大气动力学第五章

行星边界层

聂绩

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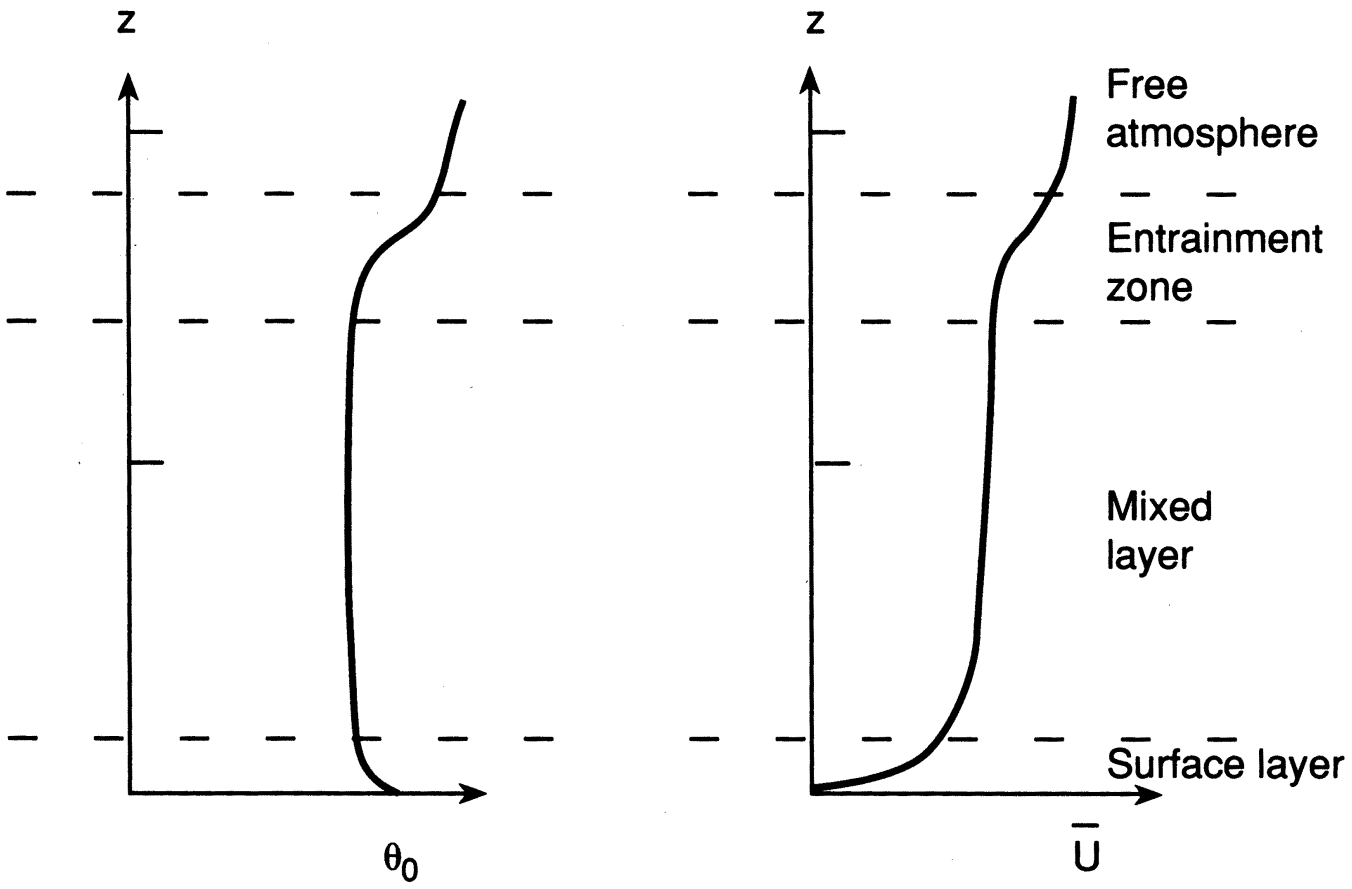
大气边界层：紧靠地球表面的1-2公里的大气层。该层占有10%的大气质量。

1、该层在地-气和海气相互作用过程中起有重要作用。
2、湍流运动该层的显著特征。
3、摩擦力与气压梯度力、科氏力同等重要。

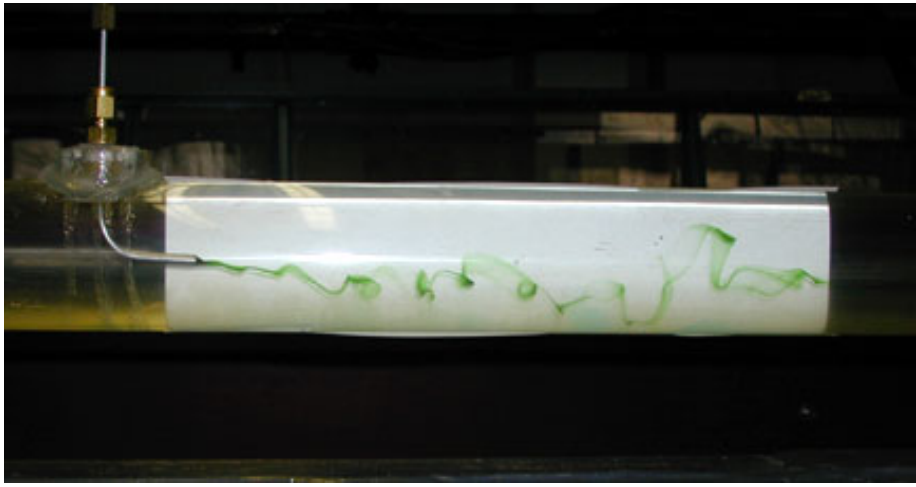
行星边界层


z
θ_0
z
Free
atmosphere
Entrainment
zone
Mixed
layer
Surface layer
$\bar{U}$

5.1 湍流

层流和湍流

laminar



transitional

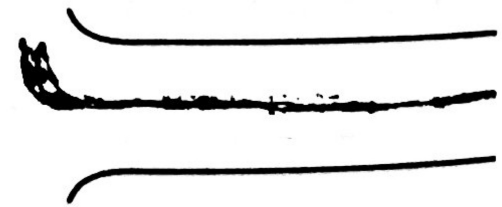
Transitional/turbulent

turbulent

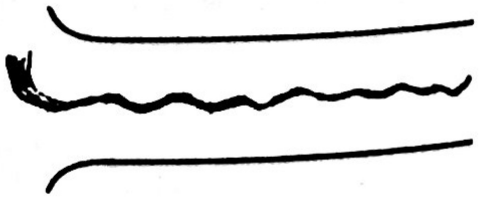
雷诺实验

https://www.youtube.com/watch?v=xiX5PfFxmIs

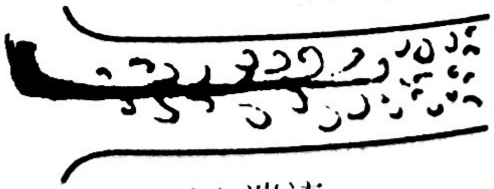
层流-临界-湍流



(a) 层流



(b) 临界状态



(c) 湍流

图 6-2　层流与湍流

$$Re = \frac{\Pi V L}{\mu}$$

雷诺数（Reynolds）：惯性力与粘性力之比

上临界雷诺数～10^5：　　层流转湍流
下临界雷诺数～2000：湍流转层流

惯性力：非线性项　$\vec{v} \cdot \nabla \vec{v}$

粘性力：线性项　$\frac{\mu}{\rho} \nabla^2 \vec{v}$

5.2 雷诺平均运动方程

平均量和脉动量

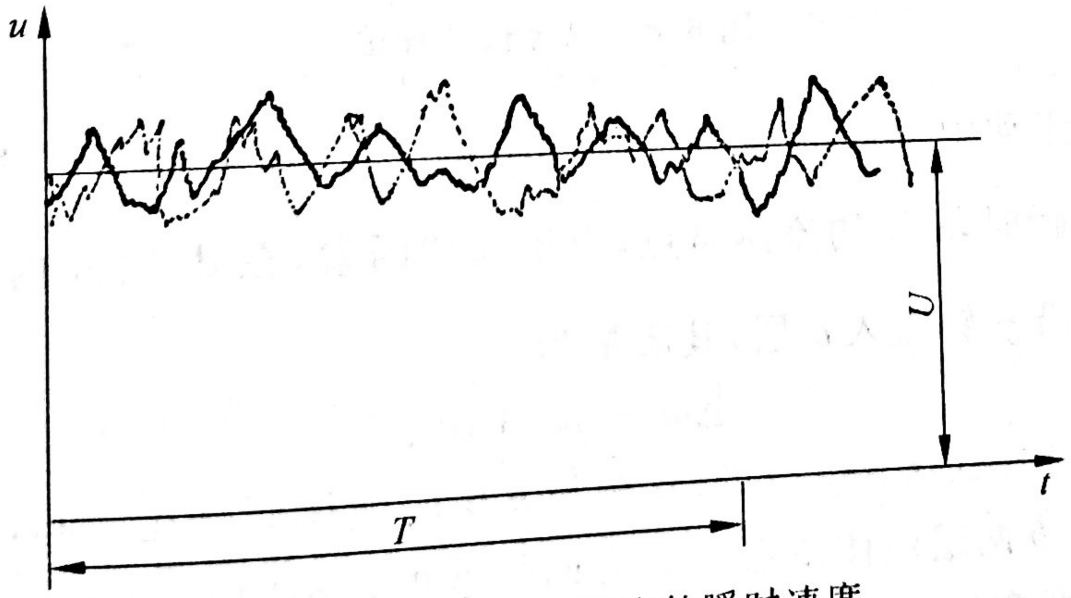


图 6-7　某一点上湍流的瞬时速度

$$\vec{A} = \overline{A} + A'$$

平均量（有意义）　　脉动量（无意义）

平均规则：

$$\overline{\overline{A}} = \overline{A}$$

$$\overline{A'} = 0$$

$$\overline{A + B} = \overline{A} + \overline{B}$$

$$\overline{AB} = \overline{A}\,\overline{B} + \overline{A'B'}$$

$$\overline{\frac{\partial A}{\partial s}} = \frac{\partial \overline{A}}{\partial s}$$

S 可以是 x，y，z，t

状态方程：

$$p = \rho RT$$

做平均：

$$\rho = \overline{\rho} \qquad \text{（简化）}$$

$$\overline{\overline{p} + p'} = \overline{\overline{\rho} R\left(T + T'\right)},$$

$$\overline{p} = R\overline{\rho}\overline{T} + R\overline{\overline{\rho}T'} = R\overline{\rho}\overline{T}$$

连续性方程：

$$\overline{\frac{\partial(\bar{\rho}+\rho')}{\partial t}}+\overline{\frac{\partial[\bar{\rho}(\bar{u}+u')]}{\partial x}}+\overline{\frac{\partial[\bar{\rho}(\bar{v}+v')]}{\partial y}}+\overline{\frac{\partial[\bar{\rho}(\bar{w}+w')]}{\partial z}}=0$$

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

$$\frac{\partial(\bar{\boldsymbol{\rho}}\,\boldsymbol{u}')}{\partial \boldsymbol{x}}+\frac{\partial(\bar{\boldsymbol{\rho}}\,\boldsymbol{v}')}{\partial \boldsymbol{y}}+\frac{\partial(\bar{\boldsymbol{\rho}}\,\boldsymbol{w}')}{\partial \boldsymbol{z}}=0$$

动量方程：

$$\frac{d\bar{u}}{dt} - f\bar{v} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x} + \bar{F}_x + \frac{1}{\bar{\rho}}\left[\frac{\partial}{\partial x}\overline{\left(-\bar{\rho}u'u'\right)} + \frac{\partial}{\partial y}\overline{\left(-\bar{\rho}u'v'\right)} + \frac{\partial}{\partial z}\overline{\left(-\bar{\rho}u'w'\right)}\right]$$

$$\frac{d\bar{v}}{dt} + f\bar{u} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial y} + \bar{F}_y + \frac{1}{\bar{\rho}}\left[\frac{\partial}{\partial x}\overline{\left(-\bar{\rho}v'u'\right)} + \frac{\partial}{\partial y}\overline{\left(-\bar{\rho}v'v'\right)} + \frac{\partial}{\partial z}\overline{\left(-\bar{\rho}v'w'\right)}\right]$$

$$\frac{d\bar{w}}{dt} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial z} - g + \bar{F}_x + \frac{1}{\bar{\rho}}\left[\frac{\partial}{\partial x}\overline{\left(-\bar{\rho}w'u'\right)} + \frac{\partial}{\partial y}\overline{\left(-\bar{\rho}w'v'\right)} + \frac{\partial}{\partial z}\overline{\left(-\bar{\rho}w'w'\right)}\right]$$

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

$$=\bar{u}\frac{\partial \bar{u}}{\partial x}+\bar{v}\frac{\partial \bar{u}}{\partial y}+\bar{w}\frac{\partial \bar{u}}{\partial z}+\overline{u'\frac{\partial u'}{\partial x}+v'\frac{\partial u'}{\partial y}+w'\frac{\partial u'}{\partial z}}$$

$$=\bar{u}\frac{\partial \bar{u}}{\partial x}+\bar{v}\frac{\partial \bar{u}}{\partial y}+\bar{w}\frac{\partial \bar{u}}{\partial z}+\frac{1}{\bar{\rho}}\left(\overline{\bar{\rho}u'\frac{\partial u'}{\partial x}}+\overline{\bar{\rho}v'\frac{\partial u'}{\partial y}}+\overline{\bar{\rho}w'\frac{\partial u'}{\partial z}}\right)$$

$$=\bar{u}\frac{\partial \bar{u}}{\partial x}+\bar{v}\frac{\partial \bar{u}}{\partial y}+\bar{w}\frac{\partial \bar{u}}{\partial z}+\frac{1}{\bar{\rho}}\left(\frac{\partial}{\partial x}\overline{(\bar{\rho}u'u')}+\frac{\partial}{\partial y}\overline{(\bar{\rho}u'v')}+\frac{\partial}{\partial z}\overline{(\bar{\rho}u'w')}\right)$$

得到最后一步时，利用了脉动运动满足的连续性方程。

雷诺应力张量：

$$\tau = \begin{pmatrix} \tau_{xx} & \tau_{yx} & \tau_{zx} \\ \tau_{xy} & \tau_{yy} & \tau_{zy} \\ \tau_{xz} & \tau_{yz} & \tau_{zz} \end{pmatrix} = \begin{pmatrix} -\overline{\bar{\rho}u'u'} & -\overline{\bar{\rho}u'v'} & \overline{\bar{\rho}u'w'} \\ -\overline{\bar{\rho}v'u'} & -\overline{\bar{\rho}v'v'} & -\overline{\bar{\rho}v'w'} \\ -\overline{\bar{\rho}w'u'} & -\overline{\bar{\rho}w'v'} & -\overline{\bar{\rho}w'w'} \end{pmatrix}$$

湍流摩擦力：　　$f_i = \frac{1}{\bar{\rho}} \frac{\partial \tau_{ji}}{\partial x_j}$

$$\tau_{zx} = -\overline{\bar{\rho}u'w'}$$

雷诺应力的意义：

表示作用在垂直z轴的平面上的应力在x方向的分量，由垂直向速度的脉动造成x向脉动量的向下输送，单位时间经过单位面积的动量净通量。

热力学能量方程

$$c_p \frac{D \ln \theta}{Dt} = \frac{J}{T}$$

$$\frac{\bar{D}\bar{\theta}}{Dt} = -\bar{w}\frac{d\theta_0}{dz} - \left[\frac{\partial \overline{u'\theta'}}{\partial x} + \frac{\partial \overline{v'\theta'}}{\partial y} + \frac{\partial \overline{w'\theta'}}{\partial z} \right]$$

湍涡脉动所引起的位温的输送，即湍流热传导。

大气雷诺平均方程组

$$\frac{\bar{D}\bar{u}}{Dt} = -\frac{1}{\rho_0}\frac{\partial \bar{p}}{\partial x} + f\bar{v} - \left[\frac{\partial \overline{u'u'}}{\partial x} + \frac{\partial \overline{u'v'}}{\partial y} + \frac{\partial \overline{u'w'}}{\partial z}\right] + \bar{F}_{rx} \tag{5.9}$$

$$\frac{\bar{D}\bar{v}}{Dt} = -\frac{1}{\rho_0}\frac{\partial \bar{p}}{\partial y} - f\bar{u} - \left[\frac{\partial \overline{u'v'}}{\partial x} + \frac{\partial \overline{v'v'}}{\partial y} + \frac{\partial \overline{v'w'}}{\partial z}\right] + \bar{F}_{ry} \tag{5.10}$$

$$\frac{\bar{D}\bar{w}}{Dt} = -\frac{1}{\rho_0}\frac{\partial \bar{p}}{\partial z} + g\frac{\bar{\theta}}{\theta_0} - \left[\frac{\partial \overline{u'w'}}{\partial x} + \frac{\partial \overline{v'w'}}{\partial y} + \frac{\partial \overline{w'w'}}{\partial z}\right] + \bar{F}_{rz} \tag{5.11}$$

$$\frac{\bar{D}\bar{\theta}}{Dt} = -\bar{w}\frac{d\theta_0}{dz} - \left[\frac{\partial \overline{u'\theta'}}{\partial x} + \frac{\partial \overline{v'\theta'}}{\partial y} + \frac{\partial \overline{w'\theta'}}{\partial z}\right] \tag{5.12}$$

$$\frac{\partial \bar{u}}{\partial x} + \frac{\partial \bar{v}}{\partial y} + \frac{\partial \bar{w}}{\partial z} = 0 \tag{5.13}$$

5.3 湍流参数化

封闭问题：大气方程组的平均，关于平均量的方程不是封闭的。要它封闭，就必须知道随机运动的规律。

$$\frac{\partial \overline{u_i u_j}}{\partial x_j} = f\left(\overline{U_i}\right)$$

$$\overline{u'w'} = -K_m \left(\frac{\partial \bar{u}}{\partial z} \right); \ \overline{v'w'} = -K_m \left(\frac{\partial \bar{v}}{\partial z} \right)$$

$$\overline{\theta'w'} = -K_h \left(\frac{\partial \bar{\theta}}{\partial z} \right)$$

普朗特混合长理论

分子，随机运动。存在一自由程。在自由程内，分子保持自己的属性；超过自由程，分子和分子发生碰撞就失掉它原来的属性。

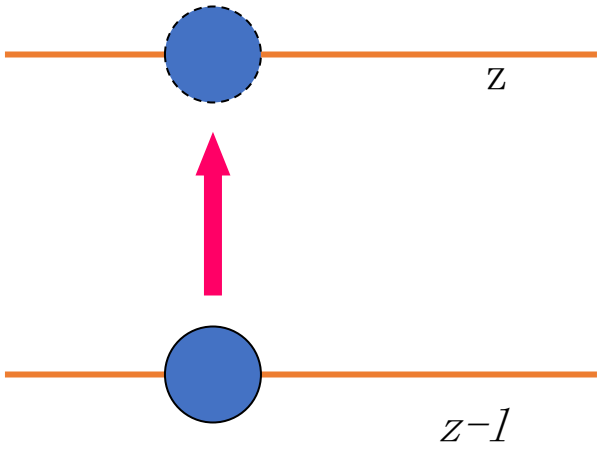
湍涡，随机运动。存在一混合长。在混合长内，湍涡保持自己的属性不变。超过混合长，湍涡和四周流体发生混合，失掉自己原来的属性。

$\overline{s'w'}$：

$$s' = s(z) - \bar{s}(z)$$

$$\begin{aligned} s' &= s(z) - \bar{s}(z) \\ &= \bar{s}(z-l) - \bar{s}(z) \\ &= -l\frac{\partial \bar{s}}{\partial z} \end{aligned}$$

$$\begin{aligned} \overline{s'w'} &= -\overline{lw'\frac{\partial \bar{s}}{\partial z}} \\ &= -K\frac{\partial \bar{s}}{\partial z} \end{aligned}$$



$K = \overline{lw'}$ ---(垂直)湍流粘性系数

对称性：

$$\overline{u'u'} = -2K_h \frac{\partial \bar{u}}{\partial x}, \quad \overline{v'u'} = \overline{u'v'} = -K_h\left(\frac{\partial \bar{u}}{\partial y} + \frac{\partial \bar{v}}{\partial x}\right)$$

$$\overline{v'v'} = -2K_h \frac{\partial \bar{v}}{\partial y}, \quad \overline{u'w'} = \overline{w'u'} = -\left(K \frac{\partial \bar{u}}{\partial z} + K_h \frac{\partial \bar{v}}{\partial x}\right)$$

$$\overline{w'w'} = -2K_h \frac{\partial \bar{w}}{\partial z}, \quad \overline{v'w'} = \overline{w'v'} = -\left(K \frac{\partial \bar{v}}{\partial z} + K_h \frac{\partial \bar{w}}{\partial y}\right)$$

$K_h = \overline{l'u'}$ -----水平湍流粘性系数

$$f_x = \frac{1}{\bar{\rho}} \frac{\partial \tau_{jx}}{\partial x_j} = \frac{1}{\bar{\rho}} \frac{\partial}{\partial x}\left(2\bar{\rho} K_h \frac{\partial \bar{u}}{\partial x} \right) + \frac{1}{\bar{\rho}} \frac{\partial}{\partial y}\left[\bar{\rho} K_h \left(\frac{\partial \bar{u}}{\partial y} + \frac{\partial \bar{v}}{\partial x} \right) \right]$$

$$+ \frac{1}{\bar{\rho}} \frac{\partial}{\partial z}\left(\bar{\rho} K \frac{\partial \bar{u}}{\partial z} + \bar{\rho} K_h \frac{\partial \bar{w}}{\partial x} \right)$$

$$f_y = \frac{1}{\bar{\rho}} \frac{\partial \tau_{jy}}{\partial x_j} = \frac{1}{\bar{\rho}} \frac{\partial}{\partial x}\left(\bar{\rho} K_h \left(\frac{\partial \bar{u}}{\partial y} + \frac{\partial \bar{v}}{\partial x} \right) \right) + \frac{1}{\bar{\rho}} \frac{\partial}{\partial y}\left(2\bar{\rho} K_h \frac{\partial \bar{v}}{\partial y} \right)$$

$$+ \frac{1}{\bar{\rho}} \frac{\partial}{\partial z}\left(K \frac{\partial \bar{v}}{\partial z} + K_h \frac{\partial \bar{w}}{\partial y} \right)$$

$$f_z = \frac{1}{\bar{\rho}} \frac{\partial \tau_{jz}}{\partial x_j} = \frac{1}{\bar{\rho}} \frac{\partial}{\partial x}\left(K\bar{\rho} \frac{\partial \bar{u}}{\partial z} + \bar{\rho} K_h \frac{\partial \bar{w}}{\partial x} \right) + \frac{1}{\bar{\rho}} \frac{\partial}{\partial y}\left(\bar{\rho} K \frac{\partial \bar{v}}{\partial z} + \bar{\rho} K_h \frac{\partial \bar{w}}{\partial y} \right)$$

$$+ \frac{1}{\bar{\rho}} \frac{\partial}{\partial z}\left(2\bar{\rho} K \frac{\partial \bar{w}}{\partial z} \right)$$

若流体均质不可压，
且K，Kh与空间无关：

$$f_x = K_h \frac{\partial^2 \bar{u}}{\partial x^2} + K_h \frac{\partial^2 \bar{u}}{\partial y^2} + K \frac{\partial^2 \bar{u}}{\partial z^2}$$

$$f_y = K_h \left(\frac{\partial^2 \bar{v}}{\partial x^2} + \frac{\partial^2 \bar{v}}{\partial y^2} \right) + K \frac{\partial^2 \bar{v}}{\partial z^2}$$

$$f_z = K_h \left(\frac{\partial^2 \bar{w}}{\partial x^2} + \frac{\partial^2 \bar{w}}{\partial y^2} \right) + K \frac{\partial^2 \bar{w}}{\partial z^2}$$

若 $\boldsymbol{K_h = K_V = K}$ ，湍流粘性力的表达式就与不可压流体的分子粘性力的表达式完全一样，所不同的，湍流粘性系数比分子粘性系数要大五到六个量级。

同理：

$$\theta^* = \frac{1}{\bar{\rho}}\frac{\partial}{\partial x}\left(\bar{\rho}k_h\frac{\partial\bar{\theta}}{\partial x}\right)+\frac{1}{\bar{\rho}}\frac{\partial}{\partial y}\left(\bar{\rho}k_h\frac{\partial\bar{\theta}}{\partial y}\right)+\frac{1}{\bar{\rho}}\frac{\partial}{\partial z}\left(\bar{\rho}k\frac{\partial\bar{\theta}}{\partial z}\right)$$

k ------垂直湍流热传导系数

k_h ------水平湍流热传导系数

求湍流粘性系数K：

设 $u' \sim v' \sim w'$

由 $u' = -l\dfrac{\partial \bar{u}}{\partial z}$ ，得

$$w' = l\left|\frac{\partial \bar{u}}{\partial z}\right| \longrightarrow K = \overline{lw'} = l^2\left|\frac{\partial \bar{u}}{\partial z}\right|$$

l 由经验给出。故，混合长理论，又称为半经验理论。

5.4 近地面层

近地面层：地面和近地面空气的边界层。地面10米至20米

观测：

$$\left(\tau_{zx}\right)_s \sim 0.1 Nm^{-2} \qquad \left(\frac{\tau_{zx}}{\rho}\right)_s \sim 0.1 m^2/s^2$$

$$\frac{1}{\rho}\frac{\partial p}{\partial x} \sim 10^{-3} m/s \qquad \frac{\partial}{\partial z}\left(\frac{\tau_{zx}}{\rho}\right) \le 10^{-3} m/s^2$$

Δz =10米时

$$\Delta\left(\frac{\tau_{zx}}{\rho}\right) \le 10^{-2} m^2/s^2$$

$$\frac{\Delta \tau_{zx}}{\tau_{zx}} \sim 10^{-1} = 10\%$$

$$\frac{\partial}{\partial z}\left(\frac{\tau_{zx}}{\rho}\right) \approx 0$$

$$\frac{\tau_{zx}}{\rho} = u_*^2 = \text{常数}$$

u_* 摩擦速度

$$\frac{\tau_{zx}}{\rho} = K\frac{\partial u}{\partial z}$$

$$= l^2\left|\frac{\partial \bar{u}}{\partial z}\right|\frac{\partial u}{\partial z}$$

$$= u_*^{\,2}$$

$$\mathrm{K} = l^2\left|\frac{\partial u}{\partial z}\right|$$

$$l\frac{\partial \bar{u}}{\partial z} = u_*$$

中性层结下的对数定律：普郎特假定

$$l\frac{\partial \bar{u}}{\partial z}=u_*$$

$$l=\kappa z$$

κ ---卡曼常数

$$\frac{\partial u}{\partial z}=\frac{u_*}{kz}$$

$$u=\frac{u_*}{k}\ln\frac{z}{z_0}$$

z_0 ------粗糙高度

湍流粘性系数和应力：

$$K = l^2 \frac{\partial u}{\partial z} = l u_* = \kappa z u_* ,$$

$$\tau_{zx} = \rho u_*^{\ 2} = \rho C_D u^2$$

$$c_D = \left(\frac{u_*}{u} \right)^2 = \left(\kappa / \ln \frac{z}{z_0} \right)^2$$

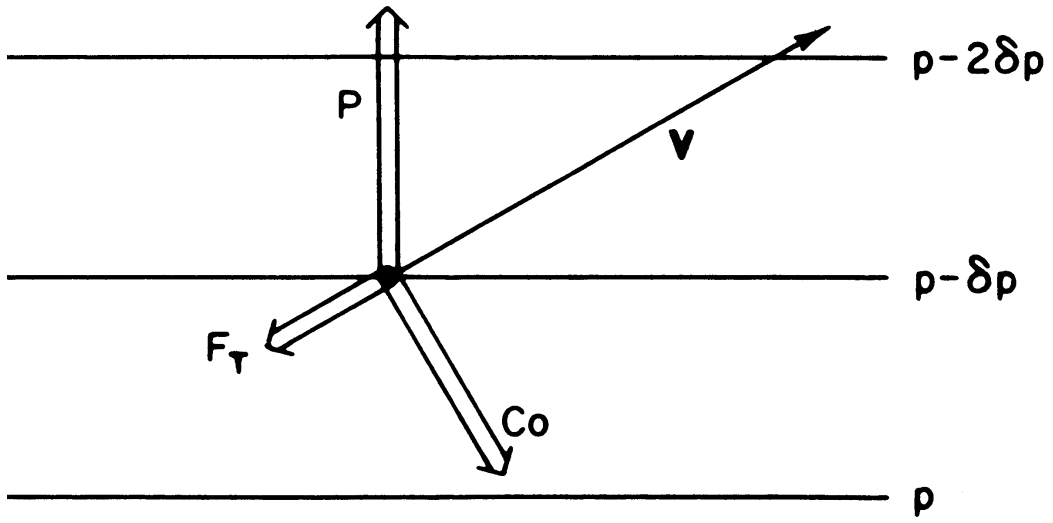
-----拖曳系数

5.5 Ekman层

大气边界层的大尺度运动摩擦力非常重要，科氏力、气压梯度力和摩擦力三力平衡是边界层力平衡的特征：

$$-fv = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{1}{\rho}\frac{\partial \tau_{zx}}{\partial z}$$

$$fu = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \frac{1}{\rho}\frac{\partial \tau_{zy}}{\partial z}$$



$$-\frac{1}{\rho}\frac{\partial p}{\partial x}+fv+\frac{1}{\rho}\frac{\partial}{\partial z}\left(\rho \mathrm{K}\frac{\partial u}{\partial z}\right)=0$$

$$-\frac{1}{\rho}\frac{\partial p}{\partial y}-fu+\frac{1}{\rho}\frac{\partial}{\partial z}\left(\rho \mathrm{K}\frac{\partial v}{\partial z}\right)=0$$

假定：1、流体均质不可压

2、K为常数

3、地转风不随高度变化

$$K\frac{\partial^2 u}{\partial z^2}+f\left(v-v_g\right)=0 \qquad K\frac{\partial^2 u}{\partial z^2}-f\left(u-u_g\right)=0$$

$$\boldsymbol{z=0,\ \ u=v=w=0}$$

$$z\to\infty,\ \ u=u_g,\ v=v_g$$

$$K\frac{\partial^2(u+iv)}{\partial z^2}-if(u+iv)=-if(u_g+iv_g)$$

$$u+iv=Ae^{\sqrt{\frac{f}{2K}}(1+i)z}+Be^{-\sqrt{\frac{f}{2K}}(1+i)z}+(u_g+iv_g)$$

边界条件定出：

$$A=0,\quad B=-(u_g+iv_g)$$

$$u=u_g-\left(u_g\cos\sqrt{\frac{f}{2K}}z+v_g\sin\sqrt{\frac{f}{2K}}z\right)e^{-\sqrt{\frac{f}{2K}}z}$$

$$v=v_g+\left(u_g\sin\sqrt{\frac{f}{2\kappa}}z-v_g\cos\sqrt{\frac{f}{2K}}z\right)e^{-\sqrt{\frac{f}{2K}}z}$$

当 $\sqrt{\frac{f}{2\mathrm{K}}}z = n\pi$

$$u = u_g\left[1+(-1)^{n+1}e^{-n\pi}\right]$$

$$v = v_g\left[1+(-1)^{n+1}e^{-n\pi}\right]$$

$$z = \delta_E = \pi\sqrt{\frac{2\mathrm{K}}{f}}$$ ----边界层的厚度

从观测可知，中纬度的边界层的厚度一般在1公里左右。若取f为 10^{-4} /秒，可得

$$\mathrm{K} = 10^5 cm^2/s$$ 湍流粘性

湍流粘性系数远远大于分子粘性系数。

$$\nu = 10^{-1} cm^2/s$$ 分子粘性

$$tg(\alpha+\beta)=\lim_{z\to 0}\frac{v}{u}$$

$$=\lim_{z\to 0}\frac{u_g-\left(u_g\cos\sqrt{\frac{f}{2\mathrm{K}}}z+v_g\sin\sqrt{\frac{f}{2\mathrm{K}}}z\right)e^{-\sqrt{\frac{f}{2\mathrm{K}}}z}}{v_g+\left(u_g\sin\sqrt{\frac{f}{2\kappa}}z-v_g\cos\sqrt{\frac{f}{2\mathrm{K}}}z\right)e^{-\sqrt{\frac{f}{2\mathrm{K}}}z}}$$

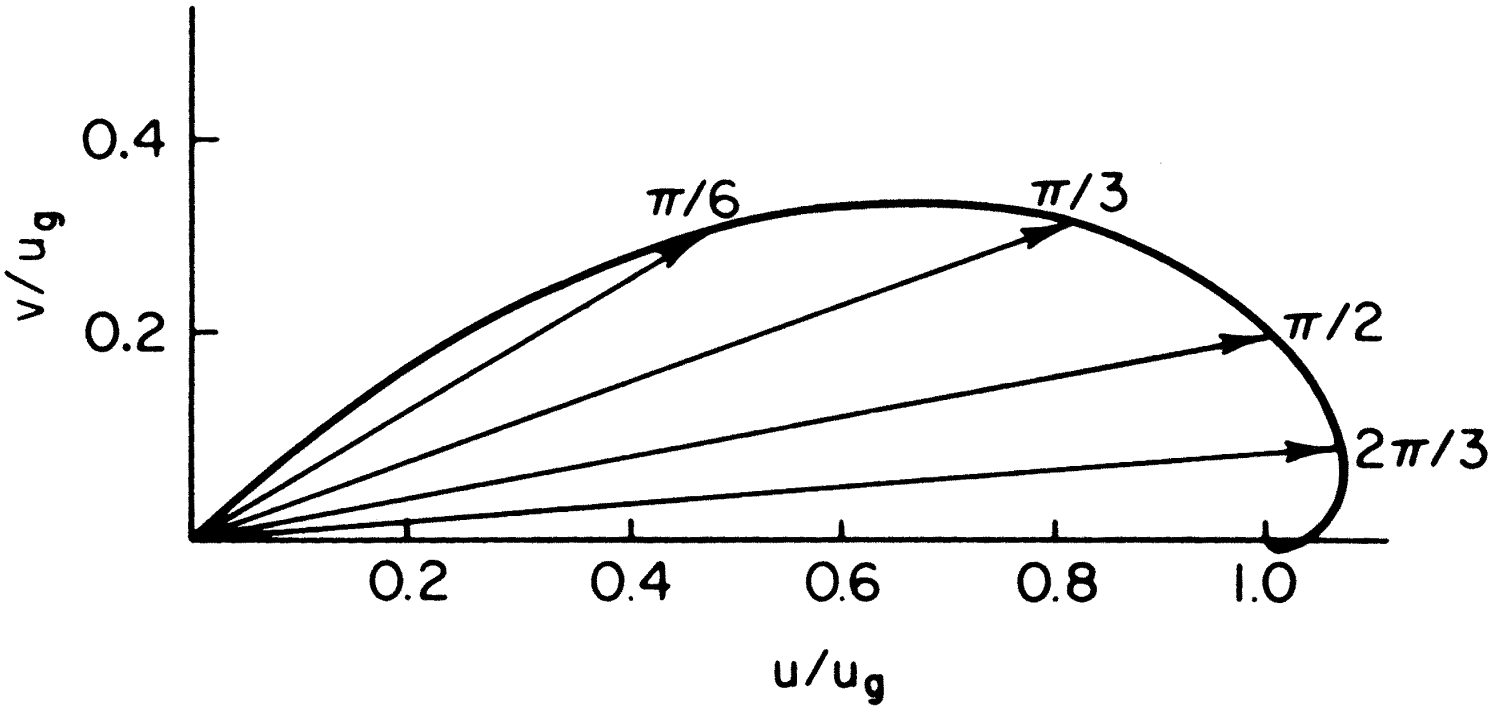
$$=\frac{u_g+v_g}{u_g-v_g}$$

$$=\frac{1+\frac{v_g}{u_g}}{1-\frac{v_g}{u_g}}$$

$$tg(\alpha+\beta)=\frac{tg\alpha+tg\beta}{1-tg\alpha\,tg\beta}$$

可知，在地面的实际风与地转风成 $\pi/4$ 的夹角。

Ekman层中的风矢量



5.6 Ekman泵与旋转减弱

Ekman泵：在边界层由于摩擦力的作用，流体运动不再沿着等压线，其流线与等压线成一定的交角，从高压流向低压。在低压幅合的地方，边界层流体被挤出边界层；在高压幅散区域，将边界层以外的流体吸入边界层。这种效应称为 Ekman 泵。

$$\frac{\partial w}{\partial z} = -\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) \qquad \int_0^{\delta_E} \frac{\partial w}{\partial z} dz = -\int_0^{\delta_E} \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) dz$$

$$w(\infty) - w(0) = \varsigma_g \int_0^{\delta_E} e^{-\sqrt{\frac{f}{2K}}z} \sin\sqrt{\frac{f}{2K}} z dz$$

$$= \varsigma_g \sqrt{\frac{K}{2f}} \left(1 + e^{-\pi}\right)$$

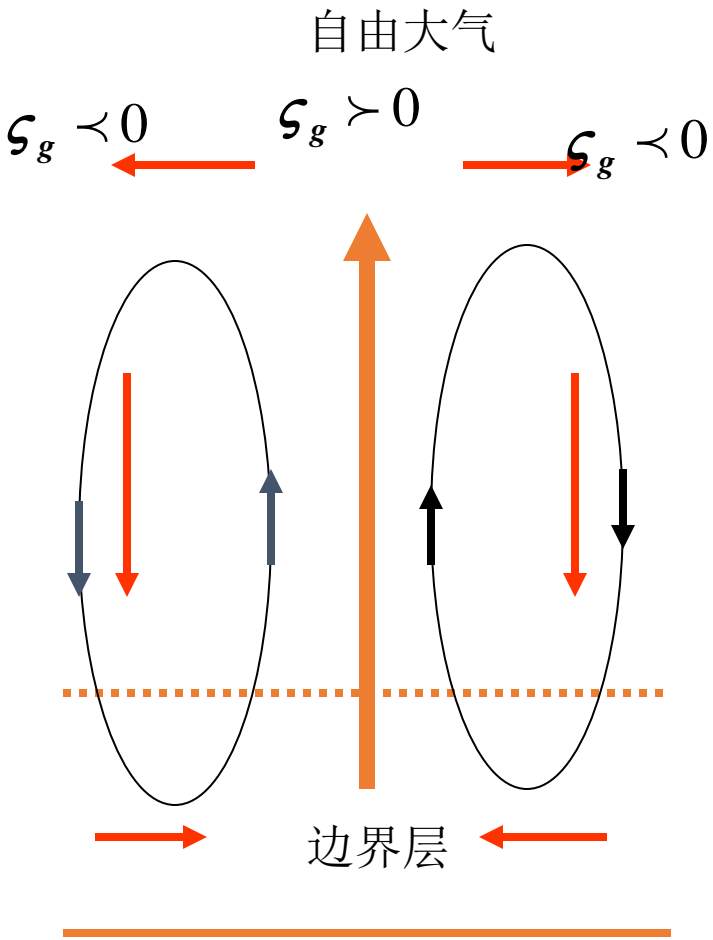
$$\approx \varsigma_g \sqrt{\frac{K}{2f}}$$

旋转减弱：自由大气在没有外部能源的情况下，在底部边界层（Ekman泵）的作用下，其运动的衰减现象，称为旋转减弱（Spin Down）。

假定：1、自由大气是均质的；
2、自由大气的顶为刚性壁；
3、f-平面近似

$$\frac{d\zeta}{dt} = -f_0\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) = f_0\frac{\partial w}{\partial z}$$

$$z = 0, \quad w = w(\delta_E); z = D, w = 0$$



Ekman泵与次级环流

旋转减弱：

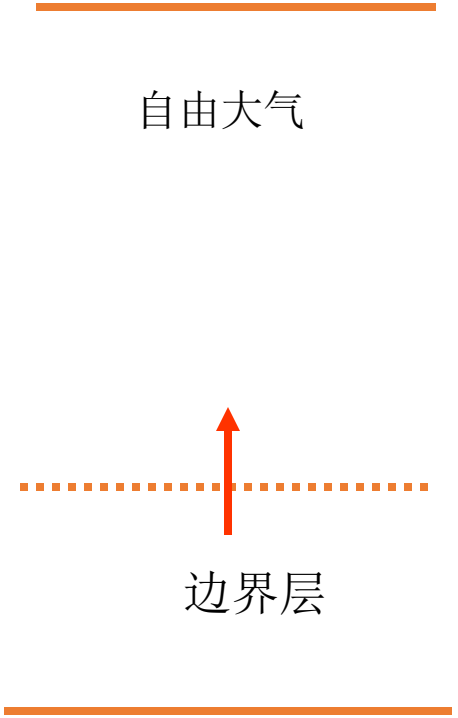
大尺度大气运动是准地转的，将涡度方程中的涡度用地转风涡度近似。

$$\int_{\delta_E}^{D}\left[\frac{d\zeta_g}{dt}=-f_0\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)=f_0\frac{\partial w}{\partial z}\right]dz$$

$$\frac{d\zeta_g}{dt}=-\frac{f_0}{D}w(\delta_E)=-\sqrt{\frac{f_0\mathrm{K}}{2D^2}}\zeta_g$$

$$\zeta_g=\zeta_g(0)\exp\left(-\sqrt{\frac{f_0\mathrm{K}}{2D^2}}t\right)$$

$$t=\tau=D\sqrt{\frac{2}{f_0\mathrm{K}}}$$



取D为10公里，f_0 为 10^{-4}/秒，，可算得涡度的衰减尺度为4天。若边界层的影响是通过湍流扩散进行，边界层影响自由大气，至少需要100天。

目录：

5.1. 湍流
5.2. 雷诺平均运动方程
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5.5 Ekman层
5.6 Ekman泵与旋转减弱

重点：湍流输送，Ekman层，Ekman泵，旋转减弱