GEOG 321 - Reading Package Lectures 1 & 2

ATMOSPHERIC SCALES

The Atmosphere is characterized by phenomena whose space and time scales cover a very wide range. The space scales of these features are determined by their typical size or wavelength, and the time scales by their typical lifetime or period. Figure 1 is an attempt to place various atmospheric phenomena (mainly associated with motion) within a grid of their probable space and time limits. The features range from small-scale turbulence (tiny swirling eddies with very short life spans) in the lower left-hand corner, all the way up to jet streams (giant waves of wind encircling the whole Earth) in the upper right-hand corner.

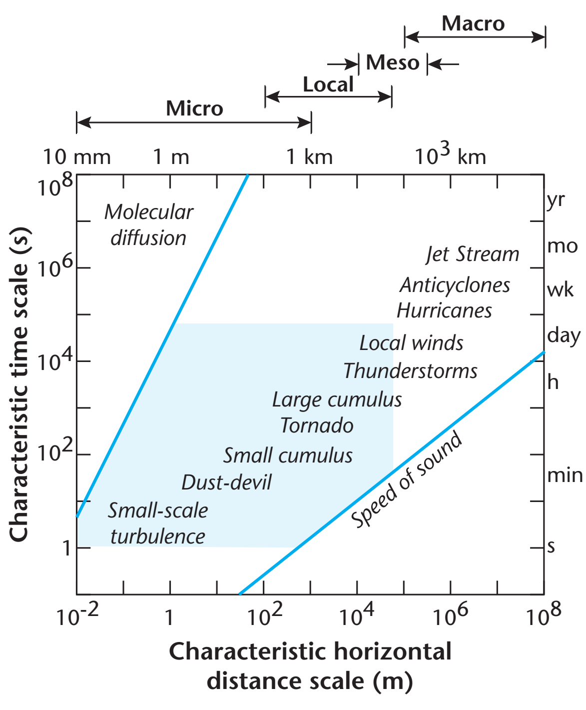

Figure 1: Time and space scales of various atmospheric phenomena. The shaded area represents the characteristic domain of features discussed in this course (modified after Smagorinsky, 1974).

In reality none of these phenomena is discrete but part of a continuum, therefore it is not surprising that attempts to divide atmospheric phenomena into distinct classes have resulted in disagreement with regard to the scale limits. Most classification schemes use the characteristic horizontal distance scale as the sole criterion. A reasonable consensus of these schemes gives the following scales and their limits (see the top of Figure 1):

Micro-scale 10^{-2} to 10^{3} m
Local scale 10^{2} to 5×10^{4} m
Meso-scale 10^{4} to 2×10^{5} m
Macro-scale 10^{5} to 10^{8} m

In these terms GEOB 300 is mainly restricted to atmospheric features whose horizontal extent falls within the micro- and local scale categories. A fuller description of its scope is given by also including characteristic vertical distance, and time scales.

This course is concerned with the interaction between the Atmosphere and the Earths surface. The influence of the surface is effectively limited to the lowest 10 km of the Atmosphere in a layer called the troposphere. Over time periods of about one day this influence is restricted to a very much shallower zone known as the planetary boundary layer, often referred to simply as the 'boundary layer'. This layer is particularly characterized by well developed mixing (turbulence) generated by frictional drag as the Atmosphere moves across the rough and rigid surface of the Earth, and by the 'bubbling-up' of air parcels from the heated surface. The boundary layer receives much of its heat and all of its water through this process of turbulence.

The height of the boundary layer (i.e. the depth of surface-related influence) is not constant with time, it depends upon the strength of the surface-generated mixing. By day, when the Earths surface is heated by the Sun, there is an upward transfer of heat into the cooler Atmosphere. This vigorous thermal mixing (convection) enables the boundary layer depth to extend to about 1 to 2 km. Conversely by night, when the Earths surface cools more rapidly than the Atmosphere, there is a downward transfer of heat. This tends to suppress mixing and the boundary layer depth may shrink to less than 100 m. Thus in the simple case we envisage a layer of influence which waxes and wanes in a rhythmic fashion in response to the daily solar cycle. Naturally this ideal picture can be considerably disrupted by large-scale weather systems whose wind and cloud patterns are not tied to surface features, or to the daily heating cycle. For our purposes the characteristic horizontal distance scale for the boundary layer can be related to the distance air can travel during a heating or cooling portion of the daily cycle. Since significant thermal differences only develop if the wind speed is light (say less than $5\,\mathrm{m\,s^{-1}}$) this places an upper horizontal scale limit of about 50 to 100 km. With strong winds mixing is so effective that small-scale surface differences are obliterated. Then, except for the dynamic interaction between airflow and the terrain, the boundary layer characteristics are dominated by tropospheric controls. In summary the upper scale limits of boundary layer phenomena (and the subject matter of this book) are vertical and horizontal distances of ~ 1 km and ~ 50 km respectively, and a time period of ~ 1 day.

The lower horizontal scale limit is dictated by the dimensions of relevant surface units and since the smallest climates covered are those of insects and leaves, this limit is of the order of 10^{-2} to 10^{-3} m. It is difficult to set an objective lower cut-off for the time scale. An arbitrary period of approximately $\sim \frac{1}{10}$ s is suggested. The shaded area in Figure 1 gives some notion of the space and time bounds to boundary layer climates as discussed in this course (except that it requires a third co-ordinate to show the vertical space scale). Two aberrations from this format should be noted. First, it should be pointed out that precipitation and violent weather events (such as tornadoes), which might be classed as boundary layer phenomena, are not discussed in this course. The former, although deriving their initial impetus near the surface, owe their internal dynamics to condensation which often occurs at the top or above the boundary layer. The latter are dominated by weather dynamics occurring at much larger scales than outlined above. Second, the boundary layer treated herein includes the uppermost layer of the underlying material (soil, water, snow, etc.) extending to a depth where diurnal exchanges of water and heat become negligible.

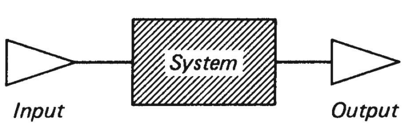

Figure 2: Energy flow through a system.

ENERGY AND MASS BALANCES

The classical climatology practised in the first half of the twentieth century was almost entirely concerned with the distribution of the principal climatological parameters (e.g. air temperature and humidity) in time and space. While this information conveys a useful impression of the state of the atmosphere at a location it does little to explain how this came about. Such parameters are really only indirect measures of more fundamental quantities. Air temperature and humidity are really a gauge of the thermal energy and water status of the atmosphere respectively, and these are tied to the fundamental energy and water cycles of the Earth-Atmosphere system. Study of these cycles, involving the processes by which energy and mass are transferred, converted and stored, forms the basis of modern physical climatology.

The relationship between energy flow and the climate can be illustrated in the following simple manner. The First Law of Thermodynamics (conservation of energy) states that energy can be neither created nor destroyed, only converted from one form to another. This means that for a simple system such as that in Figure 2, two possibilities exist. Firstly:

$$\text{Energy Input} = \text{Energy Ouptut} \tag{1.1}$$

in this case there is no change in the net energy status of the system through which the energy has passed. It should however be realized that this does not mean that the system has no energy, merely that no change has taken place. Neither does it mean that the Output energy is necessarily in the same form as it was when it entered. Energy of importance to climatology exists in the Earth-Atmosphere system in four different forms (radiant, thermal, kinetic and potential) and is continually being transformed from one to another. Hence, for example, the Input energy might be entirely radiant but the Output might be a mixture of all four forms. Equally the Input and Output modes of energy transport may be very different. The exchange of energy within the Earth-Atmosphere system is possible in three modes (conduction, convection and radiation (see Section 3 for explanation)).

The second possibility in Figure 2 is:

$$\text{Energy Input} = \text{Energy Ouptut} + \text{Storage Change} \tag{1.2}$$

For most natural systems the equality, Input = Output, is only valid if values are integrated over a long period of time (e.g. a year). Over shorter periods the energy balance of the system differs significantly from equality. The difference is accounted for by energy accumulation or depletion in the systems energy store. (The energy storage term may have a positive or negative sign. By convention a positive storage indicates the addition of energy.) In climatic terms, for example, if energy is being accumulated in a soil-atmosphere system it probably means an increase in soil and/or air temperature. Hence we see the link between process (energy flow) and response (temperature change). The whole relationship is referred to as a process- response system, which in essence describes the connection between cause and effect. The degree of detailed understanding of the system depends on how well the internal workings of the box in Figure 2 are known. Inside the box the energy is likely to be channelled into different subsystems, and converted into different combinations of energy forms and modes of transport. Some will lead to energy storage change and others to energy output from the system. This partitioning is not haphazard, it is a function of the systems physical properties. In the case of energy these properties include its ability to absorb, transmit, reflect and emit radiation, its ability to conduct and convect heat, and its capacity to store energy. In the analogous case of water flow in a soil-atmosphere system the mass of water is conserved at all times but it may be found in three different states (vapour, liquid and solid); be transported in a number of modes (including convection, precipitation, percolation, and runoff); and its accumulation or depletion in stores is measured as changes of water content (atmospheric humidity, soil moisture or the water equivalent of a snow or ice mass). Similar analogues can be extended to the mass balances of other substances cycled through systems as a result of natural or human (anthropogenic) activities including sulphur, carbon, nitrogen, and particulates. In the case of atmospheric systems the accumulation of these substances beyond certain levels constitutes atmospheric pollution. This occurs when the natural cycling of substances is upset by human activities. For example, in urban areas, if the emission (input) of these materials exceeds the physical capability of the local atmospheric system to flush itself (output) in a short period of time, the result is an increase in the local concentration of that substance (i.e. increased storage). Therefore in the most general form we may write the following energy or mass balance equation for a system:

$$\text{Input} - \text{Output} - \text{Storage Change} = 0 \qquad (1.3)$$

There are two fundamental cycles of importance in understanding atmospheric systems. These are the cycles of solar energy (heat), and water (mass). The remainder of this chapter is concerned with a description of the workings of these two cycles. This is followed in Chapter 2 by an explanation of the way these exchange processes and balances are linked to the vertical distributions of such climatological elements as temperature, humidity and wind speed in the boundary layer.

Appendix - Conventions used in GEOB 300

Typographic conventions. The reading package and lecture slides use the following typographic conventions:

Variables are typed in *italic*.

Units are in Roman letters.

$\mathbf{Bold}$ is reserved for vectors.

An $\overline{\text{overbar}}$ refers to a temporal average.

Starred equations ($\star$) are considered essential.

The SI System. The SI (Système International d'Unités) is the official unit system in science and therefore mandatory in climatology. This system utilises a small number of base units from which other derived units can be obtained.

Table 1: The seven base units in the SI-System. The two units in brackets are not used in GEOB 300.

Base unit	Definition	SI unit
Metre	Length	m
Kilogram	Mass	kg
Second	Time	s
(Ampere	Electrical current	A)
Kelvin	Thermodynamic temperature	K
Mole	Amount of a substance	mol
(Candela	Luminous intensity	cd)

Note that the unit for thermodynamic temperature is Kelvin ('K', but not '°K'). Temperatures may be also indicated in degree Celsius (°C). However, temperature-differences must be referred to as Kelvin (K).The Kelvin scale has 0 K at absolute zero (theoretically where molecular motion ceases and a body contains no heat energy), whereas the Celsius scale has 0°C at the freezing point of water. The two are therefore linked by: $^\circ\mathrm{C} = \mathrm{K} - 273.15$.

Note that you insert a blank space between the numerical value and the symbol, as well as between symbols, i.e. '5 $\mathrm{kg\,m^{-3}}$' and not '5$\mathrm{kgm^{-3}}$'.

Derived units can then be formed and related to base units by the process of multiplication or division using unity as the only multiplying factor.

Table 2: Important derived SI-units used in GEOB 300

Derived SI unit	Definition	Symbol	Relation to base units
Newton	Force	N	$\mathrm{kg\,m\,s^{-2}}$
Pascal	Pressure	Pa	$\mathrm{N\,m^{-2}}$
Joule	Energy	J	$\mathrm{N\,m}$
Watt	Power	W	$\mathrm{J\,s^{-1}}$

Important derived units used in this course are:

Force - the SI derived unit is the Newton (N) defined as the force required to accelerate a body having a mass of 1 kg at 1 metre per second per second.

Pressure - the SI derived unit is the Pascal (Pa), defined as the pressure exerted by a force of 1 N evenly distributed over an area of one square metre.

Work, energy - the SI derived unit is the Joule (J), defined as the energy required to displace a force of 1 N through a distance of 1 metre.

Power - the SI derived unit is the Watt (W) defined as the power required to equal the rate of working of 1 Joule per second.

Scientific notation. The scientific or exponential notation is a convenient 'shorthand' way of depicting very large or very small numbers without the use of many zeros. The notation x^n means that the number x is multiplied by itself n times (e.g. $2^3 = 2 \times 2 \times 2 = 8$) where n is called the exponent. Similarly x^{-n} involves a negative exponent, and is the reciprocal of x^n, that is $x^{-n} = \frac{1}{x^n}$. It is often especially convenient to express large or small numbers as powers of 10 (i.e. 10^n or 10^{-n}) and certain of these are given prefixes as listed in the table.

Examples used in this course include the micrometre (μm) for radiation wavelength; the kilowatt (kW) for power; and the megajoule (MJ) for heat energy. Note that you cannot use multiple prefixes at the same time. Any prefix is added without a space, i.e. '$\mu\mathrm{m}$' and not 'μ m'. Prefix and symbol are considered one without the need of a bracket, so they can be raised to the power, i.e. 'km^2' and not '$(\mathrm{km})^2$'

Scientific notation is also very useful in multiplying or dividing large or small numbers. If the numbers have the same base of 10 then multiplication is achieved by adding the exponents so that $10^n \times 10^m = 10^{n+m}$ (e.g. $10^2 \times 10^4 = 10^6$). Similarly for division the exponents are subtracted so that $10^n/10^m = 10^{n-m}$ (e.g. $10^6/10^4 = 10^2$). Finally, to multiply or divide complete numbers in scientific notation it is necessary to operate on both parts of the number separately. For example to multiply 1.4×10^3 by 2.7×10^{-4}, first multiply $1.4 \times 2.7 = 3.78$, then add the exponents $10^{3+(-4)} = 10^{-1}$, giving the final answer that the product of the two numbers is 3.78×10^{-1}, or 0.378.

Table 3: Prefixes used to describe multiples or fractions of ten.

Scientific notation	Prefix	Symbol	Example
10^{12}	tera-	T	Tg
10^{9}	giga-	G	Gm
10^{6}	mega-	M	Mm
10^{3}	kilo-	k	kg, kV
10^{2}	hecto-	h	hPa
10^{0}	—		K
10^{-1}	deci-	d	dl
10^{-2}	centi-	c	cm
10^{-3}	milli-	m	ml, mm
10^{-6}	micro-	μ	μmol
10^{-9}	nano-	n	nm
10^{-12}	pico-	p	ps

Table 4: The Greek alphabet is widely used in symbols in GEOB 300.

Lower case	Capital	Name	Lower case	Capital	Name
α	A	alpha	ν	N	nu
β	B	beta	ξ	Ξ	xi
γ	Γ	gamma	o	O	omicron
δ	Δ	delta	π	Π	pi
ε	E	epsilon	ρ	P	rho
ζ	Z	zeta	σ	Σ	sigma
η	H	eta	τ	T	tau
θ	Θ	theta	υ	Υ	upsilon
ι	I	iota	ϕ	Φ	phi
κ	K	kappa	χ	X	chi
λ	Λ	lambda	ψ	Ψ	psi
μ	M	mu	ω	Ω	omega