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A WRF-Chem Realtime Modeling System for Monitoring CO_2 Emissions

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Introduction

Atmospheric inversion methods, used to infer sources and sinks of greenhouse gases, require highly accurate modeling of atmospheric transport and dispersion (AT&D) processes, and this is especially challenging when applied to urban scales and complex terrain. Accuracy of the atmospheric transport and dispersion solely depends on the meteorological conditions represented in numerical weather prediction (NWP) models (Deng et al. 2004). These conditions include parameters critical to AT&D such as wind speed, wind directions and atmosphere stability, etc.

The WRF-Chem modeling system is becoming more widely used to simulate, predict and monitor the emissions and concentrations of the atmospheric trace gases and chemical species (e.g., CO_2) that have significant impact in global and local climate changes. Recently, a dense regional deployment of CO_2 surface measurements in the upper Midwest (Miles et al., 2012) was used to determine the CO_2 fluxes from agricultural activities at 10-km resolution, using WRF-Chem coupled to a Lagrangian Particle Dispersion Model in backward mode. The inverse fluxes were compared to agricultural inventories and showed the potential of the method to capture the sources and sinks of CO_2 over a region of about 1000x1000km^2 (Lauvaux et al., 2012). Several ongoing projects over Indianapolis and Los Angeles are now trying to measure urban emissions using the same inverse methodology.

To support a realtime CO_2 monitoring mission during the World Economic Forum (WEF) Annual Meeting 2012 over Davos, Switzerland, the Penn State team has developed a time-lagged WRF-Chem realtime modeling system and used it for over two months, including the week of the WEF meeting, with a specified inventory of CO_2 emissions. The WRF-Chem-simulated CO_2 concentrations are compared to the realtime CO_2 concentration observations at two different locations: one site is in the city to evaluate the emissions from Davos, and a second site is at higher altitude measuring the background concentrations. Using a simplified inverse approach, the difference between the observed- and simulated-CO_2 concentrations allowed the evaluation of the reported CO_2 emissions at the daily time scale.

Model Description

Model Physics:
1) Single-Moment 3-class simple ice scheme microphysical processes (WSM3),
2) Kain-Fritsch scheme for cumulus parameterization on the coarser outer grids,
3) RRTM for longwave atmospheric radiation, and the Dudhia scheme for shortwave atmospheric radiation,
4) TKE-predicting Mellor-Yamada Level 2.5 turbulent closure scheme (MYJ PBL),
5) 5-layer thermal diffusion scheme for land surface processes.

Data Assimilation: WRF FDDA with both analysis nudging and observation nudging (Stauffer and Seaman 1994, Deng et al. 2009). In this specific realtime application, WMO observations were assimilated into the WRF-Chem system to produce a dynamic analysis, blending the model simulations and the observations to produce the most accurate meteorological conditions possible to simulate the atmospheric CO_2 concentrations in space and time over the Davos region.

Complex Terrain Concerns: An challenging issue of WRF modeling over the Davos region is handling the complex terrain. Terrain slopes greater than 40% caused the model crash due to the instabilities associated with vertically-propagating sound waves. To address the issue, we increased the damping magnitude by increasing the damping factor, time off-centering for vertical sound waves, by a factor of two (i.e., from epssm=0.1 in the default WRF dynamics to epssm=0.2). The off-centering is accomplished by using a positive (non-zero) coefficient (i.e., damping factor) in the acoustic time-step of the vertical momentum equation and the geopotential equation. An off-centering coefficient epssm=0.1 is typically used in the ARW applications, independent of time step or grid size. The WRF dynamic solver is designed such that forward-in-time weighting of the vertically-implicit acoustic-time-step terms damps instabilities associated with vertically-propagating sound waves. The forward weighting also damps instabilities associated with sloping model levels and horizontally propagating sound waves. Our sensitivity study using varying damping factors shows that increasing the damping factor by a factor of two eliminated the instability and produced little difference in the model solutions.

System Configuration

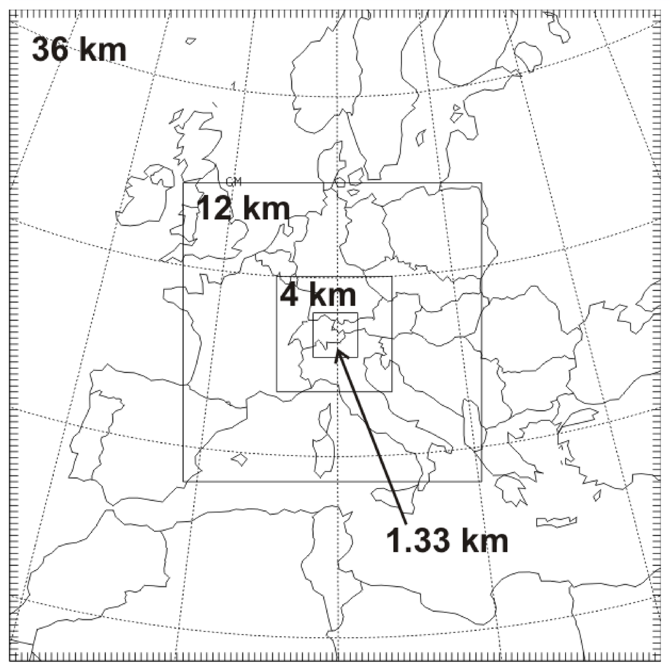

Figure 1. WRF-Chem 36/12/4/1.33-km grid configuration used in a realtime CO_2 monitoring mission during the World Economic Forum (WEF) Annual Meeting 2012 over Davos, Switzerland.

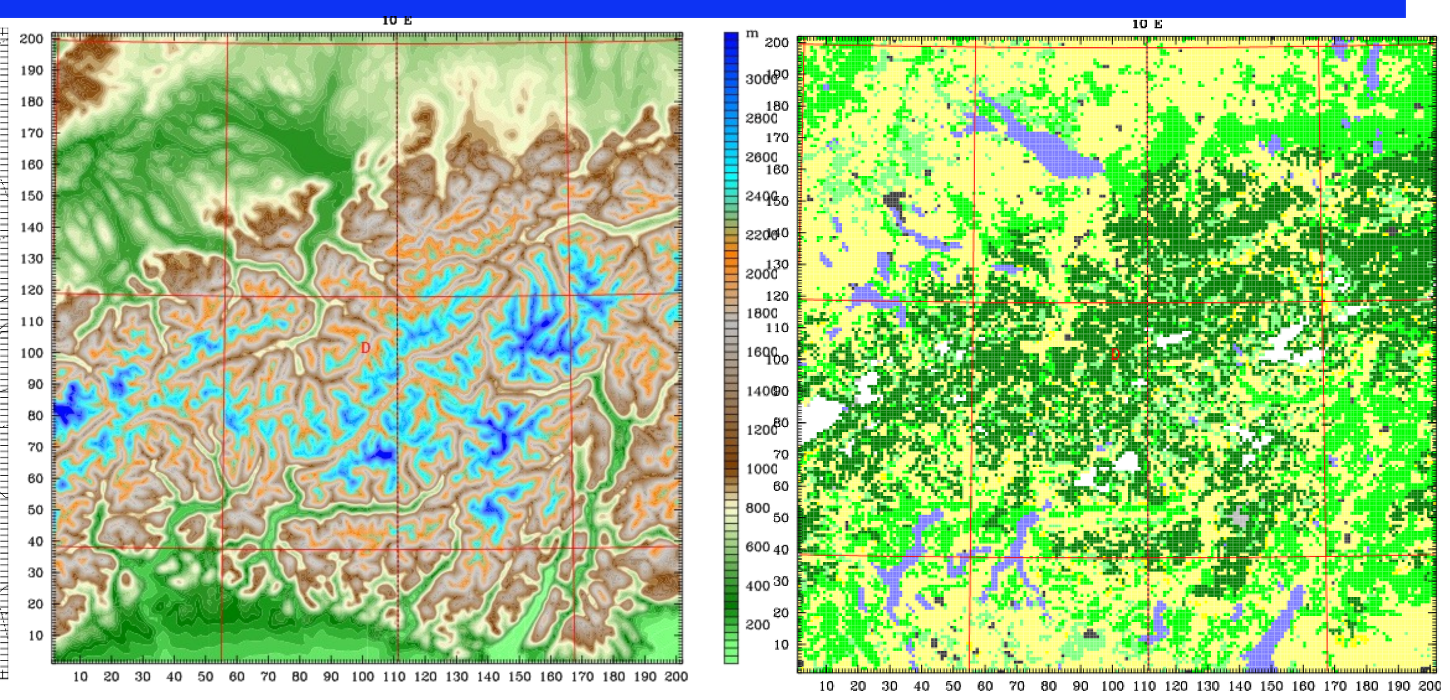

Figure 2. Terrain (Middle) and landuse (Right) of the 1.33-km grid, where D at the domain center denotes Davos, Switzerland.

Model Grids: *D01: 110x110, D02: 151x151; D03: 175x175; D04: 202x202,* fifty (50) vertical terrain-following layers,, with the center point of the lowest model layer located ~12 m above ground level (AGL), with 27 layers below 850 hPa, Ptop=100 hPa, one-way nesting.

FDDA Configuration: Multiscale FDDA with 3D analysis nudging and surface analysis nudging on both the 36- and 12-km grids with reduced nudging strength (G) on the 12-km grid, and observation nudging of WMO obs (Figure 3) on all grids with the same nudging strength. No mass fields (temperature and moisture) observations are assimilated in PBL.

Meteorological Inputs: 6-hourly GFS analyses at 0.5 degree resolution and WMO surface and upper air observations.

Table 1: Multiscale FDDA parameters used in this study. G is the nudging coefficient, RINXY is the radius of influence used in obs nudging, TWINDO is the time window used in obs nudging, and dt is the model time step.

	3D Analysis Nudging				OBS Nudging			
	36km	12km	4km	1.33km	36km	12km	4km	1.33km
G (1/sec)	3*10-4	1*10-4	N/A	N/A	4*10-4	4*10-4	4*10-4	4*10-4
Wind field	Nudging all layers	Nudging all layers	N/A	N/A	Nudging all layers	Nudging all layers	Nudging all layers	Nudging all layers
Mass field	Nudging above PBL	Nudging above PBL	N/A	N/A	Nudging above PBL	Nudging above PBL	Nudging above PBL	Nudging above PBL
RINXY (km)	N/A	N/A	N/A	N/A	150*	100*	100*	100*
TWINDO (hr)	N/A	N/A	N/A	N/A	2**	2**	2**	2**
dt (sec)	N/A	N/A	N/A	N/A	180	60	20	6

* 0.67 factor for surface, 2.0 factor at 500 hPa and above, ** 0.5 factor for surface

Emission Inventories: based on a first guess of the CO_2 emissions from a previous study (Walz et al. 2008) that presents emissions inventory data specifically for Davos This CO_2 emissions initial estimate consists of a single total number for the year 2005. In the county of Davos, 79% of the annual direct emissions are due to heating, 18% due to transportation, and 3% due to industry. The inventories account for emissions at the county scale of Davos, which is about 250 km^2, with only 6 km^2 of urban land cover. Population density maps were used to distribute the county level emissions over the urban areas over the 1.33-km grid, assuming that anthropogenic activities are mainly located within the city limit.

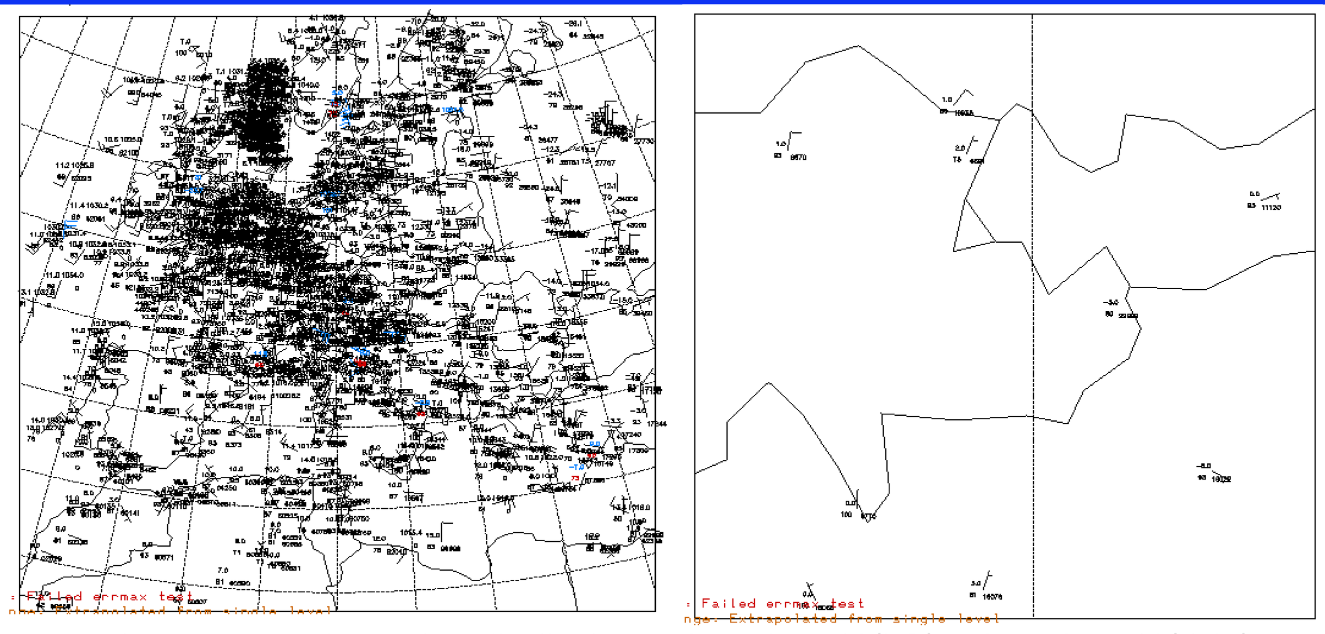

Figure 3. WMO observations distribution on the 36-km grid (left) and 1.33-km grid (tight).

Inverse Approach: based on a linear interpolation method, applicable in this situation because of the small size of the urban area compared to the grid size and the availability of a background site in the mountains surrounding Davos. First, by subtracting the background site concentrations from those measured at the urban site, we remove signals from distant sources, leaving only the Davos urban signal. The modeled inter-site difference is dependent on the first-guess emissions inventory. We apply a multiplicative factor to the initial inventory estimate such that the modeled inter-site CO_2 difference matches that observed, thus determining the daily emissions estimate from this simplified "inversion".

Preliminary Results

Figure 4 shows an example of a tracer plume predicted by the PSU WRF-Chem system over the valley of Davos, Switzerland, showing the CO_2 concentration, during the World Economic Forum Annual Meeting 2012.

Figure 5 shows the daily inverse emissions over the two-month period (with 3-day smoothing applied), and observed Heating Degree Days which correspond to the daily difference in temperature to maintain the indoor temperature constant (at 15.5 C°). As 79% of the annual inventory emissions are due to heating (Walz et al. 2008), we expect the daily inverse emissions to be correlated with the observed Heating Degree Days. During the pre-WEF period (December 21, 2011 - January 24, 2012), the emissions are 40% larger than the initial inventory estimate. Emissions estimates larger than the initial (annual) inventory are not surprising, given that lower temperatures in winter necessitate the use of domestic fuel for heating. At the daily time scale, the inverse estimates vary significantly, but are correlated with temperature (r>0.5), with lower values during warmer days. During the WEF meeting (January 25, 2012 - January 29, 2012), the inverse emissions decrease by 40% compared to the first period. Despite the activity in the city, the emissions show a clear decrease over the week, which can be related to the change of activity during the meeting. Whereas the traffic is substantially larger due to the large number of participants, several public buildings are closed near and around the urban measurement site. Several assumptions remain, such as the possible influence of strong local sources, or the footprint size which could be smaller than the city. The absence of convection near the surface, indicated by low values of observed wind stress, limits also the interpretation of the daily signals. Comparison to PBL Lidar measurements is ongoing and will provide an independent evaluation of the model performances during the period. Finally, the last period of the deployment (January 29, 2012 - March 3, 2012) includes two singular weather events, with a very cold period of about three weeks corresponding to very large emissions, and a warmer period with lower emissions compared to the first period. These two singular events show the large contribution of house heating related to temperature on the urban carbon budget and confirmed the potential of the system to detect the variability related to weather events over several days.

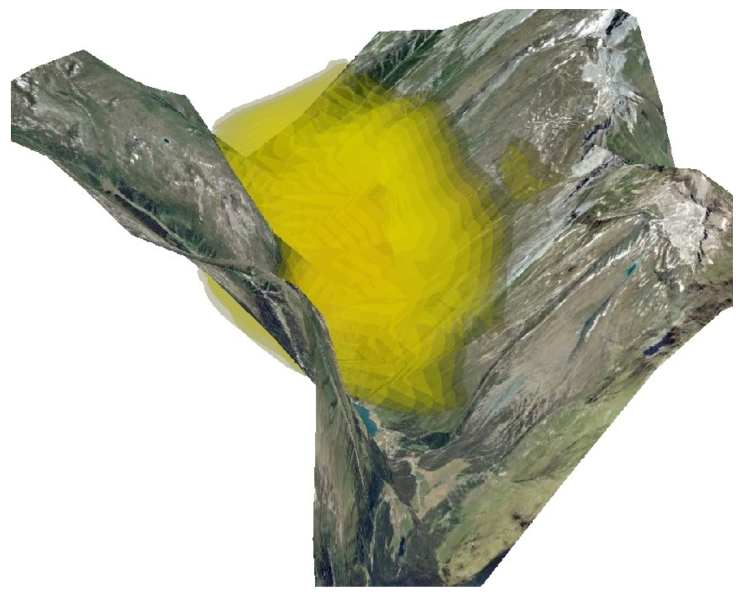

Figure 4. An example of a tracer plume predicted by the PSU WRF-Chem system over the valley of Davos, Switzerland, showing the CO_2 concentration, during the World Economic Forum Annual Meeting 2012, (more details may be found at http://cms.met.psu.edu/davos/).

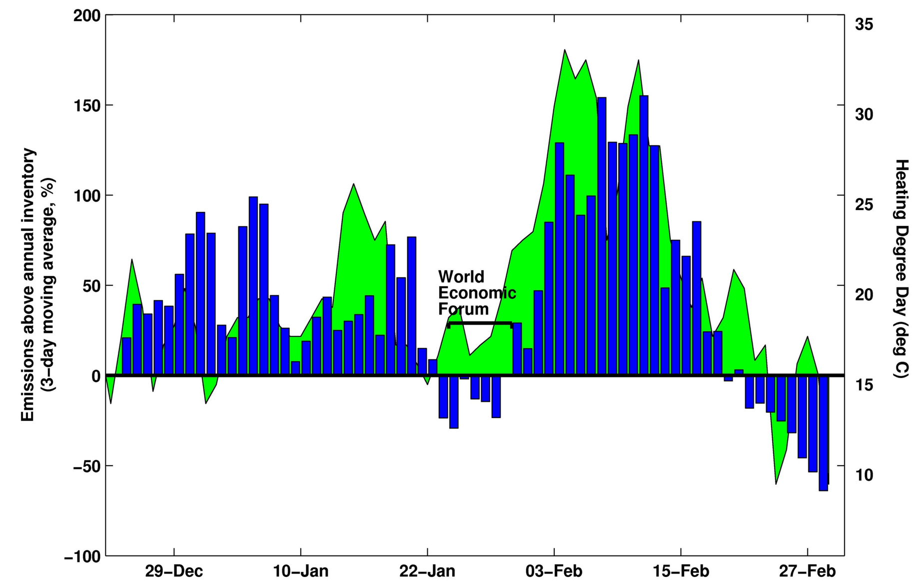

Figure 5: Inverse emissions for the city of Davos, Switzerland, (in blue) during the two-month campaign using the linear interpolation method between WRF-Chem concentrations and observations at the downtown site; Heating Degree Days indicate the number of degrees to maintain constant indoor temperature, and is used as a tracer of energy consumption for house heating (in green).

Conclusion

The Penn State team has developed a time-lagged WRF-Chem realtime modeling system and used it for a realtime CO_2 monitoring mission during the World Economic Forum (WEF) Annual Meeting 2012 over Davos, Switzerland. The system uses the multiscale FDDA capabilities that involve both analysis and observation nudging, and assimilates available meteorological observations during the entire model simulation to produce dynamic analysis meteorological fields coupled in-line with the AT&D processes within WRF-Chem model without the activation of chemical processes. For a two-month period including the WEF meeting, the WRF-Chem realtime system was run twice a day for 24 hours in a time-lagged fashion so that it ends at the current real time. It created the meteorological conditions critical to simulating the atmospheric CO_2 concentrations in space and time over the Davos region.

The WRF-Chem-simulated CO_2 concentrations are compared to the observations at two different locations, with a first site in the city used to evaluate the emissions from Davos, and a second at higher altitude measuring the background concentrations. Using a simplified inverse approach, the difference between the observed- and simulated-CO_2 concentrations allowed the evaluation of the reported CO_2 emissions at the daily time scale.

The inverse emission estimates computed daily were highly correlated with temperature, consistent with the initial inventory study which evaluated the contribution of house heating to 79% of the total carbon budget of Davos. In addition, the emissions increased significantly during the extreme cold wave affecting most of western Europe during February 2012, with a 30% increase in emissions compared to the month of January 2012. Preliminary results suggest that emissions during the WEF meeting were lower than average, suggesting that changes in the anthropogenic activities or in local sources may have been observed during that period. This first operational inverse system provided daily CO_2 emissions and showed a great potential for larger deployments, despite the complexity of the terrain and the weak vertical mixing near the surface during the campaign.

References

Deng, A., D.R. Stauffer, B.J. Gaudet, J. Dudhia, J. Hacker, C. Bruyere, W. Wu, F. Vandenberghe, Y. Liu and A. Bourgeois, 2009: Update on WRF-ARW end-to-end multi-scale FDDA system, *10th Annual WRF Users' Workshop*, Boulder, CO, June 23, 14 pp.

Miles, N. L., S. J. Richardson, K. J. Davis, T. Lauvaux, A. E. Andrews, T. O. West, V. Bandaru, and E. R. Crosson, 2012: Large amplitude spatial and temporal gradients in atmospheric boundary layer CO2 mole fractions detected with a tower-based network in the U.S. upper Midwest, *J. Geophys. Res.*, 117, G01019, doi:10.1029/2011JG001781.

Lauvaux, T., Schuh, A. E., Uliasz, M., Richardson, S., Miles, N., Andrews, A. E., Sweeney, C., Diaz, L. I., Martins, D., Shepson, P. B., and Davis, K. J., 2012: Constraining the CO2 budget of the corn belt: exploring uncertainties from the assumptions in a mesoscale inverse system, *Atmos. Chem. Phys.*, 12, 337-354, doi:10.5194/acp-12-337-2012.

Stauffer, D. R. and N. L. Seaman, 1994: Multiscale Four-Dimensional Data Assimilation. *J. Appl. Meteor.*, 33, 416-434.

Walz, A., G.-P. Calonder, F. Hagedorn, C. Lardelli, C. Lundström and V. Stöckli. 2008. Regional CO2 budget, countermeasures and reduction aims for the Davos region, *Energy Policy* 36, 811-820.