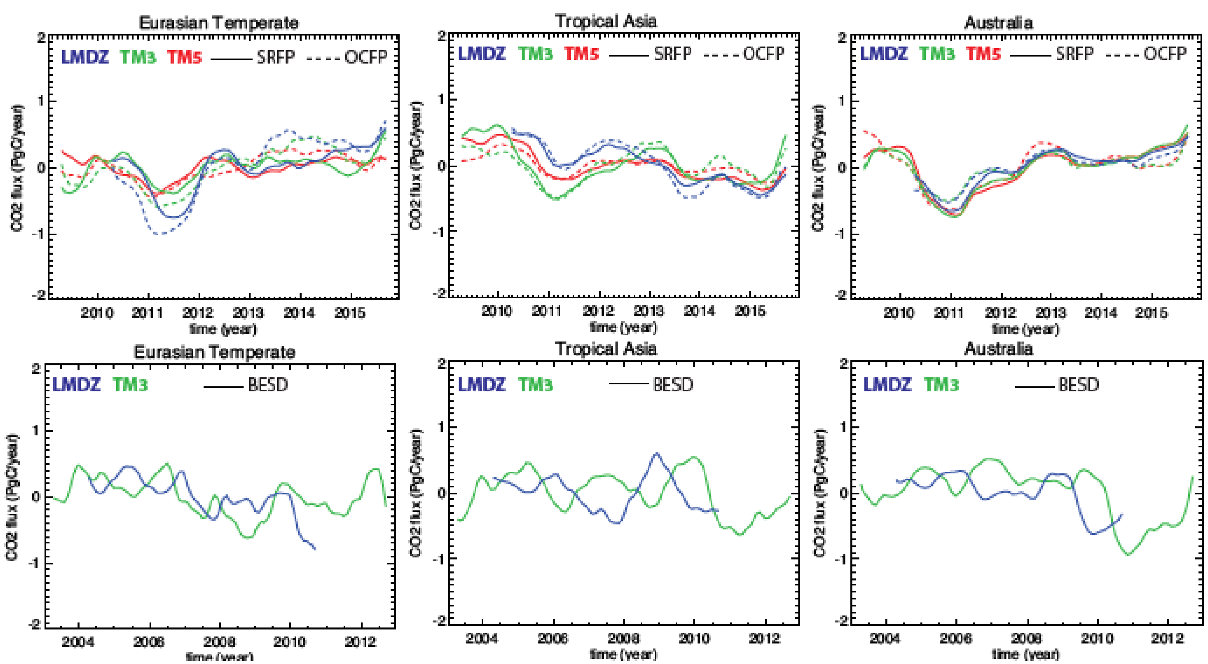
Wang et al., 2017（ACPD）

- Using PCTM + EnKF to analyze the CO2 balance when using ground and GOSAT (NASA retrieve)
- In terms of annual CO2 balance, the difference between GOSAT (6.5PgC) and the ground only (4.1PgC) is conspicuous
- In the annual balance, the shift of the CO2 absorption zone from tropical to high latitude area

Bias evaluation of satellite observation data

GHG-CCI Datasets

Satellite Retrievals				
Algorithm	**Provider**	**Instrument**	**Coverage**	**Reference**
BESD	iUP-UB	SCIAMACHY	Land, 2003-2012	Reuter et al, 2011
OCFP	Univ. Leicester	GOSAT	Global, 2009-2015	Cogan et al, 2012
SRFP	SRON/KIT	GOSAT	Global, 2009-2015	Butz et al, 2011
EMMA	iUP-UB	SCIA/GOSAT	Land, 2009-2012	Reuter et al, 2013
Inverse Models				
Algorithm	**Provider**	**Method**	**Model Res.**	**Reference**
CCDAS	Inversion Lab.	CCDAS	5°x7.5° (lat x lon)	Kaminski et al, 2017
LMDZ	LSCE	Flux Inversion	1.9°x3.8° (lat x lon)	Chevallier et al, 2014
TM3	MPI-BGC	Flux Inversion	3.8°x5.0° (lat x lon)	Rödenbeck etal,2005
TM5	SRON	Flux Inversion	2°x3° (lat x lon)	Basu et al, 2013



Dr. Houwelling (ICDC10)

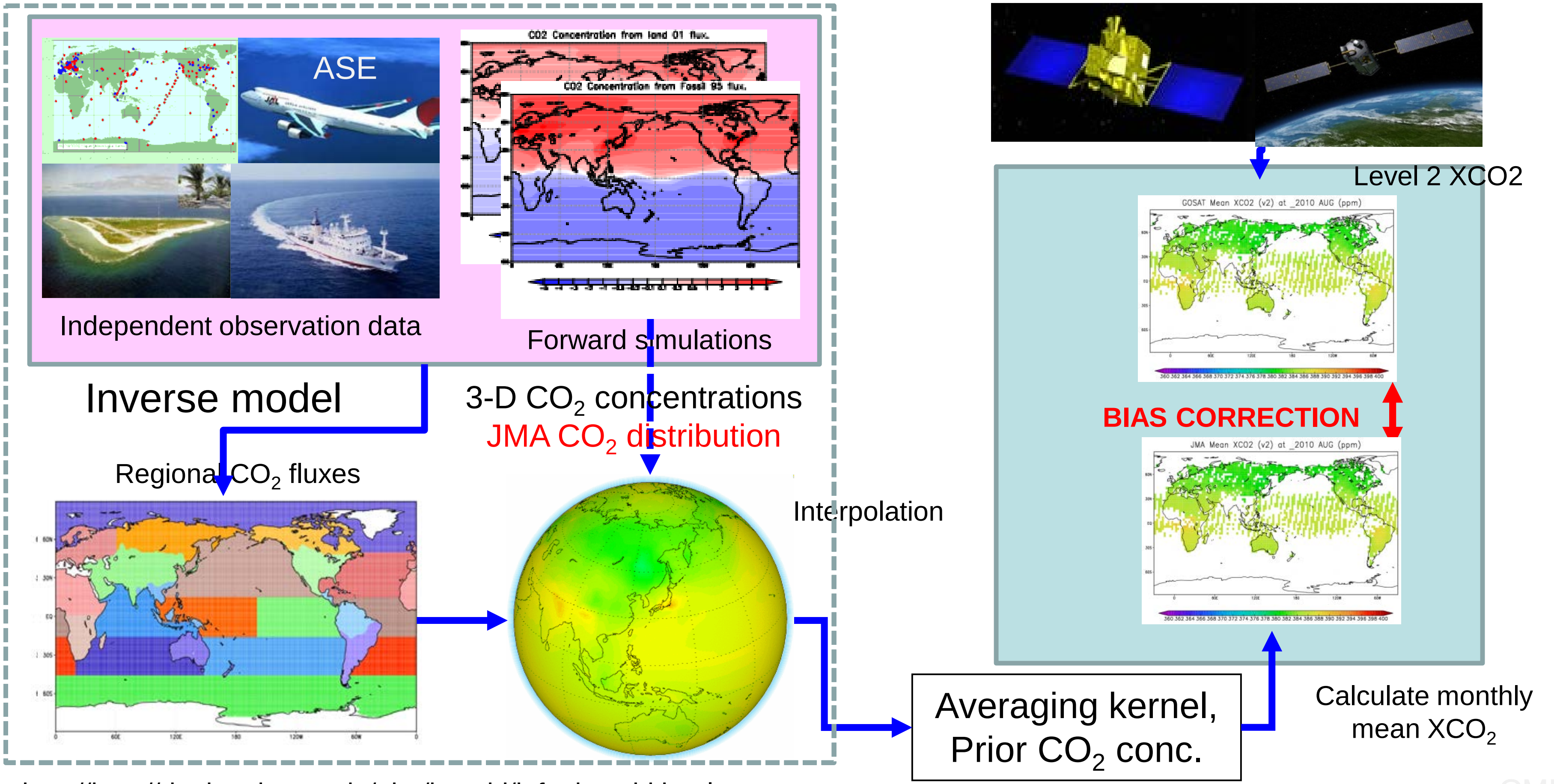
-Compared XCO2 observation data of GOSAT and SCIAMACHY with XCO2 calculated from multiple inverse analysis results, and analyzed the differences for each region.

Implemented as part of ESA's GHG-CCI project

These results demonstrate the usefulness of the inverse analysis intercomparison for evaluating the accuracy of flux estimation using satellite data.

http://www.esa-ghg-cci.org/

Concept of our analysis system



http://http://ds.data.jma.go.jp/ghg/kanshi/info_kanshi.html

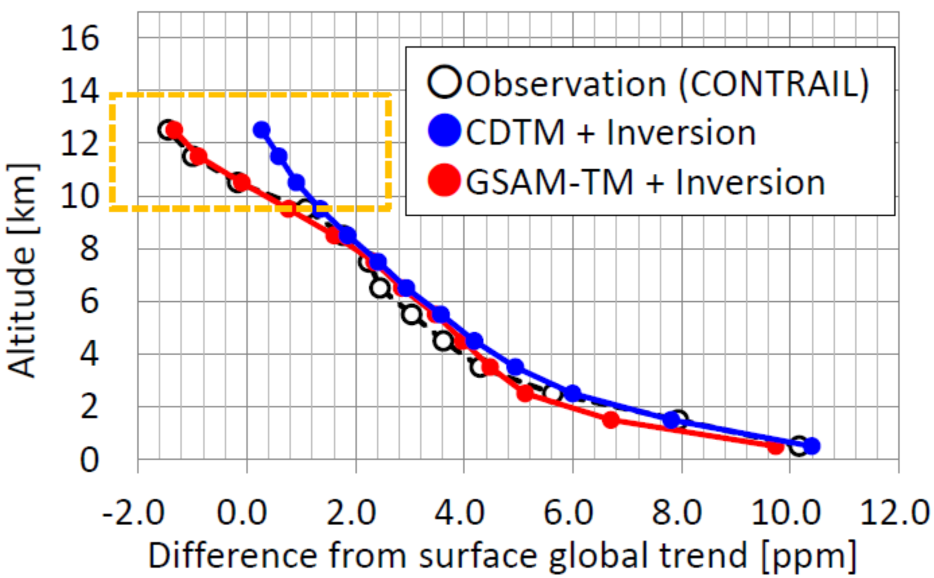
We calculate almost 9 year's GOSAT L2 bias by comparing with independent XCO2 analysis.

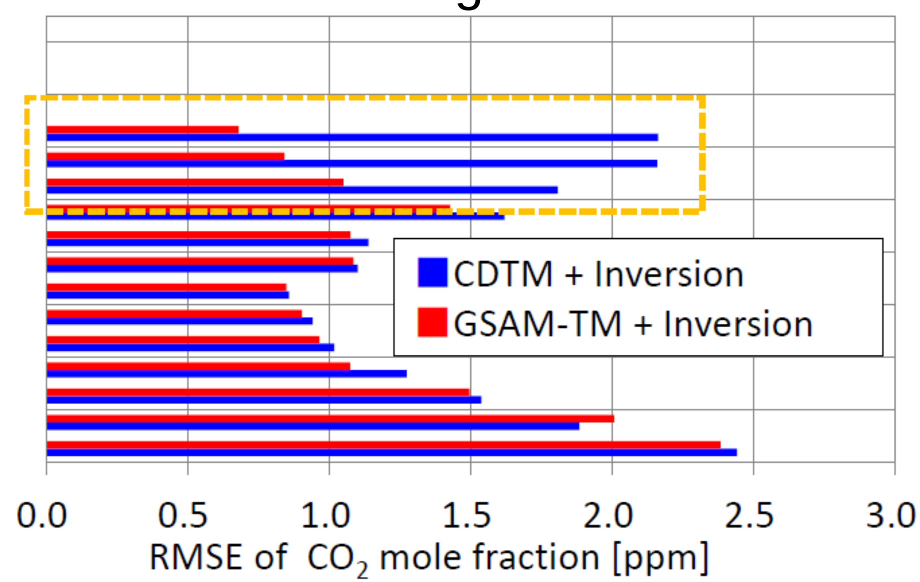
Independent CO2 analysis (JMA-CO2)

Specification of JMA CO2 distribution	
Analysis period	1985 – 2016 (Monthly)
Analysis Method	Bayesian Synthesis Inversion (TransCom 3)
Observation data	Surface, Ship and Aircraft (WDCGG)
Observation error	Difference from smoothed data
Observation data selection	Repeat inverse analysis
Number of region divisions	22 (TransCom 3)
Transport model	GSAM-TM (on-line)
Transport model resolution	TL95L60
Meteorological field	Nudged towards JRA-55
Prior flux	CDIAC, CASA, JMA Ocean analysis

We have been conducting carbon cycle analysis for over 30 years using in-situ observations (surface, ship and aircraft).

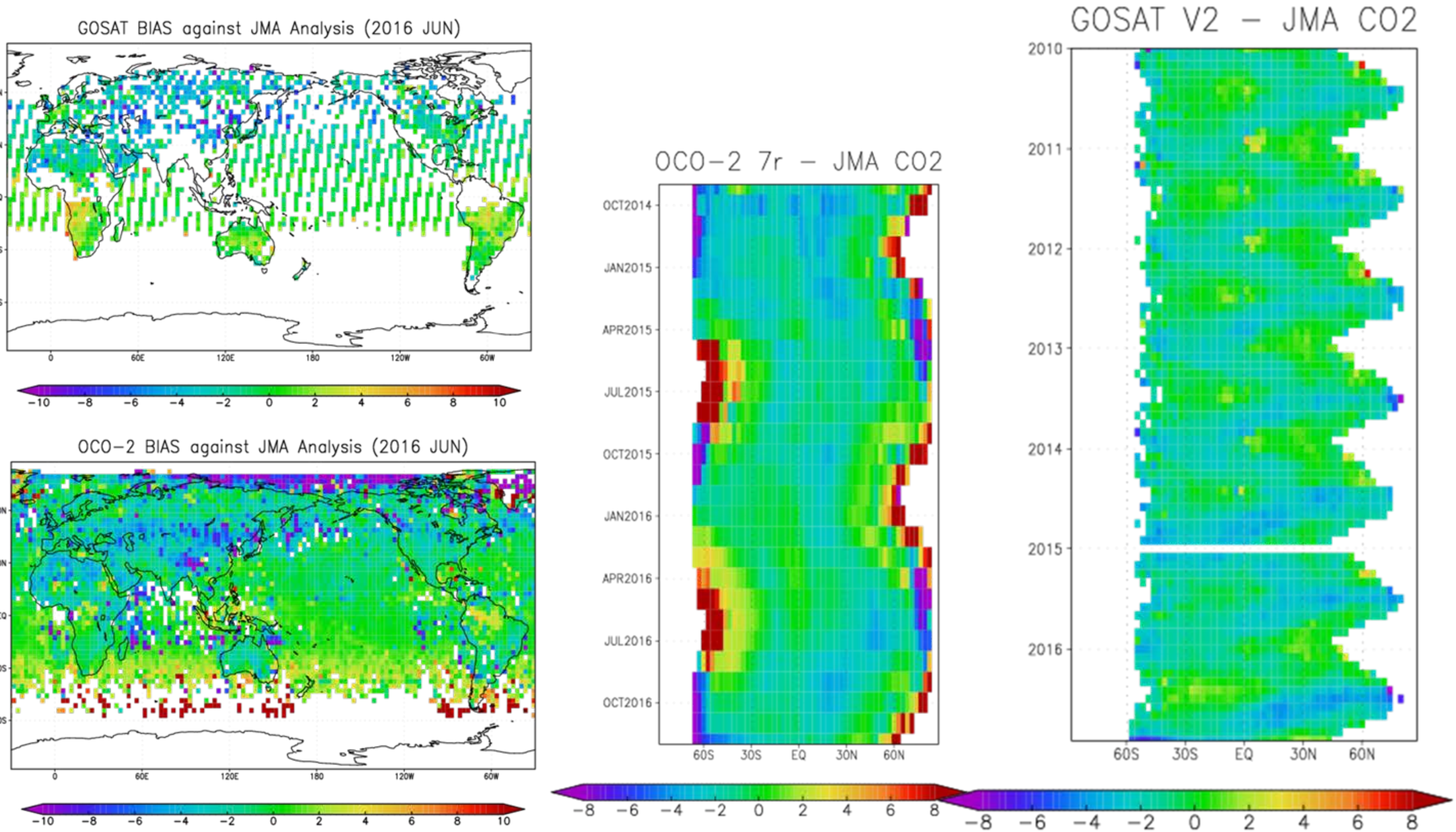
Considering the averaging kernel of GOSAT observations, large RMSE near the surface are not a big issue.





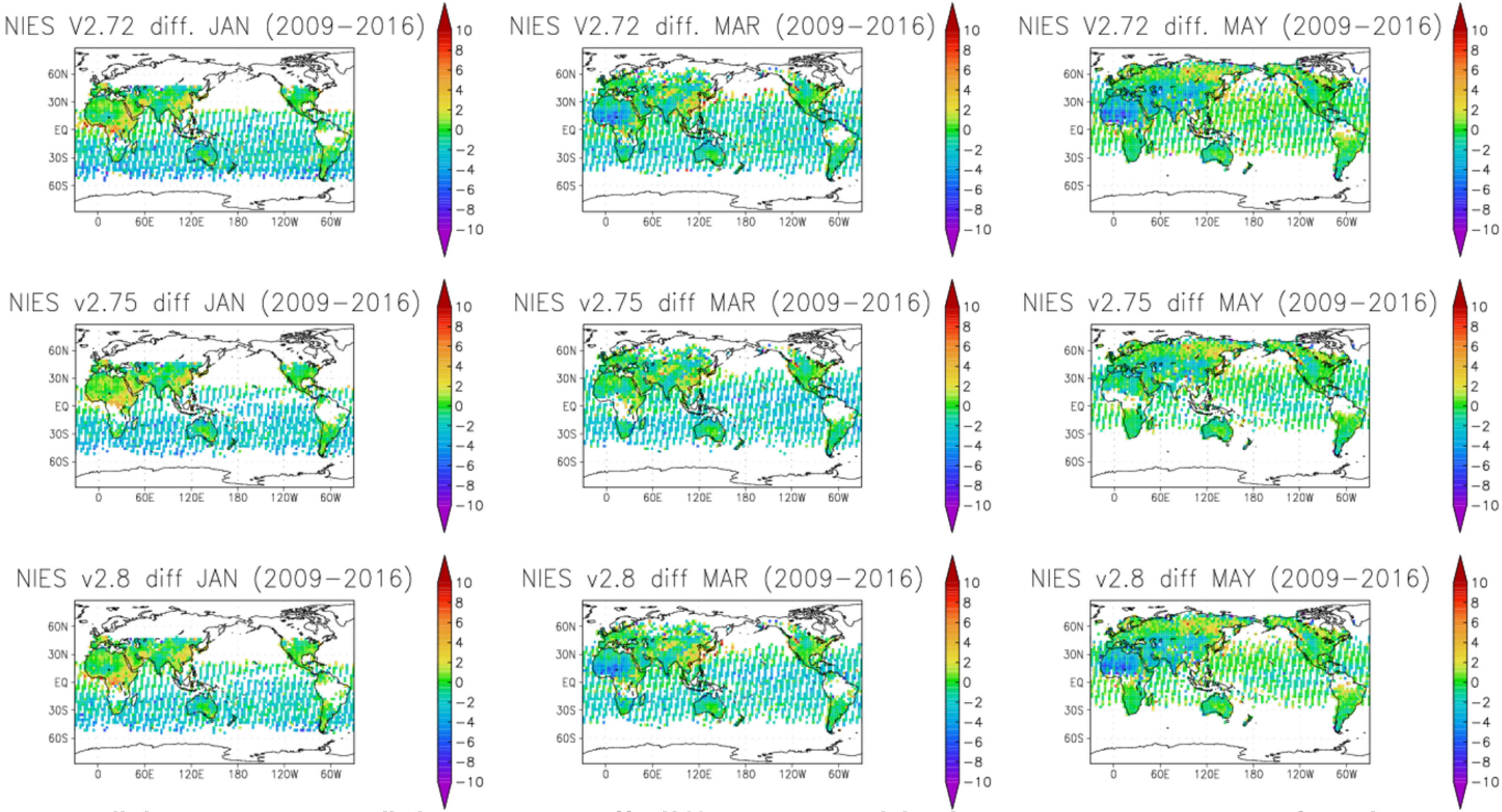
Comparison with independent observation (CONTRAIL) (Nakamura et al., TransCom meeting 2018)

Satellite products against JMA XCO2



For both GOSAT and OCO-2, seasonal and location-dependent differences are observed in the Japan Meteorological Agency's carbon dioxide distribution information (XCO2 equivalent). Especially in the high latitude zone, the difference between the two is large.

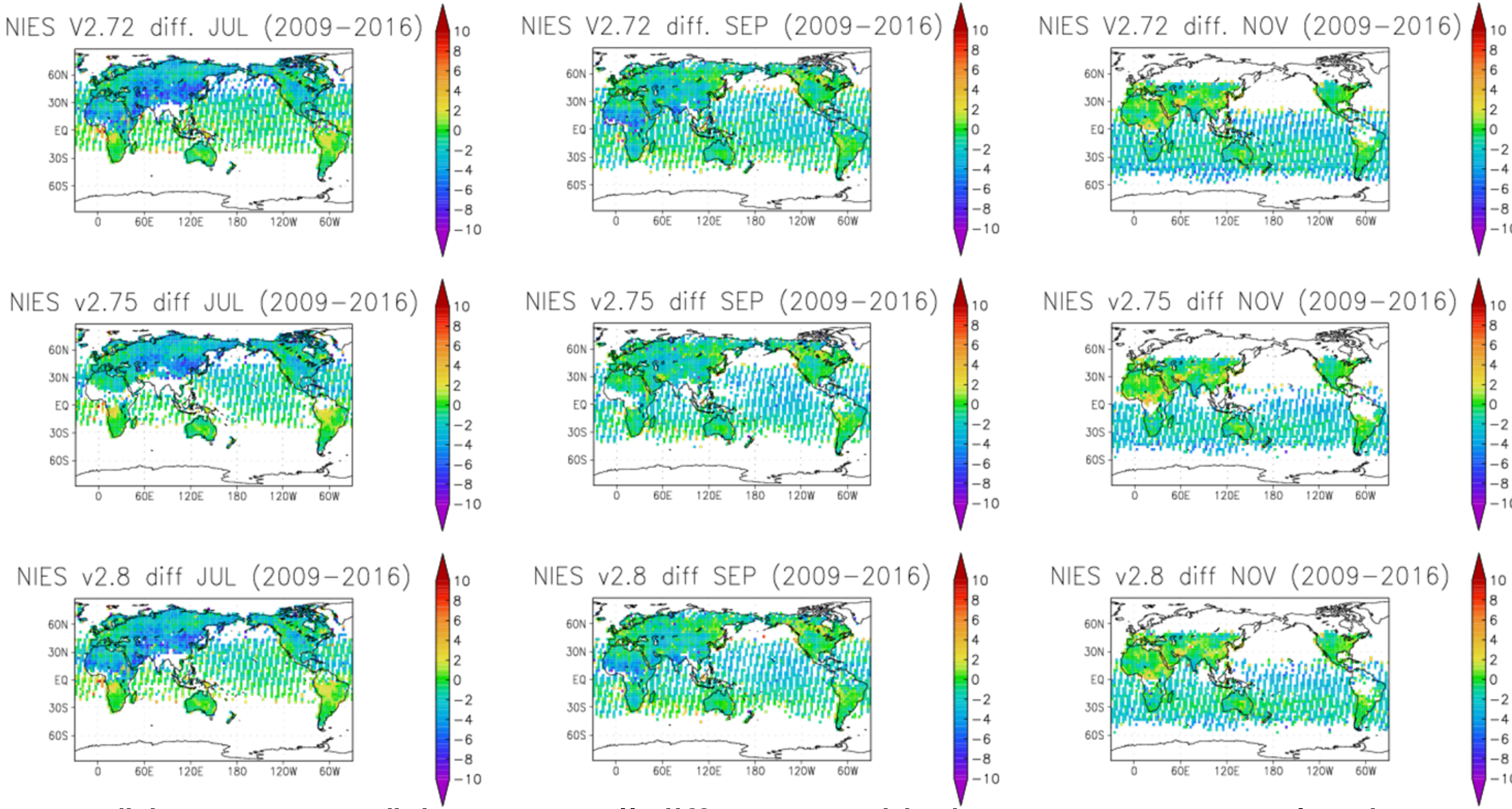
NIES GOSAT products against JMA XCO2



V2.75 (bias corrected) has a small difference with the JMA XCO2 on land compared to V2.72.

In V2.72 grid points (2.8°) with a large difference from JMA analysis values are more than V2.75 and V2.8.

NIES GOSAT products against JMA XCO2



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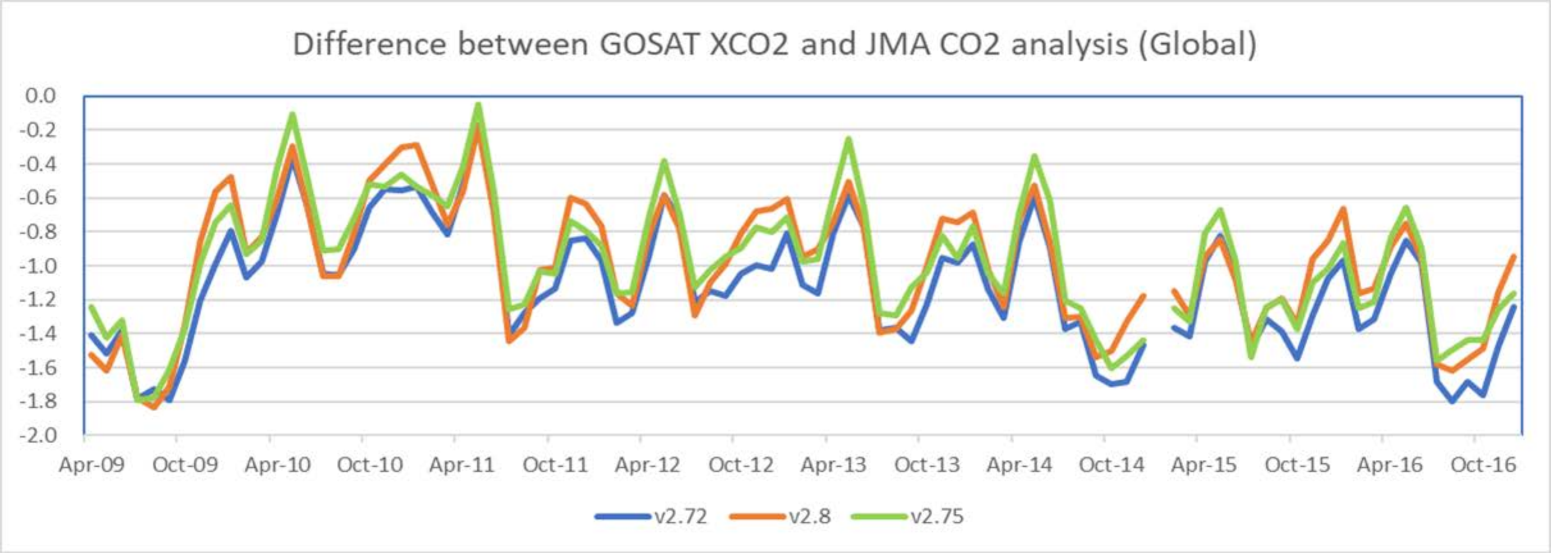
NIES GOSAT products Summary



Ver.	Global	Land	Ocean	N. Land	Tr. Land	S. Land	N. Ocean	Tr. Ocean	S. Ocean
2.72	-1.11	-0.88	-1.17	-0.93	-0.94	-0.59	-0.30	-1.17	-0.92
2.8	-0.99	-0.68	-1.17	-0.74	-0.78	-0.38	-0.19	-1.29	-0.67
2.75	-0.97	-0.45	-1.52	-0.61	-0.06	-0.39	-0.46	-1.66	-0.98

In global scale, there is no significant trend in the difference between GOSAT L2 XCO2 and JMA XCO2. We assumed that 10 year's difference as a bias of GOSAT L2 XCO2.

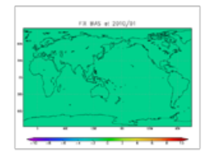
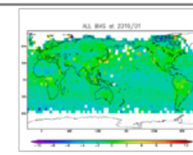
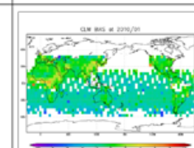
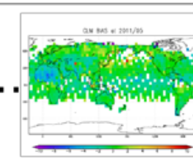
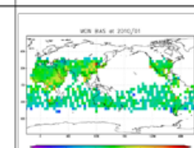
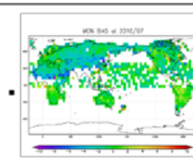
The V. 2.75 and V. 2.8 difference is smaller than V. 2.75 especially land region.

Inversion settings (CNT)

Analysis Target	Monthly CO2 flux (1985 – 2017)
Inverse model	Bayesian Synthesis
Region Number	22 (TransCom 3)
Transport model	GSAM-TM (TL95L60)
Meteorology	JRA-55
Prior Flux	CDIAC, CASA, JMA Ocean
In-situ observation	WDCGG (-150 sites)
Observation data uncertainty	1 – 3ppm (WDCGG), 3ppm (GOSAT V2.8)

Control case, we use only in-situ (surface, ship, aircraft) data from WDCGG.

Satellite bias correction experiments

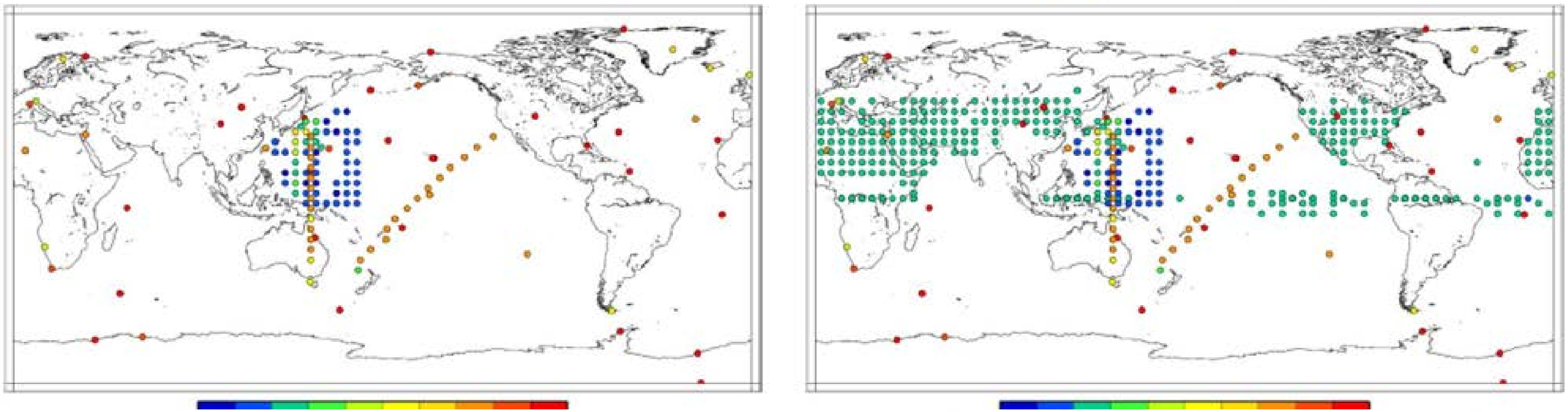
Method	Features	Satellite bias distribution
RAW (w/o bias correction)	It is possible to completely use signals of satellite observation data.	-
FIX (Calculate global mean bias)	It is possible to effectively use signals of satellite observation data.	
ALL (Calculate a bias correction map)	It is possible to remove spatial dependent bias.	
CLM (9 year's mean monthly difference)	It is possible to remove spatial and seasonal dependent bias.	 …  …
MON (JMA CO2 distribution)	It is possible to remove spatial and temporal bias against JMA distribution.	 …  …

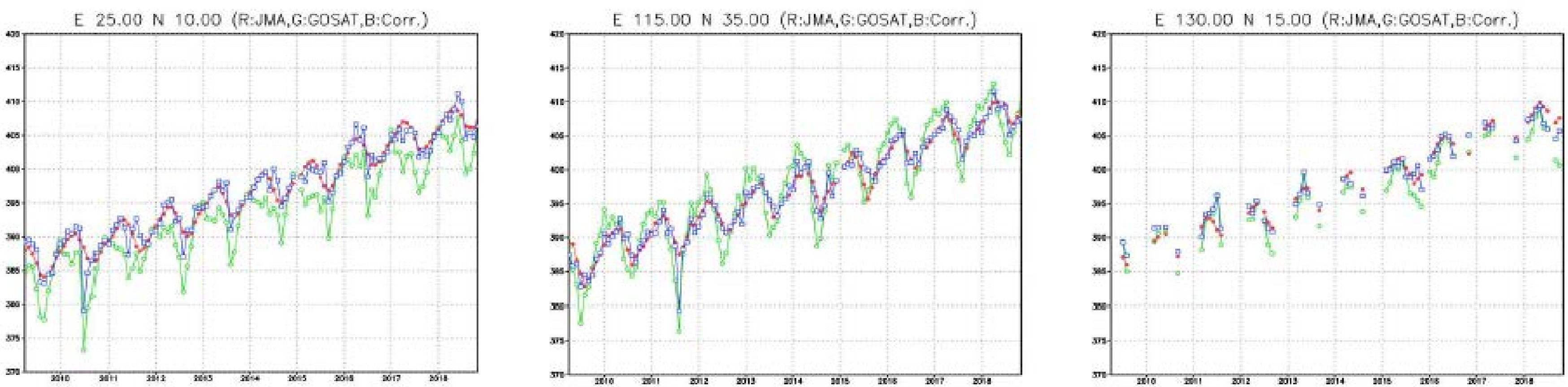
To confirm the impact of the bias correction on the reverse analysis, five bias corrections (one without correction) were performed.

We add each bias corrected data to control case.

Satellite observation distribution

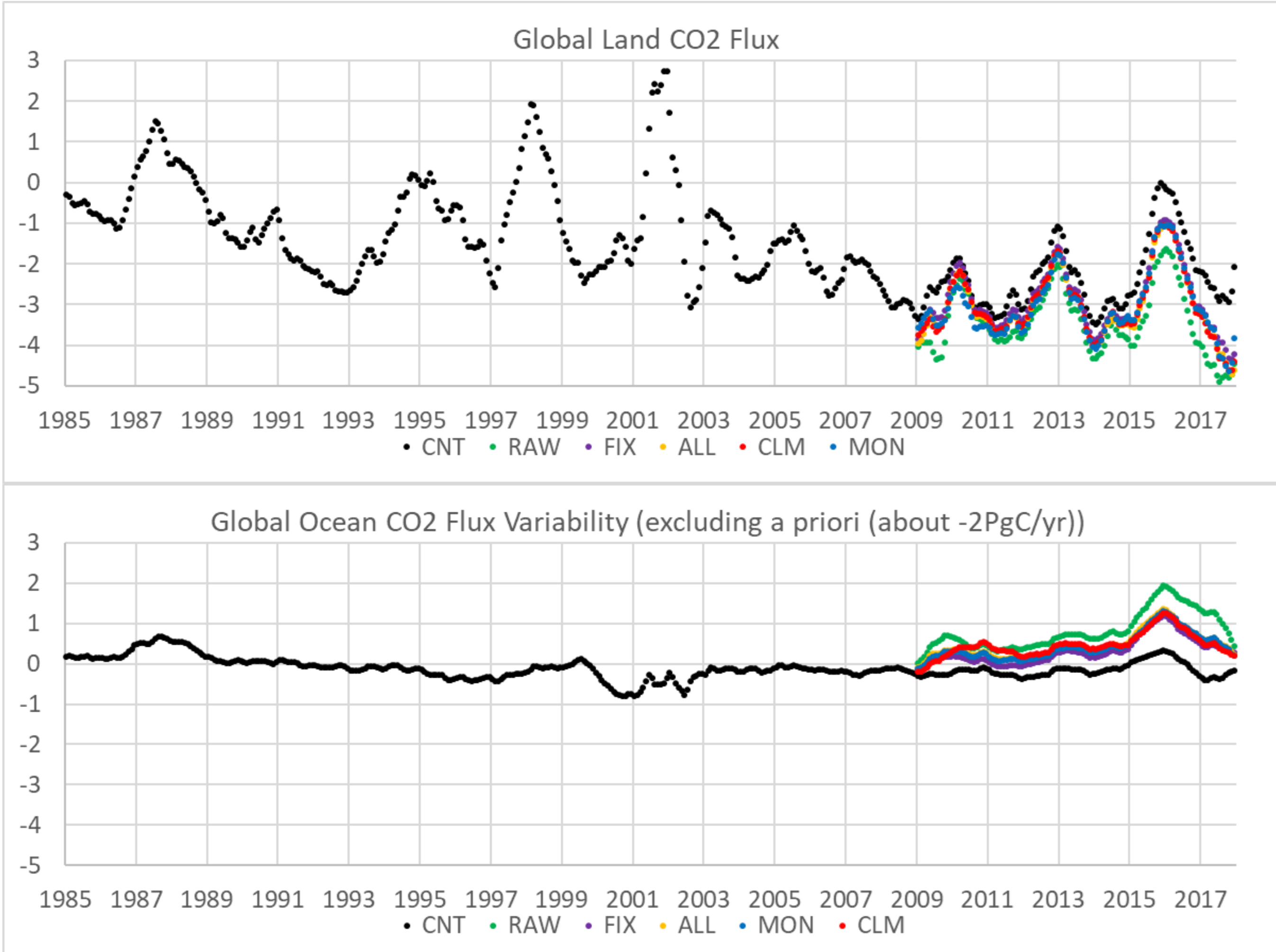
CNT case SAT2 - 6 case





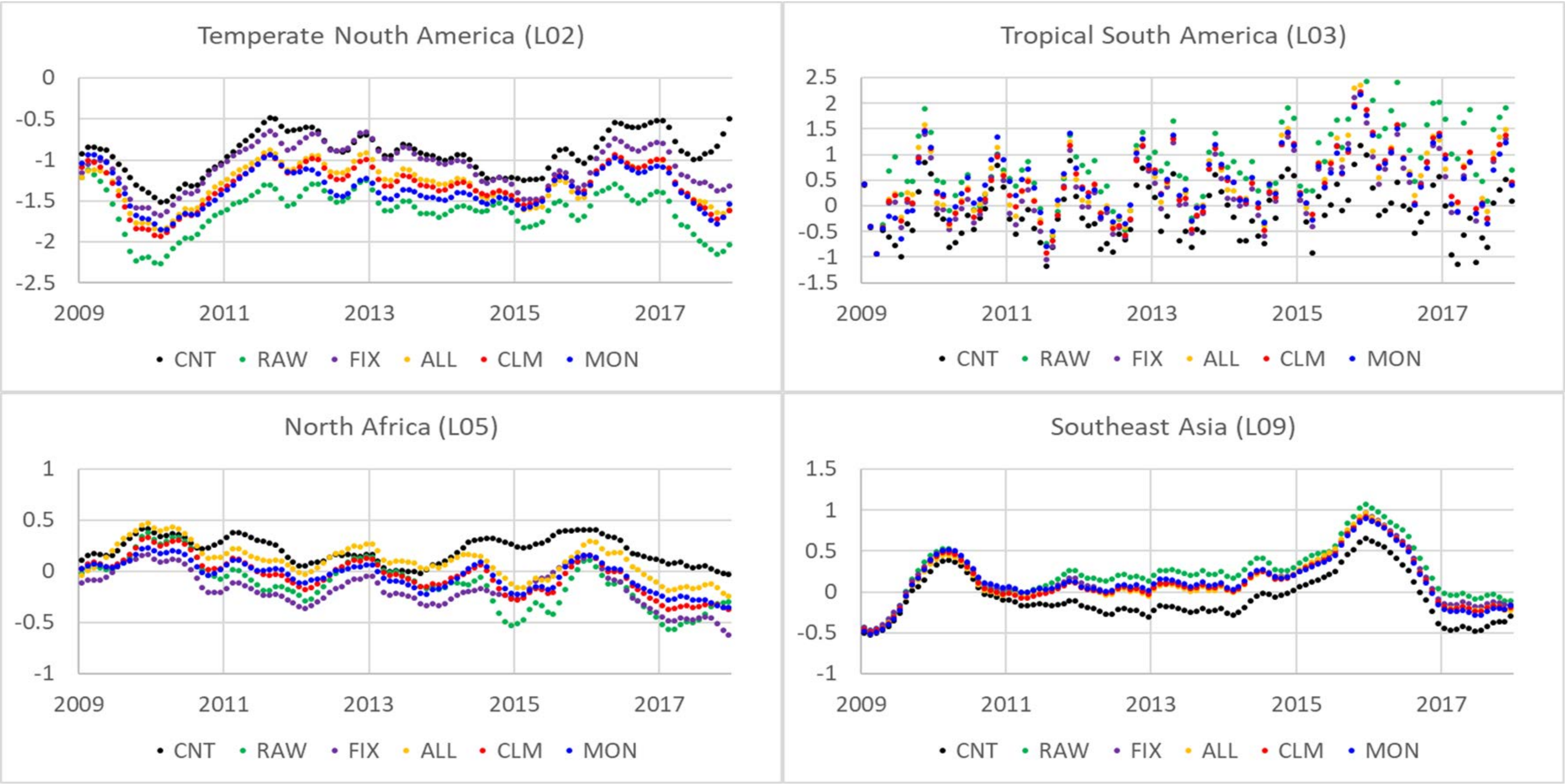
GOSAT was able to obtain observation data for land areas from the tropics to mid-latitudes (top figure).
The figure below shows the values before GOSAT correction (green), JMA inverse analysis values (red), and after GOSAT correction (blue). The bias could be corrected using the GOSAT signal using the JMA analysis.

Eestimated global CO2 flux



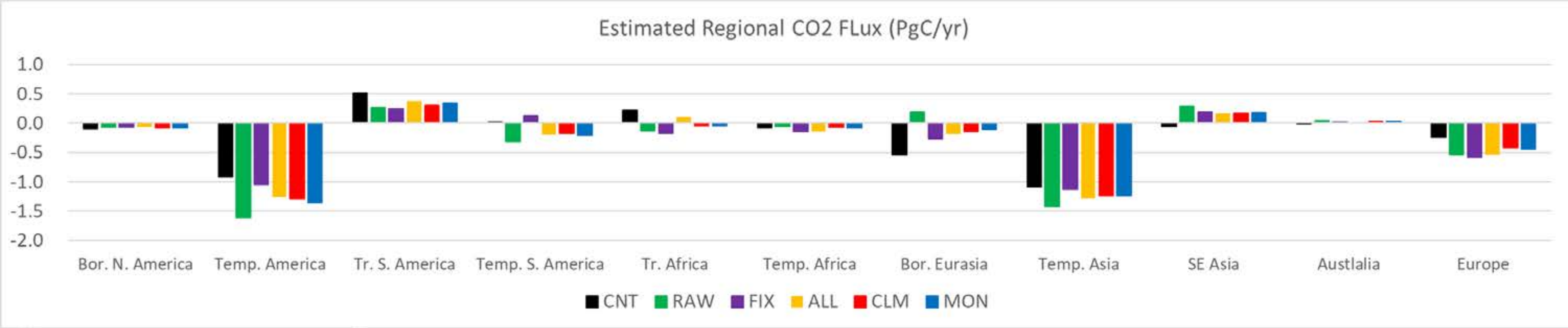
CO2 flux moving average (PgC./r) for land (top) and ocean (bottom), excluding a priori information (about 2 PgC / yr) for ocean. Colors indicate no correction (green), fixed value (purple), annual average (orange), climatic value (red), monthly average (blue).

Estimated regional CO2



In the CO2 flux moving average (PgC./r) in each area, the ocean excludes a priori information (about 2 PgC / yr). Black color is standard, no correction (green), fixed value (purple), annual average (orange), climatic value (red), monthly average (blue).

Total regional CO2 flux (2009-2017)



CO2 flux annual average (PgC./r) during the analysis period in each region is shown, black is standard, no correction (green), fixed value (purple), annual average (orange), climate value (red), monthly average (Blue).

It can be seen that the regional CO2 balance changes depending on the bias correction method of satellite observation data.

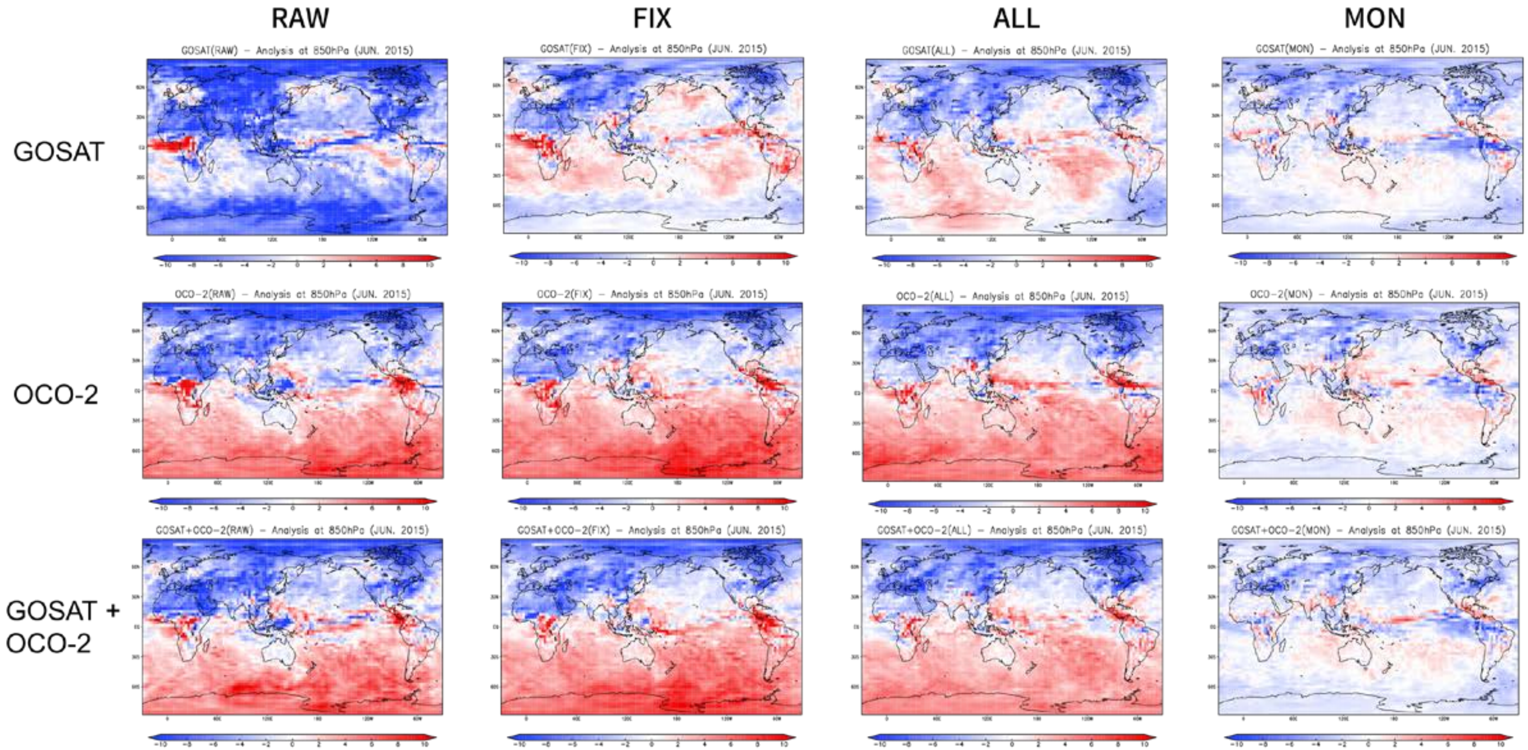
Ongoing research (LETKF)

Analysis Target	6-day mean CO_2 flux (2014/09 – 2015/12)
Data assimilation Scheme	Local Ensemble Transform Kalman Filter (Miyoshi et al., and Sekiyama et al.)
Assimilation window	6 days
Ensemble size	32 members
Localization Scale	Horizontally 3,000km with a Gaussian function
Transport Model	MJ98-CDTM (CDTM directly-coupled with MJ98)
Resolution	T42L30 (sigma-pressure hybrid coordinate)
Meteorology	Nudged towards JRA-55 (Kobayashi et al.)
Prior CO2 flux	Fossil fuel burning (CDIAC), Biosphere (CASA) and Ocean (Takahashi), adapted in TransCom 3)

We construct carbon cycle analysis system making use of LETKF with higher temporal resolution with on-line transport model.

In our experiment, we tried to assimilate multiple satellite data (GOSAT and OCO-2) with our bias correction system.

Preliminary results



MON experiment shows smallest bias against JMA CO2 analysis. RAW experiment shows large negative/positive bias due to their concentration bias. Without bias correction, differences are largest and this means that we should carefully take care of satellite bias. Global mean RMSE (bottom table) supports this consideration.

Unit: ppm	RAW	MON	ALL	MON
GOSAT	5.90	3.35	3.03	2.21
OCO-2	3.86	3.37	2.97	2.09
GOSAT+OCO-2	3.90	3.321	2.99	2.11

Today's presentation

1. Background
2. Bayesian synthesis Inversion
3. Making use of satellite data
4. Summary

Summary

・Greenhouse gases have a significant effect on global warming, etc., but can also affect weather with a short time scale due to seasonal fluctuations.

・Many satellite observations are expected in the future, but these data have not been used effectively at this time.

・We have developed a method to correct the bias of satellite observation data using independent analysis.

・By using this method, we were able to correct the bias of the satellite observation data that changes spatiotemporally and analyze the carbon budget with reduced uncertainty.

・By using this method, it is expected that multiple satellites can be analyzed simultaneously.

Future plans

Multi-satellite carbon cycle analysis using the same bias correction for other satellite observation data

Correspondence to increase in the number of matrix dimensions (surface only: 60,000 x 10,000, addition of satellite: 200,000 x 10,000)

・Increase in the number of area divisions (22 ➔ 64, etc.)

Correspondence to matrix dimension increase

・Implementation of more advanced data assimilation method (higher resolution while avoiding the above problems)

Currently conducting experiments using LETKF

・Transport model update (from GSAM-TM to GSAM-MRI)

Evaluation of North-South transportation, Age of year, etc.

・Evaluation of impact on weather forecast

May work for seasonal forecasts

Sense of low temperature in summer and high temperature in winter on land

Acknowledgement

GOSAT Observation data are provided from GOSAT Research Announcement office. We thank the NOAA/ESRL and other institutions for making their observation data available to us.

This work is supported by the Environment Research and Technology Development Fund (2-1701) of the Environmental Restoration and Conservation Agency of Japan and JSPS KAKENHI Grant Number 19K12312 and 19H04316.

We also thank R. Law, K. Gurney, and P. J. Rayner for providing the time-dependent inversion (TDI) model code to us.

We also thank T. Miyoshi and T. Sekiyama for providing LETKF code to us.

Thank you very much for your attention!