# A Global Perspective of Atmospheric $CO_2$ Concentrations

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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't 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.

The $CO_2$ concentrations seen in this visualization are produced by a high-resolution (7-km) non-hydrostatic global mesoscale simulation using the Goddard Earth Observing System (GEOS-5) model. This 7-km GEOS-5 Nature Run (7km-G5NR) product will provide synthetic observations for observing systems like OCO-2. While global models like GEOS-5 are regularly applied in seasonal-to-decadal climate simulations at much coarser resolutions, GEOS-5 is also uniquely adaptable for application as a global mesoscale model in pursuit of global 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 scales, although production applications like the 7km-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 7km-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 a remarkable time of 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 7km-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 understating and predictability of weather and climate around the globe.

## The visualization

This visualization compresses nearly 2 years of data into a few short minutes. It begins with a global view of clouds and aerosols as seen from space on a satellite projection of the Earth. High resolution 'blue marble' images from the Moderate Resolution Imaging Spectroradiometer

(MODIS) aboard the Terra (EOS AM) and Aqua (EOS PM) satellites and 'black marble' images from the Visible Infrared Imaging Radiometer Suite on the Suomi National Polar-orbiting Partnership (Suomi NPP) satellite provide the backdrop for our model data on the surface of the globe.

As the satellite projection shifts to a full Cartesian view, global clouds highlight complex weather systems across the world while dust, organic/black carbon, and sulfate aerosols are transported within the prevailing circulation of the global weather. Clouds play a critical role in the Earth's weather/climate system. With horizontal resolution increased to 7-km, GEOS-5 now resolves clusters of clouds rather than simply relying on the statistical effects of cloud systems over large grid boxes. Simulated cloud clusters within the ITCZ, tropical storms, and mid-latitude storms begin to resemble clouds as observed from space.

Aerosols have a significant effect on both weather and climate. They are transported around the globe far from their source regions, interacting with weather systems, scattering and absorbing solar and terrestrial radiation, and modifying cloud micro- and macro-physical properties. They are recognized as one of the most important forcing agents in the climate system (Forster et al. 2007). Several missions in the Decadal Survey portfolio (e.g., ACE, Geo-CAPE), as well as the Cloud-Aerosol Transport System (CATS) mission, that will fly on the International Space Station (ISS), aim to get new information on aerosol distributions and properties.

Sulfur dioxide ($SO_2$), produced during the burning of fossil fuels and from volcanic eruptions, is a short lived gas which can act as pollutant near the surface with detrimental health and acidifying effects. With a mean lifetime of just a couple of days in the troposphere, emitted $SO_2$ is quickly converted to sulfate aerosol ($SO_4$) through oxidation by OH or by reaction with $H_2O_2$ within clouds. The resulting $SO_4$ exerts a direct radiative effect on the atmosphere and it can also have an indirect radiative effect by inducing changes in cloud and precipitation microphysics. The October 2005 eruption of the Sierra Negra Volcano on Isabella Island in the Galapagos Islands produces a large plume of sulfate aerosols, as seen being dispersed in the 7-km GEOS-5 Nature Run from October 25th into early November 2005.

Carbon exists in many forms e.g., $CO_2$, carbon monoxide (CO) and continually cycles through Earth's atmosphere, ocean, and terrestrial ecosystems. This visualization shifts to column concentrations of atmospheric $CO_2$ (colored shades) and CO (white shades underneath) from January 1, 2006 to December 31, 2006. $CO_2$ variations are largely controlled by fossil fuel emissions and seasonal fluxes of carbon between the atmosphere and land biosphere. $CO_2$ concentrations are enhanced by carbon sources, mainly from human activities. During Northern Hemisphere spring and summer months, plants absorb a substantial amount of $CO_2$ through photosynthesis, thus removing $CO_2$ from the atmosphere. Atmospheric CO, a pollutant harmful to human health, is produced mainly from fossil fuel combustion and biomass burning. Here, high concentrations of CO (white) are mainly from fire activity in Africa, South America, and Australia.

Due to the steady increase in global $CO_2$ concentrations, visualizing multiple years of data presents a unique challenge for representing this dynamic gas. The annual drawdown of $CO_2$ by plants in northern hemisphere summer months is clearly evident in this visualization. During these summer months, plumes of CO emissions stream from biomass burning in boreal forests

across Canada and Siberia, while fires throughout Africa, Australia and southeast Asia continue to produce large amounts of CO and $CO_2$. The growth in $CO_2$ concentration throughout the simulation becomes clear as we move into 2007 where northern hemisphere $CO_2$ concentrations reach in excess of 395 ppmv and is highlighted by sampling the $CO_2$ concentration from the simulation at Mauna Loa, Hawaii. This location is the longest on record for $CO_2$ concentration across the globe [Keeling et al, 1976 and Thoning et al 1989]. The growth of $CO_2$ concentration at Mauna Loa over these two years exceeds 4 ppmv in this GEOS-5 simulation. The variability of $CO_2$ across the northern hemisphere is striking. The highest concentrations are focused around major emission sources over North America, Europe and Asia, and the dispersion of these emissions are controlled by the large-scale weather patterns within the global circulation creating sharp gradients of $CO_2$ along frontal boundaries and swirling within large weather systems.

OCO-2 will be the first NASA satellite mission to provide a global view of atmospheric $CO_2$ to better understand both human emissions and natural fluxes. OCO-2 observations and atmospheric models like GEOS-5 will work closely together to fully understand carbon flux processes and help guide climate models toward more reliable predictions of future conditions. The 7km-G5NR will provide synthetic observations for observing systems like OCO-2 as seen during the first few months of 2007 in this visualization. While actual swath data from OCO-2 was not available at the time this visualization was completed, OCO-2 is part of the A-Train constellation of satellites and a generic polar orbiting swath was used to sample the 7km-G5NR for this visualization.

**The GEOS-5 Model**

High-resolution global atmospheric models provide a unique tool to study the role of weather within the global climate system. NASA supercomputing resources facilitate the development of high-performance global modeling with the GEOS-5 model [Rienecker et al, 2008] at the highest resolutions run to date for any global model [Putman and Suarez, 2011]. These global mesoscale simulations with GEOS-5 represent multiple scales of atmospheric events from clusters of deep convection and mesoscale convective complexes, to hurricanes, to 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 (2004), it has been extended to operate in a general curvilinear coordinate system on the cubed-sphere grid [Putman and Lin (2007) and Putman and Lin (2009)]. The hydrostatic formulation of Lin (2004) 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 allows GEOS-5 to easily move from climate simulations on the order of 50- to 100-km resolutions, to cloud permitting resolutions of 7- to 3.5-km.

A version of the Goddard Chemistry, Aerosol, Radiation, and Transport model (GOCART, Chin et al. 2002) run online and radiatively coupled in GEOS-5 as first described in Colarco et al. (2010). 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.

In addition to aerosol species, GEOS-5 simulates the emission and transport of CO and $CO_2$. CO is emitted from biomass burning, fossil and bio-fuel combustion, and produced chemically from biogenic hydrocarbon and methane oxidation; the CO chemistry used in the 7km-G5NR is described in Ott et al. (2010). $CO_2$ is also emitted by fossil fuel combustion and biomass burning. Natural fluxes of $CO_2$ between the atmosphere and land and ocean carbon reservoirs, calculated as part of NASA's Carbon Monitoring System (CMS) Flux Pilot Project (Ott et al., 2014, in review), are included.

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