In Search of Thermal Precursors to Earthquakes in California Using Remote Sensing Data

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Are there thermal precursors to earthquakes?

Previous Studies

- Temperature increases of 2-4 ^{0}C
- Preceding earthquakes for several days to two weeks
- Spatial extent 10s to 1000s km
- Usually magnitudes $M \geq 7$
- Two studies for $M \geq 4.7$ and $4 < M < 5.5$
- Eqs in China, Greece, India, Indonesia, Turkey, USA
- Sensors: AVHRR, METEOSAT, GOES, and MODIS

Reported Eq. Precursors – cont'd

- **Small scale**
  - 100s km
  - area includes eq. epicenter
  - some reports – larger anomalies over larger areas before larger earthquakes
  - short time periods – e.g., 50-60 days before an eq. compared with same months in another year, when there was no eq.
  - TIR imagery – 1-km to 5-km spatial resolution (AVHRR, Metosat, GOES, GMS, MODIS)
  - examples – Tronin (2000), Ouzounov et al. (2002, 2006), Bryant et al. (2002)

Reported Eq. Precursors – cont'd

- **Large scale**
  - 1000s kms
  - precursors may be away from the epicentral area (e.g., along tectonic boundaries)
  - usually large eqs., but also M4 to M5.5
  - years of data
  - statistics is used (RAT="robust analysis techniques")
  - examples - Tramutoli (1998), Filizzola et al. (2004), Corrado et al. (2005), Tramutoli et al. (2005) – further referred to as the "Italian group"

Physical basis

- Ouzunov et Freund (2004) list five possible reasons
  - piezoelectric and elastic strain dilatation forces
  - rising fluids leading to increased gas seepage (hence, emanation of warm gases)
  - transient highs in the thermal conductivity of subsurface rocks
  - rising water levels
  - CO_2 spreading laterally and causing local “greenhouse” effect
- Freund (2003) – PHP (normally stabilized p-hole pairs)
  - split under mechanical deformation or passage of seismic waves and release p-hole charge carriers – photons are emitted in the mid-IR range (luminescence, i.e., not actual temperature increase)
  - Nevin Bryant (JPL, pers. comm.) – example where satellite TIR data show apparent rise in t^0, but surface and atm. t^0 are not increased

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Physical Basis – cont'd

- Pulinets (2007); Pulinets et al (2006) – explain why thermal precursors may appear far away from epicenters
  - Increased radon concentration – ionization of the near-ground atm. layer – increased water condensation – released latent heat of evaporation – increase of surface temperature
  - Vidale (EOS, June 2007) and Rishbeth (EOS, July 2007) – challenged the above interpretation

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Our project

- "Long" time interval
  - Up to 7 years of MODIS data with 2 images per night from Terra and Aqua:
    - Terra: Feb 2000 – Dec 2006 (~ 7 years)
    - Aqua: Jul 2002 – Dec 2006 (~4.5 years)
- Intermediate size area
  - ~1200 km x 1200 km (10^0 x 10^0) tile covering California and parts of Nevada, Arizona, New Mexico and northern Mexico
- Statistically based index for anomalies
  - Takes into account background variability in temperatures – based on developments by the Italian group, plus our improvements

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MODIS Data

- Data product used: MOD11A1 – LST (land surface temperature)
  - » Spatial resolution ~1 km
  - » Tile size 10^0 x 10^0
- Terra: Feb 2000 – Dec 2006 (2442 days)
- Aqua: Jul 2002 – Dec 2006 (1625 days); follows Terra ~3 hr later
- Four images every day – 2 daytime and 2 nighttime
- Used only nighttime images:
  - » Terra – 10 pm (11 pm SST)
  - » Aqua – 1 am (2 am SST)

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Comparison of analyses

Characteristics	Italian Group	Our Project
Number of earthquakes	one at a time	many events (83 M≥4.5)
Spatial resolution	5 km (Meteosat)	1 km (MODIS)
Relating anomalies with earthquakes	visual inspection	videos, statistics
Anomalies	only positive	both negative and positive
Treatment of cloud effects	none	cloud edges removed
Treatment of fire pixels	none	fire pixels removed

RAT, RETIRA index
(developed by Italian Group)

- Robust Analysis Technique (RAT), Robust Estimator of TIR Anomalies (RETIRA) – will further use R, for brevity
- $R = [\Delta T - \mu_t(\Delta T)] / \sigma_t(\Delta T)$ – calculated for each pixel

  T - the nighttime LST of the pixel

  $\Delta T = T - \mu_s(T)$

  $\mu_s(T)$ - spatial average of LSTs over a large area

  $\mu_t(\Delta T)$ and $\sigma_t(\Delta T)$ - statistics over time ("month specific")
- + anomalies -> warmer temperatures
- – anomalies -> cooler temperatures

Comparison of techniques

R type	*Means/ St. dev.*	*Cloud edges*	*Area size*	*Cloud %*	*Fire Mask*	*Anom. R≥/R≤*	*Time periods*	*Stat. compa-rison*	*Videos*
LST	month-specific	none	whole tile	not consi-dered	none	+2.5/ –2.5	months with eqs. vs. same months (other years) without eqs.	none	no
LST differ ences	moving average	2 pix 4 pix	part of tile	50, 60, 70	**yes**	+3.5/ –3.5	***composite periods:*** **b** = before **a** = after **c** = clustered **q** = quiet	KS-statistics	yes

RED - done in original RETIRA method

YELLOW - added in our project

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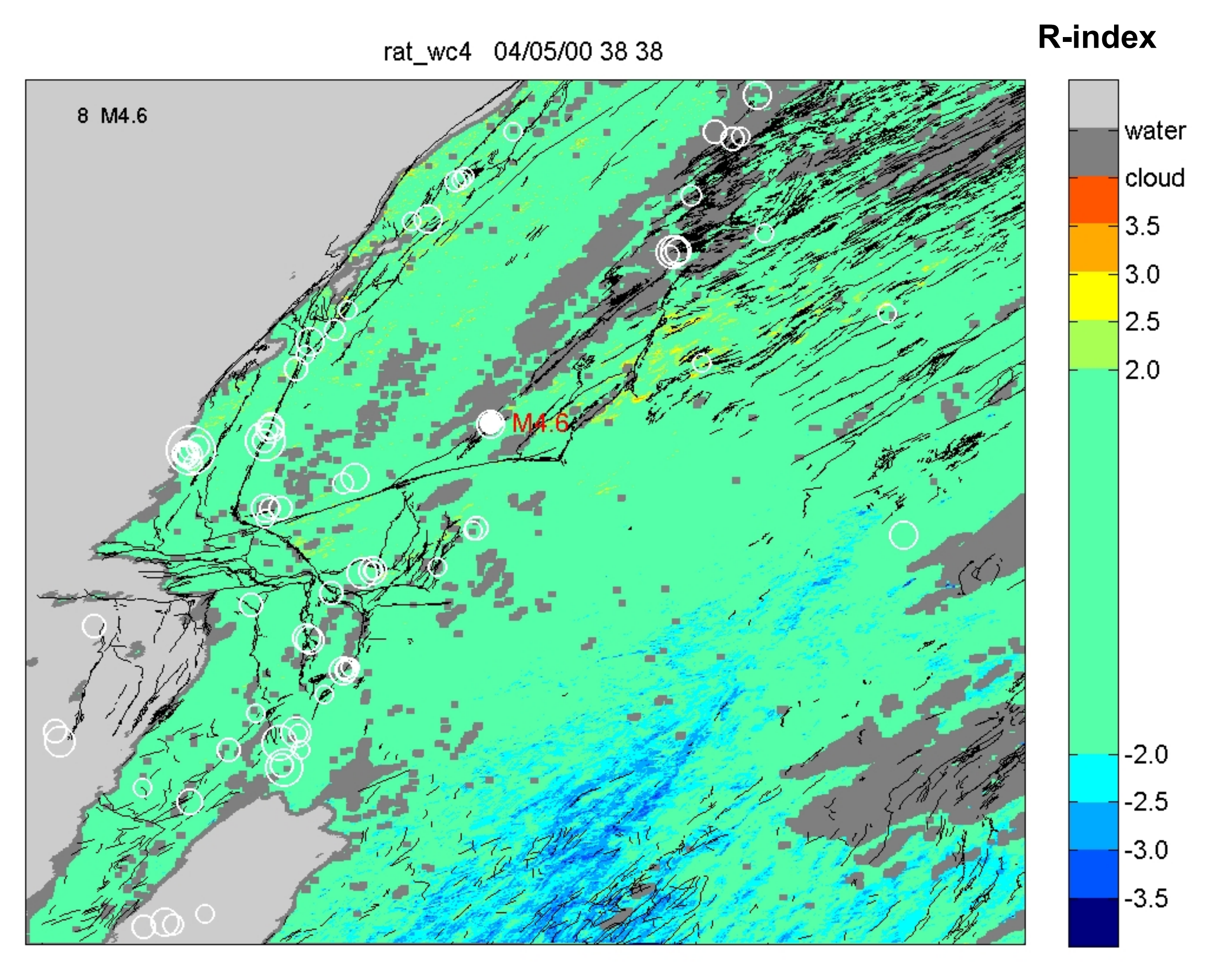
Example of a night R-index map



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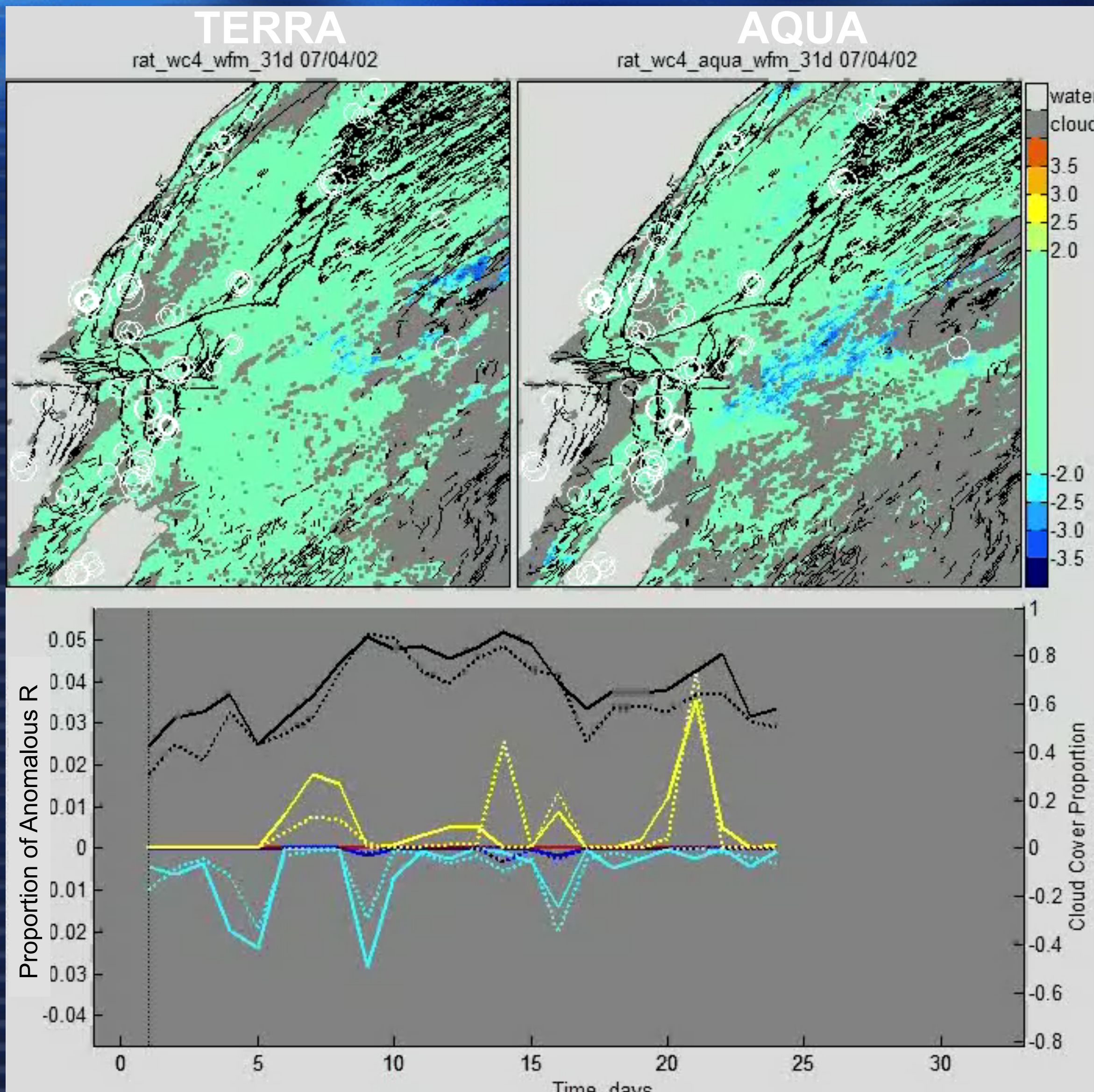
Example of a video frame



- M≥4.5 epicenters
- 15 days before occurrence
- day of occurrence
- 15 days after occurrence

Solid lines	AQUA
Dotted lines	TERRA
Black	cloud %
Yellow	R≥+2.5
Red	R≥+3.5
Cyan	R≤–2.5
Blue	R≤–3.5

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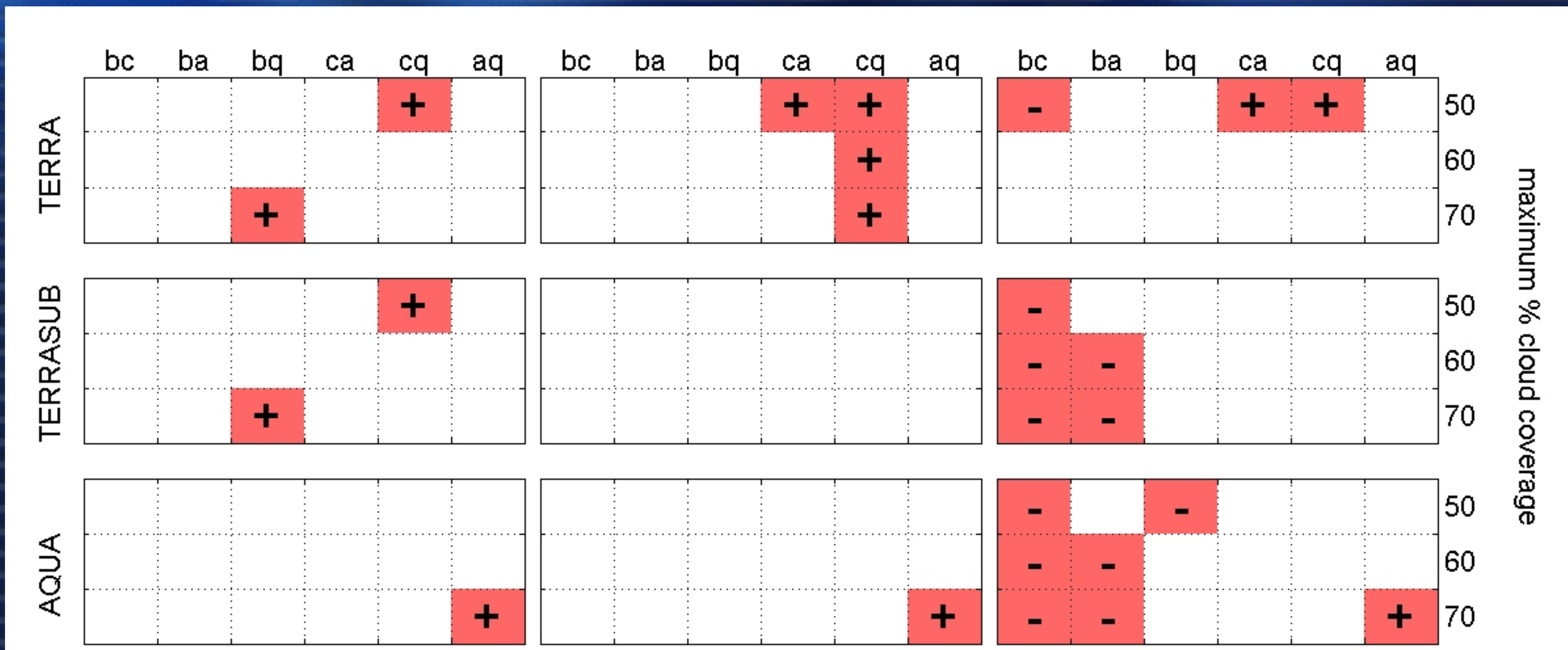
Diagrams with KS statistics

- For LST and LST differences (T_{Aqua} – T_{Terra})
- “Month-specific” vs moving averages
- No cloud effect vs. cloud edges removed
- 7 years of Terra vs 4.5 yrs (Terrasub)
- 3 hours difference (Terra, Aqua)
- Whole tile (CA, parts of NV, AZ, NM, and northern Mexico) vs. part of tile (Cal-Mex)
- Varying duration for composite periods – 20, 15, 10 days
- Varying maximum cloud coverage – 70%, 60%, 50%

Significance (KS-statistics) at 0.05 level

EXAMPLE: POSITIVE R-ANOMALIES (≥2.5), WHOLE TILE, MOVING AVERAGE, 4-PIXEL CLOUD EDGE, FIRE MASK



20 DAYS **15 DAYS** **10 DAYS**

bc=before vs clustered
ba=before vs after
bq=before vs quiet

ca=clustered vs after
cq=clustered vs quiet
aq=after vs clustered

significant difference
+ first larger than second
– first smaller than second

TERRA = Feb 2000 – Dec 2006; TERRASUB = AQUA = Jul 2002 – Dec 2006

10, 15, 20 days – length of periods “before” and “after” M≥4.5 earthquakes

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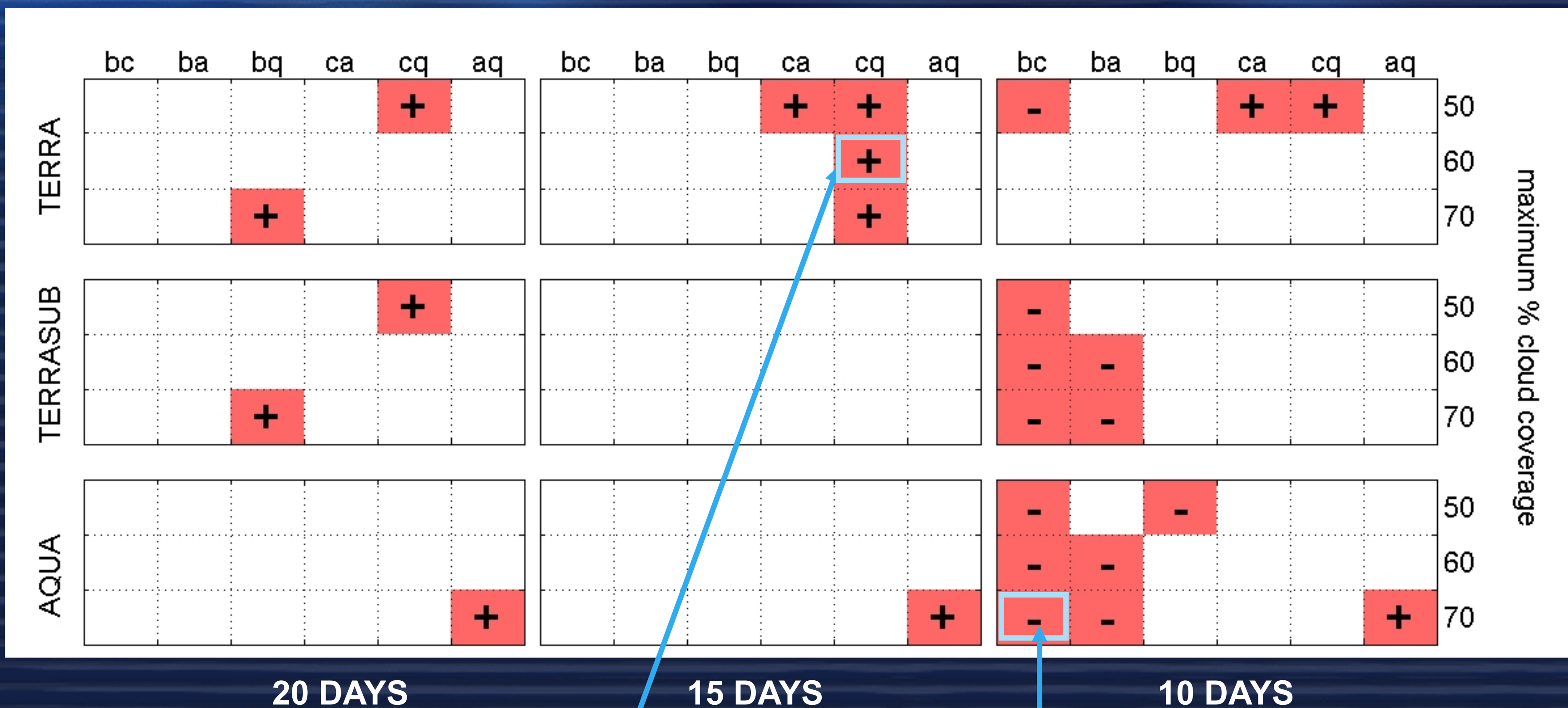
Significance (KS-statistics) cont'd – How to read diagram?

WHOLE TILE, MOVING AVERAGE, 4-PIXEL CLOUD EDGE, FIRE MASK



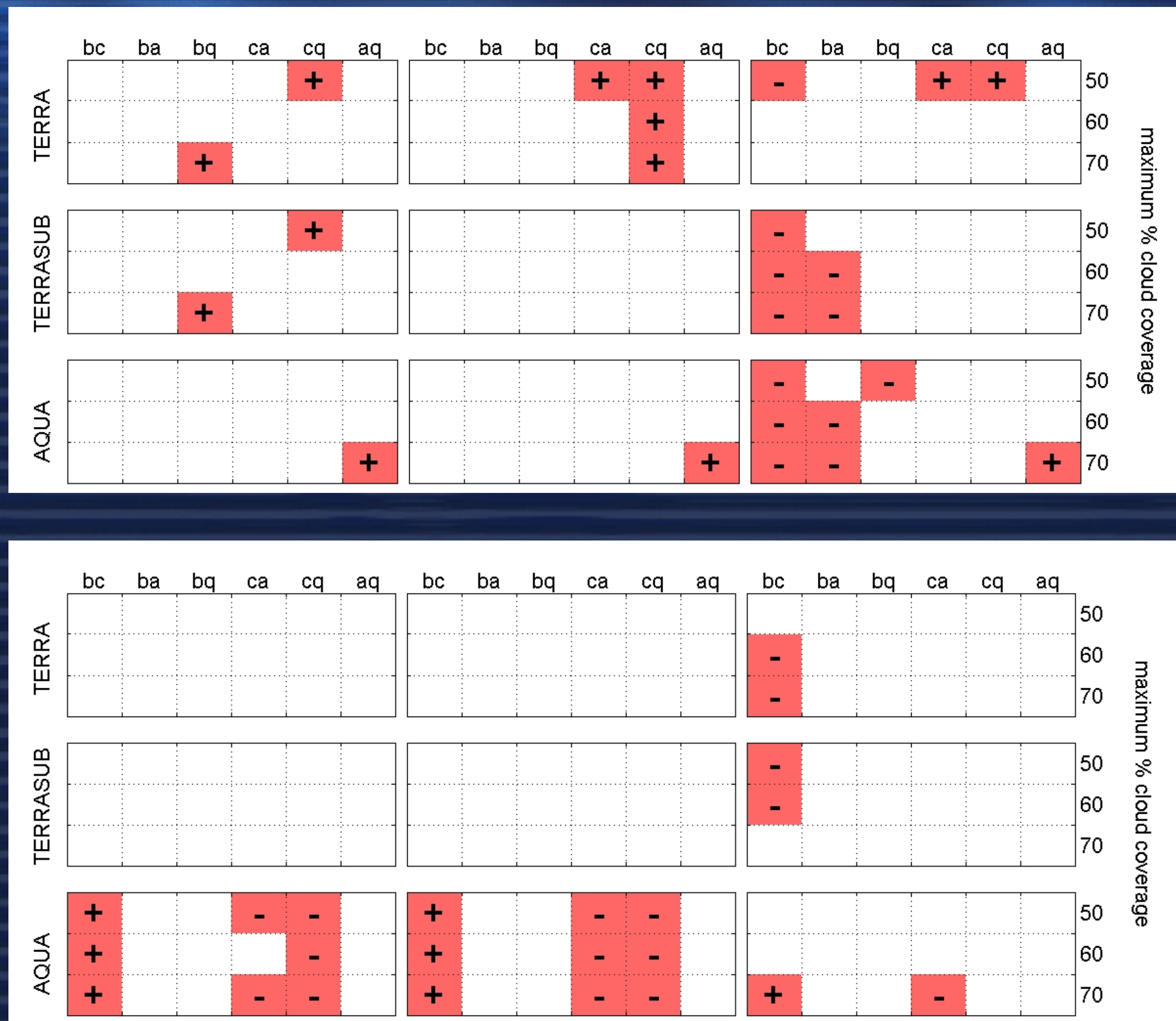
"Clustered" composite period has significantly more positive anomalies (R≥+2.5) than the "quiet" period, for the TERRA LSTs, using land pixels with no more than 60% cloud coverage

"Before " composite period has significantly fewer positive anomalies (R≥+2.5) than the "clustered" period, for the AQUA LSTs, using land pixels with no more than 70% cloud coverage

Whole tile vs. Cal-Mex., R≥2.5

WHOLE

CAL-MEX



20 DAYS **15 DAYS** **10 DAYS**

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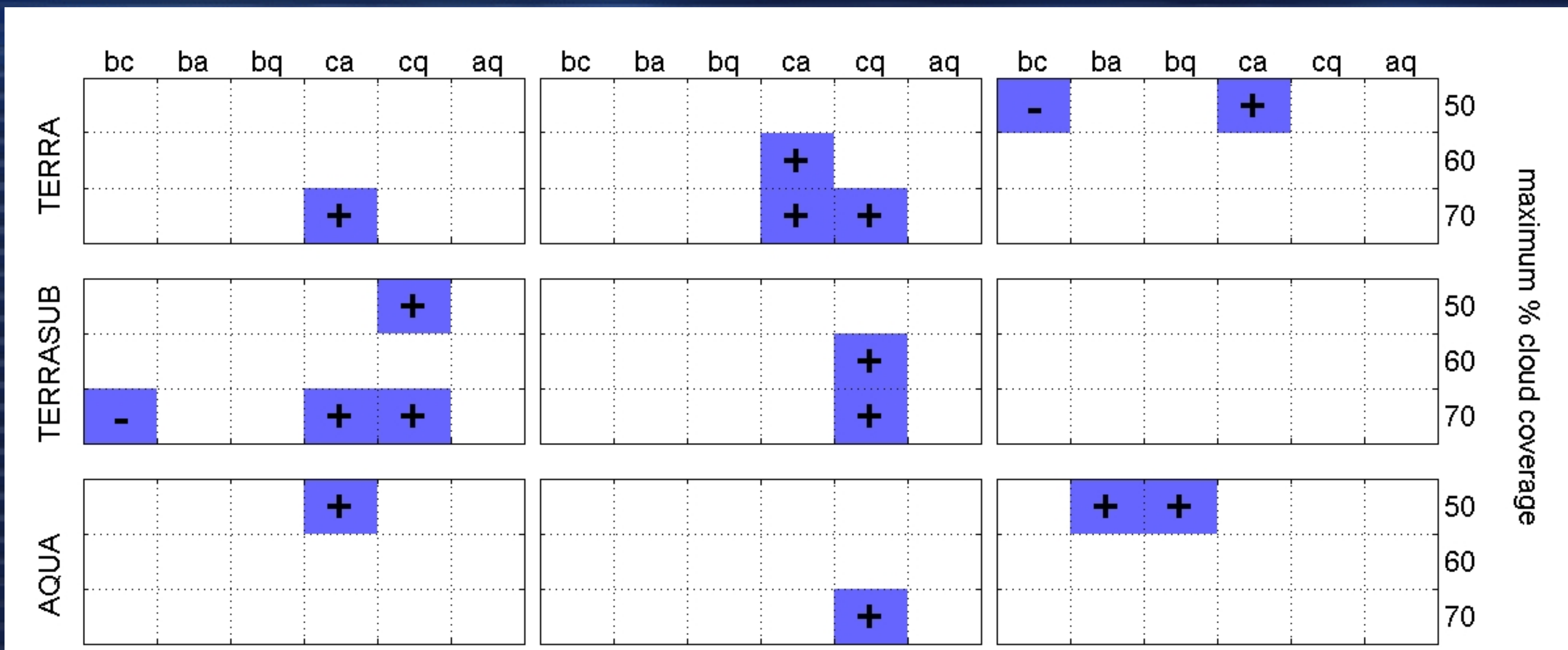
Significance (KS-statistics) cont'd – How to read diagram?



SAME AS BEFORE, BUT FOR NEGATIVE ANOMALIES R≤–2.5

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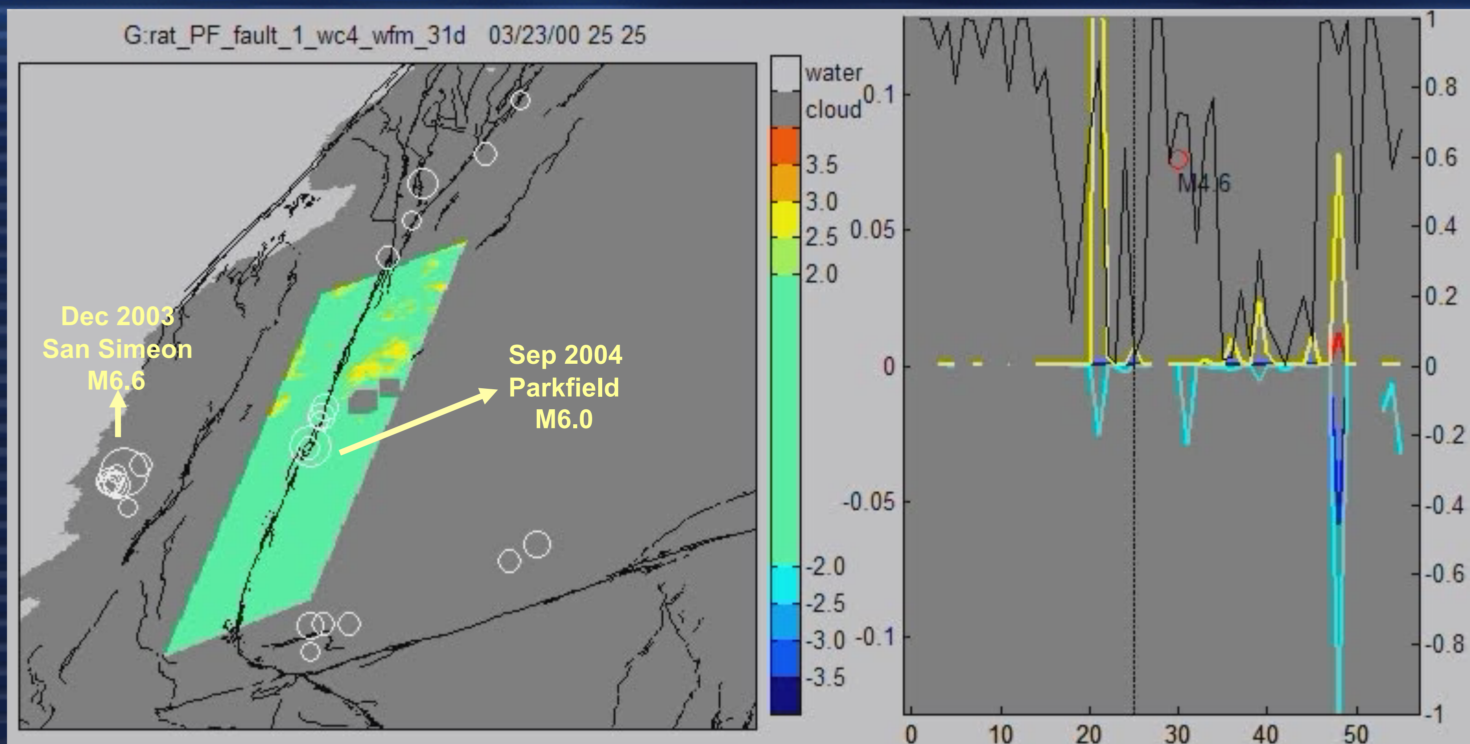
Small-scale example (Sep 2004 Parkfield M6.0) – not in report

Example of a video frame



Strip along San Andreas fault 220 km x 40 km including Sep 2004 mainshock and aftershocks

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Small-scale example (Sep 2004 Parkfield M6.0) – cont'd

Earthquakes only inside strip (5 eqs)

TERRA	bc (20 days)	ba	bq	ca	cq	aq	bc (15 days)	ba	bq	ca	cq	aq	bc (10 days)	ba	bq	ca	cq	aq
50						+						+						+
60						+						+						+
70						+						+		-				+

Earthquakes inside strip and around (25 eqs)

TERRA	bc (20 days)	ba	bq	ca	cq	aq	bc (15 days)	ba	bq	ca	cq	aq	bc (10 days)	ba	bq	ca	cq	aq
50						+						+						+
60												+						
70								-				+						

20 days **15 days** **10 days**

Observation: Significantly more positive anomalies (R>+2.5) during the "after" periods vs the "quiet" periods

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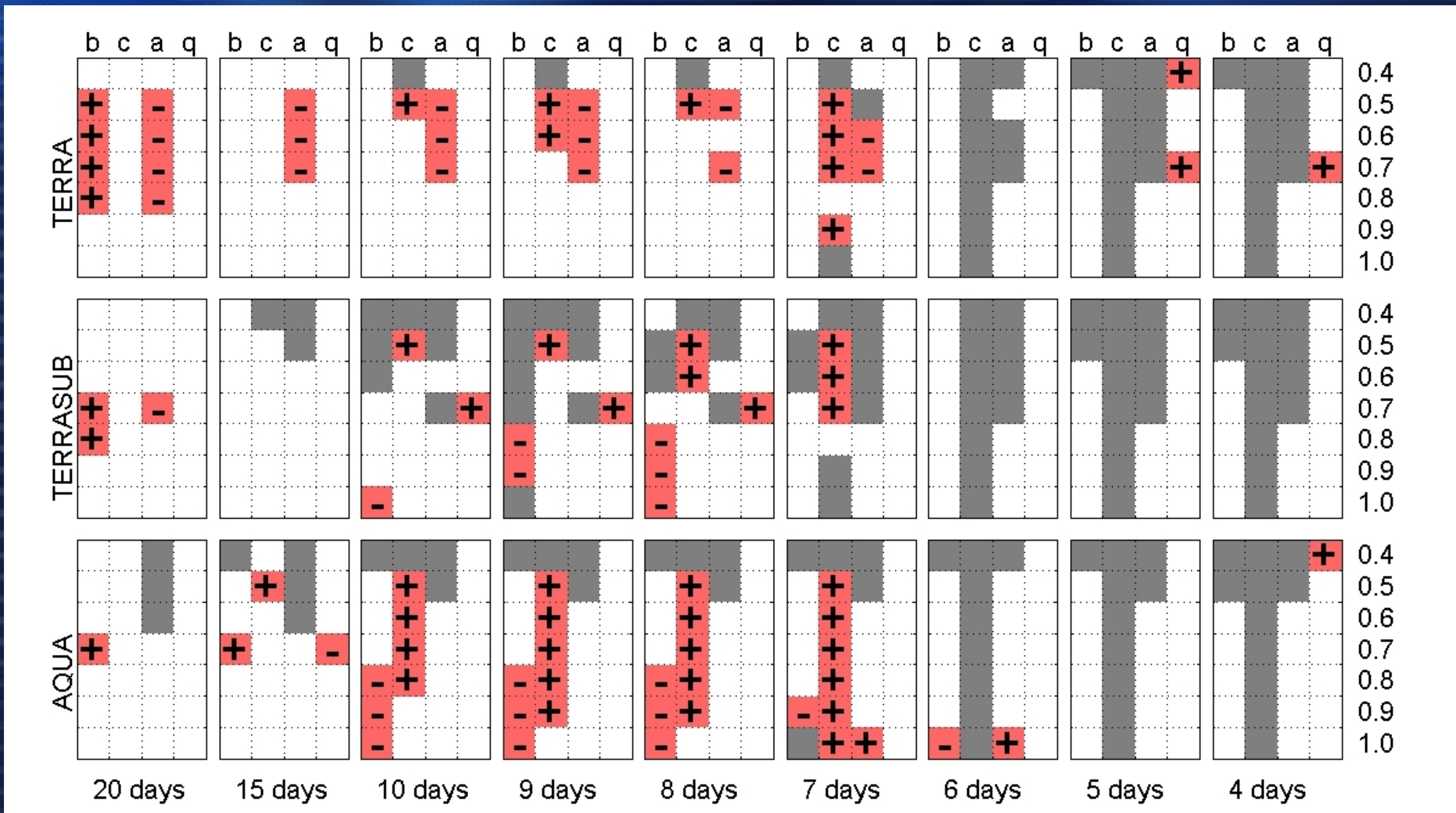
Different way of measuring significance – look at top 5% (not in report)



WHOLE TILE

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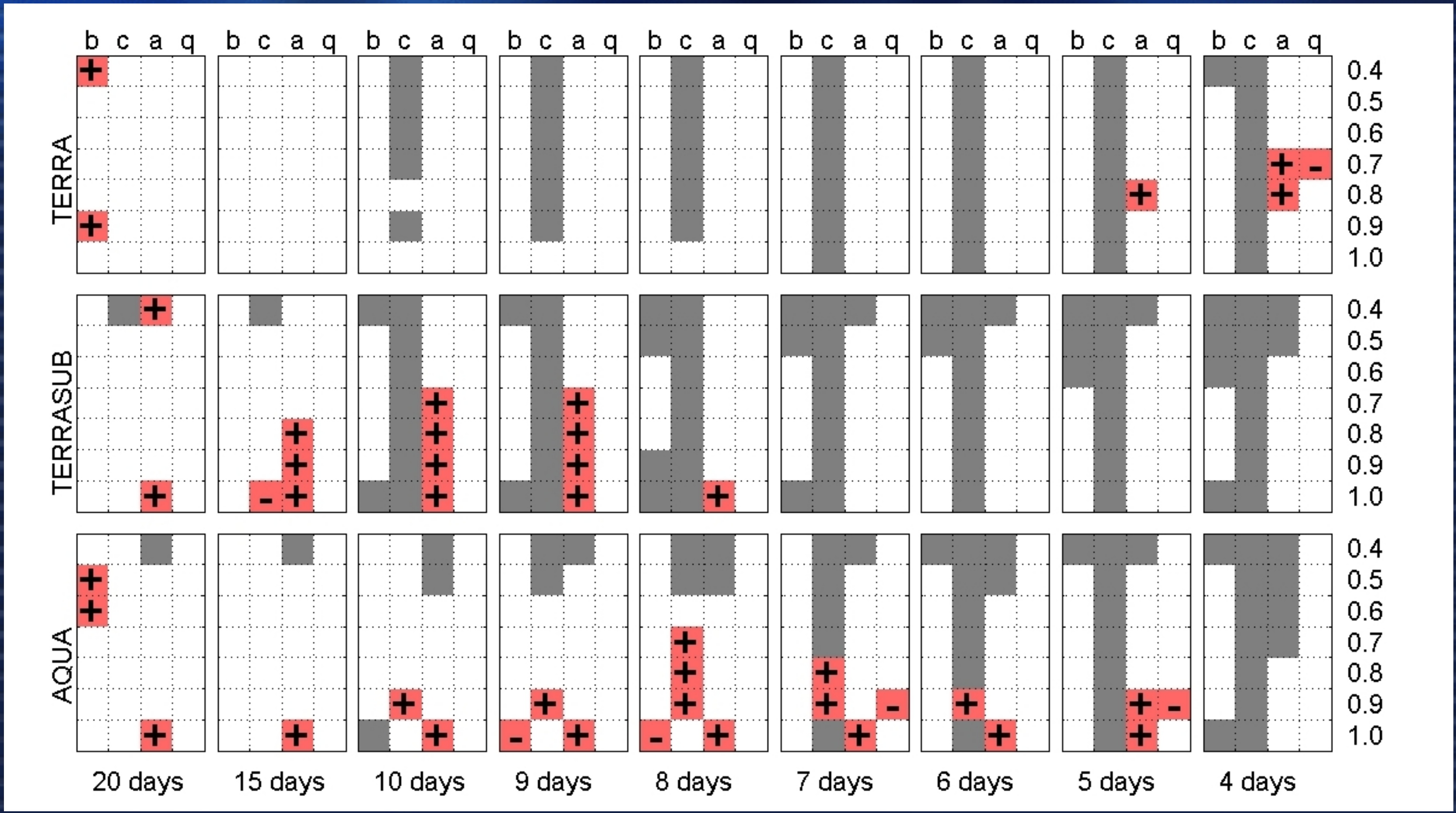
Different way of measuring significance – look at top 5% (not in report)



CAL-MEX

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Summary

- There exist R-anomalies, but they are not unique, so eq. prediction is not possible
- “Clustered” and “after” periods tend to have more positive (“warm”) anomalies than other periods – tectonic effect?
- Statistical significance is sensitive to choice of study areas and time periods
- It is very important to remove cloud edges
- Negative anomalies (cooling) are as common as positive anomalies (warming)

Summary cont'd

- Why didn't we find precursors like the ones reported by others?

Possibilities

- There were no really large (M$\geq$7.0) events 2000-2006
- California is somehow different from other areas?
- Precursors exist, but are masked by other factors?
- Are statistical techniques adequate?
- Limitations of MODIS LST data? (polar vs. geostationary)
- Thermal precursors do not really exist
- However, there still might be transient tectonic effects

Critique by Tramutoli

- He does not want to be lumped together with others claiming that thermal precursors exist. Refers to their 2005 paper (positive thermal anomalies generally associated with earthquakes, and not only prior to eqs.)

- He criticized us for looking at the “before” periods separately, rather than “before+after+clustered” vs. “quiet” periods.

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