ARC CENTRE OF EXCELLENCE FOR CLIMATE SYSTEM SCIENCE

Australian Government
Australian Research Council

Water & Climate
WITH SOME BIOLOGY

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Australian National University

Where I live, will it become more …

like this?

or

like that?

Current Concept

A place like this has:

excess (solar) energy
but not enough water

WATER-LIMITED

A place like that has:

not enough (solar) energy
with too much water

ENERGY-LIMITED

Note: highly productive environments tend to be co-limited

One commonly held perception

$CO_2 \uparrow$ causes T $\uparrow$

and (on average), it will become more arid.

this

becomes more like

that

Clear and simple message

One commonly held perception

$CO_2 \uparrow$ causes T $\uparrow$

and (on average), it will become more arid.

this

becomes more like

that

Clear and simple message

BUT: Is this clear and simple message correct?

Project into Future:
$CO_2 \uparrow$ causes T $\uparrow$ = More Arid Land

Now

Future
(Year 2100)

$CO_2 \uparrow$ T $\uparrow$: Atmosphere is warmer/moister and land becomes more arid

$CO_2 \uparrow$ causes T $\uparrow$ = More Arid Land

Reverse Argument:

Colder = Less Arid Land

Past
(Last Glacial Max)

Now

Future
(Year 2100)

The Reverse Projection:
$CO_2 \downarrow$ T $\downarrow$: Atmosphere is colder/drier and **land becomes less arid**

The Projection:
$CO_2 \uparrow$ T $\uparrow$: Atmosphere is warmer/moister and **land becomes more arid**

CO_2 ↑ causes T ↑ = More Arid Land

Reverse Argument:

Colder = Less Arid Land ????

Past
(Last Glacial Max)

Now

Future
(Year 2100)

The Reverse Projection:
CO_2 ↓ T ↓: Atmosphere is colder/drier and **land becomes less arid**

LGM was more arid?

The Projection:
CO_2 ↑ T ↑: Atmosphere is warmer/moister and **land becomes more arid**

Earth Scientists see LGM as being, in general, more arid (when colder)

Muhs (2013, Aeolian Research)

"…. A dustier Earth during glacial periods is likely due to increased source areas, greater aridity, less vegetation, lower soil moisture, possibly stronger winds, a decreased intensity of the hydrological cycle, and greater production of dust-sized particles from expanded ice sheets and glaciers."

LGM – Low CO_2 means it was more arid from a Plant's point of view

- More dust ~ less vegetation
- Reduced CO_2 at LGM (~180 ppm) is part of the reason for less vegetation
- CONCLUDE: cannot understand past/future climate-water-vegetation interactions unless we **COUPLE water and carbon**

Translation:

Hydrologists, Atmospheric Scientists and Biologists all have to contribute to make progress

A good reason for OzEWEX to exist

Prentice & Harrison (2009, Clim. Past)

One commonly held perception

CO_2 ↑ causes T ↑

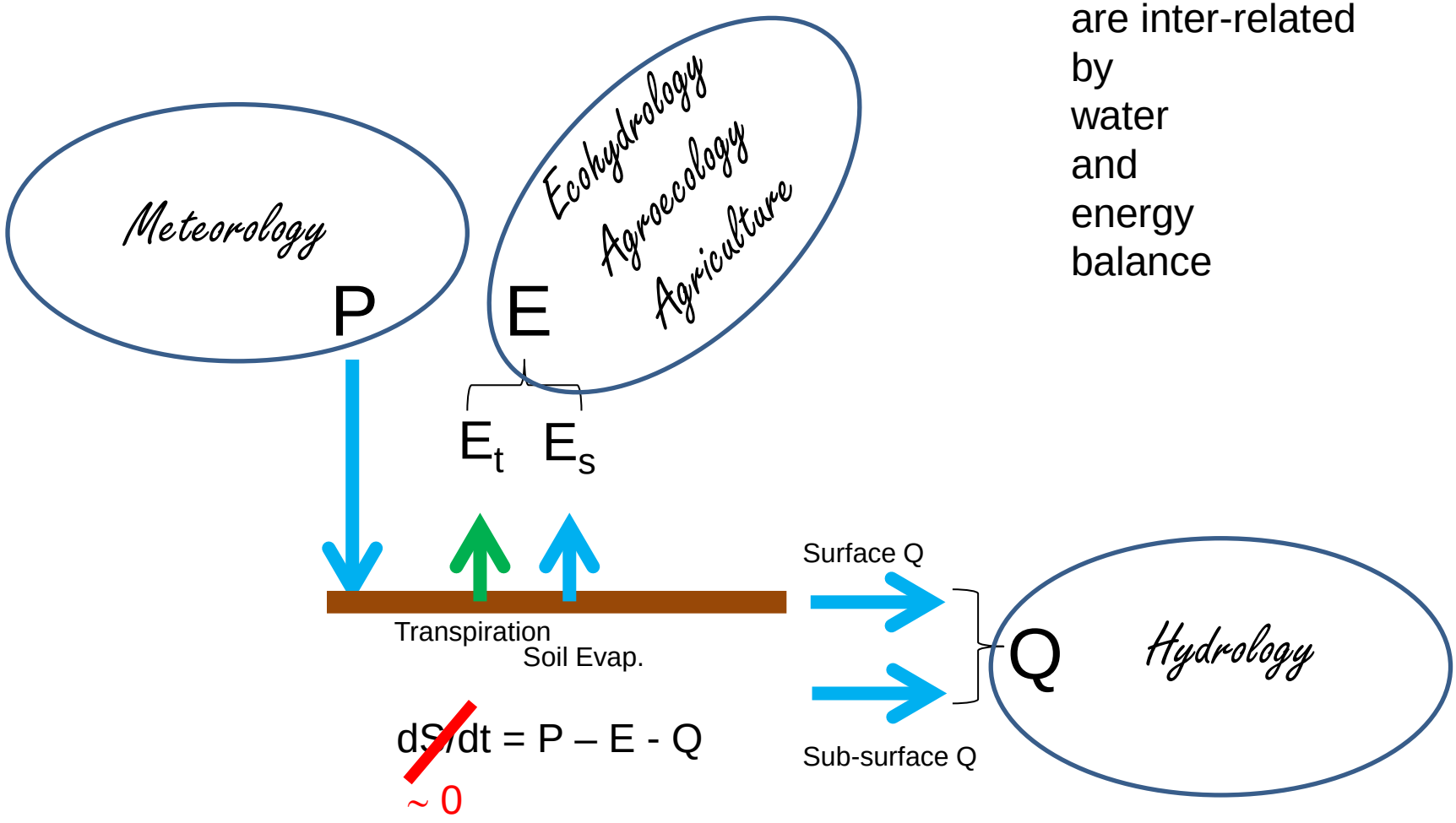
and (on average), it will become more arid.

Is this simple message correct?

NO. It is too simple to be useful.

PERSPECTIVES

Separate
but all
are inter-related
by
water
and
energy
balance

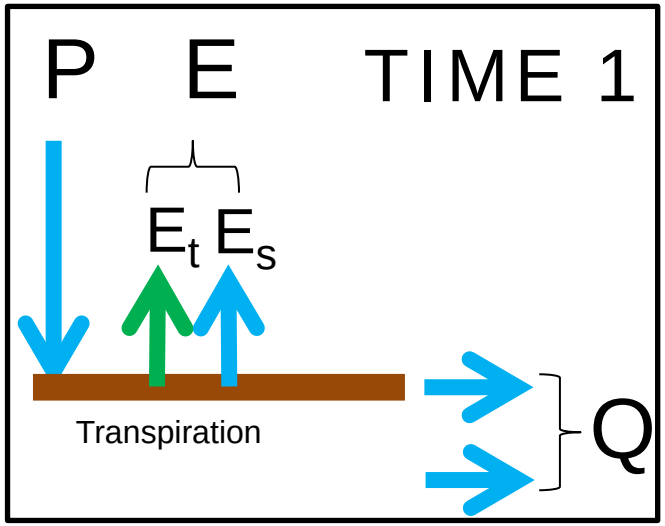


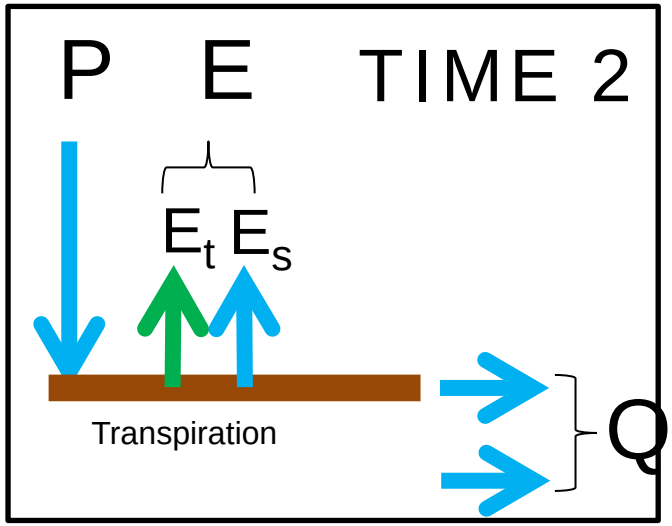
Over climatic time scales, e.g. 30 year averages, we use an approximate steady state:

$$P \approx E + Q$$

Note: we cannot use the steady state formulation to examine variations around the long term mean (e.g. droughts, floods, etc.) – we need to add soil moisture for that!

PERSPECTIVES on ARIDITY





Meteorology	**More or less P**
Agriculture/Ecology	**More or less ?what?**
Hydrology	**More or less Q**

How are P, E, Q projected to change

Region	Area	1970–1999 (20C3M)			2070–2099 (A1B)		
		P	E	$P-E$	ΔP	ΔE	$\Delta(P-E)$
	($\times 10^{14}$ m^2)	(mm a^{-1})			(mm a^{-1})		
GLOBE	5.09	1045	1045	0	47 [4.5 %]	47 [4.5 %]	0 [0 %]
OCEAN	3.62	1153	1248	−95	50 [4.3 %]	58 [4.7 %]	−8 [8.4 %]
LAND	1.47	775	542	+233	41 [5.3 %]	20 [3.7 %]	+21 [9.0 %]

= 1.6% K^{-1}

Over GLOBE: more E = more P

Over OCEAN: E increases faster than P
Over LAND: P increases faster than E (= more runoff)

Roderick et al. 2014 HESS

How are P, E, Q projected to change

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		P	E	$P-E$	ΔP	ΔE	$\Delta(P-E)$
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Over Land, more P, more E, more Q

Meteorology **More (global) P**

Agriculture/Ecology **More or less ?what?**

Hydrology **More (global) Q**

Roderick et al. 2014 HESS

Regional P, E, Q

Some places get more P, E, Q while others get less - the regional imperative

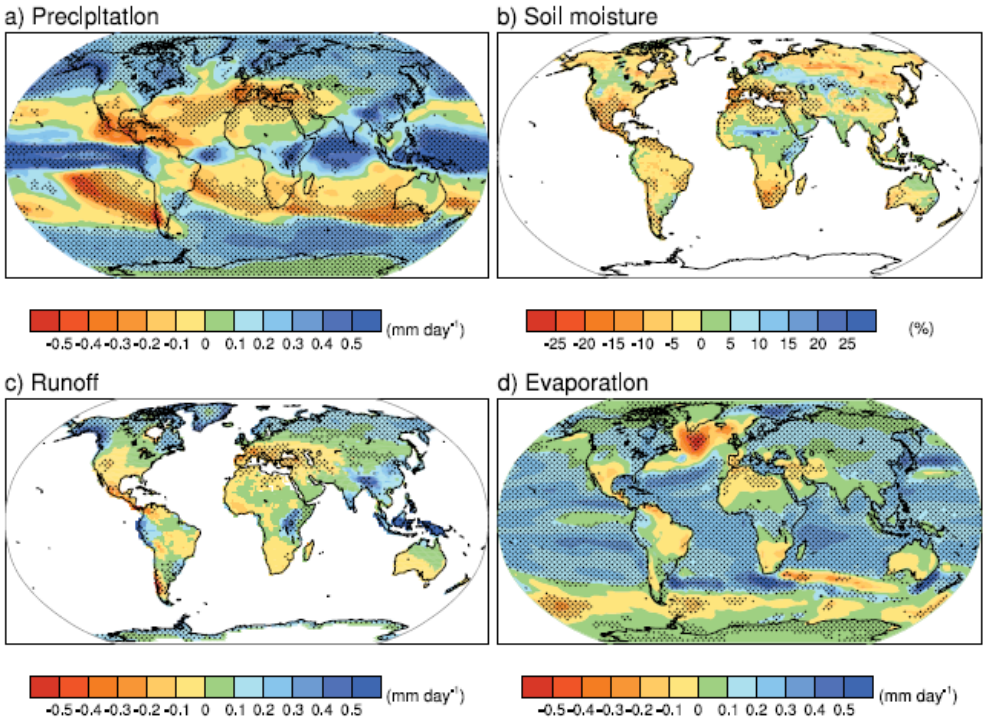


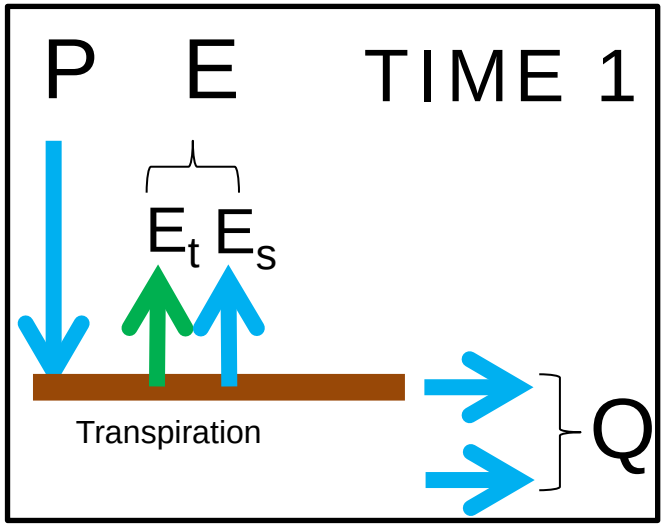
Figure 10.12. *Multi-model mean changes in (a) precipitation (mm day^{-1}), (b) soil moisture content (%), (c) runoff (mm day^{-1}) and (d) evaporation (mm day^{-1}). To indicate consistency in the sign of change, regions are stippled where at least 80% of models agree on the sign of the mean change. Changes are annual means for the SRES A1B scenario for the period 2080 to 2099 relative to 1980 to 1999. Soil moisture and runoff changes are shown at land points with valid data from at least 10 models. Details of the method and results for individual models can be found in the Supplementary Material for this chapter.*

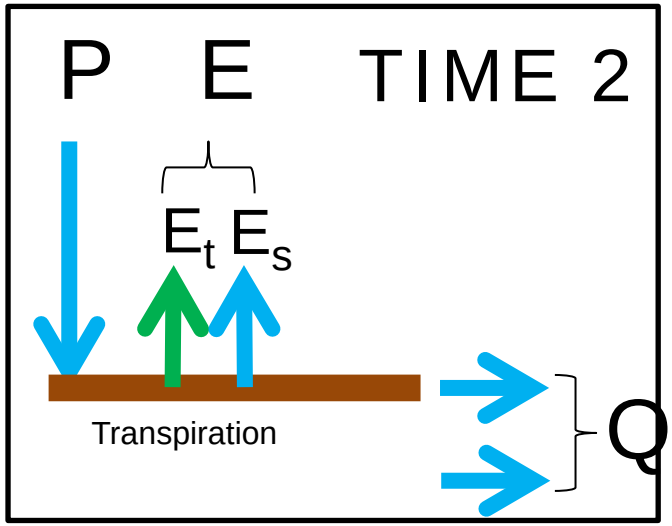
So,
some places
get wetter,
some get drier.
CRITICAL FOR REGIONAL CC.

But overall
the land gets
wetter in terms of
P, E, Q

IPCC 2007 AR4

PERSPECTIVES





Meteorology	More global P = WETTER
Agriculture/Ecology	**<u>More or less ?what?</u>**
Hydrology	More global Q = WETTER

[and more global E:
but how is this related to Agriculture/Ecology]

Aridity is defined, in meteorology and climatology, as "the degree to which a climate lacks effective, life-promoting moisture" (*Glossary of Meteorology*, American Meteorological Society).

physical

biological

Aridity from an Agricultural/Ecological perspective:

What we really want to know is how much Carbon is fixed.

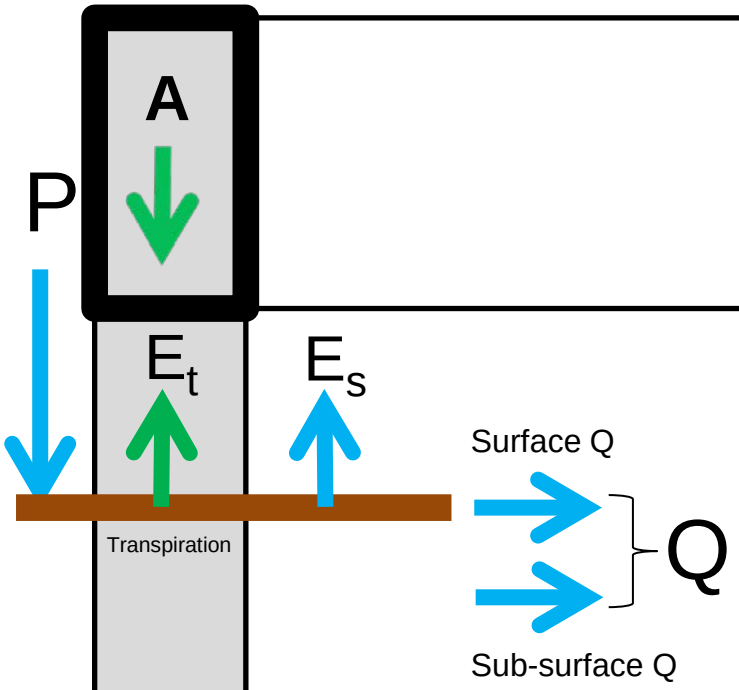
Figure 1.1: Vegetation - barren areas of the world

The vegetation-barren areas of the desert biome are clearly discernible in this satellite image of the earth, both north and south of the equator.

Source: NASA 2004

Aridity from the perspective of vegetation depends directly on C uptake.

BIOLOGY – A NEW PERSPECTIVE



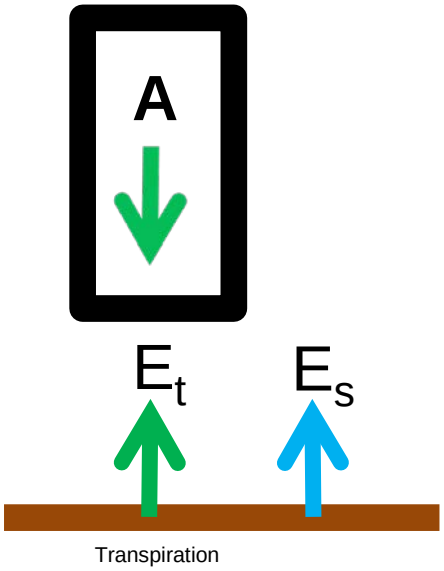
From the viewpoint of a plant,
aridity depends on water **and carbon**
A = assimilation of CO_2
$A = E_t$ * Water Use Efficiency

Meteorology — More global P = WETTER

Agriculture/Ecology — **More or Less CO_2 uptake**

Hydrology — More global Q = WETTER

How are A and E_t related?



A = assimilation of CO_2

$A = E_t * W$

$W = A/E_t$ **Water Use Efficiency**

Early work assumed: more E_t means more A (Briggs & Shantz, 1913)

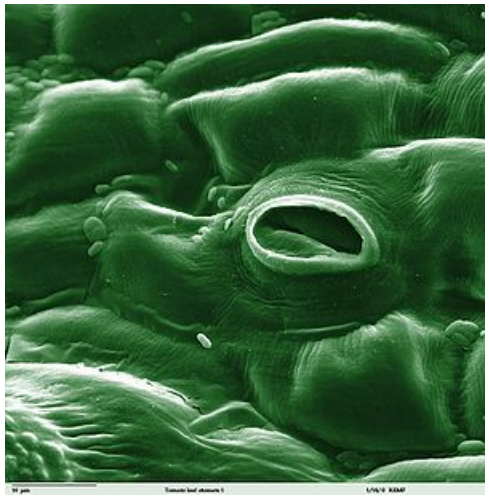
- assumption was that water flux controls the carbon flux

Leaf scale investigations suggest: more A means more E_t (Wong et al, 1979)

- interpretation is that carbon flux controls the water flux

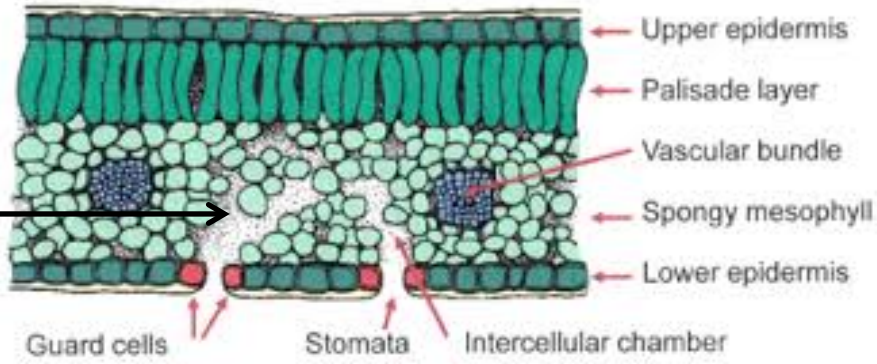
PRACTICAL IMPLICATION: <u>A and E_t are VERY TIGHTLY COUPLED</u>

CO_2 uptake and Water loss



C_i, $e_s(T_L)$ →

C_a, $e_a(T_a)$ →



C - CO_2 concentration
e - Vapour pressure
Inside the leaf: C_i, $e_s(T_L)$
In the atmosphere: C_a, $e_a(T_a)$

$$W = A/E_t \propto (C_a - C_i) / (e_s(T_L) - e_a(T_a))$$

Water Use Efficiency (W), C_a is atmospheric CO_2 concentration, D is vapour pressure deficit that is used as a surrogate for leaf-air vapour pressure difference.

$$\frac{dW}{W} \approx \frac{dC_a}{C_a} - \frac{1}{2}\frac{dD}{D}$$

W increases with CO_2
W decreases with D

Which is bigger?

Donohue et al 2013 GRL

Aridity – BIOLOGICAL Viewpoint

NOW

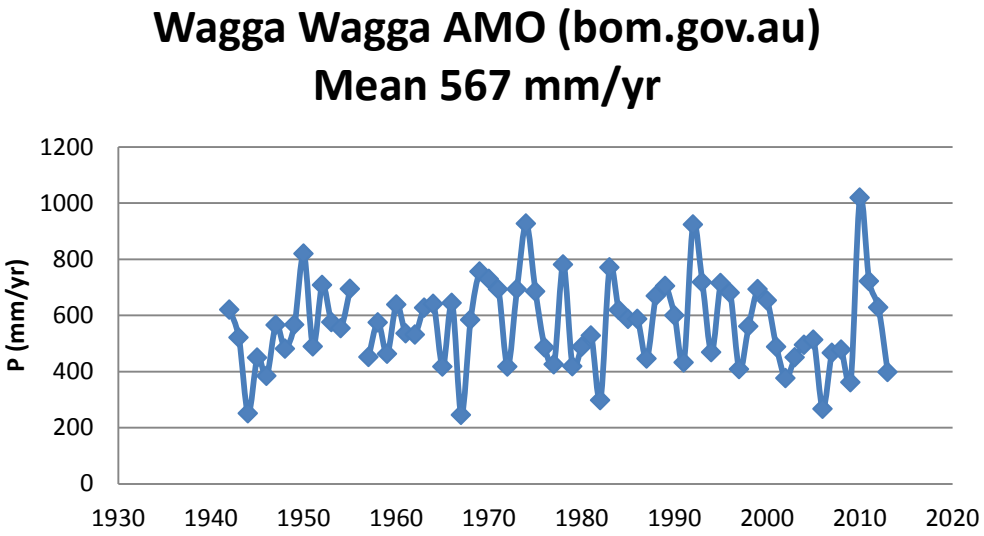
A_{NOW}
$= (E_t \times W)_{NOW}$

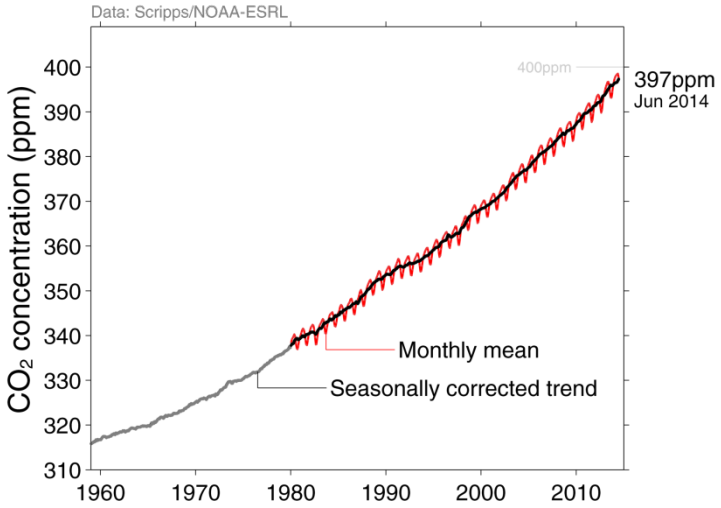
FUTURE

A_{FUTURE}
$= (E_t \times W)_{FUTURE}$

WHICH PRODUCT IS BIGGER (i.e., LESS ARID)?

CO_2 matters





Source: NOAA-ESRL; Global Carbon Budget 2014

Year	P	E_t	CO_2
	(mm)	(mm)	(ppm)
1958	575	200	315

In 2013, CO_2 is now ~ 395 ppm.

Q: How much E_t in 2013 will give the same A as in 1958?
(fine print: for constant D and some other things)

A: $dC_a/C_a = (395-315)/315 = 0.25$
200 / 1.25 = **160 mm**.

With same partition (160/200 * 575 =) P = 460 mm.

So P = 460 mm in 2013 gives same A as P = 575 mm in 1958.

Mean RH Change – RCP8.5

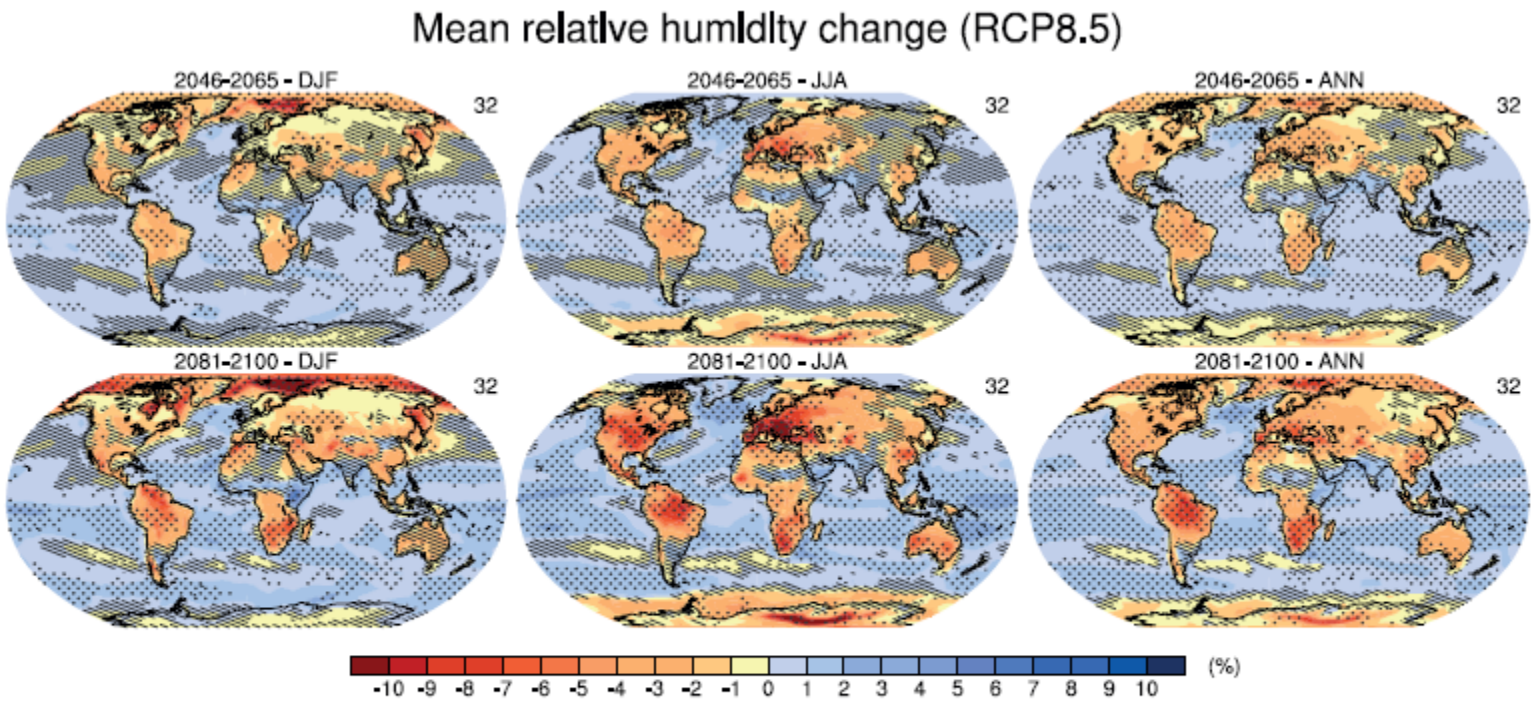


Figure 12.21 | Projected changes in near-surface relative humidity from the CMIP5 models under RCP8.5 for the December, January and February (DJF, left), June, July and August (JJA, middle) and annual mean (ANN, right) averages relative to 1986–2005 for the periods 2046–2065 (top row), 2081–2100 (bottom row). The changes are differences in relative humidity percentage (as opposed to a fractional or relative change). Hatching indicates regions where the multi-model mean change is less than one standard deviation of internal variability. Stippling indicates regions where the multi-model mean change is greater than two standard deviations of internal variability and where at least 90% of models agree on the sign of change (see Box 12.1).

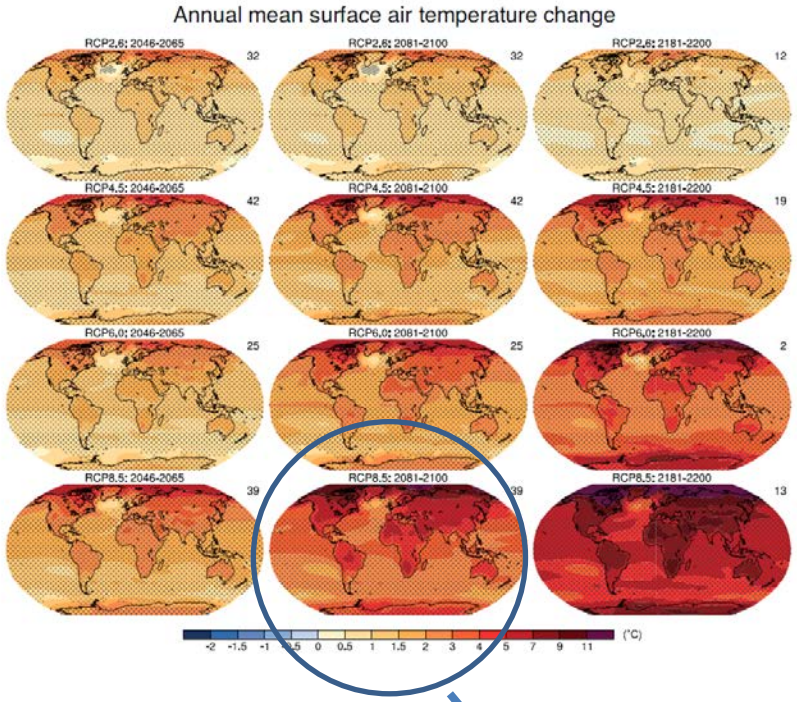
Note: Global RH at surface is projected to remain ~ constant

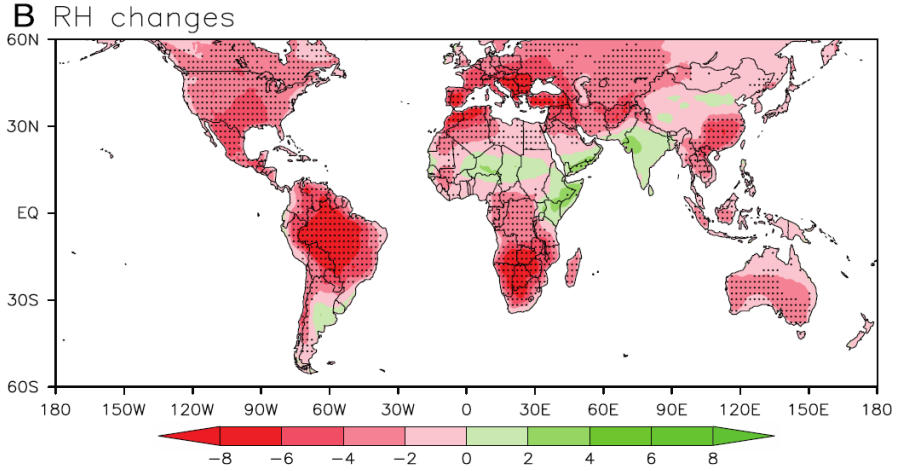
BUT

RH is projected to increase over oceans, decrease over land.

IPCC AR5 (2013)

How much are CO_2 & D projected to change?





Extreme Example (RCP8.5 to the year 2100):

	T	RH	dT	dRH	dD
Amazon	25°C	0.70	+5°C	-0.08	= 1612 – 950 = 662 Pa

RCP8.5: CO_2 goes from 390 ppm to ~ 900 ppm

Sherwood & Fu 2014 Science; IPCC AR5 2013

Who Wins the Race to the Year 2100: C_a or D?

$$\frac{dW}{W} \approx \frac{dC_a}{C_a} - \frac{1}{2}\frac{dD}{D}$$

dW/W ~ (900-390)/390 - (0.5) (1612-950) / 950
~ 1.31 - (0.5) (0.70)
~ **1.31** - **0.35**
~ **0.96**

<u>CO_2 wins by a long way. W will double by 2100.</u>

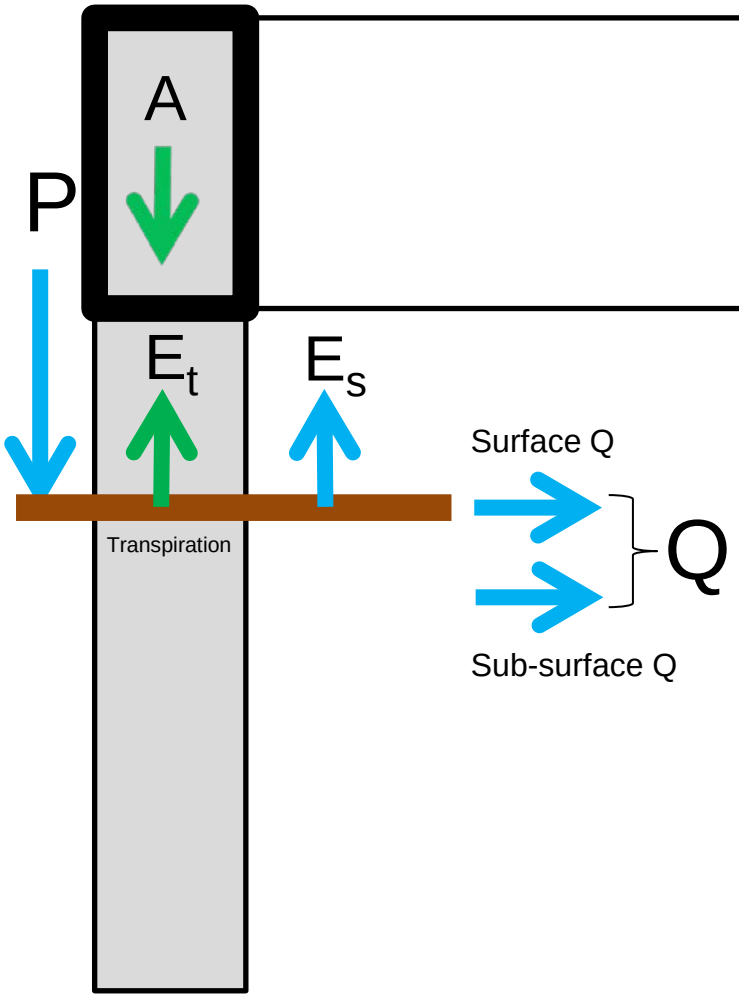
Extreme Example (RCP8.5 to the year 2100):

	T	RH	dT	dRH	dD
Amazon	25°C	0.70	+5°C	-0.08	= 1612 – 950 = 662 Pa

RCP8.5: CO_2 goes from 390 ppm to ~ 900 ppm

W_{2100} = W_{2000} + dW = W_{2000} + 0.96 W_{2000} = 1.96 W_{2000} ~ **2 W_{2000}**

BIOLOGY – From Water to Carbon



From the viewpoint of a plant,
aridity depends on water **and carbon**
A = assimilation of CO_2
$A = E_t$ * Water Use Efficiency

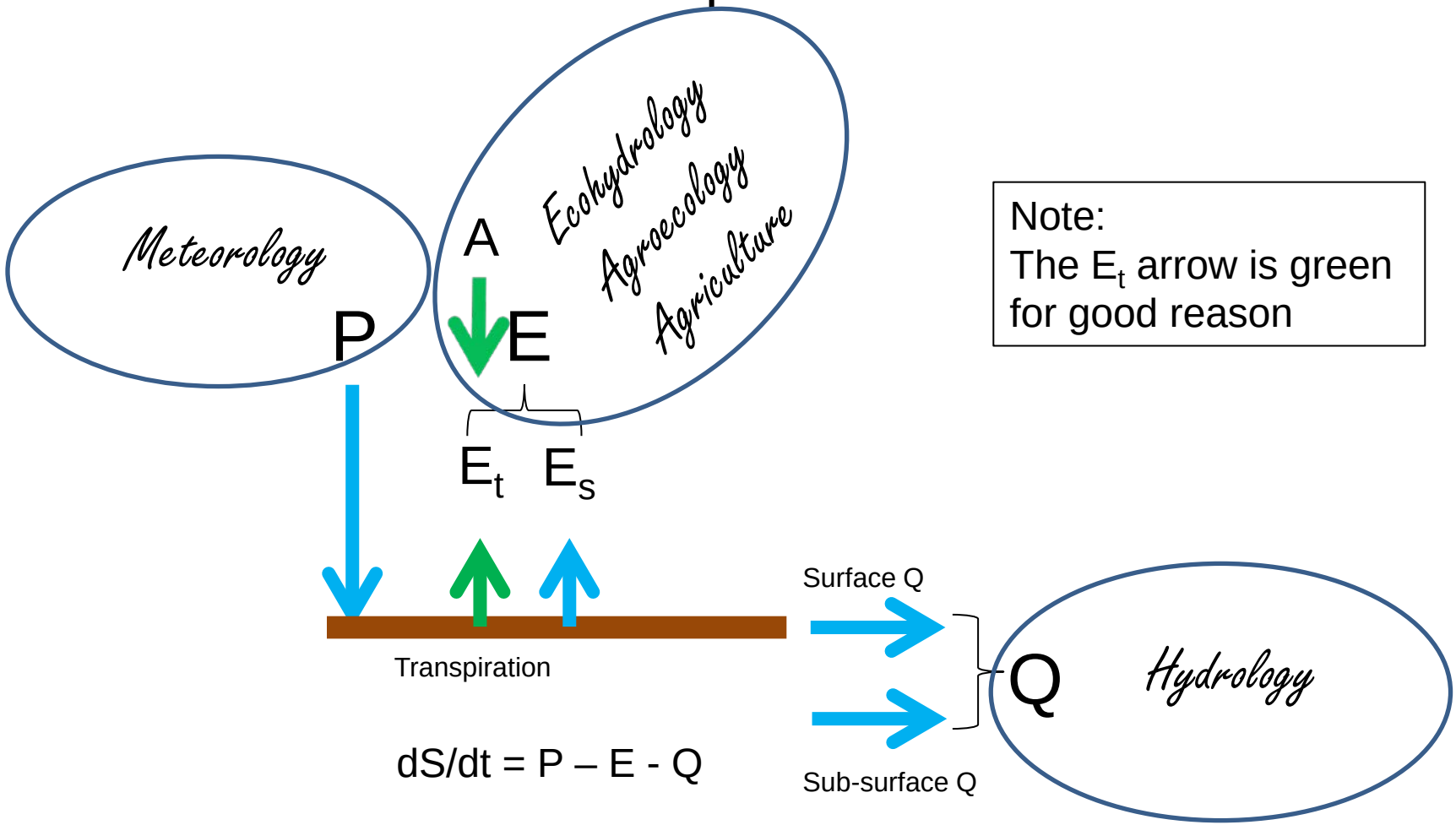
Higher water use efficiency due to elevated CO_2 overwhelms the projected changes in VPD.

WORDS OF CAUTION:
This is only the start of the Carbon cycle.

To predict vegetation
(as opposed to photosynthesis) requires;

allocation, respiration,
nutrient cycles
reproduction
community
biome
disturbance (fire, land use, …..)
etc……..

PERSPECTIVES on ARIDITY per CLIMATE MODELS

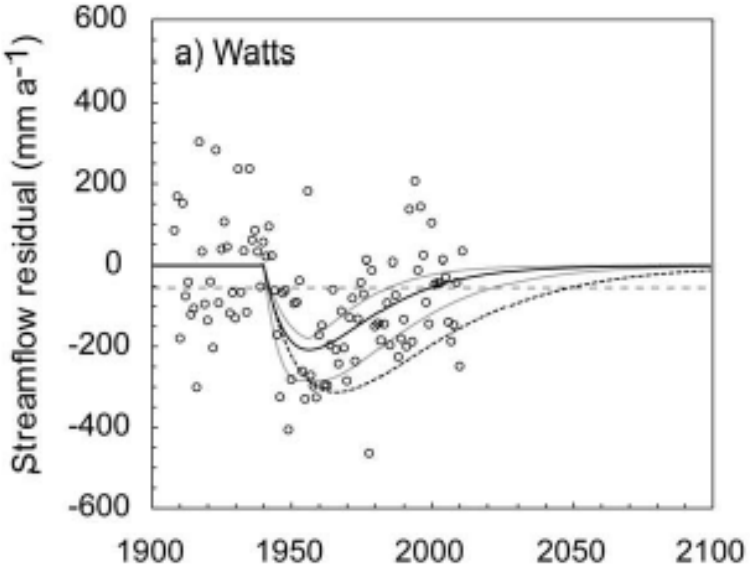


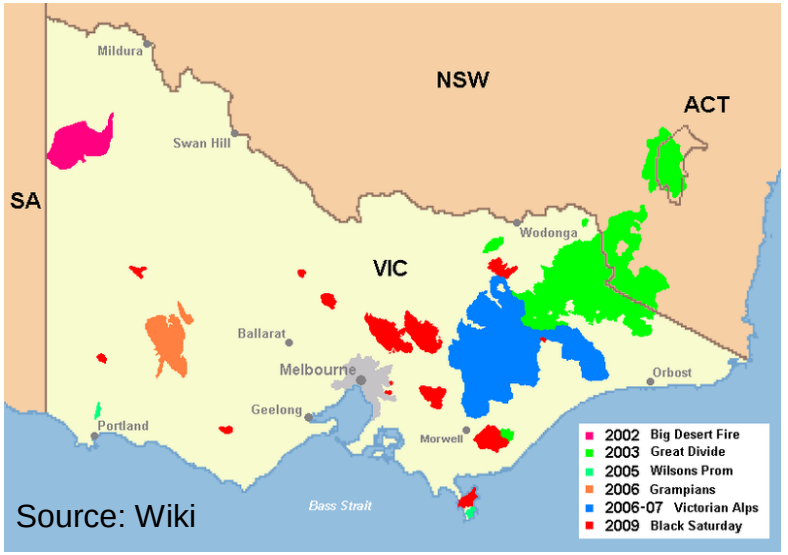
Note:
The E_t arrow is green for good reason

WARMER = WETTER on all GLOBAL (but not local) PERSPECTIVES

Meteorology	More global P = WETTER
Agriculture/Ecology	**Biologically Wetter (=A) Nearly Everywhere**
Hydrology	More global Q = WETTER

Will post-fire regrowth in SE Australian forests use extra water?





Biology: After fire, millions of seedlings per Ha, young Ash forests are thirstier

CONSEQUENCE: At constant rainfall there is a plausible REDUCTION in MDB Inflows ~ 1000 GL/yr by 2023

Kuczera 1987 J. Hydrology; Brookhouse, Farquhar, Roderick, 2013, WRR

Take Home Messages

- There is no single index that will measure aridity from all perspectives under changing CO_2.
  - Have to use multiple perspectives. ← *A good reason for OzEWEX to exist*
- P – Precipitation
  - (meteorologists, hydrologists, …)
- Q – Runoff
  - (hydrologists, ecologists, …)
- A – CO_2 assimilation & E_t – Transpiration
  - (biologists, agronomists, foresters, …)

All tied together by mass and energy balance

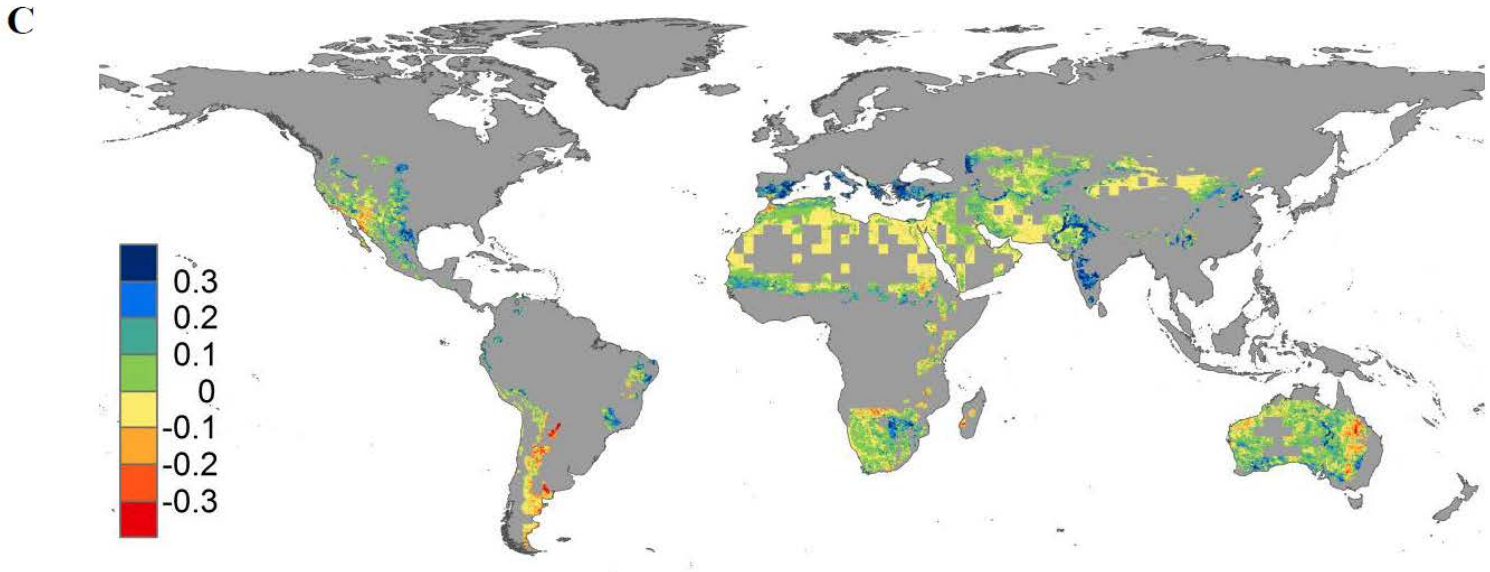
Take Home Messages

- A simple and clear message is only useful
  - if it is correct
    - An incorrect simple message is one way to polarise a complex issue

Take Home Messages

- Increasing CO_2 has impacts on water-carbon coupling (via vegetation) that are happening now!

SATELLITE OBSERVED CHANGES in ARID LAND FOLIAGE COVER , 1982-2010



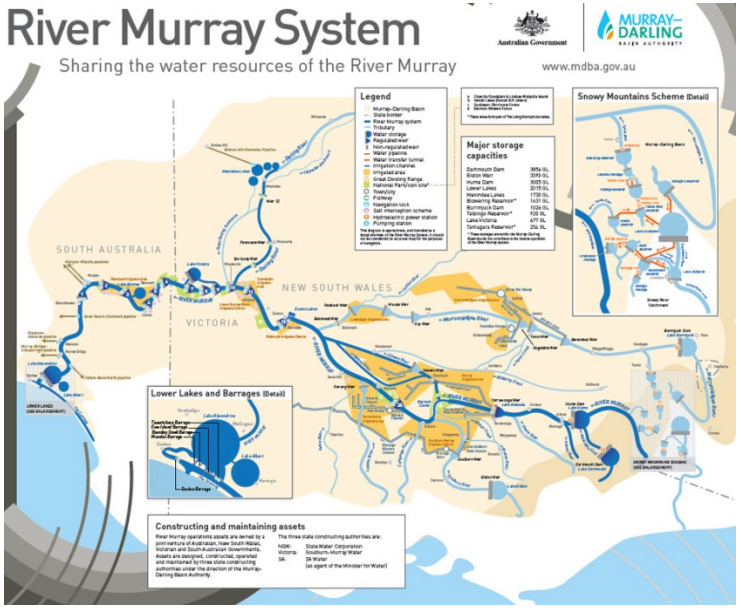
Donohue et al 2013 GRL

Biology again ……..

Scientific classification	
Kingdom:	Animalia
Phylum:	Chordata
Class:	Mammalia
Order:	Primates
Family:	Hominidae
Tribe:	Hominini
Genus:	*Homo*
Species:	***H. sapiens***

Homo sapiens (Latin: "**wise man**"):

- Mass: ~ 50-100 kg, Height: 1-2 m tall, Bipedal Mammal,
- Sexual maturity: ~13 years, Lifespan: ~ 50-100 years
- Gestation: 9 months, Diet: omnivorous (with a few exceptions), Habitat: terrestrial
- When evolved: < 1,000,000 years
- Very interesting creatures
  - Highly adaptable, successful colonizers of most habitat types
    - Lives in colonies with outposted workers who produce and export food to main colony
      - Likes to rearrange surface water (e.g. dams, diversions, extractions, ...)
        - Some similarities to Beavers (*Castor canadensis)*



Map Source: Murray Darling Basin Authority

THANK YOU

QUESTIONS