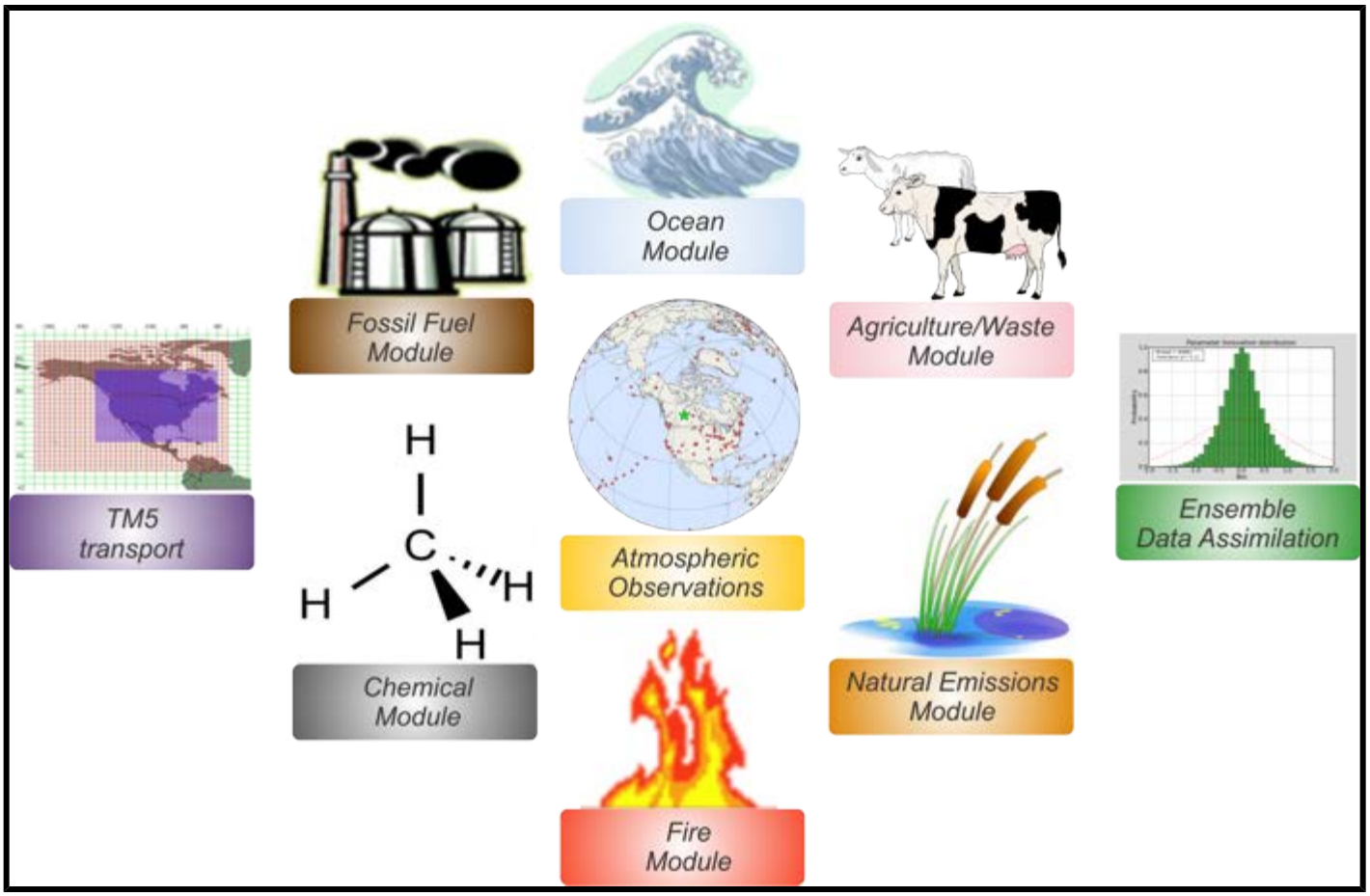
Documentation (CarbonTracker-CH_4)



To learn more about a CarbonTracker component, click on one of the above images.
Or download the full PDF version for convenience.

Oceans [goto top]

Introduction

The oceans play a relatively small role in the budget of atmospheric methane, contributing only ~2-3% of the global emissions (~10-15 $TgCH_4$/yr). A significant portion of this is assumed to come from methane seeps in shallow coastal waters (~5 $TgCH_4$/yr). In order for this to happen, the overlying water column must be shallow since methane is efficiently removed by aerobic microbial processes. Meaning that the water column must be shallow enough for bubbles to deliver methane directly to the air at the surface. Shallow coastal waters can be supersaturated in CH_4, and may emit about 6 $TgCH_4$/yr to the atmosphere, while the open ocean waters may add another 3 $TgCH_4$/yr (Houweling et al., 1999; Lambert and Schmidt, 1993).

Detailed Description

Rhee et al. (2009) have suggested that global ocean methane emissions, excluding natural seeps, is much smaller than the ~9 $TgCH_4$/yr we have used in this version of CarbonTracker-CH_4; only about 0.6-1.2 $TgCH_4$/yr. On the other hand, recent studies conducted in the coastal waters of the Eastern

Siberian Arctic, hint at the possibility that a significant source of methane is sourced from methane bubbling of continental shelf sediments (Shakova et al., 2010). There is considerable uncertainty in the contribution of the ocean to atmospheric methane. To account for this in CarbonTracker-CH_4 we decided to follow the approach of Bergamaschi et al. (2009) and used the estimates of Houweling et al., (1999) and Lambert and Schmidt (1993) as prior flux estimates. We also assumed an uncertainty on these prior flux estimates of 75%.

Further Reading

- Bergamaschi 2009
- Houweling 1999
- Rhee 2009
- Shakhova 2010

Agriculture and Waste [goto top]

Introduction

The largest source of methane emitted by human activity is associated with agriculture, animals and their waste (230-250 $TgCH_4$/yr). Ruminants, such as cattle, goats, sheep and buffalo are able to convert hard-to-digest forage to energy through a process called enteric fermentation, in which microbes produce easily digested material inside the animal's gut. Most of the methane produced in this way exits the animal via belching, however, a small portion emerges as the result of flatulence. Methane emissions from animals can be reduced by use of more easily digested feed. Emissions from enteric fermentation are expected to increase as global population grows and standards of living are improved.

Animal waste, wastewater and landfills produce methane when conditions favor anaerobic decomposition. This is the process in which organic material decomposes in low oxygen conditions by chains of microbial processes that results in the production of mostly methane and carbon dioxide. Methane produced in landfills or waste treatment facilities is now often captured and used as fuel rather than being vented to the atmosphere.

Rice agriculture is also a significant source of methane to the atmosphere. This is because warm, waterlogged rice paddies are ideal for development of anaerobic conditions and methanogenesis. Bottom-up estimates of emissions from rice agriculture are about ~50 $TgCH_4$/yr, and emissions can be significantly reduced by drainage of paddies between harvests, application of fertilizer and development of varieties of rice that tolerate drier conditions.

Detailed Description

This release of CarbonTracker-CH_4 uses the 1x1 degree gridded emissions from the EDGAR 3.2FT2000 as prior emission estimates for emissions from rice agriculture, enteric fermentation, animal waste management, wastewater and landfills. This data set is based on emission inventories by country and sector for the years 1990 and 1995 extrapolated to 2000 using production and consumption statistics. We have not extrapolated this data over the period covered by CarbonTracker, and have instead kept prior emission estimates constant at 2000 levels. This will allow us to test whether the assimilation is able to recover trends in emissions since all of these emission processes can be expected to increase with population unless steps are taken to mitigate emissions.

Further Reading

- International Rice Research Institute
- U.S. Environmental Protection Agency

Chemicals

[goto top]

Introduction

Methane is removed from the atmosphere primarily by its reaction with the hydroxyl radical (OH), but also by its reaction with atomic chlorine (Cl) and excited-state oxygen (O^1D) in the stratosphere. Closer to the surface of the Earth, in the troposphere, the average lifetime of methane is about a decade. The chemical loss of methane over a year is roughly equal to the total input from its sources (~520 $TgCH_4$/yr). However, small differences in the total emissions and losses of methane, lead to trends in observed methane levels changing.

It is difficult to characterize the global distribution of OH because it is extremely reactive as well as it has a short lifespan within the atmosphere. Instead, observations of atmospheric species that have relatively well-known anthropogenic sources and are destroyed only by reaction with OH, such as methyl chloroform (CH_3CCl_3), are used to estimate the abundance of atmospheric OH. Utilizng an empirical approach, Montzka et al. (2011) noted that the inter-annual variability in atmospheric OH is likely to be within about ~2%. Errors in OH distributions arise from uncertainty in the sources of CH_3CCl_3 used to estimate OH, as well as uncertainties in transport models. Krol et al. (1998) estimates that the uncertainty of OH distribution is 10%.

About 10% of total chemical loss of methane is due to transport and breakdown in the stratosphere. A small amount of this methane-depleted air is returned to the troposphere, and has the potential to influence the interpretation of high-altitude (aircraft) measurements of methane. In addition, errors in simulating stratosphere-troposphere transport have the potential to produce biases for long term model simulations.

Errors in the chemical loss of methane, and the inability to adequately resolve inter-annual variability of OH, make the estimation of methane fluxes challenging. A 2% variation in the global methane sink is equivalent to ~10 $TgCH_4$/yr, roughly the size of estimated inter-annual variability in methane sources. Currently, the best approach is to use OH fields that are as consistent as possible with existing records of species whose chemistry is significantly linked with OH. Examples include, carbon monoxide (CO) and methyl chloroform (CH_3CCl_3).

Detailed Description

For this version of CarbonTracker-CH_4 we use pre-calculated OH fields from a global chemical model that have been optimized against global observations of methyl chloroform. The chemical loss fields consist of a single and repeating seasonal cycle, and result in a methane lifetime of about 9.5 years. Details of the chemical loss fields may be found in Bergamaschi et al. (2005). Currently CarbonTracker-CH_4 does not attempt to adjust the global chemical data through the assimilation of methane observations.

Further Reading

- Bergamaschi 2005
- Krol 2003
- Montzka 2011

Natural Emissions [goto top]

Introduction

The largest source of methane from natural sources is wetlands. Wetlands are defined as regions that are permanently or seasonally water logged. Wetlands are a broad category that includes both high-latitude peat bogs and typically low-latitude tropical swamps. Saturated soils in warm tropical environments tend to produce the most methane, however, warming Arctic temperatures raise concern for increasing output from high-latitude wetlands and future decomposition of carbon that is currently stored in the frozen soils of the Arctic (e.g. Schaefer et al., 2011).

Methane is easily oxidized in overlying aerobic water columns or wetlands. Because of this, for a wetland to be most productive, the water table must be at or near the surface and the depth of overlying water must be shallow. Over time, wetland plants have adapted to low oxygen environments by having hollow stems to allow delivery of oxygen and other gases to their root systems. These hollow stems also allow delivery of methane directly to the atmosphere, which along with bubbles, accounts for most of the methane transport into the atmosphere. Diffusion also occurs but is thought to be significantly smaller. Estimates of global emissions from wetlands are about 150-200 $TgCH_4$/yr with most of this occurring in tropical regions. Because emissions are sensitive to temperature and precipitation, they exhibit significant seasonal cycles, especially at high latitudes with inter-annual variability.

Other natural sources of methane include enteric fermentation in insects (mainly termites) and wild ruminants. Both of these sources are thought to be much smaller than that from wetlands (~ 25 $TgCH_4$/yr).

A natural sink of atmospheric methane is oxidation in dry soils (~40 $TgCH_4$/yr). Wetlands that undergo dry and wet seasons can actually switch between being sources and sinks of methane.

Detailed Description

Methane emissions from wetlands are difficult to quantify for two reasons; their global spatial distribution is difficult to accurately pinpoint and there is large variability in conditions that lead to methane production. This version of CarbonTracker-CH_4 uses the prior flux estimates of Bergamaschi et al. (2007) which are based on the wetland distribution of Matthews and Fung (1989) and the wetland emission model of Kaplan (1988). The global total of the prior flux estimate is 175 $TgCH_4$/yr and we assume a prior flux uncertainty of 75%.

The soil sink of methane is based on the study of Ridgwell et al. (1999) and the termite and wild animal sources are from Sanderson (1996) and Houweling et al. (1999).

Further Reading

- Bustamante 2009
- Houweling 1999
- Ridgwell 1999
- Sanderson 1996

Fire [goto top]

Introduction

Fire is an important part of the carbon cycle and has been for many millennia. Even before human civilization began to use fire to clear land for agricultural purposes, most ecosystems were subject to

natural wildfires. These fires rejuvenated old forests in various ways including reintroducing important minerals to the soils. As fires consume a landscape, in either controlled or natural burning, carbon dioxide, carbon monoxide and methane (amongst many other gases and aerosols) are released in significant quantities. Each year, vegetation fires emit around 2 PgC as CO_2 into the atmosphere, mostly in the tropics. Fires are a relatively small part of the atmospheric CH_4 budget: ~15-20 $TgCH_4$/yr out of a total of ~520 $TgCH_4$/yr, however, they are an important contribution to the inter-annual variability of methane. Currently, a large fraction of these fires are started by humans, with most of them started intentionally to clear land for agriculture, or to re-fertilize soils before a new growing season. Fires are monitored mostly from space, with sophisticated 'biomass burning' models that are used to estimate the amount of carbon emitted by each fire. Such estimates are then used in CarbonTracker to prescribe emissions. In CarbonTracker-CH_4, the prescribed emissions are adjusted through the assimilation of observations.

Detailed Description

The fire module used in CarbonTracker is based on the Global Fire Emissions Database (GFED). The GFED uses the CASA biogeochemical model as described in the CarbonTracker-CO_2 terrestrial biosphere model documentation to estimate the carbon fuel in various biomass pools. The dataset consists of 1° x 1° gridded monthly burned area, fuel loads, combustion completeness, and fire emissions (Carbon, CO_2, CO, CH_4, NMHC, H_2, NO_x, N_2O, PM2.5, Total Particulate Matter, Total Carbon, Organic Carbon, Black Carbon) for the time period spanning January 1997 - December 2009, of which we currently only use CO_2.

In 2010, the GFED team switched the satellite product driving the CASA terrestrial productivity submodel from AVHRR NDVI to the MODIS fPAR product. For CT2010, we use fire emissions from the NDVI-driven GFED version 2 for the period 2000-2006, and fire emissions from the fPAR-driven GFED 3.1 for the period 2007-2009.

The GFED burned area is based on MODIS satellite observations of fire counts. These, together with detailed vegetation cover information and a set of vegetation specific scaling factors, allow predictions of burned area over the time span that active fire counts from MODIS are available. The relationship between fire counts and burned area is derived, for the specific vegetation types, from a 'calibration' subset of 500 m resolution burned area from MODIS in the period 2001-2004.

Once a burned area has been estimated globally, emissions of trace gases are calculated using the CASA biosphere model. The seasonally changing vegetation and soil biomass stocks in the CASA model are calculated based on the burned area estimate, and converted to atmospheric trace gases using estimates of fuel loads, combustion completeness, emission ratios and burning efficiency.

Further Reading

- CASA with fires model overview
- CASA results from Jim Randerson
- GFED2 results from Guido van der Werf, Jim Randerson, and colleagues
- Giglio et al., 2006 paper
- Interannual variability in global biomass burning emissions from 1997 to 2004, G. R. van der Werf, J. T. Randerson, L. Giglio, G. J. Collatz, P. S. Kasibhatla, and A. F. Arellano Jr., Atmospheric Chemistry and Physics 6: 3423-3441 Aug 21 2006.

Observations [goto top]

Introduction

The observations of CH_4 mole fraction by NOAA ESRL and partner laboratories are at the heart of CarbonTracker-CH_4. They inform us about the atmospheric methane buget, whether they are regular (such as the seasonal wetland emissions), or irregular (such as the release of tons of carbon by a wildfire). The results in CarbonTracker depend directly on the quality, frequency, density and location of observations available. The degree of detail at which we can monitor the atmospheric methane budget increases strongly with the density, or the number of samples collected, within our observing network.

Detailed Description

This study uses measurements of air samples collected at surface sites in the NOAA ESRL Cooperative Global Air Sampling Network except those identified as having analysis or sampling problems, or those thought to be influenced by local sources. The sites for which data are available thus varies each week depending on successful sampling and analysis, and each site's sampling frequency. In addition, we use in situ quasi-continuous CH_4 time series from the following towers operated by Environment Canada (EC):

- the 30 m level of the tower at Candle Lake (CDL, formerly Old Black Spruce), Saskatchewan, Canada operated by EC
- the 105m level of the tower in East Trout Lake, Saskatchewan, Canada (ETL) operated by EC
- the 40 m level of the tower in Fraserdale, Ontario, Canada (FRD) operated by EC
- the 10 m level of the tower in Lac Labiche, Alberta, Canada (LLB) operated by EC

Other in situ quasi-continuous CH_4 time series used are from the EC Canadian sites at Alert, Nunavut (ALT), Sable Island, Nova Scotia (SBL) and Egbert, Ontario (EGB).

Note that all of these observations are calibrated against the WMO GAW CH_4 mole fraction scale (NOAA 2004). Also, note that aircraft observations from the NOAA ESRL program were NOT assimilated, but used for independent assessment of the CarbonTracker-CH_4 results.

For most quasi-continuous sampling sites, we construct an afternoon daytime average mole fraction for each day from the time series, recognizing that our atmospheric transport model does not always capture the continental nighttime stability regime while daytime well-mixed conditions are better matched. Moreover, observations at sub-daily time scales are likely to be strongly correlated and therefore add relatively little independent information to our results.

Also based on Transcom continuous simulations, we decided to move a set of coastal sites by one degree into the ocean to force the model sample to be more representative of the actual site conditions. These sites are labeled for reference in the complete table of sites used in CarbonTracker. Table 1 summarizes how data from the different measurement programs are preprocessed for this study.

The preprocessed data used in CarbonTracker-CH_4 are available on request. Preprocessed data are **not** the original measurement data. Users are encouraged to review the literature and contact the measurement labs directly for details about and access to the actual observations.

Table 1: Summary of CarbonTracker data preprocessing.

Measurement Program	Data Preprocessing
ESRL discrete	All valid[1] data. Multiple values from the same day and location are averaged. No sample time-of-day

surface	restriction (see exception below).
EC in situ sites	All valid data from highest intake. Day average using 12-16 LST.

[1]In this context "Valid Data" means the observation is thought to be free of sampling and analytical problems and has not been locally influenced.

We apply a further selection criterion during the assimilation to exclude non-marine boundary layer (MBL) observations that are very poorly forecasted in our framework. We use the so-called model-data mismatch in this process, which is the random error ascribed to each observation to account for measurement errors as well as modeling errors of that observation. We interpret an observed-minus-forecasted (OmF) mole fraction that exceeds 3 times the prescribed model-data mismatch as an indicator that our modeling framework fails. This can happen for instance when an air sample is representative of local exchange not captured well by our 1° x 1° fluxes, when local meteorological conditions are not captured by our offline transport fields, or when strong, localized emissions that cannot be resolved by our flux modules are suspected.

CarbonTracker-CH_4 Observational Network Click on any site marker for more information. Double-click on a site marker to center the map on that site.

Table 2 (below) gives a summary of the observing sites used in CarbonTracker, and the performace of the assimilation scheme at each site. These diagnostics are useful for evaluating how well CarbonTracker does in simulating observed CH_4.

Table 2. Summary of Observational Sites Used in CarbonTracker.

				Elevation	#	#	Model-Data	Mean	σ	2

Site Code	Laboratory	Latitude	Longitude	(masl)	Obs.	Rejected	Mismatch (ppb)	Bias (ppb)	(ppb)	X
abp_01d0	ESRL	12.77S	38.17W	1.0masl	112	3	7.5	-8.4	7.7	2.0
alt_01d0	ESRL	82.45N	62.51W	200.0masl	532	0	15.0	-2.2	8.7	0.3
alt_06c0	EC	82.45N	62.51W	200.0masl	3181	10	15.0	-1.2	10.2	0.4
amt_01d0	ESRL	45.03N	68.68W	50.0masl	267	4	30.0	-6.1	22.8	0.4
amt_01p0	ESRL	45.03N	68.68W	50.0masl	174	0	30.0	0.8	16.5	0.3
asc_01d0	ESRL	7.97S	14.4W	74.5masl	961	79	7.5	-10.0	9.3	3.0
ask_01d0	ESRL	23.18N	5.42E	2728.0masl	491	0	25.0	-6.9	9.1	0.2
azr_01d0	ESRL	38.77N	27.38W	40.0masl	350	16	15.0	-12.0	15.9	1.7
bal_01d0	ESRL	55.35N	17.22E	3.0masl	974	0	75.0	1.4	29.4	0.1
bhd_01d0	ESRL	41.41S	174.87E	85.0masl	165	0	7.5	-4.1	5.4	0.7
bkt_01d0	ESRL	0.2S	100.32E	864.5masl	345	0	75.0	6.8	30.8	0.2
bme_01d0	ESRL	32.37N	64.65W	30.0masl	256	14	15.0	-13.6	17.4	2.1
bmw_01d0	ESRL	32.27N	64.88W	30.0masl	352	7	15.0	-13.2	12.8	1.4
brw_01d0	ESRL	71.32N	156.61W	11.0masl	514	13	15.0	-5.8	16.1	1.1
bsc_01d0	ESRL	44.17N	28.68E	3.0masl	501	1	75.0	-14.4	56.2	0.5
cba_01d0	ESRL	55.21N	162.72W	21.34masl	892	23	15.0	-10.6	13.4	1.1
cdl_06c0	EC	53.99N	105.12W	600.0masl	1390	77	25.0	-24.7	30.3	2.1
cgo_01d0	ESRL	40.68S	144.69E	94.0masl	416	0	7.5	-4.1	4.6	0.6
chr_01d0	ESRL	1.7N	157.17W	3.0masl	426	79	7.5	-14.6	9.9	5.2
crz_01d0	ESRL	46.45S	51.85E	120.0masl	453	0	7.5	-2.9	4.3	0.5
egb_06c0	EC	44.23N	79.78W	251.0masl	1810	0	75.0	-6.9	28.7	0.1
eic_01d0	ESRL	27.15S	109.45W	50.0masl	323	3	7.5	-7.3	5.3	1.4
esp_06c0	EC	49.58N	126.37W	7.0masl	403	0	25.0	-6.8	12.3	0.3
etl_06c0	EC	54.35N	104.98W	492.0masl	1780	135	25.0	-30.1	31.9	2.8
fsd_06c0	EC	49.88N	81.57W	210.0masl	3409	10	25.0	-9.4	18.3	0.6
gmi_01d0	ESRL	13.43N	144.78E	3.0masl	802	11	15.0	-10.2	13.0	1.2
hba_01d0	ESRL	75.58S	26.5W	30.0masl	506	0	7.5	0.5	4.6	0.3
hpb_01d0	ESRL	47.8N	11.01E	985.0masl	241	17	25.0	-13.8	35.7	1.4
hun_01d0	ESRL	46.95N	16.65E	248.0masl	530	3	75.0	-14.0	43.7	0.3
ice_01d0	ESRL	63.4N	20.29W	118.0masl	529	7	15.0	-3.3	13.1	0.6
izo_01d0	ESRL	28.31N	16.5W	2360.0masl	443	2	15.0	-8.5	11.4	0.9
key_01d0	ESRL	25.67N	80.16W	3.0masl	388	3	25.0	-7.0	20.1	0.6
kum_01d0	ESRL	19.52N	154.82W	3.0masl	720	42	7.5	-6.8	10.6	2.2
kzd_01d0	ESRL	44.06N	76.82E	601.0masl	454	4	75.0	5.2	44.0	0.2
kzm_01d0	ESRL	43.25N	77.88E	2519.0masl	447	2	25.0	-2.8	20.2	0.6
lef_01d0	ESRL	45.95N	90.27W	472.0masl	505	6	30.0	-9.7	28.6	0.8
lef_01p0	ESRL	45.95N	90.27W	472.0masl	341	7	30.0	-2.1	30.9	0.9
llb_06c0	EC	54.95N	112.45W	540.0masl	1152	84	75.0	-79.9	122.4	3.7
lln_01d0	ESRL	23.47N	120.87E	2862.0masl	222	1	25.0	-4.1	24.4	0.9

lmp_01d0	ESRL	35.52N	12.62E	45.0masl	206	1	25.0	-0.7	20.5	0.5
mhd_01d0	ESRL	53.33N	9.9W	5.0masl	416	0	25.0	-4.6	11.4	0.2
mid_01d0	ESRL	28.21N	177.38W	3.7masl	525	5	15.0	-10.7	10.9	1.0
mkn_01d0	ESRL	0.05S	37.3E	3897.0masl	146	0	25.0	-14.3	14.8	0.7
mlo_01d0	ESRL	19.54N	155.58W	3397.0masl	565	0	15.0	-2.4	10.9	0.5
nmb_01d0	ESRL	23.58S	15.03E	456.0masl	164	0	25.0	-7.8	11.4	0.3
nwr_01d0	ESRL	40.05N	105.58W	3523.0masl	543	18	15.0	-11.1	15.2	1.5
oxk_01d0	ESRL	50.03N	11.8E	1022.0masl	202	2	75.0	-12.5	42.9	0.3
pal_01d0	ESRL	67.97N	24.12E	560.0masl	377	54	15.0	16.7	35.1	0.2
poc000_01d1	ESRL	0.0N	155.0W	10.0masl	173	33	7.5	-13.9	9.5	4.7
pocn05_01D1	ESRL	5.0N	151.0W	10.0masl	174	29	7.5	-15.1	9.5	5.3
pocn10_01D1	ESRL	10.0N	149.0W	10.0masl	174	45	7.5	-16.0	14.0	7.6
pocn15_01D1	ESRL	15.0N	145.0W	10.0masl	168	26	7.5	-11.0	11.1	4.1
pocn20_01D1	ESRL	20.0N	141.0W	10.0masl	166	13	7.5	-6.8	11.5	2.9
pocn25_01D1	ESRL	25.0N	139.0W	10.0masl	155	14	7.5	-7.0	11.2	2.6
pocn30_01D1	ESRL	30.0N	135.0W	10.0masl	153	18	7.5	-4.7	13.9	2.7
pocn35_01D1	ESRL	35.0N	137.0W	10.0masl	5	0	7.5	-4.0	8.6	1.4
pocs05_01D1	ESRL	5.0S	159.0W	10.0masl	159	31	7.5	-15.3	8.6	5.2
pocs10_01D1	ESRL	10.0S	161.0W	10.0masl	170	41	7.5	-14.6	10.1	5.4
pocs15_01D1	ESRL	15.0S	171.0W	10.0masl	163	15	7.5	-10.4	9.5	3.4
pocs20_01D1	ESRL	20.0S	174.0W	10.0masl	169	8	7.5	-7.3	7.9	2.0
pocs25_01D1	ESRL	25.0S	171.0W	10.0masl	164	0	7.5	-5.3	6.3	1.1
pocs30_01D1	ESRL	30.0S	176.0W	10.0masl	166	0	7.5	-5.0	5.0	0.8
pocs35_01D1	ESRL	35.0S	180.0E	10.0masl	14	1	7.5	-0.5	8.2	0.5
psa_01d0	ESRL	64.92S	64.0W	10.0masl	542	0	7.5	-2.7	3.7	0.3
pta_01d0	ESRL	38.95N	123.74W	17.0masl	427	1	25.0	-4.6	16.9	0.4
rpb_01d0	ESRL	13.17N	59.43W	45.0masl	519	2	15.0	-10.7	10.0	0.9
sct_01p0	ESRL	33.41N	81.83W	115.2masl	351	0	75.0	-23.5	33.7	0.3
sey_01d0	ESRL	4.67S	55.17E	3.0masl	514	43	7.5	-6.5	12.3	3.1
sgp_01d0	ESRL	36.8N	97.5W	314.0masl	443	10	75.0	-56.1	57.4	0.8
shm_01d0	ESRL	52.72N	174.1E	40.0masl	482	0	25.0	-8.7	11.4	0.3
smo_01d0	ESRL	14.25S	170.56W	42.0masl	568	70	7.5	-10.5	9.9	3.6
spo_01d0	ESRL	89.98S	24.8W	2810.0masl	566	0	7.5	-4.1	4.7	0.7
stm_01d0	ESRL	66.0N	2.0E	0.0masl	917	9	15.0	-1.4	13.5	0.5
sum_01d0	ESRL	72.58N	38.48W	3238.0masl	468	0	15.0	-4.7	8.4	0.4
syo_01d0	ESRL	69.0S	39.58E	11.0masl	260	0	7.5	-2.6	3.6	0.3
tap_01d0	ESRL	36.73N	126.13E	20.0masl	441	3	75.0	10.2	61.7	0.5
tdf_01d0	ESRL	54.87S	68.48W	20.0masl	206	0	7.5	-4.2	4.1	0.6
thd_01d0	ESRL	41.05N	124.15W	107.0masl	400	0	25.0	-7.0	14.6	0.4
uta_01d0	ESRL	39.9N	113.72W	1320.0masl	525	12	25.0	-5.5	28.7	0.4

uum_01d0	ESRL	44.45N	111.1E	914.0masl	533	1	25.0	-1.2	22.7	0.3
wbi_01p0	ESRL	41.72N	91.35W	241.7masl	296	12	30.0	-8.3	38.0	1.4
wgc_01p0	ESRL	38.27N	121.49W	0.0masl	339	53	75.0	-118.5	158.8	6.9
wis_01d0	ESRL	31.13N	34.88E	400.0masl	552	3	25.0	-6.2	23.7	0.8
wkt_01d0	ESRL	31.31N	97.33W	251.0masl	409	55	30.0	-48.6	43.7	3.8
wkt_01p0	ESRL	31.31N	97.33W	251.0masl	298	38	30.0	-46.7	58.7	5.8
wlg_01d0	ESRL	36.29N	100.9E	3810.0masl	462	17	15.0	-1.8	20.6	0.8
wsa_06c0	EC	49.93N	60.02W	5.0masl	2314	52	25.0	3.8	25.5	0.9
zep_01d0	ESRL	78.9N	11.88E	475.0masl	588	11	15.0	2.2	14.2	0.5

Further Reading

- ESRL Carbon Cycle Program
- WMO/GAW Reports: No. 168, 2006

Fossil Fuels [goto top]

Introduction

Humans first began influencing the carbon cycle by adapting their environment to fit their needs. Early humans used fire to control animals and later cleared forest for agriculture. Over the last two centuries, following the industrial and technical revolutions as well as significant increase in global population, fossil fuel combustion is now the largest anthropogenic source of CO2. Coal, oil and natural gas are the most common energy sources in both developed and developing countries. Methane is the principle component of natural gas. Methane leaks to the atmosphere durring natural gas production and transport and these leaks contribute a considerable amount to the overall atmospheric methane levels. Additionally, natural gas can be a side product of oil production and is often flared, or vented to the atmosphere. Together, anthropogenic emissions from oil and gas production are thought to contribute about 50 $TgCH_4$/yr (~10% of the global annual methane sources). Methane is also associated with coal deposits and can be released when pulverizing coal, an important step in preparing coal for power production. Other times it is vented directly to the atmosphere from coal mines, which contribute an additional ~20 $TgCH_4$/yr.

Compared to other options, coal is a relatively inexpensive source for power. In the U.S., coal has the added advantage of being produced domestically and as a result, provides roughly half of our energy needs. Unfortunately however, coal has high environmental costs. Leveling of mountains, pollution of waterways, emissions of sulfur and nitrogen oxides, as well as mercury are all associated with coal production and combustion. In addition, the amount of CO2 emitted per unit of energy produced is about twice that for natural gas, making coal an environmentally costly choice for energy production. As Asian economies have grown, coal production has increased in these countries by a factor of about two since 2000, while it has remained stable for much of the rest of the world. In 2010, Chinese production of coal increased by 9% from the previous year (BP Statistical Energy Review, 2011).

Combustion of natural gas is currently used to generate about one quarter of the electricity produced in the U.S.. Its popularity as a fuel has recently grown due to its efficiency and relatively clean nature. Recent technological advances in the recovery of natural gas, principally hydraulic fracturing, have led to increases in reserve estimates. It is now thought that the U.S. has a large enough natural gas supply to last nearly a century based on current consumption. The impact of hydraulic fracturing on greenhouse gas emissions is currently a topic of intense research. One study suggests that

methane emissions from hydraulic fracturing may be 30% higher than emissions from conventional wells (Howarth et al., 2011). In any case, it is likely that as natural gas reserves are increasingly exploited, emissions related to its production will also rise.

Detailed Description

This release of CarbonTracker-CH_4 uses a 1x1 degree gridded emission levels from the EDGAR 3.2FT2000. This 1x1 degree grid is used as prior emission estimates for fugitive emissions from coal, oil and gas production. This data set is based on emission inventories by country and sector for the years 1990 and 1995 and is extended for the year 2000 by utilizing production and consumption statistics. We have not extrapolated this data over the period covered by CarbonTracker, and have instead kept prior emission estimates constant at 2000 levels. This allow us to test whether the assimilation is able to recover. For example, the large increase in emissions from coal production in Asia. It turns out that this is a very stringent test of the assimilation system because few observation sites are likely to be located near fossil fuel production locations, making it very difficult to detect emission changes.

Further Reading

- Howarth and Santoro

TM5 Nested Transport [goto top]

Introduction

The link between the observation of atmospheric trace constitutents in the air and their exchange at the Earth's surface, is their transport: storm systems, cloud complexes, and various other types of weather, cause winds that transport atmospheric trace constituents around the world. As a result, local events like fires and fossil fuel emissions often impact remote locations. To simulate winds and weather, CarbonTracker uses sophisticated numerical models that are driven by the daily weather forecasts from specialized meteorological centers of the world. After accounting for any chemical loss, the influence of emissions and uptake in locations such as North America and Europe, are seen in our measurements, including places like the South Pole! Despite seeing the influence of emissions in our model, figuring out the specific transport of atmospheric trace species remains a challenge. Not only is it difficult but it is also technologically expensive, costing almost 90% of the computer resources for CarbonTracker. To represent the atmospheric transport, Transport Model 5 (TM5) is used. This is a community-supported model whose development is shared among many scientific groups with different areas of expertise. TM5 is used for many applications other than CarbonTracker, including forecasting air-quality, studying the dispersion of aerosols in the tropics, tracking biomass burning plumes, and predicting pollution levels that future generations will have to deal with.

Detailed Description

TM5 is a global model with two-way nested grids. This means that using TM5, regions for which high-resolution simulations are desired, can be nested in a coarser grid spanning the global domain. The advantage to this approach is that transport simulations can be performed with a regional focus without the need for boundary conditions from other models. Further, this approach allows measurements outside the "zoom" domain to constrain regional fluxes in the data assimilation, and ensures that regional estimates are consistent with global constraints. TM5 is based on the predecessor model TM3, but has seen improvements in the advection scheme, vertical diffusion parameterization, and meteorological preprocessing of the wind fields (Krol et al., 2005). The model is developed and maintained jointly by the Institute for Marine and Atmospheric Research Utrecht

(IMAU, The Netherlands), the Joint Research Centre (JRC, Italy), the Royal Netherlands Meteorological Institute (KNMI, The Netherlands), and NOAA ESRL (USA). In CarbonTracker, TM5 separately simulates advection, convection (deep and shallow), and vertical diffusion in the planetary boundary layer and free troposphere.

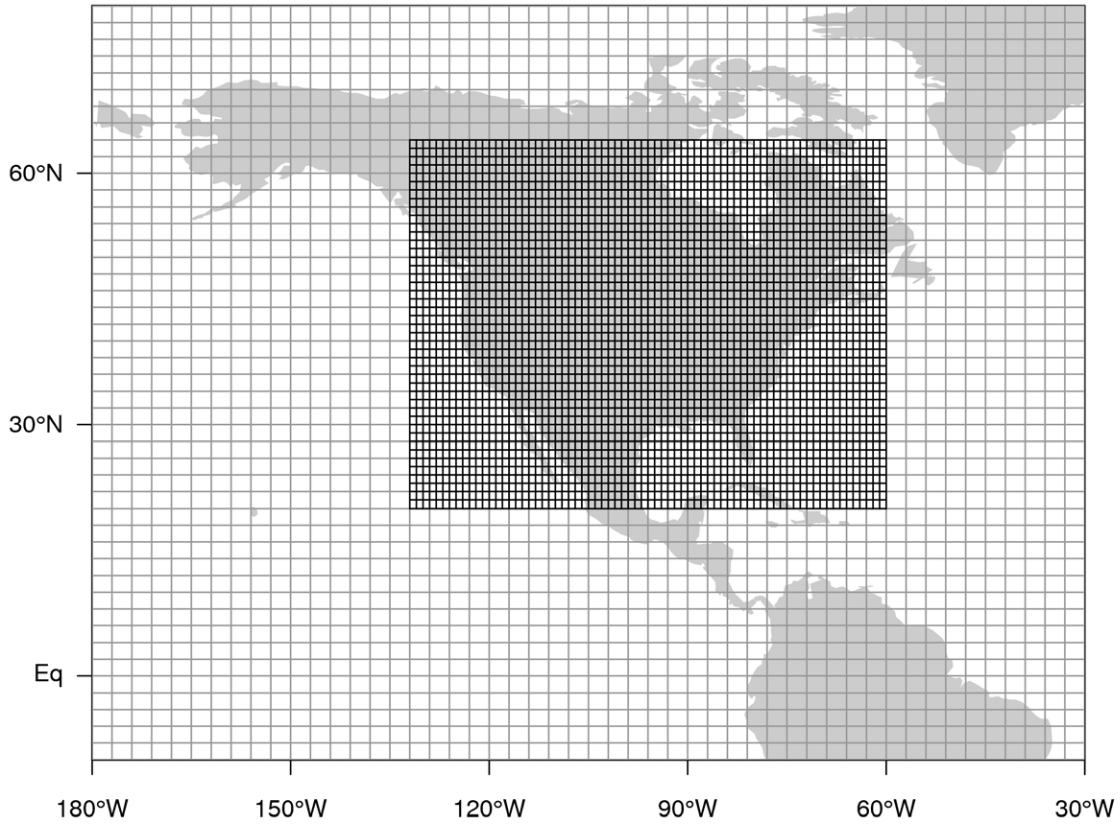


Figure 1. TM5 grids used in CarbonTracker. Figure shows the 1°x 1° nested regional grid over North America and a portion of the global 3°x 2° grid.

The winds which drive TM5 come from the European Center for Medium range Weather Forecast (ECMWF) operational forecast model. This "parent" model currently runs with ~25 km horizontal resolution and 60 layers in the vertical prior to 2006 (and 91 layers in the vertical from 2006 onwards). The carbon dioxide levels predicted by CarbonTracker do not feed back onto these predictions of winds.

For use in TM5, the ECMWF meteorological data are preprocessed into coarser grids. In CarbonTracker, TM5 is run at a global 3°x 2° resolution with a nested regional grid over North America at 1° x 1° resolution (Figure 1). TM5 runs at an external time step of three hours, but due to the symmetrical operator splitting and the refined resolution in nested grids, processes at the finest scale are repeated every 10 minutes. The vertical resolution of TM5 in CarbonTracker is 34 hybrid sigma-pressure levels (from 2006 onwards; 25 levels for 2000-2005). These levels are unevenly spaced, with more levels near the surface. Approximate heights of the mid-levels (in meters, with a surface pressure of 1012 hPa) are:

Level	Height (m)	Level	Height (m)
1	34.5	14	9076.6
2	111.9	15	10533.3
3	256.9	16	12108.3
4	490.4	17	13874.2
5	826.4	18	15860.1
6	1274.1	19	18093.2
7	1839.0	20	20590.0
8	2524.0	21	24247.3
9	3329.9	22	29859.6
10	4255.6	23	35695.0
11	5298.5	24	42551.5
12	6453.8	25	80000.0
13	7715.4		

Further Reading

- The TM5 model homepage
- User guide to ECMWF forecast products
- The NCEP reanalysis meteo data
- Peters et al., 2004, JGR paper on transport in TM5
- Krol et al., 2005, ACP overview paper of the TM5 model

Ensemble Data Assimilation [goto top]

Introduction

Data assimilation is a process by which observations of the 'state' of a system help to constrain the behavior of the system in time and space. An example of one of the earliest applications of data assimilation is the system in which the trajectory of a flying rocket is constantly (and rapidly) adjusted based on information of its current position to guide it to its exact final destination. Another example is weather prediction models that are updated every few hours with measurements of temperature, winds and other variables, to improve the accuracy of its forecasts for future times. Data assimilation is usually a cyclical process; estimates are refined over time as more observations about the "truth" become available. Mathematically, data assimilation can be done with a number of techniques. For large systems, so-called variational and ensemble techniques are most successful. Because of the size and complexity of the systems studied in most fields, data assimilation projects inevitably involve supercomputers to model the known physics of a system. Success in guiding these models in time often depends strongly on the number of observations available to inform on the true system state.

In CarbonTracker, the model that describes the system contains relatively simple descriptions of greenhouse gas emissions from anthropogenic and natural processes. In time, we alter the behavior of this model by adjusting a small set of parameters as described in the next section.

Detailed Description

Five surface flux modules drive instantaneous CH_4 fluxes in CarbonTracker-CH_4 so that the total emission of CH_4 to the atmosphere is described by:

$$F(x, y, t) = \lambda \bullet F_{natural}(x, y, t) + \lambda \bullet F_{fossil\ fuel}(x, y, t) + \lambda \bullet F_{agriculture/waste}(x, y, t) + \lambda \bullet F_{fire}(x, y, t) + \lambda \bullet F_{ocean}(x, y, t)$$

Where λ represents a set of linear scaling factors applied to the fluxes (F) that are to be estimated in the assimilation. These scaling factors multiply prior estimates of methane fluxes to produce the emissions presented on the CarbonTracker-CH_4 web site. A total of 121 parameters are estimated, 10 terrestrial emission processes for 12 continental regions (corresponding to the TRANSCOM continental regions but with the addition of a tropical African region), and global fluxes from the ocean. The terrestrial emissions include anthropogenic emissions due to fugitive emissions from coal, oil and gas production; agriculture and waste emissions (rice production, for example); livestock and their waste; and emissions from landfills and wastewater. Natural emissions include contributions from wetlands, termites, uptake in dry soils and wild animals. The final terrestrial emission category is fires, and this is treated as a separate category due to the existence of strong spatial constraints coming from satellite observations of hot spots. In general, the spatial distribution of the prior flux estimates is an important constraint on the assimilation, i.e. known location of fossil fuel production provides information to the assimilation system on whether a signal measured at a particular observation site could have a fossil fuel component. (More information on the prior flux estimates may be found here.)

A. Ensemble Size and Localization

The ensemble system used to solve for the scalar multiplication factors is similar to that described by Peters et al. [2005], and is based on the square root ensemble Kalman filter of Whitaker and Hamill, [2002]. We have restricted the length of the smoother window to only five weeks as we found the derived flux patterns within North America to be robustly resolved well within that time. We caution the CarbonTracker users that although the North American flux results were found to be robust after five weeks, regions of the world with less dense observational coverage (the tropics, Southern Hemisphere, and parts of Asia) are likely to be poorly observable even after more than a month of transport and therefore less robustly resolved.

Ensemble statistics are created from 500 ensemble members, each with its own background CH_4 concentration field to represent the time history (and thus covariances) of the filter. To dampen spurious noise due to the approximation of the covariance matrix, we apply localization [Houtekamer and Mitchell, 1998] for non-MBL sites only. This ensures that tall-tower observations within North America do not inform on concentrations, for instance tropical African fluxes, unless a very robust signal is found. In contrast, MBL sites with a known large footprint and strong capacity to see integrated flux signals are not localized. Localization is based on the linear correlation coefficient between the 500 parameter deviations and 500 observation deviations for each parameter, with a cut-off at a 95% significance in a student's T-test with a two-tailed probability distribution.

B. Dynamical Model

In CarbonTracker, the dynamical model is applied to the mean parameter values λ as:

$$\lambda_t^b = (\lambda_{t-2}^a + \lambda_{t-1}^a + \lambda^p) \ / \ 3.0$$

where "a" refers to analyzed quantities from previous steps, "b" refers to the background values for the new step, and "p" refers to real a-priori determined values that are fixed in time and chosen as part of the inversion set-up. Physically, this model describes that parameter values λ for a new time

step are chosen as a combination between optimized values from the two previous time steps, and a fixed prior value. This operation is similar to the simple persistence forecast used in Peters et al. [2005], but represents a smoothing over three time steps thus dampening variations in the forecast of λ^b in time. The inclusion of the prior term λ^p acts as a regularization [Baker et al., 2006] and ensures that the parameters in our system will eventually revert back to predetermined prior values when there is no information coming from the observations. Note that our dynamical model equation does not include an error term on the dynamical model, for the simple reason that we don't know the error of this model. This is reflected in the treatment of covariance, which is always set to a prior covariance structure and not forecast with our dynamical model.

C. Covariance Structure

Prior values for λ^p are all 1.0 to yield fluxes that are unchanged from their values predicted in our modules. The prior covariance structure describes the magnitude of the uncertainty on each parameter, plus their correlation in space. For the current version of CarbonTracker-CH_4, we have assumed a diagonal prior covariance matrix so that no prior correlations between estimated parameters exist. The effect of this choice may be strong anti-correlations between estimated parameters in regions where few observational constraints exist; however, larger-scale aggregations of these regions are expected to yield more robust estimates. In our standard assimilation, the chosen standard deviation is 75% on all estimated parameters.

Further Reading

- Whitaker and Hamill, 2002 paper
- Peters et al., 2005 paper