大气边界层流体运动的湍流机制方程及其结构的相似性理论描述

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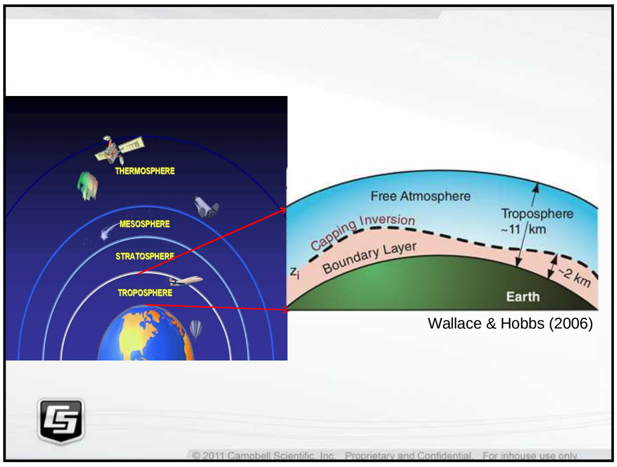
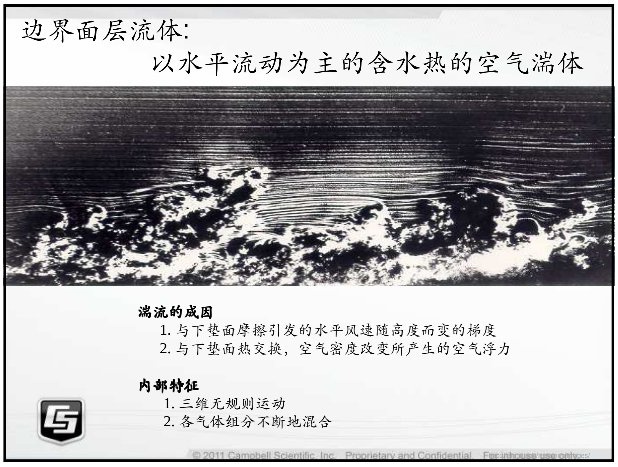
第14次 ChinaFLUX 通量理论与技术培训

2019年8月6日



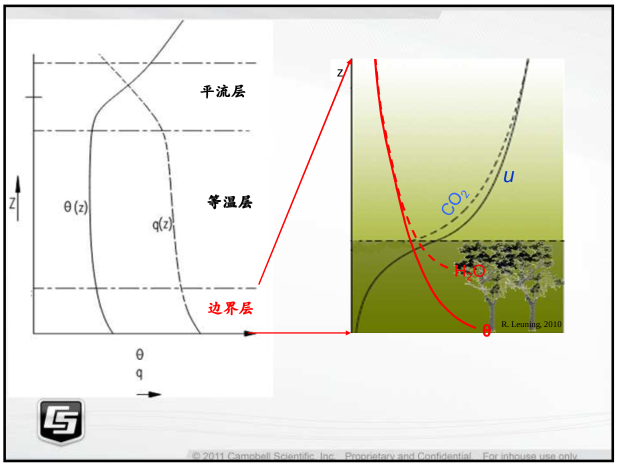
Wallace & Hobbs (2006)



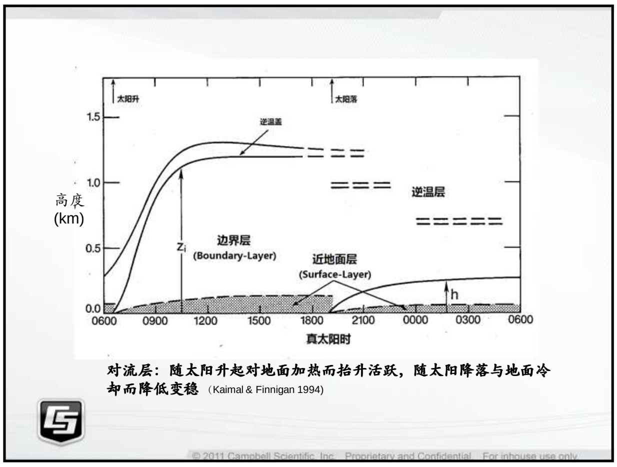
边界面层流体:
以水平流动为主的含水热的空气湍体

湍流的成因
1. 与下垫面摩擦引发的水平风速随高度而变的梯度
2. 与下垫面热交换，空气密度改变所产生的空气浮力

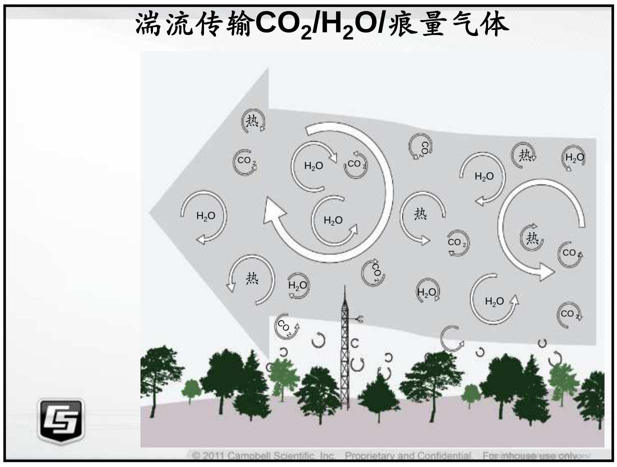
内部特征
1. 三维无规则运动
2. 各气体组分不断地混合



R. Leuning, 2010



对流层：随太阳升起对地面加热而抬升活跃，随太阳降落与地面冷却而降低变稳 （Kaimal & Finnigan 1994)

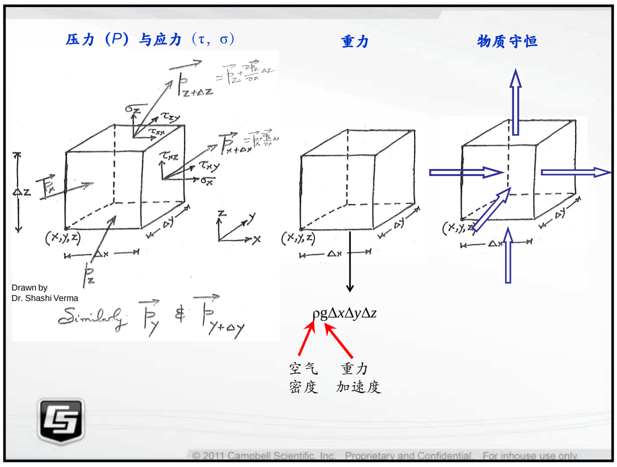


湍流传输CO_2/H_2O/痕量气体

以上的六张图片

1. 边界层及其高度
2. 湍流的产生和耗散与其随机运动
3. CO_2/H_2O/温度/风速垂直梯度（结构）
4. 湍流传输CO_2/H_2O/热

流体运动的物理数学描述



压力（P）与应力（τ，σ） **重力** **物质守恒**

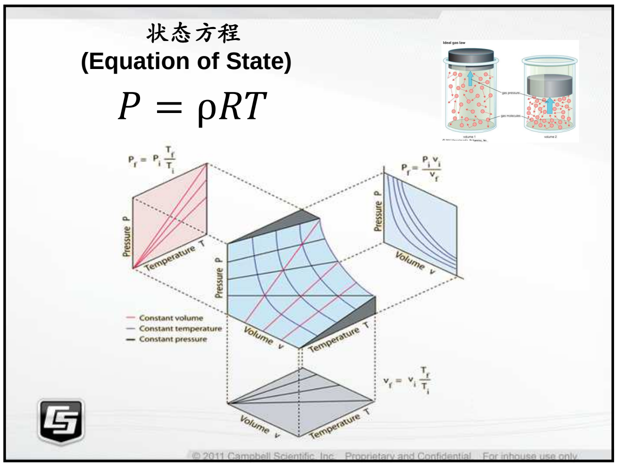
Drawn by
Dr. Shashi Verma

Similarly $\vec{P}_y$ & $\vec{P}_{y+\Delta y}$

ρgΔxΔyΔz

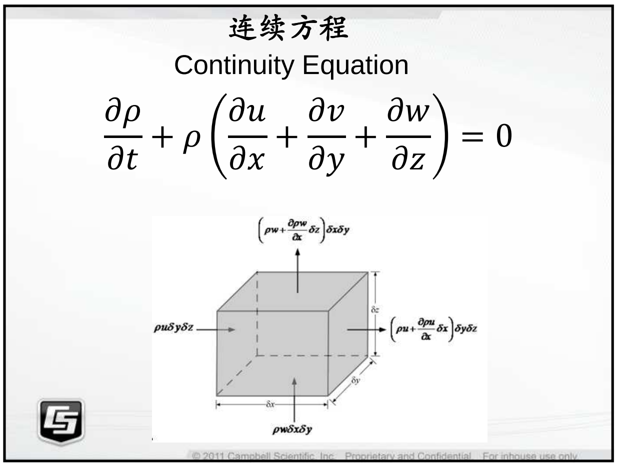
空气
密度

重力
加速度



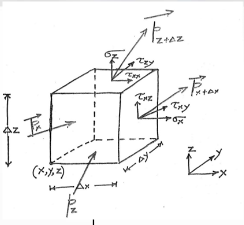
状态方程
(Equation of State)

$$P = \rho RT$$



连续方程
Continuity Equation

$$\frac{\partial \rho}{\partial t} + \rho\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right) = 0$$



变量之间的关系

$$\vec{P} = \vec{P}_x + \vec{P}_y + \vec{P}_z$$

以 x 方向为列

$$\vec{P}_x = \sigma_x \vec{e}_x + \tau_{xy}\vec{e}_y + \tau_{xz}\vec{e}_z$$

$$\downarrow$$

$$\rho g \Delta x \Delta y \Delta z$$

空气 密度 重力 加速度

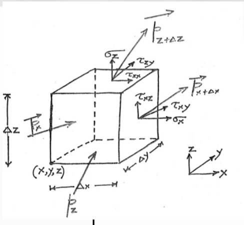
Stocks' law of fraction

$$\sigma_x = -P$$

$$\tau_{xy} = \mu\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)$$

$$\tau_{xz} = \mu\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)$$

μ- 空气年度系数 （182.5 g/m s at 20 C)



$$\downarrow$$

$$\rho g \Delta x \Delta y \Delta z$$

空气 密度 重力 加速度

由压力在 x 方向上产生的的力

$$P_x = \left(\vec{P}_{x+\Delta x} - \vec{P}_x\right)\Delta y \Delta z = \frac{\partial \vec{P}}{\partial x}\Delta x \Delta y \Delta z$$

在三个方向的力

$$F_x = 0, \quad F_y = 0$$

$$F_z = \rho g \Delta x \Delta y \Delta z$$

牛顿第二定律

$$\rho\frac{du}{dt} = \frac{\partial \vec{P}}{\partial x}$$

$$\rho\frac{dv}{dt} = \frac{\partial \vec{P}}{\partial y}$$

$$\rho\frac{dw}{dt} = \frac{\partial \vec{P}}{\partial z} - \rho g$$

空气速度的全导：以u为列

$$u = u(t,x,y,z)$$

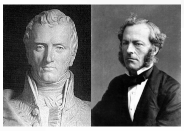
$$du = \frac{\partial u}{\partial t}dt + \frac{\partial u}{\partial x}dx + \frac{\partial u}{\partial y}dy + \frac{\partial u}{\partial z}dz$$

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

$$\frac{du}{dt} = \frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}$$

运动方程

(Navier-Stokes Equations)



$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right) = -\frac{\partial P}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right)$$

$$\rho\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}\right) = -\frac{\partial P}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right)$$

$$\rho\left(\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}\right) = -\frac{\partial P}{\partial z} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) - \rho g$$

Tensor notation
（普矢量表达）

$x \to x_1$ $u \to u_1$

$y \to x_2$ $v \to u_2$

$z \to x_3$ $w \to u_3$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}$$

$$u_J\frac{\partial u_1}{\partial x_J}$$

$$\delta_{ij} = \begin{cases} 0 & i \neq j \\ 1 & i = j \end{cases}$$

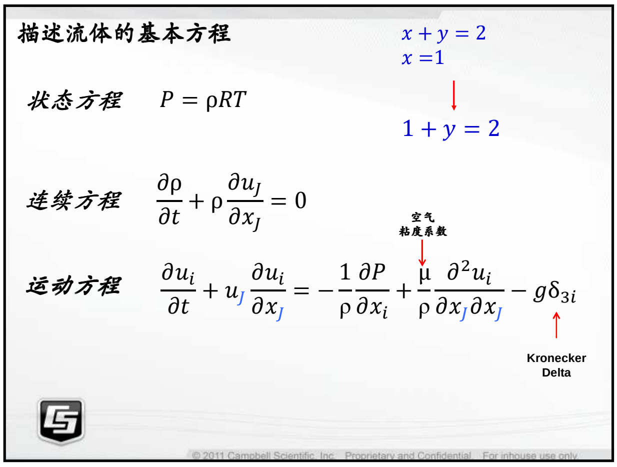
$$\boxed{\begin{aligned} &\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right) = -\frac{\partial P}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) \\ &\rho\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}\right) = -\frac{\partial P}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) \\ &\rho\left(\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}\right) = -\frac{\partial P}{\partial z} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) - \rho g \end{aligned}}$$

$$\boxed{\begin{aligned} &\rho\left(\frac{\partial u_1}{\partial t} + u_1\frac{\partial u_1}{\partial x_1} + u_2\frac{\partial u_1}{\partial x_2} + u_3\frac{\partial u_1}{\partial x_3}\right) = -\frac{\partial P}{\partial x} + \mu\left(\frac{\partial^2 u_1}{\partial x_1^2} + \frac{\partial^2 u_1}{\partial x_2^2} + \frac{\partial^2 u_1}{\partial x_3^2}\right) \\ &\rho\left(\frac{\partial u_2}{\partial t} + u_1\frac{\partial u_2}{\partial x_1} + u_2\frac{\partial u_2}{\partial x_2} + u_3\frac{\partial u_2}{\partial x_3}\right) = -\frac{\partial P}{\partial y} + \mu\left(\frac{\partial^2 u_2}{\partial x_1^2} + \frac{\partial^2 u_2}{\partial x_2^2} + \frac{\partial^2 u_2}{\partial x_3^2}\right) \\ &\rho\left(\frac{\partial u_3}{\partial t} + u_1\frac{\partial u_3}{\partial x_1} + u_2\frac{\partial u_3}{\partial x_2} + u_3\frac{\partial u_3}{\partial x_3}\right) = -\frac{\partial P}{\partial z} + \mu\left(\frac{\partial^2 u_3}{\partial x_1^2} + \frac{\partial^2 u_3}{\partial x_2^2} + \frac{\partial^2 u_3}{\partial x_3^2}\right) - \rho g \end{aligned}}$$

$$\boxed{\rho\left(\frac{\partial u_j}{\partial t} + u_J\frac{\partial u_j}{\partial x_J}\right) = -\frac{\partial P}{\partial x_i} + \mu\frac{\partial^2 u_i}{\partial x_J \partial x_J} - \rho g \delta_{3i}}$$

$$\begin{cases} \delta_{31} = 0 \\ \delta_{32} = 0 \\ \delta_{33} = 1 \end{cases}$$

Kronecker Delta



描述流体的基本方程

$$x + y = 2$$
$$x = 1$$
$$\downarrow$$
$$1 + y = 2$$

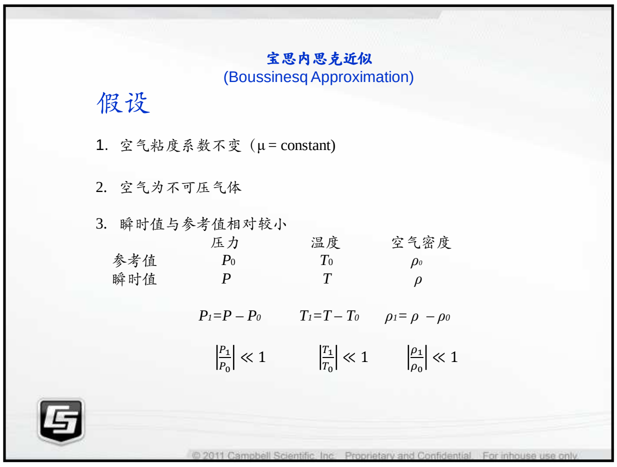
状态方程 $P = \rho RT$

连续方程 $\dfrac{\partial\rho}{\partial t} + \rho\dfrac{\partial u_J}{\partial x_J} = 0$

空气
粘度系数

运动方程 $\dfrac{\partial u_i}{\partial t} + u_J\dfrac{\partial u_i}{\partial x_J} = -\dfrac{1}{\rho}\dfrac{\partial P}{\partial x_i} + \dfrac{\mu}{\rho}\dfrac{\partial^2 u_i}{\partial x_J \partial x_J} - g\delta_{3i}$

Kronecker
Delta



宝思内思克近似
(Boussinesq Approximation)

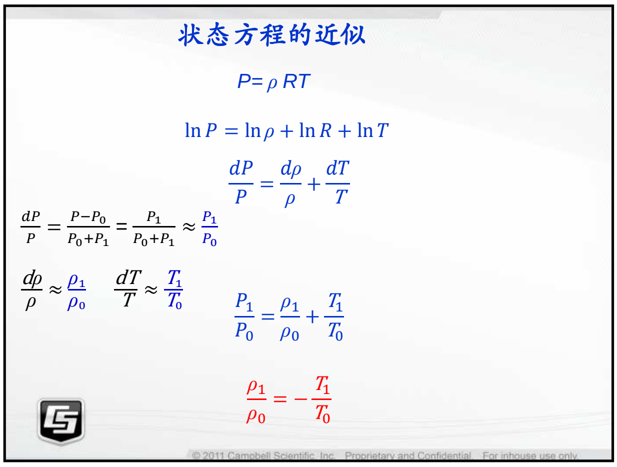
假设

1. 空气粘度系数不变（μ = constant)
2. 空气为不可压气体
3. 瞬时值与参考值相对较小

	压力	温度	空气密度
参考值	P_0	T_0	ρ_0
瞬时值	P	T	ρ

$P_1 = P - P_0$ $T_1 = T - T_0$ $\rho_1 = \rho - \rho_0$

$\left|\dfrac{P_1}{P_0}\right| \ll 1$ $\left|\dfrac{T_1}{T_0}\right| \ll 1$ $\left|\dfrac{\rho_1}{\rho_0}\right| \ll 1$



状态方程的近似

$$P = \rho RT$$

$$\ln P = \ln\rho + \ln R + \ln T$$

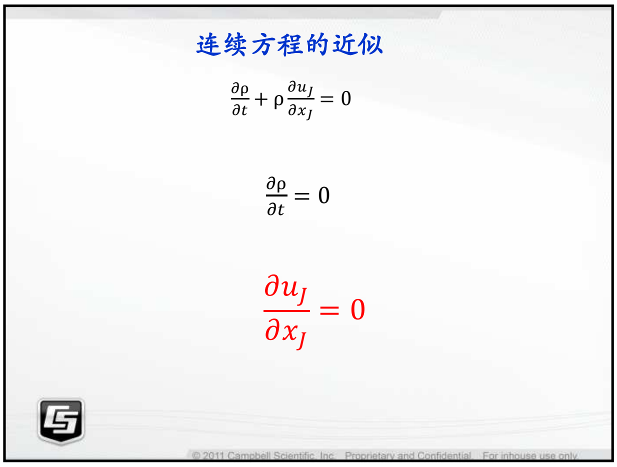
$$\frac{dP}{P} = \frac{d\rho}{\rho} + \frac{dT}{T}$$

$$\frac{dP}{P} = \frac{P-P_0}{P_0+P_1} = \frac{P_1}{P_0+P_1} \approx \frac{P_1}{P_0}$$

$$\frac{d\rho}{\rho} \approx \frac{\rho_1}{\rho_0} \qquad \frac{dT}{T} \approx \frac{T_1}{T_0}$$

$$\frac{P_1}{P_0} = \frac{\rho_1}{\rho_0} + \frac{T_1}{T_0}$$

$$\frac{\rho_1}{\rho_0} = -\frac{T_1}{T_0}$$

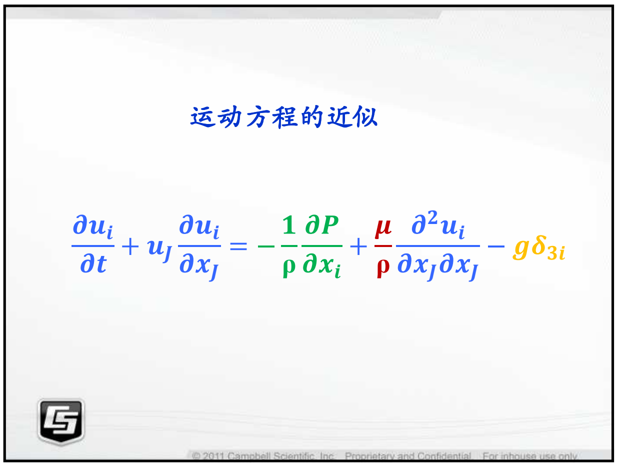


连续方程的近似

$$\frac{\partial\rho}{\partial t} + \rho\frac{\partial u_J}{\partial x_J} = 0$$

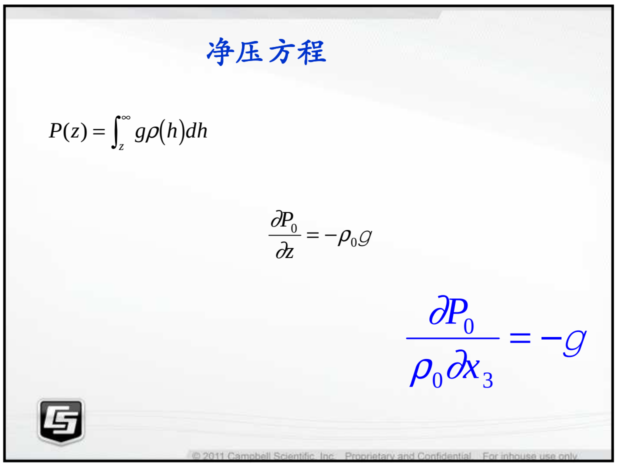
$$\frac{\partial\rho}{\partial t} = 0$$

$$\frac{\partial u_J}{\partial x_J} = 0$$



运动方程的近似

$$\frac{\partial u_i}{\partial t} + u_J\frac{\partial u_i}{\partial x_J} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\mu}{\rho}\frac{\partial^2 u_i}{\partial x_J \partial x_J} - g\delta_{3i}$$



净压方程

$$P(z) = \int_z^{\infty} g\rho(h)dh$$

$$\frac{\partial P_0}{\partial z} = -\rho_0 g$$

$$\frac{\partial P_0}{\rho_0 \partial x_3} = -g$$

运动方程的近似

$$-\frac{1}{\rho}\frac{\partial P}{\partial x_i} = -\frac{1}{\rho_0+\rho_1}\frac{\partial(P_0+P_1)}{\partial x_i} = -\frac{1}{\rho_0}\left(1-\frac{\rho_1}{\rho_0}\right)\left(\frac{\partial P_0}{\partial x_i}+\frac{\partial P_1}{\partial x_i}\right)$$

$$\frac{\partial P_0}{\rho_0 \partial x_3} = -g$$

$$= -\frac{\partial P_0}{\rho_0 \partial x_i} - \frac{1}{\rho_0}\frac{\partial P_1}{\partial x_i} + \frac{\rho_1}{\rho_0}\frac{\partial P_0}{\rho_0 \partial x_i} + \frac{\rho_1}{\rho_0^2}\frac{\partial P_1}{\partial x_i}$$

$$\frac{\rho_1}{\rho_0} = -\frac{T_1}{T_0}$$

$$= \quad g\delta_{3i} - \frac{1}{\rho_0}\frac{\partial P_1}{\partial x_i} - \frac{\rho_1}{\rho_0} g\delta_{3i} \quad - \quad 0$$

$$-\frac{1}{\rho}\frac{\partial P}{\partial x_i} - g\delta_{3i} = -\frac{1}{\rho_0}\frac{\partial P_1}{\partial x_i} + \frac{T_1}{T_0} g\delta_{3i}$$

运动方程的近似

$$\frac{\partial u_i}{\partial t} + u_J\frac{\partial u_i}{\partial x_J} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} - g\delta_{3i} + \frac{\mu}{\rho}\frac{\partial^2 u_i}{\partial x_J \partial x_J}$$

$$-\frac{1}{\rho}\frac{\partial P}{\partial x_i} - \quad g\delta_{3i} = -\frac{1}{\rho_0}\frac{\partial P_1}{\partial x_i} + \frac{T_1}{T_0} g\delta_{3i}$$

$$\frac{\partial u_i}{\partial t} + u_J\frac{\partial u_i}{\partial x_J} = -\frac{\partial P_1}{\rho_0 \partial x_i} + \nu\frac{\partial^2 u_i}{\partial x_J \partial x_J} + \frac{T_1}{T_0} g\delta_{3i}$$

温度波动与重力偶联
可有效地绕动气流

热传输方程

$$\frac{\partial T}{\partial t} + u_J\frac{\partial T}{\partial x_J} = \frac{k_1}{\rho_0 C_p}\frac{\partial^2 T}{\partial x_J \partial x_J}$$

分子运动方程

$$\frac{\partial s}{\partial t} + u_J\frac{\partial s}{\partial x_J} = D_S\frac{\partial^2 s}{\partial x_J \partial x_J}$$

运动方程

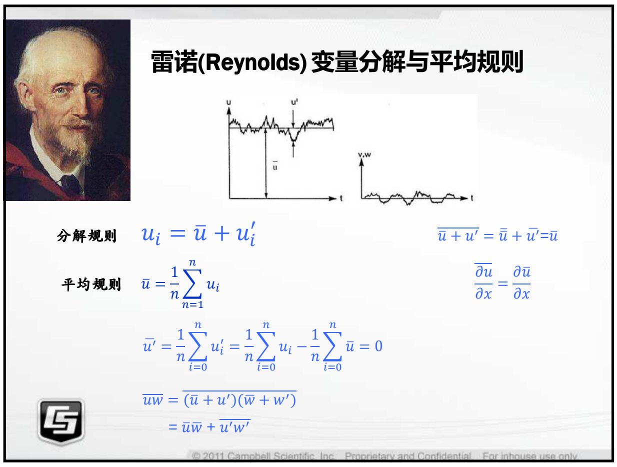
$$\frac{\partial u_i}{\partial t} + u_J\frac{\partial u_i}{\partial x_J} = -\frac{\partial P_1}{\rho_0 \partial x_i} + \nu\frac{\partial^2 u_i}{\partial x_J \partial x_J} + \frac{T_1}{T_0} g\delta_{3i}$$

热传输方程

$$\frac{\partial T_1}{\partial t} + u_J\frac{\partial T_1}{\partial x_J} = \frac{k_1}{\rho_0 C_p}\frac{\partial^2 T_1}{\partial x_J \partial x_J}$$

分子运动方程

$$\frac{\partial s}{\partial t} + u_J\frac{\partial s}{\partial x_J} = D_S\frac{\partial^2 s}{\partial x_J \partial x_J}$$



雷诺(Reynolds) 变量分解与平均规则

分解规则 $u_i = \bar{u} + u_i'$

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

平均规则 $\bar{u} = \frac{1}{n}\sum_{n=1}^{n} u_i$

$$\overline{\frac{\partial u}{\partial x}} = \frac{\partial \bar{u}}{\partial x}$$

$$\bar{u'} = \frac{1}{n}\sum_{i=0}^{n} u_i' = \frac{1}{n}\sum_{i=0}^{n} u_i - \frac{1}{n}\sum_{i=0}^{n} \bar{u} = 0$$

$$\overline{uw} = \overline{(\bar{u}+u')(\bar{w}+w')}$$

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

运动方程描述湍流

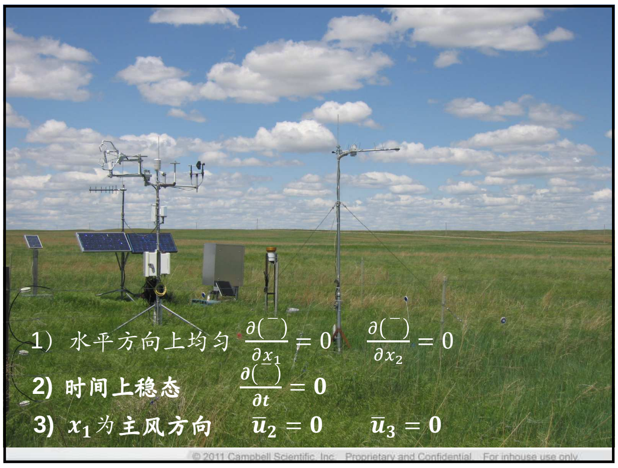
宝思内思克近似运动方程

$$\frac{\partial u_i}{\partial t} + u_J\frac{\partial u_i}{\partial x_J} = -\frac{\partial p_1}{\rho_0 \partial x_i} + \frac{\mu}{\rho_0}\frac{\partial^2 u_i}{\partial x_J \partial x_J} + \frac{T_1}{T_0} g\delta_{3i}$$

$$\frac{\partial(\bar{u} + \mathrm{u}_i')}{\partial t} + (\bar{u}_J - u_J')\frac{\partial(\bar{u}_i + \mathrm{u}_i')}{\partial x_J} = -\frac{\partial(\bar{p}_1 + p_1')}{\rho_0 \partial x_i} + \frac{\mu}{\rho_0}\frac{\partial^2(\bar{u}_i + \mathrm{u}_i')}{\partial x_J \partial x_J} + \frac{\bar{T}_1 - \theta'}{T_0} g\delta_{3i}$$

$$\downarrow$$

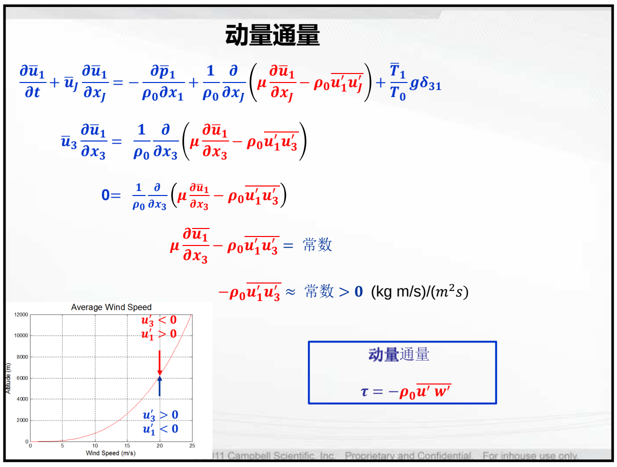
$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_J\frac{\partial \bar{u}_i}{\partial x_J} = -\frac{\partial \bar{p}_1}{\rho_0 \partial x_i} + \frac{1}{\rho_0}\frac{\partial}{\partial x_J}\left(\mu\frac{\partial \overline{u_i}}{\partial x_J} - \rho_0\overline{u_i' u_J'}\right) + \frac{\bar{T}_1}{T_0} g\delta_{3i}$$



1） 水平方向上均匀 $\frac{\partial(\overline{\ })}{\partial x_1}=0$ $\frac{\partial(\overline{\ })}{\partial x_2}=0$

2) 时间上稳态 $\frac{\partial(\overline{\ })}{\partial t}=0$

3) x_1为主风方向 $\bar{u}_2=0$ $\bar{u}_3=0$



动量通量

$$\frac{\partial \bar{u}_1}{\partial t}+\bar{u}_J\frac{\partial \bar{u}_1}{\partial x_J}=-\frac{\partial \bar{p}_1}{\rho_0\partial x_1}+\frac{1}{\rho_0}\frac{\partial}{\partial x_J}\left(\mu\frac{\partial \bar{u}_1}{\partial x_J}-\rho_0\overline{u_1'u_J'}\right)+\frac{\bar{T}_1}{T_0}g\delta_{31}$$

$$\bar{u}_3\frac{\partial \bar{u}_1}{\partial x_3}=\frac{1}{\rho_0}\frac{\partial}{\partial x_3}\left(\mu\frac{\partial \bar{u}_1}{\partial x_3}-\rho_0\overline{u_1'u_3'}\right)$$

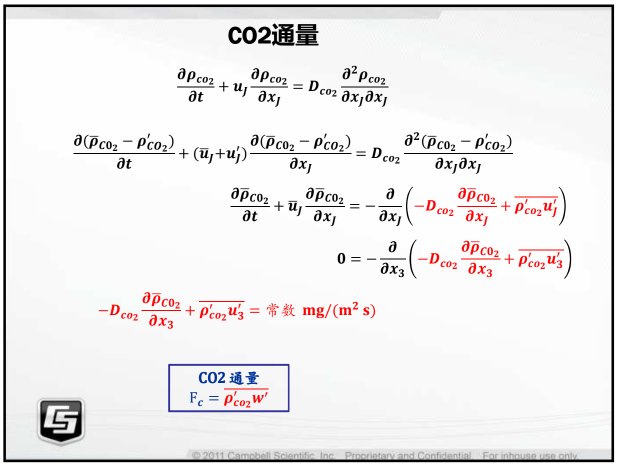
$$0=\frac{1}{\rho_0}\frac{\partial}{\partial x_3}\left(\mu\frac{\partial \bar{u}_1}{\partial x_3}-\rho_0\overline{u_1'u_3'}\right)$$

$$\mu\frac{\partial \overline{u_1}}{\partial x_3}-\rho_0\overline{u_1'u_3'}=\text{常数}$$

$$-\rho_0\overline{u_1'u_3'}\approx\text{常数}>0\ \text{(kg m/s)/}(m^2s)$$

动量通量

$\tau=-\rho_0\overline{u'\,w'}$



CO2通量

$$\frac{\partial \rho_{co_2}}{\partial t}+u_J\frac{\partial \rho_{co_2}}{\partial x_J}=D_{co_2}\frac{\partial^2\rho_{co_2}}{\partial x_J\partial x_J}$$

$$\frac{\partial(\bar{\rho}_{CO_2}-\rho'_{CO_2})}{\partial t}+(\bar{u}_J+u_J')\frac{\partial(\bar{\rho}_{CO_2}-\rho'_{CO_2})}{\partial x_J}=D_{co_2}\frac{\partial^2(\bar{\rho}_{CO_2}-\rho'_{CO_2})}{\partial x_J\partial x_J}$$

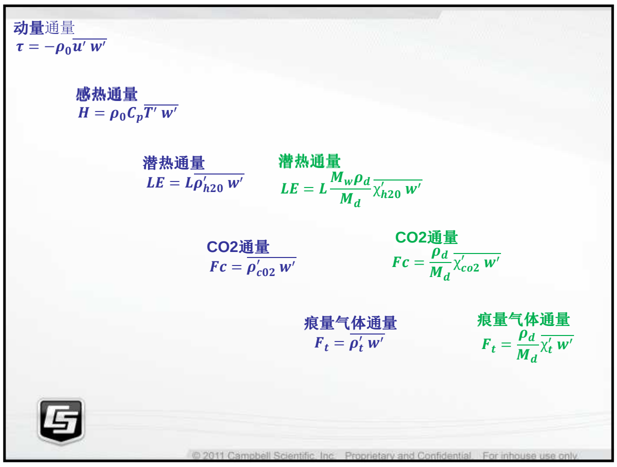
$$\frac{\partial \bar{\rho}_{CO_2}}{\partial t}+\bar{u}_J\frac{\partial \bar{\rho}_{CO_2}}{\partial x_J}=-\frac{\partial}{\partial x_J}\left(-D_{co_2}\frac{\partial \bar{\rho}_{CO_2}}{\partial x_J}+\overline{\rho'_{co_2}u_J'}\right)$$

$$0=-\frac{\partial}{\partial x_3}\left(-D_{co_2}\frac{\partial \bar{\rho}_{CO_2}}{\partial x_3}+\overline{\rho'_{co_2}u_3'}\right)$$

$$-D_{co_2}\frac{\partial \bar{\rho}_{CO_2}}{\partial x_3}+\overline{\rho'_{co_2}u_3'}=\text{常数}\ \mathrm{mg/(m^2\ s)}$$

CO2 通量

$F_c=\overline{\rho'_{co_2}w'}$



动量通量
$\tau=-\rho_0\overline{u'\,w'}$

感热通量
$H=\rho_0C_p\overline{T'\,w'}$

潜热通量
$LE=L\overline{\rho'_{h20}\,w'}$

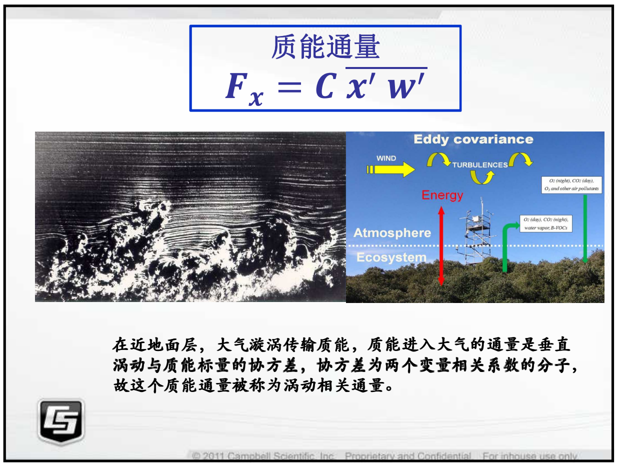
潜热通量
$LE=L\frac{M_w\rho_d}{M_d}\overline{\chi'_{h20}\,w'}$

CO2通量
$Fc=\overline{\rho'_{c02}\,w'}$

CO2通量
$Fc=\frac{\rho_d}{M_d}\overline{\chi'_{co2}\,w'}$

痕量气体通量
$F_t=\overline{\rho'_t\,w'}$

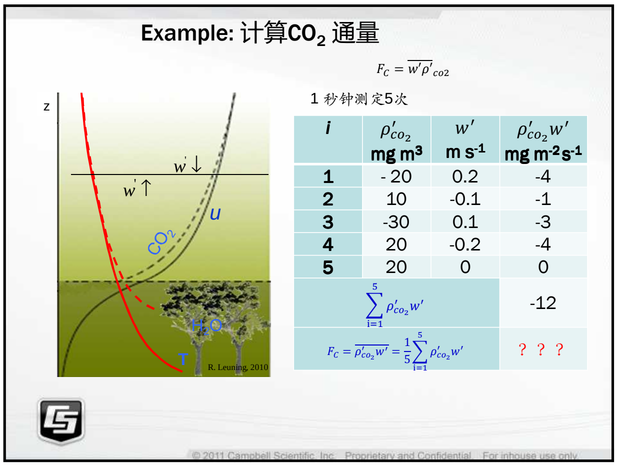
痕量气体通量
$F_t=\frac{\rho_d}{M_d}\overline{\chi'_t\,w'}$



质能通量

$$F_x=C\,\overline{x'\,w'}$$

在近地面层，大气漩涡传输质能，质能进入大气的通量是垂直涡动与质能标量的协方差，协方差为两个变量相关系数的分子，故这个质能通量被称为涡动相关通量。

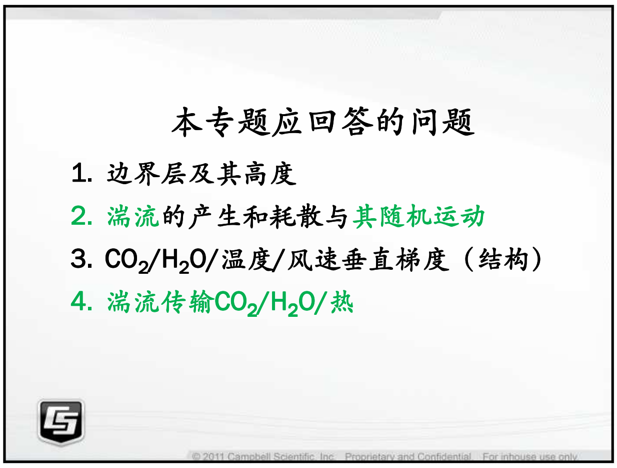


Example: 计算CO_2 通量

$$F_C = \overline{w'\rho'}_{co2}$$

1 秒钟测定5次

i	ρ'_{co_2} mg m³	w' m s⁻¹	$\rho'_{co_2}w'$ mg m⁻²s⁻¹
1	- 20	0.2	-4
2	10	-0.1	-1
3	-30	0.1	-3
4	20	-0.2	-4
5	20	0	0
$\sum_{i=1}^{5}\rho'_{co_2}w'$			-12
$F_C = \overline{\rho'_{co_2}w'} = \frac{1}{5}\sum_{i=1}^{5}\rho'_{co_2}w'$			？？？



本专题应回答的问题

1. 边界层及其高度
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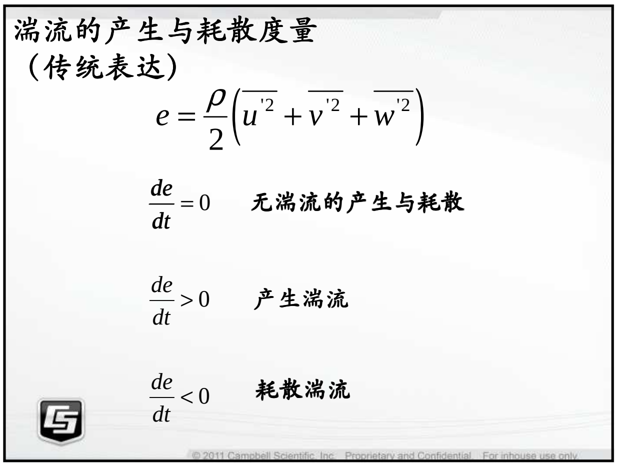
湍流的产生与耗散及其综合描述原理



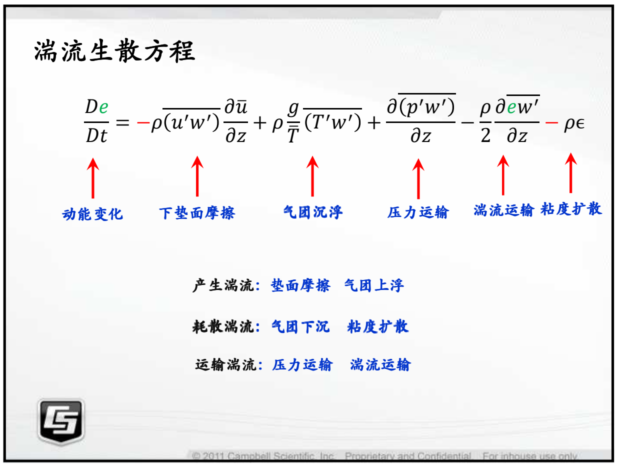
湍流的产生与耗散度量（传统表达）

$$e = \frac{\rho}{2}\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right)$$

$\frac{de}{dt} = 0$ 无湍流的产生与耗散

$\frac{de}{dt} > 0$ 产生湍流

$\frac{de}{dt} < 0$ 耗散湍流



湍流生散方程

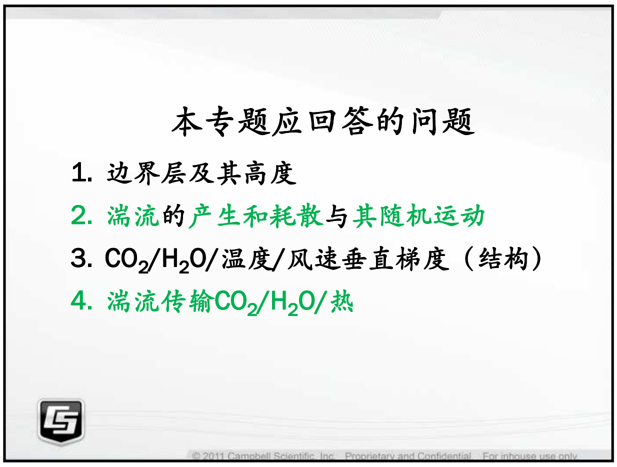
$$\frac{De}{Dt} = -\rho\overline{(u'w')}\frac{\partial\bar{u}}{\partial z} + \rho\frac{g}{\bar{T}}\overline{(T'w')} + \frac{\partial\overline{(p'w')}}{\partial z} - \frac{\rho}{2}\frac{\partial\overline{ew'}}{\partial z} - \rho\epsilon$$

动能变化　下垫面摩擦　气团沉浮　压力运输　湍流运输　粘度扩散

产生湍流：垫面摩擦　气团上浮

耗散湍流：气团下沉　粘度扩散

运输湍流：压力运输　湍流运输



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摩尼奥布科夫长度与大气边界层稳定度

$$\frac{De}{Dt} = -\rho\overline{(u'w')}\frac{\partial\bar{u}}{\partial z} + \rho\frac{g}{\bar{T}}\overline{(T'w')} + \frac{\partial\overline{(p'w')}}{\partial z} - \frac{\rho}{2}\frac{\partial\overline{ew'}}{\partial z} - \rho\epsilon$$

$$u_* = [(\overline{u'w'})^2]^{\frac{1}{4}}$$

摩尼奥布克瓦长度
Monin-Obukhov length

$$L = -\frac{u_*{}^3/k}{(g/\bar{T})\overline{(T'w')}_0}$$

描述整个大气近地面

近地面层
大气稳定度

$$\frac{z}{L} = -\frac{(g/\bar{T})\overline{T'w'}}{u_*{}^3/kz}$$

无量纲

大气边界层稳定度的应用

$$\frac{z}{L} = -\frac{(g/\bar{T})\overline{T'w'}}{u_*{}^3/kz}$$

According to Monin-Obukhov hypothesis, various atmospheric parameters and statistics such as gradients, variances, and covariance; when normalized by appropriate of the scaling velocity u_* and scaling temperature T_* ; become universal functions of z/L

[p15,Kaimal & Finnigan(1994).

$$u_* = \left[-\left(\overline{u'w'}\right)_0\right]^{1/2} \qquad T_* = \frac{-\left(\overline{w'T'}\right)_0}{u_*}$$

风速和温度梯度为大气边界层稳定度的函数

p14, Kaimal & Finnigan(1994)

$$\frac{\partial u}{\partial z} = \frac{u_*}{kz}\begin{cases}\left(1+16\left|\frac{z}{L}\right|\right)^{1/4} & -2 \le \frac{Z}{L} \le 0\\ \left(1+5\frac{z}{L}\right) & 0 \le \frac{z}{L} \le 1\end{cases}$$

$$\frac{\partial \theta}{\partial z} = \frac{T_*}{kz}\begin{cases}\left(1+16\left|\frac{z}{L}\right|\right)^{1/2} & -2 \le \frac{Z}{L} \le 0\\ \left(1+5\frac{z}{L}\right) & 0 \le \frac{z}{L} \le 1\end{cases}$$

风速和温度波动为大气边界层稳定度的函数

p14, Kaimal & Finnigan(1994)

$$\sigma_w = u_*\begin{cases}1.25\left(1+3\left|\frac{z}{L}\right|\right)^{1/3} & -2 \le \frac{Z}{L} \le 0\\ 1.25\left(1+0.2\frac{z}{L}\right) & 0 \le \frac{z}{L} \le 1\end{cases}$$

$$\sigma_\theta = T_*\begin{cases}2\left(1+9.5\left|\frac{z}{L}\right|\right)^{-1/3} & -2 \le \frac{Z}{L} \le 0\\ .2\left(1+0.5\frac{z}{L}\right)^{-1} & 0 \le \frac{z}{L} \le 1\end{cases}$$

湍流动能耗散系数为大气边界层稳定度的函数

p14, Kaimal & Finnigan(1994)

$$\varepsilon = \frac{u_*^3}{kz}\begin{cases}\left(1+0.5\left|\frac{z}{L}\right|^{2/3}\right)^{3/2} & -2 \le \frac{Z}{L} \le 0\\ \left(1+5\frac{z}{L}\right) & 0 \le \frac{z}{L} \le 1\end{cases}$$

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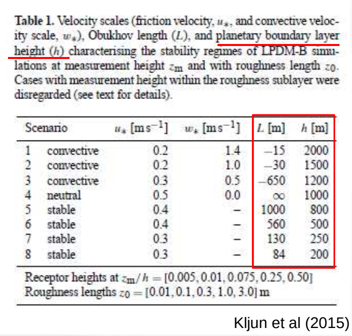

Table 1. Velocity scales (friction velocity, u_*, and convective velocity scale, w_*), Obukhov length (L), and planetary boundary layer height (h) characterising the stability regimes of LPDM-B simulations at measurement height z_m and with roughness length z_0. Cases with measurement height within the roughness sublayer were disregarded (see text for details).

Scenario		u_* [m s^{-1}]	w_* [m s^{-1}]	L [m]	h [m]
1	convective	0.2	1.4	−15	2000
2	convective	0.2	1.0	−30	1500
3	convective	0.3	0.5	−650	1200
4	neutral	0.5	0.0	∞	1000
5	stable	0.4	–	1000	800
6	stable	0.4	–	560	500
7	stable	0.3	–	130	250
8	stable	0.3	–	84	200

Receptor heights at $z_m/h = [0.005, 0.01, 0.075, 0.25, 0.50]$
Roughness lengths $z_0 = [0.01, 0.1, 0.3, 1.0, 3.0]$ m

Kljun et al (2015)

回答问题完毕

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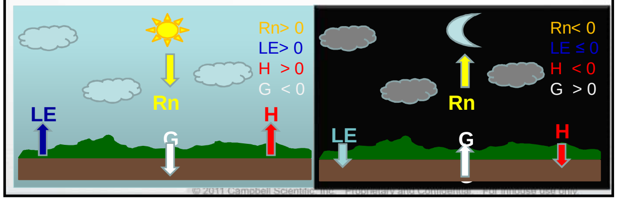
近地面层大气稳定度

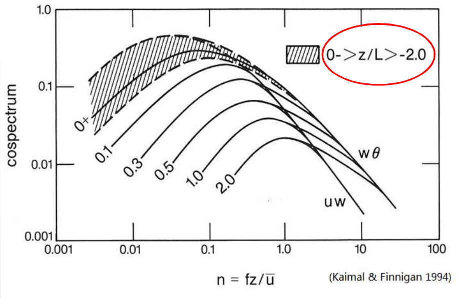
$$\frac{z}{L} = -\frac{\left(g_0 / \overline{T}\right)\overline{w'T'}}{u_*^3 / kz}$$

$\frac{z}{L} < 0$ 近定地面层非稳定

$\frac{z}{L} > 0$ 近地面层稳定



垂直风速与水平风速或温度
在大气边界层不同稳定性下的协湍流谱



(Kaimal & Finnigan 1994)

主要参考文献

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Lumley, J.L. and Panofsky. 1964. The structure of Atmospheric Turbulence. John Wiley and Sons, Inc. 239 pp.

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Questions ?

谢谢！