and boundary conditions differs for the initial conditions, but not for the lateral boundary conditions. The meteorology is initialized with ECMWF fields every day. The initialization of the tracer variables is taken from the final output of the WRF-GHG simulation at 24 UTC the previous day to ensure continuity. The motivation for re-initializing the meteorology each day is a better data constraint of the WRF meteorological fields.
Which tracers are initialized depends on the region for which the simulations are performed. Since the WRF-Chem code does not allow any tracer with negative mixing ratios, advected tracer fields "disappear" in case the mixing ratios become negative. This occurs even though the positive definite advection scheme is used if very strong gradients in the fluxes evolve. It is avoided by initializing all tracer with the global fields or an offset (and force them with lateral boundary conditions). The offset or the global background, which can be transported inside the WRF-GHG model as a separate tracer, is later subtracted. Special care has to be taken for the tracers *CO2_2* and *CH4_6*–atmospheric mixing ratios from VPRM and soil uptake fluxes. Their corresponding fluxes can become negative. In case they are not initialized with the global fields they have to be set to a constant offset (0.0002 for *CO2_2* and 10^{-7} for *CH4_6*, respectively) to avoid problems in WRF-GHG with negative atmospheric mixing ratio values.

4.4 WRF-GHG in official WRF-Chem release

The WRF-GHG code described in the previous section was modified to fullfill the requirements for a distribution within the official WRF-Chem code from version 3.4 onwards. This work was accomplished in collaboration with Ravan Ahmadov at the NOAA Earth System Research Laboratory, Boulder, Colorado, US. In this section the differences to the standard WRF-GHG model are described. The general intention was to shape the WRF-GHG code in WRF-Chem structure, using the existing WRF-Chem capabilities and provide an user friendly code.
According to the WRF-Chem conventions, the flux variables described in Table 4.3 are grouped into anthropogenic fluxes (`emis_ant`), biogenic fluxes (`eghg_bio`), and biomass burning fluxes (`ebu`). The anthropogenic and biomass burning flux arrays in WRF-Chem were augmented for the addition of the required greenhouse gas flux variables and the biogenic flux array was newly introduced. Table 4.7 illustrates the new partitioning of the flux variables. A test flux for all three species was included and the dimension of the anthropogenic fluxes is chosen in the `namelist.input` file by the `kemit` option. With this option the injection level of the anthropogenic emissions can be explicitly specified.
The tracers (now in units of [ppm]) are defined according to their emission origin. They are added up to the total contribution of the atmospheric mixing ratio in a post-processing step. Table 4.8 illustrates the different tracers of the greenhouse gas model as defined in the official WRF-Chem release. The chemistry option previously defined as `chem_opt = 98` was now moved to the package `co2_tracer` with `chem_opt = 16` including CO_2 and anthropogenic CO and the package `ghg_tracer` with `chem_opt = 17` including all tracers of `chem_opt = 16` and additionally the complete CH_4 tracers and the biomass burning tracers for CO_2, CH_4, and CO. The biomass burning emissions are now fully compatible with the previously established biomass burning option in the WRF-Chem code and are activated by setting `biomass_burn_opt = 5` in the `namelist.input` file. The code was made accessible for the MODIS landuse data set (a different set of landuse data that can be chosen within WRF compared to the standard data set from the U. S. Geological Survey).

One new file has been added to the WRF-Chem code of the official release, which is `module_ghg`

Variable	Assigned Array	Dimension [Space]	Flux component
ebio_gee	eghg_bio	2	Biospheric CO_2 GEE
ebio_res	eghg_bio	2	Biospheric CO_2 respiration
ebio_oce	eghg_bio	2	CO_2 ocean
ebio_ch4wet	eghg_bio	2	CH_4 wetland
ebio_ch4soil	eghg_bio	2	CH_4 soil uptake
ebio_ch4term	eghg_bio	2	CH_4 termite
e_co2	emis_ant	2–3	CO_2 anthropogenic
e_co	emis_ant	2–3	CO anthropogenic
e_ch4	emis_ant	2–3	CH_4 anthropogenic
e_co2tst	emis_ant	2–3	CO_2 test flux
e_cotst	emis_ant	2–3	CO test flux
e_ch4tst	emis_ant	2–3	CH_4 test flux
ebu_co2	ebu	3	CO_2 biomass burning
ebu_co	ebu	3	CO biomass burning
ebu_ch4	ebu	3	CH_4 biomass burning

Table 4.7: *Flux variables defined for the usage of the greenhouse gas module in the official WRF-Chem version 3.4.*

`_fluxes.F` including the “online" calculation of the VPRM model, the Kaplan wetland model, soil uptake, and termite emissions and the addition of the anthropogenic and biogenic fluxes to the corresponding tracers. This was previously split into two different modules (`module_greenhouse_gases.F` and `module_add_emissions.F`). The variables previously defined in `registry.ghg` are now included in `registry.chem`. The fully included biomass burning option now uses the already existing plumerise module in the WRF-Chem code.
The number of newly introduced namelist options was reduced from 12 to 4. Table 4.9 demonstrates the new `namelist.input` options.
A general practice within the WRF-Chem community is the initialization of tracers with standardized profiles. For simplicity, all tracers listed in Table 4.8 are initialized with a constant background value (380 ppm for CO_2; 0.1 ppm for CO; 1.77 ppm for CH_4) that has to be subtracted in the post-processing step. These values are also used for the forcing at the lateral boundaries. The initialization with background values further prevents the tracers from mass conservation problems that were observed for cases where strong gradients occur. Fig. 4.5 illustrate the biogenic online simulated biospheric CH_4 fluxes from WRF-ChemV3.4 and the anthropogenic and biomass burning fluxes for the South American WRF domain (cf. Table 4.7). In Fig. 4.6 the simulation of the CH_4 tracer distribution is illustrated (cf. Table 4.8).

4.5 Conclusions

The development of the WRF-GHG model enables high-resolution tracer transport of greenhouse gases such as CO_2 and CH_4. Biospheric flux models are integrated in the WRF-Chem code for online calculation of CO_2 fluxes using the VPRM model and CH_4 fluxes from the Kaplan wetland

Variable (chem)	Tracer	chem_opt
co2_ant	mixing ratio CO_2 anthropogenic	16,17
co2_bio	mixing ratio CO_2 biogenic	16,17
co2_oce	mixing ratio CO_2 oceanic	16,17
co2_atst	mixing ratio CO_2 test tracer	16,17
co2_bbu	mixing ratio CO_2 biomass burning	17
co2_bck	mixing ratio CO_2 background	16,17
co_ant	mixing ratio CO anthropogenic	16,17
co_tst	mixing ratio CO test tracer	17
co_bbu	mixing ratio CO biomass burning	17
co_bck	mixing ratio CO background	16,17
ch4_ant	mixing ratio CH_4 anthropogenic	17
ch4_bio	mixing ratio CH_4 biogenic	17
ch4_tst	mixing ratio CH_4 test tracer	17
ch4_bbu	mixing ratio CH_4 biomass burning	17
ch4_bck	mixing ratio CH_4 background	17

Table 4.8: *Overview over all tracer variables corresponding to the two chemistry options 16 and 17 for the transport of greenhouse gases.*

Variable	Default value	Description
vprm_opt	"VPRM_param_US"	VPRM parameters for North America
	"VPRM_param_EUROPE"	VPRM parameters for Europe
	"VPRM_param_TROPICS"	VPRM parameters for tropical regions
term_opt	"CH4_termite_NW"	Termite parameters for the American continent and Australia
	"CH4_termite_OW"	Termite parameters for Europe, Asia, and Africa
wpeat	0.05	Scaling factor peatland wetland emissions
wflood	0.19	Scaling factor floodplain wetland emissions

Table 4.9: *Options in the* namelist.input *for the new established chemistry options 16 and 17 in the official WRF-Chem release.*

model, termite emissions, and atmospheric soil uptake. External flux fields, e.g. for the description of anthropogenic and biomass burning emissions and other external biospheric emissions, e.g. from the Walter wetland model can be used within WRF-GHG. Different namelist options enable to use the WRF-GHG model in different configurations. A modified version of WRF-GHG is part of the official WRF-Chem V3.4 release in spring 2012. The application of WRF-GHG in the Amazon basin is described in Ch. 6.