

## Turning to Meteorology for Teaching and Learning Resources Part III.

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Two earlier parts of a larger work were published by the Mathematical Association of Victoria in their in-house magazine, *Vinculum*, (Volume 44, Terms 2 and 3, 2007). These two parts were subsequently reprinted together in the Bulletin of the Australian Meteorological and Oceanographic Society (Volume 20, No. 5, 2007). The following and concluding part of the article should ideally be read in conjunction with the earlier two parts.

### Introduction to Part III

Adolescents are essentially inquisitive and are keen to explore their natural environment. This article provides opportunities to support and encourage that enthusiasm. These days, it is too easy to fall into the trap of becoming pre-occupied with abstract ideas and submerging oneself in the remoteness of the computing environment. Meteorology provides the student a rich avenue through which to connect to Nature and appreciate some of its wonders. Meteorology deals with a non-linear atmosphere. The “misbehaviour” of the atmosphere is due to the complex arrangement of feedback mechanisms that typify this system (Figure 1). Recursive procedures in mathematics have analogous surprising behaviours on occasions. An appreciation of a complex, non-linear system can be epitomised by a recursive numeric example. (Refer to Burger and Starbird’s book for some examples.) Drawing on meteorology allows this to occur in a manner that assists the student in developing skills, knowledge, experience and their attitudes. This article provides teachers with some ideas and resources, which are aimed at stimulating the teacher. It is a basis for further discussion and distillation of appropriate ideas and resources to enthuse and support the teacher. Yet the ultimate focus is aimed especially for the Level 6 student. In the spirit of free interchange of ideas, the Australian Meteorological and Oceanographic Society (AMOS) is preparing meteorological and oceanographic resources (HREF1) aimed at secondary school teaching and learning in a structured manner.

At Years 9 and 10 (Level 6) (see HREF2 and HREF3), students are looking towards becoming more specialised in their studies. So this is a good time to inspire the students, showing them what diverse opportunities there really are. Outcome-driven training in the workplace is only recently revisiting the advantages of developing helpful attitudes in concert with the skills and knowledge. If we can provide stimulating resources and ideas, we can encourage useful forward-looking attitudes in the students. It is said that our attitudes are very much the product of conditioning. Even common sense and blatant facts do not necessarily change attitudes! Perhaps the positive conditioning of secondary school students is the best way an older generation can hope to assist the younger generation to fulfil a brighter future.

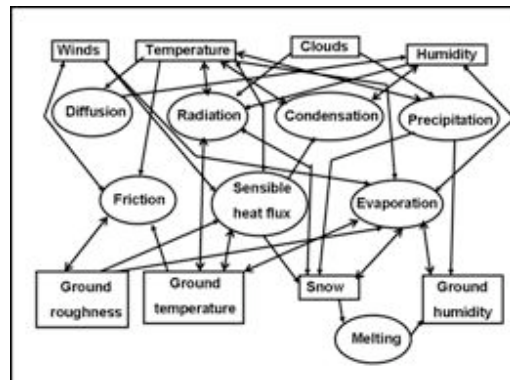


Figure 1: Schematic of inter-related atmospheric feedback mechanisms. Taken from figure 6 (page 85) of Pasini, A, 2005, From Observations to Simulations: A Conceptual Introduction to Weather and Climate Modelling, World Scientific, Hackensack, NJ, USA

### Statistics and probability

The Bureau of Meteorology presides over mountains of data. Typically, climate data is summarised using standard statistical parameters. In its interaction with the public, the Bureau has had difficulty communicating clearly what certain statistics and probabilities mean. The Bureau continues to develop its communication regarding probability and statistics. Sometimes the forecaster couches

the likelihood of an event as a one in ten chance. The public tend to understand this approach better than terms such as likelihood of 0.10 or a chance of 10%. It is not surprising that at times statistical information is followed too literally, leaving the client open to bitter disappointment.

People can apply different meanings to the word, “probability”. If we assume that the *probability of an event* occurring,  $Pr(x)$ , relates to the “population”, while through statistics, the “*likelihood of an event*” is similarly related to a “sample”, then:

- Through probability theory we can *deduce* information about the sample from the population and, through statistics we can *infer* properties of the population (the model) from the sample (the observations)
- The value of  $Pr(x)$  may be available via a general rule or mathematical formula
- An underlying assumption is that in practical terms, the actual value of  $Pr(x)$  is *approached* only after multiple experiments or samplings
- The value of  $Pr(x)$  is not the same as predicting an event will happen or will not happen. If we experiment many times, we will get closer to the theoretical  $Pr(x)$ . A one-off experiment could lead to other values
- A similar argument follows for “likelihoods”. Should likelihood be as accurate as the theoretical,  $Pr(x)$ ? We note that a statistically based “likelihood” may be easier to approximate especially if a theoretical model or formula is not known, or when probability theory only approximates the actual frequency distribution at hand
- Similarly to probability, an underlying assumption is that a “likelihood” is *approached* only after multiple experiments or samplings
- The value of a likelihood of an event happening is not the same as predicting an event will happen or will not happen. If we experiment many times, we will get closer to the “likelihood” of the event. A one-off experiment could lead to other values
- When we make use of a statistically derived “likelihood”, we assume that, given the past experience, the future experience should follow the same pattern, (a linear extrapolation of past experience). There may be no physical connection between this extrapolation and the previous experience. Unfortunately, in the complex, non-linear

atmosphere, no two events are ever identical, (please refer to F Nebeker (c2005) for a history of the development of numerical weather prediction)

- Statistics are useful parameters to describe behaviour of events, however the user has to know how to “hedge one’s bets” to diversify resources and be prepared for the long haul of many repeated experiments to be sure to derive the long term benefits of this sort of information. “Banking the farm” on one likelihood of rain could be ruinous!

As far as the student of meteorology is concerned, there is an enormous amount of freely available “real-time” data as well as archived data to plunder. One can practise the use and interpretation of various descriptive statistical parameters such as the mean, the median, the standard deviation (and variance), extreme values, range of values, and correlation. An excellent example is El Niño – Southern Oscillation (ENSO) data. How do Darwin monthly pressure values correlate with the Southern Oscillation Index?

Other useful statistical methods are the application of deciles, and percentiles. See figure 2 for the derivation of quartiles, four equal areas below the Normal Distribution curve. Quartiles, quintiles, deciles, percentiles are similarly derived. The use of anomalies is another often used approach. An anomaly is the result of subtracting some measure of a mean value of a variable from the current values of that variable. This information alludes to the departure from the norm.

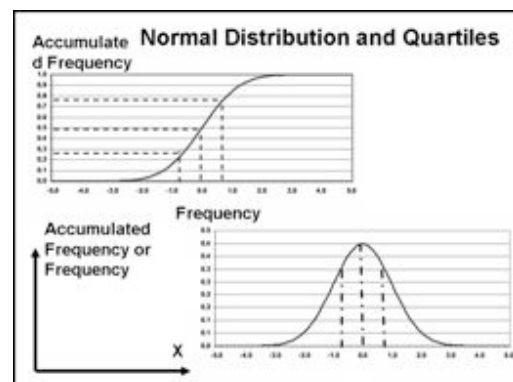


Figure 2 Derivation of quartiles, and so for terciles, quintiles, deciles and percentiles

The fourteenth session of World Meteorological Organization’s Commission for Climatology held in Beijing recognised the importance of working with users to develop a clear understanding of their needs for data and products. The Commission developed a list of action items, including the following:

- Demonstrate to users how to interpret probabilistic forecasts in the context of their specific decision path
- Provide verification information from the user point of view on past forecasts, having them compared with the average climate experience and other alternatives of seasonal climate prediction
- Ensure the reliability and timeliness of the forecasts, and base timeliness on an understanding of the lead-time requirements of the users
- Provide information in sector-specific language, so that users could see the information had been tailored to their interests
- Ensure users were aware of confidence levels and uncertainties associated with the predictions
- Develop partnerships with the media to ensure effective communication of forecast products

Access to the Bureau of Meteorology's climate data, such as rainfall figures, temperatures, winds, and its Seasonal Climate Outlook service is via the Climate Information link (HREF4). In the public domain, there remains a perceived need for applying risk analysis strategies and for a better appreciation of probability and statistics applications in order to interpret the Seasonal Climate Outlook service in particular.

Clients, from farmers depending on climatic advice, to airline companies relying on forecasts for recognised relatively uncertain events such as fog formation, tend to have little confidence in the statistical approach due to an inherent distrust of statistics. The "probabilistic forecast" is really an expression of the confidence placed on an outcome, usually based on past experience. On the other hand, a "forecast" provides a projection of certain specified event to occur or not occur. It is the client's responsibility to work out a threshold of risk that will be acceptable. The Swiss Reinsurance Company's risk perception article *Opportunities and Risks of Climate Change* (Schneider, 2002) states that:

- Statistics never indicate why something happens
- Climate follows natural mechanisms, not statistics
- No reliable forecasts can be derived from purely statistical climatic observations

The non-intuitive nature of probability theory and statistics is discussed in the Neville Nicholls paper, *Cognitive Illusions, Heuristics, and Climate Prediction* (Nicholls, 1999), which he wrote with climate issues in mind.

An example of the distinction between *probability* and *statistics*: Theory says that if I flip a "fair" coin many times, say 100 times, the *probability* of a "head" should be  $\text{Pr}(\text{head}) = 0.5$  (or out of every 100 throws probability theory predicts that 50 "heads" will eventuate). If one actually takes a "fair" coin, flips it 100 times and then performs this experiment a number of times, 49, 51, 48, etc "heads" may result. If there were no theory to guide us, the experiment suggests that flipping 100 "fair" coins, the *likelihood of a head* is around 50 heads in every 100 flips.

A good classroom experiment to explore probability and statistics is to give each team in a class a box of exactly 100 thumbtacks. Before any action, ask each team to estimate the likelihood of a thumbtack landing on its head with its pin pointing upwards. Each team then spills their box of thumbtacks (away from other teams to avoid interference). Each team counts the number of thumbtacks found resting on their heads; results are collated and discussed. Working out a mathematical model, which mirrors the thumbtacks' behaviour could be quite difficult (or, out of the reach of school students at least). Hence there is no easy way to calculate the *probability* in this case and we approximate this value with likelihood - the experiment's outcome.

Communication is a two-way activity. Clarifying the meteorological and climatological terms assists the teacher and the student. It is also important for meteorological and climate specialists to be aware of the public's difficulties in understanding their environment and the various services' attempts to convey their picture of the world.

In order to follow a lifetime of tackling the topic of uncertainty, the book *Understanding Uncertainty* is recommended, (Lindley, c2006).

### **Meteorological and climate issues**

Climate issues are extremely complex and confusing, calling for clear and yet critical thinking. Ideally, we should be balanced and relatively dispassionate in our thinking.

How can we clarify some of the Climate Issues?

- We have to get used to the fact that climate is not static. For example, natural

climate variability means that, depending on the length of record employed, statistics may depict different climatic behaviour.

- Differentiate between Climate Variability and Climate Change. Although there is a cross-over effect (for example, greater climate variability can be the result of climate change) it is preferable to treat the two terms separately. A well-developed appreciation of the natural variability of weather and climate is necessary before an appreciation of climate change is possible.
- Be sure that climate arguments proceed on the same footing. For example, if opposing sides base their arguments on different time scales, there can be no agreement.
- Differentiate between the various climate issues: *The Enhanced Greenhouse Effect* and *Stratospheric Ozone Depletion* are different issues (although there can be a cross-over effect, with global warming affecting the efficiency of stratospheric ozone depletion). It is preferable to treat climate issues separately.

Fresh water supplies are one of the most crucial issues of our time. There is an expectation that if the global patterns of fresh water use persist into the future, there will not be enough fresh water to go around. As a whole, Australia, which is largely placed beneath the sub-tropical pressure ridge line, is probably the driest inhabitable continent. It has the most variable rainfall regime as well, as shown by the Australian Annual and Seasonal Rainfall Variability Maps, the link to which is found in the References below. There are at least three definitions of drought in Australia: rainfall deficiencies (as monitored by the Bureau of Meteorology), insufficient feed due to low rainfall (farmers' definition) and the declared drought, when government pledges aid to the community. The Bureau's rainfall deficiency reports are based on monitoring of drought by statistically comparing the current situation with the past record. (Percentiles and deciles are the statistical tools often used for this sort of task.) Knowledge of the hydrological cycle, where water resides, and how long it takes to recycle in each arm of the cycle, helps us appreciate the fresh water issue. The web-based article *Water Science for Schools: The Water Cycle* (HREF5) prepared by the US Geological Survey is a useful starting point.

When we think of observations and the precision we place on them, and then compare the precision we can attribute to a forecast, we must be aware of the differing time-scales involved, when "looking into the future".

Different time-scales have different precisions and different levels of confidence associated with them. This is why seasonal climate outlooks, based on statistical relationships of past events, can be misunderstood. The Seasonal Climate Outlook service prepared by the Bureau of Meteorology's National Climate Centre is based mainly on statistical relationships (El Niño Southern Oscillation (ENSO) with rainfall and temperature). The Seasonal Climate Outlook refers to rainfall districts (which are relatively broad-scale target areas). These target areas differ in geographic size, and are found in very diverse rainfall regimes around Australia. The estimates are intended to span a three-month forecast period. That is to say, the seasonal climate outlook is far more generalised than tomorrow's weather forecast. The public would gain more benefit from these services if there were a better understanding of probability and statistics and the expectations of the services were more realistic (and the principles of risk management were applied more rigorously).

Our forebears were wise in designing their homes with verandas around the perimeter of their houses, in order to optimise shade. Some took special care in orienting their homes in a certain direction. For example, in Melbourne, it was often thought auspicious if one could have one's property facing north. If one designed a long corridor cutting through the house so that any sea breeze would flow naturally down that corridor, it could act as a cheap and effective cooling system. Bureau resources about house building and related topics are located at the *Climate Information – How Climate Affects Us* web site (HREF6). Sustainability Victoria (HREF7) have other resources, from which excellent practical exercises may be designed.

There are opportunities to make climate issues more applicable to students by quantifying some of the "commodities" that crop up in climate discussions. Visualising what one tonne of carbon dioxide gas is like at standard temperature and pressure is a good example of this. The book *Waterwise House & Garden: A Guide for Sustainable Living* (Windust, 2003) is a practical approach to problem solving with many opportunities for applicable calculations.

The media responses to climate issues are useful practice for students' analysis and application of critical thinking. A classic introduction to climate issues is in *Climate, History, and the Modern World* (Lamb, 1982).

## Geography

Geography teachers have worked with Bureau staff in the past to create curriculum resources. Project Atmosphere Australia Online (HREF8) provides examples of meteorology being used in the Geography curriculum.

The links between meteorology and geography are indeed quite strong. Mapping and map projections are common to both disciplines. Forecasters become quite adept at moving between different map projections in order to cover a great deal of detail during their operational shift. For example, the satellite imagery may be presented in “satellite projection”, or it may be remapped into polar stereographic or Lambert conformal mapping. The tropics may be best suited to Mercator projection, whereas the mid-latitudes may be best represented with a Lambert conformal projection. In terms of meteorology, the forecaster has to consider all geographic scales from global to micro-scale. He or she must learn to specify directions in universal terms, in order to be unambiguous. For example, instead of using “movement towards the south”, often the meteorologist will refer to the motion as moving pole-wards (as distinct from equator-wards). In many ways, the atmospheric motions in both hemispheres are reflections of each other through the plane of the equator. If one were to ask how to define the “tropics” say, the meteorologist finds it more useful to refer to that part of the globe bounded by the sub-tropical pressure ridge in each hemisphere, as the flow near the surface tends to be an easterly flow (coming from the east), whereas in the extra-tropics, between the sub-tropical ridge and the ring of polar front low pressure systems, the flow close to the surface tends to be westerly.

The contour maps showing lines of equal elevation on a geographic map are analogues of the mean sea level pressure (MSLP) pattern on a synoptic-scale map. If one were to follow a low pressure trough line on a synoptic map, it is a bit like following the line of a valley on a topographic map, as by looking to the left and right, one sees higher pressures (higher ground). Following the high pressure ridge line is analogous to walking along a real topographic ridge. The skills a young orienteer picks up by following contour maps for path optimisation are excellent physical activity that could become an entrée into reading synoptic scale weather maps for this reason.

The other aspect of the terrain, which is critical to meteorology, is how topography interacts with the winds to cause local effects, and

generate mechanical turbulence in the boundary layer. This is still a very difficult area to quantify. Modelling turbulence for the sake of more useful forecasts, especially for the Aviation industry, has got a long way to go. Some of the local winds around the world have been named, almost personified (eg the Fremantle Doctor, a sea breeze known to most cricket fans around the world). The result of moist air flowing over mountains has been given a special name, the Föhn Wind: precipitation on the wind-ward side of the mountains causes the moisture content of the air to diminish, so by the time the air flows down the lee side of mountains, it has become relatively dry. The east coast of Tasmania is known locally as the *Riviera* because of the relative balmy conditions there compared to the wet and windy west coast.

## Radiation

Radiation is one of the fundamental disciplines associated with meteorology. It is the differential heating due to the unequal distribution of incoming and outgoing radiation that drives the general circulation. Radiation’s fundamental role in meteorology and weather forecasting can be found at the Bureau’s tutorial *Forecasting the weather* (HREF9).

Ultraviolet radiation is a danger to human life. There is a growing incidence of skin cancer and cataracts in the community. Appreciation of ultraviolet radiation and its impact on life can be linked to the Stratospheric Ozone Depletion issue as well. SunSmart (HREF10) is an initiative of the anti-cancer movement in conjunction with government radiation agencies and the Bureau of Meteorology.

Through many fascinating optic effects observable at times in the atmosphere, such as rainbows, coronas etc, there is ample opportunity to explore the use of geometry. The scattering of radiation from the sun, giving rise to red sunsets and sunrises, yet blue skies during daytime can be explained mathematically by scattering relationships. References covering the topic of natural colour and atmospheric optical effects are Lynch and Livingston (1995) and Minnaert (c1993).

Interest in making use of solar energy and building design can be underpinned with the elementary appreciation of the relationship between, sun, earth, season and latitude.

Satellite imagery interpretation is based on radiation theory. Just appreciating the disposition of the sun, the satellite sensor and the top of a thunderstorm cloud

(cumulonimbus) can help the forecaster to interpret cloud shadows and highlighting in visible images. The interpretation of infrared imagery does have a little trap: the signal from the sensor is purposely re-coded into a grey scale with white for cold surfaces, and black for the warmest surfaces. This convention assists the forecaster to interpret the infrared images. This is counter-intuitive in terms of extrapolating the radiation theory – “the warmer the body becomes the brighter it glows”. The Bureau’s *Satellite Picture help pages* (HREF11) can explain how to interpret infrared imagery as well as visible imagery that is routinely available via the Bureau’s web site. (Much of the Bureau’s satellite imagery is provided by the Japanese Meteorological Agency through its generous and cooperative arrangements between it and the Bureau.)

The radiative properties of various atmospheric gases are the basis for the understanding of the Enhanced Greenhouse Effect. The atmosphere is relatively transparent to solar radiation (short wave radiation) but tends to absorb and reradiate radiation in the infrared bands of radiation (long wave radiation).

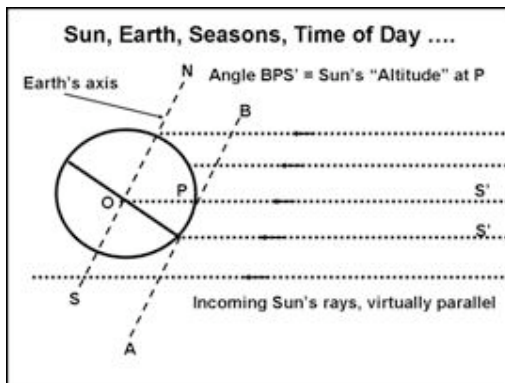


Figure 3 For mid-summer or mid-winter and theoretical mid-day, the sun’s “azimuth” is  $0^\circ$

An example follows of the use of simple secondary school geometry applied to radiation theory. The sun angle depends on the time of year, the latitude of the location, and the time of day (figure 3). Why not look at a special case or two, where the location is the city of Melbourne (latitude  $37^\circ 49'$  longitude  $144^\circ 58'$ ). Take the time to be at noon on mid-winter’s day (or mid-summer’s day)? What is the elevation (or altitude) of the sun (the angle the line to the sun makes with the horizontal plane) at this time in Melbourne? The design of the sundial is based on this principle. The Geoscience Australia web site (HREF12) allows calculation of sun altitude and azimuth for any Australian location at any time of the day, during any time of the year. Geoscience

Australia defines the term “azimuth” as the clockwise horizontal angle (in degrees, minutes and seconds) from true north to the object. There is also listed here a qualification to the above definition of “altitude” or “elevation” for the sake of a deeper appreciation of calculations. Visit the Bureau of Meteorology web site on Solar elevation (or altitude) and solar access (HREF13), to see how sun elevation and azimuth can be utilised in building design.

### Conclusion

The formal study of meteorology, oceanography and climatology requires highly qualified tertiary level students. By including some aspects of meteorology in the curriculum, not only are we providing resources for students to practise important skills and understanding, but these will also be a certain degree of flow-on to these professions in the future. It is hoped as well that there will be flow-on effect to public education. If the general community understands meteorology and weather forecasting products just that much better, the community’s expectation of weather forecasts and warnings will be more realistic, allowing weather forecasting and meteorology to become more effectively used in the community. Subject areas such as probability, statistics and climate issues require interpretative skills. By interacting with the teachers and students, forecasters and meteorologist have the opportunity to improve the utility of forecast products.

Finally, some questions. Do you believe that weather and climate modelling will have deterministic solutions in the future, or do you believe that these activities will continue to have incremental improvements over time? For a phenomenon occurring in the Earth’s boundary layer where surface friction is significant and turbulent flow is a norm, could the relationship between the phenomenon’s typical life-time Time Scale and the corresponding size or Space Scale, the straight line in figure 4, actually have a different slope for these small scale disturbances? At this point we consider one of the Clay Mathematics Institute Millennium Problems (HREF14) in summary:

*“The Navier-Stokes equations describe the movement of liquids and gases. Although they were found in the 19th century, they still are not well understood. The problem is to make progress toward a mathematical theory*

*that will give us insight into these equations. ...”*

It is through the unexpected behaviour of the atmospheric systems that we surely should tantalise the interested teacher and the keen secondary student.

Together with the plethora of easily accessed data, ideas to explore, the availability of background information and the added value of the wonder of our natural environment, the surprises provided by a non-linear (or “misbehaving”) atmosphere should prove to be rich hunting grounds, well into the future.

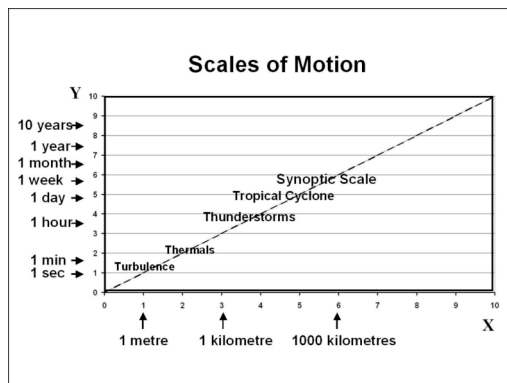


Figure 4 How time and space scales of motion seem to be related meteorologically

### Acknowledgements

The author wishes to give special thanks to Antonello Pasini, for his and his publisher’s permission to use the diagram in figure 3.

The author thanks his wife, Joan Mitchell, for checking over the manuscripts and suggesting corrections and improvements in expression.

As well as:

Dr David Leigh-Lancaster, Key Learning Area Manager, Mathematics, Victorian Curriculum and Assessment Authority; Dr Jeff Kepert, Centre for Australian Weather and Climate Research, formerly of the Bureau of Meteorology Training Centre; John Kennedy, Victorian Curriculum and Assessment Authority; Professor Michael Reeder, School of Mathematical Sciences, Monash University, AMOS Education Subcommittee member; Dr Deryn Griffiths, New South Wales Region, Bureau of Meteorology, AMOS Education Subcommittee convenor; Lachlan Braden, Victoria Region, Bureau of Meteorology

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#### Web-based resources

HREF1: AMOS Education / School Level Links  
<http://www.amos.org.au/education/cid/5/parent/0/pid/5/t/education>

HREF2: Victorian Curriculum and Assessment Authority, Prep to Year 10 Curriculum and Standards  
<http://vels.vcaa.vic.edu.au/essential/index.html>

HREF3: Victorian Curriculum and Assessment Authority, Victorian Certificate of Education studies  
<http://www.vcaa.vic.edu.au/vce/studies/index.html>

HREF4: Climate Data On-line: Data, Statistics and Maps  
<http://www.bom.gov.au/climate/averages/>

HREF5: Water Science for Schools: The Water Cycle  
<http://ga.water.usgs.gov/edu/watercycle.html>

HREF6: Climate Education Site Map  
<http://www.bom.gov.au/site-map/climate-edu-map.shtml>

HREF7: Sustainability Victoria  
<http://www.sustainability.vic.gov.au/www/html/1517-home-page.asp>

HREF8: Project Atmosphere Australia Online (PAA) Geography resources derived from meteorology  
<http://www.schools.ash.org.au/paa2/>

HREF9: Forecasting the weather - A Tutorial  
<http://www.bom.gov.au/info/ftweather/>

HREF10: SunSmart  
<http://www.sunsmart.com.au/>

HREF11: About the Satellite Images: Help pages on satellite imagery and products  
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List of Local Winds  
<http://mediatheek.thinkquest.nl/~11118/en/development/types.list.html>

#### **Other Bureau of Meteorology Web-based Resources:**

Bureau's Climate information: Main menu – includes: Climate Education, The Recent Climate, Australian Maps, Atmospheric Circulation Patterns, Seasonal Outlooks, Drought, Climate, Averages & Extremes, Climate Change, How Climate Affects Us, Data and Further Information, SILO Services for Agriculture  
<http://www.bom.gov.au/climate/>

Water and the Land site  
<http://www.bom.gov.au/watl/index.shtml>

Australian Rainfall Patterns, El Niño Years  
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Australian Annual and Seasonal Rainfall Variability Maps  
[http://www.bom.gov.au/climate/averages/climatology/variability/IDCJCM0009\\_rainfall\\_variability.shtml](http://www.bom.gov.au/climate/averages/climatology/variability/IDCJCM0009_rainfall_variability.shtml)

#### **Books**

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*Making Light of Weighty Ideas.* W. W. Norton & Company, New York, USA

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