A storm brewing

Efforts to model the complexities of storm development are fraught with complication due to the myriad feedbacks and contributing factors involved. **Dr Frank Robinson** leads an innovative modelling study that aims to overcome these challenges and significantly improve knowledge of continental convection

What are the main principles of your project? What questions are you seeking to answer?

In essence, by using a combination of numerical simulation and observational data we aim to improve the understanding of where on the Earth the strongest storms occur and why they form in these locations.

The specific goal of the study is to better understand why continental convection is so much stronger than maritime convection. Differences in moisture (convective available potential energy – CAPE), aerosols or topography do not appear to be large enough to account for the observed differences in convective severity over land compared with oceans. For example, updraft speeds in continental storms are consistently stronger by about an order of magnitude than maritime storms. We propose that this variation in updraft speed is the primary reason why lightning is ~10 times more likely to occur over land than over water.

Why has research into the substantial variations in the intensity of both tropical and mid-latitude summertime deep convection not been conducted before?

It has – but previous studies typically focussed on other causes such as thicker continental boundary layers leading to fatter updrafts that entrain less and thus lose less buoyancy to dilution, or the influence of humidity, CAPE or aerosols (ie. microphysics). In contrast, our research has shown that the primary reason for stronger updrafts is surface heterogeneity. Certain 'resonant' horizontal heating length scales (ie. hot spot size or width of heated patches) dynamically force strong updrafts. In other words, we find that dry boundary layer dynamics (0-2 km) plays a major role in determining the vigour of deep moist convective updrafts (5-15 km).

Moreover, what are the major shortcomings of established methodologies that have hindered such research efforts, and how will you address them?

Our approach uses a combination of satellite observations and numerical modelling to examine what controls the intensity of storms (more specifically updraft speed). By running a large number of simulations of 2D idealised islands and comparing directly with satellite measurements such as brightness temperatures and radar reflectivity, we are able to identify robust trends in the observations and corresponding simulations, rather than draw conclusions based on one or two sophisticated 3D high resolution computer intensive simulations.

What efforts have been made to supplement the Weather Research and Forecasting (WRF) model to help understand departures of convective cloud vigour?

We have taken WRF simulation output and run it through a satellite simulator code (SDSU) to compute observable quantities such as brightness temperatures and radar reflectivity. Once we identify a signal in the observations that is also picked up by the simulations, we can examine the dynamics and thermodynamics of the simulated data and try to establish causal relationships.

Have you made any significant progress in advancing our basic understanding of moist, buoyantly-driven atmospheric convection? How have you approached this?

Our results indicate the potentially greater role of boundary layer dry dynamics in determining storm strength. More specifically, we believe that the diameter of an island and the proximity of that diameter to the resonance length may play an important role in determining how much lighting/severe weather will occur over a particular island. Our results imply that aerosols or CAPE play a minor role compared to heterogeneity in determining the severity of deep convection.

How are you seeking to establish the connection between these clouds and turbulence within the global atmospheric circulation? What are the potential consequences of this?

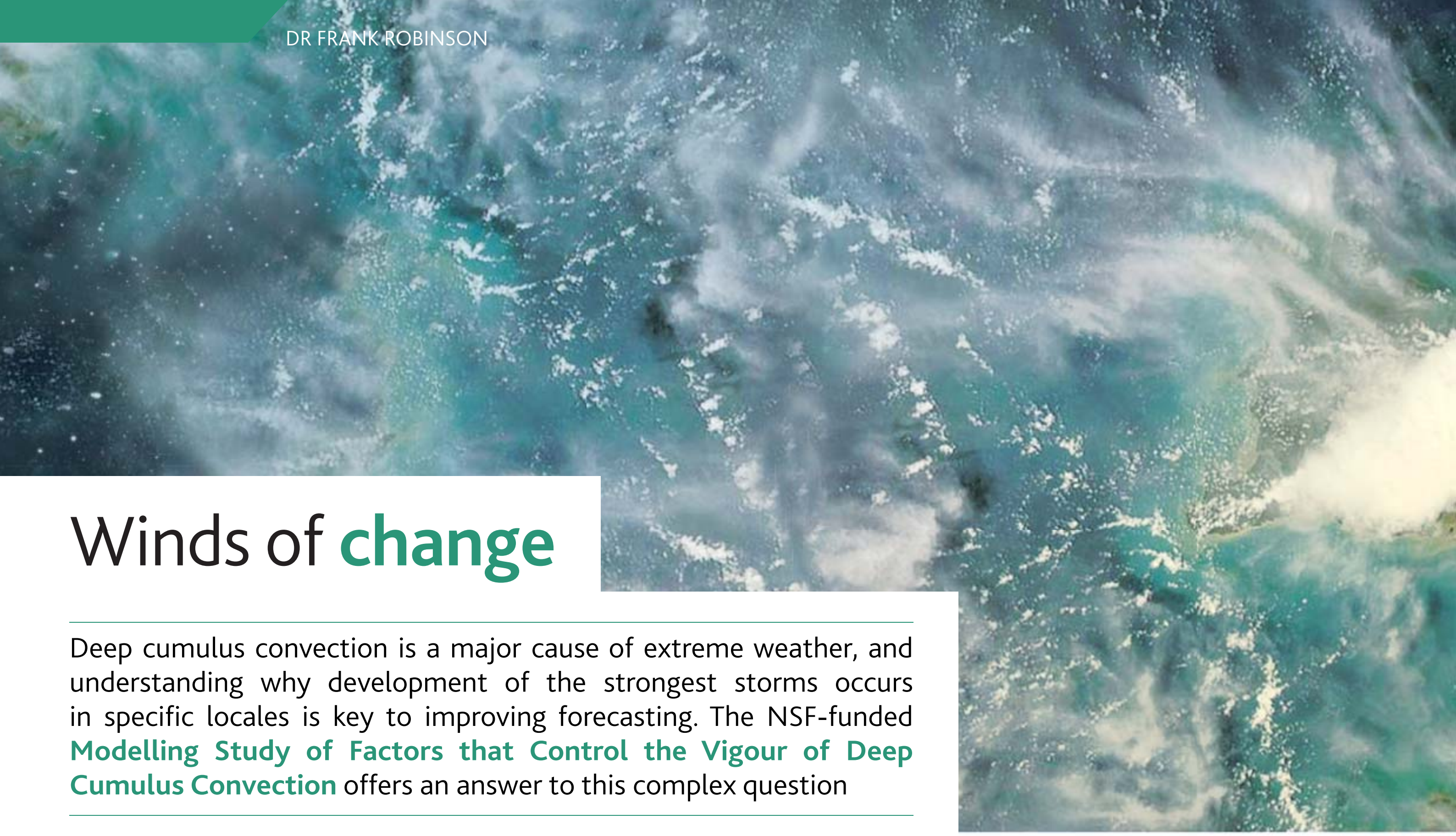
Convection in the atmosphere is a significant weak spot in our ability to model the global atmosphere and how it will change as more CO_2 is added to it. Our strategy for gaining traction by using island-driven convection as a test bed for ideas on how convection works could lead to improved treatments generally for convection in global circulation models.

Moreover, how are you engaged in outreach and what impact does it have?

I use parts of this research project in my undergraduate teaching. Movies of super strong cumulonimbus events, such as Hector near Darwin, and simulations of them, show students what we are currently capable of achieving with computers and state-of-the-art of regional climate modelling.

What do you hope to achieve before the project's conclusion?

We hope to demonstrate the importance of our resonance mechanism in determining storm strength and that incorporating this effect into large scale modelling can improve predictions made by models.



Winds of **change**

Deep cumulus convection is a major cause of extreme weather, and understanding why development of the strongest storms occurs in specific locales is key to improving forecasting. The NSF-funded **Modelling Study of Factors that Control the Vigour of Deep Cumulus Convection** offers an answer to this complex question

IN 2011, MORE extreme weather events occurred than in any previous year on record. Large parts of the U.S. were ravaged by a total of 1,706 tornadoes, leaving 552 confirmed dead. To better understand such weather incidences, and ultimately improve forecasting techniques, researchers are studying the multifarious factors associated with deep cumulus convection.

Atmospheric convection is the result of atmospheric layers with differing temperatures coming into contact. The rate of change in temperature observed while moving upward through the Earth's atmosphere is known as the lapse rate, and different lapse rates within dry and moist air cause instability. This instability expands the height of the planetary boundary layer and results in increased winds and cumulus cloud development. Moist convection leads to thunderstorms responsible for severe weather including hail, downbursts and tornadoes.

Observations show substantial variations in the intensity of deep convection on land that are not explained by standard measures of instability. One feature that distinguishes land surfaces from those of the ocean is their heterogeneity. Data from islands therefore provide an ideal focus for modelling, allowing researchers to establish effective comparisons between the two surface types. The potential importance of all factors controlling deep cumulus convection – including land surface-atmosphere dynamics – is under investigation by a collaborative project headed by Dr Frank Robinson, Research Scientist in the Department of Geology and Geophysics, Yale University.

The research group, funded by the U.S. National Science Foundation (NSF) Physical and Dynamical Meteorology Program, aims to meet its objectives by calculating the atmospheric response to localised, transient surface heating by combining two models: a configuration of the Weather Research and Forecasting (WRF) numerical model with moist physics; and the linearised equations of motion. They are employing these techniques to better understand and quantify the role of variable mid-level atmospheric moisture, heterogeneity in surface heating, and topography in determining the vigour of cumulus convection: "Rather than attempting to simulate a particular island as comprehensively as possible, we simulated hundreds of different 2D islands and compare with overall trends in observations," Robinson elucidates. "In doing so, we try to eliminate other possible causes of convective vigour such as changes in convective available potential energy (CAPE), aerosols or fatter updrafts over continents compared with oceans."

BUILDING ON PAST WORK

Previous studies by researchers in the field have shown that boundary layer convection prefers certain scales that are not limited to those of the boundary layer thickness itself, while others have revealed that deep convection can be organised by waves, including self-generated ones. Robinson's modelling study directly augments these assertions: "Our results indicate wave modulation is a function not only of the horizontal organisation of convection, but also its strength, even for deep convection in a conditionally unstable environment," he states. "These findings have several implications. Variations in convective intensity can result from mesoscale thermal forcing without changing the thermodynamic values." This aspect of the research group's activities highlights the limitations of parcel theory in fully explaining updraft strengths and convective severity, suggesting a greater appreciation of wave dynamics is required.

The role of wave dynamics can be understood as a resonant interaction between heated rising air and surrounding air. Convection produces buoyancy waves; indeed it cannot proceed without doing so. Convective growth and latent heat release are necessarily accompanied by large-scale motions – including upper-level divergence and surrounding subsidence – and these motions initiate waves. It appears that convection is stronger in instances when it is forced in a way that allows buoyancy waves to develop unimpeded. Further work is underway to confirm this explanation.

OPENING ROUTES TO NEW RESEARCH

One significant result is that the WRF updraft speeds and parcel sizes were about 30 per cent higher for a colder sounding (the measurement of vertical distribution of the atmospheric column) even though the atmospheric soundings had the same profiles of buoyancy

FIGURE 1. An example of strong deep moist convection over Melville Island (known as the hector) – a 50 by 100 km island north of Darwin which has daily updrafts that reach up to 15-20 km during the monsoon season.

> Moist convection leads to thunderstorm development, which is often responsible for severe weather including hail, downbursts and tornadoes

and relative humidity: "If this result is robust, it implies that in different climates, the variance of dry static stability may lead to different convective strength for dynamical reasons in addition to whatever microphysical effects the differing water vapour mixing ratios might have," Robinson explains. It is possible that this temperature sensitivity is due to differences in the role of latent heating and cooling at the edges of the convective drafts, but the collaborators have left this topic for future research.

Another path for pursuit in future research is the topography of the islands: "While we did not find that 3D cloud-scale behaviour made a significant difference, we did find that simulated storm severities are quite sensitive to, among other things, the shape of islands in 3D," Robinson outlines. "This will complicate idealised studies in 3D and is worthy of further investigation."

FUTURE IMPACTS

Ultimately, Robinson and his collaborators have shown that strong continental convection is attributable to size of surface heating and that the contributions of sounding differences, boundary layer thickness, or aerosols are negligible. This supports the finding made by Robinson *et al* that convective strengthening is due to wave dynamics.

The research group at Yale have therefore made significant progress to date, generating results which, on one hand, progress the understanding of this complex field of meteorology, and on the other, have highlighted significant areas to explore in future studies. The researchers have also been pragmatic in understanding where areas of weakness lie and identifying likely outcomes in these areas: "It should be noted that, due to the large number of simulations required, the mechanism we have developed is yet to be tested in 3D simulations," Robinson states. While the same dynamics should apply in 3D, he elucidates that their importance relative to other factors such as draft entrainment could be altered: "We have compared a linear model with periodic time forcing with a numerical calculation of a single event; possible problems with this have not been studied carefully, but may not be overly important in light of the consistent behaviour between the two calculations".

The broader impacts of this work include contributions toward more accurate simulations of local/regional weather and global climate, as well as offering a means to more reliably anticipate expected changes in convective activity in the presence of climate change. Beyond this, Robinson highlights that their work is not only applicable to weather events and climate: "We anticipate that the ability of volcanic eruptions and nuclear blasts to reach into the stratosphere will also be significantly affected by the horizontal extent of heating". Robinson's group have clearly made efforts to maximise the potential of the modelling study, offering a framework which other atmospheric modelling projects are able to utilise as a point of departure.

INTELLIGENCE

A MODELING STUDY OF FACTORS THAT CONTROL THE VIGOR OF DEEP CUMULUS CONVECTION

OBJECTIVES

To employ model calculations capable of resolving multiple factors influencing such clouds to better understand and quantify the role of variable mid-level atmospheric moisture, heterogeneity in surface heating, and surface orography (ie. sloped and elevated terrain) in determining their vigour.

KEY COLLABORATORS

Professor Steve Sherwood, University of New South Wales

Professor Daniel Kirshbaum, McGill University

David Gerstle, MIT

Dr Yanping Li, University of Hawaii

FUNDING

U.S. National Science Foundation (NSF) Physical and Dynamical Meteorology Program – award no. 0758550

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DR FRANK ROBINSON is a Lecturer and Research Scientist at Yale University and has degrees from Leeds, Oxford and Hong Kong (HKUST). While at Yale, he has published numerous peer reviewed articles on stellar physics, atmospheric convection and laboratory convection experiments. He is also heavily involved in undergraduate teaching and has created and taught several new classes in Yale College, such as 'Movie Physics' and 'Science and Pseudoscience'. He is a fellow of Timothy Dwight College.

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