# Integration of satellite and ground-based observations and multi-disciplinarity in earthquake and volcano eruption forecast based on the LAIC physical model

Sergey Pulinets [1], Dimitar Ouzounov[2]

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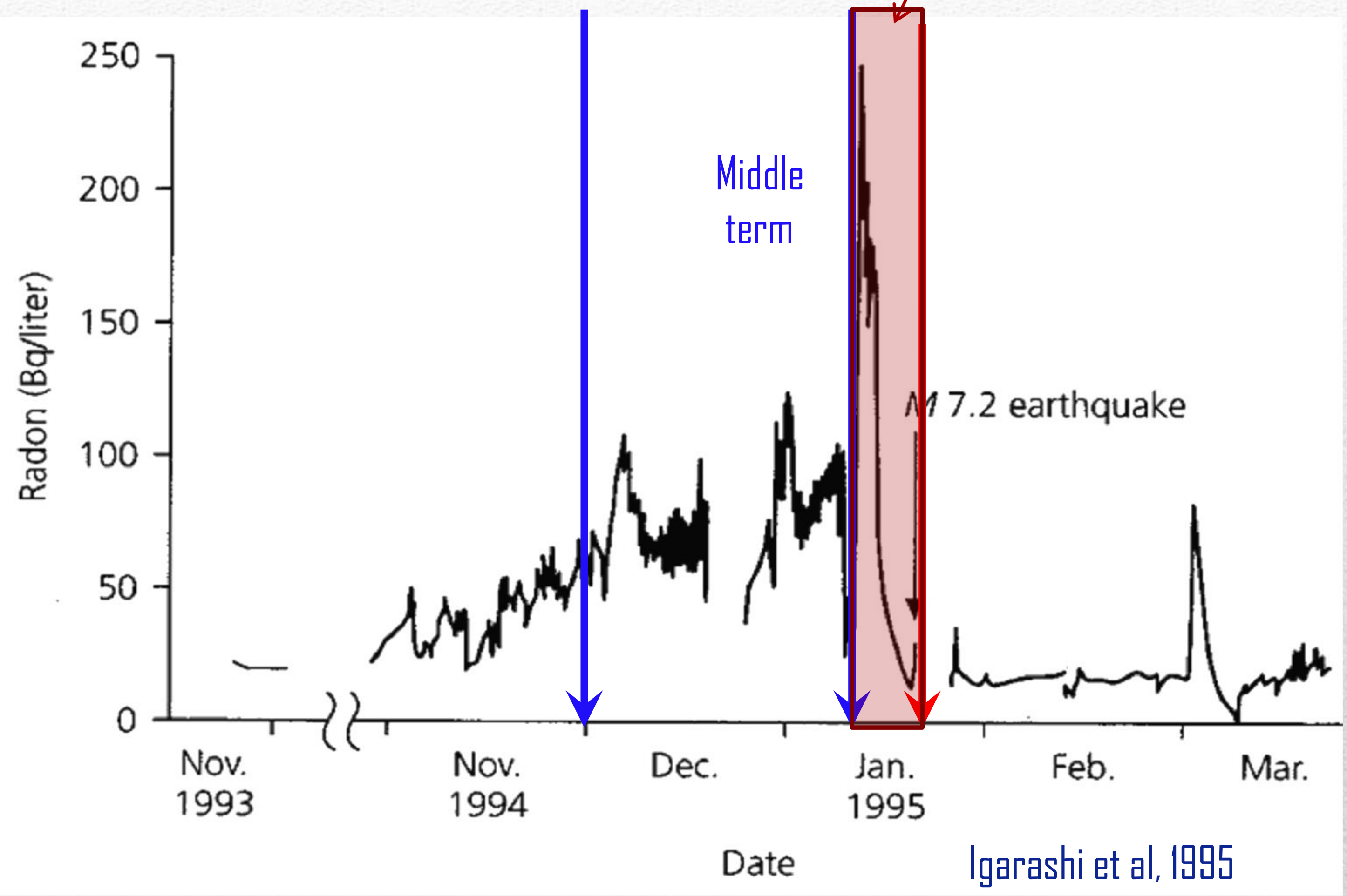
[2]CEESMO, Chapman University, Orange, CA, USA

# Middle and short-term pre-EQ phenomena

**23 years ago...**

Short
Term pre-EQ phenomena

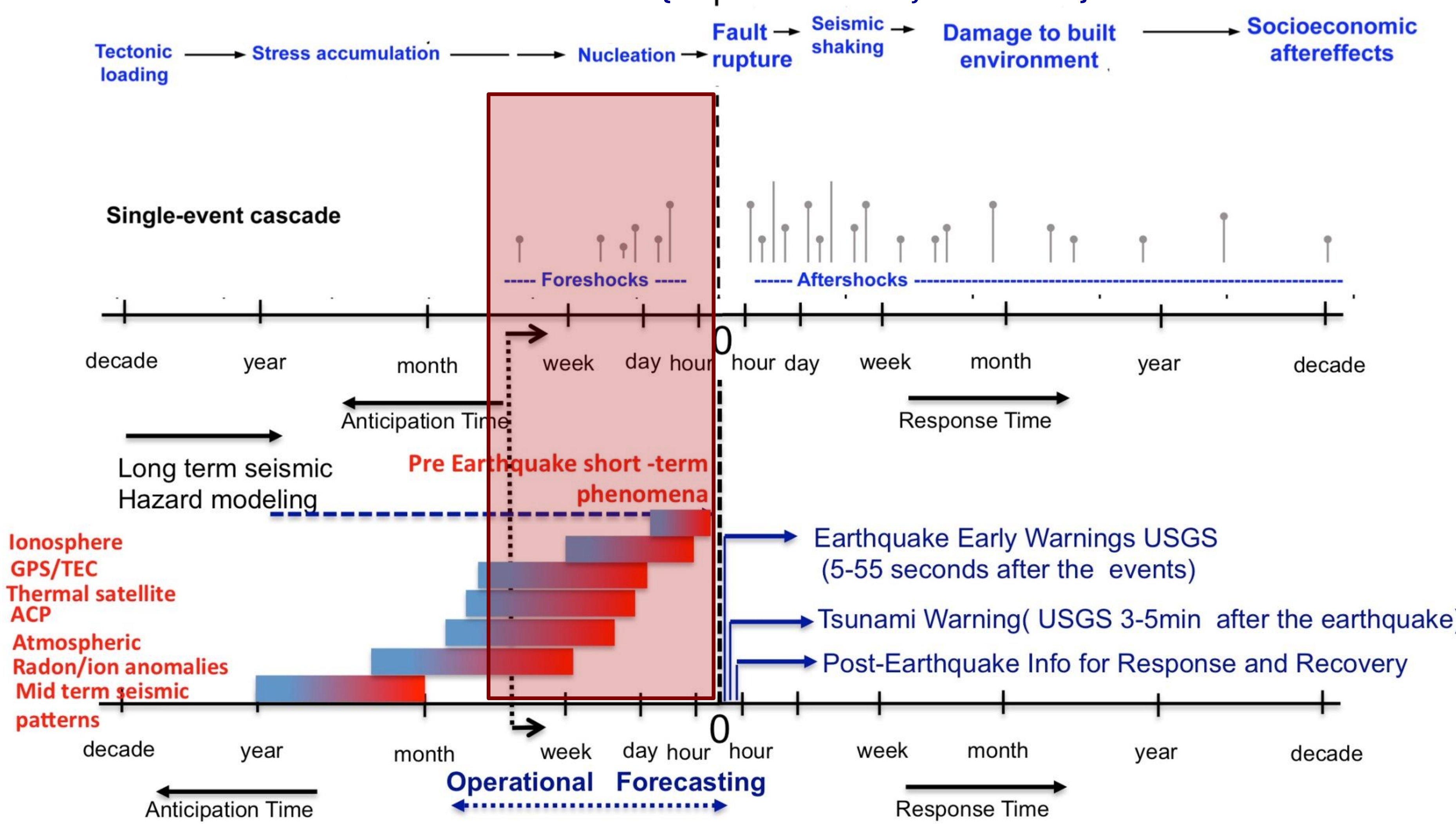
*Kobe, Japan*
*1994-1995*



# 8 years ago...Tohoku earthquake in Japan

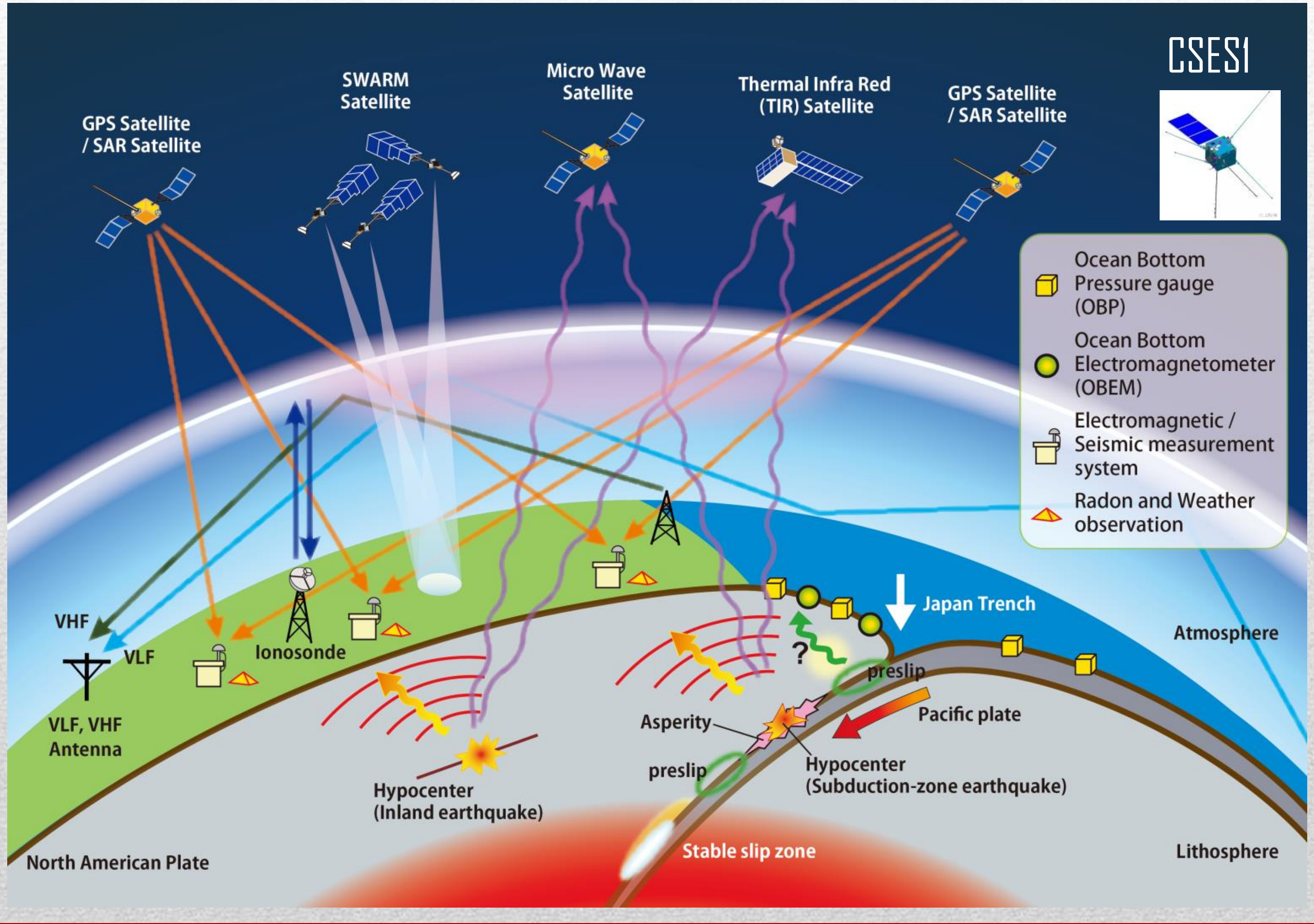
## Earthquakes progress as chain reactions

After Tom Jordan (SCEC, Monterey CA,2011)



# Integrated satellite and terrestrial framework (ISTF) for multi- parameter observations of pre-earthquake signals in Japan

## Today ...

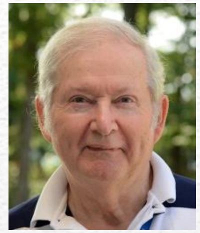


# We asked for help from the experts in the field


Dimitar Ouzounov


Sergey Pulinets


Katsumi Hattori


Patrick Taylor


Seiya Uyeda


Toshyasu Nagao


Dmitry Davidenko


Lou-Chuang Lee Lee


Cheng-Ling Kuo


Ben Tsai


Masashi Hayakawa


Michel Parrot


Xuhui Shen


Alexander Karelin


Antonella Peresan


Gerassimos Papadopoulos

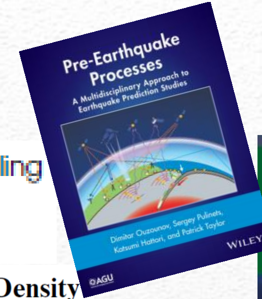

Peter Shebalin


Jann-Yenq (Tiger) Liu

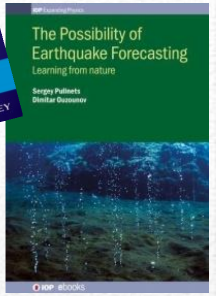

Giovanni Martinelli


Valerio Tramutoli

# LAIC evolution




2018




Lithosphere–Atmosphere–Ionosphere–Magnetosphere Coupling —A Concept for Pre-Earthquake Signals Generation

Sergey Pulinets[1], Dimitar Ouzounov[2], Alexander Karelin[3], and Dmitry Davidenko[1]

**The Nocturnal Positive Ionospheric Anomaly of Electron Density as a Short-Term Earthquake Precursor and the Possible Physical Mechanism of Its Formation**

S. A. Pulinets[a, *] and D. V. Davidenko[a, b, **]

**Physical Bases of the Generation of Short-Term Earthquake Precursors: A Complex Model of Ionization-Induced Geophysical Processes in the Lithosphere–Atmosphere–Ionosphere–Magnetosphere System**

S. A. Pulinets[a], D. P. Ouzounov[b], A. V. Karelin[c], and D. V. Davidenko[a, d]

2015

Ionospheric precursors of earthquakes and Global Electric Circuit

Sergey Pulinets[a,*], Dmitry Davidenko[b]

2014


**Chapter 09. Atmospheric Signals Associated with Major Earthquake A Multi-Sensor Approach.**

2012

*Dimitar Ouzounov[1,2], Sergey Pulinets[3], Katsumi Hattori[4], Menas Kafatos[1], Patrick*

Lithosphere–Atmosphere–Ionosphere Coupling (LAIC) model – An unified concept for earthquake precursors validation

2011

S. Pulinets[a,b,*], D. Ouzounov[c,d]

2009

**9 Lithosphere-atmosphere-ionosphere coupling (laic) model**

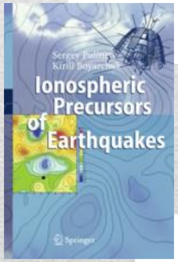
Sergey Pulinets

The physical nature of thermal anomalies observed before strong earthquakes

2006

**Enlightenment**

S.A. Pulinets[a,*], D. Ouzounov[b], A.V. Karelin[c], K.A. Boyarchuk[c], L.A. Pokhmelnykh[d]




TAO, Vol. 15, No. 3, September 2004

**Ionospheric Precursors of Earthquakes; Recent Advances in Theory and Practical Applications**

Sergey Pulinets[1,*]

Mid-infrared emission prior to strong earthquakes analyzed by remote sensing data

D. Ouzounov[a,*], F. Freund[b,c]

**Critical Mass**

**2004**

**Conception and model of seismo-ionosphere-magnetosphere coupling**

S. A. Pulinets, K. A. Boyarchuk, V. V. Hegai, and A. V. Karelin

2002

2000

**QUASIELECTROSTATIC MODEL OF ATMOSPHERE-THERMOSPHERE-IONOSPHERE COUPLING**

S.A.Pulinets[1], K.A.Boyarchuk[2], V.V.Hegai[1], V.P.Kim[1] and A.M.Lomonosov[2]

PACS number: 94.20.–y

**The atmospheric electric field as a source of variability in the ionosphere**

S A Pulinets, V V Khegaĭ, K A Boyarchuk, A M Lomonosov

1998

Pergamon

Adv. Space Res. Vol. 20, No. 11, pp. 2173–2176, 1997
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PII: S0273-1177(97)00666-2

RADON AND METALLIC AEROSOLS EMANATION BEFORE STRONG EARTHQUAKES AND THEIR ROLE IN ATMOSPHERE AND IONOSPHERE MODIFICATION

S. A. Pulinets*, V. A. Alekseev**, A. D. Legen'ka* and V. V. Khegai*

1997

Dusty and Dirty Plasmas, Noise, and Chaos in Space and in the Laboratory

Edited by Hiroshi Kikuchi

Plenum Press • New York and London

1994

S.A. Pulinets, A.D. Legen'ka, V.A. Alekseev, Pre-earthquakes effects and their possible mechanisms

USSR ACADEMY OF SCIENCES

INSTITUTE OF TERRESTRIAL MAGNETISM, IONOSPHERE AND RADIO WAVE PROPAGATION

Preprint N 34a(981)

S.A.Pulinets, A.D.Legen'ka, A.T.Karpachev, N.A.Kochenova, V.V.Migulin, V.N.Oraevsky, M.D. Fligel

THE EARTHQUAKE PREDICTION POSSIBILITY ON THE BASE OF TOPSIDE SOUNDING DATA

Moscow, 1991

1991

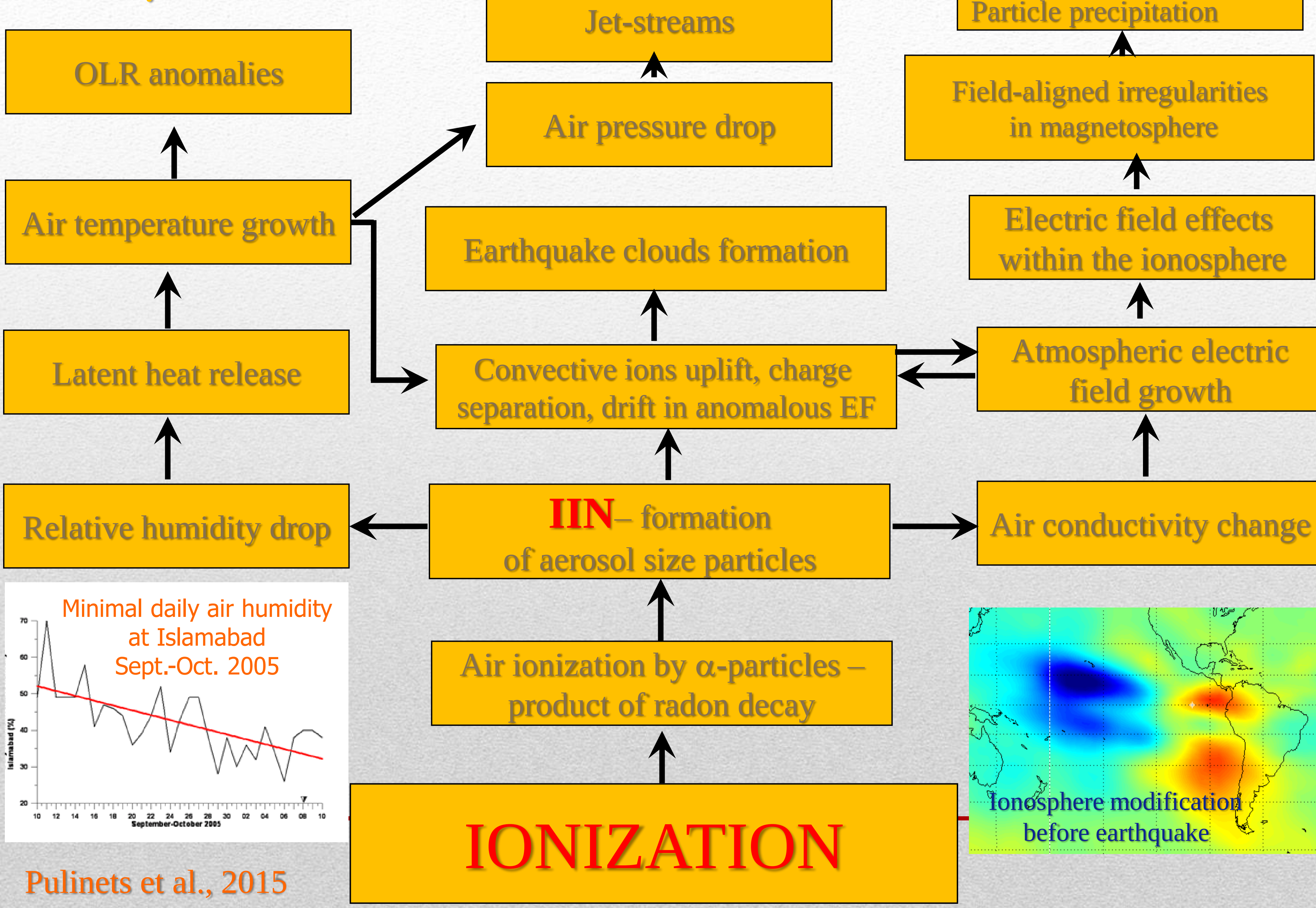
**Integrations of satellite and ground-based observations and multi-disciplinarity in research and prediction of different types of hazards in Solar system**

**10-13 May 2019 Petnica Science Centre, Valjevo, Serbia**

# Matter and energy transformations on the way of precursor's generation

| № | Sources | Consequences |
|---|---|---|
| 1 | Mechanical sources: tectonic movements, deformations, scale transformation, deformations, pressure variations, cracks formation | Gas and fluid migration, mechanic oscillations, foreshocks, triboelectricity, pressure-induced electricity, electrokinetic effects, slipping |
| 2 | Chemical sources: fluids and gases dissolution, chemical and plasma-chemical reactions, ion's hydration, catalytic processes | Heat release/absorption, change of atmosphere composition due to chemical reactions, ion clusters formation, change of electric properties of atmosphere, aerosol formation |
| 3 | Radon activity in air/radioactive decay | Air ionization, local modification of the Global Electric Circuit, generation of space charges, anomalous electric field, change of ionosphere potential |
| 4 | Troposphere modification | Formation of aerosol layers, anomlaies of VLF-VHF radiowaves propagation, local time dependence of ionosphere pre-earthquake anomalies |
| 5 | Ionosphere modification | Formation of anomalous magnetospheric ducts, particles precipitation, VLF anomalous emissions |

# Most recent view of the LAIC conception




Pulinets et al., 2015

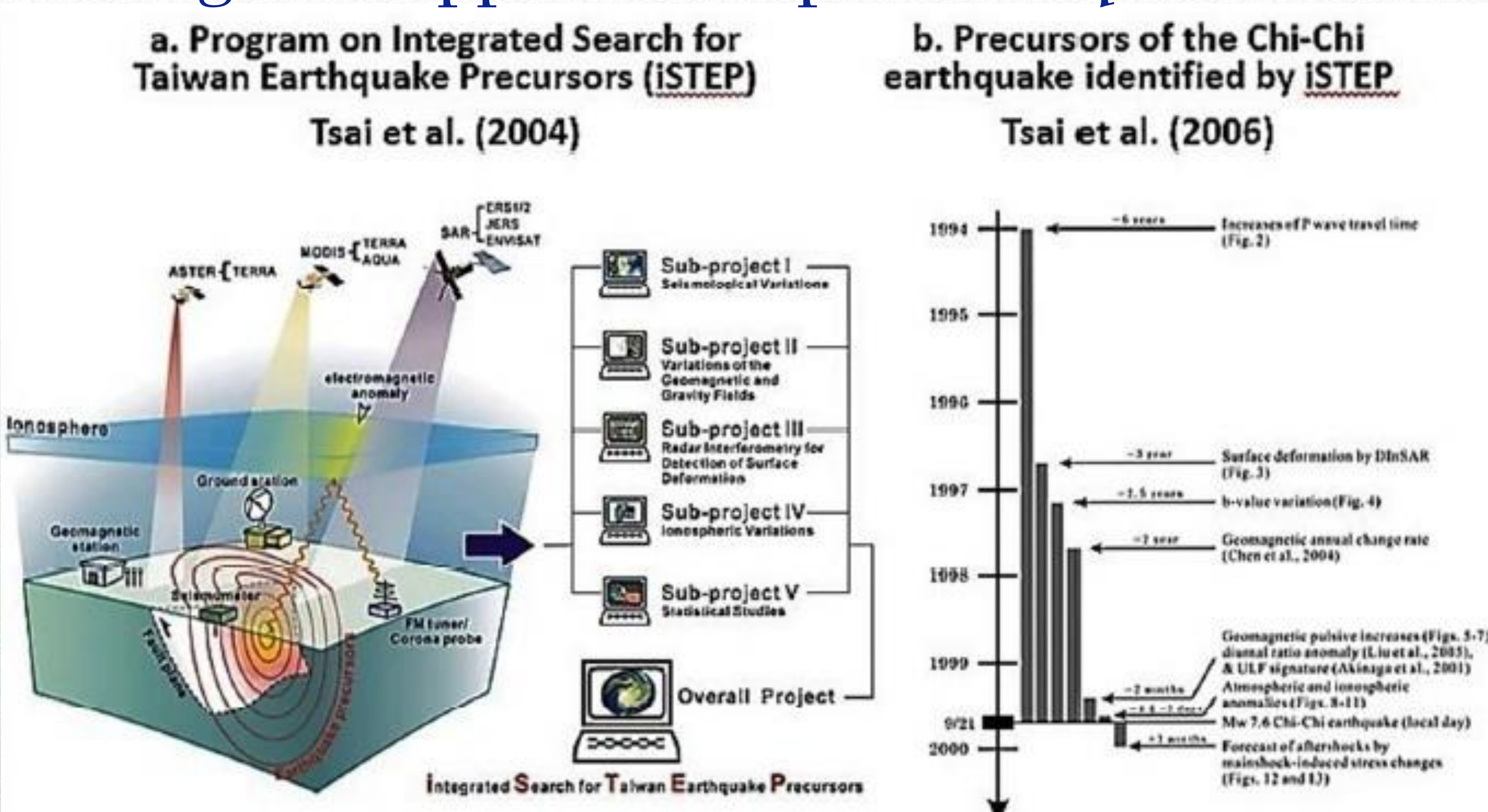
# Questions we asked about Pre- Earthquake processes

1) Are any **reliable** multidisciplinary observations and models for pre-earthquake processes - seismic precursors, crustal geochemical fluids and gases; ULF/VLF magnetic signals; atmospheric effects including ionospheric TEC measurements?

2) Statistical **correlation** of pre-Earthquake signals with subsequent seismic events?

3) What is the **potential** of Pre-Earthquake signals for inter disciplinary earthquake predication /forecasting?

# Integrated approach for pre-earthquake studies




The general and five component projects; b. Precursors of the M7.6 Chi-Chi earthquakee identified as of 2006 under the multidisplinary 'integrated Search for Taiwan Earthquake Precursors' (iSTEP) Program (Tsai et al., 2006, Tsai et al, 2018)

# Following projects

2011-2013 under grant agreement No. 263502 – PRE-EARTHQUAKES project: Processing Russian and European EARTH observations for earthQUAKE precursors Studies (P.I.'s Tramutoli, Pulinets)

2013-2015 international team: Multi-instrument Space-Borne Observations and Validation of the Physical Model of the Lithosphere- Atmosphere-Ionosphere-Magnetosphere Coupling (P.I.'s Pulinets & Ouzounov)

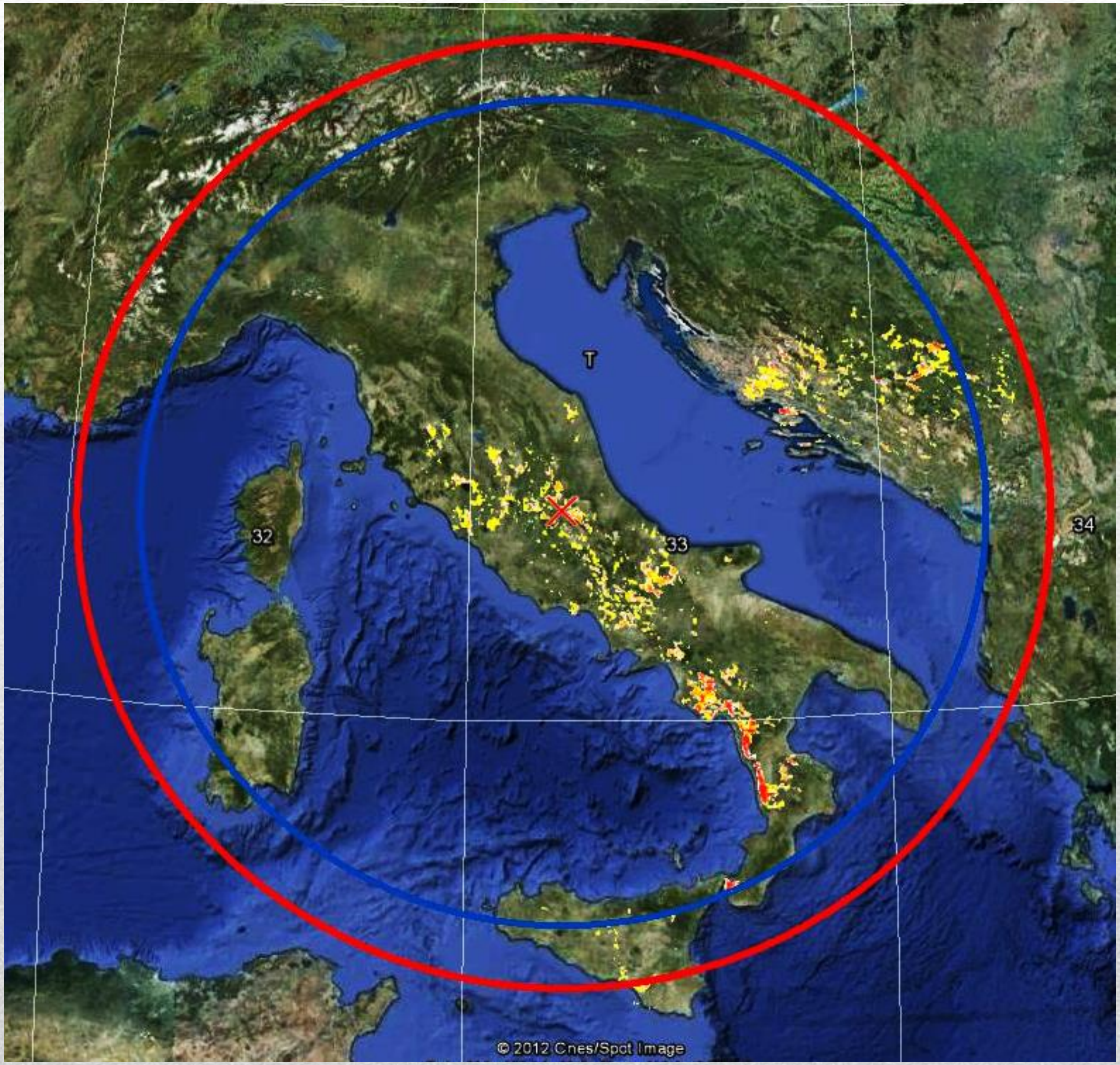
2014-2016 Ionospheric Sounding for Identification of Pre-Seismic Activity, INSPIRE project (P.I.'s Krankowski & Pulinets)

# What is the advantage of the satellite observations?

What is this?

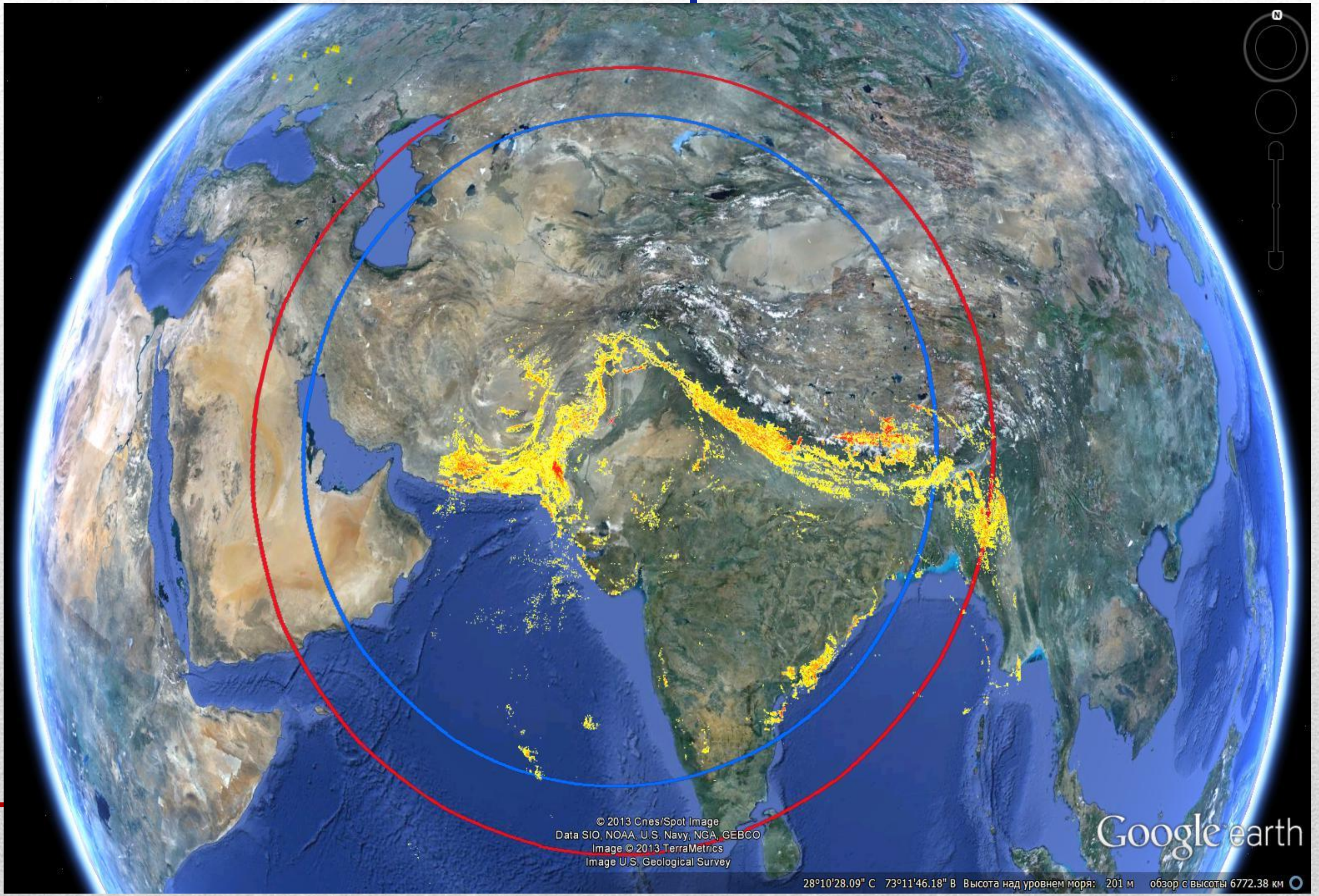
Ground point observations do not permit to reveal the integral picture of the precursors distribution

# Earthquake preparation zone conception

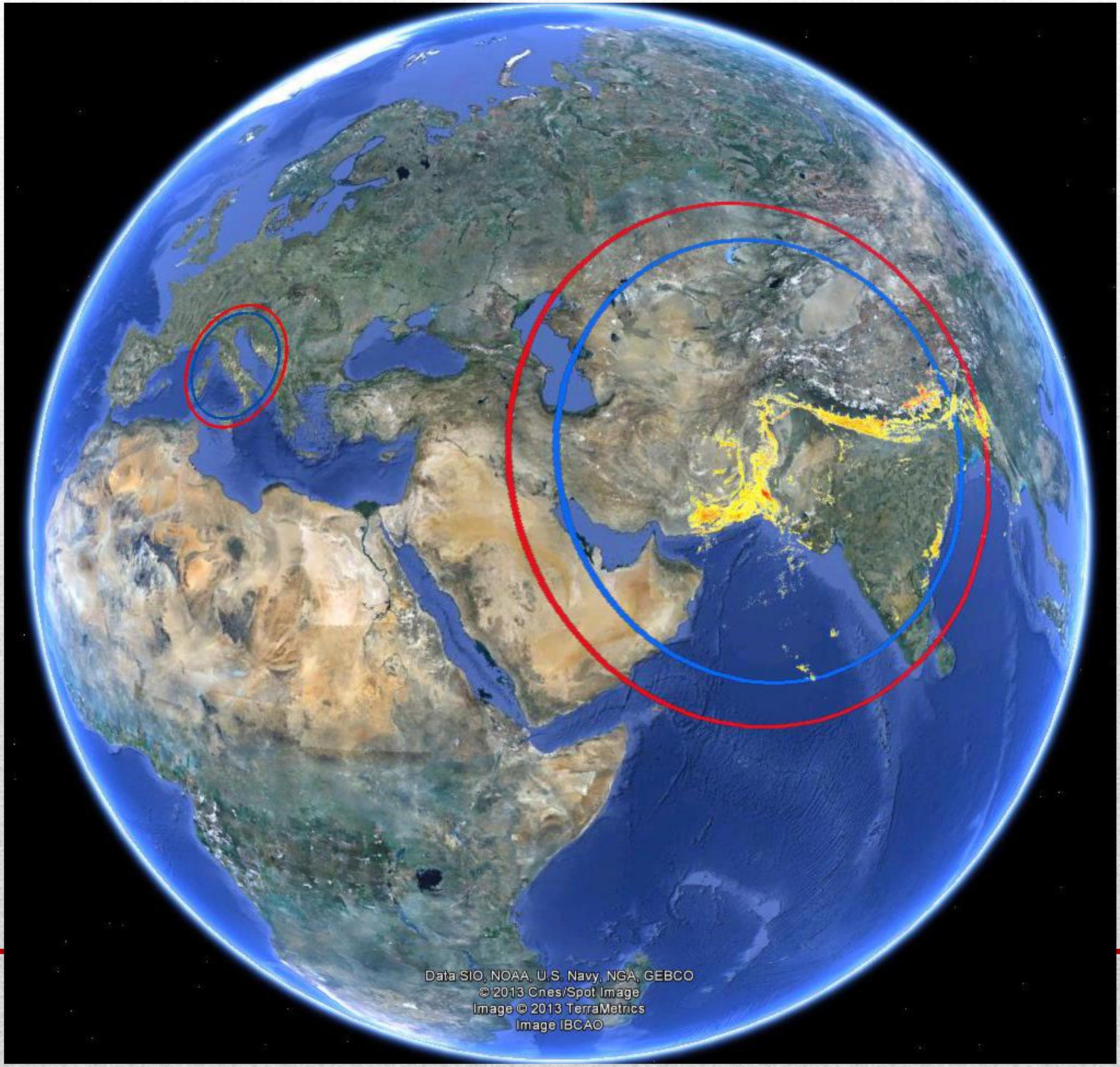



Yellow and red spots – ground layer thermal anomalies,L'Aquila earthquake epicenter is marled by cross, blue circle – Earthquake preparation zone by Dobrovolsky $R=10^{0.43M}$, red circle – earthquake activation zone by Bowman et al., 1998 $R=10^{0.44M}$

# Earthquake preparation zone for Gujarat M7.7 earthquake



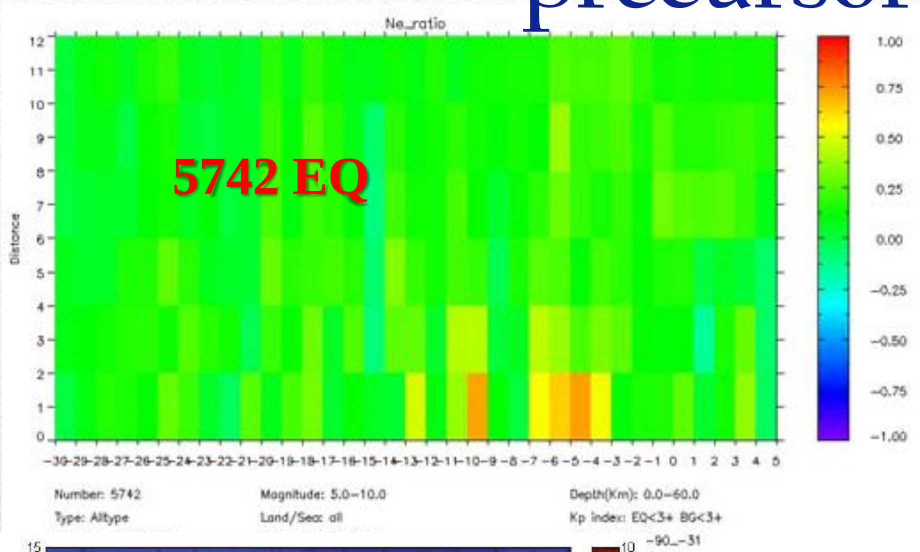
# Gujuarat and L'Aquila

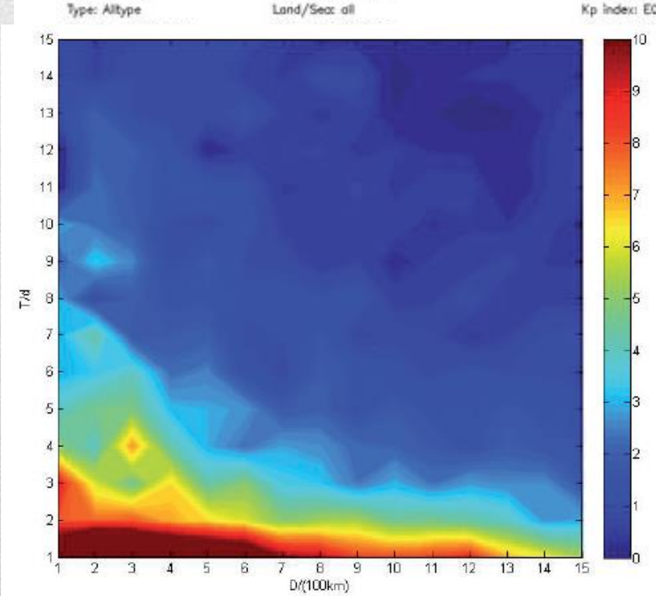


# Multi-disciplinarity from space

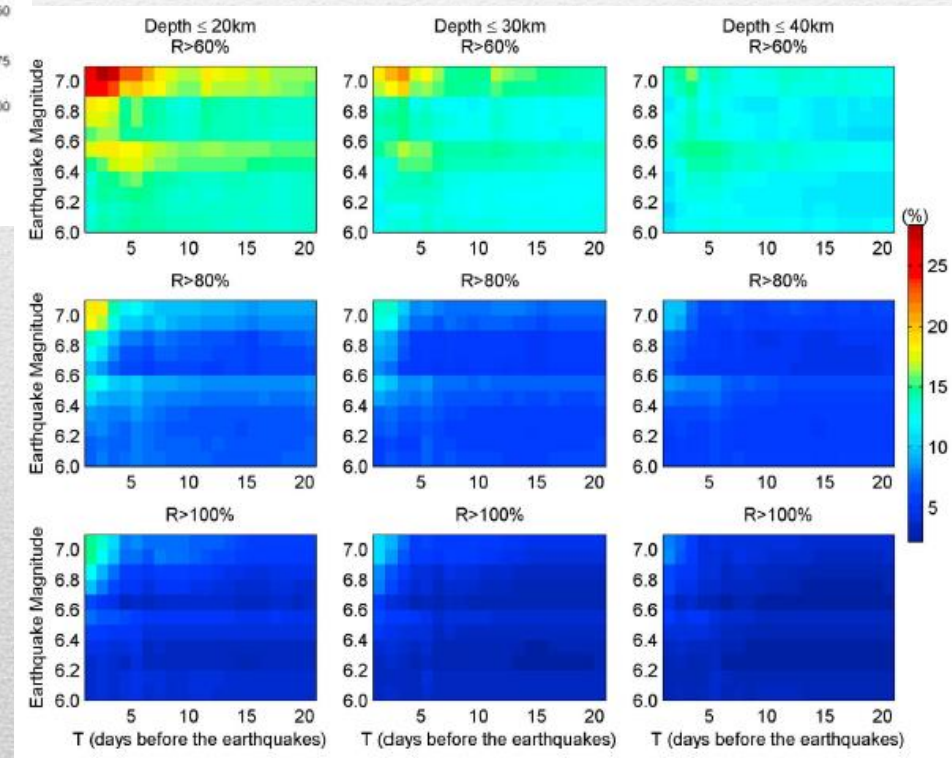
- Surface TIR anomalies
- Anomalous latent heat flux
- OLR (Outgoing Longwave Radiation)
- Chemical Potential Correction
- Electron concentration and temperature in the ionosphere
- GPS TEC anomalies
- GPS occultation measurements
- Ionosphere ion composition
- EF and EM emissions
- Topside sounding
- Low and high orbiting ionospheric tomography
- Particle precipitation

# Statistics and reliability of the ionospheric precursors (global)



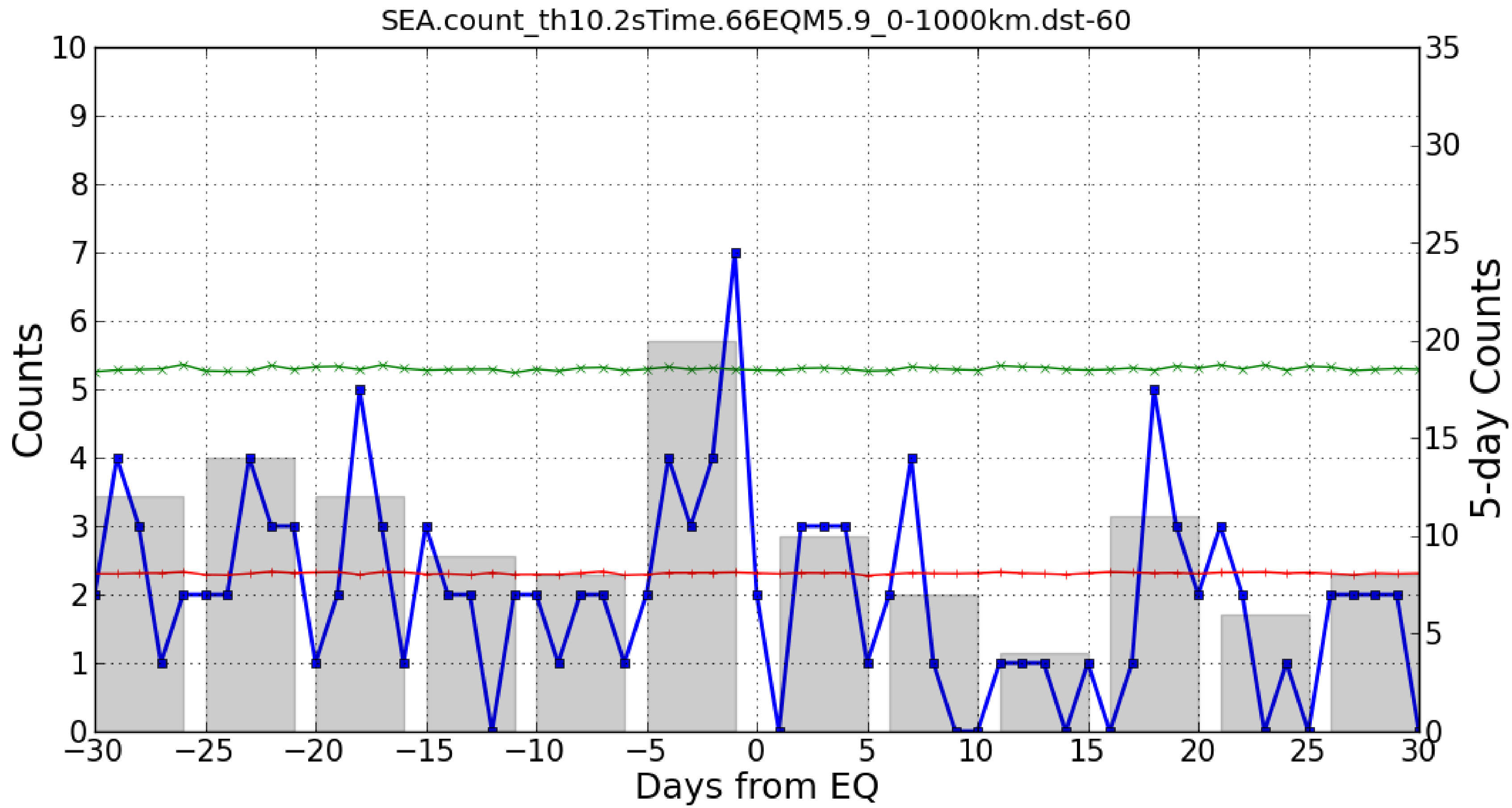

## GPS TEC



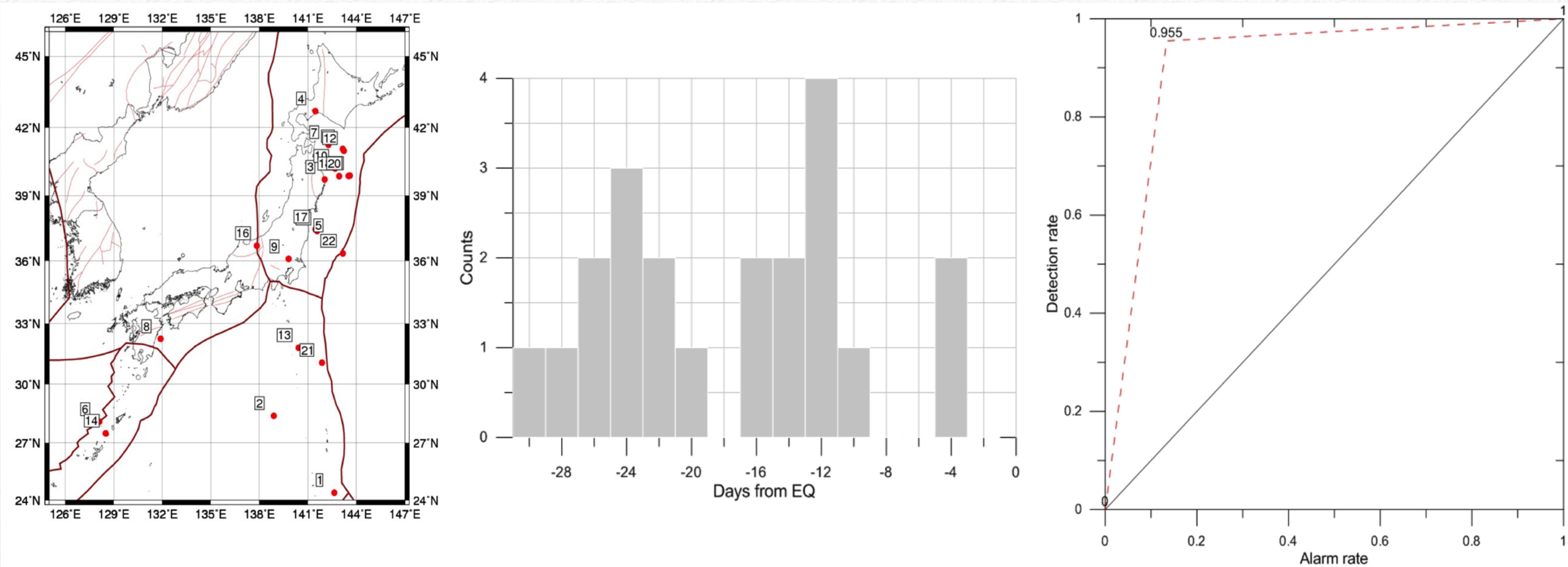
# Statistics of ionospheric precursors (Japan)

Positive GIM-TEC* anomaly

M >=5.9 140EQs
(Region A: 0<R＜1000 km)



# Statistics of OLR thermal precursors (Japan)




Evaluation of TRA earthquake anomalies with Molchan's Error Diagram for Japan, 2014-2015 (Left to right) A. Distribution map for M>5.5 earthquakes, 2014-15; B. Temporal distribution (time-lag) of OLR anomalies in relation to the time occurrence of EQ; C: MED diagram. Ouzounov et al, 2018

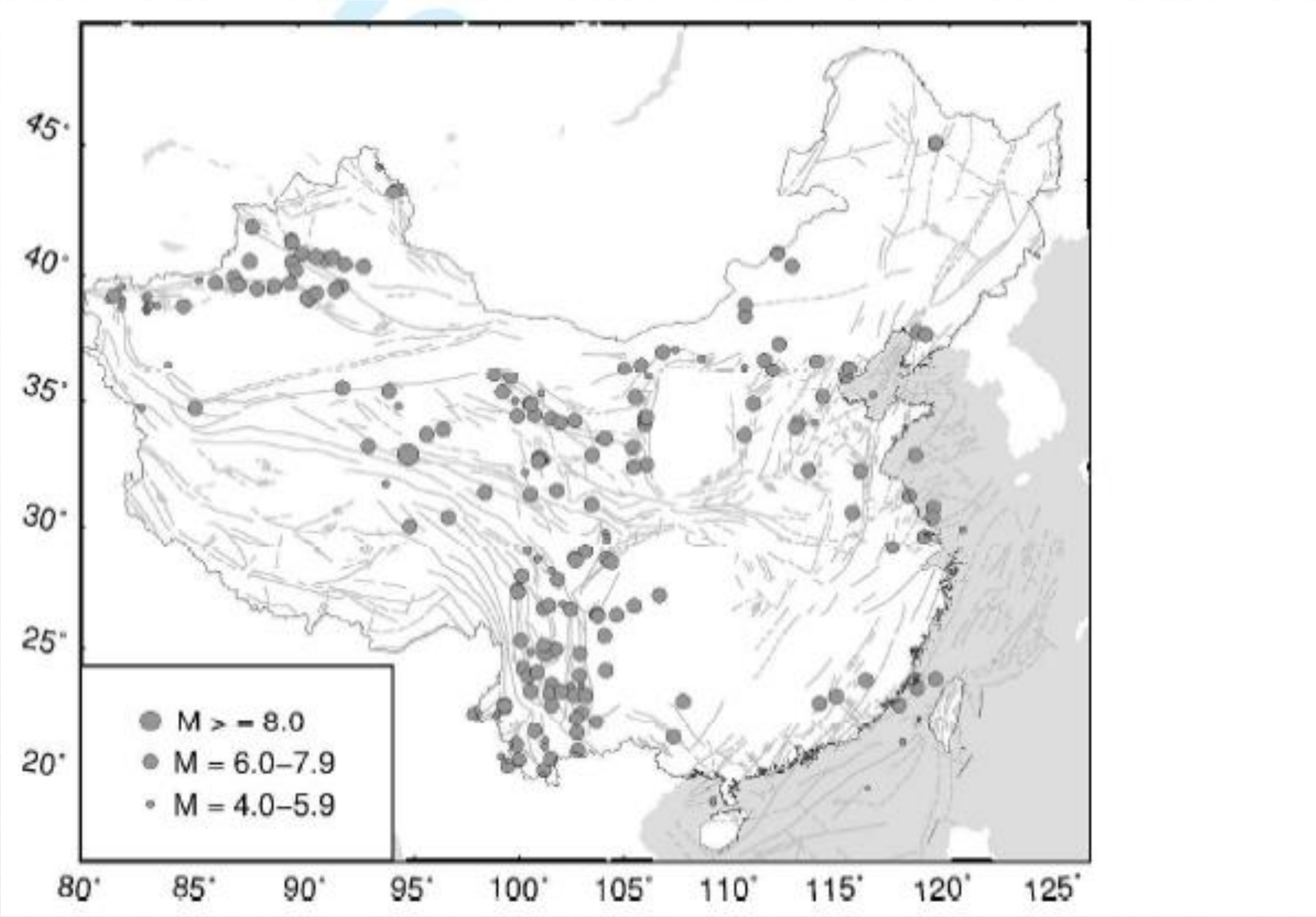
# Multi-disciplinarity from on the ground

- Seismometers
- Deformographs, inclinometers
- Radon variations
- CO2 flux
- Aerosol content (AERONET, lidars)
- Atmospheric electric field
- Ion concentration and composition (mass distribution)
- Air conductivity
- Anomalies of radio waves propagation in different frequency bands (from VLF to VHF)
- Meteorological anomalies (air temperature, relative humidity)
- Ground based ionosondes (vertical and oblique sounding)
- GPS receivers
- Magnetometers

# What advantage of the ground-based observations?

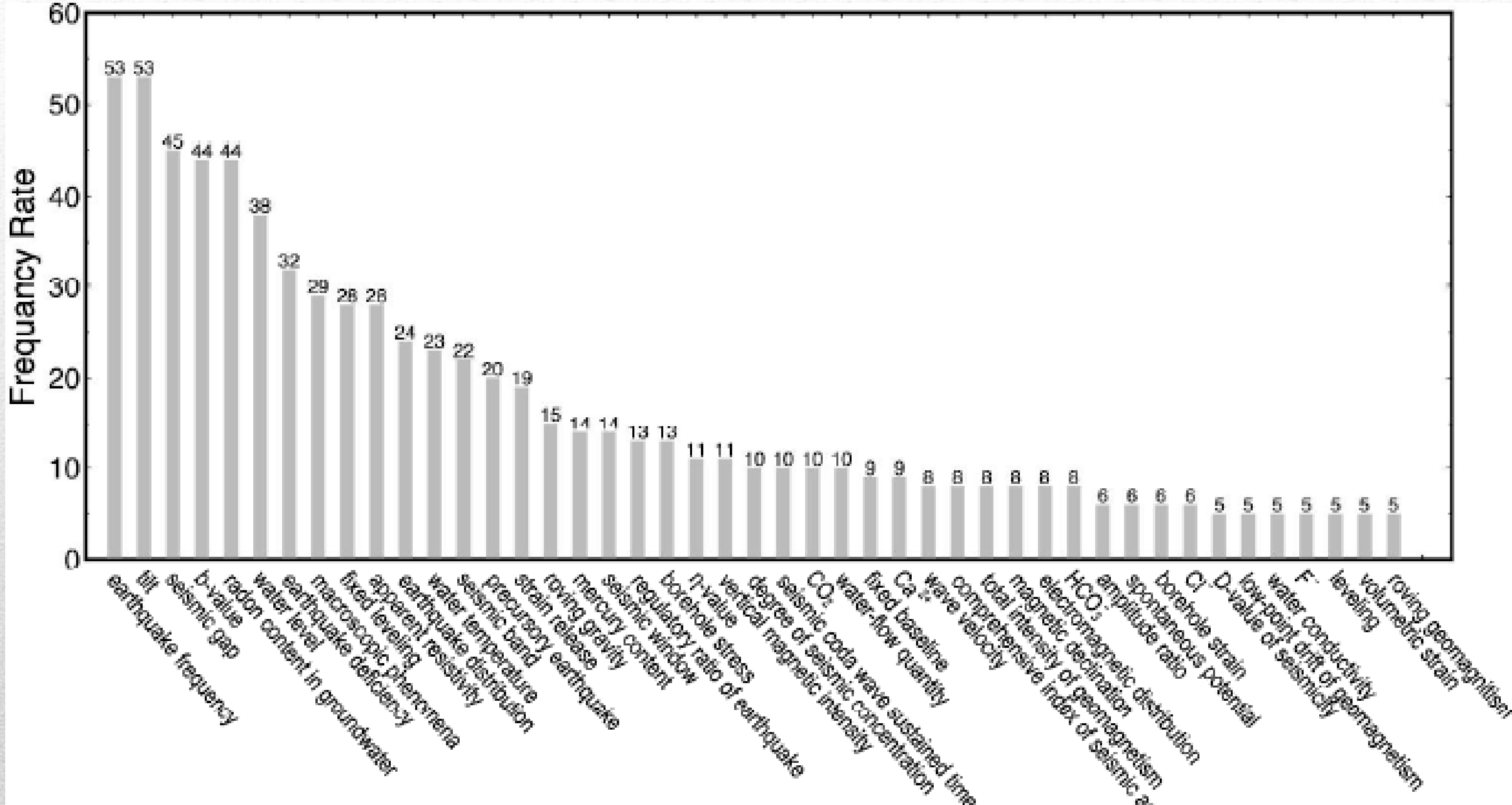
- Higher sensitivity (starting from ~M2)
- Higher operativity (real-time)
- Continuity in time
- Expert decisive role
- Direct connection with seismological measurements
- Local control

# China: Map of earthquakes in main land China studies for pre-earthquake signals during 1966-2006




[Hui et al, 2018)

# Frequency of pre-earthquake phenomena (>3000) that appeared prior to more then 270 earthquakes during 1986-2006, in China

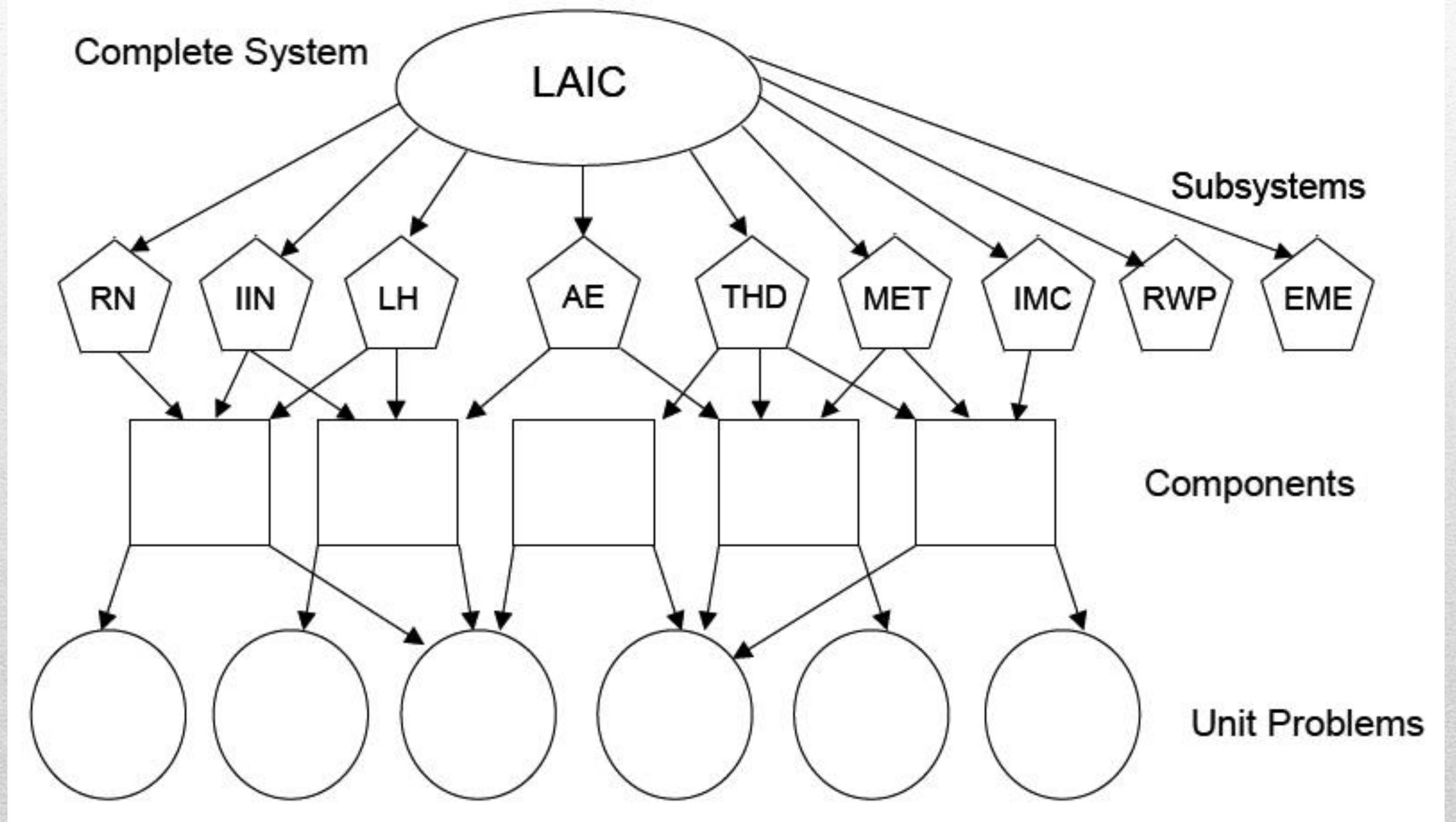



[Hui et al, 2018]

# Indicators of the synergetic character of the processes initiated by earthquake preparation

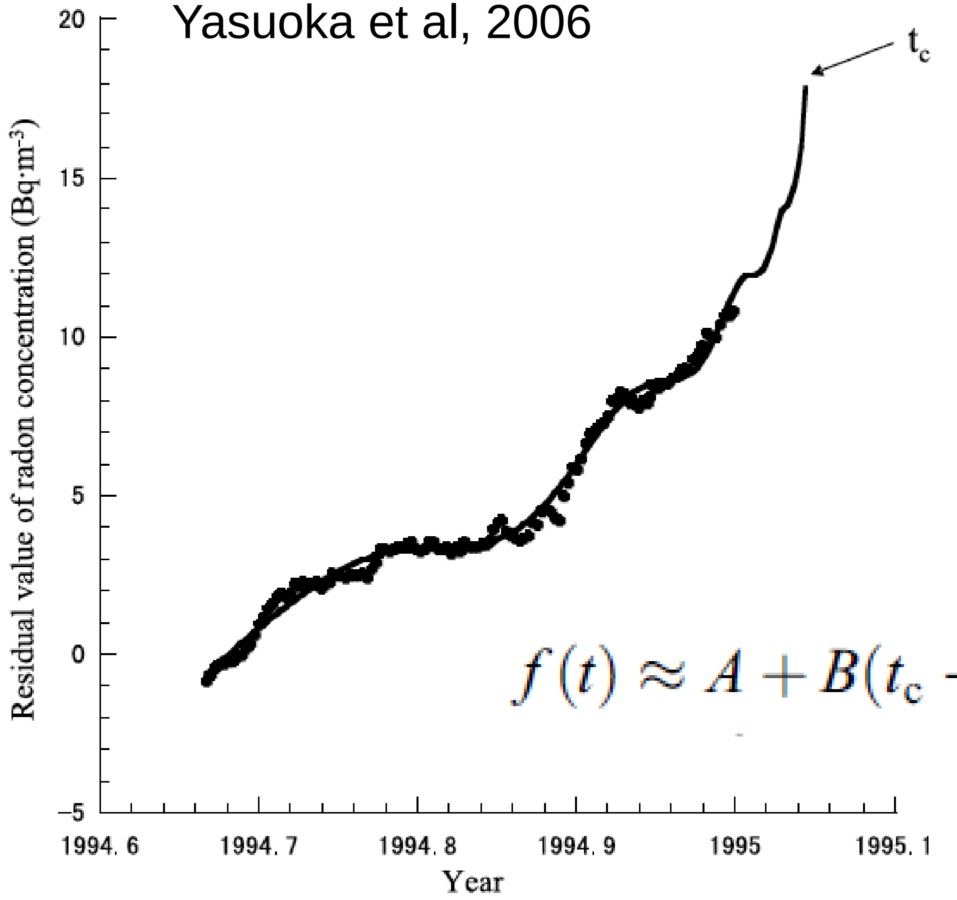
- Mutual dependence of precursor's parameters (earthquake preparation – the complex system)
- Synchronization in time and space
- Presence of the critical parameters (criticality concept)
- Presence of the non-linear processes
- Co-existance of the different phase states (vapor, condensate) in non-equilibrium state
- Catalytic reactions
- Cascade processes with the scale changes
- Presence of the non-reversable process indicator o "arrow of time"
- Presence of the common time scale – 5 days

# Earthquake preparation as a complex system



# Radon repeats the cumulative law of the strain storing

Yasuoka et al, 2006




$$f(t) \approx A + B(t_c - t)^z$$

Ben-Zion and Lyakhovsky (2002)

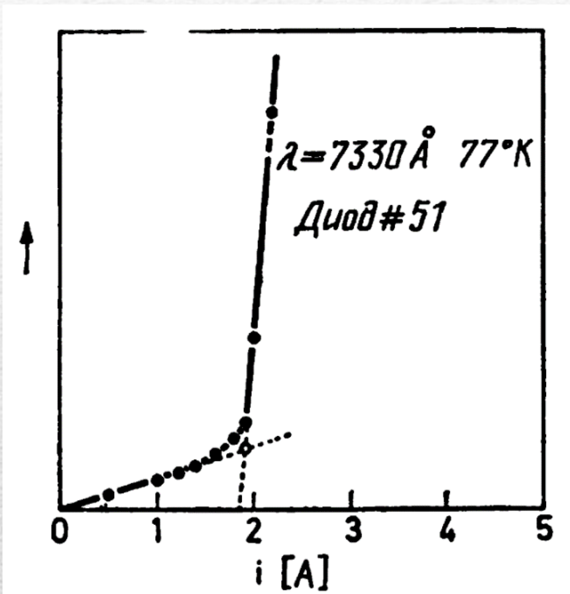
power-law of the Benioff strain

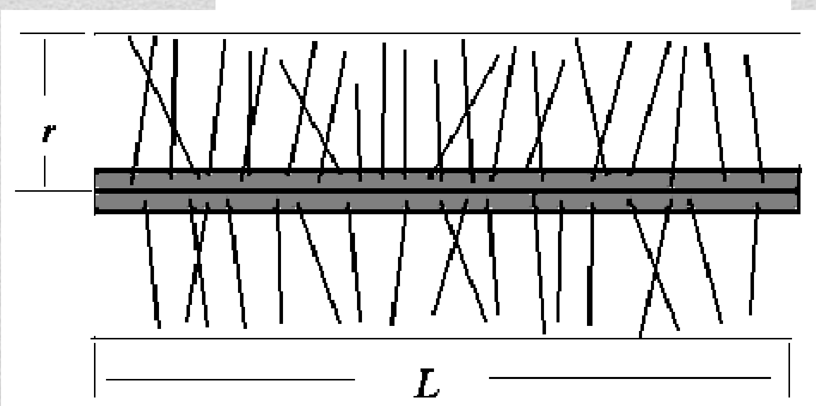
$$f(t) \approx A + B(t_c - t)^z[1 + C\cos(\omega \log(t_c - t) + \psi)]$$

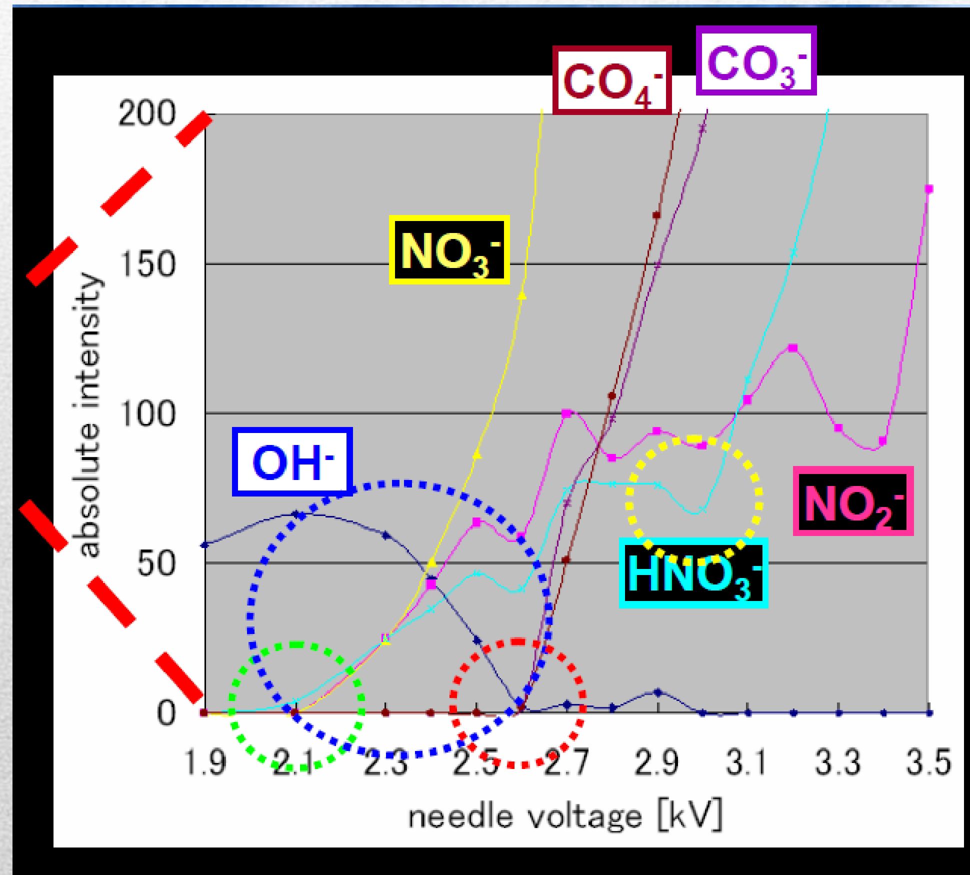
Sornette and Sammis (1995)

log-periodic oscillation model

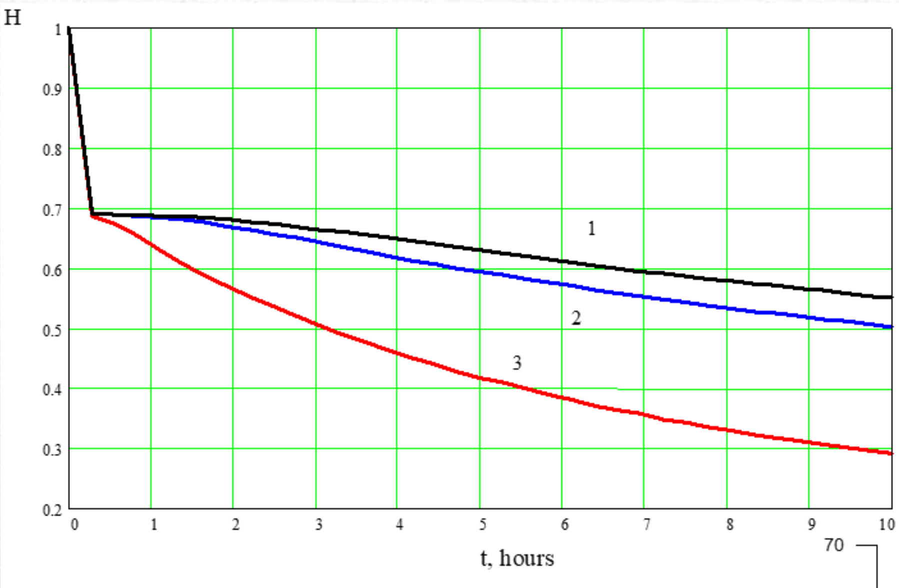
# Laser pumping effects in IIN



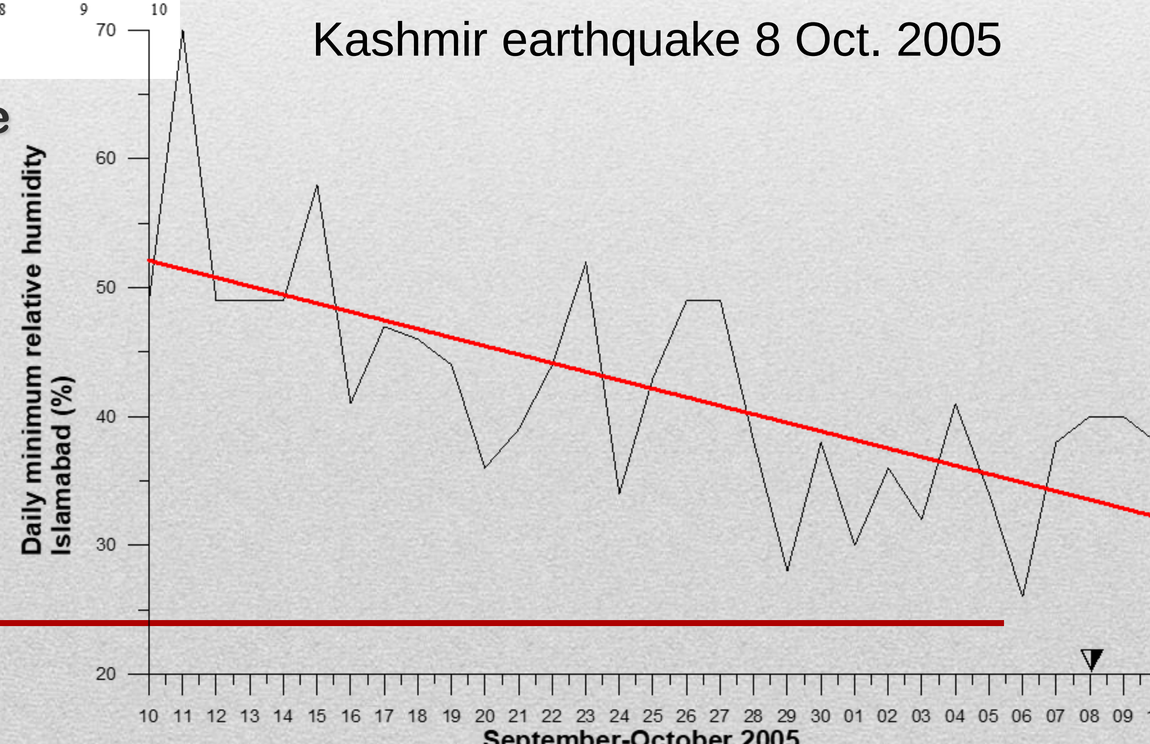



# Model and experimental records of humidity variations under ionization




Theoretical calculation of the humidity changes under different ionization rates (Pulinets et al., 2006)

Minimal daily humidity at Islamabad before the Kashmir earthquake on 8 October 2005.



# Entropy of Earthquakes

Gutenberg-Richter Law
$$\log n(M) = a - bM$$

*n*(*M*) EQs magnitude ≥ *M*
*a*, *b* several interpretation

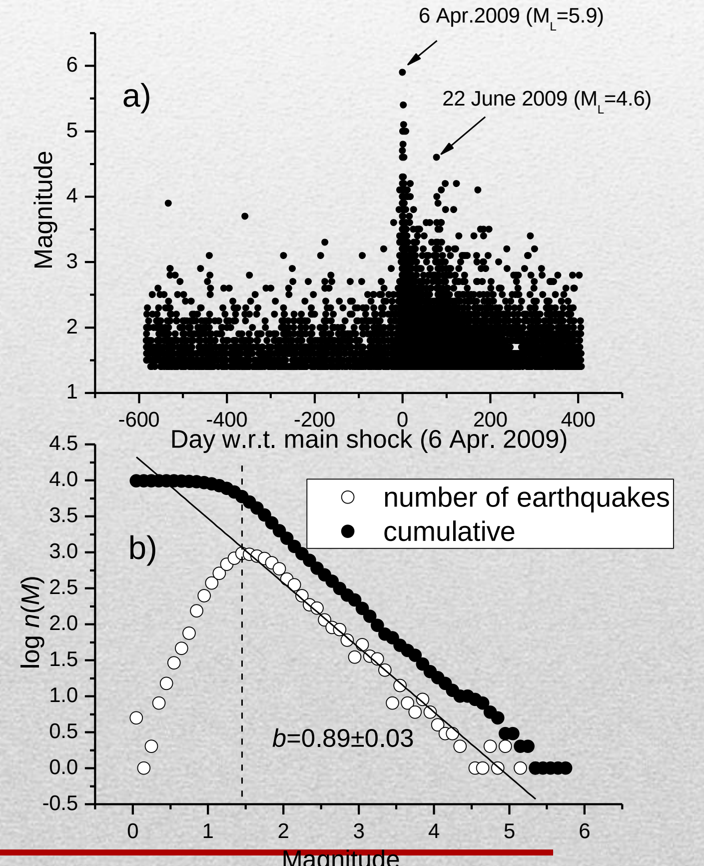
Shannon Entropy
$$H(t) = -\sum_{i=1}^{N} p_i(t) \cdot \log p_i(t)$$

$p_i$ probability of the *i*-th state of the system

*b*-value and Entropy

$$H(t) = \log(e \cdot \log e) - \log b = k' - \log b$$

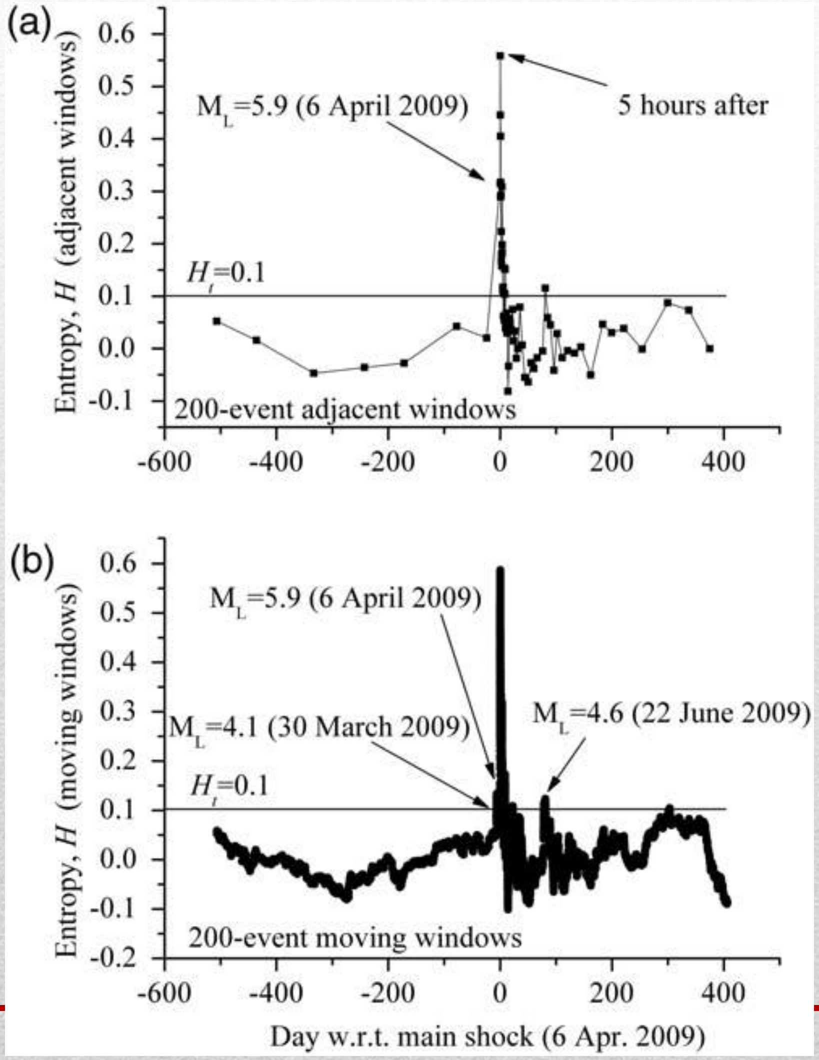
$$b = \frac{b_{\max}}{10^H} \approx \frac{1.2}{10^H}$$



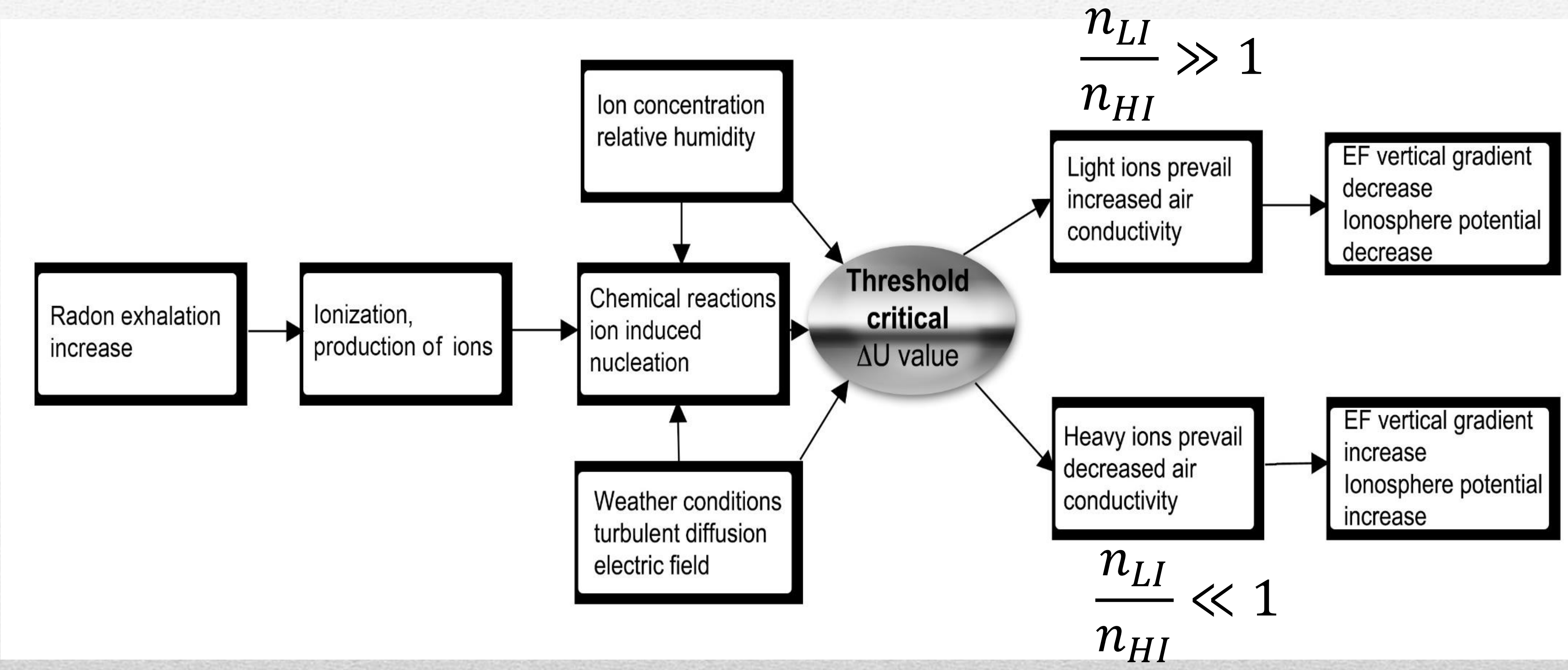

**So, this is a new insight into the b value!**

*(De Santis et al., BSSA, 2011)*

# Shannon entropy maximum (L'Aquial earthquake)



# Nonlinearity – the branching points (threshold)



# Some estimations

Each $\alpha$-particle emitted by $^{222}Rn$ with the average energy of $E\alpha=5.46$ MeV can produce ~ $3\cdot10^5$ electron-ion pairs.

Radon activity before earthquake is ~2000 Bq/m$^3$ (Inan, 2008)

The ion production rate is ~$6\cdot10^8$ s$^{-1}$

The particle 1000 nm size contains $0.4\cdot10^{12}$ water molecules

During water vapor condensation process the latent heat release is $U_0 \sim 40.68\cdot10^3$ J/mol (1 mol = $6.022\cdot10^{23}$)

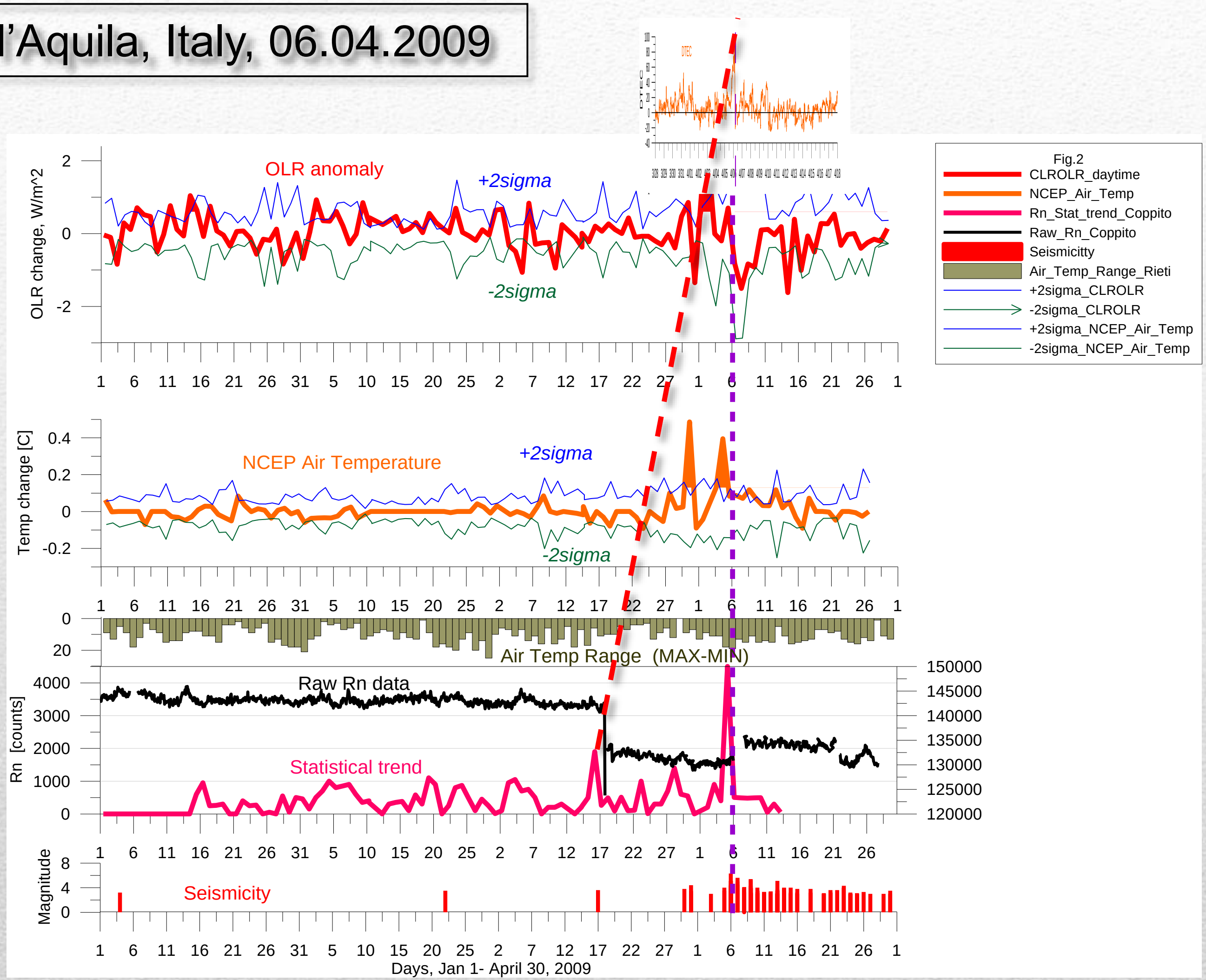
The given radon activity with formation of particles of 1000 nm size gives the thermal energy output 16 W/m$^2$

1 eV = $1.6\cdot10^{-19}$J , with radon activity 2000 Bq/m$^3$s it will give $1.7\cdot10^{-9}$ W

The energy gain of ionization process is $16/1.7\cdot10^{-9} \sim 10^{10}$

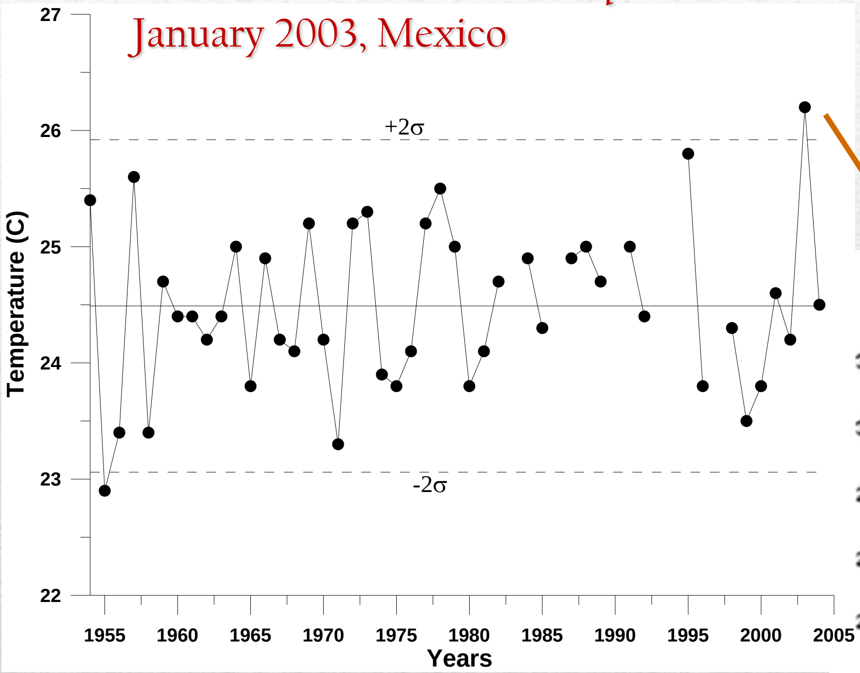
# Synergy of the short-term earthquake precursors

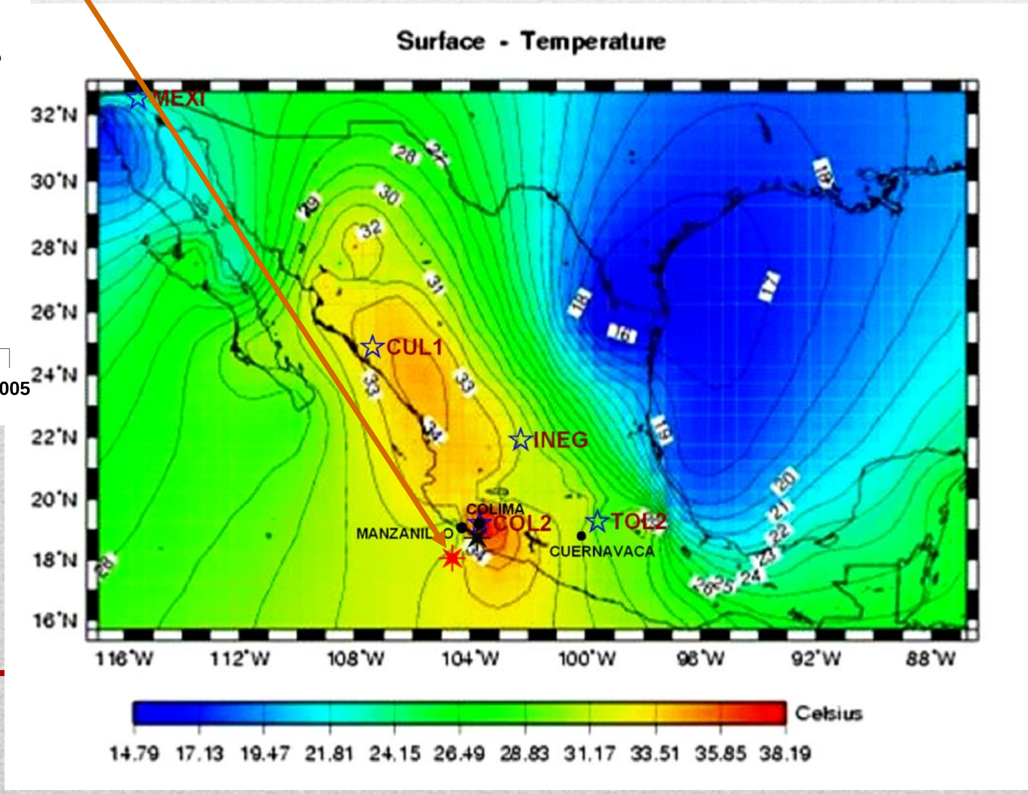
I'Aquila, Italy, 06.04.2009



# Ground air temperature anomaly before the M7.6 Colima earthquake at Mexico 22 January 2003

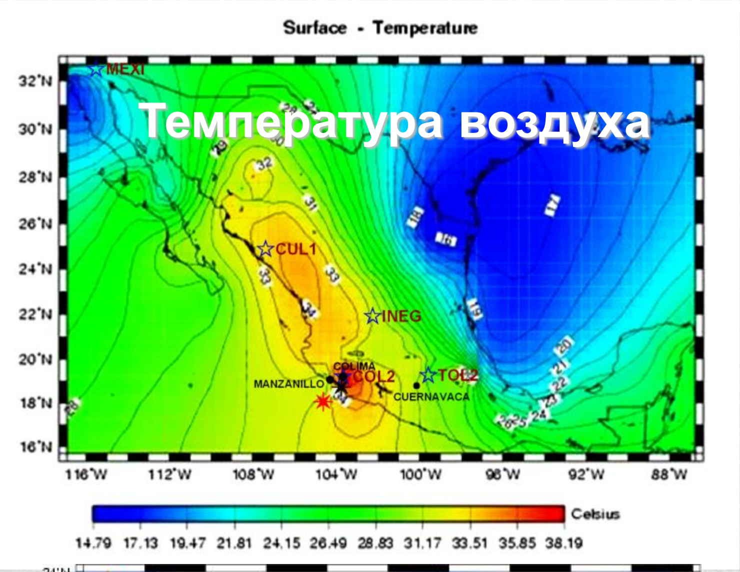
50-year (1955-2005) January monthly average temperature anomaly at Manzanillo for M7.6 earthquake on 22 January 2003, Mexico

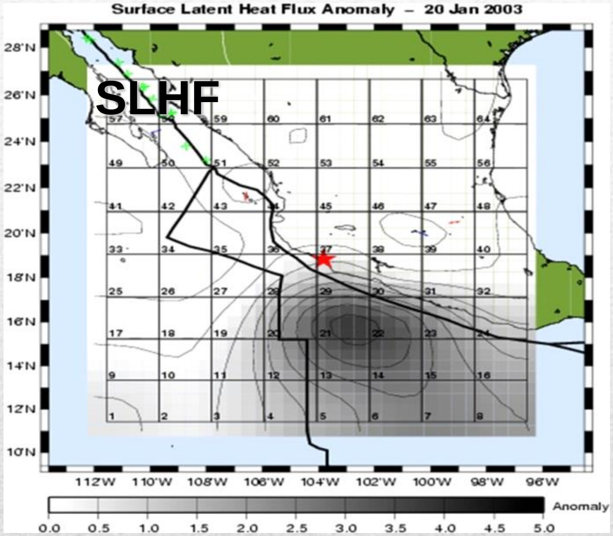


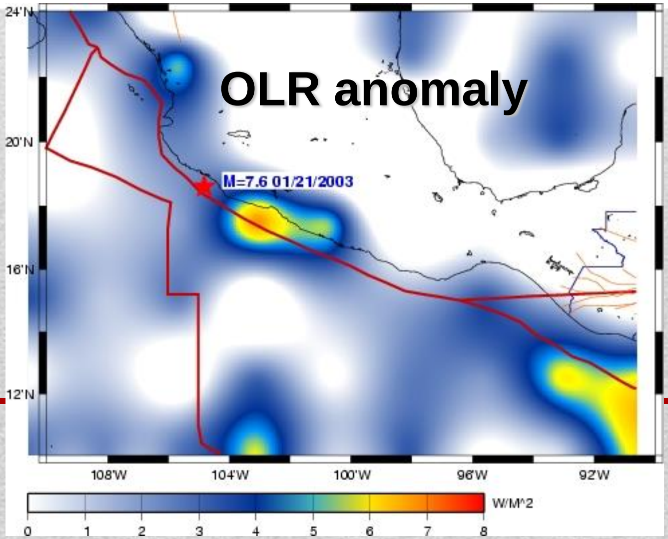



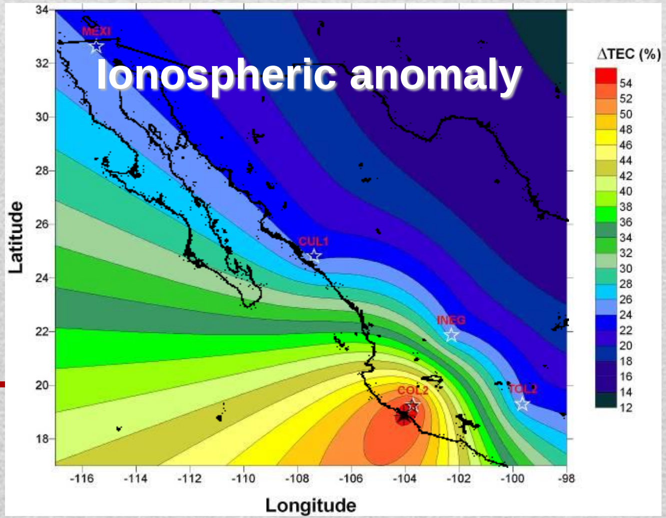
# Spatial synchronization

**Colima, Mexico 2003**

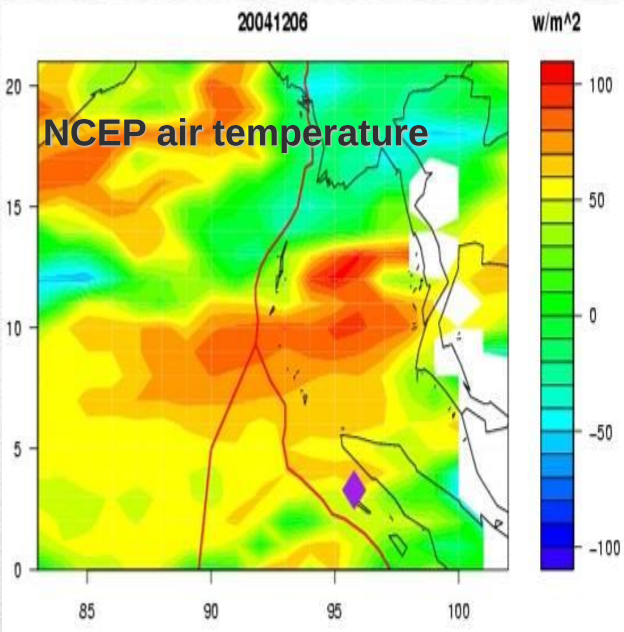


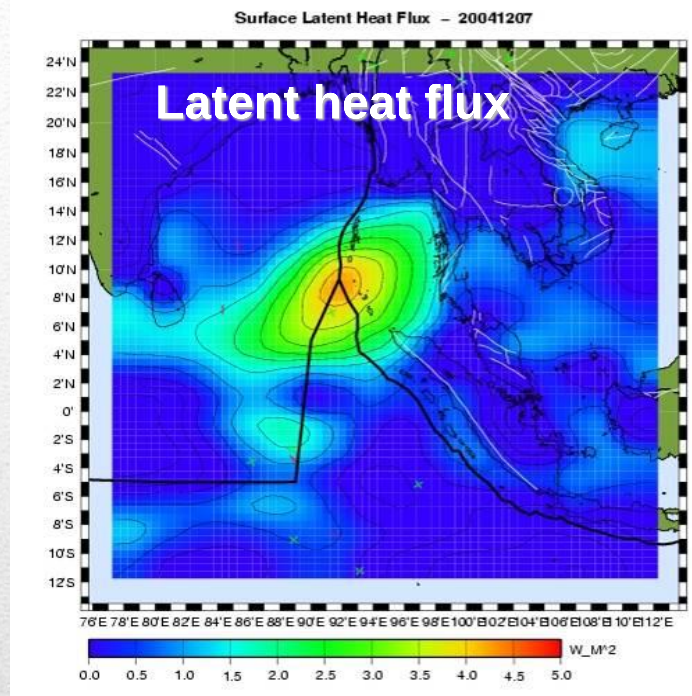



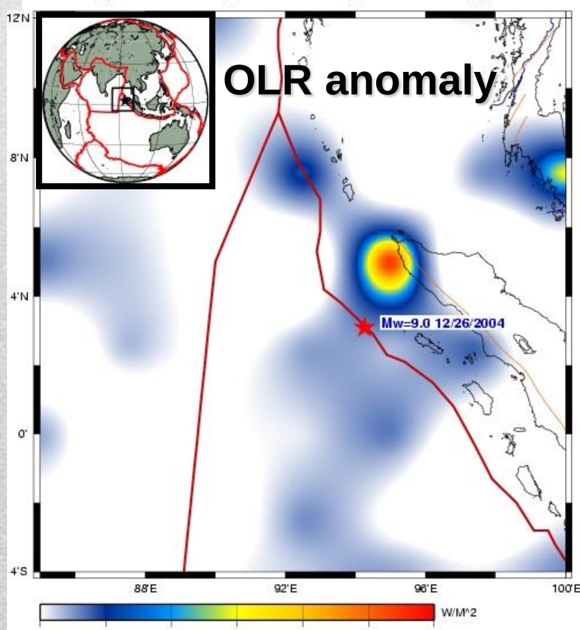



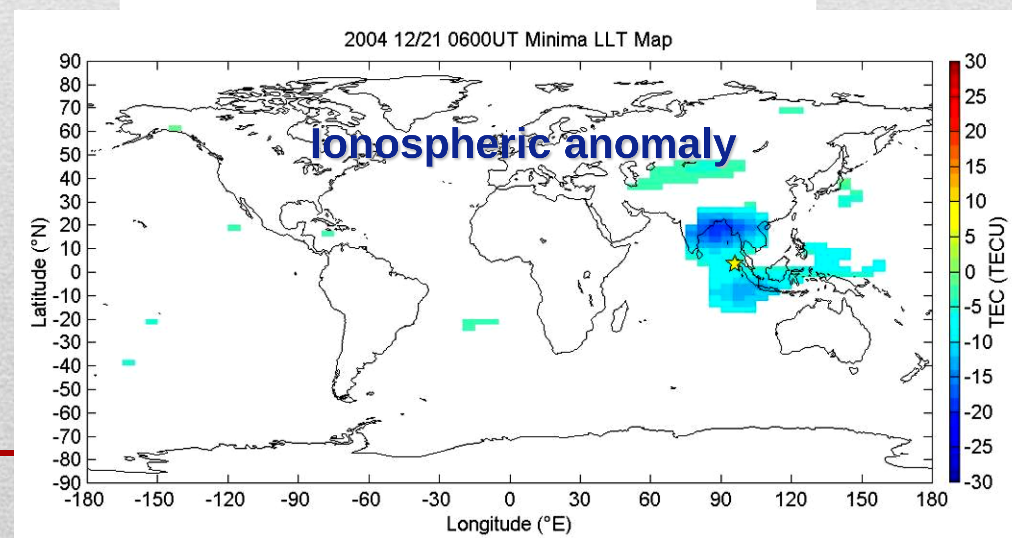



# Sumatra M9 earthquake 26 Dec 2004

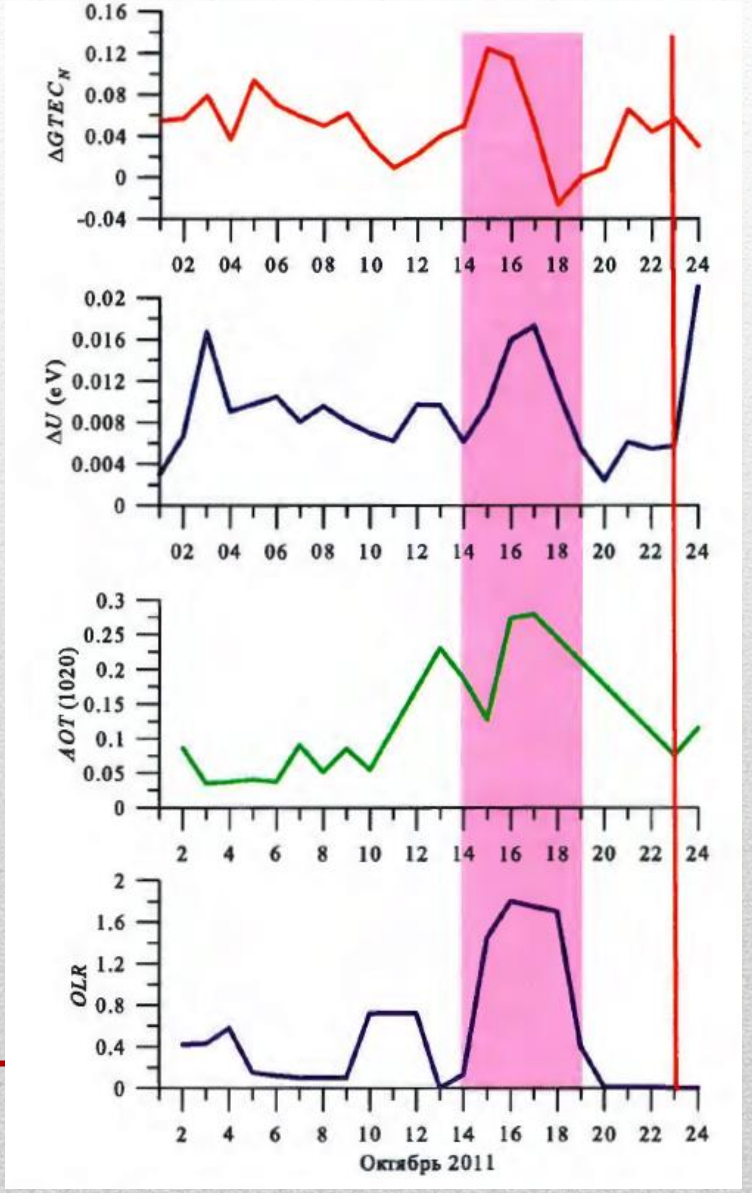


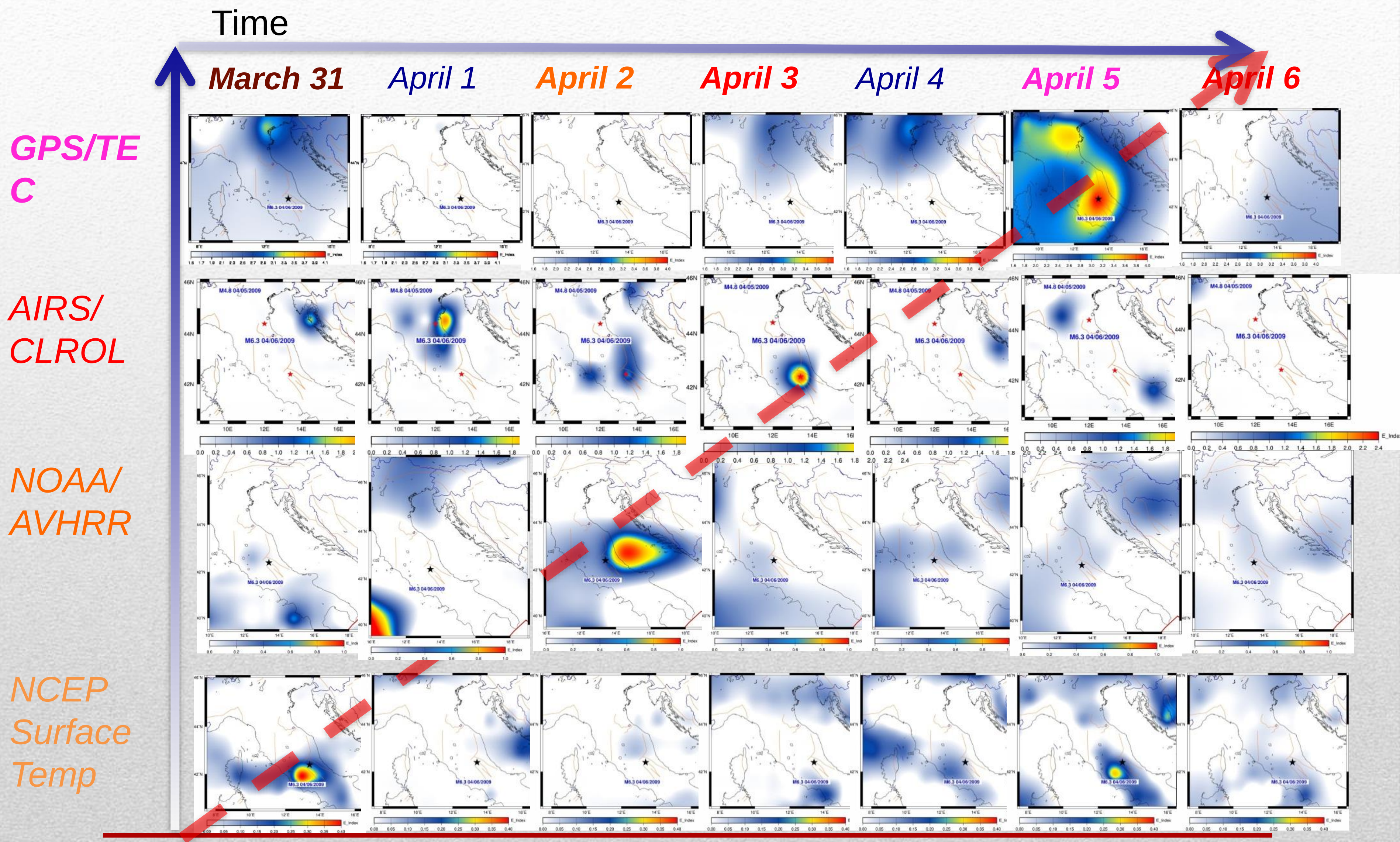



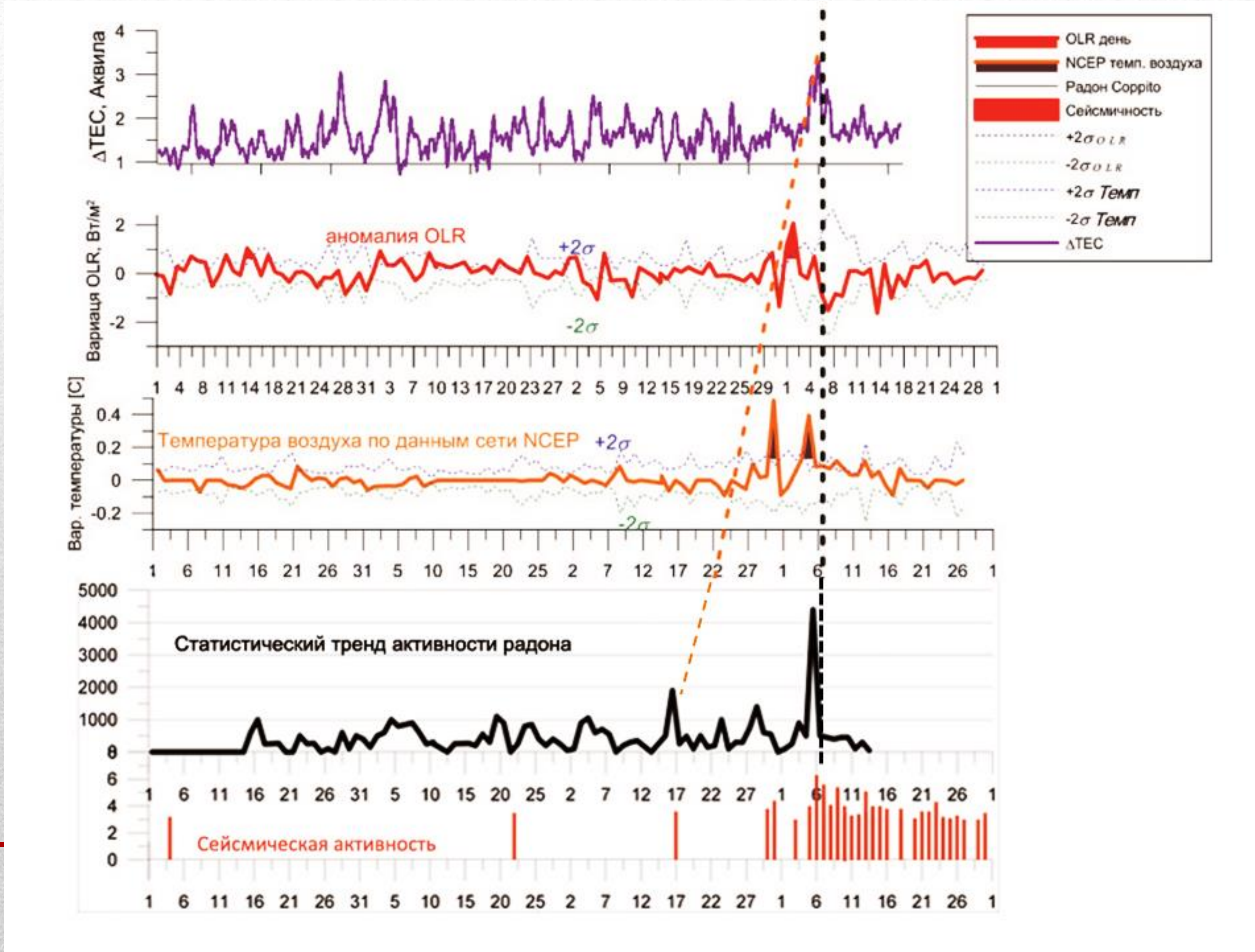
# Time synchronization (Van earthquke, Turkey, 23.10.2011)



# Time arrow

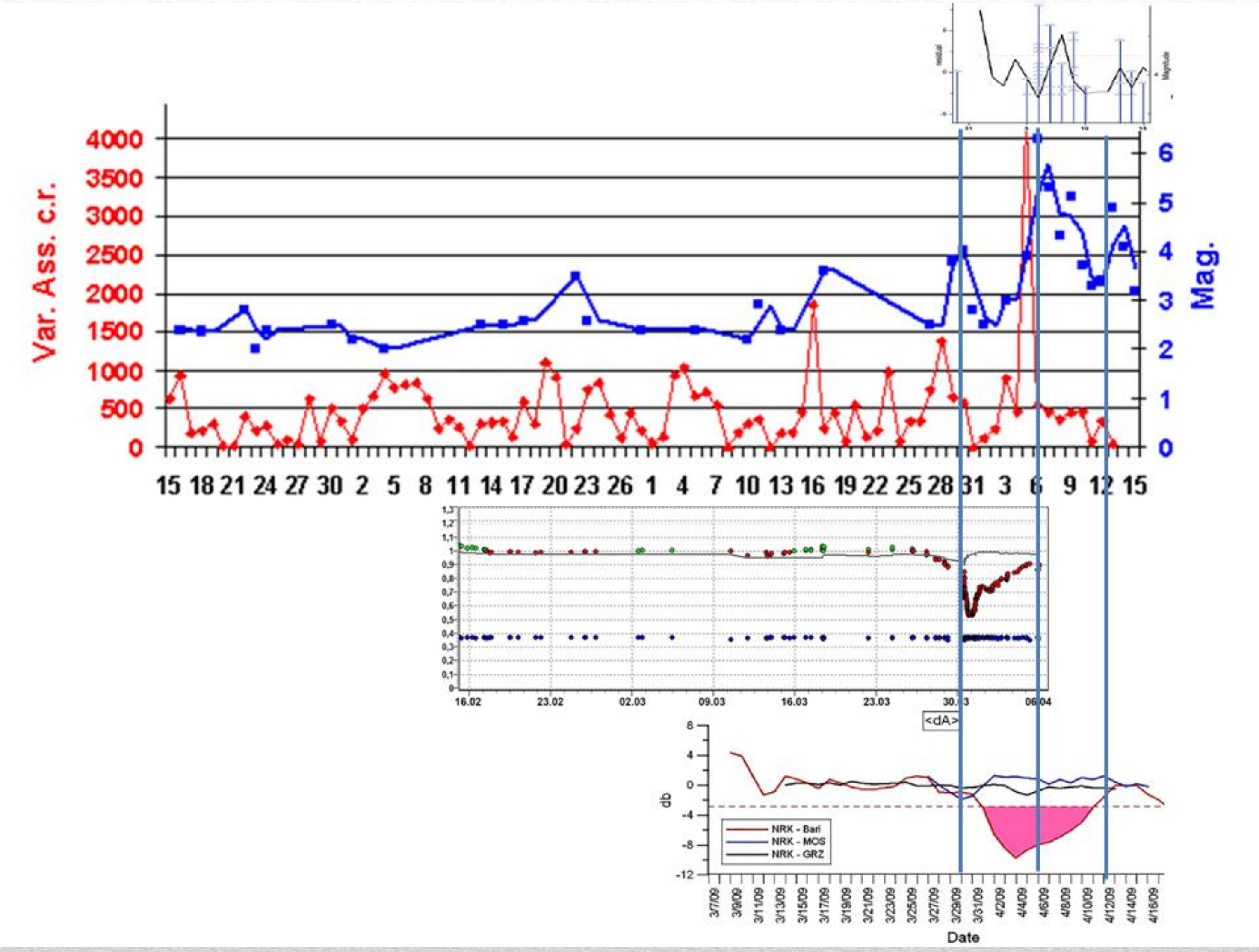

Time
March 31
April 1
April 2
April 3
April 4
April 5
April 6
GPS/TEC
AIRS/CLROL
NOAA/AVHRR
NCEP Surface Temp
M4.8 04/05/2009
M6.3 04/06/2009

# Synergy

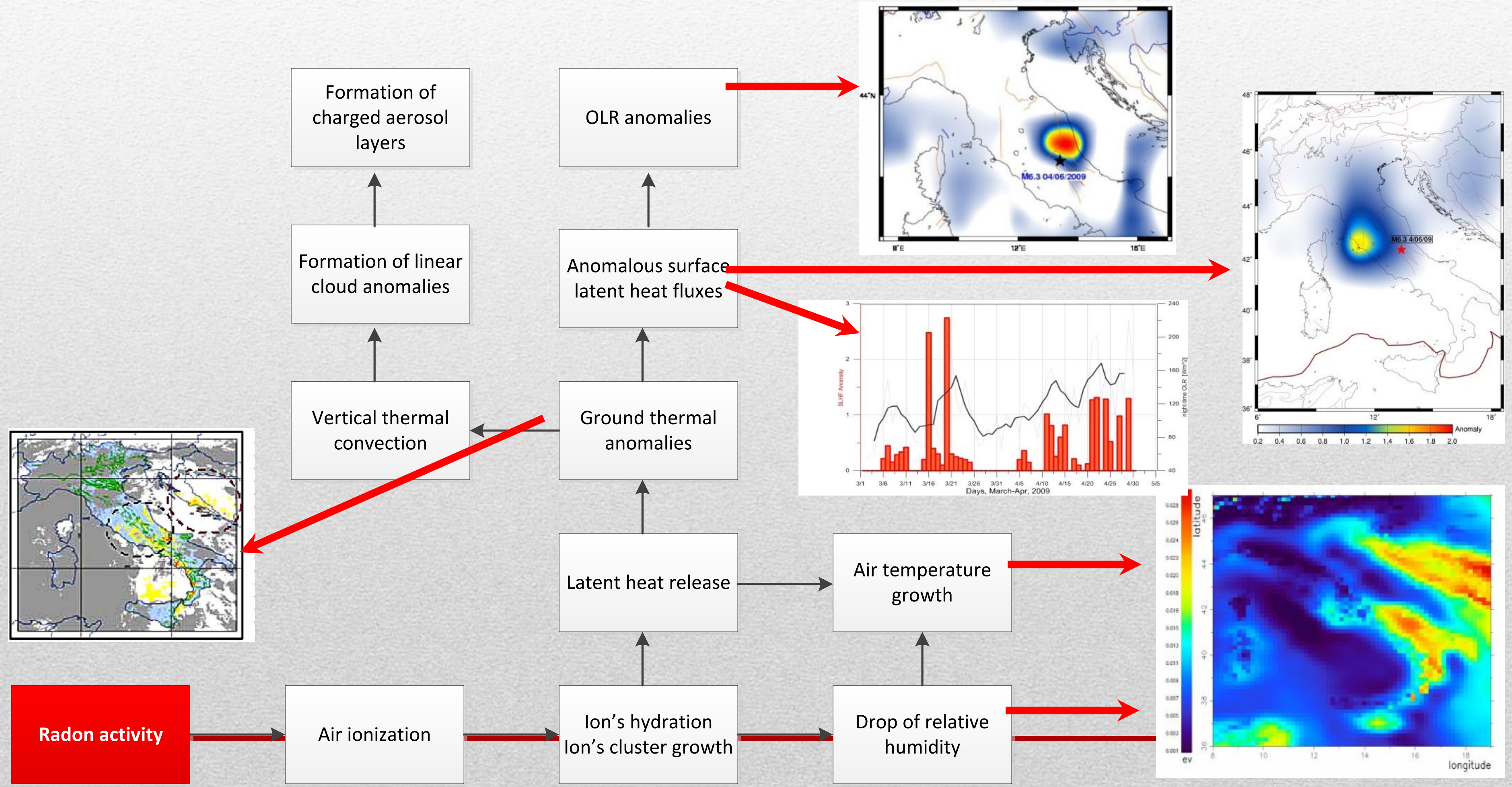


ΔTEC, Аквила
Вариаця OLR, Вт/м²
аномалия OLR
+2σ
-2σ
Вар. температуры [C]
Температура воздуха по данным сети NCEP
Статистический тренд активности радона
Сейсмическая активность
OLR день
NCEP темп. воздуха
Радон Coppito
Сейсмичность
+2σ OLR
-2σ OLR
+2σ Темп
-2σ Темп
ΔTEC

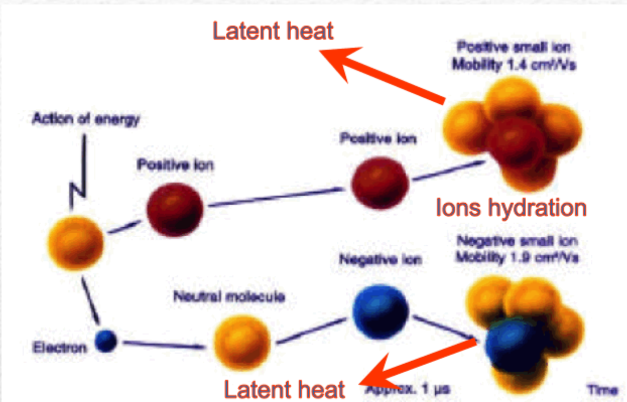
# Connection with seismology

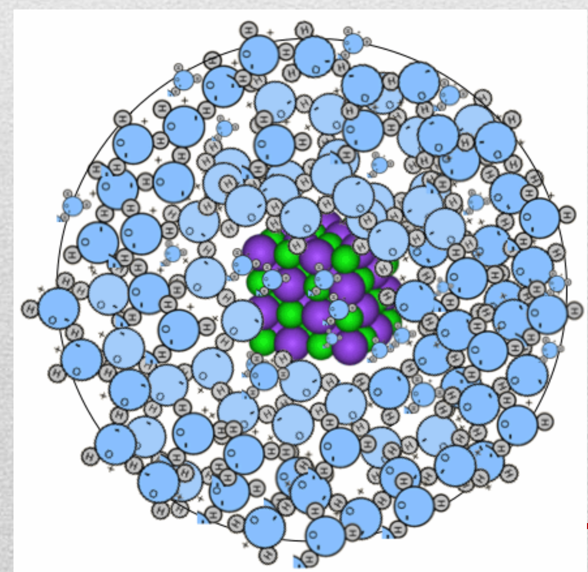


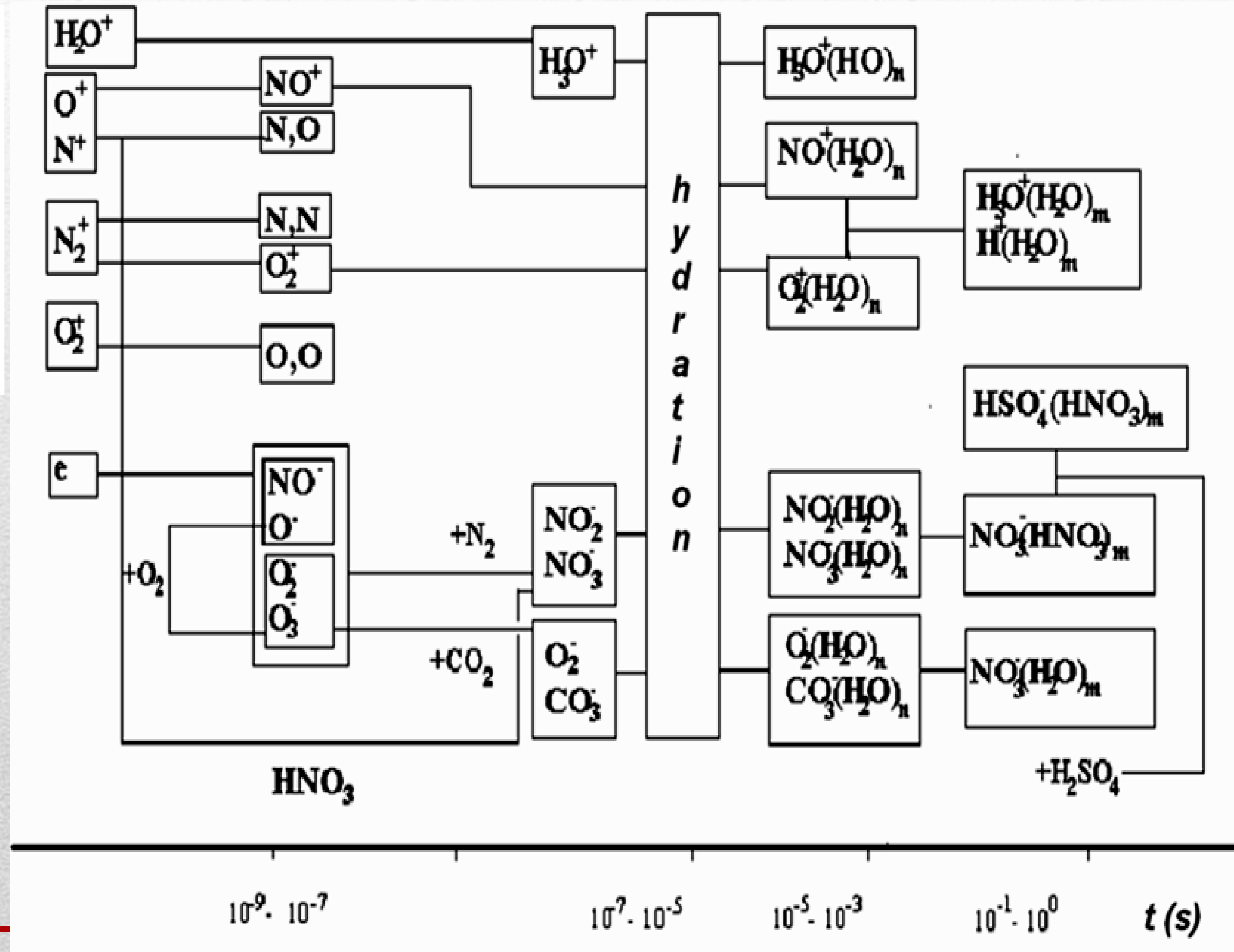
# Plasmachemistry-Thermal interface



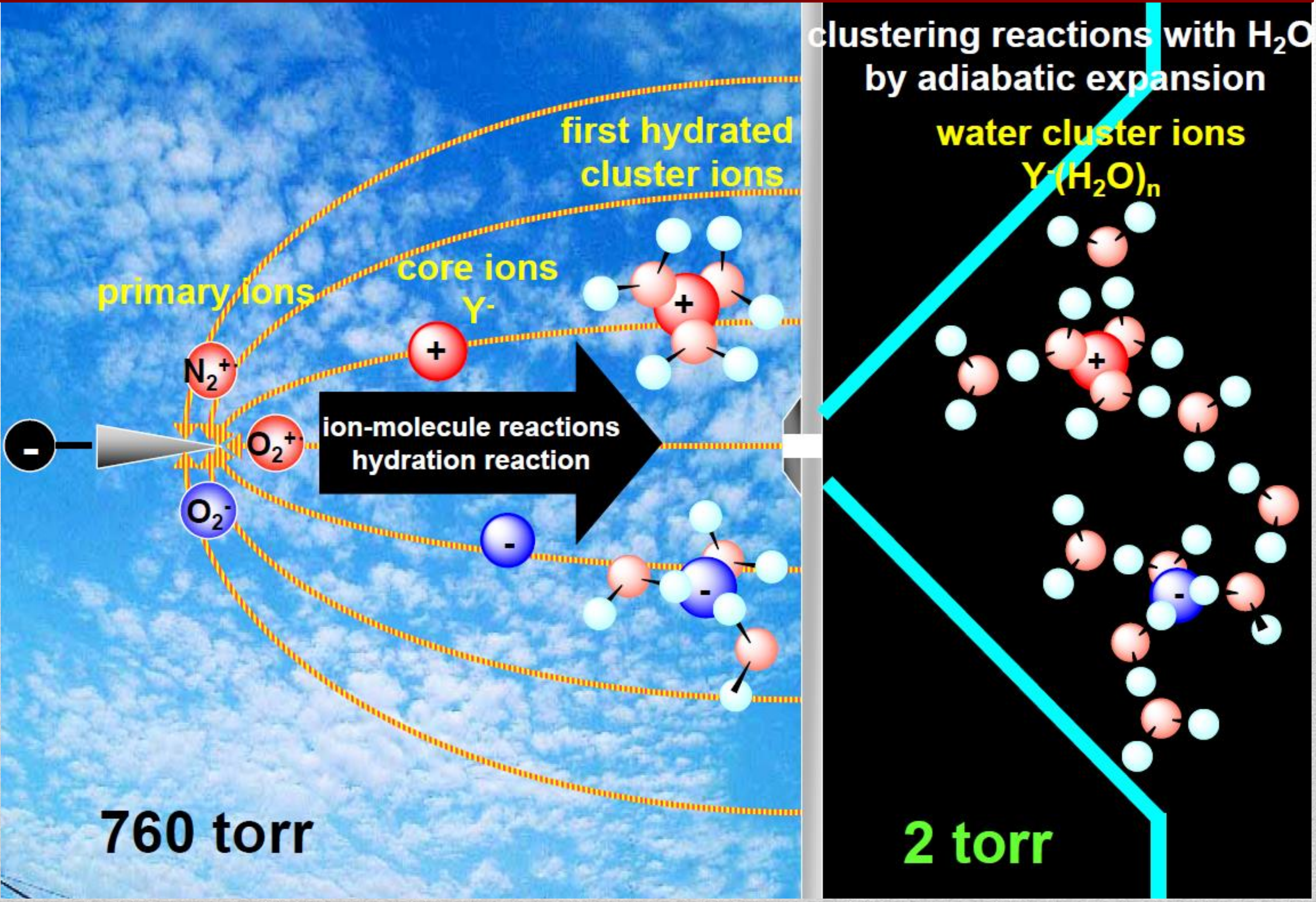
# Ionization, latent heat release and nucleation – (IIN)

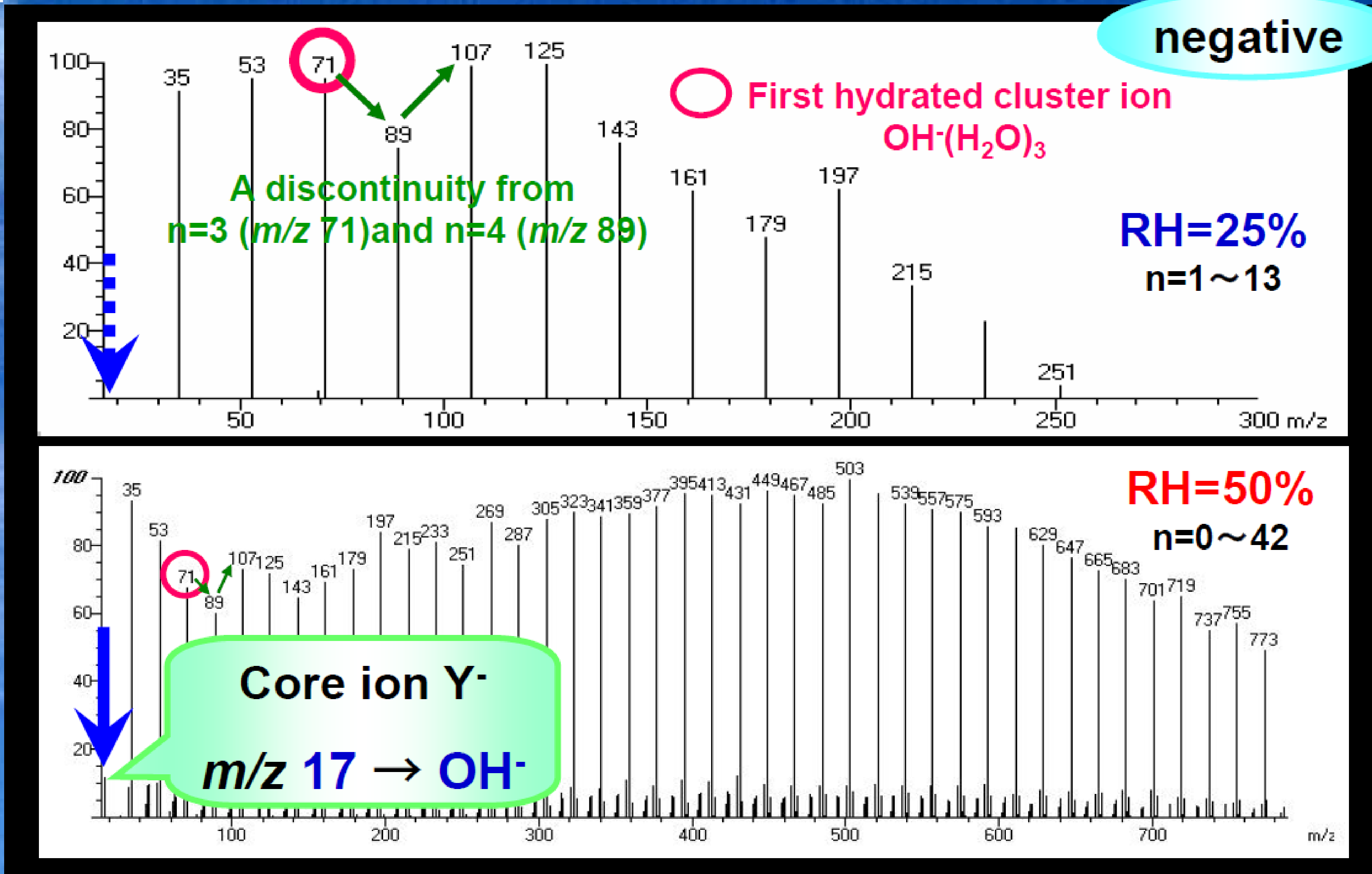


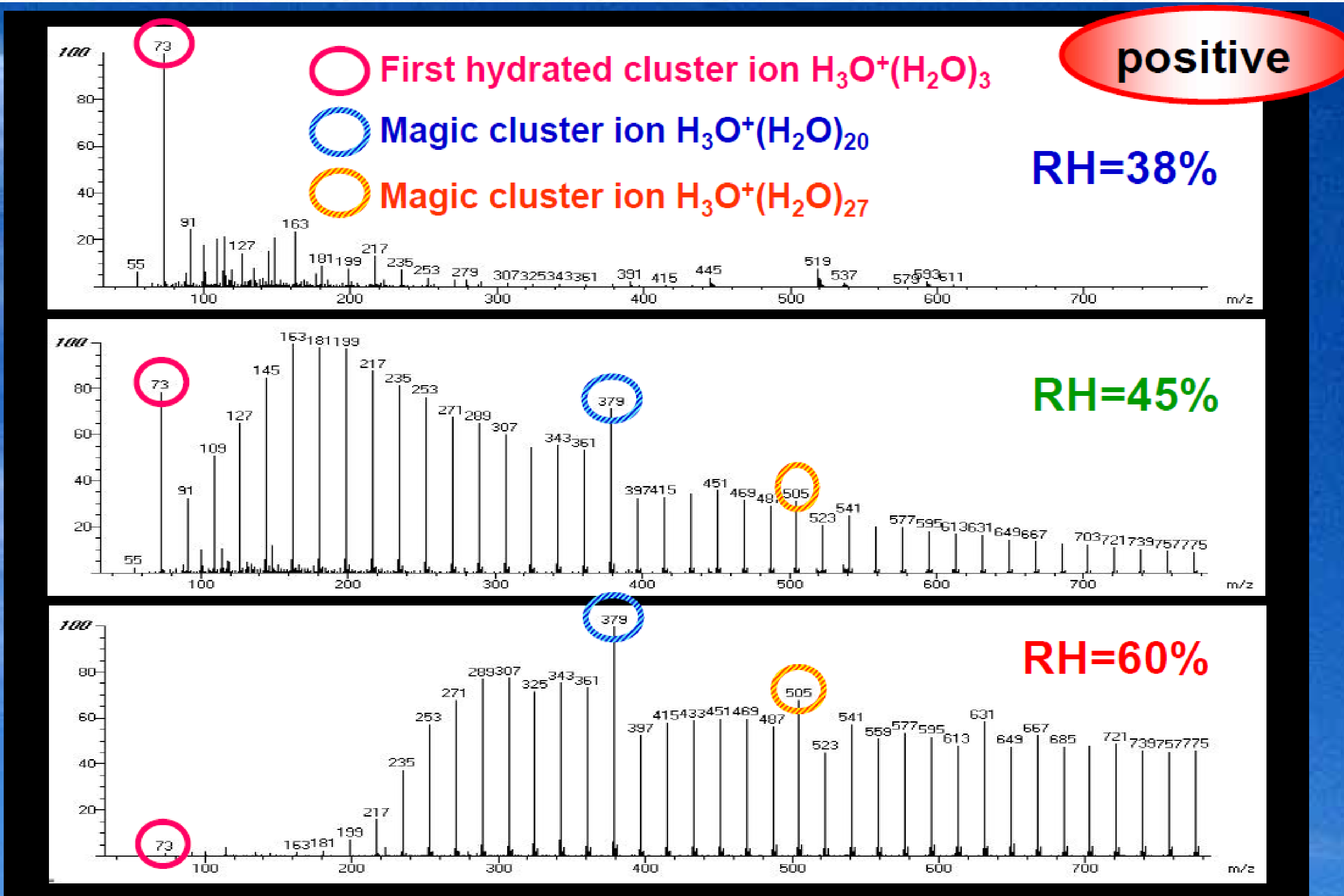


# Cluster ion's formation in the laboratory experiments



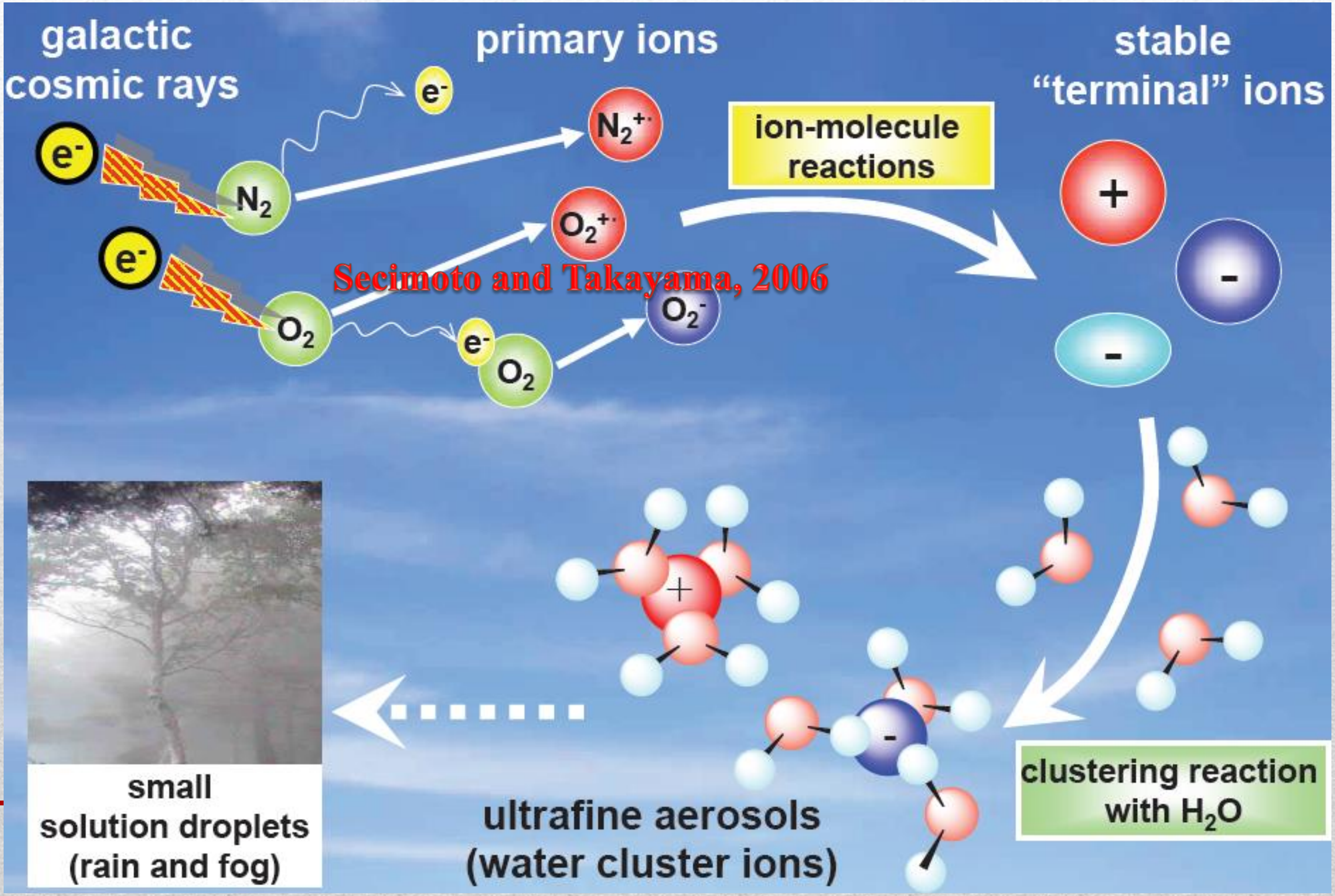



The mass spectra of $OH^-(H_2O)_n$ in ambient air with two different relative humidities at 24℃.



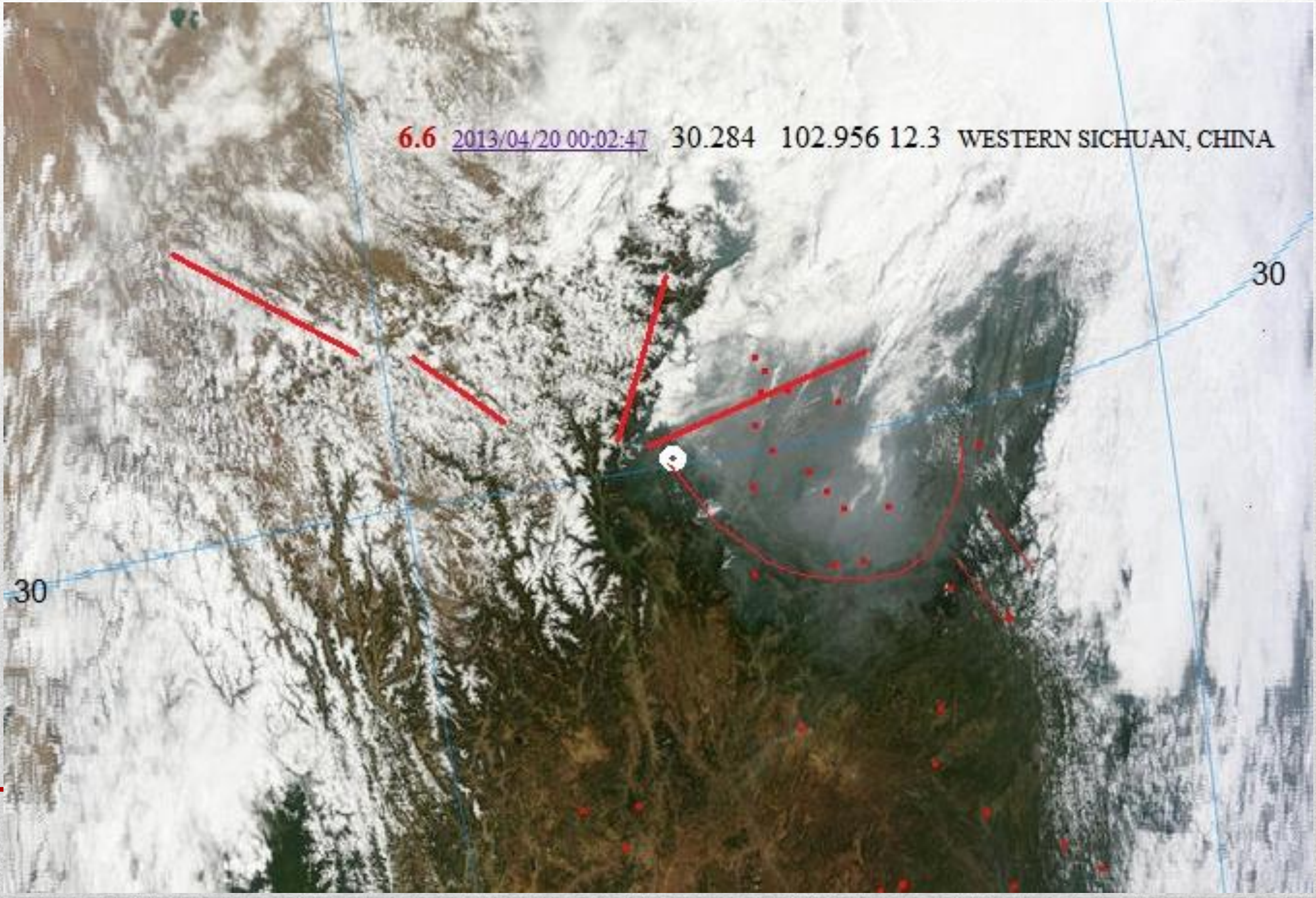

**The mass spectra of $H_3O^+(H_2O)_n$ in ambient air with three different relative humidities at 24℃.**

# Mechanism of cluster ion's formation in the lower troposphere

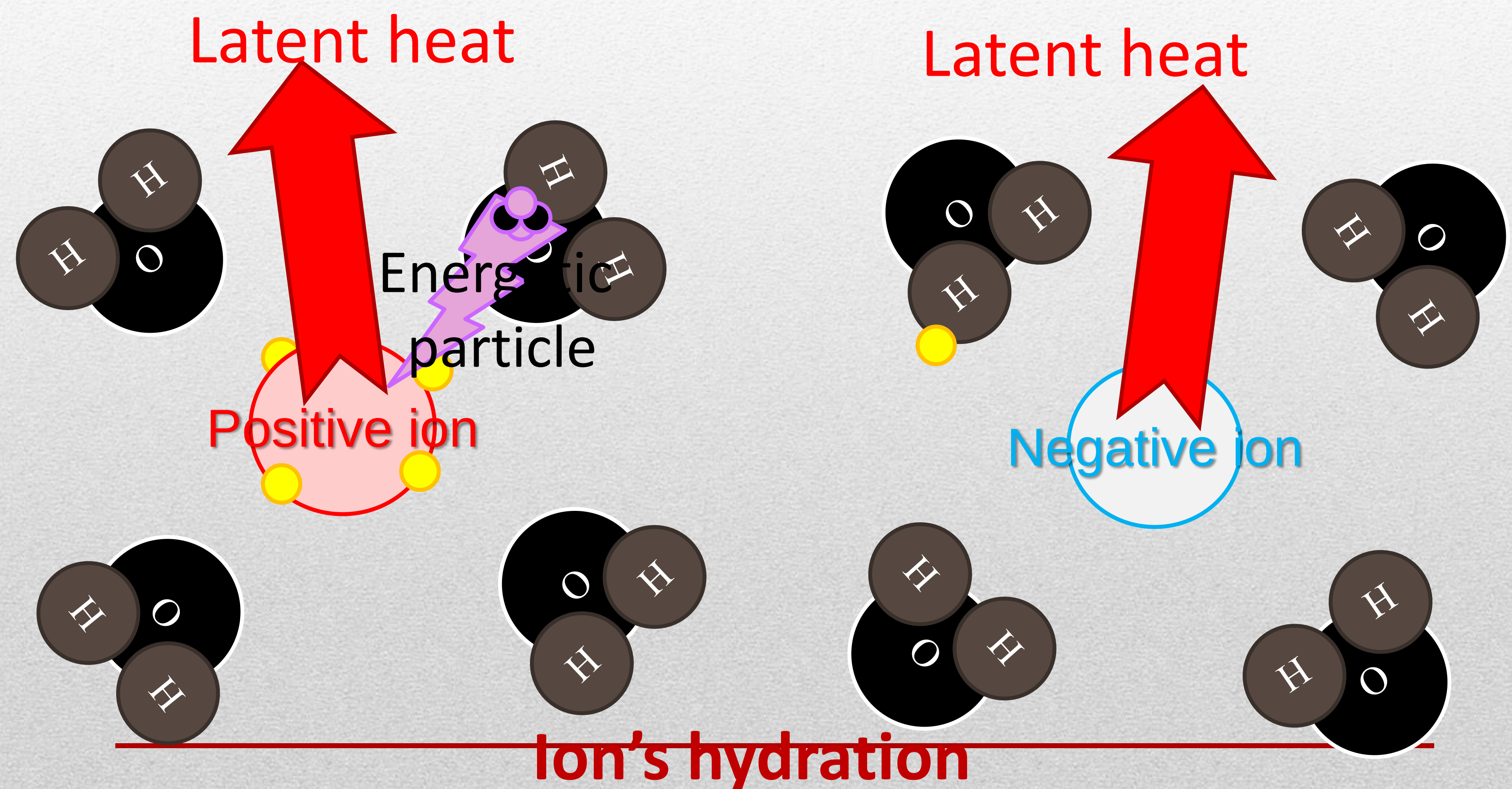


# How it works in nature

Morozova, 2013



# The factor which was not taken into account by previous studies



# Laboratory proof

| Time (hr) | $Rn^{222}$ ($kBq/m^3$) | Temperature °C | Relative Humidity (%) | Absolute Humidity ($g/m^3$) |
|---|---|---|---|---|
| 1 | 0.043 | 20.2 | 28.5 | 5.0 |
| 2 | 0.029 | 20.2 | 75 | 13.2 |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 4 | 6.144 | 20.6 | 71.5 | 12.9 |
| 5 | 6.144 | 20.6 | 70.5 | 12.7 |
| 6 | 5.696 | 20.6 | 70.5 | 12.7 |
| 7 | 5.792 | 20.6 | 68.7 | 12.4 |

**More than 5000 J were released**

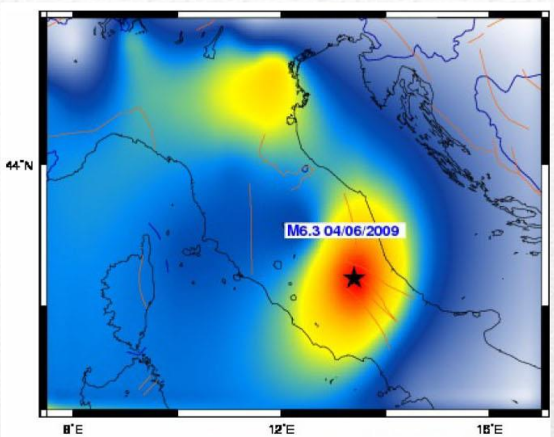
Drop in absolute humidity = 0.8 ($g/m^3$)

Specific Latent heat 2256 J/g

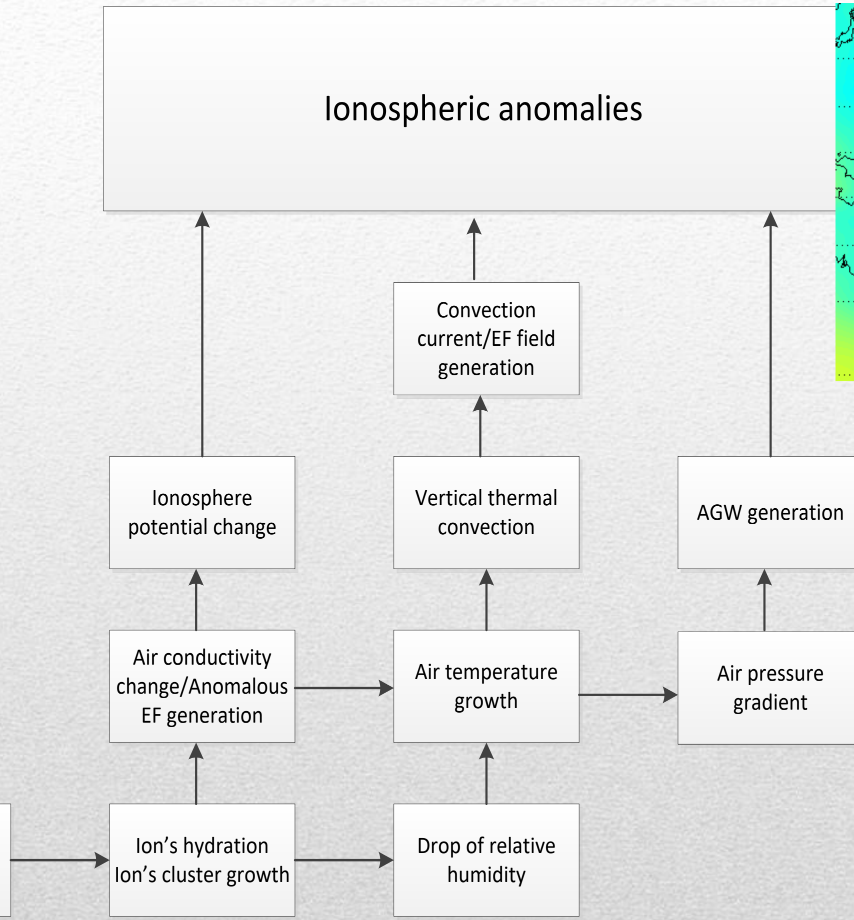
Expected temperature rise = 0,34 (°C)

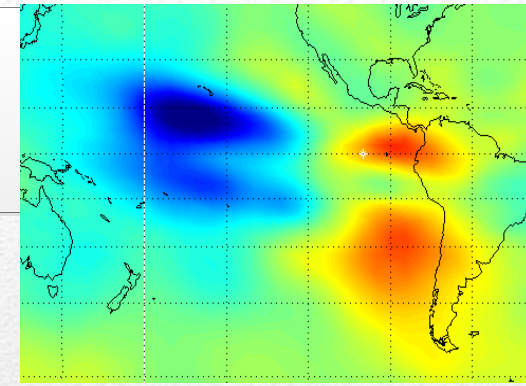
Observed temperture rise = 0.4 (°C)

# Plasmachemistry-Electromagnetic interface

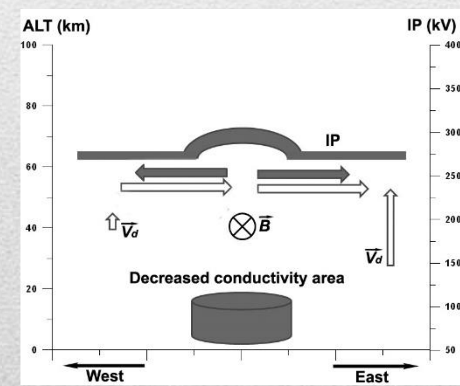



**ΔTEC anomaly L'Aquila 2009**



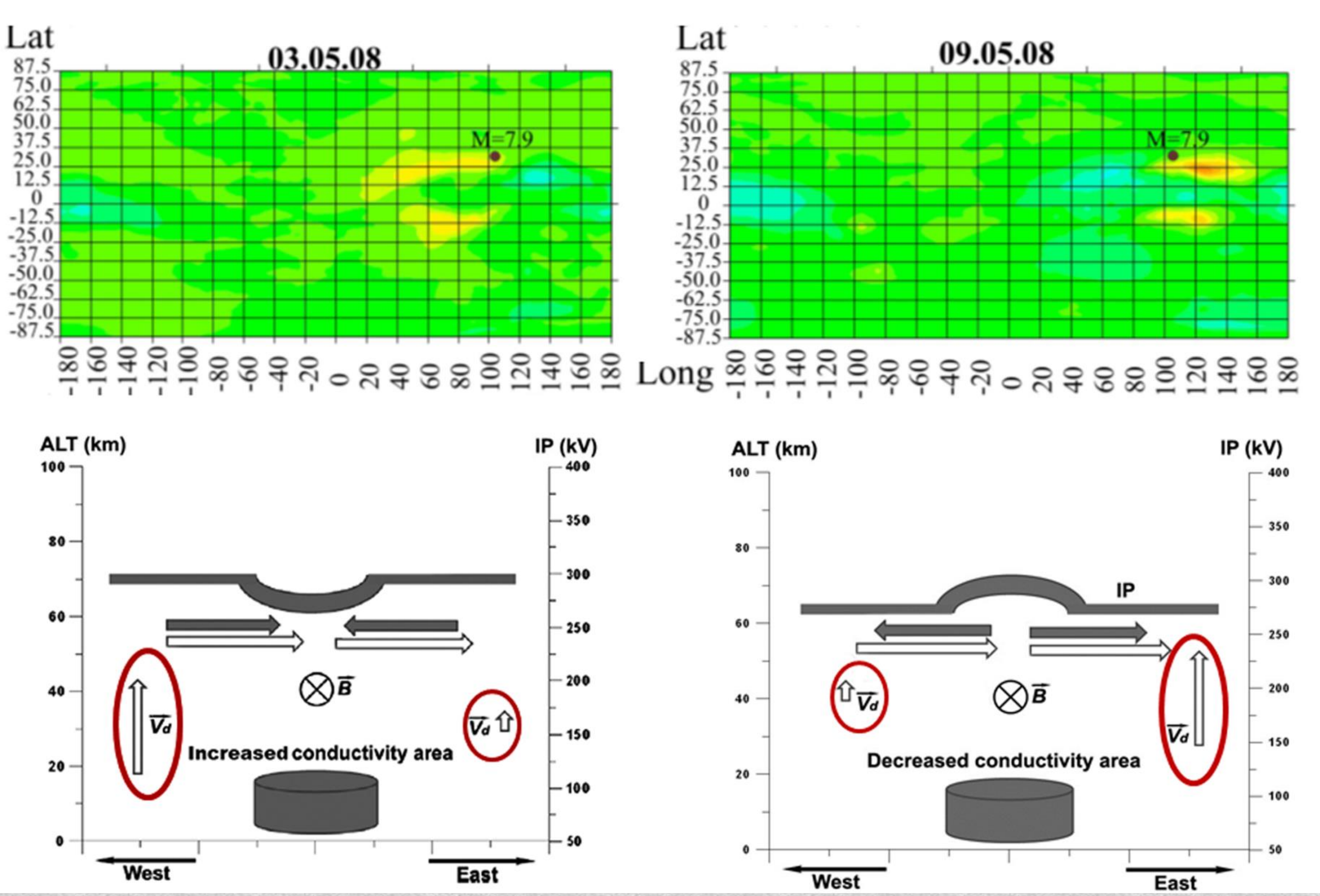



**ΔTEC GIM Central America EQ**

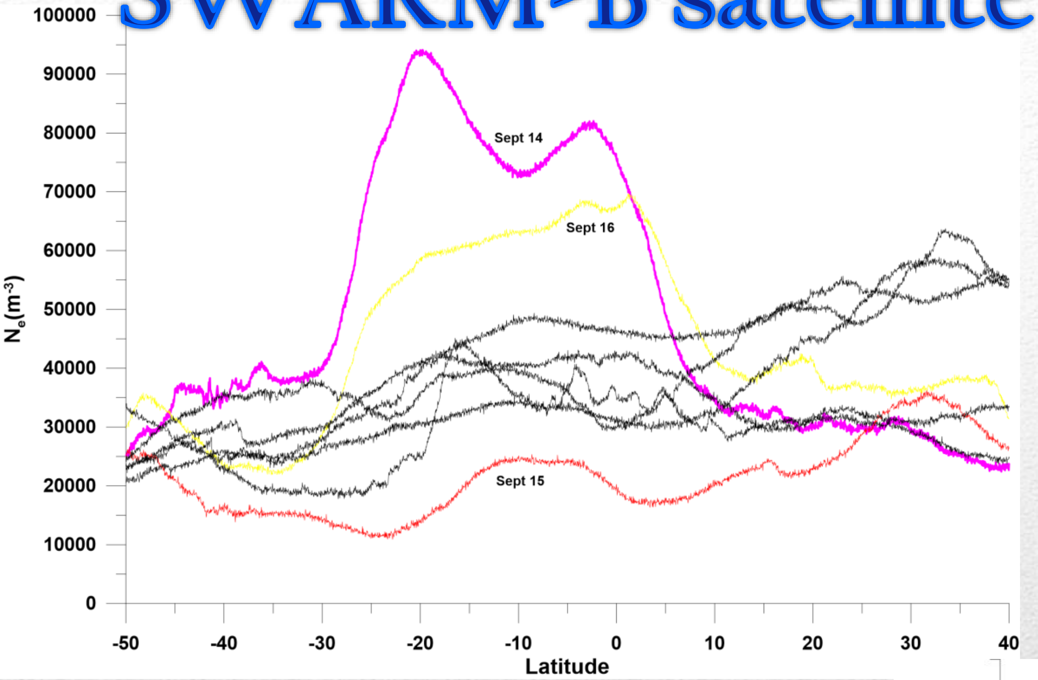


# Boundary layer conductivity effect on the ionosphere

Pulinets and Davidenko, 2014

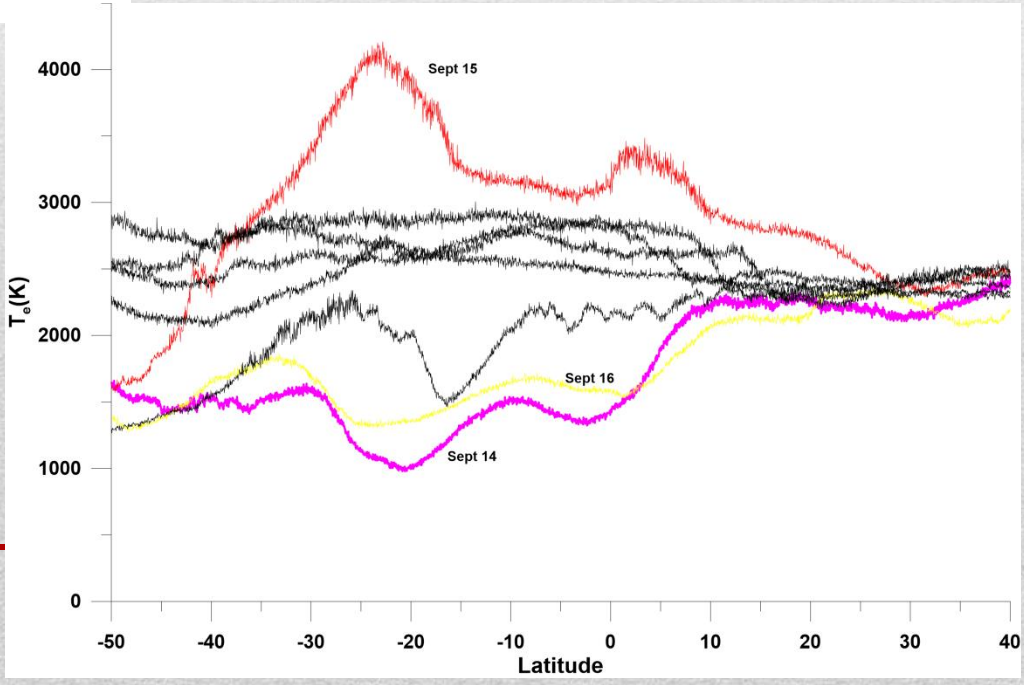


# SWARM-B satellite

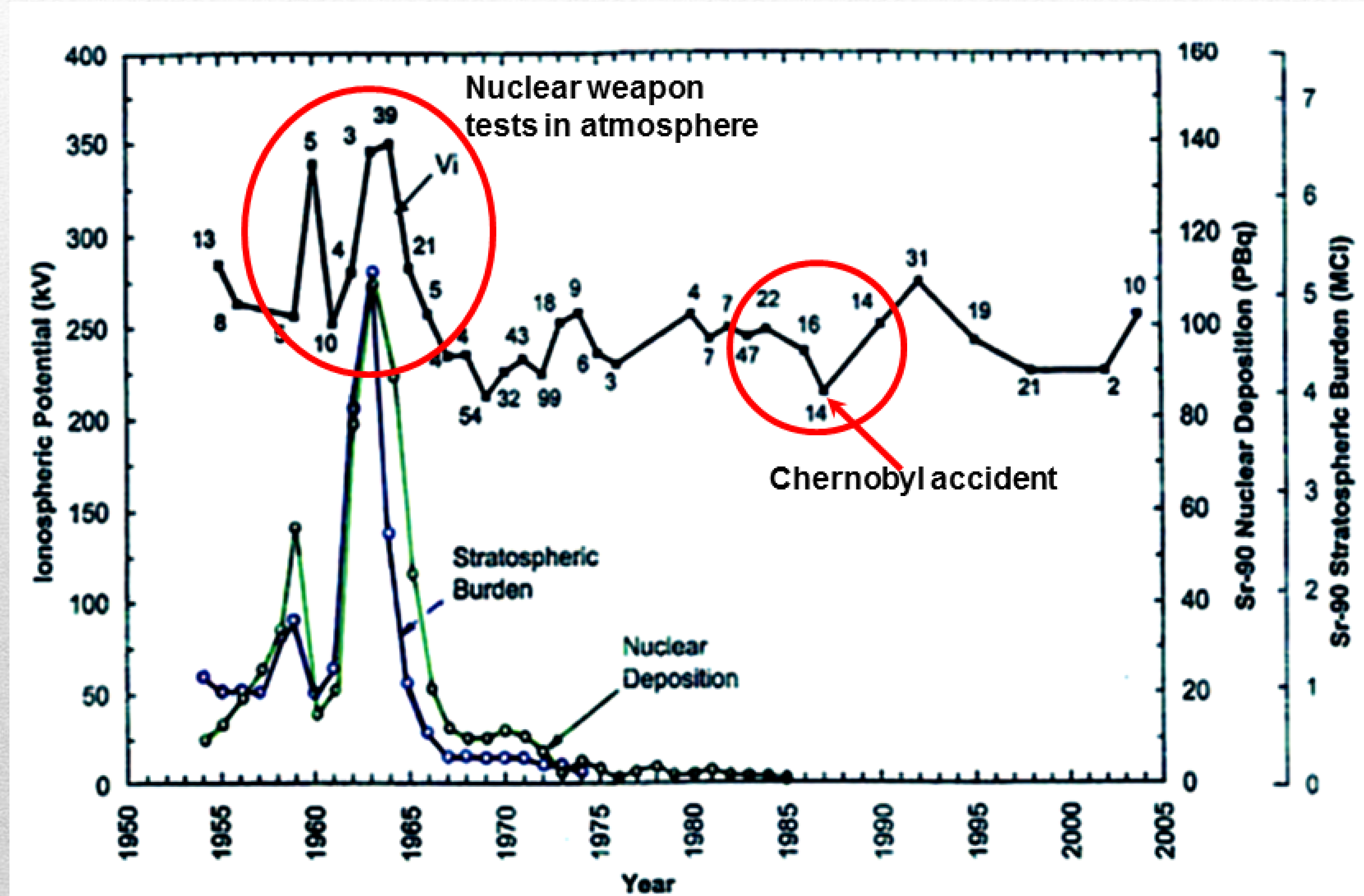



Electron concentration

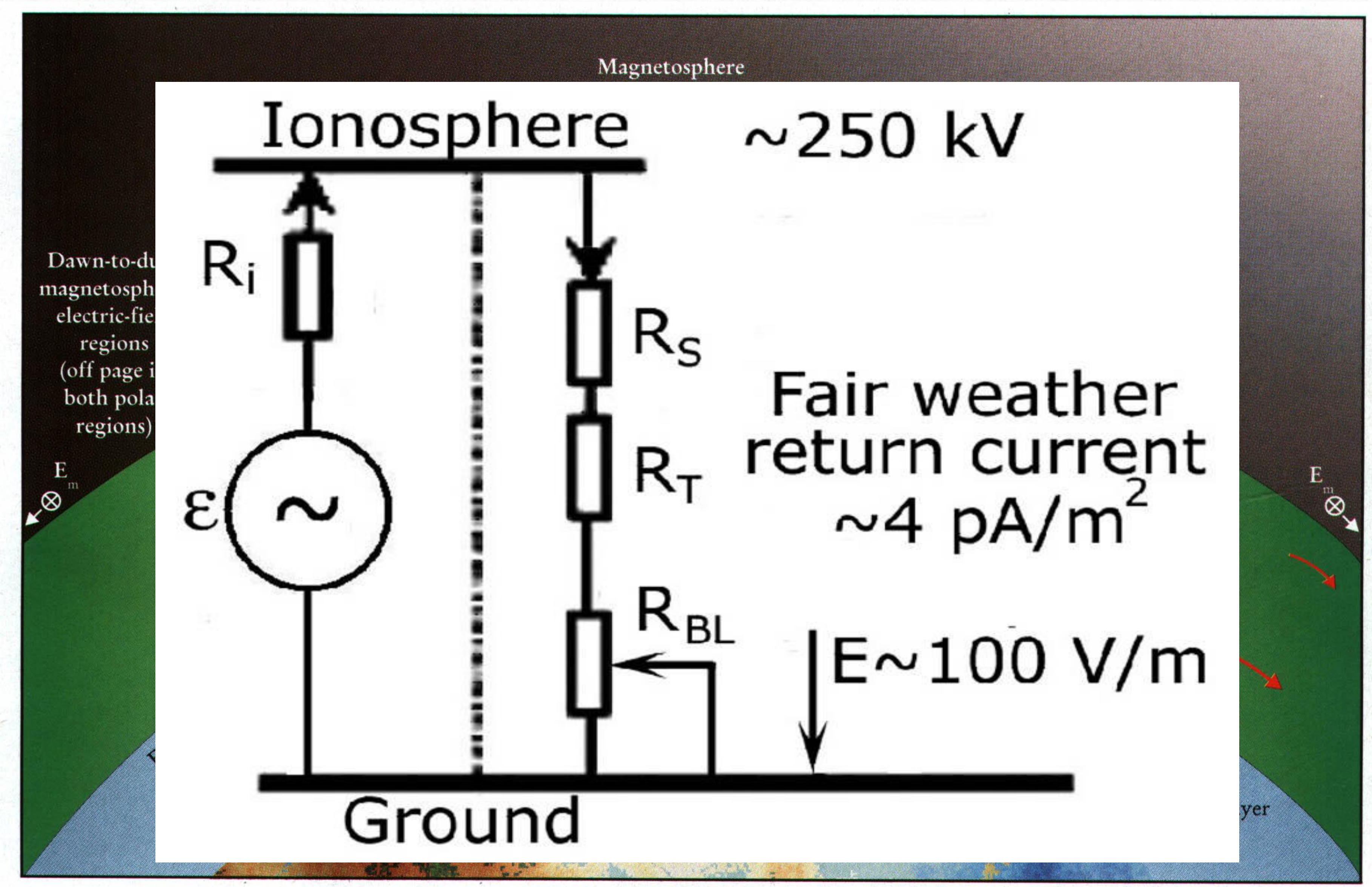
Electron temperature



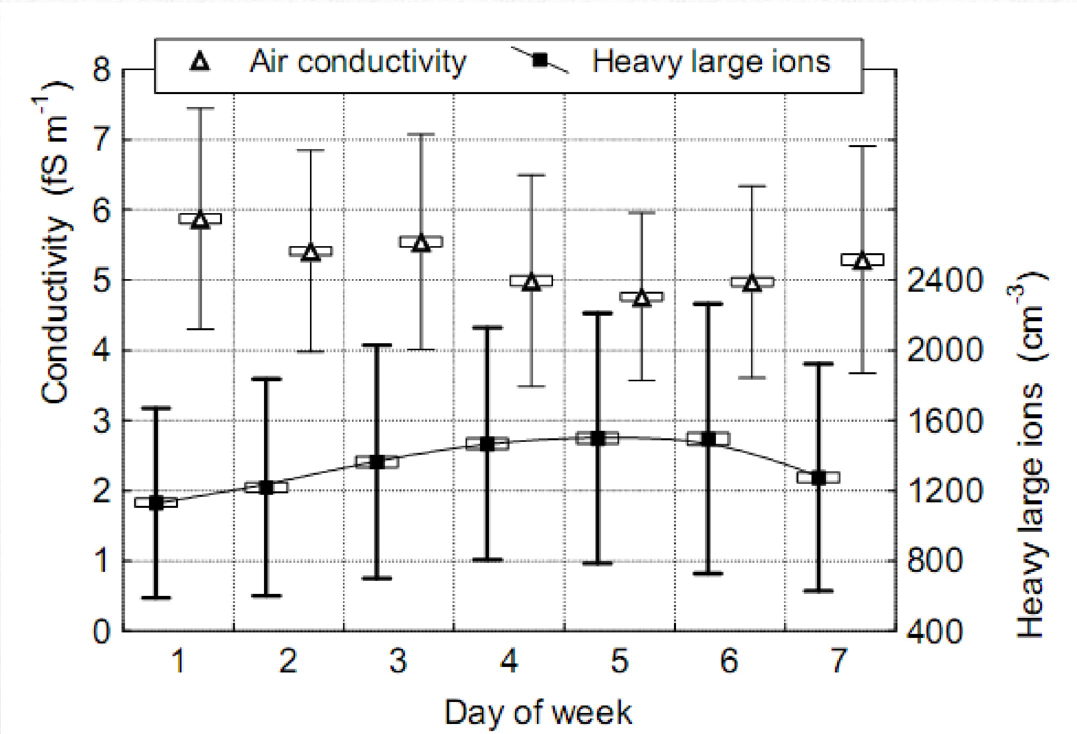
# Ionospheric potential changes during period of nuclear weapon tests in atmosphere

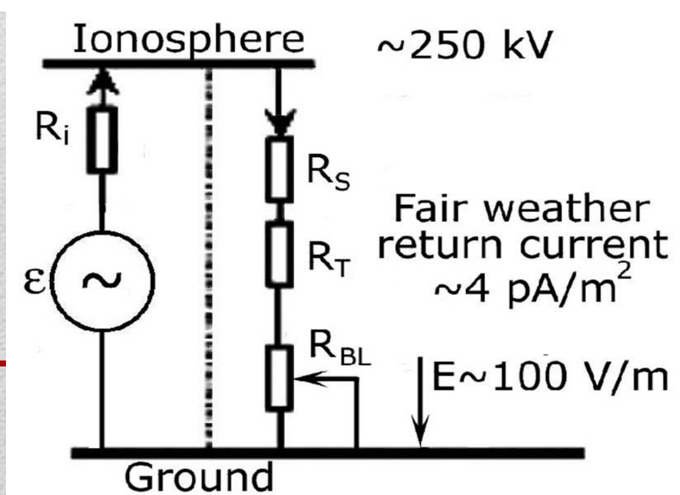


# Clobal Electric Circuit concept



# Aerosols and atmosphere conductivity




| Analyzer | Fraction | Mobility $cm^2 V^{-1} s^{-1}$ | Diameter nm |
|---|---|---|---|
| | *Small Cluster Ions* | | |
| $IS_1$ | $N_1/P_1$ | 2.51–3.14 | 0.36–0.45 |
| $IS_1$ | $N_2/P_2$ | 2.01–2.51 | 0.45–0.56 |
| $IS_1$ | $N_3/P_3$ | 1.60–2.01 | 0.56–0.70 |
| $IS_1$ | $N_4/P_4$ | 1.28–1.60 | 0.70–0.85 |
| | *Big Cluster Ions* | | |
| $IS_1$ | $N_5/P_5$ | 1.02–1.28 | 0.85–1.03 |
| $IS_1$ | $N_6/P_6$ | 0.79–1.02 | 1.03–1.24 |
| $IS_1$ | $N_7/P_7$ | 0.63–0.79 | 1.24–1.42 |
| $IS_1$ | $N_8/P_8$ | 0.50–0.63 | 1.42–1.60 |
| | *Intermediate Ions* | | |
| $IS_1$ | $N_9/P_9$ | 0.40–0.50 | 1.6–1.8 |
| $IS_1$ | $N_{10}/P_{10}$ | 0.32–0.40 | 1.8–2.0 |
| $IS_1$ | $N_{11}/P_{11}$ | 0.25–0.32 | 2.0–2.3 |
| $IS_2$ | $N_{12}/P_{12}$ | 0.150–0.293 | 2.1–3.2 |
| $IS_2$ | $N_{13}/P_{13}$ | 0.074–0.150 | 3.2–4.8 |
| $IS_2$ | $N_{14}/P_{14}$ | 0.034–0.074 | 4.8–7.4 |
| | *Light Large Ions* | | |
| $IS_2$ | $N_{15}/P_{15}$ | 0.016–0.034 | 7.4–11.0 |
| $IS_3$ | $N_{16}/P_{16}$ | 0.0091–0.0205 | 9.7–14.8 |
| $IS_3$ | $N_{17}/P_{17}$ | 0.0042–0.0091 | 15–22 |
| | *Heavy Large Ions* | | |
| $IS_3$ | $N_{18}/P_{18}$ | 0.00192–0.00420 | 22–34 |
| $IS_3$ | $N_{19}/P_{19}$ | 0.00087–0.00192 | 34–52 |
| $IS_3$ | $N_{20}/P_{20}$ | 0.00041–0.00087 | 52–79 |

# Ion's mobility and atmosphere conductivity

$$i = e\left(n^+\mu^+ + n^-\mu^-\right)E = \sigma E$$

$$\sigma = e\left(n^+\mu^+ + n^-\mu^-\right)$$

$$\sigma = e\sum_{i=1}^{n}\left(n_i^+\mu_i^+ + n_i^-\mu_i^-\right)$$

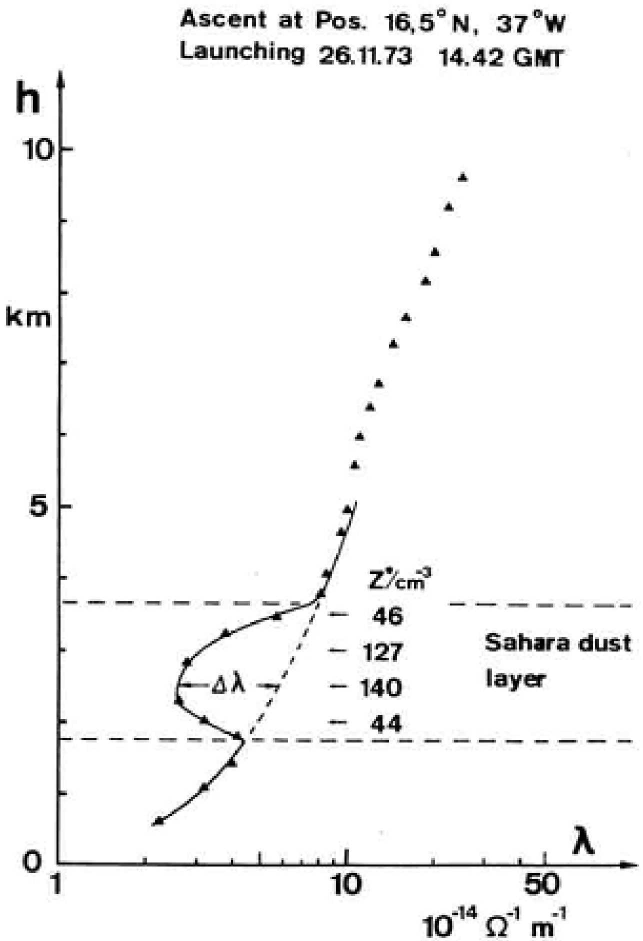
| Analyzer | Fraction | Mobility $cm^2 V^{-1} s^{-1}$ | Diameter nm |
|---|---|---|---|
| | | *Small Cluster Ions* | |
| $IS_1$ | $N_1/P_1$ | 2.51–3.14 | 0.36–0.45 |
| $IS_1$ | $N_2/P_2$ | 2.01–2.51 | 0.45–0.56 |
| $IS_1$ | $N_3/P_3$ | 1.60–2.01 | 0.56–0.70 |
| $IS_1$ | $N_4/P_4$ | 1.28–1.60 | 0.70–0.85 |
| | | *Big Cluster Ions* | |
| $IS_1$ | $N_5/P_5$ | 1.02–1.28 | 0.85–1.03 |
| $IS_1$ | $N_6/P_6$ | 0.79–1.02 | 1.03–1.24 |
| $IS_1$ | $N_7/P_7$ | 0.63–0.79 | 1.24–1.42 |
| $IS_1$ | $N_8/P_8$ | 0.50–0.63 | 1.42–1.60 |
| | | *Intermediate Ions* | |
| $IS_1$ | $N_9/P_9$ | 0.40–0.50 | 1.6–1.8 |
| $IS_1$ | $N_{10}/P_{10}$ | 0.32–0.40 | 1.8–2.0 |
| $IS_1$ | $N_{11}/P_{11}$ | 0.25–0.32 | 2.0–2.3 |
| $IS_2$ | $N_{12}/P_{12}$ | 0.150–0.293 | 2.1–3.2 |
| $IS_2$ | $N_{13}/P_{13}$ | 0.074–0.150 | 3.2–4.8 |
| $IS_2$ | $N_{14}/P_{14}$ | 0.034–0.074 | 4.8–7.4 |
| | | *Light Large Ions* | |
| $IS_2$ | $N_{15}/P_{15}$ | 0.016–0.034 | 7.4–11.0 |
| $IS_3$ | $N_{16}/P_{16}$ | 0.0091–0.0205 | 9.7–14.8 |
| $IS_3$ | $N_{17}/P_{17}$ | 0.0042–0.0091 | 15–22 |
| | | *Heavy Large Ions* | |
| $IS_3$ | $N_{18}/P_{18}$ | 0.00192–0.00420 | 22–34 |
| $IS_3$ | $N_{19}/P_{19}$ | 0.00087–0.00192 | 34–52 |
| $IS_3$ | $N_{20}/P_{20}$ | 0.00041–0.00087 | 52–79 |

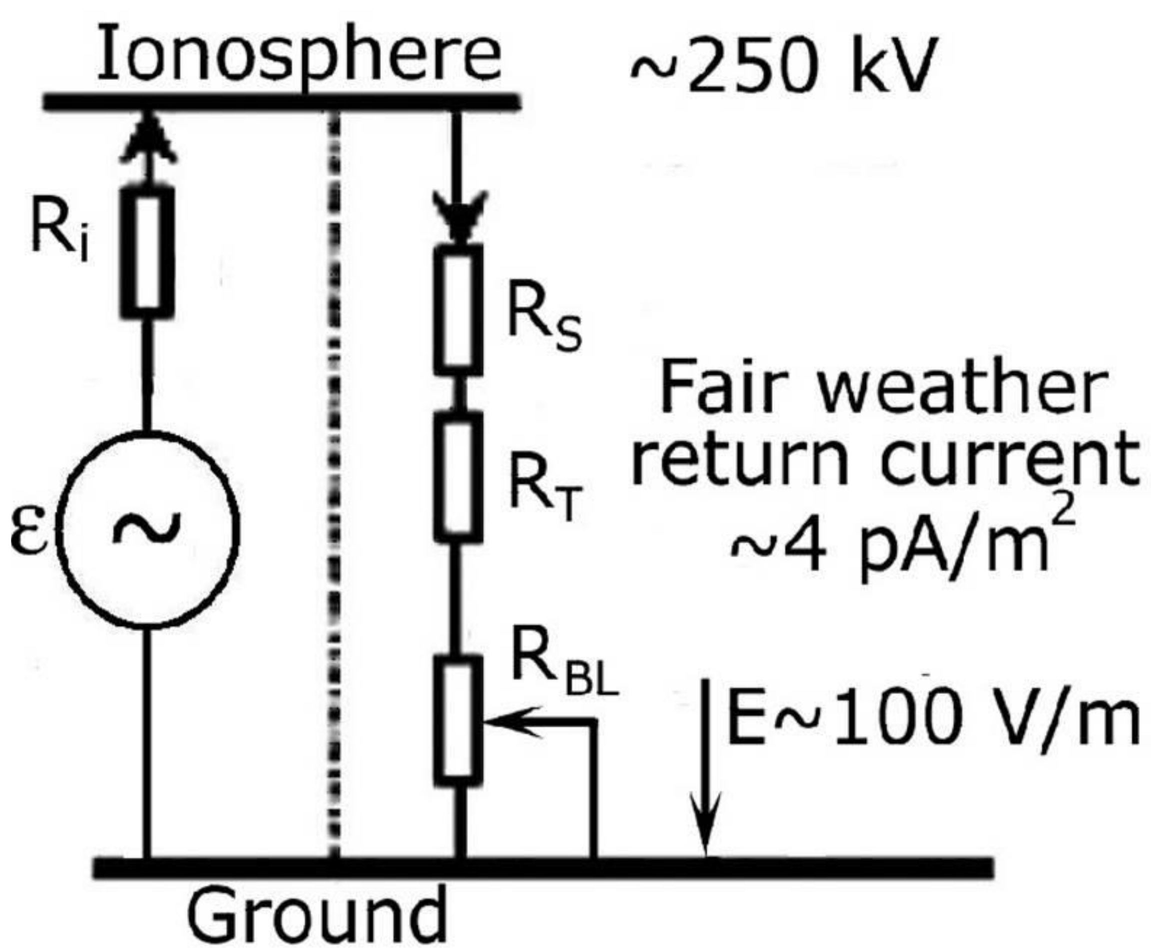
# Key parameters

- Ion production rate $q_{i0} \approx 10^7$ - $10^{10}$ $m^{-3}s^{-1}$
- Ion's concentration $n_i \approx 10^5$ - $10^8$ $sm^{-3}$
- Nucleus size 1 - 3 μm
- Ion's mobility:

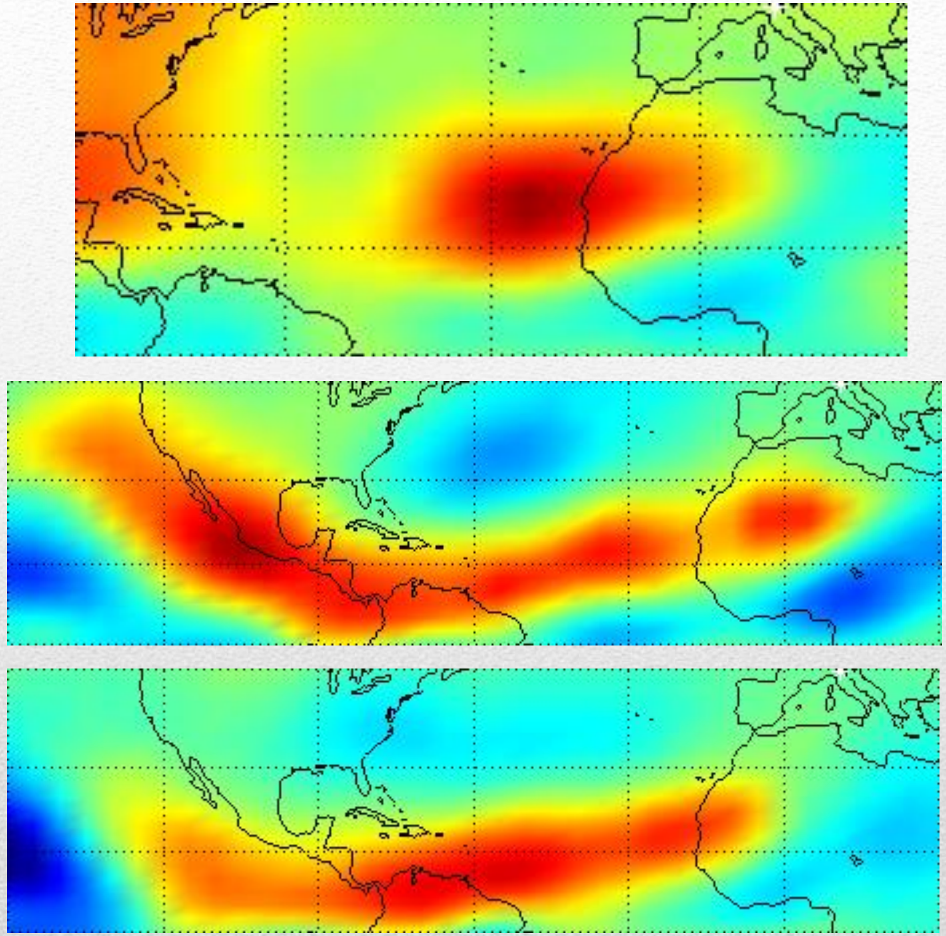
$\frac{n_{LI}}{n_{HI}} \square\ 1$ air conductivity increase

$\frac{n_{LI}}{n_{HI}} \square\ 1$ air conductivity decrease



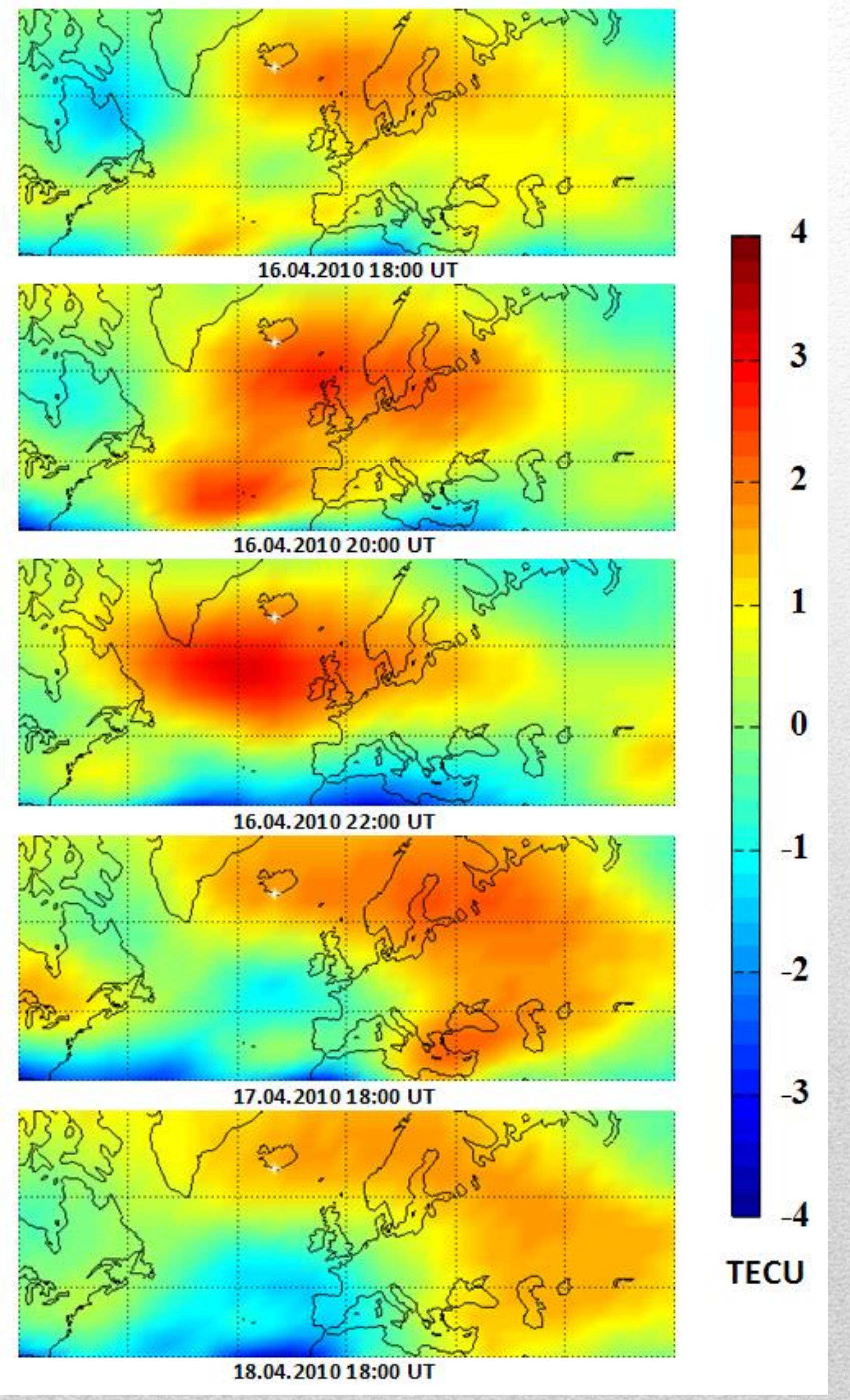




# Changes of conductivity of the boundary layer of atmosphere during sand storms

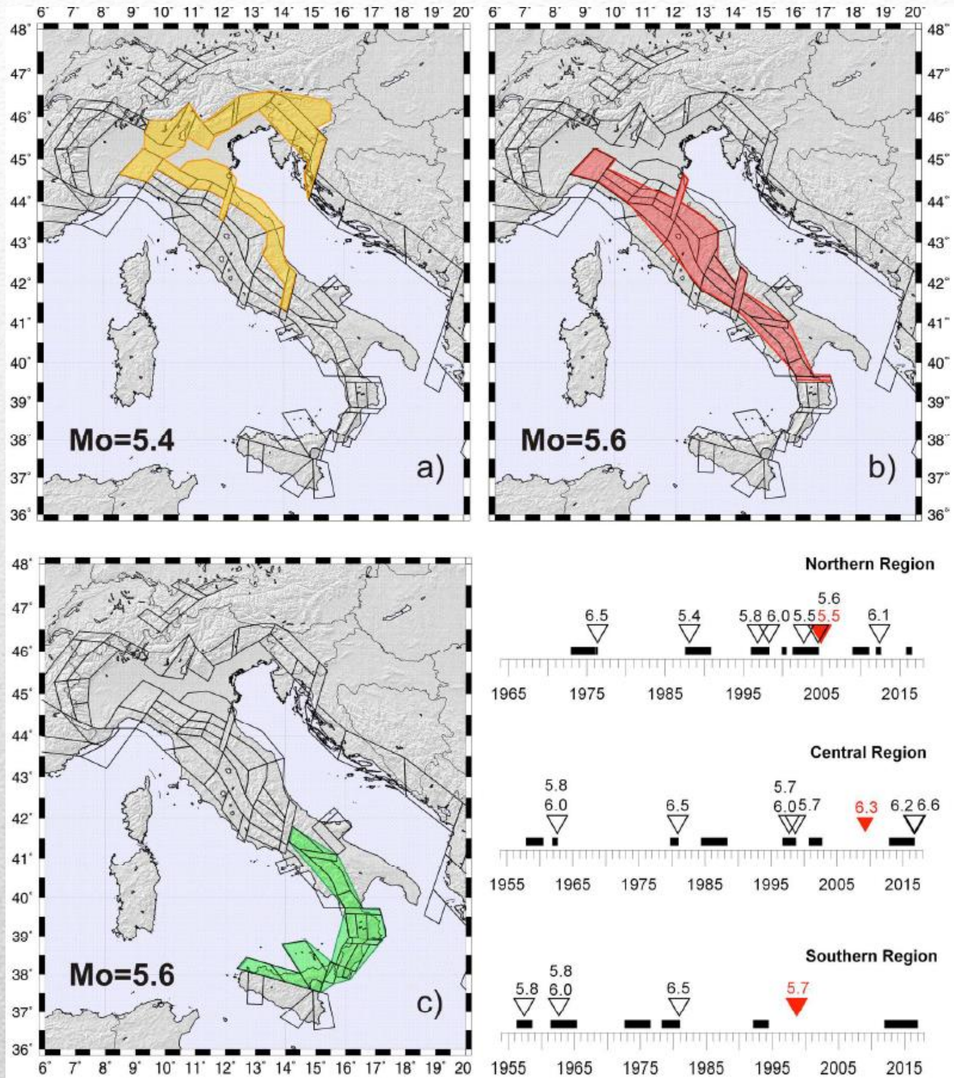


# Ionospheric effect of Aug 12-13/2012 sand storms

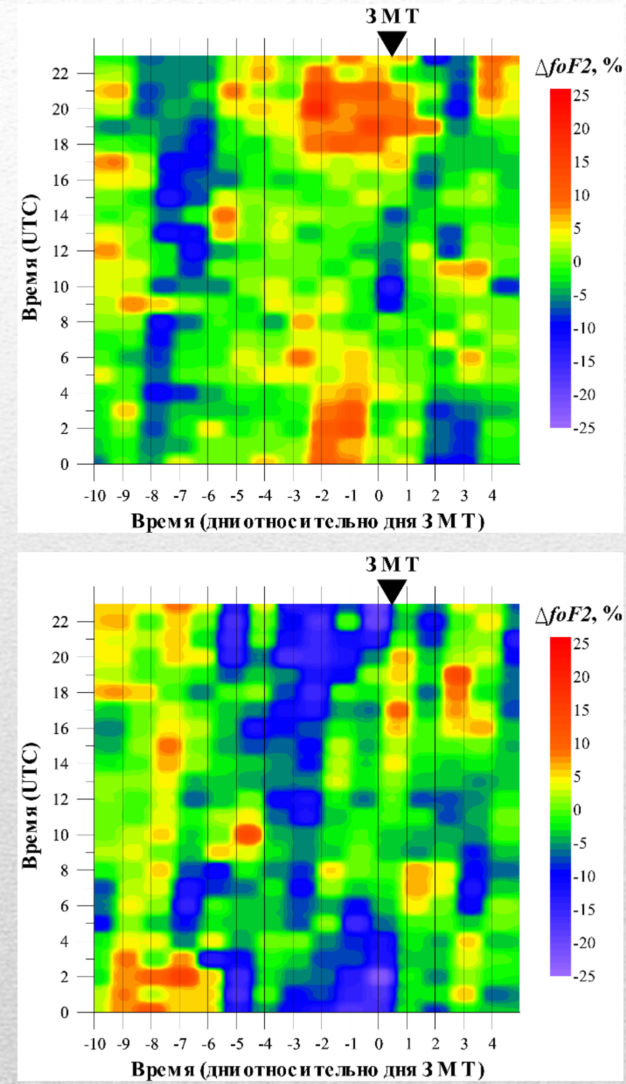
# Ионосферный эффект извержения вулкана в Исландии в 2010 г.



# Connection with tectonics

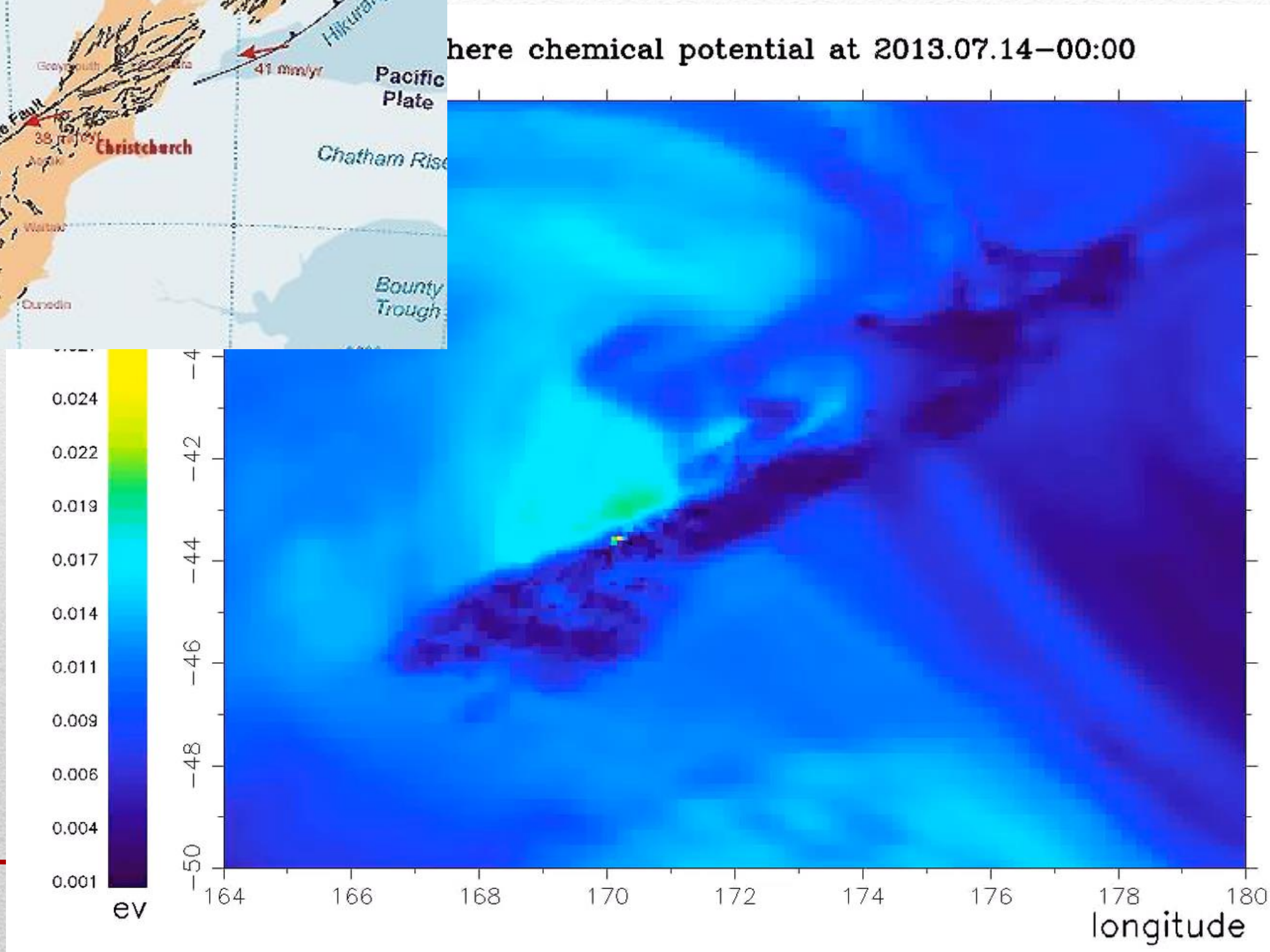



Regionalization for the application of CN algorithm in Italy (Peresan, 2018)



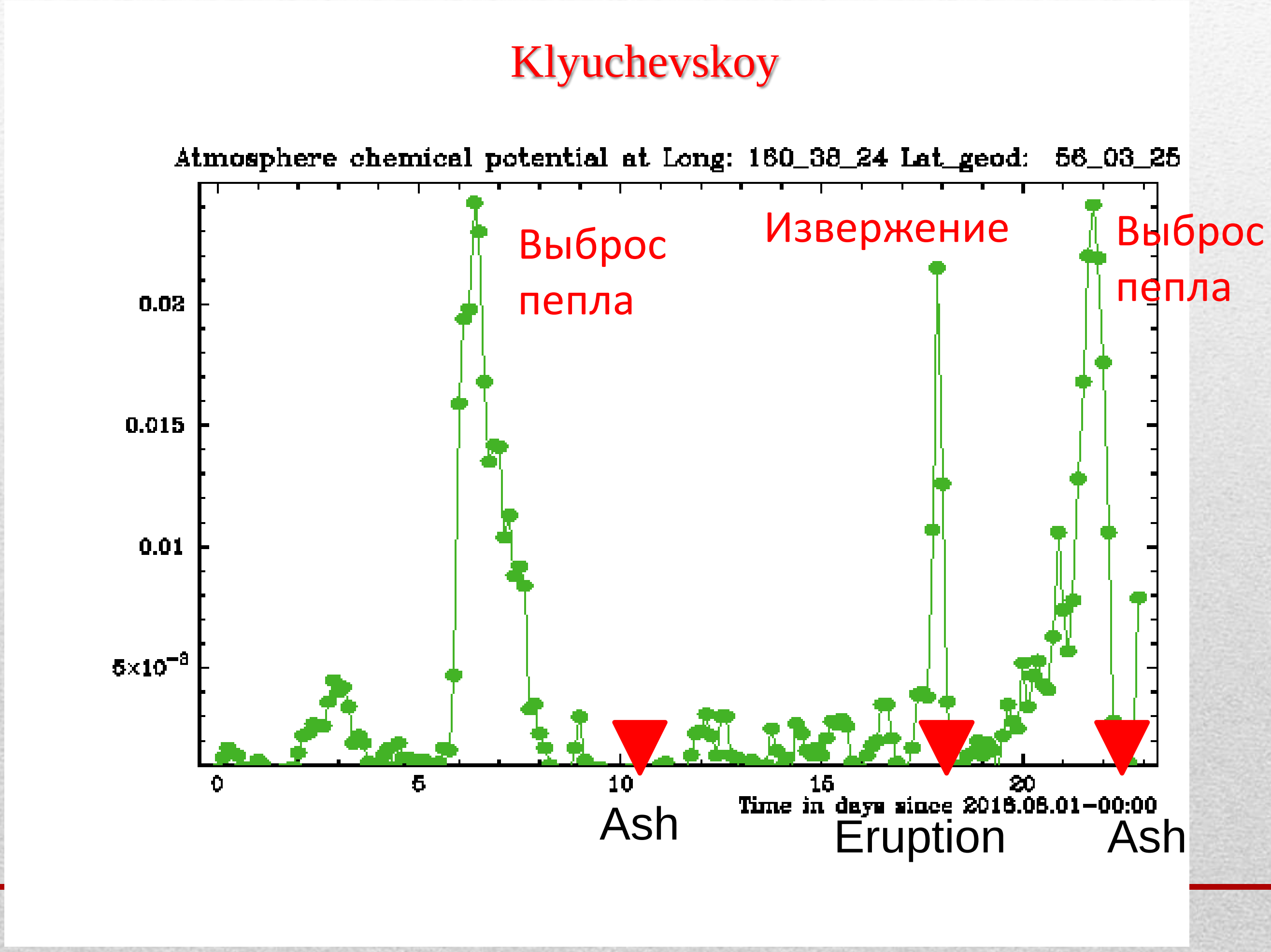

Davidenko and Pulinets, 2019


Challenger Plateau
Taranaki Basin
Australian Plate
Hikurangi Trough
41 mm/yr
Pacific Plate
Alpine Fault
Christchurch
Chatham Ris
37 mm/yr
Bounty Trough

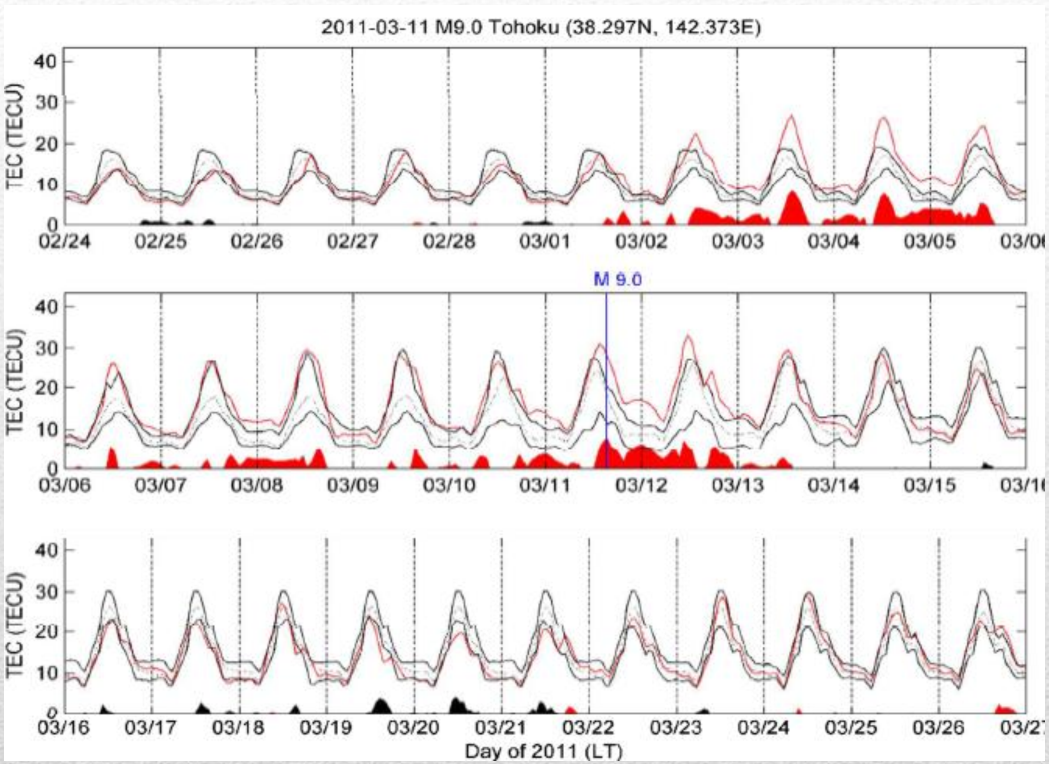

here chemical potential at 2013.07.14−00:00
0.024
0.022
0.019
0.017
0.014
0.011
0.009
0.006
0.004
0.001
ev
−42
−44
−46
−48
−50
164
166
168
170
172
174
176
178
180
longitude

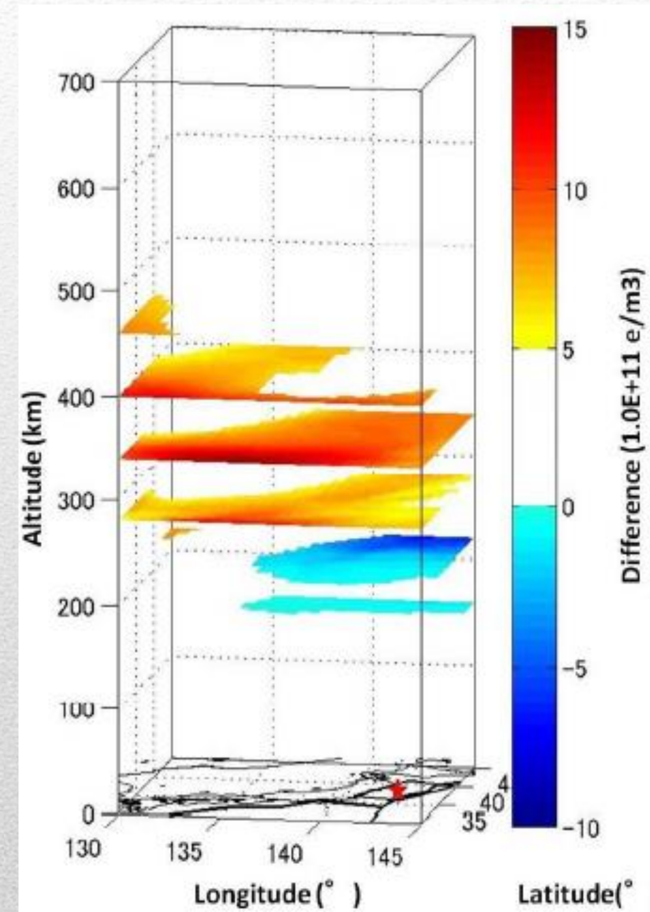
# Volcano monitoring

Активность вулкана Ключевской в июне 2016 г.



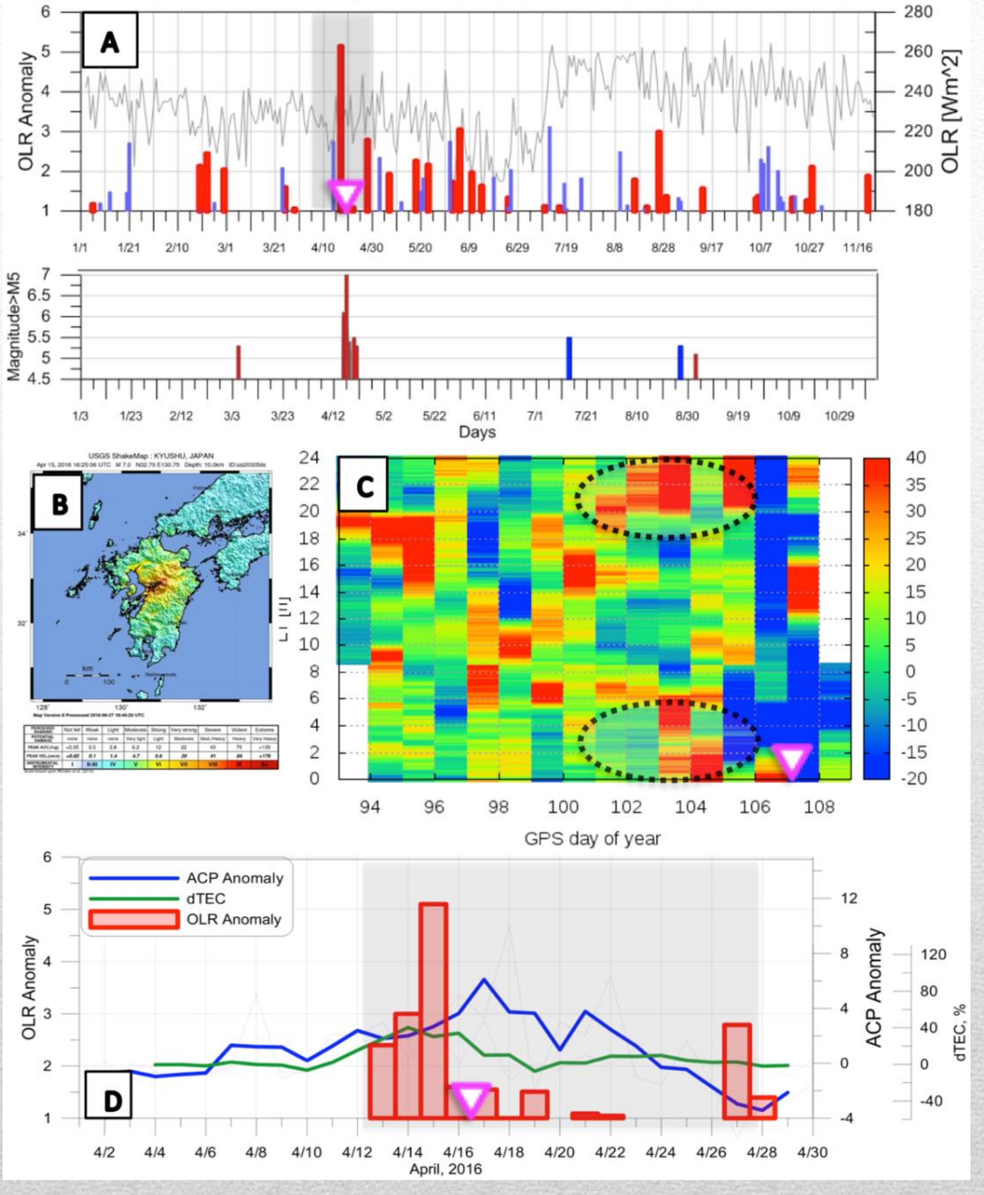
# Application of the GNSS total electron content (TEC) for detecting earthquake precursors




J.Y.Liu , H.Katsumi et al, 2018

# Atmosphere- Ionospheric Integrated study for M7 earthquake in Kumamoto, Japan



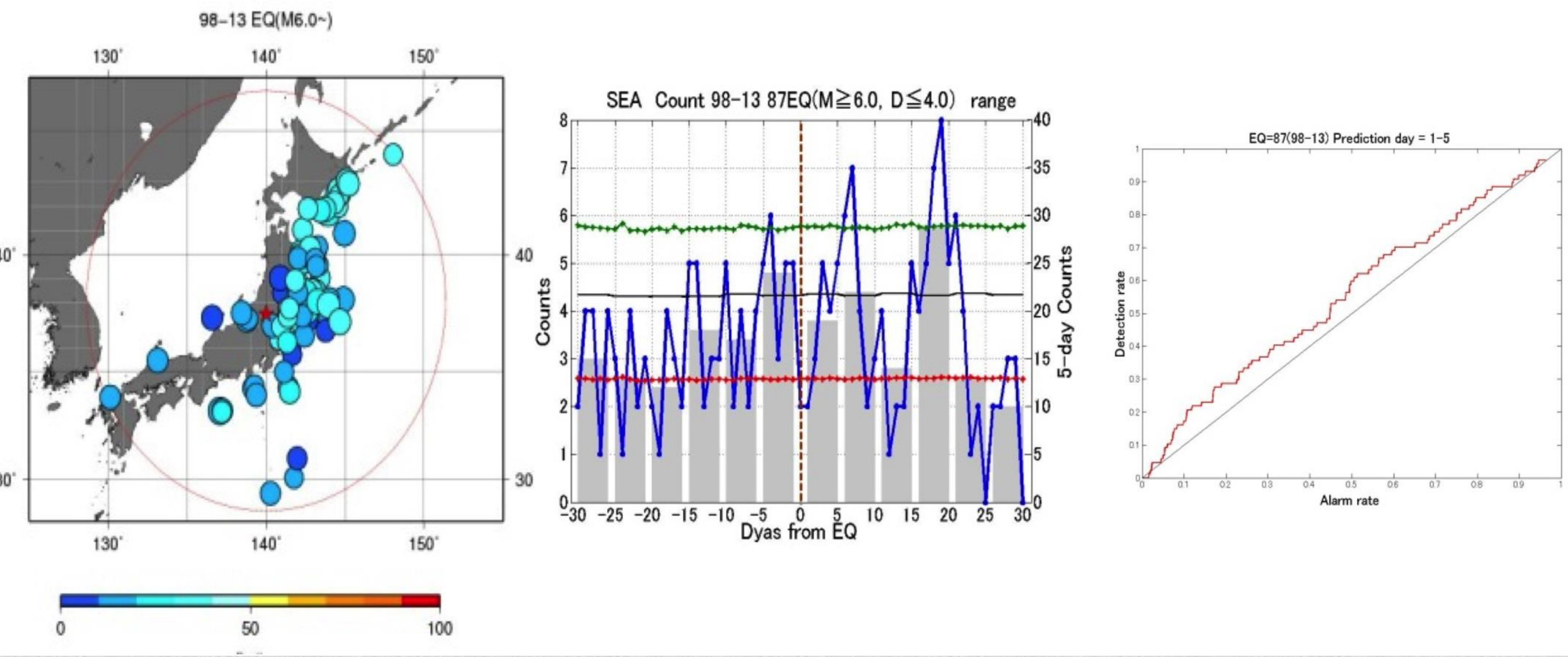

[Ouzounov et al. 2018]

# Long term correlation analyses among SSTAs and EQs occurrences

| Test Area | Study Period | Number of processed TIR images | Number of Significant Sequences of TIR Anomalies (SSTAs) | SSTAs in possible connection with Eqs> 4 | | False Positive | |
|---|---|---|---|---|---|---|---|
| **Italy**[9] [*Tramutoli* et al., 2015c] | June 2004 – December 2014 (01:00 LT ) | **2.861** | **28** | **17** | **61%** | **11** | **39%** |
| **Greece** [*Eleftheriou* et al., 2015] | May 2004 – December 2013 (02:00 LT) | **3.151** | **62** | **58** | **93%** | **4** | **7%** |
| **S-W US (California)** [*Tramutoli* et al., 2014b] | June-July-August 2006–2011 (00:00 LT) | **402** | **17** | **11** | **65%** | **6** | **35%** |
| **Taiwan** [*Genzano* et al., 2015] | September 1995 - 2002 (21:00 LT) | **240** | **18** | **18** | **100%** | **0** | **0%** |
| **Turkey**[10] [*Lisi* et al.,2016] | May 2004 – October 2015 (02:00 LT) | **3.831** | **155** | **115** | **74%** | **40** | **26%** |
| **Japan**[11] [*Genzano* et al., 2016] | June 2005 – December 2015 (00:30 LT) | **2.006** | **60** | **37** | **62%** | **23** | **38%** |
| **TOTALS** | **57 YEARS** | **12.491** | **340** | **256** | **75%** | **84** | **25%** |

(Tramutoli et al, 2018)

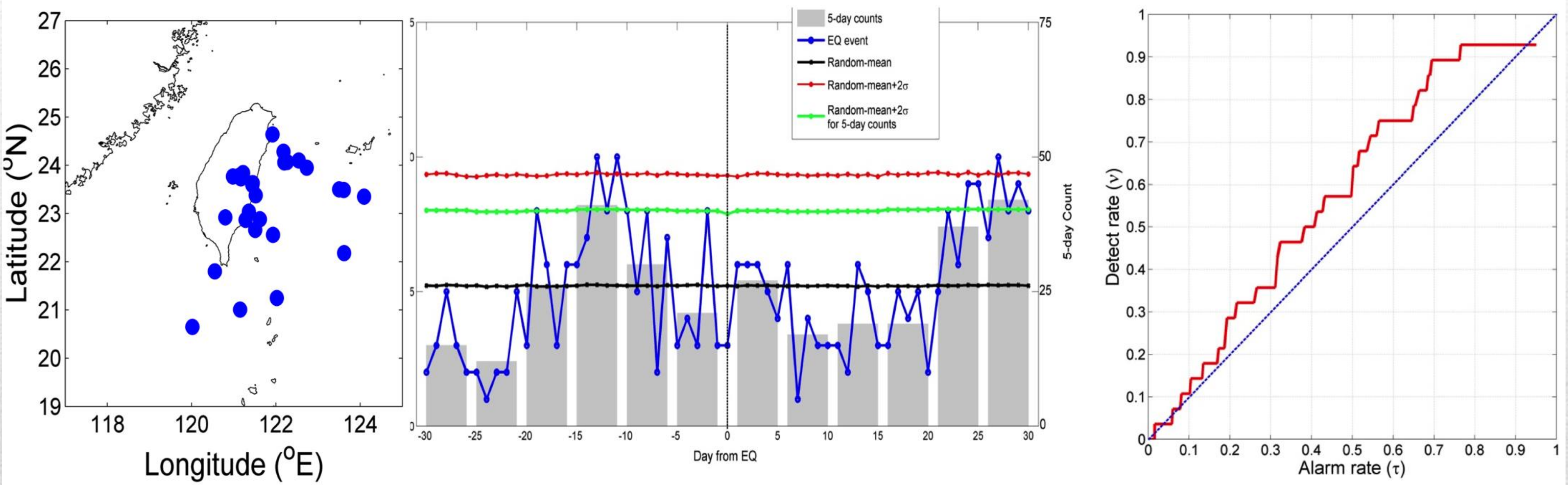
## JAPAN: Statistical analysis




Evaluation of GPS/TEC Seismic Earthquake Anomalies (SEA) with Molchan's Error Diagram (MED) for Japan, 1998-2013 (Left to right) A. Distribution map for M>6 earthquakes, 1998-2013; B. Anomalous distribution: with green f- one day, with black 5-days accumulation data; C: MED diagram of 5-days accumulation data.

[Hattori , 2018]

# TAIWAN: Statistical analysis



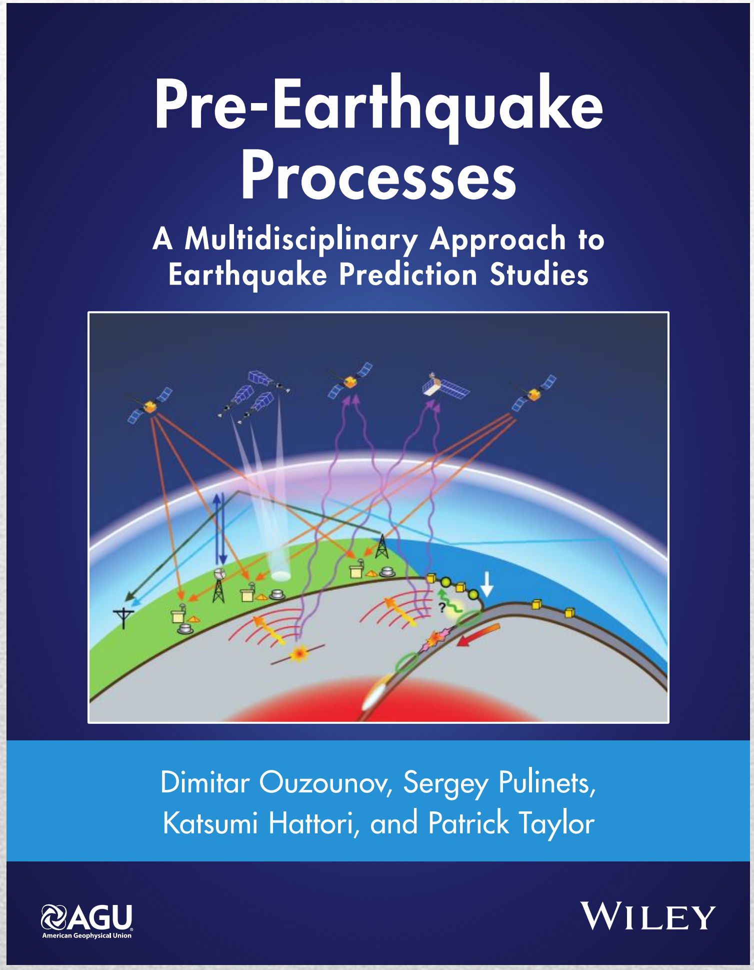

Evaluation of GIM/TEC Seismic Earthquake Anomalies (SEA) with Molchan's Error Diagram for Taiwan, 1998-2013. (Left to right) A. Distribution map for M>6 earthquakes, 1998-2013; B. Anomalous distribution: with green - one day, with black - 5-days accumulation data; C: MED diagram for 5-days accumulation data

.[Liu et al, 2018]

# *Points to take home*

1. Our current knowledge of the pre-earthquake phenomena has developed over last twenty-five centuries originating from the earliest scientific observation;
2. Pre- earthquake process is observable physical phenomena that precede seismic release;
3. Statistical connection has been established between pre-earthquake activity and the characteristics of subsequent seismic events;
4. The multi -disciplinary approach covers the data from seismic , physical, atmospheric and geochemical characteristics of pre-earthquakes;
5. Satellite and ground data integration - Thermal Infrared, seismo–ionospheric and other satellite –and ground-based pre-earthquake anomalies could reveal the location, intensity and timings of major earthquakes;
6. There is a strong potential of applying these multidisciplinary data to earthquake forecasting/prediction.
7. **What is still missing? – comprehensive validation trough operational testing**

# Vol.234, AGU Geophysical Monograph Series




Available in July 2018