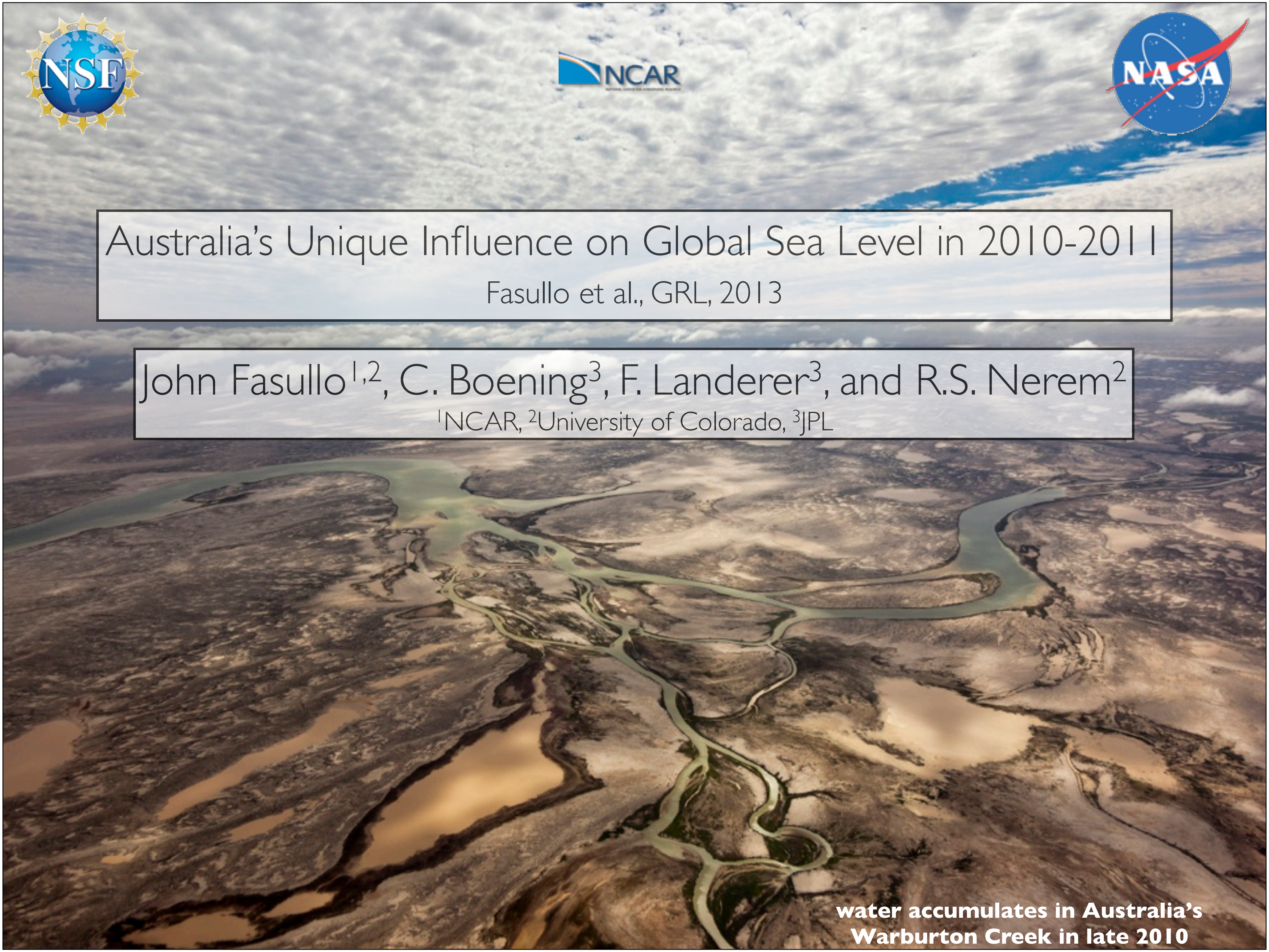
water accumulates in Australia’s
Warburton Creek in late 2010

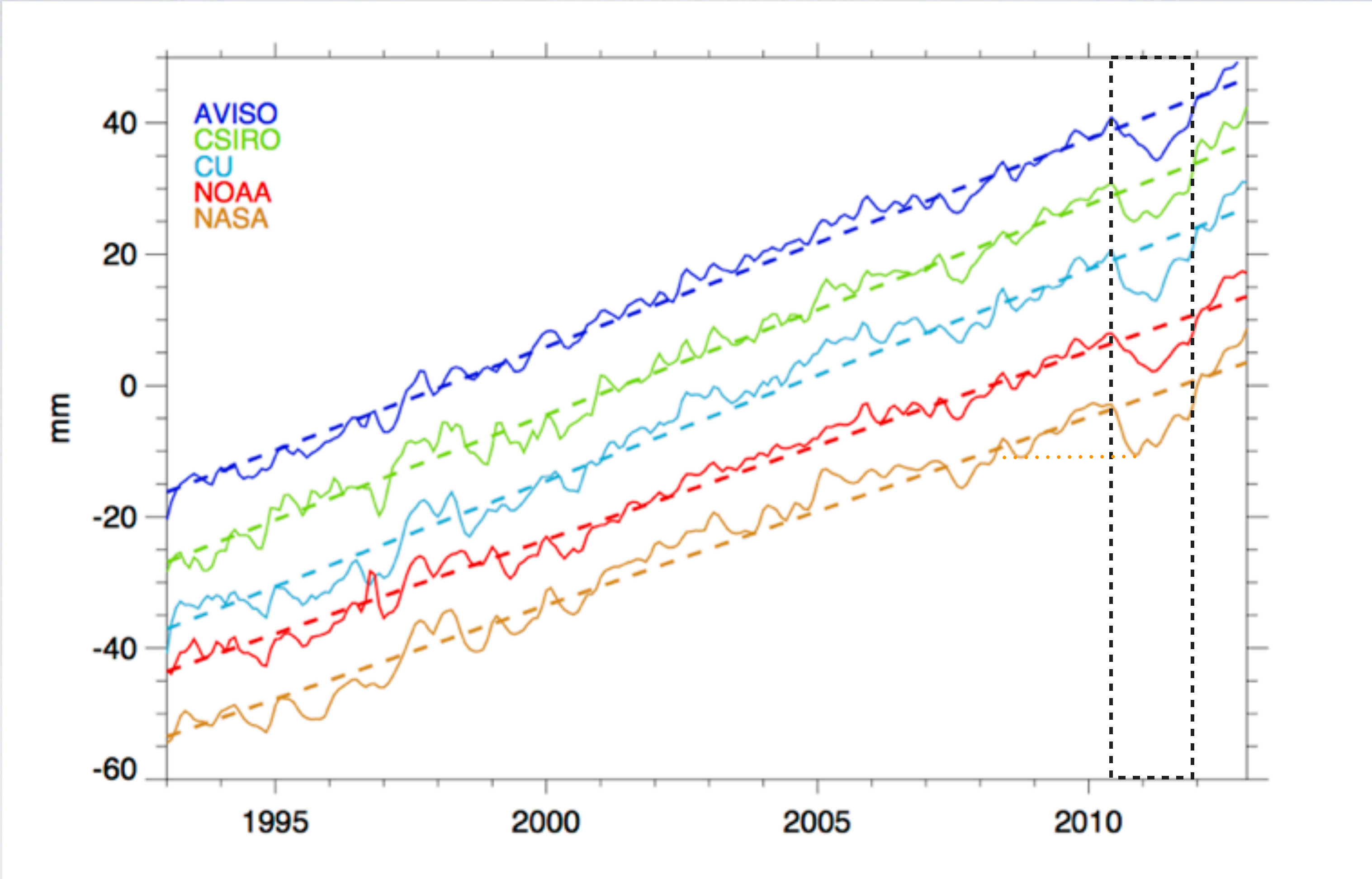
Australia’s Unique Influence on Global Sea Level in 2010-2011

Fasullo et al., GRL, 2013

John Fasullo[1,2], C. Boening[3], F. Landerer[3], and R.S. Nerem[2]
[1]NCAR, [2]University of Colorado, [3]JPL



water accumulates in Australia’s Warburton Creek in late 2010

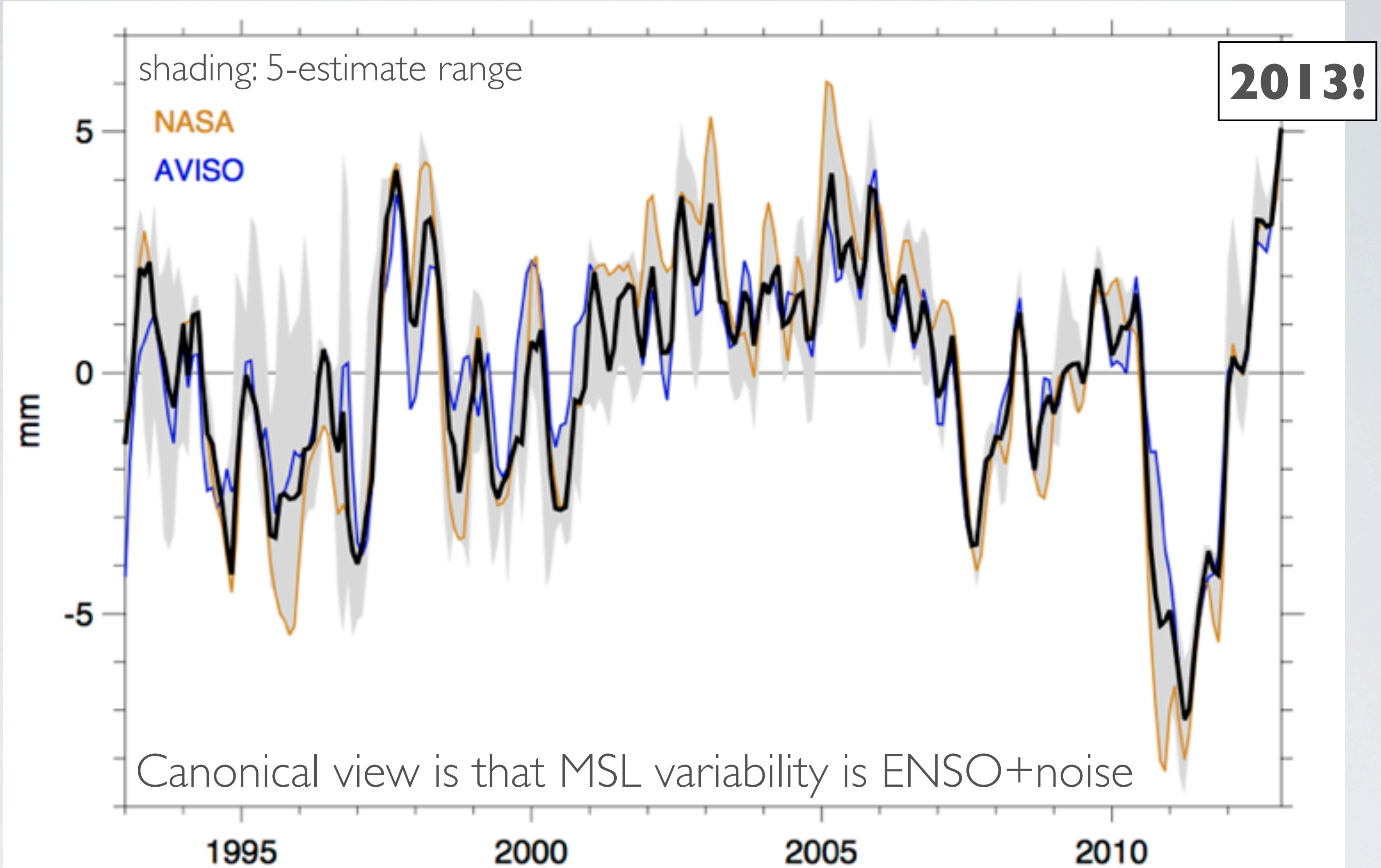


GLOBAL MEAN SEA LEVEL

Trend of ~3 mm yr $^{-1}$

1-sigma anoms ~ 3 mm

The 2010-2011 Drop: How and why did occur and can we model it?

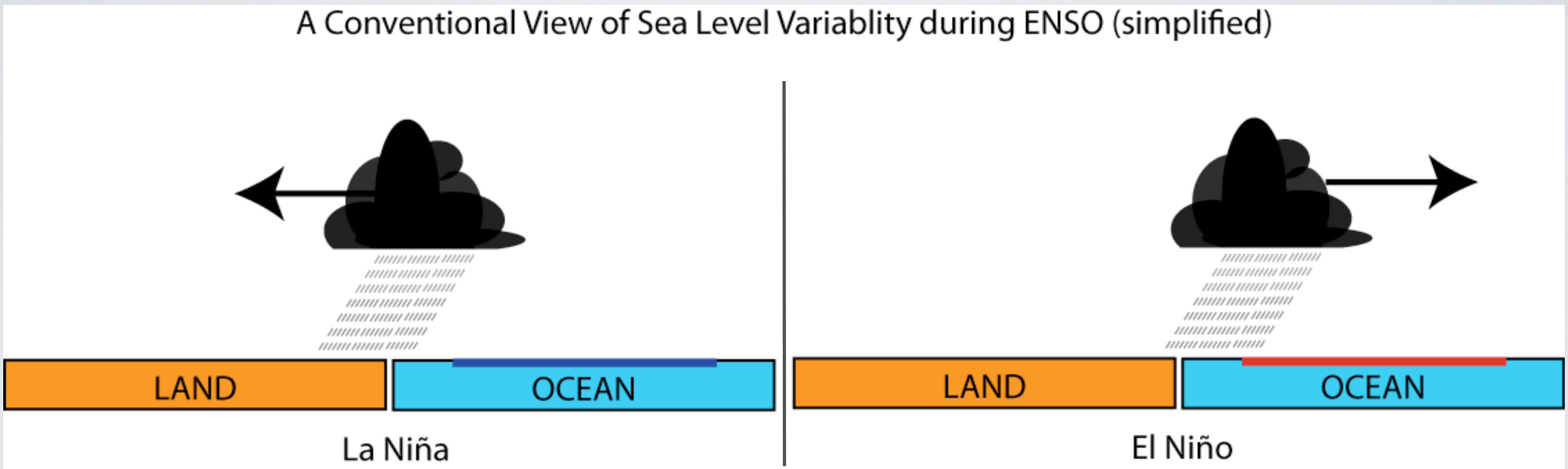


DE-TRENDED GMSL

Excellent S/N in 2010/11, not in other years ("in the noise")

(Modest S/N in 1997-8 but no GRACE and no ARGO, r(MEI,ENSO)~.5, 2013!)

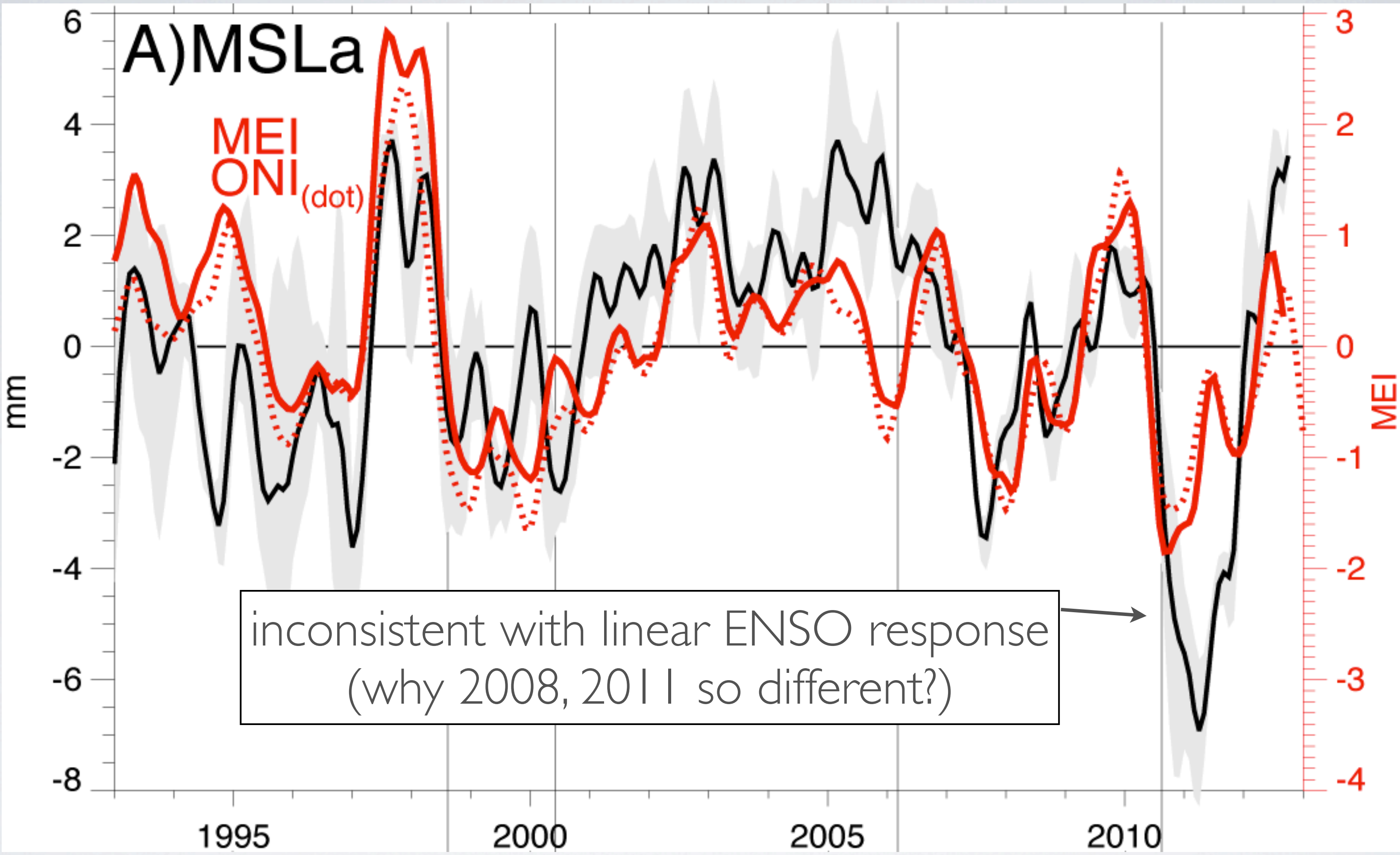
ENSO-MSL INTERACTION



During La Niña, cold tropical oceans favor terrestrial rainfall while during El Niño warm tropical oceans suppress it.

But does the data show a strong link between P_L and MSL?

(schematic overlooks the complex 1) behavior of ENSO and 2) relationship between P_L and TWS)



DE-TRENDED GMSL

Even when the fit is exaggerated for prior El Niño events, not possible to fit 2010-11
e.g. 2008 La Niña modestly weaker than 2011 but MSLa much smaller/briefer

QUESTIONS

What happened in 2011 and why? (attribution)
Can we model the event? (process-level understanding)

- Was the 2011 drop primarily eustatic or steric?
- Can the surface mass budget be reconciled with altimetry?
- What "caused" the drop?
- How unusual was the event? 1 in 10-yr or 100-yr? (leverage obs of P?)
- What processes do models need to resolve?
  (models don't explicitly simulate GMSL but do have the 1st order terms on IA timescales, MSLa = OHCa + terrestrial storage anom + atm storage + second order terms; in effect, MSLA can be 'backed-out')

THE 2011 LA NIÑA: SO STRONG THE OCEANS FELL

BOENING, WILLIS, LANDERER, NEREM, FASULLO, 2012 GRL

- found the event was primarily eustatic (GRACE/ARGO/altimetry/CERES)
- closure in the mass budget and altimetry (land uptake ≈ MSLa)
- alluded to the influence of La Niña on the tropical monsoons (sea level governed primarily by tropical land storage; NOT OHC or melt)

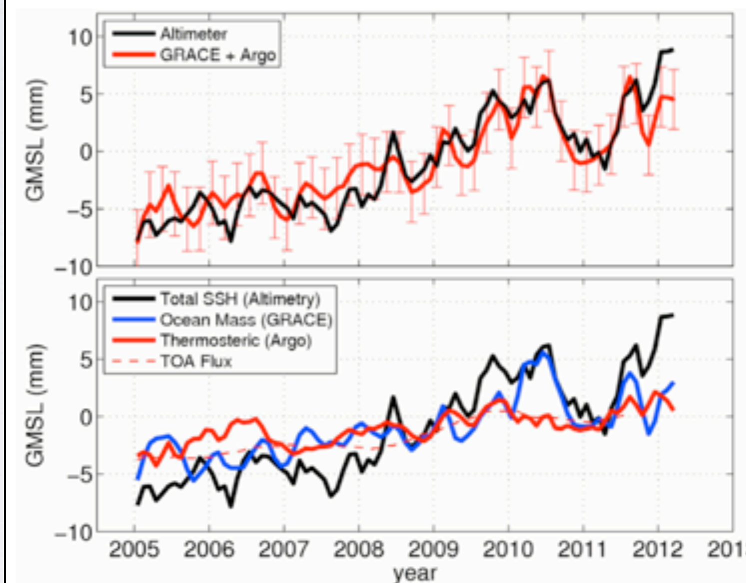


Figure 2. (top) Global mean sea level from altimetry from 2005 to 2012 (black line). The red line shows the sum of the ocean mass contribution (as measured by GRACE) and thermal expansion contribution (as measured by Argo). Error bars are 2.5 mm (as discussed in the Methods Section). (bottom) Contributions to global sea level rise from 2005 to 2012. As in the top panel, the black line shows GMSL as observed by satellite altimeters. Ocean mass changes are shown in blue and thermosteric sea level change is shown in red. The red dashed line shows an estimate of ocean warming based on estimates of radiative imbalance at the top of the atmosphere. The mean warming rate is adjusted to agree with Argo and heat content is scaled assuming that 3×10^{22} J is equivalent to 5 mm of thermosteric sea level rise as in *Church et al.* [2005].

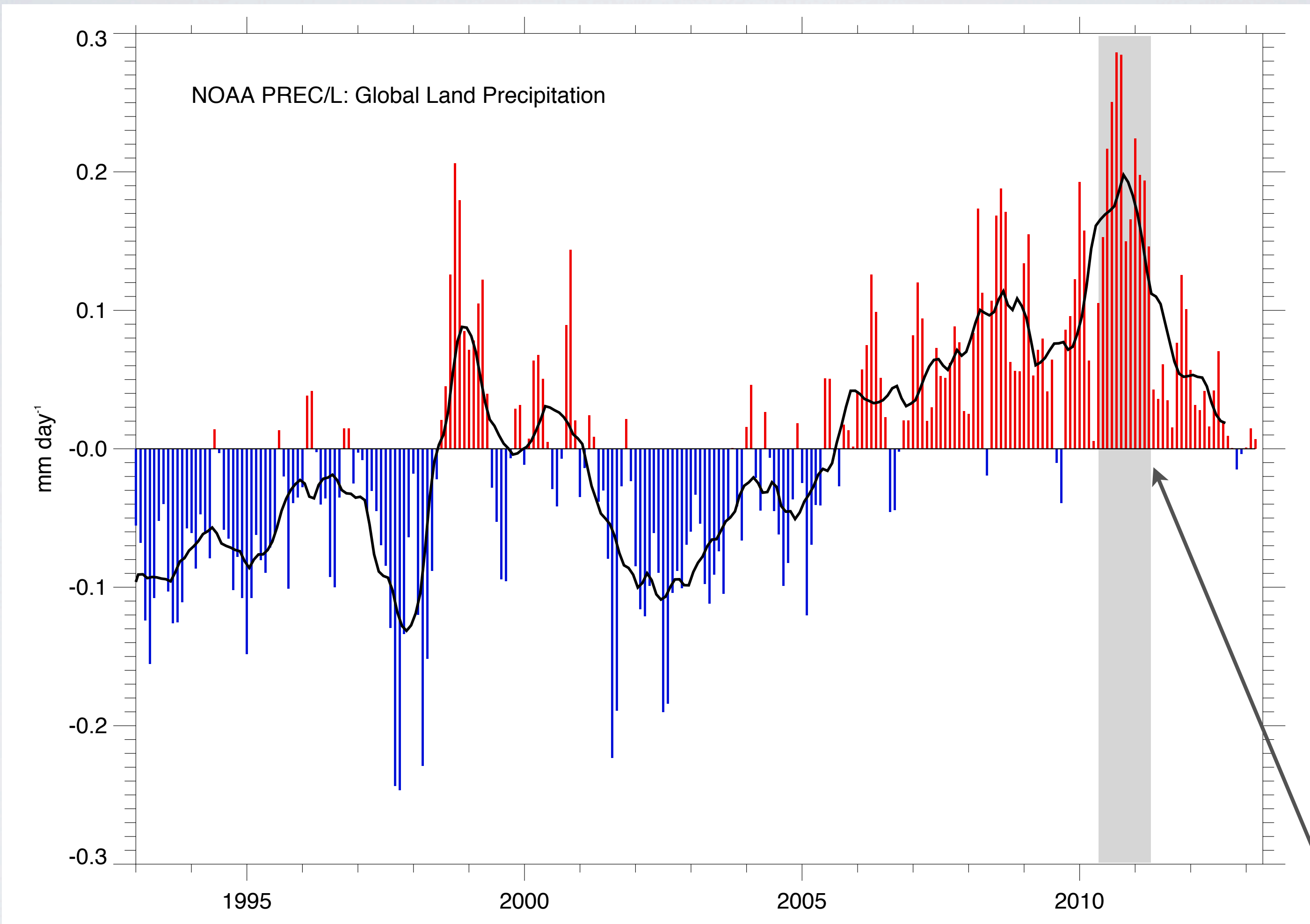
QUESTIONS

Boening et al 2012

- Was the 2011 drop primarily eustatic or steric? — Eustatic
- Can the surface mass budget be reconciled with altimetry? — Yes, to within OHC error bars
- What "caused" the drop? — La Niña?
- How unusual was the event? 1 in 10-yr or 100-yr? (leverage obs of P?) — As unusual as the 2011 La Niña?
- What processes do models need to resolve? — Rainfall and runoff over land?

  (models don't explicitly simulate GMSL but do have the terms that dominate on IA timescales, MSLa = OHCa + terrestrial storage anom + atm storage + second order terms; in effect, GMSLa can be 'backed-out')

P_L - REALLY THE "CAUSE"?

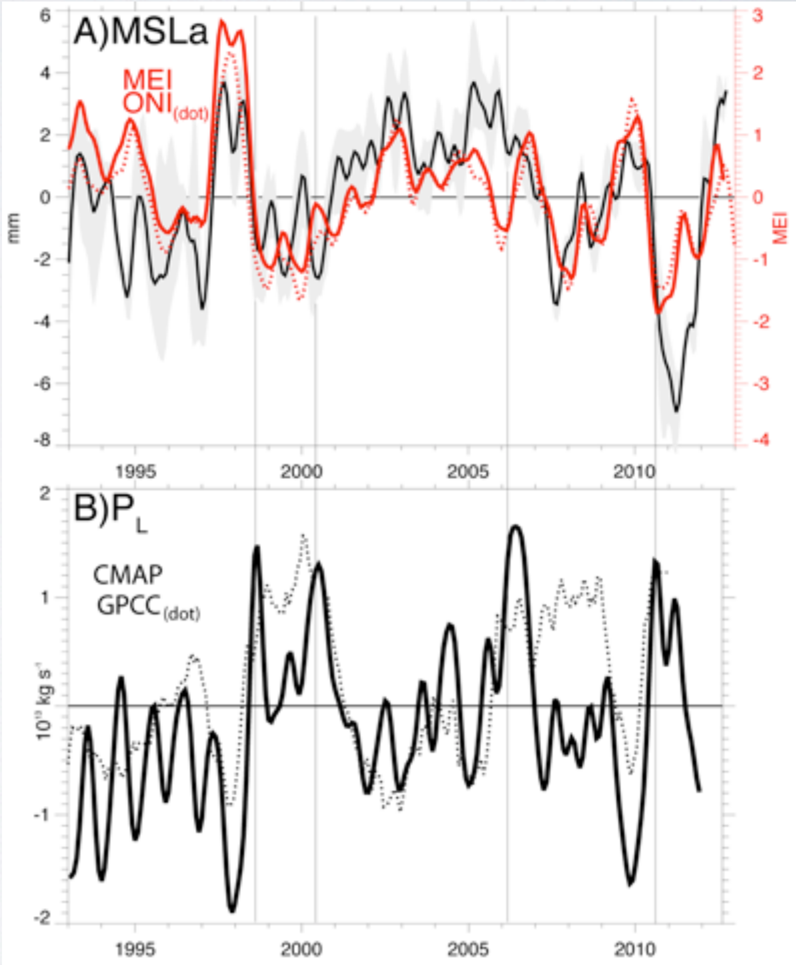


According to NOAA PREC/L, 2010-2011 was altimeter-era peak in P_L.

(Independently corroborated by MERRA/ERAI reanalysis budgets P-E! But not by more recent data.)

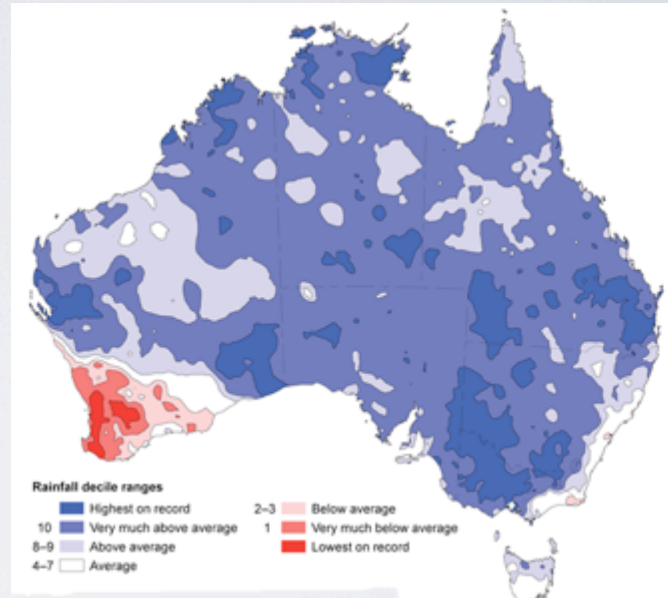
P_L - ALTIMETER ERA MAX?

- Latest rainfall datasets show 2011 P_L to be large but not unique. [also GPCP and TRMM]
- NOAA PREC/L was found to have spurious variability (alias PDO?)- GPCC incorporates many more gauges
- **If P_L not unique, why was GMSL so unique?**

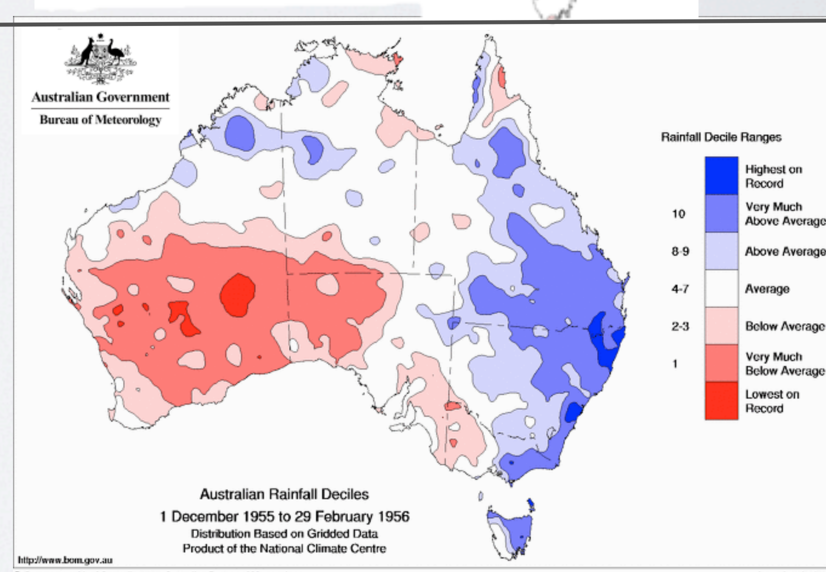


LA NIÑA - REALLY THE "CAUSE"?

- **2010/11**: 2nd Strongest La Niña on record since 1950 (per MEI)
- Continent-wide rainfall much above average (~80%).
- Numerous all time records



- **1955/6**: Strongest La Niña since 1950
- Flooding in east. Mostly negative rainfall anomalies in central/western Australia
- Why such a contrast with 2010/11?



NEW DATA

- Multiple GRACE monthly gridded land mass data(RL05/200 km from JPL, CSR, GFZ)
- GPCC v6 land rainfall
- Runoff from UNH/GRDC V1.0

Questions

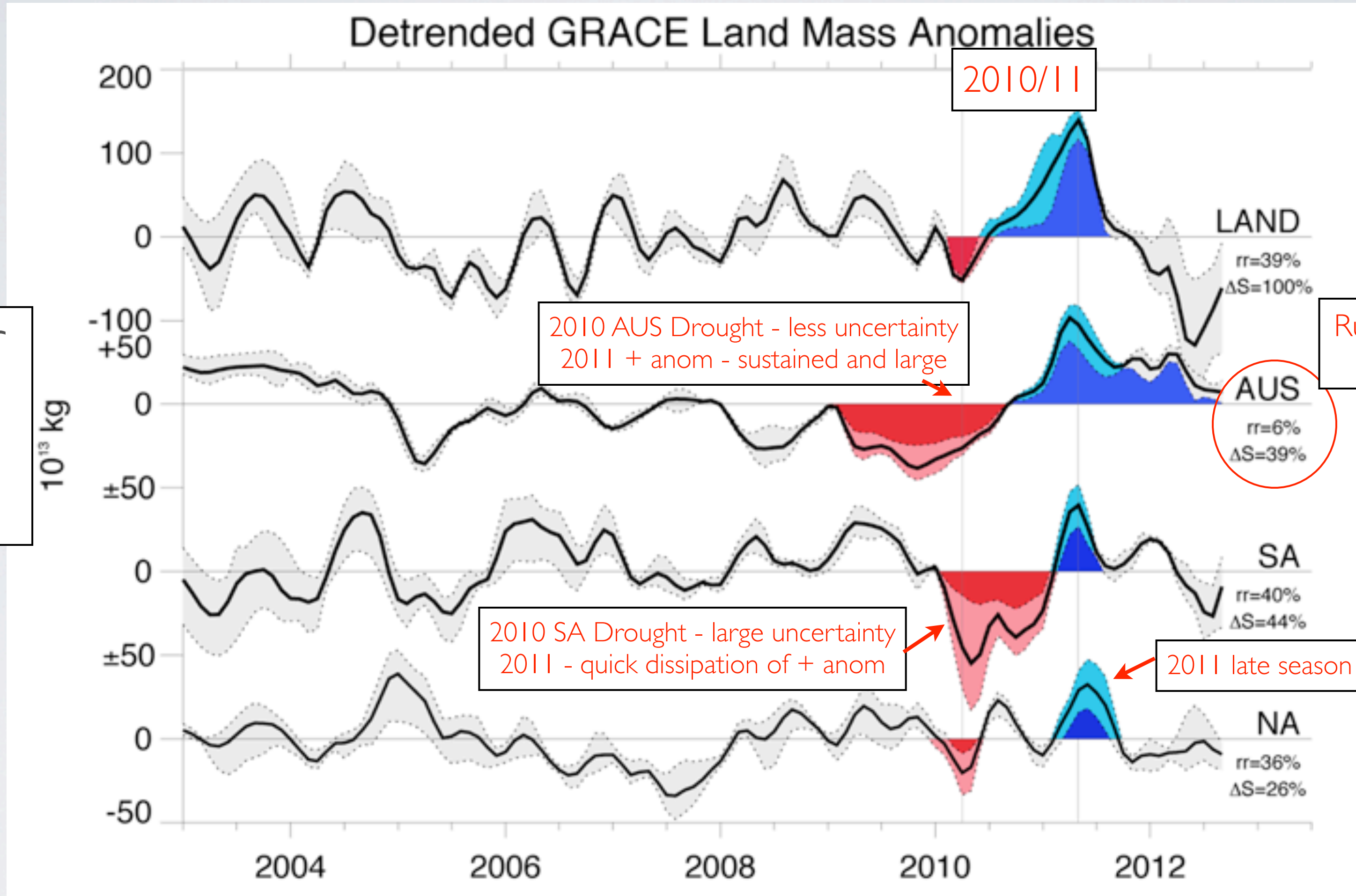
1) Is La Niña the sole cause?

2) How can rainfall over land drive prolonged sea level anomalies when the runoff timescale for most river basins is on the order of 3 months?

3) Why does the MEI fit explain such a small part of the variance in altimetry and vastly underestimate the 2011 drop?

REVISITING THE 2011 DROP

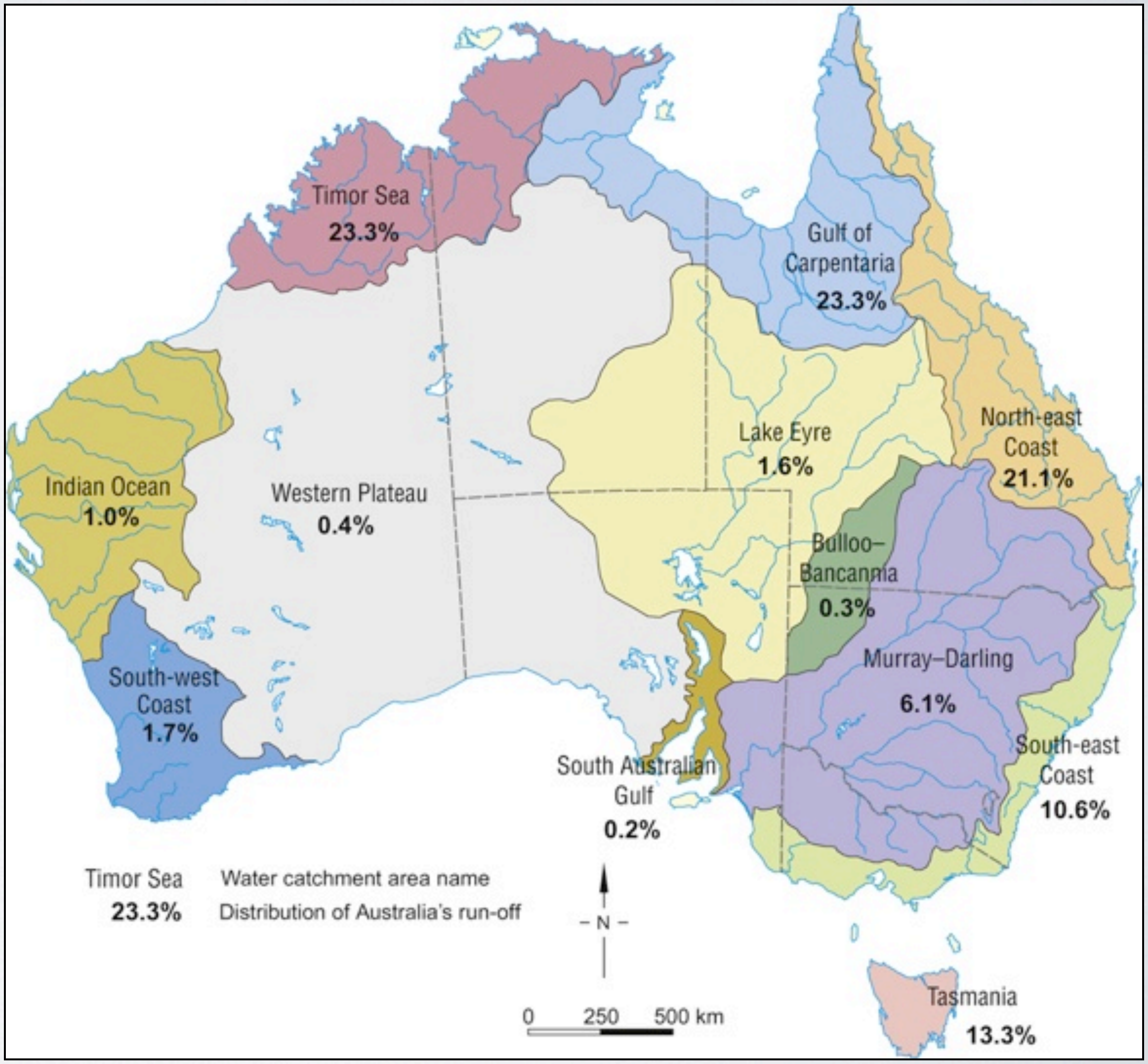
Units of Total Mass



Australia's low frequency contribution to land storage is unequaled by other continents.

AUSTRALIA'S MAJOR CATCHMENTS: SOURCES OF LOW FREQUENCY VARIABILITY

- Major arheic and endorheic basins: Western Plateau and Lake Eyre
- No coordinated runoff to ocean
- In arheic basins (WP), wind rather than rain is the main erosive force.
- In endorheic basins (Eyre), flow is inland.
- Increases storage persistence.
- **Basins NOT well simulated by models**. **P and E also poorly simulated**.



INFLUENCES ON AUSTRALIAN RAINFALL

[RISBEY ET AL. 2009]

3234 MONTHLY WEATHER REVIEW VOLUME 137

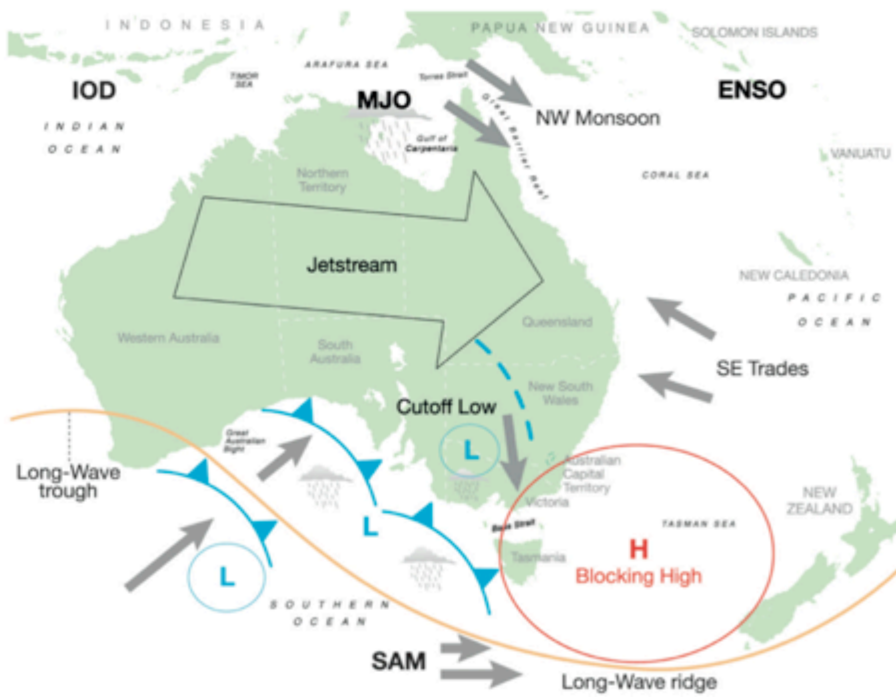
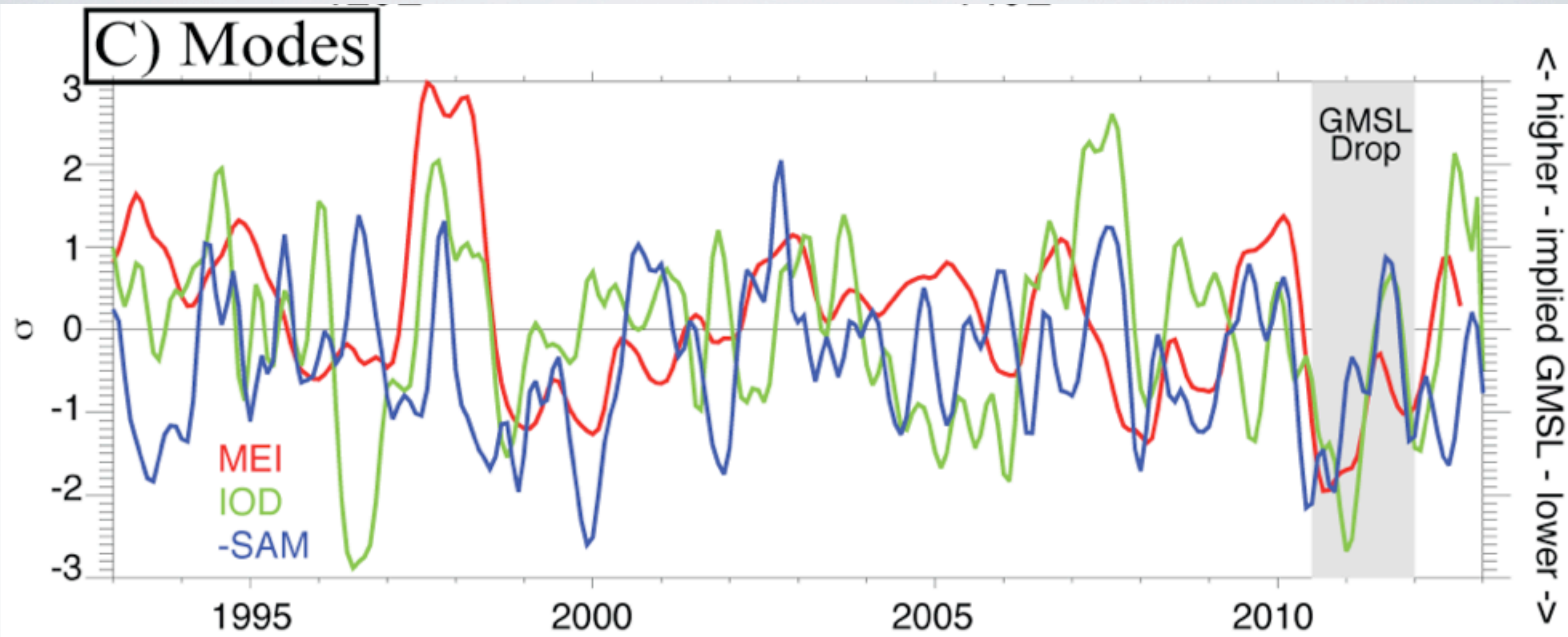


FIG. 1. Schematic representation of the main drivers of rainfall variability in the Australian region. The dominant features are the IOD, MJO, and ENSO in the tropics, and the SAM and blocking in the extratropics. The influence of the subtropical jet is indicated by the "jet stream" arrow. A schematic cutoff low in a typical position to influence southeast Australian rainfall is shown next to the blocking high. The longwave pattern in the midtroposphere consistent with the blocking high is also indicated with a trough over Western Australia and a ridge in the Tasman Sea.

GRACE allows for the extension of regional rainfall attribution to global sea level.

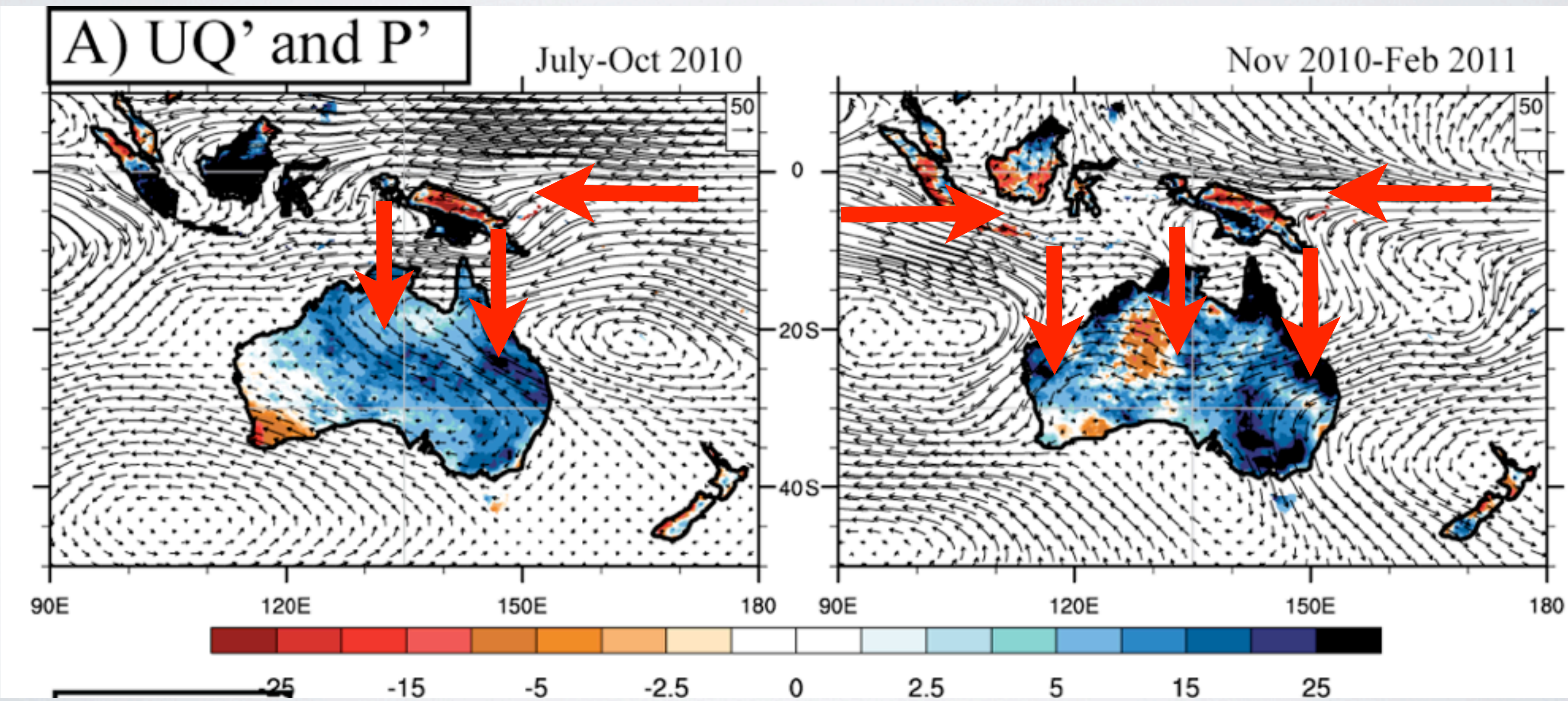
INFLUENCES ON AUSTRALIAN RAINFALL
[RISBEY ET AL. 2009]



During the 2011 GMSL drop, extremes in all modes coincided.

INFLUENCES ON AUSTRALIAN RAINFALL

- **SAM** pulls tropical easterly moisture transports (La Niña) across the continent.
- **IOD** westerly transport converges with La Niña easterlies, drives them into Aus



CONCLUSIONS

Australia is a key player in global terrestrial water storage due to its unique surface hydrology and proximity to major modes of variability.

~~2011 La Niña → P_L → 2011 Sea Level Drop~~

(1)[{2010 El Niño + 2011 La Niña + **IOD/SAM**} → $P_{\text{AUS Arehic/Endorheic Basins}}$ +

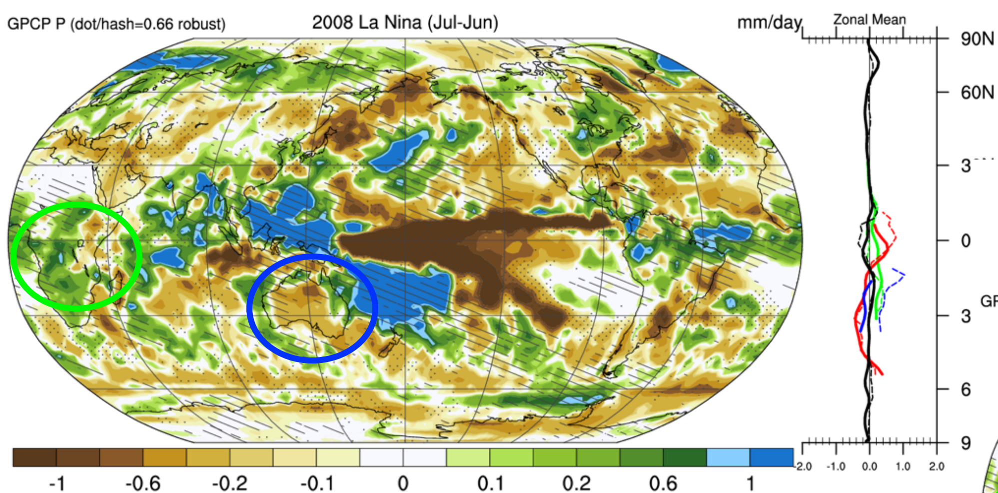
(2) {2010 El Niño+2011 La Niña} → P_{SA}] + P_{NA} (noise?) **(3)**

→ **2011 Sea Level Drop**

Best 20th C analogue: 1973/4. We cannot simulate the event in most coupled models.
Were we to get the surface hydrology correct, +P biases would fill Australia's interior basins

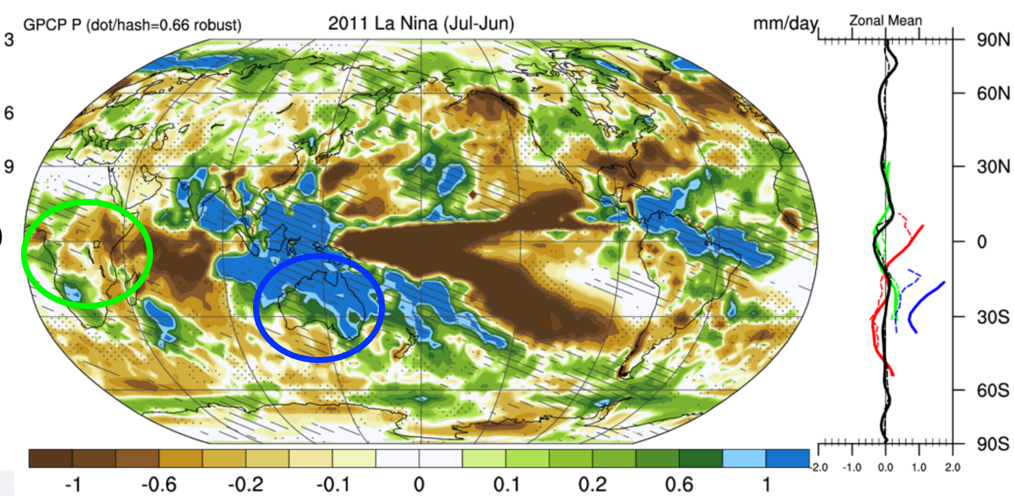
2008 vs 2011 La Niñas

2008: drought in Aus., flood in Africa



LAND
SA
AFR
AUS

2011: flood in Aus., less in Africa



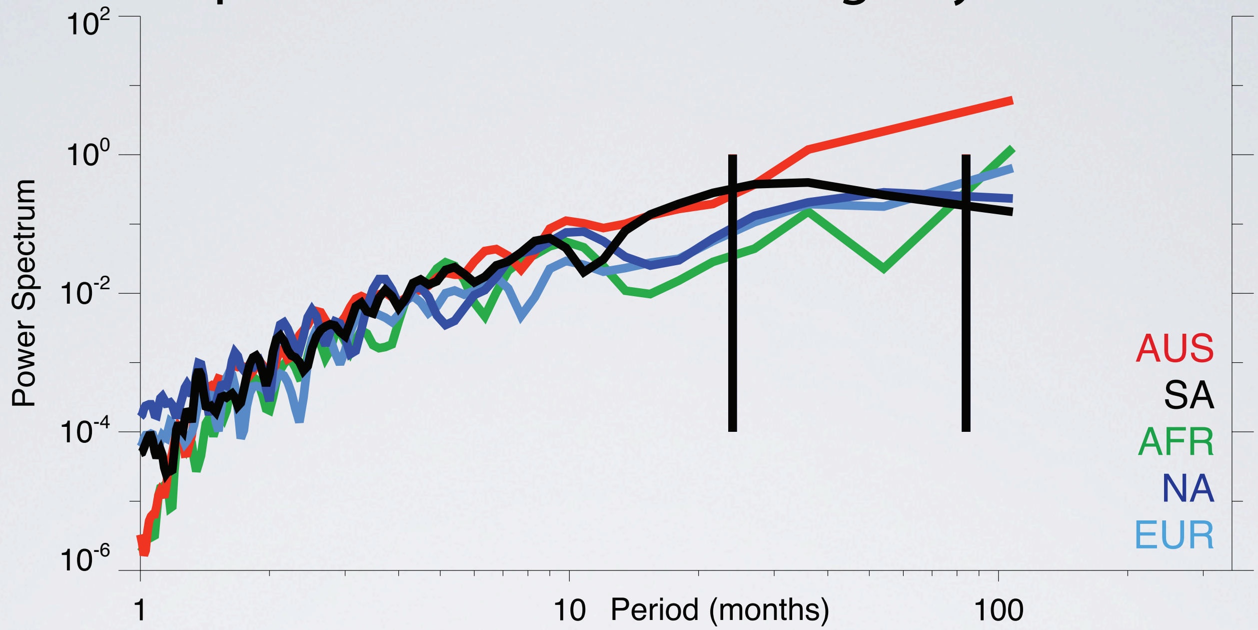
LAND
SA
AFR
AUS

END

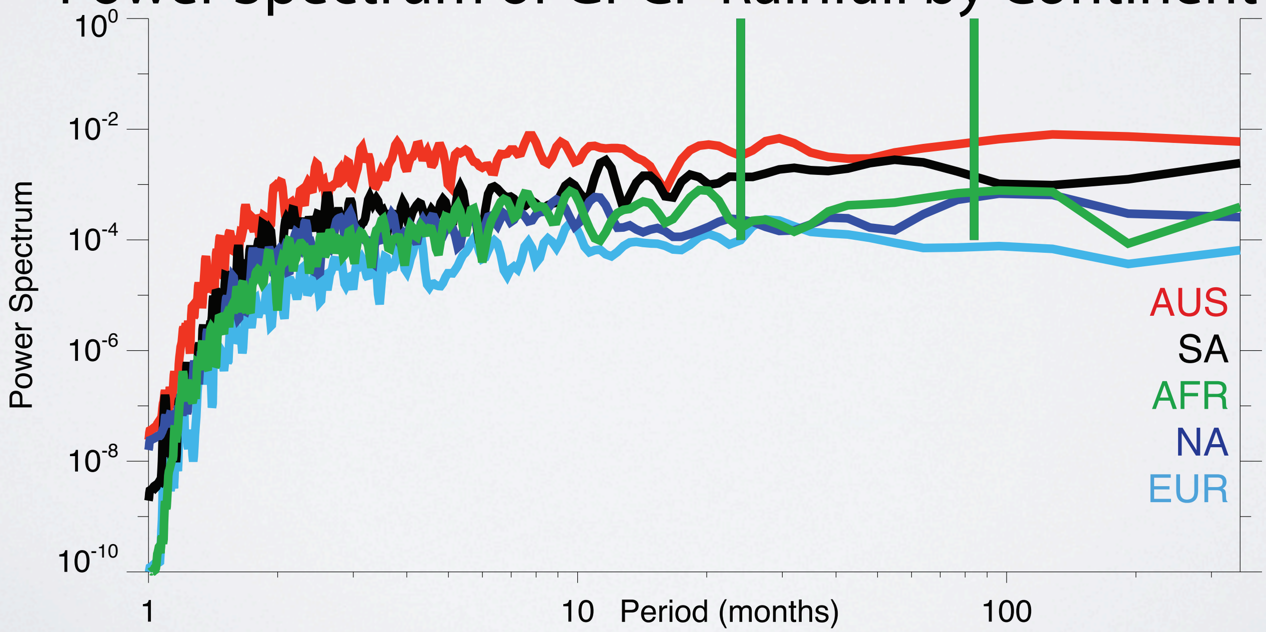
CONTRIBUTIONS TO 2011 DROP

- SA contribution to the 2010-11transition due both to the elimination of drought and brief positive anom (large uncertainty regarding how large the 2010 negative anomaly was.)
- Australia was the dominant contributor to the +storage anom in 2011
- But how can Australia sustain a prolonged storage anomaly. Short rivers, runoff timescale is very short!

Power Spectrum of GRACE Storage by Continent



Power Spectrum of GPCP Rainfall by Continent



ATTRIBUTION OF AUSTRALIAN RAINFALL

Reframing the problem in terms of Australian rainfall allows for leveraging attribution work done on it for understanding MSL.

e.g Risbey et al 2009 MWR

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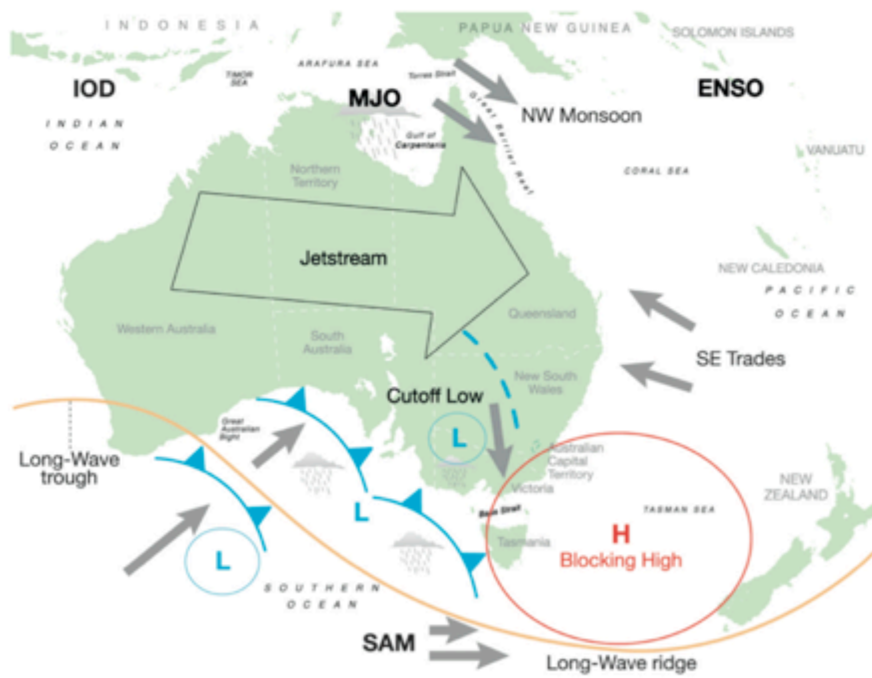


FIG. 1. Schematic representation of the main drivers of rainfall variability in the Australian region. The dominant features are the IOD, MJO, and ENSO in the tropics, and the SAM and blocking in the extratropics. The influence of the subtropical jet is indicated by the "jet stream" arrow. A schematic cutoff low in a typical position to influence southeast Australian rainfall is shown next to the blocking high. The longwave pattern in the midtroposphere consistent with the blocking high is also indicated with a trough over Western Australia and a ridge in the Tasman Sea.

CHANNEL COUNTRY

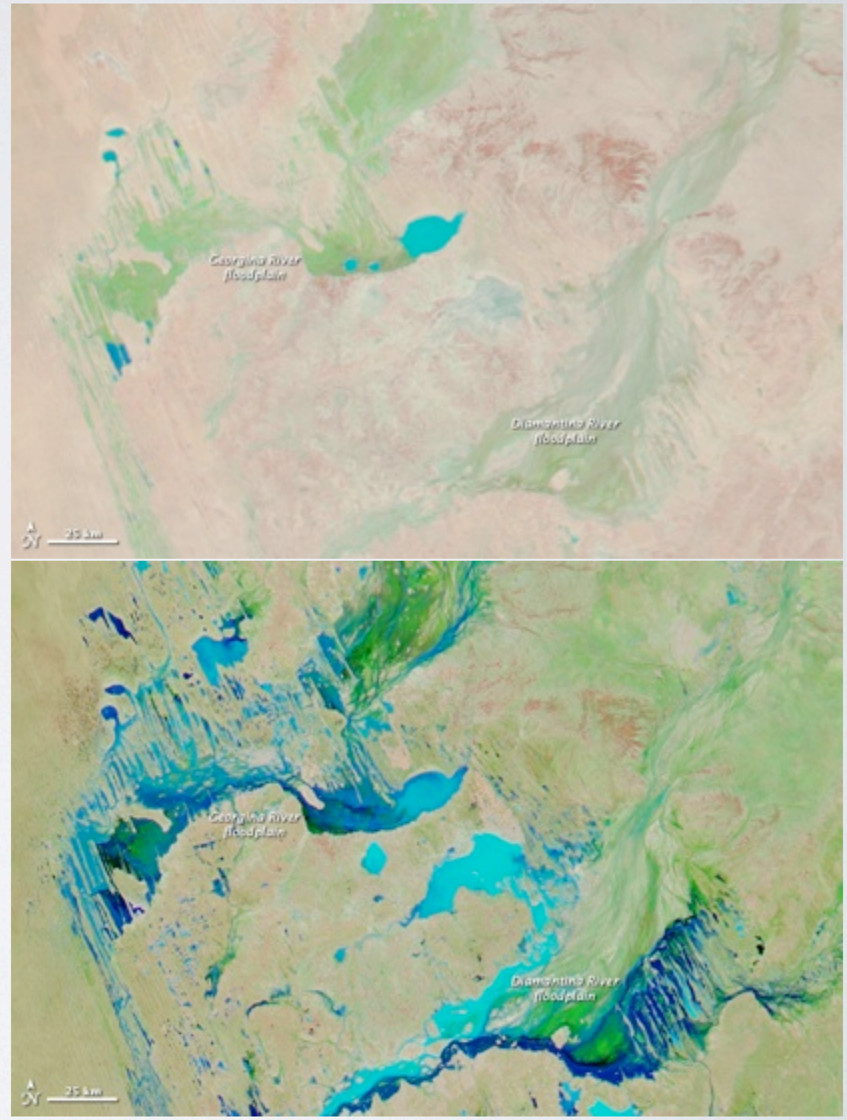
It’s not unusual for a rainy season to [transform a landscape,] but what’s unusual about Australia’s Channel Country is that the transforming rains often fall hundreds of kilometers away. Like the [Okavango Delta of Botswana,] the Channel Country is an inland delta. It is fed by rain that falls on the [Mitchell Grass Downs] to the north. Instead of flowing to the coast, the rivers arising from these grassy plains flow toward the low-elevation Australian interior, sending water over expansive floodplains.

Just about every year brings some seasonal changes to the Channel Country, though not every year brings the same amount of flooding. The [Moderate Resolution Imaging Spectroradiometer] (MODIS) on NASA’s [Aqua] satellite captured a dry-season scene on September 26, 2009 (top), and a flooded scene on March 26, 2011 (bottom). These images show floodplains in southwestern Queensland, just west of Australia’s Northern Territory and north of the state of South Australia.

Both images use a combination of visible and infrared light to better distinguish between water and land. Water is blue, and darker blue implies greater water depth. Vegetation is bright green and bare ground in pink-beige. The flooding is significant in March 2011, but the water isn’t high enough to crest many of the [linear dunes] that run northwest-southeast in this region.

Much of the water in the Georgina and Diamantina River systems results from monsoonal weather systems. Floods in the Channel Country typically happen between November and June, and flooding is especially likely in February or March.

When the Channel Country floods with water that flowed in from elsewhere, the phenomenon is known as a dry flood. Sometimes rain falls locally, but the region is generally arid, with less than 250 millimeters (10 inches) of rain a year. Either way, where the water flows, plants, fish, and waterfowl follow. Dormant plants quickly revive, as indicated by the abundant green in the March 2011 image. Australia’s newly watered interior provides breeding grounds for about 70 bird species, including [parrots] and [pelicans.]
The vibrant flood season is fleeting, however, and typically dry conditions quickly return. Some animals don’t survive the return to dry weather, but most leave for lakes, water holes, or coastal regions, bolstering populations in those areas.

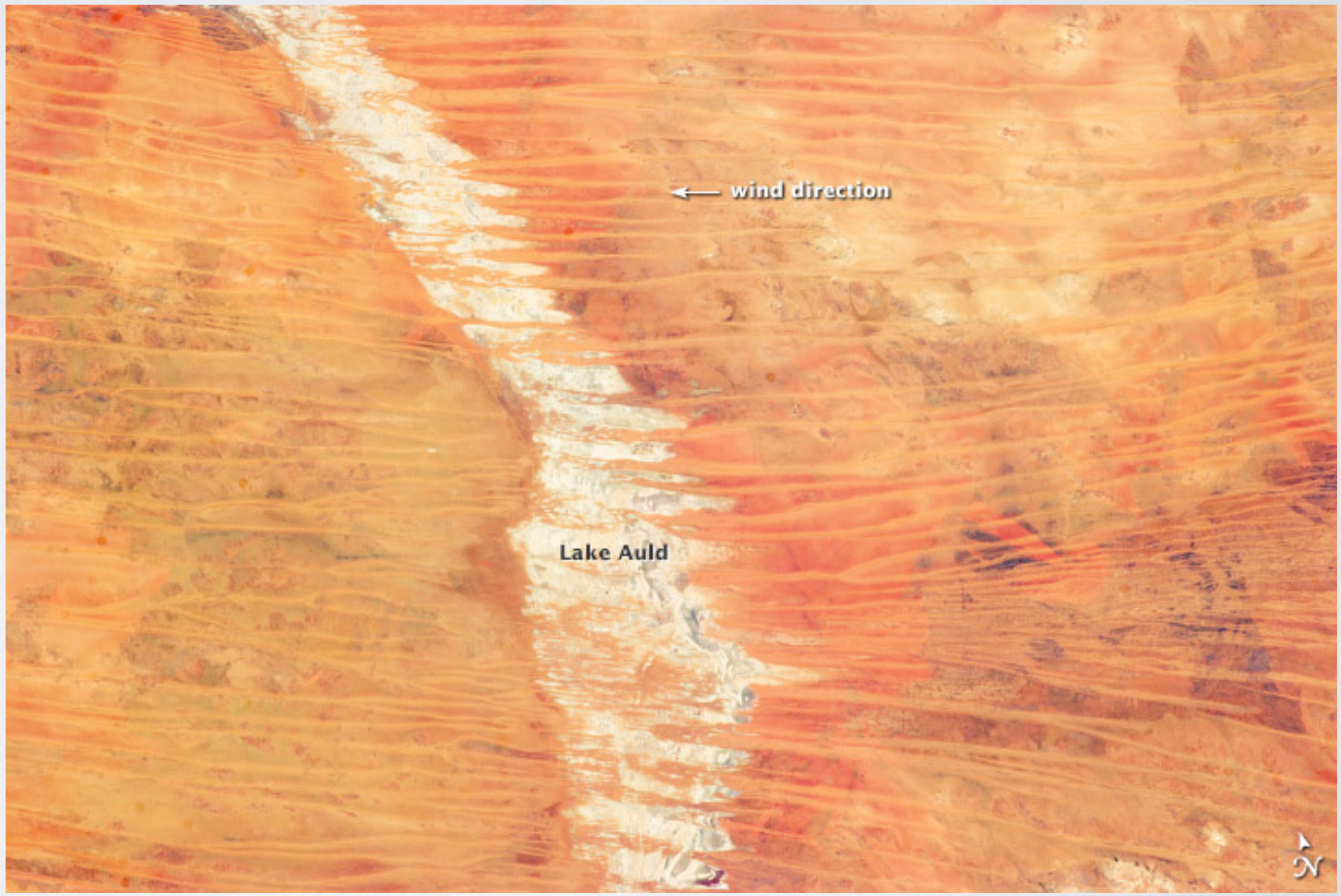


- http://earthobservatory.nasa.gov/IOTD/view.php?id=80023

EROSIVE FORCES IN WESTERN AUSTRALIA

Astronaut photograph ISS035-E-9454 was acquired on March 25, 2013, with a Nikon D3S digital camera using a 400 millimeter lens, and is provided by the ISS Crew Earth Observations experiment and Image Science & Analysis Laboratory, Johnson Space Center.

The image was taken by the Expedition 35 crew. It has been cropped and enhanced to improve contrast, and lens artifacts have been removed.



http://earthobservatory.nasa.gov/IOTD/view.php?id=80850

LAKE EYRE BASIN

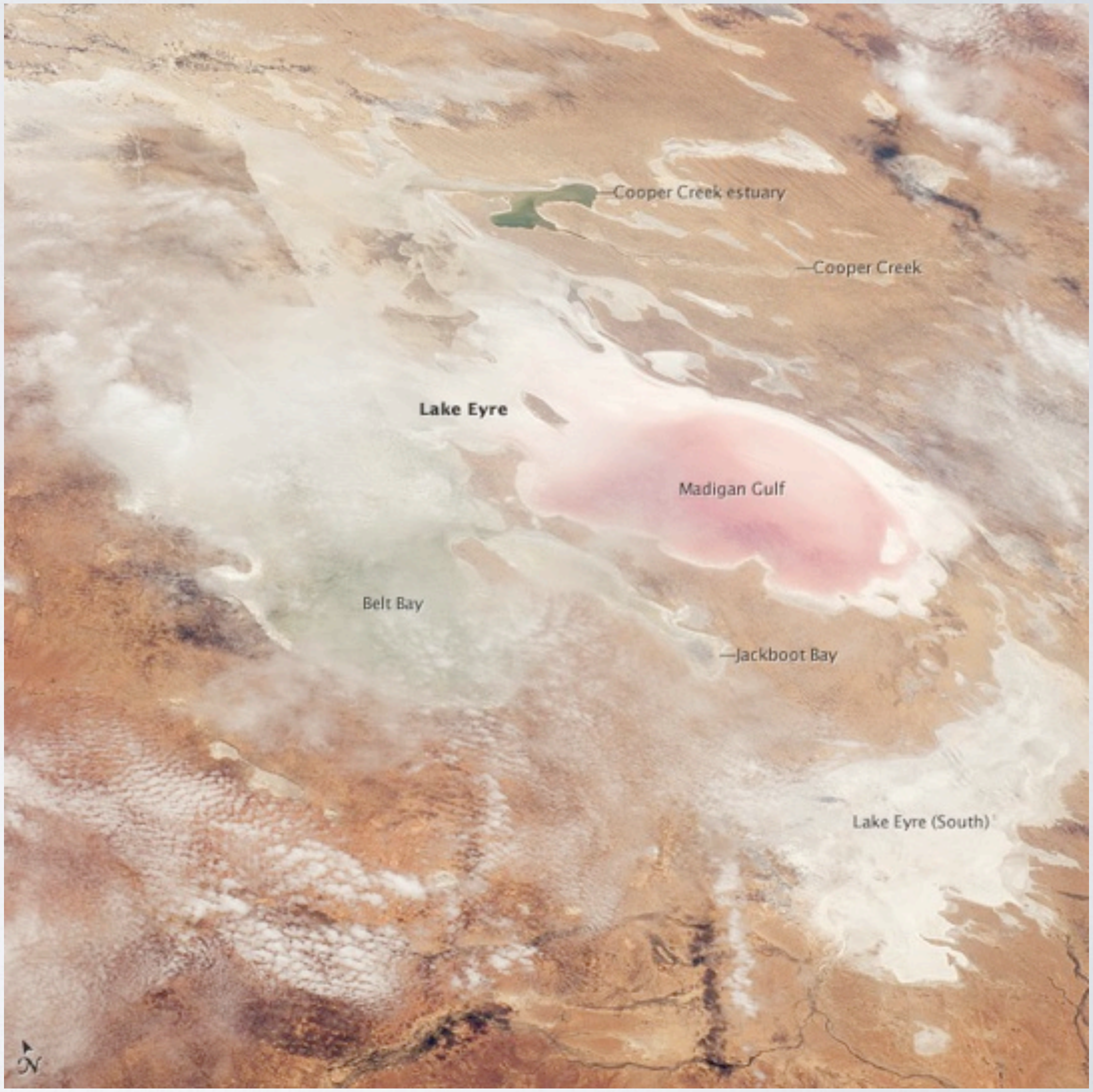
Heavy rain in March 2011 produced a relatively unusual event: water flowing into Lake Eyre.

The southernmost and deepest lobes, Belt Bay and Lake Eyre South, were filled first. In this northeast-looking view from the International Space Station, water appears in the southern basins of Lake Eyre, especially Belt Bay (where it appears green) and in Madigan Gulf (where it appears in shades of pink and red). Despite some clouds, water is also apparent in narrow Jackboot Bay and at the estuary where Cooper Creek—one of the most important inflow rivers—fills a small, dark green lake.The varying colors are the result of different water depthsand different resident microorganisms.The green color of Belt Bay is likely related to its depth, which was reported in early December 2011 to be just less than 1 meter.The red color of Madigan Bay appears to be related to salt-loving bacteria. At half the depth of Belt Bay (0.4 m), evaporation raised salt concentrations high enough to allow salt-loving bacteria to flourish when this image was taken.

In Australian lakes with salinities above 30 percent, the majority of microbes are haloarchaea (family Halobacteriaceae, domain Archaea).The density of microbes in Australia's salt lakes can reach 107 to 108 cells per milileter—so dense that the pink-red carotenoid pigments in the cell membranes color the water.

By August 2011, more than half the lake floor was covered by shallow water, with local creeks continuing to deliver water. Lake Eyre is an internal drainage basin, which means that all of the water accumulates in the lake, without an outlet to the sea. Any water that reaches the lake evaporates in subsequent months.

Water levels were reported to be falling everywhere in late 2011, when this image was acquired.The bright white salt of the floor of Lake Eyre South shows that this lake is entirely dry.



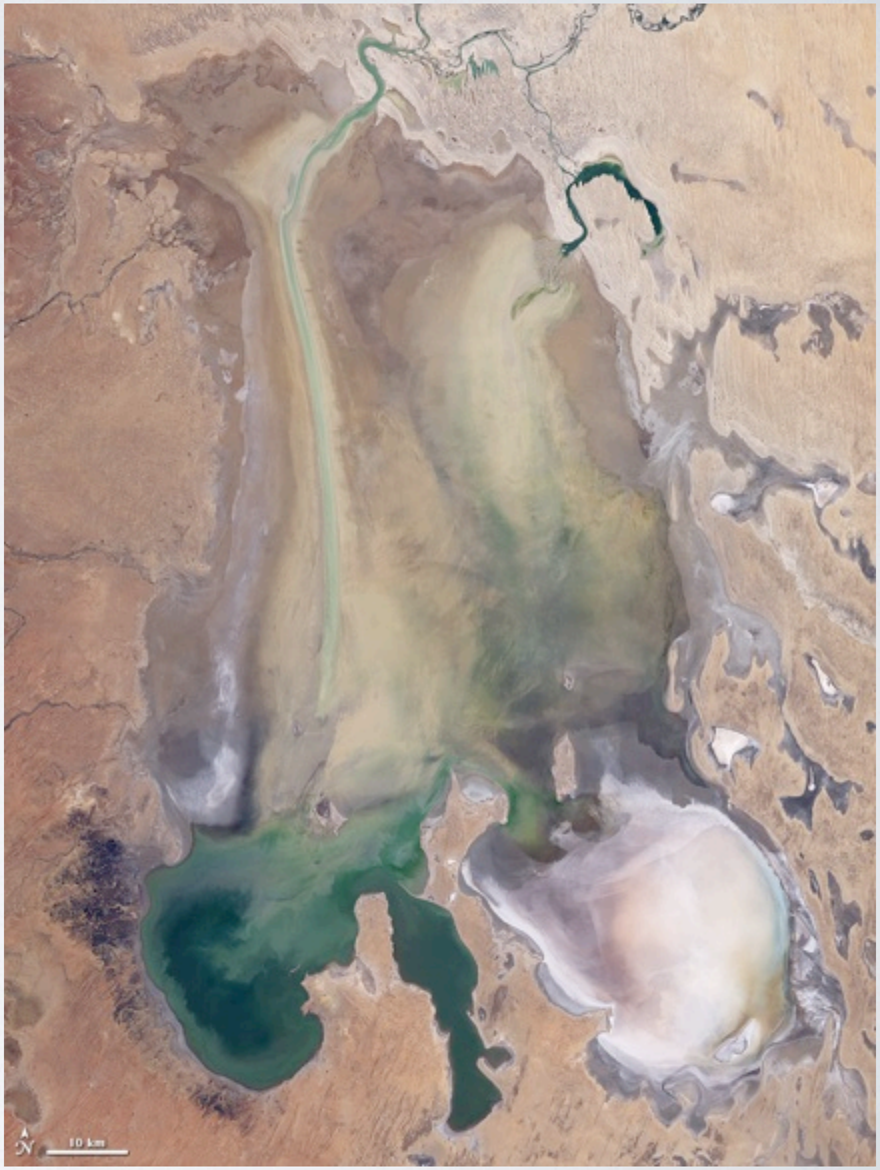
http://earthobservatory.nasa.gov/IOTD/view.php?id=76680

THE LAKE EYRE BASIN

Australia's Lake Eyre drainage basin sprawls across about 1.2 million square kilometers, stretching from Northern Territory to South Australia. Rain, when it falls, drains inward through the Simpson Desert basin into Lake Eyre, which has no outlet. According to the Australian government, Lake Eyre is the fifth largest terminal lake in the world.

But Lake Eyre does not always hold water. In fact, the lake is dry except in the wake of a rare, steady rainy season. In 2009, intense rains fell over northern Australia. A total of 17 million megaliters of water flowed through the Channel Country, soaking into the soil and sustaining grasses, reported ABC News. By March (see second large image), water had begun to reach Lake Eyre. By June 10, when the Landsat satellite captured this image, the flow of water had slowed: Lake Eyre was as full as it was going to get in 2009.

Shallow water covers most of the lake bed. The water is colorful, tinted green and blue by sediment and algae. The southwestern lobe of the lake is darkest in color. According to the Lake Eyre Yacht Club, it is also the deepest portion of the lake at 1.4 meters (4.6 feet). When it fills, Lake Eyre and the wetlands in the basin provide an important habitat for birds and fish. Birds flocked to the lake when it began to fill in 2009.



ROLE OF THE SOUTHERN ANNULAR MODE?

The Southern Annular Mode (SAM)

The Southern Annular Mode (SAM), also known as the Antarctic Oscillation (AAO), describes the north–south movement of the westerly wind belt that circles Antarctica, dominating the middle to higher latitudes of the southern hemisphere.

The changing position of the westerly wind belt influences the strength and position of cold fronts and mid-latitude storm systems, and is an important driver of rainfall variability in southern Australia.
In a positive SAM event, the belt of strong westerly winds contracts towards Antarctica. This results in weaker than normal westerly winds and higher pressures over southern Australia, restricting the penetration of cold fronts inland.

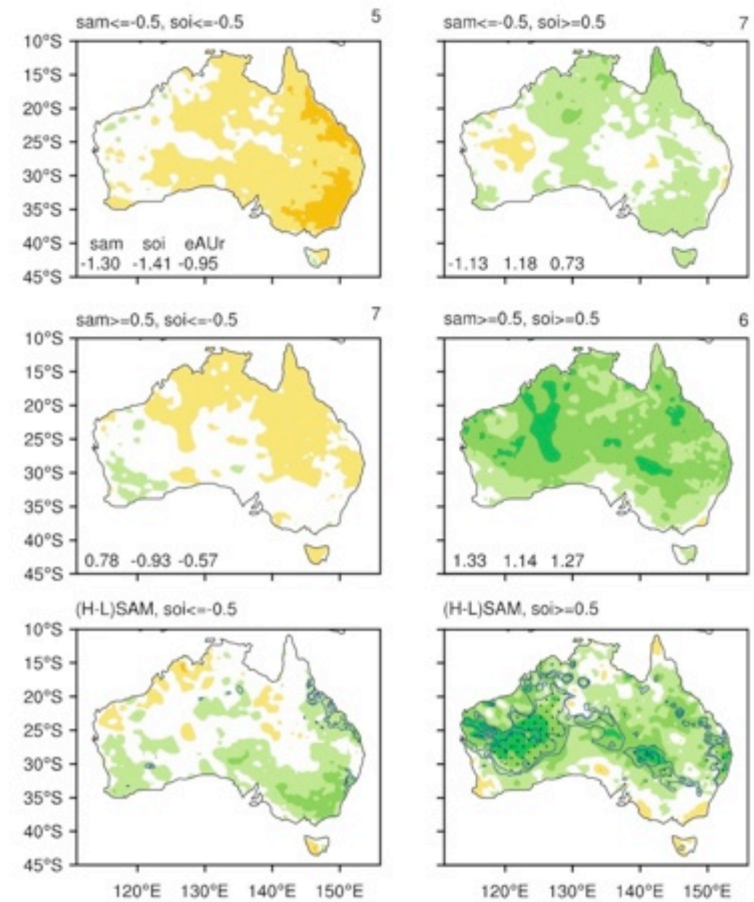
Conversely, a negative SAM event reflects an expansion of the belt of strong westerly winds towards the equator. This shift in the westerly winds results in more (or stronger) storms and low pressure systems over southern Australia.

During autumn and winter, a positive SAM value can mean cold fronts and storms are farther south, and hence southern Australia generally misses out on rainfall. However, in spring and summer, a strong positive SAM can mean that southern Australia is influenced by the northern half of high pressure systems, and hence there are more easterly winds bringing moist air from the Tasman Sea. This increased moisture can turn to rain as the winds hit the coast and the Great Dividing Range.

In recent years, a high positive SAM has dominated during autumn–winter, and has been a significant contributor to the 'big dry' observed in southern Australia from 1997 to 2010.

Causes and predictability of the record wet east Australian

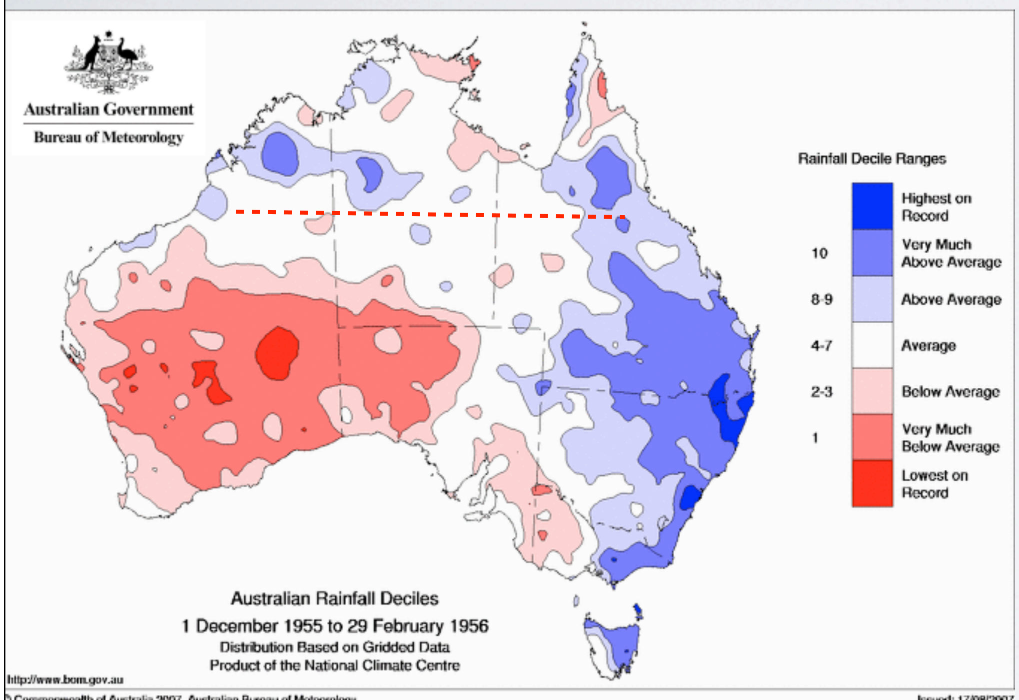
Fig. 8 Composites of standardized rainfall anomalies for negative ($\leq -0.5\sigma$) and positive ($\geq 0.5\ \sigma$) episodes of SOI and SAM. Rainfall anomalies are from the AWAP analyses for 1960–2010. *Color shading* indicates standardized rainfall anomalies with 0.6 standard deviations shading interval. The number of samples in each category is shown in the upper right of each map. The mean amplitudes of standardized SAM, SOI and eastern Australia area averaged rainfall for each category are displayed at the bottom left the maps in the *top two rows*. *Blue curves* in the *bottom panels* surround regions where the difference between the *top two panels* is statistically significant at the 90 and 95 % confidence levels. Stippling indicates the significance levels greater than 95 %

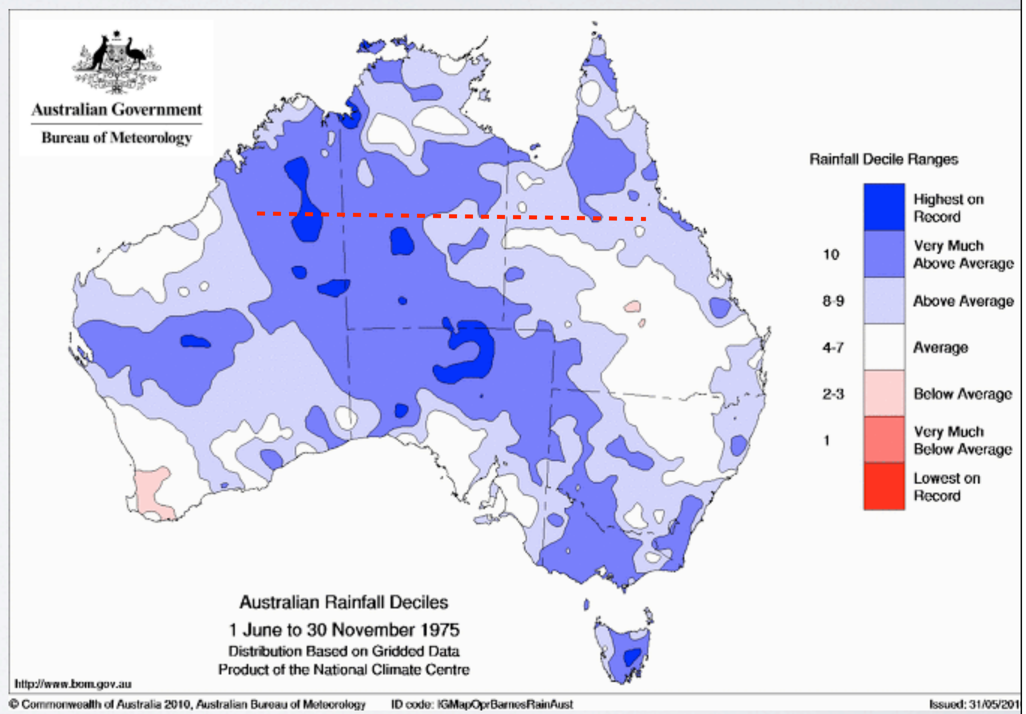


suggested as key to 2010 in publication in press in Climate Dynamics by Hendon et al. (2013)

ROLE OF THE INDIAN OCEAN DIPOLE

- 1955-6 (strongest MEI since 1950, IOD neut)
- 1975-6 (comparable to 2011, IOD neg)





much attribution work has already been done e.g. Cai et al. 2009

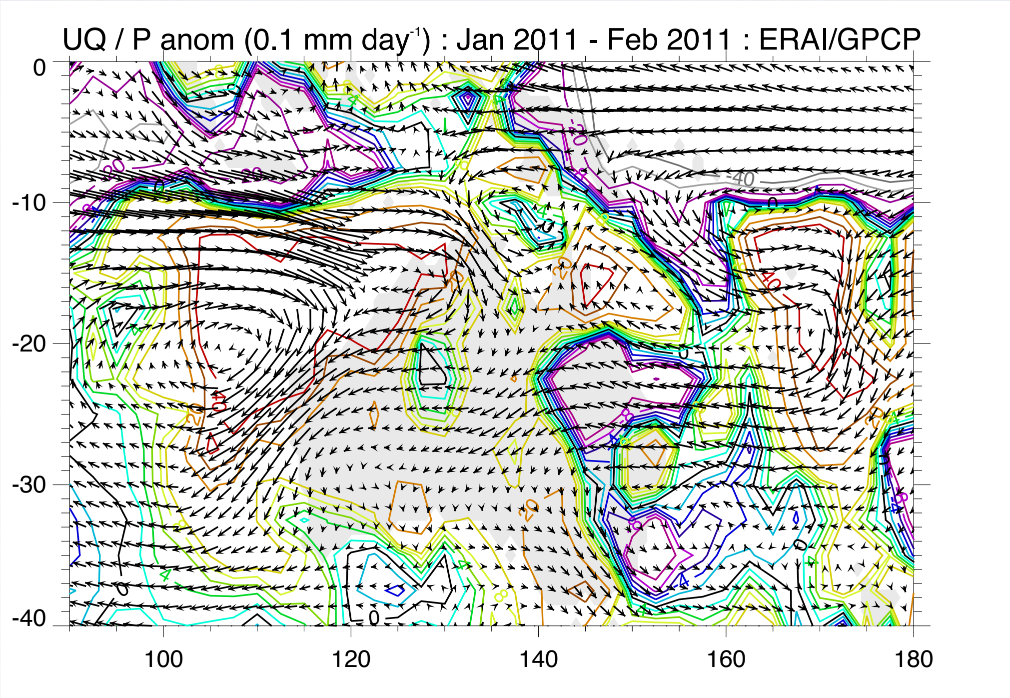
AUSTRALIA: The LITTLE CONTINENT That Could™ INFLUENCE GLOBAL SEA LEVEL

J. Fasullo

I THINK I CAN!

ROLE OF THE INDIAN OCEAN DIPOLE

Moisture Budget in 2011



Strong north-westerly anomalies emanating from the IO