WRF-STILT Footprints for Carbon Tracker Lagrange

Table of Contents

1. Dataset Overview

This collection of four datasets provides Weather Research and Forecasting (WRF) Stochastic Time-Inverted Lagrangian Transport (STILT) particle trajectory data products for particle receptors co-located with atmospheric column observations from the GOSAT and OCO-2 satellites and TCCON ground network. Meteorological fields from the WRF model are used to drive STILT. STILT applies a Lagrangian particle dispersion model backwards in time from a measurement location (the "receptor" location), to create the adjoint of the transport model in the form of a "footprint" field. The footprint, with units of mixing ratio (ppm) per surface flux (umol m-2 s-1), quantifies the influence of upwind surface fluxes on greenhouse gas concentrations measured at the receptor and is computed by counting the number of particles in a surface-influenced volume and the time spent in that volume. For each column observation location, the receptors are located at 23 (GOSAT and TCCON) or 14 (OCO2) discrete vertical levels throughout the atmospheric column. The four datasets listed in table 1 are organized by the sensor and geographic location.

Table 1.

Title	DOI
CarbonTracker-Lagrange North America GOSAT Vertical Profile of Footprints	https://doi.org/10.5067/3341FLTH3CBP
CarbonTracker-Lagrange North America TCCON Vertical Profile of Footprints	https://doi.org/10.5067/EQMKOJJ9L16B
CarbonTracker-Lagrange North America OCO-2 Vertical Profile of Footprints	https://doi.org/10.5067/LBWCS6CTHX9D
CarbonTracker-Lagrange South America OCO-2 Vertical Profile of Footprints	https://doi.org/10.5067/SUUR6I3N1PME

North America: Gridded footprints are provided at three temporal and spatial scales:

1 ten days of surface influence over the whole North American coverage area at 1-degree resolution, compatible with the resolution of NOAA's Carbon Tracker fluxes
2 ten days of surface influence over the whole North American coverage area at 1-degree latitude by 1.25-degree longitude resolution, compatible with the resolution of NASA's CASA fluxes
3 24 hours of surface influence within a smaller region close to the given receptor location ('near field') at 0.1-degree resolution

South America: Gridded footprints are provided at two temporal and spatial scales:

1 ten days of surface influence over the whole South American coverage area at 1-degree resolution, compatible with the resolution of NOAA's Carbon Tracker fluxes
2 24 hours of surface influence within a smaller region close to the given receptor location ('near field') at 0.1-degree resolution

The files are provided in NetCDF (.nc4) format. Each file consists of NetCDF groups where there is 1 group for each receptor's gridded STILT footprint and particle trajectory snapshots, as well as, 1 group containing vertical profile information from WRF for the column observation location and time. The number of files and simulation time periods are given in Table 2.

Table 2.

observation type	**domain**	**# daily data files**	**time period**
GOSAT	N. America	19105	2009/07/01 - 2010/12/31
TCCON	N. America	29326	2007/01/01 - 2012/08/31
OCO-2	N. America	133147	2014/09/06 - 2016/01/31
OCO-2	S. America	25433	2015/09/01 – 2016/05/31

2. Data Characteristics

Spatial Coverage and Spatial Temporal Resolutions:

North American: Footprints are provided on latitude-longitude grids as follows:
foot1:

- 1 deg x 1 deg grid covering 170W to 50W and 10N to 80N
- 1 deg x 1 deg grid covering 180W to 10W and 10N to 80N (9/2014 and after)
- Hourly for 10 days

foot2:

- 1 deg lat x 1.25 deg lon grid covering 170.625W to 49.375W and 9.5N to 80.5N
- 1 deg lat x 1.25 deg lon grid covering 179.375E to 10.625W and 9.5N to 80.5N (9/2014 and after)
- Hourly for 10 days

footnearfield1:

- a 0.1 deg x 0.1 deg grid centered on the receptor location, covering 31 deg in longitude and 21 deg in latitude
- hourly for 24 hours

South American: Footprints are provided on latitude-longitude grids as follows:
foot1:

- 1 deg x 1 deg grid covering 85W to 15W and 55S to 15N
- Hourly for 10 days

footnearfield1:

- a 0.1 deg x 0.1 deg grid centered on the receptor location, covering 31 deg in longitude and 21 deg in latitude
- hourly for 24 hours

3. Data File Information

The NetCDF files contain particle trajectories and gridded footprints from WRF-STILT simulations for vertically discrete receptors at a single column observation location/time. There is 1 netCDF group for each receptor's STILT footprint and particle trajectory information, as well as, 1 group containing vertical profile information from WRF for the column observation location and time.

The gridded footprints aggregate particle footprints on a lat/lon/time grid starting at the STILT simulation start time.

The first diagnostic surface influence field, represented by the foot1 variable of one receptor in the NetCDF files, provides 10 days of surface influence representing the response of the receptor to a unit surface emission (ppm/umol m-2 s-1) of a greenhouse gas (e.g. CO2, CH4) in each 1 x 1-degree grid cell within the whole footprint domain at hourly temporal resolution.

The second diagnostic surface influence field, represented by the footnearfield1 variable of one receptor in the NetCDF files, provides 24 hours of surface influence representing the response of the receptor to a unit surface emission (ppm/umol m-2 s-1) of a greenhouse gas (e.g. CO2 or CH4) in each 0.1- x 0.1-degree grid cell, within a small region close to the measurement location at hourly temporal resolution.

The WRF-STILT model as run for this project is described further in Rastogi et al 2021. The File naming convention is described in Table 1.

Table 1. Naming convention for NetCDF files and netCDF groups within the files generated by WRF-STILT.
Example file name:
CMS_CTL_NA_OCO2_FOOTPRINTS_L4_V1.0_20160131T1337Z_41.5030N_010.8092W.nc
Containing groups:
WRF2016x01x31x13x37x41.5030Nx010.8092W
stilt2016x01x31x13x37x41.5030Nx010.8092Wx00050
stilt2016x01x31x13x37x41.5030Nx010.8092Wx00250
stilt2016x01x31x13x37x41.5030Nx010.8092Wx00500
stilt2016x01x31x13x37x41.5030Nx010.8092Wx01000
stilt2016x01x31x13x37x41.5030Nx010.8092Wx01500
stilt2016x01x31x13x37x41.5030Nx010.8092Wx02000
stilt2016x01x31x13x37x41.5030Nx010.8092Wx02500
stilt2016x01x31x13x37x41.5030Nx010.8092Wx03500
stilt2016x01x31x13x37x41.5030Nx010.8092Wx04500
stilt2016x01x31x13x37x41.5030Nx010.8092Wx05500
stilt2016x01x31x13x37x41.5030Nx010.8092Wx08000
stilt2016x01x31x13x37x41.5030Nx010.8092Wx10000
stilt2016x01x31x13x37x41.5030Nx010.8092Wx12000
stilt2016x01x31x13x37x41.5030Nx010.8092Wx14000

Name element	**Example values**	**Units**
Domain	NA (North America) or SA (South America)	
Instrument	OCO2 or GOSAT or TCCON	
Year	2016	YYYY
Month	01	MM
Day	31	DD
Hour	13	hh (UTC)
Minute	37	mm (UTC)
Latitude	41.5030N	decimal degrees
Longitude	010.8092W	decimal degrees
Height (receptor groups)	50, 250, 500,1000, 1500, 2000, 2500, 3500, 4500, 5500, 8000, 10000, 12000, 14000	m (agl)

For example, the above file contains the modeled particle trajectories and footprints for a column of receptors located at 41.5030N, 10.8092W on January 31, 2016 at 13:37 UTC. The

corresponding column observation is from an OCO2 measurement in the North America domain. The groups within the file are named after this location/date/time information and contain WRF profile information and the STILT particle trajectories and gridded footprints for specific receptors in the column.

4. Data Variables

Table 2. Data variables in WRF-STILT NetCDF file, WRF group (e.g. WRF2016x01x31x13x37x41.5030Nx010.8092W). Fill values or missing data were set to -1.0E34 for all variables.

Variable Name	Units	Description
ident		Identifier string
lat	Degrees latitude	Latitude of model fields
lon	Degrees longitude	Longitude of model fields
nchar		Numeric identifier
utctime	UTC	Time in UTC corresponding to model fields
utctimeformat		Utctime format
vars2d	m, hPa, K, m	surface or 2D variables extracted from model fields at lat, lon, and utctime: terrain height, surface pressure, temperature at 2m, height of planetary boundary layer
vars2dnames		column names of vars2d
vars3dhalf	K, kg kg-1, m, hPa	profiles of 3D variables on model half levels (unstaggered) extracted from model fields at lat, lon, and utctime: potential temperature, water vapor mixing ratio, height above ground level, pressure
vars3dhalfnames		column names of vars3dhalf

Table 3. Data variables in WRF-STILT NetCDF file, STILT group (e.g. stilt2016x01x31x13x37x41.5030Nx010.8092Wx00050). Fill values or missing data were set to -1.0E34 for all variables.

Variable name	Units	Description
checkbasic		basic output from Trajeccheck()
checkbasicnames		names for checkbasic 1D array
checksum		checksum array
checksumdate	days since 2000-01-01 00:00:00 UTC	dates of checksum
checksumnames		column names for checksum array
emitwindow	hours, x grid lengths, y grid lengths, z grid lengths	emission time and space window of particle releases at receptor
emitwindownames		names for emitwindow 1D array
endpts		stilt particle location array thinned to retain rows containing trajectory endpts
endptsdate	days since 2000-01-01 00:00:00 UTC	dates of endpts
endptsnames		column names for particle array

foot1	ppm per (micromol m-2 s-1)	gridded stilt footprint
foot1date	days since 2000-01-01 00:00:00 UTC	dates of foot1
foot1hr	hours	stilt footprint hours back from stilt start time
foot1lat	degrees north	degrees latitude of center of grid boxes
foot1lon	degrees east	degrees longitude of center of grid boxes
foot2	ppm per (micromol m-2 s-1)	gridded stilt footprint
foot2date	days since 2000-01-01 00:00:00 UTC	dates of foot2
foot2hr	hours	stilt footprint hours back from stilt start time
foot2lat	degrees north	degrees latitude of center of grid boxes
foot2lon	degrees east	degrees longitude of center of grid boxes
footnearfield1	ppm per (micromol m-2 s-1)	gridded stilt footprint
footnearfield1date	days since 2000-01-01 00:00:00 UTC	dates of footnearfield1
footnearfield1hr	hours	stilt footprint hours back from stilt start time
footnearfield1lat	degrees north	degrees latitude of center of grid boxes
footnearfield1lon	degrees east	degrees longitude of center of grid boxes
ident		identifier string
nchar		numeric identifier
origagl	m	original receptor height above ground
origlat	degrees north	original receptor latitude
origlon	degrees east	original receptor longitude
origutctime	UTC	original receptor time
origutctimeformat		origutctime format
part3d		stilt particle location array thinned to retain rows approximately every so many hours
part3ddate	days since 2000-01-01 00:00:00 UT	dates of part3d
part3dnames		column names for part3d

5. Application and Derivation

WRF-STILT footprints support accurate estimates of surface-atmosphere fluxes of greenhouse gases (e.g.CO2 and CH4). They were applied in a carbon flux estimation study (Rastogi et al 2021).

6. Quality Assessment

Verification was performed for WRF meteorological fields. A discussion of WRF-STILT transport errors in carbon flux estimation is included in (Rastogi et al 2021).

7. Data Acquisition, Materials, and Methods

Column measurements

The netCDF column locations, dates, and times each correspond to a GOSAT, OCO2, or TCCON column measurement. WRF-STILT footprints were simulated for a temporally thinned subset of the total available GOSAT and OCO-2 column measurements. Each column was simulated as particle receptors at discrete levels above ground level. The levels in meters (agl) are:

GOSAT & TCCON: 2, 5, 10, 25, 50, 100, 250, 500, 1000, 1500, 2500, 3500, 4500, 5500, 6500, 7500, 8500, 9500, 10500, 11500, 12500, 13500, 14500

OCO-2: 50, 250, 500, 1000, 1500, 2000, 2500, 3500, 4500, 5500, 8000, 10000, 12000, 14000

WRF-STILT Simulations

The influence of upwind surface fluxes on each particle receptor's mixing ratio is simulated using the Stochastic Time-Inverted Lagrangian Transport (STILT) model coupled with meteorology fields from the Weather and Research Forecasting (WRF; Powers et al. 2017) model. The WRF-STILT coupled model is described in Nehrkorn et al. (2010). Details of the WRF configuration used in these simulations are in Table 4.

Table 4. Basic WRF configuration used in simulations by domain and time period:

domain	time period	nested grid horizontal resolution	vertical resolution	initial/boundary conditions
North America	1/2007-1/2009	40km, 10km	31 levels	NARR
North America	2/2009-8/2014	30km, 10km	41 levels	NARR
expanded N. Am	9/2014-1/2016	30km, 10km	41 levels	MERRA
expanded N. Am	2/2016-8/2016	30km, 10km	60 layers	ERA5
South America	9/2015-5/2016	36km, 12km	41 levels	MERRA-2

STILT applies a Lagrangian particle dispersion model backwards in time from a measurement location (the "receptor" location), to create the adjoint of the transport model in the form of a "footprint" field (Nehrkorn et al., 2010; Henderson et al., 2015). The footprint, with units of mixing ratio per unit flux (ppm/(umol m-2 s-1)), quantifies the influence of upwind surface fluxes on concentrations measured at the receptor and is computed by counting the number of particles in a surface-influenced volume and the time spent in that volume.

8. Data Access

These data are available through the Goddard Earth Sciences Data and Information Services Center (GES DISC).

Contact for Data Center Access Information:

E-mail: gsfc-dl-help-disc@mail.nasa.gov
Telephone: 301-614-5224

9. References

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