

Abstract

The Weather Research and Forecasting Model (WRF) is considered a “next generation” mesoscale meteorology model. The inclusion of a chemistry module (WRF-Chem) allows transport simulations of chemical and aerosol species such as those observed during NASA’s Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS) in 2008. The ARCTAS summer deployment phase during June and July coincided with large boreal wildfires in Saskatchewan and Eastern Russia.

One of the most important aspects of simulating wildfire plume transport is the height at which emissions are injected. WRF-Chem contains an integrated one-dimensional plume rise model to determine the appropriate injection layer. The plume rise model accounts for thermal buoyancy associated with fires and the local atmospheric stability. This study compares results from the plume model against those of two more traditional injection methods: Injecting within the planetary boundary layer, and in a layer 3–5 km above ground level. Fire locations are satellite derived from the GOES Wildfire Automated Biomass Burning Algorithm (WF_ABBA) and the MODIS thermal hotspot detection. Two methods for preprocessing these fire data are compared: The prep_chem_sources method included with WRF-Chem, and the Naval Research Laboratory’s Fire Locating and Monitoring of Burning Emissions (FLAMBE). Results from the simulations are compared with satellite-derived products from the AIRS, MISR and CALIOP sensors.

Results show that the FLAMBE pre-processor produces more realistic injection heights than does prep_chem_sources. The plume rise model using FLAMBE provides the best agreement with satellite-observed injection heights. Conversely, when the planetary boundary layer or the 3–5 km AGL layer were filled with emissions, the resulting injection heights exhibit less agreement with observed plume heights. Results indicate that differences in injection heights produce different transport pathways. These differences are especially pronounced in areas of strong vertical wind shear and

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when the integration period is long.

1 Introduction

The Arctic acts as a barometer for the Earth's atmosphere since many processes affect the polar regions before the more populated middle and lower latitudes (Arctic Climate Impact Assessment, 2004). The Arctic's lack of large population centers fosters the falsehood that it is a pristine environment. However, the Arctic has experienced large scale reported pollution events since the 18th century (Garrett, 2006), with pilots describing visibility reducing haze during the 1950's (Mitchell, 1957). Understanding the mechanisms leading to pollution transport into the Arctic and its chemical composition is pivotal to assessing the threat of climate change.

Arctic pollution occurs seasonally, with the greatest episodic increases in particle concentration observed during the winter and spring months (Quinn et al., 2007; Shaw, 1995; Barrie, 1986). These pollution events, often called "Arctic Haze", are observed after polar sunrise and can persist until May. The haze consists mainly of sulfate and organics, with NO_x, volatile organic compounds, nitrates, black carbon (BC), dust aerosols, and ammonium also present (e.g., Quinn et al., 2007; Solberg et al., 1996). Although these species mostly are transported from outside the Arctic, they pose an array of environmental threats to the Arctic's radiation budget. Greenhouse gases such as carbon dioxide trap thermal radiation in the lower troposphere (Arctic Climate Impact Assessment, 2004). Black carbon deposits on snow and ice sheets decrease the surface albedo (Hansen and Nazarenko, 2004; Koch and Hansen, 2005; McConnell et al., 2007). And, direct atmospheric warming occurs because some aerosols absorb in the visible and thermal spectrum (Sharma et al., 2006; Quinn et al., 2008).

Chemical transport models play a critical role in understanding source-receptor relationships between pollutants and the Arctic. Transport models can be functionally subdivided into "online" and "offline" categories depending on their integration with a host meteorological model. Offline models calculate transport based on wind data

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generated by another model, and sometimes include mechanisms for simulating meso- and micro-scale processes such as convection and turbulence. Since offline models are run post facto, they cannot feed back to the meteorological fields effects such as radiative absorption by aerosols or latent heat release from chemical bonding. The FLEXPART Lagrangian particle dispersion model (Stohl et al., 1998, 2005) is an example of an offline model that uses global winds from a meteorological model.

Online chemical transport models attempt to provide improved representations of atmospheric chemical and aerosol interactions. For example, the Weather Research and Forecasting Model with Chemistry (WRF-Chem) (Grell et al., 2005) incorporates radiative and chemical feedbacks into the atmospheric energy budget that an offline model cannot do. A detailed description of WRF-Chem can be found in Grell et al. (2005), with study specific details provided in Sect. 2 below.

Model-derived data have been used extensively to characterize pollution pathways to the Arctic. Stohl et al. (2006) and Law and Stohl (2007) used FLEXPART to develop a transport climatology that revealed three primary mechanisms for transport to the Arctic's lower troposphere: Ascent outside the Arctic followed by settling (primarily from North America, Asia and Europe), low level transport with ascent within the Arctic (primarily from Europe), and continuous low level transport (primarily from Europe during winter). Klonecki et al. (2003) showed that transport into the Arctic is consistent with isentropic flow, i.e., ascent along isentropic surfaces as a plume moves north.

Boreal wildfires recently have been recognized as an important seasonal source of pollutants into the Arctic (Warneke et al., 2009; Hegg et al., 2009; Kasischke et al., 2005; Andreae and Merlet, 2001; Crutzen and Andreae, 1990), and they can produce hemispheric influences (Wotawa et al., 2006; Damoah et al., 2004; van der Werf et al., 2003). Andreae et al. (2004) showed that the large aerosol loading from fires suppresses wet deposition, significantly enhancing aerosol transport. Although the total forest area burned within the tropics exceeds that of boreal fires, boreal fires have been increasing steadily in recent decades (Stocks et al., 2003; Lavoue et al., 2000). Despite currently containing less burn area than tropical forest fires, boreal

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forests have denser growth and rich surface layers that increase the available organic fuel and emissions (Kasischke et al., 2005; Kasischke and Bruhwiler, 2002).

The convective motions that often occur with wildfires increase the likelihood that emissions will be lofted to the faster winds of the free atmosphere. While small emission sources with minimal excess energy often are turbulently mixed into the PBL (Labonne et al., 2007), plumes from crown fires have been observed to maintain more cohesive structures that extend into the free troposphere (Lavoue et al., 2000; Cofer et al., 1996; Generoso et al., 2007). This process relies on sensible heat flux and latent heat of condensation to enhance a plume's buoyancy (Freitas et al., 2007). Previous research has suggested a linear correlation between fire intensity and emission injection height (Lavoue et al., 2000). Plumes often escape the boundary layer (Val Martin et al., 2010; Kahn et al., 2008) and have been observed to accumulate in layers of relative stability (e.g., Kahn et al., 2007). The wildfire smoke can even reach the lower stratosphere during cases of strong pyroconvection (e.g., Fromm, 2008; Trentmann et al., 2006). Releasing simulated emissions at appropriate altitudes has been a crucial and difficult problem to successfully modeling plume transport (e.g., Colarco et al., 2004, Westphal and Toon, 1991).

Near source vertical plume distributions (i.e., "injection heights") often have been represented in transport models using empirical or arbitrary procedures. These methods have included linearly filling estimated injection columns (e.g., Damoah et al., 2004; Forster et al., 2001; Spichtinger et al. 2001), restricting emissions to surface layers (Leung et al., 2007; Lamarque et al., 2003), assumed turbulent mixing by filling the planetary boundary layer (Fisher et al., 2010; Leung et al., 2007; Hyer et al., 2007), release in the upper atmosphere as occurs in pyroconvection (Hyer et al., 2007), or more complex distributions with emissions unevenly released at varying heights (Leung et al., 2007). Explicitly resolving three-dimensional microscale plume properties over large areas is limited by current computational capabilities. To avoid such constraints, Freitas et al. (2007) embedded a one-dimensional (1-D) plume-rise model into a larger scale grid to parameterize injection heights. Based on Lantham (1994), this

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1-D system uses meteorological model-derived column data to calculate atmospheric stability. Once vertical motion decreases to less than 1 m s^{-1} , a near equilibrium state is assumed, and the injection height is defined.

The Freitas et al. (2007) 1-D plume-rise model has been incorporated into WRF-Chem. This inclusion is important since many transport models rely on coarse horizontal scale (e.g., 45–200 km) global meteorological models for their transport parameters (e.g., Stohl et al., 2007; Damoah et al., 2004). Although these models generally have produced satisfactory results, global models do compound interpolation error both spatially and temporally and can produce non-physical results within transport models (Stohl et al., 1995, 2004). The importance of WRF's increased resolution to improve the forecast skill of low level winds has been demonstrated by Mass et al. (2002).

The present study evaluates the ability of WRF-Chem's 1-D plume rise model to diagnose the injection heights of fire emissions during NASA's Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS) campaign during 2008 (Jacob et al., 2010). Two preprocessing methods for preparing biomass burning emissions are investigated, the standard WRF-Chem package (Prep_chem_sources) and the Naval Research Laboratory's (NRL) Fire Locating and Monitoring of Burning Emissions (FLAMBE). We compare injection heights from the plume rise model with those where pollutants are injected only within the boundary layer or between 3-5 km above the surface. We also evaluate the ability of WRF-Chem to model the downwind evolution of fire plumes. Finally, model-derived plume characteristics are compared with those remotely observed by satellite sensors.

2 Data and methodology

2.1 Numerical simulations

Our research domain was centered on the North Pole, extended over most of the Northern Hemisphere, and used a polar stereographic projection (Fig. 1a). Since the goal

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was to explore the transport of emissions into the Arctic, the domain encompassed major historic source regions of biomass burning and anthropogenic emissions, including Russia, Alaska, Canada, and eastern Europe. These locations were far enough from the domain edge to minimize lateral boundary error (Warner et al., 1997).

5 The ARCTAS summer phase during June and July 2008 coincided with boreal wildfires in eastern Asia and Saskatchewan. Most of the observed fires in eastern Asia were located on the Stanovoy Mountain range that extends westward from the Sea of Okhotsk (Fig. 1b). Much of the mountain range is at 700 to 1500 m.m.s.l. (Fig. 1c). A Siberian fire outbreak from 28–30 June (Fig. 1b) produced emissions that were
10 observed to pool over Asia prior to being transported over the Pacific Ocean and into the Arctic. Fires also occurred during this period in the Canadian provinces of Saskatchewan and the Northwest Territories, producing outflow to Greenland and Europe; however, these fires were not as intense or widespread as those in Asia. Our ten-day computational period encompassed this period of active Asian and Canadian
15 fires between 28 June–8 July 2008.

Transport simulations were performed using WRF-Chem version 3.1.1 which is based on the Advanced Research WRF (ARW) (Skamarock et al., 2008). WRF is a non-hydrostatic, mesoscale model utilizing 2nd and 3rd order Runge-Kutta time integration schemes. WRF-Chem supports several physical, dynamic, and chemical
20 parameterizations (Grell et al., 2005). To simulate turbulent chemical transport within the boundary layer, our configuration used the Yonsei University PBL parameterization which diagnoses PBL height from the buoyancy profile (Hong et al., 2006). We used a horizontal grid resolution of 45 km with 50 vertical sigma levels packed near the surface and mean jet stream levels. Further information about model configuration is provided
25 in Table 1.

Meteorological initial and boundary conditions for the WRF-Chem simulations were interpolated from the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS; Global Climate and Weather Modeling Branch, 2003). GFS is a spectral model operating on an approximate 0.5×0.5 deg Gaussian grid with 64

vertical sigma levels.

The gas phase chemical mechanisms in WRF-Chem originally were developed for the Regional Acid Deposition Model, version 2 (RADM2, Chang et al., 1991). Although WRF-Chem can simulate dozens of organic and inorganic species, we focused on carbon monoxide (CO) as a gas phase tracer of the biomass burning plumes. Initial and boundary conditions were represented by an idealized, northern hemispheric, mid-latitude, clean environmental profile from the NOAA Aeronomy Lab Regional Oxidant Model (NALROM, Liu et al., 1996). The parameterization of aerosols was incorporated from the Modal Aerosol Dynamics Model for Europe (MADE, Ackermann et al., 1998), with the Secondary Organic Aerosol Model (SORGAM) simulating the formation of secondary organic aerosols (Schell et al., 2001).

Global emissions were incorporated into WRF-Chem. Anthropogenic emissions were based on the 0.5×0.5 deg REanalysis of the TROpospheric (RETRO) chemical composition dataset (Schultz, 2008; <http://retro.enes.org/index.shtml>). Biomass burning emissions were based on satellite retrievals. The GOES Wildfire Automated Biomass Burning Algorithm (WF_ABBA) relies on the method of Matson and Dozier (1981) to identify sub-pixel anomalies in the thermal infrared band that are associated with fires. WF_ABBA provides half-hourly hot-spot identification for the majority of the Western Hemisphere. Outside of this region, the MODerate-Resolution Imaging Spectrometer (MODIS) sensors on the Terra and Aqua satellites provide global scale fire detection using the sensor's infrared bands (Justice et al., 2002; Giglio et al., 2003). MODIS identifies fires utilizing a method similar to WF_ABBA. Since Terra and Aqua fly in near-polar orbits with ascending and descending equator crossings at 1:30 and 10:30 LST, respectively, the temporal resolution of their active fire products is limited. However, enhanced filtering does reduce false positives and increases the detection of cooler fire pixels (Giglio et al., 2003). MODIS products were available from <http://rapidfire.sci.gsfc.nasa.gov/>.

Two preprocessing methods for inserting the satellite-derived fire locations into WRF-Chem were tested. WRF-Chem's officially supported package relies on geographic

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coordinates for each wildfire. Emission factors from Andreae and Merlet (2001) account for variations in surface types. When the fire radiative power or burn area are not supplied, an area of 228 000 m² per fire grid point is assumed.

The second preprocessor of wildfire locations was based on the Fire Locating and Modeling of Biomass Burning Emissions (FLAMBE) dataset (Reid et al., 2009). FLAMBE provides carbon and aerosol emissions at hourly intervals. Fire data again are from the WF_ABBA and MODIS active fire products. Emissions are calculated by matching fire locations to a 1 km land use database. FLAMBE simulates diurnal variability by releasing 90 percent of the emissions between 09:00–19:00 LST (local standard time). The reported burn area also accounts for temporal variability, splitting the estimated 625,000 m² burn area per fire into 24 hourly segments that are proportional to diurnal fire activity (i.e., a larger burn area in the afternoon than overnight). This approach is necessary since a MODIS sensor may only cross a specific location four times per day. Hourly FLAMBE emissions were converted and re-gridded to be consistent with our WRF-Chem configuration.

WRF-Chem's one-dimensional plume rise model is based on the continuity equations for water in all phases, the vertical equation of motion, and the first law of thermodynamics (Latham, 1994; Freitas et al., 2007). To reduce the limitations of 1-D simulation, the model includes parameterizations for autoconversion (Berry, 1968), ice formation (Ogura and Takahashi, 1971), cloud microphysics, and accretion (Kessler, 1969), with entrainment defined as proportional to vertical velocity. To estimate heat flux, fires are divided into four surface categories based on WRF's land use dataset: Savanna, grassland, tropical and extra-tropical forests. Simulated atmospheric sounding data for the plume rise model are computed every hour at each grid point containing an active fire. Updated emission layers are produced based on column stability.

Vegetative combustion increases the surface heat flux and buoyancy of a rising plume. However, entrainment of environmental air into the column results in rapid cooling, causing near-source plume temperatures to be only slightly warmer than the environment. Buoyancy also is affected by radiative cooling and latent heat release if

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the plume reaches the lifting condensation level (LCL). Strong horizontal winds can enhance the entrainment processes and prevent the plume from reaching the LCL (Freitas et al., 2009; Val Martin et al., 2010). Strong winds also produce enhanced turbulent mixing in the boundary layer. Regardless, the influence of horizontal wind on vertical plume development is not considered in the WRF-Chem 3.1.1 plume rise model (S. Freitas, personal communication, 2009).

To evaluate the efficacy of the WRF-Chem plume rise model, we made additional simulations using two traditional column filling emission schemes: Emissions throughout the PBL, and emissions throughout the 3–5 km layer. These methods previously have been used to estimate turbulently mixed surface emissions and lofted emissions, respectively. Since the PBL height varies by location and time of day, approximate heights were calculated using a separate, initial WRF run. The emissions then were distributed within the PBL by the chemically enabled WRF-Chem runs.

2.2 Verification methods

Observations of near-source injection heights as well as horizontal and vertical plume specifications after long range transport were used to assess the simulations. To evaluate WRF-Chem's near-source injection heights, we used stereo height products from the Multi-angle Imaging SpectroRadiometer (MISR, Muller et al., 2002; Diner et al., 1999; Kahn et al., 2007). Plumes were processed and digitized as part of NASA's MISR Plume Height Climatology Project. Using the MISR INTERactive eXplorer (MINX) software (Nelson et al., 2008), ~250 plumes were identified over Siberia and Canada during our ten day model integration period (<http://www-misr2.jpl.nasa.gov/EPA-Plumes/>). To compare the MISR-derived plumes with those from WRF-Chem, we matched maximum plume heights with the nearest model grid point in space and time. Given the limitations of model resolution, if multiple plumes were located within the same WRF-Chem grid cell, the average of their heights was assigned.

We used the total column carbon monoxide (CO) product from the Atmospheric InfraRed Sounder (AIRS) on Aqua to evaluate the downwind evolution of the simu-

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lated plumes. Several previous studies have employed AIRS CO to investigate the horizontal extent of combustion products (e.g., Peffers et al., 2009; Zhang et al., 2008; Stohl et al., 2007). AIRS provides ~70 percent coverage of the Earth's surface on a daily basis (McMillan et al., 2005). CO measurement sensitivity is greatest near the surface, with previous aircraft-based studies showing non-polar retrieval uncertainty to be 15-20% at 500 hPa (McMillan et al., 2005). The CO products have not been validated over polar regions, suggesting uncertainties of 10-50% at 500 hPa (http://disc.sci.gsfc.nasa.gov/AIRS/documentation/v5_docs/). AIRS CO data at very high latitudes currently exhibit a low bias (J. Warner, personal communication, 2009). Filtering procedures were applied to the retrievals to increase their quality (AIRS Version 5.0 Released Files Description). Specifically, total column CO data were restricted to the best retrievals (Qual_CO = 0), representing values obtained primarily from the retrievals instead of values assumed a priori. The data then were simplified into normalized fields for comparison with WRF-Chem.

The lidar instrument on the Cloud-Aerosol Lidar and Infrared Satellite Observation (CALIPSO) satellite provides high vertical resolution aerosol and cloud identification within a 100 m across track footprint (Winker et al., 2010). Labonne et al. (2007) utilized CALIPSO's Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) retrievals to represent the total emission plume by assuming that the chemical and aerosol constituents were collocated. Importantly, we make this same assumption in our research. The CALIOP sensor onboard CALIPSO provides higher resolution atmospheric profiles than most other satellite-derived products. We evaluated WRF-Chem's long range vertical accuracy using the CALIOP vertical feature mask (VFM, Vaughan et al., 2004) that provides a simplified view of a retrieval swath.

To quantify WRF-Chem's forecasting skill compared to AIRS, we used the Model Evaluation Tools (MET) package produced by the Developmental Testbed Center (DTC) (<http://www.dtcenter.org/met/users/>). MET contains tools for comparing gridded model output to regularly or irregularly spaced measurements or other gridded model output. Point-to-point comparisons between collocated grid points can lead to

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double penalties if forecasts are even marginally displaced. However, the Method for Object-Based Diagnostic Evaluation (MODE) tool in MET is distinguished from traditional evaluation methods by using fuzzy logic to compare “objects.” These objects can be any cohesive field (e.g., CO for our study). Skill is assessed by identifying and evaluating the similarity between matched objects in the observed and forecast fields. AIRS total column CO was mapped to the same model grid as the simulated WRF-Chem total column CO. MODE then uses these inputs to compute statistical skill scores for the forecast.

2.3 Test cases

Six 10-day WRF-Chem simulations (28 June–8 July 2008) were run to evaluate the various emission source and injection height strategies. The two emission preprocessing methods, Prep_chem_sources (PC) and FLAMBE (FB), were run with three injection height schemes: 1-D plume rise (PLR), filling the boundary layer (PBL), and releasing between 3–5 km AGL (35K). Subsequent references will refer to these combinations by their abbreviations (i.e., PC_PLR, FB_35K, etc., Table 2).

3 Injection height evaluation

We evaluated the ability of WRF-Chem’s 1-D plume rise configuration to produce appropriate injection heights by comparing with MISR-derived plume heights. Fig. 2 is an example of a Canadian smoke cloud observed by MISR on 30 June 2008. The maximum and median heights derived for this plume (Fig. 2c) represent planes that are fit to the wind-corrected heights after removing values outside of 1.5 standard deviations. We investigated whether to use the maximum or median MISR height of each plume in our comparisons with WRF-Chem. However, results (not shown) indicated that using the maximum top produced a better Spearman correlation coefficient (r_s) with the WRF-Chem plumes ($r_s = 0.34$) than did the median heights ($r_s = 0.11$). In

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addition, choosing MISR's median height potentially could leave significant emissions above the top of this assumed injection layer (Fig. 2c), which would be inappropriate when comparing with discrete model levels.

Considering the entire ten day simulation period, the use of FLAMBE emissions (FB_PLR) in WRF-Chem produces better agreement with MISR's maximum stereo heights than do heights from PC_PLR, e.g., a Spearman correlation of 0.45 versus 0.07 (Fig. 3). FB_PLR also simulates 54 percent of the plumes within the estimated \pm 560 m error range of the MISR stereo heights, compared to 41 percent from PC_PLR. Differences between the injection heights produced by PC_PLR and FB_PLR are due to how the 1-D model in WRF-Chem parameterizes the entrainment of environmental air. Specifically, entrainment is based on an inverse relationship with plume radius, i.e., the larger the plume radius, the less inhibition that entraining cooler, unsaturated environmental air will have on the relatively warm, saturated plume. Thus, larger (smaller) plumes rise to higher (lower) altitudes than smaller (larger) plumes, all other factors being equal. This effect can be seen in Fig. 3, where the constant area (22.8 ha) that is assumed by PC_PLR for MODIS fire detections (Fig. 3b) produces a relatively narrow range of injection heights compared to those from FB_PLR (Fig. 3a) whose plume sizes range from 1.25 to 62.5 ha. Due to MISR's descending daytime overpass, our Northern Hemisphere retrievals occur before MISR's 10:30 LST equator crossing time (at high latitudes the local crossing time can be different). Since retrieval times are compared with the nearest model output time, the smaller morning burn areas in FB_PLR produce better agreement with the satellite retrievals. Based on this more realistic portrayal of injection heights, the long range transport simulations described in later sections will be limited to using the FLAMBE (FB) emission data.

Atmospheric stability plays an important role in simulating injection heights within WRF Chem's 1-D plume rise model. Figure 4 shows two simulated soundings over boreal plumes. Panel a) depicts a classic subsidence inversion that creates a stable layer near \sim 1.5 km AGL. The maximum height of the simulated injection layer of this case reaches 1.1 km, in good agreement with the 1.3 km height observed by MISR. Con-

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versely, the injection layer is overestimated in the conditionally unstable WRF-Chem sounding in Fig. 4b. MISR observed an aerosol layer at 2.5 km, well below the simulated 5.4 km heights. This suggests that the simulated sounding is less stable than the real atmosphere. Thus, limitations in the simulated stability profile are compounded by the plume rise mechanism to produce erroneous emission layers. It is clear that accurately modeling the atmospheric state is important for reasons other than just simulating the evolution of the three dimensional wind field.

The distribution of WRF-Chem injection heights during the entire ten day integration period (Fig. 5a, b) (not just locations matched to MISR retrievals) shows that FB_PLR produces somewhat lower injection layers than PC_PLR. Both median simulated injection heights are ~ 2.1 km, whereas MISR's median height is closer to 1.5 km (Fig. 5c). Thus, the median simulated injection heights are ~ 600 m higher than observed by MISR. This difference is partially caused by a sampling bias; the total number of observed MISR plumes is less than half the simulated plumes (Fig. 5c) because the MISR plume heights are derived only from the Terra satellite, while fire locations for WRF-Chem are obtained from Terra, Aqua (a second polar orbiting platform), as well as GOES which provides continuous, full disc coverage.

Extensive cloud cover over Canada prevented the satellite detection of many Canadian plumes. Thus, the observed (simulated) Russian plumes, which average ~ 900 m (~ 1.5 km) lower than the Canadian plumes, comprise 96 percent (87 percent) of the MISR (WRF-Chem) plumes during our ten day period. This greater representation (96 percent in the observations versus 87 percent in the simulations) of the taller Canadian plumes in the model data produces a higher average injection height than observed by MISR.

Numerous previous studies have released emissions between the surface and the top of the planetary boundary layer (e.g., Fisher et al., 2010; Leung et al., 2007; Hyer et al., 2007). To examine simulated injection that is limited to the PBL, we first matched MISR maximum plume heights to our model grid points. We then compared them with the WRF-Chem PBL height at each location. Results show that most of the MISR-

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derived emission layers are above the simulated PBL (Fig. 6a).

Thus, if one assumes that the simulated PBL heights are reliable, there is a strong preference for injection into the free troposphere. This contrasts with the research of Kahn et al. (2008) and Val Martin et al. (2010) who compared MISR stereo heights to GEOS-4 simulated PBL heights. They found that between about 5 to 18% of MISR plumes extended above the PBL over Alaska during 2004 and over North America during a four year period, respectively, with the majority remaining within the layer. Some of this difference may occur because GEOS-4 uses a different procedure for computing PBL heights than does WRF-Chem. And, it should be noted that Kahn et al. utilized median plume heights, whereas we employed maximum heights. They also compared many more MISR plumes, more than 600 compared to the 250 during our ten day period. Labonne et al. (2007) also found most emissions remaining in the PBL. They were above the PBL only in cases of large scale lofting. However, Kahn et al. (2008) noted that Labonne et al. used only CALIOP data, making the observed heights very dependent on how closely the lidar profile was to the source. Current results show that both the FB_PLR and PC_PLR plume rise models simulate most maximum injection heights to be above the top of the PBL. This is especially true for PC_PLR (Fig. 6b), likely due to its static MODIS fire size and the resulting effect on entrainment and plume height as described previously.

WRF-Chem's relatively low PBL heights compared to MISR's higher plume tops are due partially to MISR's overpass time. Specifically, our comparisons in the Northern Hemisphere had to be done prior to 10:30 LST when the simulated PBL height is relatively low. However, the height of the continental PBL typically increases rapidly during the late morning. WRF-Chem's low PBL heights also may be related to the delayed heating caused by insufficient heat flux in the surface layer (Pagowski, 2004). Finally, differences between the current results and those of previous studies might be due in part to the ways that the various studies have parameterized PBL height. Although current results indicate that most emissions escape the simulated PBL, further testing at other times and locations is needed to verify the current results. However, based

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solely on the Russian and Canadian plumes in our study, limiting injections to the PBL does not appear to be an optimum parameterization.

Some previous studies also have injected emissions in the 3-5 km layer. However, current results show that this alternative agrees poorly with observed heights (Fig. 6).

The triangular area above the diagonal but below the yellow shading represents the most common injection layer, above the PBL but below 3 km. Thus, very few of the matched plumes are injected above 3 km during the ARCTAS period. Additional evaluations in other areas and other meteorological settings are needed to confirm these results.

4 Long range transport

Since wind direction and speed vary with altitude, differing injection heights will influence the direction and speed of long range plume transport. This aspect is described next. Before doing so, however, it is important to examine meteorological conditions during the 10 day simulation period.

4.1 Meteorological conditions

Flow patterns during the summer phase of ARCTAS mostly were within climatological norms, except that a quasi-stationary polar low was displaced toward northern Russia, thereby enhancing transport into the Arctic (Fuelberg et al., 2010). The counterclockwise winds around the displaced quasi-stationary polar low (Fig. 7a, b; Fuelberg et al., 2010) provide one of two primary transport pathways off the Asian continent during our integration period (28 June–8 July 2008). The northern path toward the Arctic begins over the Chukotski Peninsula, located on the opposite side of the Bering Strait from Alaska. The southern path transports Asian pollutants eastward. It is created by an exiting mid-latitude cyclone southeast of the Kamchatka Peninsula. Once this cyclone moves offshore, high pressure over the Stanovoy Range clears the sky, dries

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the surface, and promotes the fire activity whose plumes are examined in the following sections. The stream bifurcation between these two paths begins at the saddle point between the two low pressure systems, and is most clearly visible in the 850 hPa streamline analysis on 29 June (arrow in Fig. 7a). However, the northern pathway does not fully form until the saddle point degrades on 6 July (Fig. 7c). A mid-latitude cyclone approaches the Aleutian archipelago on 2 July before merging with the Aleutian low on 6–8 July.

The fires in Canada and Alaska were ignited by lightning from a succession of cyclonic storms beginning with a shortwave trough on 28 June that passes over Saskatchewan (Fig. 7e–h). This cyclone is followed by a second system that also initiates thunderstorms, including a pyroconvective cell on 29 June in the Northwest Territories (M. Fromm, personal communication, 2008). The flow downwind of the Canadian fires is dominated by two semi-permanent lows located over Ontario/Quebec and southeast of Greenland, respectively. This combination produces a transport pathway toward the North Atlantic Ocean which limits transport into the Arctic.

4.2 AIRS-derived observed transport

AIRS-derived CO serves as our standard for comparison with the WRF-Chem simulations. The AIRS Level 3 total column CO product (Fig. 8) exhibits several distinctive features during the 10 day simulation period. Although a potential low bias in the data over northern latitudes and the sensor's weak sensitivity in the surface layers may prevent accurate measurement in some regions (J. Warner, personal communication, 2009; Fisher et al., 2010), general CO patterns still can be deduced. A large CO plume is located over Russia and China on 28 June with extensions over the Pacific Ocean (Fig. 8a). This Russian plume was evident during the week prior to our integration period (not shown) as a combination of smaller plumes over the region, together with another plume farther south over China. These plumes formed prior to our study period and were not part of the initial conditions.

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Beginning on 2 July (Fig. 8c), the dominant transport pathway from Russia extends over the Sea of Okhotsk northward over the Kamchatka Peninsula. The bulk of the plume flows eastward over the northern Pacific Ocean, but small CO concentrations are located north of the Chukotski Peninsula. By 6 July (Fig. 8e), flow around the quasi-stationary polar low begins to advect larger concentrations of CO northward toward the Bering Strait and the Arctic (the arrow in Fig. 8e). This panel clearly displays the two transport routes mentioned earlier. On 8 July (Fig. 8f), the CO plume diffuses across the Pacific; however, partial cloud cover prevents retrievals in the Arctic north of Canada and Greenland.

The Canadian CO plumes are much smaller and weaker than those from Russia, and they exhibit a simple path toward the Atlantic Ocean. Their CO signal can be seen early during the study period spreading from central Canada to south of Hudson and James Bays (Fig. 8b). CO first is transported east-south-eastward across the central provinces. Flow around the low pressure systems keeps the plumes south of Hudson Bay and Greenland before transport over the North Atlantic (Fig. 8e). The influence of fires in California and the previously described Russian plume also can be seen on 6–8 July (Fig. 8e, f).

4.3 Simulated Russian transport

We next compare plumes from the three model configurations with each other and with the AIRS imagery. Recall that the three injection procedures were in the PBL (FB.PBL), using the 1-D plume model (FB.PLR), and between 3 and 5 km above ground level (FB.35K). Except for these different injections, all other aspects of the model configuration were identical. The comparison is done both qualitatively (with CALIOP and AIRS) and quantitatively (with AIRS). One should recall that we assume that the CO and aerosols comprising the plumes are collocated. Plumes from Russia are examined first.

Figure 9a shows injection heights for plumes originating over Russia (a subset of the locations in Fig. 6b). The three injection procedures produce very different alti-

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tudes. Injections in the PBL generally are closest to the surface; the 1-D plume model generally injects the plumes at higher altitudes; and injection between 3-5 km occurs at the highest altitudes. Since wind direction and speed almost always vary between the surface and 5 km, the transport of these plumes will be affected. The three procedures for injecting biomass emissions (FB_PLR, FB_PBL, FB_35K) produce similarly shaped plumes on 2 July (4 days into the simulation, Fig. 10a, c, e), with flow over the Sea of Okhotsk and subsequent branching southward and northward. This similarity indicates that low level winds vary little with height in the vicinity of the plumes. The branches are similar to those observed in the AIRS CO data (Fig. 8c) except that the simulated plumes are located slightly farther northwest, not over the southern tip of the Kamchatka Peninsula. On 5 July (not shown), FB_PBL's plume over the Chukotski Peninsula moves southeastward, and by 6 July (7 days into the simulation, Fig. 10f) forms a branch into the Arctic near the Date Line. Conversely, plumes from FB_PLR and FB_35K are stretched northward, west of FB_PLR, by 6 July (Fig. 10b, d). AIRS detects a region of enhanced CO stretching from the Chukotski Peninsula to the Bering Strait (Fig. 8e), agreeing best with FB_PLR and FB_35K. These differences in plume locations (Figs. 8, 10) occur because plumes based on FB_PLR and FB_35K are transported northward, mostly above the PBL, while the plume from FB_PBL takes a more eastbound course due to the lower level flow in which the injection occurs.

Vertical cross sections along the CALIPSO track (Fig. 11) allow plume altitudes to be compared. The 00:34 UTC 6 July ascending CALIPSO overpass (Fig. 11a) crosses the dateline near 30° N, heading northwest over the Chukotski Peninsula. This track passes over the northbound plume arch in Fig. 10b, d and the FB_PBL plume over the North Pacific Ocean. The cross sections from FB_PLR and FB_35K (Fig. 11b, d) exhibit similarities, with the core of the Arctic-bound plume lofted to between 3–7 km. FB_PLR and FB_35K exhibit especially strong concentrations between ~4–7 km (Fig. 11b, d). The FB_PBL plume (Fig. 11e) is advected northeast at a much lower altitude (~2 km) than the other two plumes.

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All three simulations place a small pocket of aerosols at differing altitudes at the southern (left) edge of the cross sections near 43° N (Fig. 11b, d, e). Although the CALIOP Vertical Feature Mask (VFM, Fig. 11c, Vaughan et al. (2004)) shows an aerosol (orange) layer near 48° N, it is embedded in clouds and is not considered reliable. However, the VFM also indicates an aerosol layer at ~9 km altitude farther north near 60° N, 175° W that does not appear to be cloud contaminated. This altitude agrees best with those from FB_PLR and FB_35K (Fig. 11b, d). Unfortunately, the VFM shows frontally induced clouds (light blue) even farther north (right) where the simulated plumes from PLR and 35K are strongest. Frontally related cloud formations such as this often contain enhanced emissions (Crawford et al., 2003); however, the clouds frequently limit their remote detection using infrared techniques. One should note, however, that the presence of the FB_PLR and FB_35K plumes over the Chukot-ski peninsula is corroborated in the AIRS CO data (Fig. 8e).

AIRS total column CO data on 2 and 6 July (Fig. 10) are used to quantitatively compare CO structures from the three WRF-Chem configurations. Although MODE's object-based evaluation (Sect. 2.2) produces several statistical measures, we will consider the critical success index (CSI) whose values range from 0 (no skill) to 1 (perfect agreement). One should note that MODE scores are limited by the quality of the AIRS data. Although we insured that areas masked by clouds in the AIRS data also were masked in the model fields, even this procedure can either hurt or help a MODE-derived score depending on the accuracy of the region that is removed. For example, if WRF-Chem overestimates a plume that is located in a region where clouds mask the AIRS retrievals, when the overestimated region is removed, the score is spuriously increased. Nonetheless, we consider the MODE procedure to be superior to schemes that compare grid points instead of objects.

CSI scores for the Russian plume on 2 July, four days into the simulation, are FB_PLR (0.52), FB_35K (0.49), and FB_PBL (0.42). Thus, the 1-D injection procedure scores better than the other two schemes. CSI scores four days later (6 July, day 8) are FB_PLR (0.71), FB_35K (0.67), and FP_PBL (0.41). The values for PLR and 35K have

increased considerably while the score for PBL decreased slightly. The 1-D injection approach continues to produce the best agreement with the AIRS retrievals. The smaller scores on 2 July than 6 July likely are influenced by emissions in the AIRS data that originated before our modeling period began. FB_PBL's relatively low score on 6 July (0.41) probably is due to under representing the emissions over the northern Chukotski Peninsula. The spreading of the simulated plumes into China (Fig. 9) could not be evaluated since the region is largely masked by clouds in the AIRS product (Fig. 8e).

4.4 Simulated Arctic transport

The previous section noted that the major Russian plume splits into northbound and southbound components (Fig. 10). We now describe the northbound plume as it moves into the Arctic. The location of the plume with respect to the overall Russian plume is shown by the arrow in Fig. 10b, while details are in Fig. 12. On 3 July (five days into the simulation, Fig. 12a, c, e), all three injection procedures produce a CO intrusion between 160 and 180° E. On the following day (not shown), the three versions of plumes reach the North Pole. These locations correspond to weak AIRS CO enhancements in the area (Fig. 8d). The plumes then move slowly across the pole toward northern Norway on 6 July (not shown).

The three model plumes differ in size and orientation (Fig. 12) because they have experienced different flow patterns since being injected at different altitudes (Fig. 9). The plume based on injection between 3–5 km (Fig. 12c) is the largest of the three on 3 July, while 1-D injection (Fig. 12a) yields the smallest plume. One should note that the emissions from FB_PBL and FB_35K exhibit an anticyclonic hook near the date line (Fig. 12c, e) that is not observed with FB-PLR (Fig. 12a). This occurs because the CO from PLR and 35K is lofted earlier into the mid- and upper-troposphere than is PLR. All three plumes enter the Arctic at similar altitudes (~6 km, Fig. 13b, d, e), and have similar values along CALIPSO's path. Unfortunately, the light blue region in the CALIOP VFM (code 2) indicates that the area of the plume is shrouded with

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clouds. Thus, we cannot verify the altitudes of the simulated plumes with CALIOP's observations.

Synoptic analyses (e.g., Fig. 7) indicate that the Arctic transport event is due to a warm conveyor belt (WCB) associated with a wave cyclone over extreme northern Russia. The WCB transports Russian pollution northward and to higher altitudes in advance of the surface cold front. The role of middle latitude cyclones on pollution transport has been studied widely (e.g., Jaffe et al., 1999, 2003; Cooper et al., 2004; Liang et al. 2004; Dickerson et al., 2007). Climatological trajectory analyses have shown that northeastern China and Russia have a large frequency of WCB events (Eckhardt et al., 2004; Stohl, 2001). And, WCBs have been found to be a dominant mechanism in vertically redistributing pollution in the middle latitudes (Bethan et al., 1998; Wild and Akimoto, 2001; Miyazki et al., 2003; Kiley and Fuelberg, 2006). Ding et al. (2009) examined a plume that originated near the megacities of Beijing and Tianjin during Summer 2007. They concluded that a WCB played a major role in exporting the plume to the Arctic and North America. Their study period appears very similar to the current ARCTAS case.

A second Arctic transport event occurred during the final two days of the ten day simulation period (7-8 July) when another portion of the overall Russian plume "breaks off" and heads toward the Arctic. A WCB associated with a later middle latitude cyclone over northeastern Russia again is the cause for the northward intrusion. The location of the Arctic bound plume on 6 July is depicted by the arrow in the AIRS CO image (Fig. 8e). By 8 July (Fig. 12b, d, f), the three simulated plumes have reached the western hemispheric portion of the Arctic Ocean and southward along the Bering Strait. The different injection heights, coupled with the longer time since injection (8 days), produce greater differences in these plumes than seen in the previous comparisons. Plumes resulting from FB_PLR and FB_35K injection exhibit some horizontal similarity (Fig. 12b, d), with both oriented along coastal Alaska and approaching Canada's Queen Elizabeth Islands. However, the overall horizontal extent of the 35K plume is much greater than its PLR counterpart, as is the area of greatest concentra-

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tions. The vertical distributions of these two simulated plumes are similar (Fig. 14b, d) in that they generally are oriented along the sloping isentropic surfaces. The position of the plume arising from PBL injection (FB_PBL, Fig. 12f) is very different from those of the other two injections. FB_PBL's emissions reach the Arctic earlier than those from the other runs, producing enhanced transport toward Europe and weaker emission loading near North America. These differences in horizontal placement appear in the vertical cross section (Fig. 14).

Cloud cover severely limits investigation of the second Arctic plume using CALIOP data from the 19:25 UTC 7 July polar overpass (Fig. 14c) and prevents meaningful quantitative comparisons of the simulated plumes using MODE. The two arrows on the VFM denote locations of the FB_PLR and FB_35K plumes in Fig. 14b, d. These regions either are shrouded in clouds (light blue), exhibit low confidence (red), or meet the criteria for being stratospheric (yellow). We have little confidence in the single pixel at location 2 that is denoted aerosol (orange) since it is embedded in the clouds. These clouds that are detected by CALIOP correspond to a gap in the AIRS CO field on 8 July (Fig. 8f). We noted earlier that frontally related cloud features such as WCBs often coincide with important chemical plumes (Crawford et al, 2003), and that certainly is the case here. The winds associated with FB_PBL's early entrance into the Arctic steer much of the plume away from North America resulting in a transport path that is oriented poorly with respect to CALIPSO's track (Fig. 12f).

4.5 Simulated transport from Canada

Our final example is a plume emitted by the Canadian wildfires. Figure 9b shows injection heights for plumes originating over Canada (a subset of the locations in Fig. 6b). The three injection procedures again produce very different altitudes. As seen for the Russian plumes (Fig. 9a), the Canadian injections in the PBL are closest to the surface, extending only to 2 km AGL; the 1-D plume model injects the plumes at higher altitudes; and injection between 3–5 km occurs at the highest altitudes. Some injection heights from the 1-D plume rise model extend into the 3–5 km layer.

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Results show that the three injection procedures have little effect on the location or altitude of the resulting plumes. This similarity again is due to weak vertical wind shear in the lower troposphere.

Emissions from fires between Great Slave Lake and Reindeer Lake first move toward the south due to northerly winds and then eastward across Lake Winnipeg. The mid-latitude cyclone responsible for the southward transport moves east by 6 July (Fig. 7h), producing westerly flow that transports the plume farther east. The locations and areas of the plumes on 2 July (Fig. 15a, c, e) are similar, whether due to injection by the 1-D plume model, within the PBL, or between 3-5 km. Time series (not shown) reveal that the weaker simulated concentrations connecting the Canadian plume to James Bay (best seen in Fig. 15b) are due to emissions from the more distant Alaskan wildfires. Although this region contains little AIRS data because of clouds, a CO enhancement is evident over James Bay (Fig. 8c). After 2 July, emissions from each injection procedure are transported rapidly over the warm sector of the passing cyclone where they are lofted to similar transport altitudes. The plumes then pass over central Canada (not shown) at altitudes between ~3.0–3.8 km before moving over the North Atlantic.

Once the three versions of the simulated Canadian fire plume are over the Atlantic on 7 July (Fig. 15b, d, e), each splits, with part transported northward toward Greenland by a closed low over Hudson Bay, while the major portion continues eastward. The split region of CO just south of Greenland is evident in the AIRS imagery (Fig. 8f). The bifurcation is similar to the branching seen in the Russian plume over the Sea of Okhotsk (left panels of Fig. 10). However unlike the Russian plume, the northern branch of the Canadian plume does not fully develop and does not reach the Arctic. The relatively small Arctic plume seen on 6 June (Fig. 10c) crossed over the North Pole (not shown) and now is located between Iceland and the United Kingdom (Fig. 15d). It is unique to the higher altitude FB_35K simulation.

The three cross sections of normalized CO along the CALIOP track also are very similar (Fig. 16 b, d, f). Each type of injection produces an area of enhanced CO along the northern (right) side of the track that is centered near 6 km altitude. These areas

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slope downward in the southerly (left) direction. Each cross section also exhibits a second, weaker area of enhancement farther south between ~6-10 km altitude.

The two arrows on the CALIOP VFM product (Fig. 16c) denote regions of the modeled CO plumes (Fig. 16b, d, f). Unfortunately, these areas again coincide with areas of extensive cloud cover that correspond to frontal systems. In the cloud labeled “1”, there are two orange layers (indicating aerosols) between 5 and 10 km altitude. However, a close examination of Level 1 browse images (not shown) does not indicate aerosols. Instead, there are cloud fragments that typically cause misclassifications. At the base of the cloud labeled “2”, the red layer is an artifact, and the orange (aerosol) layer just below it likely is an artifact as well based on the Level 1 browse images. The vertically oriented orange layer also appears to be an artifact of the type often seen below attenuating clouds. Thus, CALIOP provides only weak evidence for enhanced aerosols at these altitudes. On a more positive note, the aerosol (orange) layers that are indicated below 3 km in both areas do appear valid. They are not located beneath the higher level clouds, and their aerosol designation is supported by the Level 1 browse product. Thus, the CALIOP VFM shows evidence of enhanced aerosol in the low troposphere beneath and between the higher level clouds. This horizontal location is consistent with those of the three injection procedures (Fig. 16b, d, e). However, the clouds at higher altitudes prevent solid evidence of aerosols at higher altitudes where the simulations produce maxima. Cloud cover on both 2 and 7 July again prevent reliable quantitative comparisons of the plumes with MISR products.

5 Summary and conclusions

Episodic events such as boreal wildfires represent a threat to the Arctic environment and to the Earth’s radiation budget. To accurately simulate wildfire events, it is important to inject their emissions at the appropriate altitudes so they are properly transported by the wind.

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This study has examined the ability of the WRF-Chem online chemical transport model to diagnose the injection layers of biomass burning emissions. Ten-day simulations were performed during the Summer 2008 ARCTAS period. Three methods of injection were considered – an imbedded 1-D plume rise model at each grid point, releasing emissions within the PBL, and releasing them between 3–5 km above the surface. Results of the simulations were compared with AIRS-patterns of total column CO and MISR-derived aerosol plume heights, as well as downwind aerosol vertical distributions from CALIPSO. We assumed that CO and aerosol plumes from the wildfires were co-located.

WRF-Chem was run using two different preprocessing methods for wildfires, prep_chem_sources and FLAMBE. Prep_chem_sources produced a comparatively narrow distribution of injection heights because of the way that the plume rise model parameterizes entrainment. Plume height is reduced by entrainment, which is inversely proportional to the burn area. The majority of the fires that were studied were identified by MODIS, to which prep_chem_sources applied a single value of burn area, regardless of time of day. This constant value limited the range of injection heights.

FLAMBE produced a wider range of injection layers that more closely agreed with the MISR-derived heights. Although FLAMBE begins with a single burn area for each detection, these areas then are modified to be proportional to the diurnal cycle of burning intensity, with size increasing during the afternoon and decreasing at night. The inclusion of smaller burn areas during the morning produced lower injection heights that were more consistent with those observed during MISR's morning overpass.

MISR stereo heights also were used to evaluate results from injecting the emissions confined to the planetary boundary lower, and emissions released between 3 km and 5 km AGL. The majority of the MISR heights were above the simulated planetary boundary layer but below the 3–5 km layer. These results from our ARCTAS simulations indicated that limiting injection to these layers was not ideal for the geographic and meteorological settings of the study. The majority of injection heights simulated by the WRF-Chem plume rise model were between the top of the PBL and 3 km AGL.

Thus, the 1-D plume rise model produced the most realistic approximation of the top of injection layers during the study period.

Since wind direction and speed vary with altitude, different injection altitudes often lead to different transport pathways, especially when longer time periods are considered. We evaluated simulated long range plume transport both qualitatively and quantitatively against data from the AIRS and CALIOP satellite sensors. Based on our earlier results, we only used the FLAMBE dataset in this evaluation. We again considered three methods of injection (plume rise, FB_PLR; planetary boundary layer, FB_PBL; 3–5 km a.g.l., FB_35K). Results for these injection configurations were compared for four plumes: An eastern Russian plume over the Sea of Okhotsk, two cases when the northern branch of the Russian plume was transported into the Arctic, and a Canadian plume over eastern Canada and the Atlantic Ocean. Where possible, quantitative scores were produced using an object-based method in the MODE software package.

Results showed that differences in transport between the injection methods were most prominent in situations of large vertical wind shear and when the integration period was long. The stronger vertical wind shear over Siberia than southern Canada increased the impact of the different smoke injection heights for the Siberian fires. Differences in transport were most evident in the northern branch of the Russian plume and its subsequent transport into the Arctic. The higher altitude emission layers from FB_PLR and FB_35K were transported into the Arctic, while the lower altitude FB_PBL emissions were lofted later and followed a different path. Transport into the Arctic from high-mid-latitude sources was mediated by the occurrence of warm conveyor belt meteorological events, convolved with smoke injection into the appropriate levels within the atmospheric vertical structure. The satellite-derived products supported the higher altitude emission schemes over northeastern Russia and into the Arctic. And, MODE-derived CSI scores confirmed that the 1-D plume rise configuration produced the best agreement with the satellite observations.

Our long range transport evaluations were limited by two factors. First, satellite data were limited in heavily clouded regions such as central Canada and the Arctic. This is

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unfortunate since emissions often are transported within cloudy regions. Large regions of the simulated Canadian and Arctic plumes could not be qualitatively or quantitatively compared because of cloud contamination. The presence of emissions released prior to the study period also produced observed enhancements over Canada and Russia that were not represented in the simulations. This problem could be reduced with the assimilation of satellite-derived CO data into WRF-Chem. Improvements in satellite data quality would enhance the WRF-Chem simulations during with input and later during verification.

To summarize, the 1-D plume rise model within WRF-Chem produced injection heights and plumes that agreed best with observed data during our study period. The greatest differences between injection methods occurred in cases of relatively strong vertical wind shear and when the integration period was long. The current results are based on a small study period during the Arctic summer. Additional studies should be performed to determine whether they are applicable to other regions and meteorological conditions.

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Table 1. WRF-Chem domain and parameterization settings used in this study. Details about the parameterizations can be found in Grell et al. (2005).

Field	Setting
Horizontal Resolution	45 km
Vertical Levels	50 non-linear sigma levels
Shortwave Radiation	Goddard
Longwave Radiation	RRTM
Surface Layer Physics	MM5 Similarity
Land Surface Physics	Noah
Planetary Boundary Layer	YSU
Cumulus Parameterization	Grell-Devenyi

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Table 2. Configurations used during our study as defined by the biomass burning preprocessor and injection layer scheme.

	1-D Plume Rise	Filled PBL	Filled 3–5 km Layer
Prep_chem_sources	PC_PLR	PC_PBL	PC_35K
FLAMBE	FB_PLR	FB_PBL	FB_35K

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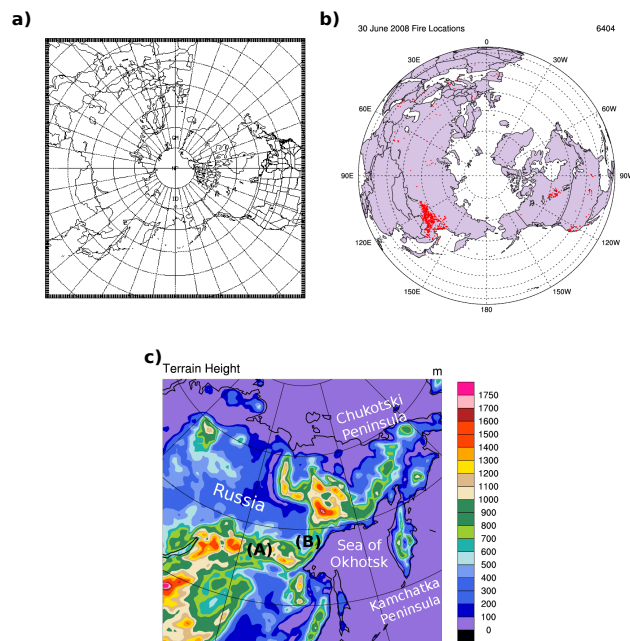


Fig. 1. (a) WRF-Chem domain, (b) satellite derived fire locations on 30 June 2008 during major Siberian and Canadian fire outbreaks, and (c) topographic map of northeastern Asia. Observed fires primarily were near the Stanavoy Mountains and the Dzhugdzhur coastal range west of the Sea of Okhotsk.

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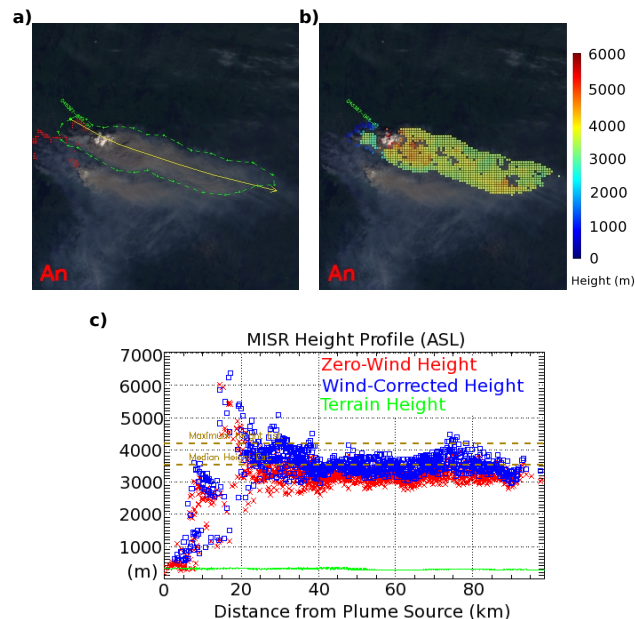


Fig. 2. Example of plume digitization produced by the MINX software package for a Canadian plume on 30 June 2008. Panel (a) shows a smoke cloud (outlined in green) with associated MODIS fire pixels (red dots). Panel (b) depicts the same plume with a stereo height overlay. The label “An” indicates that these are nadir images. Panel (c) shows individual stereo heights within the plume in relation to their distance from the source. Planar maximum and median plume heights are shown as dashed lines. MINX images courtesy the MISR Plume Height Climatology Project. (<http://www-misr2.jpl.nasa.gov/EPA-Plumes/>)

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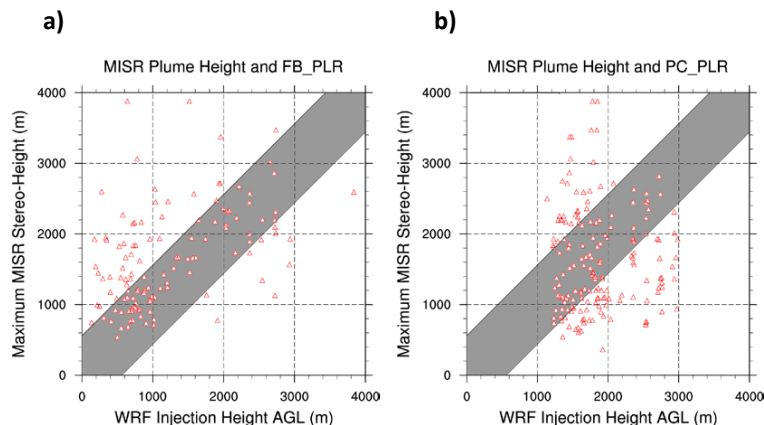


Fig. 3. (a) Injection heights using FB_PLR plotted against MISR maximum stereo heights for the entire ten day model run. The Spearman correlation is 0.45. (b) Same as (a), but based on PC_PLR. The Spearman correlation is 0.07. Shaded regions represent a hypothetical perfect correlation with MISR when assuming a stereo height error of ± 560 m.

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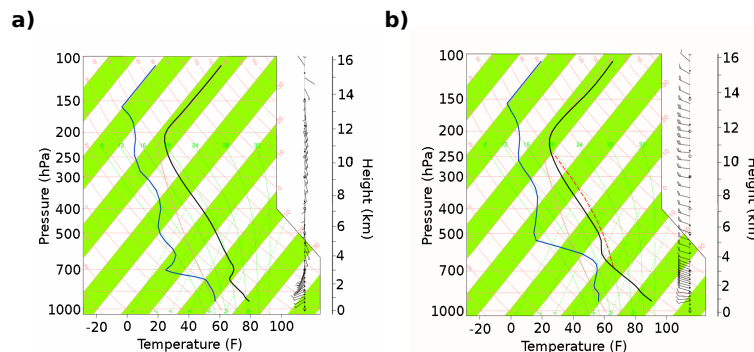


Fig. 4. Sample soundings from WRF-Chem (PC_PLR) at example locations of **(a)** low (1.1 km) and **(b)** high (5.4 km) injection heights. Temperature and dew point are in black and blue, respectively. Convective Available Potential Energy (CAPE) is indicated by a dashed red line.

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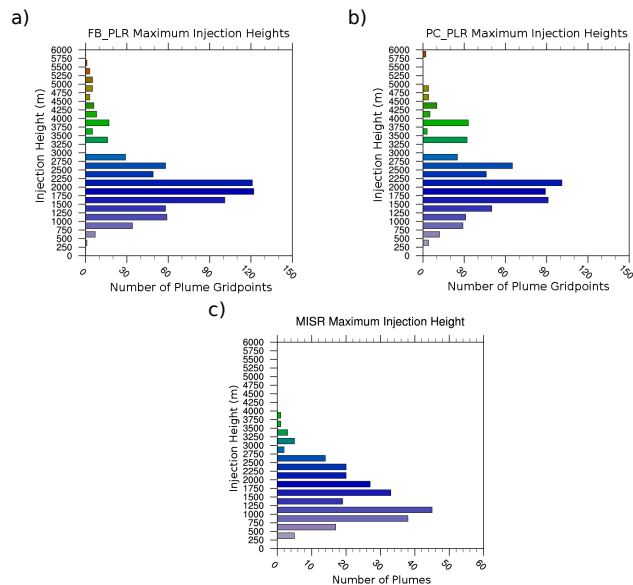


Fig. 5. Distribution of WRF-Chem maximum injection heights over Siberia and Canada during the entire ten day simulation period for (a) FB_PLR and (b) PC_PLR biomass burning emissions. (c) MISR stereo-height distribution for the same period. Note the difference in scale between (c) and (a–b).

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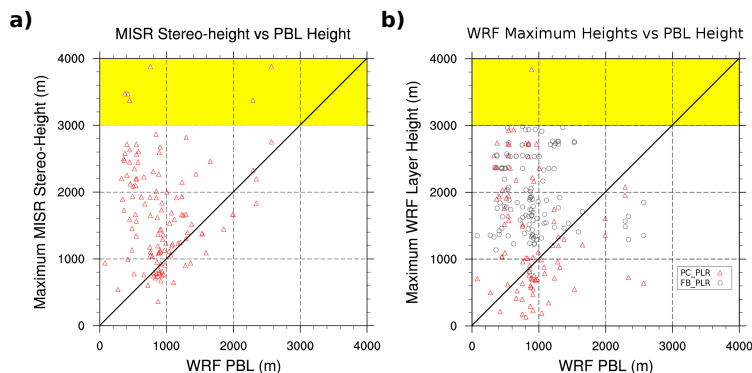


Fig. 6. (a) MISR stereo heights for ARCTAS plumes plotted against PBL heights from WRF-Chem. (b) Maximum simulated injection heights for PC_PLR (black circles) and FB_PLR (red triangles) plotted against simulated PBL heights. Points above the diagonal in (a) represent MISR injections above the simulated PBL. The yellow shaded region represents the lower half of the injection layer for the 35K simulations. Injections occur uniformly in the 35K layer; thus, the maximum injection height is at 5 km. Injection from PLR occurs in a layer determined by the 1-D plume model. The top of this layer (the maximum height) is shown in Fig. 6b.

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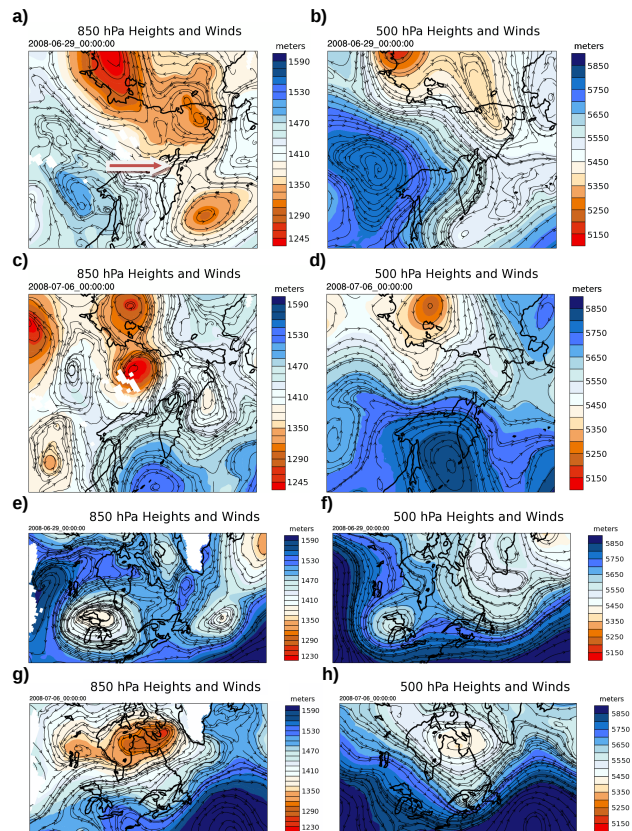


Fig. 7. Geopotential heights (color filled lines) and streamlines over northeastern Asia and the North Pacific Ocean (a–d) and North America (e–h) at 850 hPa (left column) and 500 hPa (right) for 00:00 UTC 29 June and 00:00 UTC 6 July 2008. The arrow in panel (a) denotes the saddle point where the north and south pathways from Russia split. Note that streamlines and trajectories are not equivalent

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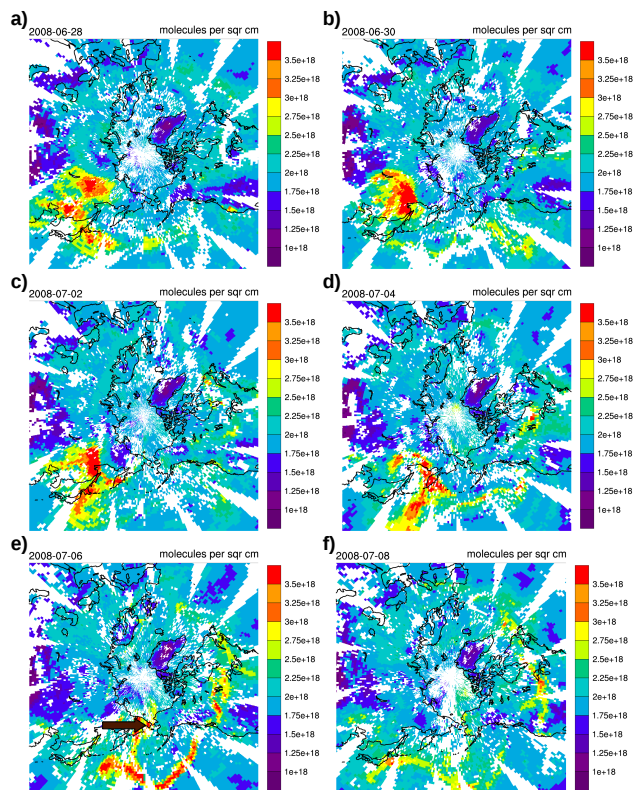


Fig. 8. AIRS 1×1 deg Level 3 Total Column CO (molecules cm⁻²) between 28 June–8 July 2008. The arrow in panel (e) is the second plume discussed in the Arctic long range transport section.

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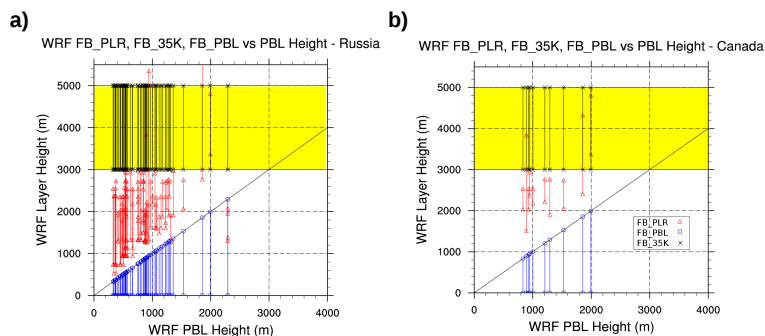


Fig. 9. Simulated injection heights for FB_PLR (red triangles) and FB_PBL (blue circles), and FB_35K (black crosses) plotted against simulated PBL heights from WRF-Chem for **(a)** injections in Russia and **(b)** injections in Canada. The yellow shaded region represents the injection layer for the 35K simulations. Since the emissions were not released at a single altitude, the various vertical lines represent the layer over which injection occurred.

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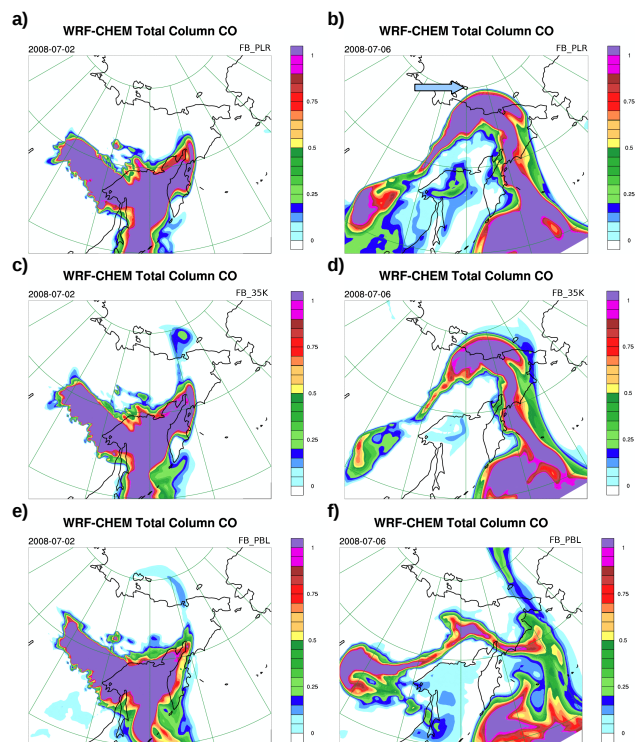


Fig. 10. Normalized WRF-Chem Total Column CO for the Russian plume over Asia and the western Pacific Ocean for (a, b) FB_PLR, (c, d) FB_35K, and (e, f) FB_PBL for (a, c, d) 2 July and (b, d, e) 6 July 2008. The arrow in panel (b) denotes one of the plumes discussed in the Arctic transport section.

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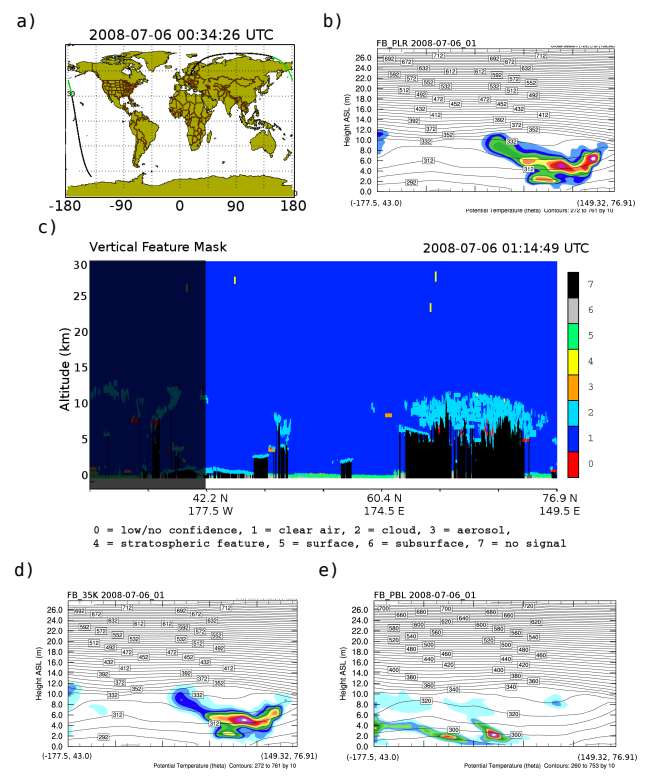


Fig. 11. (a) Map of CALIPSO path at 00:34 UTC 6 July 2008 with the analyzed segment over Russia in green and (c) the CALIOP vertical feature mask (VFM). Normalized WRF aerosol plumes for (b) FB_PLR, (d) FB_35K, and (e) FB_PBL along the CALIPSO track. The left side of each cross section is the south eastern starting point, while the right side is the north western ending point.

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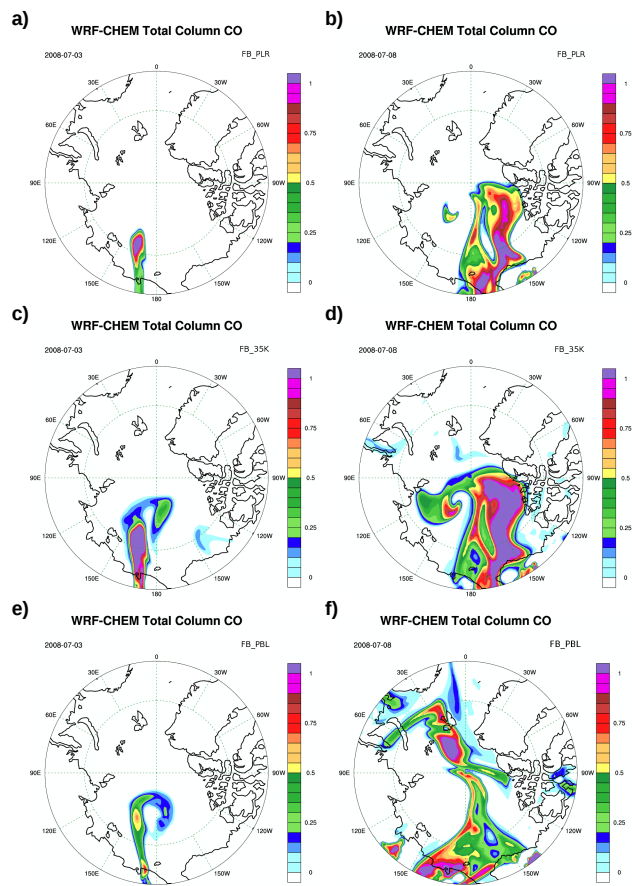


Fig. 12. Normalized WRF-Chem Total Column CO for two northern branches of the Russian plume over the Arctic Ocean for (a, b) FB_PLR, (c, d) FB_35K, and (e, f) FB_PBL on (a, c, d) 4 July and (b, d, e) 8 July 2008.

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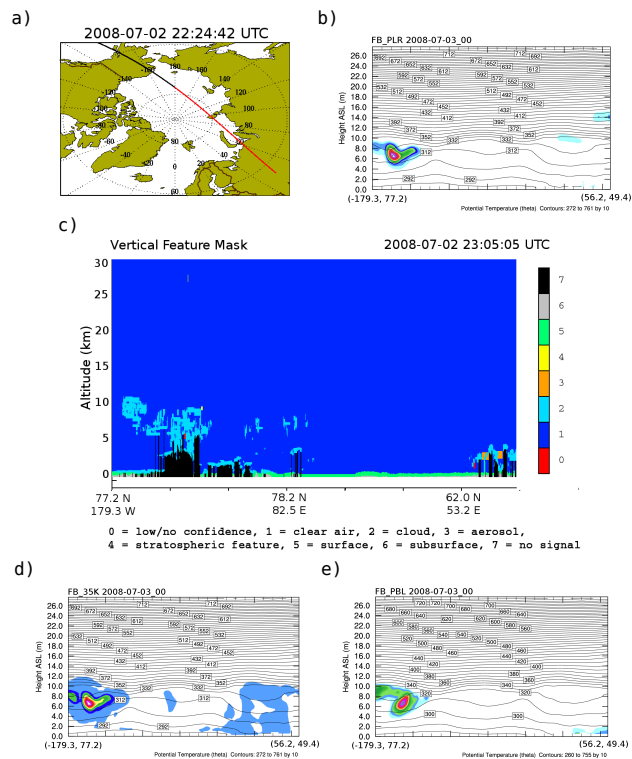


Fig. 13. (a) Map of CALIPSO path at 22:24 UTC 2 July 2008 with analyzed segment near the North Pole in red and (c) the CALIOP vertical feature mask (VFM). Normalized WRF aerosol plumes for (b) FB_PLR, (d) FB_35K, and (e) FB_PBL along the CALIPSO track.

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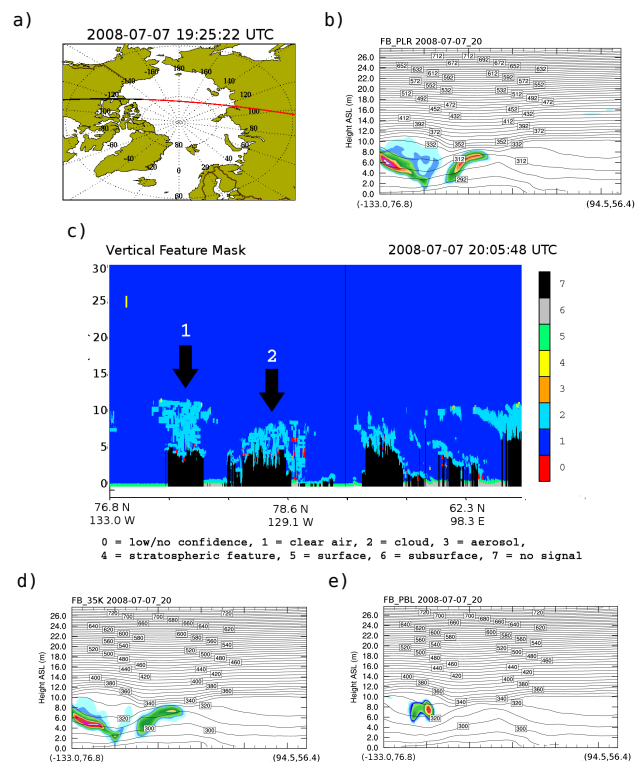


Fig. 14. (a) Map of CALIPSO path at 19:25 UTC 7 July 2008 with analyzed segment near the North Pole in red and (c) the CALIOP vertical feature mask (VFM). Normalized WRF aerosol plumes for (b) FB_PLR, (d) FB_35K, and (e) FB.PBL along the CALIPSO track. Arrows in panel (c) represent features described in the text.

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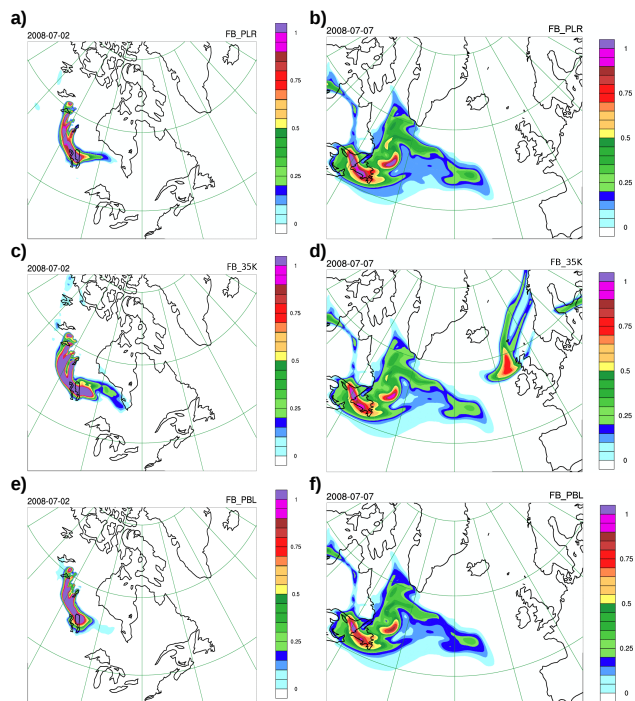


Fig. 15. Normalized WRF-Chem Total Column CO for the North American plume over Canada on (a, c, e) 2 July and (b, d, f) 7 July.

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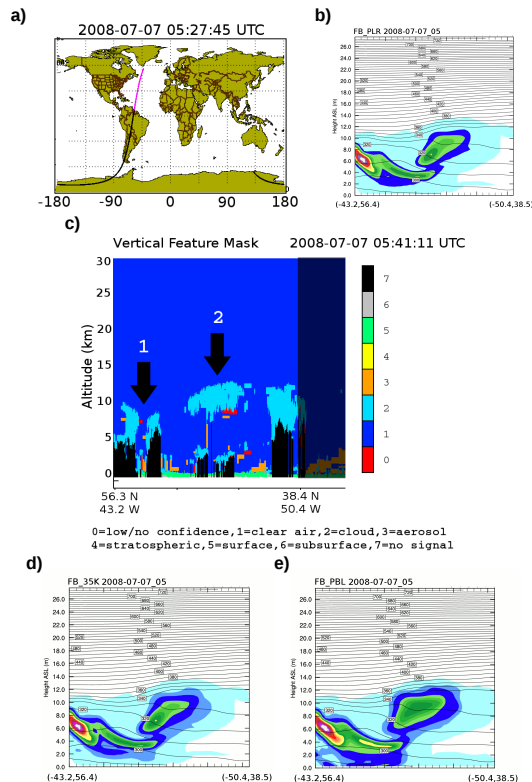


Fig. 16. (a) Map of CALIPSO path at 05:27 UTC 7 July 2008 with analyzed segment over the Atlantic Ocean in violet and (b) CALIOP vertical feature mask (VFM). Normalized WRF aerosol plume for (b) FB_PLR, (d) FB_35K, and (e) FB_PBL along the CALIPSO track. This is a descending overpass; north is to the left. Arrows in (c) indicate features discussed in the text.