WORLD METEOROLOGICAL ORGANIZATION

COMPENDIUM ON TROPICAL METEOROLOGY FOR AVIATION PURPOSES

by

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NOTE

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# CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foreword</td>
<td>v</td>
</tr>
<tr>
<td>Preface</td>
<td>vii</td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Objective of the Compendium</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Definition of the tropics</td>
<td>1</td>
</tr>
<tr>
<td>1.3 Scope of the Compendium</td>
<td>1</td>
</tr>
<tr>
<td>1.4 Units</td>
<td>1</td>
</tr>
<tr>
<td>2. SEASONAL AND LARGE-SCALE INFLUENCES</td>
<td>2</td>
</tr>
<tr>
<td>2.1 General circulation of the atmosphere</td>
<td>2</td>
</tr>
<tr>
<td>2.2 Major wind and pressure zones</td>
<td>3</td>
</tr>
<tr>
<td>2.3 Trade winds</td>
<td>4</td>
</tr>
<tr>
<td>2.4 Inter-tropical convergence zone</td>
<td>5</td>
</tr>
<tr>
<td>2.5 Monsoons</td>
<td>6</td>
</tr>
<tr>
<td>2.6 El Niño/Southern Oscillation</td>
<td>11</td>
</tr>
<tr>
<td>2.7 Walker circulation</td>
<td>11</td>
</tr>
<tr>
<td>2.8 Observing large-scale circulation from geostationary satellites</td>
<td>12</td>
</tr>
<tr>
<td>3. SYNOPTIC-SCALE PHENOMENA AND TROPICAL CYCLONES</td>
<td>19</td>
</tr>
<tr>
<td>3.1 Synoptic-scale systems</td>
<td>19</td>
</tr>
<tr>
<td>3.2 Synoptic-scale disturbances</td>
<td>19</td>
</tr>
<tr>
<td>3.3 Tropical cyclones</td>
<td>21</td>
</tr>
<tr>
<td>4. MESOSCALE PHENOMENA</td>
<td>27</td>
</tr>
<tr>
<td>4.1 Importance of mesoscale phenomena</td>
<td>27</td>
</tr>
<tr>
<td>4.2 Land and sea breezes</td>
<td>27</td>
</tr>
<tr>
<td>4.3 Orographic effects</td>
<td>28</td>
</tr>
<tr>
<td>4.4 Thunderstorms</td>
<td>28</td>
</tr>
<tr>
<td>4.5 Severe storms</td>
<td>29</td>
</tr>
<tr>
<td>4.6 Thunderstorm development and prediction</td>
<td>30</td>
</tr>
<tr>
<td>4.7 Thunderstorm-related phenomena</td>
<td>30</td>
</tr>
<tr>
<td>4.8 Lightning</td>
<td>32</td>
</tr>
<tr>
<td>4.9 Dust and sandstorms</td>
<td>33</td>
</tr>
<tr>
<td>4.10 Dust devils</td>
<td>33</td>
</tr>
<tr>
<td>4.11 Low-level wind shear</td>
<td>34</td>
</tr>
<tr>
<td>4.12 Turbulence</td>
<td>34</td>
</tr>
<tr>
<td>4.13 Low-level jet streams</td>
<td>35</td>
</tr>
<tr>
<td>4.14 Mountain waves</td>
<td>35</td>
</tr>
<tr>
<td>5. VOLCANIC ACTIVITY</td>
<td>36</td>
</tr>
<tr>
<td>5.1 Incidents involving volcanic ash</td>
<td>36</td>
</tr>
<tr>
<td>5.2 Volcanic ash as an aviation hazard</td>
<td>37</td>
</tr>
<tr>
<td>5.3 Nature of the damage to aircraft</td>
<td>38</td>
</tr>
<tr>
<td>5.4 Monitoring volcanic ash clouds</td>
<td>38</td>
</tr>
<tr>
<td>5.5 Warning systems</td>
<td>38</td>
</tr>
<tr>
<td>6. GENERAL HINTS FOR WEATHERWISE FLYING IN THE TROPICS</td>
<td>41</td>
</tr>
<tr>
<td>6.1 Introduction</td>
<td>41</td>
</tr>
<tr>
<td>6.2 Guidance material for the provision of meteorological service to aviation</td>
<td>41</td>
</tr>
<tr>
<td>6.3 Understanding basic tropical meteorology relevant to aviation</td>
<td>41</td>
</tr>
<tr>
<td>6.4 Avoiding hazards in-flight</td>
<td>41</td>
</tr>
<tr>
<td>6.5 Pilot reports</td>
<td>42</td>
</tr>
<tr>
<td>6.6 Glossaries for aviation</td>
<td>42</td>
</tr>
<tr>
<td>6.7 Concluding remarks</td>
<td>42</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>43</td>
</tr>
</tbody>
</table>
The WMO Commission for Aeronautical Meteorology (CAeM), at its ninth session in September 1990, noted that pilots based in temperate latitudes were mainly trained in temperate latitude meteorology and that a need existed for training pilots in tropical meteorology. The session agreed that a loose-leaf compendium on tropical meteorology should be developed. The manuscript for this publication was initially prepared by experts from National Meteorological Services in tropical areas headed by Mr J. R. Dear (Australia), the then chairperson of the Working Group on the Provision of Meteorological Information Required Before and During Flight (PROMET). The eleventh session of CAeM in 1999 felt that every effort should be made to finalize and publish the compendium and requested the WMO Secretariat to investigate the possibility for hiring a consultant to review the manuscript further and to prepare the remaining material for publication.

In August 1999, Professor T. N. Krishnamurti of the Florida State University, in Tallahassee, United States, kindly agreed to assist the Secretariat to review the draft and prepare the remaining material. Professor Krishnamurti made a thorough review of the existing material and provided the latest scientific and technical knowledge on tropical meteorology in a language that aviation users, namely pilots, are likely to understand. Professor Krishnamurti provided a large number of illustrations in colour to make the compendium easily understandable and attractive.

The publication was subsequently finalized by the Secretariat, assisted by the president of CAeM, Mr Neil Gordon.

I wish to express my sincere thanks to all those who gave their time and effort to develop and publish this *Compendium on Tropical Meteorology for Aviation Purposes*. I thank in particular, Mr J. R. Dear and the experts who started the work on this publication. I wish to convey my special appreciation and gratitude to Professor T. N. Krishnamurti and Mr T. S. V. Vijaya Kumar for their excellent contribution to the development of this publication.

I hope that this publication will prove useful to the aviation community worldwide for which it is primarily intended, and will also be a valuable handy reference material to the aeronautical meteorological community.

G. O. P. Obasi
Secretary-General
PREFACE

This *Compendium* was prepared at the request of Mr Nouhou Tata Diallo, Chief of the Aeronautical Meteorology Unit at the WMO Secretariat in Geneva. The Working Group for the Provision of Meteorological Information Required by Civil Aviation (PROMET) felt the need for a simple manual that would help the aviation users who have to fly through tropical weather. This was not an easy task since our experience is more on tropical weather, but less on the needs for aviation. We have provided a simple publication that, we believe, can help the needs of aviation. We have provided a large number of illustrations to make the *Compendium* easily understandable. Examples of severe weather related to aircraft accidents involving downbursts, severe turbulence and volcanic ash are highlighted. Supplementary reading material is also provided. Overall, the goal has been to keep the *Compendium* within a limited scope so that it would be helpful to pilots who will not be over loaded with excessive instrumental, observational and modeling details. Finally, thanks go to Mr N. T. Diallo for his cooperation and useful discussions in issuing out this *Compendium* successfully.

Tallahassee, May 2002

T. N. Krishnamurti
CHAPTER 1
INTRODUCTION

1.1 OBJECTIVE OF THE COMPENDIUM
1.1.1 The objective of this Compendium is to provide information on tropical meteorology and the hazards that weather in the tropics might pose for aviation operations.
1.1.2 This material is intended for use by aviation planners, air traffic controllers and aircrew to improve their knowledge of the basic processes governing weather in the tropics and the detailed climate and weather of the individual regions in, and adjacent to, the tropics. This Compendium could also be used by meteorologists as a handy reference material.

1.2 DEFINITION OF THE TROPICS
1.2.1 The tropics are the zone between the Tropic of Cancer, latitude 23.5 degrees north and the Tropic of Capricorn, latitude 23.5 degrees south. In meteorology, this definition should not be interpreted too strictly because tropical types of weather often extend into the subtropics; for example, tropical cyclones sometimes move out of the tropics without losing the characteristics of a tropical storm. Similarly, cold fronts and other weather phenomena of the middle latitudes sometimes penetrate into the tropics.
1.2.2 Meteorology of the tropics is normally treated as a distinct subject. This is because the meteorological systems in this region are different from those outside the tropics. The differences are mainly in the behaviour of winds (geostrophic approximation), temperature gradients, seasonality of weather and the diurnal cycle.

1.3 SCOPE OF THE COMPENDIUM
1.3.1 Some fundamental aspects of meteorological phenomena over the tropics that affect aviation in general are presented in this Compendium. Accurate aviation weather information helps optimal flight planning and the avoidance of hazardous weather due to abnormal changes in the weather en route the path of the aircraft as well as weather during take off and landing.
1.3.2 The characteristics of atmospheric phenomena that adversely affect aviation have also been described in this Compendium. The modern methods of monitoring severe weather conditions that affect flight operations directly or indirectly are described in detail.
1.3.3 The Compendium consists of six chapters. Chapters 2, 3, and 4 discuss in general terms, the major influences on tropical meteorology using three-scale categories.

Chapter 2: Seasonal and large-scale influences — This chapter deals in general terms with the broad-scale pressure and wind regimes affecting the tropics including the equatorial trough, the doldrums, the intertropical convergence zone, the monsoons, the trade winds and the subtropical high pressure belt.

Chapter 3: Synoptic-scale phenomena and tropical cyclones — This chapter provides a general discussion of the different approaches required for synoptic meteorology in the tropics and gives a brief description of the more important synoptic disturbances. Special attention is given to severe tropical cyclones (hurricanes, typhoons), the most violent storms encountered in the tropics.

Chapter 4: Mesoscale phenomena — This chapter deals with local effects, such as land and sea breezes and orographic effects, and provides a summary description of significant weather phenomena including thunderstorms and related phenomena, duststorms and sandstorms.

Chapter 5: Volcanic activity — This chapter deals with the specific hazards to aircraft posed by ash clouds resulting from volcanic eruptions.

Chapter 6: General hints for weatherwise flying in the tropics — This chapter provides, again in general terms, advice on using knowledge of tropical meteorology to ensure safe flying.

1.4 UNITS
1.4.1 Mixed units are used in the provision of meteorological information for aviation; cloud base heights are usually given in feet, runway visual range in metres, visibility in metres and kilometres, and wind speed in knots. To be consistent, the following units have been adopted for this Compendium:

<table>
<thead>
<tr>
<th>Vertical distance (heights, altitudes, elevations)</th>
<th>feet (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal distance</td>
<td>metres (m), kilometres (km)</td>
</tr>
<tr>
<td>Wind speed</td>
<td>knots (kt)</td>
</tr>
<tr>
<td>Pressure</td>
<td>hectoPascals (hPa)</td>
</tr>
<tr>
<td>Temperature</td>
<td>Degrees Celsius (°C)</td>
</tr>
<tr>
<td>Rainfall amount</td>
<td>millimetres (mm)</td>
</tr>
</tbody>
</table>

1.4.2 It should be noted that these units might differ from those used in some parts of the world. Where this occurs, every effort has been made to include both sets of units.
CHAPTER 2
SEASONAL AND LARGE-SCALE INFLUENCES

2.1 GENERAL CIRCULATION OF THE ATMOSPHERE

2.1.1 The Sun, as the prime source of energy, is the dominant influence on the weather. Differences in the solar radiation received at various parts of the Earth's surface provide the driving forces for the wind circulations of the atmosphere and ocean currents, which result in a transfer of energy around the globe.

2.1.2 The average annual solar radiation received per unit area of the Earth's surface is a maximum in equatorial regions and falls off to a minimum at the poles. Nevertheless, as indicated in Figure 2.1, there is a net surplus of radiation energy in low latitudes and a net deficit in high latitudes with a balance at around latitude 37 degrees north and south. This surplus is offset to some extent by the outgoing longer wave radiation from the Earth, which depends on temperature and is much greater in the warm equatorial regions than in the polar regions. The incoming solar radiation exceeds the net outgoing radiation (reflected solar and outgoing long wave) in the tropics.

Since the thermal stratification remains nearly time invariant, the excess energy is transported out of the tropics. The Hadley cell and stationary eddies play an important role in transferring this excess energy from the tropics to higher latitudes. This subject is discussed further in paragraph 2.1.4.

2.1.3 Mechanisms are needed to balance these surpluses and deficits otherwise the tropics would be getting hotter and the polar regions colder. The three main mechanisms to transfer heat energy from the tropics to higher latitudes are latent heat transfers, atmospheric circulations and ocean currents:

(a) Latent heat transfers — Energy is used in the tropics to evaporate water and this results in the absorption of latent heat. Some of the water vapour is transported poleward and latent heat is released when it condenses as liquid water or deposits as ice crystals to form clouds;

(b) Atmospheric circulations — Major wind belts and giant eddies in the atmosphere transport warm air poleward and cold air equatorward as part of the general circulation of the atmosphere;

(c) Ocean currents — Heat is carried poleward by warm ocean currents such as the Gulf Stream which flows from east of the United States towards Europe and cold water is carried equatorwards by cold currents such as the Humboldt which flows north along the western coast of South America.

2.1.4 The simplest model for the atmospheric circulation is a huge convection cell with warm air ascending in the tropics and then proceeding poleward while a return current of cold air flows towards the equator at the surface. Such a model was proposed in 1735 by an Englishman, George Hadley, and the convection cell was called the Hadley cell. This model was shown to be far too simple. The actual circulations are very complicated due to the following:

(a) The spherical shape of the Earth;

(b) The rotation of the Earth which causes winds to be deflected to the right in the northern hemisphere and to the left in the southern hemisphere. This is known as the Coriolis effect which results in the formation of giant eddies (cyclones and anticyclones);

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Figure 2.1 — The average annual incoming solar radiation (dashed line) absorbed by the Earth and the atmosphere and the average annual infrared radiation (solid line) emitted by the Earth and the atmosphere.
Seasonal effects due to the north/south movements of the Sun relative to the Earth; and

Marked differences in the rate at which the continents and the oceans cool down and heat up as a result of the outgoing and incoming solar radiation. These marked differences lead to the monsoonal wind circulations.

A more realistic model of the average large-scale circulations is shown in Figure 2.2. In this model we have three major wind circulations between each of the poles and the equator, namely the Hadley cell, Ferrel cell and Polar cell. Near the equator, strong convection causes the air to rise, which flows northward and southward away from the equator at high level. The air moving away from the equator curves in direction due to the Coriolis effect and becomes concentrated in the form of a jet stream (sub-tropical jet) where wind speeds of 150 kt or more are not uncommon. Conversely, at the poles, cold dense air flows away from the region, at the surface, towards the equator and is replaced by less cold air from aloft. In the middle temperate latitudes, the warm tropical air interacts with the cold polar air resulting in the formation of cyclonic and anticyclonic eddies embedded in the prevailing westerly winds.

As shown in Figure 2.2(a), the model includes three vertical cells in each hemisphere. The actual airflow is complex because it includes large zonal (east/west) components as shown on the right-hand side of the figure. The westerlies are strong in each hemisphere and the cores are known as jet streams. Figure 2.2(b) shows major wind and pressure zones at the surface.

There are two major areas of high pressure and two major areas of low pressure at the surface in each hemisphere. Areas of high pressure exist near latitude 30° of each hemisphere and the poles; and areas of low pressure exist over the equator and near 60° latitude of each hemisphere in the vicinity of the polar front. The trade winds extend from the subtropical high to the equatorial low pressure. There is a belt of westerlies from the tropical high to the polar front, and the polar easterlies from the poles to the polar front.

As indicated in Figure 2.2, the major wind and pressure zones are:

(a) The doldrums, the inter-tropical convergence zone (ITCZ) and monsoons then, in each hemisphere as we proceed towards the poles;
(b) The trade wind zone (large areas are within the tropics) or monsoons;
(c) The subtropical high pressure belt;
(d) The mid-latitude westerlies;
(e) The belt of migratory low pressure areas;
(f) The subpolar lows; and
(g) The polar easterlies.

Figure 2.2 also shows an idealized version of the surface features affecting the tropics — the equatorial trough of low pressure, the subtropical high pressure belts and the trade wind zones. Because of the rotation of the Earth, air at the surface flowing out of the subtropical high pressure does not flow directly towards the equatorial low-pressure trough. The air streams are deflected to the right in the northern hemisphere to become north-east trades and to the left in the southern hemisphere to become south-east trades by an apparent force known as the Coriolis force.

The subtropical high pressure belts which are areas of generally light winds are sometimes called the “horse latitudes” because in the days of sail, ships frequently became becalmed in the areas of light winds associated with the vast high pressure systems (anticyclones). Horses were sometimes thrown overboard to lessen the strain on water and food supplies; hence the name horse latitudes.

The air gently subsides in the subtropical high pressure belts and therefore rain bearing clouds are few and rainfall is low.

Figure 2.2 — (a) shows the idealized wind and surface pressure distribution over the Earth, while (b) gives the names of surface winds and pressure systems over the Earth (Ahrens, 1994).
Most of the world’s great deserts are located in this zone. These include the vast desert area stretching from the Sahara Desert of northern Africa through Saudi Arabia and the Middle East, the Atacama Desert of Chile, the Kalahari Desert of south-west Africa, the deserts of the south-western United States and adjacent parts of Mexico and the vast tracts of inland and western Australia. In the summer, temperatures in these regions are usually very high.

2.2.5 The equatorial trough (ET) is a quasi-continuous belt of low pressure lying between the subtropical high-pressure belts of the two hemispheres. The equatorial trough has three active areas over the land during the northern winter season. These are located near Borneo, central and east Asia and northern Brazil over Amazonia and the foothills of the Andes. The oceanic equatorial trough during the northern winter is located north of the equator near 5°N over the Atlantic Ocean and eastern Pacific Ocean. The equatorial trough over the Indian Ocean during the northern winter is generally located near 7°S. The western Pacific (and even the Indian Ocean) is known to have a dual equatorial trough, one located near 5°N and the other in the southern hemisphere near 7°S. The western Pacific also sees an active equatorial trough along the south Pacific convergence zone to the east of northern Australia. This belt exhibits an extension from north-west to south-east. During the northern summer, the equatorial trough shows a large zonal asymmetry. It is located between 7°N and 10°N over most oceans. Between West and East Africa it is located near 15°N (mostly over the dry deserts), over India near 20°N and over Indo-China near 15°N.

2.2.6 The oceanic parts of the equatorial trough are called the doldrums — a nautical term — and are usually hot and humid regions of light and variable winds. The air is homogeneous in terms of atmospheric pressure and temperature but the humidity is so high that slight variations in stability can cause major variations in the weather. Showers and rain occur frequently.

2.2.7 The structure of the subtropical high pressure belts and the equatorial trough vary significantly from day to day as a result of changes in the wind circulations. In addition, there are seasonal northward and southward movements during the year, which are distorted due to the unequal heating over land and sea with both seasonal and diurnal changes.

2.2.8 Figure 2.3(a) shows an idealized version of the convection cell of the general circulation relative to the tropics. The ascending branch of the cell is associated with generally low atmospheric pressure in the equatorial zone and the descending branch with generally high atmospheric pressure in the subtropics. In Figure 2.3(b), an idealized Hadley cell circulation over the tropics is shown in relation to the mid-latitude westerlies and the jet streams.

2.3 TRADE WINDS

2.3.1 The trade wind zones occupy a substantial part of the tropics. The trade winds are most fully developed on the equatorial sides of the great subtropical anticyclones, particularly over the Atlantic Ocean. In the northern hemisphere, they begin as north-north-easterly winds at about latitude 30°N in January and 35°N in July and gradually veer to the north-easterly and then east-north-easterly as they approach the equator. In the southern hemisphere the direction changes from south-south-easterly through south-easterly to east-south-easterly. In the Pacific, the trade winds are well developed only in the eastern half of the ocean.

2.3.2 The trade wind belts are usually broader and closer to the equator in winter than they are in summer in each hemisphere. The winds are characterized by their constancy, particularly in their direction. They are primarily surface winds and the trade

Figure 2.3 — Idealized Hadley circulation over the Tropics. (a) Hadley circulation cell (b) Tropical Hadley circulation in relation to the mid-latitude westerlies.

Figure 2.4 — Monthly mean surface wind chart for July 1998.
wind layer is capped by a temperature inversion caused by broad scale subsidence of air in the eastern part of the subtropical anticyclones. The inversion is typically at 3,000 ft over the eastern parts of the oceans and gradually becomes higher to the west. Above the inversion, the air is warm and dry and the wind usually blows from a different direction. Figure 2.4 illustrates the global mean surface wind flow (streamlines) for July 1988 highlighting the trade winds of the Atlantic and Pacific Ocean, the ITCZ and the monsoon winds over the Indian Ocean.

2.3.3 A large part of the world’s evaporation of surface moisture takes place in the trade wind belts. As a result, they are sprinkled with characteristic block-like Cumulus clouds that form in the relatively warm moist air under the trade wind inversion. Their vertical growth is restricted by the inversion so their tops are at about 3,000 ft over the eastern parts of the oceans. However, further west, they may reach 6,000 ft, which is sufficiently deep for rain showers to occur.

2.3.4 As a result of cloud development, islands in the eastern parts of the oceans are likely to have drier climates than those in the western parts. Different microclimates are found on individual islands lying within the trade wind belt, particularly the larger and more mountainous ones. It is usually much wetter on the windward than on the lee sides, but mountains projecting through the trade wind inversion will be arid on their upper slopes.

2.4 INTER-TROPICAL CONVERGENCE ZONE

2.4.1 The ITCZ is the zone in the tropics where the air of the two hemispheres converges to produce extensive areas of clouds and precipitation. Convective clouds in the ITCZ often extend to the tropopause with tops as high as 70,000 ft. In some cases, cloud tops break through the tropopause (i.e., the so-called “over shooting”) even higher (see paragraph 4.4.4). Cloud bases in some areas may be as low as 200 ft above surface, sometimes even lower. The ITCZ may be several hundreds of kilometres in width and frequently includes large areas of heavy rain, frequent thunderstorms, and sometimes violent squalls. Other terms with slightly different connotations are sometimes used for the zones along or close to the equator. Among them, the equatorial trough (ET), the intertropical discontinuity (ITD) and the monsoon trough (MT) are quite popular in the meteorological literature.

2.4.2 A monsoon trough is a trough of low pressure in the tropics which has surface winds with a significant westerly component on its equatorward side. Another example of different names of ITCZ is the near-equatorial trough (NET), a semi-permanent trough of low pressure found north of the equator in the Indian Ocean and south-east Asia. When the ITCZ is north of the equator the NET is coincident with it but, in the northern winter when the ITCZ moves into the southern hemisphere, the NET remains in the northern hemisphere.

2.4.3 The heavy cloud areas associated with the ITCZ are not continuous and the axis of the zone may not coincide with that of the lowest pressures in the equatorial trough. Equally marked day-to-day variations in the cloudy areas occur as a result of diurnal and geographical influences on the development of the clouds. The convective clouds, which are due to diurnal heat, will sometimes enhance the ITCZ over land. The ITCZ moves northward and southward with the seasons in a similar manner to the equatorial trough. Its mean positions in January and July are shown in Figure 2.5.

2.4.4 The seasonal movements of the ITCZ are relatively small over the oceans compared to those over the continents except over the Indian Ocean, particularly Asia and the eastern part of Africa. In the northern winter, cold dense air accumulates over Asia and a strong permanent anticyclone (high pressure) is established over Siberia while summer heating results in a semipermanent low pressure developing over northern Australia, and as a result, the ITCZ moves into the southern hemisphere.
2.4.5 In the northern summer, the reverse applies. Strong seasonal heating sets up a region of low pressure over Iran and northern India and cooling results in a semi-permanent anticyclone over Australia; and so the ITCZ swings well up into Asia.

2.4.6 The average sea-level pressure distributions and surface windflow patterns for January are shown in Figure 2.6 and for July in Figure 2.7. Large differences can be seen in the circulation patterns in the areas where there are large seasonal movements in the average position of the ITCZ; these are monsoon areas.

2.4.7 Figures 2.5, 2.6 and 2.7 present average and simplified pictures of the ITCZ and the pressure and wind distributions. There are significant variations of these simplified figures from day-to-day, week-to-week, and year-to-year. The structure of the ITCZ is sometimes complex. There may be more than one zone of convergence in the equatorial region and further complications are introduced by the different names given to these zones in various parts of the tropics.

2.4.8 The ITCZ is not always located at the centre of the equatorial trough. The major exception is over West Africa and Australia where it is shifted by almost 10 degrees latitude towards the equator. Thus pilots looking at sea-level pressure charts over the tropics must not assume that the ITCZ and tall Cumulonimbus clouds would be found near the axis of the lowest pressure over all regions. The heat lows over the African, Australian and the Mexican deserts do have low pressure with rather dry conditions.

2.4.9 The resulting large-scale distribution of precipitation — showing clearly where it is dry and where there is heavy rainfall — can be seen in global precipitation maps, based on satellite measurements. Figures 2.8 and 2.9 show typical monthly distributions of the estimated precipitation for January and July.

2.5 MONSOONS

2.5.1 The word “monsoon” is derived from the Arabic word “mausim” meaning season. It was first applied to the winds over the Arabian Sea, which blow for six months from the north-east and for six months from the south-west, but has been extended to similar wind regimes in other parts of the world. In India, the term is usually applied to the south-west monsoon and, by extension, to the rain that it brings. The seasonal march of the monsoon from the southern to the northern hemispheres and its return is best seen from what is called a ‘principal axis of the monsoon’. That is a rainfall belt with rainfall amounts approaching and even exceeding 200 inches (about 5 100 mm) per season. This belt migrates from the Java Sea to the eastern foothills of the Himalayas between January and middle June. Between September and late December, a return phase of this rainfall belt is noted. Above this rainfall belt (always from the equatorial belt 7°S to 7°N) an upper tropospheric anticyclone is usually present at 200 hPa (39 000 ft). This is useful information for flights crossing the belt of the principal axis of the monsoon. The tropical easterly jet is another wind system of some interest to pilots. This jet is a summer time phenomenon (June, July and August). It is generally located between the longitudes 120°E and the Greenwich Meridian between 5°N and 10°N latitudes. Its maximum wind is found around 47 000 ft above sea level. The maximum wind is generally only of the order of 80 kt.
2.5.2 The primary cause of monsoons is the much greater seasonal temperature range over the continents than the oceans which produces the seasonal movements of the ITCZ. The great land masses heat up more quickly during the summer months and cool down quickly during the winter season becoming much colder than the oceans in winter. These effects are shown schematically for the Asian-Australian region in Figure 2.10.

2.5.3 Monsoonal rains are by no means constant or continuous. The heaviest precipitation is associated with disturbances in the ITCZ. However, there are breaks or fluctuations in the monsoonal rains with periods of a day or so to over a week of cloudy weather, heavy showers and thunderstorms being interspersed with sunny, hot, and humid days.

**Monsoon over the Asia/Australia region:**

2.5.4 Monsoon effects are best developed in the Asian/Australian region as indicated in the schematic diagrams of wind flows in July and January (Figures 2.11 and 2.12), compared to other regions over the tropics. However, a similar development in the monsoon winds occurs over the western side of the Indian Ocean where there is also a large change in the position of the ITCZ between January and July. In the northern winter (January) outflow from the large Siberian anticyclone leads to northerly or north-easterly flow across southern China, Indo-China, Burma, and India. The air then moves across the Indian Ocean to the ITCZ lying south of the equator. In this situation, the north-west monsoon prevails over northern Australia with periods of heavy rain and thunderstorms. It is the tropical cyclone season over the tropical oceans adjacent to northern Australia.

2.5.5 The Siberian anticyclone weakens in March, as land temperatures begin to rise and, as the northern summer progresses, low pressure develops over Iran and northern India and a semi-permanent anticyclone builds up over Australia. The wet season in northern Australia begins to weaken gradually towards the end of March. April is a transitional month and, by May, the dry south-easterlies are well established. However, the onset of the south-westerly monsoon on the Indian subcontinent takes place later. The average date of onset of the monsoon in Sri Lanka is late in May and, as indicated in Figure 2.13, the onset of the monsoon becomes progressively later as we move northward up the subcontinent. Normal dates of the withdrawal of the monsoon are given in Figure 2.14.

![Figure 2.11 - Asia/Australia monsoon circulations in July.](image1)

![Figure 2.12 - Asia/Australia monsoon circulations in January.](image2)

![Figure 2.13 - Normal dates of onset of south-west monsoon over India (Rao, 1976).](image3)

![Figure 2.14 - Normal dates of withdrawal of south-west monsoon over India (Rao, 1976).](image4)
2.5.6 In Thailand and adjacent parts of south-east Asia, the south-west monsoon is well developed and flows from May to October bringing plentiful but not extreme rainfalls. November to February is relatively cool in this area, particularly in the north; March and April are hot and drier. Along the east coast and eastward facing slopes of south-east Asia, the north-east winter monsoon brings rain.

2.5.7 Monsoonal flows over Indonesia are weak because of the low latitude and the large expanses of water but there is a definite seasonal reversal of the winds. From April to October, drier southeasterlies flow from Australia which, on crossing the equator, tend to become moist southwesterlies. Between November and May the north-easterly flow of the winter monsoon from Asia becomes a moist north-westerly south of the equator bringing heavy clouds and rain to most of Indonesia. The wettest months are December over most of Sumatra and January in most of the other islands, but rainfall patterns are highly localized. In Java for example, at sea level alone there are two major regions, an “equatorial” west with no dry season and a “monsoonal” east with very dry weather in August and September.

2.5.8 Northern Australia has the classic pattern of marked wet and dry seasons with relatively short intervening transitional periods. However, in some parts of the tropics, monsoonal rains are not an entirely summer phenomenon. Rain is also associated with the winter north-easterly monsoon in eastern parts of Sri Lanka and southern India. The northeasterlies pick up moisture as they traverse across the Bay of Bengal. As we have seen for east Africa, some areas have two wet periods.

African monsoon

2.5.9 Figures 2.15 and 2.16 respectively show the climatological near surface wind flows (at 850 hPa, or around 5000 ft) and monthly mean precipitation in January and July over tropical Africa. The corresponding upper level wind patterns during January and July are shown in Figure 2.17.

2.5.10 The monthly mean streamline isotachs at 850 hPa and monthly mean precipitation for January and July in Figures 2.15 and 2.16 clearly indicate the seasonal migration of the precipitation zones above and below the ITCZ. The upper level flows in Figure 2.17 highlight the subtropical westerly jet stream with wind speeds exceeding 50 m s^{-1} (100 kt) during January along 25°N. This jet stream is more prominent during winter than summer.

2.5.11 Over tropical eastern Africa, there are large seasonal changes in the position of the ITCZ. There are two rainy periods associated with the latitudinal migrations of the ITCZ. In its southward journey, the ITCZ results in rains, known locally as the “short rains” over Kenya and Uganda from mid-October to mid-December. Rains, known locally as the “long rains” occur in these areas from about the middle of March to the beginning of June associated with the northward movement of the ITCZ. South

Figure 2.15 — (a) Mean climatological winds (m s^{-1}) at 850 hPa (5000 ft) over Africa during January; (b) Monthly mean climatological precipitation (mm) over Africa for January.

Figure 2.16 — (a) Mean climatological winds (m s^{-1}) at 850 hPa (5000 ft) over Africa during July; (b) Monthly mean climatological precipitation (mm) over Africa for July.
Tanzania gets rain in the period of November to March. Along the coast of East Africa, north-easterly and northerly winds replace southeasterlies in the period of the short rains, and in the period of the long rains, southeasterlies move up from the south.

2.5.12 Seasonal movements of the ITCZ are much smaller over tropical West Africa. The average positions of the ITCZ are in the northern hemisphere in all seasons because of the uneven distribution of landmasses in the two hemispheres, but further north in July than in January. The south-west monsoon flows as a shallow layer of humid air, less than 6,000 ft in depth, which undercuts the deep north-easterly wind of dry dusty air which blows from the Sahara. At the surface, this north-easterly wind is known as the “harmattan.” The West African monsoon is essentially the transition between the humid southwesterlies and the harmattan as the ITCZ moves northward and southward with the seasons.

2.5.13 Precipitation patterns also move northward and southward with the ITCZ. The humid south-westerly winds are too shallow in the immediate vicinity of the ITCZ to produce precipitation and the main areas of monsoonal rains and thunderstorms occur to the south, perhaps 200 to 300 km from the ITCZ where the moist air is deeper. The movements of the ITCZ are important in predicting seasonal weather because characteristic patterns of weather at various places depend on the distance from the position of the ITCZ. Distinct climate zones can be identified depending upon the latitude and the season.

2.5.14 The structure of the ITCZ, also known as the “meteorological equator” in the Sahel regions, is an important aspect for pilots flying over western Africa. The meteorology of western Africa can be expressed in schematic terms by meridional displacements of the discontinuity which separates, at the surface level, air originating from the northern and southern hemispheres. 2.5.15 That discontinuity, which corresponds to the ground track of the meteorological equator, is known in western and eastern Africa as the “intertropical front”. Its seasonal displacements, linked to apparent solar movement, are characterized by:
(a) The most southerly position on 1 February; and
(b) The most northerly position on 15 August.

Figures 2.18(a) and 2.18(b) illustrate these positions and the average surface meteorological situation.

2.5.16 The fluxes originating in the northern hemisphere are the trade winds, a cool damp northern sector flux, linked to the Azores anticyclone, which affects the coasts of Senegal and Mauritania; and the harmattan, a very dry eastern-sector flux linked to the Sahel regions and affecting the continental Sahel region. The flux originating in the southern hemisphere is the monsoon, a hot, damp south-western sector flux linked to the Saint Helena anticyclone (a cross-equator deviated wind).

2.5.17 In the month of August, three constituents can be observed:
(a) The monsoon flux is in the low atmospheric layers; it is rarely more than 200 m (about 600 ft) thick over the Sahel zone;
(b) A tube of strong winds, the East African Jet, in the mid-troposphere; this is one of the elements of the mean meridional structure of the meteorological equator. The tube reaches its maximum at about 600 hPa (14,000 ft); and
(c) A second tube of strong winds, the Tropical Easterly Jet, in the upper troposphere; this is an element of general circulation, formed in south-east Asia, which provides a link between the Indian and African monsoons in July and August.

Figure 2.17 — Monthly mean climatological winds (m s⁻¹) at 200 hPa (39,000 ft) over Africa for (a) January and (b) July.

Figure 2.18 — (a) Average surface meteorological situation over the Sahel region during January–February; and (b) July–August (WMO, 1989).
The meridional cross-section of the meteorological equator over continental western Africa along 15°E/10°W in August is depicted in Figure 2.19. In the average structure, it is possible to distinguish five climatic zones, whose characteristics are given in Table 2.1. Only zones A, B and C1 regularly affect the Sahel zone. Occasionally, the southern part of the Sahel zone may be affected briefly by zone C2.

Table 2.1
Climatic zones associated with regions of the ITCZ over West Africa (WMO, 1989)

<table>
<thead>
<tr>
<th>Zone</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone A</td>
<td>Very dry and hot air (harmattan), strong diurnal temperature development.</td>
</tr>
<tr>
<td></td>
<td>Wind from the eastern sector.</td>
</tr>
<tr>
<td></td>
<td>Clear to slightly clouded sky (Altocumulus and Cirrus clouds linked to polar troughs).</td>
</tr>
<tr>
<td></td>
<td>The only significant phenomena are lithometeors: blowing and drifting sand and haze.</td>
</tr>
<tr>
<td>Zone B</td>
<td>Hot and humid air (monsoon).</td>
</tr>
<tr>
<td></td>
<td>Wind from the south-western to western sector.</td>
</tr>
<tr>
<td></td>
<td>Unstable diurnal development with isolated storms forming towards evening.</td>
</tr>
<tr>
<td>Zone C1</td>
<td>Hot and humid air (monsoon).</td>
</tr>
<tr>
<td></td>
<td>Wind from the south-western sector.</td>
</tr>
<tr>
<td></td>
<td>Unstable diurnal development with squall lines forming (over the Sahel zone, 80 per cent of precipitation is connected to this type of disturbance).</td>
</tr>
<tr>
<td>Zone C2</td>
<td>Hot and humid air (monsoon).</td>
</tr>
<tr>
<td></td>
<td>Wind from the south-western sector.</td>
</tr>
<tr>
<td></td>
<td>Sky cloudy with medium clouds; weak instability.</td>
</tr>
<tr>
<td></td>
<td>Abundant rainfall.</td>
</tr>
<tr>
<td>Zone D</td>
<td>Cool and humid air.</td>
</tr>
<tr>
<td></td>
<td>Wind from the southern sector.</td>
</tr>
<tr>
<td></td>
<td>Sky cloudy with low clouds (Stratocumulus and Cumulus).</td>
</tr>
<tr>
<td></td>
<td>The most significant phenomena are fogs and low clouds.</td>
</tr>
</tbody>
</table>

**American monsoon**
Over Central America, the monsoonal change is not as dramatic as over Africa and, particularly, Asia, but there are marked changes in the prevailing winds, particularly to the north of the Gulf of Mexico. The North American monsoon is a summer time phenomenon that first affects Mexico and Arizona. Along the Sierra Madre Occidental, convection proceeds northward around...
the middle of June as the monsoon advances from Mexico and Arizona. The rains have a large diurnal component with heavier rain occurring over the western foothills of the mountains in the afternoon hours. Maximum rainfall amounts over a season are around 150 to 200 inches (about 3 800 to 5 100 mm). The lower tropospheric flow over this region includes a south-easterly moisture influx from the Gulf of Mexico towards the east of the mountains and a more southerly flow of moist air from the Pacific Ocean to the west of the mountains. In the upper troposphere, an anticyclone called the Mexican High (somewhat of a counterpart to the Tibetan High of the Asian monsoon) provides a warm troposphere over the rain area.

2.6 EL NIÑO/SOUTHERN OSCILLATION

2.6.1 The El Niño phenomenon occurs on the western coast of South America near the equator, close to Peru and Ecuador. It is mainly an oceanic phenomenon but has spectacular manifestations through atmospheric events. The anomalous appearance of unusually warm oceanic surface temperatures along the tropical west coast of South America is named the El Niño (Spanish: "The Christ Child"). El Niño is usually observed during the month of December. In most years, the warming lasts for only a few weeks to a month, but during major El Niño events, the warming may extend over a large part of the eastern equatorial Pacific ocean and can last for many months.

2.6.2 Strong El Niño events are associated with droughts in Indonesia, Australia, and north-eastern South America with altered patterns of tropical storms in the tropical belt. During the stronger El Niño episodes, the atmospheric “teleconnections” are extensive enough to cause unusual, mostly warmer than normal winter weather at the higher latitudes of North and South America. During such events, deep convection, heavy precipitation and intense thunder activities can occur in some areas that normally experience much less of such activities. This can result for these areas in unusually frequent SIGMET warnings and special reports during this period.

2.6.3 The reverse occurs during the La Niña event, when the oceanic surface temperatures along the tropical east Pacific are cooler than normal. Major La Niña events usually coincide with opposite features to those of major El Niño events.

2.6.4 Beginning with the work of Sir Gilbert Walker in the 1930s, climatologists recognized a similar interannual change in the tropical atmosphere, which Walker termed the Southern Oscillation. El Niño and the Southern Oscillation appear to be the oceanic and atmospheric components of a single large-scale, coupled interaction — the El Niño/Southern Oscillation (ENSO). During the warm phase of ENSO, the South Pacific trade-wind system undergoes a change of state, or “see-saw,” in which the westward blowing trades weaken along the equator as the normally high pressure in the eastern South Pacific decreases and the low pressure over northern Australia and Indonesia rises. The pressure change and diminished trade winds cause warm surface water to move eastward along the equator from the western Pacific, while the warm surface layer in the east becomes thicker.

2.7 WALKER CIRCULATION

2.7.1 Variations from the mean in the tropical atmospheric and oceanic circulations and in sea-surface temperatures have significant impacts on the strength of the monsoons and associated weather. An important example is the Walker Circulation, an east-west vertical circulation in the tropical atmosphere, which extends across the Pacific and the area to the north of Australia. The easterly trade winds form the lower part of this circulation; they bring warm moist air towards the Indonesian region, where it ascends to the higher levels of the atmosphere and then flows eastward and sinks over the eastern Pacific Ocean. The ascending air in the Indonesian region is associated with a region of low pressure and rain and the sinking air over the eastern Pacific Ocean is associated with high pressure and arid conditions.

2.7.2 The strength of the Walker Circulation can vary from year-to-year. When it is well developed, the low-level easterly trade winds blow strongly across the Pacific bringing moist air over Indonesia and northern Australia. As a result, there is a high probability that eastern Australia will be wetter than normal and the onset of the monsoon in northern Australia will be earlier than normal. The Southern Oscillation Index (SOI) indicates the strength of the Walker Circulation by measuring the difference in monthly averaged air pressure between Tahiti and Darwin. A positive index indicates that the Walker Circulation is well developed.

2.7.3 Waters in the western Pacific are normally three to eight degrees warmer than in the eastern Pacific in periods when the Walker Circulation is strong. However during El Niño events, warmer equatorial water floods towards the northern coast of South America and the normal circulation and sea-surface temperature patterns across the tropical Pacific are disturbed. These El Niño events are correlated with drier than normal weather or drought over large areas of Australia. Figure 2.20 illustrates the typical intensity of the east-west Walker circulation during the northern winter and northern summer, as well as a schematic outline of the vertical circulation cells in the east-west vertical plane (WMO, 1979). During the northern summer, the major centre of the Walker Circulation is found over the northern part of the Bay of Bengal. This centre shifts towards Indonesia-Borneo during the northern winter season.

Figure 2.20 — Intensity of the east-west Walker circulation during the northern winter and northern summer, and a schematic outline of the vertical circulation cells in the east-west vertical plane (WMO, 1979).
2.8 OBSERVING LARGE-SCALE CIRCULATION FROM GEOSTATIONARY SATELLITES

2.8.1 A geostationary meteorological satellite hovering 36000 km over the equator can provide cloud images of about a third of the globe and, collectively, current satellites in orbit provide excellent and simultaneous coverage of the entire tropical region. The present array of geostationary satellites include GOES East (over the Atlantic Ocean), GOES West (over eastern Pacific Ocean), GMS (over the Western Pacific), FY-2 (over Asia), METEOSAT (India Ocean Data Coverage (IODC)) and METEOSAT (mostly over Africa and Europe). These satellites provide a variety of data sets, including those derived from basic imagery, which contribute to the preparation of operational weather forecasts. These data sets include infrared and visible data for imagery, cloud tracked winds over the lower and upper troposphere, water vapour winds (mostly in the upper troposphere) and the net outgoing long-wave radiation. Some of these data sets, for example cloud track winds, can be transmitted via the WMO.
Global Telecommunication System. These data are also very useful resource of meteorological information for aviation since the frequency of this data is normally half-hourly or hourly, and can be more frequent if required, for example during severe weather events.

2.8.2 Figures 2.21 through 2.30 depict some examples of infrared and visible images that are available on a real-time basis, taken from different geostationary satellites presently in operation. The position of the ITCZ, subtropical highs and other major features discussed in this chapter can be seen through these images.

2.8.3 Figure 2.31 illustrates a typical upper tropospheric wind product distribution obtained from the European geostationary satellite (METEOSAT). This particular product represents the winds near 200 hPa extracted from the cloud tracking of high level Cirrus. The quantity of data available at a particular hour (in this instance 1200 UTC) is indeed comprehensive. Figure 2.32 depicts METEOSAT-derived winds over the European and part of the African regions. Figure 2.33 illustrates a similar product for the upper tropospheric winds over the central Atlantic Ocean, based on the United States geostationary satellite (GOES-E). Again, a very dense distribution of upper-air data is noted (based on cloud tracking). The wind barbs in these illustrations provide the estimates in knots (or m s\(^{-1}\)). Figure 2.34 illustrates a similar panel for the east Pacific sector from GOES-W. In Figures 2.35 and 2.36 the
Table 2.2
List of Web sites

<table>
<thead>
<tr>
<th>Description</th>
<th>Web site address</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid-upper-level winds, Low-mid-level winds, Low-level winds, wind shear and wind shear tendency: (based on both visible, infrared and water vapour channels)</td>
<td>Western North Atlantic: (GOES-E) <a href="http://cimss.ssec.wisc.edu/tropic/real-time/atlanic/winds/winds.html">http://cimss.ssec.wisc.edu/tropic/real-time/atlanic/winds/winds.html</a></td>
</tr>
<tr>
<td></td>
<td>Eastern North Atlantic: (METEOSAT-7) <a href="http://cimss.ssec.wisc.edu/tropic/real-time/europe/winds/winds.html">http://cimss.ssec.wisc.edu/tropic/real-time/europe/winds/winds.html</a></td>
</tr>
<tr>
<td></td>
<td>Western North Pacific: (GMS-5) <a href="http://cimss.ssec.wisc.edu/tropic/real-time/westpac/winds/winds.html">http://cimss.ssec.wisc.edu/tropic/real-time/westpac/winds/winds.html</a></td>
</tr>
<tr>
<td></td>
<td>Eastern North Pacific: (GOES-W) <a href="http://cimss.ssec.wisc.edu/tropic/real-time/eastpac/winds/winds.html">http://cimss.ssec.wisc.edu/tropic/real-time/eastpac/winds/winds.html</a></td>
</tr>
<tr>
<td></td>
<td>Australian region: (GMS-5) <a href="http://cimss.ssec.wisc.edu/tropic/real-time/shemi/winds/winds.html">http://cimss.ssec.wisc.edu/tropic/real-time/shemi/winds/winds.html</a></td>
</tr>
<tr>
<td></td>
<td>Indian Ocean region: (METEOSAT-5) <a href="http://cimss.ssec.wisc.edu/tropic/real-time/indian/winds/winds.html">http://cimss.ssec.wisc.edu/tropic/real-time/indian/winds/winds.html</a></td>
</tr>
</tbody>
</table>

2.8.4 These images, together with estimated winds, are available on a real-time basis and can be useful for a "quick-look" impression of what the wind flows are. However, it is also important to recognize that these winds are just one input into comprehensive global analyses, and subsequent predictions, of weather systems using the global models at the two World Area Forecast Centres. Table 2.2 contains a list of currently available Web sites that provide this kind of data globally.

2.8.5 Similar cloud tracking for the lower troposphere (near 900 hPa, or roughly 3000 ft) is also a major real-time data source currently available. Figures 2.37 to 2.42 show the typical examples of lower tropospheric real-time wind and cloud cover data sets that are readily available on real-time from Web sites. In these figures the low-level cloud tracking winds (one full barb is 10 kt) are shown. These figures cover the Indian Ocean and European sectors from METEOSAT; the Atlantic Ocean sector from OES-E; the east Pacific sector from GOES-W; and the west Pacific and Australian sectors from GMS, respectively.

Figure 2.31 — Upper-level IR/WV winds from METEOSAT — Indian Ocean sector.
CHAPTER 2 — SEASONAL AND LARGE-SCALE INFLUENCES

Figure 2.32 — Upper-level IR/WV winds from METEOSAT — European sector.

Figure 2.33 — Upper-level IR/WV winds from GOES-E — Atlantic sector.

Figure 2.34 — Upper-level IR/WV winds from GOES-W — East Pacific sector.
Figure 2.35 — Upper-level IR/WV winds from GMS — West Pacific sector.

Figure 2.36 — Upper-level IR/WV winds from GMS — Australian sector.

Figure 2.37 — Low-level IR winds from METEOSAT — Indian Ocean sector.
CHAPTER 2 — SEASONAL AND LARGE-SCALE INFLUENCES

Figure 2.38 — Low-level IR winds from Meteosat — European sector.

Figure 2.39 — Low-level IR winds from GOES-E — Atlantic sector.

Figure 2.40 — Low-level IR winds from GOES-W — East Pacific sector.
Figure 2.41 — Low-level IR winds from GMS – West Pacific sector.

Figure 2.42 — Low-level IR winds from GMS – Australian sector.
CHAPTER 3
SYNOPTIC-SCALE PHENOMENA AND TROPICAL CYCLONES

3.1 SYNOPTIC-SCALE SYSTEMS
3.1.1 Traditionally, meteorologists have sought to forecast the weather of middle and high latitudes by predicting the development, changes in intensity and the movement of synoptic-scale systems, such as anticyclones, cyclones and associated warm and cold frontal systems marking the boundary between polar and tropical air masses. The relationship between the pressure and wind fields through the geostrophic approximation has been a very effective tool.

3.1.2 These methods do not apply well in the tropics. The Coriolis force explained in paragraph 2.2.2 is weak and the geostrophic approximation breaks down. In general, the geostrophic approximation is valid in the extratropics where the horizontal motions are in balance with the pressure gradient force. However, in the tropics, with the notable exception of tropical cyclones, synoptic-scale pressure systems are usually ill-defined and there is a tendency for the wind to blow directly from high to low pressure rather than to circulate around centres of high and low pressure as in middle and high latitudes. This means that the conventional isobaric charts are of limited use in the tropics and meteorologists prefer to rely on analyses of the actual wind fields — streamline analyses of the wind direction and isotach analyses of the wind speed. These charts can be used to detect zones (areas or lines) where the air is converging or diverging. Abundant deep clouds and heavy precipitation are normally associated with the zones of convergence.

3.1.3 Despite their limitations, conventional isobaric charts do have some applications. Monitoring the position and intensity of the anticyclones in the subtropical high pressure belt can provide useful information on the location and movements of the ITCZ. Strengthening of a subtropical anticyclone usually results in the strengthening of the trade winds on the equatorward side of the anticyclone. The strengthening of the subtropical anticyclone is called a surge of the trades.

3.2 SYNOPTIC-SCALE DISTURBANCES
3.2.1 Tropical cyclones are the most significant synoptic scale storms in the tropics. Tropical cyclones will be treated in more detail later in subchapter 3.3.

3.2.2 Pressure systems in the tropics are normally weak and it was thought for a time that thunderstorms and precipitation in the tropics were random and disorganized. Improved observations, particularly from satellites, have demonstrated that there is a considerable degree of organization of these events and that rainfall in the humid tropics occurs predominantly in extensive disturbances that may persist for days, drifting slowly and irregularly usually towards the west. Rainless days are not uncommon over vast areas of the humid tropics. These features are strikingly evident on satellite pictures. Vast relatively clear areas can often be seen interspersed between the heavy cloud masses associated with disturbances.

3.2.3 The scale and nature of these tropical disturbances differ considerably. Figures 3.1 to 3.5 give typical temporal and spatial scales of motion for various atmospheric phenomena. Some important generic examples are presented below:

(a) Disturbances due to low-level convergence of air within deep moist currents — These disturbances do not have any evident cyclonic circulation and can take a variety of forms ranging from massive thunderstorms over areas of some hundreds of kilometres in diameter to more extensive areas of low cloud and lighter rain. They occur in the vicinity of the ITCZ over the oceans and widely over the continents during the monsoonal wet seasons. The disturbances are common in the westerly currents which develop over the Indian Ocean and southern India when the south-east trades cross the equator during the northern hemisphere summer. Winds are not usually strong but local squalls occur.

The winds in the tropics generally blow from the east, northeast or south-east. Because the variation of sea-level
pressure is normally quite small, drawing isobars on a weather map provides little useful information. Instead of isobars, drawn streamlines depict wind flow showing where surface air converges and diverges. Occasionally, the streamlines are disturbed by a weak trough of low pressure called an “easterly wave”, or tropical wave;

(b) Easterly waves or squall line systems — These disturbances occur within the tropical easterlies. They are westward moving lines of thunderstorms and showers, orientated north-south, often accompanied by shallow troughs. Strong easterly winds may occur near the trough line so that it appears as a squall line advancing westward. These disturbances occur above the south-west monsoon in West Africa and across the tropical Atlantic to the Caribbean, mainly in the northern summer. Figure 3.1 schematically depicts a northern hemisphere easterly wave in the vicinity of bending streamlines;

The infrared satellite view of a mid-latitude squall line (Figure 3.2), extending from the Ohio River Valley south-westward into subtropical Louisiana, shows the extreme lengths that thunderstorm lines can achieve. The lower, warmer anvils on the north end of the line and the colder, higher cloud tops at the south end reveal the tendency for older, weakening storms to be shed on the north side of the line with newer and stronger development near the south end.

During the northern summer, the ITCZ lies entirely to the north of the equator. Easterly waves are more likely seen in the neighborhood of the ITCZ than elsewhere. The origin of all tropical cyclones generally lies in these easterly waves. Typical wavelength of the easterly waves is about 2,500 km. These waves have a lifetime of about four days and move with a phase speed of about 12 kt from east to west. As seen from the northern hemisphere example in Figure 3.1, on the western side of the trough (heavy dashed line), where easterly and north-easterly surface winds diverge, sinking air produces generally fair weather. On its eastern side, where the south-easterly winds converge, rising air generates showers and thunderstorms. Consequently, the main area of showers forms behind the trough. Occasionally, over the oceans an easterly wave may intensify and grow into a hurricane. At the trough line of these waves, large cumulus and cumulonimbus clouds develop causing severe weather;

Figure 3.3 — A vertical view of the weather across a typical cold front. Note that the temperatures in this figure are in degrees Fahrenheit and the wind shifts are for the northern hemisphere (Ahrens, 1994).

| Table 3.1 |
| Typical weather conditions associated with a cold front in the northern hemisphere |

<table>
<thead>
<tr>
<th>Weather element</th>
<th>Before passing</th>
<th>While passing</th>
<th>After passing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winds</td>
<td>South to south-west</td>
<td>Gusty, shifting</td>
<td>west to northwest</td>
</tr>
<tr>
<td>Temperature</td>
<td>Warm</td>
<td>Sudden drop</td>
<td>Steadily dropping</td>
</tr>
<tr>
<td>Pressure</td>
<td>Falling steadily</td>
<td>Minimum, then sharp rise</td>
<td>Rising steadily</td>
</tr>
<tr>
<td>Clouds*</td>
<td>Increasing Cl, Cs, then either TCU or CB</td>
<td>TCU or CB</td>
<td>Often CU</td>
</tr>
<tr>
<td>Precipitation</td>
<td>Short period of showers</td>
<td>Heavy showers of rain or snow, sometimes with hail, thunder and lightning</td>
<td>Decreasing intensity of showers, then clearing</td>
</tr>
<tr>
<td>Visibility</td>
<td>Fair to poor in haze</td>
<td>Poor, followed by improvement</td>
<td>Good except in showers</td>
</tr>
<tr>
<td>Dew point</td>
<td>High, remains steady</td>
<td>Sharp drop</td>
<td>Lowering</td>
</tr>
</tbody>
</table>

* TCU stands for towering Cumulus clouds, such as Cumulus Congestus, CB for Cumulonimbus, CI for Cirrus, CS for Cirrostratus and CU for Cumulus.
Remnants of cold fronts in the tropics — In winter when the continental anticyclones are strong, cold fronts frequently penetrate into the tropics. The cold polar air stream and the cold front mixes to become part of the trade wind flow. However, while the polar air is altering its characteristics, as it mixes with the tropical air, for a time it can produce sharp increases in wind speed along identifiable shear lines, which may also be accompanied by showers or thunderstorms. Figure 3.3 illustrates a vertical view of the weather across the cold front. It can be seen from this figure that, at the front, the cold dense air wedges under the warm air, forcing it upward. As the moist unstable air rises, it condenses into a series of Cumuliform clouds. Strong, upper-level westerly winds blow the delicate ice crystals from the top of the Cumulonimbus into Cirrostratus and Cirrus. These clouds usually appear far in advance of the approaching front. At the front itself, a relatively narrow band of thunderstorms produces heavy showers with gusty winds. Behind the front, the air cools quickly. The winds shift in the northern hemisphere from south-westerly to north-westerly, pressure rises and precipitation ends. As the air dries out, the skies clear, except for a few lingering fair weather Cumulus clouds. The leading edge of the front is very steep due to friction and this slows the airflow near the ground. The air aloft pushes forward, blunting the frontal surface. With slow moving cold fronts, clouds and precipitation usually cover a broad area behind the front. When the ascending warm air is stable, stratiform clouds become predominant and fog may even develop in the rainy area. Occasionally, out ahead of a fast moving front, a line of active showers and thunderstorms (squall line) develops parallel to, and ahead of, the advancing front, producing heavy precipitation and strong gusty winds. Typical weather conditions associated with a cold front are shown in Table 3.1.

Cold-cored cyclones — Small areas of low pressure surrounded by winds rotating cyclonically (anticlockwise in the northern hemisphere, clockwise in the southern hemisphere) are fairly common a few degrees of latitude away from the equator (the term "cyclone" in this context does not necessarily imply strong winds). Some of these are "warm cored" and may give rise to severe tropical cyclones (see subchapter 3.3). However, some are cold cored which means that they have cooler air near their centres, particularly in the mid-troposphere. These relatively small cold-cored cyclones have extensive areas of cloud with scattered showers or rain but they rarely develop destructive winds. They occur over the western Atlantic and adjacent seas, and over the south Pacific north and east of Australasia (Australia, New Zealand and surrounding areas). The upper tropospheric vortices usually do not extend below 20 000 ft. A weak inverted wave in the easterlies is usually found beneath these vortices. They may be associated with broad areas of high clouds. Downward growth of an upper-level vortex results in the appearance of a surface vortex and an increase in convective clouds. Vortex movement is usually slowly west-south-westward in the northern hemisphere.

The tropical upper tropospheric cold-core cyclones have the following characteristics:

(i) An in-phase relationship between the upper tropospheric cold-core low and lower tropospheric easterly wave trough can enhance the convection. An out-of-phase relationship between them can suppress the convection;

(ii) The upper tropospheric troughs are frequently associated with troughs in the subtropical westerlies. When the subtropical disturbances in the northern hemisphere actively move southward, the area between the upper tropospheric anticyclone (or ridge) to its west and cold-core low (or trough) to its east usually has strong north-easterly flows and fast development of active convection;

(iii) The cloud bands associated with the upper tropospheric cyclonic vortices are typically aligned with the vertical wind shear.

Animated satellite cloud imagery is a good tool for the early identification and tracking of upper tropospheric cyclonic vortices.

3.3 TROPICAL CYCLONES

3.3.1 Severe tropical cyclones are the most destructive larger-scale storms in the world. The generic term "tropical cyclone" is used to describe these non-frontal synoptic-scale storms occurring over tropical oceans.

3.3.2 Tropical cyclone is a generic term for four stages that are defined as:

(a) Tropical disturbance — A region of organized convection with diameter of 200–600 km having a non-frontal migratory character;

(b) Tropical depression — A weak tropical cyclone with a definite closed surface circulation and highest sustained wind speeds (averaged over one minute or longer period) of less than 34 kt;

(c) Tropical storm — A tropical cyclone with closed isobars and highest sustained wind speeds of 34 to 63 kt;

(d) Tropical cyclone/typhoon/hurricane — A tropical cyclone with highest sustained wind speeds of more than 64 kt. The term "typhoon" is used in the western Pacific north of the equator including the China Sea. "Hurricane" is used in the United States for severe tropical cyclones originating in the Caribbean Sea, the Gulf of Mexico and the Pacific Ocean off the west coast of Mexico. Elsewhere, this is called a "tropical cyclone".

3.3.3 Tropical cyclones develop from heavy clouds formed in the equatorial easterly winds when conditions are favourable. These favourable conditions include:

(a) High sea-surface temperatures greater than 26°C giving an abundant supply of latent heat as evaporation occurs from the ocean surface; and

(b) An area of divergent winds aloft which facilitates upward convection. For example, thick clouds in easterly waves moving westward across the Atlantic, from West Africa, meet the warm Caribbean waters which intensify cloud development. These clouds may intensify further when divergent winds are found aloft. In some cases, when these conditions are found off the south-east coast of the United States, an explosive development can occur resulting in the formation of a violent hurricane. Hurricanes with strong or destructive winds also usually develop from clusters of thunderstorms and are warm cored because of the release of abundant latent heat in the inner parts of the developing
storm. Figure 3.4 shows a vertical view of the air motions, clouds and precipitation associated with a hurricane.

3.3.4 As seen in Figure 3.4, a hurricane (or typhoon, or tropical cyclone) is composed of an organized convection as part of the storm’s circulation. The moist tropical air from the surface flows in towards the centre of the hurricane and rises and condenses into huge amounts of rainfall adjacent to the eye region. Near the top of the circulation, the relatively dry air flows outward away from the centre and produces a clockwise flow several hundred kilometres away from the eye of the hurricane in the northern hemisphere. Tropical cyclones originate over the oceanic regions and grow rapidly until they reach the land surface. As they make landfall, they dissipate rapidly since their moisture supply is cut off.

3.3.5 Severe tropical cyclones vary considerably in size and 500 km is a typical diameter but the area of high winds is usually no more than about 150 to 250 km across. At the center of the storm is the "eye", a roughly circular area, typically 20 to 50 km

Figure 3.5 — Satellite pictures showing the movement and intensity of Hurricane Floyd during 12–16 September 1999.
in diameter, with few clouds and light winds. The eye region is warm due to release of latent heat and subsidence that takes place on the region. The eye is surrounded by a massive wall of clouds extending to the tropopause or higher, with heavy rains and very strong winds. Outside the eye wall, the intensity of precipitation and wind decrease and the strongest activity often occurs in the great bands of convective cloud that spiral inwards towards the centre of the storm. The satellite pictures in Figure 3.5 show Hurricane Floyd’s movement and landfall during September 1999. The structure of the spiral cloud bands and the eye of the storm are clearly seen in these pictures.

3.3.6 The release of latent heat provides the energy which drives the tropical cyclone and this has important implications for its development and dissipation:
(a) Tropical cyclones develop over the oceans where sea-surface temperatures exceed 26°C and there is therefore an abundant supply of water vapour;
(b) Tropical cyclones weaken or change their characteristics when they move out of the tropics over the colder waters of the subtropical oceans;
(c) Tropical cyclones weaken rapidly when they move over land because the supply of water vapour is drastically reduced. Many of these dying cyclones continue to produce heavy rain for a day or more after the winds have weakened substantially.

3.3.7 Awareness of hurricane/typhoon/tropical cyclone track climatology is important for aviation operators. Operators must become aware of the seasons and regions when and where such storms can be expected.

3.3.8 As seen in Figure 3.6(b) and Table 3.2, these storms are frequent over the tropical North Atlantic and North Pacific Oceans during the months June through November. Occasionally one can

Figure 3.6 — (a) WMO Regional Specialized Meteorological Centres (RSMCs) responsible for tropical cyclones; (b) Regions where tropical storms form, the names given to the storms, and the typical paths they take (Ahrens, 1994).
Table 3.2
Typical storm frequencies over various ocean basins

<table>
<thead>
<tr>
<th>Region</th>
<th>Season</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Western North Pacific</td>
<td>January to December</td>
<td>38%</td>
</tr>
<tr>
<td>North Indian Ocean</td>
<td>April to June and September to December</td>
<td>6%</td>
</tr>
<tr>
<td>South-west Indian Ocean (Mauritius and Seychelles)</td>
<td>1 November to 30 April</td>
<td>10%</td>
</tr>
<tr>
<td>Eastern North Pacific</td>
<td>15 May to 30 November</td>
<td>17%</td>
</tr>
<tr>
<td>South Pacific and south-east Indian Ocean</td>
<td>1 November to 30 April</td>
<td>18%</td>
</tr>
<tr>
<td>North Atlantic Ocean, Caribbean Sea and Gulf of Mexico</td>
<td>1 June to 30 November</td>
<td>11%</td>
</tr>
</tbody>
</table>

also encounter early or late season storms. On the Indian Ocean side over the Bay of Bengal and Arabian Sea, these storms are only seen during pre- and post-monsoon months, i.e. April, May, October and November. Exceptions again can occur but during months adjacent to the above. Westward-propagating disturbances from the western tropical Pacific Ocean amplify along the tropical belt. The western Pacific Ocean is another region for typhoon activity. Typhoons occur in this region during the months of July and October.

3.3.9 The southern hemisphere storms have a different climatology. No such storms are seen over the southern Atlantic Ocean. This is understood to be due to the ocean temperature in the storm belt 5°S to 15°S which is generally colder than 26°C and the vertical wind shear (westerlies increasing with height) which is too great to sustain storms. Over the southern hemisphere, the months of January and February are prominent for these storms near northern Australia. These happen to be the months of the Australian monsoon activity when the equatorial trough (and the ITCZ) resides roughly across northern Australia.

3.3.10 This Compendium will not dwell on detailed observational and modelling aspects of hurricanes/typhoons and tropical storms. Several textbooks that deal with these issues are recommended as reference texts in this Compendium, i.e., Anthes (1982) and WMO (1995a).

3.3.11 The map in Figure 3.6(a) shows WMO Regional Specialized Meteorological Centres (RSMCs) responsible for tropical cyclones which are also Tropical Cyclone Advisory Centres of the International Civil Aviation Organization (ICAO).

Table 3.3
Classification of tropical storms based on the maximum sustained wind speed

<table>
<thead>
<tr>
<th>Tropical storm</th>
<th>Maximum sustained wind speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical depression</td>
<td>&lt; 34 kt</td>
</tr>
<tr>
<td>Tropical storm</td>
<td>34-63 kt</td>
</tr>
<tr>
<td>Typhoon/hurricane</td>
<td>&gt; 64 kt</td>
</tr>
</tbody>
</table>

Table 3.4
Saffir-Simpson hurricane damage potential scale

<table>
<thead>
<tr>
<th>Scale no. (Category)</th>
<th>Central pressure (hPa)</th>
<th>Winds (knots)</th>
<th>Storm surge (m)</th>
<th>Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>≥ 980</td>
<td>64-82</td>
<td>~ 1.5</td>
<td>Damage mainly to trees, shrubbery and unanchored mobile homes</td>
</tr>
<tr>
<td>2</td>
<td>965-979</td>
<td>83-95</td>
<td>~2.0-2.5</td>
<td>Some trees blown down; major damage to exposed mobile homes; some damage to roofs of buildings</td>
</tr>
<tr>
<td>3</td>
<td>945-964</td>
<td>96-113</td>
<td>~2.5-4.0</td>
<td>Foliage removed from trees; large trees blown down; mobile homes destroyed; some structural damage to small buildings</td>
</tr>
<tr>
<td>4</td>
<td>920-944</td>
<td>114-135</td>
<td>~4.0-5.5</td>
<td>All signs blown down; extensive damage to roofs, windows and doors; complete destruction of mobile homes; flooding inland as far as 10 km; major damage to lower floors of structures near shore</td>
</tr>
<tr>
<td>5</td>
<td>&lt; 920</td>
<td>&gt;135</td>
<td>&gt; 5.5</td>
<td>Severe damage to houses and constructions, heavy flooding within 500 m of the shore.</td>
</tr>
</tbody>
</table>
decay or acquire the characteristics of extratropical cyclones. There are many variations from this pattern; for example, many cyclones degenerate into tropical rain depressions after crossing a tropical coast. By way of an example, Figure 3.7 provides tropical cyclone tracks for the year 1999 over the Atlantic.

3.3.13 Table 3.2 provides a short summary of seasons and frequencies of tropical storm activity over various ocean basins and Table 3.3 provides a classification of tropical storms as a function of sustained wind speeds. Although there are not many differences from one ocean basin to another, there is a slight tendency for storms over the western Pacific to be slightly larger. The maximum intensity falls over quite a similar range among the conventional intensity categories given in Table 3.4. In this table, the Saffir-Simpson damage potential scale is described.

3.3.14 Currently, many meteorological offices, aeronautical meteorological stations and Meteorological Watch Offices (MWOs) have access to local weather radars that can be used to monitor the passage of severe weather from squall lines, tropical cyclones and heavy rain systems. Figure 3.8 illustrates a typical radar image during passage of a severe storm (hurricane and squall lines). This particular image is of Hurricane Georges, one of the most severe hurricanes that ever affected the Caribbean and the east coast of the United States. Figures 3.9 and 3.10 are further examples of typical hurricane radar images. Such radar images are usually available in real-time on various Web sites in the United States and also in some other countries. Tropical cyclones are also detected and monitored by a combination of satellite, radar and surface-based observing systems and in some areas by specially
equipped aircraft flying a meteorological reconnaissance flight. Satellites are vital, particularly when the cyclone is over the ocean where there are few, if any, other observations. Coastal radar is very effective in providing continuous monitoring when the cyclone is within about 200 km of the coast. Automatic weather stations on offshore reefs and islets can be a very effective component of the supporting surface-based networks.

3.3.15 Aircraft in flight should avoid tropical cyclones and aircraft at airports in threatened areas should be secured or evacuated to another location away from the path of the storm. The main risks arise from destructive surface winds, which exceed 64 kt in a severe cyclone (hurricane, typhoon) and can reach 160 kt or more, and from the heavy rain that can exceed 500 mm a day. In coastal areas, storm surge poses an additional hazard. The storm surge is produced by the combined effects of sudden reductions in atmospheric pressure and strong winds of the cyclone piling up sea water, which causes severe flooding when it strikes the coast. The height of the surge depends on several factors including tides, currents, the shape of the seabed and the coastline, and the angle and speed at which the surge approaches the shore. Typically, the raised dome of water is about 60 to 80 km across and 2–5 metres (6–15 ft) above normal tide level.

3.3.16 Pilots should know of the position and possible short-range tracks of tropical cyclones along their flight plans. A corridor of tropical cyclone surface wind speed in excess of 80 kt is generally to be avoided. Most aircraft fly at upper levels near 30 000 to 39 000 ft above sea level where the winds are generally much lower, but in these areas there can be severe turbulence in the heavy convective portions of the eye wall and the inner rain bands.

3.3.17 Information provided by WMO RSMCs responsible for tropical cyclones, ICAO Tropical Cyclone Advisory Centres, and SIGMETs issued by the MWOs are vital for monitoring tropical cyclones. In addition, it is helpful if pilots are aware of the available Web sites with relayed information. The following is a list of some useful Web sites:

- Kansas City Aviation Weather Center: http://www.awc-ke.noaa.gov/
- National Hurricane Center, USA: http://www.nhc.noaa.gov
- US Navy: http://kauai.nrl.navy.mil/tc-bin/tc_home
- WMO Web Site Link to Tropical Cyclone RSMCS: http://www.wmo.ch/web/www/TCP/rsmcs.html

Figure 3.9 — Radar image of Hurricane Andrew.

Figure 3.10 — Radar image of Hurricane Bertha.
CHAPTER 4

MESOSCALE PHENOMENA

4.1 IMPORTANCE OF MESOSCALE PHENOMENA

4.1.1 A number of smaller (meso) scale phenomena discussed in this chapter are not exclusively tropical in nature and can be found at other latitudes as well. However, because of their importance in the tropics and the hazards they represent for the safety of flight operations and for the discomfort of passengers during eventual encounters, pilots should be reminded or informed about their possible impacts on flights. This is particularly the case when orographic effects, low-level wind shear, clear air turbulence, mountain waves and aircraft icing are discussed.

4.1.2 Smaller scale effects, such as land and sea breezes, are also very important in the tropics, not only in the doldrums where winds are often light and variable, but also in the steady wind regimes of the trade wind belts. The diurnal cycle of the land and sea breezes often introduces a rhythm which governs the changes in wind, temperature, and precipitation and may be similar day after day unless the area is affected by a disturbance, as discussed briefly in Chapter 3. The shape, size, and orientation or mountains are often major factors in determining the location and intensity of wet areas and rain shadows.

4.2 LAND AND SEA BREEZES

4.2.1 Land and sea breezes are usually more pronounced in the tropics compared to areas in the middle latitudes because of stronger solar heating resulting in a larger land/sea temperature contrast. They are very common and very pronounced over tropical coasts and islands where winds are light and variable. The key factor for land/sea breezes is the temperature difference between the land and the adjacent ocean and it does not depend much on the temperature maximum.

4.2.2 In coastal regions, the arrival of the sea breeze is usually accompanied by changes in wind speed and direction, a fall in temperature, and rise in relative humidity and sometimes showers or even thunderstorms. Typically, these changes are experienced within 15 to 50 km of the coast in middle latitudes but the penetration is far greater in the tropics often extending inland to about 100 to 150 km. In addition, the diurnal heating cycle in the tropics is so strong that the airflow may be affected at even greater distances, perhaps several hundred kilometres inland. There may be no change in temperature or humidity, but the airflow may be affected for hundreds of kilometres to a large depth in the troposphere.

4.2.3 The sea breeze is generally a shallow phenomenon whose lower onshore and upper offshore flows occupy the lowest 10 000 ft of the atmosphere. The scale of inward penetration of the sea breeze can be of the order of a few hundred kilometres at most. The night-time land breeze is generally weaker and is not of much consequence to aviation. The ascending lobe of the sea breeze can, under formidable synoptic scale support, develop lines of deep convection, i.e. Cumulonimbus clouds. The prevailing synoptic situation has a strong control on the inward penetration of the sea breeze. Onshore flows support a deeper inland penetration and the converse is true when the synoptic flows are off shore.

4.2.4 The land and sea breeze cycle is an important factor in the markedly different weather often experienced on the windward and lee sides of islands in the trade wind belt. As the day progresses, the sea breeze strengthens the prevailing wind on the windward side but there are no sudden changes in the speed or the direction of the wind. On the lee side, the sea breeze is in opposition to the prevailing trade wind. Sometimes the sea breeze is not able to overcome the prevailing trade wind, and sometimes its onset is delayed. A zone of convergence may build up and the sea breeze will come in as a miniature front when it finally overcomes the trade wind. The development of these sea and land breezes is schematically shown in Figure 4.1.

4.2.5 In the doldrums where there are no prevailing winds, interesting effects occur on islands or peninsulas where sea breezes may converge over land from different directions. This convergence may result in the development of convective clouds, showers, and thunderstorms as the day progresses. A similar effect is sometimes seen in the vicinity of Lake Victoria, in eastern Africa. During the afternoon, the sky over the lake may be clear while clouds form over the adjacent land. This is sometimes strikingly evident on cloud images from Meteosat. During the evening and night, the sea breeze retracts back over the lake as a land breeze develops and increases due to cooling of the surrounding land. In this situation, cloud and showers may occur over the lake during the night. A similar effect is experienced over the east African coast. As the sea breeze develops and moves inland,
showers occur first over the coast, in the morning, and then further inland during the afternoon as the sea breeze penetrates inland. During the evening, the land breeze develops pushing the ocean air back across the coast, the showers move back across the coast and then occur over the ocean overnight as the land breeze extends out over the Indian Ocean.

4.2.6 Double sea breezes have been observed over Florida (just north of the Tropic of Cancer) and the Cape York Peninsula in Australia. In the latter case, convergence between the two sea breezes is thought to be the origin of the magnificent roll clouds, known as the “Morning Glory” that appear over the Gulf of Carpentaria.

4.3 OROGRAPHIC EFFECTS

4.3.1 Mountains are a major factor in determining the pattern of precipitation in areas where there are prevailing winds. In the trade wind belt, the heaviest rainfalls are on the exposed windward side of the mountain and islands and there are rain shadows on the lee sides. If the mountain tops are above the trade wind inversions, then those tops are arid on their upper slopes.

4.3.2 Mount Waialeale (rippling water) on the island of Kauai in Hawaii is one of the wettest places in the world. It is located on the south-eastern edge of a plateau and is directly in the path of the moisture laden north-east trades. The average annual rainfall over a period of 32 years was 11 680 mm, but a few kilometres away there is a dramatic rain shadow and the average rainfall drops to around 250 mm.

4.3.3 Mountains are also important in monsoonal areas. Cherrapunji, another of the world’s wettest spots, is located on the Shillong Plateau in north-east India, where the monsoonal winds sweep up the slope and regularly dump enormous quantities of water from their moisture laden clouds.

4.3.4 Clouds and rain associated with mountains often pose hazards for aircraft operating at relatively low levels in the tropics, as explained in the next paragraph. These hazards are evident, for example, in the mountainous areas of Papua New Guinea.

4.3.5 Mountains affect the local wind flow in a number of ways. For example, funneling between the high ground can result in very strong low-level winds along valleys. Unequal heating, such as when the high slopes are exposed to the Sun in the morning and heat up quickly, results in upslope winds blowing out of the valleys which can be strong in places and which facilitate the onset of a sea breeze if near the coast. In contrast, cooling during the evening leads to a downward flow of cold air into the valleys, which can result in strong winds at times and which facilitates the development of the land breeze out over the sea. In the trade wind belt, a temperature inversion is found between the lower level (easterly) winds and the higher level (westerly) winds. When the inversion is just above the height of a range of hills, mountain wave flow can become established in the air stream. A very strong downslope wind sometimes results over the lee side of the high ground that can pose a threat to low flying aircraft because of its severity. This type of situation is frequently found along the Rift Valley in East Africa, but can occur in similar locations when conditions are favourable.

4.4 THUNDERSTORMS

4.4.1 Thunderstorms occur much more frequently in the tropics than in higher latitudes.

4.4.2 Thunderstorms occur most frequently in the humid continental regions of the tropics, particularly in South America, in Africa and south-east Asia. Maps showing the distribution of “thunderstorm days” for the months of December through February and June through July highlight the strong relationship that exists between the incidence of thunderstorms and the locations and movements of the ITZC. This is particularly evident where there are large seasonal movements of the ITZC as in the south-east Asia/Australia regions. Thunder days near Darwin, northern Australia are rare in the June–August period but increase to an average of 80 days during the wet monsoonal December–February period.

4.4.3 Over tropical oceanic areas, almost all thunderstorms are associated with synoptic-scale disturbances and appear as clusters

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Figure 4.2 — Simplified model depicting the life cycle of an air-mass thunderstorm that is nearly stationary. Arrows show vertical air currents. Dashed line represents freezing level, 0°C isotherm (Ahrens, 1994).
or super clusters. These disturbances sometimes develop into tropical cyclones. Many thunderstorms over land are also associated with disturbances but air mass thunderstorms due to convective heating and orographic lifting are commonly observed and often appear as isolated or scattered storms.

4.4.4 Cumulonimbus (convective) clouds incur substantial vertical development where their tops usually reach well into the upper levels of the troposphere. However, most cumulonimbus cloud tops are restricted in height by the tropopause, the boundary between the troposphere and the stratosphere. This level is significantly higher in the tropics compared to the middle latitudes. As a result, Cumulonimbus clouds with the greatest vertical development are also found in the tropics. As a norm, Cumulonimbus tops reach between 35,000 and 60,000 ft; and when they penetrate into the stratosphere their tops can reach 70,000 ft or more.

4.4.5 Over tropical continents and large islands, thunderstorm frequency shows a pronounced diurnal variation with a maximum in the afternoon period. Over the ocean, the maximum tends to be in the evening or at night.

4.4.6 The life cycle of an air-mass thunderstorm, which is a more dominant type in the tropics, may be divided into three stages, which are illustrated in Figure 4.2. The three stages are the cumulus stage, the mature stage and the dissipation stage:

(a) Cumulus stage — Rising warm air results in a Cumulus cloud growing in moist unstable air. The updrafts in the cloud prevent any precipitation from falling since, at this stage, the cloud droplets are too small. Several small Cumulus clouds may combine to form a single cell. This stage is some 10–5 minutes in duration from the time that radar echoes are first detectable and this occurs soon after the visible cloud crosses the freezing level;

(b) Mature stage — As the cloud continues to develop, both ice and water particles form in the upper part of the cloud, which become sufficiently large and heavy to fall down through the cloud despite the general rising air within the cloud. As a result of this process, downward currents form within the cloud and the droplets accelerate downwards as they continue to grow in size. Some evaporation of the droplets occurs as they fall into drier air. This process consumes latent heat causing the temperature within the “downflow” to fall, which then reinforces the downward plume of air as it becomes denser. As the descending water droplets and ice crystals continue within the cloud, they may cause heavy rain to fall out of the cloud. Both vigorous rising and falling air currents occur within the cloud at this stage. So, if an aircraft penetrates the cloud, severe turbulence could be experienced due to the close proximity of the rising and descending air. The cloud droplets can become charged with static electricity in this turbulent environment which builds up until a discharge occurs in the form of a lightning flash and accompanying thunder. This mature stage of the cloud lasts between 15 and 30 minutes. Some clouds, however, can become multi-cell clouds during the mature stage which means that as one cell declines another cell builds up to take its place. If this occurs, an individual cloud mass can exist much longer than 30 minutes in its mature stage;

(c) Dissipation stage — At this stage, downdrafts spread through much of the cloud, which is then deprived of its energy supplied from the rising core of warm air. As this stage progresses, water droplets within the cloud may completely evaporate leaving only the top half of the cloud composed of ice crystals which are slower to evaporate. The period from the commencement of this stage until vertical motion within the dissipating thundercloud becomes insignificant is of the order of 30 minutes. However, some tropical thunderstorms spread out to form sheets of Cirrostratus and Altostratus layer clouds when conditions are favourable. When these layer clouds are thick enough there may be steady rain overnight with low clouds below persisting into the morning.

4.4.7 The complete life cycle of a single cell convective cloud is typically 55 to 75 minutes. But as indicated above, when a cloud mass contains more than one cell, the cloud can persist much longer. This is particularly the case when severe storm clouds occur which contain several cells within the single cloud mass and conditions are suitable for the cloud to continue to regenerate itself. When this occurs, thunderstorms, sometimes accompanied by tornadoes, can last several hours and travel a long distance. These complex cloud masses are referred to as severe storms.

4.5 SEVERE STORMS

4.5.1 In order for a Cumulonimbus cloud to develop into a severe storm there needs to be a mechanism to maintain the core of rising air and protect it from the effects of the cold falling precipitation. Figure 4.3 illustrates schematically such a mechanism and its possible effects on aircraft during cruise and landing. Rising air is lifted by an advancing squall line and results in a tilted updraft that is protected from the effects of falling precipitation. New Cumulus growth takes place continuously on the left, in the direction of the storm movement, and develops into the main updraft. Precipitation falls from the cloud base into the air which is overtaking it. The colder air of the downdraft spreads forward to regenerate the squall. Thus the storm is able to propagate itself and the updraft is constantly renewed. The updraft may have a superimposed rotation, resulting in helical air motion.

4.5.2 The development of severe storm clouds, as illustrated in Figure 4.3, requires a strong feed of warm moist air into the base of the cloud and a contrasting feed of cooler air into the middle layers of the cloud. This change of wind flow with height can occur with cold fronts and squall lines. These conditions occur

Figure 4.3 — The overall structure of a typical severe storm cloud (Mahapatra, et al., 1999).
more frequently in middle latitudes than they do in the tropics and this is the explanation of what might appear to be a paradox. Although thunderstorms are far more frequent in the tropics than in middle latitudes, the reverse is true for severe storms, namely, they are more frequent in middle latitudes than in the tropics.

4.6 THUNDERSTORM DEVELOPMENT AND PREDICTION

4.6.1 Pilots must be informed of the possibility of expecting thunderstorms for all phases of flight. Nowcasting and very-short-range forecasting, over the duration of flight (plus a few hours) are important for meeting the needs of aviation. In this regard, local convective or potential instabilities, the availability of sufficient water vapour, vertical wind shear and mesoscale convergence are important elements that forecasters watch for. The following are some of the procedures that are most commonly used for the nowcasting and short-range prediction of thunderstorms.

4.6.2 Thunderstorms occur in air masses that exhibit local convective or potential instabilities. Potential instability (also called convective instability) is usually measured in terms of the vertical gradient of the wet bulb potential temperature. If that vertical gradient is positive (or negative), the atmosphere is stable (or unstable). When a layer of air is lifted, saturation can occur, in which case absolute instability can be present. The presence of strong potential instability and a mesoscale convergence area are important factors to watch during take off and landing at airports. More important is the need to predict these features in short-range forecasts with lead time of the order of 12 hours. Such forecasts are now possible with very high resolution non-hydrostatic mesoscale models.

4.6.3 The availability of water vapour is another essential ingredient for thunderstorm development. The total amount of water (measured as precipitable water) varies geographically. Over semi-arid regions and high latitudes, thunderstorms can develop with precipitable water amounts of the order of 5 to 10 mm. In tropical air masses, such as found with the ITCZ, precipitable water amounts can be as high as 50 mm.

4.6.4 Vertical wind shear is another important parameter over the thunderstorm environment. Strong wind shear is a favourable factor for thunderstorms over the middle latitudes. Strong vertical shear of the order of $10^4$ s$^{-1}$ (this corresponds to around 60 kt over a vertical distance of 10 000 ft) is commonly noted in most mid-latitude thunderstorm situations. If the shear significantly exceeds that order, then one can often see weak squall line structures without strong super cells. The situation in the tropics is different. Air-mass thunderstorms (though somewhat infrequent) over the tropical oceans can occur in an environment with much weaker shear. Over West Africa, thunderstorms do occur over regions with strong environmental easterly shear confined between 300 and 150 hPa. Information on the climatology of wind shear with superimposed climatological thunderstorm frequency could be particularly useful to pilots.

4.6.5 Mesoscale convergence is necessary to lift the surface air to the level of free convection before large-scale buoyant convection occurs. That convergence is usually manifested by cycloonic disturbances and even gravity waves. In most cases where moisture of the surface layer air exhibits a stable stratification, the mesoscale disturbances initiate deep convection and resulting thunderstorms.

4.6.6 The presence of warm air advection is also regarded as a parameter for thunderstorm occurrence in middle latitudes. In the tropics, many of the above-mentioned features are not as important. Single cell thunderstorms and clusters of thunderstorms are both abundant in the tropics. The presence of mesoscale convergence and strong potential instability are very characteristic for tropical thunderstorms.

4.6.7 Above all, pilots must rely on information contained in the flight documentation and/or provided during the briefing as well as any additional information passed on to them during the flight. In addition, pilots can use the aircraft radar to assess information on convective activity en route and plan to avoid direct encounter of severe events.

4.7 THUNDERSTORM-RELATED PHENOMENA

4.7.1 A thunderstorm in its mature stage poses many hazards for aircraft. At or near the ground, damage can be caused by wind squalls, turbulence, hail, heavy precipitation and lightning. Downdrafts, microbursts, and related phenomena are potentially lethal. Irregularities in the terrain caused by buildings or natural features can result in the development of small-scale vortices which add to the hazards. In the thundercloud, aircraft can encounter severe turbulence, hail, icing, and heavy rain.

4.7.2 When the downdraft from a thunderstorm hits the ground and spreads out ahead of it, the leading edge of the cool downdraft air is called a "gust front". This can be dangerous for aircraft operations, both because of the strong winds involved (which can exceed 80 kt), and the rapid shift in direction. Gust fronts can generate new thunderstorms more than 200 km away.

4.7.3 Large hailstones occur with severe thunderstorms, but in the tropics severe thunderstorms can occur without damaging hail. This is because of the high freezing level (melting level) found in the tropics, which results in the growth of hailstones being limited so that only relatively small hailstones are experienced. The average annual number of thunderstorm days in central Florida (north of the Tropic of Cancer but typical of the tropics) is over 90 and more than twice as high as over the western Great Plains area of the United States. Another factor is the depth of the surface layer of warm moist air. In the summer, a thick layer of warm moist air extends along the Gulf of Mexico and most hailstones falling into this layer will melt before reaching the surface.

4.7.4 Hail is one unusual byproduct of thundershower raindrops that take a roller coaster ride, eventually becoming hailstones. Warm and cold air currents collides, raindrops fall and hit a strong updraft, which tosses them up to freezing altitudes. They fall and are tossed again, getting larger each time, until they are heavy enough to resist the updraft. Layers in a baseball-sized hailstone show how many times it has been tossed up and frozen. The faster the updraft, the bigger the hailstone will be. Most hailstones are the size of peas. Large hailstones can wipe out a field of crops in minutes, not to mention the damage to cars and windows of homes and other buildings.

4.7.5 Parts of tropical East Africa experience hail during five days per year on the average and in India hailstorms do occur over the northern part of the country and the south-west coast. In tropical Australia, hail occurs occasionally but much less frequently than in east Africa and northern India.

4.7.6 Tornadoes are the most fearsome and destructive of the smaller-scale storms; they occur with severe thunderstorms and are
4.7.9 Downbursts are powerful winds that blast down from a near the ground. Fujita classified downbursts into two types: the 7 August 1975 in Denver, Colorado, that was attributed to a downburst. When the stmm drops rain, it evaporates in the upper levels to the lower levels during the occurrence of downbursts. These occur in the vicinity of ordinary and supercell thunderstorms.

4.7.7 Waterspouts are a relatively small-scale phenomenon similar to, but not nearly as violent as, tornadoes. They occur over water and do not need to be associated with a severe thunderstorm. They appear to be common in tropical regions, particularly over enclosed or semi-enclosed bodies of water.

4.7.8 The "downburst" is considered one of the major hazards to aviation operations. This phenomenon was first described by Fujita (1985). Basically, downbursts consist of rapid descent and surface spread of air. There was a major aircraft accident on 7 August 1975 in Denver, Colorado, that was attributed to a downburst. Figure 4.4 illustrates this major downburst activity based on Fujita (1985). Strong wind shear brings strong winds from the upper levels to the lower levels during the occurrence of downbursts. These occur in the vicinity of ordinary and supercell thunderstorms.

4.7.9 Downbursts are powerful winds that blast down from a thunderstorm. These can be a major hazard for pilots flying in or near a thunderstorm. When the storm drops rain, it evaporates in the dry layer and cools the air. The cooled air is so heavy that it plunges straight down, creating powerful downburst winds on, or near, the ground. Fujita classified downbursts into two types: (a) Macroburst — Greater than 4 km wide and lasts from five to 30 minutes, with wind speeds of up to 154 kt; (b) Microburst — Less than 4 km wide and lasts fewer than five minutes, but has winds up to 200 kt.

4.7.10 Sophisticated Doppler radar systems such as the terminal Doppler weather radar (TDWR) installed at many airports in the United States can be used to detect and warn of the likelihood of downbursts affecting a runway complex. Aside from that, there is no reliable way to predict downburst winds, but one clue is the presence of dust clouds, roll clouds or intense rainfall.

4.7.11 Macrobursts result from larger downbursts and are characterized by a large dome of cold air created by successive downdrafts beneath the parent cloud. As the cold air pushes outward, gusty winds behind the leading edge of the outflow are induced. An aircraft crossing the gust front experiences a sharp discontinuity in wind velocity, which appears as strong localized wind shear. Also associated with the gust front is a high level of turbulence located behind the front. Low visibility due to dust, sand and debris picked up by the turbulent winds are experienced in the gust front. While gust fronts originate from thunderstorm outflow and are found at the leading edge of a macroburst, they can propagate long distances from the parent storm. As a result, it is not always possible for aircraft to avoid a gust front by skirting around visible thunderstorms.

4.7.12 A microburst is a strong concentrated downburst of cold air from the base of a convective cloud, inducing an outburst of strong winds near the surface over a limited horizontal area. The peak gust usually lasts only two to five minutes, but the associated downdraft and horizontal wind shear can represent a very serious hazard to aircraft operating at low altitudes. It should be noted that, while microbursts occur more frequently in higher latitudes, they are nevertheless a common feature in the tropics.

4.7.13 Microbursts may be associated with heavy convective precipitation (the "wet" microburst), or there may be little or no rain reaching the surface (the "dry" microburst). Typically, the wet version emanates from a large convective cell or thunderstorm. However, in situations where the cloud base is high and the subcloud layer is unstable and relatively dry, a very light shower from a thin layer of cloud is sufficient to generate a microburst. In such circumstances, the precipitation may not even reach the ground.

![Figure 4.4 — Example of a microburst-related aircraft accident (Fujita, 1985).](image-url)
Examples of dry and wet microbursts are shown schematically in Figure 4.5.

4.7.14 Downdrafts associated with microbursts are typically less than a kilometre across. When the downdraft reaches the ground, it spreads horizontally and may form one or more vortex rings (Figure 4.6). The region of outflow is typically two to four kilometres across and the horizontal vortices may extend to over 2 000 ft above ground level.

4.7.15 When an aircraft flies through a microburst at low altitudes, it initially encounters an increasing headwind, followed rapidly by a strong downdraft and increasing tailwind. This may result in rapid and potentially hazardous changes in airspeed and may decrease in angle of attack in the downdraft. In Figure 4.7, the effect of a microburst on an aircraft in its vicinity is illustrated schematically. As a microburst affects an oncoming aircraft, it creates an increased headwind which increases lift. To compensate this, the pilot often decreases power only to encounter a sharp tailwind as he exits the microburst. The associated decrease in lift along with the decrease in engine power can bring the plane all the way to ground. Doppler radar wind measurements indicate the wind change that might be expected when flying through an “average” microburst is around 45 kt, although differences of up to 100 kt have been measured. The crash of a large commercial airliner in Dallas-Fort Worth in 1985 promoted a wave of research into on-board detection of possible wind shear for commercial aircraft.

4.7.16 Convection in the tropical atmosphere presents the potential for microbursts. If the conditions are hot and dry, and there is a high cloud base with strong vertical shear, it takes only small Cumuliform clouds and virga (showers not reaching the ground) to generate “dry” microbursts.

4.7.17 Clues to microburst presence (aside from warnings which may come from TDWR-type systems) include:
(a) Reports of hazardous wind shear from other aircraft in the area;
(b) Unusual vertical air speed fluctuations during take off or in the final stages of landing;
(c) Blowing dust, particularly if it has a circular pattern;
(d) Virga, particularly if the cloud base is high and the sub-cloud layer is hot and relatively dry;
(e) Precipitation from convective clouds which has a curling outflow near the surface.

4.8 LIGHTNING

4.8.1 Another important feature associated with the thunderstorms is lightning. A unique property of thunderstorms is their...
4.9 DUST AND SANDSTORMS

4.9.1 Duststorms and sandstorms occur where there is an abundant supply of dry dust or sand, and strong, turbulent winds capable of lifting and transporting dust or sand. In the tropics, dust storms and sand storms can occur in monsoonal regions in the dry season and in any season in areas where the deserts of the subtropical high pressure belt extend into the tropics; northern Africa is an example.

4.9.2 Strong turbulent winds associated with cold fronts or squall lines can cause sandstorms or duststorms extending over hundreds of kilometres. Spectacular examples are the haboobs which occur around Khartoum in Sudan with a frequency of about 24 events per year. Strong, turbulent winds associated with the cold downdrafts preceding a thunderstorm raise dust and sand to form a dense whirling wall which can be 3 000 ft high, filling the space between the surface and the base of the thunderstorm. Their horizontal extent may exceed 150 km and their average duration is about three hours. Sand and dust storms are most common in June but they have been observed in every month except November. Sand and dust storms are most severe in April and May when the soil is driest.

4.9.3 Fine dust raised by winds may be kept in suspension and transported large distances to cause dust haze hundreds of kilometres from the source. An important example is the harmattan, a dry dust bearing east or north-east wind that blows from the Sahara over West Africa from late November until mid-March. In summer, the cooler offshore south-west monsoon undercuts the harmattan but it continues to blow at heights of 3 000 to 6 000 ft and sometimes deposits dust on ships at sea.

4.9.4 Geostationary satellite imagery can help identifying dust and sand storms. Widespread dust and sand storms will be forecast on significant weather charts provided for aviation. Aircraft operators may also look at the available satellite imagery for any possible indications of dust and sand storms.

4.10 DUST DEVILS

4.10.1 Dust devils are relatively small vortices which occur over arid areas of the tropics and subtropics. They form when the ground is dry and dusty, solar heating is strong, the air in the surface layer is unstable and winds are light. Their diameters vary from a few metres to over a thousand metres. Typically, they extend from about 70 to 700 m or more.
4.10.2 Dust devils may rotate either cyclonically or anticyclonically but cyclonic rotation is probably more common in the larger ones. Relative humidity is so low over the arid areas where they occur that the water vapour does not condense and they are denied the latent heat energy that powers thunderstorms and tornadoes. They are given many local names around the world — dancing dervishes, dancing devils, desert devils, sand augers, satans, shaitans, and willy willy.

4.11 LOW-LEVEL WIND SHEAR

4.11.1 Wind shear is a significant hazard to aviation and is a factor in numerous weather-related aircraft accidents. Low-level wind shear is primarily caused by thunderstorms, including the downbursts described in subchapter 4.7. Wind shear is associated with spatial and temporal variations in wind speed or wind direction and can occur at any level in the atmosphere. Low-level wind shear can be especially dangerous as it affects an aircraft's performance during landing and takeoff when small changes in trajectory have potentially hazardous results.

4.11.2 Both horizontal and vertical wind shears can have serious effects on the flight of an aircraft. Wind shear produces changes in the speed of the aircraft, which results in a corresponding change in the lift force. Examples of the effect of vertical and horizontal wind shear on an aircraft flight path are given in Figures 4.8 and 4.9. The loss of height due to wind shear may be irreversible under certain conditions such as when the wind shear is strong and persistent or when the loss of air speed is strong enough to cause the aircraft to enter a stall condition. Low-level wind shear influences aircraft performance near the surface and needs to be quickly corrected or avoided altogether. Therefore, it is important to provide pilots with timely and accurate forecasts of strong wind shear events.

4.11.3 Significant low-level wind shear may also be associated with low-level jets, frontal activity and temperature inversions and orographic influences. While these sources do not compare to the intensity of wind shear associated with microbursts and other wind shear events generated from thunderstorms (see subchapter 4.7), they are important factors of which pilots should be aware.

4.12 TURBULENCE

4.12.1 Turbulence is not an exclusive tropical phenomenon but needs to be discussed here because of the hazard that it may cause

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Figure 4.8 — Examples of the effect of vertical wind shear on flight. An aircraft taking off from ambient headwind conditions into a layer of tailwind through a shear layer would suffer a trajectory drop (a) and possibly stall, and an aircraft descending from a layer of strong headwind to one of tailwind through a shear layer would experience a steeper-than-expected descent (b) leading to a hard landing or crash (Mahapatra, et al., 1999).

Figure 4.9 — The effect of horizontal wind shear on aircraft flight path. The nominal flight path is deflected upward due to increasing headwind (a) and downward due to decreasing headwind (b) along the flight path (Mahapatra, et al., 1999).
to aircraft operations everywhere including the tropics. The phenomenon of turbulence involves random motion of air. It is different from wind shear, which refers to the systematic component of air motion. The scales of random air motion that induce aerodynamic forces of high and medium frequencies are important for aircraft operations as these forces can induce the aircraft to oscillate as a whole. The results of such turbulence can be instability in altitude, loss of control, oscillations in the aircraft's trajectory and structural oscillations. The most visible effects of turbulence on aviation are rough flights which are experienced by most frequent air travelers at one time or another. Flight through a highly turbulent atmosphere causes the airflow into jet engines to vary randomly resulting in erratic variation of the thrust developed by the engines. This further accentuates the problems associated with the vibration and control of the aircraft.

4.12.2 The most frequent and strongest source of atmospheric turbulence that affect flights is associated with thunderstorms, but significant turbulence may also arise from jets, strong surface winds, mountain waves and other topographic factors affecting wind flows.

4.12.3 Clear air turbulence (CAT) is also hazardous for aviation. Middle and upper tropospheric fronts sometimes do not reach the ground. These fronts often contain stable air with strong wind shear. The Richardson number, defined as the ratio of the stability of the air and the square of the wind shear, is an important index for the likely generation of CAT from vertical wind shear. This ratio often becomes much less than 1; values such as $< 0.25$ are often considered important for the generation of clear air turbulence from vertical shear. This can occur with a tropopause fold and the incursion of sloping stratospheric stable air into the troposphere. Across this layer, rather strong wind shears of the order of 20 to 40 kt per 100 hPa can be encountered. Those are possible regions of clear air turbulence.

4.12.4 This type of information is not generally available from Weather Services in advance since the scale of these upper fronts are very small and are often missed by upper-air data sets. However, CAT is indicated on WAFS SIGWX charts distributed to pilots before they fly or while flying, and SIGMETs will be issued based on reported and/or forecast significant CAT. Airborne measurements of wind shear can provide some advance warning of the possibility of CAT. Sometimes aircraft following each other can produce what is called 'aircraft wash' that can amplify the CAT. In such cases, an aircraft following another can experience more severe turbulence.

4.13 LOW-LEVEL JET STREAMS

4.13.1 Low-level jets or nocturnal jets can produce wind speeds of the order of 20 to 60 kt at a height of approximately 1 000 ft above the surface. Although this type of jet is not exclusively a tropical feature, as it can also form at other latitudes, it is nevertheless important to mention it here because of the serious hazard it represents for aviation and its importance in the tropics. The wind speeds below this level are often much lower due to friction. As a result, significant vertical wind shear may be experienced by an aircraft ascending or descending through this region. The occurrence of a low-level jet above a temperature inversion can lead to strong shearing effects. Temperature inversions often form on calm nights under clear skies where significant cooling takes place at the surface, resulting in a layer of cold air below and warm air above. At the interface of the warmer and colder layers, wind shear occurs. When this shear is coupled with the effect of a low-level jet, strong wind shear may be generated in the region between the low-level jet and the temperature inversion.

4.13.2 Differences in air pressure on either side of the developing low-level jet help to concentrate the flow of air into a corridor or stream a few hundred kilometres across. Winds in the stream can flow at speeds of 50 kt or more. Mountain ranges can further enhance low-level jet stream winds.

4.13.3 Night-time, low-level jet streams are marked by a rapid change in wind speed with height. The sudden shift in wind can catch late-night fliers by surprise and be hazardous to landing aircraft. And low-level jet streams can form other hazards for pilots.

4.13.4 When strong winds blow across a body, water waves form. The atmosphere reacts in a similar manner forming waves of air (turbulence) on the edges of the inversion layer.

4.13.5 Daylight brings an end to the night-time low-level jet. Once the Sun heats the surface, the lower atmosphere begins to mix as the warm air rises. The temperature inversion set up the night before is broken and the jet rises in some places and sinks in others like a giant roller coaster. Without a smooth surface to glide over, the jet encounters friction and its speed slows.

4.14 MOUNTAIN WAVES

4.14.1 Mountain (lee) waves are often encountered by aircraft on the immediate downwind side of mountains. Very-high resolution aerial and satellite photographs often show a linear grid-like pattern (parallel to a mountain range) of clouds and clearing. It can be encountered during ascent and descent of aircraft if the airports are located close to such regions of encounter.

4.14.2 The horizontal scale of the mountain waves is generally of the order of 10 to 20 km. The associated vertical motion can be of the order of a few metres per second. They generally form when winds have a component normal to the linear mountain range of the order of 20 to 40 kt or larger. Weaker mountain waves (in the lee of mountains) are often used by glider pilots for lift. Stable thermal stratification is favoured for the occurrence of these waves. Cloud lines form if saturation is encountered over the ascending air currents of the mountain waves. Breaking mountain waves leading to rotor clouds are known to be hazardous to aviation. In some of these instances, severe turbulence has lead to some major aircraft accidents.
5.1 INCIDENTS INVOLVING VOLCANIC ASH

5.1.1 The majority of active volcanoes occur where two lithospheric plates occur and one overlaps the other. Long chains of islands, known as island arcs, form in these zones. The mid-ocean ridge system, where the plates move apart on both sides of the ridge, is a second major zone of active volcanoes. A relatively small number of volcanoes occur within plates.

5.1.2 Most of the “arc” volcanoes are found in the circle of fire that rings the Pacific. New Zealand, Papua New Guinea, the Philippines, the Solomon Islands, Tonga and Vanuatu all have active volcanoes but the greatest concentration is found in Indonesia. There are some 130 active volcanoes in the 6,000 km long Indonesian archipelago, including nearly 80 volcanoes that have erupted in the past 400 years. As indicated in Figure 5.1, they occur in chains and groups. Other active volcanoes are located in Central America and the Caribbean. Although volcanic eruptions and volcanic ash clouds are not exclusively found in the tropics, the large concentration of active volcanoes in the Indonesian archipelago, and other tropical areas as well as the threat that volcanic ash represents for the safety of air traffic merit to be highlighted in this Compendium.

5.1.3 A volcanic eruption can throw up enormous quantities of gas and solid particles into the upper troposphere and the stratosphere. It has been estimated that in a single day, 18 May 1980, the Mt St Helens eruption in the United States ejected about a cubic kilometre of dust into the atmosphere. The finer particles of dust may remain in the stratosphere for a year or more but larger particles capable of abrading aircraft windshields and engine fans normally fall to the ground within about four days.

5.1.4 The cloud forming above a volcanic crater after an eruption resembles a Cumulonimbus cloud in its vertical development and may be topped by an anvil at an altitude of 60,000 ft or more. The shape of the cloud will be distorted by variations in horizontal winds at various levels in the atmosphere (wind shear) and the top of the cloud will spread in the direction of the wind prevailing at that level. The ash plume could spread downwind for 1,500 km or more within 24 hours of the eruption. Plumes may attain huge dimensions and be a hazard to aircraft operating over a wide area. The composition of a plume will undergo continued and significant physical and chemical changes during its lifespan.

5.1.5 Ash clouds vary enormously in their composition. Essentially, the ash is produced by the pulverization of rocks or by the discharge of gas into the liquid magnum of the Earth to form a multitude of bubbles (pumice stone). During the eruption, this “soup” of melted rocks bursts into small fragments composed mainly of silica (about 40 to 60 per cent) and smaller quantities of calcium, potassium and sodium. These fragments give the ash its abrasive quality. Volcanic gases released at temperatures of around 1,000°C are composed of water vapor (60 to 99 per cent) and varying amounts of sulfur, chlorine, fluorine, carbon and nitrogen, and very small amounts of other elements are also present.

5.1.6 The mixture changes when ejected into the atmosphere due to the sudden reduction in its temperature (from around 1,000°C to about 20°C) and due to contact with oxygen in the air. Water condenses into fine droplets which react with sulfur, chlorine and other elements to form acid fogs which have a corrosive effect when brought into contact with an aircraft.

5.1.7 Electrical discharges occur in the plumes during the volcanic eruptions, particularly those heavily loaded with ashes, but these discharges tend to disappear when the turbulence in the plume decreases and the plume becomes more stable. An aircraft flying through the plume may reactivate the electrical discharges.
and give rise to the St Elmo’s fire phenomenon. The effects of the electrical discharges on an aircraft are similar to those encountered when flying through a thunderstorm.

5.1.8 In 1982, the Indonesian volcano Mt Galunggung erupted and sent plumes of volcanic ash high into the atmosphere to the operating levels of commercial jet aircraft. A series of incidents followed that alerted the aviation industry to the serious hazards posed by these clouds of volcanic ash. Documented incidents resulting from aircraft encounters with volcanic ash clouds that took place between 1982 and early 1990s include the following:

(a) 5 April 1982 — A domestic Indonesian DC-9 on the Jakarta Yogyakarta route flew through the ash cloud from Mt Galunggung. There was some damage but no abnormal engine operations were reported;
(b) 24 June 1982 — A British Airways B747 (Flight BA9) flew into the Mt Galunggung ash cloud while cruising at 37 000 ft on route from Kuala Lumpur to Perth. St Elmo’s fire, a form of static electricity, was observed on the windshield and an acrid smell was noted on the flight deck and in the main cabin. Within minutes, one engine failed and the other three stalled soon afterwards. The aircraft descended for some 14 minutes to 13 000 ft where the engines were restarted progressively in the oxygen-rich air. Subsequently one engine surged and was shut down. The aircraft landed safely at Jakarta International Airport but damage was extensive; three engines and the front windshields were replaced;
(c) 24 June 1982 — Forty minutes after BA9, a Singapore Airlines B747 flew through the ash cloud, smoke contamination was reported in the main cabin. The aircraft reached Perth safely but an inspection revealed fragments of rock in all engine tailpipes;
(d) 13 July 1982 — A Singapore Airlines B747 at about 33 000 ft flew through a Mt Galunggung ash cloud resulting in multiple engine failures and damage to airframe and power plant systems. The aircraft descended to about 26 000 ft before the engines could be re-ignited and the experience was as terrifying as that suffered by the BA9 three weeks earlier.

5.1.9 Advisory systems were put in place following the 1982 eruption of Mt Galunggung to assist aircraft in avoiding potentially dangerous volcanic ash clouds, but there were further incidents reported in the 1980s which caused considerable concern:

(a) 23 July 1983 — A British Airways B747 at about 35 000 ft that had been rerouted around Mt Galunggung, encountered an ash cloud from Colo volcano. The aircrew noted an acrid smell, very poor visibility and St Elmo’s fire around the windshield. Damage to the aircraft was not significant and it returned to Singapore without further incident;
(b) 19 May 1985 — A Quantas B747 flew through ash from the Soputan volcano in Sulawesi, Indonesia on route from Hong Kong to Melbourne. The aircraft experienced severe vibration for several minutes, the cabin filled with dust and, again, St Elmo’s fire was seen around the windshield but the engines did not fail;
(c) In 1989 — A wide-body passenger jet (KLM 747) destined for Anchorage airport flew into the volcanic ash cloud generated by Mount Redoubt, Alaska and lost thrust on all four engines. The plane entered the ash cloud at 25 000 ft, climbed, lost power, and then rapidly descended to 13 000 ft. The pilot was finally able to restart its engines. The Alaska Range in the area where the plane lost power has peaks from 7 000 to 11 000 ft, so this was an extremely close call;

(d) In 1992 — The effects of volcanic eruptions on aviation were felt well beyond Alaska when a volcanic ash cloud from the Mount Spurr (Alaska) eruption drifted across the continental United States and Canada, shutting down airports in the Midwest and Northeast two days after the eruption. The Mount Spurr ash cloud affected citizens who are normally not concerned about volcanoes.

5.1.10 The unprecedented problems with volcanic ash in the 1980s were no doubt due to the increase in the number of wide-bodied jet operations in particular over Indonesia, a region where there are many active volcanoes.

5.1.11 Some of the lessons learnt from studies of volcanic ash clouds have implications on national and international aviation, particularly:

(a) Ash clouds may occur during as well as after volcanic eruptions and may affect aviation operations far from the cloud’s source;
(b) Communications between commercial, operational and scientific personnel are critical in avoiding volcanic hazards;
(c) It is critical to continue to evaluate the strengths and weaknesses of the current hazard warning system to ensure that the system is capable of meeting the safety of aviation;
(d) Satellite data can show the location of ash plumes;
(e) Dispersion model runs can provide trajectory forecasts of the ash cloud and vital estimates of ash particle size and concentration;
(f) Currently, nine Volcanic Ash Advisory Centres (VAACs) are tasked to provide volcanic ash advisories to MWOs for the preparation of volcanic ash SIGMET messages disseminated to relevant Area Control Centres (ACCs) and Flight Information Centres (FICs).

5.2 VOLCANIC ASH AS AN AVIATION HAZARD

5.2.1 There are several known instances where the particles generated from volcanic ash have been a major aviation hazard. This hazard arises when the particles of volcanic ash are injected by aircraft engines. Near the ground, this hazard is more local, but as the ash and smoke particles disperse in the upper atmosphere, a more widespread region around the volcano is affected. The major hazard to aviation occurs in the upper air if the volcanic ash particles are suspended and the aircraft makes a direct encounter with such a region. In the lower troposphere, the oxygen content intake in the aircraft engine is somewhat higher and the hazard is somewhat lower unless the aircraft makes a direct pass over the volcanic emission.

5.2.2 Aircrews should always be aware of active volcanic regions around the globe. Reports of recent activities that may affect flights to, and from, an airport should be available at the airport. Sudden occurrences of volcanic activities can be most hazardous for flights. The aircrew should watch for strange acrid smell and any unusual signs of scraping sounds and fires. These signs should be taken seriously and efforts should be made to ascertain if volcanic material is the possible cause. Aircrew and flight operators should carefully assess alternate flight plans during such events. Pilots should descend to lower levels, keeping away from the volcanic eruptions and volcanic ash clouds and, if necessary, choose alternate landing sites.
5.3 NATURE OF THE DAMAGE TO AIRCRAFT
5.3.1 The flying time through an ash cloud may only be a few minutes but during that time the engines may be starved for oxygen and considerable damage to the aircraft may be caused by the multitude of tiny rock fragments and acid droplets. Engine surge may be caused by the alteration of the fans' surface due to the abrasive action of silicon particles in the ash cloud. Engine overheating may result from the clogging of cooling holes on the turbine fans after solidification of droplets in the ash plume.

5.3.2 Volcanic dust can cause rapid erosion and damage to the internal components of engines. The problem is that volcanic ash melting point is around 1100°C and the hot section of the jet engine about 1400°C. As a result, when volcanic ash enters the engine, it melts and deposits randomly as it cools. As it builds up, blockage of the high pressure turbine nozzle guide vanes and high pressure turbine cooling holes can cause surge, loss of thrust and/or high exhaust gas temperature. Because the greatest constituent of volcanic ash is silicon, it forms a glazing on the hot turbine components. The dust may block the pilot static system and result in unreliable air speed indications. It is highly abrasive and may cause serious damage not only to the engines but also to the leading wing edges, windshields and landing lights.

5.3.3 Other effects of volcanic ash may include:
(a) Choking of filters and pipes (pitot circuits), a combined effect of aerosols solidification through dehydration and the piling up of dust particles;
(b) The modification of kerosene performance by the introduction in the fuel tanks, through free air holes, of ashes containing lead, zinc, and copper;
(c) Frosting up of cockpit windows by the abrasive action of ashes and abrasion of leading edges and stabilizers;
(d) General corrosion of the metallic skin of the aircraft by acid droplets in the ash cloud.

5.4 MONITORING VOLCANIC ASH CLOUDS
5.4.1 Major international efforts to warn the aviation community about the hazards of volcanic ash clouds are being undertaken. Two major approaches to this problem are the development of new sensors to detect and ultimately to predict the paths of volcanic ash clouds, and to bring educational technologies to pilots, aircraft manufacturers and other stakeholders who must be aware of this serious aviation hazard.

5.4.2 In addition to documented encounters highlighted earlier in this chapter, volcanic cloud encounters by aircraft have become more common in recent years (Casadevall, 1994; Casadevall and Krohn, 1995). Awareness of the need to mitigate such encounters has been heightened by increased air traffic in the western Pacific rim where the Earth’s volcanoes are concentrated. The most serious effects of aircraft/volcanic cloud encounters result from volcanic ash (Rose, 1986) which are distributed into jet flight levels by approximately eight to 15 volcanoes every year (Miller and Kirianov, 1996). Radar systems on-board jet aircraft cannot detect volcanic clouds because of the small size of volcanic ash particles; the visual detection of these clouds by flight crews may be difficult, especially in poor visibility or at night. The problem is exacerbated by the fact that there are many hundreds of potentially active volcanoes that could threaten major air routes. Most of these volcanoes are not monitored and can erupt very sporadically and without warning. However, once an eruption is confirmed, its volcanic cloud dispersal can be predicted with trajectory models based on forecasted global wind fields (Heffter and Stunder, 1993; D’Amours, 1994).

5.4.3 Two satellite-based systems can detect volcanic clouds:
(a) In the ultraviolet spectrum, the total ozone mapping spectrometer (TOMS) on-board the NASA probe satellite detects sulphur dioxide gas and collects volcanic cloud position data globally about once each day (Krueger, et al., 1995) during daylight hours only;
(b) Infrared detectors on-board geostationary and polar orbiting weather satellite platforms are by far the most useful volcanic cloud detectors because they detect volcanic ash directly (Rose and Schneider, 1996), and because these satellites very frequently (about every 15–60 minutes) give nearly global coverage.

5.4.4 As such, these two satellite-based systems are currently the only robust methods that can be used to track systematically volcanic clouds. The two-band thermal infrared algorithm (Wen and Rose, 1994) for volcanic cloud detection has been applied to a number of different eruptions demonstrating that it works well for a variety of different types of volcanic activity. The development of a retrieval method to obtain the mass of ash in a drifting volcanic ash cloud as well as its position has greatly expanded the utility of the two-band infrared method.

5.4.5 Based on these techniques, new sensors have been developed which will change the way ash clouds are detected and monitored.

5.5 WARNING SYSTEMS
5.5.1 Ash clouds commonly look like normal water/ice clouds but cannot be seen by the weather radar carried in the cockpit. Currently, providing warnings to pilots requires close coordination of information between volcanologists, seismologists, meteorological observers, weather forecasters, controllers, dispatchers and the pilots themselves. New sensing technology that can be used to detect and predict volcanic ash clouds is being developed.

5.5.2 Immediately after the BA9 incident in June 1982, meteorologists realized that the ash cloud from Mt Galunggung was detectable in imagery from the Japanese GMS. This provided the basis for early advisory warning systems. Although this was reasonably successful, it soon became evident that:
(a) Rapid and reliable communications are required to provide timely warnings for flight planning and particularly for aircraft in flight;
(b) Timely reports of volcanic eruptions are required from ground based observers and from aircraft in flight (AIREPs); and
(c) In many cases it is not possible to distinguish volcanic ash clouds from water/ice clouds on GMS imagery.

5.5.3 During the past two decades, communications systems have been improved. Equally, there have been improvements in ground based systems for monitoring volcanoes, especially in countries such as Indonesia, Papua New Guinea and the Philippines. However, further improvement in the early detection of impending volcanic eruptions and the subsequent discharges of volcanic ash cloud would be very valuable in all regions.

5.5.4 Research has demonstrated that the use of advanced very high resolution radiometer (AVHRR) data from the United States polar orbiting satellites substantially improves the detection and monitoring of ash clouds. The AVHRR data makes it
much easier to distinguish between water/ice clouds and volcanic ash clouds, but the AVHRR data is only available at six-hour intervals and should be used in combination with imagery from a geostationary meteorological satellite where data is more frequently available.

5.5.5 In collaboration with WMO, ICAO has established a network of VAACs tasked with the provision of advisory information to the aviation community. Volcanic ash advisory information is also intended to assist specialized MWOs in the preparation of SIGMET for aircraft in flight. At present, nine VAACs are operational around the world. A list of the Centres is given in the table below. The activities of these Centres can be found in the Web site addresses provided in this table. Figure 5.2 shows the geographical locations covered by each of the VAACs.

5.5.6 On receipt of information from a MWO, or any other source, that a volcanic eruption has been reported, and/or a volcanic ash cloud has been observed in the flight information region for which the MWO is responsible, a VAAC is expected to take the following actions:

(a) Activate the volcanic ash computer trajectory/dispersion model in order to provide advisory information on volcanic ash trajectories for MWOs, Area Control Centres (ACCs) and, to the extent possible, for airlines concerned;
(b) Review satellite images/data of the area for the time of the event to ascertain whether a volcanic ash cloud is identifiable and, if so, to evaluate its extent;
(c) Prepare and issue advisory information on the extent, and forecast trajectory, of the volcanic ash cloud for transmission to the MWOs, ACCs and, to the extent possible, to airlines concerned, to the London and Washington World Area Forecast Centres (WAFCS), the Vienna International OPMET data bank, to other VAACs, and to Regional Area Forecast Centres (RAFCs) responsible for the issuance of SIGWX forecasts for the area concerned;
(d) Monitor subsequent satellite information to assist in tracking the movement of volcanic ash cloud;
(e) Continue to issue updated advisory information to MWOs, ACCs and airlines concerned at least at six-hour intervals;
(f) Maintain regular contact with other VAACs, as necessary, and the Smithsonian Institution Global Volcanic Network, in order to keep up to date on the activity status of volcanoes in the VAAC area of responsibility; and
(g) In cases where volcanic ash cloud crosses the boundary between VAAC areas of responsibility, the first VAAC should retain responsibility for the issuance of advisories

<table>
<thead>
<tr>
<th>Location</th>
<th>Web site</th>
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<tr>
<td>Washington, United States</td>
<td><a href="http://www.ssd.noaa.gov/VAAC/washington.html">http://www.ssd.noaa.gov/VAAC/washington.html</a></td>
</tr>
<tr>
<td>Anchorage, Alaska, United States</td>
<td><a href="http://www.alaska.net/~aawu/vaacdesc.html">http://www.alaska.net/~aawu/vaacdesc.html</a></td>
</tr>
<tr>
<td>Buenos Aires, Argentina</td>
<td><a href="http://www.ssd.noaa.gov/VAAC/OTH/AG/messages.html">http://www.ssd.noaa.gov/VAAC/OTH/AG/messages.html</a></td>
</tr>
<tr>
<td>London, United Kingdom</td>
<td><a href="http://www.ssd.noaa.gov/VAAC/OTH/UK/messages.html">http://www.ssd.noaa.gov/VAAC/OTH/UK/messages.html</a></td>
</tr>
<tr>
<td>Montreal, Canada</td>
<td><a href="http://www.cmc.ec.gc.ca/cmc/CMOF/vaac/A-vaac.html">http://www.cmc.ec.gc.ca/cmc/CMOF/vaac/A-vaac.html</a></td>
</tr>
<tr>
<td>Tokyo, Japan</td>
<td><a href="http://www.ssd.noaa.gov/VAAC/OTH/JP/messages.html">http://www.ssd.noaa.gov/VAAC/OTH/JP/messages.html</a></td>
</tr>
<tr>
<td>Toulouse, France</td>
<td><a href="http://www.meteo.fr/aeroweb/info/vaac">http://www.meteo.fr/aeroweb/info/vaac</a></td>
</tr>
<tr>
<td>Wellington, New Zealand</td>
<td><a href="http://www.ssd.noaa.gov/VAAC/OTH/NZ/messages.html">http://www.ssd.noaa.gov/VAAC/OTH/NZ/messages.html</a></td>
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Figure 5.2 — The geographical area covered by different Volcano Ash Advisory Centres.
until such time as the hand-over of responsibility has been agreed between the two VAACs.

5.5.7 The Australian warning and advisory system: The Australian system can serve as a useful model. There are no active volcanoes on the Australian mainland but, as required, the Australian Bureau of Meteorology issues a SIGMET if a volcanic ash cloud enters Australian airspace. In addition, the Bureau acting as a VAAC provides a volcanic ash advisory service for the Australian region and areas to the near north. Warnings and advisory messages describe, if known from information provided on the location and height of the ash cloud, the forecast movement of the ash cloud and if possible the dispersion of the gas and particles. The success of these services depends on ground-based volcano monitoring systems in countries to the north of Australia. In particular it relies on Indonesia and Papua New Guinea to provide accurate information on the time of an eruption, the location and nature of ash cloud discharge and the altitude of the ash cloud. Forecasts of the movement and spread of ash clouds are based on numerical forecast data using all available upper wind observations from balloon soundings, aircraft and satellite measurements.

5.5.8 The issue of the warning/advisory messages involves a complex communications network and cooperation between volcanological, meteorological and aviation authorities.

5.5.9 Satellite imagery from geostationary satellites has been used successfully in the past (in conjunction with three-dimensional wind analyses and prognoses) to track volcanic ash plumes; for example the spectacular plume from Mt Rinjani on the island of Lombok, Indonesia, from an eruption on 2 July 1994 is shown in Figure 5.3. The ash plume can be clearly seen stretching from northern Lombok west across the island of Bali, interfering with the heavily used airspace of this popular tourist destination.

5.5.10 However, volcanic ash plumes are difficult to distinguish from normal clouds on conventional infrared and visible imagery. For example, in the image given in Figure 5.3, there is no way of knowing which parts of the smoke plume contain dangerous ash and which parts are simply water or other harmless substances. When the eruption occurs into an already cloudy sky, the problems become complex.

5.5.11 Modern satellites, such as the American NOAA polar orbiting satellites and the Japanese GMS provide a way to distinguish ash from water. These satellites take images at several different wavelength bands, including visible light and several infrared bands. Volcanic ash and normal water/ice clouds have different radiative characteristics in two key infrared bands. While clouds appear cooler at longer wavelengths, ash appears warmer at longer wavelengths. By simply subtracting one band from another, it is possible to identify areas of volcanic ash and process the satellite imagery to show where an apparent ash signature exists.

5.5.12 Having identified where the ash is, and having also used wind analysis to estimate the height of the plume, meteorologists can use numerical modelling techniques to forecast where the plume will move and, as a result, airlines can reroute aircraft accordingly.

5.5.13 In practice, this method of volcanic ash detection has been shown to be quite sensitive. However, it is far from perfect. In particular, the practice suffers from a ‘false alarm’ problem caused by the radiative characteristics of tall tropical thunderstorm (Cumulonimbus) clouds that penetrate into the stratosphere. The effect of volcanic ash can also be masked by the presence of ice in the ash clouds, which was the case with the Rabaul eruption in Papua New Guinea in 1994, where sea water entered the volcano vents and mixed with the ash cloud to form a coating of ice over ash particles. Operational detection and tracking of volcanic ash relies on this method in combination with reports from ground-based observers, pilots and unprocessed satellite imagery. The quality of satellite imagery and the sophistication of processing routines will continue to improve, and new techniques such as the use of TOMS satellite data are becoming available, so the skill of VAACs in detecting ash is expected to continue to improve.

5.5.14 The procedures and techniques described above were tested with considerable success following the eruption of Mt Pinatubo in the Philippines in June 1991.

5.5.15 Reliable equipment, which could be mounted on aircraft to detect ash clouds would be very valuable just as on-board radar is very valuable in detecting thunderstorms and possible turbulence areas occurring ahead of the aircraft.

Figure 5.3 — Satellite image of volcanic plume from Mt Rinjani on the island of Lombok, Indonesia.
CHAPTER 6

GENERAL HINTS FOR WEATHERWISE FLYING IN THE TROPICS

6.1 INTRODUCTION

6.1.1 The tropics often present a weather scenario very different from that ever experienced at higher latitudes. In particular, on occasion, extensive tropical areas are subject to prolonged adverse or, at least, difficult conditions.

6.1.2 Safe flying in the tropics involves a basic theoretical understanding of tropical meteorology, the ability to assess the current weather situation, plan accordingly and modify plans in-flight if circumstances change. These principles are treated broadly in this Compendium. However, for each principle, the pilot should expand his or her knowledge by reference to this Compendium or other relevant publications to learn more about the weather conditions in the country in which the pilot is flying.

6.2 GUIDANCE MATERIAL FOR THE PROVISION OF METEOROLOGICAL SERVICE TO AVIATION

6.2.1 Meteorological service for aviation operators and flight crew members are specified in Technical Regulation [C.3.1.] (WMO, 2001), as well as in ICAO Annex 3, both entitled “Meteorological service for international air navigation”. Information for pre-flight planning and in-flight re-planning as well as for the necessary flight documentation including upper wind and upper air temperature and significant weather forecasts are fully specified. Detailed information on meteorological entities serving aviation, aerodrome meteorological observations, reports and forecasts, SIGMET information and the dissemination of such information to aviation users can be found in ICAO (1997) and in WMO (1990). Aviation users including pilots benefit from having access to real-time meteorological data from various Web sites in addition to the standard, accurate, and timely weather forecasts and operational meteorological information (OPMET data) provided by aeronautical meteorological offices. Some of these Web sites have been indicated in this Compendium.

6.2.2 In collaboration with WMO, ICAO has implemented the World Area Forecast System (WAFS) to provide cost effective, high quality and timely en-route upper wind and temperature forecasts as well as significant weather forecasts that are used for flight planning and flight documentation. The WAFS products and collected operational meteorological information (OPMET) are being disseminated globally to aviation users by satellite broadcasts from two WAFCs, London and Washington. The WAFS satellite broadcasts comprise the satellite distribution system (SADIS) for information relating to air navigation from London covering Europe, Africa, the Middle East and the western part of Asia, and the International satellite communications system (ISCS) from Washington covering the Americas, the Pacific and the eastern part of Asia. Almost all meteorological offices have now access to these WAFS satellite broadcasts and therefore are able to provide timely WAFS information to aviation users.

6.3 UNDERSTANDING BASIC TROPICAL METEOROLOGY RELEVANT TO AVIATION

6.3.1 Chapters 2 to 4 of this Compendium discuss the major tropical weather influences, systems, and weather elements. For each of these elements, the pilot should be able to translate the influence/system into a mental picture of the conditions likely to be experienced along and adjacent to the planned route. For example, an active ITCZ or monsoon trough, conjures up a cloud and weather picture well beyond the limits of visual flight rules. A quiet phase of the ITCZ or monsoon trough present hazardous clouds but with possible gaps enabling safe flight. All the relevant meteorological information should be used during flight briefings to build a mental picture of the weather and clouds to be expected during the flight. It will be important to check cloud base reports against cloud clearance requirements along the route. Most importantly, a pilot should seek advice from a meteorologist or any relevant available source to obtain any clarification of the weather information, if needed.

6.3.2 Adverse weather conditions may be experienced in the tropics well away from major synoptic weather systems. For example, dry season fires could present a very significant visibility problem over a large area as experienced over south-east Asia recently. In these circumstances, a temperature inversion may vertically separate a zone of significantly reduced visibility (below the inversion) from a zone of good visibility (above the inversion). The optimum cruising level can be chosen taking into account the height of the inversion.

6.3.3 A feature of many tropical regions is the relatively strong diurnal consistency in certain weather elements in some seasons. For example, at Darwin (Australia) there is a relatively high frequency of thunderstorms in the late afternoon and early morning in January. This type of information can be useful in the pre-planning stage to avoid the most likely times of adverse weather.

6.3.4 Strong diurnal patterns of weather elements at many locations such as thunderstorms and unique tropical phenomena (such as the “Morning Glory” around the Australian Gulf of Carpentaria), are sometimes associated with certain seasons and times of day. Pilots should learn about any such phenomena and their characteristics prior to flying into unfamiliar tropical areas.

6.3.5 Another feature to be aware of when planning a flight in tropical areas is the effect on take-off performance, of high temperatures and humidity during the day, especially at high altitude aerodromes.

6.4 AVOIDING HAZARDS IN-FLIGHT

6.4.1 Weatherwise, flying demands to keep in touch with the weather not only as it is observed during in-flight, but also as reported by other pilots and ground observations. If reports indicate that the flight is approaching a worsening weather conditions, then the options are to make an alternate landing, hold until the situation improves, or divert. Pilots must keep a safe distance away from the adverse weather conditions, while other options are being considered, or must stay on hold if no improvement in the conditions is expected. While on hold, it is better to stay within a known distance in the vicinity of an airport where it will be safe to land, when such a need arises.

6.4.2 In some instances, it is generally not possible to climb above a towering Cumulus or developing Cumulonimbus cloud in
the tropics. However, one must avoid flying under such clouds. An eight-kilometre leeway from developing Cumulus clouds is recommended, and one should stay as far away as possible from Cumulonimbus clouds. In particular, one should keep away from the clear air under the higher level anvil of the Cumulonimbus clouds where there could be a danger of encountering hail and turbulence. It might prove difficult to continue a planned route when confronted by an extensive line of Cumulonimbus clouds moving as a squall line. The safest procedure in those circumstances would be to make a detour away from the clouds.

6.4.3 One could be confronted with small-scale potentially hazardous weather conditions which may not necessarily be forecast, but which must be given due importance. For example, any funnel shaped column descending from the base of a cloud (whether or not it reaches the Earth's surface) indicates severe or extreme turbulence. The funnel-shaped column may take the form of a tornado, waterspout or funnel cloud. Waterspouts are common in large semi-enclosed tropical waters such as the Gulf of Mexico (United States) and the Gulf of Carpentaria (Australia). Another small-scale hazard is the dust devil, sometimes found over the tropical deserts and semi-arid regions. Dust devils should be avoided laterally and by at least 2 000 ft above the visible top of the dust devil. Landing and take-off should be delayed if dust devils are in the vicinity of a service runway.

6.5 PILOT REPORTS

Many tropical areas, in particular tropical oceans, have few meteorological observations from ground-based meteorological observation network. For this reason, aircraft weather reports (AIREPs) are very important to both the meteorologists and pilots. AIREPs will help to improve weather forecasts over these areas and enable other pilots to build-up a picture of the weather. In particular, if a pilot encounters a severe turbulence or severe icing, it is essential that a special aircraft report (SPECIAL AIREP) is sent without delay to the Air Traffic Service in that area. This will enable the MWO to issue a SIGMET message giving a wide distribution of the information and ensuring that other pilots in the area are warned about the hazards.

6.6 GLOSSARIES FOR AVIATION

The aerodrome weather conditions are essentially described under the METAR, SPECI and TAF codes, METAR and TAF arc, respectively, aviation routine weather reports and aerodrome forecast provided to aviation as part of the flight documentation kit. An excellent summary of these codes are provided under the website http://www.faa.gov/avr/news/metar.htm. All pilots must be familiar with the METAR, SPECI and TAF codes as well as SIGMET data, and with the accessibility of these coded messages and other documentation prior to flight takeoff. These codes are found in WMO (1995c; 1996). Aeronautical requirements that prompted the development of the codes are found in WMO (2001). The Web site http://www.nw-weather.net.com/wx_terms.htm also provides an additional source of weather terms.

6.7 CONCLUDING REMARKS

6.7.1 This Compendium was prepared with pilots and other aviation users in mind. Therefore, the thrust of this Compendium has been to provide the essential meteorological background for flight planning. The knowledge of basic climatology at different vertical levels of the atmosphere has been addressed as a starting point. The amount of real-time aviation weather depiction has increased enormously in recent years. As a complement to the conventional flight documentation available at meteorological offices, Web site addresses that contain a large amount of real-time graphics and visualization are provided throughout the Compendium focusing on identifying only some of the most important sources of weather information.

6.7.2 The issue of lightning threats to the aircraft has been briefly addressed. Pilots do tend to avoid clouds exhibiting a high degree of lightning activity. In Chapter 4, a major emphasis was placed on the aviation hazards arising from severe weather that include thunderstorms, hail, turbulence, wind shear and microbursts. The surveillance of these phenomena using satellite imagery, radar lightning detectors and other conventional surface and airborne instrumentation are addressed.

6.7.3 Chapter 5 discussed volcanic ash in view of the serious threats to the safety of flight operations caused by this type of phenomena. Documented encounters were reported, the nature of the hazards and the available warning systems put in place by ICAO in collaboration with WMO were discussed.

6.7.4 Finally, a wealth of reference material is given at the end of the Compendium for pilots who are interested in more detailed and extended knowledge of tropical meteorology.
REFERENCES


