Severe Convective Storms

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Outline

- Definitions: What is convection and what makes it severe?
- Basic convective dynamics and characteristics
- Parcel theory
- Convection initiation
- Vertical wind shear and convection organisation
- Convective hazards
- Severe convective storms in Australia
- Severe convective storms and climate variability and climate change

Definitions

Convection: Thermally direct circulations that result from the action of gravity upon an unstable vertical distribution of mass (AMS Glossary)

A convective storm is defined by the BoM as severe if it produces one or more of the following:

- large hail (≥ 2 cm in diameter)
- strong winds (≥ 90 km/h)
- a tornado
- Heavy rainfall conducive to flash flooding **

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Basic dynamics

Vertical momentum equation:

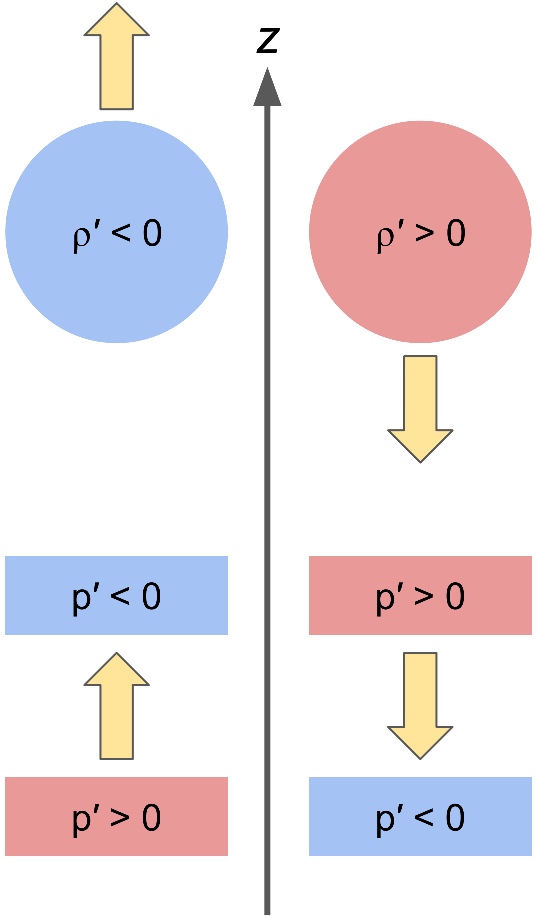
$$\frac{dw}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g$$

Defining a horizontally homogeneous base state that is in hydrostatic balance, we obtain

$$\frac{dw}{dt} = -\frac{1}{\rho}\frac{\partial p'}{\partial z} - \frac{\rho'}{\rho}g$$

Buoyancy

Vertical perturbation pressure gradient (VPPG)



Buoyancy

Buoyancy can be expressed as a function of the virtual temperature of a parcel of air and its environment:

$$B = -\frac{\rho'}{\rho} g \approx g\left(\frac{T_{\mathrm{v}}'}{\overline{T_{\mathrm{v}}}}\right) = g\left(\frac{T_{\mathrm{v,par}} - T_{\mathrm{v,env}}}{T_{\mathrm{v,env}}}\right)$$

If the parcel of air contains hydrometeors which are falling at their terminal velocity then there is additional hydrometeor loading term:

$$B = -\frac{\rho'}{\rho} g \approx g\left(\frac{T_{\mathrm{v}}'}{\overline{T_{\mathrm{v}}}} - r_{\mathrm{h}}\right)$$

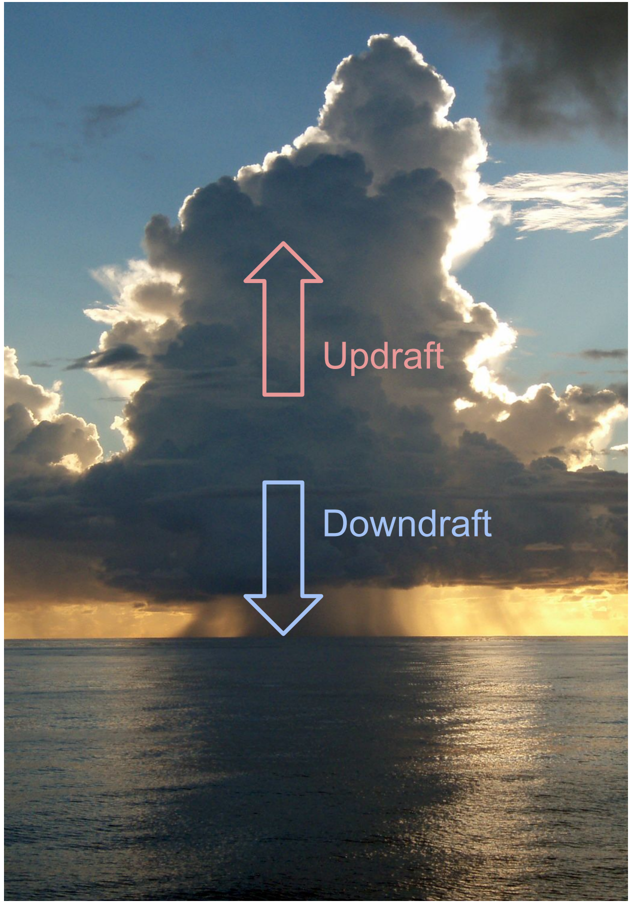
$$T_{\mathrm{v}} = T\left(\frac{1 + r/\epsilon}{1 + r}\right) \approx T\,(1 + 0.61r)$$

Updrafts and downdrafts

Updraft: The ascending portion of a convective cloud associated with positive buoyancy and/or an upward-directed VPPG

Downdraft: The descending portion of a convective cloud associated with negative buoyancy and/or a downward-directed VPPG

N.B. Convective downdrafts are distinct from compensating subsidence and are primarily driven by hydrometeor loading + evaporation



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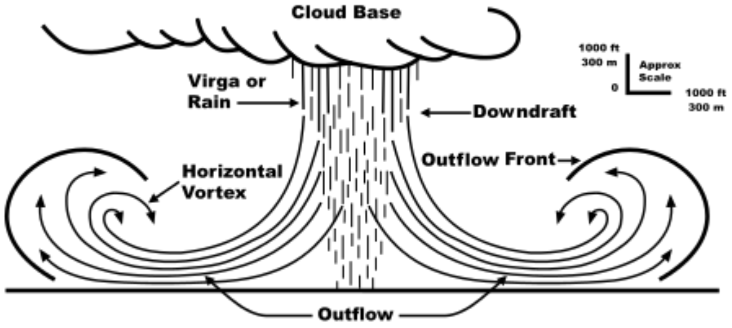
Cold pools and outflow boundaries

Upon reaching the surface, negatively buoyant downdraft air spreads out laterally as a density current, forming a *cold pool*

The leading edge of the cold pool is known as an *outflow boundary* or gust front

Convergence and ascent along an outflow boundary may lead to *secondary convective initiation*



Parcel theory

Neglect pressure perturbations

Neglect contribution of hydrometeors to buoyancy

Neglect exchange of momentum, moisture, and temperature between parcel and its environment

Neglect additional latent heating due to freezing and deposition

Neglect effects of compensating subsidence on the environment

Lapse rates

The temperature of an unsaturated air parcel decreases with height at the *dry adiabatic lapse rate* (DALR):

$$\Gamma_\mathrm{d} = -\frac{dT}{dz} = \frac{g}{c_{p\mathrm{d}}} \approx 9.8\ \mathrm{K\ km}^{-1}$$

The temperature of a saturated air parcel decreases with height at the *saturated adiabatic lapse rate* (SALR):

$$\Gamma_\mathrm{s} = -\frac{dT}{dz} = \frac{g}{c_{p\mathrm{d}}} \frac{1 + L_\mathrm{v} r_\mathrm{s} / R_\mathrm{d} T}{1 + L_\mathrm{v}^2 r_\mathrm{s} / R_\mathrm{v} T^2}$$

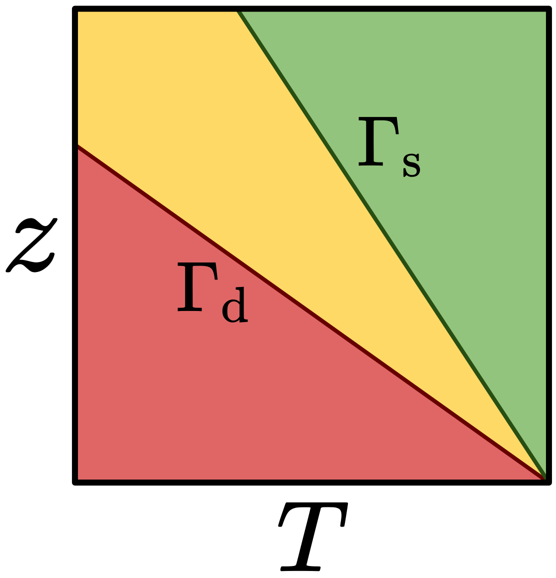
Static stability

If the environmental lapse rate is less than the SALR then it is said to be **absolutely stable**

If the environmental lapse rate is greater than the DALR then it is said to be **absolute unstable**

If the environmental lapse rate is between the DALR and SALR then it is said to be **conditionally unstable**

If the environmental lapse rate is equal to the DALR (SALR) then it is said to be **neutral** (**moist neutral**)



LCL, LFC, LNB, CAPE, and CIN

Lifting Condensation Level (LCL): Height at which an ascending parcel of air first becomes saturated

Level of Free Convection (LFC): Height above which an ascending, saturated parcel of air first becomes positively buoyant

Level of Neutral Buoyancy (LNB): Height above which an ascending, saturated parcel of air becomes negatively buoyant

Convective Available Potential Energy (CAPE): Energy available to a parcel of air as it ascends from the LFC to the LNB

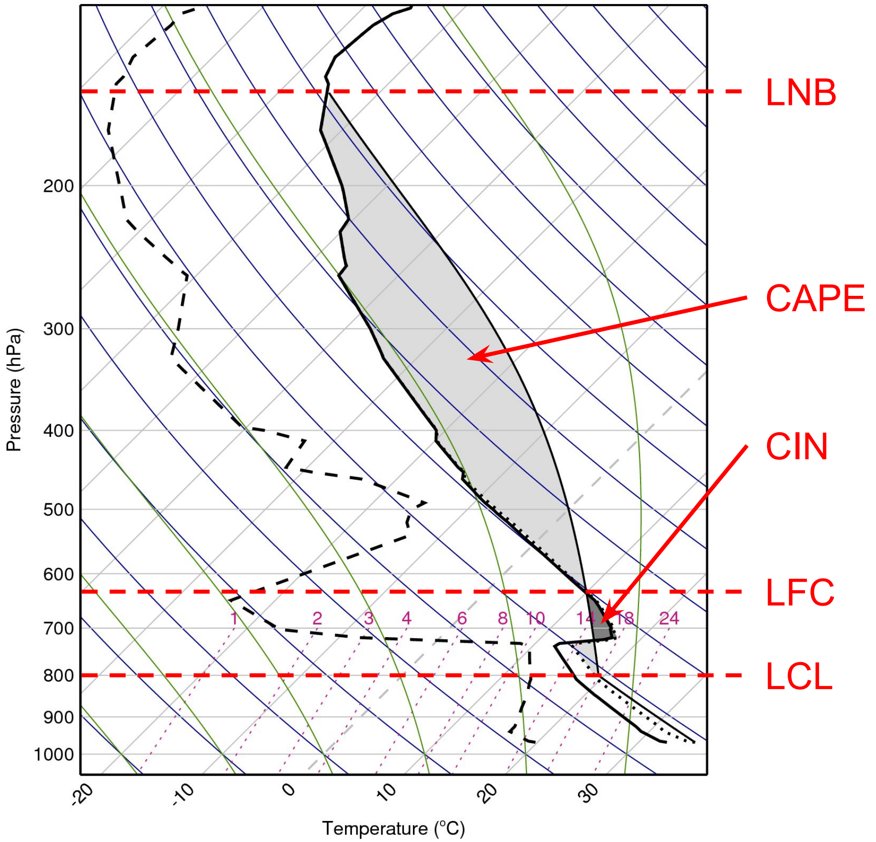
Convective Inhibition (CIN): Energy required by a parcel of air to reach the LFC

Thermodynamic diagrams

$$\text{CAPE} = \int_{\text{LFC}}^{\text{LNB}} B\,dz$$

$$\text{CIN} = -\int_{0}^{\text{LFC}} B\,dz$$

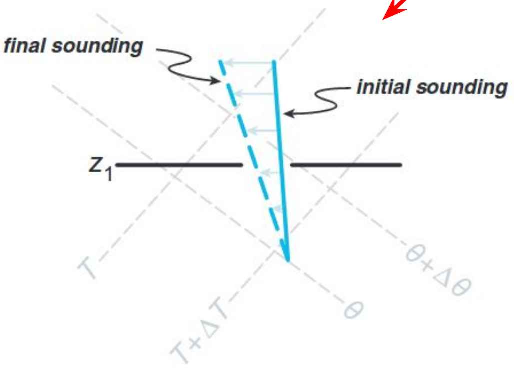
$$w_{\text{max}} = \sqrt{2\text{CAPE}}$$

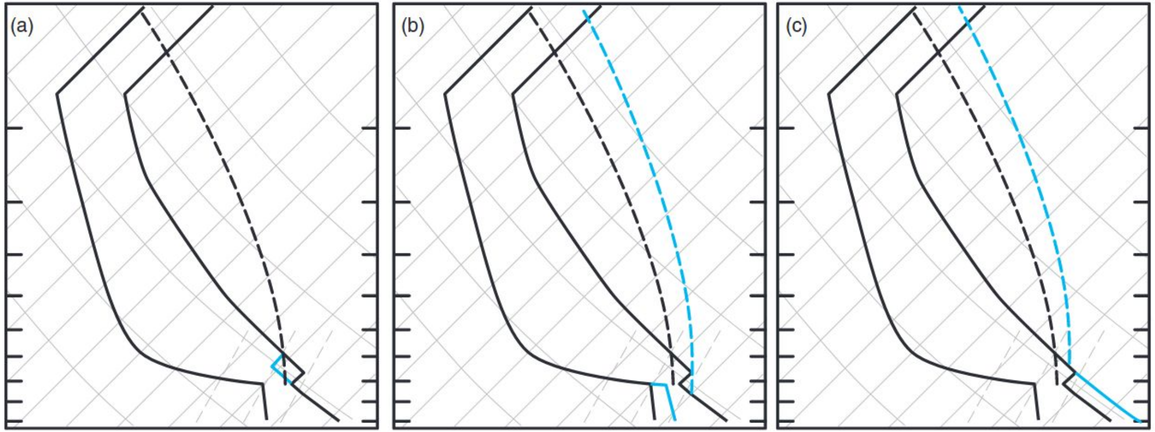


Generation of CAPE and removal of CIN

Environmental lapse rate tendency equation:

$$\frac{\partial \gamma}{\partial t} = -\frac{\partial}{\partial z}(-v_{\mathrm{h}} \cdot \nabla_{\mathrm{h}} T) - w\frac{\partial \gamma}{\partial z} + \frac{\partial w}{\partial z}(\Gamma_{\mathrm{d}} - \gamma) - \frac{1}{c_p}\frac{\partial Q}{\partial z}$$



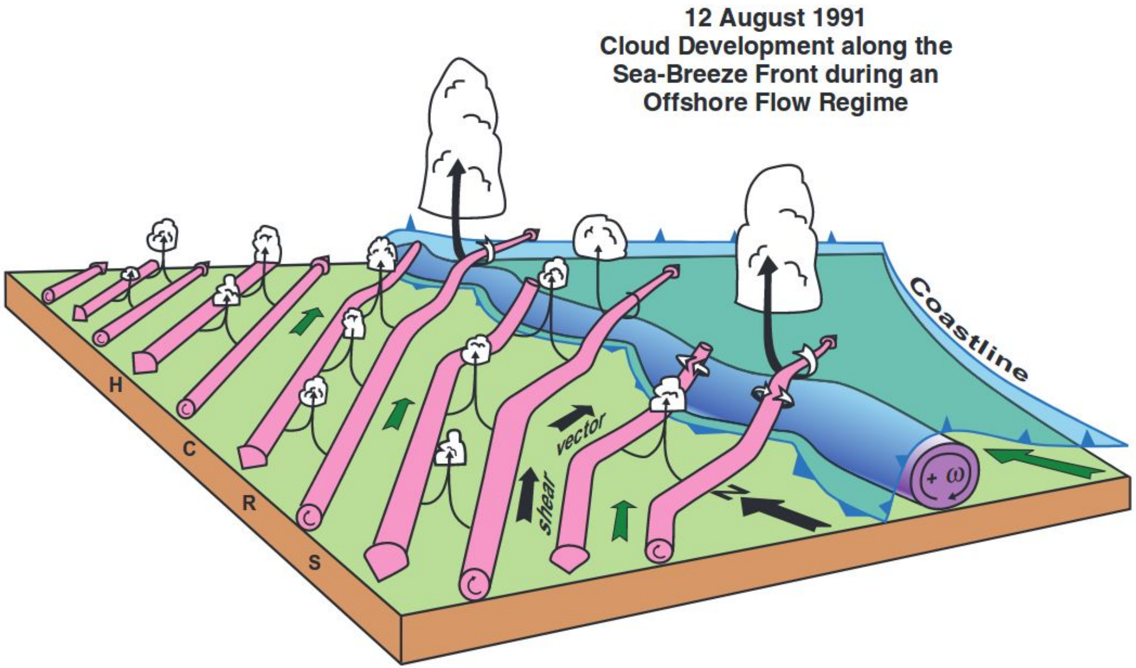


Markowski and Richardson (2010)

Convection initiation (triggering)

Lifting mechanisms:

- Fronts
- Drylines
- Convergence lines
- Sea breezes
- Outflow boundaries
- Gravity waves
- Upslope flow
- Horizontal Convective Rolls (HCRs)

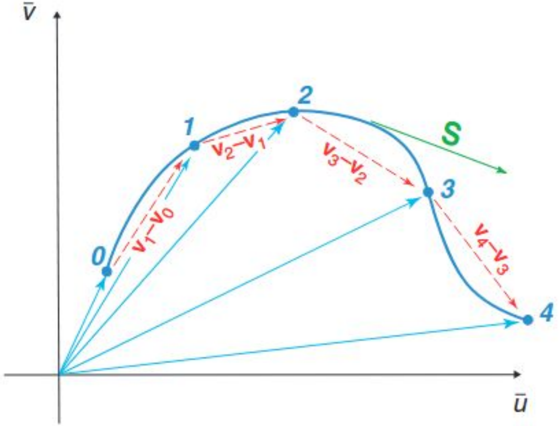


Markowski and Richardson (2010)

Vertical wind shear and convection organisation

Three important effects of vertical wind shear (VWS):

1. Separates updraft and downdraft
2. Prevents rain-cooled outflow from undercutting the updraft
3. Promotes the development of VPPGs which can augment the updraft



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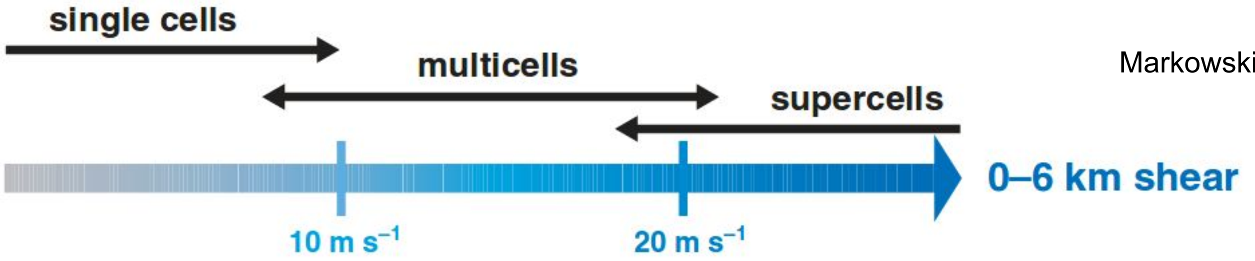


Single-cell convection

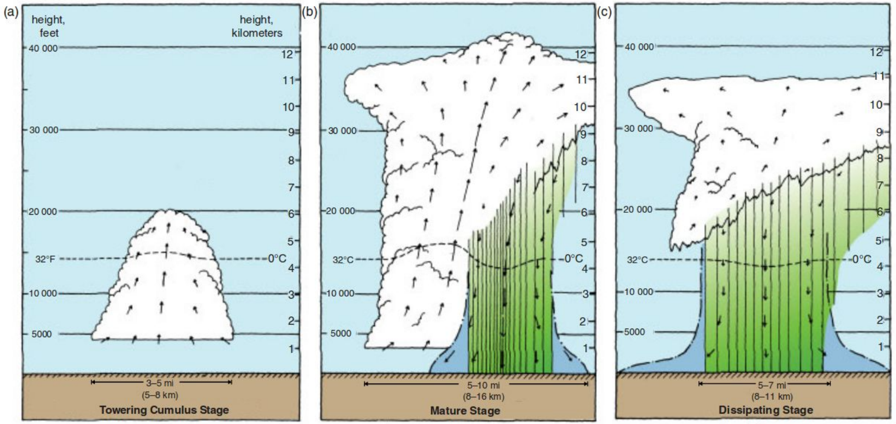
Occurs in environments of weak VWS

Consists of a single updraft

Outflow does not initiate subsequent convection in any organised manner

Short lived (30–60 min)

Hazards: small hail, damaging straight-line winds (microbursts), weak tornadoes (land/waterspouts)



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Multicell convection

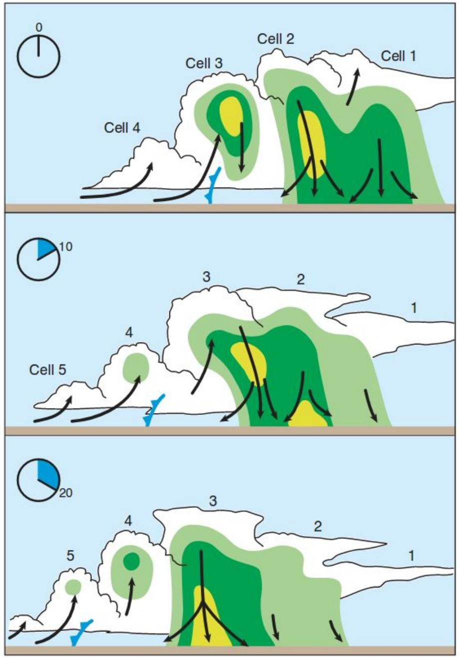
Occurs in environments of moderate VWS

Consists of multiple updrafts at different stages of their lifecycle

Outflow repeatedly triggers new cells along a preferred flank of the system

Each cell persists for only 30–60 min but convective system can persist for many hours

Hazards: hail, damaging straight-line winds, tornadoes, heavy rainfall



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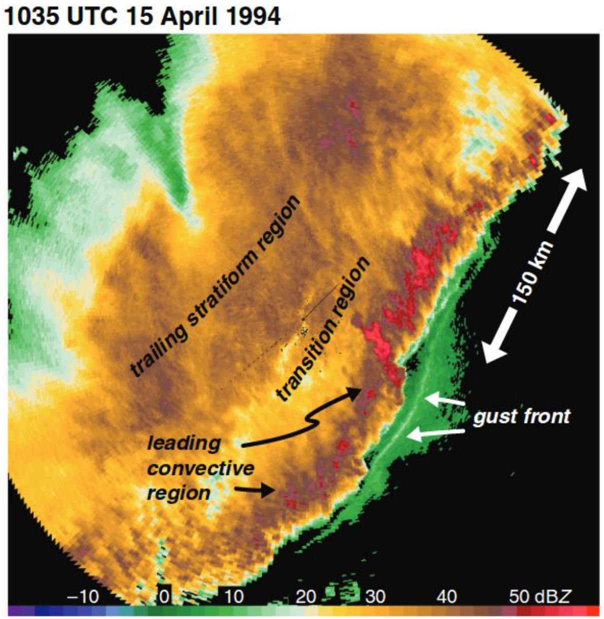
Multicell convection: MCSs and bow echoes



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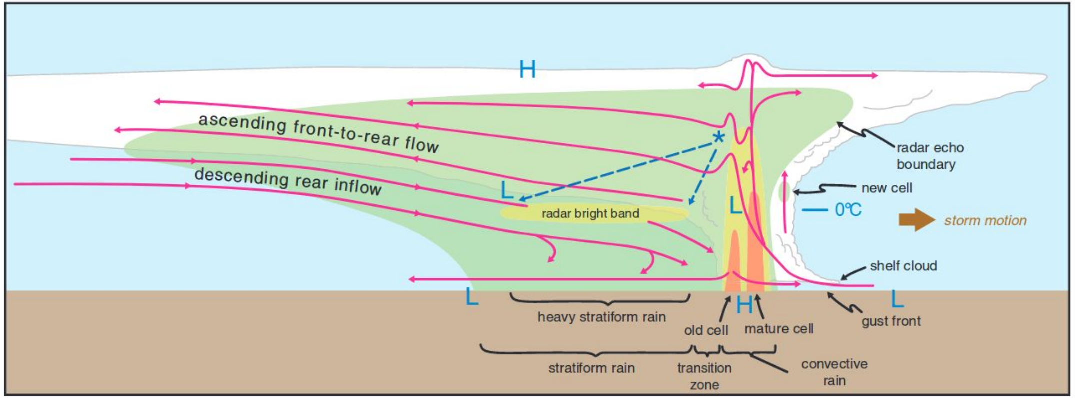

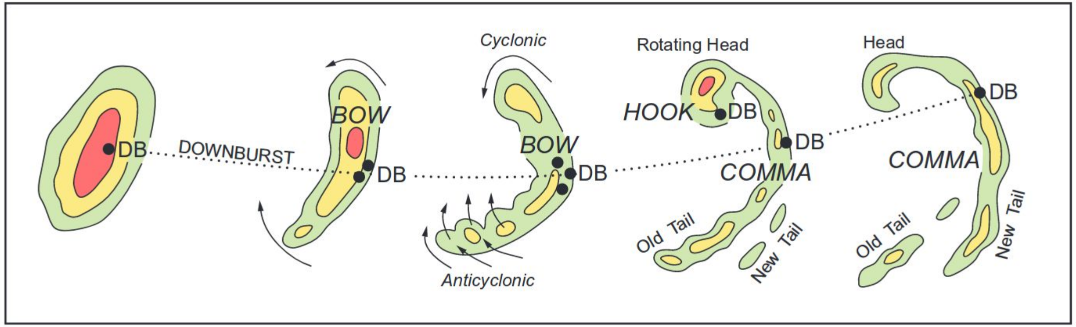

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Supercell convection

Occurs in environments of strong VWS

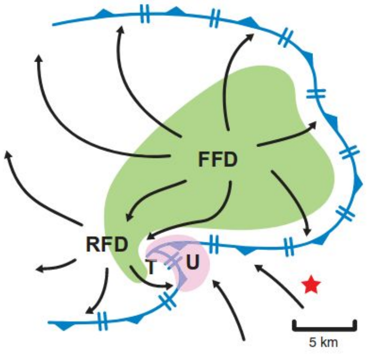
Consists of a single, quasi-steady, rotating updraft (mesocyclone)

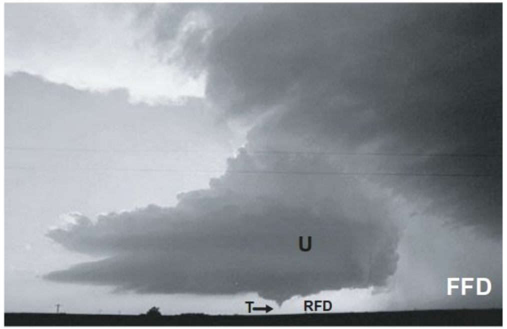
Organised inflow provides continuous supply of moist, potentially buoyant air

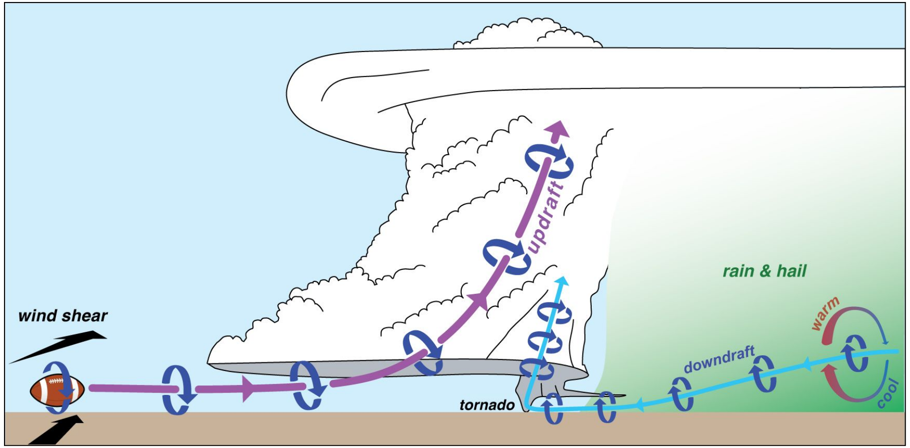
May persist for many hours

Hazards: large hail, damaging straight-line winds, strong tornadoes, heavy rainfall

Markowski and Richardson (2010)







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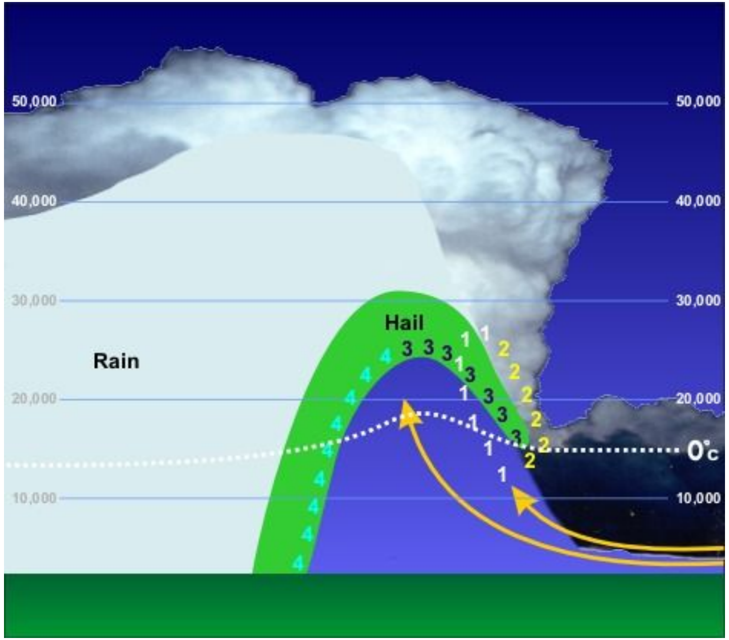
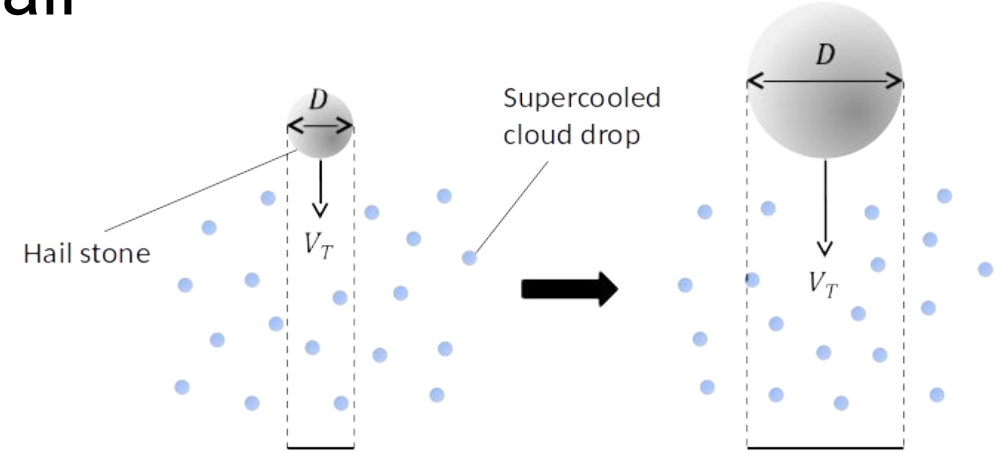
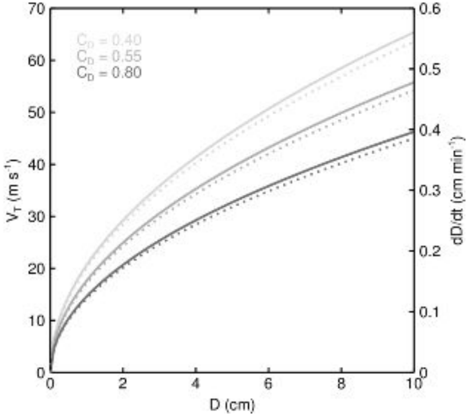
Convective hazards: Hail



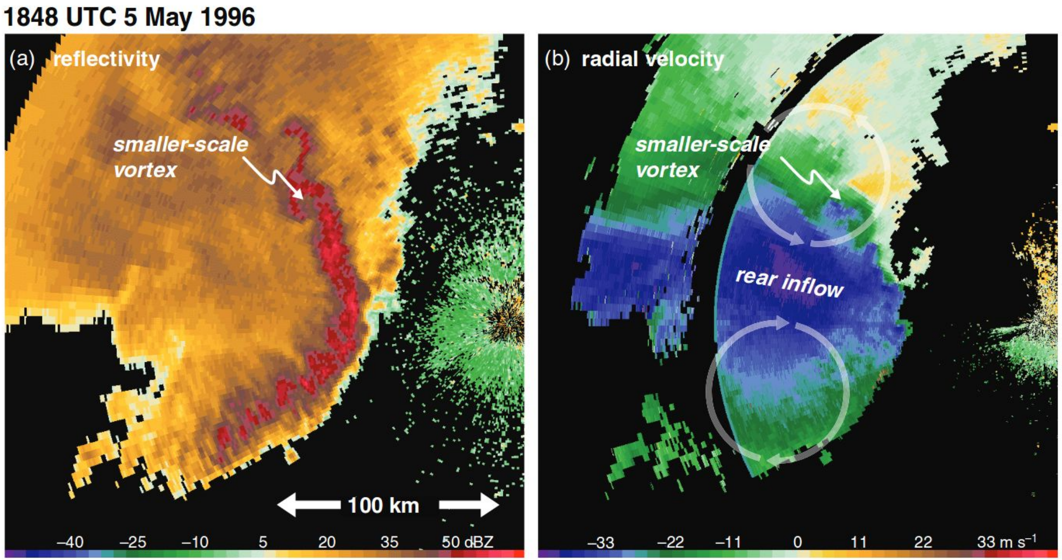


$$V_T = \left(\frac{4 g \rho_i D}{3 C_D \rho_a}\right)^{1/2}$$

$$\frac{dD}{dt} = \frac{V_T \times \mathrm{LWC}_{\mathrm{eff}} \times \rho_w / \rho_i}{2}$$



Convective hazards: Straight-line winds



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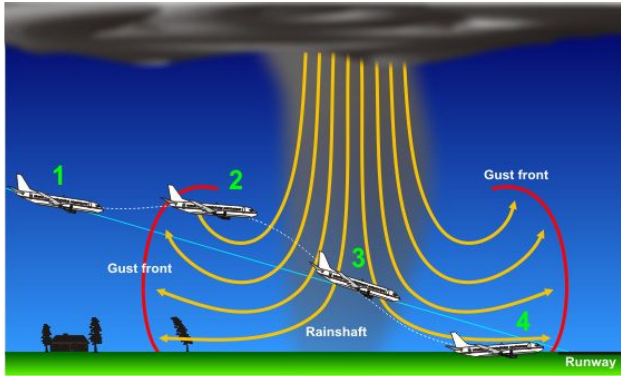

Convective hazards: Tornadoes

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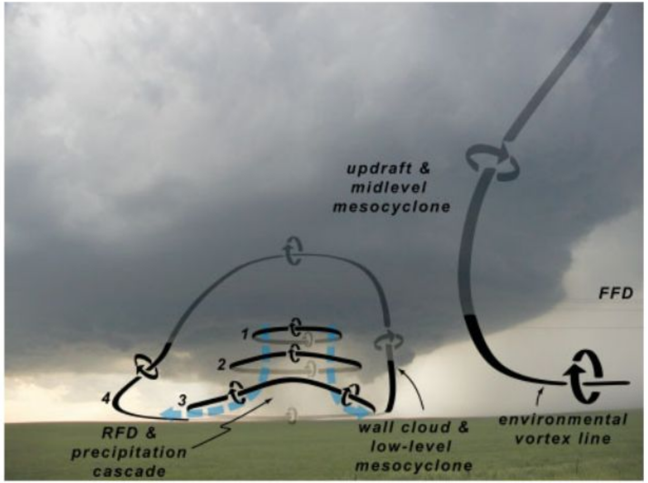
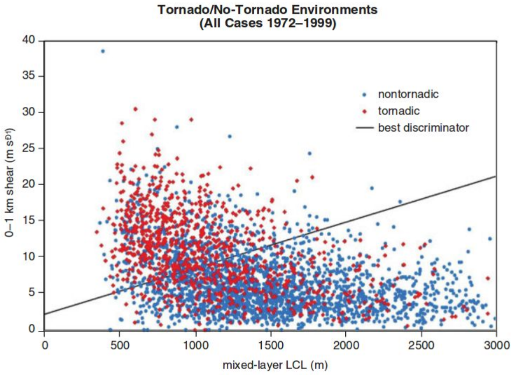
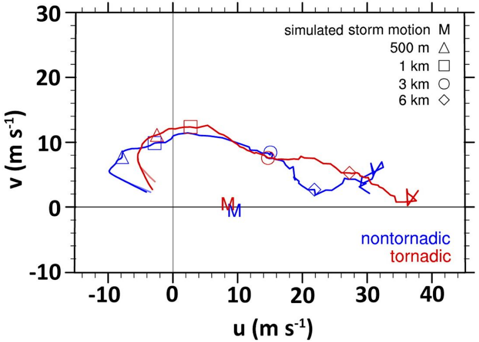
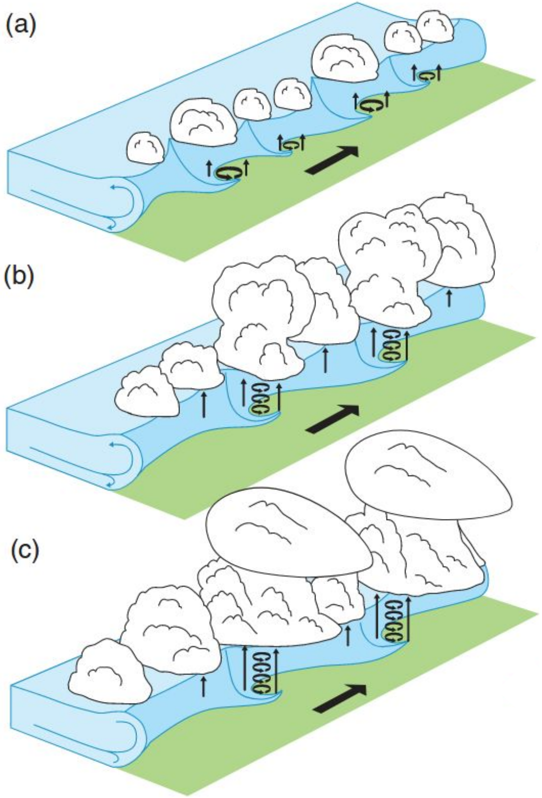






Coffer and Parker (2017)



Markowski and Richardson (2010)

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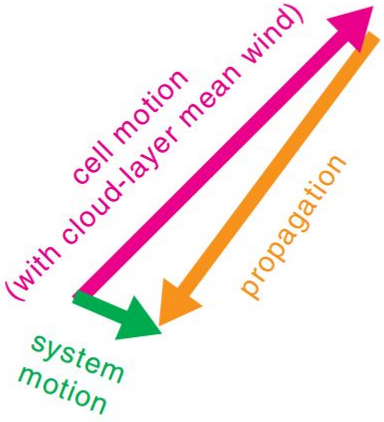
Convective hazards: Heavy rainfall and flash floods

$$P = \overline{R}D$$



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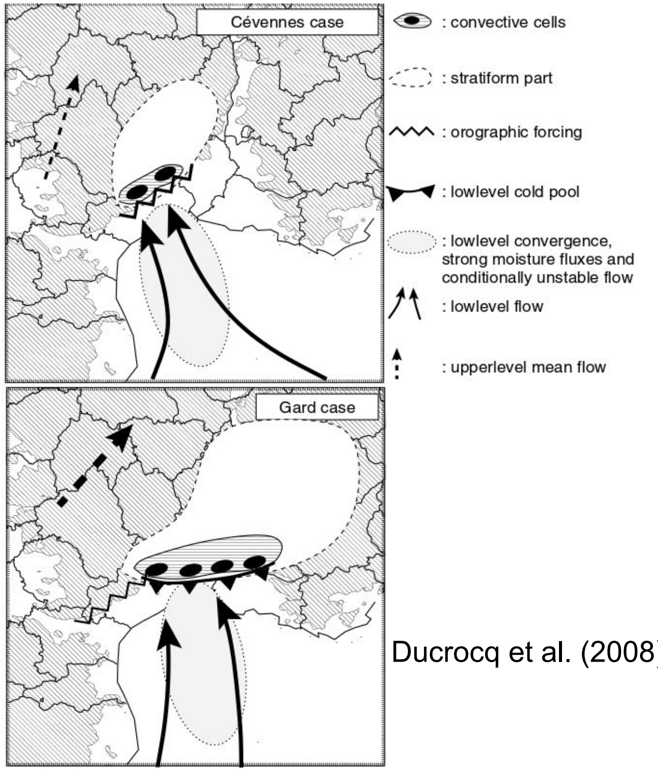
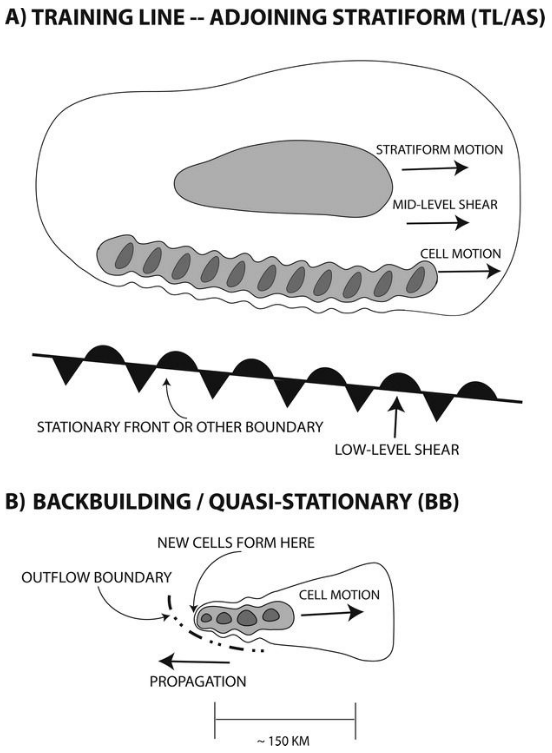


Ducrocq et al. (2008)



Schumacher and Johnson (2008)

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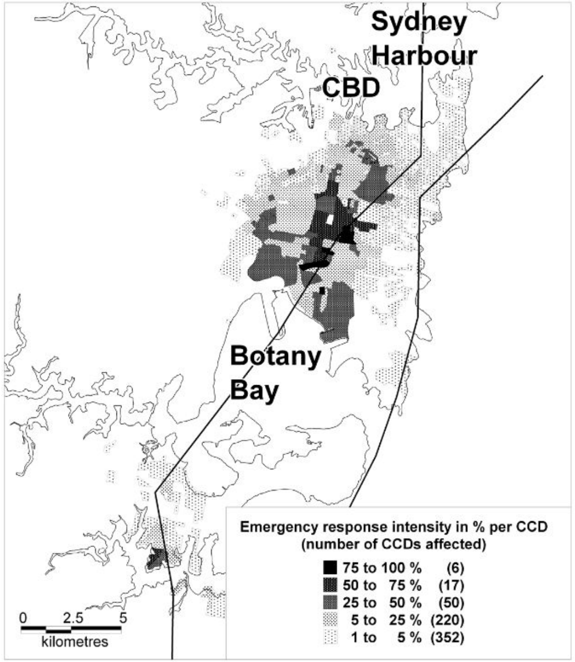
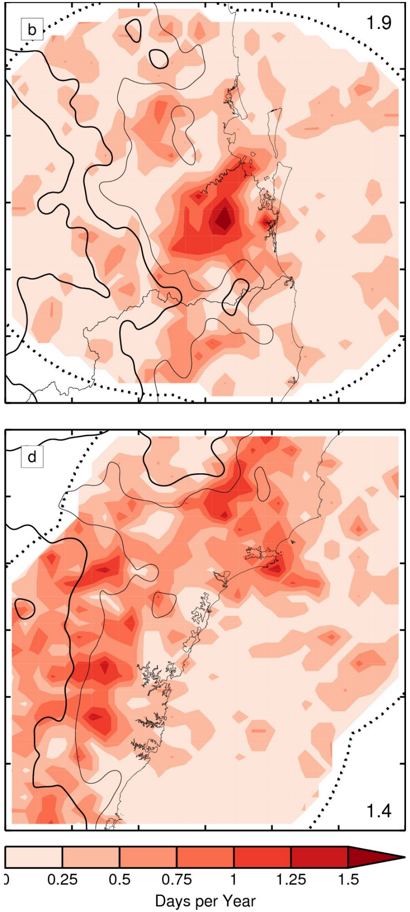
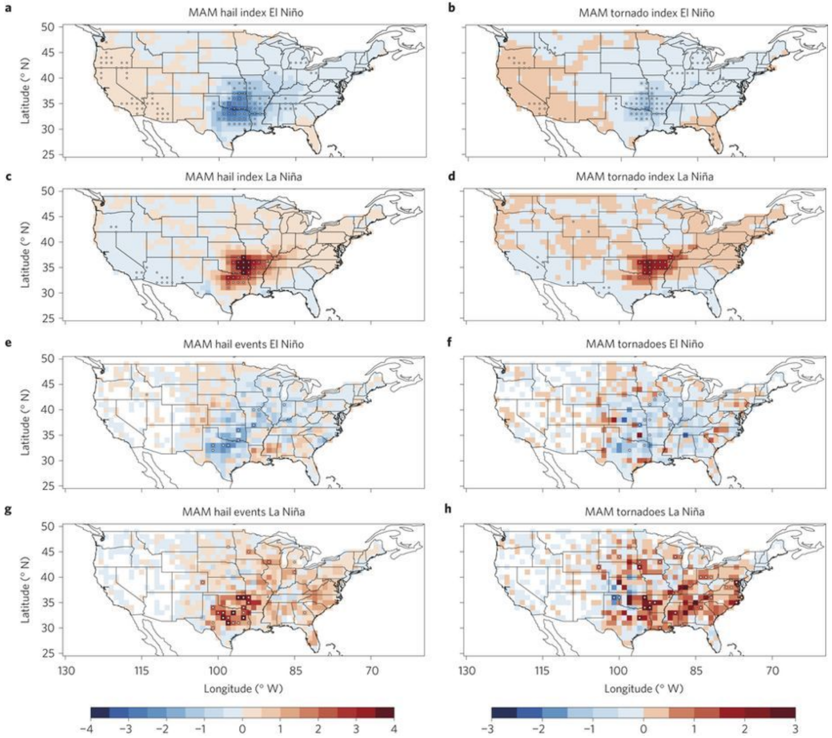
Severe convective storms in Australia

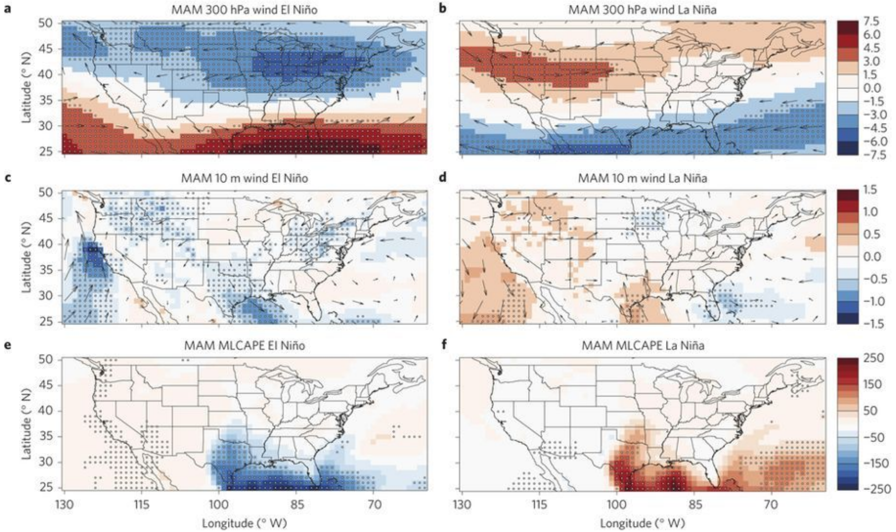
Schuster et al. (2005)



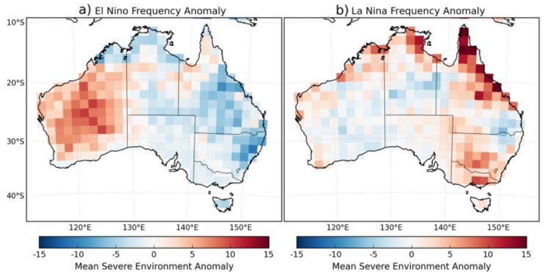


Severe convective storms and climate variability





Allen et al. (2015)



Allen and Allen (2016)

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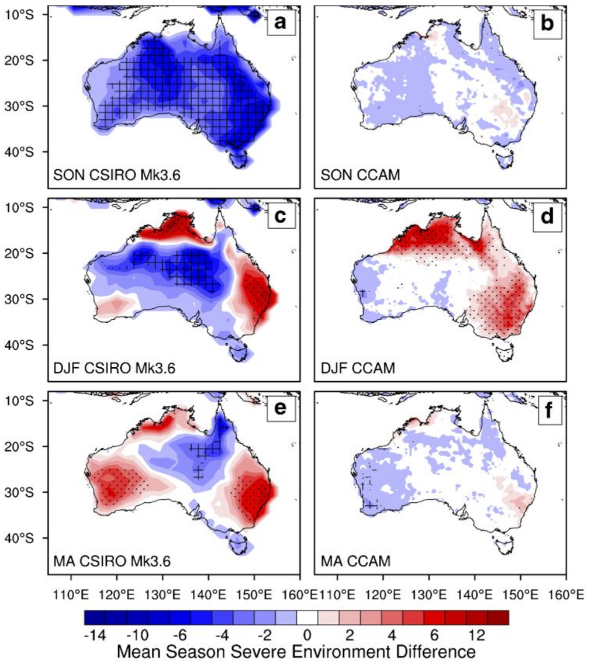
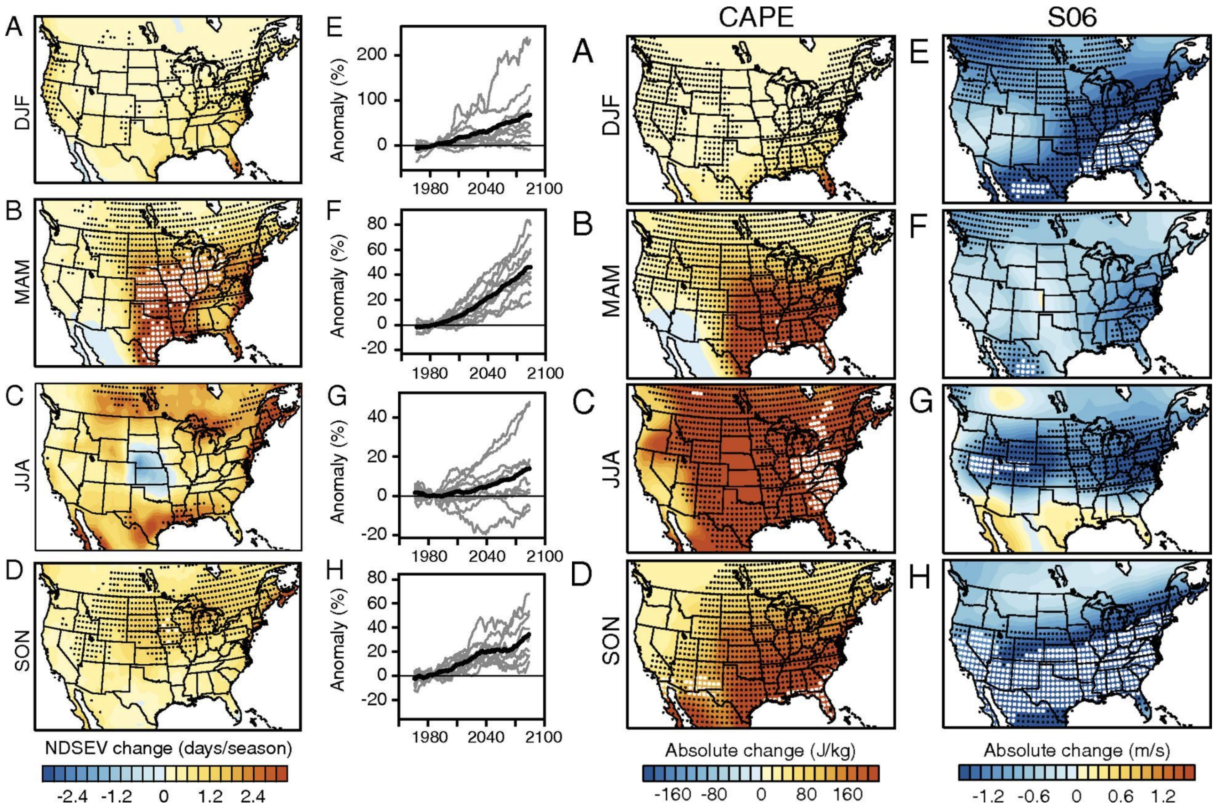
Severe convective storms and climate change

Allen et al. (2014)





Diffenbaugh et al. (2013)

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