第三篇 结构抗风
Part 3 Wind-resistant structure

第八章 大气边界层的平均风特性
Chapter 8 characteristics of mean wind in the atmospheric boundary layer

第九章 平均风的概率计算

Chapter 9 Probabilistic calculation of mean wind

第十章 脉动风的概率特性

Chapter 10 Probabilistic characteristics of fluctuating wind

第11章 结构顺风向随机风振响应

Chapter 11 Structural downwind dynamic response

第十二章 风振控制
Chapter 12 Wind vibration control

Introduction

一、风的概念 Concept of wind

空气从气压大的地方向气压小的地方流动而形成风，风是空气的水平运动

Wind is caused by the movement of air from the higher to the lower pressure areas. Wind is the horizontal movement of air.

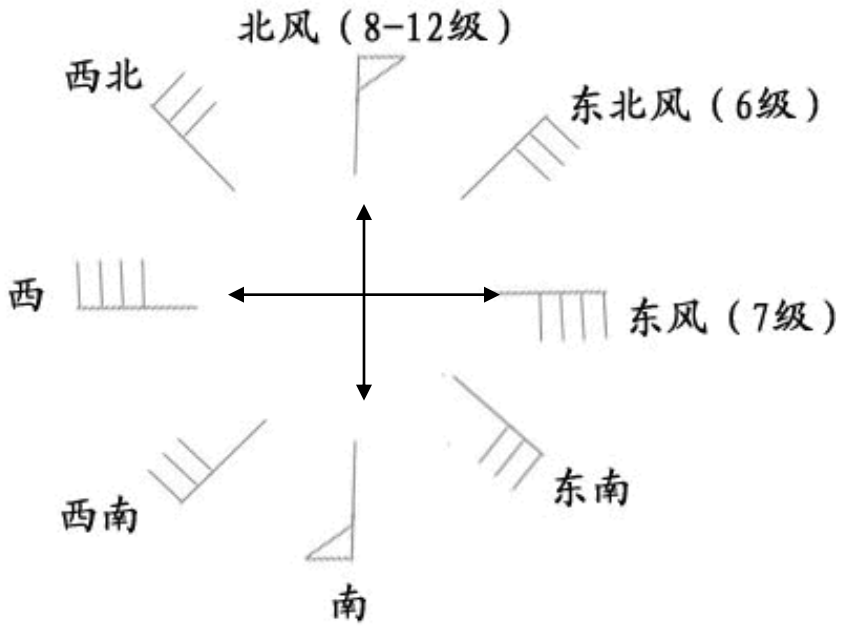
- **赤道和低纬度地区：受热量较多，气温高，空气密度小、气压小,且大气因加热膨胀，由地表向高空上升**
- **At equator and low latitudes: more heat and higher temperature cause the atmosphere expanding, lower density and pressure, rising from the surface into sky**
- **极地和高纬度地区：受热量较少，气温低，空气密度大、气压大，且大气因冷却收缩由高空向地表下降**
- **Arctic and high latitudes: Less heat and lower temperature cause the atmosphere shrinking, higher density and pressure, dropping to the surface from sky**

Introduction

风的两个基本要素：风向和风速，由风向标和风速仪测量

Two basic elements described wind: direction and speed, measured by Vane and anemometer

Wind Cup



原理：利用风杯在风作用下的旋转速度来测量风速。

Principle: Measuring wind speed by the rotational speed of the wind cup under wind

风速 Wind Speed

风速常用风级表示
Wind speed is usually described by
Beaufort wind force scale

风级 Beaufort number	名称 Description	风速(米/秒) Speed(m/s)	陆地物象 Land conditions	海面波浪 Sea conditions	浪高（米） Wave height(m)
0	无风 Calm	0.0-0.2	烟直上 Smoke rises vertically.	平静 mild	0.0
1	软风 Light air	0.3-1.5	烟示风向 Smoke drift indicates wind direction	微波峰无飞沫 Ripples with the appearance of scales are formed, but without foam crests	0.1
2	轻风 Light breeze	1.6-3.3	感觉有风 Wind felt on exposed skin	小波峰未破碎 Small wavelets. crests do not break	0.2
3	微风 Gentle breeze	3.4-5.4	旌旗展开 light flags extended	小波峰顶破裂 Large wavelets. Crests begin to break	0.6

风速 Wind Speed

风级 Beaufort number	名称 Description	风速（米）* Speed(m)	陆地物象 Land conditions	海面波浪 Sea conditions	浪高（米） Wave height(m)
4	和风 Moderate breeze	5.5-7.9	吹起尘土 Dust and loose paper raised.	小浪白沫波峰 Small waves with breaking crests. Fairly frequent whitecaps.	1.0
5	劲风 Fresh breeze	8.0-10.7	小树摇摆 Small trees in leaf begin to sway	中浪折沫峰群 Moderate waves of some length. Many whitecaps.	2.0
6	强风 Strong breeze	10.8-13.8	电线有声 Whistling heard in overhead wires	大浪到个飞沫 Long waves begin to form. White foam crests are very frequent.	3.0

风速 Wind Speed

风级 Beaufort number	名称 Description	风速(米)* Speed(m/s)	陆地物象 Land conditions	海面波浪 Sea conditions	浪高（米） Wave height(m)
7	疾风 High wind, moderate gale, near gale	13.9-17.1	步行困难 Progress on foot is seriously impeded	破峰白沫成条 Moderately high waves with breaking crests forming spindrift	4.0
8	大风 Gale, fresh gale	17.2-20.7	折毁树枝 Some branches break off trees	浪长高有浪花 High waves whose crests sometimes roll over	5.5
9	烈风 Severe gale	20.8-24.4	小损房屋 structural damage likely	浪峰倒卷 Very high waves with overhanging crests	7.0

风速 Wind Speed

风级 Beaufort number	名称 Description	风速（米）* Speed(m)	陆地物象 Land conditions	海面波浪 Sea conditions	浪高（米） Wave height(m)
10	狂风storm	24.5-28.4	拔起树木 Trees are broken off or uprooted	海浪翻滚咆哮 Considerable tumbling of waves with heavy impact	9.0
11	暴风Violent storm	28.5-32.6	损毁普遍 Widespread vegetation	波峰全呈飞沫 Very large patches of foam	11.5
12	飓风 hurricane	32.7-	摧毁巨大 Severe widespread damage to vegetation and structures	海浪滔天 Huge waves	14.0

颶风 hurricane

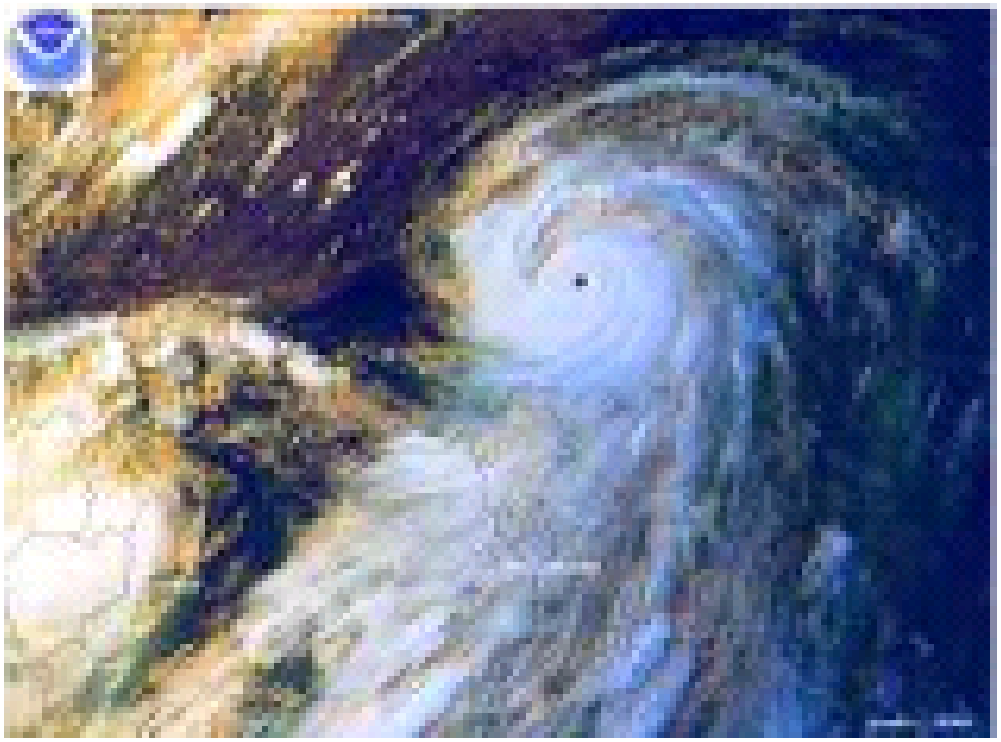
台风
typhoon

绪 论 Introduction

二、风的分类 Types of wind

1、热带气旋

Tropical cyclone



热带气旋按中心附近地面最大风速划分为四个等级

名称	属性
台风 （Typhoon）	最大风速出现＞32．6 米/秒，也即 12 级以上（64 海里/小时或以上）
强热带风暴 (Severe tropical storm)	最大风速出现 24．5-32．6 米/秒，也即风力 10-11 级（48-63 海里/小时）
热带风暴 (Tropical storm)	最大风速出现 17．2-24．4 米/秒，也即风力 8-9 级（34-47 海里/小时）
热带低压 (Tropical depression)	最大风速出现＜17．2 米/秒，也即风力为 6-7 级（22-33 海里/小时）

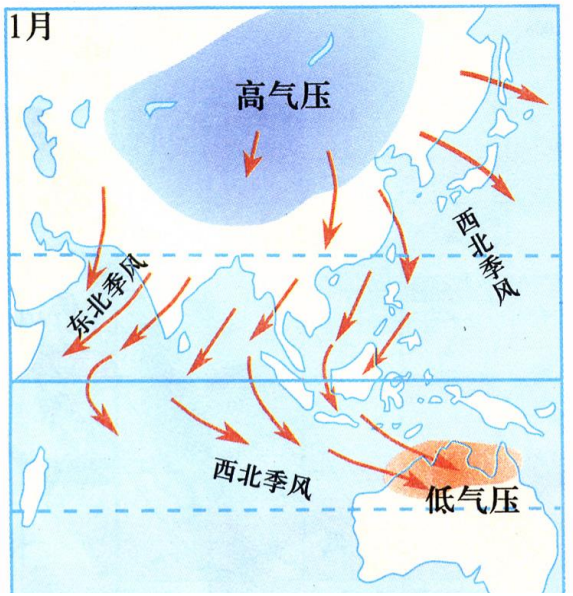
2、季风(monsoon wind)

冬季:大陆温度低、气压高；相邻海洋温度比大陆高、气压低

Winter: Lower temperature and higher pressure in continent. higher temperature and lower pressure in the adjacent ocean

⇒ 风从大陆吹向海洋

Wind blows from continent to ocean

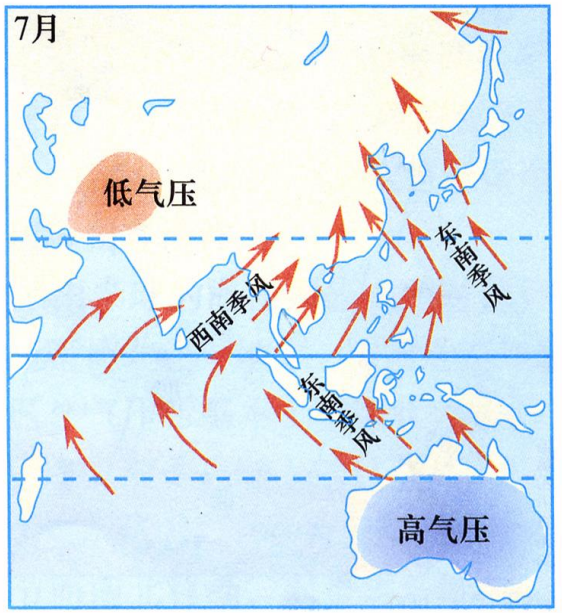


✦**夏季:**大陆温度高、气压低；相邻海洋温度比大陆低 、气压高

Summer: Higher temperature and lower pressure in continent. lower temperature and higher pressure in the adjacent ocean

⇒ **风从海洋吹向大陆**

Wind blows from ocean to continent



3、龙卷风(tornado)

✦ 形成条件复杂

complex formation conditions

所有风暴中最强的风，但发生概率低

The strongest storm, but with a low probability of occurrence

龙卷风——范围小而时间短的强烈旋风，切向速度达100m/s。 Tornado - small range and short duration intense cyclones with a tangential speed of up to 100m / s

- 猛烈旋转的圆形空气柱
- 直径平均在200~300m之间
- 寿命大多在几分钟到几十分钟，不超过几个小时
- 移动速度平均15m/s，最快可以到70m/s
- 移动长度大多在10km左右
- 破坏宽度一般1~2km
- 一般风速50~150m/s，极端情况可以达到300m/s以上

规范中未考虑
No considered in the codes

Introduction

三、结构的风灾 Wind disaster of structure

国内外统计资料表明，在所有自然灾害中，风灾造成的损失为各种灾害之首。例如1999年，全球严重自然灾害共造成800亿美元的经济损失，其中，在被保险的损失中，飓风造成的损失占70%。

According to the foreign statistical data，the damage caused by wind disaster is the severest among all kinds of disaster. For example, in 1999, natural disasters resulted in over 80 billion dollars of economic loss, in which 70% insured losses are caused by hurricane

1. 台风引起“风灾+水灾”
Wind disasters and floods caused by hurricane

低矮房屋破坏

台风“海棠”登陆我国东南沿海

Typhoon Haitang landing southeast coast of China

？缺乏对台风特性的直接观测资料，无法建立我国台风的数学模型，并进行台风的危险性分析。

？Because of the lack of the direct observation data on the characteristic of typhoon, the mathematical model of the typhoons in our country can not be established and the risk analysis of them can not be carried out

1．台风引起“风灾＋水灾”
Wind disasters and floods caused by hurricane

？对台风对低矮建筑群体的作用缺乏系统的研究，无法对其进行有效的抗风设计

？the lack of systematic research on the effect of typhoon on low-rising building groups makes the effective wind-resistant design of the buildings difficult

2009年8月9日台风“莫拉克“袭击台湾

Typhoon landing Taiwan

2. 风力引起高耸结构的倒塌

Collapse of high-rising buildings caused by wind

2004年江苏某地，50米高通讯塔

2005年8月6日被强台风麦莎摧毁的高压输电塔

？对输电塔横风向的作用机理缺乏研究，此类结构的抗风设计没考虑此作用

？ Because of the lack of research on the horizontal wind action on transmission towers, the wind resistance is not considered in the design of this kind of structures

？对风力作用下的“线——塔”耦联结构的振动机理及设计方法缺乏研究

？the lack of research on the mechanics and design methods of the vibration of wire-tower coupling structures under wind action

3. 风力对大跨度空间结构的破坏 Damage on large-span structures by wind

2003年08月03日雷暴雨中突如其来的旋风，把上海大剧院的屋顶掀去了一大块

On August 3rd, a sudden whirlwind during a thunderstorm blew off a large piece of roof from Shanghai Theatre

？对风力对大跨度空间结构的作用，完全依赖于风洞试验，缺乏对其作用的系统研究

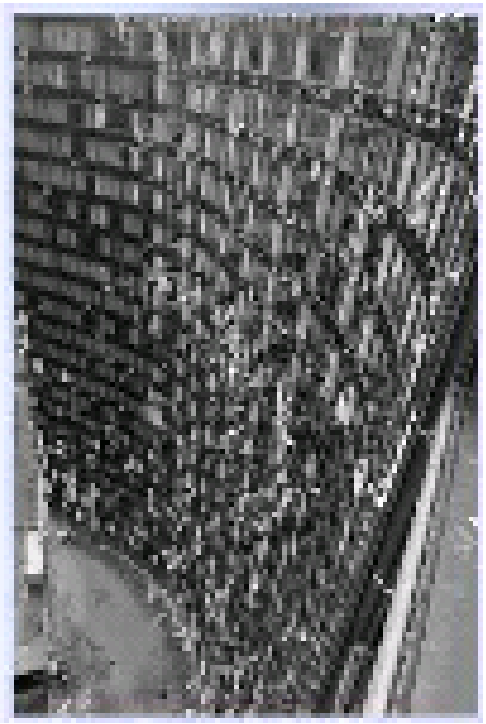
Lacking systematic research, the wind action on large-span structures is complete dependent on wind tunnel test.

4. 风力对大跨度桥梁结构的破坏 Wind damage on large-span bridges

2004年 IVAN飓风
Hurricane Ivan in 2004

Takoma-narrow bridge

5. 风力对高层建筑的破坏 Wind damage on high-rise buildings



2005年8月29日，飓风卡特里娜摧毁了许多建筑的窗户，幕墙和外墙装饰
Hurricane Katrina destroyed the windows, curtain walls and exterior decorations of many buildings

1999年9月16日，9915号台风摧毁香港湾仔数栋办公楼玻璃幕墙
On September 16th, The glass curtain walls of several buildings in Hongkong was destroyed by Typhoon York.

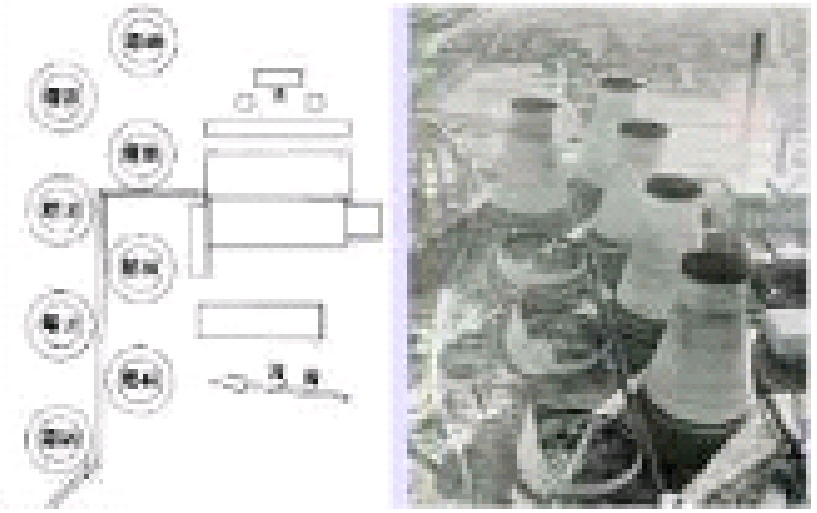
人体振动舒适度控制界限
comfort limits of Vibration for human

程度 Degree	使人烦恼 Annoying	非常烦恼 Very annoying	无法忍受 Unbearable
界限 Limit[a]	15gal	50gal	150gal

注： 其中 1gal=1/100m/s^2

6. 风力对其它结构的破坏 damage on other structures by wind

1996年台风莎莉袭击下，广东湛江500吨集装箱桥吊刮翻，12台龙门吊被刮翻



美国fenybridge热电厂冷却塔群，8个高116m冷却塔组成，1965年一场20m/s的大风把其中3个吹毁

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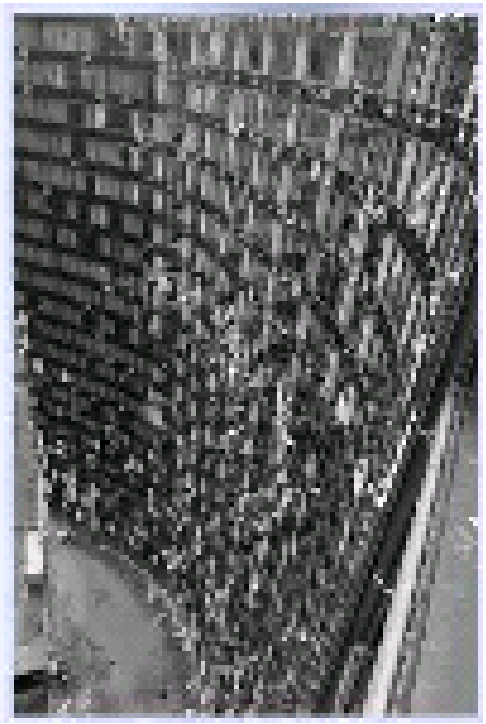

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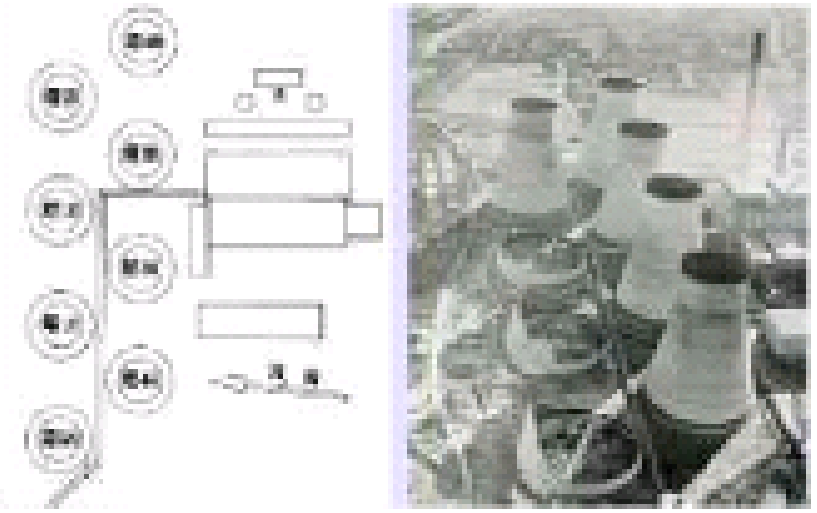

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2.4 结构总效应 Total wind effect on structure

- 考虑顺风向动力作用效应（脉动效应）与横风向动力作用效应（风振效应）的最大值不一定在同一时刻发生
- Generally it is seldom occurs that the alongwind dynamic effect (fluctuating effect) and the lateral wind dynamic effect reach the maximum values at the same time

➔ 采用平方和开方近似估算总的风动力效应

➔ The total dynamic wind effects are evaluated by SRSS (square root of the sum of the squares)

↓结构顺风向静力效应 alongwind static effect

Total structural wind effect→ $$S = S_s + \sqrt{S_{dD}^2 + S_{dL}^2}$$

结构顺风向脉动效应↑ alongwind fluctuating effect

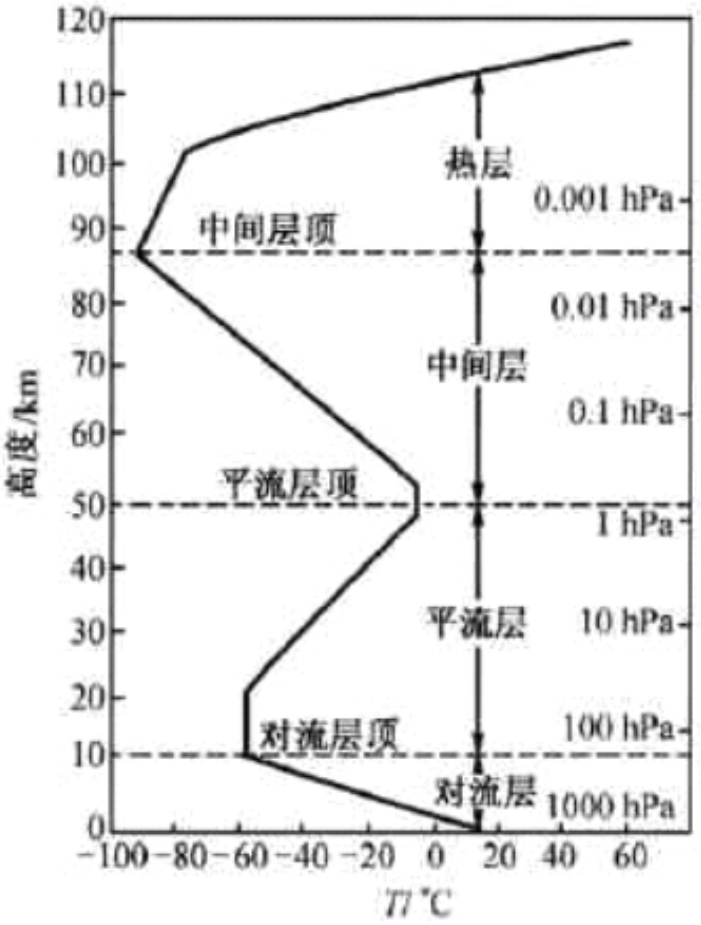
↖结构横风向风振效应 Crosswind dynamic effect

第八章 大气边界层的平均风特性
Chapter 8 characteristics of mean wind in the atmospheric boundary layer

8.1 大气边界层 the atmospheric boundary layer

地球被一层厚度大1000km的大气所环绕。环绕大气的大气层可分为**对流层、平流层、中间层和热层。**

The earth is surrounded by an atmosphere of 1000km thick. The atmosphere can be divided into the troposphere, stratosphere, thermosphere and middle layer.



风是大气中气团运动形成的,在靠近地球表面，地面上各种粗糙元，如草、沙粒、庄稼、树木、房屋等会使大气流动受阻.

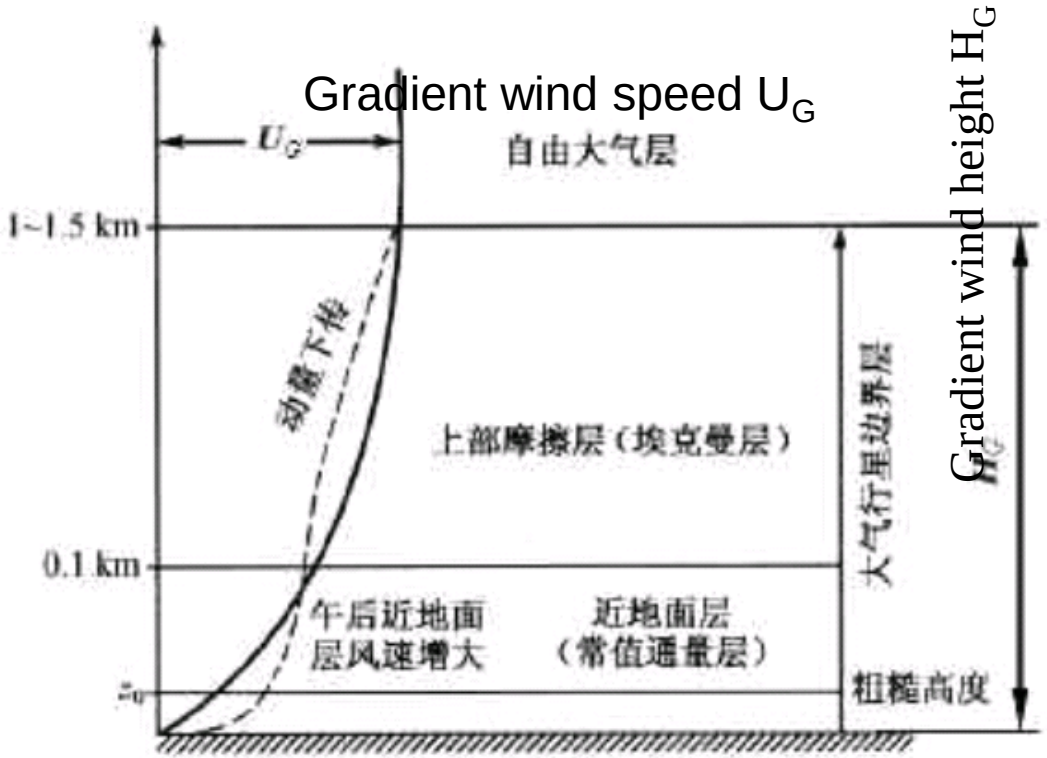
Wind is formed by the movement of air masses in the atmosphere. For winds near the ground surface, frictional effects play a significant role. Ground obstructions retard the movement of air close to the ground surface, causing a reduction in wind speed.

这种摩擦阻力由于大气中的湍流而向上传递，并随高度的增加而逐渐减弱，达到某一高度后便可忽略。此高度称为大气边界层厚度，它随气象条件、地形、地面粗糙程度而变化，大致为300~600米。

This frictional resistance transmits upward due to atmospheric turbulence, decreases with the height, and at a certain height above ground, the movement of air is no longer affected by ground obstruction. This height is called the thickness of atmospheric boundary layer (gradient height), which changes with the weather conditions, terrain, and is roughly 300 to 600 meters. The unobstructed wind speed is called gradient wind speed.

8.1 大气边界层 Atmospheric boundary layer

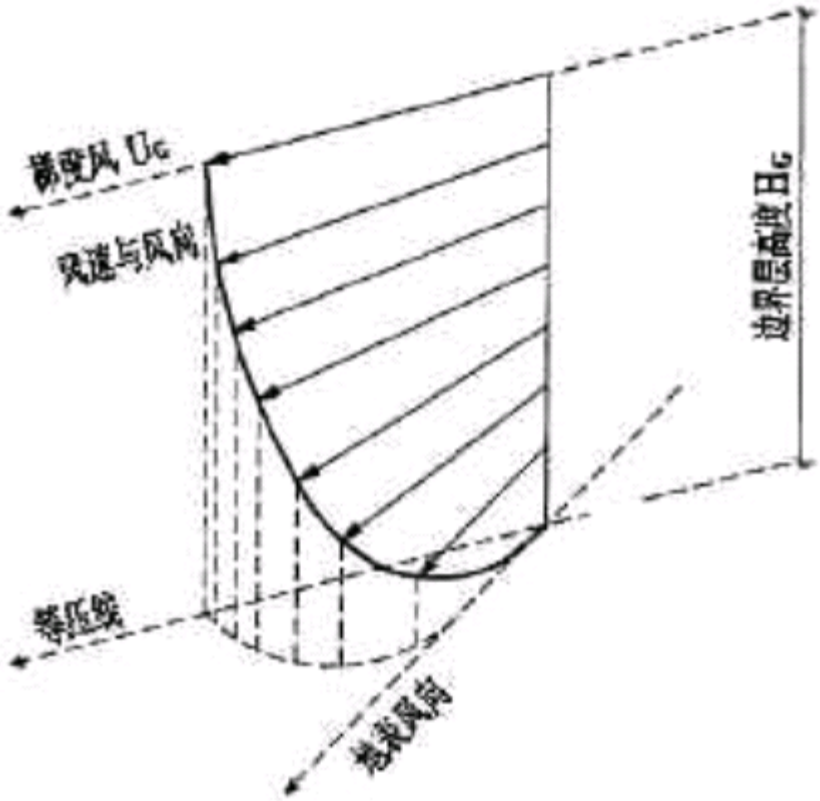
按照大气运动的动力学性质可以将对流层中的大气沿垂直向粗略分为自由大气层、大气行星边界层（简称大气边界层）



In accordance with the properties of atmospheric motion, **troposphere** along the height can be roughly divided into free atmosphere and atmospheric star boundary star (simplified as atmospheric boundary layer)

8.2 平均风特性 The characteristics of mean wind

- 大气边界层内近地层的气流是**湍流**，湍流掺混使地表阻力的影响扩展到大气边界的整个区域。The airflow near ground surface within the atmospheric boundary is turbulent flow, which is mixed to make the impact of surface resistance extends to the whole atmospheric boundary. 在自由大气中的风流动是**层流**,基本上是沿等压线以梯度风速流动。



- Laminar flow is the wind flow in the free atmosphere, which is essentially along the isobars and at the speed of the gradient wind speed.

8.2 平均风特性 The characteristics of mean wind

说明：

层流（Laminar flow）、湍流（turbulent flow）

当流速很小时, 流体分层流动，互不混合，称为层流，或称为片流；

When the flow speed is small, fluid flows stratified, and do not mix, called laminar flow, or called sheet flow;

逐渐增加流速，流体的流线开始出现波浪状的摆动，摆动的频率及振幅随流速的增加而增加，此种流况称为过渡流；

With the gradual increment of the flow speed, wavy wobbles of the fluid flow lines appear. wobble frequency and amplitude increase with the flow rate, this flow is called transient flow;

8.2 平均风特性 The characteristics of mean wind

当流速增加到很大时，流线不再清楚可辨，流场中有许多小漩涡，称为湍流，又称为乱流、扰流或紊流、流体这种变化可用雷诺数（Reynolds number）来量化。一般管道雷诺数Re <2300为层流状态，Re>4000为湍流状态，2300<Re<4000为过渡状态。

When the flow speed increases greatly, the flow lines are no longer clearly visible. And in the flow field, there are many small vortex called turbulence, such changes can be quantitized using Reynolds number.

Generally, if pipe Reynolds number Re <2300，it is laminar flow, for Re> 4000 it is turbulent flow and for 2300 <Re <4000 it is transition state.

图 5-58
烟缕向湍流突变

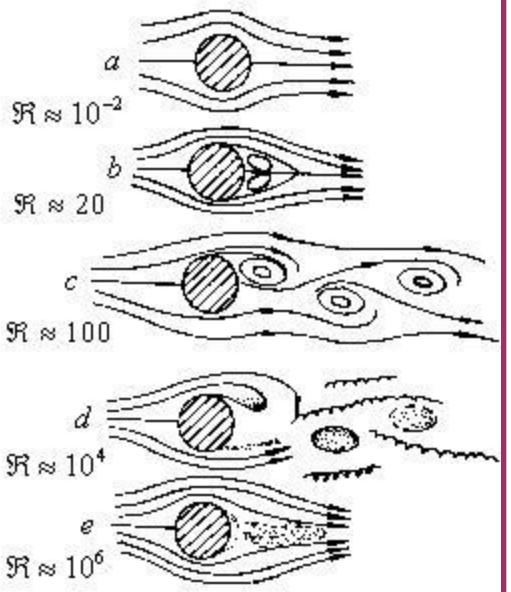
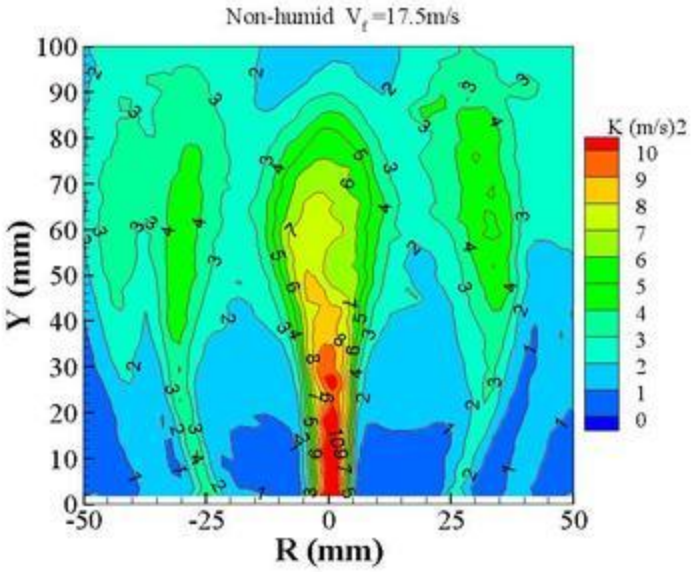
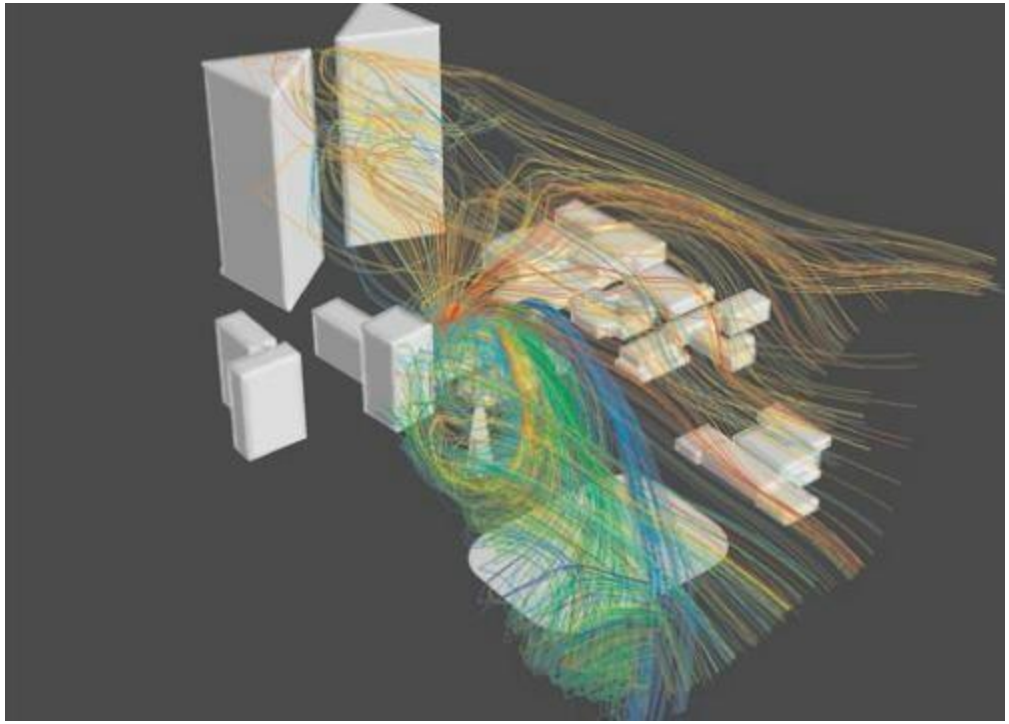


图 5-59 不同雷诺数下的圆柱绕流



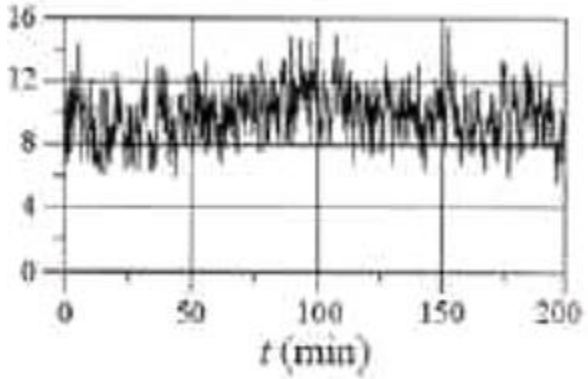


湍流模拟
Simulation of laminar flow

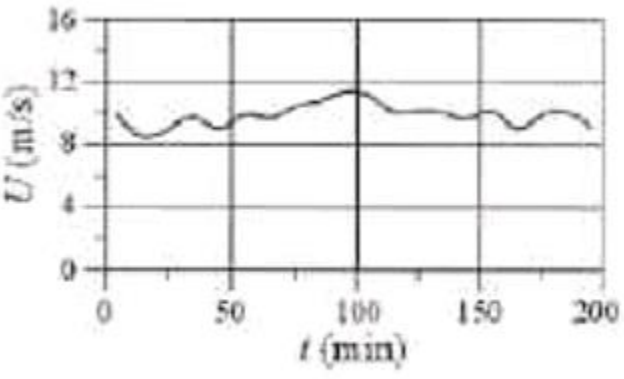
湍流自然现象

Natural phenomenon of Turbulence

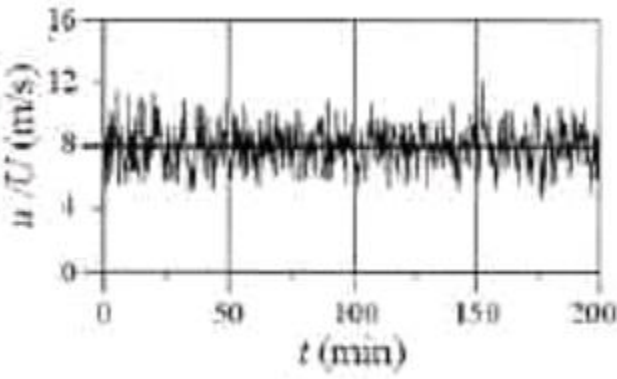
8.3 平均风剖面 Mean wind profile



（a）瞬时风速



（b）平均风速



（c）规格化脉动风速

空间特征、时间特征、统计特征

Spatial characteristics, temporal characteristics, statistical characteristics

8.3 平均风剖面 Mean wind profile

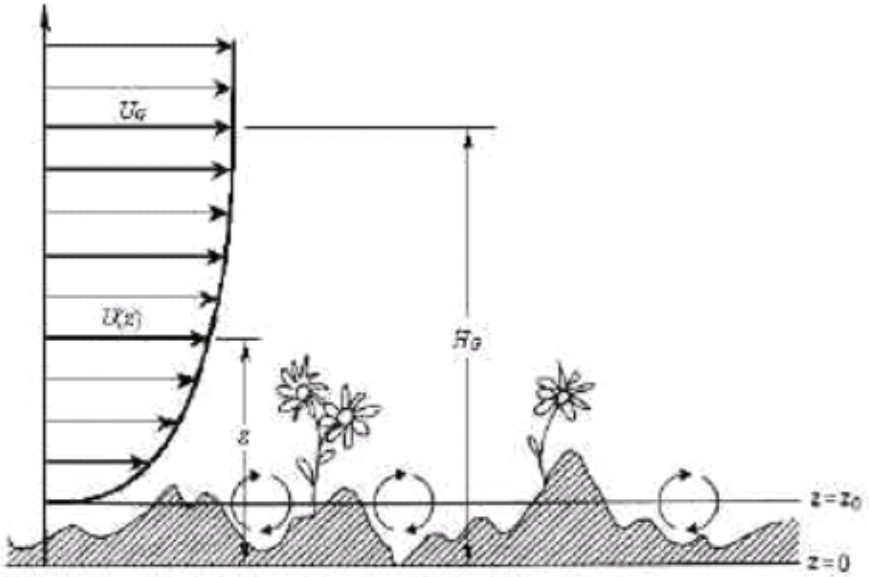
空间特征 Spatial Characteristics

风速的平均值随高度变化的规律

The variation of mean wind speed with height

描述这种变化规律的函数和图线称为风速廓线或者风剖面

The function and graph that describe this variation law are called wind profile



平均风剖面通常采用指数律或者对数律来表达

Mean wind profile are usually denoted by exponential law or logarithmic law

通常忽略风向的改变

The change of wind direction is generally neglected

8.3 平均风剖面 Mean wind profile

对数律 Logarithmic law

$$\bar{u}(z) = \frac{u^*}{k}(\ln z' - \ln z_0) = \frac{u^*}{k}\ln(\frac{z'}{z_0}) \qquad u^* = \sqrt{\frac{\tau_0}{\rho}}$$

u^*是剪切速度；τ_0是地表剪切力；$k = 0.4$；Z_0是地面粗糙度长度，反映了地表粗糙度；z'并不代表实际离地高度而是离地有效高度，是实际离地高度和零平面位移的差值

u^* is the shear velocity; τ_0 is the surface shear force; k = 0.4; Z_0 is ground roughness length which reflects the surface roughness; z'does represents the effective height above the ground, which is the difference between the actual height above the ground and the zero-plane displacement, rather than the actual height,

对数律风剖面模型是在满足基本假定的前提下经理论推导得到的平均风剖面模型，其有关参数则是通过观测统计得到

Logarithmic wind profile model is the mean wind profile which is derived theoretically under the premise of the basic assumptions, and the relevant parameters are obtained by observing the statistics

研究表明它适用于离地面较近范围内大气边界层平均风速剖面的描述

Studies show that it applicable to the description of the mean wind profile of the atmosphere boundary layer near the ground.

8.3 平均风剖面 Mean wind profile

- 对数律

$$\bar{u} = \bar{u}_{10} \frac{\lg Z - \lg Z_0}{\lg 10 - \lg Z_0}$$

$\bar{u}$：高度Z处的平均风速

Z_0：地表粗糙度长度，即零风速处的离地高度

地面类型	z_0(m)	地面类型	z_0(m)
砂　地	0.0001～0.001	矮棕榈	0.10～0.30
雪　地	0.001～0.006	松树林	0.90～1.00
割过的草地(≈0.01 m)	0.001～0.01	稀疏建成市郊	0.20～0.40
矮草地、空旷草原	0.01～0.04	密集建成市郊、市区	0.80～1.20
休耕地	0.02～0.03	大城市中心	2.00～3.00
高草地	0.04～0.10		

8.3 平均风剖面 Mean wind profile

指数律 Exponential law

$$\frac{\bar{u}(z)}{\bar{u}_G} = \left(\frac{z}{z_G}\right)^{\alpha} \qquad \alpha = \frac{1}{\ln(z_{ref} / z_0)}$$

α是又地貌粗糙度决定的幂指数，$\bar{u}_G$和Z_G分别为梯度风速和梯度风高度

α is another exponent determined by surface roughness, $\bar{u}_G$and Z_G are gradient wind speed and gradient wind height respectively.

指数律风剖面是一种纯经验模型，它的基本参数、是在风洞试验和现场观测的基础上，通过统计方法回归得到的。

Exponential wind profile is a purely empirical model, the basic parameters of which are obtained through statistical regression on the basis of tunnel tests and field observations。.

大量的研究表明，指数律风剖面模型比较适合于风梯度高度范围内离地面较高的大气边界层内平均风速的描述

Numerous studies show that the exponential wind profile model is more suitable for descripting the mean wind speed in the atmosphere boundary layer which is far from the surface and in the range of wind gradient height

8.3 平均风剖面 Mean wind profile

我国规范采用指数律的平均风剖面，并采用高度系数来反映平均风的空间特性

Chinese code adopts exponential wind profile and reflects the spatial characteristic using height coefficient

规定10米为标准高度，并将地貌分成四类，B类为标准地貌

10m is specified as standard height, and topography is divided into 4 categories, with category B being the standard topography

$$\bar{u}(z) = \bar{u}_{10}(\frac{z}{10})^{\alpha}$$

地表粗糙度 Surface roughness	地表状况 Surface conditions	a	边界层高度 Boundary layer thickness
A	近海面和海岛、海岸、湖岸、湖岸及沙漠地区 offshore islands, coast, lakeshore, lakeshore and desert areas near sea	0.12	300
B	田野、乡村、丛林、丘陵以及比较稀疏的乡镇和城市郊区 Field, rural, jungle, hills and sparse outskirts of towns and cities	0.16	350
C	有密集建筑群的城市市区 Urban areas with dense buildings	0.22	400
D	有密集建筑群且房屋较高的城市市区 Urban areas with dense and high-rise buildings	0.30	450

8.3 平均风剖面 Mean wind profile

基本规律 Basic Laws

平均风速随地高度的增大而增大

The mean wind speed increases with height

平均风速随高度的变化规律同地表粗糙程度有密切的关系，地面越粗糙，则平均风速趋于梯度风速就越慢，相应的梯度风高度就越高

The variation of wind speed with height is closely related with the surface roughness. The rougher the surface, the more slowly the mean wind speed approaches wind gradient speed, and the larger the corresponding gradient wind height is.

地形条件的修正 modification for terrain conditions

The mean wind profile in the following terrain need to modified:

山峰和山坡 Peaks and slopes

山间谷地、谷地等闭塞地区 Isolated areas such as mountain valleys and valleys, etc.

与风向一致的谷口、山口 Valley entry and mountain entry Consistent with the wind direction

8.3 平均风剖面 Mean wind profile

指数律和对数律都不能用来描述台风以及雷暴等极端天气现象的风剖面.

Exponential and logarithmic law can not be used to describe wind profiles of typhoons, thunderstorms and other extreme weather phenomena.

然而规范中所采用的基本风速是年最大风速，对于沿海地区显然对应的是台风风速.

However, the basic wind speed adopted in the code annual maximum wind speed, which is apparently the typhoon wind speed in coastal areas.

因此，规范所采用的基本风速平均风剖面不匹配，可能会过大估计风荷载.

Thus, the basic mean wind profile adopted in the code is inconsistent with the actual situation and may be overestimated.

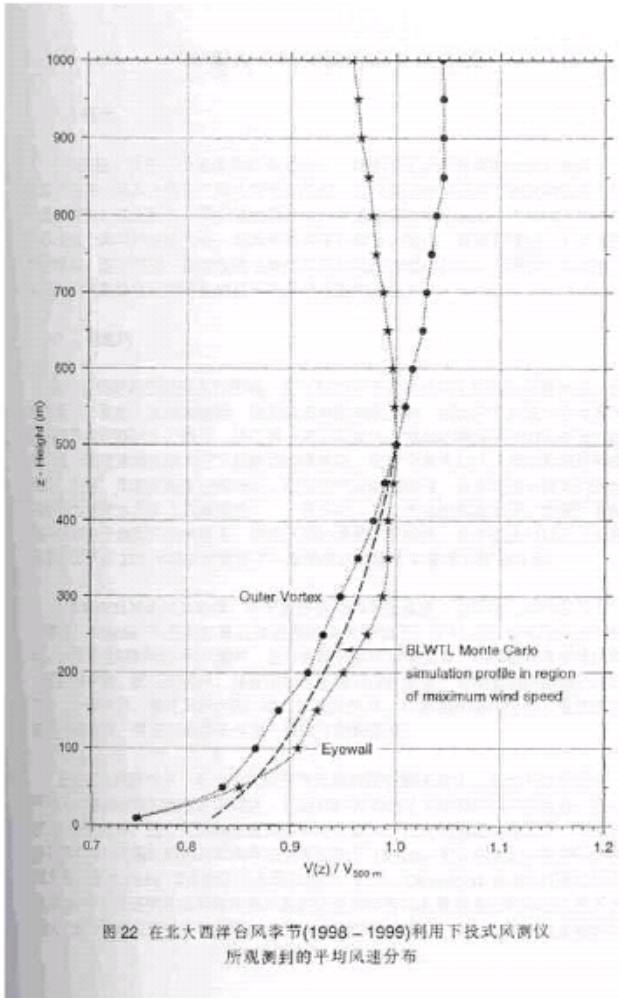


图 22 在北大西洋台风季节(1998 – 1999)利用下投式风测仪所观测到的平均风速分布

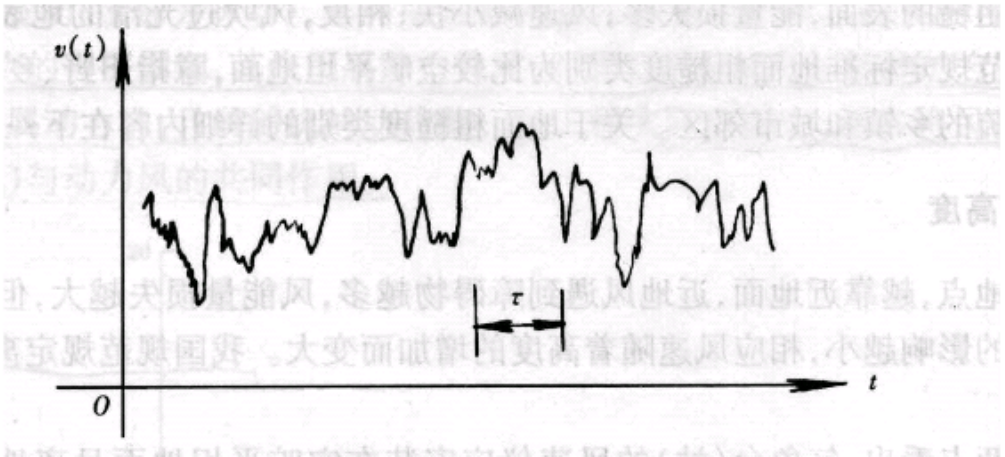
8.3 平均风剖面 Mean wind profile

时间特征 temporal characteristics

平均风速是大气边界层中自然按一定时距进行平均所得到的值，故其值大小取决于所取的平均时距。随着平均时距的缩短对应于该时距的平均风速将越大，反之平均风速将减小

The mean wind speed is an average of the instantaneous wind speed over a certain averaging period in the atmospheric boundary layer. So the value is determined by the averaging period. the shorter the averaging period, the larger the corresponding mean wind speed is. Conversely, the longer the averaging period, the smaller the corresponding mean wind speed is.

$$\overline{u} = \frac{1}{\tau}\int_{t_0-\tau/2}^{t_0+\tau/2} u(t)dt$$



8.3 平均风剖面 Mean wind profile

风速记录表明，阵风的卓越周期为1分钟，若取若干个周期作为平均时距，一般取10-60个周期时（对应于10分钟-1小时），平均风速基本上是一个稳定值。包括我国在内的多数国家采用10分钟平均时距的平均。

Records of wind speed demonstrate that the predominant period is 1 minute. If we take a certain number of periods as the averaging period, generally 10 to 60 periods (which corresponds to 10 minutes to an hour) , the mean wind speed is, by and large, a constant value. Many countries including China adopts 10 minutes as averaging period.

时距	1h	10min	5min	2min	1min	30s	20s	10s	5s
统计比值	0.94	1.00	1.07	1.16	1.20	1.26	1.28	1.35	1.39