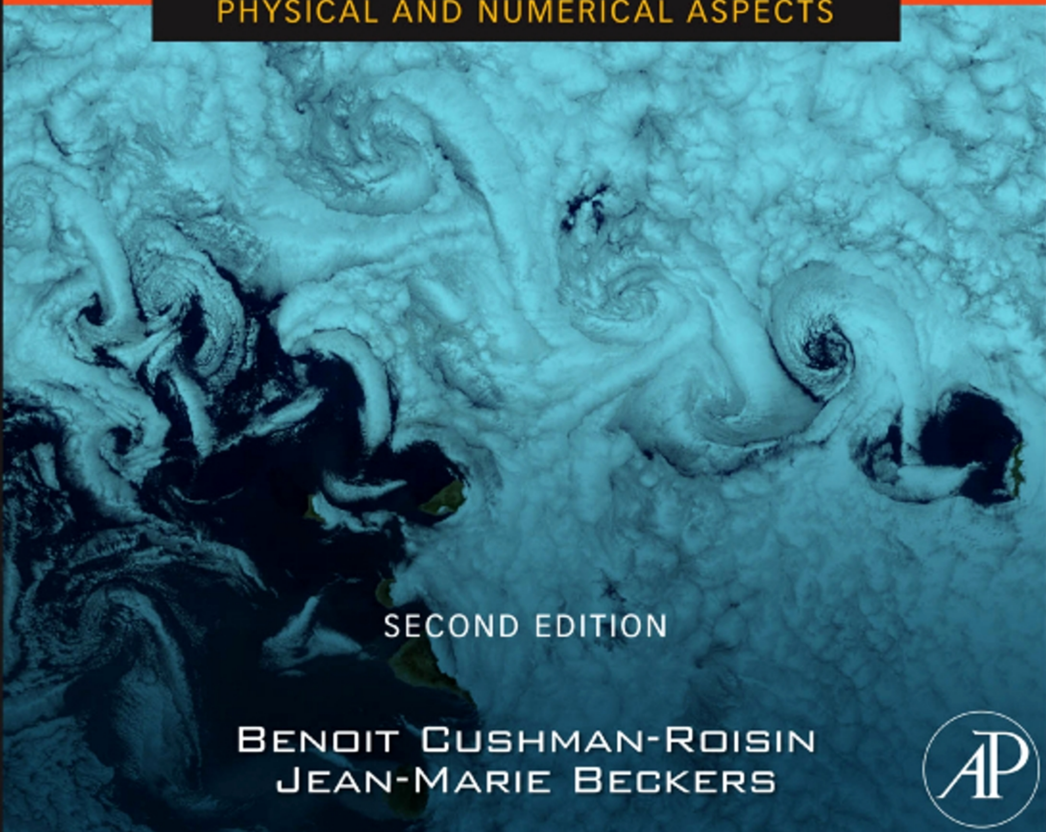
INTERNATIONAL GEOPHYSICS SERIES

VOL. 101

Introduction to GEOPHYSICAL FLUID DYNAMICS

PHYSICAL AND NUMERICAL ASPECTS



SECOND EDITION

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Chapter 1

Introduction

ABSTRACT

This opening chapter defines the discipline known as geophysical fluid dynamics, stresses its importance, and highlights its most distinctive attributes. A brief history of numerical simulations in meteorology and oceanography is also presented. Scale analysis and its relationship with finite differences are introduced to show how discrete numerical grids depend on the scales under investigation and how finite differences permit the approximation of derivatives at those scales. The problem of unresolved scales is introduced as an aliasing problem in discretization.

1.1 OBJECTIVE

The object of geophysical fluid dynamics is the study of naturally occurring, large-scale flows on Earth and elsewhere, but mostly on Earth. Although the discipline encompasses the motions of both fluid phases – liquids (waters in the ocean, molten rock in the outer core) and gases (air in our atmosphere, atmospheres of other planets, ionized gases in stars) – a restriction is placed on the *scale* of these motions. Only the large-scale motions fall within the scope of geophysical fluid dynamics. For example, problems related to river flow, microturbulence in the upper ocean, and convection in clouds are traditionally viewed as topics specific to hydrology, oceanography, and meteorology, respectively. Geophysical fluid dynamics deals exclusively with those motions observed in various systems and under different guises but nonetheless governed by similar dynamics. For example, large anticyclones of our weather are dynamically germane to vortices spun off by the Gulf Stream and to Jupiter's Great Red Spot. Most of these problems, it turns out, are at the large-scale end, where either the ambient rotation (of Earth, planet, or star) or density differences (warm and cold air masses, fresh and saline waters), or both assume some importance. In this respect, geophysical fluid dynamics comprises rotating-stratified fluid dynamics.

Typical problems in geophysical fluid dynamics concern the variability of the atmosphere (weather and climate dynamics), ocean (waves, vortices, and currents), and, to a lesser extent, the motions in the earth's interior responsible for the dynamo effect, vortices on other planets (such as Jupiter's Great

Introduction to Geophysical Fluid Dynamics, Volume 101, ISSN 0074-6142, **DOI: 10.1016/B978-0-12-088759-0.00001-8**

Red Spot and Neptune's Great Dark Spot), and convection in stars (the sun, in particular).

1.2 IMPORTANCE OF GEOPHYSICAL FLUID DYNAMICS

Without its atmosphere and oceans, it is certain that our planet would not sustain life. The natural fluid motions occurring in these systems are therefore of vital importance to us, and their understanding extends beyond intellectual curiosity—it is a necessity. Historically, weather vagaries have baffled scientists and laypersons alike since times immemorial. Likewise, conditions at sea have long influenced a wide range of human activities, from exploration to commerce, tourism, fisheries, and even wars.

Thanks in large part to advances in geophysical fluid dynamics, the ability to predict with some confidence the paths of hurricanes (Figs. 1.1 and 1.2) has led to the establishment of a warning system that, no doubt, has saved numerous lives at sea and in coastal areas (Abbott, 2004). However, warning systems are only useful if sufficiently dense observing systems are implemented, fast prediction capabilities are available, and efficient flow of information is ensured. A dreadful example of a situation in which a warning system was not yet adequate to save lives was the earthquake off Indonesia's Sumatra Island on

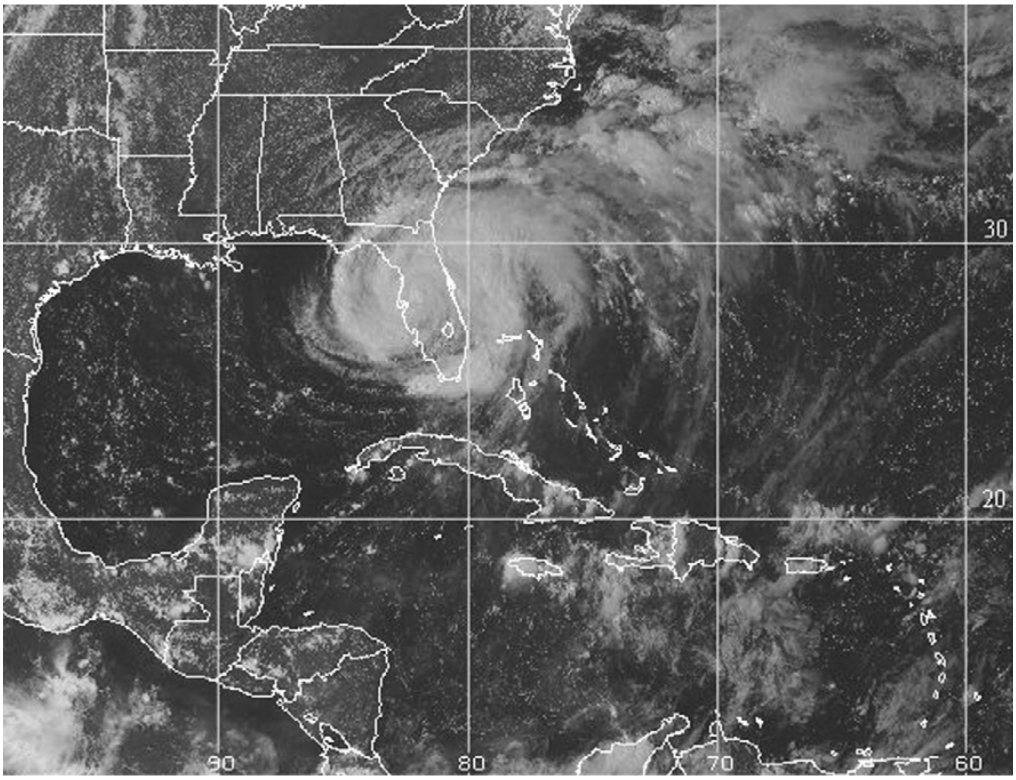

FIGURE 1.1 Hurricane Frances during her passage over Florida on 5 September 2004. The diameter of the storm was about 830 km, and its top wind speed approached 200 km per hour. (*Courtesy of NOAA, Department of Commerce, Washington, D.C.*)

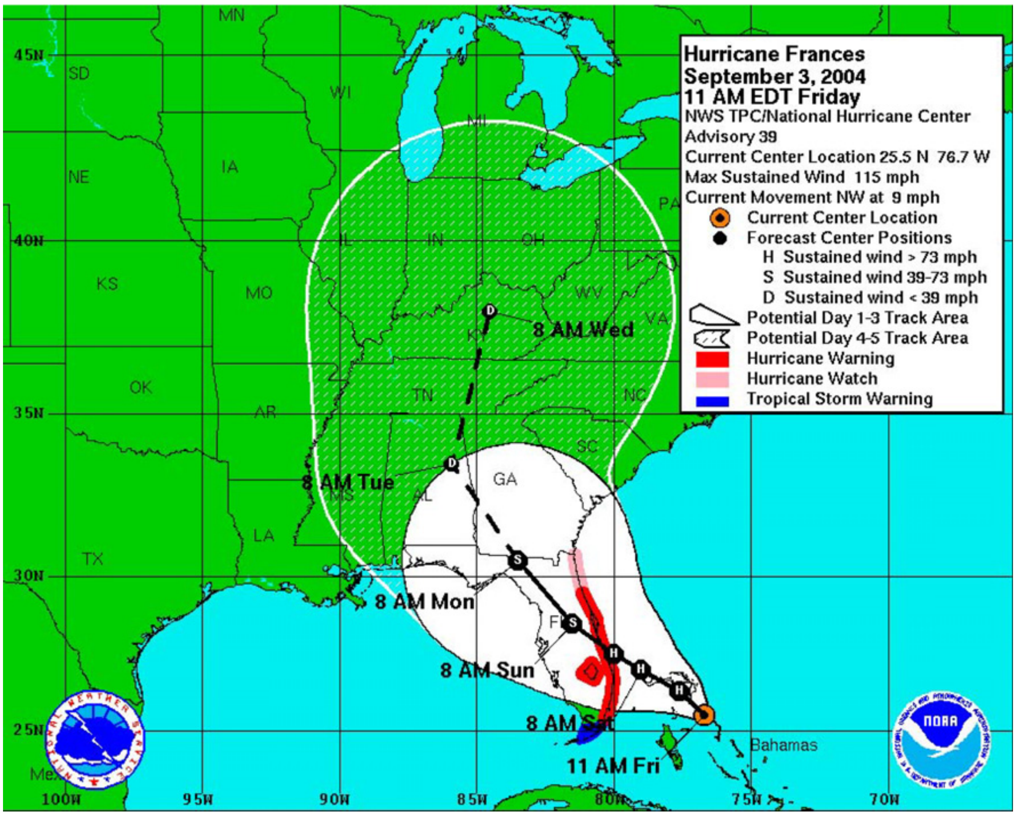

FIGURE 1.2 Computer prediction of the path of Hurricane Frances. The calculations were performed on Friday, 3 September 2004, to predict the hurricane path and characteristics over the next 5 days (until Wednesday, 8 September). The outline surrounding the trajectory indicates the level of uncertainty. Compare the position predicted for Sunday, 5 September, with the actual position shown on Fig. 1.1. (*Courtesy of NOAA, Department of Commerce, Washington, D.C.*)

26 December 2004. The tsunami generated by the earthquake was not detected, its consequences not assessed, and authorities not alerted within the 2 h needed for the wave to reach beaches in the region. On a larger scale, the passage every 3–5 years of an anomalously warm water mass along the tropical Pacific Ocean and the western coast of South America, known as the El-Niño event, has long been blamed for serious ecological damage and disastrous economical consequences in some countries (Glantz, 2001; O'Brien, 1978). Now, thanks to increased understanding of long oceanic waves, atmospheric convection, and natural oscillations in air–sea interactions (D'Aleo, 2002; Philander, 1990), scientists have successfully removed the veil of mystery on this complex event, and numerical models (e.g., Chen, Cane, Kaplan, Zebiak & Huang, 2004) offer reliable predictions with at least one year of *lead time*, that is, there is a year between the moment the prediction is made and the time to which it applies.

Having acknowledged that our industrial society is placing a tremendous burden on the planetary atmosphere and consequently on all of us, scientists, engineers, and the public are becoming increasingly concerned about the fate of pollutants and greenhouse gases dispersed in the environment and especially about their cumulative effect. Will the accumulation of greenhouse gases in the atmosphere lead to global climatic changes that, in turn, will affect our lives and societies? What are the various roles played by the oceans in maintaining our present climate? Is it possible to reverse the trend toward depletion of the ozone in the upper atmosphere? Is it safe to deposit hazardous wastes on the ocean floor? Such pressing questions cannot find answers without, first, an in-depth understanding of atmospheric and oceanic dynamics and, second, the development of predictive models. In this twin endeavor, geophysical fluid dynamics assumes an essential role, and the numerical aspects should not be underestimated in view of the required predictive tools.

1.3 DISTINGUISHING ATTRIBUTES OF GEOPHYSICAL FLOWS

Two main ingredients distinguish the discipline from traditional fluid mechanics: the effects of rotation and those of stratification. The controlling influence of one, the other, or both leads to peculiarities exhibited only by geophysical flows. In a nutshell, this book can be viewed as an account of these peculiarities.

The presence of an ambient rotation, such as that due to the earth's spin about its axis, introduces in the equations of motion two acceleration terms that, in the rotating framework, can be interpreted as forces. They are the Coriolis force and the centrifugal force. Although the latter is the more palpable of the two, it plays no role in geophysical flows; however, surprising this may be.[1] The former and less intuitive of the two turns out to be a crucial factor in geophysical motions. For a detailed explanation of the Coriolis force, the reader is referred to the following chapter in this book or to the book by Stommel and Moore (1989). A more intuitive explanation and laboratory illustrations can be found in Chapter 6 of Marshall and Plumb (2008).

In anticipation of the following chapters, it can be mentioned here (without explanation) that a major effect of the Coriolis force is to impart a certain vertical rigidity to the fluid. In rapidly rotating, homogeneous fluids, this effect can be so strong that the flow displays strict columnar motions; that is, all particles along the same vertical evolve in concert, thus retaining their vertical alignment over long periods of time. The discovery of this property is attributed to Geoffrey I. Taylor, a British physicist famous for his varied contributions to fluid dynamics. (See the short biography at the end of Chapter 7.) It is said that Taylor first arrived at the rigidity property with mathematical arguments alone. Not believing that this could be correct, he then performed laboratory experiments that revealed, much to his amazement, that the theoretical prediction was indeed correct. Drops of dye released in such rapidly rotating, homogeneous

[1] Here we speak about the centrifugal force associated with the earth's planetary rotation, not to be confused with the centrifugal force associated with the strong rotation of eddies or hurricanes.

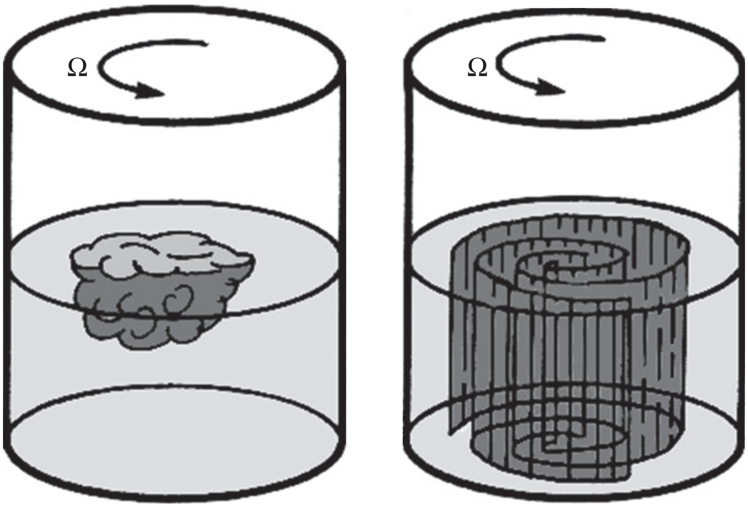

FIGURE 1.3 Experimental evidence of the rigidity of a rapidly rotating, homogeneous fluid. In a spinning vessel filled with clear water, an initially amorphous cloud of aqueous dye is transformed in the course of several rotations into perfectly vertical sheets, known as *Taylor curtains*.

fluids form vertical streaks, which, within a few rotations, shear laterally to form spiral sheets of dyed fluid (Fig. 1.3). The vertical coherence of these sheets is truly fascinating!

In large-scale atmospheric and oceanic flows, such state of perfect vertical rigidity is not realized chiefly because the rotation rate is not sufficiently fast and the density is not sufficiently uniform to mask other, ongoing processes. Nonetheless, motions in the atmosphere, in the oceans, and on other planets manifest a tendency toward columnar behavior. For example, currents in the western North Atlantic have been observed to extend vertically over 4000 m without significant change in amplitude and direction (Schmitz, 1980).

Stratification, the other distinguishing attribute of geophysical fluid dynamics, arises because naturally occurring flows typically involve fluids of different densities (e.g., warm and cold air masses, fresh and saline waters). Here, the gravitational force is of great importance, for it tends to lower the heaviest fluid and to raise the lightest. Under equilibrium conditions, the fluid is stably stratified, consisting of vertically stacked horizontal layers. However, fluid motions disturb this equilibrium, in which gravity systematically strives to restore. Small perturbations generate internal waves, the three-dimensional analogue of surface waves, with which we are all familiar. Large perturbations, especially those maintained over time, may cause mixing and convection. For example, the prevailing winds in our atmosphere are manifestations of the planetary convection driven by the pole-to-equator temperature difference.

It is worth mentioning the perplexing situation in which a boat may experience strong resistance to forward motion while sailing under apparently calm conditions. This phenomenon, called *dead waters* by mariners, was first

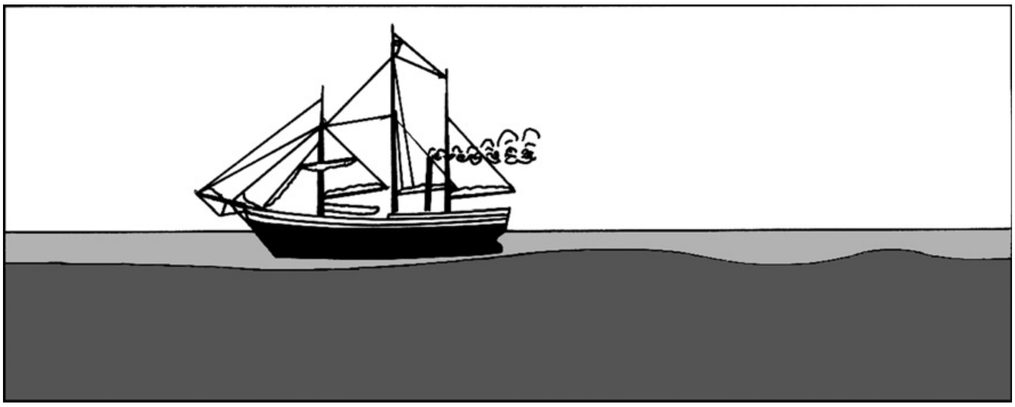

FIGURE 1.4 A laboratory experiment by Ekman (1904) showing internal waves generated by a model ship in a tank filled with two fluids of different densities. The heavier fluid at the bottom has been colored to make the interface visible. The model ship (the superstructure of which was drawn onto the original picture to depict Fridtjof Nansen's *Fram*) is towed from right to left, causing a wake of waves on the interface. The energy consumed by the generation of these waves produces a drag that, for a real ship, would translate into a resistance to forward motion. The absence of any significant surface wave has prompted sailors to call such situations *dead waters*. (*From Ekman, 1904, and adapted by Gill, 1982*)

documented by the Norwegian oceanographer Fridtjof Nansen, famous for his epic expedition on the *Fram* through the Arctic Ocean, begun in 1893. Nansen reported the problem to his Swedish colleague Vagn Walfrid Ekman who, after performing laboratory simulations (Ekman, 1904), affirmed that internal waves were to blame. The scenario is as follows: During times of dead waters, Nansen must have been sailing in a layer of relatively fresh water capping the more saline oceanic waters and of thickness, coincidently, comparable to the ship draft; the ship created a wake of internal waves along the interface (Fig. 1.4), unseen at the surface but radiating considerable energy and causing the noted resistance to the forward motion of the ship.

1.4 SCALES OF MOTIONS

To discern whether a physical process is dynamically important in any particular situation, geophysical fluid dynamicists introduce *scales of motion*. These are dimensional quantities expressing the overall magnitude of the variables under consideration. They are estimates rather than precisely defined quantities and are understood solely as *orders of magnitude* of physical variables. In most situations, the key scales are those for time, length, and velocity. For example, in the dead-water situation investigated by V.W. Ekman (Fig. 1.4), fluid motions comprise a series of waves whose dominant wavelength is about the length of the submerged ship hull; this length is the natural choice for the length scale L of the problem; likewise, the ship speed provides a reference velocity that can be taken as the velocity scale U; finally, the time taken for the ship to travel the distance L at its speed U is the natural choice of time scale: $T = L/U$.

As a second example, consider Hurricane Frances during her course over the southeastern United States in early September 2004 (Fig. 1.1). The satellite picture reveals a nearly circular feature spanning approximately 7.5° of latitude (830 km). Sustained surface wind speeds of a category-4 hurricane such as Frances range from 59 to 69 m/s. In general, hurricane tracks display appreciable change in direction and speed of propagation over 2-day intervals. Altogether, these elements suggest the following choice of scales for a hurricane: $L = 800$ km, $U = 60$ m/s, and $T = 2 \times 10^5$ s (=55.6 h).

As a third example, consider the famous Great Red Spot in Jupiter's atmosphere (Fig. 1.5), which is known to have existed at least several hundred years. The structure is an elliptical vortex centered at 22°S and spanning approximately 12° in latitude and 25° in longitude; its highest wind speeds exceed 110 m/s, and the entire feature slowly drifts zonally at a speed of 3 m/s (Dowling & Ingersoll, 1988; Ingersoll et al., 1979). Knowing that the planet's equatorial radius is 71,400 km, we determine the vortex semi-major and semi-minor axes (14,400 km and 7,500 km, respectively) and deem $L = 10{,}000$ km to be an appropriate length scale. A natural velocity scale for the fluid is $U = 100$ m/s. The selection of a timescale is somewhat problematic in view of the nearly

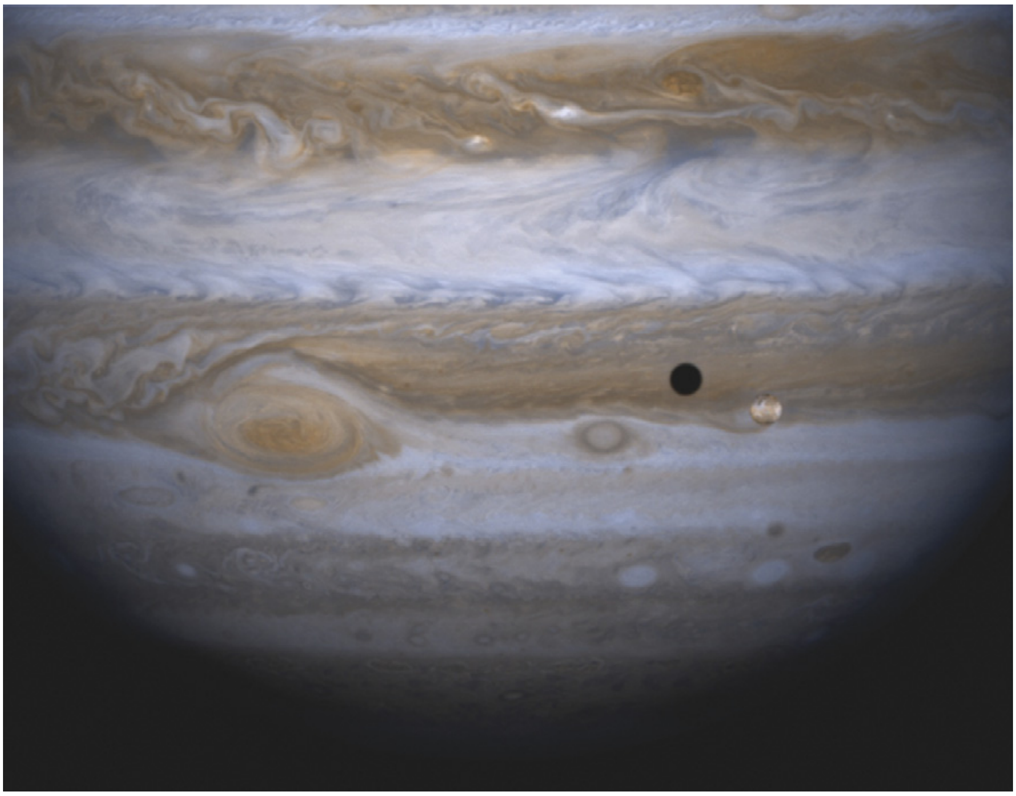

FIGURE 1.5 Southern hemisphere of Jupiter as seen by the spacecraft *Cassini* in 2000. The Jupiter moon Io, of size comparable to our moon, projects its shadow onto the zonal jets between which the Great Red Spot of Jupiter is located (on the left). For further images, visit http://photojournal.jpl.nasa.gov/target/Jupiter. (*Image courtesy of NASA/JPL/University of Arizona*)

steady state of the vortex; one choice is the time taken by a fluid particle to cover the distance L at the speed U ($T = L/U = 10^5$ s), whereas another is the time taken by the vortex to drift zonally over a distance equal to its longitudinal extent ($T = 10^7$ s). Additional information on the physics of the problem is clearly needed before selecting a timescale. Such ambiguity is not uncommon because many natural phenomena vary on different temporal scales (e.g., the terrestrial atmosphere exhibits daily weather variation as well as decadal climatic variations, among others). The selection of a timescale then reflects the particular choice of physical processes being investigated in the system.

There are three additional scales that play important roles in analyzing geophysical fluid problems. As we mentioned earlier, geophysical fluids generally exhibit a certain degree of density heterogeneity, called stratification. The important parameters are then the average density ρ_0, the range of density variations $\Delta\rho$, and the height H over which such density variations occur. In the ocean, the weak compressibility of water under changes of pressure, temperature, and salinity translates into values of $\Delta\rho$ always much less than ρ_0, whereas the compressibility of air renders the selection of $\Delta\rho$ in atmospheric flows somewhat delicate. Because geophysical flows are generally bounded in the vertical direction, the total depth of the fluid may be substituted for the height scale H. Usually, the smaller of the two height scales is selected.

As an example, the density and height scales in the dead-water problem (Fig. 1.4) can be chosen as follows: $\rho_0 = 1025$ kg/m^3, the density of either fluid layer (almost the same); $\Delta\rho = 1$ kg/m^3, the density difference between lower and upper layers (much smaller than ρ_0), and $H = 5$ m, the depth of the upper layer.

As the person new to geophysical fluid dynamics has already realized, the selection of scales for any given problem is more an art than a science. Choices are rather subjective. The trick is to choose quantities that are relevant to the problem, yet simple to establish. There is freedom. Fortunately, small inaccuracies are inconsequential because the scales are meant only to guide in the clarification of the problem, whereas grossly inappropriate scales will usually lead to flagrant contradictions. Practice, which forms intuition, is necessary to build confidence.

1.5 IMPORTANCE OF ROTATION

Naturally, we may wonder at which scales the ambient rotation becomes an important factor in controlling the fluid motions. To answer this question, we must first know the ambient rotation rate, which we denote by Ω and define as

$$\Omega = \frac{2\pi \text{ radians}}{\text{time of one revolution}}. \tag{1.1}$$

Since our planet Earth actually rotates in two ways simultaneously, once per day about itself and once a year around the sun, the terrestrial value of Ω consists of two terms, $2\pi/24$ hours + $2\pi/365.24$ days = $2\pi/1$ sidereal day = 7.2921×10^{-5} s^{-1}. The *sidereal day*, equal to 23 h 56 min and 4.1 s, is the period of time spanning the moment when a fixed (distant) star is seen one day and the moment on the next day when it is seen at the same angle from the same point on Earth. It is slightly shorter than the 24-hour solar day, the time elapsed between the sun reaching its highest point in the sky two consecutive times, because the earth's orbital motion about the sun makes the earth rotate slightly more than one full turn with respect to distant stars before reaching the same Earth–Sun orientation.

If fluid motions evolve on a timescale comparable to or longer than the time of one rotation, we anticipate that the fluid does feel the effect of the ambient rotation. We thus define the dimensionless quantity

$$\omega = \frac{\text{time of one revolution}}{\text{motion timescale}} = \frac{2\pi/\Omega}{T} = \frac{2\pi}{\Omega T}, \tag{1.2}$$

where T is used to denote the timescale of the flow. Our criterion is as follows: If ω is on the order of or less than unity ($\omega \lesssim 1$), rotation effects should be considered. On Earth, this occurs when T exceeds 24 h.

Yet, motions with shorter timescales ($\omega \gtrsim 1$) but sufficiently large spatial extent could also be influenced by rotation. A second and usually more useful criterion results from considering the velocity and length scales of the motion. Let us denote these by U and L, respectively. Naturally, if a particle traveling at the speed U covers the distance L in a time longer than or comparable to a rotation period, we expect the trajectory to be influenced by the ambient rotation, so we write

$$\begin{aligned}\epsilon &= \frac{\text{time of one revolution}}{\text{time taken by particle to cover distance } L \text{ at speed } U} \\ &= \frac{2\pi/\Omega}{L/U} = \frac{2\pi U}{\Omega L}.\end{aligned} \tag{1.3}$$

If ϵ is on the order of or less than unity ($\epsilon \lesssim 1$), we conclude that rotation is important.

Let us now consider a variety of possible length scales, using the value Ω for Earth. The corresponding velocity criteria are listed in Table 1.1.

Obviously, in most engineering applications, such as the flow of water at a speed of 5 m/s in a turbine 1 m in diameter ($\epsilon \sim 4 \times 10^5$) or the air flow past a 5-m wing on an airplane flying at 100 m/s ($\epsilon \sim 2 \times 10^6$), the inequality is not met, and the effects of rotation can be ignored. Likewise, the common task of emptying a bathtub (horizontal scale of 1 m, draining speed in the order of 0.01 m/s and a lapse of about 1000 s, giving $\omega \sim 90$ and $\epsilon \sim 900$) does not fall under the scope of geophysical fluid dynamics. On the contrary, geophysical flows (such as an ocean current flowing at 10 cm/s and meandering over a distance of 10 km or a wind blowing at 10 m/s in a 1000-km-wide anticyclonic formation) do meet the inequality. This demonstrates that rotation is usually important in geophysical flows.

TABLE 1.1 Length and Velocity Scales of Motions in Which Rotation Effects are Important

$L = 1$ m	$U \leq 0.012$ mm/s
$L = 10$ m	$U \leq 0.12$ mm/s
$L = 100$ m	$U \leq 1.2$ mm/s
$L = 1$ km	$U \leq 1.2$ cm/s
$L = 10$ km	$U \leq 12$ cm/s
$L = 100$ km	$U \leq 1.2$ m/s
$L = 1000$ km	$U \leq 12$ m/s
$L =$ Earth radius $= 6371$ km	$U \leq 74$ m/s

1.6 IMPORTANCE OF STRATIFICATION

The next question concerns the condition under which stratification effects are expected to play an important dynamical role. Geophysical fluids typically consist of fluid masses of different densities, which under gravitational action tend to arrange themselves in vertical stacks (Fig. 1.6), corresponding to a state of minimal potential energy. But, motions continuously disturb this equilibrium, tending to raise dense fluid and lower light fluid. The corresponding increase of potential energy is at the expense of kinetic energy, thereby slowing the flow. On occasions, the opposite happens: Previously disturbed stratification returns toward equilibrium, potential energy converts into kinetic energy, and the flow gains momentum. In sum, the dynamical importance of stratification can be evaluated by comparing potential and kinetic energies.

If $\Delta\rho$ is the scale of density variations in the fluid and H is its height scale, a prototypical perturbation to the stratification consists in raising a fluid element of density $\rho_0 + \Delta\rho$ over the height H and, in order to conserve volume, lowering a lighter fluid element of density ρ_0 over the same height. The corresponding change in potential energy, per unit volume, is $(\rho_0+\Delta\rho)\ gH - \rho_0 gH = \Delta\rho gH$. With a typical fluid velocity U, the kinetic energy available per unit volume is $\frac{1}{2}\rho_0 U^2$. Accordingly, we construct the comparative energy ratio

$$\sigma = \frac{\frac{1}{2}\rho_0 U^2}{\Delta\rho g H}, \tag{1.4}$$

to which we can give the following interpretation. If σ is on the order of unity ($\sigma \sim 1$), a typical potential-energy increase necessary to perturb the stratification consumes a sizable portion of the available kinetic energy, thereby modifying the flow field substantially. Stratification is then important. If σ is much less

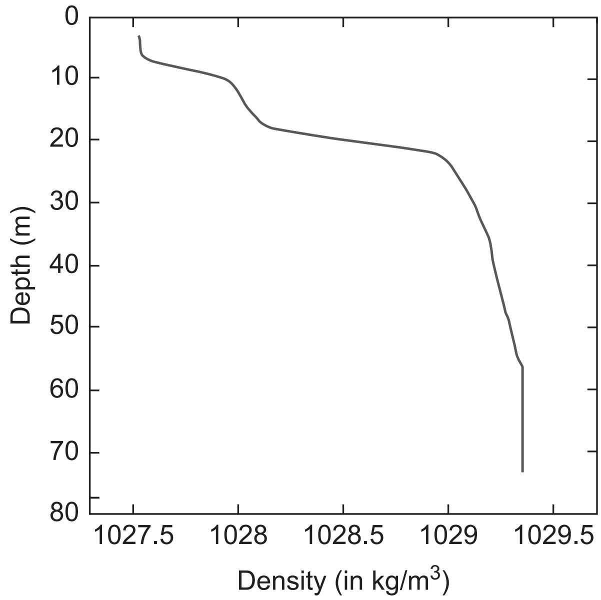

FIGURE 1.6 Vertical profile of density in the northern Adriatic Sea (43°32′N, 14°03′E) on 27 May 2003. Density increases downward by leaps and bounds, revealing the presence of different water masses stacked on top of one another in such a way that lighter waters float above denser waters. A region where the density increases significantly faster than above and below, marking the transition from one water mass to the next, is called a *pycnocline*. (*Data courtesy of Drs. Hartmut Peters and Mirko Orlić*)

than unity ($\sigma \ll 1$), there is insufficient kinetic energy to perturb significantly the stratification, and the latter greatly constrains the flow. Finally, if σ is much greater than unity ($\sigma \gg 1$), potential-energy modifications occur at very little cost to the kinetic energy, and stratification hardly affects the flow. In conclusion, stratification effects cannot be ignored in the first two cases—that is, when the dimensionless ratio defined in Eq. (1.4) is on the order of or much less than unity ($\sigma \lesssim 1$). In other words, σ is to stratification what the number ϵ, defined in Eq. (1.3), is to rotation.

A most interesting situation arises in geophysical fluids when rotation and stratification effects are simultaneously important, yet neither dominates over the other. Mathematically, this occurs when $\epsilon \sim 1$ and $\sigma \sim 1$ and yields the following relations among the various scales:

$$L \sim \frac{U}{\Omega} \quad \text{and} \quad U \sim \sqrt{\frac{\Delta\rho}{\rho_0} gH}. \tag{1.5}$$

(The factors 2π and $\frac{1}{2}$ have been omitted because they are secondary in a scale analysis.) Elimination of the velocity U yields a fundamental length scale:

$$L \sim \frac{1}{\Omega} \sqrt{\frac{\Delta\rho}{\rho_0} gH}. \tag{1.6}$$

In a given fluid, of mean density ρ_0 and density variation $\Delta\rho$, occupying a height H on a planet rotating at rate Ω and exerting a gravitational acceleration g, the scale L arises as a preferential length over which motions take place. On Earth ($\Omega = 7.29 \times 10^{-5}$ s^{-1} and $g = 9.81$ m/s^2), typical conditions in the atmosphere ($\rho_0 = 1.2$ kg/m^3, $\Delta\rho = 0.03$ kg/m^3, $H = 5000$ m) and in the ocean ($\rho_0 = 1028$ kg/m^3, $\Delta\rho = 2$ kg/m^3, $H = 1000$ m) yield the following natural length and velocity scales:

$$\begin{array}{llll} L_{\text{atmosphere}} \sim 500 \text{ km} & U_{\text{atmosphere}} \sim 30 \text{ m/s} \\ L_{\text{ocean}} \quad\sim 60 \text{ km} & U_{\text{ocean}} \quad\sim 4 \text{ m/s.} \end{array}$$

Although these estimates are relatively crude, we can easily recognize here the typical size and wind speed of weather patterns in the lower atmosphere and the typical width and speed of major currents in the upper ocean.

1.7 DISTINCTION BETWEEN THE ATMOSPHERE AND OCEANS

Generally, motions of the air in our atmosphere and of seawater in the oceans that fall under the scope of geophysical fluid dynamics occur on scales of several kilometers up to the size of the earth. Atmospheric phenomena comprise the coastal sea breeze, local to regional processes associated with topography, the cyclones, anticyclones, and fronts that form our daily weather, the general atmospheric circulation, and the climatic variations. Oceanic phenomena of interest include estuarine flow, coastal upwelling and other processes associated with the presence of a coast, large eddies and fronts, major ocean currents such as the Gulf Stream, and the large-scale circulation. Table 1.2 lists the typical velocity, length and time scales of these motions, whereas Fig. 1.7 ranks a sample of atmospheric and oceanic processes according to their spatial and temporal scales. As we can readily see, the general rule is that oceanic motions are slower and slightly more confined than their atmospheric counterparts. Also, the ocean tends to evolve more slowly than the atmosphere.

Besides notable scale disparities, the atmosphere and oceans also have their own peculiarities. For example, a number of oceanic processes are caused by the presence of lateral boundaries (continents, islands), a constraint practically nonexistent in the atmosphere, except in stratified flows where mountain ridges can sometimes play such a role, exactly as do mid-ocean ridges for stratified ocean currents. On the other hand, atmospheric motions are sometimes strongly dependent on the moisture content of the air (clouds, precipitation), a characteristic without oceanic counterpart.

Flow patterns in the atmosphere and oceans are generated by vastly different mechanisms. By and large, the atmosphere is thermodynamically driven, that is, its primary source of energy is the solar radiation. Briefly, this shortwave solar

TABLE 1.2 Length, Velocity and Time Scales in the Earth's Atmosphere and Oceans

Phenomenon	Length Scale L	Velocity Scale U	Timescale T
Atmosphere			
Microturbulence	10–100 cm	5–50 cm/s	few seconds
Thunderstorms	few km	1–10 m/s	few hours
Sea breeze	5–50 km	1–10 m/s	6 h
Tornado	10–500 m	30–100 m/s	10–60 min
Hurricane	300–500 km	30–60 m/s	Days to weeks
Mountain waves	10–100 km	1–20 m/s	Days
Weather patterns	100–5000 km	1–50 m/s	Days to weeks
Prevailing winds	Global	5–50 m/s	Seasons to years
Climatic variations	Global	1–50 m/s	Decades and beyond
Ocean			
Microturbulence	1–100 cm	1–10 cm/s	10–100 s
Internal waves	1–20 km	0.05–0.5 m/s	Minutes to hours
Tides	Basin scale	1–100 m/s	Hours
Coastal upwelling	1–10 km	0.1–1 m/s	Several days
Fronts	1–20 km	0.5–5 m/s	Few days
Eddies	5–100 km	0.1–1 m/s	Days to weeks
Major currents	50–500 km	0.5–2 m/s	Weeks to seasons
Large-scale gyres	Basin scale	0.01–0.1 m/s	Decades and beyond

radiation traverses the air layer to be partially absorbed by the continents and oceans, which in turn re-emit a radiation at longer wavelengths. This second-hand radiation effectively heats the atmosphere from below, and the resulting convection drives the winds.

In contrast, the oceans are forced by a variety of mechanisms. In addition to the periodic gravitational forces of the moon and sun that generate the tides, the ocean surface is subjected to a wind stress that drives most ocean currents. Finally, local differences between air and sea temperatures generate heat fluxes,

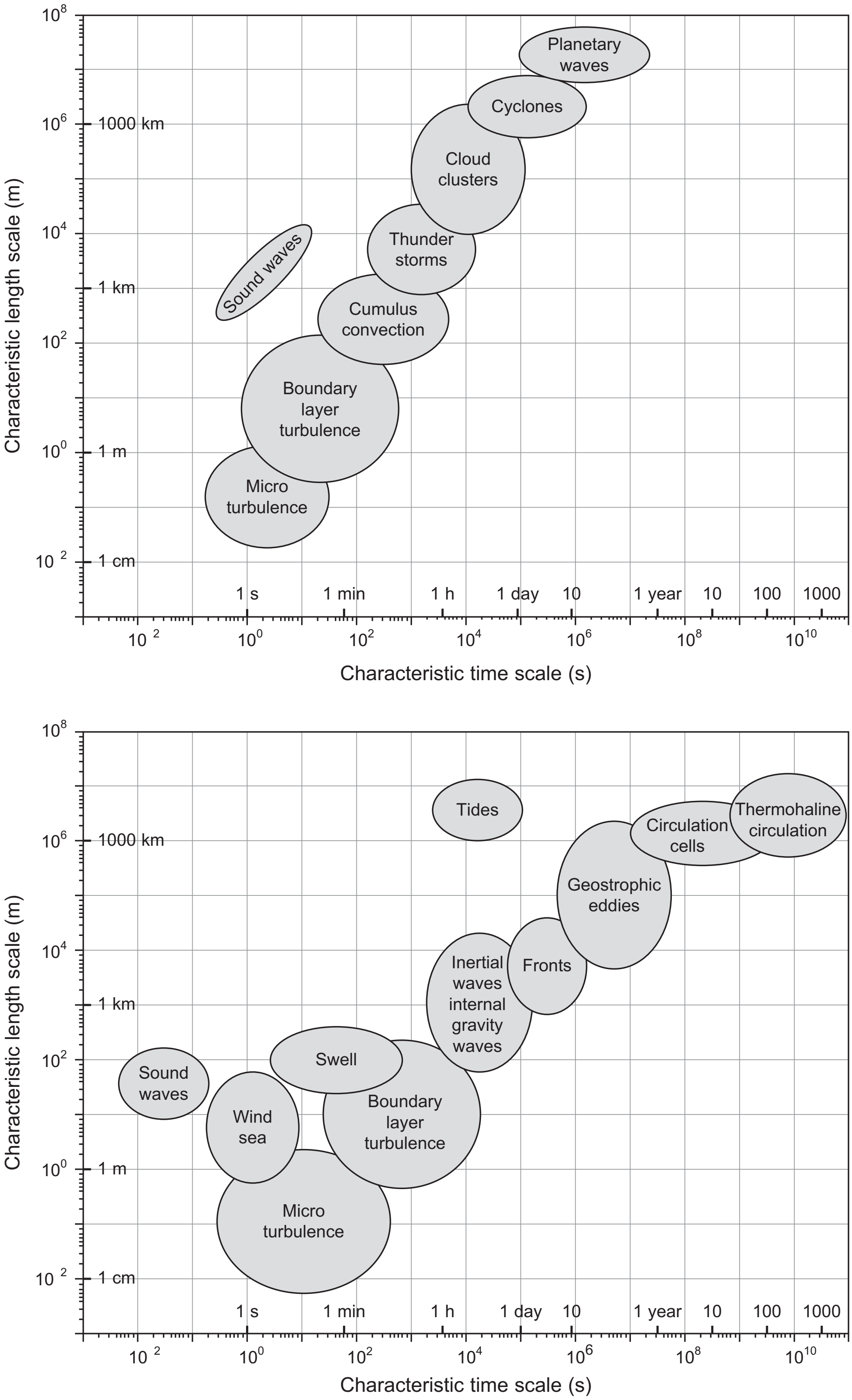

FIGURE 1.7 Various types of processes and structures in the atmosphere (top panel) and oceans (bottom panel), ranked according to their respective length and time scales. (*Diagram courtesy of Hans von Storch*)

evaporation, and precipitation, which in turn act as thermodynamical forcings capable of modifying the wind-driven currents or producing additional currents.

In passing, while we are contrasting the atmosphere with the oceans, it is appropriate to mention an enduring difference in terminology. Because meteorologists and laypeople alike are generally interested in knowing from where the winds are blowing, it is common in meteorology to refer to air velocities by their direction of origin, such as easterly (from the east—that is, toward the west). On the contrary, sailors and navigators are interested in knowing where ocean currents may take them. Hence, oceanographers designate currents by their downstream direction, such as westward (from the east or to the west). However, meteorologists and oceanographers agree on the terminology for vertical motions: upward or downward.

1.8 DATA ACQUISITION

Because geophysical fluid dynamics deals exclusively with naturally occurring flows and, moreover, those of rather sizable proportions, full-scale experimentation must be ruled out. Indeed, how could one conceive of changing the weather, even locally, for the sake of a scientific inquiry? Also, the Gulf Stream determines its own fancy path, irrespective of what oceanographers wish to study about it. In that respect, the situation is somewhat analogous to that of the economist who may not ask the government to prompt a disastrous recession for the sake of determining some parameters of the national economy. The inability to control the system under study is greatly alleviated by simulations. In geophysical fluid dynamics, these investigations are conducted via laboratory experiments and numerical models.

As well as being reduced to noting the whims of nature, observers of geophysical flows also face length and timescales that can be impractically large. A typical challenge is the survey of an oceanic feature several hundred kilometers wide. With a single ship (which is already quite expensive, especially if the feature is far away from the home shore), a typical survey can take several weeks, a time interval during which the feature might translate, distort, or otherwise evolve substantially. A faster survey might not reveal details with a sufficiently fine horizontal representation. Advances in satellite imagery and other methods of remote sensing (Conway & the Maryland Space Grant Consortium, 1997; Marzano & Visconti, 2002) do provide synoptic (i.e., quasi-instantaneous) fields, but those are usually restricted to specific levels in the vertical (e.g., cloud tops and ocean surface) or provide vertically integrated quantities. Also, some quantities simply defy measurement, such as the heat flux and vorticity. Those quantities can only be derived by an analysis on sets of proxy observations.

Finally, there are processes for which the timescale is well beyond the span of human life if not the age of civilization. For example, climate studies require a certain understanding of glaciation cycles. Our only recourse here is to be clever and to identify today some traces of past glaciation events, such as geological