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A global perspective of atmospheric carbon dioxide concentrations

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ABSTRACT

A high-resolution (7 km) non-hydrostatic global mesoscale simulation using the Goddard Earth Observing System (GEOS-5) model is used to visualize the flow and fluxes of carbon dioxide throughout the year. Carbon dioxide (CO_2) is the most important greenhouse gas affected by human activity. About half of the CO_2 emitted from fossil fuel combustion remains in the atmosphere, contributing to rising temperatures, while the other half is absorbed by natural land and ocean carbon reservoirs. Despite the importance of CO_2, many questions remain regarding the processes that control these fluxes and how they may change in response to a changing climate. This visualization shows how column CO_2 mixing ratios are strongly affected by local emissions and large-scale weather systems. In order to fully understand carbon flux processes, observations and atmospheric models must work closely together to determine when and where observed CO_2 came from. Together, the combination of high-resolution data and models will guide climate models towards more reliable predictions of future conditions.

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1. Introduction

Carbon dioxide (CO_2) is the most important greenhouse gas affected by human activity. About half of the CO_2 emitted from fossil fuel combustion remains in the atmosphere, contributing to rising temperatures, while the other half is absorbed by natural land and ocean carbon reservoirs. Despite the importance of CO_2, many questions remain regarding the processes that control these fluxes and how they may change in response to a changing climate. The Orbiting Carbon Observatory-2 (OCO-2), launched on July 2, 2014, is NASA's first satellite mission designed to provide the global view of atmospheric CO_2 needed to better understand both human emissions and natural fluxes. This visualization shows how column CO_2 mixing ratio, the quantity observed by OCO-2, varies throughout the year. By observing spatial and temporal gradients in CO_2 like those shown, OCO-2 data will improve our understanding of carbon flux estimates. But, CO_2 observations can not do that alone. This visualization also shows that column CO_2 mixing ratios are strongly affected by large-scale weather systems. In order to fully understand carbon flux processes, OCO-2 observations and atmospheric models will work closely together to determine when and where observed CO_2 came from. Together, the combination of high-resolution data and models will guide climate models towards more reliable predictions of future conditions.

A high-resolution (7 km) non-hydrostatic global mesoscale simulation using the Goddard Earth Observing System (GEOS-5) model produced the CO_2 concentrations seen in this visualization. This 7-km GEOS-5 Nature Run (7 km-G5NR) product will provide synthetic observations for observing systems like OCO-2. While global models are regularly used

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for seasonal-to-decadal climate simulations at much coarser resolutions, GEOS-5 is uniquely adaptable global mesoscale modeling in pursuit of cloud resolving applications at horizontal resolutions much finer than the highest resolution weather models used around the world. Recent computing advances have permitted experimentation with global atmospheric models at these resolutions, although production applications like the 7 km-G5NR have remained limited. Utilizing 480 2.8 GHz 16-core Xeon Sandy Bridge nodes of the NASA Center for Climate Simulation (NCCS) "Discover" cluster, the 7 km-G5NR produced over 2-years of high-resolution weather and chemistry data at 30-minute intervals for the period May 2005 to June 2007. The output from this massive computation totaled nearly 4 Petabytes and was produced in just over 75-days of dedicated computation on the Discover cluster. More than 20 Terabytes of data are used to produce this visualization in a parallel image-processing mode using 128 ENVI/IDL processes (Exelis Visual Information Solutions/Interactive Data Language, Boulder, Colorado) on the NCCS data analysis cluster "Dali". Simulations like the 7 km-G5NR and these visualizations provide a valuable resource to assist weather/climate scientists in determining how new observations from space can help us improve our understanding and predictability of weather and climate around the globe.

2. Carbon observations

The Mauna Loa CO_2 record, also known as the "Keeling Curve," is the world's longest unbroken record of observed atmospheric CO_2 concentrations [7,15]. Daily observations of CO_2 taken near the top of Mauna Loa on the big island of Hawaii began in 1958 and continue today. Local surface observations taken in remote locations provide a representative picture of global trends in atmospheric CO_2 concentration. The Keeling Curve provides evidence of the continued growth in atmospheric CO_2 due to human activities; the seasonal trend is superimposed on this growth as plants provide a natural sink for CO_2 during the spring and summer growing seasons. Surface measurements, however, are not sufficient to understand regional sinks and sources of CO_2 because of their sparse spatial coverage. Mid-tropospheric satellite observations, like those from the atmospheric infrared sounder (AIRS, [1]) provide information on latitudinal gradients and season cycles in CO_2 on a global scale. However, their coarse resolution and lack of sensitivity to near surface CO_2 changes has limited their utility for constraining regional scale sources and sinks.

OCO-2, launched in July 2014, collects column CO_2 measurements from space with sensitivity to near-surface CO_2 and finer spatial resolution, providing more information on the spatial distribution of CO_2 throughout Earth's atmosphere. OCO-2 is expected to provide the most complete picture of observed global CO_2 concentrations to date. These measurements combined with data from ground-based networks and global atmospheric models provide scientists with information to better understand the regional processes that regulate atmospheric CO_2 and the changing carbon cycle.

A significant obstacle in relating CO_2 observations with global models to infer sources and sinks has been the scale mismatch between the observations (3 km^2 footprint for OCO-2) and our models (on the order of 10,000 km^2). The use of high resolution global models, like GEOS-5, with resolutions on the order of 10 km^2 provide a new tool to bridge this gap in scales and improve our understanding of how representative our measurements of CO_2 are of the large areas over which we infer regional fluxes.

3. The GEOS-5 model

NASA supercomputing resources facilitate the development of high-performance global modeling with the GEOS-5 atmospheric model [14] at the highest resolutions possible for any global model [13]. These global mesoscale simulations with GEOS-5 represent multiple scales of atmospheric weather from clusters of deep convection and mesoscale convective complexes, to hurricanes, and large mid-latitude storm systems, all within a cohesive simulation of the global circulation.

The *finite-volume (FV) dynamics* utilized within GEOS-5 evolved from the original FV algorithm of Lin [8] and has been extended to operate in a general curvilinear coordinate system on the cubed-sphere grid [11,12]. The hydrostatic formulation of Lin [8] has been extended to the fully compressible non-hydrostatic flow (essentially the un-approximated Euler equations on the sphere). To maintain the advantages of the "vertically Lagrangian discretization" of the hydrostatic system, an explicit sound wave solver based on the conservation of Riemann invariants was developed.

The GEOS-5 AGCM physics includes parameterization schemes for atmospheric convection, large-scale precipitation and cloud cover, longwave and shortwave radiation, turbulence, gravity wave drag, a land surface model, and a simple glacier model. These physics parameterizations are scale aware and dynamically adapt to the horizontal resolution of GEOS-5. This multi-scale design coupled with increased computational capability in recent years allows GEOS-5 to make the transition from climate simulations on the order of 50- to 100-km resolutions, to cloud permitting resolutions of just a few kilometers. This permits GEOS-5 to execute at resolutions between the synoptic scale and the cloud scale producing global weather and climate simulations approaching the spatial resolution of our observing systems.

The 7 km-G5NR uses a version of the Goddard Chemistry, Aerosol, Radiation, and Transport model (GOCART, [2]) run online and radiatively coupled in GEOS-5 as first described in Colarco et al. [3]. GOCART treats the sources, sinks, and chemistry of dust, sulfate, sea salt, and black and organic carbon aerosols. Both dust and sea salt have wind-speed dependent emission functions, while sulfate and carbonaceous species have emissions principally from fossil fuel combustion, biomass burning, and biofuel consumption, with additional biogenic sources of organic carbon. Sulfate has additional chemical production from oxidation of SO_2 and DMS, and we include a database of volcanic SO_2 emissions and injection heights.