A Global Perspective of Atmospheric CO_2 Concentrations

William M Putman, Lesley Ott, Anton Darmenov and Arlindo daSilva
Global Modeling and Assimilation Office, NASA/Goddard Space Flight Center

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 global 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 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 understanding and predictability of weather and climate around the globe.

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) and 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.

The 7km-G5NR uses 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.

Models Assisting Observations

The global mesoscale nature of GEOS-5 (the capability to produce global weather at local scales much finer than the highest resolution global weather models used around the world) enhances our ability to maximize the impact of satellite observations in climate, weather and atmospheric composition prediction. Exploring the impact of new observations is a key element of this mission. By conducting observing system simulation experiments (OSSEs, e.g., Errico et al., 2012) scientists at NASA and NOAA can estimate the usefulness of various configurations of observing systems and data assimilation methods in an entirely simulated context. This 7km-

G5NR has been produced as a reference *Nature Run* for OSSEs, it serves as a virtual earth for producing synthetic observations to explore the potential impact of future observing systems.

OSSEs are designed to mimic the process of data assimilation, in which real imperfect observations are used to produce estimates of global atmospheric states at sequences of time. In an atmospheric OSSE, simulated observations with simulated errors are drawn from a simulated atmosphere (*Nature Run*) and provided to a data assimilation system to produce estimates of those *Nature Run* states. Since the OSSE deals entirely with simulations, it is not restricted to using only observations that already exist. Also, the underlying "true" atmospheric state (the *Nature Run*) is known precisely. These two properties of the OSSE facilitate many types of informative experiments relevant to NASA's missions.

OSSEs may be used to help guide development of new instruments, as OSSEs may be performed during their planning stages. By estimating impacts of the envisioned observations on data assimilation and forecast system performance, project requirements and design implications can be better determined. The OSSE setup may also be used to investigate more theoretical questions, as even impractical observations can be generated with relative ease; e.g., because the quality of the observations can be strictly controlled in the OSSE context, how the accuracy of data assimilation products depend on instrument error characteristics can be easily examined. Unlike when assimilating real observations, the *Nature Run* states from which the OSSE observations are drawn are known perfectly and analysis errors therefore can be explicitly and precisely determined. This OSSE property can therefore be used to greatly expedite development and testing of new data assimilation algorithms.

The 7km-G5NR resolves robust weather systems and high-impact events ideal for simulating observations for OSSEs. In addition to standard meteorological fields, the 7km-G5NR includes a suite of aerosol types (dust, seasalt, sulfate, black and organic carbon) and trace gas concentrations (O_3, CO and CO_2), with emissions downscaled to 10-km using ancillary information such as power plant location, population density and night-light information. This free running 7km-G5NR develops its own weather around the Earth in a purely synthetic environment constrained only by surface boundary conditions for sea-surface temperatures and sea-ice, daily volcanic and biomass burning emissions, as well as high-resolution inventories of anthropogenic sources. This produces a long dynamically consistent atmospheric state that matches the climatology and variability of the real atmosphere. A full suite of synthetic observations with calibrated observational error will be created from the 7km-G5NR to replicate the entire observational network. The GEOS-5 atmospheric data assimilation system, consisting of the Gridpoint Statistical Interpolation (GSI) analysis scheme and GEOS-5 forecast model, will ingest the synthetic observations and generate experimental forecasts.

The Visualization

The visualizations in this journal article stem from a movie made for the Visualization Showcase at the SC14 conference. This movie compresses nearly two 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 (Figure 1).

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. OCO-2 will fly in a sun-synchronous, near-polar orbit providing near-global coverage of the sunlit portion of Earth over a 16-day (233-revolution) repeat cycle. A sample of this orbit has been taken using March 2006 data from the 7km-G5NR data for this visualization.

Conclusion

The ability to visualize the dynamic flow and fluxes of CO_2 around the globe provides valuable insight into the natural and anthropogenic variability of this critical greenhouse gas. As computing capabilities increase, GEOS-5 will continue to facilitate the development of global carbon monitoring satellites and the use of observational data to improve the predictability of global climate variability. By simulating the evolution of CO_2 at finer spatial resolution and over longer time periods the global modeling capability of GEOS-5 can be used to improve instrument design and data assimilation techniques to advance our understanding of the carbon cycle around the world.

References

Chin, M., Ginoux, P., Kinne, S., Holben, B. N., Duncan, B. N., Martin, R. V., Logan, J. A., Higurashi, A., and Nakajima, T. (2002), Tropospheric aerosol optical thickness fromt he GOCART model and comparisons with satellite and sunphotometer measurements, J. Atmos. Sci., 59, 461–483, doi:10.1175/1520-0469.

Colarco, P., A. da Silva, M. Chin and T. Diehl, 2010: Online simulations of global aerosol distributions in the NASA GEOS-4 model and comparisons to satellite and ground-based aerosol optical depth. *J. Geophys. Res.*, **115**, D14207, doi:10.1029/2009JD012820.

Errico, R. M., R. Yang, N. Privé, K.-S. Tai, R. Todling, M. Sienkiewicz, and J. Guo, 2013. Development and validation of observing-system simulation experiments at NASA's Global Modeling and Assimilation Office. *Q. J. Roy. Meteor. Soc*, **139**, 1162-1178. doi: 10.1002/qj2027

Keeling C.D., R.B. Bacastow, A.E. Bainbridge, C.A. Ekdahl, P.R. Guenther, and L.S. Waterman, (1976), Atmospheric carbon dioxide variations at Mauna Loa Observatory, Hawaii, *Tellus,* vol. 28, 538-551

Lin, S.-J. 2004 A 'vertically Lagrangian' finite-volume dynamical core for global models. *Mon. Wea. Rev.*, **132**, 2293–2307

Ott, L., B. Duncan, S. Pawson, P. Colarco, M. Chin, C. Randles, T. Diehl, E. Nielsen, 2010: Influence of the 2006 Indonesian biomass burning aerosols on tropical dynamics studied with the GEOS-5 AGCM. *J. Geophys. Res.,* **115***, doi:10.1029/2009JD013181.*

Ott, L. E., S. Pawson, G. J. Collatz, W. Gregg, D. Menemenlis, H. Brix, C. Rousseaux, K. Bowman, J. Liu, A.

Eldering, M. Gunson, S. R. Kawa, 2014: Quantifying the observability of CO_2 flux uncertainty in atmospheric CO_2 records using products from NASA's Carbon Monitoring Flux Pilot Project, in review for *J. Geophys. Res*.

Putman, W. M. and S.-J. Lin, 2007: Finite-volume transport on various cubed-sphere grids. *J. Comput. Phys.,* **227**, 55-78.

Putman W. M., and S.-J. Lin, 2009: A finite-volume dynamical core on the cubed-sphere grid. Preprints, Numerical Modeling of Space Plasma Flows: ASTRONUM-2008, Astronomical Society of the Pacific Conference Series, vol 406, pp 268-276

Putman, W. M., and M. Suarez, 2011: Cloud-system resolving simulations with the NASA Goddard Earth Observing System global atmospheric model (GEOS-5), *Geophys. Res. Lett.*, 38, L16809, doi:10.1029/2011GL048438.

Rienecker, M.M., M.J. Suarez, R. Todling, J. Bacmeister, L. Takacs, H.-C. Liu, W. Gu, M. Sienkiewicz, R.D. Koster, R. Gelaro, I. Stajner, and E. Nielsen, 2008: The GEOS-5 Data Assimilation System - Documentation of Versions 5.0.1, 5.1.0, and 5.2.0. *Technical Report Series on Global Modeling and Data Assimilation 104606*, **v27**.

Thoning K.W., P.P. Tans, and W.D. Komhyr, (1989), Atmospheric carbon dioxide at Mauna Loa Observatory 2. Analysis of the NOAA GMCC data, 1974-1985, *J. Geophys. Research,* vol. 94, 8549-8565