Climate and Oceans Support
Program in the Pacific

ACCESS-S Workshop

MODULE: Coupled Global Ocean-Atmosphere Climate Model Predictions in general

Topics in this module

- What is a model?
- History of weather models
- Numerical weather prediction
- Model initialisation
- Difference between weather and climate models
- Ensemble predictions

Expected learning outcomes

- History of climate models
- General understanding of what is required to run a dynamical weather or climate model

These outcomes are important for understanding and interpreting ACCESS-S outputs and products

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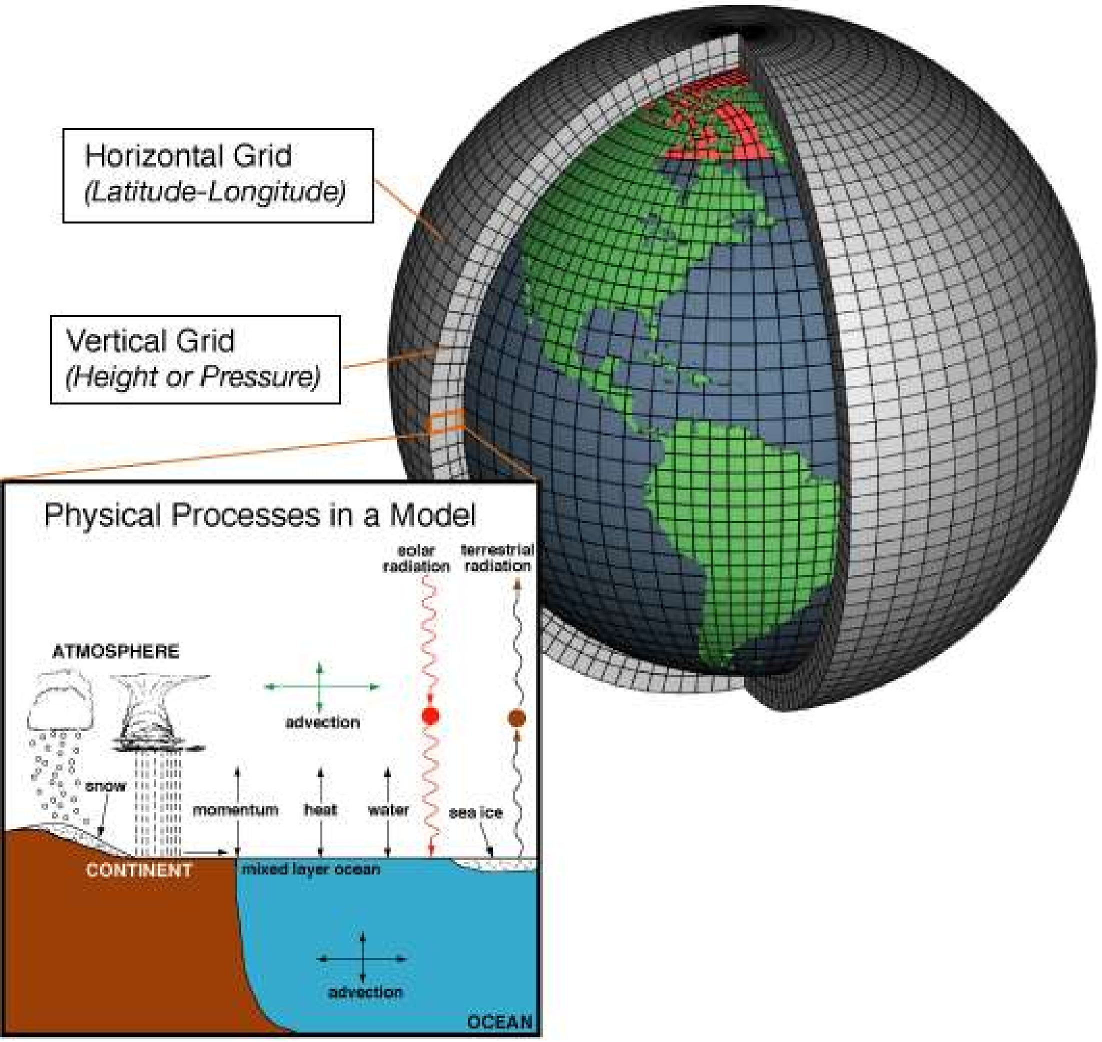
What's in a Model? Numerical Weather Prediction (NWP)



Models are often simplified by the term Numerical Weather Prediction (NWP), but they also include oceans! Models use a coordinate system which **divides the planet into a 3D grid**.

Models are systems of **differential equations** based on the **laws of physics** which cover**:**

- fluid motion
- thermodynamics
- radiative transfer, and
- chemistry.

Models calculate in each grid cell:

- Winds
- Heat transfer
- Relative humidity
- Phase changes of water
- Surface hydrology

Each grid cell interacts with neighbouring cells to calculate information for the future. **Coupled models** include the atmospheric model and an ocean model.

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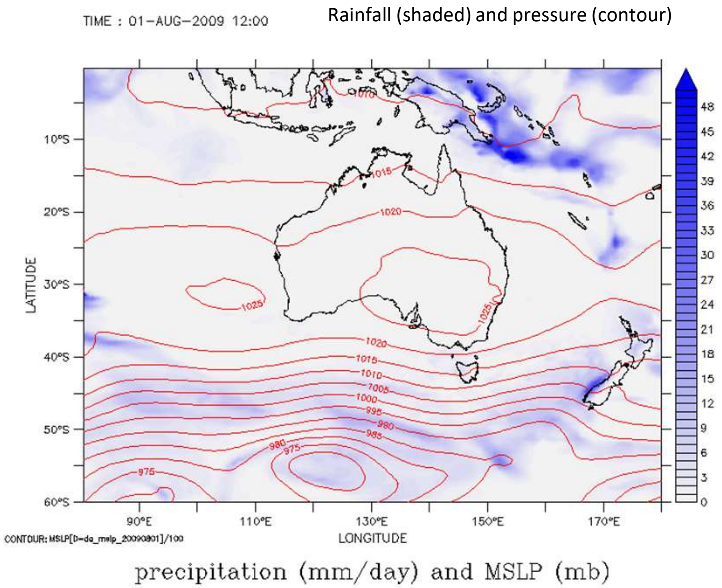
The model simulates the weather: ACCESS-S example

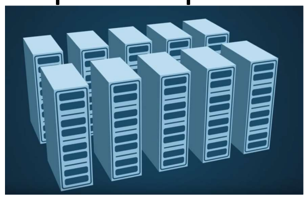


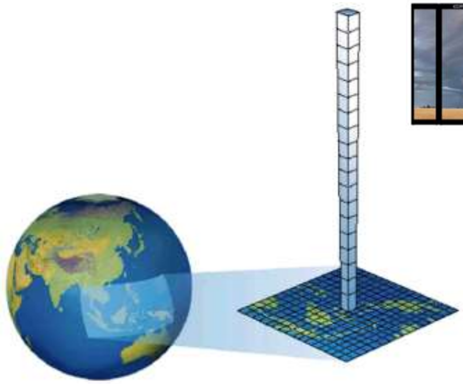
Evolution of atmosphere over the Australian region from a single ACCESS-S forecast

$$d\overline{\mathbf{V}}/dt + fk\times\overline{\mathbf{V}} + \nabla\overline{\phi} = \mathbf{F},$$
$$d\overline{T}/dt - \kappa\overline{T}\omega/p = Q/c_p,$$
$$\nabla\cdot\overline{\mathbf{V}} + \partial\overline{\omega}/\partial p = 0,$$
$$\partial\overline{\phi}/\partial p + R\overline{T}/p = 0,$$
$$d\overline{q}/dt = S_q.$$

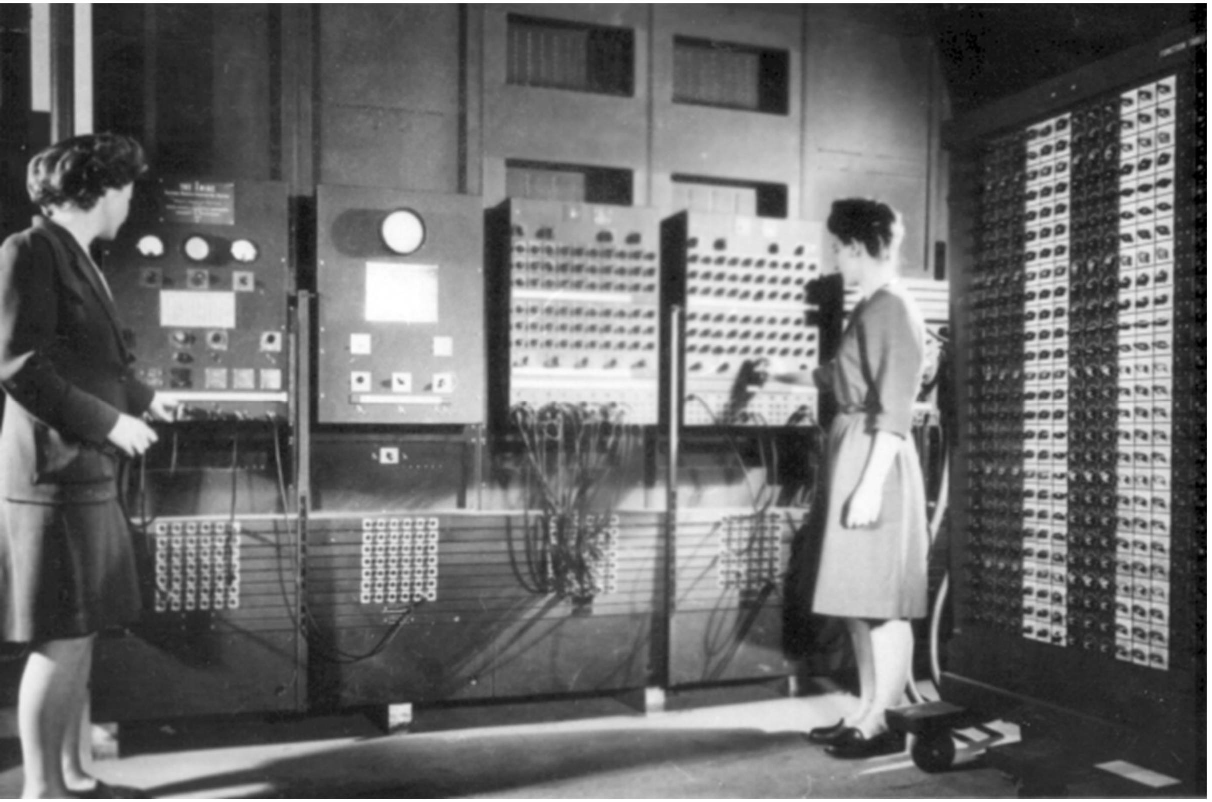
The forecasts are created using a model that simulates the physics of the atmosphere, land and ocean and how they interact and evolve over time.

Run on a supercomputer





Brief History of Weather Models



The ENIAC main control panel at the Moore School of Electrical Engineering operated by Betty Jennings and Frances Bilas.

NWP History

1920s: Lewis Richardson used **pen and paper** to produce a six-hour forecast for the state of the atmosphere over two points in central Europe, taking **at least six weeks** to do so. His forecasts were a **dismal failure!**

1950: The **ENIAC** (Electronic Numerical Integrator and Computer) was used to create the **first** weather forecasts via **computer**

1954: Carl-Gustav Rossby's group at the Swedish Meteorological and Hydrological Institute used the same model to produce the **first operational forecast**

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Brief History of Weather Models

"Primitive" Weather Forecasting Equations

$p = \rho R T$ *Ideal Gas Law* (Equation of State)

$$\vec{a}_h = \sum \left(\vec{F}_h / m \right)$$ *Newton's Second Law of Motion*

$$\Delta p = -\rho g \Delta z$$

$$(PGA)_v = g$$

$$\vec{a}_v = \sum \left(\vec{F}_v / m \right) = (\vec{P}\vec{G}\vec{A})_v - \vec{g}$$

Hydrostatic Law (Obtained from the Equation of Vertical Motion)

$$\Delta T = \Delta q / c_p + (1/\rho)\Delta p$$ *First Law of Thermodynamics*

$$(1/\rho)\Delta\rho/\Delta t = -DIV$$

Conservation of Mass Applied to the Atmosphere (Equation of Continuity)

Zonal wind:

$$\frac{\partial u}{\partial t} = \eta v - \frac{\partial \Phi}{\partial x} - c_p \theta \frac{\partial \pi}{\partial x} - z \frac{\partial u}{\partial \sigma} - \frac{\partial \left(\frac{u^2+v^2}{2}\right)}{\partial x}$$

Meridional wind:

$$\frac{\partial v}{\partial t} = -\eta \frac{u}{v} - \frac{\partial \Phi}{\partial y} - c_p \theta \frac{\partial \pi}{\partial y} - z \frac{\partial v}{\partial \sigma} - \frac{\partial \left(\frac{u^2+v^2}{2}\right)}{\partial y}$$

Temperature:

$$\frac{\delta T}{\partial t} = \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z}$$

Precipitable water:

$$\frac{\delta W}{\partial t} = u \frac{\partial W}{\partial x} + v \frac{\partial W}{\partial y} + w \frac{\partial W}{\partial z}$$

Pressure thickness:

$$\frac{\partial}{\partial t} \frac{\partial p}{\partial \sigma} = u \frac{\partial}{\partial x} x \frac{\partial p}{\partial \sigma} + v \frac{\partial}{\partial y} y \frac{\partial p}{\partial \sigma} + w \frac{\partial}{\partial z} z \frac{\partial p}{\partial \sigma}$$

$$\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + \omega \left(\frac{\partial T}{\partial p} + \frac{RT}{p c_p} \right) = \frac{J}{c_p} \qquad \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial \omega}{\partial p} = 0 \qquad 0 = -\frac{\partial \phi}{\partial p} - \frac{RT}{p}$$

"Perhaps some day in the dim future it will be possible to advance the computations faster than the weather advances and at a cost less than the saving to mankind due to the information gained. But that is a dream." – Lewis Fry Richardson, 1922

NWP History

1966: West Germany and the United States began producing **operational** forecasts based on **primitive-equation** models, followed by the United Kingdom in 1972 and Australia in 1977

Late 1960s: The **first general circulation climate model** that combined **both oceanic and atmospheric** processes was developed at the NOAA Geophysical Fluid Dynamics Laboratory (GFDL)

1970s and 1980s: Model Output Statistics (MOS) relating the output of a numerical weather model and the ensuing conditions at the ground

1990s to present: Model **ensemble** forecasts have been used to help define the forecast uncertainty

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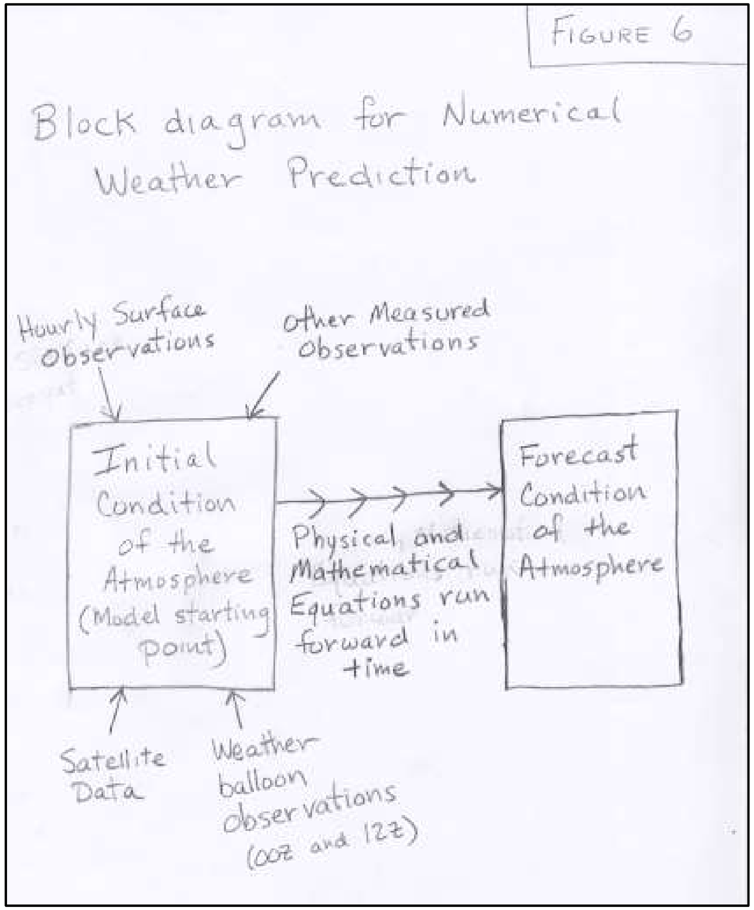
Initialisation & Computation



Ready, Set, Go

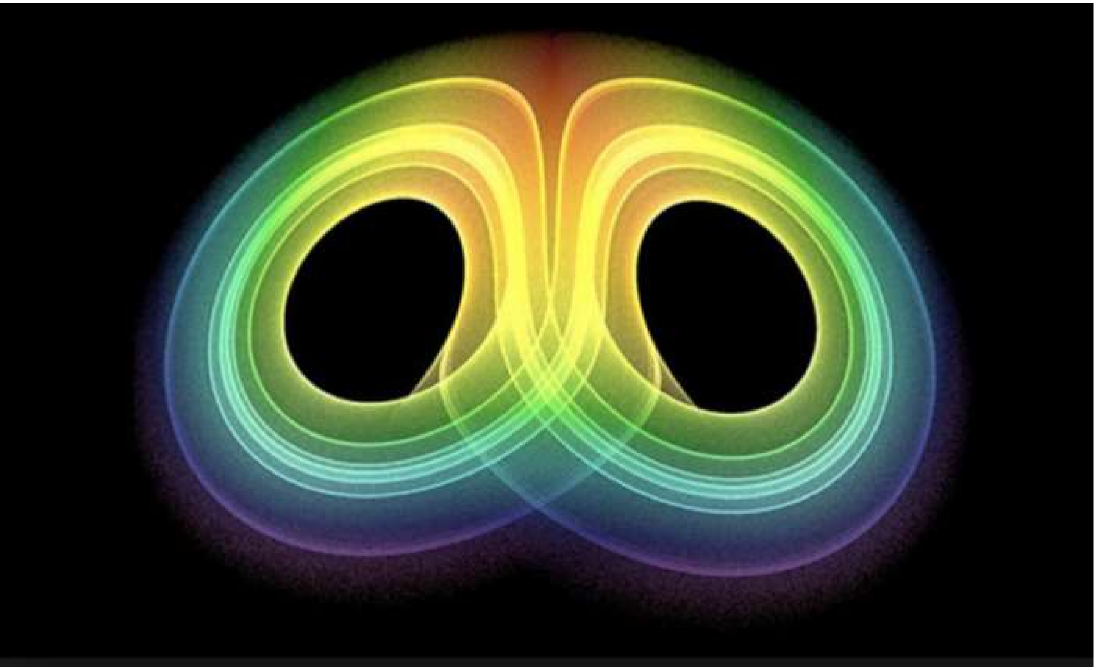
Start: An initial analysis is the start point for our primitive equations. Therefore, the model is **initialised** with a global set of observations and **rates of change**.

Go, Stop: These rates of change **predict** the state of the atmosphere a **short time** into the **future**; the time increment for this prediction is called a **time step**.

Go again: This future atmospheric state is then used as the starting point for **another application** of the predictive equations to find **new rates** of change, and these new rates of change predict the atmosphere at a yet **further time step** into the future. This time **stepping is repeated** until the solution reaches the desired forecast time.

Length of time step: is chosen to preserve numerical stability. For **global** models, the length of time step is of the order of **tens of minutes**.

Limitations of NWP



Chaos Theory Could Save the World, by Rob Adamson

Huge amounts of Data and Chaos

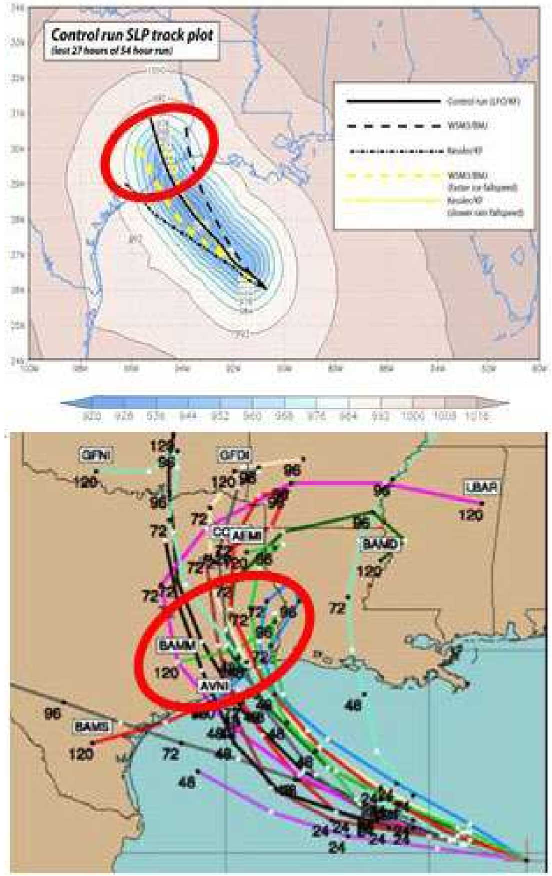
Computing Power: Manipulating the **vast** datasets and performing the **complex** calculations necessary to modern numerical weather prediction requires some of the world's most powerful **supercomputers**

Skill: Even with the power of supercomputers, the **forecast skill** of weather models only extends to about **six days**

Chaos: The fundamental problem lies in the **chaotic nature** of the **partial differential equations** that govern the atmosphere. It is impossible to **solve** these equations **exactly**, and **small errors grow** with time (doubling about every five days)

And also: We can't sample every point on the globe, while **physical processes** occurring at **sub-grid** scale need to be approximated via **parameterisations**. These add to the errors over time.

Deterministic vs Ensemble Predictions



Top: Weather Research and Forecasting model simulation of Hurricane Rita (2005)
Bottom: The spread of the operational multi-model ensemble

One is not enough

A single run of a model will produce one result of the atmosphere some time into the future – a **deterministic prediction**

But **chaos** and the **inherent uncertainties** in the prediction method mean that we're not understanding all the possible outcomes by relying on a single prediction

By making **repeated** (e.g. 20 or 30 times) **small variations** to the **initial** conditions, we sample a greater part of the prediction spectrum → an **ensemble of predictions** is the result

Ensemble predictions can make **probability estimates** e.g. chance of NINO3.4 reaching El Niño levels by August

Ensemble predictions can be made using one model (e.g. ACCESS-S ensemble) or a Multi-Model Ensemble using various climate models.

Difference between weather and climate models

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Weather Prediction

Short-term accuracy is the key, so the initial conditions need to be very close to reality

Interested in **daily or sub-daily** timescales

Small ensemble spread is desirable – want high probabilities of weather outcomes for days one to five, i.e. close to a **deterministic prediction**

Can run at **high resolution** (both spatial and temporal) to increase the accuracy – depends on computing power

Run **several times per day** to accommodate the continuous stream of observations

Forecast duration is **one to two weeks**

Climate Prediction

Less emphasis on the accuracy of the initial conditions

Interested in timescales from **multi-week to multi-month**

Larger ensemble size – want to sample more possible trajectories for the evolution of the climate system

Run at **lower resolution** (both spatial and temporal) because of the larger ensemble size and longer forecast duration

Run a **few times per week** – interested in climate anomalies not high frequency weather variations

Forecast duration is **three to six months**

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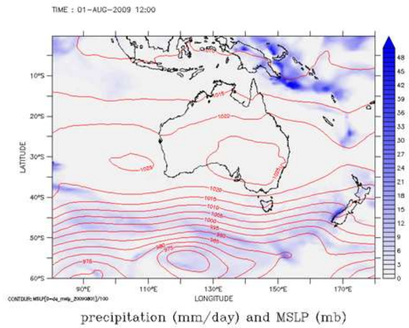
Ensemble forecasts: Creating Probabilities

We are simulating 100 of these!

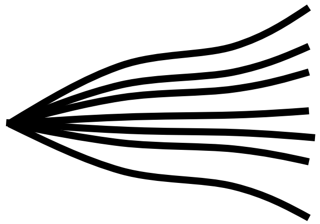


We don't just run one forecast….

100 equally likely outcomes/scenarios ("ensemble" of forecasts)

There is uncertainty in how the weather will evolve.

We address this by running the model numerous times for any given outlook



The ensemble is used to create the forecast probabilities

e.g., if 80 of these 100 outlooks predict above average rainfall for a season, then the likelihood of a wetter than average season for the location is 80% (but 20 are drier!).

"Probability"

"Risk"

"Shift in the odds/likelihood"

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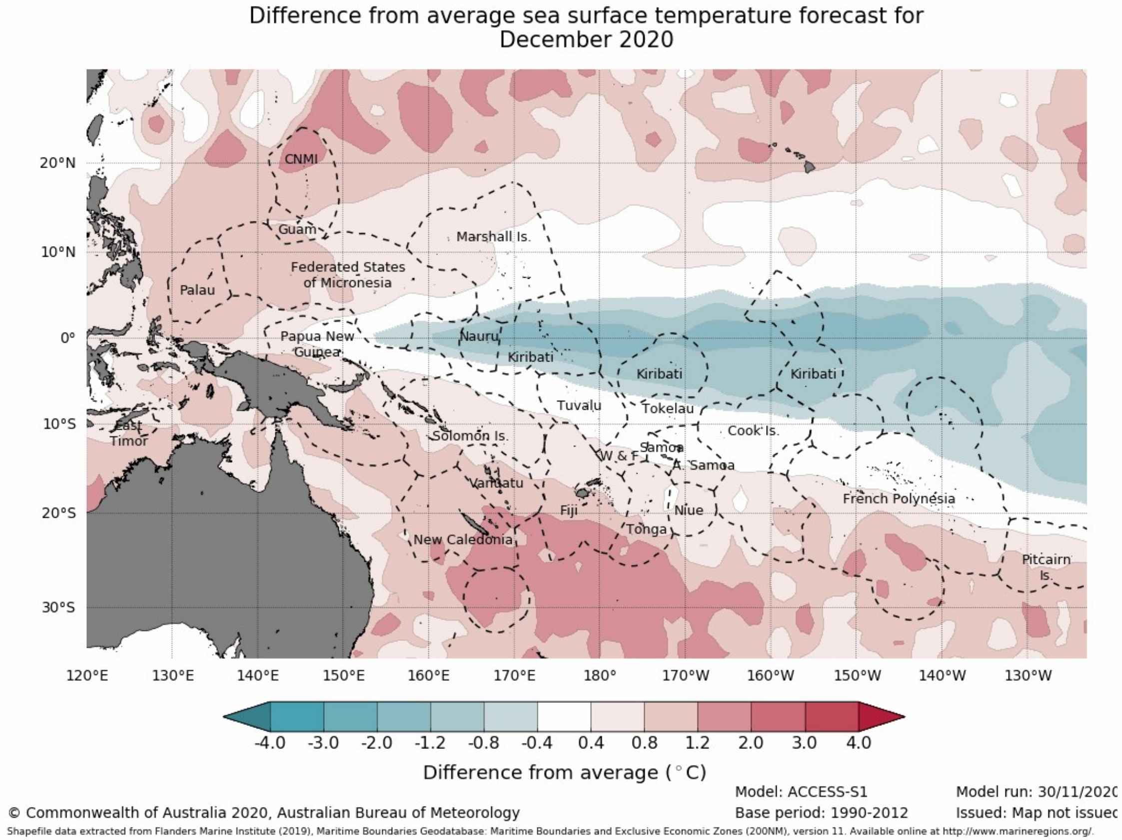
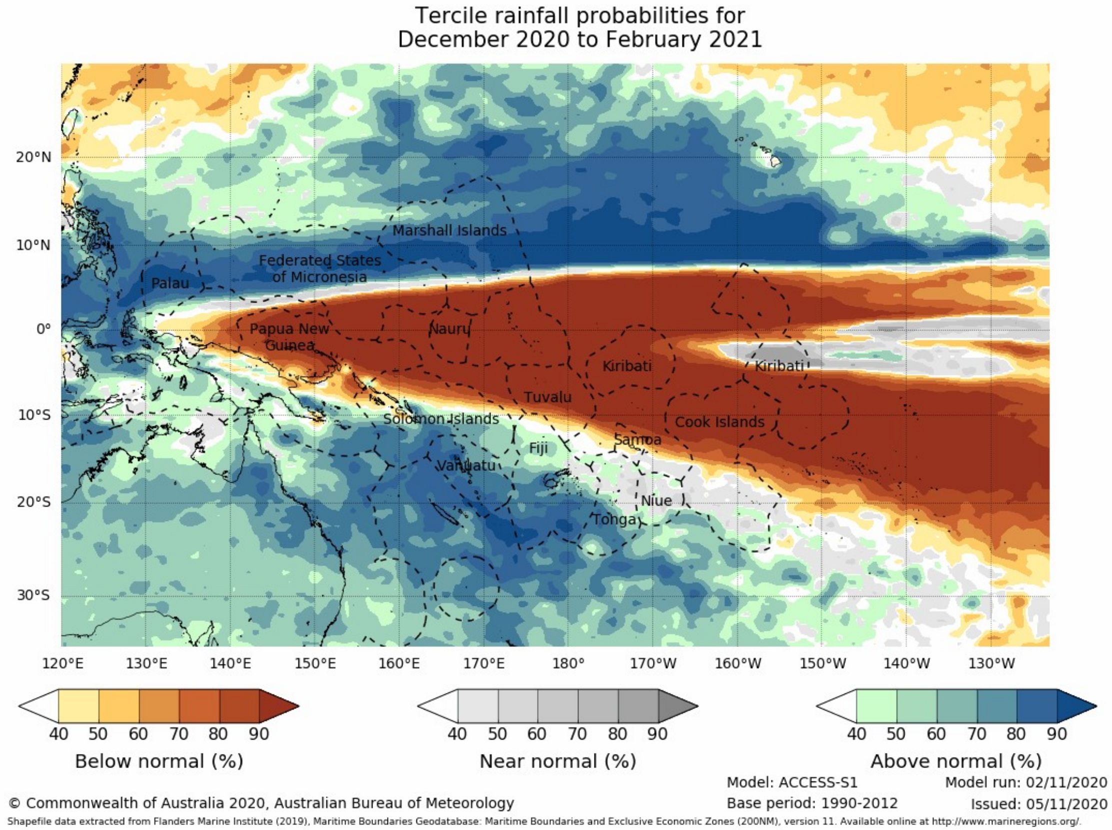
Ensemble Climate Predictions - Examples

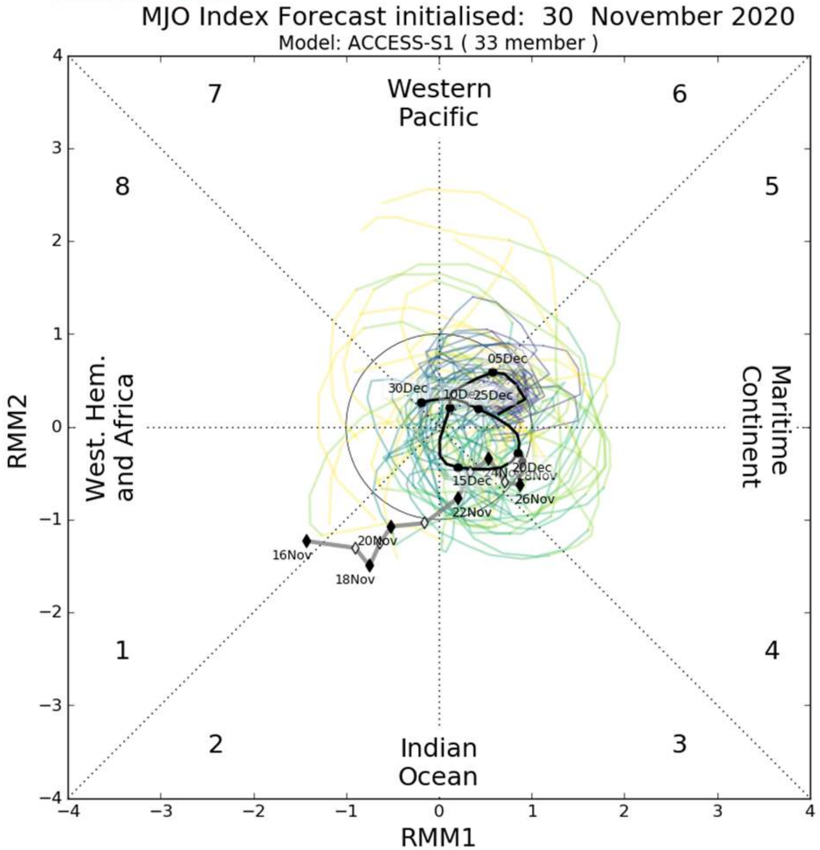


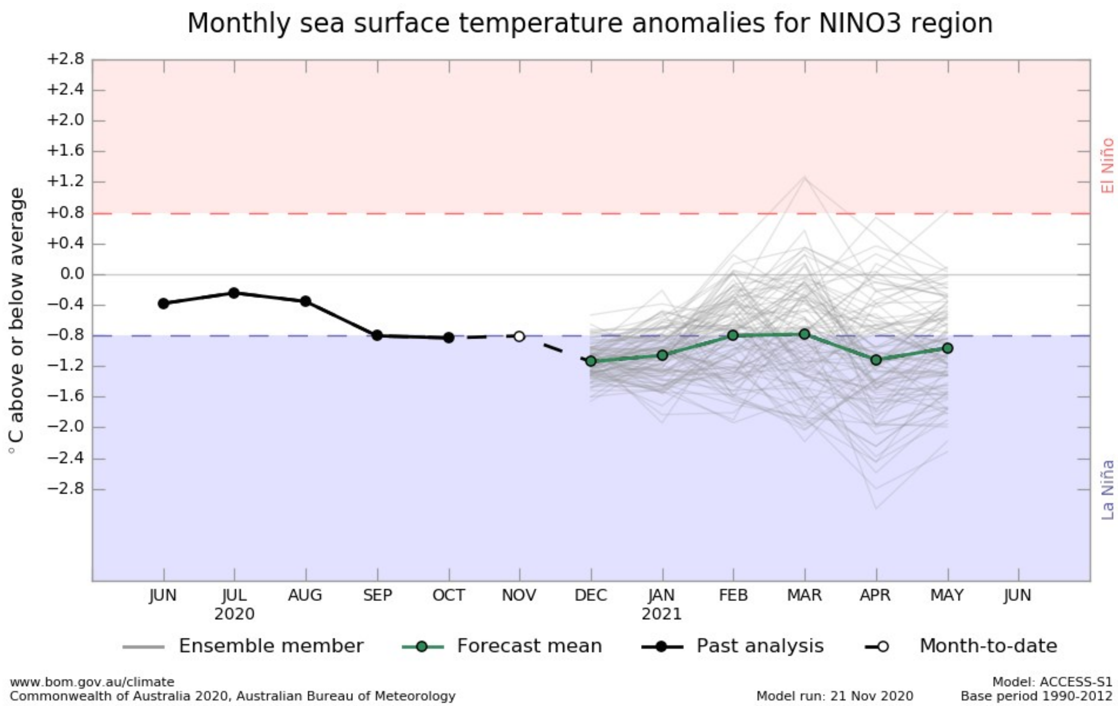


Ensemble Mean SST anomaly.

Tercile rainfall outlook with **probabilities** derived from **Ensemble spread**

Ensemble Climate Predictions - Examples





Ensemble Mean MJO index forecast plus individual **ensemble members**

Ensemble Mean NINO3 SST index forecast plus individual **ensemble members**