Supplement of

A single-point modeling approach for the intercomparison and evaluation of ozone dry deposition across chemical transport models (Activity 2 of AQMEII4)

Olivia E. Clifton et al.

Correspondence to: Olivia E. Clifton (olivia.e.clifton@nasa.gov)

Table S1: Aerodynamic resistance parameterizations for the single-point models.

Model	Aerodynamic resistance (r_a)	Reference
WRF-Chem Wesely	$r_a = \begin{cases} \frac{1}{k\,u^*}\left(0.74\,\ln\left(\frac{z_r}{z_0}\right) + 4.7\,\frac{z_r - z_0}{L}\right), & 1/L > 0 \\ \frac{1}{k\,u^*}\,0.74\left(\ln\left(\frac{\sqrt{1 - 9\frac{z_r}{L}} - 1}{\sqrt{1 - 9\frac{z_r}{L}} + 1}\right) - \ln\left(\frac{\sqrt{1 - 9\frac{z_0}{L}} - 1}{\sqrt{1 - 9\frac{z_0}{L}} + 1}\right)\right), & 1/L < 0 \end{cases}$	McRae (1981)
GEOS-Chem Wesely, IFS, TEMIR models	In aerodynamically smooth conditions ($Re_r < 0.1\ r_a$) where roughness Reynolds number ($Re_r = u^* z_0/\nu$) then r_a equals 10^4 s m^{-1}. Otherwise, $r_a = \begin{cases} \frac{1}{k\,u^*}\left(5\ln\left(\frac{z_r - d}{z_0}\right) + \frac{z_r - d - z_0}{L}\right), & (z_r - d)/L > 1 \\ \frac{1}{k\,u^*}\left(\ln\left(\frac{z_r - d}{z_0}\right) + 5\left(\frac{z_r - d - z_0}{L}\right)\right), & 0 \le (z_r - d)/L \le 1 \\ \frac{1}{k\,u^*}\left(\ln\left\lvert\frac{\sqrt{1 - 15\frac{z_r - d}{L}} - 1}{\sqrt{1 - 15\frac{z_r - d}{L}} + 1}\right\rvert - \ln\left\lvert\frac{\sqrt{1 - 15\frac{z_0}{L}} - 1}{\sqrt{1 - 15\frac{z_0}{L}} + 1}\right\rvert\right), & (z_r - d)/L < 0 \end{cases}$	
GEM-MACH Wesely	$r_a = \frac{1}{k\,u^*}\left(\ln\left(\frac{z_r - d + z_0}{z_0}\right) - \psi_{heat}\right)$ $\psi_{heat} = \begin{cases} -5\left(\frac{z_r - d - z_0}{L}\right), & \frac{z_r - d}{L} > 0.01 \\ e^{0.598 + 0.39\ln\left(-\frac{z_r - d}{L}\right) - 0.18\ln\left(-\frac{z_r - d}{L}\right)} - e^{0.598 + 0.39\ln\left(-\frac{z_0}{L}\right) - 0.18\ln\left(-\frac{z_0}{L}\right)}, & \frac{z_r - d}{L} < -0.01 \\ 0, & -0.01 \le \frac{z_r - d}{L} \le 0.01 \end{cases}$	Voldner et al. (1986); Makar et al. (2018)
GEM-MACH Zhang	$r_a = \frac{1}{k\,u^*}\left(0.74\ln\left(\frac{z_r}{z_0}\right) - \psi_{heat}\right)$ $\psi_{heat} = \begin{cases} -4.7\,\frac{z_r}{L}, & \frac{z_r}{L} \ge 0 \\ 2\ln\left(0.5\left(1 + \sqrt{1 - 9\frac{z_r}{L}}\right)\right), & \frac{z_r}{L} < 0 \end{cases}$ The variable r_a is set to a maximum of 10 s m^{-1}.	
CMAQ M3Dry models	$r_a = \frac{1}{k\,u^*}0.95\left(\ln\left(\frac{z_r - d}{z_o}\right) - \psi_{heat}\right)$ $\psi_{heat} = \begin{cases} 1 - 8.21 - \frac{z_r - d}{L} + \frac{z_0}{L}, & \frac{z_r - d}{L} - \frac{z_0}{L} > 1 \\ -8.21\left(\frac{z_r - d}{L} - \frac{z_0}{L}\right), & 0 < \frac{z_r - d}{L} - \frac{z_0}{L} \le 1 \\ 2\ln\left(\frac{\left(1 - 11.6\,\frac{z_r - d}{L}\right)^{0.5} + 1}{\left(1 - 11.6\,\frac{z_o}{L}\right)^{0.5} + 1}\right), & \frac{z_r}{L} < 0 \end{cases}$	Högström (1988) for ψ_{heat}
CMAQ STAGE	$r_a = 0.95\,\frac{u}{(u^*)^2}$	Knauer et al. (2018); Yong et al. (2021)
DO3SE models	$r_a = \frac{1}{k\,u^*}\ln\left(\frac{z_r - d}{z_o}\right)$	Garratt (1992)

MLC-CHEM	$r_a = \begin{cases} \frac{1}{k\,u^*}\left(0.74\ \ln\left(\frac{z_r}{z_0}\right) + 4.7\ \frac{z_r}{L}\right), & 1/L > 0 \\ \frac{1}{k\,u^*}\ 0.74\left(\ln\left(\frac{\sqrt{1 - 9\frac{z_r}{L}} - 1}{\sqrt{1 - 9\frac{z_r}{L}} + 1}\right) - \ln\left(\frac{\sqrt{1 - 9\frac{z_0}{L}} - 1}{\sqrt{1 - 9\frac{z_0}{L}} + 1}\right)\right), & 1/L < 0 \end{cases}$	

The parameter k is the von Kármán constant [0.4]; ν [$m^2\ s^{-1}$] is kinematic viscosity of air. Otherwise, variables and parameters are defined in Table 1.

Table S2: Obukhov length parameterizations for the single-point models.

Model	Obukhov length (L)
WRF-Chem Wesely, GEOS-Chem Wesely, IFS models	$L = -\frac{u^{*3}\rho\, c_p\ (T_a + 273.15)}{k\ g\ SH}$ The variable L is fixed between -1 x 10^4 and 1 x 10^4 m.
GEM-MACH Wesely, TEMIR models	$L = -\frac{u^{*3}\rho\, c_p\ (T_v + 273.15)}{k\ g\ SH}$ The variable T_v is the virtual temperature [ºC]. The variable L is fixed between 1 x 10^5 and 1 x 10^{-1} m if L is positive, and -1 x 10^5 and -1 x 10^{-1} m if L is negative.
GEM-MACH Zhang	$L = \min\left\{\frac{\theta_v(7.5\ x\ 10^{-4} + 6.7\ x\ 10^{-5}\ u)^{1.5}u^2}{5.09\ x\ 10^{-3}\left(\theta_v - \theta_{v,s}\right)}, 5\right\}$ The variable θ_v [K] is potential temperature. The near-surface potential temperature $\theta_{v,s}$ [K] is approximated from a linear interpolation between the air and ground to a height of 1.5 m. If $\left\lvert\theta_v - \theta_{v,s}\right\rvert$ is less than or equal to 10^{-6} then $L = 10^4$.
CMAQ M3Dry models	$L = -\frac{u^{*3}\rho\, c_p\ (T_v + 273.15)}{k\ g\ SH}$ The variable T_v is the virtual temperature [ºC].

The parameter c_p is specific heat capacity of air [J $kg^{-1}\ K^{-1}$]; g [m s^{-2}] is acceleration due to gravity. Otherwise, variables and parameters are defined in Table 1.

Table S3: Quasi-laminar boundary layer resistance parameterizations for the single-point models.

Model	Quasi-laminar boundary layer resistance
WRF-Chem Wesely, GEOS-Chem Wesely, TEMIR models, IFS models, GEM-MACH Zhang, GEM-MACH Wesely, CMAQ M3Dry models, DO₃SE models	$r_b = \frac{2}{k\,u^*}\left(R_{diff,b}\right)^{\frac{2}{3}}$
CMAQ STAGE	The vegetation quasi-laminar boundary layer resistance ($r_{b,v}$) follows Massad et al. (2010) and Jensen and Hummelshøj (1995, 1997): $r_{b,v} = \frac{\nu}{D_{O_3}}\left(\frac{l\,u^*}{LAI^2\,\nu}\right)^{\frac{1}{3}}\frac{1}{u_*}$ The parameter l [m] is the leaf width (Table B13). The ground quasi-laminar boundary layer resistance ($r_{b,g}$) follows Schuepp (1977), Nemitz et al. (2001), and Massad et al. (2010): $r_{b,g} = \frac{\frac{\nu}{D_{O_3}} - ln\left(\frac{u_{*,g}}{z_1\,k\,D_{O_3}}\right)}{k\,u_g{}^*}$ The parameter z_1 [0.1 m] follows Nemitz et al. (2001); $u_g{}^*$ [m s^{-1}] is friction velocity under the canopy elements following Yi (2008): $u_g{}^* = u^*\,e^{-\frac{LAI}{2}}$
MLC-CHEM	The leaf-level quasi-laminar boundary layer resistance ($r_{b,leaf}$) is calculated according to Meyers et al. (1987):

	$r_{b,leaf} = 180 \left(R_{diff,b}\right)^{\frac{2}{3}} \sqrt{\frac{l}{u}}$ The parameter l is a characteristic leaf dimension [0.07 m].

The parameter k is the von Kármán constant [0.4]; ν [m^2 s^{-1}] is kinematic viscosity of air; $R_{diff,b}$ is defined in Table S4. Otherwise, variables and parameters are defined in Table 1.

Table S4: Ozone-specific dry deposition parameters in the single-point models.

Model	$R_{diff,st} = \frac{D_w}{D_{O_3}}$	$R_{diff,b} = \frac{Sc}{Pr}$	D_{O_3}	f_0	H
WRF-Chem Wesely	1.6	$\frac{\kappa}{D_{O_3}}$ $\kappa = 2.08 \times 10^{-5}$	1.7×10^{-5}	1	0.015
GEOS-Chem Wesely, TEMIR	~1.3	$\frac{\kappa}{D_{O_3}}$ $\kappa = 2 \times 10^{-5}$	$D_x = \frac{3\pi}{32}\left(1+\frac{M_x}{M_{air}}\right)\left(\frac{1}{\pi\left(1+\frac{M_x}{M_{air}}\right)^{1/2} n_{air}\, d_x^2}\right)\left(\frac{8\,R\,(T_a+273.15)}{\frac{\pi\,M_x}{1000}}\right)^{1/2}$ The parameter M_x is the molar mass of diffusing gas X; R is the universal gas constant [J mol^{-1} K^{-1}]; $n_{air} = \frac{A_v\ p_a}{R\,(T_a+273.15)}$ is the number density of air [molecules m^{-3}]; A_v is Avogadro's number [molecules mol^{-1}]; $d_x = 2.7 \times 10^{-10}$ m is the assumed collision diameter for the gas in air.	1	0.01
IFS SUMO Wesely	1.6	$\frac{\kappa}{D_{O_3}}$	$D_{O_3} = \frac{D_w}{\sqrt{\frac{M_{O_3}}{M_w}}}$ $D_w = 2.5 \times 10^{-5}$	1	0.01 at 298 K, varies with T_a
IFS GEOS-Chem Wesely	~1.3	$\frac{\kappa}{D_{O_3}}$	$D_x = \frac{3\pi}{32}\left(1+\frac{M_x}{M_{air}}\right)\left(\frac{1}{\pi\sqrt{\left(1+\frac{M_x}{M_{air}}\right)}\, n_{air}\, d_x^2}\right)\sqrt{\frac{8\,R\,(T_a+273.15)}{\frac{\pi\,M_x}{1000}}}$ The parameter M_x is the molar mass of diffusing gas X; R is the universal gas constant [J mol^{-1} K^{-1}]; $n_{air} = \frac{A_v\ p_a}{R\,(T_a+273.15)}$ is the number density of air [molecules m^{-3}]; A_v is Avogadro's number [molecules mol^{-1}]; $d_x = 2.7 \times 10^{-10}$ m is the assumed collision diameter for the gas in air.	1	0.01
GEM-MACH Wesely	1.23	$1.135\frac{D_w}{D_{O_3}}$	$D_{O_3} = \frac{D_w}{\sqrt{\frac{2.608}{1+\frac{M_{air}}{M_{O_3}}}}}$	1	0.01
GEM-MACH Zhang	~1.6	$\frac{\kappa}{D_{O_3}}$	$D_{O_3} = \frac{1.0\ x\ 10^{-3}\ {T_s}^{1.75}\sqrt{\frac{M_{air}+M_{O_3}}{M_{air}\ M_{O_3}}}}{\frac{p_a}{1.01325\ x\ 10^5}\left[\left(0.369\ M_{O_3}+6.29\right)^{\frac{1}{3}}+\left(0.369\ M_{air}+6.29\right)^{\frac{1}{3}}\right]^2}$ Equation follows Perry and Green (1984) with the calculation of the molar volume from the mass following Li et al. (1993). The near-surface air temperature T_s [K] is approximated from a linear interpolation between T_a and T_g to a height of 1.5 m.	n/a	n/a
CMAQ M3Dry models	1.51	$\frac{\kappa}{D_{O_3}}$ $\kappa = 1.86 \times 10^{-5}$	1.444×10^{-5}	n/a	n/a
CMAQ STAGE	~1.6	n/a	$D_{O_3} = \frac{10^{-7}(T_a+273.15)^{1.75}\sqrt{M_{air}^{-1}\ +\ M_{O_3}^{-1}}}{\left(V_{m,air}^{\frac{1}{3}}\ +\ V_{m,O_3}^{\frac{1}{3}}\right)^2}$ The parameter $V_{m,air}$ is molar volume of air [22.41 L mol^{-1}]; V_{m,O_3} is molar volume of ozone [21.0 L mol^{-1}]. Equation follows Fuller et al. (1966).	1	0.0114 at 298 K, varies with T_a

MLC-CHEM	1.28	$\frac{\kappa}{D_{O_3}}$ $\kappa = 1.89 \times 10^{-5}$	$D_{O_3} = \frac{D_w}{\sqrt{\frac{M_{O_3}}{M_w}}}$ $D_w = 2.12 \times 10^{-5}$	n/a	n/a
DO3SE models	1.66	$\frac{\kappa}{D_{O_3}}$ $\kappa = 2.08 \times 10^{-5}$	1.5×10^{-5}	n/a	n/a

The parameter M_{O_3} [g mol^{-1}] is molar mass of ozone; M_w [g mol^{-1}] is molar mass of water. Otherwise, variables and parameters are defined in Table 1.

Table S5: Site- and season-specific[a] parameters for WRF-Chem Wesely.

Site	r_i	r_{lu}	r_{ac}	r_{cl}	r_g
Auchencorth Moss	120, 10^{10}	2000, 9000	100, 100	1000, 400	200, 200
Borden Forest	100, 500	2000, 8000	2000, 1700	1000, 600	300, 300
Bugacpuszta	120, 10^{10}	2000, 9000	100, 100	1000, 400	200, 200
Easter Bush	120, 10^{10}	2000, 9000	100, 100	1000, 400	200, 200
Ispra	70, 10^{10}	2000, 9000	2000, 1500	1000, 400	200, 200
Harvard Forest	70, 10^{10}	2000, 9000	2000, 1500	1000, 400	200, 200
Hyytiala	130, 250	2000, 4000	2000, 2000	1000, 1000	200,200
Ramat Hanadiv	120, 10^{10}	2000, 9000	100, 100	1000,400	200,200

[a] Midsummer with lush vegetation, Autumn with unharvested croplands

Table S6: Site-specific parameters for GEOS-Chem Wesely.

Site	r_i	r_{lu}	r_{ac}	$r_{cl,S}$	$r_{cl,O}$	$r_{g,S}$	$r_{g,O}$
Auchencorth Moss	200	9000	300	2500	1000	0	1000
Borden Forest	200	9000	2000	2000	1000	500	200
Bugacpuszta	200	9000	100	2000	1000	350	200
Easter Bush	200	9000	100	2000	1000	350	200
Ispra	200	9000	2000	2000	1000	500	200
Harvard Forest	200	9000	2000	2000	1000	500	200
Hyytiälä	200	9000	2000	2000	1000	500	200
Ramat Hanadiv	200	9000	100	2000	1000	350	200
Snow	10^{12}	10^{6}	1	10^{12}	1000	100	3500

Table S7: Site- and season-specific[a] parameters for IFS SUMO Wesely.

Site	r_i	r_{lu}	r_{ac}	r_{cl}	r_g
Auchencorth Moss	100	2000, 9000, 9000, 9999, 4000	100, 100, 100, 10, 80	1000, 400, 400, 1000, 500	200, 200, 200, 3500, 200
Borden Forest	250	2000, 9000, 9000, 9999, 4000	2000, 1500, 1000, 1000, 1200	1000, 400, 400, 400, 500	200, 200, 200, 3500, 200
Bugacpuszta	100	2000, 9000, 9000, 9999, 4000	100, 100, 100, 10, 80	1000, 400, 400, 1000, 500	200, 200, 200, 3500, 200
Easter Bush	100	2000, 9000, 9000, 9999, 4000	100, 100, 100, 10, 80	1000, 400, 400, 1000, 500	200, 200, 200, 3500, 200
Ispra	250	2000, 9000, 9000, 9999, 4000	2000, 1500, 1000, 1000, 1200	1000, 400, 400, 400, 500	200, 200, 200, 3500, 200
Harvard Forest	250	2000, 9000, 9000, 9999, 4000	2000, 1500, 1000, 1000, 1200	1000, 400, 400, 400, 500	200, 200, 200, 3500, 200
Hyytiälä	250	2000, 4000, 4000, 6000, 2000	2000	1000, 1000, 1000, 1500, 1500	200, 200, 200, 3500, 200
Ramat Hanadiv	225	2000, 9000, 9000, 9999, 4000	100, 100, 100, 10, 80	1000, 400, 400, 400, 500	200, 200, 200, 3500, 200

[a] Midsummer, Autumn, Late Autumn, Winter/snow, Transitional spring. When one value is given, only one value is used for all seasons.

Table S8: Site-specific parameters for IFS GEOS-Chem Wesely.

Site	r_i	r_{lu}	r_{ac}	r_{cl}	r_g
Auchencorth Moss	200	9000	100	1000	200
Borden Forest	200	9000	2000	1000	200
Bugacpuszta	200	9000	100	1000	200
Easter Bush	200	9000	100	1000	200
Ispra	200	9000	2000	1000	200
Harvard Forest	200	9000	2000	1000	200
Hyytiälä	400	9000	2000	1000	200
Ramat Hanadiv	200	9000	100	1000	200

Table S9: Site- and season-specific[a] parameters for GEM-MACH Wesely.

Site	r_i	r_{ac}	r_{lu}	r_g	$r_{cl,S}$	$r_{cl,O}$	T_{max}	T_{min}	T_{opt}
Auchencorth Moss	80, 9999, 9999, 9999, 160	20, 20, 20, 20, 20	6000, 6000, 9000, 9999, 6000	1000, 800, 1000, 3500, 1000	2500, 9000, 400, 400, 3000	1000, 600, 600, 600, 600	45	5	25
Borden Forest	100, 800, 800, 800, 190	190, 150, 110, 100, 100	1000, 1500, 2000, 2000, 1000	300, 300, 300, 3500, 300	2000, 4000, 6000, 400, 3000	1000, 600, 1000, 600, 700	42	-3	21
Bugacpuszta	120, 9999, 9999, 9999, 240	40, 40, 40, 10, 30	1500, 2000, 3000, 6000, 1500	200, 200, 200, 3500, 200	2000, 9000, 9000, 9999, 4000	1000, 400, 400, 1000, 500	45	5	27
Easter Bush	120, 9999, 9999, 9999, 240	40, 40, 40, 10, 30	1500, 2000, 3000, 6000, 1500	200, 200, 200, 3500, 200	2000, 9000, 9000, 9999, 4000	1000, 400, 400, 1000, 500	45	5	27
Ispra	70, 9999, 9999,9999, 140	250, 190, 115, 100, 100	1200, 2000, 9000, 9999, 2000	200, 200, 200, 3500, 200	2000, 9000, 9000, 9000, 4000	1000, 400, 400, 400, 500	45	0	27
Harvard Forest	100, 800, 800, 800, 190	190, 150, 110, 100, 100	1000, 1500, 2000, 2000, 1000	300, 300, 300, 3500, 300	2000, 4000, 6000, 400, 3000	1000, 600, 1000, 600, 700	42	-3	21
Hyytiälä	130, 250, 250, 400, 250	100, 100, 100, 100, 100	1000, 1500, 2000, 2000, 1000	200, 200, 200, 3500, 200	2000, 2000, 3000, 200, 2000	1000, 1000, 1000, 1500, 1500	40	-5	15
Ramat Hanadiv	70, 9999, 9999, 9999, 140	60, 60, 30, 20, 30	4000, 1500, 2000, 3000, 4000	150, 150, 150, 3500, 150	2000, 9000, 9000, 9000, 4000	1000, 400, 400, 400, 500	43	0	21.5

[a] Midsummer, Autumn, Late Autumn, Winter, Spring. When one value is given, only one value is used for all seasons.

Table S10: Seasonal dependence as a function of month and latitude in GEM-MACH Wesely.

Latitude [º N]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	Sum[a]	Sum	Sum	Sum	Sum	Sum	Sum	Sum	Sum	Sum	Sum	Sum
30												
35	TrS	TrS										
40	Win	Win	TrS	TrS					Aut	Aut	Aut	TrS
45			Win								LaA	Win
50					TrS							
55				Win						LaA		
60						TrS		Aut			Win	
65					Win							
70									LaA	Win		
80						Win	TrS					
90							Win	Win	Win			

[a] "Sum" = Midsummer, "TrS" = Transitional Spring, "Win" = Winter, "Aut" = Autumn, "LaA" = Late Autumn after frost.

Table S11: Site-specific parameters for GEM-MACH Zhang.

Site	r_i	b_{rs}	T_{min}	T_{max}	T_{opt}	b_{vpd}	$\psi_{leaf,1}$	$\psi_{leaf,2}$	$c_{cut,dry}$	$c_{cut,wet}$	$r_{ac0,min}$	$r_{ac0,max}$	r_g	SD_{max}
Auchencorth Moss	150	40	0	45	20	0.27	-1.5	-2.5	1000	200	10	40	200	20
Borden Forest	150	44	-3	42	21	0.34	-2.0	-2.5	1500	300	20	20	500	10
Bugacpuszta	100	20	5	45	25	0.00	-1.5	-2.5	2000	300	20	60	200	50
Easter Bush	100	20	5	45	25	0.00	-1.5	-2.5	2000	300	20	60	200	50
Ispra	150	43	0	45	27	0.36	-1.9	-2.5	2500	200	100	250	200	200
Harvard Forest	150	44	-3	42	21	0.34	-2.0	-2.5	1500	300	20	20	500	10
Hyytiälä	250	44	-5	40	15	0.31	-2.0	-2.5	2000	200	100	100	200	200
Ramat Hanadiv	150	40	0	45	30	0.27	-2.0	-4.0	2000	400	60	60	200	50

Table S12: Site-specific parameters for CMAQ M3Dry and M3Dry-psn.

Site	f_{veg}	r_i	a	V_{cmax} at 25ºC
Auchencorth Moss	1	100	0.07	71.1 (Oleson et al., 2013)
Borden Forest	0.95	195	0.02	57.7 (Kattge et al., 2009)
Bugacpuszta	0.95	100	0.07	71.1 (Oleson et al., 2013)
Easter Bush	0.9	100	0.07	71.1 (Oleson et al., 2013)
Ispra	0.95	200	0.02	57.7 (Kattge et al., 2009; Oleson et al., 2013)
Harvard Forest	0.95	200	0.02	30 (Slevin et al., 2015; Ran et al., 2017)
Hyytiälä	0.8	175	0.02	60 (Slevin et al., 2015)
Ramat Hanadiv	0.7	200	0.02	55 (Oleson et al., 2013)

Table S13: Site-specific parameters for CMAQ STAGE.

Site	r_i	l
Auchencorth Moss	100	0.01
Bugacpuszta	100	0.01
Easter Bush	100	0.01
Ispra	200	0.05
Harvard Forest	200	0.05
Hyytiälä	175	0.005
Ramat Hanadiv	200	0.02

Table S14: Site-specific parameters for TEMIR Zhang.

Site	r_i	b_{rs}	T_{min}	T_{max}	T_{opt}	b_{VPD}	$\psi_{leaf,1}$	$\psi_{leaf,2}$	$c_{cut,dry}$	$c_{cut,wet}$	$r_{ac0,min}$	$r_{ac0,max}$	SD_{max}
Auchencorth Moss	150	40	0	45	20	0.27	-1.5	-2.5	5000	300	20	20	10
Borden Forest	150	43	0	45	27	0.36	-1.9	-2.5	6000	400	100	250	200
Bugacpuszta	150	50	5	40	30	0	-1.5	-2.5	4000	200	20	20	20
Easter Bush	150	50	5	40	30	0	-1.5	-2.5	4000	200	20	20	20
Ispra	150	43	0	45	27	0.36	-1.9	-2.5	6000	400	100	250	200
Harvard Forest	150	43	0	45	27	0.36	-1.9	-2.5	6000	400	100	250	200
Hyytiälä	250	44	-5	40	15	0.31	-2	-2.5	4000	200	100	100	200
Ramat Hanadiv	150	50	5	40	30	0	-1.5	-2.5	4000	200	20	20	20

Table S15: Site-specific parameters for TEMIR photosynthesis-based approaches.

Site	CLM4.5 plant functional type	g_{1M}	$V_{cmax,25}$
Auchencorth Moss	C_3 grass	5.25	78.19 x 10^{-6}
Borden Forest	broadleaf deciduous tree	4.45	57.68 x 10^{-6}
Bugacpuszta	C_3 grass	5.25	78.19 x 10^{-6}
Easter Bush	C_3 grass	5.25	78.19 x 10^{-6}
Ispra	broadleaf deciduous tree	4.45	57.68 x 10^{-6}
Harvard Forest	broadleaf deciduous tree	4.45	57.68 x 10^{-6}
Hyytiälä	needleleaf evergreen tree	2.35	62.48 x 10^{-6}
Ramat Hanadiv	C_3 grass	5.25	78.19 x 10^{-6}

Table S16: Site-specific parameters for DO$_3$SE models.

Site	g_{max}	f_{min}	T_{min}	T_{max}	T_{opt}	VPD_{min}	VPD_{max}	$\emptyset_a$	$\emptyset_b$	$\emptyset_c$	$\emptyset_d$	$\emptyset_e$	α	g_0	g_1	D_0	$V_{cmax,25}$
Auchencorth Moss	0.00146	0.01	1	36	18	1.0	3.0	1.0	1.0	1.0	0	0	0.009	0.006 x 10^{-6}	10	2.15	10 x 10^{-6}
Borden Forest	0.00549	0.06	0	35	20	1.0	3.0	0.4	1.0	0.4	20	40	0.003	0.0209 x 10^{-6}	8.17	2.42	36.8 x 10^{-6}
Bugacpuszta	0.00659	0.01	12	40	26	1.3	3.0	1.0	1.0	1.0	0	0	0.009	0.028 x 10^{-6}	8.17	2.15	40 x 10^{-6}
Easter Bush	0.00659	0.01	12	40	26	1.3	3.0	1.0	1.0	1.0	0	0	0.009	0.028 x 10^{-6}	8.17	2.15	40 x 10^{-6}
Ispra	0.00549	0.06	0	35	20	1.0	3.25	0.0	1.0	0.0	15	30	0.003	0.0209 x 10^{-6}	8.17	2.42	36.8 x 10^{-6}
Harvard Forest	0.00549	0.1	0	35	20	0.8	3.0	0.4	1.0	0.4	20	40	0.0045	0.0209 x 10^{-6}	8.17	2.42	36.8 x 10^{-6}
Hyytiälä	0.00463	0.1	5	33	16	1.0	3.1	0.8	1.0	0.8	20	40	0.006	0.0209 x 10^{-6}	6.355	2.55	26.4 x 10^{-6}
Ramat Hanadiv	0.00475	0.02	1	39	23	2.2	4.0	1.0	1.0	1.0	0	0	0.012	0.0021 x 10^{-6}	8.17	2.25	32 x 10^{-6}

Table S17: Ozone flux measurements at the sites.

Site	Time period and temporal frequency of data	Measurement type for ozone flux	Fast ozone analyzer	More details on ozone fluxes [a]	Measurement height for ozone fluxes	References for ozone fluxes	AQMEII4 processing of hourly/half-hourly ozone deposition velocities [b]
Auchencorth Moss	1 January 2016 00:00 – 1 January 2018 00:00 LT (UTC+0) Half hourly	Eddy covariance	Gesellschaft Für Angewandte Systemtechnik (Güsten et al., 1992; Güsten and Heinrich, 1996) clone (Coyle, 2006)	Data processing and quality control and assurance follow Muller et al. (2010) for Easter Bush. Absolute ozone fluxes are calculated via the Ratio Offset Method (Muller et al., 2010).	4.15 m		Values discarded at beginning of the time series until 6 July 2016 because observed ozone fluxes were roughly a factor of 5–10 lower during this measurement period than for the rest of the observational record and were therefore considered to be unrealistic
Borden Forest	31 December 2007 19:00 – 30 May 2013 15:00 LT (UTC-5) Half hourly	Gradient	N/A	Data are flagged if $[O_3] < 1.0$ ppbv, $u < 1.0$ m s^{-1}, $v_d > 1.5$ x the deposition velocity estimated with only aerodynamic and quasi-laminar boundary layer resistances (Wu et al., 2016), or the vertical ozone gradient < 0	33 m	Wu et al. (2016, 2018)	flag < 0 removed
Bugacpuszta	1 August 2012 00:30 – 13 January 2014 23:30 LT (UTC+1) Half hourly	Eddy covariance	Dry chemiluminescence (Zahn et al., 2012)		4 m	Horváth et al. (2018)	
Easter Bush	18 May 2001 16:00 – 1 January 2013 00:00 LT (UTC+0) Half hourly	Gradient	N/A		2.1 m	Coyle (2006); Muller et al. (2009)	
Ispra	1 January 2013 00:30 – 31 December 2015 23:30 LT (UTC+1) Half hourly	Eddy covariance	Sextant (New Zealand) FOS dry chemiluminescence	High frequency (10 Hz) data are processed with EdiRe software (Mauder et al., 2008). Quality tests are performed on ozone fluxes following Foken et al. (2004). Results of quality tests are	38 m	Visser et al. (2021)	flag = 2 removed and when $[O_3] < 0$ because there are a substantial number of negative $[O_3]$

				combined into three quality flags as described in Sabbatini et al. (2018): good quality (flag 0), acceptable quality (flag 1), and bad quality (flag 2).			
Harvard Forest	28 October 1991 00:00 – 12 December 2000 23:00 LT (UTC-5) Hourly	Eddy covariance	Ethene chemiluminescence		29 m	Munger et al. (1996); Clifton et al. (2017, 2019) Other meteorological datasets (Munger and Wofsy, 1999; Fitzjarrald and Sakai, 2009)	
Hyytiälä	1 January 2002 00:00 – 31 December 2012 23:30 UTC+2 Half hourly	Eddy covariance	Unisearch Associates Inc. (Concord, Ontario, Canada) LOZ-3 wet chemiluminescence		23 m	Keronen et al. (2003); Altimir et al. (2006); Launiainen et al. (2013); Rannik et al. (2009, 2012)	
Ramat Hanadiv	31 July 2015 10:30 - 30 June 2017 21:00 LT (UTC+2) Half hourly	Eddy covariance	Sextant (New Zealand) FOS V2.0.1 dry chemiluminescence		6.3 m	Li et al. (2018, 2019)	

[a] Details are only included here when they are missing from the peer-reviewed literature referenced in the last column, or when flagging for unreliable ozone fluxes.

[b] In addition to Hubert and Vandervieren (2008). When there is additional post-processing, the Hubert and Vandervieren (2008) step comes last.

Table S18: Meteorological and biophysical variables input to the single-point models.

Site	LAI and h	Snow	Canopy wetness	Other details[b]
Auchencorth Moss	Both variables estimated from approximately monthly measurements during 1995 and 1996; a five parameter Pseudo-Voigt peak function is fitted to the measurements using nonlinear regression	Snow depth measured (missing for around half the period)	Measured with a Campbell Scientific Inc. (Utah, USA) Model 237, which indicates whether the surface is wet or dry but may only detect periods of substantial wetness. Thus, values represent the average of measured values within the averaging interval. Values greater than 0 were set to 1 because the site operator indicates that the instrument cannot reliably provide fractional values.	Excluded wind sectors are 60–170ºN
Borden Forest	h is assumed to be constant throughout the measurement period [22 m] LAI is measured for several tree species, measured approximately weekly during the growing season,	Not observed, but snow depth measurements from the nearby (15 km) Canadian Air and Precipitation Monitoring Network	Measured with a Campbell Scientific Inc. (Utah, USA) Model 237, which indicates whether the surface is wet or dry but may only detect periods of substantial wetness. Thus, values represent the	

	and composited to develop a canopy value (Wu et al., 2018)	Egbert site (Wu et al., 2016) are used	average of measured values within the averaging interval. Values between 0.2 and 0.6 are considered unreliable by the site operator and are set to missing in this study.	
Bugacpuszta	h is measured in each quadrant of the tower every 1 to 2 weeks during summer, fall, and spring, and monthly during winter LAI is measured approximately weekly with light interception measurements (Horváth et al., 2018)	Snow depth measured	Measured with a Campbell Scientific Inc. (Utah, USA) Model 237, which indicates whether the surface is wet or dry but may only detect periods of substantial wetness. Thus, values represent the average of measured values within the averaging interval.	
Easter Bush	h measurements are daily to monthly frequency at ten locations in each wind sector LAI measured in 1999 (Milford, 2004) and estimated for other times based on an empirical relationship with h	Not observed	Measured with a Campbell Scientific Inc. (Utah, USA) Model 237, which indicates whether the surface is wet or dry but may only detect periods of substantial wetness. Thus, values represent the average of measured values within the averaging interval. Values greater than 0 were set to 1 because the site operator indicates that the instrument cannot reliably provide fractional values.	Excluded wind sectors are 130–150ºN and 305–315ºN, leaving the sectors that represent the two fields
Ispra	h assumed constant [26 m] LAI has been estimated using a network of 22 PAR sensors deployed below and above the canopy with the Xin et al. (2019) method. During winter when there are no LAI measurements, LAI is gap-filled using linear interpolation. We also fill LAI at the beginning and end of the time series. At the end of the time series, constant values of 3.6 were replaced with multiyear daily average values for 9 November –31 December 2015. At the beginning of the time series, missing values for 1 January – 23 April 2013 were replaced with multiyear daily averages.	Not observed	Measured with S. W. & W. S. Burrage (Kent, UK) SW120, a low power electronic leaf sealed in waterproof resin. The SW120 measures wet or dry and is not sensitive to changes in atmospheric humidity. Half-hourly values are given as 0 or 1. For the last nine months of the time series at Ispra, observed values were always reported as 0 and the CMAQ estimate[a] was used instead	
Harvard Forest	h is constant through the period [24 m] Measurements of LAI are available from 1998, 1999 and 2005–2014 (Barford et al., 2001; Munger and Wofsy, 2021) at weekly to biweekly intervals through the growing season using a LICOR 2000 plant canopy analyzer across an array of plots extending to 500 m from the tower in the dominant northwest (NW) and southwest (SW) wind sectors of the flux tower. We average across three plots in each sector, interpolate to daily resolution and average across years. The variable LAI differs	Not observed	Not observed; modeled[a]	Daily total precipitation measurements are from the nearby Shaler Meteorological Station (Boose and Gould, 1999) and are distributed evenly across the hours of the day in the forcing dataset.

	between these sectors on average by 0.9 m^2 m^{-2}. To capture the LAI of the flux footprint, we use NW LAI when wind comes from the NW and SW LAI when wind comes from the SW. When wind comes from the east, we use LAI from the SW. Across years except 1998 and 1999 when we have yearly LAI constraints, we use the average across years with LAI data (1998, 1999 and 2005–2014). During winter except 1999, LAI is set as the minimum observed value. For 1999, we linearly interpolate between the last fall measurement and first spring value of 2000 for a smoother transition. Otherwise, when wind direction data are missing, we interpolate between LAI with non-missing wind direction data.			
Hyytiälä	h based on biomass inventories within 200 m of the tower in 2003, 2008, 2011 and 2015 (Ilvesniemi et al., 2009); at the end of the inventory years, h is calculated as the mean height of overstory trees; in other years h is estimated by linear interpolation Seasonal maximum LAI in the inventory years is estimated with allometric equations (Repola, 2009). Seasonal maximum LAI is then interpolated yearly, with LAI estimated from below-canopy photosynthetic photon flux density measurements to capture the decrease in winter 2009-2010 when crowns of many big trees were brought down by heavy snow. The timing of canopy height and LAI growth is derived from manual measurements of pine shoot and needle elongation 2–3x per week during May–July. The variables h and LAI are assumed to increase linearly during shoot and needle elongation. Seasonal LAI minimum is 75% of maximum LAI based on average needle longevity. The decline of LAI during leaf fall is assumed to be linear from September–October. The first and last months of the year are filled with the seasonal minimum values.	Snow depth measured	Measured with a Vaisala DRD 11-A rain detector, with measured values greater than or equal to 920 indicating dry conditions and values below 920 indicating increasingly wet conditions. The raw values were converted to binary dry versus wet values based on the threshold value of 920. Because the time series suggests almost permanently wet after the start of May 2008, we use the measured values to infer wet/dry conditions through 3 May 2008 but use the CMAQ estimate[a]	For soil temperature, no measurements were available for the first four years of the time series between 1 January 2002 and 31 December 2005. These missing data were filled in with multiyear daily average soil temperature values calculated using all non-missing values present in the rest of the time series.
Ramat Hanadiv	LAI and h measured in November 2015 and are considered constant otherwise	Not measured but no snow during period	Not observed; modeled[a]	Excluded wind sectors are 233°N to 33ºN. Incoming solar radiation data are missing during some periods at this site, so estimates are provided when there is missing data. The reconstruction of the downward solar radiation (DSR) is based on the National Centers for Environmental

				Prediction/U.S. Department of Energy (NCEP/DOE) Atmospheric Model Intercomparison Project (AMIP)-II Reanalysis-2 data (Kanamitsu et al., 2002) and in-situ global solar radiation (GSR) measurements. The noontime re-analysis data is used to scale DSR. The GSR measurement is used to determine local clouds (clear sky is defined as less than 10% difference between GSR and DSR). For a clear sky day, the DSR reconstruction of that day is based on the ratio between noontime DSR and GSR. For a cloudy day, a virtual noontime GSR peak is reconstructed using Gaussian fitting based on other GSR data points on the same day, which is followed by reconstruction based on the ratio between noontime DSR and GSR.

[a] The CMAQ estimate for fractional canopy wetness (f_{wet}) is based on precipitation (P), relative humidity (RH) and wind speed (u): if $P \geq 0.005$ mm hr^{-1} , f_{wet} is set to 1, if P < 0.005 mm hr^{-1} and $(0.6 + u)(1 - RH) < 0.19$, f_{wet} is set to 0.5, and if P < 0.005 mm hr^{-1} and $(0.6 + u)(1 - RH) \geq 0.19$, f_{wet} is set to 0.

[b] This column contains information as to whether there are excluded wind sectors of the flux datasets, and if assumptions are made in a given input driving variable. If a variable (other than the variables described in other columns of this table, or soil moisture (see Table S17)) has not been described in this column, the variable can be assumed to be measured using standard techniques. We also do the following for all datasets: (1) Sometimes there are small negative observed solar radiation (G) at night in some datasets. Because some models would fail upon input of negative G; we changed all negative values to missing data except when solar zenith angle < 70º for which we changed negative values to zero. We also fill missing or negative PAR [μmol m^{-2} s^{-1}] when G is positive and non-missing with: $PAR = 4.566 * 0.45 * G$. The 4.566 is a unit conversion from W m^{-2} to μmol m^{-2} s^{-1} and the 0.45 is the assumed PAR fraction of G. (2) Ambient mixing ratios of carbon dioxide ($[CO_2]$) are required for some single-point models. Values at all sites were filled to maximize the number of hours for model prediction. Missing values were filled with the last valid data in the time series. If no previous valid data were available (i.e., the first value of the dataset is missing), the global background value at Mauna Loa (NOAA Global Monitoring Laboratory, 2022) for first year of the time series was used for gap filling.

Table S19: Soil moisture input to the single-point models.

Site	**Value used for w**	**Value used for w_2**	**Measurement depth(s)**	**Spatial heterogeneity and related measurements**	**Location of roots**	**Details regarding gap-filling**	**Temporal frequency of measurements & any related interpolation**	**References for soil moisture data**
Auchencorth Moss	Average across depths	Average across depths	6, 18, 30, and 34 cm below moss layer where peat dominates soil (average peat depth is 50 cm)	Average of four probes used			Measured continuously	
Borden Forest	2 cm	50 cm	2 and 50 cm depth	Measurements from two sites; Site B is more representative and thus used, except when there is more missing data (Site A is a bit lower and closer to a creek)		Site A values have been substituted for missing values at Site B	Measured continuously	
Bugacpuszta	3 cm	30 cm	3 and 30 cm depth		Most of the root mass between soil surface and 30 cm (Papp et al., 2018)		Measured continuously	

Easter Bush	constant (0.40)	constant (0.40)			Primary rooting zone extends to 31-cm depth (Jones et al., 2017)	Soil moisture measurements were not provided for this site. Given that soil moisture averages about 40–45%, we employ a constant soil moisture value throughout the period.		
Ispra	10 cm	30 cm	10 and 30 cm depth		About 50% of the root biomass at 0–15 cm depth (Ferréa et al., 2012)		Measured continuously	
Harvard Forest	15 cm	15 cm	15 cm depth	Measurements from three plots in each transect of NW and SW quadrants of tower Soil drainage is heterogenous within tower footprint and varies from nearly saturated surface soils in low areas to moderately well drained high points	Root biomass concentrated in top 15 cm of soil (Abramoff and Finzi, 2019) Large trees access shallow groundwater and are only limited by drought in late summer of the driest years (Urbanski et al., 2007)	Soil moisture for 1991–1994 in the forcing dataset is the 1995–2000 average[a]	Measured approximately weekly during 1995 to 2000 Linearly interpolate values from approximately weekly to daily	Davidson and Savage, (1999); Savage and Davidson (2001)
Hyytiälä	Average across 2-5 cm depths	Average across 9-14 cm depths	Measured at multiple depths	Average across five locations		Any missing soil moisture values from 1 January 2002 – 13 April 2004 were filled using preceding non-missing values (as described for carbon dioxide). In many cases, the missing values for this period were measurements at the bottom of the hour when only measurements at the top of the hour were available. Between 14 April 2004 and 12 January 2005, missing soil moisture data was more prevalent, and any missing data for this period	Measured continuously	

						was filled in with day-of-year average soil moisture values calculated using all non-missing values present in the unfilled time series.		
Ramat Hanadiv	Average across 0 to 20 cm	Average across 0 to 20 cm	Average across 0 to 20 cm depth		About 50% of the roots expected between 10 to 40 cm depth	Inferred using observed values for evergreen shrubs for January 2008 to July 2010	Measured at a frequency of approximately at few weeks to a few months Values are linearly interpolated to daily for 2008 to 2010. Daily values are then averaged across years and months to create multiyear monthly averages. Multiyear monthly averages are placed as each month's 15th day. Values are then linearly interpolated to daily frequency.	Grünzweig et al. (2010)

[a] Soil moisture from one plot is missing in 2000 because the site was flooded. Because this plot, which is adjacent to a wetland, strongly influences the site-level average, we substituted the 1995-1999 mean for this plot's missing data in creating the site-level average.

Table S20: Soil hydraulic properties.[a]

Site	w_{fc}	w_{wlt}	w_{sat}	B	$\psi_{soil,sat}$
Auchencorth Moss	0.75	0.114	0.86	2.66	-7
Borden Forest	0.24	0.078	0.402	4.46	-1.00
Bugacpuszta	0.225	0.081	0.389	4.9	-0.69
Easter Bush	0.297	0.138	0.411	6.53	-1.19
Ispra	0.209	0.059	0.393	3.97	-0.811
Harvard Forest	0.29	0.0954	0.425	4.508	-1.79
Hyytiälä	0.205	0.0522	0.397	3.66	-0.899
Ramat Hanadiv	0.304	0.1	0.43	4.52	-4.98

[a] Soil hydraulic properties are estimated from soil texture when the silt, sand and clay fraction (Table 2) are reported following Clapp and Hornberger (1978) using Colorado State University's Soil Hydraulic Properties (2022) calculator. This tool assumes a field capacity ($\psi_{soil,fc}$) and wilting point ($\psi_{soil,wlt}$) soil matric potentials of -10 kPa and -1500 kPa, respectively. When soil texture information is not completely available, qualitative soil description (e.g., course, sandy loam, fine), and the USDA Soil Texture Calculator (2022) is used to constrain textural estimates. Because the Clapp and Hornberger (1978) relationships do not consider soil organic matter, soil hydraulic properties at Auchencorth Moss are estimated from observed soil moisture data and resulted in values that are similar to undecomposed sphagnum estimated by Verry et al. (2011).