

# Notas de micrometeorologia

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# Preface

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Este texto começa com a introdução do conceito de *escala*, que é fundamental em tudo o que se segue. Vamos procurar entender a globalidade do problema descrevendo as várias camadas da atmosfera (troposfera, estratosfera, ...) e fazendo depois um “zoom” na Camada-Limite Atmosférica (CLA), que é a parte mais baixa da troposfera. Em seguida, reveremos as equações de Mecânica dos Fluidos aplicáveis à CLA, falaremos de turbulência e da sua abordagem clássica (decomposição de Reynolds e equações de transporte de covariâncias). Algumas soluções particulares simples destas equações proporcionam uma boa idéia da interação das camadas mais altas da atmosfera com a CLA. Estudaremos mais intensamente a parte mais baixa da CLA, chamada Camada Superficial (CS). Na CS, debaixo de algumas hipóteses simplificadoras, podemos utilizar a Teoria de Similaridade de Monin-Obukhov (SMO), que nos permite descrever uma série de grandezas relacionadas com a turbulência de forma extremamente simples. As equações básicas que descrevem a física da turbulência e as previsões da Teoria de Similaridade de Monin-Obukhov são utilizadas para prever o comportamento das grandezas médias  $\bar{u}$ ,  $\bar{\theta}$  e  $\bar{q}$  na CS. Além do comportamento genérico previsto pela teoria SMO, dois casos-limite cujo significado físico é importante são abordados: a estratificação independente de  $z$  numa atmosfera muito *estável*, e a convecção livre local em uma atmosfera muito *instável*. Com as previsões da teoria sobre o comportamento das grandezas médias, é possível então utilizar medições delas para calcular os fluxos  $\tau$ ,  $H$  e  $E$ . Além de alguns métodos que utilizam exclusivamente a medição de grandezas médias, apresenta-se ao fim do relatório o método da variância, que é um híbrido que utiliza tanto grandezas médias como medições de turbulência.



# 1

## Introduction

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### 1.1 – The regions of the atmosphere

The atmosphere is a relatively thin layer of gas above the Earth's surface. Upwards of 100 km above the surface, the density of the atmosphere is very low. Meanwhile, since the Earth's great circle  $C$  is approximately 40 000 km, if we set the thickness of the atmosphere to  $\mathcal{L} = 100$  km, the ratio  $\mathcal{L}/C = 0,0025$  shows how thin the atmosphere really is.

Figure 1.1 shows the main regions of the atmosphere in the first 100 km, for a standard atmosphere at 10° N in June (Houghton, 1986): in this case, the troposphere extends to 17 km; the stratosphere is a strongly stratified region ( $\frac{dT}{dz} > 0$ ) between 17 km and 50 km; the mesosphere displays a marked temperature fall between 50 km and 95 km; finally, from that point upwards the temperature rises again in the thermosphere.

Existe uma enorme riqueza de fenômenos físicos, que ainda hoje estão sendo estudados, em toda a atmosfera terrestre. No entanto, a região mais importante para a vida na Terra, e a única que os seres vivos podem “experimentar” diretamente, é a troposfera: a montanha mais alta do mundo não chega a 9 km de altitude. A faixa mais diretamente relevante é a Camada-Limite Atmosférica (CLA), que se estende no máximo até cerca de 2 km de altura (e não altitude) sobre a superfície. Isto representa no máximo 2% da figura 1.1.

Da mesma maneira que utilizamos o perfil de temperatura termodinâmica para caracterizar praticamente toda a atmosfera, a CLA é caracterizada pelo perfil de temperatura potencial. Esta será definida na próxima seção; por enquanto, basta pensarmos na temperatura potencial como um indicador da densidade do ar: quanto maior a temperatura potencial, menor a densidade. A figura 1.2 mostra um perfil típico de temperatura potencial durante o dia. Os gradientes de temperatura são grandes até cerca de 100 m de altura, que configuram aproximadamente a camada superficial CS; a partir daí, o perfil é praticamente constante até cerca de 1 100 m (esta é a camada convectiva CC); daí até 1 300 m a temperatura eleva-se gentilmente: esta é a zona de arrasto ZA, onde a CLA interage com a “atmosfera livre” AL sobre ela, na qual a densidade do ar é fortemente estratificada, a intensidade da turbulência muito baixa e valem as aproximações invíscidas das equações de Navier-Stokes, que veremos na próxima seção sob o nome de “vento geostrófico”.

Esta breve descrição da atmosfera mostra a grande riqueza de escalas ver-

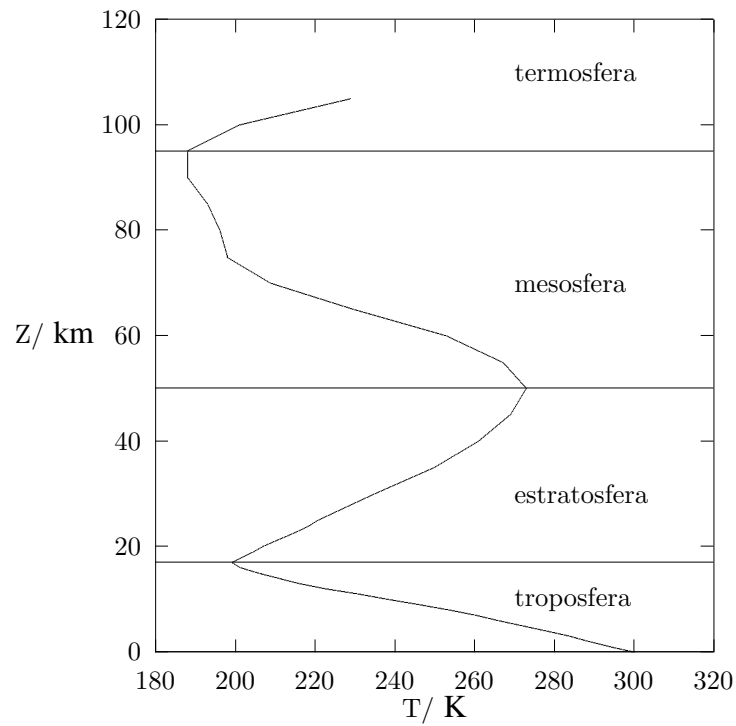


Figure 1.1: Perfil de temperatura numa atmosfera modelo, a 10°N, em junho (Houghton, 1986)

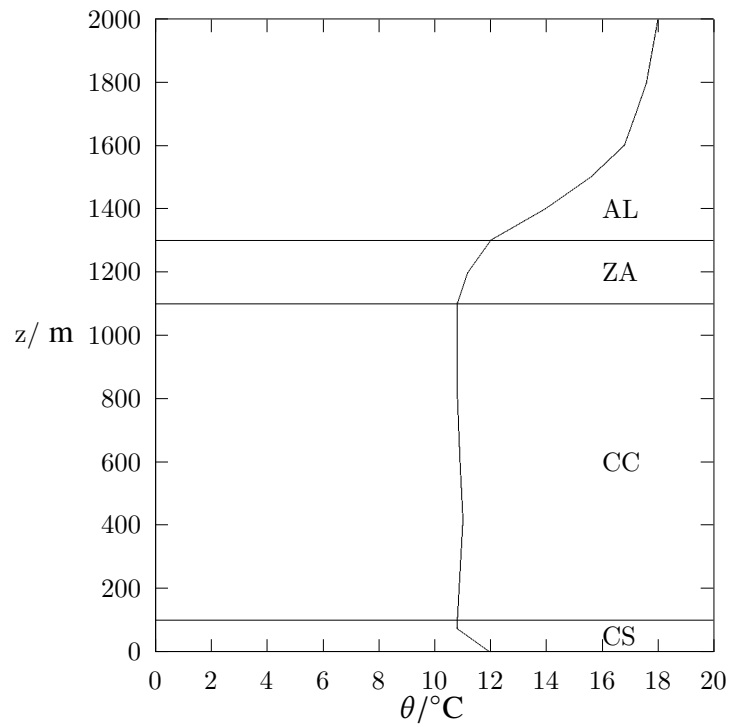


Figure 1.2: perfil de típico de temperatura potencial durante o dia na CLA (adaptado de Stull, 1988)

Table 1.1: Classificação de escalas horizontais em meteorologia

Nome	Dimensão
macro $\beta$	10.000 km
meso $\alpha$	2.000 km
meso $\beta$	200 km
meso $\gamma$	20 km
micro $\alpha$	2 km
micro $\beta$	200 m
micro $\gamma$	20 m

ticais envolvidas. Neste texto, nós estaremos preocupados essencialmente com os primeiros 100 m da atmosfera, na camada superficial.

Como é de se esperar da discussão sobre a razão  $\mathcal{L}/C$ , as escalas *horizontais* sobre as quais se observam fenômenos físicos em meteorologia são consideravelmente maiores. A Tabela 1.1 dá uma descrição das escalas horizontais em meteorologia. Para tornar mais claro o significado da classificação da tabela 1.1, observe a seguinte lista de fenômenos e suas escalas horizontais correspondentes, dada por Holton 1992:

Table 1.2: Escalas de movimentos atmosféricos (Holton, 1992)

Tipo de movimento	Escala horizontal (m)
Caminho livre médio molecular	$10^{-7}$
Menores turbilhões turbulentos	$10^{-2} - 10^{-1}$
Pequenos turbilhões turbulentos	$10^{-1} - 10^0$
Vórtices não-turbulentos	$10^0 - 10^1$
Rajadas de vento	$10^1 - 10^2$
Tornados	$10^2$
Nuvens Cumulus Nimbus	$10^3$
Frentes	$10^4$
Furacões	$10^5$
Ciclones sinóticos	$10^6$
Ondas planetárias	$10^7$

No nosso caso, estaremos trabalhando dentro das fronteiras da micrometeorologia: nossas escalas horizontais são da ordem de 2 km ou menores (micro- $\alpha$ ), e nossas escalas verticais da ordem da espessura da camada superficial, cerca de 100 m, ou menores. Este é o domínio por excelência da turbulência: movimentos turbulentos na atmosfera possuem escalas desde algumas centenas de metros (na horizontal) até poucos milímetros, que é a escala onde a turbulência é dissipada por efeitos viscosos. A modelação matemática da CLA é o assunto da próxima seção.

## 1.2 – The importance of the surface fluxes

A great deal of the physical evolution of the atmosphere is influenced by the exchange of mass, momentum and energy with the surface of the Earth. The surface of these quantities are the *surface fluxes*, and their knowledge is essential for applications in meteorology, hydrology and environmental sciences in general. In particular, the values of the *greenhouse gas* surface fluxes are needed to predict their impact on global warming and climate change.

A emissão de gases de efeito estufa (GEE) da superfície da Terra para a atmosfera é hoje, reconhecidamente, um dos grandes problemas ambientais que enfrentamos. O problema é global, tornando necessária a negociação internacional de limites para as emissões, bem como o desenvolvimento internacional de metodologias que sejam consensualmente aceitas para estimar estas emissões.

Uma das abordagens para a estimativa dos fluxos destes gases é a realização de medições micrometeorológicas. Ao evitar a complexidade dos processos que ocorrem na superfície ou abaixo dela (seja da água ou do solo/vegetação), e ao integrar as emissões e capturas de GEE tanto na vertical quanto sobre o comprimento de pista do vento, medições micrometeorológicas de GEE podem dar respostas importantes sobre o valor dos fluxos superficiais, seu padrão horário e sazonal, e sua relação com outras grandezas importantes tais como temperaturas do ar, água e solo, a qualidade da água, o tipo de vegetação, etc...

Medições micrometeorológicas de gases de efeito estufa em geral consistem em medições de grandezas atmosféricas relativamente próximo da superfície. Convencionalmente, as medições são divididas em “blocos”, que podem ser tão curtos quanto 10 minutos, ou tão longos quanto 1 hora. Dentro de cada bloco, é usual supor a estacionariedade das séries temporais medidas. As medições podem ser realizadas por sensores relativamente lentos, quando então “médias” são obtidas, ou com sensores suficientemente rápidos para capturar uma parte significativa das frequências associadas à turbulência atmosférica. Neste último caso, estatísticas da turbulência dentro do bloco, tais como desvios-padrão, covariâncias, funções de correlação cruzada e espectros podem ser medidos.

Medições de grandezas médias estão associadas ao método fluxo-gradiente (MFG) para a estimativa de fluxos. Medições de turbulência estão associadas ao método de medição de covariâncias turbulentas (MCT).

O MFG é mais antigo, e envolve mais hipóteses, do que as “medições diretas” realizadas pelo MCT. Na verdade, como veremos, estas medições não são tão diretas assim, e o MCT também envolve um grande número de hipóteses, embora talvez não tão restritivas quanto as do MFG. Devido a dificuldades tecnológicas e custo, o MFG ainda é amplamente utilizado para a estimativa de fluxos de gases tais como o CH<sub>4</sub> e o N<sub>2</sub>O, para os quais medições (principalmente de longo prazo) de flutuações turbulentas ainda são problemáticas.

O método de medição de covariâncias turbulentas (MCT), originalmente desenvolvido para a medição dos fluxos de quantidade de movimento, calor sensível e massa de vapor d’água, possui uma série de características que o tornam uma opção interessante para a medição de fluxos de GEE: medições contínuas de fluxos horários ou de 30 minutos são possíveis; as medições possuem uma representatividade espacial da ordem de centenas de metros corrente acima da

torre de medição; e as tecnologias de medição envolvidas estão hoje (2011) razoavelmente bem desenvolvidas e possuem custos acessíveis.

# 2

## The measurement of surface fluxes

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### 2.1 – Introduction

The emission of greenhouse gases from the surface of the Earth to its atmosphere is nowadays one of the largest environmental problems faced by humanity. It is a global problem, requiring the international negotiation of limits for the GEE emissions, as well as the development of internationally-accepted methodologies for their estimation.

One of the approaches to estimate these gases' fluxes is to perform micrometeorological measurements. Avoiding the complexity of the processes that occur at the surface or below it (be it water or soil/vegetation) and integrating greenhouse gas emissions vertically and over the wind fetch, micrometeorological measurements of greenhouse gases can give important answers about the value of surface fluxes, their seasonal and hourly pattern, and their relation with other important variables such as air, water, and soil temperatures, water quality, vegetation type, etc..

Micrometeorological measurements of greenhouse gases usually consist in measuring atmospheric variables close to the surface of the Earth. Conventionally, the measurements are split into “runs” that can be as short as 10 minutes, or as long as 1 hour. Within each run, it is common to assume stationarity of the measured time series. Measurements can be done by relatively slow sensors, when “averages” are obtained, or with sufficiently fast sensors to capture a significant part of the frequencies associated with atmospheric turbulence. In the latter case, turbulence statistics such as standard deviations, covariances, cross-correlation functions and spectra can be measured.

Measurements of average quantities are associated with the gradient flux method (GFM) for flux estimation. Measurements of turbulence quantities are associated with the eddy covariance method (ECM).

The GFM is older and involves more assumptions than the “direct measurements” performed by the ECM. In fact, as we will see, ECM measurements are not as direct as sometimes assumed. Due to the technological difficulties and cost, the GFM is still widely used to estimate gas fluxes such as  $\text{CH}_4$  and  $\text{N}_2\text{O}$ , for which the measurement of turbulent fluctuations (especially in long-term studies) is still problematic.

The eddy covariance method (ECM), originally developed with momentum, sensible heat and water vapor mass fluxes in mind, has several desirable characteristics that make it appealing for GHG flux measurements: continuous mea-

surements at the 30-minute or the hourly time scales can be made; spatial coverage is good, being of the order of hundreds of meters upwind of the measuring tower; and sensor technology is currently well developed and has a reasonable cost.

## 2.2 – Theoretical foundation

This section has the objective of showing the bases of the GFM and especially of the ECM. In it, we review basic concepts about atmospheric gases and their concentrations; the *Reynolds decomposition* of a turbulent flow in average and fluctuation; and different kinds of averages – and consequently turbulent fluctuations – which are found in practice.

### 2.2.1 – Atmospheric gases

Using the model of partial pressures, the model of partial volumes, and the equation of state of an ideal gas for atmospheric gases, one has

$$pV = nR^\#T, \quad (2.1)$$

$$p_\chi V = n_\chi R^\#T, \quad (2.2)$$

$$pV_\chi = n_\chi R^\#T, \quad (2.3)$$

where  $p$  is the total pressure and  $p_\chi$  is the partial pressure of the gas  $\chi$ ;  $V$  is the total volume and  $V_\chi$  is the partial volume of the gas  $\chi$ ;  $n$  is the total number of moles and  $n_\chi$  is the number of moles of the gas  $\chi$ ;  $R^\# = 8,314772 \text{ J mol}^{-1} \text{ K}^{-1}$  (in the SI) is the universal gas constant, and  $T$  is the thermodynamic temperature. In this text, the index  $\chi$  indicates the gas:  $\chi = s, v, c, m, n$  for dry air ( $\text{N}_2$  and  $\text{O}_2$ ), water vapor ( $\text{H}_2\text{O}$ ), carbon dioxide ( $\text{CO}_2$ ), methane ( $\text{CH}_4$ ) and nitrous oxide ( $\text{N}_2\text{O}$ ). In some parts of the text, to avoid repetitions,  $c$  indicates one of the greenhouse gases, especially the 3 cited above.

It follows that

$$x = \frac{p_\chi}{p} = \frac{V_\chi}{V} = \frac{n_\chi}{n} \quad (2.4)$$

defines a dimensionless concentration (traditionally expressed in %, parts per million (ppm), parts per billion (ppb), etc.) both in partial pressure fraction and partial volume fraction, or even in molar fraction. Consequently, given a concentration  $x$  in %, we have

$$p_\chi = xp, \quad (2.5)$$

and

$$\begin{aligned} p_\chi &= n_\chi \frac{R^\#}{V} T = \frac{m_\chi}{M_\chi} \frac{R^\#}{V} T = \frac{m_\chi}{V} \frac{R^\#}{M_\chi} T \Rightarrow \\ p_\chi &= \rho_\chi R_\chi T, \end{aligned} \quad (2.6)$$

where  $\rho_\chi = m_\chi/V$  is the density or the specific mass of the gas  $\chi$  (with mass  $m_\chi$  occupying the volume  $V$ ), and  $M_\chi$  is the molar mass of the gas  $\chi$  whose units in the SI are  $\text{kg mol}^{-1}$ . In (2.6),

$$R_\chi = \frac{R^\#}{M_\chi} \quad (2.7)$$

Table 2.1: Densities of several atmospheric gases. The values are approximate: the goal is the comparison of the respective orders of magnitude.

Gas	$\chi =$	%	$\rho_\chi (\text{g m}^{-3})$
N <sub>2</sub>	} <sup>s</sup>	78.000000	908.3679
O <sub>2</sub>		21.000000	279.3485
H <sub>2</sub> O	<i>v</i>	2.500000	18.7229
CO <sub>2</sub>	<i>c</i>	0.040000	0.7318
CH <sub>4</sub>	<i>m</i>	0.000175	0.0012
N <sub>2</sub> O	<i>n</i>	0.000031	0.0006

is the gas constant for gas  $\chi$ .

For a temperature of 20°C and standard atmospheric pressure of 101.325 Pa, we obtain on table 2.1 the densities of several atmospheric gases in  $\text{g m}^{-3}$ . Note the drastic progressive density reduction of the greenhouse gases H<sub>2</sub>O, CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O, in the last 4 lines of the table.

What table 2.1 reveals is that the measurement of CO<sub>2</sub> is much more difficult than the measurement of H<sub>2</sub>O; similarly, CH<sub>4</sub> measurement is harder than CO<sub>2</sub>'s, and so on, by the simple fact that it is necessary to measure increasingly smaller concentrations. Although this is possible in controlled laboratory conditions with various types of chemical analyzers, *in situ* measurements, necessary to obtain continuous data series, are substantially more difficult.

Thus, the task of measuring fluxes and performing greenhouse gas material balances is also extraordinarily hard, and one of its greatest scientific challenges is still the obtention of accurate error estimates. It is noticeable that even the H<sub>2</sub>O balance in a watershed (or a reservoir) is still very hard, and many of the terms of the “water balance” of a reservoir remain highly uncertain.

### 2.2.2 – The Reynolds and Boussinesq decompositions for turbulent flows

The Reynolds decomposition is the formal procedure by which we decompose any variable  $a$  measured in the atmosphere into its average  $\bar{a}$  and its turbulent fluctuation  $a'$ . The Reynolds decomposition consists of writing

$$a = \bar{a} + a', \quad (2.8)$$

but the subsequent manipulation of  $\bar{a}$  and  $a'$  in the Navier-Stokes equation and the transport equation for a gas  $\chi$  depends on the precise definition of the average. In this text, we will consider only 3 kinds of averages: block averages, running averages, and ensemble averages.

The Boussinesq decomposition is different. It separates the variable into its value in a reference hydrostatic state  $a_r$  and a fluctuation around it  $\delta a$ , as

$$a = a_r + \delta a. \quad (2.9)$$

### 2.2.3 – Ensemble averages

We will adopt here a variation of Kundu (1990)'s approach to calculate ensemble averages. In this approach, the realizations  $k$  of a random variable  $a$ ,



$a^{(k)}(x, y, z, t)$ , are seen as a four-dimensional stochastic process. The realizations are considered in a countable, possibly infinite, sample space. The probability of realization  $k$  is  $p_k$  (in this context, we see no danger of confusing  $p_k$  with “pressure”). The ensemble average of  $a(x, y, z, t)$  is defined as

$$\bar{a}(x, y, z, t) \equiv \sum_{k=1}^{\infty} a^{(k)}(x, y, z, t) p_k. \quad (2.10)$$

The fluctuation  $a'$  (that is also an stochastic process) is thence defined by (2.8). In turbulence, *we do not adopt the usual notation of writing uppercase letters for random variables*: the nature of the variables must be understood from the context or made explicit by the author.

When the stochastic process is stationary, the left side of (2.10) is reduced to  $\bar{a}(x, y, z)$ ; if moreover the process is horizontally homogeneous, the dependence is reduced yet to  $\bar{a}(z)$ .

Having (2.10), it is possible now to prove the so-called Reynolds’ postulates (that in this context should be properly called Reynolds’ Theorems or, even better, Reynolds’ Lemmas). They are:

$$\begin{aligned} \overline{\bar{a}(x, y, z, t)} &= \sum_{k=1}^{\infty} \bar{a}(x, y, z, t) p_k \\ &= \bar{a}(x, y, z, t) \underbrace{\left[ \sum_{k=1}^{\infty} p_k \right]}_{=1} \\ &= \bar{a}(x, y, z, t); \end{aligned} \quad (2.11)$$

$$\begin{aligned} \overline{a'(x, y, z, t)} &= \sum_{k=1}^{\infty} [a^{(k)}(x, y, z, t) - \bar{a}(x, y, z, t)] p_k \\ &= \sum_{k=1}^{\infty} a^{(k)}(x, y, z, t) p_k - \bar{a}(x, y, z, t) \sum_{k=1}^{\infty} p_k \\ &= \bar{a}(x, y, z, t) - \bar{a}(x, y, z, t) = 0; \end{aligned} \quad (2.12)$$

$$\begin{aligned}
\overline{\bar{a}(x, y, z, t)b'(x, y, z, t)} &= \sum_{k=1}^{\infty} \bar{a}(x, y, z, t) [b^{(k)}(x, y, z, t) - \bar{b}(x, y, z, t)] p_k \\
&= \bar{a}(x, y, z, t) \sum_{k=1}^{\infty} b^{(k)}(x, y, z, t) p_k \\
&\quad - [\bar{a}(x, y, z, t)] [\bar{b}(x, y, z, t)] \sum_{k=1}^{\infty} p_k \\
&= [\bar{a}(x, y, z, t)] [\bar{b}(x, y, z, t)] \\
&\quad - [\bar{a}(x, y, z, t)] [\bar{b}(x, y, z, t)] = 0; \tag{2.13}
\end{aligned}$$

$$\begin{aligned}
\overline{\frac{\partial a}{\partial x}} &= \sum_{k=1}^{\infty} \frac{\partial a^{(k)}}{\partial x} p_k \\
&= \frac{\partial}{\partial x} \sum_{k=1}^{\infty} a^{(k)}(x, y, z, t) p_k \\
&= \frac{\partial \bar{a}}{\partial x}. \tag{2.14}
\end{aligned}$$

The last equation, (2.14), tells us that the partial derivatives commute with the ensemble average. Identical results hold, obviously, for any other independent variable than  $x$ .

### 2.2.4 – Block averages

The block average is maybe the simplest one that can be imagined; for a block of length  $T$  (we see no danger of confusing  $T$  with thermodynamic temperature  $T$ ), it is defined by

$$n_t \equiv \lfloor t/T \rfloor; \quad t_n \equiv n_t T; \tag{2.15}$$

$$\bar{a}(x, y, z, t) \equiv \frac{1}{T} \int_{t_n - T/2}^{t_n + T/2} a(x, y, z, \tau) d\tau, \quad t_n - T/2 < t < t_n + T/2. \tag{2.16}$$

In (2.15),  $\lfloor \cdot \rfloor$  is the “floor” function, which gives the integer part of the number. By definition,  $\bar{a}(x, y, z, t)$  is a “step” function, that is not continuous at  $t_n$ . In the standard interpretation, the derivative of  $\bar{a}(x, y, z, t)$  is either null or it does not exist; in the sense of distributions, the derivative is a series of \*\*\* Dirac’s deltas each one over a  $t_n$ . Neither sense works for Renolds’ lemma (2.14); notice, however, that (2.11)–(2.13) are all true:

$$\begin{aligned}
\overline{\bar{a}(x, y, z, t)} &= \frac{1}{T} \int_{t_n - T/2}^{t_n + T/2} \bar{a}(x, y, z, t) dt = \bar{a}(x, y, z, t); \\
\overline{a'(x, y, z, t)} &= \frac{1}{T} \int_{t_n - T/2}^{t_n + T/2} [a(x, y, z, t) - \bar{a}(x, y, z, t)] dt \\
&= \bar{a}(x, y, z, t) - \bar{a}(x, y, z, t) = 0; \\
\overline{\bar{a}(x, y, z, t)b'(x, y, z, t)} &= \frac{1}{T} \int_{t_n - T/2}^{t_n + T/2} \bar{a}(x, y, z, t)b'(x, y, z, t) dt \\
&= \bar{a}(x, y, z, t) \int_{t_n - T/2}^{t_n + T/2} b'(x, y, z, t) dt = 0.
\end{aligned}$$

The “problem” is with the last of the lemmas; it is trivial to verify that

$$\overline{\frac{da}{dt}} = \frac{1}{T} \int_{t_n-T/2}^{t_n+T/2} \frac{da}{d\tau}(x, y, z, \tau) d\tau = \frac{a(x, y, z, t_n + T/2) - a(x, y, z, t_n - T/2)}{T}, \quad (2.17)$$

but how to define in a decent way  $d\bar{a}/dt$ , if  $\bar{a}$  is constant for  $t_n - T/2 < t < t_n + T/2$ ? Some thought will bring us to the conclusion that there are not many choices, and a choice as good as any, and certainly one of the simplest, is to *define*

$$\frac{d\bar{a}}{dt} \equiv \frac{\bar{a}(t_{n+1}) - \bar{a}(t_{n-1})}{2T} = \frac{\frac{\bar{a}(t_{n+1}) + \bar{a}(t_n)}{2} - \frac{\bar{a}(t_n) + \bar{a}(t_{n-1})}{2}}{T}. \quad (2.18)$$

Lemma (2.14) is therefore valid *approximately* for block averages as long as

$$a(t_n + T/2) \approx \frac{\bar{a}(t_{n+1}) + \bar{a}(t_n)}{2}, \quad (2.19)$$

$$a(t_n - T/2) \approx \frac{\bar{a}(t_n) + \bar{a}(t_{n-1})}{2}; \quad (2.20)$$

in this case, we have, *approximately* for block averages,

$$\overline{\frac{da}{dt}} \approx \frac{d\bar{a}}{dt}. \quad (2.21)$$

Considering that  $t_n - T/2$  and  $t_n + T/2$  are exactly at the discontinuity points of  $\bar{a}$ , the approximations above — the arithmetic average of the block averages left and right of the discontinuity point — are reasonable and certainly the simplest ones we can imagine. This is the maximum we can obtain regarding the Reynolds postulates.

### 2.2.5 – Running averages

The running average of a quantity  $a(x, y, z, t)$  is defined as

$$\bar{a}(x, y, z, t) \equiv \frac{1}{P} \int_{t-P/2}^{t+P/2} a(x, y, z, \tau) d\tau. \quad (2.22)$$

The window of the running average,  $P$ , is not to be confused with the length of the micrometeorological run,  $T$ , in (2.16); in micrometeorology, it is common to choose  $P$  in such a way that

$$\Delta t \ll P \ll T, \quad (2.23)$$

where  $\Delta t$  is the interval of data acquisition. **More about this in ???**

The main advantage of (2.22) is that a similar property to (2.14) continues to be valid for all independent variables, *including*  $t$ . In fact, from its definition we have

$$\overline{\frac{\partial a}{\partial t}} = \frac{1}{P} \int_{t-P/2}^{t+P/2} \frac{\partial a(\tau)}{\partial \tau} d\tau = \frac{1}{P} [a(t + P/2) - a(t - P/2)] \quad (2.24)$$

(where the dependence with  $(x, y, z)$  was omitted for simplicity), while

$$\begin{aligned}\frac{\partial \bar{a}}{\partial t} &= \frac{\partial}{\partial t} \left[ \frac{1}{P} \int_{t-P/2}^{t+P/2} a(\tau) d\tau \right] \\ &= \frac{1}{P} \left[ a(t+P/2) - a(t-P/2) + \int_{t-P/2}^{t+P/2} \frac{\partial a(\tau)}{\partial t} d\tau \right] \\ &= \frac{1}{P} [a(t+P/2) - a(t-P/2)] .\end{aligned}\quad (2.25)$$

(the second line of (2.25) is an application of Leibnitz's rule: note that  $\partial a(\tau)/\partial t = 0$ ). The other results (2.11)–(2.13), however, do not hold:

$$\bar{\bar{a}}(t) = \frac{1}{P} \int_{t-P/2}^{t+P/2} \left[ \frac{1}{P} \int_{\tau-P/2}^{\tau+P/2} a(\xi) d\xi \right] d\tau \neq \bar{a}(t); \quad (2.26)$$

$$\begin{aligned}\bar{a}'(t) &= \frac{1}{P} \int_{t-P/2}^{t+P/2} \left[ a(\tau) - \frac{1}{P} \int_{\tau-P/2}^{\tau+P/2} a(\xi) d\xi \right] d\tau \\ &= \bar{a}(t) - \bar{\bar{a}}(t) \neq 0;\end{aligned}\quad (2.27)$$

$$\begin{aligned}\overline{\bar{a}b'}(t) &= \frac{1}{P} \int_{t-P/2}^{t+P/2} \left\{ \bar{a}(\tau) [b(\tau) - \bar{b}(\tau)] \right\} d\tau, \\ &= \frac{1}{P} \int_{t-P/2}^{t+P/2} \bar{a}(\tau) b(\tau) d\tau - \frac{1}{P} \int_{t-P/2}^{t+P/2} \bar{a}(\tau) \bar{b}(\tau) d\tau \\ &= \overline{\bar{a}b}(t) - \bar{\bar{a}}\bar{b}(t) \neq 0.\end{aligned}\quad (2.28)$$

Results (2.26)–(2.28) mean that *a priori* it is considerably more complex to manipulate averages of the Navier-Stokes equations with running averages (2.22) than with ensemble averages (2.10) or with block averages (2.16).

One “practical” alternative in micrometeorology is to use the greater generality of (2.11)–(2.13) in the theoretical derivations, and then use the ergodic hypothesis and substitute all of the ensemble averages by running averages (that is: sample averages) in the analysis of results of micrometeorological experiments.

The use of block averages or the running averages carries with itself the necessity to estimate sample errors systematically when interpreting the experimental results. This analysis is not absolutely trivial, because these errors depend on the integral scales of the associated process (Lumley and Panofsky, 1964). There exists a considerable difficulty, and actually very few systematic research, to estimate integral scales. In the first place, integral scales need themselves to be estimated from the measured data. In principle, this is not possible: the integral scale implies an infinite averaging time to be calculated (Yaglom, 1987), which is not possible even asymptotically in the surface layer of the atmosphere, due to its non-stationarity at the hourly scale. (Stull, 1988). Moreover, in spite of what many researchers do when adopting a single value for the integral scale, each turbulence quantity has its own integral scale, and they should be calculated separately (Dias *et al.*, 2004).

Alternatives to the *a priori* calculation of integral scales, however, do exist. They are: bootstrapping methods (Gluhovsky and Agee, 1994; Garcia *et al.*, 2006), the filtering method (Salesky *et al.*, 2012; Salesky and Chamecki, 2012) and the relaxed filtering method (Dias *et al.*, 2018).

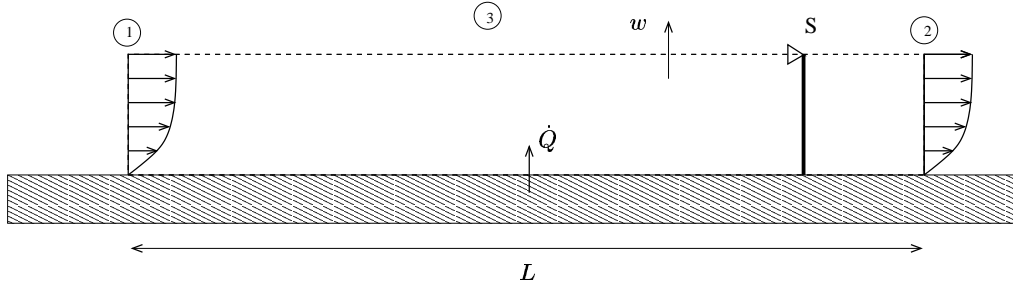


Figure 2.1: Mass balance to a virtual “box” (a control volume) of a height  $z_a$  over a homogeneous surface of length  $L$  throughout in the wind direction.

## 2.3 – The eddy covariance method (ECM)

### 2.3.1 – The integral balances for control volume

Figure 8.1 shows the essence of the eddy covariance method. We will illustrate it for several pairs of intensive quantity  $\leftrightarrow$  extensive quantity (Fox and McDonald, 1981) (identified by the extensive quantities in the following list): the mass of dry air, the mass of water vapor, and the mass of  $\text{CO}_2$ .

For the control volume  $\mathcal{V}$ , limited by the closed surface  $\mathcal{S}$ , the mass balance equation of an atmospheric gas  $\chi$  is

$$\int_{\mathcal{V}} s_{\chi} dV - \oint_{\mathcal{S}} (\mathbf{n} \cdot \mathbf{j}_{\chi}) dS = \frac{\partial}{\partial t} \int_{\mathcal{V}} \rho_{\chi} dV + \oint_{\mathcal{S}} \rho_{\chi} (\mathbf{n} \cdot \mathbf{u}) dS. \quad (2.29)$$

In (2.29),  $\mathbf{j}_{\chi}$  is the diffusive mass flux of the gas  $\chi$  on the surface of  $\mathcal{V}$  and  $s_{\chi}$  are the production sources of the gas  $\chi$  inside  $\mathcal{V}$  (for example, the production of  $\text{CO}_2$  by the respiration of plants). These terms form the *total flux* of the gas  $\chi$  into the control volume  $\mathcal{V}$ :

$$\mathcal{F}_{\chi} \equiv \int_{\mathcal{V}} s_{\chi} dV - \oint_{\mathcal{S}} (\mathbf{n} \cdot \mathbf{j}_{\chi}) dS. \quad (2.30)$$

To proceed, it is necessary to take into consideration the gaseous composition of the atmosphere, and the importance of the contributions to the sources and the diffusive fluxes at the boundaries of  $\mathcal{V}$ . Consider the atmosphere constituted essentially by 3 components. The “dry” part consists mainly of  $\text{O}_2$  e  $\text{N}_2$ , taken together as a simple gas with constant  $R_s = 287,05 \text{ J kg}^{-1} \text{ K}^{-1}$  (the gas constant for dry air; see (2.7)). The wet component is the water vapor  $\text{H}_2\text{O}$ , whose gas constant is  $R_v = 461,52 \text{ J kg}^{-1} \text{ K}^{-1}$ . Now, consider a third component formed by a greenhouse gas. To fix the ideas, suppose it is  $\text{CO}_2$ , whose gas constant is  $R_c = 188,92 \text{ J kg}^{-1} \text{ K}^{-1}$ . The air density is the sum of each component:

$$\rho = \rho_s + \rho_v + \rho_c, \quad (2.31)$$

where  $\rho_s$  is the density of dry air,  $\rho_v$  is the density of water vapor, and  $\rho_c$  is the density of  $\text{CO}_2$ . Similarly, the diffusive fluxes and the sources add up:

$$s = s_s + s_v + s_c, \quad (2.32)$$

$$\mathbf{j} = \mathbf{j}_s + \mathbf{j}_v + \mathbf{j}_c. \quad (2.33)$$

For dry air,  $s_s = 0$ , and  $\mathbf{j}_s = 0$  at the surface-atmosphere interface (Finnigan, 2009). According to Lee and Massman (2011), this hypotheses is a fundamental novelty of the theory proposed by Webb *et al.* (1980).

Expanding the derivative with respect to time in (2.29),

$$\mathcal{F}_\chi = \int_V \frac{\partial \rho_\chi}{\partial t} dV + \oint_S \rho_\chi (\mathbf{n} \cdot \mathbf{u}) dS. \quad (2.34)$$

The term involving the mass advection through the control surface needs to be evaluated for each of the surfaces ①, ② and ③:

$$\int_{\textcircled{1}} \rho_\chi (\mathbf{n} \cdot \mathbf{u}) dS = - \int_{y=0}^b \int_{z=0}^{z_a} \rho_\chi u(x=0, y, z, t) dz dy, \quad (2.35)$$

$$\int_{\textcircled{2}} \rho_\chi (\mathbf{n} \cdot \mathbf{u}) dS = + \int_{y=0}^b \int_{z=0}^{z_a} \rho_\chi u(x=L, y, z, t) dz dy, \quad (2.36)$$

$$\int_{\textcircled{3}} \rho_\chi (\mathbf{n} \cdot \mathbf{u}) dS = + \int_{x=0}^L \int_{y=0}^b \rho_\chi w(x, y, z=z_a, t) dy dx. \quad (2.37)$$

Consider now the average of (2.34), denoted by a bar. Using the commutation properties of the average with the derivative, expressed by (2.14), (2.21) and (2.24)–(2.25) respectively for the ensemble average, the block average and the running average,

$$\overline{\mathcal{F}_\chi} = \int_V \frac{\partial \bar{\rho}}{\partial t} dV + \oint_S \overline{\rho (\mathbf{n} \cdot \mathbf{u})} dS. \quad (2.38)$$

Note that  $\overline{\mathcal{F}_\chi}$  is a mass transfer rate into  $\mathcal{V}$ , in  $\text{kg}_\chi \text{s}^{-1}$  in the SI.

If the flow is *homogeneous* in  $x$  and  $y$ , then, for the ensemble average,

$$\overline{[\rho_\chi u]}(x=0, y, z) = \overline{[\rho_\chi u]}(x=L, y, z), \quad \forall y, z \quad (2.39)$$

note that this is *valid only on average*; proceeding,

$$\int_{\textcircled{1}} \overline{\rho_\chi (\mathbf{n} \cdot \mathbf{u})} dS + \int_{\textcircled{2}} \overline{\rho_\chi (\mathbf{n} \cdot \mathbf{u})} dS = 0. \quad (2.40)$$

Also note that in the case of block and running averages, (2.39) and (2.40) are valid only approximately.

Horizontal homogeneity also implies that  $\overline{[\rho_\chi w]}(x, y, z=z_a)$  is independent of both  $x$  and  $y$ , whence

$$\int_{x=0}^L \int_{y=0}^b \overline{[\rho_\chi w]}(x, y, z=z_a) dy dx = \overline{[\rho_\chi w]}(z=z_a) bL. \quad (2.41)$$

For the average density  $\bar{\rho}_\chi$  the hypothesis of horizontal homogeneity produces

$$\bar{\rho}_\chi = \bar{\rho}_\chi(z, t), \quad (2.42)$$

where (2.34), using (2.40) and (2.41), reduces to

$$\begin{aligned}\overline{\mathcal{F}_\chi} &= bL \int_0^{z_a} \frac{\partial \overline{\rho_\chi}}{\partial t} dz + bL \overline{[\rho_\chi w]}(z = z_a), \\ \frac{\overline{\mathcal{F}_\chi}}{bL} \equiv F_\chi &= \int_0^{z_a} \frac{\partial \overline{\rho_\chi}}{\partial t} dz + \overline{[\rho_\chi w]}(z = z_a),\end{aligned}\quad (2.43)$$

where  $F_\chi$  is the specific mass flux (flux per unit of surface area) of the gas. The transient term is kept in (2.43) to allow an analysis of its importance, which now follows.

By the mean value theorem of differential and integral calculus, if  $0 \leq z^* \leq z_a$ :

$$F_\chi = \frac{\partial}{\partial t} \left\{ z_a \overline{\rho_\chi}(z^*) \right\} + \overline{[\rho_\chi w]}(z = z_a). \quad (2.44)$$

The transient term can be neglected if

$$z_a \frac{\partial}{\partial t} \left\{ \overline{\rho_\chi}(z^*) \right\} \ll \overline{[\rho_\chi w]}(z = z_a); \quad (2.45)$$

in this case, we get the standard equation of the eddy covariance method for the surface flux of gas  $\chi$ :

$$F_\chi = \overline{[\rho_\chi w]}(z = z_a). \quad (2.46)$$

Note that the choice of  $z_a$  is crucial: the bigger the value, the more important becomes the effect of  $\partial \overline{\rho_\chi} / \partial t$ ; as one would expect the value of  $\overline{\rho_\chi}$  to evolve over over time as a function of the flux  $F_\chi$ , it is not realistic to assume that the transient term is identically null in a real atmosphere; strictly speaking, it is a combination of a small value of the time derivative with a “low” height of measurement (besides of course the horizontal homogeneity hypothesis) that assures that (2.46) gives us an accurate value of  $F_\chi$  in the surface.

As we saw above, for dry air  $\mathcal{F}_s \equiv 0$ , where (2.46) with  $\chi = s$ , gives

$$\frac{\overline{\mathcal{F}_s}}{bL} = 0 = \overline{[\rho_s w]}(z = z_a). \quad (2.47)$$

This is a fundamental hypothesis in the deduction of the WPL correction (Webb *et al.*, 1980), that however is only briefly mentioned in that paper. In this text, (2.47) is rigorously derived from the horizontal homogeneity hypothesis and from the stationarity and dry air budget for a control volume, in essentially the same way as in Finnigan (2009), and Lee and Massman (2011).

Under the same hypothesis of homogeneity and stationarity, and taking respectively  $\chi = v$  e  $\chi = c$ , the specific fluxes (*i.e.*, per unit of area) of water vapor mass and  $\text{CO}_2$  mass are

$$E \equiv \frac{\overline{\mathcal{F}_v}}{bL} = \overline{[\rho_v w]}(z = z_a), \quad (2.48)$$

$$F \equiv \frac{\overline{\mathcal{F}_c}}{bL} = \overline{[\rho_c w]}(z = z_a). \quad (2.49)$$

Besides the mass fluxes described above, also indispensable in micrometeorological measurements are the momentum flux,

$$\tau \equiv \frac{\overline{\mathcal{F}_u}}{bL} = \overline{[\rho u w]}(z = z_a), \quad (2.50)$$

and the sensible heat flux,

$$H \equiv \frac{\overline{\mathcal{F}_\theta}}{bL} = \overline{[\rho c_p w \theta]}(z = z_a), \quad (2.51)$$

where  $\theta$  is potential temperature.

In the name of simplicity, from now on we will omit the measurement level; in this way, for example, we write  $\overline{\rho_v w}$  instead of  $\overline{[\rho_v w]}(z = z_a)$ .

### 2.3.2 – Non-ideal conditions

Nocturnal turbulence tends to be intermittent. In strongly stable conditions with Richardson number  $Ri \lesssim 0.2$ , turbulence is strongly damped or even suppressed (Kondo *et al.*, 1978; Cheng *et al.*, 2005). This value, however, is debatable; see Zilitinkevich *et al.* (2007) and Galperin *et al.* (2007).

Two important problems of the nocturnal measurement of CO<sub>2</sub> fluxes with the eddy covariance method are (Aubinet, 2008):

1. The turbulence intermittency that produces non-stationarity conditions during which the method's hypothesis can fail; and
2. The occurrence of breezes and katabatic flows, during which the effects of horizontal advection, that also invalidate (in principle) the method can become very important.

The observation that the measurements with the eddy covariance method could be systematically underestimating the CO<sub>2</sub> fluxes appears to have been done for the first time by Goulden *et al.* (2006). Once this is realized, it is possible to correct the error (“correction approach”) or eliminate the suspect measurements (“filtering approach”) (Aubinet, 2008). The most usual approach is to eliminate the measurements associated to a friction velocity below a certain level.

Once the problems posed by the relatively simplistic measurement of the CO<sub>2</sub> flux with only one tower, and in only one level, were identified, explanations started to be searched. Among them, we found the analysis of Lee (1998), and the subsequent, and very important, comments of Finnigan (1999).

In real conditions, the perfect horizontal homogeneity and stationarity assumed in MOS theory, and used in the derivation of the equation of the eddy covariance method presented in the text, obviously fail. The degree to which this affects the surface flux measurements, however, is extremely hard to be established. Attempts to calculate, in particular, the advective terms neglected in the theory (the calculation of local advection effects) are very hard, because they involve the need to measure horizontal and vertical gradients of gas concentration. For this it is necessary that sensors placed at different points be carefully calibrated to eliminate the systematic errors, since the advective terms always involve the measurement of concentration *differences* between two points. In



this sense the study of [Heinesch \*et al.\* \(2007\)](#) suggests that it is possible to estimate CO<sub>2</sub> horizontal gradients, and therefore its local horizontal advection, but that the vertical advection term estimate, that involves the vertical velocity  $\overline{w}$  measurement, is considerably harder.

Similar conclusions, although more detailed, were obtained in the careful study of [Leuning \*et al.\* \(2008\)](#), in which all of the terms of the mass integral balance of CO<sub>2</sub> in a control volume of  $50 \times 50 \times 6 \text{ m}^3$  were measured or very well estimated: in this work, the vertical and horizontal advection terms were shown to be important in nocturnal measurements, with smaller errors occurring in diurnal conditions.

As we shall see next, an estimate of the mean vertical velocity is at the core of the WPL correction, and more studies (and possibly technological progress) are probably necessary for the improvement of the flux measurements in non-ideal conditions, such as with undulating topography and in the presence of advective and non-stationarity effects.

# 3

## A primer on the thermodynamics of the atmospheric boundary layer

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### 3.1 – Basic results for a pure substance

The perfect gas law in the form (2.1) or (2.6) is an example of a state equation in thermodynamics. It is convenient to introduce the *specific volume*  $v$ ,

$$v = \frac{1}{\rho} = \frac{V}{m}, \quad (3.1)$$

where  $m$  is the total mass occupying volume  $V$ . For a *pure substance*, then, the state equation takes one of the forms

$$p = p(v, T) \quad \text{or} \quad v = v(p, T) \quad \text{or} \quad T = T(p, v).$$

For atmospheric gases, the lower case letters indicate specific quantities (per unit mass or unit volume), and are more convenient since we will not usually treat individual “systems” or “lumps” of air.

Two important thermodynamical functions are the specific internal energy  $u$  and the specific enthalpy  $h$  defined by

$$h = u + pv. \quad (3.2)$$

For a pure substance, they are functions of two variables, chosen between  $p$ ,  $v$  and  $T$ . We usually write

$$u = u(v, T), \quad (3.3)$$

$$h = h(p, T), \quad (3.4)$$

since these pairs lead to useful definitions of measurable quantities such as specific heats. Equations (3.3) and (3.4) lead to perfect differentials

$$du = \left( \frac{\partial u}{\partial v} \right)_T dv + \left( \frac{\partial u}{\partial T} \right)_v dT, \quad (3.5)$$

$$dh = \left( \frac{\partial h}{\partial p} \right)_T dp + \left( \frac{\partial h}{\partial T} \right)_p dT. \quad (3.6)$$

The specific heats at constant volume and constant temperature are defined by

$$c_v = \left( \frac{\partial u}{\partial T} \right)_v, \quad (3.7)$$

$$c_p = \left( \frac{\partial h}{\partial T} \right)_p. \quad (3.8)$$

The subscripts  $v$  and  $p$  on the right-hand side of the equations above are used in thermodynamics as reminders that  $u$  is being taken as a function of  $v, T$ , and that  $h$  is being taken as a function of  $p, T$ .

For a perfect gas,

$$pv = RT, \quad (3.9)$$

and it is possible to show that in this case  $u$  and  $h$  are functions of  $T$  only [Adkins \(1983\)](#). Then, (3.7)–(3.8) become ordinary derivatives. Also,

$$\begin{aligned} \left( \frac{\partial h}{\partial T} \right)_p &= \left( \frac{\partial}{\partial T} [u + pv] \right)_p \\ &= \left( \frac{\partial u}{\partial T} \right)_p + p \left( \frac{\partial v}{\partial T} \right)_p \\ &= \frac{du}{dT} + p \frac{R}{p} \Rightarrow \\ c_p &= c_v + R. \end{aligned} \quad (3.10)$$

Physically,  $c_p > c_v$  due to the extra energy necessary for the expansion of the air against the constant pressure  $p$ .

### 3.2 – Moist air

Note that the equations above are not strictly valid for atmospheric air, which is not a *pure* substance; rather, it is a mixture of many gases. Each new constituent makes the thermodynamical equations more complex; in particular, functions of state such as  $u$  and  $h$  then become also functions of the concentrations of each new constituent.

We will not follow the rigorous path of treating the atmosphere as a mixture of several gases and writing down the full thermodynamical equations for that mixture; instead, we will consider “dry air” (a mixture of nitrogen and oxygen in essentially constant proportions) as the main constituent, and will introduce various indices for the concentration of water vapor (the most important varying component). Later, the concentrations of other gases and their relevant effects will also be introduced as needed. However, the rigorous modifications in the thermodynamical functions of state will not be discussed.

Consider now a certain volume  $V$  of air with total mass  $m$ , composed of dry air with mass  $m_d$  and water vapor with mass  $m_v$ . We have:

$$\begin{aligned} m &= m_d + m_v, \\ \frac{m}{V} &= \frac{m_d}{V} + \frac{m_v}{V}, \\ \rho &= \rho_d + \rho_v. \end{aligned} \quad (3.11)$$

This defines the air density  $\rho$ ; the density of dry air  $\rho_d$  and the water vapor density  $\rho_v$ . In itself,  $\rho_v$  is an index of water vapor concentration; in meteorology, it is often called absolute humidity.

The partial pressure model introduced already in subsection 2.2.1 and Equation (2.6) for the two components of moist air leads to the pair of equations

$$p_d = p - e = \rho_d R_d T, \quad (3.12)$$

$$e = \rho_v R_v T, \quad (3.13)$$

where  $p_d$  is the partial pressure of dry air;  $p$  is total atmospheric pressure, and  $e$  is the partial pressure of water vapor.  $R_d = 287.05 \text{ J kg}^{-1} \text{ K}^{-1}$  and  $R_v = 461.51 \text{ J kg}^{-1} \text{ K}^{-1}$  are the gas constants for dry air and water vapor, respectively.

The *specific humidity*  $q$  is defined as

$$q = \frac{\rho_v}{\rho}. \quad (3.14)$$

Summing (3.12) and (3.13), one obtains

$$\begin{aligned} p &= (\rho_d R_d + \rho_v R_v) T \\ &= \rho \left( \frac{\rho_d}{\rho} R_d + \frac{\rho_v}{\rho} R_v \right) T \\ &= \rho R_d \left( \frac{\rho_d}{\rho} + \frac{\rho_v}{\rho} \frac{R_v}{R_d} \right) T \\ &= \rho R_d \left( (1 - q) + \frac{R_v}{R_d} q \right) T. \end{aligned} \quad (3.15)$$

Replacing

$$\begin{aligned} \frac{R_v}{R_d} &= 1.608 \approx 1.61 \quad \Rightarrow \\ p &= \rho R_d \underbrace{(1 + 0.61q)}_{T_v} T \end{aligned} \quad (3.16)$$

The *virtual temperature*  $T_v$  defined above is the temperature of a dry atmosphere with the same density  $\rho$ . A further index atmospheric moisture is the mixing ratio

$$r = \frac{\rho_v}{\rho_d}. \quad (3.17)$$

Useful relations among the humidity indices can be derived as follows:

$$\begin{aligned} r &= \frac{\rho_v}{\rho} = \frac{\frac{e}{R_v T}}{\frac{(p-e)}{R_d T}} \\ &= \frac{R_d}{R_v} \frac{e}{p-e} = 0.622 \frac{e}{p-e}; \end{aligned} \quad (3.18)$$

$$\begin{aligned} q &= \frac{\rho_v}{\rho} = \frac{\frac{e}{R_v T}}{\frac{p-e}{R_d T} + \frac{e}{R_v T}} \\ &= \frac{R_d}{R_v} \frac{e}{p + \left(\frac{R_d}{R_v} - 1\right)e} \\ &= 0.622 \frac{e}{p - 0.378e} \approx 0.622 \frac{e}{p}. \end{aligned} \quad (3.19)$$

### 3.3 – Atmospheric humidity

The latent heat of water,  $L_w$ , is the amount of energy used to change the phase of a unit of mass from liquid to vapor, in a pure mixture of the two phases. A good approximation for  $L_w$  is the assumption that the heat capacities of the two phases are equal. This leads to (Adkins, 1983, Chap. 10, Eq. 10.16)

$$dL_w = [c_{pv} - c_{pl}]dT \quad (3.20)$$

where  $c_{pv}$  and  $c_{pl}$  are the specific heats at constant pressure of water vapor and liquid water, respectively. If the specific heats, in turn, are assumed to be constant, we obtain

$$L_w = L_a + L_b T. \quad (3.21)$$

In the SI, with  $T$  in Kelvins, Linsley *et al.* (1975) give

$$L_w = 3.1458 \times 10^6 - 2.3613 \times 10^3 T \quad (3.22)$$

in  $\text{J kg}^{-1}$ . A reasonable alternative is to use a constant value, given the very small variation of  $L_w$  with  $T$ . At  $T = 295 \text{ K}$ ,  $L_w = 2.462 \times 10^6 \text{ J kg}^{-1}$ .

For a system composed of water vapor and liquid water in equilibrium, an equation can be derived relating the derivative with respect to temperature of the *saturation vapor pressure*  $e^*$  (the vapor pressure of the gas in equilibrium with the liquid water), the change in specific volume  $v$  between the two phases and the latent heat, viz.

$$\frac{de^*}{dT} = \frac{L_w}{T \Delta v}; \quad (3.23)$$

it is the *Clausius-Clapeyron* equation (Adkins, 1983, Chap. 10, Eq. (10.11)). Assuming the validity of the perfect-gas law, and that the specific volume of the liquid phase is negligible in comparison with that of the vapor phase, the Clausius-Clapeyron equation takes the form (Adkins, 1983, Chap. 10, Eq. (10.12))

$$\frac{de^*}{dT} = \frac{Le^*}{R_v T^2} \quad (3.24)$$

Note that Eqs. (3.21)– (3.22) can be used to integrate (3.24), yielding

$$e^*(T) = \left(\frac{T}{T_0}\right)^{\frac{L_b}{R_v}} e^*(T_0) \exp \left[ \frac{L_a}{R_v} \left( \frac{1}{T_0} - \frac{1}{T} \right) \right], \quad (3.25)$$

where  $T_0$  is a reference temperature. With  $L_b = 0$ , (3.25) bears a strong resemblance to (but is not the same as) Teten's empirical formula (Murray, 1966; Dilley, 1968; Stull, 1995; Alduchov and Eskridge, 1996):

$$e^*(T) = e^*(T_0) \exp \left[ \frac{b(T - T_1)}{T - T_2} \right], \quad (3.26)$$

with  $T_0 = 273.16$ ,  $b = 17.2694 \text{ K}^{-1}$ ,  $T_1 = 273.16 \text{ K}$  and  $T_2 = 25.86 \text{ K}$ .

For most meteorological applications, Teten's formula is more than enough. Note however that the constants change for saturation vapor pressure over *ice*; also, note that the presence of salts in the water alters  $e^*$  significantly. Finally, Richards' equation (Brutsaert, 1982) is

$$e^*(T) = 101\,325 \exp \left[ 13.3185t_r - 1.9760t_r^2 - 0.6445t_r^3 - 0.1299t_r^4 \right] \quad (3.27)$$

$$\frac{de^*}{dT} = \frac{373.15}{T^2} e^*(T) \left[ 13.3185 - 3.9520t_r - 1.9335t_r^2 - 0.5996t_r^3 \right], \quad (3.28)$$

$$t_r = 1 - \frac{373.15}{T}. \quad (3.29)$$

The concept of saturation now allows for the definition of several humidity indices based on it. The *relative humidity*  $y$  is the ratio of the actual mixing ratio and the mixing ratio in water vapor saturated air at the same temperature and pressure:

$$y = \frac{r}{r^*}. \quad (3.30)$$

Note that, because it is at the same temperature and pressure, the density of dry air in the saturated atmosphere ( $\rho_{d*}$ ) is actually smaller than the density of dry air in the non-saturated atmosphere ( $\rho_d$ ). The gas law equations are

$$p - e = \rho_d R_d T, \quad e = \rho_v R_v T, \quad (3.31)$$

$$p - e^* = \rho_{d*} R_d T, \quad e^* = \rho_v^* R_v T. \quad (3.32)$$

Therefore,

$$\begin{aligned}
 y &= \frac{r}{r^*} \\
 &= \frac{\frac{\rho_v}{\rho_d}}{\frac{\rho_v^*}{\rho_{d^*}}} \\
 &= \frac{\rho_{d^*}}{\rho_d} \times \frac{\rho_v}{\rho_v^*} \\
 &= \frac{\frac{p-e^*}{R_d T}}{\frac{p-e}{R_d T}} \times \frac{\frac{e}{R_v T}}{\frac{e^*}{R_v T}} \\
 &= \frac{p-e^*}{p-e} \times \frac{e}{e^*} \\
 &= \frac{p(1-e^*/p)}{p(1-e/p)} \times \frac{e}{e^*} \\
 &\approx (1-e^*/p)(1+e/p) \frac{e}{e^*} \\
 &\approx \frac{e}{e^*}.
 \end{aligned} \tag{3.33}$$

The last form, (3.33), is the one commonly used in calculations.

The *dewpoint temperature*  $T_d$  is the temperature at which the water vapor pressure becomes the saturated vapor pressure:

$$e^*(T_d) = e. \tag{3.34}$$

Usually, temperature varies with height in the surface layer. A subscript like  $T_x$  or  $e_x$  will often be used to specify temperature, water vapor pressure, etc., at some specified level. Also, we will often use the simplified notation

$$e_x^* = e^*(T_x), \tag{3.35}$$

$$d_x = \frac{de^*(T_x)}{dT}, \tag{3.36}$$

$$\rho_{vx}^* = \rho_v^*(T_x). \tag{3.37}$$

In figure 3.1, we show in frame A the prevailing conditions in the atmosphere. In frame B, saturation is reached, from A, through an increase in water vapor content. In frame C, saturation conditions are also reached, but this time through a continuous drop in temperature down to the dew point temperature  $T_d$ .

### 3.4 – Potential temperature

Consider the adiabatic expansion of a parcel of air, from a level (higher up) where the ambient pressure is  $p$  down to a level where the ambient pressure is  $p_0$ . The first law of thermodynamics is ( $q$  is heat per unit mass added to the system;  $w$  is work per unit mass performed on the system)

$$du = \delta q + \delta w;$$

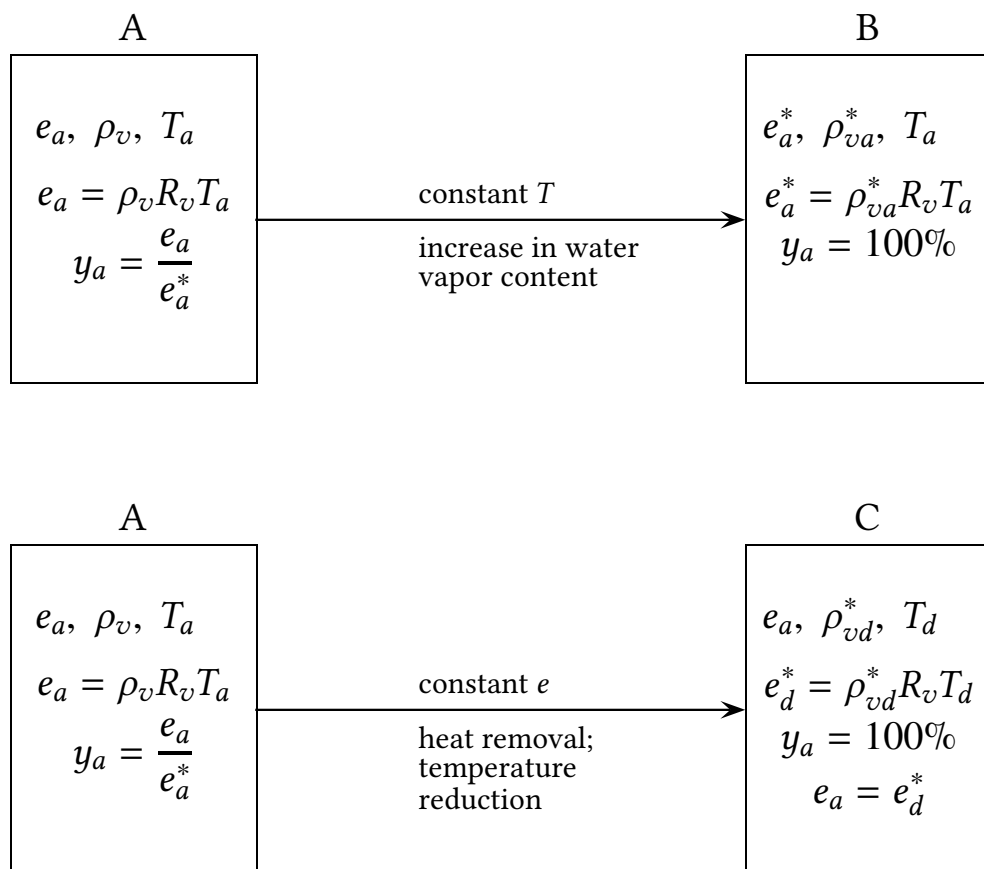


Figure 3.1: The concepts of atmospheric saturation, relative humidity and dew-point.



For an adiabatic ( $\delta q = 0$ ) and reversible process,

$$du = -pdv \quad (3.38)$$

Differentiation of (3.9) and use of (3.7) (keeping in mind that  $u = u(T)$  for a perfect gas) produce

$$\begin{aligned} pdv + vdp &= RdT \\ c_v dT &= vdp - RdT \\ (c_v + R)dT &= vdp = \frac{RT}{p} dp \\ c_p dT &= vdp = \frac{RT}{p} dp \end{aligned} \quad (3.39)$$

$$\frac{dT}{T} = \frac{R}{c_p} \frac{dp}{p}. \quad (3.40)$$

We now integrate between the temperature-pressure pairs  $(T, p)$  and  $(\theta, p_0)$ :

$$\theta = T \left( \frac{p_0}{p} \right)^{\frac{R}{c_p}}. \quad (3.41)$$

The potential temperature  $\theta$ , defined above, is therefore the temperature of a parcel of air brought adiabatically and reversibly from state  $p, T$  to a reference pressure  $p_0$ .

Equation (3.41) needs to be used with the correct value of  $R/c_p$  in the case of moist air. This is because the effective gas constant and the effective specific heat at constant pressure for moist air depend on the specific humidity  $q$ .

To see this, suppose that the total enthalpy (not the *specific enthalpy*) for a parcel of air with total mass  $m$  can be calculated by adding the enthalpies of dry and moist air:

$$m\bar{h} = m_d \bar{h}_d + m_v \bar{h}_v.$$

This produces

$$\begin{aligned} \bar{h} &= \frac{\rho_d}{\rho} \bar{h}_d + \frac{\rho_v}{\rho} \bar{h}_v, \\ \bar{h} &= (1 - q) \bar{h}_d + q \bar{h}_v, \\ c_p &= \left( \frac{\partial \bar{h}}{\partial T} \right)_p = (1 - q) c_{pd} + q c_{pv} = (1 + 0.84q) c_{pd} \end{aligned} \quad (3.42)$$

(using tabulated values for  $c_{pd}$  and  $c_{pv}$ ).

On the basis of (3.16), the effective gas constant for moist air can be written as

$$R = R_d(1 + 0.61q) \quad (3.43)$$

(note that this is an alternative interpretation to (3.16): we are now changing the gas constant  $R$ , and keeping the absolute temperature  $T$ , so that 3.9 still applies.) Therefore,

$$\frac{R}{c_p} = \frac{R_d}{c_{pd}} \frac{1 + 0.61q}{1 + 0.84q}. \quad (3.44)$$

Using the identity

$$\frac{1+ax}{1+bx} \equiv 1 - (b-a)x + \frac{(b-a)bx^2}{1+bx} \approx 1 - (b-a)x, \quad (3.45)$$

we find (for small  $x$ )

$$\frac{R}{c_p} \approx (1 - 0.23q) \frac{R_d}{c_{pd}} \quad (3.46)$$

for moist air. Therefore,

$$\theta = T \left( \frac{p_0}{p} \right)^{(1-0.23q) \frac{R_d}{c_{pd}}} \quad (3.47)$$

It is also straightforward to obtain the specific heat at constant volume for moist air:

$$c_v = \left( \frac{\partial u}{\partial T} \right)_v = (1-q)c_{vd} + qc_{vv} \quad (3.48)$$

Finally, these definitions extend to virtual temperature, but not uniquely, as discussed by (Brutsaert, 1982, section 3.2b). The *virtual potential temperature* is the virtual temperature that a parcel of moist air would have if changed adiabatically from its actual state to the standard pressure  $p_0$ :

$$\theta_{vp} = T_v \left( \frac{p_0}{p} \right)^{(1-0.23q) \frac{R_d}{c_{pd}}}. \quad (3.49)$$

This is slightly different from *potential virtual temperature*, which is the potential temperature of dry air at the same initial pressure and density, and which is given by

$$\theta_{pv} = T_v \left( \frac{p_0}{p} \right)^{\frac{R_d}{c_{pd}}}. \quad (3.50)$$

The two quantities defined by (3.49) and (3.50) are, evidently, numerically very similar. From here on, we will always use the virtual potential temperature (3.49). Also, for simplicity, we will refer to it simply as  $\theta_v$ .

# 4

## The dynamical equations for the ABL

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The transport equations express the principles of conservation of total mass, momentum, energy and mass of a mixed substance (for instance water vapor) at a point in space and instant in time. In principle, any fluid mechanics problem can be solved if we know the constitutive equation (the rate of strain – stress relation) and the boundary conditions.

In practice, the problem is much more complicated. The momentum equations are non-linear, making the solution (either analytical or numerical) much more difficult. Moreover, they display chaotic behavior, which causes very small differences in the boundary conditions to amplify very fast (Ruelle, 1994). Finally, their full solution requires the resolution of extremely small scales (the Kolmogorov microscales), rendering the problem impossible to solve on the basis of the fundamental equations alone, and requiring additional hypothesis regarding their closure at some level: this is the well known turbulence closure problem (Wyngaard, 1981).

### 4.1 – Differential operators

It is convenient to adopt a double notation for the position and velocity vectors, and the basis for  $\mathbb{R}^3$ , viz.

$$\mathbf{x} = (x, y, z) \equiv (x_1, x_2, x_3), \quad (4.1)$$

$$\mathbf{u} = (u, v, w) \equiv (u_1, u_2, u_3), \quad (4.2)$$

$$(\mathbf{i}, \mathbf{j}, \mathbf{k}) \equiv (\mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3). \quad (4.3)$$

The equations of fluid mechanics involve four differential operators: the divergence, the curl, the laplacian, and the operator for the material derivative. They are:

$$\begin{aligned} \nabla \cdot \mathbf{u} &= \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \\ &= \sum_{k=1}^3 \frac{\partial u_k}{\partial x_k}; \end{aligned} \quad (4.4)$$

$$\begin{aligned}\nabla \times \mathbf{u} &= \left( \frac{\partial w}{\partial y} - \frac{\partial v}{\partial z} \right) \mathbf{i} + \left( \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} \right) \mathbf{j} + \left( \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) \mathbf{k} \\ &= \sum_{k=1}^3 \sum_{i=1}^3 \sum_{j=1}^3 \epsilon_{ijk} \frac{\partial u_j}{\partial x_i} \mathbf{e}_k;\end{aligned}\tag{4.5}$$

$$\begin{aligned}\nabla^2 a &= \frac{\partial^2 a}{\partial x \partial x} + \frac{\partial^2 a}{\partial y \partial y} + \frac{\partial^2 a}{\partial z \partial z} \\ &= \sum_{k=1}^3 \frac{\partial^2 a}{\partial x_k \partial x_k};\end{aligned}\tag{4.6}$$

$$\begin{aligned}\frac{Da}{Dt} &= \frac{\partial a}{\partial t} + u \frac{\partial a}{\partial x} + v \frac{\partial a}{\partial y} + w \frac{\partial a}{\partial z} \\ &= \frac{\partial a}{\partial t} + \sum_{k=1}^3 u_k \frac{\partial a}{\partial x_k},\end{aligned}\tag{4.7}$$

where  $a$  represents any scalar field and  $\nabla$  is the “symbolic” vector  $(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z})$ . The first line in each of the equations above gives the formula for each operator in  $x$ ,  $y$ , and  $z$  notation. The second line shows that all operators can be written in a compact form as sums. For the curl, the permutation symbol  $\epsilon_{ijk} = +1$  for cyclic permutations  $(1,2,3)$ ,  $(2,3,1)$ ,  $(3,1,2)$ ;  $\epsilon_{ijk} = -1$  for anti-cyclic permutations  $(1,3,2)$ ,  $(2,1,3)$ ,  $(3,2,1)$ ; and  $\epsilon_{ijk} = 0$  if  $i = j$ ,  $j = k$ ,  $k = i$  or  $i = j = k$ .

In the equations that follow, we will adopt most of the time the compact sum notation. In particular cases, it will be more fruitful to shift back to the notation involving  $(x, y, z)$  and  $(u, v, w)$ .

## 4.2 – The hydrostatic reference state

Consider again the first law for an adiabatic atmosphere, as in 3.39, repeated here,

$$c_p dT_r = v_r dp_r,\tag{4.8}$$

together with the hydrostatic equation

$$\frac{dp_r}{dz} = -\rho_r g.\tag{4.9}$$

Above, the subscript  $r$  means the reference state for a hydrostatic equation. Together with the state equation (3.9), equations (4.8)–(4.9) form a system from which we can eliminate either  $T_r$ ,  $p_r$  or  $v_r = 1/\rho_r$ . Three equations result for the reference pressure, temperature or density as a function of  $z$  (bear in mind that in a moist atmosphere  $c_p$ ,  $c_v$  and  $R$  are given by 3.42, (3.48) and 3.43 respectively):

$$T_r(z) = T_0 - \frac{g}{c_p} z,\tag{4.10}$$

$$p_r(z) = p_0 \left( \frac{T_0 - \frac{g}{c_p} z}{T_0} \right)^{c_p/R},\tag{4.11}$$

$$\rho_r(z) = \rho_0 \left( \frac{T_0 - \frac{g}{c_p} z}{T_0} \right)^{c_v/R}.\tag{4.12}$$

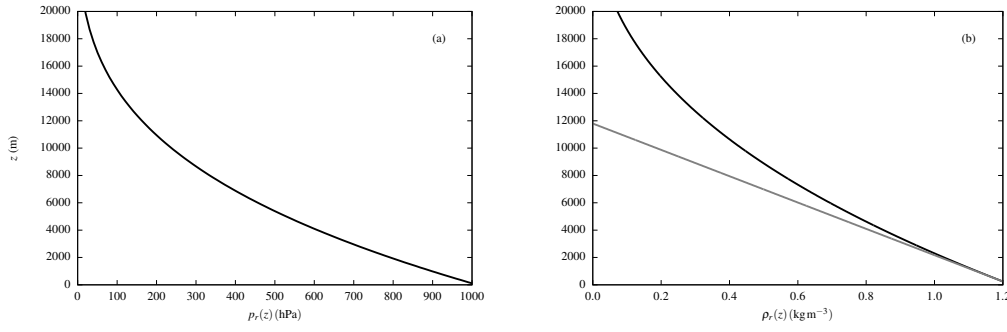


Figure 4.1: Reference pressure  $p_r$  and density  $\rho_r$  in a hydrostatic and adiabatic equation.

Figure 4.1 shows the pressure and density reference states in the atmosphere as functions of  $z$ , for  $T_0 = 15^\circ\text{C}$  and  $p_0 = 101\,325\text{ Pa}$ . The *scale height* is defined as

$$D = \left| \frac{1}{\rho_0} \frac{d\rho_r(0)}{dz} \right|^{-1}; \quad (4.13)$$

it is obtained by extrapolating the straight line with the same slope as the reference density profile at the surface up to  $\rho_r = 0$ , as seen in figure 4.1-b.

### 4.3 – Mass conservation and the Boussinesq approximation

The derivation of the transport equations for  $u, v, w, \theta, q, \theta_v, \dots$  is a long process involving a fair amount of physics and mathematics. It can be found in various texts, such as Batchelor (1967), Bird *et al.* (1960) and Landau and Lifshitz (1959). An excellent introduction to the equations in a form often used in the ABL is Stull (1988)’s book.

We will briefly analyze the dynamical equations in light of the *Boussinesq approximation*. First we define a thickness  $\ell$  such that the reference density changes little between  $z = 0$  and  $z = \ell$ . From figure 4.1-b, it can be seen that

$$\frac{\Delta\rho_r}{\rho_0} \leq \frac{\ell}{D} \equiv \epsilon_b \ll 1, \quad (4.14)$$

where  $\rho_0 = \rho_r(0)$ . In (4.14), we use any appropriately small value of  $\epsilon_b$  (say  $\epsilon_b = 0.01$ ), to define  $\ell$  rigorously.

Next we define the *Boussinesq decompositions*

$$u_i = 0 + u_{\delta i}, \quad (4.15)$$

$$\rho = \rho_r + \rho_\delta, \quad (4.16)$$

$$p = p_r + p_\delta, \quad (4.17)$$

$$T = T_r + T_\delta. \quad (4.18)$$

Above,  $u_\delta, \rho_\delta, p_\delta$  and  $T_\delta$  are the fluctuations of velocity, density, pressure, and temperature of an actual (“dynamic”) atmosphere with respect to the reference hydrostatic state.

Of course, (4.15)–(4.18) can be further expanded by means of a Reynolds’

decomposition, yielding

$$\overline{u_i} + u'_i = \overline{u_{\delta i}} + u'_{\delta i}, \quad (4.19)$$

$$\overline{\rho} + \rho' = \rho_r + \overline{\rho_\delta} + \rho'_\delta, \quad (4.20)$$

$$\overline{p} + p' = p_r + \overline{p_\delta} + p'_\delta, \quad (4.21)$$

$$\overline{T} + T' = T_r + \overline{T_\delta} + T'_\delta. \quad (4.22)$$

Then, the following relations hold (trivially) between the Reynolds decomposition and the Boussinesq decomposition:

$$\overline{u_i} = \overline{u_{\delta i}} \quad u'_i = u'_{\delta i}, \quad (4.23)$$

$$\overline{\rho} = \rho_r + \overline{\rho_\delta} \quad \rho' = \rho'_\delta, \quad (4.24)$$

$$\overline{p} = p_r + \overline{p_\delta} \quad p' = p'_\delta, \quad (4.25)$$

$$\overline{T} = T_r + \overline{T_\delta} \quad T' = T'_\delta, \quad (4.26)$$

whence

$$u_i = 0 + \overline{u_{\delta i}} + u', \quad (4.27)$$

$$\rho = \rho_r + \overline{\rho_\delta} + \rho', \quad (4.28)$$

$$p = p_r + \overline{p_\delta} + p', \quad (4.29)$$

$$T = T_r + \overline{T_\delta} + T'. \quad (4.30)$$

Clearly, the notations  $\overline{u_{\delta i}}$  and  $u'_{\delta i}$ ,  $\rho'_\delta$ ,  $p'_\delta$  and  $T'_\delta$  in (4.23)–(4.26) are excessive, and will not be used any further.

Only now we introduce the Boussinesq approximation proper: it is the assumption that the dynamic density fluctuations  $\rho_\delta$  are of the same order of magnitude of the variation of the reference density  $\rho_r$  within the layer of thickness  $\ell$ . In view of the definition of  $D$  in (4.13) and (4.14), it is

$$\rho_\delta \sim \rho_0 \frac{\ell}{D} \ll \rho_r, \quad 0 \leq z \leq \ell. \quad (4.31)$$

Now consider the full form for the equation for (total) mass conservation, which reads

$$\frac{\partial \rho}{\partial t} + \sum_{k=1}^3 \frac{\partial(\rho u_k)}{\partial x_k} = 0. \quad (4.32)$$

Its ensemble average is

$$\frac{\partial \overline{\rho}}{\partial t} + \sum_{k=1}^3 \frac{\partial \overline{\rho u_k}}{\partial x_k} = 0. \quad (4.33)$$

Expanding all terms with the help of (4.27)–(4.30) and Reynolds' postulates (2.11)–(2.14),

$$\underbrace{\frac{\partial \overline{\rho_\delta}}{\partial t}}_{\text{I}} + \sum_{k=1}^3 \underbrace{\overline{u_k} \frac{\partial \rho_r}{\partial x_k}}_{\text{II}} + \sum_{k=1}^3 \underbrace{\overline{u_k} \frac{\partial \overline{\rho_\delta}}{\partial x_k}}_{\text{III}} + \sum_{k=1}^3 \underbrace{\rho_r \frac{\partial \overline{u_k}}{\partial x_k}}_{\text{IV}} + \sum_{k=1}^3 \underbrace{\overline{\rho_\delta} \frac{\partial \overline{u_k}}{\partial x_k}}_{\text{V}} + \sum_{k=1}^3 \underbrace{\frac{\partial \overline{\rho' u'_k}}{\partial x_k}}_{\text{VI}} = 0. \quad (4.34)$$

The order of magnitude of each individual term in the sums above can be established relatively easily. For that, we need to define in some useful way a density scale  $\tilde{\rho}$  and a velocity scale  $\tilde{u}$ . Due to (4.28) and (4.31), we will define

$$\tilde{\rho} \sim \overline{\rho_\delta} \sim \rho', \quad (4.35)$$

and

$$\tilde{u} \sim \overline{u_k}; \quad \tilde{\rho}\tilde{u} \sim \overline{\rho' u'_k}. \quad (4.36)$$

With that, one finds

$$\begin{aligned} \text{I} &\sim \frac{\tilde{\rho}\tilde{u}}{\ell}; \\ \text{II} &\sim \frac{\wp_0 \tilde{u}}{D} \sim \frac{\tilde{\rho}\tilde{u}}{\ell}; \\ \text{III} &\sim \frac{\tilde{\rho}\tilde{u}}{\ell}; \\ \text{IV} &\sim \frac{\rho_0 \tilde{u}}{\ell}; \\ \text{V} &\sim \frac{\tilde{\rho}\tilde{u}}{\ell}; \\ \text{VI} &\sim \frac{\tilde{\rho}\tilde{u}}{\ell}. \end{aligned}$$

The upshot is that all individual terms in I–III, and V–VI, are much smaller than the individual terms in IV. The *sum* of all three terms in IV must be of the same order of the other terms, whence

$$\sum_{k=1}^3 \frac{\partial \overline{u_k}}{\partial x_k} \sim \frac{\tilde{\rho}}{\rho_0} \frac{\tilde{u}}{\ell} \ll \frac{\tilde{u}}{\ell} \Rightarrow \sum_{k=1}^3 \frac{\partial \overline{u_k}}{\partial x_k} \approx 0. \quad (4.37)$$

Equation (4.37) is often first found in fluid mechanics in the context of mass conservation in an incompressible flow. Here, it is only *approximately valid* (we are in the context of the Boussinesq *approximation*); it is valid (at this point) for the mean velocity field  $\overline{\mathbf{u}}$  only; and *it does not mean that there are no density fluctuations*.

The same approach can be taken for the full momentum equation, which is (for a Newtonian fluid)

$$\begin{aligned} \left[ \frac{\partial(\rho u_i)}{\partial t} + \sum_{k=1}^3 \frac{\partial(\rho u_i u_k)}{\partial x_k} + \sum_{k=1}^3 \sum_{j=1}^3 2\epsilon_{ijk} \Omega_j u_k \right] &= \rho g_i - \frac{\partial p}{\partial x_i} + \\ &\frac{\partial}{\partial x_i} \left( \lambda \sum_{k=1}^3 \frac{\partial u_k}{\partial x_k} \right) + \nu \rho \sum_{k=1}^3 \frac{\partial s_{ik}}{\partial x_k}, \quad i = 1, \dots, 3, \end{aligned} \quad (4.38)$$

where  $\Omega$  is the angular velocity of the Earth;  $\sum_{k=1}^3 \sum_{j=1}^3 2\epsilon_{ijk} \Omega_j u_k$  is the Coriolis acceleration along  $x_i$ ;  $\mathbf{g} = (0, 0, -g)$  is the acceleration of gravity, and  $\nu$  is the kinematic viscosity. Expanding and estimating orders of magnitude for (4.38) however, is now a lengthy and somewhat tedious procedure. Perhaps the most

revealing part is the effect that the Boussinesq decomposition has on the gravity and pressure terms:

$$\begin{aligned}\rho g_i - \frac{\partial p}{\partial x_i} &= (\rho_r + \rho_\delta) g_i - \frac{\partial(p_r + p_\delta)}{\partial x_i} \\ &= \rho_\delta g_i - \frac{\partial p_\delta}{\partial x_i},\end{aligned}\quad (4.39)$$

in view of the hydrostatic equation (4.9). Equation (4.39) shows very clearly that an important part of the acceleration in the fluid is caused by the differences in buoyancy caused *Boussinesq fluctuations* in density,  $\rho_\delta$ .

If one now proceeds with the Boussinesq and Reynolds decomposition, followed by averaging and simplification with (4.33) (which we omit, but encourage the reader to undertake!), the final result is

$$\rho_r \left[ \frac{\partial \bar{u}_i}{\partial t} + \bar{u}_k \frac{\partial \bar{u}_i}{\partial x_k} + \frac{\partial \bar{u}_i \bar{u}_k}{\partial x_k} \right] - \left[ \bar{\rho}_\delta g_i - \frac{\partial \bar{p}_\delta}{\partial x_i} \right] \sim \frac{\tilde{\rho} \tilde{u}^2}{\ell}. \quad (4.40)$$

Each of the individual terms above can be shown to be  $\sim \rho_0 \tilde{u}^2 / \ell$ . The Coriolis terms, which do not appear above, are of the order of  $\rho_0 \tilde{u}^2 / (\text{Ro} \ell)$  (where  $\text{Ro} = \tilde{u} / (f \ell)$  is the Rossby number, and  $f = 2\Omega \sin(\phi)$  is the Coriolis parameter). At the scale of the flow,  $\ell$ , the Rossby number is very large and consequently Coriolis effects are negligible. For the left-hand side of (4.40), therefore, one has

$$g \tilde{\rho} \sim \rho_0 \frac{\tilde{u}^2}{\ell}, \quad (4.41)$$

$$\frac{\tilde{p}}{\ell} \sim \rho_0 \frac{\tilde{u}^2}{\ell} \Rightarrow \quad (4.42)$$

$$\tilde{p} \sim \tilde{\rho} g \ell. \quad (4.43)$$

Pressure fluctuations are extremely difficult to measure in the atmosphere. Wyngaard (2010) gives the estimate  $p' \sim \rho_0 \tilde{u}^2$ ; this is the same as (4.42). Hauf *et al.* (1996) observed values of  $p'$  of the order of 2.5 Pa, which again is the same order as given by Wyngaard. The main consequence of (4.43) is that the effects of the pressure fluctuations  $p_\delta$  and  $p'$  can often be neglected in the atmosphere.

The order of magnitude of the Boussinesq pressure fluctuations now leads to the following approximation in the state equation:

$$\begin{aligned}p &= \rho R_d T_v, \\ [p_r + p_\delta] &= [\rho_r + \rho_\delta] R_d [T_{vr} + T_{v\delta}], \\ p_r + p_\delta &\approx \rho_r R_d T_{vr} + \rho_r R_d T_{v\delta} + \rho_\delta R_d T_{vr},\end{aligned}$$

where the product  $\rho_\delta R_d T_{v\delta}$  has been neglected. By definition, the equation of state,  $p_r = \rho_r R_d T_{vr}$  holds for the hydrostatic reference state; therefore,

$$\begin{aligned}p_\delta &\approx \rho_r R_d T_{v\delta} + \rho_\delta R_d T_{vr}, \\ \underbrace{\frac{p_\delta}{p_r}}_{\sim \frac{\tilde{p}}{\rho_0}} &\approx \underbrace{\frac{T_{v\delta}}{T_{vr}}}_{\sim \frac{\tilde{T}}{T_0}} + \underbrace{\frac{\rho_\delta}{\rho_r}}_{\sim \frac{\tilde{\rho}}{\rho_0}}\end{aligned}$$



But

$$\begin{aligned}\frac{\tilde{p}}{\rho_0} &\sim \epsilon_b = 0.01 \quad \text{by definition,} \\ \frac{\tilde{p}}{p_0} &\sim \frac{2.5}{101\,325} = 2.47 \times 10^{-5} \ll 0.01.\end{aligned}$$

Therefore, the Boussinesq pressure fluctuations can be safely dismissed. This leads to a much simpler linear equation of state that does not include pressure, namely

$$\frac{\rho_\delta}{\rho_r} = -\frac{T_v \delta}{T_r}. \quad (4.44)$$

### Exercise

4.1 Using Reynolds' decomposition (2.8) and Reynolds' postulates (2.11)–(2.14), show that

$$\begin{aligned}\frac{\overline{\rho_\delta}}{\rho_r} &= -\frac{\overline{T_v \delta}}{T_r}, \\ \frac{\rho'}{\rho_r} &= -\frac{T'_v}{T_r}.\end{aligned}$$

## 4.4 – The Reynolds-averaged Navier-Stokes equations

Under the validity of the Boussinesq approximation (4.31), the mass and momentum conservation equations (4.37) and (4.40) are correct to order  $\epsilon_b$ . We are unaware of works that deal with the extension of the Boussinesq approximation to the higher-order, second-moment equations that are essential to understand the mechanics of turbulent flow, and which were introduced by O. Reynolds in 1895 (Reynolds, 1895). We will however *assume* that the equations for the turbulent fluctuations of velocity and other quantities are analogous to (4.37) and (4.40) for the means.

Under these further assumptions, application of Reynolds' decomposition (2.8) to the mass and momentum equations (4.33) and (4.38), and subtraction of the equations for means, (4.37) and (4.40), eventually results in

$$\sum_{k=1}^3 \frac{\partial u'_k}{\partial x_k} = 0 \quad (4.45)$$

$$\begin{aligned}\frac{\partial u'_i}{\partial t} + \sum_{k=1}^3 \overline{u_k} \frac{\partial u'_i}{\partial x_k} &= \sum_{k=1}^3 \left[ -u'_k \frac{\partial \overline{u_i}}{\partial x_k} - \frac{\partial u'_i u'_k}{\partial x_k} \right] - \sum_{j=1}^3 \sum_{k=1}^3 2\epsilon_{ijk} \Omega_j u'_k \\ &\quad - \frac{1}{\overline{\rho}} \frac{\partial p'}{\partial x_i} - \frac{g_i}{\theta_v} \theta'_v + 2\nu \sum_{k=1}^3 \frac{\partial s'_{ik}}{\partial x_k},\end{aligned} \quad (4.46)$$

where  $\mathbf{g} = (0, 0, -g)$  with  $g = 9.81 \text{ m s}^{-2}$ . Note that the average of (4.45) and (4.46) above is zero. Multiplication of (4.46) by  $u'_j$ , exchange of the indices  $i$  and  $j$  and summation of the two resulting equations, followed by averaging, leads

the the second-order equations

$$\begin{aligned}
\underbrace{\frac{\partial \overline{u'_i u'_j}}{\partial t}}_{\text{I}} + \underbrace{\sum_{k=1}^3 \overline{u_k} \frac{\partial \overline{u'_i u'_j}}{\partial x_k}}_{\text{II}} &= \underbrace{\sum_{k=1}^3 \left( -\overline{u'_i u'_k} \frac{\partial \overline{u_j}}{\partial x_k} - \overline{u'_j u'_k} \frac{\partial \overline{u_i}}{\partial x_k} \right)}_{\text{III}} - \underbrace{\sum_{k=1}^3 \frac{\partial \overline{u'_i u'_j u'_k}}{\partial x_k}}_{\text{IV}} \\
&\quad - \underbrace{\frac{1}{\theta_{vr}} \left[ g_i \overline{u'_j \theta'_v} + g_j \overline{u'_i \theta'_v} \right]}_{\text{V}} \\
&\quad - \underbrace{2 \sum_{k=1}^3 \sum_{l=1}^3 \Omega_l \left( \epsilon_{ilk} \overline{u'_j u'_k} + \epsilon_{jlk} \overline{u'_i u'_k} \right)}_{\text{VI}} \\
&\quad - \underbrace{\frac{1}{\rho_r} \left( \frac{\partial \overline{u'_i p'}}{\partial x_j} + \frac{\partial \overline{u'_j p'}}{\partial x_i} \right)}_{\text{VII}} - \underbrace{\frac{p'}{\rho_r} \left( \frac{\partial u'_i}{\partial x_j} + \frac{\partial u'_j}{\partial x_i} \right)}_{\text{VIII}} \\
&\quad + 2\nu \underbrace{\sum_{k=1}^3 \frac{\partial}{\partial x_k} \left[ \overline{u'_j s'_{ik}} + \overline{u'_j s'_{jk}} \right]}_{\text{IX}} \\
&\quad - 2\nu \underbrace{\sum_{k=1}^3 \left[ \overline{s'_{ik} \frac{\partial u'_j}{\partial x_k}} + \overline{s'_{jk} \frac{\partial u'_i}{\partial x_k}} \right]}_{\text{X}}
\end{aligned} \tag{4.47}$$

In (4.47),

$$s'_{ik} = \frac{1}{2} \left( \frac{\partial u'_i}{\partial x_k} + \frac{\partial u'_k}{\partial x_i} \right) \tag{4.48}$$

is the fluctuation rate of deformation.

The set (4.47) is essential to understand the physics of turbulence. We borrow from (Stull, 1988) their meanings:

- I. Is the local rate of change of the covariance  $\overline{u'_i u'_j}$ .
- II. Is the advection of  $\overline{u'_i u'_j}$  by the mean wind  $\overline{u_k}$ .
- III. Is the *gradient production/destruction term*. A loose interpretation is that the average profiles are subject to perturbations that generate large-scale structures that progressively break into smaller structures, and so on. The larger structures are anisotropic, an evidence of this fact being the very existence of the mean gradients  $\partial \overline{u_j} / \partial x_k$ , but the smaller structures (“eddies”) become more and more isotropic, and their statistics more homogeneous and stationary.
- IV. This is the *transport term*: it reflects turbulence’s *closure problem*: note that in equation (4.40) for the mean  $\overline{u_i}$  there are 2<sup>nd</sup>-order moments  $\overline{u'_i u'_k}$ ; here, in the equation for the second-order moments  $\overline{u'_i u'_j}$  the 3<sup>rd</sup>-order moments  $\overline{u'_i u'_j u'_k}$  appear, and so on *ad infinitum*. Indeed, Reynold’s decomposition always leads to more equations than unknowns to any order. In the

atmospheric boundary layer, the divergence of 3<sup>rd</sup>-order moments is often important and reflects *non-local* redistribution of covariances: it adds considerable difficulty in modeling and understanding its physics.

- V. This is the buoyancy term: the buoyancy flux  $\overline{\rho' u_j'}$  has a counterpart in the virtual sensible heat flux  $\overline{u_j' \theta_v'}$ , via the simplified equation of state (4.44) that emerges from the Boussinesq approximation. Depending on the sign of  $\overline{u_j' \theta_v'}$ , it can either produce or destroy the covariance  $\overline{u_i' u_j'}$ . Production of turbulence by buoyancy makes the atmosphere more *unstable*, and destruction makes it more *stable*.
- VI. This is the Coriolis term: it is negligible in the atmospheric boundary layer (Stull, 1988).
- VII. Like III, this is a divergence term: it is called the *pressure redistribution* term, and also like III it redistributes  $\overline{u_i' u_j'}$  without creating nor destroying covariances in the overall flow domain Tennekes and Lumley (1972).
- VIII. This is the *return to isotropy* term (Rotta, 1951a,b; Hinze, 1975; Lumley and Newman, 1977; CHOI and LUMLEY, 2001). Its sum for the 3 components  $\overline{u_1' u_1'}$ ,  $\overline{u_2' u_2'}$  and  $\overline{u_3' u_3'}$  is zero, showing that it acts to reduce the anisotropy of turbulence, and to nudge the Reynolds stress tensor  $\overline{u_i' u_j'}$  to become isotropic.
- IX. This term accounts for the molecular diffusion of  $\overline{u_i' u_j'}$ : it is very small and can be neglected.
- X. This is the viscous dissipation term. It can be shown to be small for the case  $i \neq j$  Wyngaard (1981), but is very important and always when  $i = j$ ; then, it accounts for the dissipation of turbulence kinetic energy, and is of the same order of the other important terms in (4.47), such as gradient production and buoyancy.

An equation that has a central role in the understanding of the physics (or, at least, the phenomenology) of turbulence is the turbulence kinetic energy (TKE) equation. It is obtained by setting  $i = j$  in (4.47), summing from 1 to 3, and dividing by two. The quantity

$$\bar{e} = \frac{1}{2} \sum_{i=1}^3 \overline{u_i' u_i'} \quad (4.49)$$

is the kinetic energy of the flow that is due to the turbulent velocity fluctuations.

The TKE equation is

$$\begin{aligned}
 \underbrace{\frac{\partial \bar{e}}{\partial t}}_{\text{I}} + \underbrace{\sum_{k=1}^3 \bar{u}_k \frac{\partial \bar{e}}{\partial x_k}}_{\text{II}} = & - \underbrace{\sum_{k=1}^3 \overline{u'_i u'_k} \frac{\partial \bar{u}_i}{\partial x_k}}_{\text{III}} - \underbrace{\sum_{k=1}^3 \frac{\partial \overline{e' u'_k}}{\partial x_k}}_{\text{IV}} \\
 & + \underbrace{\frac{g}{\theta_r} \overline{w' \theta'_v}}_{\text{V}} - 2 \underbrace{\sum_{i=1}^3 \sum_{k=1}^3 \sum_{l=1}^3 \epsilon_{ilk} \Omega_l \overline{u'_i u'_k}}_{\text{VI}} - \underbrace{\frac{1}{\rho_r} \sum_{i=1}^3 \left[ \frac{\partial \overline{u'_i p'}}{\partial x_i} \right]}_{\text{VII}} \\
 & + 2\nu \underbrace{\sum_{i=1}^3 \sum_{k=1}^3 \frac{\partial \overline{u'_i s'_{ik}}}{\partial x_k}}_{\text{VIII}} - 2\nu \underbrace{\sum_{i=1}^3 \sum_{k=1}^3 \overline{s'_{ik} s'_{ik}}}_{\text{IX}}. \quad (4.50)
 \end{aligned}$$

In (4.50),

I is the time rate of change of  $\bar{e}$ ;

II is the advection of  $\bar{e}$  (the advective derivative of  $\bar{e}$ );

III is the gradient production term;

IV is the transport term;

V is the buoyancy production of  $\bar{e}$ ;

VI is the (negligible) Coriolis term;

VII is the pressure redistribution term;

VIII is the (negligible) diffusive transport of  $\bar{e}$ ;

IX is the dissipation of TKE.

Note that, on account of the mass conservation equation for the fluctuations, (4.45), the return to isotropy term in (4.47) now sums to zero:

$$\sum_{i=1}^3 \overline{\frac{p'}{\rho_r} \frac{\partial u'_i}{\partial x_i}} = \overline{\frac{p'}{\rho_r} \left[ \sum_{i=1}^3 \frac{\partial u'_i}{\partial x_i} \right]} = 0. \quad (4.51)$$

Further simplification can be achieved if we assume the conditions under which the Monin-Obukhov Similarity Theory is valid: horizontal homogeneity, stationarity, mean flow along the  $x$  direction only. Then one has

$$\begin{aligned}
 0 &= -\overline{u' w'} \frac{\partial \bar{u}}{\partial z} - \frac{\partial \overline{e' w'}}{\partial z} + \frac{g}{\theta_r} \overline{w' \theta'_v} - \frac{1}{\rho_r} \frac{\partial \overline{w' p'}}{\partial z} - 2\nu \sum_{i=1}^3 \sum_{k=1}^3 \overline{s'_{ik} s'_{ik}} \\
 0 &= -\overline{u' w'} \frac{\partial \bar{u}}{\partial z} - \frac{\partial \overline{e' w'}}{\partial z} + \frac{g}{\theta_r} \overline{w' \theta'_v} - \frac{1}{\rho_r} \frac{\partial \overline{w' p'}}{\partial z} - \epsilon_e \quad (4.52)
 \end{aligned}$$

# 5

## Monin-Obukhov Similarity Theory (MOST)

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The Monin-Obukhov Similarity Theory ([Obukhov, 1946 1971](#)) — MOST for short — appeared in the Soviet Union during the Second World War. It became known in the west in the 1950's and since the 1960's it has become a standard tool for micrometeorological analysis.

### 5.1 – Physical justification

The fundamental hypotheses of the MOS theory are the following:

- The flow is near stationary on average:

$$\frac{\partial(\cdot)}{\partial t} = 0. \quad (5.1)$$

- The flow is unidirectional:

$$\bar{\mathbf{u}} = (\bar{u}, 0, 0), \quad \bar{v} = \bar{w} = 0. \quad (5.2)$$

- The flow is homogeneous in  $x$  and  $y$ , on average:

$$\frac{\partial(\cdot)}{\partial x} = \frac{\partial(\cdot)}{\partial y} = 0. \quad (5.3)$$

In these conditions, the *local advection* of any quantity in the  $x$  direction is null:

$$\bar{u} \frac{\partial(\cdot)}{\partial x} = 0. \quad (5.4)$$

In particular, the vertical fluxes of momentum  $\tau$ , sensible heat  $H$ , mass of water vapor  $E$  and greenhouse gas mass  $F$  are constant along  $x$ . These surface fluxes are the desired quantities, for example: by hydrologists interested in evaporation (or evapotranspiration) and meteorologists interested in using them as boundary conditions for their weather forecast models, atmospheric dispersion models, etc..

As seen in section [2.3.1](#), from the turbulence theory point of view, the surface fluxes are turbulence statistics, next to the surface, in which one of the

variables is the vertical velocity  $w$ :

$$\tau = \overline{\rho u_*^2} = -\overline{\rho w u} \quad (5.5)$$

$$H = \overline{\rho c_p u_* \theta_*} = \overline{\rho c_p w \theta} \quad (5.6)$$

$$E = \overline{\rho u_* q_*} = \overline{\rho_v w} \quad (5.7)$$

$$H_v = \overline{\rho c_p u_* \theta_{v*}} = \overline{\rho c_p w \theta_v} \quad (5.8)$$

$$F = \overline{\rho u_* c_*} = \overline{\rho_c w} \quad (5.9)$$

These equations define new types of *scales*: the velocity scale  $u_*$ , the temperature scale  $\theta_*$ , the specific humidity scale  $q_*$ , the greenhouse gas scale  $q_*$  and the virtual temperature scale  $\theta_{v*}$ . The latter is associated to the virtual heat flux  $H_v$ . According to what we discussed in the previous section, it is necessary to measure the turbulent statistics close to the surface.

A standard justification (but not derivation!) for Monin-Obukhov Similarity Theory can be obtained from the TKE equation with *further simplifications*. Note that in a moist atmosphere we should use the virtual temperature  $\theta_v$  for the buoyancy term. Also, assuming that all fluxes are constant with height, and that the TKE transport term and pressure terms can both be neglected, (4.52) simplifies to

$$\begin{aligned} -u_*^2 \frac{d\bar{u}}{dz} + \frac{g}{\theta_{vr}} u_* \theta_* - \epsilon_e &= 0, \\ \frac{\kappa(z-d)}{u_*} \frac{d\bar{u}}{dz} + \frac{\kappa g(z-d)\theta_{v*}}{\theta_{vr} u_*^2} - \frac{\kappa(z-d)\epsilon_e}{u_*^3} &= 0. \end{aligned} \quad (5.10)$$

In applications, one typically replaces  $\theta_{vr}$  by  $\bar{\theta}_v$ , a mean virtual temperature measured close to the surface.

The Obukhov stability variable is now defined by

$$\zeta = \frac{z-d}{L_O} = -\frac{\kappa g(z-d)\theta_{v*}}{\bar{\theta}_v u_*^2} \quad (5.11)$$

and indicates the relative magnitude of the turbulent kinetic energy production by buoyancy ( $\theta_{v*}$  appears in the numerator) and by friction ( $u_*$  appears in the denominator). In (5.11),  $d$  is the “zero plane” displacement. It takes into consideration the height of the vegetation, and establishes a level  $d$  above the ground from which the effects of the surface turbulent fluxes on the atmosphere above the vegetation are felt.

The other two terms in ( ) can now be defined as

$$\phi_\tau \equiv \frac{\kappa(z-d)}{u_*} \frac{d\bar{u}}{dz}, \quad (5.12)$$

$$\phi_{\epsilon_e} \equiv \frac{\kappa(z-d)\epsilon_e}{u_*^3}. \quad (5.13)$$

The surface layer (SL) is the region inside the atmospheric boundary layer where, roughly, the surface fluxes  $\tau$ ,  $H$ ,  $H_v$ , etc., are approximately constant with  $z$ . In other words, in principle, turbulence measurements inside the SL produce the surface fluxes. The SL has many sub-layers: the interfacial sublayer,

the roughness sublayer, the dynamic sublayer, the dynamic-convective sublayer and the local free convection sublayer. The latter, depending on the author, may or may not be considered a part of the SL. The nomenclature also varies according to the author. The three first classifications are reasonably universal (Brutsaert, 1982; Garratt, 1994); the term dynamic-convective sublayer is due to Kader and Yaglom (1990); the term free convection sublayer (or layer, depending on it being considered or not a part of the SL) is due to Wyngaard *et al.* (1971). We refer the reader to these references for details on the many sublayers of the SL.

The SL is unstable when  $\zeta < 0$ , and the buoyancy term in the turbulence kinetic energy equation contributes to produce turbulence. The SL is stable when  $\zeta > 0$ , and that term helps to destroy the turbulence. The SL is neutral when  $\zeta = 0$ .

MOST predicts that all the turbulent fluctuation moments, non-dimensionalized correctly by the proper combination of  $z$ ,  $u_*$ ,  $\theta_*$ ,  $q_*$ ,  $\theta_{v*}$  and  $c_*$ , are functions of the independent variable  $\zeta$ . For the gradients of mean quantities, (moments of order 1) these functions are

$$\frac{\kappa z}{u_*} \frac{d\bar{u}}{dz} = \phi_\tau(\zeta), \quad \frac{\kappa z}{\theta_*} \frac{d\bar{\theta}}{dz} = \phi_H(\zeta), \quad \frac{\kappa z}{q_*} \frac{d\bar{q}}{dz} = \phi_E(\zeta), \quad \frac{\kappa z}{q_*} \frac{d\bar{c}}{dz} = \phi_F(\zeta). \quad (5.14)$$

The use of the ordinary derivative  $d/dz$  in the above equations, instead of the partial derivative, simply indicates that we consider that the flow is stationary and horizontally homogeneous, so that the only independent variable (from the statistical point of view of turbulence) is  $z$ .

## 5.2 – Integration of the dimensionless gradient

Equation (5.14), which defines the dimensionless gradients of Monin-Obukhov, is equivalent to postulate turbulent diffusivities. For example, consider a turbulent flow in a boundary layer with density stratification. The turbulent diffusivity of momentum,  $K_\tau$ , is defined by analogy with the molecular diffusivity as

$$\tau \equiv \bar{\rho} K_\tau \frac{d\bar{u}}{dz}. \quad (5.15)$$

From (5.5) and (5.14), the turbulent diffusivity is

$$K_\tau = \kappa z u_* / \phi_\tau(\zeta) \quad (5.16)$$

Now, consider (5.14) for the profile of horizontal mean velocity  $\bar{u}$  and  $\zeta = 0$  ( $L_O = +\infty$ ):

$$\frac{\kappa z}{u_*} \frac{d\bar{u}}{dz} = \phi_\tau(0) = 1 \quad (5.17)$$

where the value  $\phi_\tau(0) = 1$  is classically obtained in non-stratified flows (Brut-

saert, 1982). Integrating,

$$\begin{aligned}\frac{dz}{z-d} &= \kappa \frac{d\bar{u}}{u_*} \\ \int_{x=d+z_{0\tau}}^{z-d} \frac{dx}{x-d} &= \kappa \frac{\bar{u}}{u_*} \\ \frac{\bar{u}}{u_*} &= \frac{1}{\kappa} \ln \frac{z-d}{z_{0\tau}}\end{aligned}\quad (5.18)$$

Note that the integral over  $z$  has lower limit  $d+z_{0\tau}$ , and not  $d$ , because (5.18) is valid only in the fully turbulent region of the SL, but is no longer valid at the thin interfacial sublayer IL immediately above the surface where the transport by molecular diffusion is significant. The integration constant  $z_{0\tau}$  is called the roughness length for momentum.

Equation (5.18) is the logarithmic profile of velocity that appears in turbulent boundary layers without density stratification. Clearly,  $\phi_\tau(\zeta)$  “corrects” this profile for non-null stratification ( $\zeta \neq 0$ ).

The general integration procedure for the case  $\zeta \neq 0$  is the following:

$$\begin{aligned}\frac{\kappa z}{u_*} \frac{d\bar{u}}{dz} &= \phi_\tau(\zeta), \\ \frac{\kappa \zeta}{u_*} \frac{d\bar{u}}{d\zeta} &= \phi_\tau(\zeta), \\ \phi_\tau(\zeta) \frac{d\zeta}{\zeta} &= \kappa \frac{d\bar{u}}{u_*}, \\ \int_{\zeta_1}^{\zeta_2} \frac{\phi_\tau(x) dx}{x} &= \kappa \frac{\bar{u}_2 - \bar{u}_1}{u_*},\end{aligned}\quad (5.19)$$

for  $\zeta_1 < \zeta_2$ . If

$$\Phi_\tau(\zeta) \equiv \int \frac{\phi_\tau(x) dx}{x} \quad (5.20)$$

then

$$u_* = \kappa \frac{\bar{u}_2 - \bar{u}_1}{\Phi_\tau(\zeta_2) - \Phi_\tau(\zeta_1)} \quad (5.21)$$

Similarly, integrating the dimensionless gradients of temperature, specific humidity and greenhouse effect gas concentration,

$$\theta_* = \kappa \frac{\bar{\theta}_1 - \bar{\theta}_2}{\Phi_H(\zeta_2) - \Phi_H(\zeta_1)}, \quad (5.22)$$

$$q_* = \kappa \frac{\bar{q}_1 - \bar{q}_2}{\Phi_E(\zeta_2) - \Phi_E(\zeta_1)}, \quad (5.23)$$

$$c_* = \kappa \frac{\bar{c}_1 - \bar{c}_2}{\Phi_F(\zeta_2) - \Phi_F(\zeta_1)}. \quad (5.24)$$

In the same way of the case of a neutral atmosphere ( $\zeta = 0$ ), the relations (5.14) (the first of which was used in the obtaining of (5.19)) are not valid down to  $z-d=0$ . That way, when level “1” is the surface, we use  $z_1-d=z_{0\tau}$  in (5.21),  $z_1-d=z_{0H}$  in (5.22),  $z_1-d=z_{0E}$  in (5.23) and  $z_1-d=z_{0F}$  in (5.24).



It is common to assume  $\phi_H = \phi_E = \phi_F$  in the SL. The equality of the turbulent diffusivities of heat and water vapor was supposed explicitly in the first time in the micrometeorological context by Bowen in 1926 (Brutsaert, 1982), and constantly used ever since, but this hypothesis was only proved by Hill (1989) by means of dimensional analysis, and Dias (1994) and Dias and Brutsaert (1996) from the Reynolds equations for the case of homogeneous turbulence in the vertical axis. In the following events, we will assume that the similarity functions  $\phi$  for heat and water vapor are always identical, i.e.:  $\phi_H = \phi_E = \phi_F$ . Strictly speaking,  $z_{0H}$ ,  $z_{0E}$  and  $z_{0F}$  are not equal (Brutsaert, 1982); however, we'll assume in this text that they are sufficiently close ( $z_{0H} \approx z_{0E} \approx z_{0F}$ ) for practical purposes.

### 5.3 – Classical formulas of the MOS theory

The classical profiles for the velocity  $\bar{u}$  and scalars  $(\bar{\theta}, \bar{q}, \bar{c})$  most used probably are the Businger-Dyer functions (Brutsaert, 1982). For unstable conditions ( $\zeta < 0$ ):

$$\phi_\tau^2 = \phi_H = \phi_E = \phi_F(1 - 16\zeta)^{-1/2} \quad (5.25)$$

and for stable conditions ( $\zeta > 0$ ):

$$\phi_\tau = \phi_H = \phi_E = \phi_F = 1 + 5\zeta. \quad (5.26)$$

Although there is still some discussion about the constants's values and even the form of these functions, they still represent a reasonable consent; a recent revision on the  $\phi$  profiles that are similar to the ones in this text can be found in (Högström, 1988). Stimulated by the findings of Kader and Yaglom (1990), Brutsaert (1992) suggested, for example, new formulations for unstable conditions. In stable conditions, Cheng and Brutsaert (2005) also re-evaluated the similarity functions using data from the CASES-99 experiment.

Note that in a neutral atmosphere  $\zeta = 0$ , where  $\Phi_\tau(0) = \Phi_H(0) = \Phi_E(0) = \Phi_F(0) = -\infty$ . This makes it difficult to use equations (5.21)–(5.23), because of the singularity in the denominator. Therefore, it is preferable to work with functions  $\Psi$  that define the *deviation* of  $\bar{u}$ ,  $\bar{\theta}$  and  $\bar{q}$  in relation of the logarithmic profiles due to the stability  $\zeta \neq 0$ :

$$\Psi(\zeta) \equiv \int \frac{1 - \phi}{\zeta} d\zeta = \ln |\zeta| - \Phi(\zeta). \quad (5.27)$$

Starting with  $Psi_\tau$ ,

$$\begin{aligned} \Psi_\tau(\zeta) &= \int_{\zeta_{0\tau}}^{\zeta} \frac{1 - (1 - 16u)^{-1/4}}{u} du \\ &= \int_{\zeta_{0\tau}}^{\zeta} \left[ \frac{1}{u} - \frac{1}{u(1 - 16u)^{1/4}} \right] du \end{aligned} \quad (5.28)$$

To calculate the integral, do

$$x = (1 - 16u)^{1/4}; \quad x^4 = (1 - 16u); \quad \frac{1 - x^4}{16} = u; \quad du = -\frac{u^3}{4} dx; \quad (5.29)$$

$$a = (1 - 16\zeta_{0\tau})^{1/4}; \quad b = (1 - 16\zeta)^{1/4}. \quad (5.30)$$

Then,

$$\begin{aligned}
 \Psi_\tau(\zeta) &= \int_a^b \left[ \frac{16}{1-x^4} - \frac{16}{x(1-x^4)} \right] \left( -\frac{x^3}{4} \right) dx \\
 &= 4 \int_a^b \left[ \frac{x}{x(x^4-1)} - \frac{1}{x(x^4-1)} \right] x^3 dx \\
 &= \int_a^b \frac{4(x-1)x^2}{x^4-1} dx \\
 &= \int_a^b \left[ \frac{2x}{x^2+1} - \frac{2}{x^2+1} + \frac{2}{x+1} \right] dx \\
 &= \ln(x^2+1) + 2\ln(x+1) - 2\operatorname{arctg} x \Big|_a^b. \tag{5.31}
 \end{aligned}$$

Making  $a \approx 1$ :

$$\begin{aligned}
 \Psi_\tau(b(\zeta)) &= \ln(b^2+1) + 2\ln(b+1) - 2\operatorname{arctg} b - [\ln(2) + 2\ln(2) - 2\operatorname{arctg}(1)] \\
 &= \ln \frac{b^2+1}{2} + 2\ln \frac{b+1}{2} - 2\operatorname{arctg} b + \frac{\pi}{2}. \tag{5.32}
 \end{aligned}$$

Note that  $\Psi_\tau(b=1) \equiv 0$ .

For  $\Psi_H$ :

$$\begin{aligned}
 \Psi_H(\zeta) &= \int_{\zeta_{0r}}^{\zeta} \frac{1 - (1-16u)^{-1/2}}{u} du \\
 &= \int_{\zeta_{0r}}^{\zeta} \left[ \frac{1}{u} - \frac{1}{u(1-16u)^{1/2}} \right] du \tag{5.33}
 \end{aligned}$$

Using the same change of variables (5.29)–(5.30),

$$\begin{aligned}
 \Psi_H(\zeta) &= \int_a^b \left[ \frac{16}{1-x^4} - \frac{16}{x^2(1-x^4)} \right] \left( -\frac{x^3}{4} \right) dx \\
 &= 4 \int_a^b \left[ \frac{x^2}{x^2(x^4-1)} - \frac{1}{x^2(x^4-1)} \right] x^3 dx \\
 &= \int_a^b \frac{4(x^2-1)x}{x^4-1} dx \\
 &= 2\ln(x^2+1) \Big|_a^b. \tag{5.34}
 \end{aligned}$$

Making  $a \approx 1$ :

$$\Psi_H(b(\zeta)) = 2\ln \frac{b^2+1}{2}. \tag{5.35}$$

Note that, again, we have  $\Psi_H(b=1) \equiv 0$ . Finally, in stable conditions, using (5.26):

$$\begin{aligned}
 \Psi_{\tau,H,E,F} &= \int_{\zeta_0}^{\zeta} \frac{1 - (1+5\zeta)}{\zeta} d\zeta \\
 &= -5(\zeta - \zeta_{0r,0H,0E,0F}) \approx -5\zeta. \tag{5.36}
 \end{aligned}$$

Thus, equations (5.21)–(5.23) are now written as

$$u_* = \kappa \frac{\bar{u}_2 - \bar{u}_1}{\ln \frac{\zeta_2}{\zeta_1} - [\Psi_\tau(\zeta_2) - \Psi_\tau(\zeta_1)]}, \quad (5.37)$$

$$\theta_* = \kappa \frac{\bar{\theta}_1 - \bar{\theta}_2}{\ln \frac{\zeta_2}{\zeta_1} - [\Psi_H(\zeta_2) - \Psi_H(\zeta_1)]}, \quad (5.38)$$

$$q_* = \kappa \frac{\bar{q}_1 - \bar{q}_2}{\ln \frac{\zeta_2}{\zeta_1} - [\Psi_E(\zeta_2) - \Psi_E(\zeta_1)]}, \quad (5.39)$$

$$c_* = \kappa \frac{\bar{c}_1 - \bar{c}_2}{\ln \frac{\zeta_2}{\zeta_1} - [\Psi_F(\zeta_2) - \Psi_F(\zeta_1)]}. \quad (5.40)$$

Along with (5.11), which defines  $L_O$  in terms of  $u_*$ ,  $\theta_*$ ,  $q_*$  e  $c_*$ , this provides a non-linear system in the variables  $u_*$ ,  $\theta_*$ ,  $q_*$ ,  $c_*$  and  $L_O$ , that can be iteratively solved from the measurement of the mean profiles  $\bar{u}(z)$ ,  $\bar{\theta}(z)$ ,  $\bar{q}(z)$  and  $\bar{c}(z)$ . In general, this is done postulating  $|L_O| = +\infty$  initially, where  $\Psi_{\tau,H,E,F} = 0$ ; with the values of  $u_*$ ,  $\theta_*$  and  $q_*$  obtained from the initial logarithmic profiles, we recalculate  $L_O$  e then  $\zeta_1$ ,  $\zeta_2$ , that can be used in a new estimate of the turbulent scales, and so on until the process converges.

## 5.4 – The flux-gradient method (FGM)

The transfer equations quantify the surface fluxes as a function of the differences in wind velocity, temperature, humidity and greenhouse gas between the surface and one or more measurement levels. We will assume that temperature  $\bar{\theta}_a$ , specific humidity  $\bar{q}_a$ , and mass concentration  $\bar{c}_a$  are measured at height  $z_a$ , while the wind velocity  $\bar{u}_b$  is measured at height  $z_b$ . The sub-index 0 indicates the surface. In his case, the transfer equations are

$$\tau = \bar{\rho} C_\tau \bar{u}_b^2, \quad (5.41)$$

$$H = \bar{\rho} c_p C_H \bar{u}_b (\bar{\theta}_0 - \bar{\theta}_a), \quad (5.42)$$

$$E = \bar{\rho} C_E \bar{u}_b (\bar{q}_0 - \bar{q}_a), \quad (5.43)$$

$$F = \bar{\rho} C_F \bar{u}_b (\bar{c}_0 - \bar{c}_a), \quad (5.44)$$

where  $C_\tau$ ,  $C_H$ ,  $C_E$  and  $C_F$  are *dimensionless transfer coefficients* (respectively for momentum, heat, H<sub>2</sub>O mass and (an unspecified?) gas mass). The use of the transfer equations for the estimation of surface fluxes is often called the *flux-gradient method*.

To derive (5.41)–(5.43), we start from (5.37)–(5.39). They aren't directly applicable in  $z = 0$ , for  $\ln 0 = -\infty$ ; hence, we need to assume that the values  $\bar{u}_0 = 0$ ,  $\bar{\theta}_0$ ,  $\bar{q}_0$  and  $\bar{c}_0$  in the surface occur at the corresponding roughness lengths  $z_{0\tau}$ ,  $z_{0H}$ ,  $z_{0E}$  and  $z_{0F}$ . For each quantity, we then take level 1 as being equal to its roughness length, and level 2 as being equal to its measurement level. At level 1, the roughness lengths are very small, so that it is reasonable to write

$$\frac{z_{0\tau}}{L_O} \approx 0, \quad \frac{z_{0H}}{L_O} \approx 0, \quad \frac{z_{0E}}{L_O} \approx 0, \quad \frac{z_{0F}}{L_O} \approx 0, \quad (5.45)$$

whence

$$\Psi\left(\frac{z_{0r}}{L_O}\right) \approx 0, \quad \Psi\left(\frac{z_{0H}}{L_O}\right) \approx 0, \quad \Psi\left(\frac{z_{0E}}{L_O}\right) \approx 0, \quad \Psi\left(\frac{z_{0F}}{L_O}\right) \approx 0. \quad (5.46)$$

Using (5.5)–(5.7) and (5.37)–(5.40):

$$\tau = \bar{\rho} \frac{\kappa^2}{\left[\ln \frac{z_b-d}{z_{0r}} - \Psi_\tau\left(\frac{z_b-d}{L_O}\right)\right]^2} \bar{u}_b^2, \quad (5.47)$$

$$H = \bar{\rho} c_p \frac{\kappa^2}{\left[\ln \frac{z_b-d}{z_{0r}} - \Psi_\tau\left(\frac{z_b-d}{L_O}\right)\right] \left[\ln \frac{z_a-d}{z_{0H}} - \Psi_H\left(\frac{z_a-d}{L_O}\right)\right]} \bar{u}_b (\bar{\theta}_0 - \bar{\theta}_a), \quad (5.48)$$

$$E = \bar{\rho} \frac{\kappa^2}{\left[\ln \frac{z_b-d}{z_{0r}} - \Psi_\tau\left(\frac{z_b-d}{L_O}\right)\right] \left[\ln \frac{z_a-d}{z_{0E}} - \Psi_E\left(\frac{z_a-d}{L_O}\right)\right]} \bar{u}_b (\bar{q}_0 - \bar{q}_a), \quad (5.49)$$

$$F = \bar{\rho} \frac{\kappa^2}{\left[\ln \frac{z_b-d}{z_{0r}} - \Psi_\tau\left(\frac{z_b-d}{L_O}\right)\right] \left[\ln \frac{z_a-d}{z_{0F}} - \Psi_E\left(\frac{z_a-d}{L_O}\right)\right]} \bar{u}_b (\bar{c}_0 - \bar{c}_a). \quad (5.50)$$

The penultimate equation above is, naturally, “Dalton’s Law”. In the same way that occurs in the energy balance method, it is more commonly written with vapor pressure  $e$  instead of the specific humidity  $q$ ,

$$E = \frac{0,622\bar{\rho}}{\bar{p}} \frac{\kappa^2}{\left[\ln \frac{z_b-d}{z_{0r}} - \Psi_\tau\left(\frac{z_b-d}{L_O}\right)\right] \left[\ln \frac{z_a-d}{z_{0E}} - \Psi_E\left(\frac{z_a-d}{L_O}\right)\right]} \bar{u}_b (\bar{e}_0 - \bar{e}_a). \quad (5.51)$$

This equation should be compared with many empirical formulas of evaporation of the nineteenth century and the first half of the twentieth century, of the kind

$$E = (a + b\bar{u})(\bar{e}_0 - \bar{e}_a). \quad (5.52)$$

From the micrometeorological point of view,  $a$  does not have physical meaning (*i.e.*: shouldn’t be in the equation) if (5.52) is used over time scales that are not compatible with atmospheric turbulence, between 30 minutes and one hour. Historically, however, we find that equations like (5.52) are widely used at the daily and monthly scales. Finally notice that, strictly speaking,  $b$  is not constant; for fixed measurement heights  $z_a$  and  $z_b$  and roughness lengths (note that the surface roughness can vary over an agricultural area, or with wind direction),  $b$  still depends on the MO stability length, which varies in a (semi-)hourly scale along the day.

Os momentos de ordem 2 mais relevantes são

$$\frac{\overline{w'w'}}{u_*^2} = \phi_{ww}(\zeta) \quad \frac{\overline{\theta'\theta'}}{\theta_*^2} = \phi_{\theta\theta}(\zeta) \quad \frac{\overline{q'q'}}{q_*^2} = \phi_{qq}(\zeta) \quad (5.53)$$

e

$$\frac{\overline{w'p'}}{\bar{\rho}u_*^3} = \phi_{wp}(\zeta), \quad \frac{\kappa z \epsilon_e}{u_*^3} = \phi_{\epsilon_e}(\zeta) \quad (5.54)$$

e alguns momentos de ordem 3 importantes são

$$\frac{\overline{w'e'}}{u_*^3} = \phi_{we}(\zeta) \quad \frac{\overline{w'\theta'\theta'}}{u_*\theta_*^2} = \phi_{w\theta\theta}(\zeta) \quad \frac{\overline{w'q'q'}}{u_*q_*^2} = \phi_{wqq}(\zeta) \quad (5.55)$$

Voltando agora à equação (??) vemos que ela pode ser totalmente escrita em termos dos  $\phi$ 's de Monin-Obukhov:

$$0 = \phi_\tau - \frac{1}{2}\kappa\zeta \frac{\partial \phi_{we}}{\partial \zeta} - \zeta - \kappa\zeta \frac{\partial \phi_{wp}}{\partial \zeta} - \phi_{\epsilon_e} \quad (5.56)$$

Outro processo totalmente análogo é a produção/dissipação de variância de um escalar — por exemplo, a temperatura.

Fazendo-se  $i = j = 4$  em (4.47), *sem que isto implique em somatório*, obtém-se

$$0 = -2 \overline{w'\theta'} \frac{\partial \bar{\theta}}{\partial z} - \frac{\partial \overline{w'\theta'\theta'}}{\partial z} - 2\epsilon_{\theta\theta} \quad (5.57)$$

(observe a analogia com a equação de balanço de energia cinética turbulenta), a qual pode ser adimensionalizada pelo produto com  $(\kappa z)/(u_*^2 \theta_*)$ , do que resulta

$$0 = 2\phi_H - \kappa\zeta \frac{\partial \phi_{w\theta\theta}}{\partial \zeta} - 2\phi_{\epsilon_{\theta\theta}} \quad (5.58)$$

Novamente, o mesmo quadro de produção por gradientes versus destruição por viscosidade molecular pode ser imaginado.

Como toda teoria baseada em Análise Dimensional, a teoria SMO é incapaz, em princípio, de nos fornecer a forma analítica das funções  $\phi$ . Estas entretanto podem ser mais ou menos bem determinadas experimentalmente. Uma vez conhecidas, as funções  $\phi$  abrem caminho para um grande número de técnicas com as quais é possível “inverter o jogo”, e determinar  $u_*$ ,  $\theta_*$  e  $q_*$  e portanto calcular os fluxos superficiais  $\tau$ ,  $H$  e  $E$  que são os objetos últimos de interesse no caso de modelos de previsão atmosférica e em Hidrologia. Este é o conteúdo da próxima seção.

## 5.5 – Aplicações clássicas

### 5.5.1 – O método do balanço de energia-razão de Bowen

Considere uma superfície sobre a qual incide uma irradiância líquida  $R_l$  [ $\text{W m}^{-2}$ ]. Na literatura micrometeorológica, o termo “radiação líquida” é mais comum. O conceito de radiação líquida já envolve as complexidades da incidência, reflexão e emissão da radiação em diversos comprimentos de onda. Esta energia disponível na superfície é utilizada de três maneiras:

- para aquecer/resfriar o ar, sob a forma do fluxo de calor sensível  $H$ ;
- para evaporar/condensar a umidade da superfície; se o calor latente de evaporação é  $L$ , o fluxo de calor latente associado é  $LE$ ; e
- para aquecer/resfriar as camadas sub-superficiais, por meio do fluxo de calor sub-superficial  $G$ .

A equação de balanço de energia da superfície é

$$R_l = H + LE + G \quad (5.59)$$

Das equações definidoras dos fluxos superficiais (5.5)–(5.7), e das equações para os perfis médios (5.22) e (5.23), segue-se que, debaixo da hipótese  $\phi_H = \phi_E$  mencionada na seção anterior, a *razão de Bowen*  $B_o$  é dada por

$$B_o = \frac{H}{LE} = \frac{c_p}{L} \frac{\bar{\theta}_1 - \bar{\theta}_2}{\bar{q}_1 - \bar{q}_2} \quad (5.60)$$

Das equações de estado para ar seco e vapor de água, (??), (??) e (??), obtém-se a fórmula bem conhecida

$$q \approx 0,622 \frac{e}{p} \quad (5.61)$$

donde

$$B_o = \frac{c_p p}{\underbrace{0,622 L}_\gamma} \frac{\bar{\theta}_1 - \bar{\theta}_2}{\bar{e}_1 - \bar{e}_2} \quad (5.62)$$

em termos das pressões parciais de vapor de água  $\bar{e}$ ;  $\gamma$  é a “constante psicrométrica”. Segue-se que é possível calcular  $LE$  como

$$LE = \frac{R_l - G}{1 + \gamma \frac{\bar{\theta}_1 - \bar{\theta}_2}{\bar{e}_1 - \bar{e}_2}} \quad (5.63)$$

que é a equação do método do balanço de energia-razão de Bowen para o cálculo de  $E$ .

### 5.5.2 – Medição de umidade do ar

Um segundo exemplo, mais corriqueiro, é a medição de umidade do ar por psicrômetros aspirados. Se calcularmos o balanço de energia para o bulbo úmido de um termômetro à temperatura  $\bar{\theta}_h$  sobre o qual sopra ar à temperatura  $\bar{\theta}_a$  do bulbo seco,  $R_l - G = 0 \Rightarrow B_o = -1$ ; a umidade do ar em contato com o bulbo úmido é dada pela pressão de saturação de vapor de água à temperatura do bulbo úmido,  $e^*(\bar{\theta}_h)$ , e a umidade do ar que se deseja medir é  $\bar{e}_a$ . De (5.60), então,

$$\begin{aligned} -1 &= \gamma \frac{\bar{\theta}_h - \bar{\theta}_a}{e^*(\bar{\theta}_h) - \bar{e}_a} \\ \bar{e}_a - e^*(\bar{\theta}_h) &= -\gamma (\bar{\theta}_a - \bar{\theta}_h) \\ \bar{e}_a &= e^*(\bar{\theta}_h) - \gamma (\bar{\theta}_a - \bar{\theta}_h) \end{aligned} \quad (5.64)$$

que é a equação de um psicrômetro aspirado.

### 5.5.3 – Momentos de 2ª ordem

Para os momentos de 2ª ordem na CS, valem as seguintes formulações (Tillman, 1972; Hicks, 1981; Wesely, 1988):

$$\phi_{ww}^{1/2} = \begin{cases} 1.3(1 - 2\zeta)^{1/3} & \zeta > 0 \\ 1.3 & \zeta \leq 0 \end{cases} \quad (5.65)$$

$$\phi_{\theta\theta}^{1/2} = \phi_{qq}^{1/2} = \begin{cases} (2 - \zeta)^{-1/3} & \zeta > 0 \\ 2 & \zeta \leq 0 \end{cases} \quad (5.66)$$

O leitor deve notar que as constantes que aparecem nessas equações, bem como sua própria forma, são ajustadas empiricamente e podem variar consideravelmente de autor para autor. Os valores, assim como as formas funcionais, apresentados acima tentam ser um consenso entre diversos resultados.

## 5.6 – Atmosferas muito estáveis e muito instáveis

### 5.6.1 – Estratificação independente de $z$

O efeito da estabilidade atmosférica é criar uma força restauradora de empuxo que tende a retornar parcelas de ar deslocadas verticalmente às suas posições de equilíbrio. Isto significa que numa atmosfera fortemente estratificada a turbulência é *destruída* pelas forças de empuxo. Quanto mais estável a atmosfera, menores são as excursões verticais permitidas às parcelas de ar, com a consequência de que  $z$  deixa de ser uma escala relevante do problema. Outra maneira de ver isto é assumir que as estatísticas da turbulência são independentes de  $z$ , ou seja: a turbulência é *homogênea* na vertical. A consequência desta situação na equação de balanço de energia cinética turbulenta, (??), é imediata: as derivadas em relação a  $z$  das momentos  $\overline{w'e'}$  e  $\overline{\theta'q'}$  são nulas, enquanto que  $\overline{w'w'}$ ,  $\overline{w'\theta'_v}$  e  $\epsilon_e$  que também são momentos turbulentos, devem ser independentes de  $z$ . Logo, a derivada de  $\overline{u}$  em relação a  $z$  também não pode ser função de  $z$ , donde  $\partial\overline{u}/\partial z = \text{constante}$ , e o perfil de velocidade média é linear. Naturalmente, tem que haver uma transição do perfil logaritmico em condições neutras para o perfil linear em condições fortemente estáveis: isto é o que expressam as fórmulas (5.36) do perfil log-linear. O mesmo raciocínio pode ser aplicado para as equações de balanço de  $\overline{\theta'\theta'}$  e  $\overline{q'q'}$ , com o resultado de que  $\partial\overline{\theta}/\partial z$  e  $\partial\overline{q}/\partial z$  também são constantes em condições de estratificação independente de  $z$ . No que concerne aos momentos de ordem 2 em condições estáveis, a previsão teórica passa a ser

$$\phi_{ww} = \text{cte} \quad \phi_{\theta\theta} = \text{cte} \quad \phi_{qq} = \text{cte} \quad (5.67)$$

Isto está de acordo com as formas de (5.65) e (5.66) na região estável. Entretanto, evidências muito recentes (Pahlow *et al.*, 2001) sugerem que estas funções de similaridade de Monin-Obukhov voltam a crescer para valores de  $\zeta$  muito grandes.

### 5.6.2 – Convecção livre local

No topo da CS, a influência da produção de energia cinética turbulenta por gradiente tende a se reduzir, porque  $\partial\overline{u}/\partial z \downarrow 0$ , já que o perfil de velocidade tende a ser muito mais uniforme na camada convectiva CC sobrejacente; o mesmo acontece com a produção de variância  $\overline{\theta'\theta'}$  e com o perfil de temperatura média  $\overline{\theta}$ . A importância da velocidade de atrito  $u_*$  nestas condições desaparece, e se torna necessário encontrar uma outra escala de velocidade representativa destas condições locais. Considere portanto um balanço de energia cinética turbulenta altamente simplificado e irrealista, no qual se retém entre tanto uma característica física fundamental do topo da CS: a produção por empuxo e a dissipação molecular devem ser da mesma ordem de grandeza:

$$\frac{g}{\theta_v} \overline{w'\theta'_v} \sim \epsilon_e \quad (5.68)$$

Ao multiplicarmos ambos os lados pela escala de comprimento  $z$  “natural” do problema, obtemos

$$1 \sim \frac{z\epsilon_e}{\left[ \frac{zg \overline{w'\theta'_v}}{\overline{\theta_v}} \right]} \quad (5.69)$$

e agora, por analogia com  $\phi_{\epsilon_e} = \kappa z \epsilon_e / u_*^3$  fica fácil identificar a escala convectiva de velocidade

$$w_* = \left[ \frac{zg \overline{w'\theta'_v}}{\overline{\theta_v}} \right]^{1/3} \quad (5.70)$$

É preciso compreender que o conceito de convecção livre local não implica que  $u_* = 0$ , mas sim que a importância relativa do termo de produção de turbulência por gradiente é assintoticamente decrescente. De fato,  $u_* \neq 0$  na CS sempre, e é possível formar o grupo adimensional

$$\frac{w_*}{u_*} = \frac{1}{\sqrt[3]{\kappa}} \left[ \frac{\kappa z g u_* \overline{\theta_v}}{\overline{\theta_v} u_*^3} \right]^{1/3} = \frac{1}{\sqrt[3]{\kappa}} \left( \frac{-z}{L_O} \right)^{1/3} \quad (5.71)$$

Da mesma maneira que  $z, g, \overline{w'\theta'_v}$  e  $\overline{\theta_v}$  formam uma escala de velocidade convectiva  $w_*$ ,  $z, g, \overline{w'\theta'}$  e  $\overline{\theta}$  são capazes de formar uma escala de temperatura convectiva, que nós chamaremos de  $\vartheta_*$ . Para vermos isso, lançamos mão do balanço de variância de temperatura turbulento sem o termo de produção por gradiente,

$$-\frac{\partial \overline{w'\theta'\theta'}}{\partial z} - 2\epsilon_{\theta\theta} = 0 \quad (5.72)$$

Ambos os termos têm que ser estimados. Uma análise clássica de ordem de grandeza dos momentos turbulentos envolvidos ([Tennekes and Lumley, 1972](#)) fornece:

$$-\frac{\partial \overline{w'\theta'\theta'}}{\partial z} \sim \frac{\overline{w'\theta'} \vartheta_*}{z} \quad (5.73)$$

$$\epsilon_{\theta\theta} \sim \frac{w_* \vartheta_*^2}{z} \quad (5.74)$$

substituindo estas estimativas em (5.72) obtém-se

$$\vartheta_* = \left[ \frac{(\overline{w'\theta'})^2 \overline{\theta}}{zg} \right]^{1/3} \quad (5.75)$$

Novamente, é possível relacionar a “nova” escala  $\vartheta_*$  com a “velha” escala  $\theta_*$ ,

$$\frac{\vartheta_*}{\theta_*} = \kappa^{1/3} \left( \frac{-z}{L_O} \right)^{-1/3} \quad (5.76)$$

Vale a pena analisar o que acontece com diversas funções de similaridade neste limite; por exemplo,

$$\begin{aligned} \phi_\tau &= \frac{\kappa z}{u_*} \frac{\partial \overline{u}}{\partial z} \\ &= \frac{\kappa z w_*}{u_* w_*} \frac{\partial \overline{u}}{\partial z} \\ &= \frac{\kappa z}{w_*} \frac{\partial \overline{u}}{\partial z} \frac{1}{\sqrt[3]{\kappa}} (-\zeta)^{1/3}. \end{aligned} \quad (5.77)$$



Se nós supusermos que  $w_*$  é uma grandeza natural para definir a escala do gradiente de velocidade média nesta região (Garratt (1994) faz o mesmo),

$$\frac{\partial \bar{u}}{\partial z} \sim \frac{w_*}{z} \quad (5.78)$$

e, no limite de convecção livre,

$$\phi_\tau(\zeta) = \text{cte}(-\zeta)^{1/3}. \quad (5.79)$$

No caso de  $\phi_{H_v}$ ,

$$\begin{aligned} \phi_{H_v} &= -\frac{\kappa z}{\theta_{v*}} \frac{\theta_{v*}}{\theta_{v*}} \frac{\partial \bar{\theta}_v}{\partial z} \\ &= -\frac{\kappa z}{\vartheta_*} \frac{\partial \bar{\theta}_v}{\partial z} (-\zeta)^{-1/3}. \end{aligned} \quad (5.80)$$

Supondo, de forma análoga ao que fizemos com  $w_*$ , que  $\vartheta_*$  é uma escala válida para o gradiente de temperatura potencial virtual nesta região,

$$\frac{\partial \bar{\theta}_v}{\partial z} \sim \frac{\vartheta_*}{z}, \quad (5.81)$$

donde

$$\phi_{H_v} = \text{cte}(-\zeta)^{-1/3}. \quad (5.82)$$

Da mesma forma, os momentos de 2ª ordem de  $w$  e  $\theta_v$  produzem

$$\phi_{ww} = \frac{\overline{w'w'}}{w_*^2} \left( \frac{w_*}{u_*} \right)^2 = \text{cte} \left( \frac{-z}{L_O} \right)^{2/3} \quad (5.83)$$

$$\phi_{\theta\theta} = \frac{\overline{\theta'\theta'}}{\vartheta_*^2} \left( \frac{\vartheta_*}{\theta_*} \right)^2 = C_{\theta\theta}^2 \left( \frac{-z}{L_O} \right)^{-2/3} \quad (5.84)$$

Novamente, note que a forma de (5.65) e (5.66) é assintoticamente correta e corresponde às equações (5.65) e (5.66) acima.

Note também que  $w_*$  já tem a altura  $z$  “embutida” em sua definição; assim, enquanto que a Teoria de Similaridade de Monin-Obukhov trabalha com quatro escalas,

$$u_*, \quad \theta_{v*}, \quad g/\bar{\theta}_v \quad \text{e} \quad z,$$

em condições de convecção livre nós “perdemos”  $u_*$ , ficando com

$$g/\bar{\theta}_v, \quad z \quad \text{e} \quad \overline{w'\theta'_v}|_0.$$

Em particular, isto significa que

$$\frac{\overline{w'w'}}{w_*^2} = \text{cte} \quad (\text{e independente de } u_*). \quad (5.85)$$

Consequentemente, não se pode mais usar  $\overline{w'w'}$  para estimar  $u_*$  em condições de convecção livre.

## 5.7 – O método da variância

Existem muitas maneiras de calcular os fluxos  $\tau$ ,  $H$  e  $E$  a partir de medições micrometeorológicas. Nós já vimos duas delas: o método do balanço de energia – razão de Bowen, e o método de medição de perfis médios. Ambos utilizam apenas grandezas médias. A medição “direta” de fluxos consiste em medir as flutuações turbulentas  $w'$ ,  $u'$ ,  $\theta'$  e  $q'$  com instrumentos de resposta rápida (frequências de medição típicas situam-se entre 10 e 100 Hz). Estas entretanto são medidas caras e difíceis, que ainda não podem ser feitas rotineiramente. Por outro lado, os métodos baseados em medição de perfis médios sofrem do fato de que as diferenças de temperatura  $\bar{\theta}_1 - \bar{\theta}_2$  na CS podem ser de apenas alguns décimos, ou mesmo centésimos, de Kelvin. “Um híbrido” muito interessante é a estimativa de  $u_*$  e  $\theta_*$  por meios diferentes. Por exemplo, pode-se estimar  $u_*$  a partir de medidas de velocidade média do vento  $\bar{u}$  em dois níveis, com 2 anemômetros, por meio de (5.37), e medir apenas as flutuações de temperatura  $\theta'$ , obtendo

$$\theta_* = \sqrt{\frac{\overline{\theta'\theta'}}{\phi_{\theta\theta}}} \quad (5.86)$$

e então calcular  $H$  por meio de (8.13). Este método, que é uma das variantes do método da variância (Tillman, 1972; Hicks, 1981; Wesely, 1988) obviamente envolve algumas iterações partindo do perfil logaritmico, da mesma forma que no caso de medição de perfis médios. Ele apresenta uma considerável economia em relação a medições turbulentas de fluxo, e é um candidato a um sistema contínuo de monitoramento de fluxos superficiais Kustas *et al.* (1994).

O método original de Tillman (1972) envolvia também o conhecimento da assimetria da temperatura:

$$\gamma_\theta \equiv \frac{\overline{\theta^3}}{\sigma_\theta^3}. \quad (5.87)$$

Tillman (1972) constatou que  $\gamma_\theta$  depende de  $\zeta$ . Supondo-se a validade da Teoria de Similaridade de Monin-Obukhov, isto pode ser previsto:

$$\begin{aligned} \gamma_\theta &= \frac{\overline{\theta^3}}{\sigma_\theta^3} \\ &= \frac{\overline{\theta^3}}{\theta_*^3} \frac{\theta_*^3}{\sigma_\theta^3} \\ &= \phi_{\theta\theta\theta} [\phi_{\theta\theta}]^{-3/2}. \end{aligned} \quad (5.88)$$

A relação obtida por Tillman é

$$\zeta = -A \exp(B\gamma_\theta), \quad (5.89)$$

com  $A = 0,0137$ ,  $B = 4,39$ . Seja agora uma relação de variância para a temperatura na forma (Dias *et al.*, 2009)

$$\frac{\sigma_\theta}{\theta_*} = A(1 + B|\zeta|)^{-1/3}; \quad (5.90)$$

rearranjando a equação:

$$\begin{aligned} \frac{\sigma_\theta}{H} \wp c_p u_* &= A(1 + B|\zeta|)^{-1/3} \\ \sigma_\theta(1 + B|\zeta|)^{1/3} &= A \frac{H}{\wp c_p u_*} \end{aligned} \quad (5.91)$$

Mas

$$\begin{aligned} \frac{1}{L} &= -\frac{\kappa g H}{\wp c_p \bar{\Theta} u_*^3} \Rightarrow \\ u_*^3 &= -\frac{\kappa g}{\bar{\Theta}} \frac{H}{\wp c_p} L \Rightarrow \\ u_* &= \left[ \frac{\kappa g}{\bar{\Theta}} \right]^{1/3} \left[ \frac{H}{\wp c_p} \right]^{1/3} (-L)^{1/3}. \end{aligned} \quad (5.92)$$

Substituindo-se (5.92) em (5.91):

$$\begin{aligned} \sigma_\theta(1 + B|\zeta|)^{1/3} &= A \frac{H}{\wp c_p} \left[ \frac{\bar{\Theta}}{\kappa g} \right]^{1/3} \left[ \frac{\wp c_p}{H} \right]^{1/3} \left[ \frac{-1}{L} \right]^{1/3} \\ &= A \left[ \frac{H}{\wp c_p} \right]^{2/3} \left[ \frac{\bar{\Theta}}{\kappa g} \right]^{1/3} \left[ \frac{-1}{L} \right]^{1/3} \Rightarrow \\ \left[ \frac{H}{\wp c_p} \right]^{2/3} &= \frac{\sigma_\theta}{A} (1 + B|\zeta|)^{1/3} \left[ \frac{\kappa g}{\bar{\Theta}} \right]^{1/3} \left[ \frac{1}{|\zeta|} \right]^{1/3} \Rightarrow \\ \frac{H}{\wp c_p} &= \left[ \left( \frac{\sigma_\theta}{A} \right)^3 \left( \frac{\kappa g}{\bar{\Theta}} \right) \left( \frac{1 + B|\zeta|}{|\zeta|} \right) \right]^{1/2}. \end{aligned} \quad (5.93)$$

Esta é uma equação quase milagrosa, pois ela mostra que é possível calcular  $H$  desde que se conheça  $\sigma_\theta$  e  $|\zeta|$ , em condições instáveis. O método é interessante e promissor, e a questão é estendê-lo para outros escalares, e verificar qual é a melhor forma de se estimar  $\zeta$ : se com a assimetria da própria medição de temperatura, ou se com dados da velocidade média  $\bar{U}$  (ver esta última alternativa em [Dias et al. \(2009\)](#)).

## 5.8 – Número de Richardson

Considere a razão dos termos de produção de energia cinética turbulenta por empuxo e por gradiente:

$$R_f \equiv \frac{\frac{g}{\bar{\theta}_v} \overline{w' \theta'_v}}{\overline{u'_i u'_k} \frac{\partial \bar{u}_i}{\partial x_k}}; \quad (5.94)$$

Se a turbulência é homogênea na horizontal e não há efeitos verticais significativos,

$$R_f = \frac{\frac{g}{\bar{\theta}_v} \overline{w' \theta'_v}}{\overline{w' u'} \frac{\partial \bar{u}}{\partial z} + \overline{w' v'} \frac{\partial \bar{v}}{\partial z}}. \quad (5.95)$$

Esta é a forma usual do *Número de Richardson para fluxos*. Agora, se supusermos que todos os fluxos turbulentos cinemáticos podem ser escritos em termos de uma difusividade turbulenta comum  $K$ ,

$$\overline{w'\theta'_v} = K \frac{\partial \bar{\theta}_v}{\partial z}, \quad (5.96)$$

$$\overline{w'u'} = K \frac{\partial \bar{u}}{\partial z}, \quad (5.97)$$

$$\overline{w'v'} = K \frac{\partial \bar{v}}{\partial z}, \quad (5.98)$$

o número de Richardson se “transforma” em

$$R_g \equiv \frac{\frac{g}{\theta_v} \frac{\partial \bar{\theta}_v}{\partial z}}{\left(\frac{\partial \bar{u}}{\partial z}\right)^2 + \left(\frac{\partial \bar{v}}{\partial z}\right)^2}. \quad (5.99)$$

Esta é a forma usual do *Número de Richardson para gradientes*.

## 5.9 – Sobre a consistência da aplicação de análise dimensional direcional à camada superficial

### 5.9.1 – Introdução

Num trabalho de grande importância teórica e grande volume de dados experimentais até então inéditos, [Kader and Yaglom \(1990\)](#) (daqui para frente, K&Y-1990) reintroduziram o conceito de análise dimensional direcional (ADD) em micrometeorologia, corroborando-o fartamente com medições realizadas no sítio de Tsimlyansk (atual Rússia) em condições extremamente instáveis no topo da camada superficial (CS). A essência da formulação teórica de [Kader and Yaglom](#) é a consideração de que os comprimentos ao longo da direção  $x$  e os comprimentos ao longo da direção  $z$  (as condições sendo uniformes e a turbulência, homogênea, em  $y$ ) possuem dimensões físicas diferentes,  $L_x$  e  $L_z$ .

Para entendermos a análise dimensional direcional em ação de maneira simples, vamos considerar o momento de inércia de um retângulo de base  $b$  e altura  $h$  em relação ao seu centróide em torno do eixo  $x$ , com  $b$  paralelo a  $Ox$  e  $h$  paralelo a  $Oy$ ; o seu valor é  $I_{xx} = bh^3/12$ . A menos do coeficiente  $1/12$ , deveria ser possível obter esta fórmula por meio de análise dimensional; entretanto, mesmo que nos atenhamos a expoentes inteiros, é impossível distinguir entre  $b^4$ ,  $bh^3$ ,  $b^2h^2$ ,  $b^3h$  e  $h^4$  no contexto de análise dimensional tradicional, uma vez que todas estas fórmulas possuem as mesmas dimensões ( $L^4$ ). Já se supusermos que  $[b] = L_x$ ,  $[h] = L_y$ , e  $[I_{xx}] = L_x L_y^3$ , a obtenção da forma correta é imediata.

De volta a K&Y-1990, algumas de suas consequências instigantes são: (a) algumas “constantes” de análise dimensional tradicional passam a possuir dimensões; notadamente, para a constante de von Kármán,  $[\kappa] = L_z^{1/2} L_x^{-1/2}$ ; (b) passa a ser possível subdividir (e classificar) racionalmente a CS em sub-camada dinâmica (SDN), sub-camada dinâmico-convectiva (SDC) e sub-camada de convecção livre (SCL); em cada uma destas sub-camadas a forma da função de similaridade é determinada a menos de uma constante; (c) na SDC, surge uma nova escala de velocidade  $u_{**}$  com dimensões  $L_x T^{-1}$  que deve ser utilizada *apenas*

para adimensionalizar os gradientes de velocidade horizontal média  $d\bar{u}$  e as flutuações de velocidade horizontal  $u'$ .

Zilitinkevich (1994) (daqui para frente Z-1994) propôs uma versão diferente de ADD, em que a dimensão de uma grandeza é função não de sua direção no espaço, mas da origem de sua produção. Essencialmente, ele decompõe cada flutuação turbulenta de velocidade  $u'$  e  $w'$  em uma componente produzida mecanicamente e outra produzida pela convecção. Embora a interpretação de direcionalidade seja radicalmente diferente da de K&Y-1990, os resultados de Z-1994 em termos de funções de similaridade são muito parecidos. Na sequência será dada preferência à abordagem de K&Y-1990, por ser mais clara e mais simples. Conforme será mostrado, ambas as abordagens produzem resultados intrinsecamente inconsistentes entre as 3 sub-camadas da CS, apesar de seu sucesso em explicar o comportamento das funções de similaridade.

O objetivo deste trabalho *não* é apresentar resultados experimentais *nem* uma teoria totalmente nova sobre o comportamento da CS: os comportamentos das funções de similaridade são rigorosamente os mesmos de K&Y-1990. Deseja-se enfatizar as inconsistências da teoria (extremamente bem-sucedida!) de K&Y-1990: justamente devido ao seu sucesso, acreditamos que ela merece ser formulada de maneira consistente para toda a CS. Para que isto seja feito, é necessário (a) explicitar as escalas individuais dos 2 escalares mais importantes na atmosfera, temperatura e umidade, e (b) introduzir escalas de velocidade horizontal adicionais na SDN e na SCL no papel de variáveis independentes ou de controle nas formulações de análise dimensional. Esta tarefa não é elementar para a SCL, onde nos limitamos a estabelecer as condições que uma escala adequada de velocidade horizontal deve possuir.

Kader e Yaglom dão a seguinte definição, potencialmente muito útil, para a camada superficial:

$$z \lesssim 50 \text{ m} \quad \text{e} \quad z \lesssim 0,1z_i \quad (5.100)$$

Nesta região, os balanços para *cada componente* da energia cinética turbulenta são

$$-\overline{w'u'} \frac{d\bar{u}}{dz} + \frac{1}{\bar{\rho}} \overline{p' \frac{\partial u'}{\partial x}} = \epsilon_{uu} + \frac{1}{2} \frac{\partial}{\partial z} (\overline{u'u'w'}), \quad (5.101)$$

$$\frac{1}{\bar{\rho}} \overline{p' \frac{\partial v'}{\partial y}} = \epsilon_{vv} + \frac{1}{2} \frac{\partial}{\partial z} (\overline{v'v'w'}), \quad (5.102)$$

$$\frac{g}{\bar{\theta}_v} \overline{w'\theta'_v} + \frac{1}{\bar{\rho}} \overline{p' \frac{\partial w'}{\partial z}} = \epsilon_{ww} + \frac{1}{2} \frac{\partial}{\partial z} \left( \overline{w'w'w'} + \frac{2}{\bar{\rho}} \wp \right), \quad (5.103)$$

onde os termos envolvendo flutuações de pressão no lado esquerdo são responsáveis pela redistribuição direcional de energia; repare que a sua soma é

$$\frac{1}{\bar{\rho}} \left[ \overline{p' \left( \frac{\partial u'}{\partial x} + \frac{\partial v'}{\partial y} + \frac{\partial w'}{\partial z} \right)} \right] = 0, \quad (5.104)$$

em virtude da equação da continuidade. Note que a soma de (5.101)–(5.103) recupera a equação de balanço de energia cinética turbulenta.

### 5.9.2 – A sub-camada dinâmica e as escalas individuais de temperatura e umidade

Na teoria clássica de similaridade de Monin-Obukhov, a sub-camada dinâmica é identificada como a região da camada superficial onde os efeitos de estratificação de densidade e produção convectiva de turbulência são desprezíveis diante da produção mecânica. Isto significa que o parâmetro de fluabilidade  $\beta = g/\bar{\theta}_v$  não entra na lista das variáveis que determinam as características da turbulência, as quais ficam então reduzidas aos fluxos cinemáticos de quantidade de movimento,  $-\overline{w'u'}$  e temperatura virtual,  $\overline{w'\theta'_v}$ , além da própria distância até a superfície,  $z - d_0$ . Nestas circunstâncias, as escalas relevantes de velocidade ( $u_*$ ) e temperatura potencial virtual ( $\theta_{v*}$ ) são

$$u_*^2 \equiv -\overline{w'u'}, \quad (5.105)$$

$$\theta_{v*} \equiv \overline{w'\theta'_v}/u_*. \quad (5.106)$$

A lista de adimensionalizações possíveis para gradientes e momentos de ordem 1, 2 e 3 inclui (sem ser exaustiva):

$$\frac{d\bar{u}}{dz} = A_{\bar{u}} \frac{u_*}{z - d_0}, \quad (5.107)$$

$$\frac{d\bar{\theta}_v}{dz} = A_{\bar{\theta}_v} \frac{\theta_{v*}}{z - d_0}, \quad (5.108)$$

$$\sigma_{\theta_v} = A_{\theta_v \theta_v} \theta_{v*}, \quad (5.109)$$

$$\sigma_w = A_{ww} u_*, \quad (5.110)$$

$$\sigma_u = A_{uu} u_*, \quad (5.111)$$

onde os  $A$ 's são constantes. Na teoria clássica,  $A_{\bar{u}} = A_{\bar{\theta}_v} = \kappa^{-1} = 2,5$  (Brutsaert, 1982). Note que (5.109)–(5.111) implicam que  $\overline{\theta'_v \theta'_v}$ ,  $\overline{w'w'}$  e  $\overline{u'u'}$  são constantes em  $z$  na SDN — i.e.: a turbulência parece ser homogênea na vertical nesta sub-camada.

Para separar as escalas de temperatura e umidade, basta considerar a equação para a temperatura potencial virtual,

$$\theta_v = (1 + 0.61q)\theta, \quad (5.112)$$

onde  $q$  é a umidade específica e  $\theta$  é a temperatura potencial; aplicando-se uma decomposição de Reynolds a  $\theta_v$ ,  $q$  e  $\theta$ , e fazendo-se a média do produto das flutuações resultantes com  $w'$ , obtém-se

$$\bar{\theta}_v = a\bar{\theta}, \quad (5.113)$$

$$\theta'_v = a\theta' + b\bar{\theta}q', \quad (5.114)$$

$$\theta_{v*} = a\theta_* + bq_*, \quad (5.115)$$

$$a = (1 + 0.61\bar{q}), \quad (5.116)$$

$$b = 0.61\bar{\theta}. \quad (5.117)$$

onde  $\theta_*$  e  $q_*$  são definidos de forma análoga a (5.106).

Levando (5.113) e (5.114) em (5.108),

$$(1 + 0.61\bar{q}) \frac{d\bar{\theta}}{dz} + 0.61\bar{\theta} \frac{d\bar{q}}{dz} = (1 + 0.61\bar{q}) A_{\bar{\theta}_v} \frac{\theta_*}{z} + 0.61\bar{\theta} A_{\bar{\theta}_v} \frac{q_*}{z}. \quad (5.118)$$

Se os termos em  $(1 + 0.61\bar{q})$  e  $(0.61\bar{\theta})$  forem iguais dois a dois, segue-se que

$$\frac{d\bar{\theta}}{dz} = A_{\bar{\theta}}, \frac{\theta_*}{z} \quad (5.119)$$

$$\frac{d\bar{q}}{dz} = A_{\bar{q}}, \frac{q_*}{z} \quad (5.120)$$

com  $A_{\bar{\theta}_v} = A_{\bar{\theta}} = A_{\bar{q}}$ , isto é: os gradientes de temperatura potencial e umidade específica apresentam similaridade perfeita na SDN. O mesmo exercício de decomposição da temperatura potencial quando aplicado a (5.109) resulta em

$$a^2 \overline{\theta' \theta'} + 2ab \overline{\theta' q'} + b^2 \overline{q' q'} = A_{\theta_v \theta_v}^2 (a^2 \theta_*^2 + 2ab \theta_* q_* + b^2 q_*^2). \quad (5.121)$$

Supondo-se que a relações análogas a (5.109) sejam aplicáveis a  $\theta$  e a  $q$  separadamente, segue-se que

$$\sigma_{\theta}^2 = A_{\theta\theta}^2 \theta_{v*}^2, \quad (5.122)$$

$$\sigma_q^2 = A_{qq}^2 q_*^2, \quad (5.123)$$

$$\overline{\theta' q'} = A_{\theta q}^2 \theta_* q_*, \quad (5.124)$$

onde, mais uma vez,  $A_{\theta\theta} = A_{qq} = A_{\theta q} = A_{\theta_v \theta_v}$ , ou seja, as variâncias de temperatura e de umidade e a covariância entre ambas são perfeitamente similares na SDN. O conjunto das equações (5.122)–(5.124) implica

$$r_{\theta q} = \frac{\overline{\theta' q'}}{\sigma_{\theta} \sigma_q} = \pm 1, \quad (5.125)$$

isto é: a correlação entre as flutuações de temperatura e umidade é perfeita. Este tipo de resultado foi obtido pela primeira vez por Hill (1989), e depende fundamentalmente da hipótese de que as adimensionalizações do tipo de (5.108) e (5.109) valem tanto para  $\theta$  e  $q$  individualmente como para qualquer combinação linear deles (inclusive a temperatura potencial); confirmações do resultado por outros meios foram depois obtidas para diversas condições de estabilidade (Dias and Brutsaert, 1996; McNaughton and Laubach, 1998; de Bruin *et al.*, 1999)

### Implicações de ADD para a SDN

Para Kader e Yaglom, a SDN é a região onde

$$\frac{1}{\bar{\rho}} \overline{p' \frac{\partial w'}{\partial z}} > \frac{g}{\theta_v} \overline{w' \theta'_v}. \quad (5.126)$$

Mas

$$\frac{1}{\bar{\rho}} \overline{p' \frac{\partial w'}{\partial z}} \sim \frac{1}{\bar{\rho}} \overline{p' \frac{\partial u'}{\partial x}} \sim \frac{(\kappa u_*)^3}{z}. \quad (5.127)$$

Note que dimensionalmente

$$\left[ \frac{(\kappa u_*)^3}{z} \right] = \frac{(L_z^{1/2} L_x^{-1/2} L_x^{1/2} L_z^{1/2} T^{-1})^3}{L_z} = L_z^2 T^{-3}. \quad (5.128)$$

Então a sub-camada dinâmica SDN deve ser a região onde

$$\frac{1}{z} \frac{(\kappa u_*)^3 \bar{\theta}_v}{g w' \theta'_v} > 1. \quad (5.129)$$

Kader e Yaglom definem portanto a SDN como a região onde

$$z < L_* \equiv \frac{(\kappa u_*)^3 \bar{\theta}_v}{g w' \theta'_v}. \quad (5.130)$$

É elementar mostrar que

$$\frac{L_*}{L_O} = \kappa^2 = 0,16. \quad (5.131)$$

Este é um excelente critério objetivo para a altura da sub-camada dinâmica.

Se  $[u] = L_x T^{-1}$ ,  $[w] = L_z T^{-1}$ ,  $[\theta] = \Theta$ , e  $[q] = M_v M^{-1}$ , onde  $\Theta$  é a dimensão de temperatura,  $M$  é a dimensão de massa total de ar e  $M_v$  a dimensão de massa de vapor d'água, há várias consequências para a teoria de similaridade na SDN. Note que embora nos livros-texto seja usual apresentar a análise dimensional apenas em termos das 3 dimensões fundamentais “clássicas” em mecânica,  $M$ ,  $L$  e  $T$ , a adoção de uma dimensão de temperatura independente é justificável em problemas em que a conversão de energia mecânica em térmica (ou vice-versa) não seja importante; analogamente, se não há reação química envolvendo a massa total de vapor d'água, é igualmente válido considerar  $M_v$  como uma dimensão independente da massa total de ar (Dias, 1986; Fischer *et al.*, 1979). Esta interpretação “heterodoxa” de análise dimensional é necessária para a obtenção dos resultados clássicos da teoria de similaridade de Monin-Obukhov, e *análoga às extensões de direcionalidade para o comprimento* discutidas neste trabalho.

As consequências das hipóteses de dimensionalidade e de direcionalidade são então:  $[u_*] = L_x^{1/2} L_z^{1/2} T^{-1}$ ;  $[\theta_{v*}] = L_x^{-1/2} L_z^{1/2} \Theta (1 + M_v M^{-1})$ ;  $[A_{\bar{u}}] = [A_{\bar{\theta}_v}] = [A_{\bar{\theta}}] = [A_{\bar{q}}] = L_x^{1/2} L_z^{-1/2}$ ;  $[A_{\theta_v \theta_v}] = [A_{\theta \theta}] = [A_{qq}] = L_x L_z^{-1}$ . Note portanto que as diversas constantes  $A$ 's deixam de ser adimensionais e passam a ter dimensões envolvendo  $L_x$  e  $L_z$ . Em outras palavras, a aplicação de ADD na SDN leva a constantes *dimensionais* nas relações (5.107)–(5.111).

### 5.9.3 – A sub-camada dinâmico-convectiva: escalas individuais de temperatura e umidade

Nesta região,  $z > L_*$  *ma non troppo*, a produção de turbulência por empuxo passa a ser da mesma ordem de grandeza que a produção mecânica. O parâmetro de flutuabilidade  $g/\bar{\theta}_v$  deve portanto entrar na lista de variáveis que controlam a dinâmica da turbulência. Segundo Kader e Yaglom,  $u'$  e  $v'$  são produzidas mecanicamente, enquanto que  $w'$  é produzida por empuxo, enquanto que as trocas direcionais são relativamente pequenas. Isto conduz imediatamente a duas novas escalas de turbulência; a escala de velocidade convectiva

$$w_* = \left( \frac{g}{\bar{\theta}_v} \overline{w' \theta'_v} z \right)^{1/3} \quad (5.132)$$

e à escala de temperatura convectiva

$$\vartheta_{v*} = \frac{\overline{w' \theta'_v}}{w_*}. \quad (5.133)$$



Supondo, como é natural no contexto de ADD, que  $[z] = L_z$  e  $[g] = L_z T^{-2}$ , segue-se que  $[w_*] = L_z T^{-1}$ , e  $[\vartheta_{v*}] = \Theta(1 + M_v M^{-1})$ . No entanto, como nesta região a produção mecânica *ainda* é importante,  $u_*$  também é uma das variáveis que controlam a turbulência desta sub-camada. Consequentemente, por analogia com (5.133), é possível formar uma escala de velocidade horizontal convectiva

$$u_{**} = -\frac{\overline{w'u'}}{w_*}, \quad (5.134)$$

cujas principais características são possuir dimensões horizontais de comprimento:  $[u_{**}] = L_x T^{-1}$ . Agora é possível formar as seguintes relações adimensionais envolvendo as escalas acima, gradientes de grandezas médias estatísticas da turbulência:

$$\frac{d\bar{u}}{dz} = B_{\bar{u}} \frac{u_{**}}{z}, \quad (5.135)$$

$$\frac{d\bar{\theta}_v}{dz} = B_{\bar{\theta}_v} \frac{\vartheta_{v*}}{z}, \quad (5.136)$$

$$\sigma_{\theta_v} = B_{\theta_v \theta_v} \vartheta_{v*}, \quad (5.137)$$

$$\sigma_w = B_{ww} w_*, \quad (5.138)$$

$$\sigma_u = B_{uu} u_{**}. \quad (5.139)$$

Note como escalas diferentes de velocidade,  $u_{**}$  e  $w_*$ , são utilizadas para adimensionalizar flutuações (gradientes) envolvendo  $u$  e  $w$ , respectivamente. Estas previsões são um resultado original do trabalho de K&Y-1990: enquanto que na teoria clássica de estabilidade de Monin-Obukhov apenas a existência de funções adimensionais era prevista, aqui é possível prever a sua *forma*. Para demonstrar este fato, basta apresentar um exemplo, envolvendo o gradiente “adimensional” (a palavra precisa ser usada com cuidado à luz da ADD) de velocidade média: rearrumando (5.135) obtém-se

$$\begin{aligned} \frac{zw_*}{u_*^2} \frac{d\bar{u}}{dz} &= B_{\bar{u}}, \\ \frac{1}{\kappa^{4/3}} \underbrace{\frac{\kappa z}{u_*} \frac{d\bar{u}}{dz}}_{\phi_\tau} \underbrace{\left( \frac{\kappa g z \overline{w'\theta'_v}}{\bar{\theta}_v u_*^3} \right)^{1/3}}_{-\zeta} &= B_{\bar{u}}, \\ \phi_\tau(\zeta) &= B_{\bar{u}} \kappa^{4/3} (-\zeta)^{-1/3}. \end{aligned} \quad (5.140)$$

Esta equação contém a definição da variável de estabilidade de K&Y-1990,  $\zeta$ , que é equivalente à variável de estabilidade de Obukhov exceto pela ausência da constante de von Kármán  $\kappa$ .

A extensão da teoria de K&Y-1990 para as escalas individuais de temperatura e umidade na SDC é imediata; sem repetir o desenvolvimento que se segue a (5.113)–(5.115), a escala convectiva de temperatura potencial virtual se decompõe naturalmente:

$$\vartheta_{v*} = (1 + 0.61\bar{q})\vartheta_* + (0.61\bar{\theta})\chi_*, \quad (5.141)$$

com

$$\vartheta_* = \overline{w'\theta'}/w_*, \quad (5.142)$$

$$\chi_* = \overline{w'q'}/w_*. \quad (5.143)$$

### Implicações de ADD para a SDC

A SDC é a única das 3 sub-camadas da CS onde a aplicação de ADD não produz constantes dimensionais: de fato, todos os  $B$ 's em (5.135)–(5.139) são adimensionais, como o leitor pode constatar facilmente. O outro fato notável é a consistência de sua aplicação: todas as flutuações (gradientes) envolvendo  $u$  são adimensionalizados por  $u_{**}$ , enquanto que todas as flutuações envolvendo  $w$  o são por  $w_*$ .

#### 5.9.4 – A sub-camada de convecção livre

Nesta última e mais alta sub-camada da CS, argumenta-se com base no balanço de energia cinética turbulenta que  $u_*$  deixa totalmente de ser uma variável relevante (Wyngaard, 1973): a única escala de velocidade disponível para “adimensionalizar” gradientes e estatísticas turbulentas passa a ser  $w_*$ . Nesta região,  $z \gg L_*$ , é a produção por empuxo que agora alimenta as flutuações  $u'$  e  $v'$  além, naturalmente, de  $w'$ . Note como  $\overline{p'}/\overline{\rho}\partial w'/\partial z$  troca de sinal entre a SDN, a SDC e a SCL. Por outro lado, não há novas escalas de temperatura potencial virtual, temperatura potencial ou umidade específica a se formar. Consequentemente, nesta sub-camada devemos ter:

$$\frac{d\bar{u}}{dz} = C_{\bar{u}} \frac{w_*}{z}, \quad (5.144)$$

$$\frac{d\bar{\theta}_v}{dz} = C_{\bar{\theta}_v} \frac{\vartheta_{v*}}{z}, \quad (5.145)$$

$$\sigma_{\theta_v} = C_{\theta_v \theta_v} \vartheta_{v*}, \quad (5.146)$$

$$\sigma_w = C_{ww} w_*, \quad (5.147)$$

$$\sigma_u = C_{uu} w_*. \quad (5.148)$$

Kader e Yaglom introduzem

$$L_{**} \equiv \frac{(\kappa_1 u_*)^3 \bar{\theta}_v}{g w' \theta'_v} \quad (5.149)$$

como o limite *inferior* da camada de convecção livre, onde

$$\kappa_1 = C_{\bar{u}}^{-1/2}. \quad (5.150)$$

### Implicações de ADD para a SCL

Observe que agora flutuações  $u'$  e gradientes  $d\bar{u}$  também são “adimensionalizados” por  $w_*$ ; portanto, *alguns* dos  $C$ 's acima *não* são adimensionais (à semelhança do que ocorre com os  $A$ 's na SDN):  $[C_{\bar{\theta}_v}] = [C_{\theta_v \theta_v}] = [C_{ww}] = 1$ , mas:  $[C_{\bar{u}}] = L_x L_z^{-1}$  e  $[C_{uu}] = L_x L_z^{-1}$ .

#### 5.9.5 – Crítica da ADD e algumas correções formais

As previsões de ADD para a CS são amplamente confirmadas na SDC por dados experimentais (K&Y-1990): esta é a sub-camada onde seu teste é mais rigoroso, uma vez que o comportamento assintótico das funções de similaridade de Monin-Obukhov na SDN e na SCL já tinham sido previstos, e em boa parte confirmados, anteriormente. Uma novidade a partir dos dados experimentais

em K&Y-1990 foi a confirmação da previsão de (5.144) para  $\frac{d\bar{u}}{dz}$ , uma vez que as funções de similaridade empíricas anteriormente conhecidas (por exemplo, a bem conhecida formulação de Businger-Dyer) (Businger *et al.*, 1971) não incluíam valores de  $\zeta$  suficientemente altos que permitissem a identificação do seu comportamento na SCL.

Entretanto, este sucesso vem ao preço de tornar as formulações de similaridade para a SDN e a SCL dimensionalmente inconsistentes, uma vez que todos os  $A$ 's e alguns dos  $C$ 's passam a ser constantes *dimensionais*. Em outras palavras, a dimensionalidade de algumas destas constantes sugere que a teoria de ADD na forma utilizada em K&Y-1990 *deixou* de identificar algumas variáveis importantes na CS que poderiam torná-la totalmente consistente. Certamente, este não é um erro grave do ponto de vista da capacidade da teoria de *explicar* as observações, uma vez que as formulações para a SDN e a SCL são *anteriores* a K&Y-1990, na sua forma clássica pressupõem que os  $A$ 's e os  $C$ 's são todos adimensionais, e são bem sucedidas em explicar seus respectivos regimes de turbulência. O “defeito” a que nos referimos parece ser antes de mais nada puramente formal.

### Correção de ADD para a sub-camada dinâmica

Na sub-camada dinâmica utilizando-se apenas as variáveis  $\overline{w'u'}$ ,  $\overline{w'\theta'}$  e  $z$  é impossível produzir variáveis com dimensões  $L_x T^{-1}$  ou  $L_z T^{-1}$ , isto é: com dimensões de velocidade horizontal ou velocidade vertical. Portanto, para tornar a ADD consistente na SDN é indispensável introduzir uma nova escala de velocidade; além disso, esta escala precisa estar associada a uma hipótese sobre o seu comportamento em função da altura  $z$ . Uma lista completa e compatível com a teoria clássica de Monin-Obukhov é:  $\{u_* = -\overline{w'u'}$ ,  $z$ ,  $\theta_{v*} = \overline{w'\theta'}/u_*$ ,  $\sigma_u = (\overline{u'u'})^{1/2}\}$ . Note que nesta abordagem  $\sigma_u$  é uma variável *independente* que introduz a necessária dimensão  $L_x$  na lista de dimensões da SDN; note também que além da hipótese de fluxo constante,  $\partial \overline{w'u'}/\partial z = 0$ , será necessário supor o mesmo para a variância da velocidade horizontal:  $\partial \overline{u'u'}/\partial z = 0$ . Com a introdução formal de  $\overline{u'u'}$  na lista de variáveis de controle, obtém-se imediatamente as seguintes formulações dimensionais alternativas a (5.107)–(5.110):

$$\frac{d\bar{u}}{dz} = A'_u \frac{\sigma_u u_*}{z}, \quad (5.151)$$

$$\frac{d\bar{\theta}_v}{dz} = A'_{\theta_v} \frac{\sigma_u \theta_{v*}}{z}, \quad (5.152)$$

$$\sigma_{\theta_v} = A'_{\theta_v \theta_v} \frac{\sigma_u}{u_*} \theta_{v*}, \quad (5.153)$$

$$\sigma_w = A'_{ww} \frac{u_*}{\sigma_u} u_*. \quad (5.154)$$

Finalmente, é possível *definir* uma variável dependente na SDN:

$$\kappa \equiv \frac{u_*}{A'_u \sigma_u} \quad (5.155)$$

que é numericamente igual à constante de von Kármán da teoria clássica (não-direcional): neste sentido, justifica-se a afirmação encontrada em K&Y-1999 de que  $\kappa$  é uma variável; na SDN,  $\kappa$  é constante em  $z$ .

### Correção de ADD para a sub-camada de convecção livre

Assim como ocorre na SDN, para que a ADD forneça previsões consistentes na SCL, é preciso retirar o desvio-padrão da velocidade vertical (ou alguma outra escala de velocidade horizontal alternativa) da lista de variáveis dependentes de  $w_*$ , e elevá-la ao *status* de variável independente de controle da turbulência. É importante lembrar aqui que o objetivo deste trabalho não é a previsão de novos comportamentos físicos (isto foi feito em K&Y-1990), mas reinterpretar formalmente a teoria de ADD (assim como feito em Z-1994); portanto, não está em discussão, por exemplo, a validade de (5.144) ou (5.148) (cujas constantes  $C_{\bar{u}}$  e  $C_{uu}$ , por possuírem dimensões segundo a ADD, as tornam formalmente inconsistentes). O objetivo é *reinterpretar* estas constantes de maneira que surja uma formulação de ADD totalmente consistente incluindo apenas constantes adimensionais, variáveis independentes ou de controle (que variam em cada sub-camada) e demais variáveis “dependentes” da turbulência.

Consequentemente, uma vez que (5.144) e (5.148) possuem confirmação experimental, é forçoso não somente incluir  $\sigma_u$  na lista de variáveis de controle, mas também admitir que  $\sigma_u$  e  $w_*$  possuem o mesmo comportamento  $\sim z^{1/3}$ . Estas equações então podem ser reescritas (lembrando que (5.145)–(5.147) já são dimensionalmente consistentes):

$$\frac{d\bar{u}}{dz} = C'_{\bar{u}} \frac{\sigma_u}{w_*} \frac{w_*}{z}, \quad (5.156)$$

$$\sigma_u \sim z^{1/3}. \quad (5.157)$$

É importante observar também que devido ao argumento físico de que a importância relativa da produção mecânica é assintoticamente nula na SCL, não é possível utilizar em hipótese alguma  $u_*$  na tentativa de “construir” escalas horizontais de velocidade nesta camada. Neste sentido, (5.157) é ao mesmo tempo uma *consequência* da teoria clássica e uma hipótese necessária (que precisa ser validada independentemente) para que a ADD possa ser aplicada.

## 5.10 – Conclusões

A teoria de K&Y-1990 é um dos exemplos mais bem-sucedidos de aplicação de análise dimensional a problemas da camada-limite atmosférica. Ao reduzir o número de graus de liberdade das funções de similaridade na CS em 1, ela permitiu a previsão acurada da dependência funcional destas funções com a variável de estabilidade  $\zeta$  de Obukhov, restando apenas constantes a determinar.

Para obter este sucesso, entretanto, foi necessário conviver com uma mistura de constantes dimensionais nas sub-camadas dinâmica e de convecção livre e adimensionais (na “nova” sub-camada dinâmico-convectiva, de acordo com a nova teoria). Além do mais, algumas escalas da teoria clássica, como por exemplo  $\theta_{v*}$  possuem agora dimensões que envolvem  $L_x$  e  $L_z$ , e não apenas  $\Theta$ . Embora este estado de coisas não seja impeditivo do sucesso da teoria, ele é certamente indesejável do ponto de vista formal: *por que a análise dimensional direcional deveria “funcionar” com constantes à sua vez dimensionais e adimensionais em diferentes partes da camada superficial?*

Inicialmente, estendemos a formulação de K&Y-1990, que foi feita apenas com a temperatura (potencial), para o caso mais geral de temperatura (potencial)

virtual: isto dá lugar naturalmente à bem-conhecida escala  $q_*$  de umidade e a uma nova escala convectiva de umidade, que denominamos  $\chi_*$ .

Nós procurarmos também reformular a ADD com o objetivo de obter um conjunto de constantes uniformemente adimensionais em toda a CS. Este esforço foi bem-sucedido na SDN, onde a hipótese de homogeneidade vertical da turbulência, que é bem confirmada experimentalmente, pode ser utilizada para fornecer a escala de velocidade horizontal faltante nesta sub-camada. A SDN já possui uma formulação totalmente consistente em K&Y-1990, e portanto não são necessárias modificações. O problema mais difícil de reformulação está na SCL: ali, o impedimento (*físico*: a produção mecânica de turbulência é desprezível) de se utilizar  $u_*$  como uma variável torna a busca de uma escala alternativa de velocidade horizontal mais complicada. Dado o sucesso das formulações de convecção livre (diga-se de passagem, bem anteriores à teoria de K&Y-1990), e admitindo-se que a ADD seja uma teoria válida, é forçoso que tal escala exista. Sua principal característica deverá ser uma dependência funcional com  $z$  igual à experimentada por  $w_*$ .

### 5.11 – Evolution of the measurement technology of H<sub>2</sub>O, CO<sub>2</sub>, and CH<sub>4</sub> with the ECM

According to [Baldocchi \(2003\)](#), the first measurements of scalar turbulent fluxes in the atmosphere were made by [Swinbank \(1951\)](#). The fluxes in question were the sensible heat flux  $H$  and the latent heat flux  $LE$ ; the scalars were temperature  $\theta$  and water vapor pressure  $e$ . The humidity sensor actually measured the wet-bulb temperature, then

*The psychrometric element consists of two fine wet-bulb thermocouples built into an electrical network so designed that it simulates the behavior of Regnault's psychrometric equation for small changes in the variables (vapor pressure, saturation vapor pressure at the wet-bulb temperature, and the wet-bulb depression). The output of the circuit gives a measure of the fluctuations of vapor pressure practically linear over the range of variation that occurs naturally.*

In other words, the Swinbank apparatus included an analog computer that converted the measurements of dry and wet bulb temperature to water vapor pressure fluctuations in real time.

As one would expect in any seminal, and in hindsight, many limitations can be found in this first attempt of flux measurement by Swinbank: the averaging time, 5 minutes, was too short; the measurement of water vapor concentration fluctuations was done with thermocouples of dry and wet bulb, which certainly limited their response time, and the frequency of the measurements, after digitizing of the graphical records, was only 1 Hz (currently, measurement frequencies of at least 10 Hz are used in the eddy covariance method, and averaging times of at least 10 minutes are used, 30 minutes being the most commonly found averaging time).

The works of [Baumgartner \(1969\)](#) and [Deanmead \(1969\)](#) among others at the same time, report the measurement of *average* concentrations of CO<sub>2</sub>, and inferred the fluxes using a flux-gradient method.

CO<sub>2</sub> flux measurements with the eddy covariance method, however, only became possible in the 1970's. The first measurements seem to be due to [Desjardins \(1974\)](#). The vertical velocity sensor was a propeller anemometer, and air was pumped through a closed-path CO<sub>2</sub> analyser. Strictly speaking, the method wasn't exactly what we call today the eddy covariance method, since the system integrated the vertical movements registered by the propeller anemometer. Some preliminary results obtained with the CO<sub>2</sub> flux measurements were shown, along with discussions about measurements performed over naked soil, and over hay. Numerous limitations of the anemometer used were discussed.

In the same year, [Desjardins and Lemon \(1974\)](#) analyzed many of the uncertainty sources in the CO<sub>2</sub> measurement, which are still subject of research now.

[Leuning \*et al.\* \(1982\)](#) performed measurements of CO<sub>2</sub> flux with the flux-gradient method and with the eddy covariance method. They found that the covariance  $\overline{w'\rho'_c}$  produced incoherent results and disagreed with the flux-gradient method. This provided the first verification of the importance of the WPL correction ([Webb \*et al.\*, 1980](#)), and also allowed the authors to identify that previous works had already proposed similar corrections to the WPL correction ([Bakan, 1978](#); [Jones and Smith, 1978](#)), but with incorrect boundary conditions. [Leuning \*et al.\* \(1982\)](#) observed that in a posterior note, [Smith and Jones \(1979\)](#) recognized that the correct condition was originally proposed by [Webb and Pearman \(1977\)](#), which corresponds to the equation (6.27) of this text.

Here, it is remarkable that corrections for the CO<sub>2</sub> measurements with the eddy covariance method were already being considered in 1976, a very short time after the pioneering measurements of [Desjardins \(1974\)](#).

Fundamental problems identified by [Leuning \*et al.\* \(1982\)](#) and that somehow persist to this day are the alignment of the anemometer, the correction for air density through temperature fluctuations, which were later studied by [Webb \*et al.\* \(1980\)](#), the non-stationarity of the atmosphere during the measurement period, and their time average. Some of these subjects are the theme of the next session.

The effective implementation of the ECM for the measurement of turbulent gas fluxes depends critically on the gas analyzers. In the mid 1970's, gas analyzers for water vapor [Buck \(1976\)](#) and CO<sub>2</sub> [Desjardins \(1974\)](#) were emerging, and from then on the measurement of water vapor and CO<sub>2</sub> has become increasingly common in meteorological experiments.

Another substantial process has been the gradual substitution of closed-path sensors, in which the gas is aspirated through a tube and measured in a closed chamber inside the analyzer, with open-path sensors, in which the gas is measured along an open path, between an emitter and a receptor, in the atmosphere itself. The general principle of these sensors is the absorption by the gas of part of the radiation emitted. As always, the measurement is harder the smaller the gas concentrations are.

The tendency is always to initially use slow sensors, only capable of measuring mean concentrations; moving to the use of closed-path fast sensors, and finally reaching a stage in which the open-path sensors are available. An excellent revision of the evolution of the CO<sub>2</sub> measurement technologies can be found in [Baldocchi \(2003\)](#).



# 6

## Turbulence data processing

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### 6.1 – The separation of the average and the fluctuation

There is no universally accepted methodology for the definition of what represents the “average”  $\bar{a}$  and the fluctuation  $a'$  of a variable  $a$  measured in a turbulent flow. The usual practice is to perform some kind of filtering of the original measured data,  $a(t)$ , initially producing a component  $\bar{a}(t)$ , and then to extract the fluctuation  $a'(t)$  by (2.8). The problem is that in practice there are many different ways to calculate  $\bar{a}(t)$ . Figure 6.1-a shows a series of CO<sub>2</sub> concentrations measured at 2 meters above a turf farm in Tijucas do Sul, PR, in 2011-02-17 between 10:30 and 10:40 h. This 10-minute series will be used to illustrate some of the most common averaging procedures in what follows.

**Block averages.** The block average was defined in (2.16). As we know, the value  $\bar{a}$  calculated remains constant for  $-T/2 < t < T/2$ . The fluctuation  $a'(t)$  is calculated around this constant average. Figure 6.2-a shows the fluctuations of CO<sub>2</sub> density after the extraction of a block average. Essentially, it is the same figure 6.1-a, with the average shifted to zero. Note the pronounced negative asymmetry of  $\rho'_c$ .

**Running average.** This is equation (2.22): the value of  $\bar{a}(t)$  varies continuously over time, and the fluctuation  $a'(t)$  is calculated around this variable value. Figure 6.1-b shows the running average calculated with  $P = 2$  min.. Note that, unless the data of 10 minutes earlier or later are available, is not possible to calculate the running average for  $t < 1$  min. or for  $t > 9$  min.. At these ends, the running average is replaced by the block average of the first 2 minutes and the last 2 minutes.

Figure 6.2-b shows the extracted fluctuations around the mobile averaging.

**Linear first-order recursive filter.** This is one of the most widely used procedure, perhaps because it is equivalent to analog filtering of a signal using a RC circuit. For a continuous function, the linear first-order recursive filter 1 is the solution of the differential equation

$$\frac{d\bar{a}}{dt} + \frac{1}{P}\bar{a} = \frac{1}{P}a(t). \quad (6.1)$$

In 6.1,  $P$  is the filter’s “window”: in practice, recommendation (2.23) remains valid also for a recursive filter.

Figure 6.1-c shows the result of applying the recursive filter (low-pass) to the CO<sub>2</sub> series. The first minute is used to “warm up” the filter, with a block

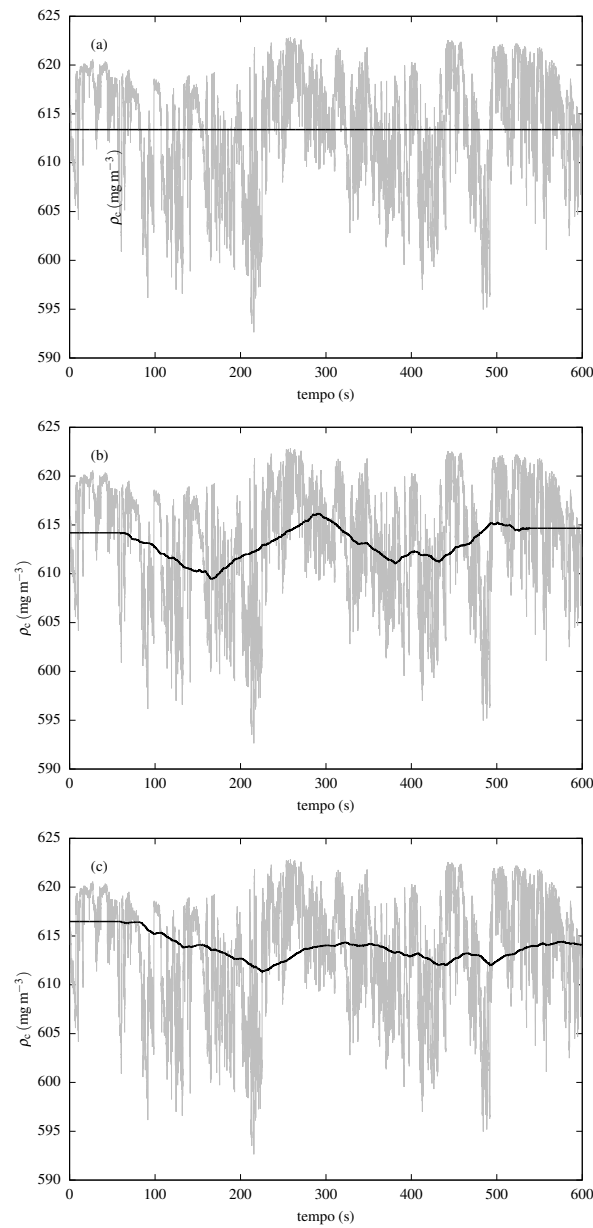


Figure 6.1: 10 minutes of CO<sub>2</sub> concentration measurements over a grass surface in Tijucas do Sul, PR, on 02/17/2011, 10:30 - 10:40; (a) raw series and block average; (b) Running average with  $P = 2$  min. (c) Low-pass recursive filter with  $P = 2$  min..



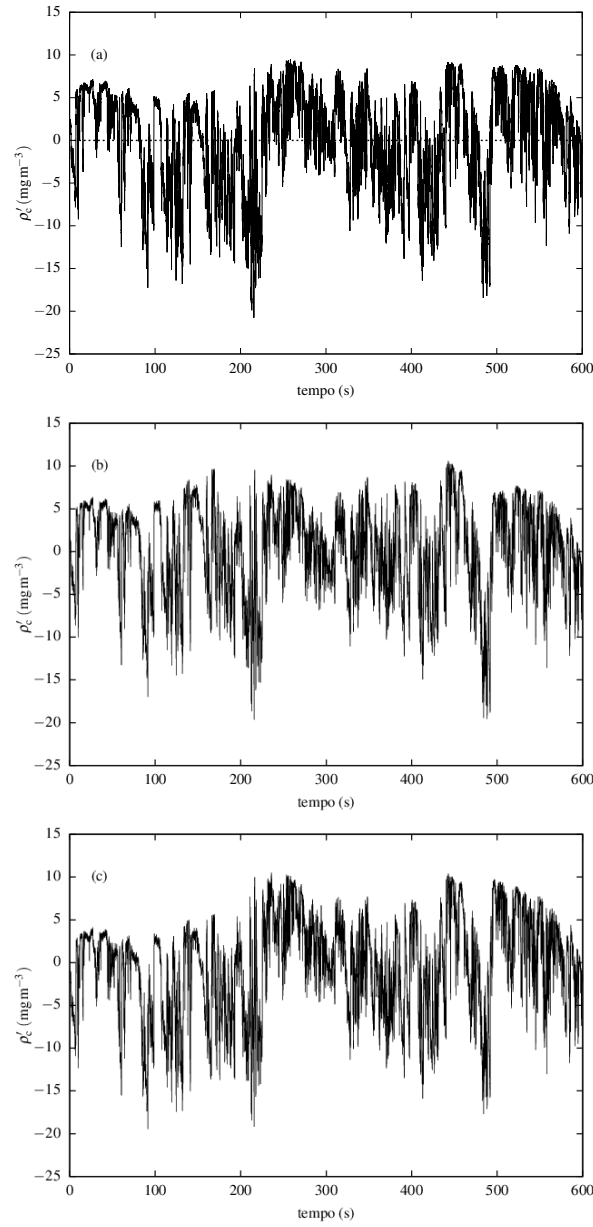


Figure 6.2: Fluctuations of  $\rho'_c$ : (a) around a block average; (b) around a running average of 2 minutes; (c) around a low-pass filter of 2 minutes.

average (1 minute), during which the fluctuations are calculated around the constant average. After this time, we apply (6.1) in the discretized form

$$\bar{a}_{n+1} = \frac{\Delta t}{P} a_{n+1} + \left(1 - \frac{\Delta t}{P}\right) \bar{a}_n. \quad (6.2)$$

Figure 6.2-c shows the CO<sub>2</sub> fluctuations around the low-pass filter.

It's important to observe, in figure 6.2, that the fluctuations arising from the the different ways of calculating the average are *different* (although in this case it's hard to notice without close scrutiny). In particular, for the running averag and the low-pass filter, *the sample mean of the fluctuations is no longer identically null*. In these cases, it's common to do additional post-processing, subtracting the residual sample mean from these series.

The calculation of averages is ultimately subjective and the result of a personal decision. Consequently, what is considered “mean” and “fluctuation” varies according to the method used; the corresponding statistics will also vary, as well as turbulent fluxes like  $\overline{w'\rho'_c}$ .

## 6.2 – Coordinate rotation

The Monin-Obukhov similarity theory, MOST, assumes a stationary and horizontally homogeneous flow. Under these conditions, it is assumed that the average velocity vector is constant and strictly horizontal, and it is common practice to align the  $Ox$  axis with this direction. Therefore, it is usual to write

$$\bar{\mathbf{u}} = [\bar{u} \ 0 \ 0]^T \quad (6.3)$$

for the coordinates of the average wind velocity. Horizontal homogeneity also implies that there are no Reynolds shear stresses in the directions  $xy$  and  $yz$ :

$$\overline{u'v'} = 0, \quad \overline{v'w'} = 0. \quad (6.4)$$

Under these idealized conditions, the Reynolds tensor simplifies to

$$\boldsymbol{\tau} = \begin{bmatrix} \overline{u'u'} & 0 & \overline{u'w'} \\ 0 & \overline{v'v'} & 0 \\ \overline{u'w'} & 0 & \overline{w'w'} \end{bmatrix}. \quad (6.5)$$

Then, the turbulent stress vector in the horizontal plane whose normal is  $\mathbf{k}$  is

$$\mathbf{t} = \mathbf{k}^T \cdot \boldsymbol{\tau} = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \overline{u'u'} & 0 & \overline{u'w'} \\ 0 & \overline{v'v'} & 0 \\ \overline{u'w'} & 0 & \overline{w'w'} \end{bmatrix} = \begin{bmatrix} \overline{u'w'} \\ 0 \\ \overline{w'w'} \end{bmatrix}. \quad (6.6)$$

Therefore, under ideal conditions, the horizontal component of  $\mathbf{t}$  is aligned with  $\bar{\mathbf{u}}$ . This makes sense physically, since we expect that the direction of the shear stress is the same (with the opposite sign) as that of the wind velocity.

Given two successive rotation between the bases

$$\begin{aligned} E &= (\mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3), \\ F &= (\mathbf{f}_1, \mathbf{f}_2, \mathbf{f}_3), \quad \mathbf{e} \\ G &= (\mathbf{g}_1, \mathbf{g}_2, \mathbf{g}_3), \end{aligned}$$

the relations between the vectors of these bases are

$$\mathbf{f}_j = C_{ij}\mathbf{e}_i, \quad (6.7)$$

$$\mathbf{g}_k = D_{jk}\mathbf{f}_j = D_{jk}C_{ij}\mathbf{e}_i = C_{ij}D_{jk}\mathbf{e}_i, \quad (6.8)$$

where  $C$  and  $D$  are the respective rotation matrices. Therefore, the rotation matrix from  $E$  to  $G$  is the product

$$CD$$

in this order. In Figure 6.3 we see two successive rotations: the first of an angle  $+\alpha$  around  $z_E$  in the horizontal plane of basis  $E$  which aligns the horizontal wind velocity vector with the axis  $x_F$ ; the second of a vertical angle  $\beta$  around  $y_F$  which aligns the “total” velocity vector of the average wind  $\bar{\mathbf{u}}$  with the axis  $x_G$ .

The equations for the components of the rotation matrices are

$$C_{ij} = (\mathbf{e}_i \cdot \mathbf{f}_j), \quad (6.9)$$

$$D_{jk} = (\mathbf{f}_j \cdot \mathbf{g}_k). \quad (6.10)$$

In basis  $E$ , the coordinates of the vectors  $\mathbf{e}_i$  and  $\mathbf{f}_j$  are:

$$\begin{array}{ccc} [1, 0, 0]^\top & [0, 1, 0]^\top & [0, 0, 1]^\top, \\ [\cos \alpha, \sin \alpha, 0]^\top & [-\sin \alpha, \cos \alpha, 0]^\top, & [0, 0, 1]^\top. \end{array}$$

(Note that, in figure 6.3, the angle  $\alpha$  is *positive*, because represents a positive rotation around  $z_E$ .) Therefore,

$$C = \begin{bmatrix} \cos \alpha & -\sin \alpha & 0 \\ \sin \alpha & \cos \alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (6.11)$$

In basis  $F$ , the coordinates of the vectors  $\mathbf{f}_j$  and  $\mathbf{g}_k$  are:

$$\begin{array}{ccc} [1, 0, 0]^\top & [0, 1, 0]^\top & [0, 0, 1]^\top, \\ [\cos \beta, 0, -\sin \beta]^\top & [0, 1, 0]^\top, & [\sin \beta, 0, \cos \beta]^\top. \end{array}$$

(Note, in figure 6.3, that the angle  $\beta$  is *negative*, because it represents a negative rotation around  $y_F$ .) Therefore,

$$D = \begin{bmatrix} \cos \beta & 0 & \sin \beta \\ 0 & 1 & 0 \\ -\sin \beta & 0 & \cos \beta \end{bmatrix} \quad (6.12)$$

The “total” rotation matrix, given by the product  $CD$  will be

$$\begin{bmatrix} \cos \alpha \cos \beta & -\sin \alpha & \cos \alpha \sin \beta \\ \cos \beta \sin \alpha & \cos \alpha & \sin \alpha \sin \beta \\ -\sin \beta & 0 & \cos \beta. \end{bmatrix}$$

Finally, the coordinates of the wind velocity vector in basis  $E$ , given by  $[u, v, w]_E^\top$  will be rotated to basis  $G$  according to

$$\mathbf{u}_G = D^\top C^\top \mathbf{u}_E, \quad (6.13)$$

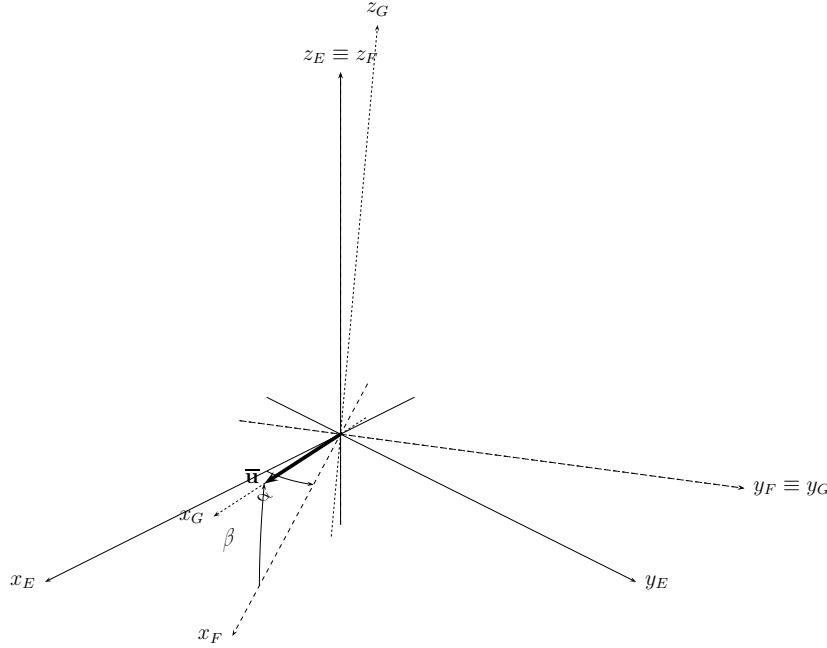


Figure 6.3: 2D coordinate rotation for the alignment of the wind velocity

that is,

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix}_G = \begin{bmatrix} \cos \alpha \cos \beta & \cos \beta \sin \alpha & -\sin \beta \\ -\sin \alpha & \cos \alpha & 0 \\ \cos \alpha \sin \beta & \sin \alpha \sin \beta & \cos \beta \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix}_E. \quad (6.14)$$

The angles  $\alpha$  and  $\beta$  are easily calculated from  $\bar{u}$ ,  $\bar{v}$  and  $\bar{w}$  measured in basis  $E$ : typically, this is the reference system connected to a sonic anemometer installed in the field and carefully leveled, so that the axis  $z_E$  is as vertical as possible. These angles are

$$\alpha = +\arctg2(\bar{v}_E, \bar{u}_E), \quad (6.15)$$

$$\beta = -\arctg2\left(\bar{w}_E, \sqrt{\bar{u}_E^2 + \bar{v}_E^2}\right) \quad (6.16)$$

(remember that angle  $\beta$  is negative in figure 6.3). The function  $\arctg2(y, x)$  gives the angle formed with axis  $x$  by a two-dimensional vector  $(x, y)$  (notice to the order); in the programming languages C, MATLAB and Python,  $\arctg2$  is implemented as  $\text{atan2}(y, x)$ ; in FORTRAN, as  $\text{ATAN2}(Y, X)$ .

The scalar fluxes should be rotated similarly. In particular, if  $\eta'$  is a density fluctuation, mixing ratio, temperature, etc., of a scalar, equation (6.14) is almost completely repeated:

$$\begin{bmatrix} \overline{u'\eta'} \\ \overline{v'\eta'} \\ \overline{w'\eta'} \end{bmatrix}_G = \begin{bmatrix} \cos \alpha \cos \beta & \cos \beta \sin \alpha & -\sin \beta \\ -\sin \alpha & \cos \alpha & 0 \\ \cos \alpha \sin \beta & \sin \alpha \sin \beta & \cos \beta \end{bmatrix} \begin{bmatrix} \overline{u'\eta'} \\ \overline{v'\eta'} \\ \overline{w'\eta'} \end{bmatrix}_E. \quad (6.17)$$

The change of basis for the Reynolds stress tensor is a little more elaborate. Defining the full tensor,

$$\boldsymbol{\tau} \equiv \overline{\mathbf{u}'\mathbf{u}'} = \begin{bmatrix} \overline{u'u'} & \overline{u'v'} & \overline{u'w'} \\ \overline{v'u'} & \overline{v'v'} & \overline{v'w'} \\ \overline{w'u'} & \overline{w'v'} & \overline{w'w'} \end{bmatrix}, \quad (6.18)$$

it follows from (6.13) that

$$\tau_G = D^T C^T \tau_E C D. \quad (6.19)$$

The coordinate rotations shown in this section form the basis of the data processing of scalar fluxes and momentum measured in micrometeorological experiments. A third rotation is possible, which makes  $\overline{v'w'_G} = 0$ , but its use is questionable and many authors consider it “non-physical” (Finnigan *et al.*, 2003).

An more recent alternative, the *planar fit method* of Wilczak *et al.* (2001), decomposes the rotations in a sequence of two, one of them (analogous to the  $D$  rotation in this text) being applied to every micrometeorological block available followed by a rotation (analogous to the  $C$  rotation in this text) applied separately to each block, to align the horizontal wind vector with the final  $x$  axis. According to the authors, the method minimizes the errors in the calculation of the turbulent shear stresses. The method calculates a mean offset in the vertical axis (typically smaller than the accuracy of the sonic anemometers) with a least squares method, and it has been gaining wide acceptance.

### 6.2.1 – The WPL correction for the average vertical velocity

A quick inspection of table 2.1 shows that  $\rho_c \ll \rho$ , and that

$$\rho \approx \rho_s + \rho_v \quad (6.20)$$

is an excellent approximation. The state equation for air will be (approximately)

$$p = [\rho_s R_s + \rho_v R_v] T. \quad (6.21)$$

Now, applying the Reynolds decomposition to all of the quantities in (6.21), and neglecting the higher-order products of fluctuations, we have

$$\begin{aligned} \bar{p} + p' &= (\bar{\rho}_s + \rho'_s) R_s (\bar{T} + T') + (\bar{\rho}_v + \rho'_v) R_v (\bar{T} + T') \\ &= (\bar{\rho}_s R_s + \bar{\rho}_v R_v) \bar{T} + \bar{\rho}_s R_s T' + \rho'_s R_s \bar{T} + \bar{\rho}_v R_v T' + \rho'_v R_v \bar{T}. \end{aligned} \quad (6.22)$$

This allows an obvious interpretation for  $\bar{p}$  and  $p'$ :

$$\bar{p} = (\bar{\rho}_s R_s + \bar{\rho}_v R_v) \bar{T}, \quad (6.23)$$

$$p' = (\bar{\rho}_s R_s + \bar{\rho}_v R_v) T' + \bar{T} (R_s \rho'_s + R_v \rho'_v). \quad (6.24)$$

Making the observation that, in the surface layer, the pressure fluctuation can be neglected *vis-à-vis* the temperature and density fluctuations (Fleagle and Businger, 1980) (see also the discussion leading to (4.44)),

$$0 = (\bar{\rho}_s R_s + \bar{\rho}_v R_v) T' + \bar{T} (R_s \rho'_s + R_v \rho'_v). \quad (6.25)$$

Multiplying (6.25) by the vertical velocity fluctuation  $w'$ , taking a time average and using Reynolds' postulates, we obtain

$$0 = (\bar{\rho}_s R_s + \bar{\rho}_v R_v) \overline{w' T'} + \bar{T} (R_s \overline{w' \rho'_s} + R_v \overline{w' \rho'_v}). \quad (6.26)$$

Note here a difficulty in this derivation: as already mentioned, strictly speaking, the Reynolds postulates do not apply fully to the block and running

averages — see (2.21) and (2.26)–(2.28) — and its approximate validity must be assumed. To the best of our knowledge, a detailed analytical evaluation of the effects of these approximations hasn't been done.

Equation (6.26) plays a central role in the WPL approximation. In fact, applying Reynolds's decomposition to (2.47),

$$\begin{aligned}\overline{w\rho_s} &= \overline{w}\overline{\rho_s} + \overline{w'\rho'_s} = 0 \Rightarrow \\ \overline{w} &= -\frac{\overline{w'\rho'_s}}{\overline{\rho_s}}.\end{aligned}\tag{6.27}$$

Note that  $\overline{w}$  can be effectively calculated from (6.26)–(6.27), using measurements of  $\overline{w'T'}$  and of  $\overline{w'\rho'_v}$ . A fact rarely mentioned is that the WPL correction stems from the hypothesis of a non-null value of  $\overline{w}$ ; however, in most measurements turbulent fluxes using the eddy covariance method, it is common to apply a coordinate rotation, whose effect is precisely to force  $\overline{w} = 0$ . This produces an apparent conflict between simultaneous application of the coordinate rotation and the WPL correction (Massman and Lee, 2002; Dias *et al.*, 2007). However, notice also that the vertical velocity value  $\overline{w}$  estimated by the WPL correction is *very small*; in fact, it is smaller than the accuracy of the measurements using sonic anemometers (Finnigan, 2009). In practice, therefore, the procedure of first applying a coordinate rotation that makes  $\overline{w} = 0$ , and *then* applying the WPL correction which is equivalent to stipulate a small value of  $\overline{w}$  — too small to be measured with the currently available measuring instruments — is justifiable.

Continuing, now we will calculate the water vapor mass flux taking into account (6.27), this is, taking into account the WPL correction.

For the water vapor mass flux  $E$ , start from (5.7) and apply the Reynolds decomposition:

$$E = \overline{w\rho_v} = \overline{w}\overline{\rho_v} + \overline{w'\rho'_v}.\tag{6.28}$$

Typically, the eddy covariance method generates the second term in (6.28); the WPL correction consists of calculating, and adding, the first term. For this, we calculate  $\overline{w}$  explicitly. From (6.26),

$$\begin{aligned}\overline{w'\rho'_s} &= -\frac{1}{T} \left[ \overline{\rho_s} + \frac{R_v}{R_s} \overline{\rho_v} \right] \overline{w'T'} - \frac{R_v}{R_s} \overline{w'\rho'_v} \Rightarrow \\ \overline{w} &= \frac{1}{\overline{\rho_s}} \left\{ \frac{1}{T} \left[ \overline{\rho_s} + \frac{R_v}{R_s} \overline{\rho_v} \right] \overline{w'T'} + \frac{R_v}{R_s} \overline{w'\rho'_v} \right\}.\end{aligned}\tag{6.29}$$

Putting  $\mu = R_v/R_s$ , and taking expression (6.28) to  $E$ ,

$$\begin{aligned}E &= \frac{\overline{\rho_v}}{\overline{\rho_s}} \left\{ \frac{1}{T} \left[ \overline{\rho_s} + \frac{R_v}{R_s} \overline{\rho_v} \right] \overline{w'T'} + \frac{R_v}{R_s} \overline{w'\rho'_v} \right\} + \overline{w'\rho'_v} \\ &= \overline{\rho_v} \left\{ \left( 1 + \mu \frac{\overline{\rho_v}}{\overline{\rho_s}} \right) \frac{\overline{w'T'}}{T} \right\} + \frac{\overline{\rho_v}}{\overline{\rho_s}} \mu \overline{w'\rho'_v} + \overline{w'\rho'_v} \\ &= \overline{\rho_v} (1 + \mu \overline{r_v}) \frac{\overline{w'T'}}{T} + (1 + \mu \overline{r_v}) \overline{w'\rho'_v} \\ &= (1 + \mu \overline{r_v}) \left[ \overline{w'\rho'_v} + \overline{\rho_v} \frac{\overline{w'T'}}{T} \right],\end{aligned}\tag{6.30}$$

where

$$\bar{r}_v = \frac{\bar{\rho}_v}{\bar{\rho}_s} \quad (6.31)$$

is the mixing ratio for water vapor. Equation (6.30) is the expression obtained by Webb *et al.* (1980) for the correction of the water vapor turbulent flux.

Now, proceeding to the case of a greenhouse gas such as CO<sub>2</sub>, start from (5.9) and apply the Reynolds decomposition:

$$\begin{aligned} F_c &= \bar{w} \bar{\rho}_c + \overline{w' \rho'_c} \\ &= \left\{ -\frac{\overline{w' \rho'_s}}{\bar{\rho}_s} \right\} \bar{\rho}_c + \overline{w' \rho'_c} \\ &= -\frac{\bar{\rho}_c}{\bar{\rho}_s} \left\{ -\frac{1}{\bar{T}} (\bar{\rho}_s + \mu \bar{\rho}_v) \overline{w' T'} - \mu \overline{w' \rho'_v} \right\} + \overline{w' \rho'_c} \\ &= \bar{r}_c \left[ \bar{\rho}_s (1 + \mu \bar{r}_v) \frac{\overline{w' T'}}{\bar{T}} + \mu \overline{w' \rho'_v} \right] + \overline{w' \rho'_c} \\ &= \frac{\bar{\rho}_c}{\bar{\rho}_s} \bar{\rho}_s (1 + \mu \bar{r}_v) \frac{\overline{w' T'}}{\bar{T}} + \mu \bar{r}_c \overline{w' \rho'_v} + \overline{w' \rho'_c} \\ &= \bar{\rho}_c (1 + \mu \bar{r}_v) \frac{\overline{w' T'}}{\bar{T}} + \mu \bar{r}_c \overline{w' \rho'_v} + \overline{w' \rho'_c}, \end{aligned} \quad (6.32)$$

where

$$\bar{r}_c = \frac{\bar{\rho}_c}{\bar{\rho}_s} \quad (6.33)$$

it is the mixing ratio for CO<sub>2</sub>.

For measurements of greenhouse gases fluxes, it is essential to apply the WPL correction.

### 6.3 – Energy fluxes and greenhouse gas measurements in different biomes

This section presents a brief review of some results of CO<sub>2</sub> flux measurements performed in many parts of the world. The goal is not to produce a comprehensive review of this type of measurement, but to provide a connection with the material of the previous sections through some examples and critical discussions of these measurements.

#### 6.3.1 – BOREAS

The BOREAS project (*Boreal Ecosystem - Atmosphere Study*) took place in the central region of Canada as part of NASA's Earth Science Research and Analysis program, with the goal of understanding the interactions between the boreal forest's biome and the atmosphere. A part of this project consisted in flux measurements of energy, water, carbon and other gases, in order to support the climate change and the global warming studies. The field phase of this project happened between 1993 and 1997 (Sellers *et al.*, 1997). The boreal regions correspond to the largest ecosystems in the world, covering something between 6 and 8.5% of the planet's land surface (Simpson *et al.*, 1997), which makes this project an extremely important one for global change research.

The CO<sub>2</sub> flux measurements were performed at micrometeorological towers erected in various sites throughout the boreal forest. Besides the measurement of mean meteorological data such as temperature, humidity and pressure, the towers also quantified the turbulent exchange of energy and mass between the forest and the atmosphere, mostly by means of the eddy covariance method. The measurements were always performed a few above the canopy, using tridimensional sonic anemometers and open-path infrared gas analysers with a frequency of 15 Hz. The fluctuations were calculated by means of a recursive filter with a time constant equal to 400 s; a coordinate rotation was performed to make the mean vertical velocity of each block equal to zero; and the WPL correction was applied.

From the field measurements performed in this experiment, the CO<sub>2</sub> flux in the boreal forest varied from an absorption of 130 gC m<sup>-2</sup>ano<sup>-1</sup> in the “southern old aspen” region to an emission of 50 gC m<sup>-2</sup>ano<sup>-1</sup> in the “northern old black spruce” region (Sellers *et al.*, 1997).

Simpson *et al.* (1997) presented the results obtained in the studies of methane and nitrous oxide exchange between the “aspen” boreal forest and the atmosphere. The emission of nitrous oxide in this type of forest is associated with the bacterial processes of nitrification and denitrification occurring in the soil, whereas methane is produced in the anaerobic microbial decomposition of organic matter, and consumed by oxidizing bacteria in aerobic conditions.

The measurements of Simpson *et al.* (1997) were made in a sequence of 5 consecutive months, in a 40 m high tower, over a forest approximately 21 m high. The method used for the CH<sub>4</sub> and N<sub>2</sub>O flux measurements was the flux-gradient method, based on the MOST, in which the scalar flux is given by:

$$F = 1,3 \frac{u_* \kappa (\overline{\rho_{\chi_1}} - \overline{\rho_{\chi_2}})}{\ln \left( \frac{z_2 - d}{z_1 - d} \right) - [\Psi_F(\zeta_2) - \Psi_F(\zeta_1)]}. \quad (6.34)$$

In this case, the same similarity functions for both CH<sub>4</sub> and N<sub>2</sub>O temperature gradients were used. Compare (6.34) with the definition of fluxes and turbulence scales in (5.5)–(5.9), and with (5.24). For the stability functions  $\Psi_F$ , Simpson *et al.* (1997) used the same equations presented in section 5.3.

It is important to note that Simpson *et al.* (1997) applied a correction factor of 1,3 in (6.34), with a somewhat questionable justification based on the contributions of convective circulation cells to the surface fluxes. Strictly speaking, this kind of adjustment is often applied in an *ad hoc* way to force the closing of the surface energy balance (Twine *et al.*, 2000), but a systematic approach to explain the lack of closure of the energy balance has not been attained yet; in this sense it is worth mentioning the works of Sakai *et al.* (2001) and Finnigan *et al.* (2003) about the contribution of the mesoscale components to the surface fluxes.

For the measurement of high-frequency data, a sonic anemometer (20cm path Kaijo-Denki DAT-310) was used, placed at 39,1 m, and run at a frequency of 100 Hz with 20-Hz block averaging, undergoing a coordinate rotation to eliminate the mean vertical velocity. The gas concentration difference between two levels was measured with two Campbell Scientific Inc. *Tunable diode laser Trace Gas Analysis System* sensors, placed at  $z_2 = 37,5$  m and  $z_1 = 26,8$  m. The mea-



sured fluxes were  $1,4 \pm 0,5 \text{ ng m}^{-2} \text{ s}^{-1}$  and  $15,7 \pm 2,8 \text{ ng m}^{-2} \text{ s}^{-1}$  respectively for  $\text{CH}_4$  and  $\text{N}_2\text{O}$ , for the 5-month period.

$\text{CH}_4$  flux measurements using the same technique were also made in the “southern boreal fen” region, and  $\text{CH}_4$  emission rates of the order of  $2250 \text{ ng m}^{-2} \text{ s}^{-1}$  were obtained (Simpson *et al.*, 1997), which is expected due to the anaerobic characteristic of this type of ecosystem.

### 6.3.2 – LBA

The Large-Scale Biosphere-Atmosphere Experiment in Amazonia was an international research conducted in the Brazilian Amazon forest between 1995 and 2005. It had the goal of understanding the carbon and other nutrient’s dynamics between the forest and the atmosphere, and  $\text{CO}_2$  flux studies were made using, among others, the eddy covariance method.

Miller *et al.* (2004) made a study that compared the eddy covariance method, with some of its correction alternatives, with biometric inventories performed in the region. The measurements were made in the *Floresta Nacional Tapajós*, 70 km south of Santarém PA, a typical dense tropical forest region (average canopy height: 35 to 40 m), on a plateau that extends for many kilometers.

The biometric inventories are measurements of biomass that exists in a given region, and when they are continued for several years, they allow estimates of the carbon balance in the period. Miller *et al.* (2004) used three existing inventories in the region to estimate the carbon balance for 16 years (1984-2000) in the area in which the measurements of eddy covariances were undertaken.

The eddy covariance method applied by the authors consisted in the measurement of the turbulent  $\text{CO}_2$  flux at a 64 m-high tower. The high frequency measurements of wind velocity were made by a three-axis sonic anemometer. The molar density of  $\text{CO}_2$  and  $\text{H}_2\text{O}$  were measured independently by two analysers: an infrared open path gas analyser, and a closed path one. The latter sampled air through a teflon PFA overheated tube ( $65^\circ \text{C}$ ) with 9,5 mm of internal diameter. All of the measurements were performed at 4 Hz, and the delay time of the closed path analyser was 11,75 s for  $\text{CO}_2$  and 12,75 s for  $\text{H}_2\text{O}$ . Two different methods were also used, named method (1) and method (2), for the calculation of  $\text{CO}_2$  and  $\text{H}_2\text{O}$  concentrations (for further details, check Miller *et al.* (2004)).

For the closed-path analyzer, it was necessary to apply a correction for the loss of the high frequency fluctuations, which was made on the basis of the similarity between temperature and  $\text{CO}_2$  and  $\text{H}_2\text{O}$ , by means of a first-order filter that simulates the attenuation of the fluctuations in the tube. The time constant were found by comparing the spectra of temperature and  $\text{CO}_2$  or temperature and  $\text{H}_2\text{O}$ , and the result obtained was a time constant of 0,4 s for  $\text{CO}_2$  and of 0,9 s for  $\text{H}_2\text{O}$ .

The effect of the loss low-frequency flux components by the average used to estimate the fluxes, as well as the effect of the linear detrending, were also discussed by the authors. They tested 30-min. averages and 2-hour averages, to assess the effect of the time-averaging period, and also compared the results obtained with and without linear detrending.

On last correction of the flux data was applied to “calm” periods, when the eddy covariance method is not able to measure the  $\text{CO}_2$  flux. The correction,

Table 6.1: Results obtained by [Miller et al. \(2004\)](#) for CO<sub>2</sub> fluxes in Amazônia (a positive sign indicates an emission). CP = “closed path”; OP = “open path”.

Method of measurement/correction	Flux (MgC ha <sup>-1</sup> year <sup>-1</sup> )
biometric	0,8 ± 2,0
CP, 30-min, without <i>detrending</i> , w/ cor. alta frequência	-3,9
CP, 30-min, without <i>detrending</i> , wo/ cor. alta frequência	-4,2
OP, 30-min, without <i>detrending</i> , w/ WPL	-10,0
OP, 30-min, without <i>detrending</i> , wo/ WPL método (1)	-5,5
OP, 30-min, without <i>detrending</i> , w/ WPL método (2)	-5,0
CP, 120-min, without <i>detrending</i> , w/ cor. alta frequência	-3,5
OP, 30-min, with <i>detrending</i> , w/ WPL método (2)	-4,8
CP, 30-min, without <i>detrending</i> , w/ cor. alta frequência, $u_* < 0,2 \text{ m s}^{-1}$	+0,4
CP, 30-min, without <i>detrending</i> , w/ cor. alta frequência, $u_* < 0,3 \text{ m s}^{-1}$	+2,0

which is standard, consisted of applying a filter based on the friction velocity values  $u_*$ : whenever the measured  $u_*$  was below a certain cutoff value, the measured fluxes were replaced by model values based on soil and plants respiration as a function of easily-measured variables such as soil temperature.

The obtained results comparing all the correction possibilities and the biometric results are presented in table 6.1. The results give an important idea of the dispersion of results that can be obtained at a single site from measurements with the ECM.

The evidence that the CO<sub>2</sub> flux is underestimated during nights with low turbulence is confirmed in other measurements made in the project, as the work presented in [Culf et al. \(1997\)](#) and in the paper by [Chambers et al. \(2004\)](#). [Miller et al. \(2004\)](#) also conclude that using of 30 min or 2 h in the calculation of averages did not produce significant differences, as well as the utilization of methods (1) and (2) in the WPL correction. In general, the measurements using closed- and open-path analyzers were shown to be similar, and the result considered by the authors as the most correct is a CO<sub>2</sub> flux of +0,4MgC ha<sup>-1</sup> ano<sup>-1</sup>, a result consistent with the biomass inventory. It is important to emphasize that the large error associated with the biometric measurements is due to the fact that smaller plants are neglected in the study, which can represent a large part of the carbon balance of the region.

### 6.3.3 – ChinaFLUX

[Yu et al. \(2006\)](#) present an overview of ChinaFLUX (Chinese Research Network for Fluxes in Terrestrial Ecosystems), a network of micrometeorological measurements of fluxes of CO<sub>2</sub>, water vapor and energy between the biosphere and the atmosphere for long periods using chambers and the Eddy Covariance Method. The ECM, used in 8 different places, had as a focus the measurement of water vapor and CO<sub>2</sub> while the chamber method, used in 17 places, emphasized CH<sub>4</sub> and N<sub>2</sub>O measurements.

The measurements using the ECM were performed in 3 places over, 4 places

over tall forest in 1 place over an agriculture area with crop rotation (wheat and corn). The standard set of equipments in these micrometeorological stations consisted of an open-path infrared gas analyzer model *Li-Cor* LI-7500 (measuring  $\text{H}_2\text{O}$  and  $\text{CO}_2$ ), a sonic anemometer *Campbell* CSAT3 (measuring the three components of the wind velocity and temperature), and a datalogger storing the measurements at 10 Hz. The fluxes were calculated using block averages of 30 minutes, and were corrected with the WPL correction.

The eddy covariance measurements were supplemented with a 6-level  $\text{CO}_2/\text{H}_2\text{O}$  and a 7-level  $\text{CO}_2$  profiling system, also custom-designed by Campbell Scientific Inc., at the crop/grassland sites and the forest sites, respectively. Standard meteorological measurements included air humidity, wind speed and direction, four components of the net radiation, photosynthetically active radiation, soil heat flux, soil temperature, and soil moisture.

In one of the forests there were four-level measurements, allowing investigations about the fluxes footprint ([Leclerc and Thurtell, 1990](#)), advection effects, vertical divergence of turbulent fluxes and aerodynamic interference from the tower.

In two forests open and closed path sensors were compared, and the resulting fluxes from the two sensors were considered similar.

In an agricultural area, techniques of *ensemble blocks* were applied and ogives ([Sun et al., 2006](#)) were calculated to determine the contribution of the low frequencies to the fluxes (see above the comments on the analysis of [Sakai et al. \(2001\)](#) and [Finnigan et al. \(2003\)](#)), under the argument that the inclusion of the components of low frequency can improve the energy balance closure. However, averages over periods greater than 30 minutes did not always improve the results.

Other results reported in [Yu et al. \(2006\)](#) are not surprising, considering what we have already reviewed earlier:

- Daytime observations are less affected than nighttime ones.
- Daytime data are less affected by the ground roughness than nighttime data.
- Measurements with the ECM showed discrepancies and uncertainties mainly during nights and over complex terrain.

## 6.4 – Cerrado

[da Rocha et al. \(2002\)](#) used the ECM for measurement of the  $\text{CO}_2$  flux on a savanna (Cerrado *Sensu stricto*) near the city of Santa Rita do Passa-Quatro (SP) between October of 2000 and March of 2002. The measurements were performed from a 21 m-high tower equipped with sensors to measure meteorological variables besides a set of high-frequency sensors consisting of a sonic anemometer (A1012R *Gill Solent*), an infrared gas analyser for  $\text{CO}_2$  and  $\text{H}_2\text{O}$  (*Li-cor* 6262) and an air sampling system. The micrometeorological measurements were made at 5 Hz. The fluxes were calculated for periods of 30 minutes using coordinate rotation and algorithms for the loss of the high frequencies described in [Moncrieff et al. \(1997\)](#).

Nocturnal fluxes were filtered for the cutoff values of  $u_*$ , as proposed by Goulden *et al.* (2006); considering cutoff values of  $0,2 \text{ m s}^{-1}$  and  $0,5 \text{ m s}^{-1}$ , the  $\text{CO}_2$  balance results in  $-0,5 \text{ t}_\text{C ha}^{-1} \text{ year}^{-1}$  and  $+3,2 \text{ t}_\text{C ha}^{-1} \text{ year}^{-1}$ . The authors conclude that the cerrado is a small source of  $\text{CO}_2$ , with a net  $+0,1 \text{ t}_\text{C ha}^{-1} \text{ year}^{-1}$  emission rate.

## 6.5 – Conclusions

With various decades of effective use around the globe, the micrometeorological methods of flux-gradient and eddy covariance constitute a practical tool for the measurement of greenhouse gas surface fluxes.

Even with the almost enthusiastic adoption of the ECM by the ecological community, and its great utility for studying the physiology of ecosystems (Baldocchi, 2003), significant challenges still have to be overcome, including a better understanding of all the time scales that contribute to the surface fluxes, and their relation with atmospheric stability; of the surface energy balance; of the effects of advection and their relation with complex topography; of the non-stationarity; and of the intermittency of the nocturnal turbulence.

The continuous technological advance of the sensors, and their corresponding diminishing costs, have made the ECM widely available and allowed the generation of a large flux data base. This massive experimental approach has generated in the last decades a heretofore unseen volume of knowledge on the physics, chemistry and biology of numerous terrestrial ecosystems.

The availability of more sensors, at a relatively low cost; the increase of computer resources; and the quantitative and qualitative improvement of human resources in micrometeorology research permit an optimistic assessment of the ECM and the FGM application potential in greenhouse gas studies.

The physical hypotheses of the micrometeorological methods and their current limitations were emphasized here so that in new experiments the experimental apparatus and the theoretical analysis can provide advances in their application and in the reliability of their results.

# 7

## Energy fluxes at the surface

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# 8

## O método de medição de covariâncias turbulentas

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Este capítulo tem o objetivo de mostrar, da forma mais didática possível, as bases do método de medição de covariâncias turbulentas. Para entendê-lo, é preciso conhecer os balanços integrais de massa, quantidade de movimento e energia que são ensinados em livros de Mecânica dos Fluidos. Uma excelente referência para balanços integrais é o livro de [Fox and McDonald \(1981\)](#).

### 8.1 – Balanços integrais e covariâncias turbulentas

A figura 8.1 mostra a essência do método de medição de covariâncias turbulentas. Nós vamos ilustrá-la para um par grandeza intensiva  $\leftrightarrow$  grandeza extensiva ([Fox and McDonald, 1981](#)) específico, a saber: a entalpia específica (por unidade de massa)  $h$  e a entalpia total. Para o volume de controle mostrado, a equação de balanço de entalpia é

$$\dot{Q} + \dot{R} = \frac{\partial}{\partial t} \int_{VC} h\rho dV + \oint_{SC} h\rho(\mathbf{n} \cdot \mathbf{u}) dS. \quad (8.1)$$

Neste relatório, nós vamos usar  $u$  para a velocidade *longitudinal* (ou seja: na direção do vento médio dentro da hora ou da meia-hora),  $v$  para a velocidade *transversal*,  $w$  para a velocidade *vertical* e  $\theta$  para a temperatura. Expandindo a derivada em relação ao tempo em (8.1),

$$\dot{Q} = \int_{VC} h \frac{\partial \rho}{\partial t} dV + \int_{VC} \frac{\partial h}{\partial t} \rho dV + \oint_{SC} h\rho(\mathbf{n} \cdot \mathbf{u}) dS. \quad (8.2)$$

A entalpia por unidade de massa  $h$  pode ser linearizada em torno de uma temperatura  $\theta_0$  qualquer:

$$h = h_0 + c_p(\theta - \theta_0), \quad (8.3)$$

onde  $c_p$ , o calor específico a pressão constante, é, *por definição*, a derivada parcial de  $h$  em relação a  $\theta$  para  $p$  constante ( $p$  é a pressão atmosférica). Levando (8.3) em (8.2) e rearrumando:

$$\dot{Q} = \int_{VC} [h_0 + c_p(\theta - \theta_0)] \frac{\partial \rho}{\partial t} dV + \int_{VC} \rho c_p \frac{\partial \theta}{\partial t} dV + \oint_{SC} [h_0 + c_p(\theta - \theta_0)] \rho(\mathbf{n} \cdot \mathbf{u}) dS. \quad (8.4)$$

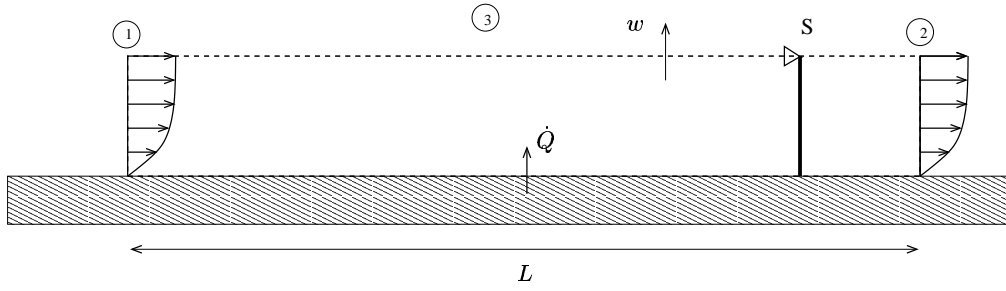


Figure 8.1: Balanço de entalpia para uma “caixa” virtual (um volume de controle) de altura  $z_a$  sobre uma superfície homogênea de comprimento  $L$  ao longo da direção do vento.

Esta equação agora pode ser re-arranjada de maneira a explicitar o balanço de massa:

$$\dot{Q} = h_o \left\{ \int_{VC} \frac{\partial \rho}{\partial t} dV + \oint_{SC} \rho(\mathbf{n} \cdot \mathbf{u}) dS \right\} - \quad (8.5)$$

$$c_p \theta_0 \left\{ \int_{VC} \frac{\partial \rho}{\partial t} dV + \oint_{SC} \rho(\mathbf{n} \cdot \mathbf{u}) dS \right\} + \quad (8.6)$$

$$\int_{VC} \frac{\partial}{\partial t} [\rho c_p \theta] dV + \oint_{SC} [\rho c_p \theta](\mathbf{n} \cdot \mathbf{u}) dS. \quad (8.7)$$

Os dois termos entre chaves acima são nulos por representarem o balanço de massa para o volume de controle; apenas o último termo do lado direito de 8.7, portanto, precisa ser considerado nas análises subsequentes.

O termo transiente pode ser escrito com a ajuda da lei dos gases,

$$p = \rho R \theta \Rightarrow \frac{\partial}{\partial t} [\rho c_p \theta] = \frac{c_p}{R} \frac{\partial p}{\partial t}. \quad (8.8)$$

A integral do termo transiente, então, torna-se

$$\int_{VC} \frac{\partial}{\partial t} [\rho c_p \theta] dV = \int_{x=0}^L \int_{y=0}^b \int_{z=0}^{z_a} \frac{c_p}{R} \frac{\partial p}{\partial t} dz dy dx, \quad (8.9)$$

onde  $b$  é a dimensão *transversal* do volume de controle. Em uma primeira análise este termo provavelmente pode ser desprezado exceto durante mudanças bruscas nas condições do tempo.

O termo envolvendo a advecção de entalpia através da superfície de controle deve ser contabilizado para cada uma das superfícies ①, ② e ③.

$$\int_{①} [\rho c_p \theta](\mathbf{n} \cdot \mathbf{u}) dS = - \int_{y=0}^b \int_{z=0}^{z_a} [\rho c_p \theta u](x=0, y, z, t) dz dy, \quad (8.10)$$

$$\int_{②} [\rho c_p \theta](\mathbf{n} \cdot \mathbf{u}) dS = + \int_{y=0}^b \int_{z=0}^{z_a} [\rho c_p \theta u](x=L, y, z, t) dz dy, \quad (8.11)$$

$$\int_{③} [\rho c_p \theta](\mathbf{n} \cdot \mathbf{u}) dS = + \int_{x=0}^L \int_{y=0}^b [\rho c_p \theta w](x, y, z=z_a, t) dy dx. \quad (8.12)$$

Considere agora a média temporal (indicada por uma barra:  $\overline{(\cdot)}$ ) de (8.4): o fluxo de calor sensível médio  $H$  é definido como

$$H \equiv \frac{\overline{\dot{Q}}}{bL}; \quad (8.13)$$

observe que  $\overline{\dot{Q}}$  é uma taxa de transferência de calor para dentro do VC, em Joules por segundo, ou Watts. As unidades SI de  $H$ , portanto, são Watts por metro quadrado ( $\text{W m}^{-2}$ ). Todos os fluxos de energia relevantes na superfície, o fluxo de calor sensível  $H$ , o fluxo de calor latente  $LE$ , o fluxo de calor no solo  $G$  e diversos componentes de radiação (radiação solar incidente, radiação solar refletida, radiação líquida, etc.) são dados em  $\text{W m}^{-2}$ .

Se o escoamento for *homogêneo* em  $x$  e  $y$ , então

$$\overline{[\rho c_p \theta u]}(x = 0, y, z) = \overline{[\rho c_p \theta u]}(x = L, y, z), \quad \forall y, z \quad (8.14)$$

(observe que esta afirmação somente é válida na média, e que estamos supondo, por simplicidade, que as médias temporais não dependem mais de  $t$ ), e portanto

$$\int_{\textcircled{1}} \overline{[\rho c_p \theta]}(\mathbf{n} \cdot \mathbf{u}) dS + \int_{\textcircled{2}} \overline{[\rho c_p \theta]}(\mathbf{n} \cdot \mathbf{u}) dS = 0. \quad (8.15)$$

A homogeneidade também implica que  $\overline{[\rho c_p \theta w]}(x, y, z = z_a, t)$  não depende de  $x$  nem  $y$ , donde:

$$\int_{x=0}^L \int_{y=0}^b \overline{[\rho c_p \theta w]}(x, y, z = z_a, t) dy dx = \overline{[\rho c_p \theta w]}(z = z_a) bL. \quad (8.16)$$

Levando todas estas simplificações em (8.7), obtém-se a equação para o fluxo de calor sensível  $H$  em função de medições em um único ponto na altura  $z = z_a$  na fronteira superior do volume de controle:

$$H = \overline{[\rho c_p \theta w]}(z = z_a). \quad (8.17)$$

Neste ponto nós introduzimos a decomposição de Reynolds para escoamentos turbulentos,

$$w = \overline{w} + w', \quad (8.18)$$

$$\rho = \overline{\rho} + \rho', \quad (8.19)$$

$$\theta = \overline{\theta} + \theta', \quad (8.20)$$

e os *postulados* de Reynolds para quaisquer variáveis  $x$  e  $y$  na atmosfera ( $x$  e  $y$  não são coordenadas espaciais),

$$\overline{\overline{x}} = \overline{x}, \quad (8.21)$$

$$\overline{x'y'} = 0, \quad (8.22)$$

juntamente com a observação de que, na camada-limite superficial, as flutuações de pressão podem ser desprezadas *vis-à-vis* as flutuações de temperatura e de densidade, resultando da lei dos gases perfeitos que (Fleagle and Businger, 1980)

$$\frac{\rho'}{\overline{\rho}} = -\frac{\theta'}{\overline{\theta}}. \quad (8.23)$$



Suponha agora que o fluxo de massa através de ③ seja nulo em média: a aplicação de (8.21) e (8.22) produz

$$\overline{\rho w} = \overline{(\bar{\rho} + \rho')(\bar{w} + w')} = \bar{\rho} \bar{w} + \overline{\rho' w'} = 0, \quad (8.24)$$

enquanto que

$$\begin{aligned} \overline{\rho w \theta} &= \overline{(\bar{\rho} + \rho')(\bar{w} + w')(\bar{\theta} + \theta')} \\ &= \overline{\bar{\rho} \bar{w} \bar{\theta}} + \underbrace{\overline{\bar{\rho} \bar{w} \theta'}}_{=0} + \underbrace{\overline{\bar{\rho} w' \bar{\theta}}}_{=0} + \underbrace{\overline{\rho' \bar{w} \bar{\theta}}}_{=0} + \\ &\quad \underbrace{\overline{\rho' w' \theta'}}_{\approx 0} + \underbrace{\overline{\bar{w} \rho' \theta'}}_{=0} + \underbrace{\overline{\bar{\theta} w' \rho'}}_{=0} + \underbrace{\overline{\rho' w' \theta'}}_{\approx 0}. \end{aligned} \quad (8.25)$$

Substituindo (8.23) e (8.24) em (8.25), e fazendo as simplificações indicadas nesta equação,

$$\begin{aligned} \overline{\rho w \theta} &\approx \overline{\bar{\rho} w' \theta'} + \overline{\bar{w} \rho' \theta'} \\ &= \overline{\bar{\rho} w' \theta'} - \bar{\rho} \frac{\overline{\theta' \theta'}}{\bar{\theta}^2} \overline{w' \theta'} \\ &= \overline{\bar{\rho} w' \theta'} \left[ 1 + \frac{\overline{\theta' \theta'}}{\bar{\theta}^2} \right]. \end{aligned} \quad (8.26)$$

A ordem de grandeza de  $\overline{\theta' \theta'}/\bar{\theta}^2$  na camada limite atmosférica é  $10^{-5}$  (note que estamos usando temperaturas *termodinâmicas*:  $\bar{\theta} \sim 300$  K); portanto, em um nível de aproximação excelente,

$$H = \bar{\rho} c_p \overline{w' \theta'}. \quad (8.27)$$

Isto mostra que é relativamente simples medir o fluxo de calor sensível que emana de uma superfície homogênea, desde que seja possível medir a *covariância*  $w' \theta'$ ; isto significa que devemos medir a componente vertical (ou, no caso mais geral, a componente do vento normal à superfície) e a temperatura com sensores rápidos (devem ter resposta rápida, reagindo a mudanças bruscas na grandeza física que está sendo medida) e sensíveis (devem ser capazes de detectar pequenas variações na grandeza que está sendo medida). É por este motivo que nós usamos anemômetros sônicos para medir a velocidade do vento, e termopares para medir a temperatura do ar.

Todo o desenvolvimento acima pode ser repetido para outras grandezas, e a medição de fluxos superficiais com esta metodologia denomina-se *Método de medição de covariâncias turbulentas* (MCT). O MCT, portanto, baseia-se na medição simultânea em alta frequência da velocidade vertical  $w$  do vento e da grandeza intensiva cujo fluxo se deseja mensurar; respectivamente,  $u$  e  $v$  (velocidade horizontal) para o fluxo de quantidade de movimento  $\tau$ ,  $\theta$  (temperatura) para o fluxo de calor sensível  $H$ ,  $q$  (umidade específica) ou  $\rho_v$  (densidade de vapor d'água) para o fluxo de vapor d'água  $E$  e  $c$  (concentração mássica) para

o fluxo  $F$  de um gás de efeito estufa tal como o  $\text{CO}_2$ :

$$|\tau| = \bar{\rho} u_*^2 = \bar{\rho} \sqrt{\overline{w'u'^2} + \overline{w'v'^2}}, \quad (8.28)$$

$$H = \bar{\rho} c_p u_* \theta_* = \bar{\rho} c_p \overline{w'\theta'}, \quad (8.29)$$

$$E = \bar{\rho} u_* q_* = \bar{\rho} \overline{w'q'}, \quad (8.30)$$

$$F = \bar{\rho} u_* c_* = \bar{\rho} \overline{w'c'}, \quad (8.31)$$

onde  $\tau = \bar{\rho} [\overline{w'u'} \mathbf{i} + \overline{w'v'} \mathbf{j}]$  é o vetor de tensões de cisalhamento turbulentas;  $u_*$ ,  $\theta_*$ ,  $q_*$  e  $c_*$  são escalas turbulentas de velocidade, temperatura, umidade e concentração. Os sensores rápidos típicos de um sistema do MCT para as diversas grandezas cuja medição em alta frequência é necessária são os seguintes:

$u$ ,  $v$ ,  $w$ : anemômetro sônico.

$\theta$ : temperatura virtual dada por um anemômetro sônico; temperatura do ar dada por um termopar de fio fino.

$q$ : higrômetro infra-vermelho ou capacitivo de resposta rápida.

$c$ : analisador de gás de caminho aberto (*open-path*) ou fechado (*closed-path*) infra-vermelho; analisadores de caminho fechado produzem atenuação do sinal e demandam um aparato experimental mais complexo, de forma que a tendência moderna tem sido o uso de analisadores de caminho aberto.

## 8.2 – O fechamento do balanço de energia

O balanço de energia de uma superfície em condições não-advectivas e estacionárias é dado por

$$R_l = H + LE + G, \quad (8.32)$$

onde  $R_l$  é a radiação líquida, que pode ser medida com um radiômetro líquido ou estimada com diversas equações, e  $G$  é o fluxo de calor no solo. Todos os termos de (8.32) estão sendo medidos de forma independente nas duas estações micrometeorológicas em terra, em Santa Cruz e Olho d'Água:  $H$  e  $LE$  com o MCT,  $R_l$  com um radiômetro líquido e  $G$  com placas de fluxo de calor no solo.

Em princípio, o MCT proporciona medições independentes de  $H$  e  $LE$ ; consequentemente, pelo menos em condições ideais (ausência de advecção local ou de larga escala, estacionariedade, etc.) a soma  $H + LE$  medida com sensores de turbulência deveria ser igual a  $R_l - G$  (medido com um radiômetro líquido e com placas de fluxo de calor no solo) em (8.32). Na prática, trabalhos que tratem explicitamente do “fechamento do balanço de energia” são (surpreendentemente) relativamente raros na literatura de micrometeorologia. Um dos motivos é a tendência das equipes experimentais se especializarem em um ou outro método: por exemplo, durante o experimento FIFE em 1987/1989, equipes de pesquisadores diferentes eram responsáveis por estações de fluxo baseadas no MCT e no MBE; neste experimento, foram encontradas discrepâncias relativamente grandes entre os fluxos medidos com os dois tipos de sistemas (Fritschen *et al.*, 1992). As eventuais discrepâncias podem ser atribuídas a numerosas causas, tais como as profundidades de medição do fluxo de calor no solo  $G$  (de Silans *et al.*, 1997), contribuições de mesoescala para  $H$  e  $LE$  que podem não ser devidamente levadas em conta pelo MCT, etc..

### 8.3 – Vantagens e desvantagens do MCT

A grande vantagem do MCT é que ele depende exclusivamente de um único conjunto de medições, feitas com 2 ou no máximo 3 sensores diferentes em um volume relativamente pequeno do espaço (tipicamente menor que  $0,20 \times 0,20 \times 0,20 \text{ m}^3$ ).

A grande desvantagem é que ele se baseia em medições de turbulência, o que implica em:

1. Medições em “alta frequência” (tipicamente, a frequência de medição é igual ou maior que 10 Hz). Isto deve ser contraposto às medições em “baixa frequência” (uma vez a cada 10 segundos, um minuto ou até mesmo uma hora) que são típicas das grandezas meteorológicas médias usadas (por exemplo) no método do balanço de energia, tais como temperatura e umidade do ar, radiação líquida, etc.
2. O custo destes sensores: tipicamente, um anemômetro sônico de qualidade de pesquisa custa em torno de US\$ 10.000,00, e um analisador de  $\text{CO}_2$  e  $\text{H}_2\text{O}$  (ambos em um mesmo aparelho), US\$ 15.000,00 (valores de 2001).
3. Anemômetros sônicos e analisadores infra-vermelhos geralmente não funcionam com chuva, embora os modelos modernos sejam capazes de *resistir* à chuva, voltando a funcionar depois de secos.
4. Técnicas estatísticas de processamento de dados relativamente sofisticadas. Frequentemente utiliza-se algum tipo de filtragem sobre a série de dados originalmente disponível para reduzir ou eliminar os efeitos de não-estacionariedade, o que pode causar subestimativas dos momentos de ordem 2 em (8.28)–(8.31) (Rannik and Vesala, 1999). Outra forma de se calcular os fluxos superficiais é mediante a integral dos co-espectros correspondentes (Dias, 1994). Qualquer que seja a metodologia adotada para o cálculo das covariâncias turbulentas, existe uma diferença de várias ordens de magnitude entre o tipo de medição que é usual em hidrologia (2 vezes por dia), na meteorologia das medições “sinóticas” (4 ou no máximo 8 vezes por dia), na hidrologia e meteorologia das estações automáticas (com sistemas de aquisição de dados a bordo — várias vezes por hora, até uma medição por segundo, com o registro entretanto apenas de valores horários), e aquele necessário no MCT (10 ou mais vezes por segundo, com o registro dos dados brutos, ou de estatísticas a cada 15, 30 ou 60 minutos destas medições). Inevitavelmente, sistemas de medição contínua ao longo de semanas, meses ou anos devem gravar apenas estatísticas (médias, variâncias e covariâncias) das variáveis em questão, o que exige que os sistemas de aquisição de dados sejam capazes de calcular estas estatísticas em “tempo real”.

# 9

## O processamento de dados micrometeorológicos

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### 9.1 – Médias probabilísticas, e os postulados de Reynolds

As medições eulerianas realizadas rotineiramente ou em modo de campanha em estações micro-, agro-, ou simplesmente “meteorológicas” podem ser compreendidas em termos de suas escalas temporais à luz da decomposição de Reynolds, via (??).

A decomposição de Reynolds, ela mesma, baseia-se fortemente na idéia de que a turbulência atmosférica é um processo estocástico superposto a uma “média” determinística:

$$U(\omega, t) = \langle U \rangle(t) + u(\omega, t). \quad (9.1)$$

Estritamente falando, (9.1) e, principalmente, os “postulados de Reynolds” que em geral se seguem, valem para médias *probabilísticas* (em Inglês, *ensemble averaging*). Vamos defini-los todos sucintamente. Sejam  $U(\omega, t)$  e  $V(\omega, t)$  dois processos estocásticos, não necessariamente estacionários, que representam duas grandezas atmosféricas quaisquer. O valor esperado de  $U$  é a sua integral em relação à medida de probabilidade  $P$  do espaço amostral (Billingsley, 1986, cap. 3, seção 21):

$$\langle U \rangle(t) \equiv \int_{\omega \in \Omega} U(\omega, t) dP(\omega). \quad (9.2)$$

Esta definição é extremamente sofisticada, e requer pelo menos alguma idéia do que significa, em termos matemáticos, uma “medida de probabilidade”. É possível torná-la um pouco mais palatável. Considere aqui um conjunto  $\Omega$ , o “espaço amostral”. Em termos simples,  $\Omega$  é o conjunto do qual serão sorteados elementos  $\omega$ . Um problema matemático gigantesco é *definir* o significado de uma integral sobre  $\Omega$  quando as probabilidades de ocorrência de cada elemento  $\omega$  não são finitas, mas sim infinitesimais. Suponhamos então que seja possível postular uma densidade de probabilidade para cada  $\omega$ , de tal maneira que a probabilidade de ocorrência de um subconjunto  $A \subset \Omega$  seja:

$$P(A) = \int_{\omega \in A} p(\omega) d\omega. \quad (9.3)$$

Esta, entretanto, é normalmente interpretada como uma integral “de Riemman”.

Em lugar de “fatiar” o eixo  $\omega$ , é possível “fatiar” o eixo  $P$ , e escrever:

$$P(A) = \int_{\omega \in A} dP(\omega). \quad (9.4)$$

A integral mais antiga com este jeito é a integral de Stieljes. Com integrais deste tipo, integrais de Stieljes e de Lesbegue, a forma elegante de definir  $\langle U \rangle(t)$  é (9.2). Segue-se que

$$\begin{aligned} u(\omega, t) &= U(\omega, t) - \int_{\xi \in \Omega} U(\xi, t) dP(\xi), \\ \langle u(\omega, t) \rangle &= \int_{\omega \in \Omega} \left[ U(\omega, t) - \int_{\xi \in \Omega} U(\xi, t) dP(\xi) \right] dP(\omega) \\ &= \int_{\omega \in \Omega} U(\omega, t) dP(\omega) - \int_{\omega \in \Omega} \int_{\xi \in \Omega} U(\xi, t) dP(\xi) dP(\omega) \\ &= \int_{\omega \in \Omega} U(\omega, t) dP(\omega) - \int_{\xi \in \Omega} \underbrace{\left[ \int_{\omega \in \Omega} dP(\omega) \right]}_{=1} U(\xi, t) dP(\xi) \\ &= 0 \end{aligned} \quad (9.5)$$

Portanto,  $u$  tem média probabilística zero.

Visto desta forma,  $\langle U \rangle(t)$  é uma função determinística (e não aleatória), porque a aleatoriedade, representada pela dependência com  $\omega$ , foi integrada. Os demais “postulados” se seguem:

$$\begin{aligned} \langle \langle U \rangle u \rangle &= \int_{\omega \in \Omega} \langle U \rangle u dP \\ &= \langle U \rangle \int_{\omega \in \Omega} u dP \\ &= 0, \end{aligned} \quad (9.6)$$

$$\begin{aligned} \langle \langle U \rangle V \rangle &= \int_{\omega \in \Omega} [\langle U \rangle (\langle V \rangle + v)] dP \\ &= \langle U \rangle \langle V \rangle + \langle U \rangle \int_{\omega \in \Omega} v dP \\ &= \langle U \rangle \langle V \rangle, \end{aligned} \quad (9.7)$$

e

$$\begin{aligned} \langle UV \rangle &= \int_{\omega \in \Omega} [(\langle U \rangle + u)(\langle V \rangle + v)] dP \\ &= \langle U \rangle \langle U \rangle + \int_{\omega \in \Omega} u(\omega, t) v(\omega, t) dP(\omega) \\ &= \langle U \rangle \langle V \rangle + \langle uv \rangle. \end{aligned} \quad (9.8)$$

Finalmente, as derivadas temporais e espaciais e seus valores esperados comu-

tam; por exemplo, no caso da derivada temporal,

$$\begin{aligned}\frac{\partial}{\partial t} \langle U \rangle &= \frac{\partial}{\partial t} \int_{\omega \in \Omega} U(\omega, t) dP(\omega) \\ &= \int_{\omega \in \Omega} \frac{\partial U(\omega, t)}{\partial t} dP(\omega) \\ &= \left\langle \frac{\partial U}{\partial t} \right\rangle.\end{aligned}\tag{9.9}$$

## 9.2 – Outras médias

Além da média probabilística, outras possibilidades existem. Por exemplo, a média temporal simples

$$\langle U(\omega, t) \rangle_T = \langle U \rangle_T(\omega) \equiv \frac{1}{T} \int_0^T U(\omega, t) dt.\tag{9.10}$$

Observe que  $\langle U \rangle_T(\omega)$  é, como a notação indica, apenas uma função de  $\omega$ , e que portanto as derivadas em relação a  $t$  não comutam:

$$\frac{\partial}{\partial t} [\langle U \rangle_T(\omega)] = 0 \neq \left\langle \frac{\partial U(\omega, t)}{\partial t} \right\rangle_T.\tag{9.11}$$

Mesmo assim, uma propriedade desejável destas médias é que a média da flutuação é zero. Para ver como, estabeleça uma “decomposição de Reynolds” da forma

$$U(\omega, t) = \langle U(\omega, t) \rangle_T + u(\omega, t),\tag{9.12}$$

mas agora  $u(\omega, t)$  possui um significado *diferente* daquele de (9.1)! Mesmo assim, é evidente que vale

$$\begin{aligned}\langle u(\omega, t) \rangle_T &= \frac{1}{T} \int_0^T u(\omega, t) dt \\ &= \frac{1}{T} \int_0^T [U(\omega, t) - \langle U(\omega, t) \rangle_T] dt \\ &= \langle U(\omega, t) \rangle_T(\omega) - \langle U(\omega, t) \rangle_T(\omega) = 0 \blacksquare\end{aligned}\tag{9.13}$$

Médias temporais, entretanto, servem para definir a *ergodicidade* de um processo; um processo é *ergódico* quando

$$\lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T U(\omega, t) dt = \langle U \rangle(t).\tag{9.14}$$

Mas haverá alguma estranheza nesta relação? Sim: o lado esquerdo é (no caso mais geral) função de  $\omega$ , enquanto que o lado direito é, no caso mais geral, função de  $t$ ; portanto, nossa definição de ergodicidade implica

$$\langle U \rangle_T(\omega) = \langle U \rangle(t) \Leftrightarrow \langle U \rangle_T = \langle U \rangle = \text{constante}.\tag{9.15}$$

Um processo em que  $\langle U \rangle = \text{constante}$  é dito *estacionário na média*; de forma mais geral, um processo estocástico é estacionário quando a distribuição conjunta de probabilidade de

$$(U(\omega, t_1 + h), U(\omega, t_2 + h), \dots, U(\omega, t_n + h))$$

(para qualquer enupla  $(t_1, t_2, \dots, t_n)$  imaginável!) é independente de  $h$  (Cramér and Leadbeter, 2004). Valendo a estacionariedade, segue-se que, *para qualquer momento de ordem  $n$ ,*

$$\begin{aligned} \langle U^n(\omega, t + h) \rangle &= \langle U^n(\omega, t) \rangle; \\ \langle U^n(\omega, t + h) \rangle - \langle U^n(\omega, t) \rangle &= 0; \\ \lim_{h \rightarrow 0} \frac{\langle U^n(\omega, t + h) \rangle - \langle U^n(\omega, t) \rangle}{h} &= 0; \\ \frac{\partial \langle U^n(\omega, t) \rangle}{\partial t} &= 0 \blacksquare \end{aligned} \quad (9.16)$$

Nem todo processo estacionário é ergódico; porém, como vimos, a estacionariedade é uma condição *necessária* para a ergodicidade.

A “extração da média” de um registro de dados turbulentos tende a ser mais complicada do que a exposição acima para os postulados de Reynolds, *porque a dependência funcional com  $\omega$  é desconhecida para dados observacionais*. A rigor, ela é uma hipótese; porém, trata-se de uma hipótese não-verificável. Para dados observacionais de turbulência atmosférica, algumas médias “empíricas” sobre os dados são tradicionalmente empregadas. A esperança costuma ser que as flutuações  $u(t)$  extraídas pelo processo sejam representativas de um processo estocástico estacionário.

As formas mais comuns de se extrair médias  $\langle U(t) \rangle$  e flutuações  $u(t)$  em micrometeorologia são as seguintes:

1. “Médias de bloco” (*block averages*).
2. “Remoção linear de tendência” (*linear detrending*).
3. “Filtragens” (*filtering*).

Médias de bloco são o equivalente discreto de (9.10). Se o *array*  $U$  é

$$U = (U_0, U_1, \dots, U_{n-1}),$$

$$\bar{U} = \frac{1}{n} \sum_{k=0}^{n-1} U_k, \quad (9.17)$$

$$u_k = U_k - \bar{U}. \quad (9.18)$$

Em um caso muito comum, o tempo de medição é de 30 minutos, e a frequência de medição é de 20 Hz, donde  $n = 30 \times 60 \times 20 = 36000$ .

No caso de remoção linear de tendência, ajusta-se uma reta de mínimos quadrados à variável tempo, na forma

$$\bar{U}_k = ak + b \quad (9.19)$$

de forma a minimizar

$$\sum_{i=k}^{n-1} [\bar{U}_k - U_k]^2.$$

O modelo contínuo equivalente para a média de tendência linear é o seguinte: dado  $U(t)$  deseja-se obter a função

$$\langle U \rangle_T(t) = at + b \quad (9.20)$$

tal que

$$S = \frac{1}{T} \int_0^T [U(t) - (at + b)]^2 dt$$

seja mínimo. Uma condição necessária (e neste caso também suficiente) para a minimização é

$$\frac{\partial S}{\partial a} = \frac{\partial S}{\partial b} = 0,$$

que leva a

$$\frac{1}{T} \int_0^T [U(t) - (at + b)] t dt = 0, \quad (9.21)$$

$$\frac{1}{T} \int_0^T [U(t) - (at + b)] dt = 0. \quad (9.22)$$

A equação (9.22) mostra que, se definirmos a decomposição

$$U(t) = \langle U \rangle_T(t) + u(t) = [at + b] + u(t), \quad (9.23)$$

então segue-se que

$$\langle u(t) \rangle_T = \frac{1}{T} \int_0^T u(t) dt = \frac{1}{T} \int_0^T [U(t) - (at + b)] dt = 0, \quad (9.24)$$

que é análogo ao postulado de Reynolds (9.5). Além disto,

$$\begin{aligned} \langle \langle U \rangle_T u \rangle_T &= \frac{1}{T} \int_0^T [at + b][U(t) - (at + b)] dt \\ &= a \underbrace{\frac{1}{T} \int_0^T t[U(t) - (at + b)] dt}_{=0} + b \underbrace{\frac{1}{T} \int_0^T [U(t) - (at + b)] dt}_{=0} = 0, \end{aligned} \quad (9.25)$$

em que os dois colchetes são nulos em virtude de (9.20)–(9.21), e que é análogo ao postulado de Reynolds (9.6).

Nesta altura algumas características desejáveis da remoção linear de tendência ficam evidentes: ela parece propiciar uma média que evolui no tempo tal que, dada a decomposição (9.23), um conjunto de teoremas para as médias temporais análogo aos postulados de Reynolds (9.5)–(9.9) pode ser deduzido.

Vale a pena verificar se isto é mesmo verdade para os postulados restantes, (9.7)–(9.9). Suporemos portanto que obtivemos tendências lineares por mínimos quadrados,

$$\begin{aligned} \langle U \rangle_T(t) &= at + b, \\ \langle V \rangle_T(t) &= ct + d \end{aligned}$$



e verificaremos:

$$\begin{aligned}\langle\langle U\rangle_{\text{T}} V\rangle_{\text{T}} &= \frac{1}{T} \int_0^T [at + b]V(t) dt \\ &= \text{constante} \\ &\neq [at + b][ct + d] = \langle U\rangle_{\text{T}} \langle V\rangle_{\text{T}}.\end{aligned}\quad (9.26)$$

Além disto,

$$\begin{aligned}\langle UV\rangle_{\text{T}} &= \langle(\langle U\rangle_{\text{T}} + u)(\langle V\rangle_{\text{T}} + v)\rangle_{\text{T}} \\ &= \langle\langle U\rangle_{\text{T}} \langle V\rangle_{\text{T}}\rangle_{\text{T}} + \langle\langle U\rangle_{\text{T}} v\rangle_{\text{T}} + \langle u \langle V\rangle_{\text{T}}\rangle_{\text{T}} + \langle uv\rangle_{\text{T}}.\end{aligned}\quad (9.27)$$

Portanto, não há analogia entre os postulados de Reynolds (9.7)–(9.8) com as médias temporais respectivas (9.26)–(9.27) utilizando remoção linear de tendência.

O último postulado a ser verificado é

$$\begin{aligned}\left\langle \frac{\partial U}{\partial t} \right\rangle_{\text{T}} &= \frac{1}{T} \int_0^T \frac{\partial U}{\partial t} dt \\ &= \frac{1}{T} \int_0^T \left[ a + \frac{\partial u}{\partial t} \right] dt \\ &= a + \frac{1}{T} [u(T) - u(0)] \neq a = \frac{\partial \langle U \rangle_{\text{T}}}{\partial t}.\end{aligned}\quad (9.28)$$

Neste caso, apesar da desigualdade estrita, vale entretanto o resultado assintótico:

$$\lim_{T \rightarrow \infty} \left\langle \frac{\partial U}{\partial t} \right\rangle_{\text{T}} = a = \frac{\partial \langle U \rangle_{\text{T}}}{\partial t}.\quad (9.29)$$

Além disto, integrando-se (9.21)–(9.22) obtém-se o sistema

$$I_0 = \frac{1}{T} \int_0^T U(t) dt = \frac{aT}{2} + b,\quad (9.30)$$

$$I_1 = \frac{1}{T} \int_0^T tU(t) dt = \frac{aT^2}{3} + \frac{bT}{2},\quad (9.31)$$

cuja solução é

$$a = \frac{12I_1 - 6I_0T}{T^2}, \quad b = \frac{4I_0T - 6I_1}{T}.$$

No caso das médias por filtragem, gera-se alguma função (do tempo) sucedânea de uma média que evolui também no tempo. Talvez o procedimento mais comum seja usar um filtro auto-recursivo de passa-baixa, com uma janela de tempo  $T_L = L\Delta t$ , onde  $n = (\Delta t)^{-1}$  é a frequência de aquisição.

Novamente, dado o vetor de dados  $U$ , aplica-se inicialmente um procedimento auto-recursivo aos valores de  $U_k$ :

$$U_k^< = \frac{U_k + (L - 1)U_{k-1}^<}{L}.\quad (9.32)$$

A série  $U_k^<$  possui escalas de tempo características longas (ou seja: baixas frequências), e desempenha o papel de uma média que evolui no tempo deterministicamente. As flutuações serão associadas com o componente de alta frequência,

e são extraídas em dois passos. Inicialmente, extrai-se as altas frequências por meio de

$$U_k^> = U_k - U_k^<. \quad (9.33)$$

Este procedimento, por si, não garante que a média dos  $U_k^>$ 's seja nula. Portanto, faz-se, ainda

$$u_k = U_k^> - \frac{1}{N} \sum_{k=1}^N U_k^> \quad (9.34)$$

para extrair a (pequena) média residual dos  $U_k^>$ 's.

É comum adotar-se  $\Delta t \ll T_L \ll T$ , onde  $T = N\Delta t$ . Valores típicos de  $T_L$  são da ordem de uns poucos minutos. [Rannik and Vesala \(1999\)](#) observaram que valores adequados de  $T_L$  para impedir a subestimativa de fluxos e variâncias são da ordem de 1/4 de  $T$ . Cada uma das equações (9.32)–(9.34) tem suas definições e razões de ser a seguir:  $U^<$  é a componente filtrada de baixa frequência: ela é um sucedâneo do sinal que seria obtido por um sensor lento com constante de tempo  $T_L$ , que seria incapaz de “ver” as flutuações turbulentas. Por definição, a componente de alta frequência  $U^>$  é a diferença entre o sinal bruto e a componente de baixa frequência.  $U^>$  tem uma aparência muito próxima das flutuações turbulentas desejadas, mas sua média, embora em geral pequena em relação a  $\bar{U}$ , não é exatamente igual a zero.

Em última análise, a sequência de operações (9.32)–(9.34) tem o objetivo de tentar remover, pelo menos em parte, a não-estacionariedade de  $U$  na camada-limite atmosférica devida ao ciclo diário da radiação líquida na superfície. De fato, suponha que  $U$  fosse um processo estacionário; então, para (a escolha óbvia)  $U^< = 0$ ,  $U^> = U$ , a série de dados brutos poderia ser diretamente decomposta em média e flutuações que atenderiam por definição aos postulados de Reynolds.

O filtro auto-recursivo de passa-baixa (9.32) é o equivalente numérico a uma operação de convolução de  $U$  com o núcleo

$$G(t) = H(t)e^{-t/T_L}/T_L, \quad (9.35)$$

onde  $H(t)$  é a função de Heaviside ([Dias, 1994](#)). Grosso modo, ele remove componentes com escalas de tempo da ordem de, ou maiores que,  $T_L$ .

Considere agora a transformada de Fourier de  $G(t)$ ,

$$\widehat{G}(n) = \int_{-\infty}^{+\infty} G(t)e^{-2\pi i n t} dt = \frac{1}{1 + 2\pi i n T_L}; \quad (9.36)$$

pelo teorema da convolução, a operação de filtragem é então equivalente ao produto  $\widehat{G}(n)\widehat{U}(n)$  no domínio da frequência. Embora  $\widehat{G}(n)$  seja uma função complexa que não pode ser visualizada em duas dimensões, é possível avaliar seu efeito sobre  $\widehat{U}$  plotando a função real  $|\widehat{G}(n)|$ . Isto é feito na figura 9.1: note que a aplicação do filtro afeta fortemente frequências muito *menores* que  $T_L^{-1}$ : por exemplo, a intensidade de  $\widehat{U}$  na frequência  $0,1T_L$  é reduzida em 30%! Já um filtro ideal de passa-baixa (também mostrado em 9.1 para comparação),

$$\widehat{G}_{\text{id}}^<(n) = \begin{cases} 1, & n < T_L^{-1} \\ 0, & n > T_L^{-1} \end{cases}, \quad (9.37)$$

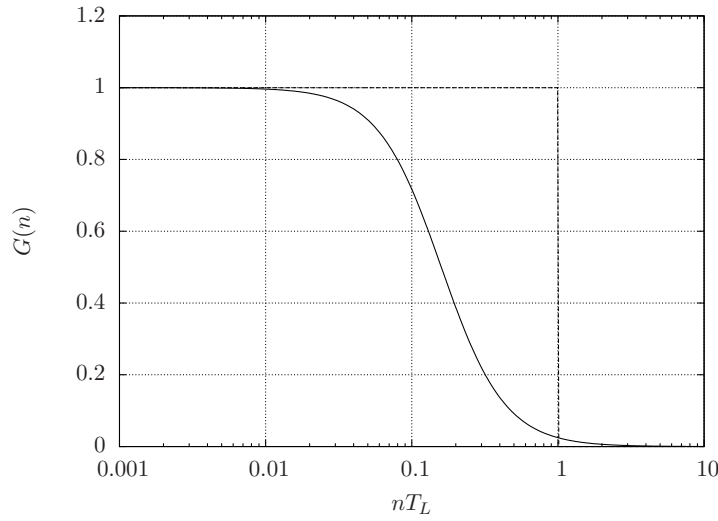


Figure 9.1: Módulo da função de transferência espectral  $\widehat{G}(n)$  do filtro de passa-baixa (9.32) (linha sólida) e de um filtro ideal (linha pontilhada)

deixa passar sem amortecimento todas as frequências menores que  $1/T_L$ , e aniquila todas as frequências maiores que este valor. Da mesma forma, um filtro ideal de passa-alta é

$$\widehat{G}_{\text{id}}^>(n) = (1 - \widehat{G}_{\text{id}}^<(n)). \quad (9.38)$$

O mesmo teorema da convolução proporciona uma sistemática simples de filtragem no domínio da frequência. Dada a série de dados brutos  $U$  de um *run*, considere uma única transformada de Fourier numérica dada por

$$\widehat{U}_m = \Delta t \sum_{k=0}^{N-1} U_k \exp \left[ \frac{-2\pi i k m}{N} \right]. \quad (9.39)$$

Para  $m \leq N/2$ ,  $\widehat{U}_m$  é a componente de Fourier associada à frequência  $n = m/(N\Delta t)$ . A partir deste ponto, há um “dobramento” da transformada de Fourier em torno da frequência de Nyquist,

$$n_c = \frac{2}{N\Delta t} \quad (9.40)$$

(vide Bendat and Piersol, 1986, p. 381–382, fig. 11.3), de tal modo que

$$\widehat{U}_m = \widehat{U}_{N-m}^*, \quad (9.41)$$

onde  $(\cdot)^*$  significa o conjugado complexo.

Este sinal pode ser agora filtrado *no domínio da frequência*, como se segue. Suponha que desejamos eliminar todas as frequências menores que  $n_b$ , ou seja, realizar uma operação de filtragem de *passa-alta*; basta então anular os componentes com frequências inferiores a  $n_b$ :

$$\widehat{U}_m = 0, \quad \frac{m}{N\Delta t} \leq n_b, \quad (9.42)$$

$$\widehat{U}_m = 0, \quad \frac{N-m}{N\Delta t} \leq n_b, \quad (9.43)$$

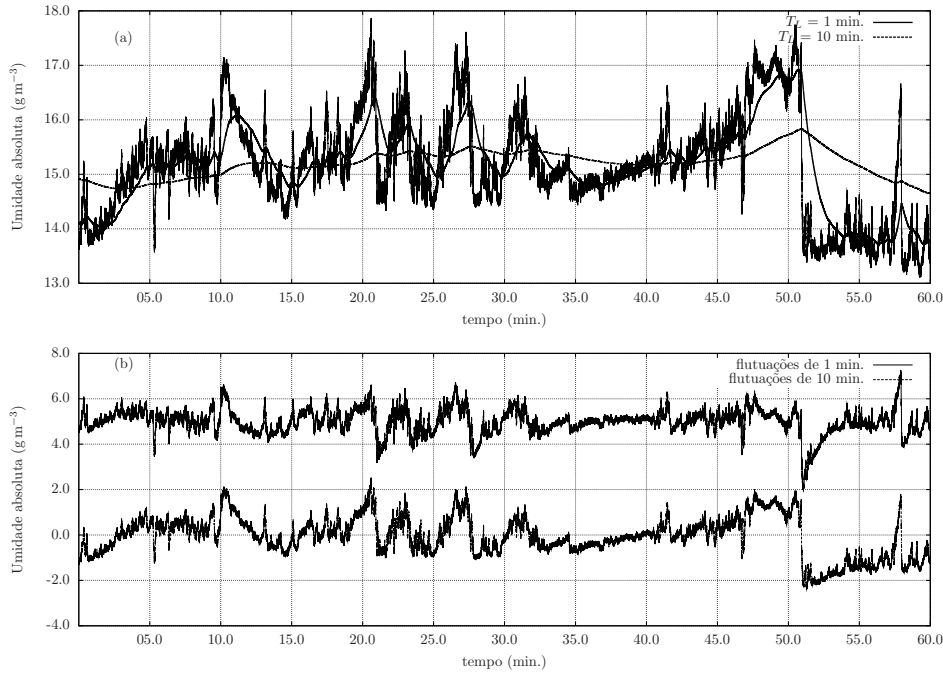


Figure 9.2: (a): filtro recursivo de passa-baixa com “janelas”  $T_L = 1$  minuto e  $T_L = 10$  minutos; (b): flutuações turbulentas de 1 minuto (deslocadas de  $+5 \text{ g m}^{-3}$ ) e de 10 minutos

onde (9.43) é consequência de (9.41), e então voltar ao domínio do tempo por meio de uma transformada de Fourier inversa. A série resultante não conterá mais nenhum harmônico de frequência inferior a  $n_b$ . Isto elimina naturalmente tendências de não-estacionariedade da média.

Nós agora vamos dar um exemplo de ambos os filtros [Nota: apenas o filtro no domínio do tempo foi feito. Um bom trabalho para este curso seria fazer uma aplicação de filtro espectral, para completar o exemplo] com medições em alta frequência de densidades de vapor d’água; nós vamos escolher um período particularmente interessante, que são as medições realizadas no Lago de Furnas durante 30 minutos terminando em 2003-06-04T14:00:00.00. Para uma descrição do experimento, veja Dias *et al.* (2007). A decomposição de Reynolds é

$$\varphi_v = \langle \varphi_v \rangle + \rho_v. \quad (9.44)$$

A figura 9.2 mostra os dados de densidade de vapor d’água medidos, a operação de filtragem de passa-baixa, e as séries de flutuações resultantes das filtrações de 1 minuto e 10 minutos. É importante observar que a escolha da “janela”  $T_L$  do filtro *modifica* a série de flutuações (neste caso,  $\rho_v$ ) resultantes.

### 9.3 – Correlação temporal

Para processos estocásticos estacionários, é possível definir diversas estatísticas de dependência e memória. A mais clássica é a função de autocovariância (muitos autores a chamam simplesmente de função de autocorrelação); para um processo geral (não necessariamente estacionário), a função de autocovariância

é uma função de *duas* variáveis:

$$R(t_1, t_2) \equiv \langle u(\omega, t_1)u(\omega, t_2) \rangle. \quad (9.45)$$

Agora, se o processo for estacionário,  $R(t_1, t_2)$  deve ser invariante sob uma translação qualquer no tempo. Em particular,

$$R(t_1, t_2) = R(0, t_2 - t_1) = \langle u(\omega, 0)u(\omega, t_2 - t_1) \rangle, \quad (9.46)$$

ou

$$R(\tau) \equiv \langle u(\omega, 0)u(\omega, \tau) \rangle, \quad (9.47)$$

que é a definição que vamos usar para a função de autocovariância de processos estacionários. Uma outra função igualmente importante é a *função de estrutura*:

$$D(\tau) \equiv \langle [u(\omega, \tau) - u(\omega, 0)]^2 \rangle, \quad (9.48)$$

que desempenha um papel fundamental na Teoria de turbulência de Kolmogorov de 1941 ([Kolmogorov, 1991](#)). Em processos estocásticos estacionários, as duas são equivalentes:

$$\begin{aligned} \langle [u(\omega, \tau) - u(\omega, 0)]^2 \rangle &= \langle u^2(\omega, \tau) - 2u(\omega, \tau)u(\omega, 0) + u^2(\omega, 0) \rangle \\ &= \langle u^2(\omega, \tau) \rangle + \langle u^2(\omega, 0) \rangle - 2\langle u(\omega, \tau)u(\omega, 0) \rangle \\ &= 2R(0) - 2R(\tau) \\ &= 2[R(0) - R(\tau)] \blacksquare \end{aligned} \quad (9.49)$$

Um estimador para a função de autocovariância a partir de dados amostrais contidos em um vetor de dados de flutuações  $\mathbf{u} = (u_0, u_1, \dots, u_{N-1})$  é

$$\widehat{R}(k\Delta t) = \widehat{R}_k = \frac{1}{N-k} \sum_{i=0}^{N-k} u_i u_{i+k}. \quad (9.50)$$

Seguimos agora para covariâncias cruzadas. Estas são definidas por

$$R_{i,j}(\tau) \equiv \langle u_i(\omega, 0)u_j(\omega, \tau) \rangle. \quad (9.51)$$

Note que  $R_{i,j}(0)$  é o fluxo (cinemático) de Reynolds:

$$R_{i,j}(0) = \langle u_i(\omega, 0)u_j(\omega, 0) \rangle \quad (9.52)$$

O estimador óbvio para dados discretos é

$$\widehat{R}_{i,j}(k\Delta t) = \frac{1}{N-k} \sum_{l=0}^{N-k} u_{il} u_{jl+k}. \quad (9.53)$$

Note a dificuldade notacional com os índices.

## 9.4 – Transformadas de Fourier

O par  $f(x)$  e sua transformada de Fourier de  $\widehat{f}(k_1)$  são definidos como

$$\widehat{f}(k_1) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} f(x) e^{-ik_1 x} dx, \quad (9.54)$$

$$f(x) = \int_{-\infty}^{+\infty} \widehat{f}(k_1) e^{+ik_1 x} dk_1. \quad (9.55)$$

A transformada de Fourier inversa da delta de Dirac é

$$\int_{-\infty}^{+\infty} \delta(k_1) e^{+ik_1 x} dk_1 = e^{ik_1 x} \Big|_{k_1=0} = 1. \quad (9.56)$$

Portanto, formalmente temos

$$\mathcal{F}\{1\} = \frac{1}{2\pi} \int_{-\infty}^{+\infty} e^{-ik_1 x} dx = \delta(k_1). \quad (9.57)$$

Em particular,

$$\delta(0) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} dx. \quad (9.58)$$

Nesta forma, estes resultados são um pouco abstratos. Considere então a versão finita,

$$\frac{1}{2\pi} \int_{-L}^{+L} [\cos k_1 x - i \operatorname{sen} k_1 x] dx. \quad (9.59)$$

A parte imaginária do integrando é uma função ímpar de  $x$ , cuja integral de  $-L$  a  $+L$  se anula. Ficamos com

$$\begin{aligned} \frac{1}{2\pi k_1} \int_{-L}^{+L} \cos k_1 x k_1 dx &= \frac{1}{2\pi k_1} \operatorname{sen} k_1 x \Big|_{-L}^{+L} \\ &= \frac{1}{2\pi k_1} [\operatorname{sen} k_1 L - \operatorname{sen}(-k_1 L)] \\ &= \frac{\operatorname{sen} k_1 L}{\pi k_1}. \end{aligned} \quad (9.60)$$

As duas propriedades mais importantes da delta de Dirac são

$$\int_{-\infty}^{+\infty} \delta(k_1) dk_1 = 1, \quad (9.61)$$

$$\int_{-\infty}^{+\infty} \delta(k_1) \widehat{f}(k_1) dk_1 = \widehat{f}(0). \quad (9.62)$$

(Na verdade, a primeira é um caso particular da segunda). A função que obtivemos,  $\operatorname{sen} k_1 L / \pi k_1$ , atende a ambas:

$$\int_{-\infty}^{+\infty} \frac{\operatorname{sen} k_1 L}{\pi k_1} dk_1 = 1, \quad \forall L; \quad (9.63)$$

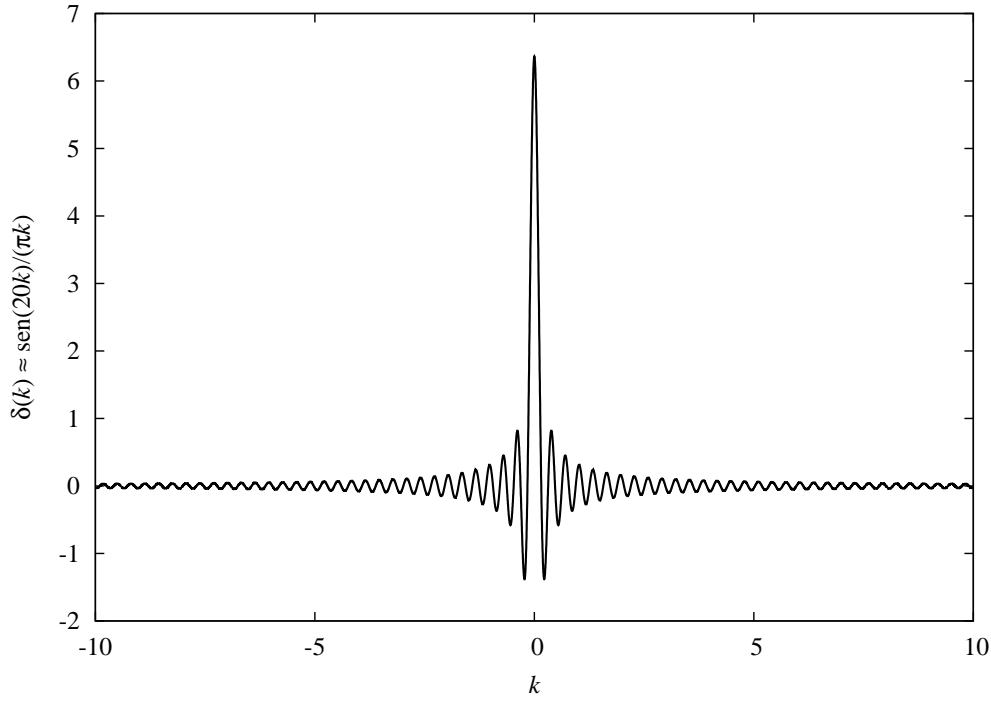


Figure 9.3: Uma representação aproximada de  $\delta(k_1)$

e

$$\begin{aligned}
 \lim_{L \rightarrow \infty} \int_{-\infty}^{+\infty} \widehat{f}(k_1) \frac{\text{sen } k_1 L}{\pi k_1} dk_1 &= \lim_{L \rightarrow \infty} \int_{-\infty}^{+\infty} \widehat{f}\left(\frac{k_1 L}{L}\right) \frac{\text{sen } k_1 L}{\pi(k_1 L)} d(k_1 L) \\
 &= \lim_{L \rightarrow \infty} \int_{u=-\infty}^{+\infty} \widehat{f}\left(\frac{u}{L}\right) \frac{\text{sen } u}{\pi u} du \\
 &= \int_{-\infty}^{+\infty} \widehat{f}(0) \frac{\text{sen } u}{\pi u} du \\
 &= \widehat{f}(0) \int_{-\infty}^{+\infty} \frac{\text{sen } u}{\pi u} du = \widehat{f}(0). \quad (9.64)
 \end{aligned}$$

Vale a pena “ver” a cara desta particular encarnação (entre infinitas outras possíveis) de  $\delta(k_1)$ , na figura 9.3. O resultado (9.58) pode ser visualizado de forma mais concreta utilizando também a versão “finita”:

$$\delta(k_1) \approx \frac{\text{sen } k_1 L}{\pi k_1} = \frac{L}{\pi} \frac{\text{sen } k_1 L}{k_1 L}; \quad (9.65)$$

$$\lim_{k_1 \rightarrow 0} \delta(k_1) = \frac{L}{\pi} = \frac{1}{2\pi} \int_{-L}^{+L} dx. \quad (9.66)$$

Portanto,  $\delta(0)$  é somente uma maneira sofisticada de escrever  $L/\pi$ .

## 9.5 – Espectros

Dado um processo estocástico  $u_i(x)$ , a função de covariância cruzada é definida como

$$R_{i,j}(r) \equiv \langle u_i(x) u_j(x+r) \rangle \quad (9.67)$$

Define-se o espectro cruzado entre  $u_i$  e  $u_j$  como

$$F_{i,j}(k_1) \equiv \frac{1}{2\pi} \int_{-\infty}^{+\infty} R_{i,j}(r) e^{-ik_1 r} dr, \quad (9.68)$$

ou seja:  $\phi_{i,j} = \widehat{R}_{i,j}$ . Agora, vale o seguinte teorema:

$$F_{i,j}(k_1) = \frac{1}{\delta(0)} \langle \widehat{u}_i^* \widehat{u}_j \rangle. \quad (9.69)$$

A prova é relativamente simples, mas há algumas sutilezas:

$$\begin{aligned} \langle \widehat{u}_i^* \widehat{u}_j \rangle &= \left\langle \left( \frac{1}{2\pi} \right)^2 \int_{x=-\infty}^{+\infty} u_i(x) e^{+ik_1 x} dx \int_{y=-\infty}^{+\infty} u_j(y) e^{-ik_1 y} dy \right\rangle \\ &= \left( \frac{1}{2\pi} \right)^2 \int_{x=-\infty}^{+\infty} \int_{y=-\infty}^{+\infty} \langle u_i(x) u_j(y) \rangle e^{-ik_1 (y-x)} dx dy \end{aligned} \quad (9.70)$$

Seja agora a mudança de variáveis

$$r = x, \quad x = r, \quad (9.71)$$

$$s = y - x, \quad y = r + s, \quad (9.72)$$

cujo jacobiano é

$$\frac{\partial(x, y)}{\partial(s, r)} = \begin{vmatrix} \frac{\partial x}{\partial r} & \frac{\partial x}{\partial s} \\ \frac{\partial y}{\partial r} & \frac{\partial y}{\partial s} \end{vmatrix} = \begin{vmatrix} 1 & 0 \\ 1 & 1 \end{vmatrix} = 1. \quad (9.73)$$

A integral (9.70) fica agora

$$\begin{aligned} \langle \widehat{u}_i^* \widehat{u}_j \rangle &= \left( \frac{1}{2\pi} \right)^2 \int_{r=-\infty}^{+\infty} \int_{s=-\infty}^{+\infty} \langle u_i(x) u_j(y) \rangle e^{-ik_1 s} \frac{\partial(x, y)}{\partial(s, r)} ds dr \\ &= \left[ \frac{1}{2\pi} \int_{-\infty}^{+\infty} dr \right] \left[ \frac{1}{2\pi} \int_{s=-\infty}^{+\infty} R_{i,j}(s) e^{-ik_1 s} ds \right] \\ &= \delta(0) F_{i,j}(k_1). \end{aligned} \quad (9.74)$$

Um resultado importante é que a integral do espectro cruzado é igual à co-variância. Pelo teorema da transformada inversa, a inversa de (9.68) é

$$\begin{aligned} R_{i,j}(r) &= \int_{k_1=-\infty}^{+\infty} F_{i,j}(k_1) e^{ik_1 r} dk_1, \\ \langle u_i u_j \rangle &= R_{i,j}(0) = \int_{k_1=-\infty}^{+\infty} F_{i,j}(k_1) dk_1 \blacksquare \end{aligned} \quad (9.75)$$

Agora, se  $R_{i,j}(r)$  é uma função real, é evidente que

$$F_{i,j}(k_1) = \text{Co}_{i,j}^F(k_1) + i \text{Qu}_{i,j}^F(k_1) \quad (9.76)$$

é uma função complexa de  $k_1$ . Em (9.76),  $\text{Co}_{i,j}^F$  é o *co-espectro*, e  $\text{Qu}_{i,j}^F$  é o *espectro de quadratura*. Além disso, é trivial que

$$F_{i,j}(-k_1) = F_{i,j}^*(k_1). \quad (9.77)$$



Portanto,  $\text{Co}_{i,j}^F(k_1)$  é uma função par de  $k_1$ , e  $\text{Qu}_{i,j}^F(k_1)$  é uma função ímpar de  $k_1$ . Segue-se imediatamente que

$$\int_{-\infty}^{+\infty} \text{Qu}_{i,j}^F(k_1) dk_1 = 0, \quad (9.78)$$

$$\int_{-\infty}^{+\infty} F_{i,j}(k_1) dk_1 = \int_{-\infty}^{+\infty} \text{Co}_{i,j}^F(k_1) dk_1. \quad (9.79)$$

Portanto,

$$\langle u_i u_j \rangle = \int_{-\infty}^{+\infty} \text{Co}_{i,j}^F(k_1) dk_1. \quad (9.80)$$

## 9.6 – Espectros eulerianos

Seja agora uma medição euleriana,  $u_i(t)$ . A sua transformada de Fourier é

$$\widehat{u}_i(\omega) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} u_i(t) e^{-i\omega t} dt \quad (9.81)$$

Note que  $\omega$  é uma frequência *angular*; para passar para a frequência cíclica, faça

$$2\pi n = \omega; \quad (9.82)$$

$$\widehat{u}_i(n) \equiv \int_{t=-\infty}^{+\infty} u_i(t) e^{-i2\pi n t} dt = 2\pi \widehat{u}_i(\omega). \quad (9.83)$$

Note a ausência do fator  $1/2\pi$  na *definição* de  $\widehat{u}_i(n)$ ! Isto é porque, com o fator  $2\pi$  como argumento da exponencial, a inversa é

$$u_i(t) = \int_{n=-\infty}^{+\infty} \widehat{u}_i(n) e^{+i2\pi n t} dn. \quad (9.84)$$

A relação (9.83) entre  $\widehat{u}_i(n)$  e  $\widehat{u}_i(\omega)$  deve ser cuidadosamente observada.

No domínio do tempo,

$$S_{i,j}(n) = \int_{t=-\infty}^{+\infty} R_{i,j}(t) e^{-i2\pi n t} dt. \quad (9.85)$$

é o espectro cruzado na variável frequência cíclica  $n$ ; novamente, o teorema da inversa de Fourier produz

$$R_{i,j}(t) = \int_{n=-\infty}^{+\infty} S_{i,j}(n) e^{+i2\pi n t} dn. \quad (9.86)$$

Não há necessidade de repetir tudo de novo: teremos

$$\begin{aligned} \langle u_i u_j \rangle &= \int_{n=-\infty}^{+\infty} S_{i,j}(n) dn \\ &= \int_{n=-\infty}^{+\infty} \text{Co}_{i,j}^S(n) dn = \int_{k_1=-\infty}^{+\infty} \text{Co}_{i,j}^F(k_1) dk_1 = \int_{k_1=-\infty}^{+\infty} F_{i,j}(k_1) dk_1. \end{aligned} \quad (9.87)$$

O principal ponto aqui é transitar entre espectros no espaço e no tempo, usando a *hipótese de turbulência congelada de Taylor* (Lumley and Panofsky, 1964, p. 56):

$$k_1 = \frac{2\pi}{\lambda} = \frac{2\pi}{U \mathcal{T}} = \frac{2\pi n}{U}, \quad (9.88)$$

onde  $\lambda$  é o comprimento de onda, e  $\mathcal{T}$  é o período. Substituindo-se (9.88) em (9.87),

$$\frac{2\pi}{U} \text{Co}_{i,j}^F \left( \frac{2\pi n}{U} \right) = \text{Co}_{i,j}^S(n) \quad (9.89)$$

proporciona a conversão de co-espectros entre frequência cíclica  $n$  e número de onda  $k_1$ . De forma um pouco mais geral,

$$\frac{2\pi}{U} F_{i,j} \left( \frac{2\pi n}{U} \right) = S_{i,j}(n). \quad (9.90)$$

## 9.7 – Espectros tridimensionais

Finalmente, precisamos estudar brevemente os espectros tridimensionais da turbulência e suas relações com os espectros unidimensionais. A transformada de Fourier tridimensional do campo de velocidade  $u_i(\mathbf{x})$  é

$$\mathcal{F}[u_i] = \widehat{u}_i = \frac{1}{(2\pi)^3} \int_{\mathbf{x} \in \mathbb{R}^3} u_i(\mathbf{x}) e^{-i(\mathbf{k} \cdot \mathbf{x})} d^3 \mathbf{x}. \quad (9.91)$$

Isto é tudo o que precisamos para definir o espectro trimensional de forma totalmente análoga à usada anteriormente para espectros unidimensionais:

$$\Phi_{i,j}(\mathbf{k}, t) \equiv \frac{1}{\delta(0)} \langle \widehat{u}_i^* \widehat{u}_j \rangle. \quad (9.92)$$

Espectros unidimensionais são médias sobre cascas esféricas:

$$E_{i,j}(k) \equiv \int_{|\mathbf{k}|=k} \Phi_{i,j}(\mathbf{k}) d^2 \mathbf{k}. \quad (9.93)$$

Finalmente, nós recuperamos os espectros unidimensionais da seção anterior integrando sobre todos os  $k_2$  e  $k_3$ :

$$F_{i,j}(k_1) \equiv \int_{k_2 \in \mathbb{R}, k_3 \in \mathbb{R}} \Phi_{i,j}(k_1, k_2, k_3) dk_2 dk_3. \quad (9.94)$$

Diversas integrais agora são iguais à covariância  $\langle u_i u_j \rangle$ :

$$\langle u_i u_j \rangle = \int_{\mathbf{k} \in \mathbb{R}^3} \Phi_{i,j}(\mathbf{k}) d^3 \mathbf{k} = \int_{k=0}^{\infty} E_{i,j}(k) dk = \int_{k_1=-\infty}^{+\infty} F_{i,j}(k_1) dk_1. \quad (9.95)$$

# 10

## A camada de mistura

### 10.1 – A espiral de Ekman

A notação deste documento está, neste momento, uma grande bagunça. Mas isto é incontornável por enquanto. Vamos começar com uma rápida revisão das equações para uma camada-limite atmosférica na forma

$$\frac{\partial \bar{U}_i}{\partial t} + \bar{U}_k \frac{\partial \bar{U}_i}{\partial x_k} + \frac{\partial (\bar{u}_i \bar{u}_k)}{\partial x_k} = \frac{\bar{\delta} \bar{\wp}}{\wp_s} g_i - \frac{1}{\wp_s} \frac{\partial \bar{\delta} P}{\partial x_i} + f_c \epsilon_{ik3} \bar{U}_k + \nu \frac{\partial^2 \bar{U}_i}{\partial x_k \partial x_k}. \quad (10.1)$$

Uma questão na qual não vou me aprofundar agora é até que ponto esta equação vale para *toda* a camada de mistura. As equações para o vento geostrófico são

$$\frac{1}{\wp_s} \frac{\partial \bar{\delta} P}{\partial x_i} = f_c \epsilon_{ik3} U_{Gk}, \quad (10.2)$$

de modo que a equação de *momentum* pode ser escrita com as componentes do vento geostrófico substituindo os gradientes horizontais de pressão:

$$\frac{\partial \bar{U}_i}{\partial t} + \bar{U}_k \frac{\partial \bar{U}_i}{\partial x_k} + \frac{\partial (\bar{u}_i \bar{u}_k)}{\partial x_k} = \frac{\bar{\delta} \bar{\wp}}{\wp_s} g_i + f_c \epsilon_{ik3} (\bar{U}_k - U_{Gk}) + \nu \frac{\partial^2 \bar{U}_i}{\partial x_k \partial x_k}. \quad (10.3)$$

Para o caso estacionário e horizontalmente homogêneo, as equações tornam-se

$$\frac{\partial (\bar{u} \bar{w})}{\partial z} = f_c (\bar{V} - V_G), \quad (10.4)$$

$$\frac{\partial (\bar{v} \bar{w})}{\partial z} = -f_c (\bar{U} - U_G). \quad (10.5)$$

Use um modelo de fechamento muito simples, com uma difusividade turbulenta  $K$ :

$$\bar{u} \bar{w} = -K \frac{\partial \bar{U}}{\partial z}, \quad (10.6)$$

$$\bar{v} \bar{w} = -K \frac{\partial \bar{V}}{\partial z}. \quad (10.7)$$

Evidentemente, a única variável independente é  $z$ , e passaremos a utilizar derivadas ordinárias em lugar de derivadas parciais:

$$K \frac{d^2 \bar{U}}{dz^2} = f_c (V_G - \bar{V}), \quad (10.8)$$

$$K \frac{d^2 \bar{V}}{dz^2} = -f_c (U_G - \bar{U}). \quad (10.9)$$

Neste ponto, introduza as variáveis complexas

$$w \equiv \bar{U} + i\bar{V}; \quad w_G \equiv U_G + iV_G; \quad (10.10)$$

o sistema de equações diferenciais ordinárias torna-se

$$\begin{aligned} K \frac{d^2 w}{dz^2} &= K \left( \frac{d^2 \bar{U}}{dz^2} + i \frac{d^2 \bar{V}}{dz^2} \right) \\ &= f_c (V_G - \bar{V}) - i f_c (U_G - \bar{U}) \\ &= -i f_c \left[ (U_G + iV_G) - (\bar{U} + i\bar{V}) \right] \\ &= -i f_c [w_G - w]. \end{aligned} \quad (10.11)$$

O problema reduz-se, então, à solução da equação diferencial complexa

$$K \frac{d^2 w}{dz^2} - i f_c w = -i f_c w_G. \quad (10.12)$$

As condições de contorno são

$$w(0) = 0, \quad (10.13)$$

$$\lim_{z \rightarrow \infty} w(z) = w_G. \quad (10.14)$$

Portanto, este é um problema de valor de contorno. Por inspeção,  $w_p = w_G$  é uma solução particular; a equação característica é

$$\lambda^2 - \frac{i f_c}{K} = 0, \quad (10.15)$$

com raízes

$$\lambda_{1,2} = \sqrt{\frac{i f_c}{K}} = \sqrt{\frac{|f_c|}{K}} \sqrt{\text{sin}(\varphi) i}. \quad (10.16)$$

A solução agora deve depender do sinal de

$$f_c = 2\Omega \sin \varphi, \quad (10.17)$$

onde  $\Omega$  é a velocidade angular da terra, e  $\varphi$  é a latitude. No Hemisfério Norte,  $f_c > 0$ , enquanto que no Hemisfério Sul,  $f_c < 0$ .

### 10.1.1 – Hemisfério Norte

Procura-se  $\sqrt{i}$ :

$$w^2 = r^2 e^{2(i\theta)} = e^{i(\frac{\pi}{2} + 2\pi)}, \quad (10.18)$$

$$r = 1, \quad (10.19)$$

$$\theta = \frac{\pi}{4} + \pi \quad (10.20)$$

Os dois valores possíveis para  $\sqrt{i}$  são

$$w_1 = \frac{\sqrt{2}}{2} (1 + i), \quad (10.21)$$

$$w_2 = -\frac{\sqrt{2}}{2} (1 + i). \quad (10.22)$$

A solução geral, portanto, é

$$w(z) = w_G + c_1 \exp\left(w_1 \sqrt{\frac{f_c}{K}} z\right) + c_2 \exp\left(w_2 \sqrt{\frac{f_c}{K}} z\right). \quad (10.23)$$

Para atender às condições de contorno (10.13)–(10.14),  $c_1 = 0$  e  $c_2 = -w_G$ . A solução é

$$w(z) = w_G \left[ 1 - \exp\left(-(1+i)\sqrt{\frac{f_c}{2K}} z\right) \right], \quad (10.24)$$

$$= w_G \left[ 1 - \exp\left(-\sqrt{\frac{f_c}{2K}} z\right) \left( \cos \sqrt{\frac{f_c}{2K}} z - i \sin \sqrt{\frac{f_c}{2K}} z \right) \right]. \quad (10.25)$$

Agora, se alinharmos o vetor vento geostrófico com o eixo  $x$ , ou seja, se  $V_G = 0$ , a solução para a velocidade média na camada-limite atmosférica é

$$\bar{U}(z) = U_G \left[ 1 - \exp\left(-\sqrt{\frac{f_c}{2K}} z\right) \cos \sqrt{\frac{f_c}{2K}} z \right], \quad (10.26)$$

$$\bar{V}(z) = U_G \left[ \exp\left(-\sqrt{\frac{f_c}{2K}} z\right) \sin \sqrt{\frac{f_c}{2K}} z \right]. \quad (10.27)$$

### 10.1.2 – Hemisfério Sul

Procura-se  $\sqrt{-i}$ :

$$w^2 = r^2 e^{2(i\theta)} = e^{i(-\frac{\pi}{2}+2\pi)}, \quad (10.28)$$

$$r = 1, \quad (10.29)$$

$$\theta = -\frac{\pi}{4} + \pi \quad (10.30)$$

Os dois valores possíveis para  $\sqrt{i}$  são

$$w_3 = \frac{\sqrt{2}}{2}(1-i), \quad (10.31)$$

$$w_4 = \frac{\sqrt{2}}{2}(-1+i). \quad (10.32)$$

A solução geral agora será

$$w(z) = w_G + c_3 \exp\left(w_3 \sqrt{\frac{f_c}{K}} z\right) + c_4 \exp\left(w_4 \sqrt{\frac{f_c}{K}} z\right). \quad (10.33)$$

Para atender às condições de contorno (10.13)–(10.14),  $c_3 = 0$  e  $c_4 = -w_G$ . A solução é

$$w(z) = w_G \left[ 1 - \exp\left((-1+i)\sqrt{\frac{f_c}{2K}} z\right) \right], \quad (10.34)$$

$$= w_G \left[ 1 - \exp\left(-\sqrt{\frac{f_c}{2K}} z\right) \left( \cos \sqrt{\frac{f_c}{2K}} z + i \sin \sqrt{\frac{f_c}{2K}} z \right) \right]. \quad (10.35)$$

Agora, se alinharmos o vetor vento geostrófico com o eixo  $x$ , ou seja, se  $V_G = 0$ , a solução para a velocidade média na camada-limite atmosférica é

$$\bar{U}(z) = U_G \left[ 1 - \exp\left(-\sqrt{\frac{f_c}{2K}} z\right) \cos \sqrt{\frac{f_c}{2K}} z \right], \quad (10.36)$$

$$\bar{V}(z) = -U_G \left[ \exp\left(-\sqrt{\frac{f_c}{2K}} z\right) \sin \sqrt{\frac{f_c}{2K}} z \right]. \quad (10.37)$$

Note que a diferença entre a solução (10.26)–(10.27) obtida anteriormente para o Hemisfério Norte, e (10.36)–(10.37) obtida agora para o Hemisfério Sul, é que  $\bar{V}$  muda de sinal, ou seja: o vetor velocidade do vento “gira” para a esquerda no Hemisfério Norte, e para a direita no Hemisfério Sul.

Neste modelo simplificado, é fácil calcular o ângulo total de giro da espiral:

$$\lim_{z \rightarrow 0} \frac{\bar{V}}{\bar{U}} = \pm 1, \quad (10.38)$$

onde o sinal de menos se aplica ao Hemisfério Sul. Portanto, o giro total é de  $\pi/4$  radianos ( $45^\circ$ ).

## 10.2 – Similaridade de Rossby e *Asymptotic Matching*

(Extraído de H. Tennekes, “Similarity relations, scaling laws and spectral dynamics”)

Suponha uma atmosfera neutra,  $|L_O| = +\infty$  sobre uma superfície horizontalmente homogênea. Nela, o vetor velocidade horizontal do vento é

$$\bar{\mathbf{u}} = \bar{u} \mathbf{i} + \bar{v} \mathbf{j}, \quad (10.39)$$

de tal forma que no topo da camada-limite atmosférica:

$$|\bar{\mathbf{u}}| \rightarrow \sqrt{u_g^2 + v_g^2} \equiv G, \quad (10.40)$$

onde  $u_g$  e  $v_g$  são as componentes do vento geostrófico. As duas escalas de comprimento possíveis para o nosso problema são  $z_0$  (a rugosidade da superfície para quantidade de movimento) e  $G/f$ , onde  $f$  é o parâmetro de Coriolis. Note que

$$\frac{G}{f} \sim L_p \quad \text{com} \quad \frac{\partial \bar{p}}{\partial x} \sim \frac{\Delta \bar{p}}{L_p}. \quad (10.41)$$

A razão entre estas duas escalas produz o *Número de Rossby de rugosidade*:

$$R_o = \frac{G}{f z_0}. \quad (10.42)$$

As equações médias de Reynolds para um problema homogêneo na horizontal e permanente são

$$f(\bar{v} - v_g) = \frac{\partial}{\partial z}(\overline{w'v'}), \quad (10.43)$$

$$f(u_g - \bar{u}) = \frac{\partial}{\partial z}(\overline{w'u'}) \quad (10.44)$$

Para tornar (10.43)–(10.44) adimensionais, divida por  $fu_*$ : nós vamos supor que dentro da CLA porém ainda suficientemente “longe” da superfície, os perfis de vento dependem do número adimensional  $zf/u_*$  de acordo com

$$\frac{\bar{v} - v_g}{u_*} = \frac{\partial(\overline{w'u'})}{\partial z f u_*} = F_y\left(\frac{zf}{u_*}\right), \quad (10.45)$$

$$\frac{\bar{u} - u_g}{u_*} = -\frac{\partial(\overline{w'v'})}{\partial z f u_*} = F_x\left(\frac{zf}{u_*}\right) \quad (10.46)$$

Devido à eq. (10.40), no topo da CLA onde  $z = z_i$ <sup>1</sup> devemos ter:

$$F_x\left(\frac{zf}{u_*}\right) = F_y\left(\frac{zf}{u_*}\right) = 0 \quad (10.47)$$

Ambas as funções adimensionais  $F_x$  e  $F_y$  devem possuir a mesma raiz, que denominaremos aqui  $e^A$  para facilitar a manipulação algébrica posterior; a constante  $A$  efetivamente *define* a espessura da CLA dinamicamente:

$$\frac{z_i f}{u_*} \equiv e^{-A} \Rightarrow z_i = \frac{e^{-A} u_*}{f} \quad (10.48)$$

*Crítica:* esta definição não funciona no equador, onde  $f = 0$ ; na prática, aparentemente a similaridade de Rossby que estamos estudando não funciona muito bem em lugar nenhum, devido a diversos complicadores; mesmo assim, nós a estamos estudando aqui por seu interesse matemático.

Agora, sabemos que a adimensionalização proposta por (10.45)–(10.46) *não* vai funcionar à medida em que nos aproximamos da superfície. Por exemplo, próximo de  $z = 0$  a previsão de (10.45) é

$$-\frac{v_g}{u_*} = \frac{1}{f u_*} \frac{d \overline{w'u'}}{dz}; \quad (10.49)$$

mas  $\overline{w'u'} = 0$  em  $z = 0$ ; em alturas verticais próximas da rugosidade  $z_0$  a contribuição viscosa para o fluxo de quantidade de movimento é significativa, e o termo de viscosidade teria que ser incluído nas equações de Reynolds para médias.

Uma alternativa, que nós já utilizamos quando estudamos os perfis de vento na sub-camada dinâmica, é tentar re-escrever as equações utilizando a rugosidade  $z_0$ ; utilizando o número de Rossby de rugosidade, obtemos:

$$\frac{z_0 f}{G} \frac{\bar{v} - v_g}{u_*} = \frac{d \overline{w'u'}/u_*^2}{dz/z_0} \quad (10.50)$$

$$\frac{z_0 f}{G} \frac{\bar{u} - u_g}{u_*} = -\frac{d \overline{w'u'}/u_*^2}{dz/z_0} \quad (10.51)$$

Ora, o número de Rossby de rugosidade é necessariamente um número muito grande; quando  $R_o \rightarrow \infty$ , é razoável supor que

$$\left| \frac{G(\bar{v} - v_g)}{u_*^2} \right| < \infty \text{ e } \left| \frac{G(\bar{u} - u_g)}{u_*^2} \right| < \infty ;$$

<sup>1</sup>Note que apesar de eu estar usando o símbolo  $z_i$ , cuja origem é “altura de inversão”, a definição da espessura da CLA utilizada aqui é *totalmente dinâmica*, e não tem nada a ver com a altura da inversão do perfil de temperatura potencial

já que  $u_*$  deve crescer com  $G$ , enquanto que  $\bar{u} \sim G$  e  $\bar{v} \sim G$  (no máximo). Portanto, quando  $R_o \rightarrow \infty$ , o lado esquerdo tende a zero, e consequentemente o lado direito também:

$$\lim_{R_o \rightarrow \infty} \frac{d \overline{w'u'} / u_*^2}{dz/z_0} = 0, \quad (10.52)$$

$$\lim_{R_o \rightarrow \infty} \frac{d \overline{w'v'} / u_*^2}{dz/z_0} = 0. \quad (10.53)$$

Então, ao orientarmos os eixos  $x$  e  $y$  de tal forma que em  $z = 0$ ,  $\bar{v} = 0$  e  $\overline{w'v'} = 0$ , obtemos:

$$\overline{w'u'} = u_*^2 = \text{cte} \quad (10.54)$$

$$\overline{w'v'} = 0 \quad (10.55)$$

Ambas as equações acima devem valer numa “camada superficial” dinamicamente definida por

$$1 \ll |z/z_0| < \infty.$$

Agora cabe fazer o *matching* propriamente dito. Nossos resultados até agora são:

1. Na “camada superficial”:

$$\frac{u}{u_*} = g(z/z_0) \quad (10.56)$$

2. Na “camada-limite atmosférica”:

$$\frac{\bar{u} - u_g}{u_*} = F_x \left( \frac{zf}{u_*} \right) \quad (10.57)$$

$$\frac{\bar{v} - v_g}{u_*} = F_y \left( \frac{zf}{u_*} \right) \quad (10.58)$$

O *matching* em si consiste em tentar “casar” estas equações quando  $zf/u_* \rightarrow 0$  e  $z/z_0 \rightarrow \infty$ . Além disso, segundo Tennekes, eu *derivo* ambas as relações de similaridade, e faço o “casamento” para  $\partial \bar{u} / \partial z$  e  $\partial \bar{v} / \partial z$ . Para  $\bar{u}$ :

$$\frac{\partial \bar{u}}{\partial z} = \frac{u_*}{z_0} \frac{\partial g}{\partial \xi}, \quad \text{onde } \xi = \frac{z}{z_0} \quad (10.59)$$

$$\frac{\partial \bar{u}}{\partial z} = u_* \frac{\partial F_x}{\partial z} = f \frac{\partial F_x}{\partial \eta}, \quad \text{onde } \eta = \frac{zf}{u_*} \quad (10.60)$$

Agora, quando  $\xi \rightarrow \infty$  e  $\eta \rightarrow 0$ , devemos ter:

$$\frac{u_*}{z_0} \frac{\partial g}{\partial \xi} = f \frac{\partial F_x}{\partial \eta} \Rightarrow \quad (10.61)$$

$$\xi \frac{\partial g}{\partial \xi} = \eta \frac{\partial F_x}{\partial \eta} \quad (10.62)$$

Numa analogia com o método de separação de variáveis, cada um dos lados de (10.62) deve ser igual a uma constante *na região do casamento*:

$$\frac{z}{u_*} \frac{\partial \bar{u}}{\partial z} = \frac{1}{\kappa}, \quad (10.63)$$



onde a constante assintótica  $\kappa$  é a própria constante de von Kármán; integrando,

$$\frac{\kappa}{u_*} (\bar{u}_2 - \bar{u}_1) = \ln \frac{z_2}{z_1}. \quad (10.64)$$

Na camada superficial, escolho  $\bar{u}_1 = 0$  em  $z_1 = z_0$  e obtenho o bem-conhecido perfil logaritmico

$$\frac{u}{u_*} = \frac{1}{\kappa} \ln\left(\frac{z}{z_0}\right). \quad (z/z_0 \gg 1) \quad (10.65)$$

Se, por outro lado, eu tomar  $\bar{u}_1$  como a velocidade dentro da CLA e  $\bar{u}_2 = u_g$ :

$$\frac{\kappa}{u_*} (u_g - \bar{u}) = \ln \frac{z_i}{z}, \quad (10.66)$$

$$\frac{\kappa}{u_*} (\bar{u} - u_g) = \ln \frac{zf}{u_*} \frac{u_*}{z_i f}. \quad (10.67)$$

usando (10.48):

$$\frac{\kappa}{u_*} (\bar{u} - u_g) = \ln \frac{zf}{u_*} + A \quad (10.68)$$

isto é:

$$\frac{\bar{u} - u_g}{u_*} = \frac{1}{\kappa} \left( \ln \left( \frac{zf}{u_*} \right) + A \right) \quad (zf/u_* \ll 1) \quad (10.69)$$

Eliminando-se agora  $\bar{u}$  entre (10.65) e (10.68), obtém-se uma *relação de arrasto*,

$$\frac{u_g}{u_*} = \frac{1}{\kappa} \left( \ln \frac{u_*}{f z_0} - A \right) \quad (10.70)$$

Para  $\bar{v}$ , em  $1 \ll z/z_0 < \infty$ ,

$$\bar{v} = 0, \quad (10.71)$$

enquanto que em  $1 \gg (zf)/u_* \rightarrow 0$ :

$$\frac{-v_g}{u_*} = F_y(0) = \frac{B}{\kappa}, \quad (10.72)$$

onde a segunda igualdade é a *definição* da constante  $B$  de forma análoga a  $A$ . Combinando-se (10.70) e (10.72):

$$\frac{G}{u_*} = \frac{1}{\kappa} \left\{ \left[ \ln \left( \frac{u_*}{f z_0} \right) - A \right]^2 + B^2 \right\}^{1/2}. \quad (10.73)$$

# 11

## Divagações equacionais

Considere a equação da difusão,

$$\frac{\partial \phi}{\partial t} = k \frac{\partial^2 \phi}{\partial x^2}. \quad (11.1)$$

Vou procurar uma solução de similaridade sem recorrer diretamente à análise dimensional, ou seja: vou supor que é possível reduzir (11.1) a uma equação diferencial ordinária via a mudança de variável

$$\xi = ax^b t^c k^d \quad (11.2)$$

```
(C1) writefile('difu-simples.out')
      Starts dribbling to difu-simples.out (2001/10/17, 11:22:44).
(D1)                                     FALSE
(C2) line1 : 100 ;
(D2)                                     100
(C3) ksi : a*x^b*t^c*k^d ;
      d c b
      a k t x
(D3)
(C4) depends(fi,ksi);
      d c b
      [fi(a k t x )]
(D4)
```

Agora introduzo a equação diferencial (11.1):

```
(C5) diff(fi,t) - k*diff(fi,x,2);
      2
      d fi      d c - 1 b      2 2      d fi      2 d 2 c 2 b - 2
(D5) a c ----- k t      x - k (a b ----- k t      x
      d c b
      da k t x
      d c b 2
      d(a k t x )
      d fi      d c b - 2
      + a (b - 1) b ----- k t x
      d c b
      da k t x
```

Note que o último termo em  $d\phi/d\xi$  será anulado se, e somente se,  $b = 1$ . É sempre possível impor esta condição elevando (11.3) a  $1/b$ , de forma que vamos tentar a transformação alternativa

$$\xi = axt^c k^{2d} \quad (11.3)$$

Na sequência, eu reinicializo a seção com `kill(all)` e em seguida redefino `ksi`:

```

(C6) kill(all);
(D0)
(C1) ksi : a*x*t^c*k^d ;
(D1)
(C2) depends(fi,ksi);
(D2)
(C3) diff(fi,t) - k*diff(fi,x,2);
(D3)

```

$$\frac{a^c \frac{d^2 fi}{d^2 k^d t^c} - \frac{d^2 fi}{d^2 k^d t^c} x - a^c \frac{d^2 fi}{d^2 k^d t^c} \frac{d^2 d+1}{d^2 c}}{d^2 k^d t^c}$$

Para o resultado ficar mais claro, removo a variável ksi e então uso o comando `scsimp` para substituir no resultado acima  $axt^ck^d$  por  $\xi$ :

```

(C4) kill(ksi);
(D4)
(C5) scsimp(d3,ksi=a*x*t^c*k^d);
(D5)
(C6) ratsimp(%);
(D6)

```

$$\frac{a^c \frac{d^2 fi}{d^2 k^d t^c} - \frac{d^2 fi}{d^2 k^d t^c} x - a^c \frac{d^2 fi}{d^2 k^d t^c} \frac{d^2 d+1}{d^2 c}}{d^2 k^d t^c}$$

Agora está claro também que para tornar a equação acima totalmente adimensional, preciso de  $c = -1/2$ ,  $d = -1/2$ ; finalmente, a escolha de  $a$  é arbitrária, e em nome da tradição usarei  $a = 1/2$ .

```

(C7) %, [c=-1/2,d=-1/2] ;
(D7)
(C8) %, a=1/2 ;
(D8)
(C9) %*(-t);
(D9)
(C10) ratsimp(%);

```

$$\frac{a^c \frac{d^2 fi}{d^2 k^d t^c} - \frac{d^2 fi}{d^2 k^d t^c} x - a^c \frac{d^2 fi}{d^2 k^d t^c} \frac{d^2 d+1}{d^2 c}}{d^2 k^d t^c}$$

```

(D10) -----
(C11) %*(4);
                                     4
                                     2
      d f i      d f i
(D11) 2 ---- ksi + ----
      dksi      2
      dksi
(C12) quit();

```

Portanto, a equação diferencial ordinária que precisa ser resolvida é

$$2\xi \frac{d\phi}{d\xi} + \frac{d^2\phi}{d\xi^2} = 0, \quad (11.4)$$

a partir da mudança de variável

$$\xi = \frac{x}{(2k\sqrt{t})} \quad \blacksquare \quad (11.5)$$

Para não perder muito tempo, vou deixar por sua conta verificar que para as condições de contorno:

$$\phi(x, 0) = 0, \quad (11.6)$$

$$\phi(0, t) = \phi_0, \quad (11.7)$$

$$\phi(\infty, t) = 0, \quad (11.8)$$

a solução é

$$\phi(x, t) = \phi_0 [1 - \text{erf}(\xi)] = \phi_0 \text{erfc}(\xi) \quad \blacksquare \quad (11.9)$$

**Exercício** Suponha que você use a solução acima para resolver o problema de Sutton,

$$u_0 \frac{\partial \phi}{\partial x} = K_0 \frac{\partial^2 \phi}{\partial z^2}. \quad (11.10)$$

Suponha  $u_0 = 5 \text{ m s}^{-1}$ ,  $u_* = 0.5 \text{ m s}^{-1}$ ,  $K_0 = \kappa(10 \text{ m})u_*$ ,  $T_0 = 28^\circ\text{C}$  e  $T_a = 24^\circ\text{C}$ . Plote o perfil do fluxo de calor sensível

$$H(z) = \rho c_p K_0 \frac{\partial T}{\partial z} \quad (11.11)$$

para  $x = 200 \text{ m}$ . Este perfil obedece à condição de constância com  $z$  usualmente aceita na teoria de similaridade de Monin-Obukhov?

### Solução

Se  $k = K_0/u_0$ , a solução para o perfil de temperatura é

$$T(x, z) = T_0 + [T_a - T_0] \text{erfc} \left( \frac{zu_0}{2K_0(z)\sqrt{x}} \right), \quad (11.12)$$

Note que o enunciado está utilizando a formulação de condições neutras para a difusividade turbulenta a uma altura equivalente a 10 m, a qual a rigor depende de  $z$ : então,

$$H(x, z) = \rho c_p (\kappa z u_*) \quad (11.13)$$

A sequência de comandos de MAXIMA abaixo calcula a “fórmula” para  $H(x, z)$ :

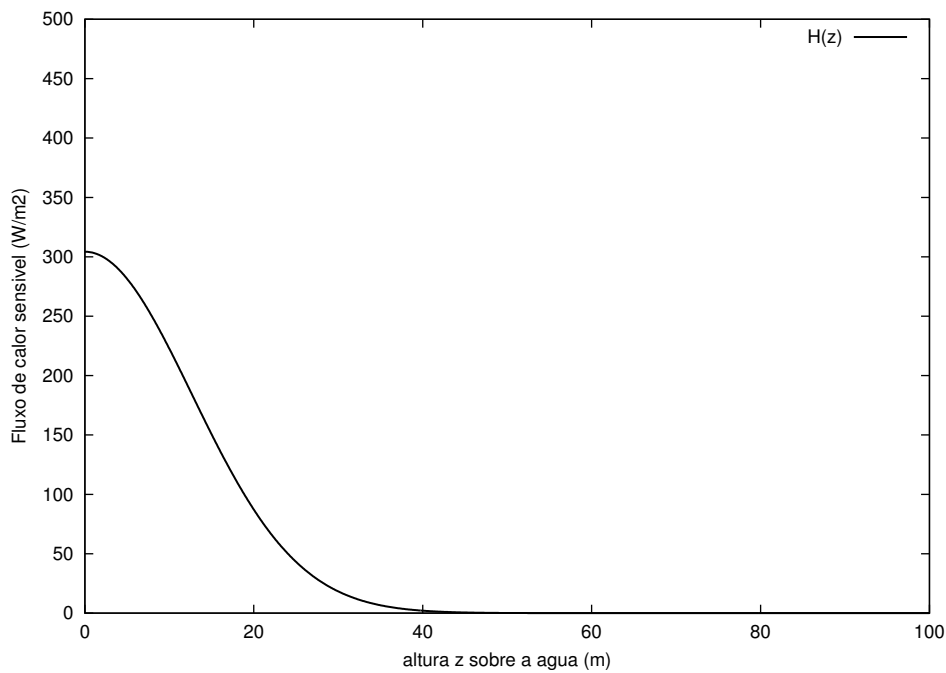


Figure 11.1: Perfil do fluxo de calor sensível previsto pela solução de Sutton com  $u_0 = \text{const.}$ ,  $K_0 = \text{const.}$

(C1)  $K_0 : \kappa \cdot 10 \cdot u_{\text{star}} ;$

(D1)  $10 \kappa u_{\text{star}}$

(C2)  $k : K_0 / u_0 ;$

(D2)  $\frac{10 \kappa u_{\text{star}}}{u_0}$

(C3)  $\kappa_i : z / (2 \cdot \sqrt{k \cdot x}) ;$

(D3)  $\frac{z}{2 \sqrt{10} \sqrt{\frac{\kappa u_{\text{star}} x}{u_0}}}$

(C4)  $T : T_0 + (T_a - T_0) \cdot (1 - \text{erf}(\kappa_i)) ;$

(D4)  $(T_a - T_0) \left( 1 - \text{ERF} \left( \frac{z}{2 \sqrt{10} \sqrt{\frac{\kappa u_{\text{star}} x}{u_0}}} \right) \right) + T_0$

(C5)  $\text{diff}(T, z) ;$

(D5)  $-\frac{(T_a - T_0) \frac{2}{u_0} z}{40 \kappa u_{\text{star}} x \sqrt{10} \sqrt{\pi} \sqrt{\frac{\kappa u_{\text{star}} x}{u_0}}}$

(C6)

O resultado deste exercício é mostrado na figura [11.1](#).

# 12

## Uma introdução à cintilometria

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### 12.1 – Theoretical background

The autocovariance function and the (isotropic) three-dimensional spectrum are related by [Lawrence and Strohbehn \(1970\)](#)

$$C_{n,n}(r) = \langle n(r_1)n(r_1 + r) \rangle = \frac{4\pi}{r} \int_0^\infty \Phi_{n,n}(k)k \sin(kr) dk. \quad (12.1)$$

Setting  $r \rightarrow 0$  and using the well-known limit  $\lim_{x \rightarrow 0} \sin(x)/x = 1$ , produces the variance

$$\sigma_{n,n}^2 = C_{n,n}(0) = 4\pi \int_0^\infty \Phi_{n,n}(k)k^2 dk. \quad (12.2)$$

Of course,  $4\pi k^2 \Phi_{n,n}(k)$  is none other than the shell-averaged spectrum. A careful review of spectra and related definitions is in order.

Let  $\widehat{u}_i$  be the Fourier transform of turbulence variable  $u_i(\mathbf{x}, t)$ . The three-dimensional spectrum is

$$\Phi_{i,j}(\mathbf{k}, t) \equiv \frac{1}{\delta(0)} \langle \widehat{u}_i^* \widehat{u}_j \rangle. \quad (12.3)$$

The *one-dimensional* shell average  $E_{i,j}(k, t)$  is

$$E_{i,j}(k, t) \equiv \int_{|\mathbf{k}|=k} \Phi_{i,j}(\mathbf{k}, t) d^2\mathbf{k}. \quad (12.4)$$

Put  $\Phi_{i,j}$  in spherical coordinates:  $\Phi_{i,j}(k, \vartheta, \varphi)$ . If turbulence is isotropic, the two last dependences (angles in space) drop and we have:  $\Phi_{i,j}(k)$ . We then have

$$E_{i,j}(k, t) \equiv \int_{\varphi=0}^{2\pi} \int_{\vartheta=0}^{\pi} \Phi_{i,j}(k, t) k^2 \sin \vartheta d\vartheta d\varphi = 4\pi k^2 \Phi_{i,j}(k, t). \quad (12.5)$$

In particular, the TKE spectrum is

$$E_e(k, t) = 4\pi k^2 \frac{\Phi_{ii}(k, t)}{2}, \quad (12.6)$$

where the summation convention applies. The K41 prediction for the inertial subrange is

$$E_e(k) = \alpha_e \epsilon_e^{2/3} k^{-5/3}. \quad (12.7)$$

Notice that the Kolmogorov constant is used here for the TKE spectrum, which is also the spectrum of velocity modulus *semi*-variance. We bear this point in mind as we deal with scalar spectra.

Now take  $E_{i,j}(k) = E_{\theta,\theta}$  to be the temperature spectrum in the inertial sub-range; according to the Kolmogorov-Corrsin theory,  $E_{\theta,\theta} \sim k^{-5/3}$ , whence  $\Phi_{\theta,\theta} \sim k^{-11/3}$ . More precisely, if

$$\frac{E_{\theta,\theta}}{2} = \alpha_{\theta,\theta} \epsilon_{\theta,\theta} \epsilon_e^{-1/3} k^{-5/3}, \quad (12.8)$$

then

$$\frac{\Phi_{\theta,\theta}}{2} = \frac{\alpha_{\theta,\theta}}{4\pi} \epsilon_{\theta,\theta} \epsilon_e^{-1/3} k^{-11/3}. \quad (12.9)$$

This is Equation (1) in Hill and Clifford (1978). It is important to stress, once and for all, that in (12.8) and in (12.9),  $\epsilon_e$  is the rate of dissipation of turbulence kinetic energy (TKE); accordingly,  $\epsilon_{\theta,\theta}$  is the rate of dissipation of temperature *semi*-variance:

$$\epsilon_e \approx \nu_u \left\langle \frac{\partial u_i}{\partial x_k} \frac{\partial u_i}{\partial x_k} \right\rangle, \quad (12.10)$$

$$\epsilon_{\theta,\theta} = \nu_\theta \left\langle \frac{\partial \theta}{\partial x_k} \frac{\partial \theta}{\partial x_k} \right\rangle. \quad (12.11)$$

Notice that we never measure any of these. What we do measure are the one-dimensional spectra  $F_{i,j}(k_1)$  or  $G_{i,j}(k_1)$  defined by

$$F_{i,j}(k_1) = \int_{k_2=-\infty}^{+\infty} \int_{k_3=-\infty}^{+\infty} \Phi_{i,j}(k_1, k_2, k_3) dk_2 dk_3 \quad (12.12)$$

$$G_{i,j}(k_1) \equiv 2F_{i,j}(k_1), \quad k_1 \geq 0. \quad (12.13)$$

Under isotropy, the relationship between  $G_{\theta,\theta}(k_1)$  and  $E_{\theta,\theta}(k)$  is

$$G_{\theta,\theta}(k_1) = \int_{k_1}^{\infty} \frac{E_{\theta,\theta}}{k} dk \quad (12.14)$$

(Monin and Yaglom, 1975, Eqn. 12.13), so we can “recover” the isotropic spectra from line measurements. Notice how dependent we are on the isotropy assumption!

Using (12.8),

$$\frac{G_{\theta,\theta}(k_1)}{2} = \frac{3}{5} \alpha_{\theta,\theta} \epsilon_{\theta,\theta} \epsilon_e^{-1/3} k_1^{-5/3}. \quad (12.15)$$

## 12.2 – The structure functions in the dissipation subrange

Let us remember a few important points about Kolmogorov’s theory. Kolmogorov’s first similarity hypothesis reads (Monin and Yaglom, 1975, p. 347):

*In the case of turbulence with a sufficiently large Reynolds number, the multi-dimensional probability distributions for the relative velocities  $\Delta \mathbf{u}(\mathbf{r}, \tau) = \mathbf{u}(\mathbf{x}_0 + \mathbf{r}, t_0 + \tau) - \mathbf{u}(\mathbf{x}_0, t_0)$ , in a space-time region  $G$  in which the turbulence is locally isotropic, are unambiguously defined by the values of  $\epsilon_e$  and  $\nu_u$ .*

Let us explain:

- “Locally” means that the hypothesis concerns only small scales, much smaller than those at which turbulence is produced by shear, buoyancy, etc.
- Reynolds’ decomposition is

$$U_i = \langle U_i \rangle + u_i. \quad (12.16)$$

- $\epsilon_e$  is the rate of dissipation of TKE, given by

$$\epsilon_e = 2\nu_u \left\langle s_{ij}s_{ij} \right\rangle, \quad s_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right). \quad (12.17)$$

Proceed: in isotropic turbulence, there is an important result which is not so easy to derive ([Tennekes and Lumley \(1972\)](#), for example, do not derive it in their book):

$$\epsilon_e = 15\nu_u \left\langle \left( \frac{\partial u_1}{\partial x_1} \right)^2 \right\rangle = \frac{15}{2} \nu_u \left\langle \left( \frac{\partial u_1}{\partial x_2} \right)^2 \right\rangle. \quad (12.18)$$

With  $\epsilon_e$  and  $\nu_u$ , one can form the famous Kolmogorov microscales:

$$\eta_u = (\nu_u^3/\epsilon_e)^{1/4}, \quad v_u = (\nu_u \epsilon_e)^{1/4}, \quad \tau_u = (\nu_u/\epsilon_e)^{1/2}. \quad (12.19)$$

Here,  $\nu_u$  is a *length* scale;  $v_u$  is a *velocity* scale; and  $\tau_u$  is a *time* scale.

Let us now look at the *longitudinal structure function*

$$D_{11}(r_1) \equiv \left\langle [u_1(x_1 + r_1, x_2, x_3) - u_1(x_1, x_2, x_3)]^2 \right\rangle \quad (12.20)$$

There is a lot about the structure function *tensor*, and tensor isotropic relations, that I am not discussing. Notice that  $D_{11}$  is relatively easy to measure in a micrometeorological tower with the help of Taylor’s hypothesis.

Now the big plunge: if  $r \ll \eta$ , the flow is *locally laminar*, very smooth and therefore

$$\begin{aligned} u_1(x_1 + r_1, x_2, x_3) - u_1(x_1, x_2, x_3) &\approx \frac{\partial u_1}{\partial x_1} r, \\ D_{11}(r_1) &\approx \left\langle \left( \frac{\partial u_1}{\partial x_1} \right)^2 \right\rangle r^2 = \frac{\epsilon_e}{15\nu_u} r^2. \end{aligned} \quad (12.21)$$

Very much like the velocity field, we can establish a Reynolds decomposition,

$$\Theta = \langle \Theta \rangle + \theta, \quad (12.22)$$

define the rate of dissipation of temperature semi-variance ([Tennekes and Lumley, 1972](#), Eqns. (3.4.3) and (3.4.4)):

$$\epsilon_{\theta\theta} = \nu_\theta \left\langle \frac{\partial \theta}{\partial x_k} \frac{\partial \theta}{\partial x_k} \right\rangle = 3\nu_\theta \left\langle \left( \frac{\partial \theta}{\partial x_1} \right)^2 \right\rangle, \quad (12.23)$$

from which we can write a Kolmogorov temperature microscale

$$\eta_\theta = (\nu_\theta^3/\epsilon_e)^{1/4}. \quad (12.24)$$



The factor 3 in the equation is found by assuming isotropy. This is not too difficult (in comparison with the result for  $\epsilon_e$ ): see (Tennekes and Lumley, 1972, p. 96).

So we see that we have *two* microscales now,  $\eta_u$  and  $\eta_\theta$ , and we must proceed with caution. A (longitudinal) temperature structure function can be defined in just the same way that the velocity structure function was defined, namely

$$D_{\theta,\theta}(r_1) \equiv \left\langle [\theta(x_1 + r_1, x_2, x_3) - \theta(x_1, x_2, x_3)]^2 \right\rangle. \quad (12.25)$$

Suppose  $r \ll \max(\eta_u, \eta_\theta)$ ; then we can, as before, admit a Taylor expansion

$$\begin{aligned} \theta(x_1 + r_1, x_2, x_3) - \theta(x_1, x_2, x_3) &= \frac{\partial \theta}{\partial x_1} r_1, \\ D_{\theta,\theta}(r_1) &\approx \left\langle \left( \frac{\partial \theta}{\partial x_1} \right)^2 \right\rangle r_1^2 = \frac{\epsilon_{\theta,\theta}}{3\nu_\theta} r_1^2. \end{aligned} \quad (12.26)$$

### 12.3 – The structure function in the inertial-convective sub-range

For scales  $r \gg \max(\eta_u, \eta_\theta)$ , the best-known result of Kolmogorov's turbulence theory is

$$D_{1,1}(r_1) = \frac{9}{10} \Gamma\left(\frac{1}{3}\right) (2\alpha_e) \epsilon_e^{2/3} r_1^{2/3} = \mathcal{C}_{1,1}^2 r_1^{2/3}, \quad (12.27)$$

$$D_{\theta,\theta}(r_1) = \frac{9}{10} \Gamma\left(\frac{1}{3}\right) (2\alpha_{\theta,\theta}) \epsilon_e^{-1/3} \epsilon_{\theta,\theta} r_1^{2/3} = \mathcal{C}_{\theta,\theta}^2 r_1^{2/3}. \quad (12.28)$$

The equations above define the *structure parameters*  $\mathcal{C}_{1,1}^2$  and  $\mathcal{C}_{\theta,\theta}^2$ . There is a lot of confusion in the value of the constants, because the Kolmogorov 5/3 law can be written both for the three-dimensional spectra  $E_e(k)$  and  $E_{\theta,\theta}(k)$ , and for the one-dimensional spectra  $F_{1,1}(k_1)$  and  $F_{\theta,\theta}(k_1)$ . The constants  $\alpha_e$  and  $\alpha_{\theta,\theta}$  above are those for the 3D-spectra. Taking (12.28) into (12.9),

$$\Phi_{\theta,\theta}(k) = \frac{2\alpha_{\theta,\theta}}{4\pi} \epsilon_e^{-1/3} \epsilon_{\theta,\theta} k^{-11/3} = \frac{10}{9\Gamma(1/3) \times 4\pi} \mathcal{C}_{\theta,\theta}^2 k^{-11/3} = B \mathcal{C}_{\theta,\theta}^2 k^{-11/3}, \quad (12.29)$$

with  $B = 0.033005$ . This is to stay in line with what is traditional in scintillometry. This equation will later be compared with (A).

### 12.4 – The inner scale

We are now ready for the inner scale definition. By equating the formulae (12.26) and (12.28) for  $D_{\theta,\theta}$  in the dissipation and the inertial-convective sub-

ranges, one finds

$$\begin{aligned}
 \frac{\epsilon_{\theta,\theta}}{3\nu_\theta} \ell_0^2 &= \frac{9}{10} \Gamma(1/3) (2\alpha_{\theta,\theta}) \epsilon_e^{-1/3} \epsilon_{\theta,\theta} \ell_0^{2/3} \\
 \frac{\ell_0^{4/3}}{3\nu_\theta} &= \frac{9}{10} \Gamma(1/3) (2\alpha_{\theta,\theta}) \epsilon_e^{-1/3} \\
 \ell_0^{4/3} &= \frac{27}{10} \Gamma(1/3) (2\alpha_{\theta,\theta}) \frac{\nu_\theta}{\nu_u} [\nu_u \epsilon_e^{-1/3}] \\
 \frac{\ell_0}{\eta_u} &= \left[ \frac{54}{10\text{Pr}} \Gamma(1/3) \alpha_{\theta,\theta} \right]^{3/4}
 \end{aligned} \tag{12.30}$$

For  $\text{Pr} = 0.72$  (air) and  $\alpha_{\theta,\theta} = 0.72$  (a convenient choice within the values reported in the literature), one finds

$$\frac{\ell_0}{\eta_u} = 7.417668, \tag{12.31}$$

which is Eqn (7) of [Hill and Clifford \(1978\)](#).

## 12.5 – The regions of the temperature spectrum

For a velocity field *not affected by the temperature field*, the classical wisdom is to divide the turbulent scales into 3 regions:

**energy-containing or production subrange:** Where  $k \sim 2\pi/L_u$ ,  $L_u$  being the integral, or production, scale.

**the inertial subrange** :  $2\pi/L_u \ll k \ll 2\pi/\eta_u$ .

**the viscous or dissipation subrange** :  $2\pi/\eta_u \ll k$ .

(Notice that it is not clear to which range  $2\pi/\eta_u$  belongs!)

The temperature, however, is *advected* by the velocity field, so its spectrum/structure function must be affected by both  $\eta_u$  and  $\eta_\theta$  microscales. To that effect it is useful to remember the definition of the molecular Prandtl number,

$$\text{Pr} \equiv \frac{\nu_u}{\nu_\theta}. \tag{12.32}$$

As for the temperature spectrum, now, we must analyze no less than 3 cases before defining sub-ranges. Here we go:

**Case 1:**  $\text{Pr} \ll 1$  , with

$$\frac{\nu_u}{\nu_\theta} \ll 1 \quad \text{and} \quad \frac{\eta_u}{\eta_\theta} \ll 1.$$

The expected temperature spectrum in this case is depicted in figure [12.1](#). There are four regions:

**energy-containing or production subrange:** Where  $k \sim 2\pi/L_\theta$ ,  $L_\theta$  being the integral, or production, scale.

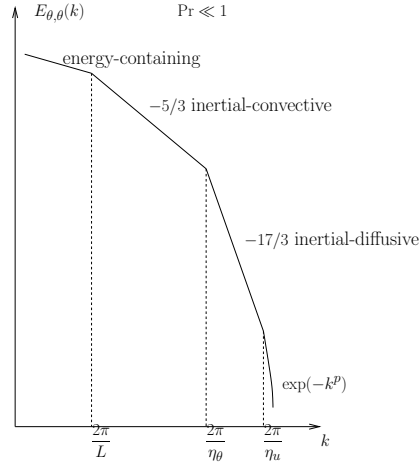


Figure 12.1: The temperature spectra for  $Pr \ll 1$ . The log-log axes are depicted in a 2:1 horizontal to vertical scale.

**inertial-convective subrange:**  $2\pi/L_\theta \ll k \ll 2\pi/\eta_\theta$ . This is essentially analogous to the inertial subrange, in that scales are still much larger than both  $\eta_u$  and  $\eta_\theta$  and are therefore not directly influenced by them.

**inertial-diffusive subrange:**  $2\pi/\eta_\theta \ll k \ll 2\pi/\eta_u$ . Note how the name has been carefully crafted: in this range, the kinematic viscosity  $\nu_u$  (and by the same token  $\eta_u$ ) is too small to influence the velocity field, which is “turbulent” and strongly advects temperature fluctuations. However, the molecular diffusivity of heat  $\nu_\theta$  (and  $\eta_\theta$ ) is large enough to dampen the temperature fluctuations, whose field is smoother.

**no name usually assigned:**  $k \gg 2\pi/\eta_u$ . This is however clearly a *diffusive-viscous subrange*, where viscosity comes last in the name because its effects appear after the effects of heat diffusion. It appears that in measurements it would be extremely difficult to indentify this subrange separately from the inertial-diffusive subrange.

**Case 2:**  $Pr \sim 1$ , with

$$\frac{\nu_u}{\nu_\theta} \sim 1 \quad \text{and} \quad \frac{\eta_u}{\eta_\theta} \sim 1.$$

The expected temperature spectrum in this case is depicted in figure 12.2. There are only three regions:

**energy-containing or production subrange:** Where  $k \sim 2\pi/L_\theta$ ,  $L_\theta$  being the integral, or production, scale.

**inertial-convective subrange:**  $2\pi/L_\theta \ll k \ll 2\pi/\eta_\theta$ . This is essentially analogous to the inertial subrange, in that scales are still much larger than both  $\eta_u$  and  $\eta_\theta$  and are therefore not directly influenced by them.

**viscous-diffusive subrange:**  $k \gg 2\pi/\eta_\theta$ .

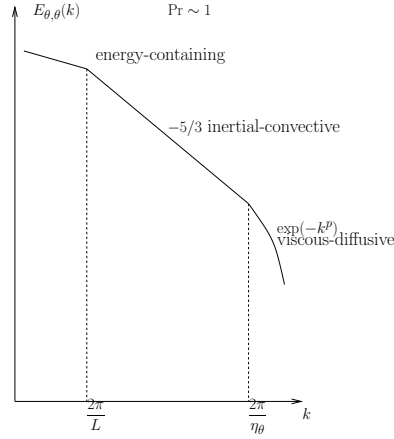


Figure 12.2: The temperature spectra for  $Pr \sim 1$ . The log-log axes are depicted in a 2:1 horizontal to vertical scale.

**Case 2:**  $Pr \gg 1$ , with

$$\frac{\nu_u}{\nu_\theta} \gg 1 \quad \text{and} \quad \frac{\eta_u}{\eta_\theta} \gg 1.$$

The expected temperature spectrum in this case is depicted in figure 12.3. There are again four regions:

**energy-containing or production subrange:** Where  $k \sim 2\pi/L_\theta$ ,  $L_\theta$  being the integral, or production, scale.

**inertial-convective subrange:**  $2\pi/L_\theta \ll k \ll 2\pi/\eta_\theta$ . This is essentially analogous to the inertial subrange, in that scales are still much larger than both  $\eta_u$  and  $\eta_\theta$  and are therefore not directly influenced by them.

**viscous-convective:**  $2\pi/\eta_u \ll k \ll 2\pi/\eta_\theta$ . Note how the name has been carefully crafted: in this range, the molecular diffusivity  $\nu_\theta$  (and by the same token  $\eta_\theta$ ) is too small to influence the temperature temperature field, which is advected by a locally “laminar” (smooth) velocity field.

**viscous-diffusive subrange:**  $k \gg 2\pi/\eta_\theta$ . The temperature fluctuations are strongly damped and the temperature range is laminar after  $\nu_\theta$ , whose effect is the last one to be felt by the temperature field, is in action.

Having said this, are there relevant cases of  $Pr$  much larger or much smaller than 1 in nature, to justify the theoretical effort? Yes! [Hill and Clifford \(1978\)](#) give two important examples:

- Temperature in water:  $Pr \simeq 8$ .
- Salt in Water:  $Pr \simeq 700$ .

[Hill \(1978\)](#) developed several analytical models to represent the several features of the scalar (in our case represented by the temperature) spectrum. Figure ?? shows the fitting of Hill’s 4 models to the data of temperature measured in the surface layer by [Champagne et al. \(1977\)](#): Hill calls the bump in the figure a

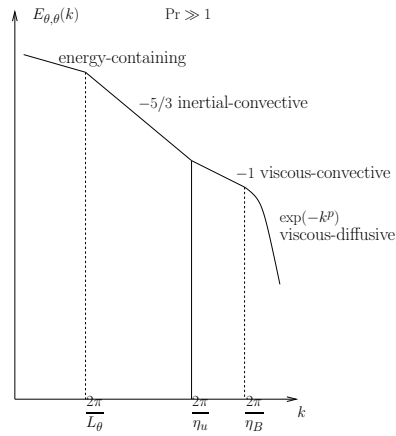
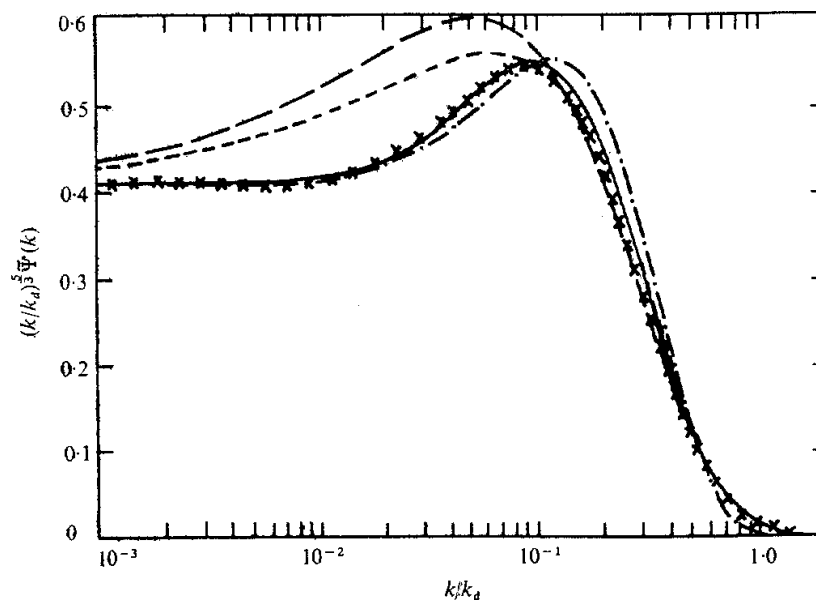


Figure 12.3: The temperature spectra for  $Pr \gg 1$ . The log-log axes are depicted in a 2:1 horizontal to vertical scale.



viscous-convective subrange *even though*  $Pr = 0.72$  *for air*! Clearly, there is an inconsistency here.

Yet, the proposal by Hill that a viscous-convective subrange exists in the temperature spectra in the air still holds, in spite of the inner contradiction. Here is [Hartogensis \(2006\)](#), p. 6–7 (symbols have been changed to follow this text's notation):

The existence of the Hill bump can be understood as follows. For  $Pr \approx 0.72$  the inertial-dissipation range transition is of a viscous-convective nature, i.e. viscosity already starts to break up TKE when  $\theta$ -diffusion still is characterised by convection (the inertial range). Since  $\nu_u$  is much smaller than the turbulent  $u$ -diffusion coefficient the breaking up of turbulent eddies halts, but at the same time the  $\theta$ -diffusion is still at its convective intensity thus leading to a build up of spectral energy at these scales (a bump). At smaller scales, the  $\theta$  gradients are finally large enough for the molecular diffusivity to compensate the lack of turbulent mixing.

# A

## O fator 2 nos espectros de escalares

Uma boa notícia é que [Monin and Yaglom \(1975\)](#) usam na página 139 a mesma notação que eu, quando escrevem

$$\int_0^\infty E_{\vartheta\vartheta}(k) dk = \overline{\vartheta'^2}.$$

Na página 123 nós encontramos o espectro de energia cinética da turbulência (ECT), na forma

$$E(k, t) = 4\pi k^2 F(k, t)$$

Ao que tudo indica, por comparação com (12.6),

$$F(k, t) = \frac{\phi_{ii}(k, t)}{2}$$

Isto é confirmado na página 20, equação 11.58:

$$F(\mathbf{k}) = \frac{1}{2} F_{jj}(\mathbf{k}).$$

Começo a compilar uma tabela de equivalência de símbolos:

A primeira aparição da lei dos 5/3 é (parece ser) na equação (16.37):

$$E(k) = C_1 \epsilon^{2/3} k^{-5/3}.$$

As diversas relações entre as constantes de Kolmogorov aparecem na equação (21.25), página 355. Em [Monin and Yaglom \(1975\)](#), tudo parece girar em torno da função de estrutura longitudinal para velocidade, que eles definem como (Eq. (21.10))

$$D_{LL}(r) = \overline{(\Delta_r u_L)^2}.$$

Table A.1: M, Y & Eu

M& Y	Eu
$F_{ij}(\mathbf{k})$	$\Phi_{i,j}(\mathbf{k})$
$F(\mathbf{k})$	—
$E(k)$	$E_e(k)$
$E_{\vartheta\vartheta}(k)$	$E_{\theta,\theta}(k)$
$\overline{\epsilon}$	$\epsilon_e$
$\overline{N}$	$\epsilon_{\theta,\theta}$

Vamos agora em direção à temperatura, que é o que nos interessa no momento. [Monin and Yaglom \(1975\)](#) definem a taxa de dissipação de semi-variância de temperatura na página 379, logo após a equação (21.80). O símbolo,  $\bar{N}$ , vai para a tabela [A.1](#).

Agora um pouco de confusão: na página 385 nós vamos encontrar  $E_{\vartheta\vartheta}(k) = E^{(\vartheta)}(k)$ , e logo em seguida (equação (21.89))

$$E^{(\vartheta)}(k) = B^{(\vartheta)} \bar{N} \bar{\epsilon}^{-1/3} k^{-5/3}$$

A função de estrutura de temperatura é

$$D_{\vartheta\vartheta}(r) = C_{\vartheta} \bar{N} \bar{\epsilon}^{1/3} r^{2/3}$$

e

$$B^{(\vartheta)} = \frac{10C_{\vartheta}}{9\Gamma(1/3)}.$$

Compare com [\(12.28\)](#), que eu repito aqui,

$$\begin{aligned} D_{\theta,\theta}(r_1) &= \underbrace{\frac{9}{10}\Gamma\left(\frac{1}{3}\right)(2\alpha_{\theta,\theta})}_{C_{\vartheta}=C_{\theta,\theta}} \epsilon_e^{-1/3} \epsilon_{\theta,\theta} r_1^{2/3} \Rightarrow \\ (2\alpha_{\theta,\theta}) &= \frac{10C_{\theta,\theta}}{9\Gamma(1/3)}, \end{aligned}$$

o que é *valida* minha interpretação:

$$B^{(\vartheta)} = 2\alpha_{\theta,\theta}.$$



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