The Challenge of Weather Prediction

1. The Basic Driving

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This three part series brings into focus problems and challenges involved in weather forecasting. The first part deals with the fundamental forces governing weather and climate while the second part deals with the practical and conceptual difficulties. The last part describes old and new ways of weather forecasting.

Happy with the forecast from the meteorological department for a sunny day, you decided to take your family to the beach only to be drenched by a heavy afternoon thundershower! Such experiences have made weather forecasters a favourite subject matter for the cartoonist. But have we ever asked, why do the meteorologists go wrong? Is it because the meteorologists are incompetent or is it that the weather is intrinsically difficult to predict? Certain systems governed by physical laws can be predicted with precision well in advance, for example, the precise occurrence of the ocean tides or the positions of the planets around the sun. If weather is also governed by physical laws, why then is it so difficult to predict?

In this article, I want to enlighten you on certain common myths about weather forecasting and illustrate the inherent complexity of the problem. I will discuss what can be predicted and what cannot. I will also describe how weather forecasting evolved from an empirical science in the pre-second world war days to a quantitative analytical science in recent years.

The Basic Driving

To appreciate why it is so difficult to predict the weather, let us start by understanding what causes weather. The atmosphere is a gaseous (fluid) envelope around the earth. The weather is nothing but the day to day fluctuations of the atmospheric state. These fluctuations are due to the movement of air in the gaseous envelope. What causes the air to move?

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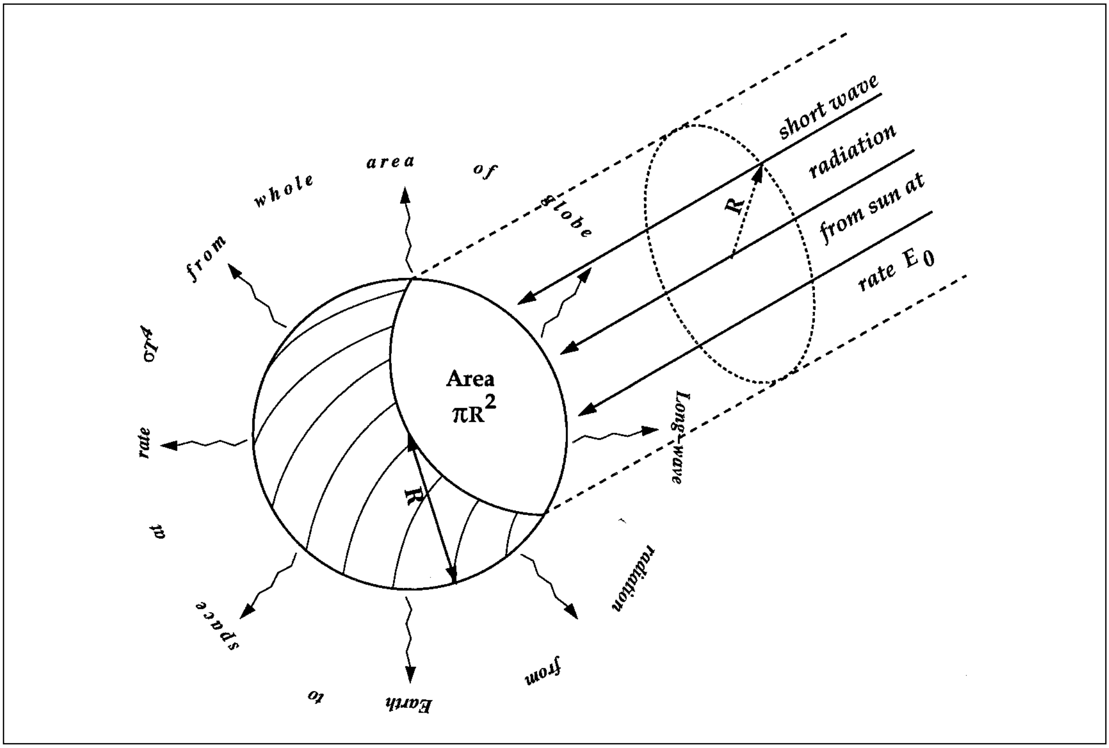
The air moves because it is under the action of a number of forces. The primary force acting on the atmosphere is solar heating which is an external force. As we know, hot bodies radiate according to Planck's law (higher the temperature of the black body, shorter the mean wavelength at which it radiates). As a result of the very high mean temperature of the sun, the solar electromagnetic radiation has maximum energy at the visible wavelengths. The gases in the atmosphere (mainly nitrogen, oxygen, water vapour, and carbon dioxide) cannot absorb much of this radiation. Part of it gets reflected from the clouds and the surface of the earth and the rest is absorbed by the solid earth. This heat raises the temperature of the earth's surface and it radiates as a black body. At the temperature of the earth-atmosphere system, the radiation emitted from the earth is concentrated in the infrared range. Measurements on earth indicate that the rate at which solar energy impinges on an area perpendicular to the sun's rays at the mean earth-sun distance is about 2.0 cal/cm^2/min or 1390 Watts/m^2. Let us call this the solar constant, S. Now, we can estimate the annual and global average equilibrium temperature of the earth (T_e) as a balance between incoming solar radiation and outgoing terrestrial (or emitted from the earth) radiation as shown in *Figure 1*.

The mean radiative equilibrium temperature of the earth can be estimated as a balance between incoming shortwave solar radiation and outgoing longwave radiation emitted by the earth.

The solar rays only intercept a disc of area πR^2 (where R is the mean radius of the earth) at any time. But the earth radiates in all directions with an area of $4\pi R^2$. A fraction α (called *albedo*) of the incident solar radiation is reflected back into space. This is found to be about 30% or 0.30. If the emissivity of the earth is ε and assuming that the atmosphere is also transparent to the longwave radiation, the balance demands that

$$4\pi R^2 \varepsilon\sigma T_e^4 = (1-\alpha)\pi R^2 S, \qquad (1)$$

Figure 1 Calculation of planetary temperature.



where α is the Stefan-Boltzmann constant(=5.6703×10^{-8} Wm^{-2} K^{-4}). Assuming that the earth is a perfect black body ($\varepsilon = 1$), the mean equilibrium temperature of the earth would be T_e =256°K (or –17°C). If this were the case, the whole earth would be ice covered and devoid of any life form! However, much to our delight the observed global average temperature is close to a comfortable 288°K (or 15°C). This is due to the *greenhouse effect* of the atmospheric gases. Some of the molecules of the atmosphere such as water vapour (H_2O) and carbon dioxide (CO_2) have natural oscillations with frequencies corresponding to the frequencies of the infrared waves emitted by the earth. When the electromagnetic waves (EM) fall on these molecules, they produce resonant excitation of these natural oscillations. In the process the EM waves lose energy. Thus, these gases are effective in absorbing the emitted infrared radiation. When the air absorbs such energy, it gets heated and radiates some energy back to earth and some to the outer space. Taking this into account, the infrared transmissivity Γ of the atmosphere is less than unity (in equation (1) Γ is 1). From the amount of H_2O and CO_2 in the atmosphere, it may be estimated that the infrared transmissivity of the atmosphere is $\Gamma \approx 0.62$. Therefore, the average surface temperature of the earth T_s may be estimated from the modified form of equation (1) as

$$4\pi R^2 \varepsilon \Gamma \sigma T_s^4 = \pi R^2 (1-\alpha) S, \tag{2}$$

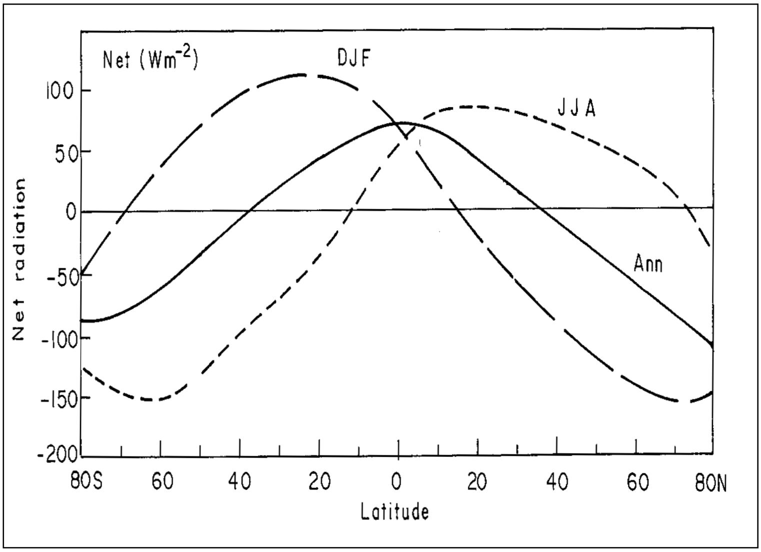
with $\varepsilon = 1$ and $\Gamma = 0.62$, $\alpha = 0.3$, the surface temperature is found to be $T_s \approx 288°K$.

The earth's atmosphere is unique as it has just the right amount of greenhouse gas such as CO_2 and H_2O without which the equilibrium temperature would have been an inhospitable –17°C.

We note from equation (2) that there are two factors that can change the global average annual mean surface temperature T_s, the external solar forcing (S) and the infrared transmissivity (Γ) of the atmosphere. It is known that the incident solar energy changes slowly with periodicities of 22,000 years, 41,000 years and 100,000 years. These are due to changes in the earth's orbital parameters such as the eccentricity of the orbit (100,000 years), axial precession (22,000 years) and change in the obliquity of the ecliptic or the axial tilt (41,000 years). In fact paleoclimatic reconstruction shows fluctuations in the earth's temperature with such periodicities. Thus, if the constituents of the atmosphere never change (Γ constant), the prediction of the earth's long-term mean temperature would be easy (just like the tides)! However, the concentration of some of the constituent gases such as CO_2 is increasing in the atmosphere mostly due to human activity. As a result Γ is becoming smaller. From equation (2), it is clear that as Γ becomes smaller, the equilibrium surface temperature increases. This is the basis for the green house gas induced global warming. In fact, observed global mean temperature has shown an increase of a little over half a degree Celsius over the past hundred years.

If temperature was uniform everywhere on the earth, there would not be any motion. Although globally averaged temperature is a gross measure of the earth's climate, due to the

Figure 2 Net radiation (incoming shortwave-outgoing longwave) at the top of the atmosphere at different latitudes averaged over each latitude circle in the east-west direction. Annual mean and seasonal averages for June-July-August (JJA) and December-January-February (DJF) are shown. No corrections are made for global radiation balance.



geometry of the earth and its orbital revolution around the sun, the net radiation received at the top of the atmosphere is positive near the equator while it is negative near the poles (*Figure 2*) and varies with the season. This net radiative forcing is the result of a complex interaction of the incident solar radiation and the emitted longwave radiation with the atmosphere. *Figure 3* shows the processes involved in the shortwave radiation budget while *Figure 4* shows those associated with the longwave radiation budget. Each of these processes involves quite complex interactions between radiation and particles of different shapes and sizes in the atmosphere. For example, absorption of incident solar radiation by the atmosphere and clouds depends on the distribution of different gases and aerosols and droplet sizes in the cloud. Similarly reflection from the cloud also depends on the cloud characteristics. The reflection from the earth's surface depends on soil characteristics, distribution of vegetation, snow accumulation etc. Calculation of the longwave radiation budget is even more complex. For example, the absorption of longwave radiation by H_2O and CO_2 does not occur at one wavelength, but over a band of wavelengths. Therefore, one has to estimate how much is absorbed in all the wavelengths in the band and then sum them up. This is an involved process. In addition, a certain amount of energy is

Nonuniform radiative forcing (heating in the tropics and cooling in the polar regions) is the primary cause of atmospheric motions. Actual trajectory of an air parcel is determined by the balance between a number of forces such as the Coriolis force, the pressure gradient force, the gravitational force and the frictional force.

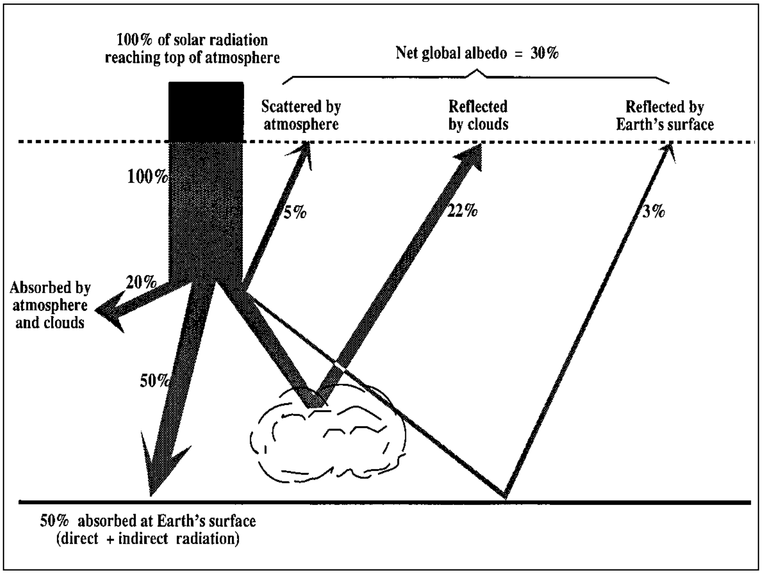
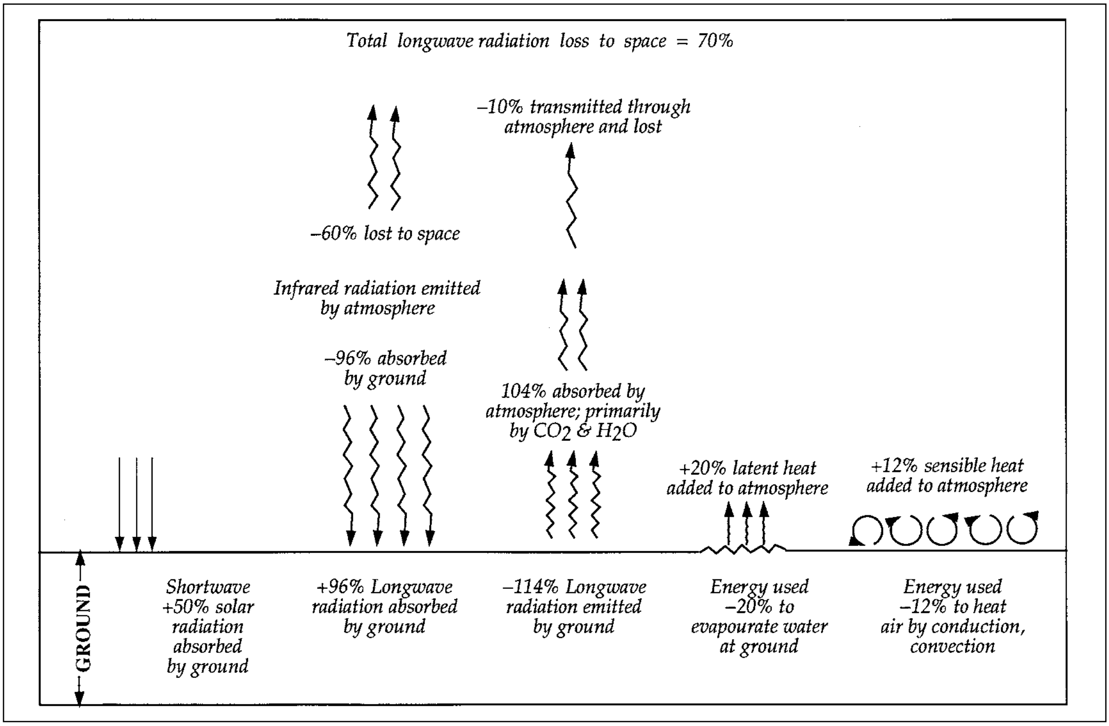


Figure 3 Incoming solar radiation budget of the earth and the atmosphere.

exchanged between the atmosphere and the underlying surface. This exchange takes place through transport by conduction and convection in the atmosphere. However, as we shall explain shortly, it is not molecular diffusion but turbulent diffusion that achieves this. This exchange can be divided into two parts. One part is termed as *latent heat flux* while the other is called *sensible heat flux*. The word latent refers to energy stored in molecules that is released (or taken) when phase change takes place. For example, wind blowing against the surface of a wet land or the ocean, produces evaporation. During evaporation liquid water changes to water vapour. The land or the ocean loses the latent energy required for this change of state. The heat energy lost by the surface is gained by the atmosphere when the water vapour condenses back to water during the formation of clouds. The sensible heat flux refers to the exchange that takes place through conduction and convection when the atmosphere literally 'senses' the surface.

This nonuniform radiative forcing is the primary reason for motion in the atmosphere. Air in the hotter tropics becomes lighter and rises while the colder air in the polar region sinks and tries to flow to the tropics to replace the depleted air, thereby

Figure 4 Outgoing longwave radiation budget of the earth and the atmosphere.



setting up a huge convection cell. Once the air is set into motion, it is affected by several other forces. They are:

- *Coriolis Force*: This force arises due to the rotation of the earth. Consider an air parcel moving towards the equator from the north pole. As the earth moves from the west to east and as the air is not rigidly attached to the surface, it will be deflected to its right. As a result, to an observer sitting on the surface of the earth it would appear to be blowing from northeast to southwest rather than from north to south.

- *Pressure Gradient Force*: This force arises if the pressure at two points are different. Then fluid at high pressure tends to move to low pressure. When the tropics get heated, the air becomes light and pressure becomes low while the high latitude has a high pressure due to cold heavy air. So air would move from high latitude to low latitude.

• *Gravitational Force*: The air is also being continuously pulled by the gravitational force of the earth. This force acts vertically downward. One may ask, if the gravitational force is pulling the air all the time towards the centre of the earth, why then does all the air not accumulate near the surface? This is because, the gravitational force directed vertically downwards is normally balanced by a vertical pressure gradient force directed vertically upwards. We know that the air density decreases from the surface upwards. This sets up a pressure gradient force directed upwards from the surface. So, if the gravitational force were not there, the air from high pressure near the surface would tend to flow upwards towards the low pressure region. The gravitational force balances this tendency of the air and keeps the atmosphere in place. This balance may not hold always as in the case of a thunderstorm. Any imbalance between these two forces results in vertical motion.

Due to turbulent eddies dissipation of atmospheric motion near the earth's surface takes place a million times faster than molecular diffusion.

• *Frictional Forces*: In addition to the above forces that tend to produce acceleration, there are forces that retard the motion. These are the frictional forces primarily active near the surface of the earth. The frictional forces essentially result in dissipation of energy. For a *laminar* flow above a rigid surface, this occurs through molecular diffusion. The molecules immediately in contact with the rigid surface will be slowed down. Then molecules just above them will be slowed down as they are in contact with these layers. This way, the solid surface would try to retard the flow up to a certain height. The rate at which the molecular diffusion slows down a flow is well known from laboratory experiments. Studies indicate that dissipation of energy and transfer of momentum near the earth's surface take place about a million times faster than molecular diffusion! How does this happen? This is because the typical atmospheric flow near the earth's surface is not *laminar* but *turbulent*. Such flow generates myriads of small scale (horizontal scale of the order of one meter) eddies. These eddies behave like big molecules and produce small scale vertical circulations that mix the air near the surface with the air above much more effectively than the individual air molecules. Therefore, in order to study how the exchange of momentum as well as heat takes place between the atmosphere and the surface below, we have to deal with the turbulent eddies!

Seven Equations and Seven Unknowns

Thus the evolution of the atmosphere from a given state to some future state is determined by certain laws of physics. For most, but not all, meteorological problems the relevant laws of physics can be expressed in terms of seven equations which govern the behaviour of seven variables (*Table 1*).

Table 1

Variables	Equations
1. Pressure (P)	Gas law or equation of state. Relates temperature, pressure and density, $P = \rho RT$.
2. Temperature (T)	First law of thermodynamics. Relates temperature changes to external heating or cooling, eddy diffusion and changes in pressure, external heating or cooling due to radiative balance and latent heat released during cloud formation.
3. Density (ρ)	Continuity equation for air; expresses conservation of mass of air.
4. Water vapour (q)	Continuity equation for water vapour; expresses rate of change of water vapour in terms of source (evaporation) and sink (precipitation) and diffusion due to turbulent eddies.
5. West to East component of wind (u) 6. South to North component of wind (v) 7. Vertical component of wind (w)	Newton's second law (force = mass × acceleration) applied to west-east, south-north and vertical direction separately. The pressure gradient force, the Coriolis force, gravitational force and frictional force are taken into account.

Suggested Reading

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