$CO_2/H_2O/$痕量生态系统交换方程：Yang et al 方程的推导解析及其应用讨论

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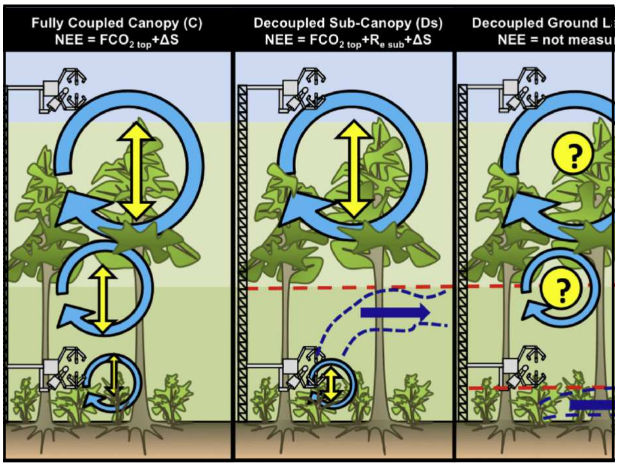
第14次 ChinaFLUX 通量理论与技术培训

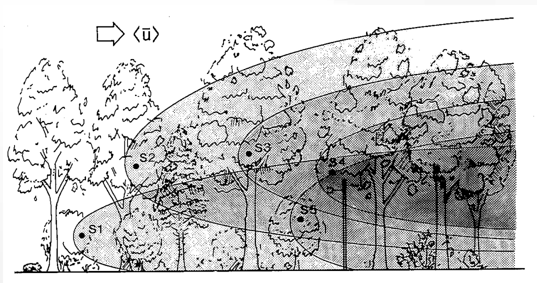
2019年8月6日

水汽滞留时间不确定，也可经平流远途运输后进入大气

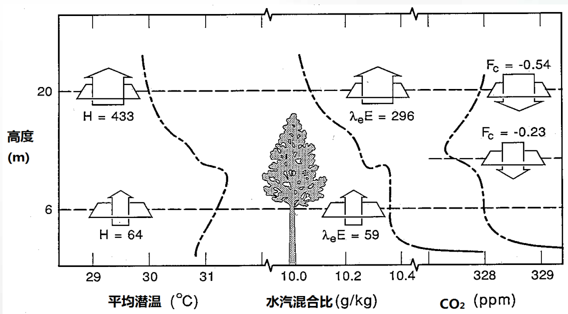
http://img.ksl.com/weatherpics/6/609/60925.jpg?filter=ksl/pgallery



林内的源和汇使林内通量复杂化



林下通量可逆梯度而行

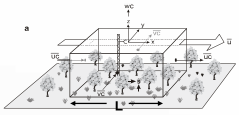


Denmead & Bradley 1985

NEE: Net Ecosystem Exchange （净生态系统交换）

生态系统中动植物包括土壤及微生物与其环境之间的单位面积CO_2平衡量（生态系统吸收为负值，排出为正值）。

Full mass balance on a control volume



$$\overline{F_c} = \overline{F_0} + \int_0^h \overline{S_c}\,dz = \frac{1}{L^2}\int_0^L\int_0^L\int_0^h \overline{c_d}\frac{\partial \overline{\chi_c}}{\partial t}\,dxdydz$$

$$+\frac{1}{L^2}\int_0^L\int_0^L\int_0^h \left[\overline{u}\overline{c_d}\frac{\partial \overline{\chi_c}}{\partial x} + \overline{v}\overline{c_d}\frac{\partial \overline{\chi_c}}{\partial y} + \overline{w}\overline{c_d}\frac{\partial \overline{\chi_c}}{\partial z}\right] dxdydz$$

$$+\frac{1}{L^2}\int_0^L\int_0^L\int_0^h \left[\frac{\partial \overline{c_d}\,\overline{u'\chi_c'}}{\partial x} + \frac{\partial \overline{c_d}\,\overline{v'\chi_c'}}{\partial y} + \frac{\partial \overline{c_d}\,\overline{w'\chi_c'}}{\partial z}\right] dxdydz$$

$$S(t,x,y,z) = \frac{d\rho(t,x,y,z)}{dt}$$

$$d\rho = \frac{\partial\rho}{\partial t}dt + \frac{\partial\rho}{\partial x}dx + \frac{\partial\rho}{\partial y}dy + \frac{\partial\rho}{\partial z}dz$$

$$\frac{d\rho}{dt} = \frac{\partial\rho}{\partial t} + \frac{\partial\rho}{\partial x}\frac{dx}{dt} + \frac{\partial\rho}{\partial y}\frac{dy}{dt} + \frac{\partial\rho}{\partial z}\frac{dz}{dt}$$

$$S = \frac{\partial\rho}{\partial t} + u\frac{\partial\rho}{\partial x} + v\frac{\partial\rho}{\partial y} + w\frac{\partial\rho}{\partial z}$$

Reynolds 平均与分解 (感谢杨柏)

$$S = \frac{\partial\rho}{\partial t} + u\frac{\partial\rho}{\partial x} + v\frac{\partial\rho}{\partial y} + w\frac{\partial\rho}{\partial z}$$

$\rho = \overline{\rho} + \rho'$

$S = \overline{S} + S'$

$u = \overline{u} + u'$

$v = \overline{v} + v'$

$w = \overline{w} + w'$

$$\overline{S} + S' = \frac{\partial(\overline{\rho}+\rho')}{\partial t} + (\overline{u}+u')\frac{\partial(\overline{\rho}+\rho')}{\partial x} + (\overline{v}+v')\frac{\partial(\overline{\rho}+\rho')}{\partial y} + (\overline{w}+w')\frac{\partial(\overline{\rho}+\rho')}{\partial z}$$

$$\overline{S} + S' = \frac{\partial(\overline{\rho}+\rho')}{\partial t} + (\overline{u}+u')\frac{\partial(\overline{\rho}+\rho')}{\partial x} + (\overline{v}+v')\frac{\partial(\overline{\rho}+\rho')}{\partial y} + (\overline{w}+w')\frac{\partial(\overline{\rho}+\rho')}{\partial z}$$

平均后再用Tensor notation:

$$\overline{S} = \frac{\partial\overline{\rho}}{\partial t} + \overline{(\overline{u}_j + u_j')\frac{\partial(\overline{\rho}+\rho')}{\partial x_j}}$$

展开后

$$\overline{S} = \frac{\partial\overline{\rho}}{\partial t} + \overline{u}_j\frac{\partial\overline{\rho}}{\partial x_j} + \overline{u_j'}\frac{\partial\overline{\rho}}{\partial x_j} + \overline{u}_j\frac{\partial\overline{\rho'}}{\partial x_j} + \overline{u_j'\frac{\partial\rho'}{\partial x_j}}$$

$$\overline{S} = \frac{\partial\overline{\rho}}{\partial t} + \overline{u}_j\frac{\partial\overline{\rho}}{\partial x_j} + \overline{u_j'\frac{\partial\rho'}{\partial x_j}}$$

对两个变量乘积求导

$$\frac{\partial\overline{u_j'\rho'}}{\partial x_j} = \overline{u_j'\frac{\partial\rho'}{\partial x_j} + \rho'\frac{\partial u_j'}{\partial x_j}}$$

$$\overline{S} = \frac{\partial\overline{\rho}}{\partial t} + \overline{u}_j\frac{\partial\overline{\rho}}{\partial x_j} + \frac{\partial\overline{\rho' u_j'}}{\partial x_j} - \overline{\rho'\left(\frac{\partial u_j'}{\partial x_j}\right)}$$

$$\bar{S} = \frac{\partial \bar{\rho}}{\partial t} + \bar{u}_j \frac{\partial \bar{\rho}}{\partial x_j} + \frac{\partial \overline{\rho' u_j'}}{\partial x_j} - \overline{\rho'\left(\frac{\partial u_j'}{\partial x_j}\right)}$$

不可压气体

$$\frac{\partial u_j}{\partial x_j} = 0 \qquad \frac{\partial \bar{u}_j}{\partial x_j} = 0 \qquad \frac{\partial u_j}{\partial x_j} = \frac{\partial(\bar{u}_j + u_j')}{\partial x_j} = \frac{\partial \bar{u}_j}{\partial x_j} + \frac{\partial u_j'}{\partial x_j} = 0$$

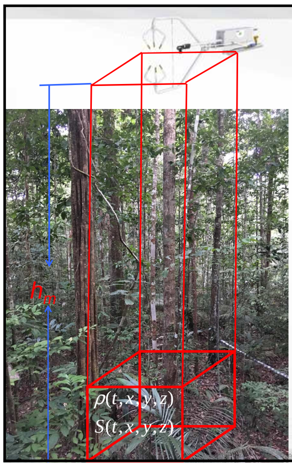
$$\frac{\partial u_j'}{\partial x_j} = 0$$

$$\bar{S} = \frac{\partial \bar{\rho}}{\partial t} + \bar{u}_j \frac{\partial \bar{\rho}}{\partial x_j} + \frac{\partial \overline{\rho' u_j'}}{\partial x_j}$$

$$\bar{S} = \frac{\partial \bar{\rho}}{\partial t} + \bar{u}_j \frac{\partial \bar{\rho}}{\partial x_j} + \frac{\partial \overline{\rho' u_j'}}{\partial x_j}$$

$$\left|\frac{\partial \overline{\rho' u_1'}}{\partial x_1} + \frac{\partial \overline{\rho' u_2'}}{\partial x_2}\right| << \left|\frac{\partial \overline{\rho' u_3'}}{\partial x_3}\right|$$

$$\bar{S} = \frac{\partial \bar{\rho}}{\partial t} + \bar{u}_j \frac{\partial \bar{\rho}}{\partial x_j} + \frac{\partial \overline{\rho' u_3'}}{\partial x_3}$$



$$\bar{S} = \frac{\partial \bar{\rho}}{\partial t} + \bar{u}_j \frac{\partial \bar{\rho}}{\partial x_j} + \frac{\partial \overline{\rho' u_3'}}{\partial x_3}$$

在单位面积上垂直积分至观测高度

$$\int_0^{h_m} \bar{S} dx_3 = \int_0^{h_m} \frac{\partial \bar{\rho}}{\partial t} dx_3 + \int_0^{h_m} \bar{u}_j \frac{\partial \bar{\rho}}{\partial x_j} dx_3 + \int_0^{h_m} \frac{\partial \overline{\rho' u_3'}}{\partial x_3} dx_3$$

$$NEE = \int_0^{h_m} \frac{\partial \bar{\rho}}{\partial t} dx_3 + \int_0^{h_m} \bar{u}_j \frac{\partial \bar{\rho}}{\partial x_j} dx_3 + \overline{\rho' u_3'}\Big|_{x_3 = h_m}$$

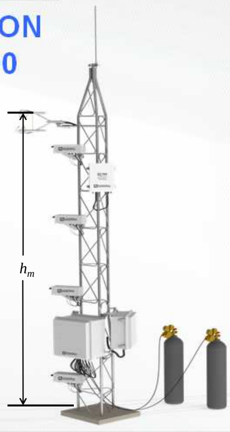
$$NEE = \int_0^{h_m} \frac{\partial \bar{\rho}}{\partial t} dx_3 + \int_0^{h_m} \bar{u}_j \frac{\partial \bar{\rho}}{\partial x_j} dx_3 + \overline{\rho' u_3'}\Big|_{x_3 = h_m}$$

再写为传统表达方式

$$NEE = \int_0^{h_m} \frac{\partial \bar{\rho}}{\partial t} dz + \int_0^{h_m} \left(\bar{u}\frac{\partial \bar{\rho}}{\partial x} + \bar{v}\frac{\partial \bar{\rho}}{\partial y} + \bar{w}\frac{\partial \bar{\rho}}{\partial z}\right) dz + \overline{\rho' w'}\Big|_{z = h_m}$$

IRGASON
AP200

$$NEE = \int_0^{h_m} \frac{\partial \bar{\rho}}{\partial t} dz + \int_0^{h_m} \left(\bar{u}\frac{\partial \bar{\rho}}{\partial x} + \bar{v}\frac{\partial \bar{\rho}}{\partial y} + \bar{w}\frac{\partial \bar{\rho}}{\partial z}\right) dz + \overline{\rho' w'}\Big|_{z = h_m}$$



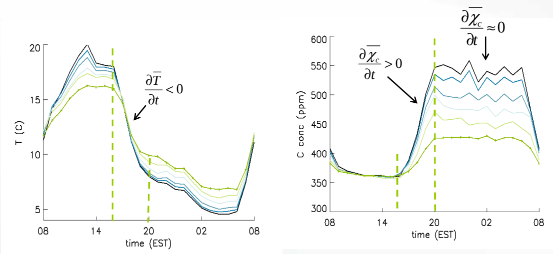
AP200 Profile System – Hawaii, USA

$$NEE = \int_0^{h_m} \frac{\partial \bar{\rho}}{\partial t} dz + \int_0^{h_m} \left(\bar{u} \frac{\partial \bar{\rho}}{\partial x} + \bar{v} \frac{\partial \bar{\rho}}{\partial y} + \bar{w} \frac{\partial \bar{\rho}}{\partial z} \right) dz + \overline{\rho' w'} \Big|_{z=h_m}$$

观察值计算模型

$$NEE = \sum_{i}^{i=m} \frac{\bar{\rho}_i(t_1) - \bar{\rho}_i(t_0)}{t_1 - t_0} \frac{\Delta h_i}{h_m} + \sum_{i}^{i=m} \left(\bar{u}_i \frac{\bar{\rho}_i(t_1, x_1) - \bar{\rho}_i(t_0, x_0)}{x_1 - x_0} + \bar{v}_i \frac{\bar{\rho}_i(t_1, y_1) - \bar{\rho}_i(t_0, y_0)}{y_1 - y_0} + \bar{w}_i \frac{\bar{\rho}_i(t_1, z_1) - \bar{\rho}_i(t_0, z_0)}{z_1 - z_0} \right) \frac{\Delta h_i}{h_m} + \overline{\rho' w'}(h_m)$$

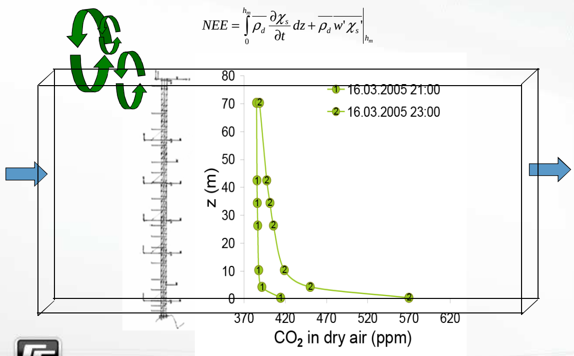
近地面层随植被表面辐射冷确而形成稳定层结使湍流渐消失失



Slide courtesy of Ray Leuning.

Looking at the real world… An example site from Ray Leuning.

$$NEE = \int_0^{h_m} \bar{\rho}_d \frac{\partial \bar{\chi}_s}{\partial t} dz + \bar{\rho}_d \overline{w' \chi_s'} \Big|_{h_m}$$



Slide courtesy of Ray Leuning.

Gu et al 模型

Ag For Meteorol (2012)

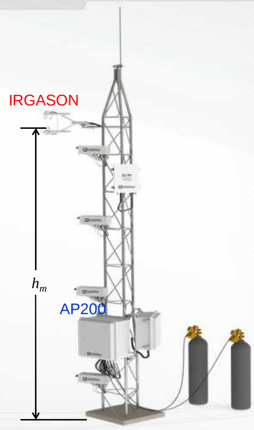
净生态系统CO2交换 (NEE_{co2})

$$NEE_{CO2} = \int_0^{h_m} \frac{\partial \bar{\rho}}{\partial t} dz - \frac{\bar{\rho}}{\bar{\rho}_d} \int_0^{h_m} \frac{\partial \bar{\rho}_d}{\partial t} dz + \overline{\rho' w'}(h_m) + \frac{\bar{\rho}}{\bar{\rho}_d} \overline{\rho_{H2O}' w'} + \bar{\rho}_a \frac{\overline{T' w'}}{\bar{T}}$$

干空气密度　湿空气密度

净生态系统H2O交换 (NEE_{h2o})

$$NEE_{H2O} = \int_0^{h_m} \frac{\partial \bar{\rho}_{H2O}}{\partial t} dz - \frac{\bar{\rho}_{H2O}}{\bar{\rho}_d} \int_0^{h_m} \frac{\partial \bar{\rho}_d}{\partial t} dz + \overline{\rho_{H2O}' w'}(h_m) + \frac{\bar{\rho}_{H2O}}{\bar{\rho}_d} \overline{\rho_{h2o}' w'} + \bar{\rho}_a \frac{\overline{T' w'}}{\bar{T}}$$



主要参考文献

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谢谢！