Part I

GENERALITIES

Chapter 1

Introduction

SUMMARY: In this opening chapter, we define the discipline known as Environmental Fluid Mechanics, discuss its importance, and outline its most distinctive attributes.

1.1 Fluids in the Environment

All living creatures are immersed in a fluid or another, be it the air of the atmosphere or the water of a river, lake or ocean; even, soils are permeated with moisture, without which life would be impossible. So, it is no exaggeration to say that life, including our own, is bathed in fluids. A slightly closer look at the situation further reveals that it is the mobility of fluids that actually makes them so useful to the maintenance of life, both internally and externally to living organisms. For example, it is thanks to the mobility of air that our lungs can be constantly supplied with oxygen. The forced air flow created by our respiration, however, is not sufficient; without atmospheric motion around us, we would choke sooner or later in our own exhaust of carbon dioxide. Likewise, most aquatic forms of life rely on the natural transport of water for their nutrients. Our industrial systems, which release pollution on a continuing basis, would not be permissible in the absence of transport and dilution of nearly all emissions by natural air and water flows. In sum, natural fluid motions in the environment are vital, and we have a strong incentive to study the naturally occurring fluid flows, particularly those of air in the atmosphere and of water in all its streams, from underground aquifers to surface flows in rivers, lakes, estuaries and oceans.

The study of these flows has received considerable attention over the years, and several distinct disciplines have emerged: meteorology, climatology, hydrology, hydraulics, limnology and oceanography. Whereas the particular objectives of each of these disciplines, such as weather forecasting in meteorology and design of water-resource projects in hydraulics, encourage disciplinary segregation, environmental concerns compel experts in those disciplines to consider problems that are essentially similar: the flow around an object of complex geometry, the rise of a buoyant plume, the effect of turbulence on the dispersion of a dilute contaminant, and the transfer of a substance between the fluid and a boundary. Such common points encourage interdisciplinarity to a degree that is increasing in proportion to the acuity of our environmental problems. This overlap between the various disciplines concerned with the environmental aspects of natural fluid flows has given rise to a body of knowledge that has become known as Environmental Fluid Mechanics.

1.2 Scope of Environmental Fluid Mechanics

In the light of the preceding remarks, we can propose a definition: *Environmental Fluid Mechanics* (EFM) is the scientific study of naturally occurring fluid flows of air and water on our planet Earth, especially of those that affect the environmental quality of those fluids. Scales of relevance range from millimeters to kilometers, and from seconds to years.

According to the preceding definition, EFM does not extend to fluid flows inside organisms, such as air flow in lungs and blood flow in the vascular system, although these can be classified as natural. Rather, these topics more properly belong to specialized biological and medical sciences, which have little in common with studies of outdoor fluid flows.

The preceding definition also distinguishes EFM from classical fluid mechanics, the latter being chiefly concerned with artificial (engineered) fluid motions: flows in pipes and around airfoils, in pumps, turbines, heat exchangers and other machinery that utilizes fluids. In so doing, it treats many different types of fluids and under vastly different pressures and temperatures (Munson et al., 1994). By contrast, EFM is exclusively concerned with only two fluids, air and water, and moreover under a relatively narrow range of ambient temperatures and pressures. Ironically, while classical fluid mechanics tends to view turbulence as a negative element, because it creates unwanted drag and energy loss, EFM accepts turbulence as beneficial, because it is conducive to rapid dispersion and dilution.

The objective of EFM also differs from that of hydraulics, which deals exclusively with free-surface water flow (Chow, 1959; Sturm, 2001). Traditionally, problems in hydraulics have addressed the prediction and control of water levels and flow rates, but the realm of hydraulics has recently been shifting considerably toward environmental concerns (Singh and Hager, 1996; Chanson, 2004). This situation has arisen because it has now become equally important to estimate the effect of bottom turbulence on erosion and sedimentation as it has been to calculate water levels and pressures against structures. Because of its similarities with other natural fluid flows, the environmental component of hydraulics is incorporated in EFM.

Geophysical fluid dynamics, which studies the physics of atmospheric and oceanic motions on the planetary scale (Cushman-Roisin, 1994), is another branch of fluid mechanics that overlaps with EFM. In geophysical fluid dynamics, however, the strong constraints brought about by the rotation of the earth relegate turbulence to secondary status. Put another way, the two main ingredients of geophysical fluid dynamics are stratification and rotation, whereas those of EFM are stratification and turbulence.

Other cousin disciplines are limnology (study of lakes; ex. Imberger, 1998) and hydrology (study of surface and subsurface water; ex. Bras, 1990, Ward & Trimble, 2004). Table 1.1 recapitulates the commonalities and differences among EFM and other disciplines.

Table 1.1 Topical comparison between Environmental Fluid Mechanics and related disciplines

	Environmental Fluid Mechanics	Fluid Mechanics	Geophysical Fluid Dynamics	Hydraulics	Hydrology
Air example	Sea breeze	Airfoil	Storm	—	—
Water example	Danube River	Pump	Gulf Stream	Dam	Watershed
Turbulence	Beneficial (Dilution)	Detrimental (Drag)	Secondary importance	Secondary importance	Unimportant
Human control	Limited	Dominant	Nil	Dominant	Limited
Purpose	Prediction & Decision	Design & Operation	Prediction & Warnings	Design & Operation	Prediction & Decision

Finally, it is worth situating the purpose of EFM among that of the other disciplines. Because no one can affect in any direct way the flow of air and water on planetary scales, geophysical fluid dynamics, meteorology and oceanography aim solely at the understanding and prediction of those flows. In contrast, the primary objectives of traditional fluid mechanics and hydraulics are design and operation. Environmental fluid mechanics finds its purpose between those extremes; like hydrology and limnology, it is aimed at prediction and decision. Indeed, typical problems in EFM concern the prediction of environmental-quality parameters that depend on natural fluid flows, such as pollution levels. EFM also extends into decision making. Decisions in the realm of EFM, however, do not address how natural fluid flows can be controlled or modified, but how inputs from human activities can be managed as to minimize their impact downstream. A typical example is the design of a smokestack (with decisions regarding its location, height, diameter and rate of output) in order to avoid certain levels of ground pollution within a certain radius around its base.

1.3 Stratification and Turbulence

Stratification and turbulence are two essential ingredients of EFM. Stratification occurs when the density of the fluid varies spatially, as in a sea breeze where masses of warm and cold air lie next to each other or in an estuary where fresh river water flows over saline seawater. Such situations with adjacent masses of lighter and denser fluid create buoyancy forces that strongly control the flow by either generating or restricting vertical motion.

Stratification is to be distinguished from compressibility. Compressibility, or the variation of density under changing pressure, is responsible for the propagation of sound waves. Intuitively, it is evident that the propagation of sound waves (acoustics) is not relevant to environmental fluid motions. This is because the typical speeds associated with motions of air and water in nature are far less than the sound speed; i.e. the Mach number (ratio of fluid velocity to sound speed) is much less than one. In contrast to compressibility, stratification arises because density varies with temperature through what is commonly called thermal expansion: heat dilates the fluid, so that warm fluid expands and cold fluid contracts. This effect is often important in natural fluid systems because thermal contrasts across the system create buoyancy forces that may not be negligible, imparting to the fluid a tendency to arrange itself vertically with the denser fluid sinking to the lowest places and the lighter fluid floating on top. Such layering of the fluid according to density, from the heaviest at the bottom to the lightest at the top is what is properly called stratification. But, the word stratification has been enlarged to encompass any situation in which density differences are important, regardless of whether they occur in the vertical or the horizontal or both, and whether they are caused by heat or another agent such as salinity (in seawater) and moisture (in atmosphere).

Although a certain degree of stratification is always present in environmental systems, its dynamical effects are not necessarily important in every single instance. There are indeed cases, such as shallow-river flows, where buoyancy forces exert a negligible effect among the other forces at play. To ascertain the importance of density stratification in a particular situation, we can use the following rule. Under the action of gravity, fluid masses of different densities tend to flow so that the heavier ones occupy the lower portion of the domain and the lighter ones the upper portion. In the absence of mixing along the way and of other forces besides gravity, the ultimate result would be a vertical arrangement of horizontal layers with density increasing monotonically downward, which corresponds to a state of least potential energy. The action of other forces, however, creates motions that disturb such equilibrium, tending to raise heavier fluid and lower lighter fluid against their respective buoyancy forces. The result is an increase of potential energy at the expense of a portion of the kinetic energy contained in the motion. Therefore, the dynamical importance of stratification can be estimated by comparing the levels of potential and kinetic energies present in the system under consideration.

In most environmental applications, fluid parcels (air or water) undergo only very moderate density variations. For example, a water parcel on the surface of a lake when subjected to solar heating that increases its temperature by 10°C (which almost never occurs) has its density reduced by less than 0.3%! By contrast, we think of the air in the atmosphere as being very compressible, and it is so, but nonetheless the compressibility of air is unimportant in most environmental analyses, because air parcels travelling with winds remain within a narrow range of pressures and temperatures and undergo density variations that are usually less than 5%. With this in mind, we can write the density ρ of the fluid (defined as mass per volume, in kg/m^3), as the sum of two terms

$$\rho \;=\; \rho_0 \;+\; \rho' \;, \tag{1.1}$$

where ρ_0 is a constant and ρ' a variable but small perturbation. For ρ_0, we can adopt the following values:

- for air at standard temperature (15°C) and pressure (101.33 kPa):
  $\rho_0 = 1.225$ kg/m^3,
- for freshwater at standard temperature (15°C) and atmospheric pressure:
  $\rho_0 = 999$ kg/m^3,
- for seawater at standard temperature (10°C) and salinity of (35 ppt):
  $\rho_0 = 1027$ kg/m^3.

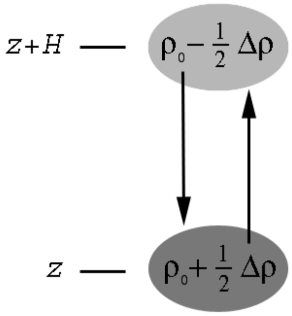

Figure 1.1: Exchange between fluid parcels of different densities and at different heights. Because each displacement is performed either against or with the force of gravity, the exchange causes a modification in potential energy.

If the density perturbation ρ' changes by a value $\Delta\rho$ over a height H of the fluid (height over which vertical excursions are taking place), so that a fluid parcel at some level z has a density equal to $\rho_0 + \Delta\rho/2$ and one at level $z + H$ a density equal to $\rho_0 - \Delta\rho/2$ (Figure 1.1), an exchange of volume V between those two parcels causes a rise in potential energy of the heavier one by $mgH = (\rho_0 + \Delta\rho/2)VgH$ and a simultaneous drop in potential energy of the lighter parcel by $(\rho_0 - \Delta\rho/2)VgH$. The net change in potential energy is $\Delta\rho VgH$. On the other hand, the kinetic energy is on the order of $mU^2/2$ per parcel, where U is a measure of the fluid velocity in the system (such as a velocity at some inlet). For the pair of parcels, this adds to $(\rho_0 + \Delta\rho/2)VU^2/2 + (\rho_0 - \Delta\rho/2)VU^2/2 = \rho_0 VU^2$. A comparison of potential energy to kinetic energy leads to forming the ratio

$$Ri \ = \ \frac{gH\Delta\rho}{\rho_0 U^2} \ , \tag{1.2}$$

after division by V. This is called the *Richardson number*[1].

The value of the dimensionless ratio Ri permits to determine how important stratification effects can be in a given system. If Ri is on the order of unity (say $0.1 < Ri < 10$, customarily written as $Ri \sim 1$), a significant perturbation to the stratification can consume a major part of the available kinetic energy, thereby modifying the flow field significantly. Stratification is then important. If Ri is much greater than unity ($Ri \gg 1$, or in practice $Ri > 10$), then there is insufficient kinetic energy to perturb the stratification in any significant way, and the latter greatly constrains the flow. But, on the other hand, when Ri is much less than unity ($Ri \ll 1$, or in practice $Ri < 0.1$), potential-energy variations created by vertical excursions of the fluid against their buoyancy forces cause a negligible drop in kinetic energy, and the stratification is easily erased by vertical mixing. In sum, stratification effects are negligible whenever $Ri \ll 1$ and important otherwise.

Turbulence is the term used to characterize the complex, seemingly random motions that continually result from instabilities in fluid flows. Turbulence is ubiquitous in natural fluid flows because of the large scales that these flows typically occupy. (The only significant exception is the subsurface flow in porous soils where the flow is very slow.) By vigorously stirring the fluid, turbulence is an extremely efficient agent of dilution. This is a major advantage. On the other hand, turbulence comes with a substantial handicap: The complex

---

[1] in honor of Lewis Fry Richardson (1881–1953), a British meteorologist

motions that it generates are beyond any easy description, even by a statistical approach. Some specific types of turbulent flow, such as homogeneous turbulence and shear turbulence, can be described by limited theories and modeled with a good dose of empiricism, but no complete theory of turbulence has yet been formulated.

The level of turbulence in a fluid system is estimated by comparing the amount of kinetic energy and the work of viscous forces. If ρ_0 is again the average density value in the system, U a typical velocity value, L a characteristic length of the domain (such as its width or height), and μ the viscosity of the fluid, then a measure of the kinetic energy per unit volume is $\rho_0 U^2/2$, while the dissipative work done by viscous forces per unit volume is $\mu U/L$. The ratio of these two quantities is (after removal of the factor 2 which is inconsequential in a definition):

$$Re \;=\; \frac{\rho_0 U L}{\mu}\ . \tag{1.3}$$

This ratio bears the name of *Reynolds number*[2]. When Re is large, there is ample kinetic energy and comparatively little viscous dissipation; the fluid flows relatively freely and is thus apt to exhibit complex spatial patterns and much temporal variability. This is the case of turbulence. Hence, turbulence occurs whenever the Reynolds number is large. There is rarely a precise value of the Reynolds number below which the flow is simply structured (laminar flow) and above which turbulence occurs, but the transition typically occurs at a Reynolds number of a few thousands. In environmental systems, with large values of L and small values of μ [$\mu = 1.8 \times 10^{-5}$ kg/m.s for air and 1.0×10^{-3} kg/m.s for water], the value of Re almost invariably exceeds 10^6, and the flow is turbulent.

The two ingredients of EFM, stratification and turbulence, act generally in competition with each other. Oftentimes, the buoyancy forces of stratification tend to quench turbulence, because vertical motions against buoyancy forces consume kinetic energy to increase potential energy. On the other hand, turbulent motions are capable of mixing the fluid and therefore act to reduce the density differences that create stratification. An exception to the rule is convection, which occurs when an unstable, top-heavy stratification releases potential energy that feeds turbulent kinetic energy.

1.4 Environmental Transport and Fate

A convenient way of framing almost all environmental problems is the source-pathway-receptor paradigm (Figure 1.2). Pollution has a root cause, a *source*, from which contaminants are released, in either predictable or accidental ways. These travel through one or several media, such as the atmosphere, a river, an aquifer or a food chain, the *pathway*; along the way, they are diluted and modified. Eventually, they encounter objects, animate or inanimate, on which they have adverse effects, the *receptor*. Environmental management is brought to bear on one, two or all three components of the system. Protection of a beach from an offshore oil spill or relocation of residents away from a contaminated area

---

[2] in honor of Osborne Reynolds (1842-1912), who pioneered laboratory experiments and theory of turbulent flows.

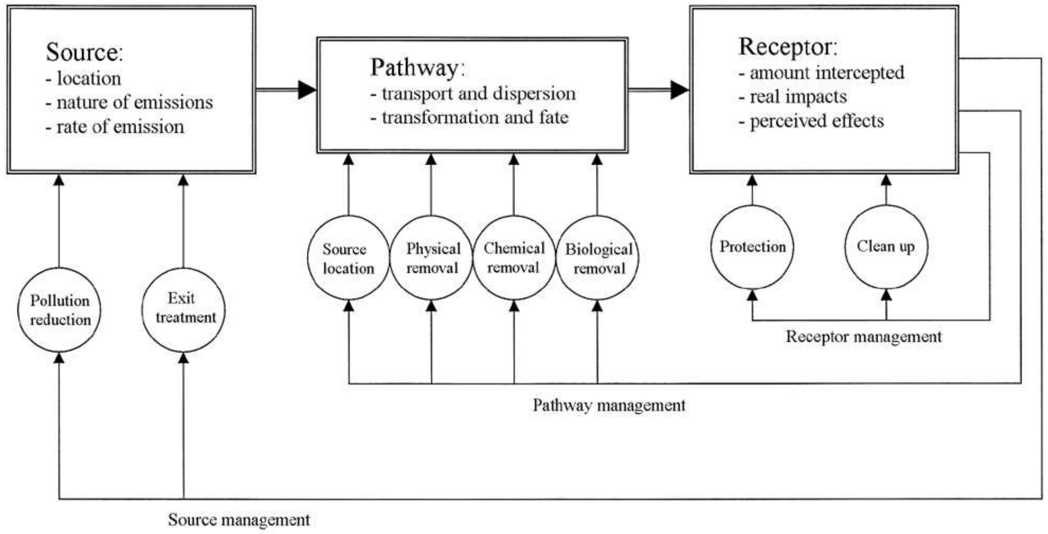

Figure 1.2: The Source-Pathway-Receptor paradigm of environmental transport and fate.

are examples of management at the receptor level. Such action is typically the quickest but least satisfactory approach, although it is occasionally the only possible way out of an urgent problem. Control at the source, by means of prevention, reduction or treatment, is a far better option. Examples are the burning in a power plant of coal with a lower sulphur content and biological treatment of sewage. As an intermediate alternative, pathway management offers great flexibility and, typically, also at a reasonable cost. Techniques range from the siting of the source (so as to take maximum advantage of favorable ambient conditions), to the design of settling ponds (to promote removal at low-energy costs) and the concomitant release of chemicals to enhance chemical degradation of the contaminant along its journey in the environment.

Because pathways are often multiple and not every route can be easily identified, and because movement along a particular pathway can be episodic, pathway management must be preceded by a careful analysis of both the transporting mechanisms and the transformations that can occur along the way. Such analysis is the object of the discipline known as *Environmental Transport and Fate* (Hemond & Fechner, 1994). As its name indicates, this discipline has two distinct aspects: It implicates both the physics of transport (How do pollutants travel? Where do they go?) and the biochemistry of fate (What do pollutants become? What other secondary pollutants do they generate?). In this context, Environmental Fluid Mechanics is the chapter that addresses the physical aspects of fluid pathways.

Natural fluid flows of air and water do not simply transport their load from a source to a receptor. As different parts of the same patch of pollutant travel at different speeds, a progressive deformation takes place, leading eventually to a very complex shape. This deformation, which by itself does not increase the patch size and does not reduce the pollutant concentration, promotes, however, contacts between the fluid inside the patch and that in

Figure 1.3: A smokestack plume. Note the turbulent billowing inside the plume, which is the cause of its gradual dispersion in the ambient atmosphere. (Photo by the author)

the surroundings. Those contacts in turn facilitate an exchange of properties, which disperses the pollutant, enlarges its patch and reduces its concentration. In sum, environmental fluid flows have a triple effect: transport, deformation and dispersion.

As an example, consider the smokestack plume shown in Figure 1.3. Three processes can be identified in this photograph: vertical rise due to the buoyancy of the hot fumes, horizontal transport by the ambient wind, and turbulent billowing. While the plume follows a traceable path, turbulence causes it to be gradually mixed with ambient air and to widen. The concentration of the combustion fumes inside the plume diminishes in proportion to the dilution.

1.5 Scales, Processes and Systems

Environmental problems appear different at different scales, requiring various approaches for their investigation and solution. Likewise, Environmental Fluid Mechanics takes different forms depending on the scale of investigation.

The shortest relevant scale is the atomic-molecular level. At that level, the emphasis is on elementary processes such as nuclear and chemical reactions. This is almost exclusively the realm of the “Fate” component of Environmental Transport and Fate. There is nonetheless an important fluid aspect at this level, namely molecular diffusion by thermal (Brownian) motions. The next shortest scale of interest is the level of a single organism, where the investigation turns mostly to biology.

The next scale at which fluid motions intervene is the local level, where pollutants no longer appear as individual units and where their quantity is best measured in terms of concentrations in a continuous fluid medium. And, although one may still talk loosely about a fluid particle or parcel, one now means a large ensemble of individual particles, large enough to allow the fluid to be considered as a smooth continuum but small enough to appear point-like at the length scale of interest. At this level, the focus is on the flow in the vicinity of a single source, such as the jet caused by the discharge of an industrial waste in a body of water or the plume originating from a release of hot gases from a smokestack (Figure 1.3). The understanding of such phenomena proceeds from studies of specific processes. In the present book, this task is undertaken in Part II (Chapters 4 to 12). The same process is likely to be present in different environmental systems under almost identical forms. For example, shear-flow instability occurs in the lower atmosphere, in estuaries and also in the near-surface circulation of a lake. The same mathematical formulation will therefore be useful in more than one application.

Table 1.2 Length, velocity and time scales of environmental fluid processes and systems

	Horizontal Length Scale L	Vertical Length Scale H	Velocity Scale U	Time scale T
Processes:				
Microturbulence	1–10 cm	1–10 cm	1–10 cm/s	few seconds
Shear turbulence	0.1–10 m	0.1–10 m	0.1–1 m/s	few minutes
Water waves	0.1–10 m	1–100 cm	1–10 m/s	seconds to minutes
Convection	10–1000 m	1–1000 m	0.1–1 m/s	hours, days or seasons
Atmospheric systems:				
Urban airshed	1–10 km	100–1000 m	1–10 m/s	hours
Sea breeze	1–10 km	100–1000 m	1–10 m/s	hours
Thunderstorms	1–10 km	100–5000 m	1–10 m/s	hours
Mountain waves	10–100 km	10–1000 m	1–10 m/s	days
Tornado	10–100 m	100–1000 m	100 m/s	minutes to hours
Hurricane	100–1000 km	10 km	100 m/s	days to weeks
Weather patterns	100–1000 km	10 km	1–10 m/s	days to weeks
Climatic variations	global	50 km	1–10 m/s	decades and beyond
Water systems:				
Aquifers	1–1000 km	10–100 m	1–10 mm/s	seasons to decades
Wetlands	10–1000 m	1–10 m	0.1–10 cm/s	days to seasons
Small stream	1–10 m	0.1–1 m	10–100 cm/s	seconds to minutes
Major river	10–1000 m	1–10 m	1–100 cm/s	minutes to hours
Lakes	1–100 km	10–1000 m	1–10 m/s	days to seasons
Ocean tides	basin scale	basin depth	0.1–10 m/s	hours
Estuaries	1–10 km	1–10 m	0.1–1 m/s	hours to days
Coastal ocean	1–100 km	10-1000 m	0.1–1 m/s	few days
Deep ocean	basin scale	basin depth	0.01–1 m/s	weeks to decades

At the next larger level, one considers entire systems, such as a river, a lake, an aquifer or an urban airshed. In those systems, fluid motions result from several processes acting simultaneously. For example, lake dynamics are characterized by a mix of wind-driven currents, gravity waves, thermal stratification and winter convection. Chapters 13 to 21 address the major environmental fluid systems.

Table 1.2 lists the typical velocity, length and time scales of the most common environmental fluid processes and systems. Not surprisingly, larger systems evolve on longer time scales, with the exception of ocean tides. Depending on the size of the system under consideration, the spatial scale can be regional, continental or even global. As the scale increases, some processes may yield precedence to others. For example, as one approaches continental and planetary scales, turbulence becomes increasingly less important, and the effect of the earth's rotation becomes dominant.

Problems

1-1. Name four naturally occurring flows in the atmosphere.

1-2. Explain how naturally occurring motions in the atmosphere are essential to our breathing.

1-3. What are the principal differences bewteen water flows in rivers and lakes? (*Hint*: Think of the forces driving those flows.)

1-4. The Fly River Estuary in Papua New Guinea has an average depth of 6 m and an intermittent tidal flow of 1.2 m/s. From river to ocean, the salinity varies from 0 to 30 ppt (ppt = parts per thousand). Knowing that the water density ρ varies with salinity according to

$$\rho \ = \ (1000 \text{ kg/m}^3)[1 + 7.6 \times 10^{-4} S], \tag{1.4}$$

where S is the salinity expressed in ppt, determine whether density differences induced by the salinity gradient are dynamically significant. Also, do you expect the tidal flow to be turbulent? [Water viscosity is $\mu = 1.0 \times 10^{-3}$ kg/(m.s).]

1-5. A 10 m/s wind blows around a tower that is 15 m wide. The ambient density and viscosity of air are respectively ρ_0=1.20 kg/m^3 and $\mu = 1.8 \times 10^{-5}$ kg/(m.s). Show that the flow must be turbulent. How weak should the velocity be to make the Reynolds number fall below 1000? Is such value realistic? What can you conclude about the state of the flow in the wake of the tower on any day of the year?

1-6. Give an example of a water system in which the presence of stratification significantly reduces the level of turbulence.

1-7. In first approximation, the depth-average velocity in a river is given by

$$U \ = \ C \ \sqrt{gHS} \ , \tag{1.5}$$

where C is called the Chézy coefficient, g is the gravitational acceleration, H the local water depth, and S the bottom slope. A default value for C is $C = 18$. If the critical value of the Reynolds number for the onset of turbulence by shear along a boundary is $Re = 5 \times 10^5$ and if the bottom slope is 1 m per kilometer, what are the minimum water depth and water velocity that will cause the river flow to be turbulent? Are these values realistic? What can you conclude about the level of turbulence if the water depth is 70 cm?

1-8. From the weather chart in today's newspaper or internet site of your choice, identify the horizontal extent of a major atmospheric feature at mid-latitudes and find the associated wind speed. From these length and velocity scales, determine a time scale. Then, knowing that atmospheric motions are significantly affected by the rotation of the earth over time periods of half a day (12 hours) and longer, what can you conclude about its effect in this case? [*Hint*: When converting latitudinal and longitudinal spans on a map into kilometers, use the earth's radius, 6371 km.]