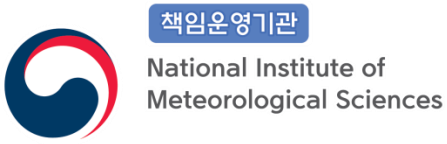
The project proposal for WMO IG^{3}IS endorsement



National Institute of Meteorological Sciences

Korea Meteorological Administration

Republic of Korea

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Contents

1. Project title

INVERSE-KOREA: INverse modeling for **V**alidating and **E**valuating of the **R**eduction of **S**ectoral greenhouse gas **E**missions in KOREA

2. Contact information

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3. Background

As the concerns on the impacts of climate change on the human and natural sectors increase, limiting or reducing greenhouse gas (GHG) emisisons from the significant emitter nations has become critical. Towards the globally-coordinated efforts for limiting future GHG concentrations, a number of nations including South Korea have pledged goals for future GHG emissions amounts. For meeting these goals, every nation needs reliable monitoring of GHG inventory in the region.

As a part of the efforts for meeting the national GHG emissions goal in South Korea, National Institute of Meteorological Sciences/Korea Meteorological Administration (NIMS/KMA) proposes to develop a system INVERSE-KOREA (INverse modeling for Validating and Evaluating of the Reduction of Sectoral greenhouse gas Emissions in KOREA) to monitor the GHG inventory in South Korea. NIMS/KMA has a long history and extensive specialties in measuring atmospheric greenhouse gases and has been contributing to the World Meteorological Organization/Global Atmospheric Watch (WMO/GAW) GHG measurements. NIMS/KMA is also carrying out various projects for tracking the GHG sources and sinks within South Korea such as the measurements for mole fractions and fluxes using various platforms including WMO/GAW in-situ stations, an airplane, a research vessel, a Total Carbon Column Observing Network (TCCON) station, and a tall tower (307 m). On the basis of the extensive experience, KMA installed one of the WMO/GAW central facilities, World Calibration Centre for SF_6 (WCC-SF_6), which led to improvements in the quality of the SF_6 measurements at the GAW stations. These efforts at NIMS/KMA resulted in a number of high-impact peer-reviewed publications (Oh et al.,2018; Lee et al., 2019; Lee et al., 2020; Li et al., 2020).

The government of South Korea declared a policy to achieve carbon neutrality by 2050 as stated in the President of the Republic of Korea, Moon. Supports for the policy

comes not only from government levels but also from a majority of general public in South Korea on the science basis. In those context, NIMS/KMA lanched the IG^{3}IS project to support the national GHG reduction policy by reducing the uncertainty in the national emission inventory through reconciliation of the bottom-up estimates and the top-down estimates of the national GHG inventory as well as by frequent sectoral emissions monitoring.

4. Purpose

This project aims to develop a high-resolution (1~10 km horizontal resolution) GHG inversion system for top-down GHG inventory estimates over South Korea based on a state-of-the-art NWP model and the GHG observation network to understand the sources and sinks of GHGs including CO_2, CH_4, and SF_6 in South Korea.

We will frequently estimate the sectoral emissions changes in GHG to support the national GHG reduction policy for individual emission sectors in a timely manner. The top-down estimates to be established in this project can minimize the uncertainty in the national emission inventory for reliable verification of the Nationally Determined Contributions (NDC) that are critical in carrying out the policy for achieving carbon neutral by 2050. The project products will be used to provide consulting to individual emission sectors to conform to the emissions policy.

The top-down estimates generated using the proposed system will also be examined against the current bottom-up emissions estimates. The cross-examination of the two different estimates will help to quantify the uncertainties in the estimated emissions to support the decision makers.

5. Project Outline

- Target: South Korea (National Scale)

- Cooperative institutes (Figure 1 and Table 1):
  - National Institute of Meteorological Sciences/Korea Meteorological Administration (NIMS/KMA)
  - Seoul Research Institute of Public Health and Environment/Seoul Metropolitan Government (SRIPH/SEOUL)
  - Korea Research Institute of Standard and Science (KRISS)

- Yonsei University

➢ Main Users:

- National GHG Inventory Management Committee
- Greenhouse Gas Inventory and Research Center

➢ Funding: Annual funding of 900,000 US dollars for model developments, and 1,000,000 US dollars for observations during the first phase, 2021-2023. The funding can be increased from 2024 on the basis of the evaluation of the first-phase performance in 2023. This funding plan is fully supported by KMA.

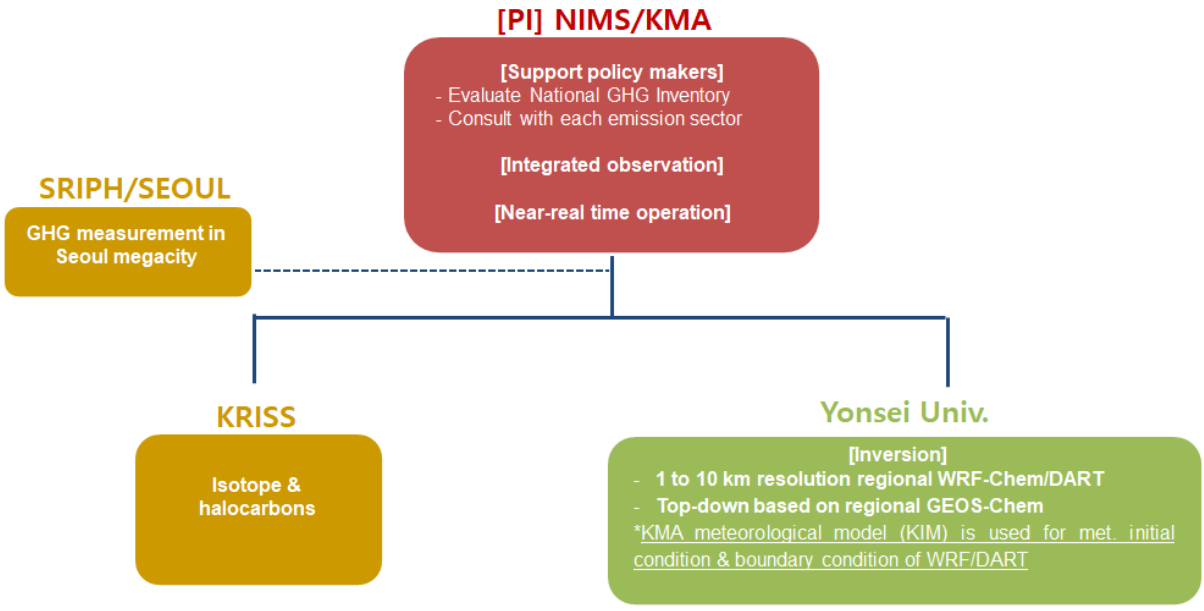

Figure 1. The organization for this project. The institutes connected with solid lines are funded by NIMS/KMA for research and development. The SRIPH/SEOUL joins the project based on the MoU with NIMS/KMA.

Table 1. Role of each institute

Institute *Project manager*	**Role**
NIMS/KMA ***(PI)****Dr. Sangwon Joo* *Dr. Haeyoung Lee*	**- PI of this project** **[Support policy makers]** -Demonstrate, modify, and submit the products to National GHG Inventory Management Committee -Consult with each emission sector **[Near-real time operation and service]** **[National scale GHG observation]** -In situ observation (3), TCCON station (1) -An aircraft (1) -A vessel (1) -A tall tower (1) **[Meteorological observation]** **[City scale GHG obervation in Seoul]** -In situ flux measurement of CO_2 (9)
SRIPH/SEOUL *Dr. Hochan Lee*	**[City scale GHG obervation in Seoul megacity]** -In situ surface observation (3)
KRISS *Dr. Jeongsik Lim*	**[Observation]** -Isotopes and halocarbons
Yonsei Univ. *Prof. Jinkyu Hong*	**[Main-Inversion]** -Top-down emission estimation based on 1 to 10 km resolution regional WRF-DART* *Weather Research and Forecasting Model- Data Assimilation Research Testbed **[Sub-Inversion]** -Top-down emission estimateion based on Geos-Chem** ** Goddard Earth Observing System- Chemical Transport Model

6. Observation

A. GHG observations

(a) **In-situ observations**: Since 1999, KMA has been monitoring the atmospheric CO_2, CH_4, N_2O, SF_6 and CFCs mole fractions at Anmyeondo (AMY, 36.53°N, 126.32°E, 47 m above ground level from a 40 m tower). In 2012, KMA expanded the monitoring network towards the southwest (Jeju Gosan Suwolbong, JGS, 33.30°N, 126.16°E, 74.47 m with 12 m tower) and the east (Ulleungdo, ULD, 37.48°N, 130.90°E, 220.9 m with 10 m tower) in order to cover the entire South Korea region for a better understanding of GHG sources and sinks (Figure 2(a)). National Oceanic and Atmospheric Administration/ Earth System Research Laboratory (NOAA/ESRL) flasks are collected at AMY not only for halocarbons but also for other major gases. More quasi-continuous measurements for halocarbons and isotopes will be made from 2021 in cooperation with KRISS.

(b) **Tall tower**: A tall tower is operated at Bo-Seoung (BS) station located in southwest Korea (Figure 2 (a)). The samples are taken at 150 m and 300 m above ground level (AGL) and are analyzed using Cavity Ring-Down Spectroscopy (CRDS) for CO_2 and CH_4.

(c) **Research aircraft:** CRDS onboard a Beechcraft King Air 350, a KMA research aircraft ("Nara" hereafter) measurement platform since 2018, has been used to measure in situ CO_2, CH_4, and CO dry mole fractions. The atmospheric profiles of these gases are measured for the altitude range between 0.6 km and 9.0 km over the western (AMY) and eastern (ULD) background stations for South Korea. In addition, low-altitude (below 1 km Above Mean Sea Level (AMSL), mostly within the boundary layer) surveys over the Yellow Sea monitor the westerly trans-boundary pollutants transports. The results are intercompared against the Fourier Transform Spectrometer (FTS) measurements located in AMY (see item (e) for more detail information). We plan a total of 41-day flights per year over South Korea (Figure 2(b)).

(d) **Research vessel:** CRDS is also installed on, the KMA research vessel (named as "Gisang 1"), to analyze CO_2 and CH_4 during specific measurement campaigns (See item (f) for more details).

(e) **FTS**: The high-resolution ground-based Fourier Transform Spectrometer (g-b FTS) aims to verify the spaceborne carbon observations and to calculate the vertical profiles of mole fractions of GHGs within the atmosphere. The solar

spectra are recorded by the g-b FTS. The AMY staiton is also one of the TCCON and uses its own retrieval software to retrieve column-averaged mixing ratios of several climate-relevant gases, including CO_2, N_2O, CH_4, and CO, from g-b FTS solar absorption spectra.

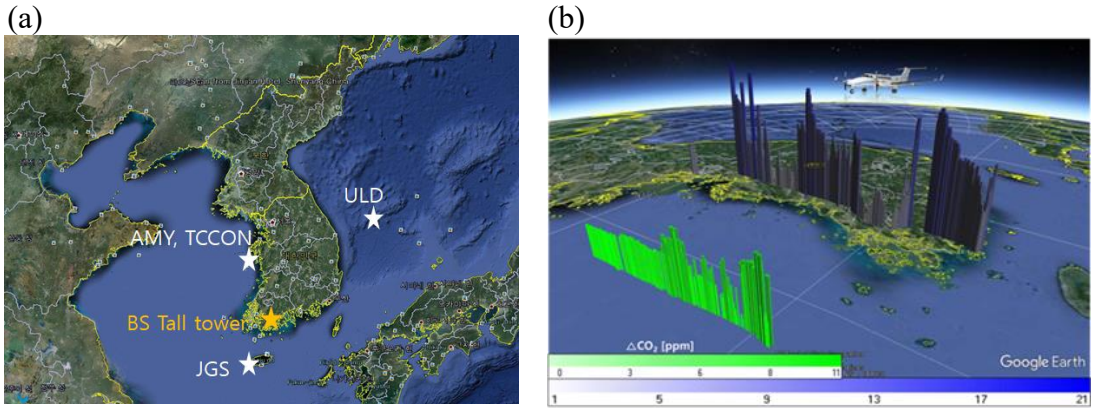

Figure 2. The in situ measurements from (a) surface stations of AMY (Anmyeondo), ULD (Ulleungdo), JGS (Jeju Gosan Suwolbong), and BS (Bo-Seoung) tall tower, and (b) the flight ("Nara").

(f) **Observation Campaigns**: Yellow-Sea Air Quality Campaign (YES-AQ) is conducted from March to April (or May) every year to monitor the air from Asia-Continent in spring. All 7 institutes join this campaign. During the campaign, the "Gisang 1" (research vessel) covers a track on the Yellow Sea between AMY and JGS; "Nara" (research aircraft) also covers the same track during the campaign. A data conference is organized in September to share the measurement data and to discuss the result of the campaign among the participating institutions. The data gathered in the data base with an integrated format.

(g) **Isotope**: The isotope data were collected since 2013 with NOAA flasks. From 2021 quasi-continuous measurements of CO_2 isotopes will begin at AMY and will be expanded to include CH_4 in 2022. ^{14}C in CO_2 analysis was perfomred on the samples collected from 2014 to 2016; it has been resumed this year (2021).

(h) **Portable total column GHG observing sensor**: To monitor GHGs, we are developing a sensor for measuring the atmospheric composition, mainly focusing on GHGs such as CO_2 and CH_4. This relatively inexpensive optical equipment (column) provides extensive environmental information (urban and

non-urban) and is characterized by small size and weight, minimal power consumption, and wireless communications. This project is currently ongoing with Harvard Medical School.

(i) **Seoul Megacity Observations**: Within the Seoul metropolitan area, there are 9 flux towers operated by NIMS/KMA and 3 in situ measurement sites operated by SRIPH/SEOUL (Figure 3). NIMS/KMA and SRIPH/SEOUL have established an MoU for sharing data and observation techniques for a collaborative effort for GHGs monitoring. The two institutions also agreed to collect data at additional observation sites. These data will be used for megacity campaign in 2023 to expand the INVERS-Korea project to city-scale

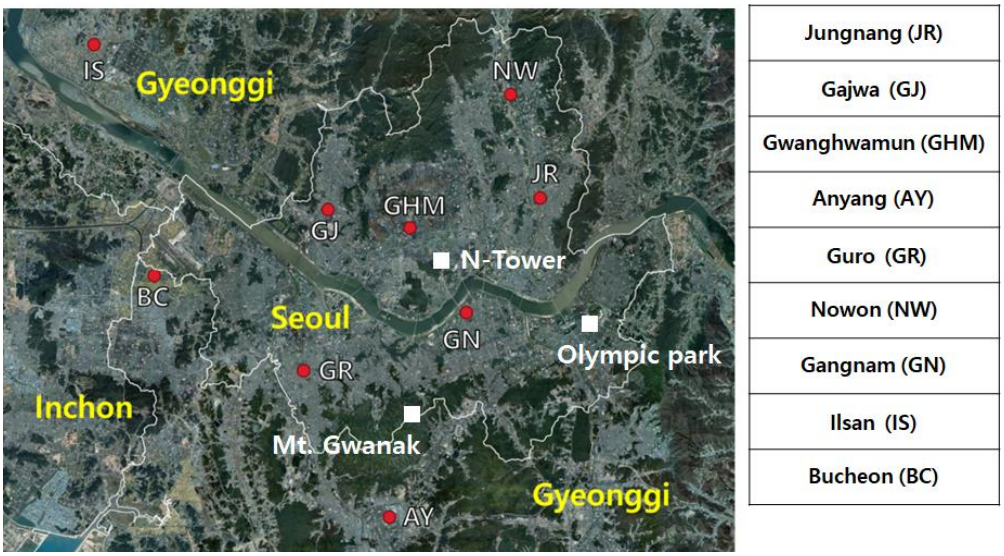

Figure 3. The GHG flux measurement network in Seoul managed by NIMS/KMA (red circles in a map) and CRDS network by SRIPH/SEOUL (white square).

B. Meteorological observations

(a) Nation-wide observation : Korea is well known for a dense weather observation network in WMO. South Korea is covered with about 600 surface observation stations in 13 km resolution, 26 upper air observation stations (8 radiosonde observations, 9 windprofilers and 9 microwave radiometers) (Figure 4). In addition, 128 marine observation stations and 15 weather radars, are in operation. PBL information is an important weather component for accurate transport and dispersion of GHGs. Automated Shipboard Aerological Programme (ASAP) equipped in research vessel and dropsonde onboard research aircraft are operated to observe weather processes at the planetary

boundary layer (PBL) over the ocean. Five doppler Lidars and 95 ceilometer backscatter data will be used to retrieve PBL heights. The PBL observations are used to evaluate the weather model performance at first and will be assimilated in the inversion framework later. The distribution of the ceilometers is depicted in Figure 5.

(b) City-specific observation at Seoul: NIMS/KMA maintains city specific observational sites centered in the city of Seoul, including 26 surface observations, 6 wind lidars, 2 aerosol lidars, 7 radiometers, 2 ceilometers and 14 flux towers. The observation network is shown in Figure 6.

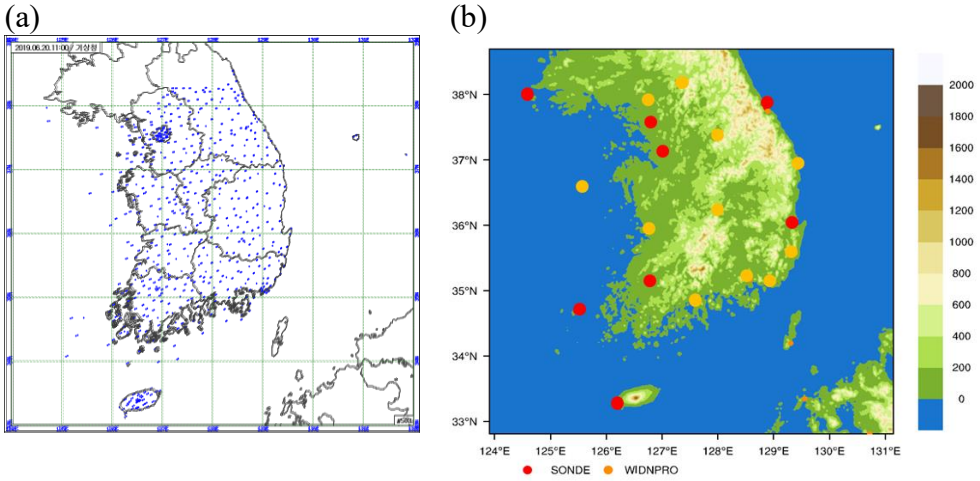

Figure 4. Horizontal distribution of (a) surface weather stations and (b) upper level observations such as radiosondes (red) and windprofilers (orange).

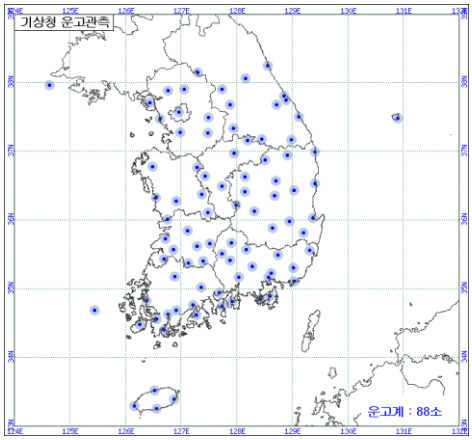

Figure 5. Horizontal distribution of ceilometers in Korean Peninsula.

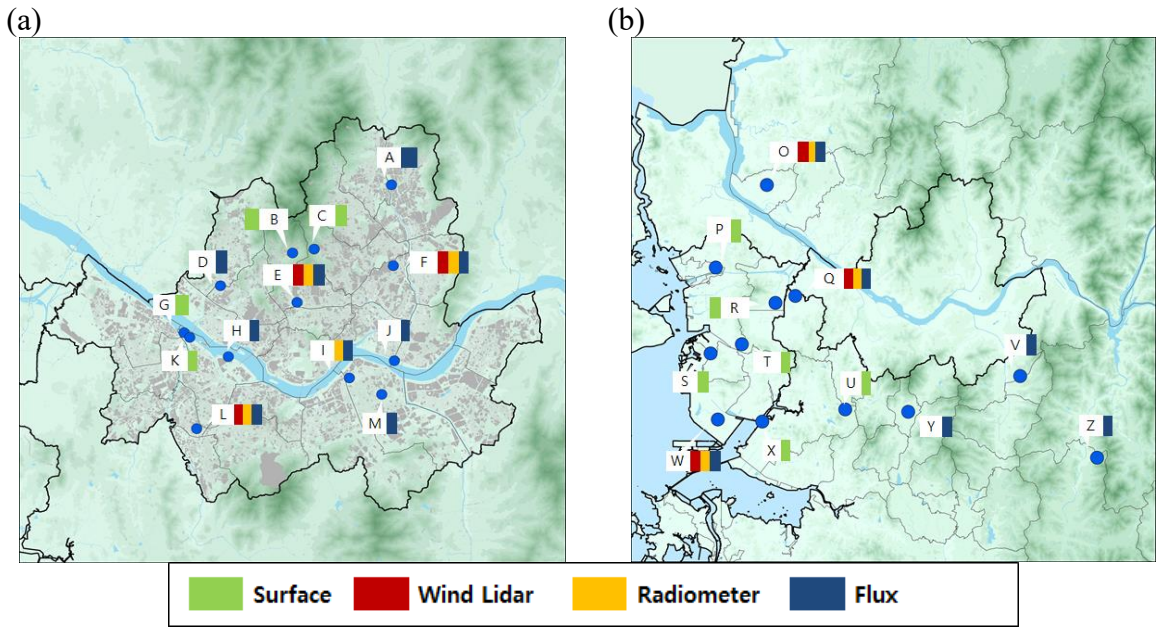

Figure 6. Observation network in Seoul(a) and outskirt of Seoul(b) operated by the NIMS/KMA. The observation sites are located in the blue dots and the deployed instruments are shown in coloured bars at the right side of the site name.

7. Inversion method

A. Weather model

KMA operates a NWP model, Korean Integrated Model (KIM) since 2020. The 12-km resolution KIM system consisting of a spectral-element non-hydrostatic dynamical core on a cubed-sphere grid and a state-of-the-art physics parameterization package has been developed in a real-time forecast framework, with initial conditions from the advanced hybrid four-dimensional ensemble variational data assimilation (4DEnVar) over its native grid (Hong et al. 2018). The advantage of the KIM is that it incorporates all of the local weather observations over South Korea including AWS data, local Aircraft Meteorological Data Relay (AMDAR) data, ground Global Navigation Satellite System (GNSS) data, wind profiler data and so on into operational forecasts. The KIM analyses are used as the initial and boundary weather conditions of the regional transport models in the inversion system (i.e. WRF) and it helps to depict the atmospheric flow better over the Korean Peninsula and results in better inversion results.

B. Transport and inversion method

We will conduct regional-scale CO_2 and CH_4 simulations using the WRF-Vegetation Photosynthesis and Respiration Model (VPRM) (KIM analysis is used as a meteorological initial and boundary conditions for the WRF simulation) that

has been previously used in the Korea-United States Air Quality (KORUS-AQ) 2016 field campaign. WRF-VPRM has been developed specifically for emissions estimates at regional scales and for predicting CO_2 and CH_4 mole fractions at fine horizontal resolutions (1 to 10 km). Coupling WRF-VPRM to the DART system will allow us to optimize not only the total CO_2 and CH_4 emissions, but also to estimate separate contributions of these gases from the anthropogenic, terrestrial, and oceanic emissions sources.
The large uncertainties in CO_2 and CH_4 emission estimates mainly originate in the uncertainties in terrestrial emissions. In WRF-VPRM, they mainly stem from the uncertainties in four parameters related to Gross Ecosystem Exchange (GEE) and respiration rate. The two GEE-related parameters include the maximum quantum yield and the half-saturation value of photosynthetically active radiation. The other two are the slope and the intercept of the respiration rate linear model. In WRF-VPRM, each of the eight land use types is assigned a default set of values for these parameters. More advanced applications include location-specific empirically-derived parameter values. So far, due to the lack of relevant observational data, only default values of these parameters have been used in studies for South Korea.

Prior emissions in our project will include Regional Emission inventory in ASia (REAS) v3 for anthropogenic emissions, Carbon Tracker Asia for terrestrial biosphere flux and Estimating the Circulation and Climate of the Ocean, Phase II (ECCO2)-Darwin available at an 18-km horizontal grid spacing for ocean flux. For CH_4 emissions, we will use Emission Database for Global Atmospheric Research (EDGAR) v5 gridded emissions, combined with a new dataset on fuel exploitation dataset. Wetland and termite emissions will be modeled in VPRM. For both CO_2 and CH_4 emissions, we will use Fire INventory (FINN) from NCAR emissions for wildfire. Once the WRF-VPRM/DART framework is well tested for both CO_2 and CH_4, we will also include SF_6 into the framework. It will be introduced as a single tracer into WRF-VPRM, as the lifetime of SF_6 is 3200 years. Because of the sparse observational data available for SF_6, we will consider conducting a country-level inverse modeling estimate, rather than estimating emissions at 20 km horizontal spacing.

The WRF-DART modeling system is the Eulerian model and has several advantages despite more computational cost and numerical diffusion compared to the Lagrangian models. The Lagrangian model should be driven by atmospheric forcing and highly depends on the boundary condition provided by atmospheric models accordingly. Notably, in East Asia including South Korea, surface heterogeneity is important because of its mountain regions and various land cover and land use and it is, therefore, necessary to consider such surface heterogeneities and their related spatio-temporal evolution of planetary boundary layer in

modeling atmospheric drivers. In this perspective, our modeling system will provide relevant information on carbon cycles in South Korea and useful insights for application to other regions. We are also implementing a Lagrangian model for the comparison and so can produce uncertainties in our estimation in this region.

8. Implementation Plan

The first phase takes 3 years from 2021 to 2023 and consists of 3 steps are as follows:

1) Installing the inversions system, mainly the WRF-DART based system (Sub: Geos-chem).

2) Testing and evaluating the installed inversion systems and compare with the bottom-up national inventory reports.

3) Starting the service of near-real-time top-down emission products for inventory communities (i.e. "National GHG Inventory Management Committee" and "Greenhouse Gas Inventory and Research Center") and public (Figure 7).

We target CO_2 from 2021 and will apply this inversion system to CH_4 and SF_6 successively. In 2023, we expect to have a campaign in Seoul, to expand the inversion system to a city scale. This campaign can be linked to the second phase of the INVERSE project targeting Seoul. Isotope measurements also will be deployed for this project so that the isotope ratio of $^{13}C/^{12}C$ in CO_2 will be installed at AMY in 2021 and CH_4 in 2022.

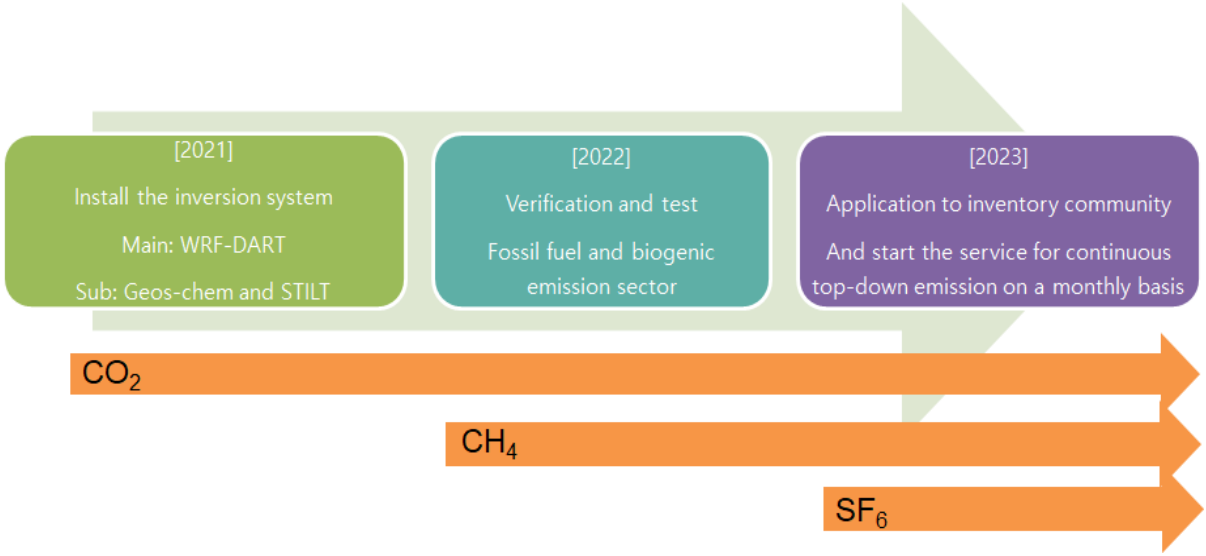

Figure 7. The schedule and main products from 2021 to 2023 as starting with CO_2.

9. Expectation

- **Policy support**
  - NIMS/KMA joined the National GHG Inventory Management Committee directed by the vice minister of the Ministry of Environment to support scientific evaluation of the national GHG emission and to finalize **the national inventory report** every year. We provide our productions to the committee and support them to compare and improve emissions data. This data can be included National Inventory Report when the committee agreed.
  - The top-down emission will be reported near-real time to ensure the quality of the emissions data by sectors and to contribute to the **national policy to achieve the GHG net zero by 2050** in the Republic of Korea.
  - Korea is a member of United Nations Framework Convention on Climate Change (UNFCCC) so that the products from IG^{3}IS projects can be used to **support and consult each emission sector** at national scales.

- **Data policy:** All observation data from surface platforms will be shared through the World Data Centre for Greenhouse Gases (WDCGG) and NIMS/KMA webpage continuously for other countires and science communities.

- **Capacity building**: As one of the WCC-SF_6 activities, NIMS/KMA has hosted the Asia-Pacific GAW workshop on Greenhouse gases since 2009 and education courses since 2014. Not only Korean students but also the technicians/researchers in other Asia-Pacific regions have attended this course. This education courses are more heavily focused on measurements but will expand to the modeling part for IG^{3}IS. Since all travel fees are covered by NIMS/KMA, this course can be productive for scientists not only from Korea but also from developing countries.

- **Initiative project**
  - **[Portable sensor campaign]** NIMS/KMA is currently developing a portable total column GHG observing sensor with Harvard Medical School. This is a new approach for low-cost sensor community and when developed, the sensor can be used for the city- to national-scale measurements

  - **[Megacity project]** The SRIPH/SEOUL has joined the project to cooperate in the observation network for the national-scale GHG emissions estimates. The project will be expanded to include a high-resolution urban GHG inversion system for Seoul to support the GHG mitigation efforts at the city level. The system will apply to other megacities in the Korean Peninsula by incorporating city-specific data.

10.References

Hong, S. Estimating the Circulation and Climate of the Ocean, Phase II H., Y. C. Kwon, T.-H. Kim, J.-E. Esther Kim, S.-J. Choi, I.-H. Kwon, J. Kim, E.-H. Lee, R.-S. Park and D.-I. Kim: The Korean Integrated Model (KIM) System for Global Weather Forecasting, Asia-Pac. J. Atmos., 54, 267–292, 2018

Lee, H., S.-O. Han, S.-B. Ryoo, J.-S. Lee, G.-W. Lee: The measurement of atmospheric CO_2 at KMA GAW regional stations, its characteristics, and comparisons with other East Asian sites. Atmos. Chem. Phys. 19, 2149–2163, doi.org/10.5194/acp-19-2149-2019, 2019

Lee H., E. J. Dlugokencky, J.C. Turnbull, S. Lee, S.J. Lehman, J.B. Miller, G. Pétron, J.-S. Lim, G. Lee, S.-S. Lee, Y.-S. Park, $^{14}CO_2$ observations in atmospheric CO_2 at Anmyeondo GAW station, Korea: implication for fossil fuel CO_2 and emission ratios, Atmos. Chem. Phys. 20, 12033-12045, 2020

Li, S. Y. Kim, J. Kim, S. T. Kenea, T.-Y. Goo, L. D. Labzovskii, Y.-H. Byun: In-situ aircraft measurements of CO_2 and CH_4: Mapping spatio-temporal variations over Western Korea in high-resolutions, Remote Sen., 12, 3093, 2020

Oh, Y.-S., S.T. Kenea, T.-Y. Goo, K.-S. Chung, J.-S. Rhee, M.-L. Ou, Y.-H. Byun, P. O. Wennberg, M. Kiel, J.P. DiGangi, G.S. Diskin, V.A. Velazco, D.W.T. Griffith.: Characteristics of greenhouse gas concentrations derived from ground-based FTS spectra at Anmyeondo, South Korea. Atmos. Meas. Tech. 11, 1–14, 2018