# WIND INDUCED PRESSURES

## Introduction

Both observation and experiment have shown that the atmospheric pressures experienced by surfaces exposed to the wind are different from the pressures on those same surfaces when the air is still but at the same density and temperature. Windward surfaces tend to have higher pressures, while leeward surfaces and surfaces parallel to the wind tend to have lower pressures.

This paper is an attempt to describe and explain wind-induced pressure changes using statistical mechanics and kinetic gas theory.

## Pressures in the Free Atmosphere

In this paper (as in most of the papers in this collection), we do not treat air pressure as an intrinsic property of the mixture of gases that make up our atmosphere. Instead, we consider it to be generally a function of both scale of place and scale of time, and specifically a function of the relationship between the air molecules and the sensor.

In dealing with parcels of air, atmospheric scientists are accustomed to the fact that the pressures sensed in one part of the parcel will be different from those sensed in a different location. Moreover, we normally expect that these same pressures will change significantly with time as the parcel moves across the landscape. That is why our symbol for pressure ( $\bar{p}_i$ ) has a bar over it. This bar denotes that the term is the mean of several values, and not a single individual value. The $i$ subscript denotes that pressure is a parameter of the interactive sub-population of molecules. The parameter only exists when the molecules of the atmosphere interact with an object of interest.

We also recognize that the pressure sensed by a sensor will have one value when both the air and the sensor are still, other values (depending upon wind direction and velocity relative to the sensor) when the wind is blowing, a third set of pressure values when the sensor is moving in still air, and a fourth set of values when both the sensor is moving and the wind is blowing.

No. Atmospheric pressures are not simple things.

Consequently, the reader is strongly urged to be familiar with the concepts and equations in both *The Nature of Atmospheric Pressures* and in *The Nature of Wind*. Without that familiarity, most of what follows will make little sense.

With that caution in mind, let us proceed to recapitulate the contents of those two papers.

## The Nature of Atmospheric Pressures

As we saw in *The Nature of Atmospheric Pressures*, the atmospheric pressure on any surface is the product of the mean number of molecules striking that surface in unit time (the mean molecular flux) and the mean impulse that these impacts transfer to that surface. This is illustrated by the ***Universal Pressure Equation***:

$$\bar{p}_i = \bar{f}_i \bar{\varphi}_i \qquad \text{WIP01}$$

Here, $\bar{p}_i$ is the mean pressure per square meter in Pascals, $\bar{f}_i$ is the mean molecular flux in number of molecular impacts per square meter per second, and $\bar{\varphi}_i$ is the mean molecular impulse per impact in newtons.

Being essentially a definition, this universal pressure equation is valid for ideal gases and for real gases, under conditions of equilibrium and under conditions of non-equilibrium, in the laboratory and in the free atmosphere, for still air and for moving air. It is even valid for moving objects in moving air.

**Limitations of the One-Dimensional Notation System** – Our current notational system is a *one-dimensional notation system* with ***p*** and ***i*** subscripts to denote **molecular** directions of movement and speeds relative to the object of interest. We need a second notation system to denote **wind** direction and speed relative to our object of interest, which in this paper will be the sensing surface of an imaginary sensor.

To do this, we will postulate a standard tri-axial orthogonal reference system; that is, an ***x***-axis, a ***y***-axis and a ***z***-axis—with all three axes at right angles to one another. This system does not replace our ***p***-axis, it supplements it. Winds are three-dimensional phenomena, therefore we need a three-dimensional notation system to describe them. This same notational system is used in other papers in this collection that also refer to winds.

**Wind System Parameters** – In our discussion of winds, we will make use of the following parameters. Unless these terms bear a directional superscript or subscript as defined below, they are solely scalar terms. When they do bear such a superscript or subscript, the parent terms are the scalar component of a vector expression.

$\bar{\varpi}$ Mean wind speed along the wind axis in meters per second.

$a$ Error function of the mean wind speed expressed in standard deviations: $a = erf(\bar{\varpi} / \sigma)$. Note that $a + b = 0.5$.

$b$ Complimentary error function of the mean wind speed expressed in standard deviations: $b = erfc(\bar{\varpi} / \sigma)$. Note that $a + b = 0.5$.

$\alpha$ Angle of incidence of the wind vector to the sensing surface in degrees. When the wind is normal to and toward that surface, $\alpha$ is +90°. When the wind is parallel to that surface, $\alpha$ is 0°. When the wind is normal to and away from that surface, $\alpha$ is -90°. Intermediate angles of incidence will have intermediate values of $\alpha$. These values will range from +90° through 0° to -90°.

$\bar{T}_i$ Mean temperature sensed by the sensing surface, in Kelvins.

| | |
|---|---|
| $\bar{p}_i$ | Mean pressure in Pascals, measured normal to the sensor. |
| $\bar{n}$ | Mean molecular number density in number of molecules per cubic meter. |
| $\bar{m}_i$ | Mean molecular impulse mass in kilograms. This is not the same as the mean molecular mass of the population of molecules. See *Molecular Masses* for the difference. |
| $\bar{u}_p$ | Mean component molecular kinetic energy of translation in joules, measured normal to and toward the sensor along a single axial arm. |
| $\Sigma u_p$ | The sum of those molecular kinetic energies of translation in joules for a particular axial arm—in this case, the $p$ arm. |
| $\bar{v}$ | Mean molecular speed in meters per second. Subscripts will indicate whether the term refers to the general population ($p$) or the interactive sub-population ($i$). |
| $k_B$ | Boltzmann's Constant in joules per molecule per Kelvin. |
| $\bar{f}_i$ | Mean molecular flux in number of molecules per square meter per second, measured normal to and toward the sensor. |
| $\bar{\varphi}_i$ | Mean molecular impulse per impact in joules, measured normal to and toward the sensor. |
| $\sigma$ | *Sigma*. This is the axial root-mean-square molecular speed in meters per second in still air at temperature $\bar{T}$ and mean molecular impulse mass $\bar{m}_i$. As such, it is also the standard deviation ($\sigma$) of the axial molecular speed distribution in still air. As a speed and not a velocity, it is a scalar term, possessing only magnitude. |

**Superscripts and subscripts: The following terms may be used as either subscripts or as superscripts, depending upon which position is available.**

$\boldsymbol{p}$ Denotes membership in that portion of the general population of molecules that has a component of movement normal to and toward the object of interest.

$-\boldsymbol{p}$ Denotes membership in that portion of the general population of molecules that has a component of movement normal to and away from the object of interest.

$\boldsymbol{i}$ Denotes membership in that portion of the interactive sub-population of molecules whose next or current interaction is with the object of interest.

$\rightarrow$ Denotes that the molecules designated by the parent expression have a component of motion in the windward direction.

$\leftarrow$ Denotes that the molecules designated by the parent expression have a component of motion in the leeward direction.

$\downarrow$ Denotes that the molecules designated by the parent expression have a component of motion normal to and toward the wind axis.

## The Nature of Wind

We were able to capture pressure with a single equation, WIP01. Wind is a far more elusive quarry. From the standpoint of kinetic gas theory and statistical mechanics, we do not, as yet, have a single equation that captures both the wind direction and its force or magnitude. The Nature of Wind gives us several such equations, depending upon the angle of incidence.

Nevertheless, let us continue our discussion of wind induced pressures by defining once more just exactly what we mean by wind:

**When a wind is blowing, a stationary reference system will measure more wind molecules with a component of movement in the windward**

**direction than molecules having a component of movement in any other direction. In addition, this system will measure the windward molecules as moving with a higher mean speed than the mean molecular component speed in any other direction.**

**A reference system moving with the wind will measure the same molecular parameters as it would in still air at the same temperature, pressure, and molecular number density. The terms and expressions in the equation of state:**

$$\bar{p}_i = \bar{n}\mathrm{k_B}\bar{T} = \bar{n}\bar{m}_i\sigma^2 \qquad \text{WIP02}$$

**have exactly the same numerical values in both still air and when the wind is blowing—as long as the sensors are moving with the wind.**

**As we will see below, the numerical values of these parameters (except for $\mathrm{k_B}$ and $\bar{m}_i$) will change significantly when measured relative to a stationary reference system when the wind blows.**

## Variability of Pressures when the Wind Blows

Both observation and experiment have shown that pressure sensors in moving air change their readings in response to changes in both wind velocity and in the angle of incidence that the wind makes with the sensing surface.

Consequently, we will examine this variability on a windward sensing surface, a leeward sensing surface, and a sensing surface that is parallel to the wind direction. From these results, we may calculate the expected values on sensing surfaces at intermediate angles of incidence.

## Pressure Variability on a Windward Surface

Let us postulate a wind blowing through an imaginary frame of reference. Table 4 in *The Nature of Winds* gives us the following increment to the static pressure upon a windward sensor:

$$\Delta\bar{p}_i = \bar{n}\bar{m}_i\bar{\omega}^2 + a\bar{n}\bar{m}_i\bar{\omega}^2 \qquad \text{WIP03}$$

This results in a total dynamic pressure on the windward surface of:

$$\bar{p}_i^{\rightarrow} = \bar{p}_i + \left(\bar{n}\bar{m}_i\bar{\omega}^2 + a\bar{n}\bar{m}_i\bar{\omega}^2\right) \qquad \text{WIP04}$$

## Pressure Variability on a Leeward Surface

Table 5 in *The Nature of Winds* gives us the following decrement to the static pressure upon a leeward sensor:

$$\Delta\bar{p}_l = -2b\bar{n}\bar{m}_i\bar{\omega}^2 \qquad \text{WIP05}$$

This results in a total dynamic pressure on the leeward surface of:

$$\bar{p}_i^{\leftarrow} = \bar{p}_i - 2b\bar{n}\bar{m}_i\bar{\omega}^2 \qquad \text{WIP06}$$

**WARNING**: These leeward pressures should be viewed strictly as limiting cases. In the free atmosphere, surfaces to the leeward of obstructions to the wind will virtually always be subject to turbulence of one sort or another. Consequently, both spatial and temporal variations in leeward pressures having significant magnitude are the rule.

## Pressure Variability on a Parallel Surface

Table 6 in *The Nature of Winds* gives us the following decrement to the static pressure upon a sensor that is parallel to the wind axis:

$$\Delta\bar{p}_i = -a\bar{n}\bar{m}_i\bar{\omega}^2 \qquad \text{WIP07}$$

This results in a total dynamic pressure on the parallel surface of:

$$\bar{p}_i^{\downarrow} = \bar{p}_i - a\bar{n}\bar{m}_i\bar{\omega}^2 \qquad \text{WIP08}$$

## Pressure Variability on Intermediate Surfaces

*The Nature of Winds* gives us the procedure for calculating the resulting incident pressures when the angle of incidence of the wind lies somewhere between normal to and toward the sensor and parallel to the sensor. That procedure is:

$$\bar{p}_i^{\alpha} = (\sin\alpha)\,\bar{p}_i^{\rightarrow} + (1 - \sin\alpha)\,\bar{p}_i^{\downarrow} \qquad \text{WIP09}$$

*The Nature of Winds* also gives us the procedure for calculating the resulting incident pressures when the angle of incidence of the wind lies somewhere between normal to and away from the sensor and parallel to the sensor. That procedure is:

$$\bar{p}_i^{\alpha} = (\sin\alpha)\,\bar{p}_i^{\leftarrow} + (1 - \sin\alpha)\,\bar{p}_i^{\downarrow} \qquad \text{WIP10}$$

# TABLES

**Introduction:** The tables in this section give numerical values for selected atmospheric parameters associated with wind-induced pressures at selected wind speeds and selected angles of incidence.

In order to do this, we have to start with a standard set of still air parameters and conditions. These initial conditions include both an absence of wind and an absence of any changes of state in the water vapor content of the atmosphere. Moreover, when the wind blows, all tables assume a completely laminar non-viscous flow, with no turbulence.

**Still Air Parameters**:

$\bar{p}_i$ 1,000 hectopascals or $10^5$ Pascals. This is the mean ambient atmosphere pressure in still air under conditions approaching equilibrium.

$\bar{n}$ 2.4293 x $10^{25}$ molecules per cubic meter. This is the molecular number density that produces an ambient pressure of 1000 hectopascals in still air at a temperature of 25°C.

$k_B$ 1.3806488 x $10^{-23}$ joules per molecule per Kelvin. This is Boltzmann's Constant. It is the constant of proportionality between molecular kinetic energy of translation and temperature.

$\bar{T}_i$ 25°C or 298.15°K. This is the ambient mean atmospheric temperature.

$\bar{m}_i$ 4.777108 x $10^{-26}$ kilograms. This is the mean molecular impulse mass at a vapor pressure of $10^3$ Pascals. At the specified temperature of 25°C, this corresponds to a relative humidity of about 32%.

$\sigma$ 293.55 meters per second. The is the square-root of the mean of the squares of the deviations of the individual molecule speeds from the mean speed (0 meters per second) along any single axis of movement in still air. In kinetic gas theory, this speed is known as the root-mean-square speed ($\boldsymbol{v}^{rms}$). In statistical mechanics, this speed is known as the standard deviation of the molecular axial speed distribution.

**Governing Equation:** In still air, all of the above parameters are related to one another by the governing equation:

$$\bar{p}_i = \bar{n}\mathrm{k_B}\bar{T}_i = \bar{n}\bar{m}_i\sigma^2 \qquad \text{WIP11}$$

Properly speaking, this equation applies only to an ideal gas under conditions of equilibrium. However, both observation and experiment have shown that it can be applied to the mixture of real gases that make the free atmosphere under conditions approaching equilibrium. That is to say, that the real atmospheric values equal the theoretical values to within the normal limits of scientific precision.

In keeping with this principle, the reader should treat the very precise numbers in the following tables with a grain of salt. They simply represent the computer doing what it does, regardless of the scientific merits of the process. You can probably accept the accuracy of three significant figures in most cases or four—if conditions are really controlled. Otherwise, use as many significant figures as you feel comfortable with in estimating the accuracy of the wind speed.

## TABLE WIP01: PRESSURE CHANGES AT SELECTED WIND SPEEDS

| Wind Speed | Mean Windward Pressure Increment | Mean Leeward Pressure Decrement | Mean Parallel Pressure Decrement |
|---|---|---|---|
| $\bar{\omega}$ | $\Delta\bar{p}_i^{\rightarrow}$ | $\Delta\bar{p}_i^{\leftarrow}$ | $\Delta\bar{p}_i^{\downarrow}$ |
| m $\mathrm{sec}^{-1}$ | hPa | hPa | hPa |
| | | | |
| 0 | 0.000 | 0.000 | 0.000 |
| 1 | 0.012 | -0.012 | -0.000 |
| 2 | 0.047 | -0.046 | -0.000 |
| 3 | 0.105 | -0.104 | -0.000 |
| 4 | 0.188 | -0.184 | -0.001 |
| 5 | 0.294 | -0.286 | -0.002 |
| 6 | 0.425 | -0.411 | -0.003 |
| 7 | 0.579 | -0.558 | -0.005 |
| 8 | 0.759 | -0.727 | -0.008 |
| 9 | 0.963 | -0.917 | -0.011 |
| 10 | 1.192 | -1.129 | -0.016 |
| 11 | 1.446 | -1.362 | -0.021 |
| 12 | 1.726 | -1.617 | -0.027 |
| 13 | 2.031 | -1.892 | -0.035 |
| 14 | 2.361 | -2.188 | -0.043 |
| 15 | 2.718 | -2.505 | -0.053 |
| 16 | 3.100 | -2.842 | -0.065 |
| 17 | 3.509 | -3.199 | -0.077 |
| 18 | 3.944 | -3.576 | -0.092 |
| 19 | 4.406 | -3.973 | -0.108 |
| 20 | 4.894 | -4.390 | -0.126 |
| | | | |

## TABLE WIP02: PRESSURE CHANGES AT SELECTED WIND SPEEDS

| Wind Speed | Mean Windward Pressure Increment | Mean Leeward Pressure Decrement | Mean Parallel Pressure Decrement |
|---|---|---|---|
| $\bar{\omega}$ | $\Delta\bar{p}_i^{\rightarrow}$ | $\Delta\bar{p}_i^{\leftarrow}$ | $\Delta\bar{p}_i^{\downarrow}$ |
| m $\sec^{-1}$ | hPa | hPa | hPa |
| | | | |
| 0 | 0.000 | 0.000 | 0.000 |
| 5 | 0.294 | -0.286 | -0.002 |
| 10 | 1.192 | -1.129 | -0.016 |
| 15 | 2.718 | -2.505 | -0.053 |
| 20 | 4.894 | -4.390 | -0.126 |
| 25 | 7.745 | -6.761 | -0.246 |
| 30 | 11.295 | -9.594 | -0.425 |
| 35 | 15.565 | -12.867 | -0.675 |
| 40 | 20.581 | -16.556 | -1.006 |
| 45 | 26.363 | -20.637 | -1.432 |
| 50 | 32.937 | -25.089 | -1.962 |
| 55 | 40.323 | -29.888 | -2.609 |
| 60 | 48.544 | -35.012 | -3.383 |
| 65 | 57.624 | -40.439 | -4.296 |
| 70 | 67.583 | -46.147 | -5.359 |
| 75 | 78.442 | -52.114 | -6.582 |
| 80 | 90.225 | -58.320 | -7.976 |
| 85 | 102.951 | -64.742 | -9.552 |
| 90 | 116.641 | -71.361 | -11.320 |
| 95 | 131.315 | -78.156 | -13.290 |
| 100 | 146.994 | -85.107 | -15.472 |
| | | | |

## TABLE WIP03: PRESSURE CHANGES AT SELECTED ANGLES OF INCIDENCE AND SELECTED WIND SPEEDS

| Angle of Incidence | Change at Wind Speed of | Change at Wind Speed of | Change at Wind Speed of | Change at Wind Speed of |
|---|---|---|---|---|
| **$\alpha$** | **5** | **10** | **15** | **20** |
| ° | $ms^{-1}$ | $ms^{-1}$ | $ms^{-1}$ | $ms^{-1}$ |
| | | | | |
| **90** | 0.294 | 0.294 | 0.294 | 0.294 |
| **85** | 0.293 | 0.293 | 0.293 | 0.293 |
| **80** | 0.289 | 0.289 | 0.289 | 0.289 |
| **75** | 0.284 | 0.284 | 0.284 | 0.284 |
| **70** | 0.276 | 0.276 | 0.276 | 0.276 |
| **65** | 0.266 | 0.266 | 0.266 | 0.266 |
| **60** | 0.254 | 0.254 | 0.254 | 0.254 |
| **55** | 0.240 | 0.240 | 0.240 | 0.240 |
| **50** | 0.225 | 0.225 | 0.225 | 0.225 |
| **45** | 0.207 | 0.207 | 0.207 | 0.207 |
| **40** | 0.188 | 0.188 | 0.188 | 0.188 |
| **35** | 0.168 | 0.168 | 0.168 | 0.168 |
| **30** | 0.146 | 0.146 | 0.146 | 0.146 |
| **25** | 0.123 | 0.123 | 0.123 | 0.123 |
| **20** | 0.099 | 0.099 | 0.099 | 0.099 |
| **15** | 0.075 | 0.075 | 0.075 | 0.075 |
| **10** | 0.049 | 0.049 | 0.049 | 0.049 |
| **5** | 0.024 | 0.024 | 0.024 | 0.024 |
| **0** | -0.002 | -0.002 | -0.002 | -0.002 |
| | | | | |

**All changes are in hectopascals.**

## TABLE WIP04: PRESSURE CHANGES AT SELECTED ANGLES OF INCIDENCE AND SELECTED WIND SPEEDS

| Angle of Incidence | Change at Wind Speed of | Change at Wind Speed of | Change at Wind Speed of | Change at Wind Speed of |
|---|---|---|---|---|
| **$\alpha$** | **25** | **30** | **35** | **40** |
| ° | $ms^{-1}$ | $ms^{-1}$ | $ms^{-1}$ | $ms^{-1}$ |
| | | | | |
| **90** | 7.735 | 11.280 | 15.545 | 20.553 |
| **85** | 7.705 | 11.235 | 15.483 | 20.471 |
| **80** | 7.614 | 11.102 | 15.299 | 20.226 |
| **75** | 7.463 | 10.881 | 14.992 | 19.819 |
| **70** | 7.254 | 10.574 | 14.567 | 19.253 |
| **65** | 6.988 | 10.183 | 14.025 | 18.534 |
| **60** | 6.666 | 9.712 | 13.372 | 17.665 |
| **55** | 6.292 | 9.163 | 12.612 | 16.655 |
| **50** | 5.868 | 8.542 | 11.751 | 15.510 |
| **45** | 5.398 | 7.852 | 10.795 | 14.239 |
| **40** | 4.884 | 7.099 | 9.752 | 12.853 |
| **35** | 4.332 | 6.289 | 8.629 | 11.361 |
| **30** | 3.745 | 5.428 | 7.436 | 9.775 |
| **25** | 3.127 | 4.522 | 6.181 | 8.106 |
| **20** | 2.484 | 3.579 | 4.874 | 6.369 |
| **15** | 1.820 | 2.605 | 3.524 | 4.575 |
| **10** | 1.140 | 1.608 | 2.143 | 2.739 |
| **5** | 0.450 | 0.596 | 0.740 | 0.875 |
| **0** | -0.246 | -0.424 | -0.673 | -1.004 |
| | | | | |

**All changes are in hectopascals.**

## TABLE WIP05: PRESSURE CHANGES AT SELECTED ANGLES OF INCIDENCE AND SELECTED WIND SPEEDS

| Angle of Incidence | Change at Wind Speed of | Change at Wind Speed of | Change at Wind Speed of | Change at Wind Speed of |
|---|---|---|---|---|
| $\boldsymbol{\alpha}$ | **45** | **50** | **55** | **60** |
| ° | $ms^{-1}$ | $ms^{-1}$ | $ms^{-1}$ | $ms^{-1}$ |
| | | | | |
| **90** | 26.328 | 32.893 | 40.269 | 48.479 |
| **85** | 26.223 | 32.760 | 40.106 | 48.282 |
| **80** | 25.907 | 32.363 | 39.617 | 47.691 |
| **75** | 25.383 | 31.705 | 38.808 | 46.712 |
| **70** | 24.654 | 30.791 | 37.683 | 45.352 |
| **65** | 23.728 | 29.627 | 36.252 | 43.621 |
| **60** | 22.610 | 28.223 | 34.525 | 41.532 |
| **55** | 21.309 | 26.590 | 32.515 | 39.101 |
| **50** | 19.834 | 24.739 | 30.238 | 36.347 |
| **45** | 18.198 | 22.685 | 27.712 | 33.291 |
| **40** | 16.413 | 20.443 | 24.954 | 29.955 |
| **35** | 14.492 | 18.031 | 21.987 | 26.366 |
| **30** | 12.450 | 15.467 | 18.832 | 22.551 |
| **25** | 10.302 | 12.770 | 15.515 | 18.538 |
| **20** | 8.065 | 9.961 | 12.059 | 14.359 |
| **15** | 5.755 | 7.062 | 8.492 | 10.044 |
| **10** | 3.391 | 4.094 | 4.841 | 5.628 |
| **5** | 0.990 | 1.079 | 1.133 | 1.143 |
| **0** | -1.429 | -1.958 | -2.604 | -3.377 |
| | | | | |

**All changes are in hectopascals.**

## TABLE WIP06: PRESSURE CHANGES AT SELECTED ANGLES OF INCIDENCE AND SELECTED WIND SPEEDS

| Angle of Incidence | Change at Wind Speed of | Change at Wind Speed of | Change at Wind Speed of | Change at Wind Speed of |
|---|---|---|---|---|
| **$\alpha$** | **65** | **70** | **75** | **80** |
| ° | $ms^{-1}$ | $ms^{-1}$ | $ms^{-1}$ | $ms^{-1}$ |
| | | | | |
| **90** | 57.546 | 67.491 | 78.335 | 90.101 |
| **85** | 57.310 | 67.213 | 78.012 | 89.728 |
| **80** | 56.606 | 66.384 | 77.045 | 88.611 |
| **75** | 55.439 | 65.009 | 75.442 | 86.760 |
| **70** | 53.817 | 63.098 | 73.215 | 84.187 |
| **65** | 51.752 | 60.666 | 70.380 | 80.914 |
| **60** | 49.262 | 57.732 | 66.960 | 76.963 |
| **55** | 46.363 | 54.318 | 62.980 | 72.367 |
| **50** | 43.079 | 50.449 | 58.471 | 67.159 |
| **45** | 39.435 | 46.156 | 53.467 | 61.379 |
| **40** | 35.458 | 41.471 | 48.006 | 55.072 |
| **35** | 31.178 | 36.430 | 42.130 | 48.285 |
| **30** | 26.629 | 31.071 | 35.883 | 41.070 |
| **25** | 21.844 | 25.434 | 29.313 | 33.482 |
| **20** | 16.860 | 19.564 | 22.470 | 25.578 |
| **15** | 11.716 | 13.503 | 15.405 | 17.419 |
| **10** | 6.449 | 7.300 | 8.174 | 9.067 |
| **5** | 1.101 | 1.000 | 0.830 | 0.585 |
| **0** | -4.288 | -5.349 | -6.570 | -7.961 |
| | | | | |

**All changes are in hectopascals.**

**The Luffing Angle:** The angle at which the windward force becomes a leeward force is known as the luffing angle. In sailing, this luffing will always occur within five degrees of the wind. This is shown in the tables above. Note that the higher the wind velocity, the closer to five degrees that the luffing angle becomes. Given the extreme variability of both the wind direction and the wind speed under natural conditions, a more precise value than this is ill-advised.

# REFERENCES

**INTERNAL REFERENCES**: These are other papers in this collection that are cited or linked during the course of the discussion.

***The Nature of Atmospheric Pressures*** – This paper defines gas pressures in terms of kinetic gas theory and statistical mechanics.

***The Nature of Winds*** – This paper defines winds in terms of kinetic gas theory and statistical mechanics.

***Molecular Flows*** **–** This paper gives the derivation of the Universal Molecular Flux equation.

***Molecular Impulses*** – This paper gives the derivation of the Universal Molecular Impulse equation.

***The Equipartition Conundrum*** – This paper shows how and why the intermolecular transfer of momentum is virtually solely translational.

***Molecular Speeds and Velocities*** – This paper shows how the various measures of molecular velocities are derived and their mathematical relationships.

***Kinetic Energies of Translation*** – This paper shows how the various measures of molecular kinetic energies of translation are derived and their mathematical relationships to one another and to the thermal term $\mathrm{k_B}\bar{T}$ .

***Molecular Masses*** – This paper shows how the values for the various atmospheric molecular masses are calculated.

***The Probability Density Curve*** – This paper gives a brief treatment of the history and utility of the probability density curve.

***The Balloon and the Tower*** – This is a thought experiment involving a drifting balloon and an airfoil-shaped tower. It shows how orientation to the wind affects both temperatures and pressures.

**EXTERNAL REFERENCES**: These are papers by other authors that contain specific statements or bits of data that are specifically incorporated in the above discussion. Specifically, these papers treat gaseous flows from the standpoints of kinetic gas theory and statistical mechanical theory.

D. Tabor; **Gases, Liquids, and Solids**; Third Edition; Cambridge University Press, 1991.

Arthur Brown; **Statistical Physics**; Elsevier, New York, 1970.

James Jeans; **An Introduction to the Kinetic Theory of Gases**; Cambridge Library Collection, 1940.

**GENERAL REFERENCES**: These are papers by other authors that contain general treatments of kinetic gas theory, statistical mechanics and thermodynamics, atmospheric physics, and other scientific fields that are used in the above discussion.

Charles Kittel; **Thermal Physics**; John Wiley & Sons, New York, 1969.

Wolfgang Pauli; **Statistical Mechanics**; Dover Press, Mineola, 1973.

William D. Sellers, **Physical Climatology**; University of Chicago Press, Chicago, 1965.

R. G. Barry and R. J. Chorley; **Atmosphere, Weather, and Climate**; Holt, Rinehart and Winston; New York, 1970.

Richmond W. Longley; **Elements of Meteorology**, John Wiley & Sons, Inc.; New York, 1970.

Herber Riehl; **Introduction to the Atmosphere**; McGraw-Hill Book Company, New York, 1972.