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## 1. Introduction

The rapid phase and amplitude fluctuations caused by severe ionospheric irregularities may induce unpredictable range errors and other serious problems in many precise applications of Global Navigation Satellite Systems (GNSS). The rate of ionospheric total electron content (TEC) change index (ROTI), defined as the standard deviation of rate of TEC change (ROT) within a short time (e.g. 5 minutes), has been commonly applied to describe the ionospheric irregularities and associated scintillations. On the basis of single-differenced ROT, a new ionosphere activity index, rate of ROT change index (RROT), is developed to characterize the perturbation degree of the ionosphere.

## 2. Methodology

### • Ionospheric scintillation indexes

Amplitude ( $S_4$ ) and phase ( $\sigma_\phi$ ) scintillation indexes obtained from the GNSS scintillation receivers are commonly used to characterize the perturbation degree of the ionosphere.

$$S_4 = \sqrt{\frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}} \quad \sigma_\phi = \sqrt{\langle \phi^2 \rangle - \langle \phi \rangle^2}$$

where  $I$  and  $\phi$  are the detrended signal intensity and signal phase, respectively.

### • Ionosphere activity indicators derived with GNSS data

These indicators take advantage of multi-GNSS tracking networks for ionospheric irregularity monitoring in both real-time and post-processing modes.

ROTI — Rate of TEC change Index

$$ROTI = \sqrt{\langle ROT^2 \rangle - \langle ROT \rangle^2} \quad \text{— reflect the fluctuations in ionospheric TEC}$$

$$ROT = \frac{TEC_{i+N}^i - TEC_i^i}{\Delta t} \quad \text{— derived from dual-frequency phase data after cycle-slip detected}$$

AATR — Along Arc vertical TEC Rate

$$AATR = \sqrt{\frac{1}{N} \sum_{i=1}^N aatr_i^2} \quad aatr_i = \frac{\Delta STEC}{(M(\epsilon))^2 \Delta t}$$

RROT — Rate of ROT change index, a new ionospheric activity index

(1) The single-differenced rot (drot) is calculated since ROT may still contain the trend term of ionospheric TEC in spite of small-scale fluctuations.

$$drot(i) = rot(i) - rot(i-1) \quad \text{— single-differenced rot, in TECu/min}^2$$

$$DROT = \sqrt{\langle drot^2 \rangle - \langle drot \rangle^2} \quad \text{— std of drot changes, in TECu/min}^2$$

(2) form the ionosphere activity indicator, RROT, in TECu/min

$$RROT = \frac{\sigma_{rot} DROT}{\sigma_{drot}} \quad \text{— } \sigma_{rot} \text{ and } \sigma_{drot} \text{ are related to the ionospheric TEC accuracy at epoch } i \rightarrow \sigma_{(i)}$$

## 3. Results and discussion

### 3.1 Data sets

GPS and GLONASS data obtained from the International GNSS Services (IGS), EUREF Permanent GNSS Network (EPN), Continuous Operating Reference Stations of the US (USCORS) and Australian Regional GNSS Network (ARGN) are used for regional and global ionospheric irregularity monitoring. More than 2000 GNSS stations are processed per day.

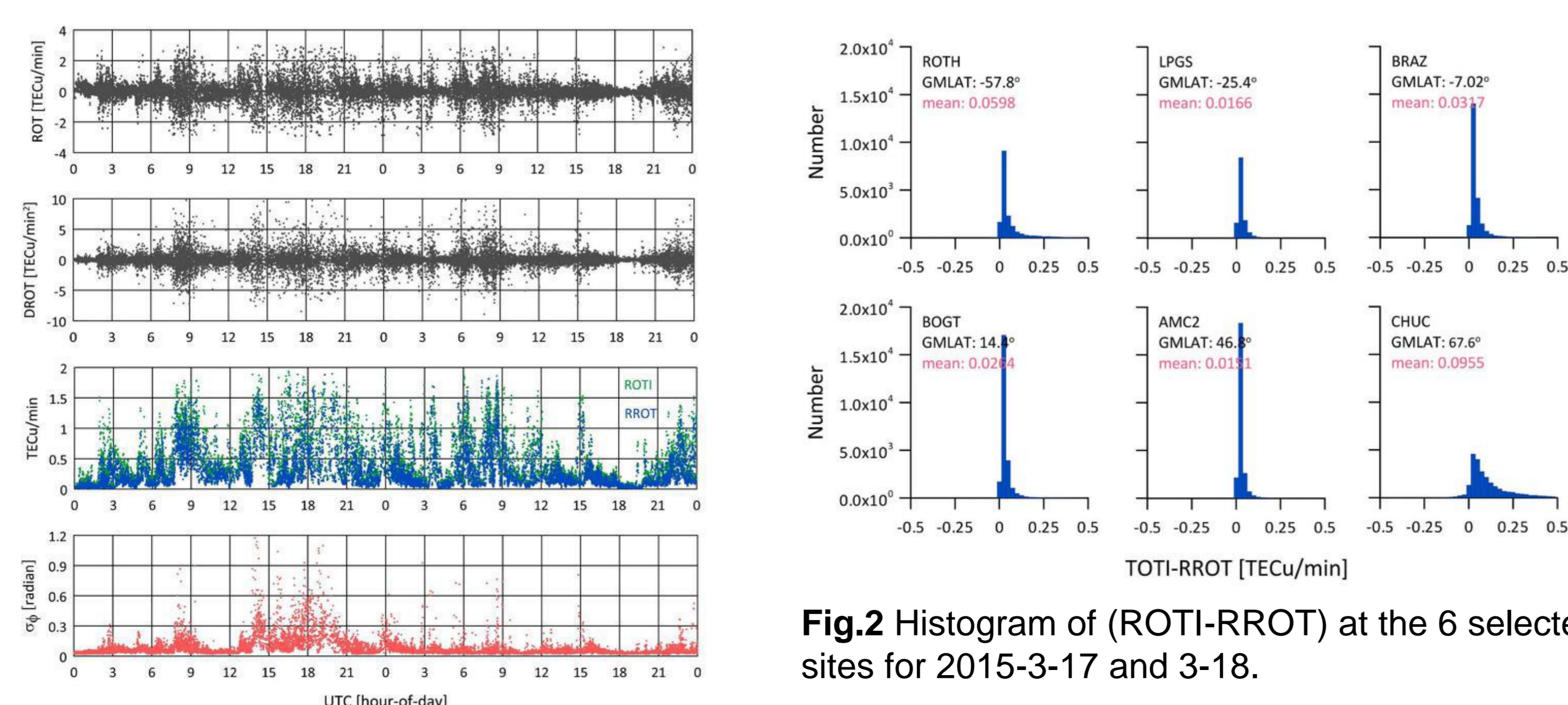


Fig.1 Data for 2015-3-17 and 3-18: comparison of ROT, DROT, ROTI, RROT and  $\sigma_\phi$  at CHUC site.

### 3.2 Comparison of ROTI, RROT, AATR and $\sigma_\phi$

Fig.1 shows time series of ROT, DROT, ROTI, RROT and phase scintillation for March 17 and 18, 2015 at high Arctic site CHUC. A strong response is seen in ROTI, RROT and phase scintillation index between 12 UT on the 17<sup>th</sup> and 3 UT on the 18<sup>th</sup>. There is also a visible sign of disturbances around 9 UT on the 17<sup>th</sup>. It is also noticeable that RROT values are a bit smaller than those of ROTI. The differences between ROTI and RROT were further examined at the 6 selected site, covering equatorial, mid- and high-latitudes, as shown in Fig.2. ROTI-RROT has significant bias for each site, which is in the range of 0.015-0.095 TECu/min.

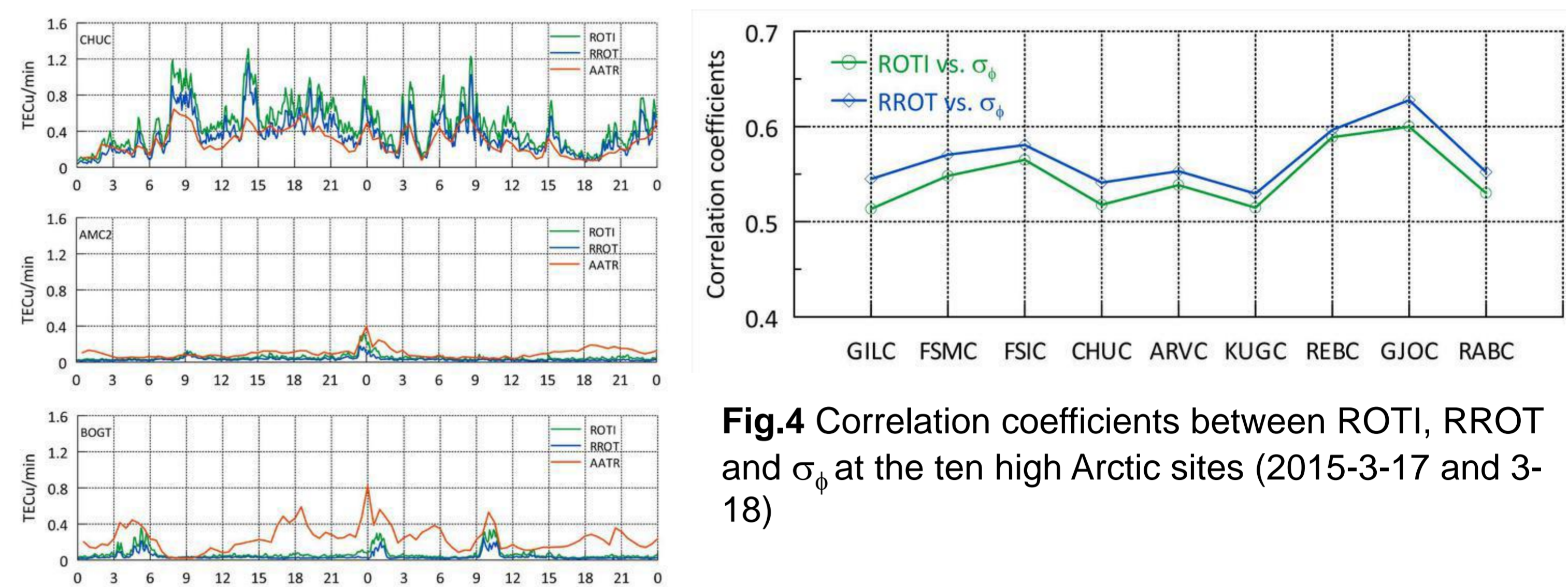


Fig.3 Data for 2015-3-17 and 2015-3-18: comparison of ROTI, RROT and AATR

Fig.3 gives the station-based ROTI, RROT and AATR indexes at high-, mid- and low-latitude receivers. It shows that high-latitude receiver CHUC presents high ROTI, RROT and AATR values, while mid- and low-latitude receivers (AMC2 and BOGT) exhibit moderate values. AATR is a bit smaller than that of ROTI and RROT at high-latitude site, but on the contrary at mid- and low-latitude sites. Fig.4 presents the correlation coefficients between ROTI, RROT and phase scintillation index. The correlation coefficients of RROT and  $\sigma_\phi$  mainly vary between 0.55 and 0.65, which is larger than those of ROTI and  $\sigma_\phi$  by 0.01-0.03 in average.

### 3.3 Examples of global ionospheric irregularity maps

With the GPS and GLONASS data obtained from around 2000 globally distributed GNSS permanent tracking stations, RROT and ROTI maps were routinely generated to analyze the occurrence and dynamics of the ionospheric irregularity. The maps are provided with a spatial resolution of 5 and 2.5 degrees in longitude and latitude, and a temporal resolution of 15 mins and 1 hour, respectively. An example of the ionospheric irregularity maps was performed during the St. Patrick's Day storm of 17 March 2015 and 20 April 2017, respectively. It is demonstrated that RROT and ROTI indexes response acutely to ionospheric irregularities with the magnitudes increasing dramatically at high latitudes of northern and southern hemispheres during the stormy days.

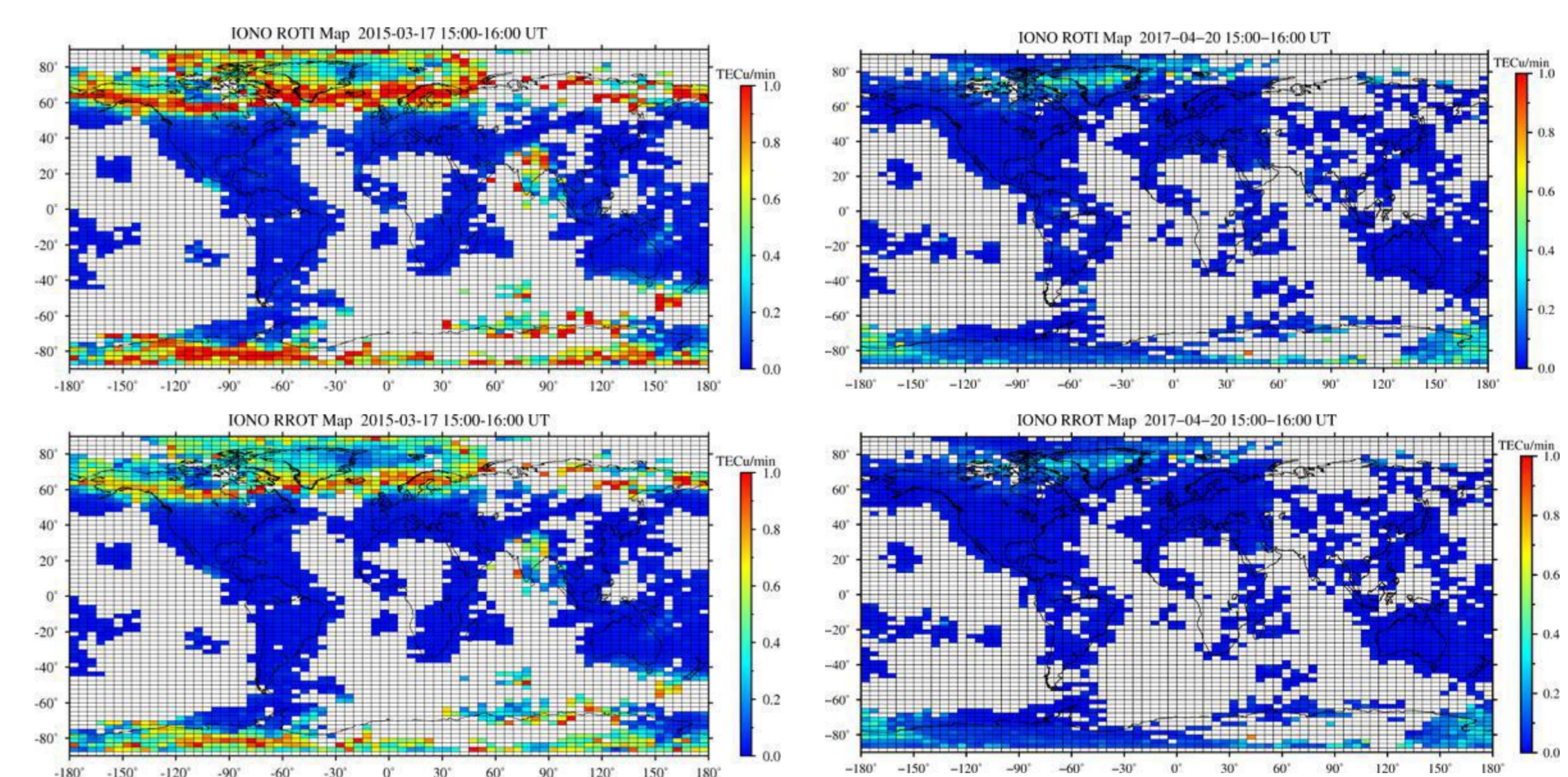


Fig.5 Global ROTI and RROT maps on 2015-3-17 (stormy day) and 2017-4-20 (quiet day)

## 4. Summary and conclusions

- New ionospheric activity index, RROT, was developed to characterize the irregularity degree of the ionosphere
- Ionospheric irregularity monitoring products are routinely provided by CAS, available at the ftp archive of CAS:
  - <ftp://ftp.gipp.org.cn/product/iondist/> (data files)
  - <ftp://182.92.166.182/product/iondist/> (images)
- with a latency of 3 days, covering the time span 001/2017-now
- Further validation of the new proposed ionospheric activity index will be conducted
- Switch to real-time mode for regional ionospheric irregularity monitoring in the following months