

Tropical weather

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1 Introduction

There are two reasons why tropical weather is different from that at higher latitudes. The sun shines more directly on the tropics than on higher latitudes (at least in the average over a year). This makes the tropics warm. And, the vertical direction (up, as one stands on the earth's surface) is perpendicular to the earth's axis of rotation at the equator, while the two are the same at the pole. Because of these two factors, clouds and rain storms in the tropics can occur more spontaneously compared to those at higher latitudes, where they are more often controlled by larger-scale forces in the atmosphere. Because of these differences, clouds and rain are more difficult to forecast in the tropics than at higher latitudes. On the other hand, temperature is easily forecast in the tropics, because it doesn't change much.

2 Heat, Moisture, clouds and rain

The higher the temperature, the more water can be in the vapor phase without condensing. As the sun shines strongly on the tropics — particularly the warm oceans which have an effectively infinite amount of water to evaporate into the air — the overlying atmosphere becomes very humid.

Temperature and pressure both drop quickly with altitude, in the tropics as elsewhere on earth. If air rises — as it can, for example, if it is a little warmer and thus lighter than the air around it — it will expand and cool, eventually causing some of the water vapor in it to condense into tiny liquid droplets, forming a cloud. The latent heat of the condensation warms the air, causing it to become still warmer, and allowing the updraft to rise further. If enough water condenses, the cloud droplets can become large enough to fall as rain.

Sometimes a tropical shower ends quickly, as the clouds and falling rain evaporate. The evaporating rain cools the air near the surface, so that it isn't warm enough to rise into a new cloud. Sometimes, though, the cooling effect as well as the weight of the rain itself can create a downdraft strong enough to create turbulence that in turn

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lifts nearby warm, humid air, making a new updraft (fig. 1) This process can feed on itself to produce a large complex of such storms that maintains rainy weather over a period of days and a region thousands of km in extent, sometimes moving coherently across the tropics and generating new storms as it moves (1). The circumstances that lead to one outcome vs. another — very rainy weather over a large region, completely clear skies, or anything in between — sometimes differ only in subtle ways.

3 Rotation and the Coriolis force

The orientation of the tropics relative to the earth's rotation axis also complicates weather prediction. At higher latitudes, where the rotation axis doesn't make too great an angle to the vertical, the Coriolis force plays a big role in determining which way the wind blows. In the extratropics, the Coriolis force makes the wind blow approximately parallel to the isobars, or lines of constant pressure. In the northern hemisphere, the wind goes clockwise around highs and counterclockwise around lows; opposite in the southern. If there were no Coriolis force, the wind would simply blow from high to low pressure, across the isobars. If that were to happen, the highs and lows wouldn't last long. The wind would equalize the pressure field, flowing out of highs and into lows and making the pressure flat. By preventing this, the Coriolis force allows the highs and lows to exist for a long time. These highs and lows — the weather systems of the extratropics — evolve in a somewhat predictable way, being pushed along by the jet stream and going through cycles of growth and decay that we understand and that computer models are able to simulate accurately, at least for a few days at a time. Strong temperature contrasts — fronts — form where the highs and lows push warm air up against cold air, and clouds and rain tend to form where they push air upwards.

In the tropics, the Coriolis force is weak, and the highs and lows flatten out. Apart from the occasional tropical cyclone, global pressure maps show almost no structure in the tropics. With the flat pressure field comes a flat temperature field (see fig. 2, which shows global maps of temperature, pressure, and a measure of cloudiness, for a single day). There are no fronts in the tropics. Though temperature still drops quickly with height, at a given level the temperature is quite similar at any point within the tropics. So one aspect of tropical weather is quite predictable: the temperature doesn't change much (see fig. 3, which compares a year's worth of surface temperature data from two Australian cities, one in the tropics and one in midlatitudes), so its easy to forecast, even far in advance. For a given upcoming date, just look up what the temperature was on that date in a few past years; it will probably have been not too different in different years, and will be within the same narrow range this year.

Winds and rain, on the other hand, are difficult to predict in the tropics. The absence of strong highs, lows and fronts mean that there are not such easily identifiable large-scale forces pushing the air around and determining where it rises to form clouds and rain. The clouds and rain appear to form more from the spontaneous bubbling up of buoyant convective clouds. When those clouds become big and organized enough,

they can generate their own large-scale weather systems. At any given moment, much of the tropics seems to have the potential for such systems to develop, but most of the time they do not, for reasons that are neither clear to scientists nor well-predicted by numerical models. The humidity field may be part of the answer; regions of higher humidity may be more prone to disturbed weather than drier regions, and humidity varies more than temperature within the tropics, particularly in the upper atmosphere. However, this is not a completely satisfying or useful answer either, because humidity in turn is strongly influenced by the weather, and can change rapidly.

4 Types of tropical weather systems

Once an organized tropical weather system does develop, it may move in a predictable way for a while. Several different types of tropical weather systems exist, each having its own typical characteristics, including its size, speed and direction of motion.

Some disturbances, for example, are known as "easterly waves" because they follow along in the direction the overall trade winds are blowing, from east to west (the opposite direction of the westerly winds at higher latitudes). The term wave indicates a wavy pattern in a map of the wind field over a large area; it has nothing to do with waves on the ocean, except by analogy. Easterly waves have long been well known in the Caribbean, for example (2), where they come after forming over west Africa and moving across the tropical Atlantic ocean. Similar weather systems also occur over the tropical Pacific (3) and Indian oceans. Some of them eventually strengthen into tropical cyclones, which are the most organized and destructive of tropical weather systems.

Some other types of tropical weather systems were first predicted in the 1960s by theoretical meteorologists studying the partial differential equations that govern the motion of a thin fluid layer on a rotating sphere (4), and then discovered to exist first in the stratosphere, above the clouds (5; 6). Later, similar waves were found in moving cloud patterns seen from satellites (7; 8; 9; 10). These are now known as convectively coupled waves (10), and come in several types including Kelvin waves (which move from west to east) and mixed Rossby-gravity waves (which move from east to west). These various waves are somewhat predictable, lasting for periods of days or even a week or more. Computer models still don't capture these tropical disturbances as well as they do midlatitude weather systems, but are improving. The regularity of the waves' motion by itself allows for some predictability using statistical methods (11) (fig. 4). These statistical forecasts essentially just assume that a given wave will continue to move in the same direction and speed as it has thus far.

The tropical climate also has slower variations that are coherent and, to some extent, predictable. The Madden-Julian oscillation (MJO) (12; 13; 14) is manifest in periods of rainy weather and westerly winds, alternating with drier weather and easterly winds. The patterns move from west to east, taking a month or two to complete a cycle. The cycles are not entirely regular, and within a rainy or dry period the weather may differ from what is prevalent during that period (there may

be some rain during a dry period or vice versa) so that knowing the state of the MJO by itself does not allow accurate daily weather prediction. It does, however, give some predictability to the broader state of the climate system over periods of 2-3 weeks or sometimes even longer. On still longer time scales, the El Nino/Southern Oscillation (ENSO) phenomenon (15; 16) causes slow variations to develop in the climate of the eastern and central Pacific, with effects throughout the tropics and higher latitudes as well. This makes some aspects of the climate predictable on horizons of months to a year, though again it does not allow prediction of the weather on any specific day that far in advance.

5 Outstanding questions

Tropical meteorology and climatology are active research fields. The fundamental physical mechanisms behind important phenomena, such as the Madden-Julian oscillation, easterly waves, and the formation of tropical cyclones are not understood. Understanding all these phenomena will require understanding why and how deep convective clouds "self-aggregate", or merge together to form larger weather systems (17; 18; 19).

Along with observations and theory, computer models will play an important role in untangling these mechanisms, but the models are still limited by their ability to represent the physics of convective clouds. Numerical weather prediction, which uses the same kinds of models as are used in basic scientific research, appears also to be similarly limited.

We don't know how far in advance tropical weather can be predicted, even with a perfect model. The answer almost certainly depends on how precise one wishes the answer to be. For day-to-day weather at a single location, it seems likely (but has not been proven) that the intrinsic range of predictability (20) is shorter in the tropics than higher latitudes (21; F. Vitart, pers. comm.). On the other hand, if one is willing to accept forecasts of weather conditions averaged over a week, or a month, and over a larger area rather than a single location, the answer is likely to change. The existence of slower tropical variations like the MJO and ENSO appears to make the tropics more predictable than the extratropics, when such averages are considered.

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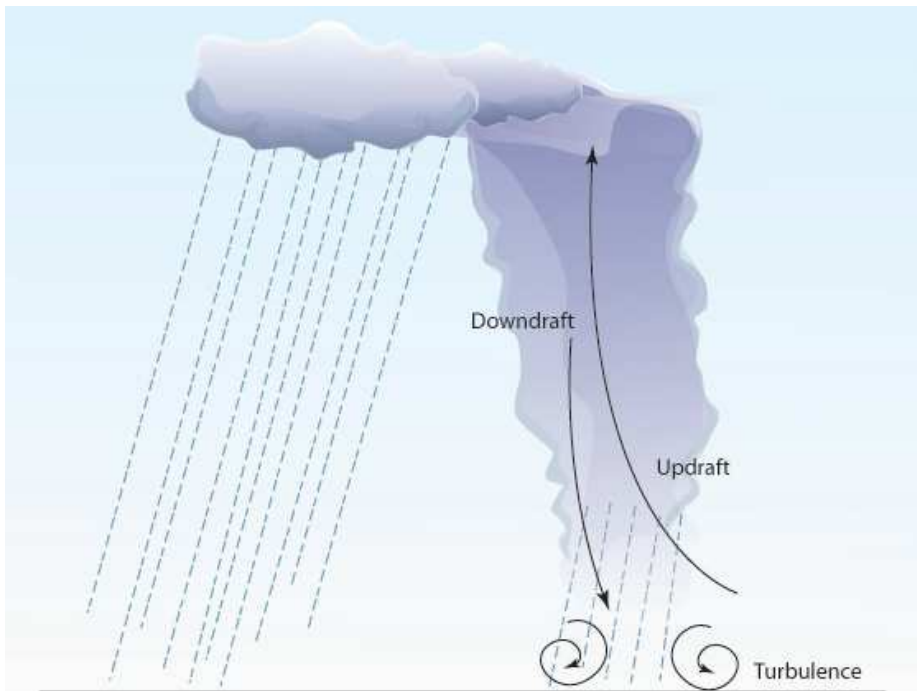


Figure 1: Schematic of deep convective cloud showing an updraft, precipitation-driven downdraft, and turbulence below cloud base.

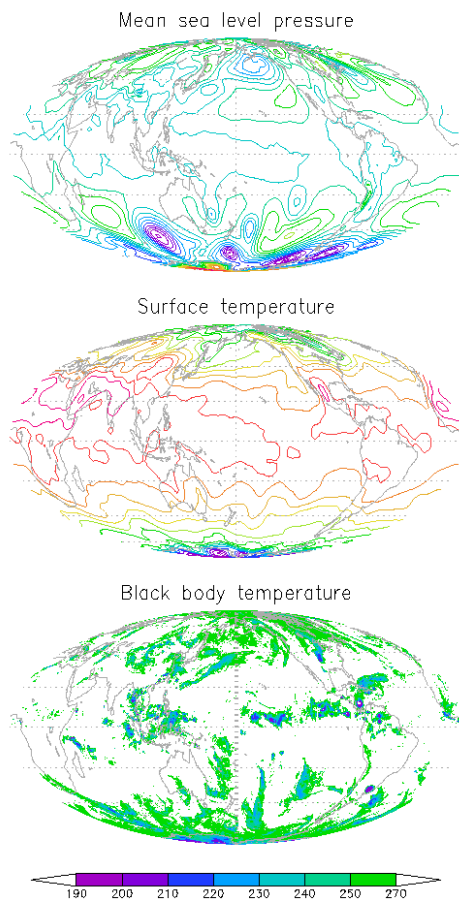


Figure 2: Three weather maps from May 15, 2005. Top: mean sea level pressure, contour interval 5 hPa. Middle: surface temperature, contour 5°C . Bottom: equivalent black body temperature, $^{\circ}\text{K}$; color scale shown below the plot, values greater than 270 are indicative of clear skies and are not shown, while lower values are indicative of clouds and rain. Note the much greater temperature and pressure variations (indicated by many more contours) in the higher latitudes compared to the tropics. Clouds and rain (as indicated by black body temperature) are nonetheless quite different from place to place within the tropics, although pressure and temperature are not.

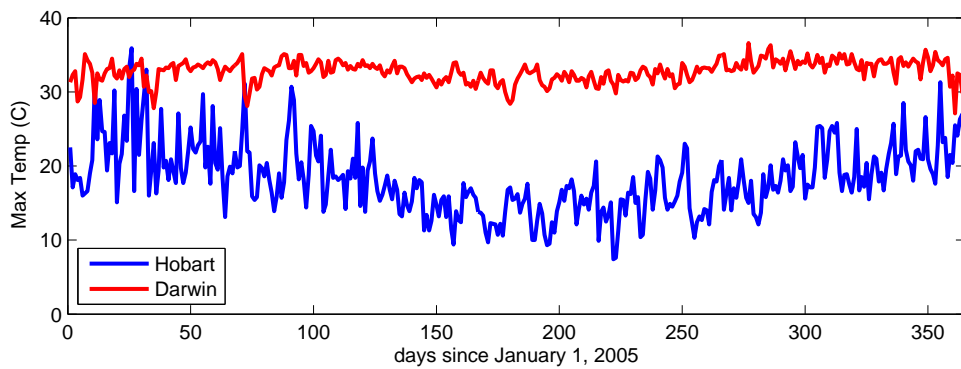


Figure 3: Daily maximum surface temperatures recorded at the airports in Darwin ($12^{\circ}S$, $131^{\circ}E$) and Hobart ($43^{\circ}S$, $147^{\circ}E$), Australia, during the year 2005. Hobart — the higher-latitude city — besides being colder overall, has much greater variations in temperature, both in the seasonal cycle and the day-to-day fluctuations, than does Darwin, the tropical city.

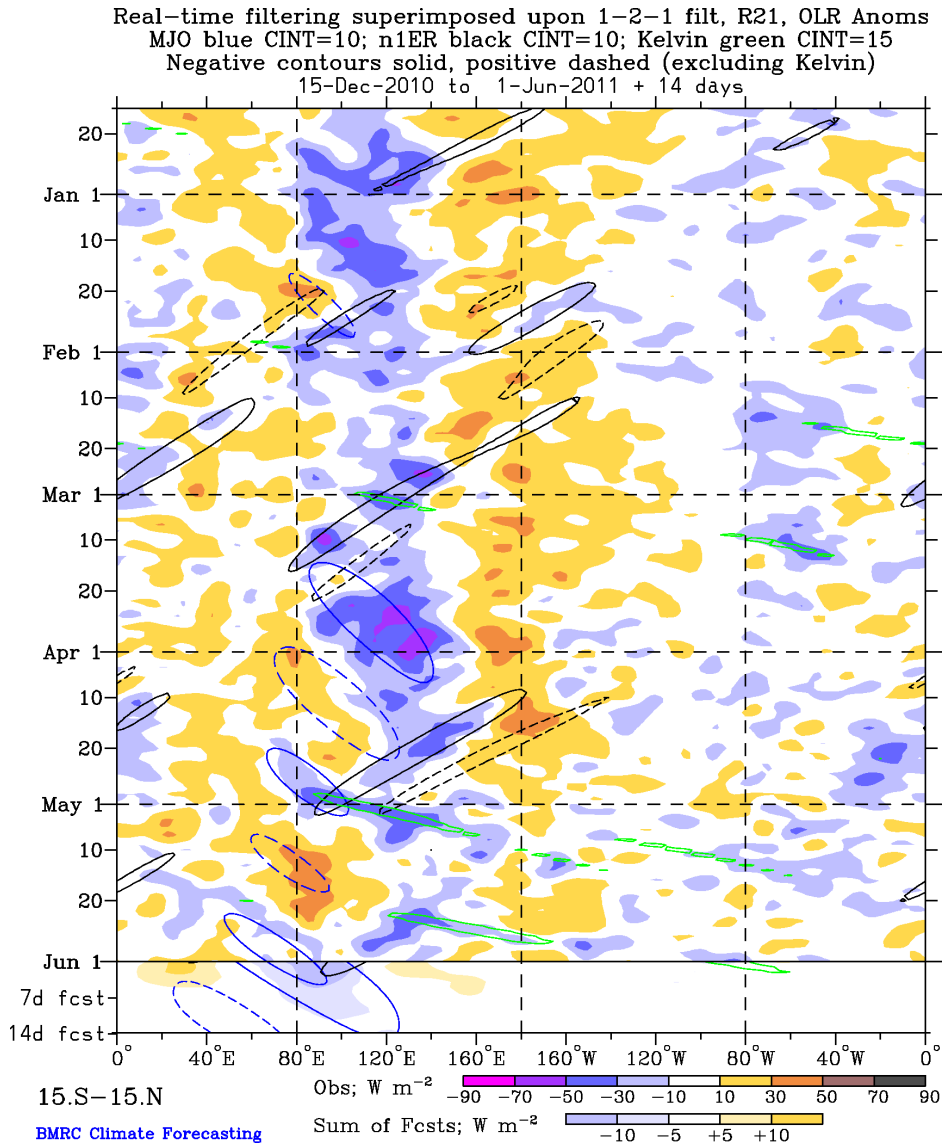


Figure 4: Longitude-time (Hovmoeller) diagram of outgoing longwave radiation (OLR, Watts per meter squared) averaged $15^{\circ}S - 15^{\circ}N$, for a period in the first half of 2011. Shading shows the total OLR anomaly, or difference from the average "climatological" conditions; blue indicates more disturbed, rainy weather while orange and red indicate drier conditions. Features tilted down to the right are moving eastward, features tilting down to the left are moving westward. The different colored contours indicate convectively coupled wave disturbances of different types: blue contours are the Madden-Julian oscillation, black are equatorial Rossby waves, green are Kelvin waves. The period after June 1 shows a forecast produced on that date by assuming propagation of these waves at their normal speeds. Figure courtesy of Matthew Wheeler, Centre for Australian Weather and Climate Research.

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