Space Climate 7 Symposium, Canton Orford, Québec, 8-11 July, 2019

Solar wind imprint on gravity waves and atmospheric circulation

Paul Prikryl[1,2]

(1) Physics Department, University of New Brunswick, Fredericton, NB, Canada
(2) Geomagnetic Laboratory, Natural Resources Canada, Ottawa, ON, Canada

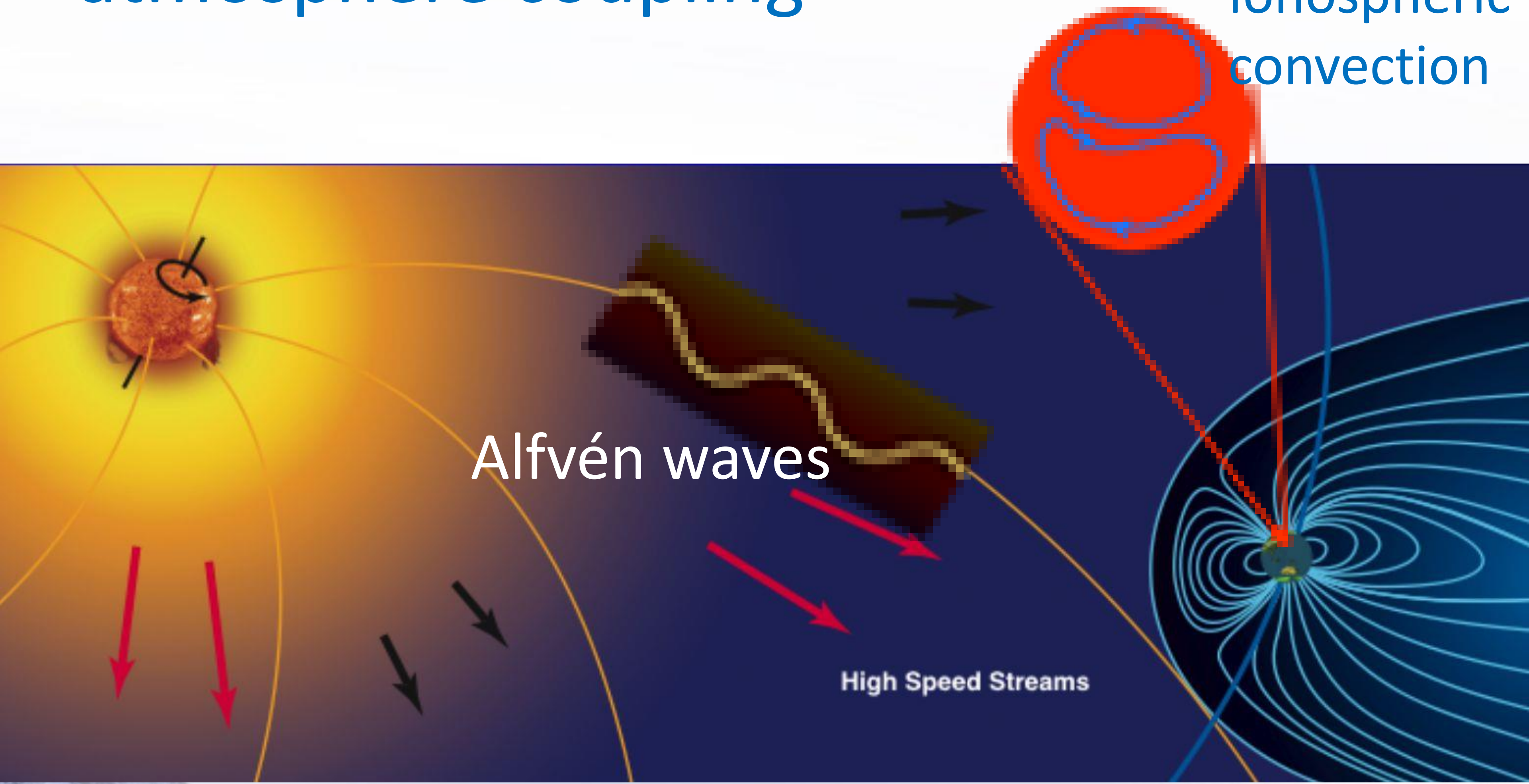
With contributions by

Lidia Nikitina[2], Donald B. Muldrew[3], Takumi Tsukijihara[4], Koki Iwao[5], Vojto Rušin[6], Milan Rybanský[7]
(3) Emeritus, Communications Research Centre, Ottawa, ON, Canada
(4) Department of Earth and Planetary Sciences, Kyushu University, Fukuoka, Japan
(5) National College of Technology, Kumamoto College, Yatsushiro, Japan
(6) Astronomical Institute, Slovak Academy of Sciences, Tatranská Lomnica, Slovakia
(7) Slovak Central Observatory, Hurbanovo, Slovakia

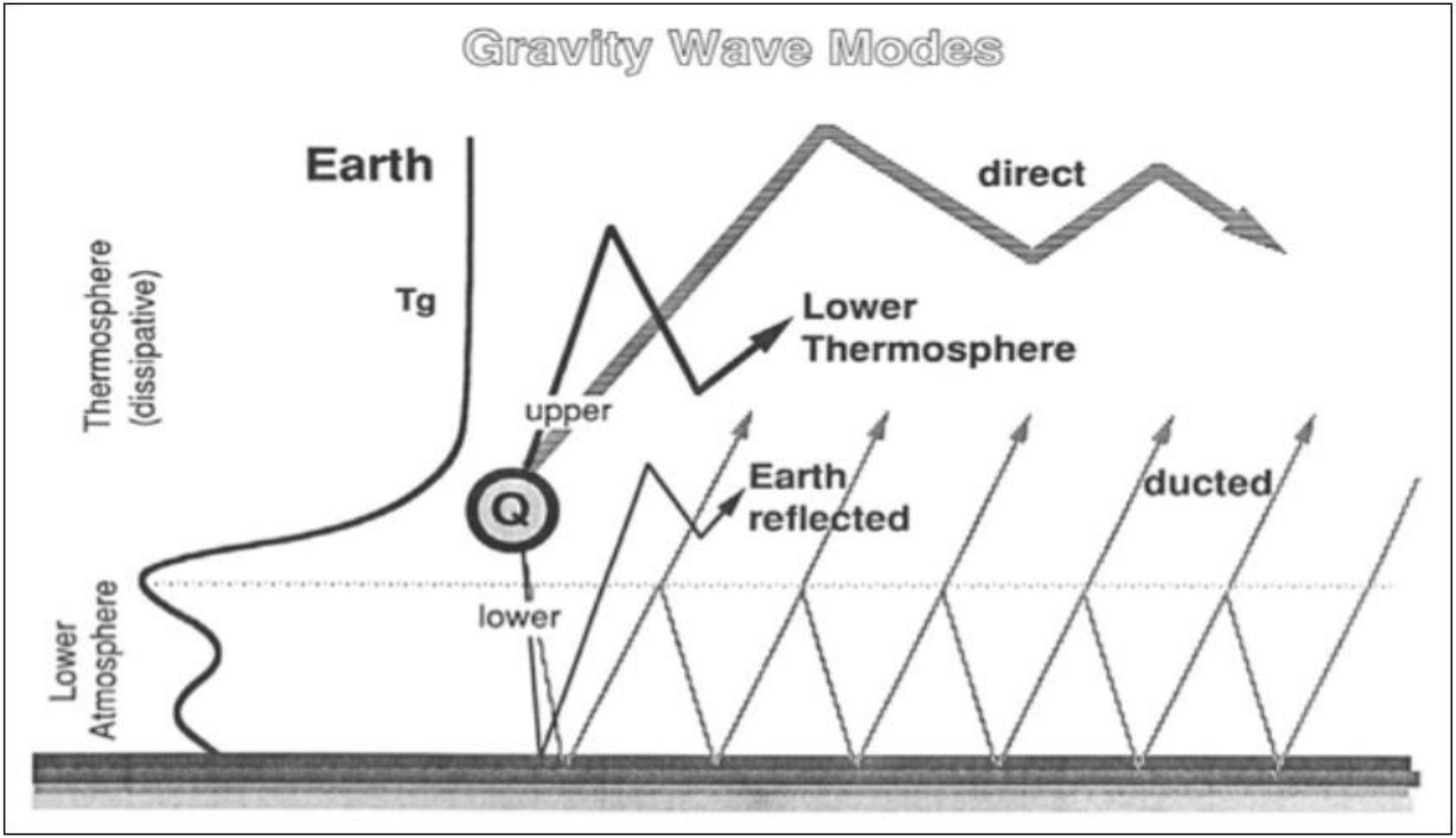
Outline

- Introduction & Motivation (Wilcox effect)
- Statistical results
  - Explosive extratropical cyclones
  - Rapid intensification of tropical cyclones
- Solar wind imprint on atmos. gravity waves
- Link between solar wind and troposphere
- Summary & Conclusions

Solar wind – magnetosphere – ionosphere – atmosphere coupling



http://www.ava.fmi.fi/~minna/researchseminar/lectures/Eijanluento.pdf

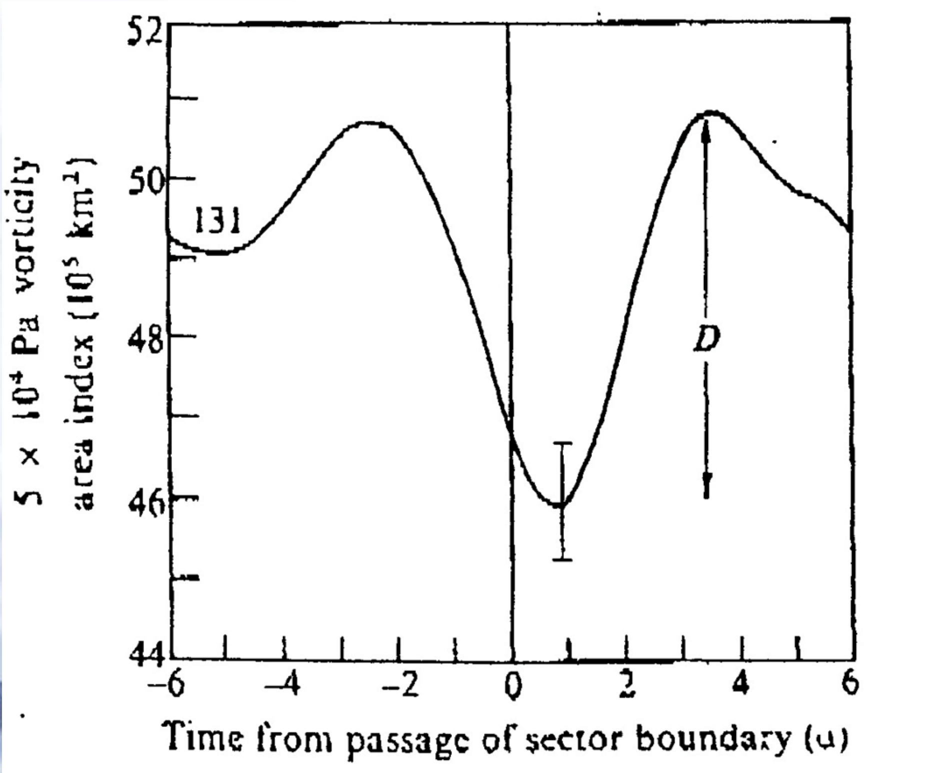


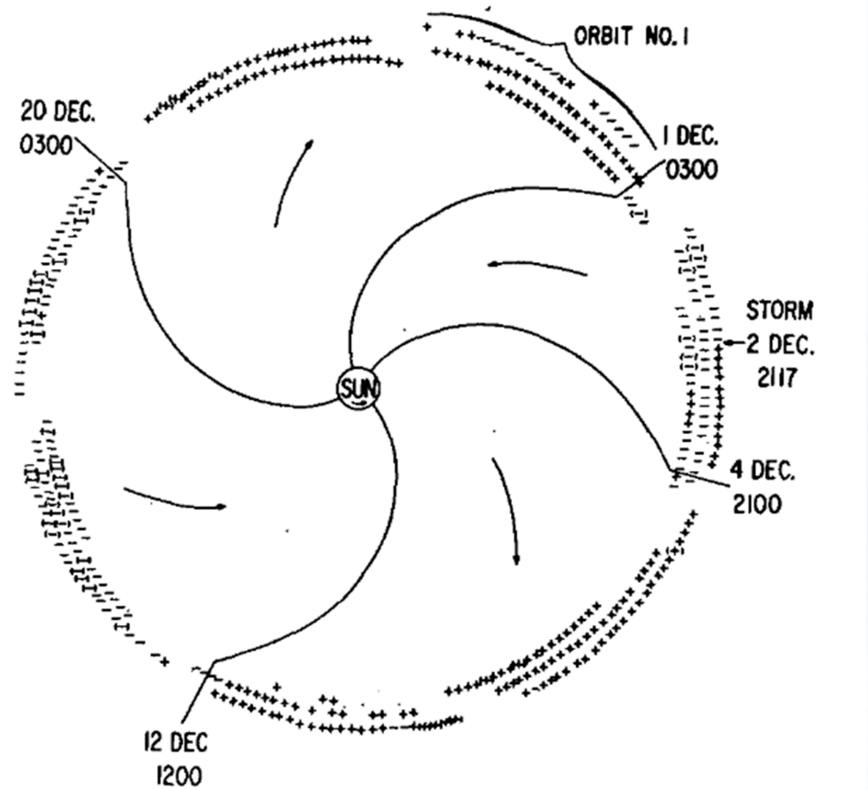
Mayr et al. (1990), Thermospheric gravity waves: Observations and interpretation using the transfer function model - Space Science Reviews 54, 297–375.

Motivation & Introduction

- Wilcox effect (Wilcox J. M., et al., Science, 180, 185-186, 1973.)

Nov-Mar 1963-1973
Vorticity Area Index

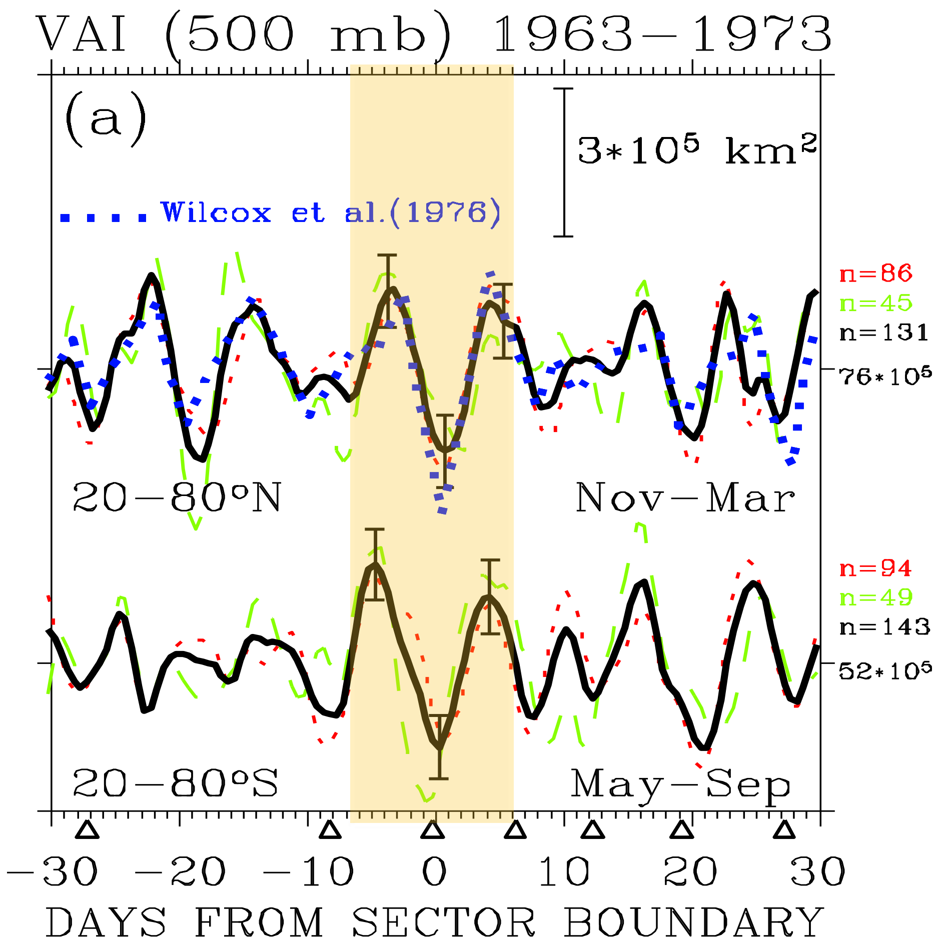




Wilcox et al., J. Atmos. Sci, Vol. 31, 581-588, 1974.

Motivation & Introduction

- Wilcox effect (Wilcox J. M., et al., Science, 180, 185-186, 1973.)
- Confirmed in the Northern and Southern Hemispheres

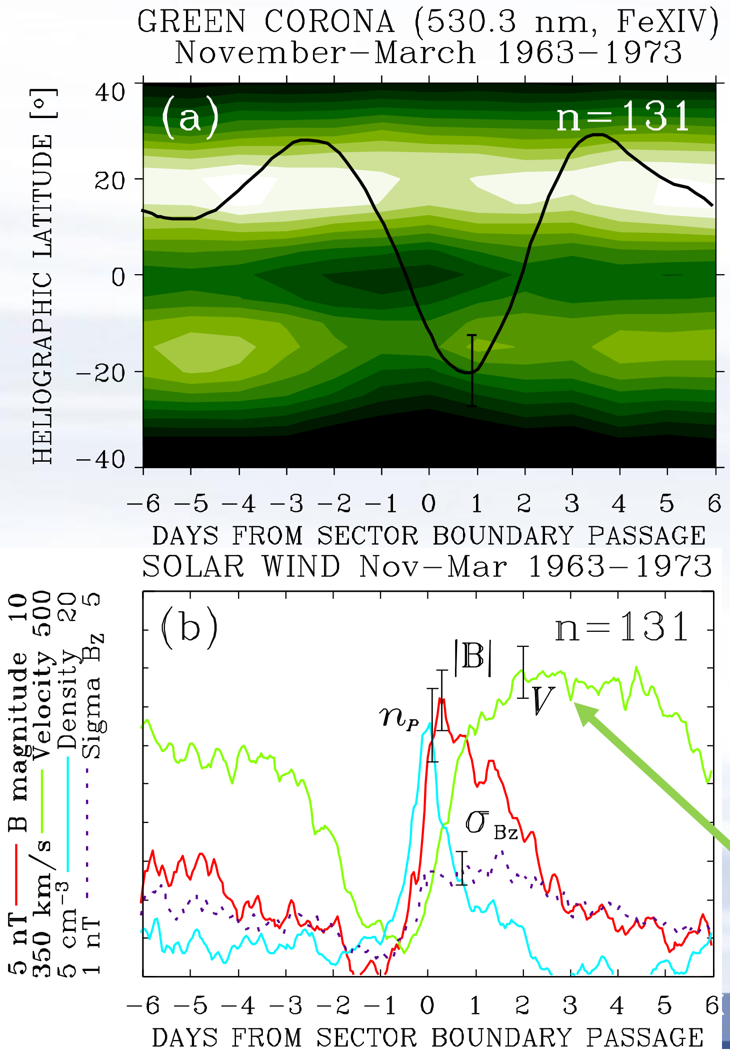


Prikryl et al., Ann. Geophys., 27, 1–30, 2009.

UNIVERSITY

Motivation & Introduction

- Wilcox effect (Wilcox J. M., et al., Science, 180, 185-186, 1973.)



131 IMF sector boundary crossings Nov-Mar 1963-1973

← **Please, note this pattern**

V B n_p σ_{Bz}

Prikryl et al., Ann. Geophys., 27, 1–30, 2009.

High Cloud Area Index (HCAI)

- high-level infrared cloud cover from the ISCCP-D1 dataset.
- Effect related to Wilcox effect

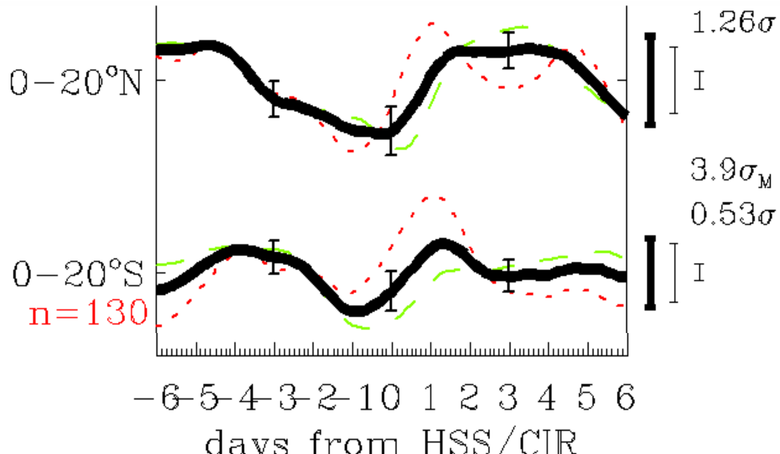
Prikryl et al., Ann. Geophys., 27, 31–57, 2009.

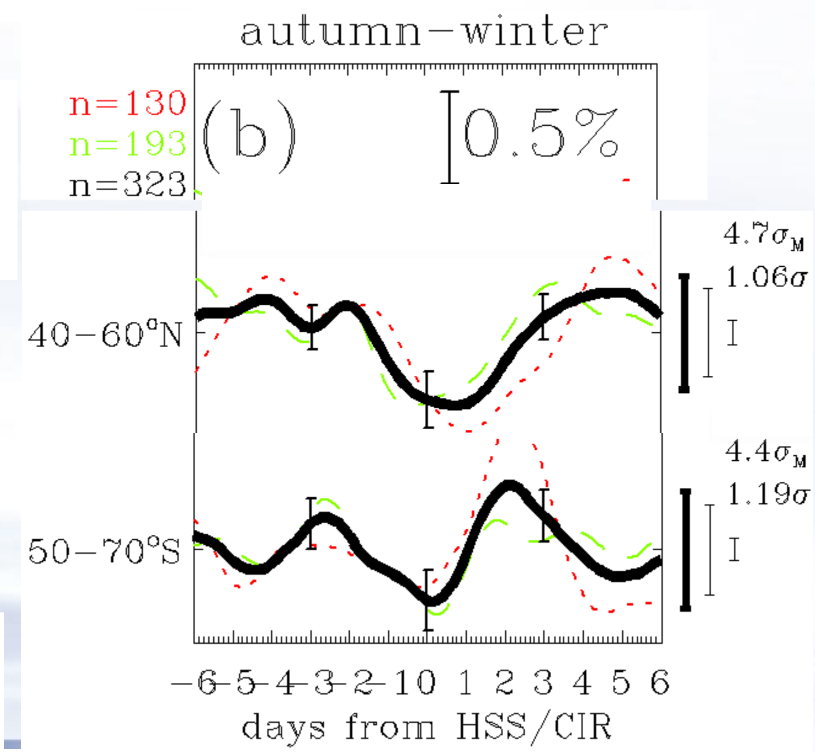
HCAI 1983-2006

Spring-summer

North:

South:





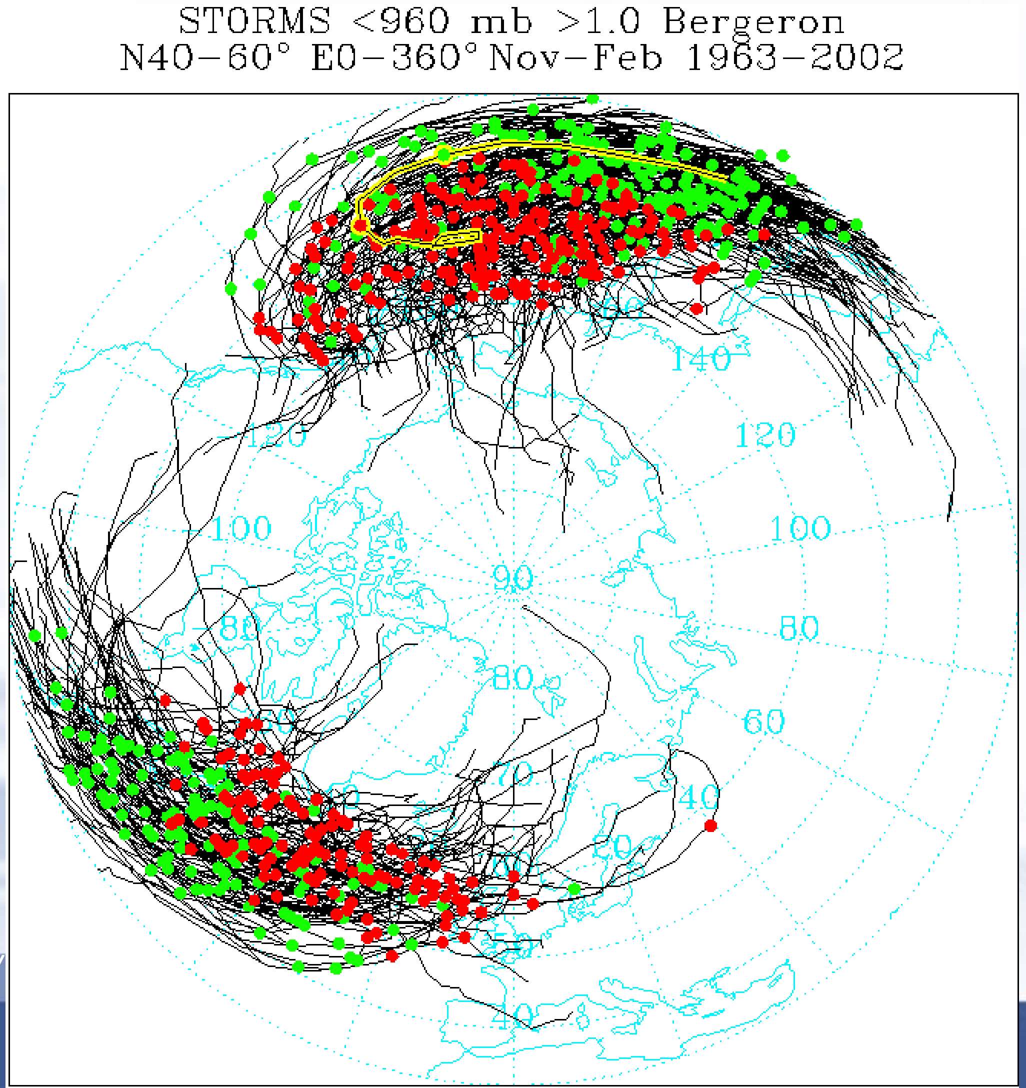
Tropical latitudes

Middle latitudes

Explosive extratropical cyclones

Storm tracks obtained from the ERA-40

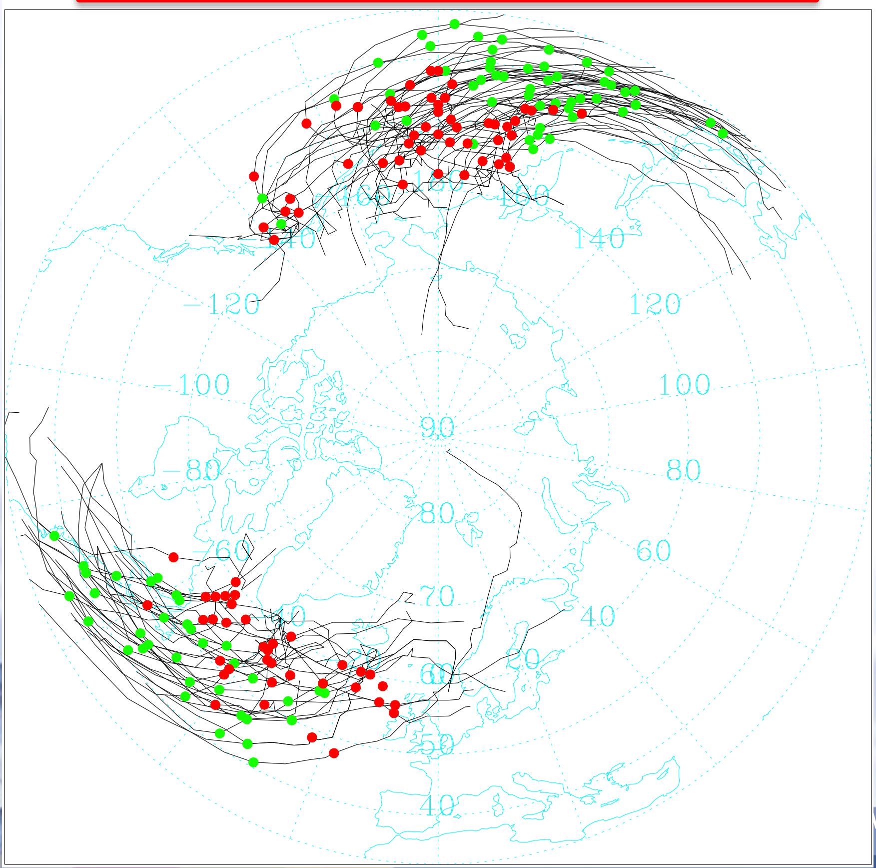
Prikryl et al., J. Atmos. Sol.-Terr. Phys., 149, 219–231, 2016.

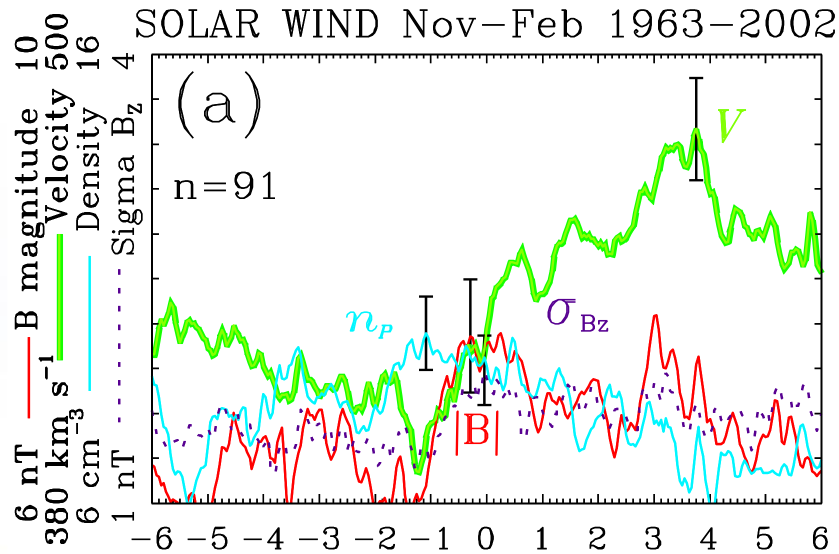


UNIVERSITY

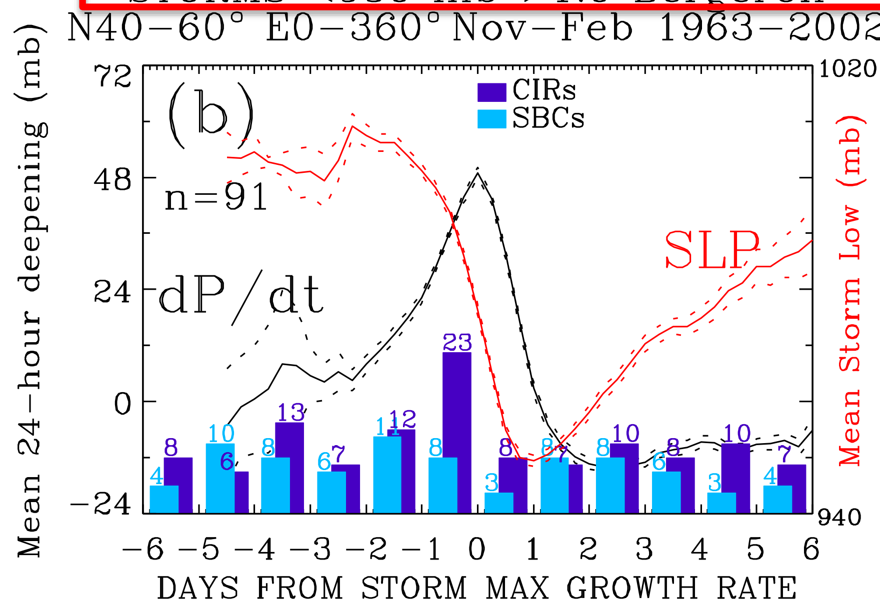
The SPE analysis keyed to max growth rate (<950mb) of 91 explosive extratropical cyclones in the Atlantic and Pacific

STORMS <950 mb >1.0 Bergeron
N40–60° E0–360° Nov–Feb 1963–2002





STORMS <950 mb >1.0 Bergeron
N40–60° E0–360° Nov–Feb 1963–2002



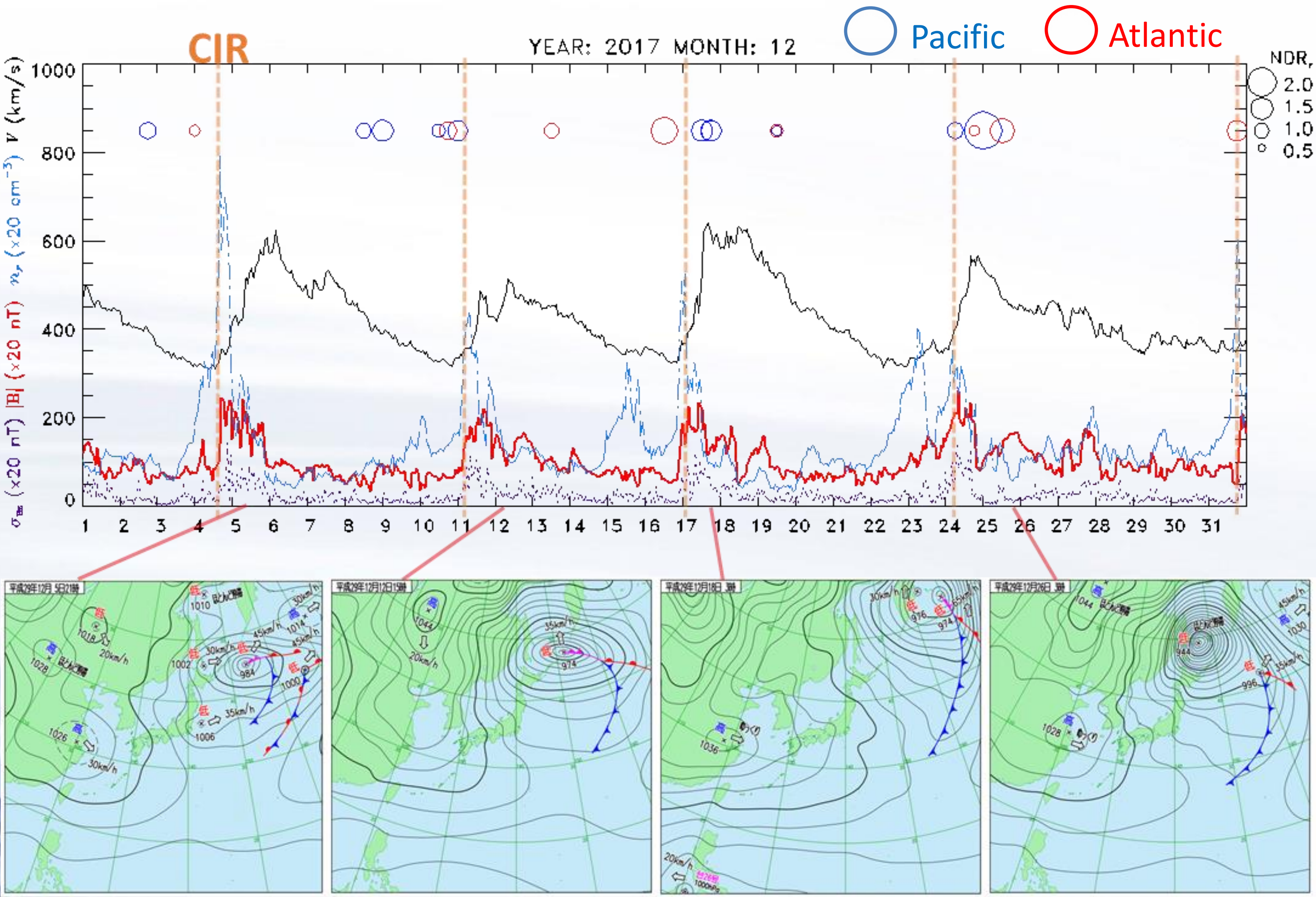
CIR: Co-rotating Interaction Region

SBC: IMF Sector Boundary Crossing

Prikryl et al., J. Atmos. Sol.-Terr. Phys., 149, 219–231, 2016.

These results indicate a tendency of explosive cyclones to follow arrivals of high-speed solar wind streams (HSS) from coronal holes, suggesting a link between the space weather and the tropospheric weather.

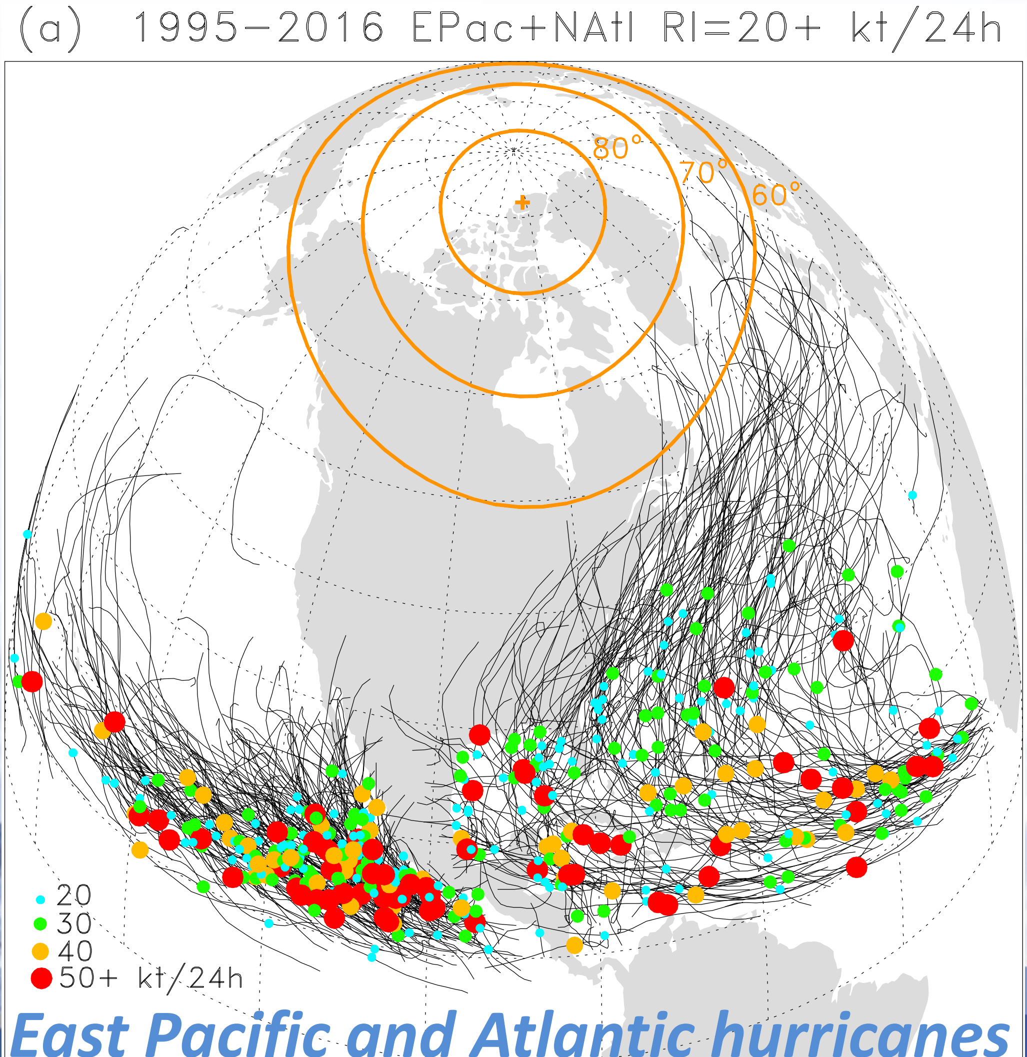
Explosive cyclones over Japan in December 2017

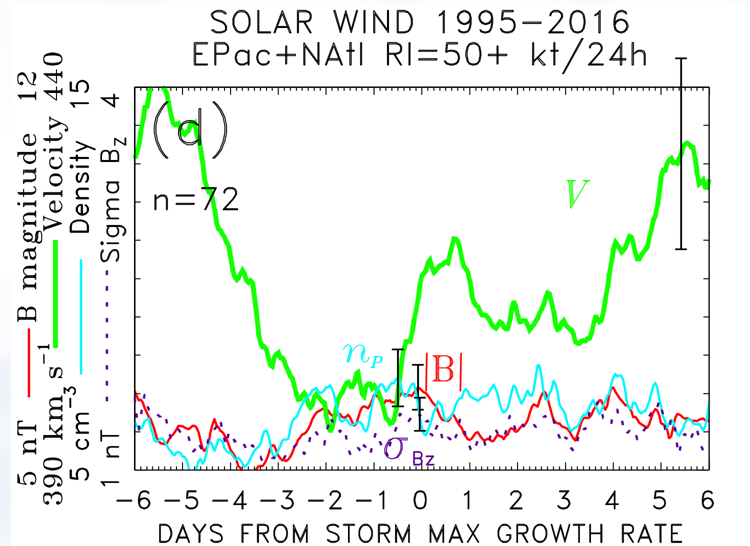


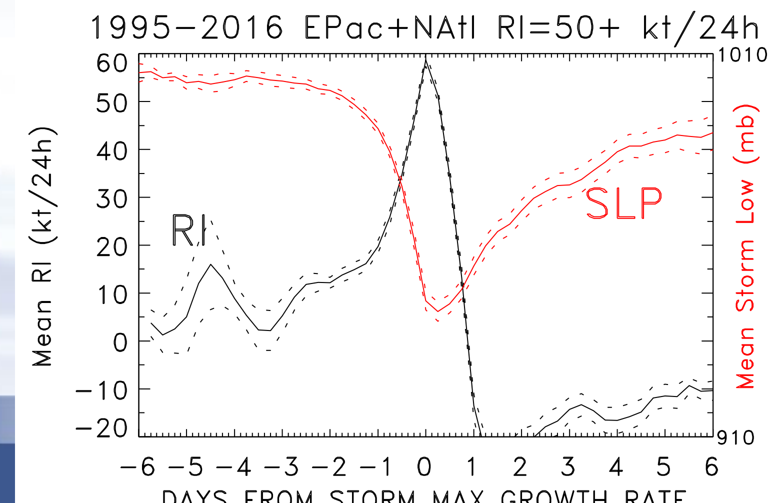
Rapid intensification of tropical cyclones

Rapid intensification (RI) of tropical cyclones is defined as the maximum sustained wind (MSW) increase of at least 30 kt (15.4 m/s) in a 24-hour period. The superposed epoch (SPE) analysis of solar wind plasma parameters and solar green corona intensity are keyed to times of maximum RI of tropical storms.

Prikryl et al., J. Atmos. Sol.-Terr. Phys., 183, 36–60, 2019.

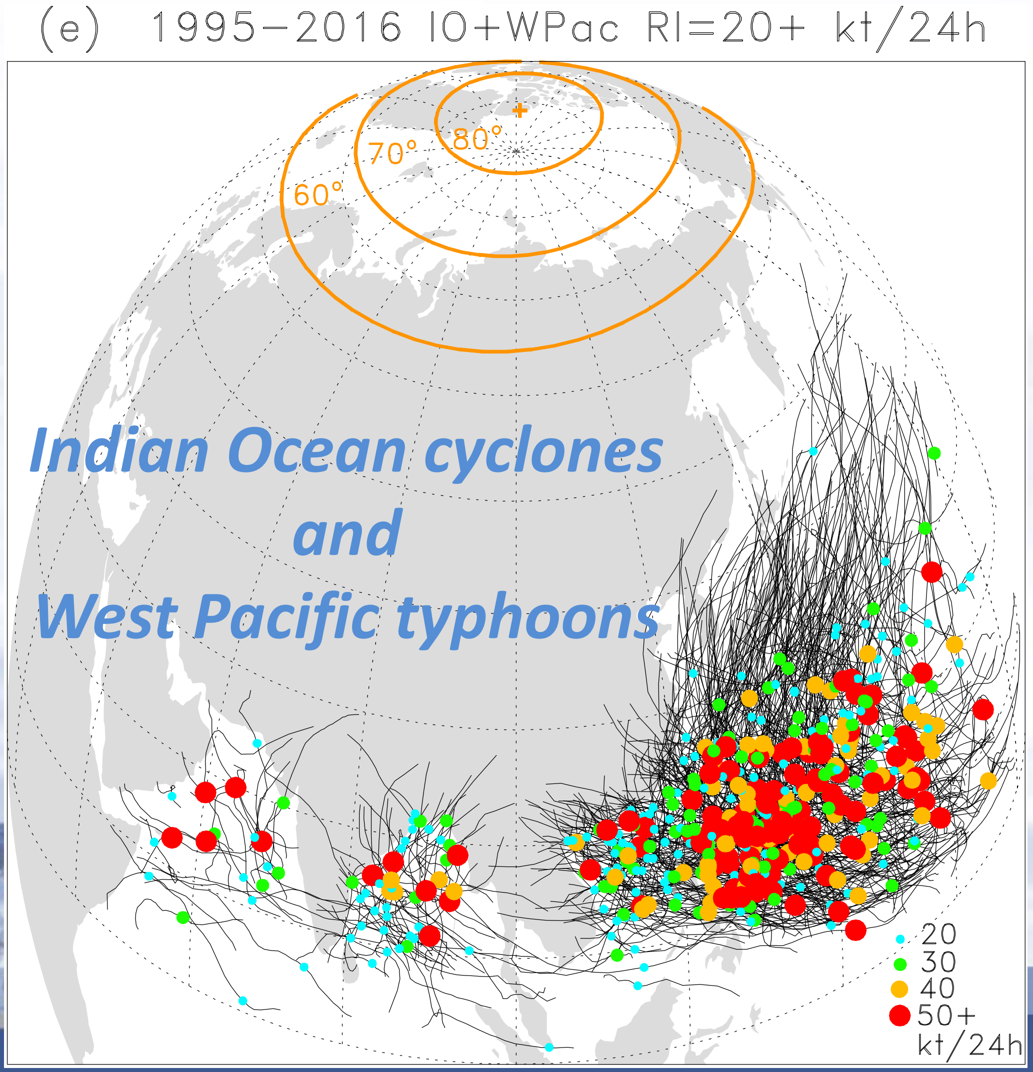


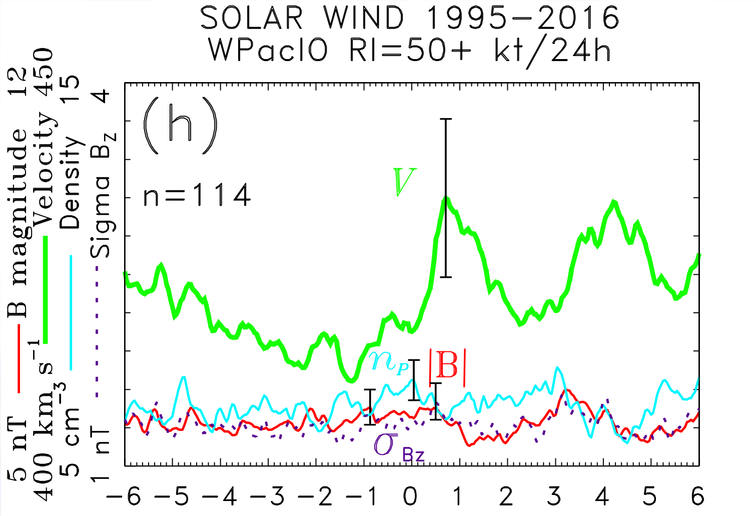


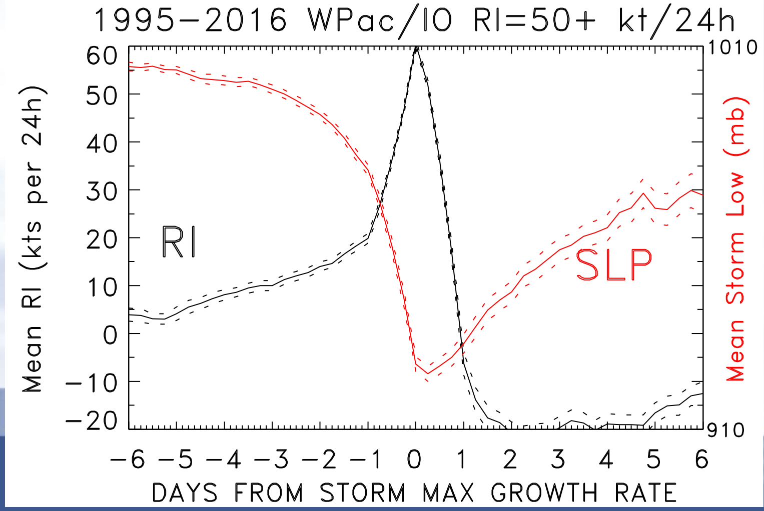


Rapid intensification (RI) of tropical cyclones is defined as the maximum sustained wind (MSW) increase of at least 30 kt (15.4 m/s) in a 24-hour period. The superposed epoch (SPE) analysis of solar wind plasma parameters and solar green corona intensity are keyed to times of maximum RI of tropical storms.

Prikryl et al., J. Atmos. Sol.-Terr. Phys., 183, 36–60, 2019.

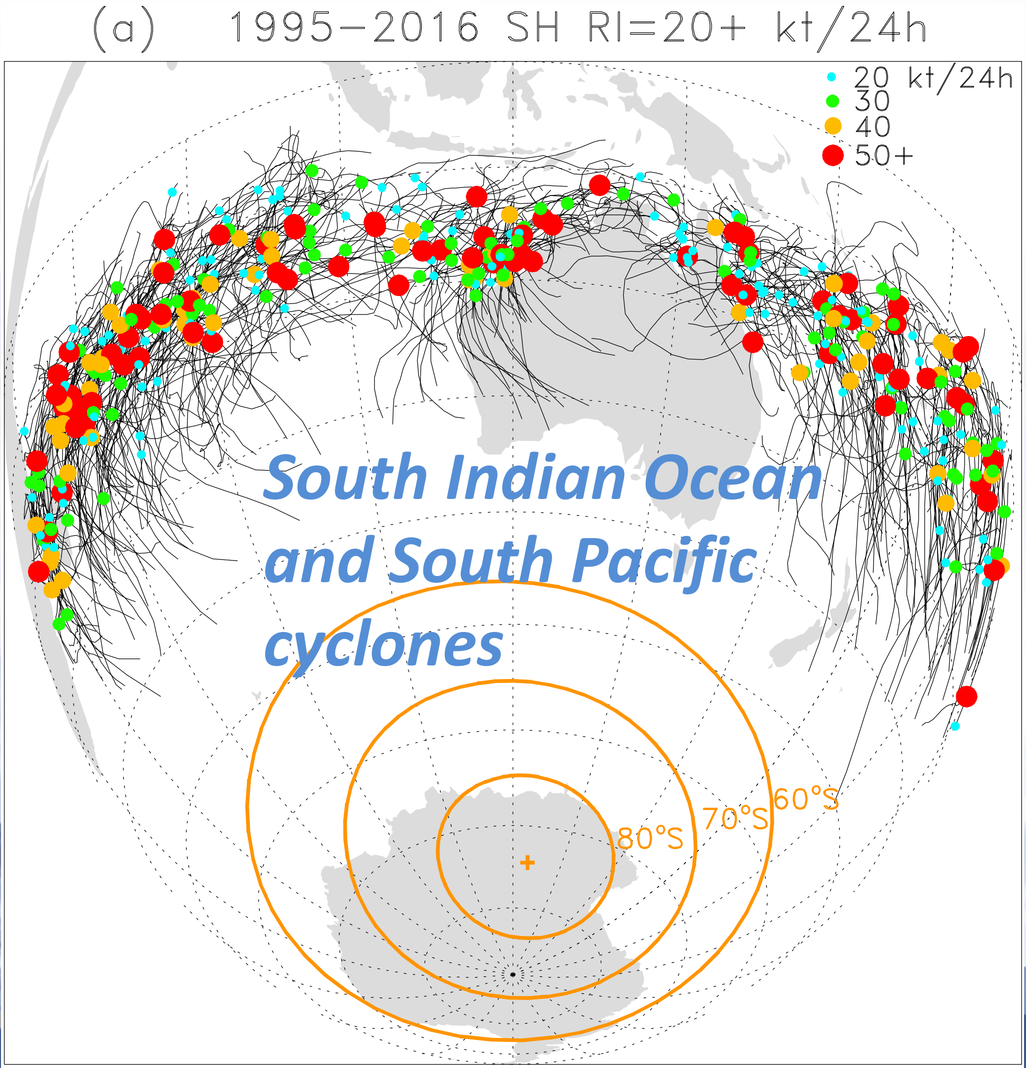


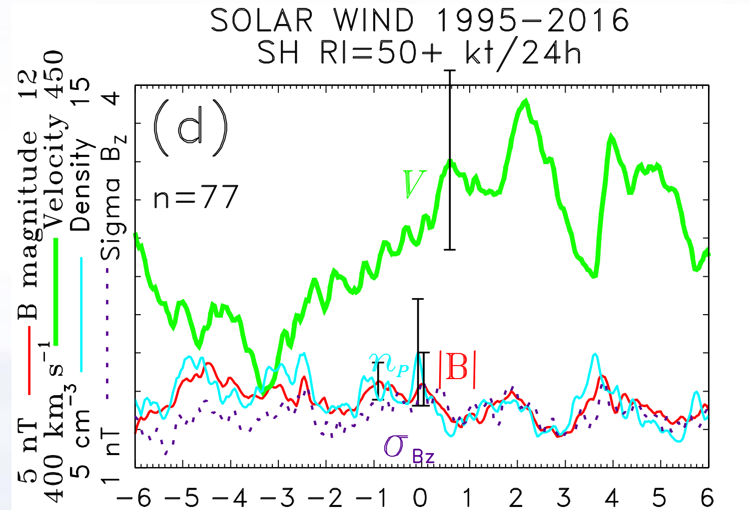


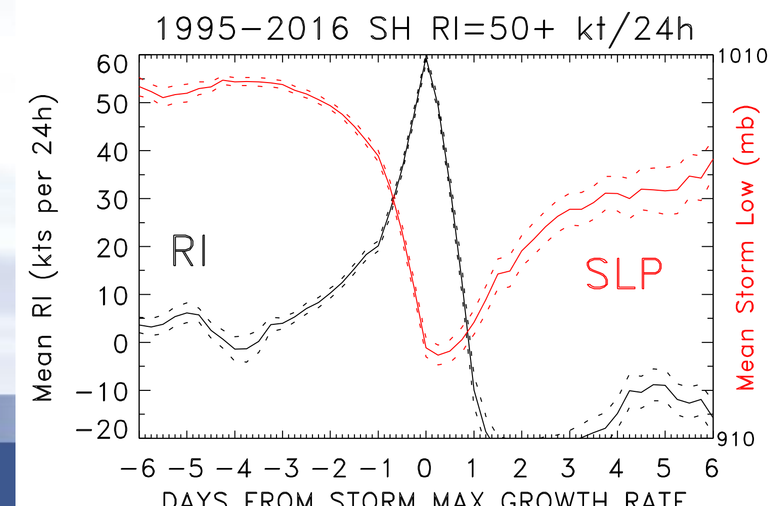


Rapid intensification (RI) of tropical cyclones is defined as the maximum sustained wind (MSW) increase of at least 30 kt (15.4 m/s) in a 24-hour period. The superposed epoch (SPE) analysis of solar wind plasma parameters and solar green corona intensity are keyed to times of maximum RI of tropical storms.

Prikryl et al., J. Atmos. Sol.-Terr. Phys., 183, 36–60, 2019.

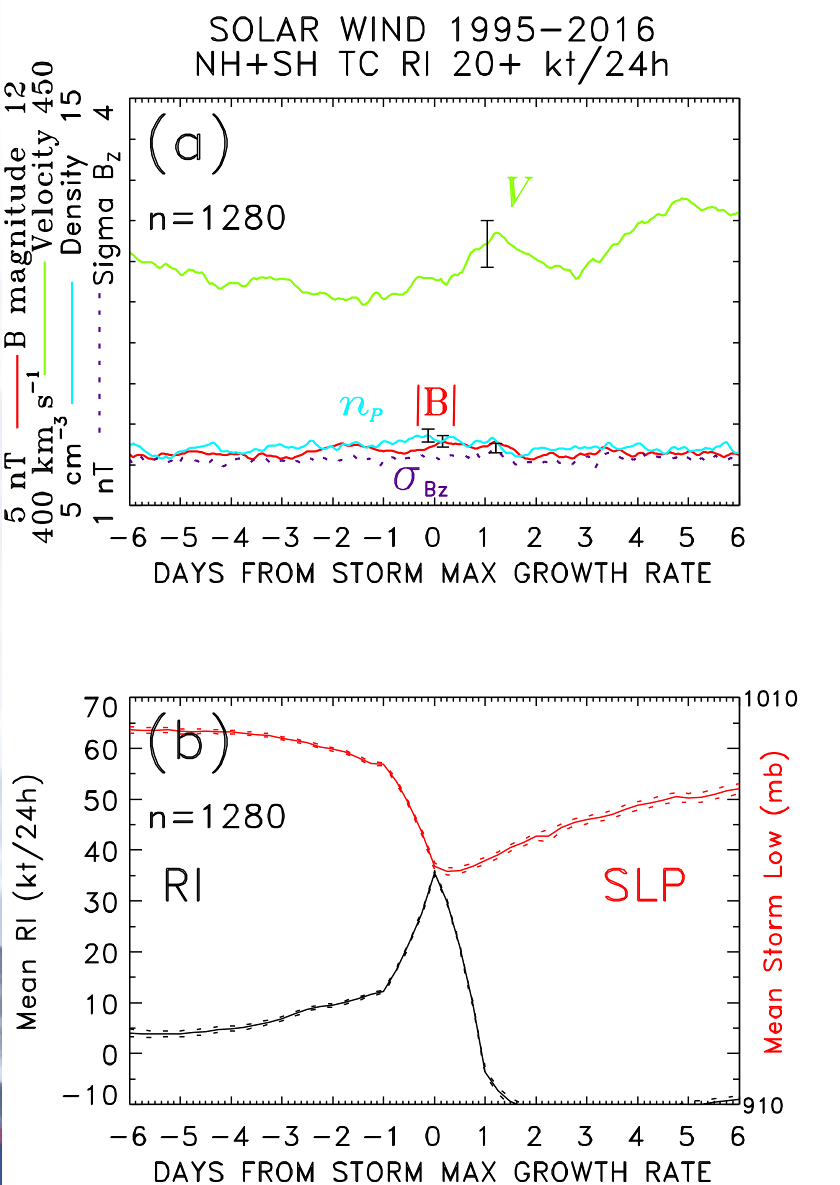




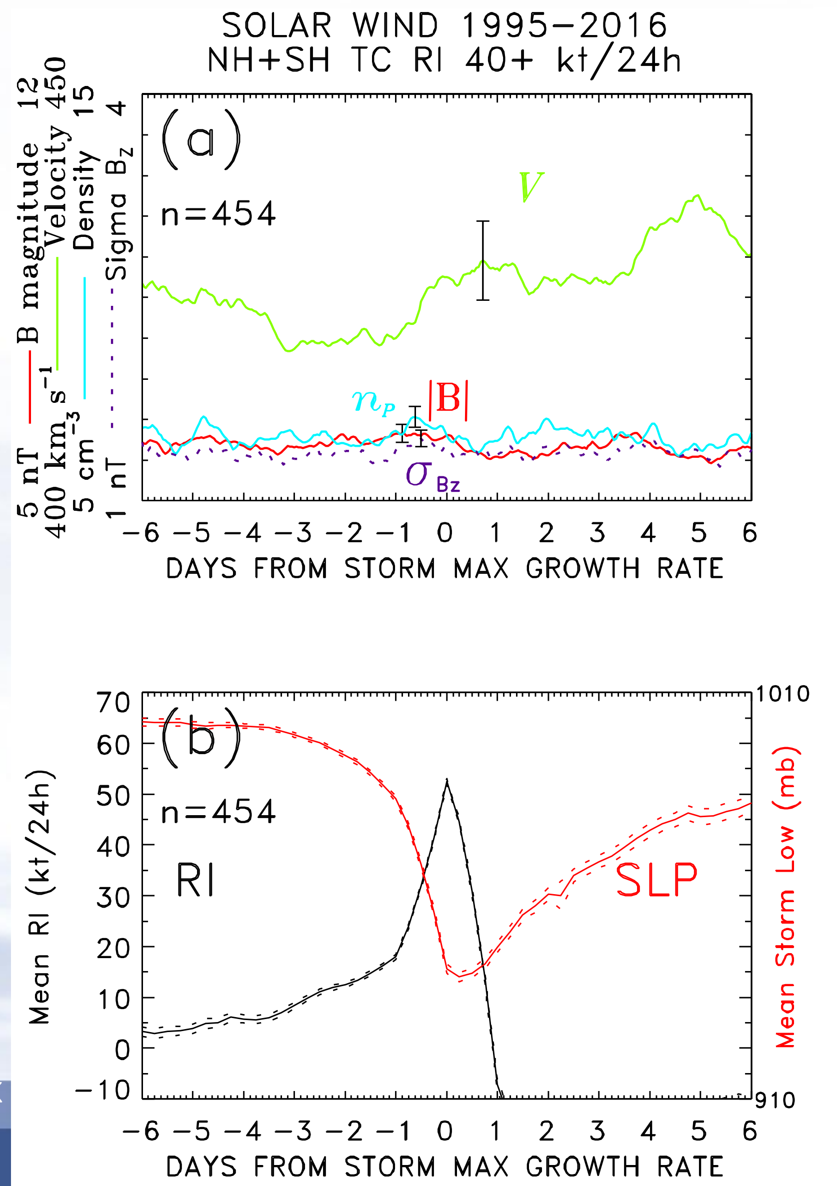


All tropical cyclones in NH + SH combined

RI= 20+ kt per 24 h



40+ kt per 24 h

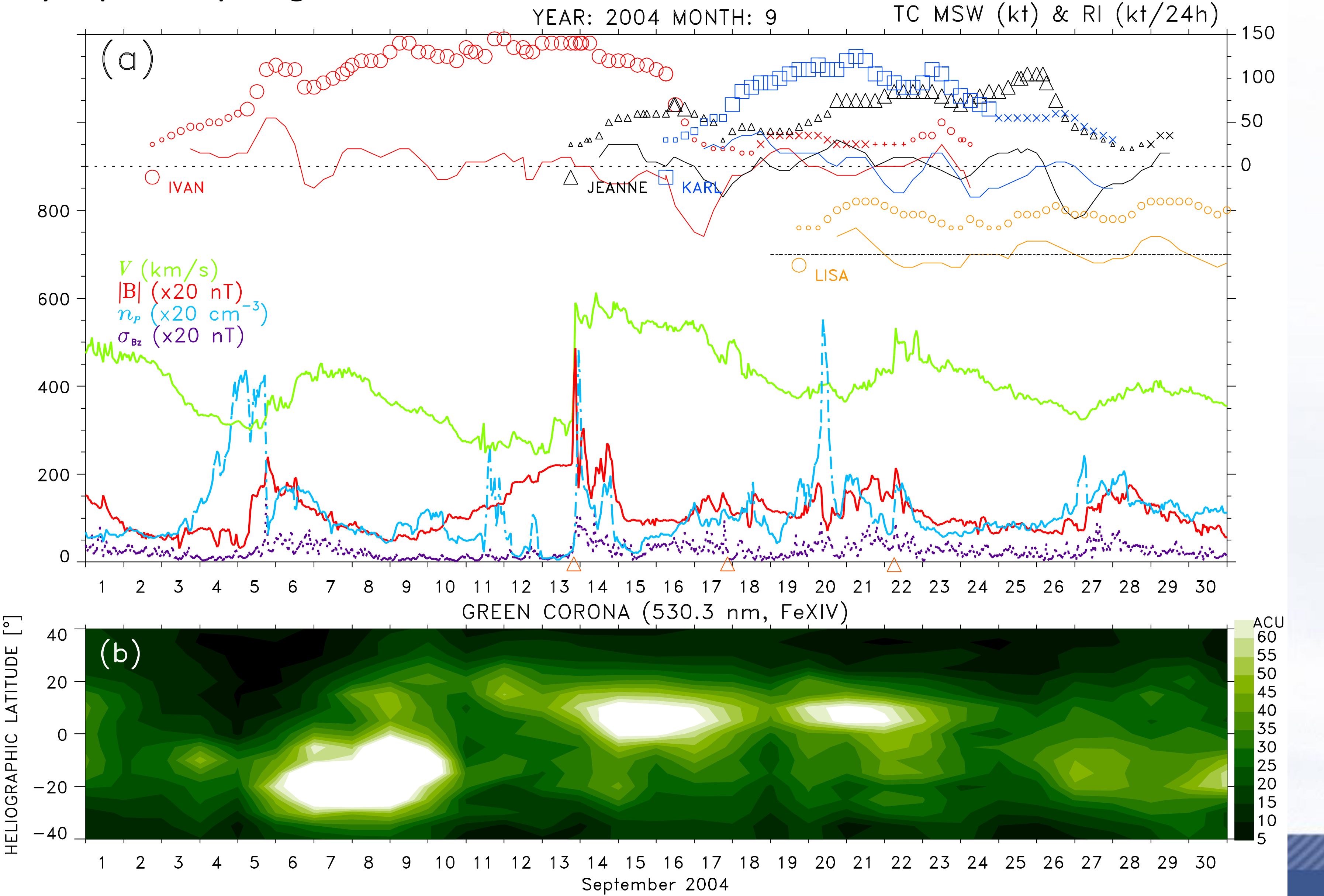


Hurricanes in the North Atlantic in September 2004.

(a) (top) The “best track” TC data and (bottom) OMNI solar wind parameters

(b) Synoptic map of green corona.

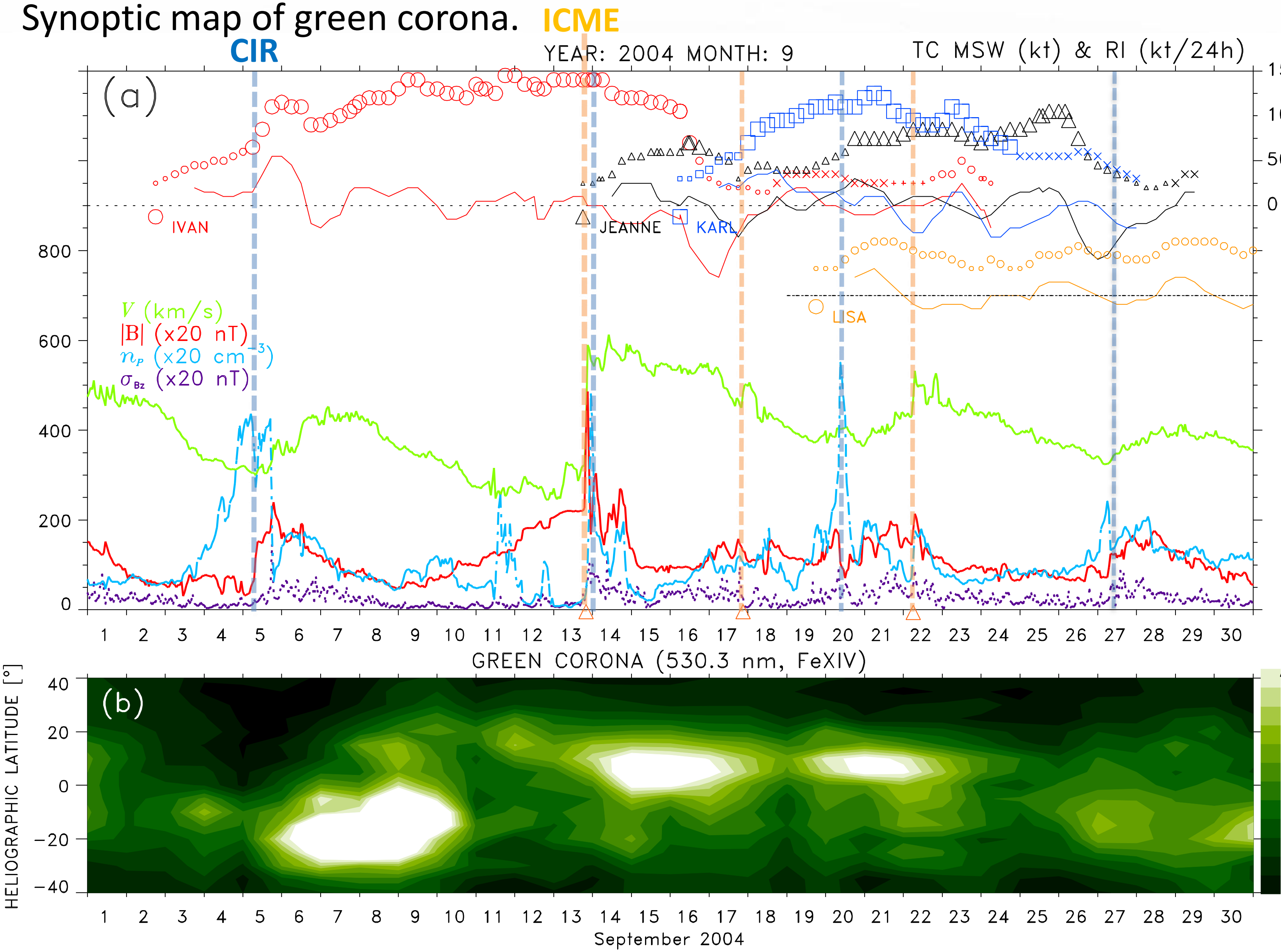
Prikryl et al., J. Atmos. Sol.-Terr. Phys., 183, 36–60, 2019.



Hurricanes in the North Atlantic in September 2004.

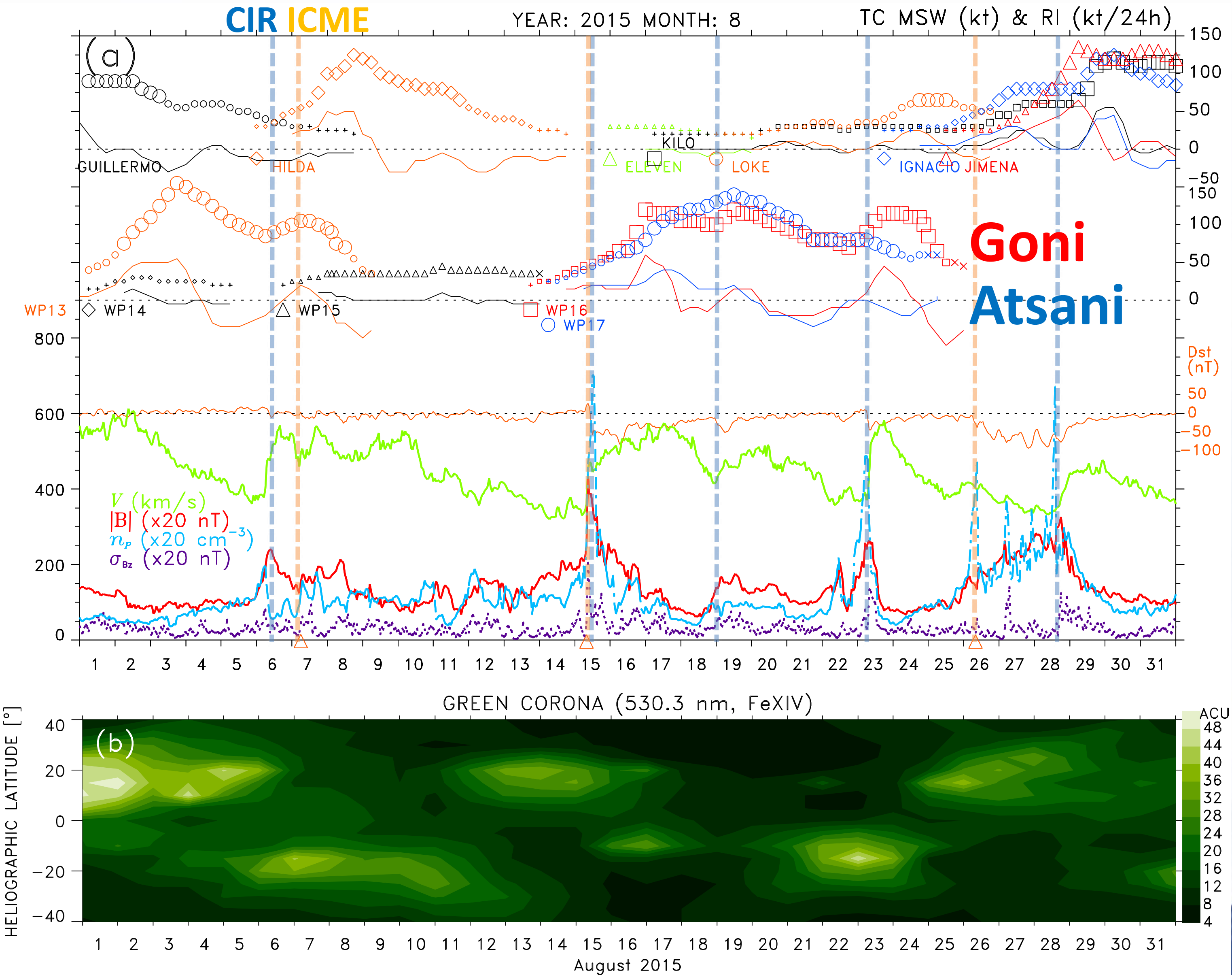
(a) (top) The “best track” TC data and (bottom) OMNI solar wind parameters

(b) Synoptic map of green corona.



Typhoons and hurricanes in the North Pacific in August 2015.

(a) (top) The “best track” TC data and (bottom) OMNI solar wind parameters and Dst index. (b) Synoptic map of green corona.



What is known about rapid intensification of TCs?

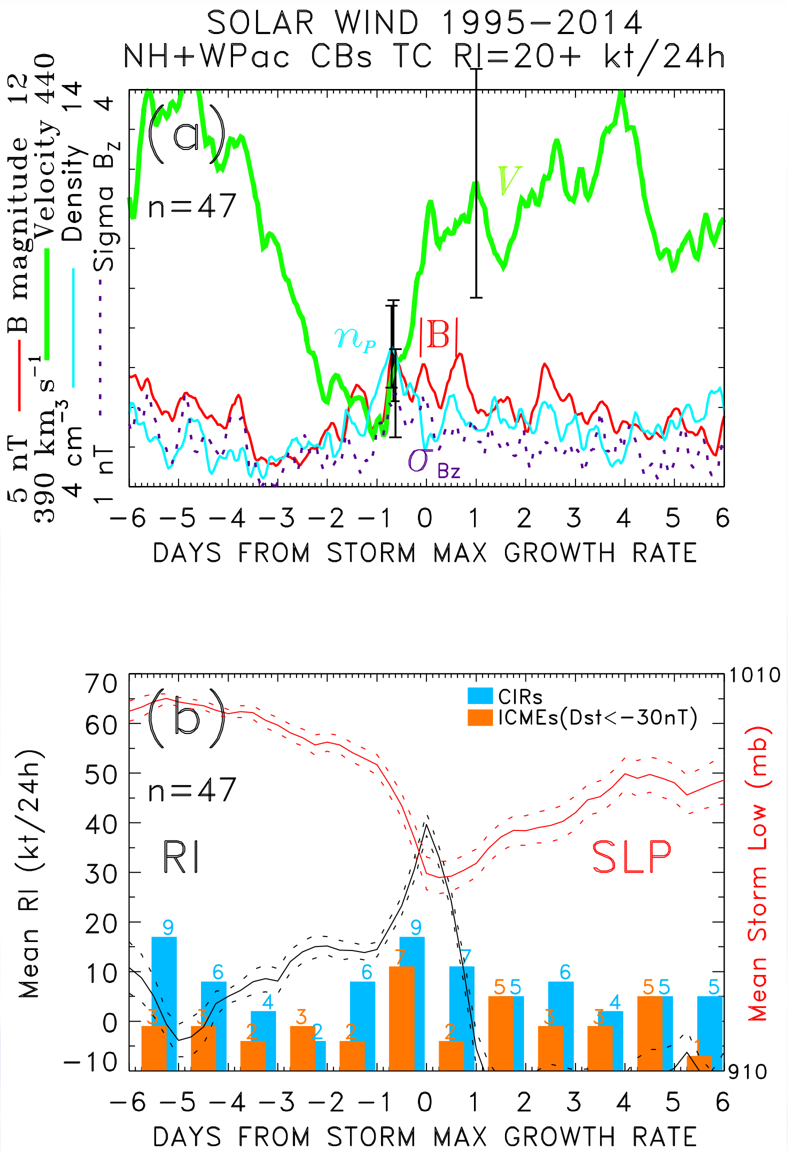
- RI of TCs still **poses a challenge to forecasting** TC intensity (Kaplan and deMaria, 2003)
- RI of TCs continues to be identified by National Hurricane Center (NHC) as their **number one priority for improvement** (Kaplan et al., 2010; Rappaport et al. 2009; Carrasco et al., 2014).
- While forecasts of motion of tropical cyclones have significantly improved over the last decades, **physical processes responsible for changes of tropical cyclone intensity are not well understood** (Wang and Wu, 2004).
- However, **convective bursts (CBs)** in TCs have been linked to tropical cyclone intensification (Steranka et al., 1986; Rodgers et al., 1998, 2000; Hennon, 2006; Oyama, 2018).

Convective bursts (CBs) and tropical cyclone intensification

TCs with CB episodes:

Rodgers et al., 1998, Mon. Wea. Rev., 126(5): 1229–1247.
Rodgers et al., 2000, J. Appl. Meteorol., 39, 1983–2006.
Hennon, (2006) Ph.D. Thesis.
Oyama, 2018, J. Meteor. Soc. Japan, 96B.

The SPE analysis of **(a)** solar wind plasma parameters and **(b)** SLP and RI keyed to the maximum intensification (RI = 20+ kt) of tropical cyclones associated with CBs. The occurrence distributions of major HSSs/CIRs (light blue) and ICMEs (orange) are shown.



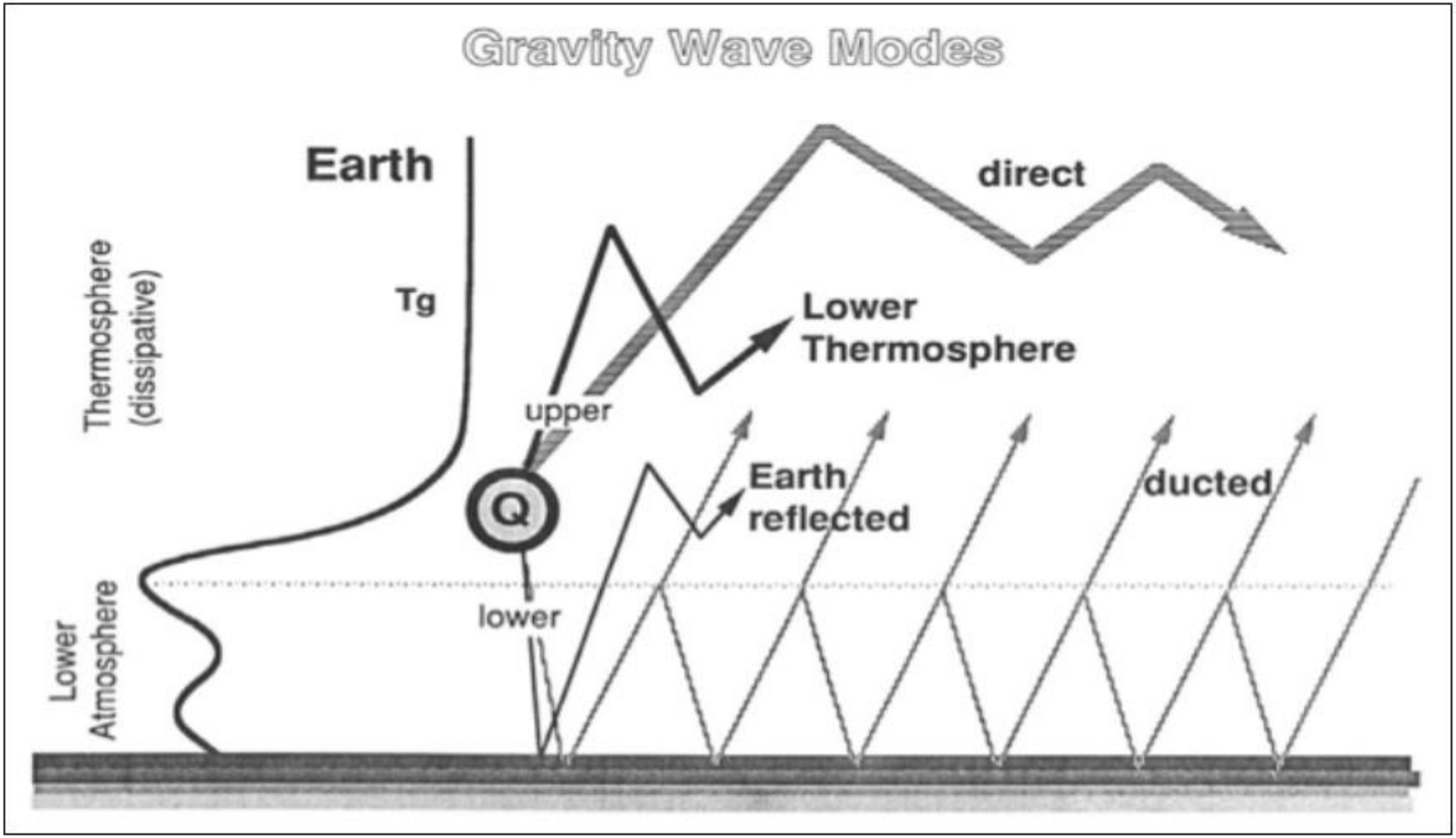
Prikryl et al., J. Atmos. Sol.-Terr. Phys., 183, 36–60, 2019.

Can convective bursts be triggered/initiated by aurorally-generated gravity waves?

Can convective bursts be triggered/initiated by aurorally-generated gravity waves?

Possible sources:

Joule heating, **Lorentz force** or energetic particle precipitation in the high-latitude lower thermosphere. (Chimonas and Hines, 1970; Chimonas, 1970; Testud, 1970; Richmond, 1978)

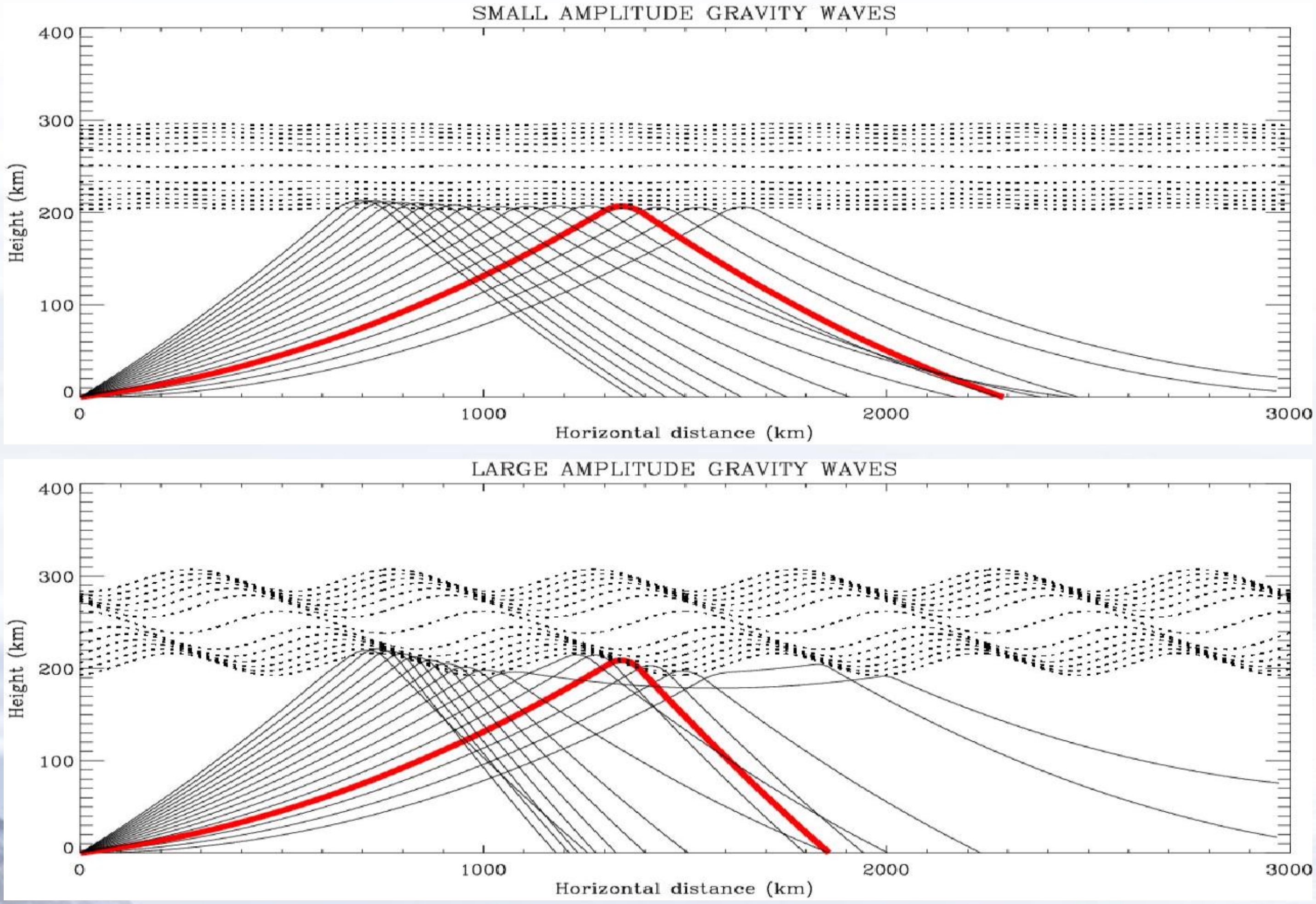


Mayr et al. (1990), Thermospheric gravity waves: Observations and interpretation using the transfer function model. Space Science Reviews 54, 297–375.

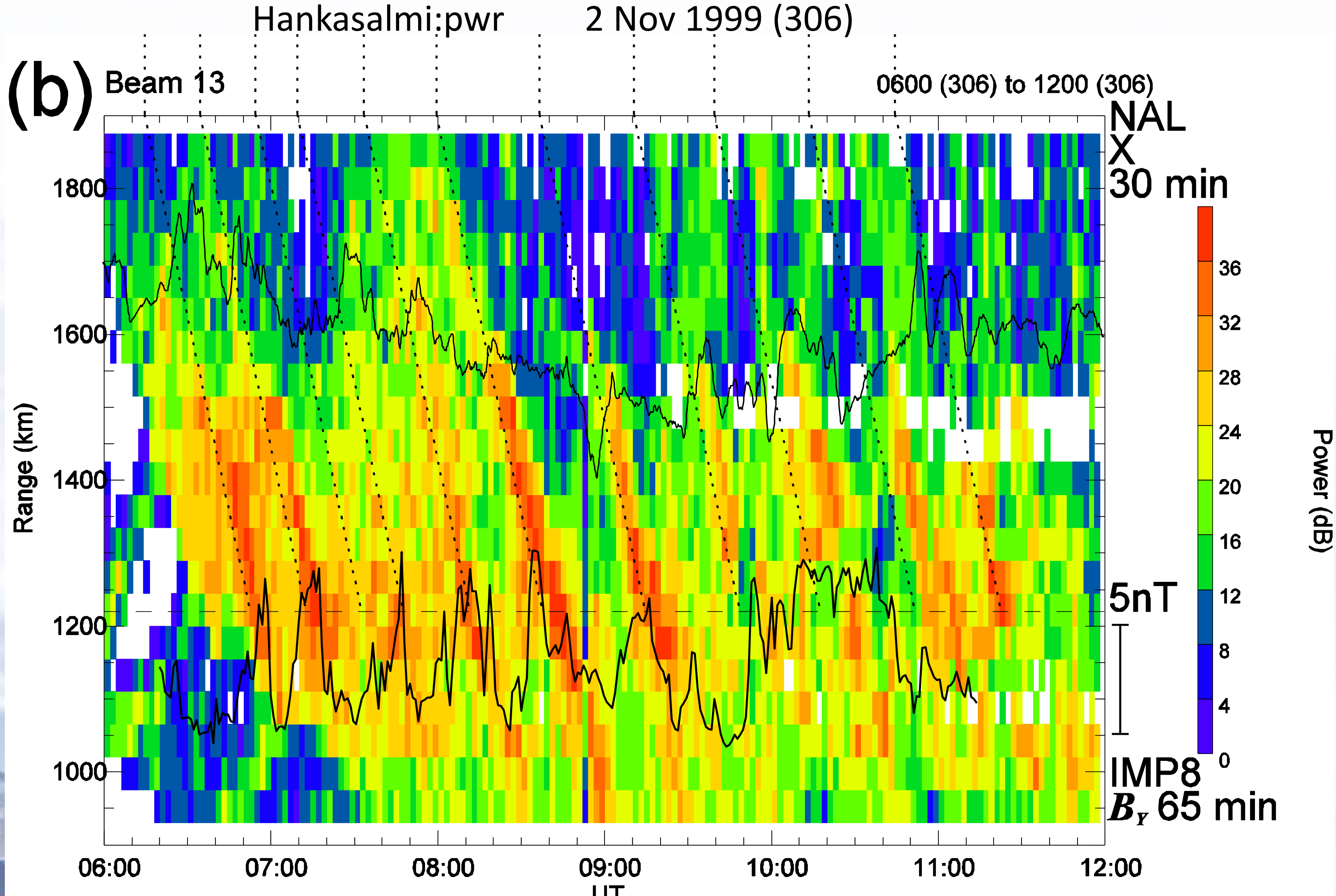
In the ionosphere, gravity waves are observed as traveling ionospheric disturbances (TIDs)

using ionosondes, HF radars, GPS/Total Electron Content (TEC)

13-MHz ray tracing in the ionosphere perturbed by atmospheric gravity waves

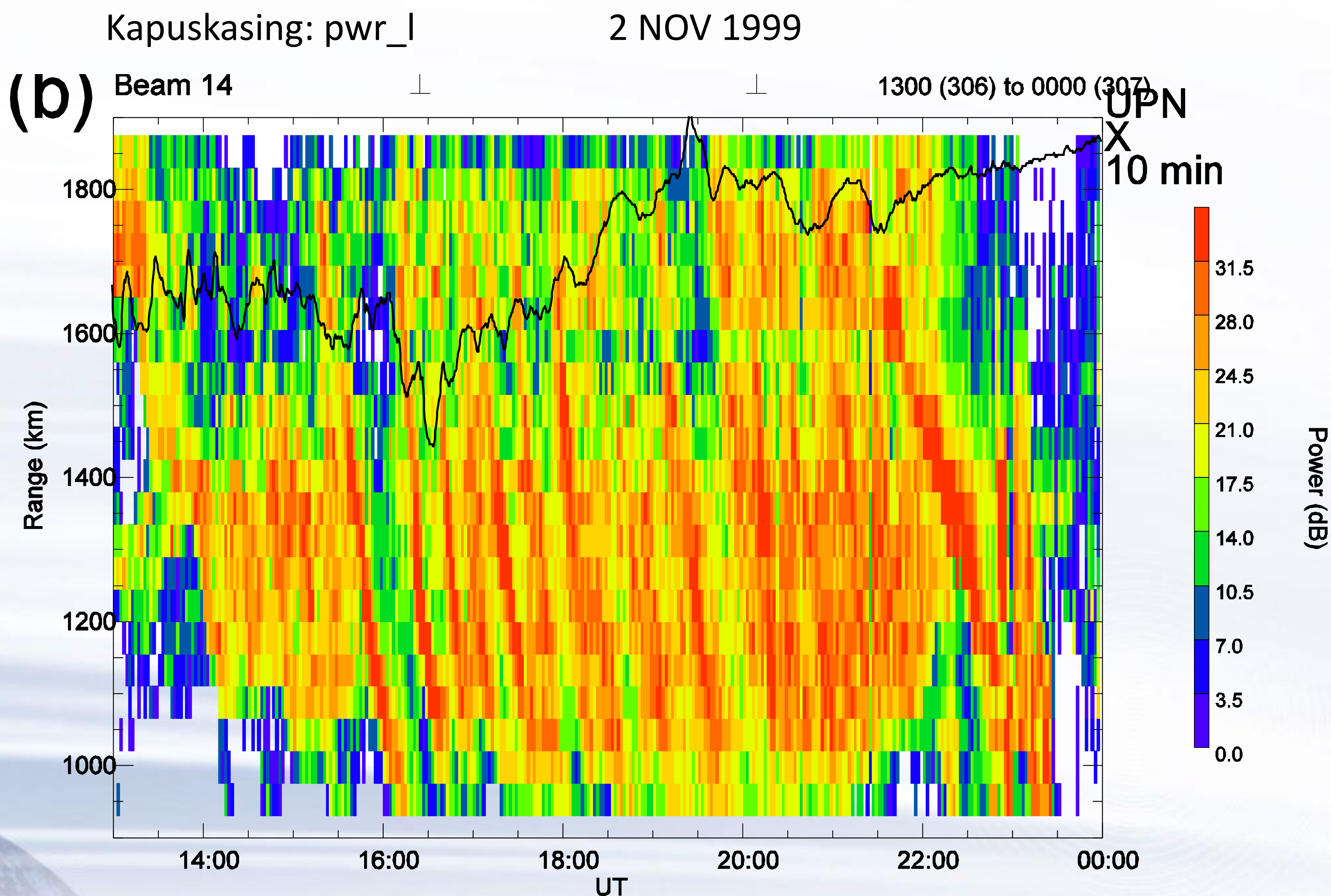


TIDs/atmospheric gravity waves generated by solar wind Alfvén wave coupling to MIA



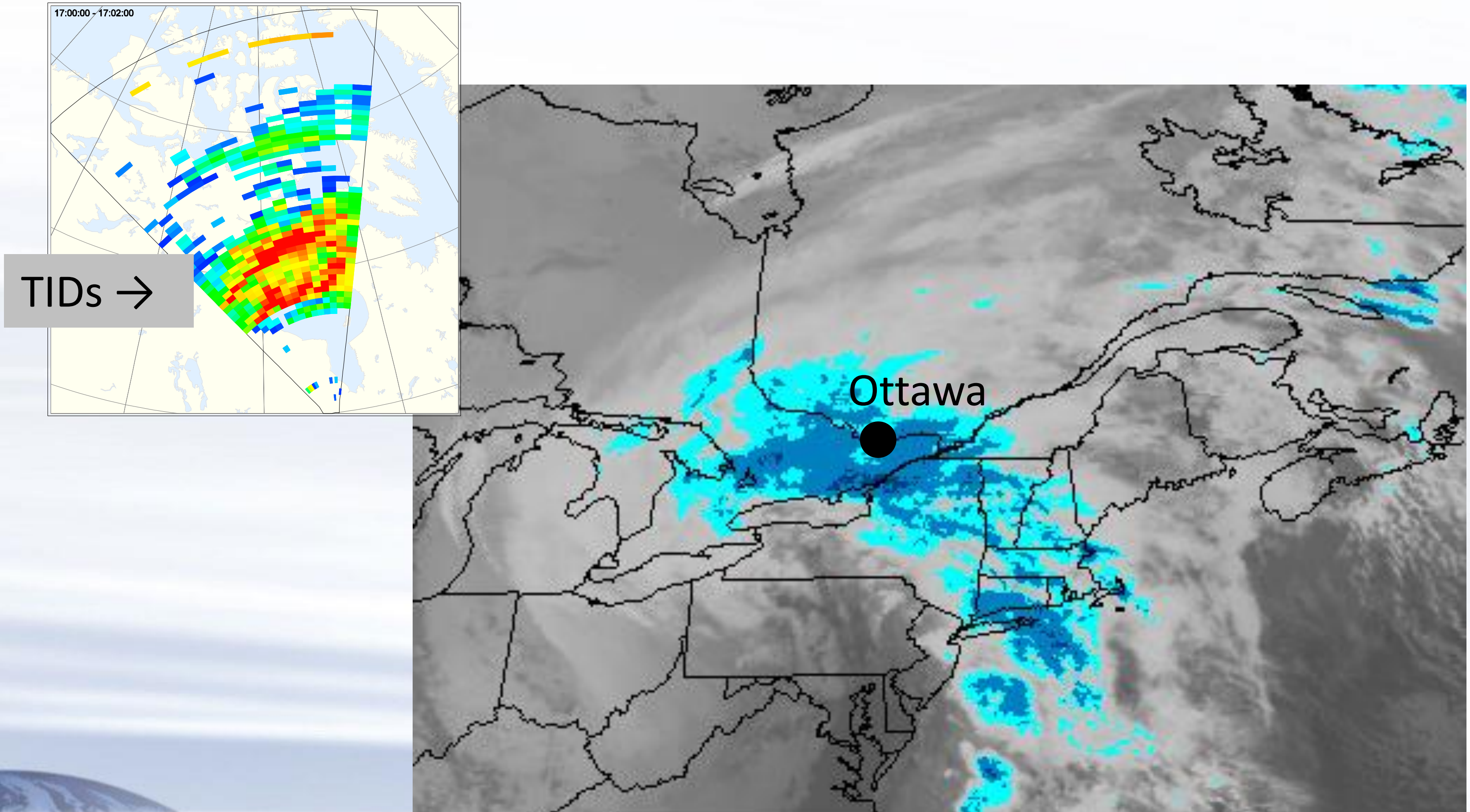
Prikryl et al., Ann. Geophys., 23, 401-417, 2005.

Traveling Ionospheric disturbances



Series of cloud bands in a mid-latitude cyclone

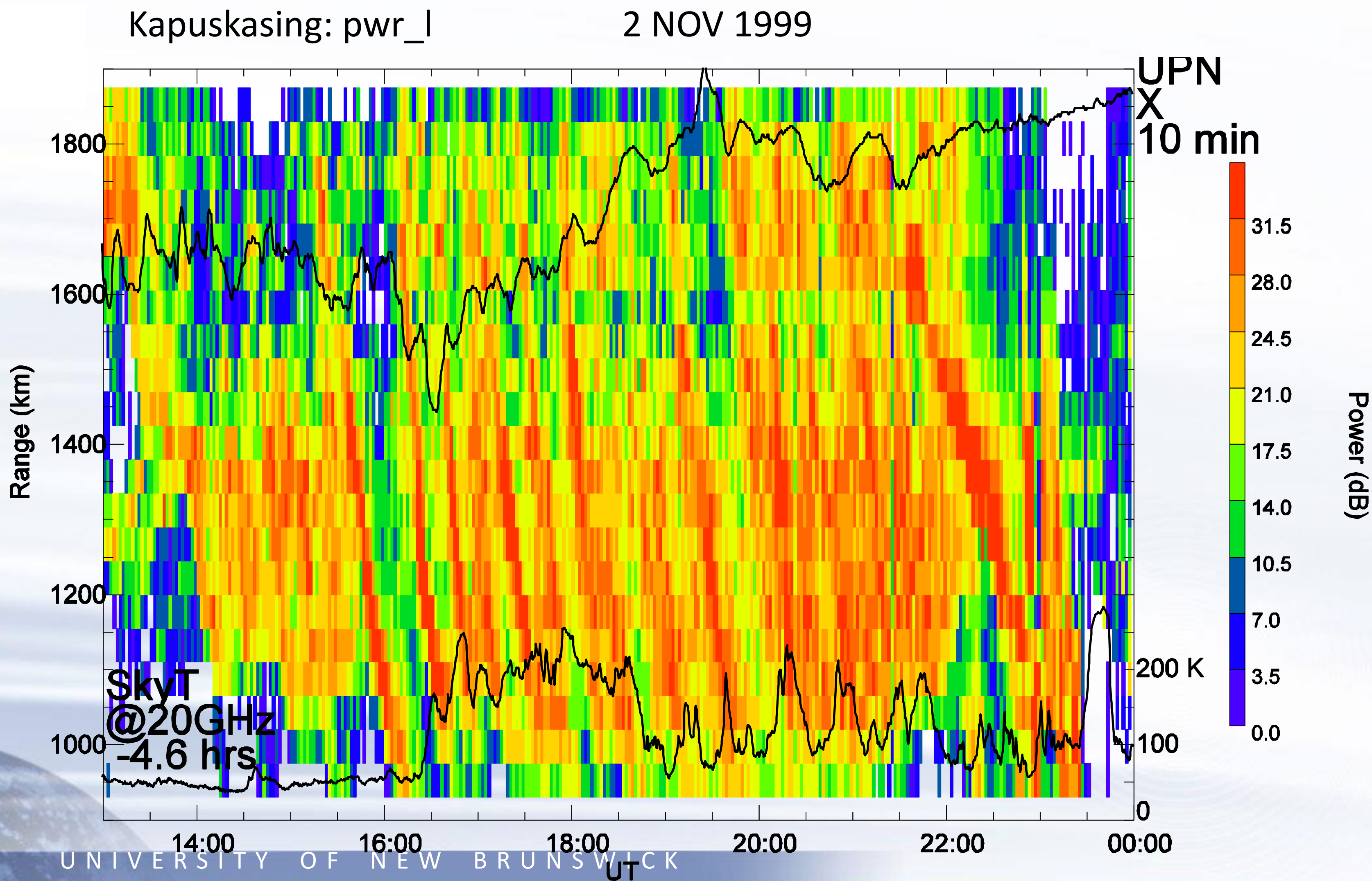
(dark blue indicates the lowest cloud-top temperature)



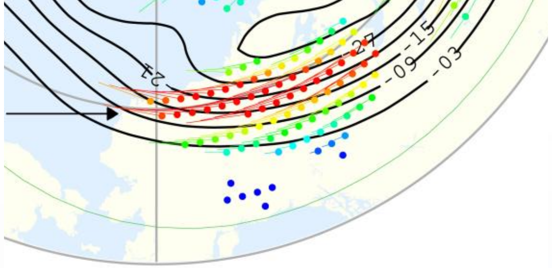
GOES-8 Infrared image 2 NOV 1999 23:45 UTC

Prikryl et al., Ann. Geophys., 27, 31–57, 2009.

Correlation between PIFs/TIDs and rain bands observed by radiometer in Ottawa

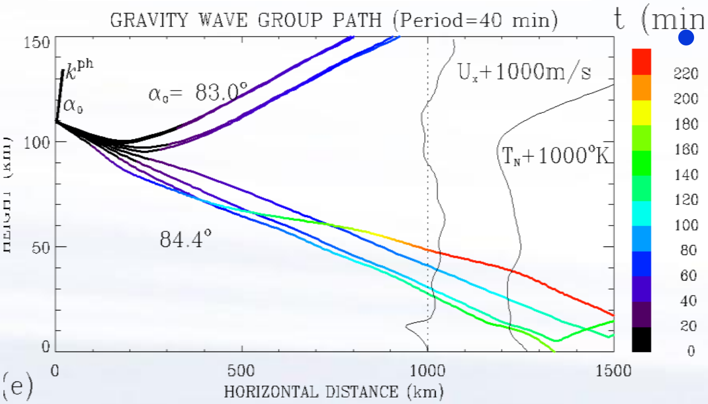


Prikryl et al., Ann. Geophys., 27, 31–57, 2009.



Ray tracing gravity waves

- Solar wind pressure pulses modulated ionospheric convection – a source of TIDs
- **Ray tracing gravity wave energy (group) using dispersion relation by Hines (1960)**

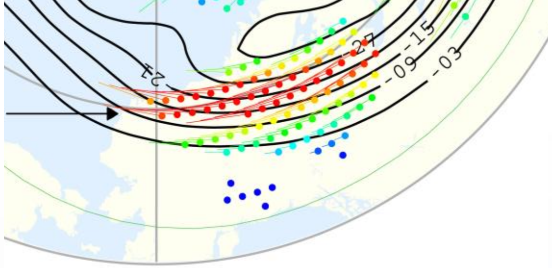


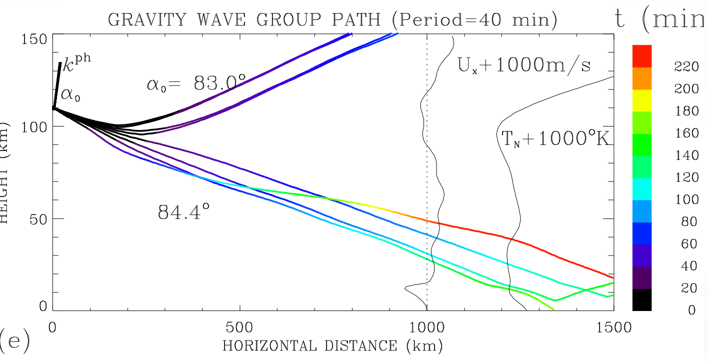
$$(\omega^2 - \omega_a{}^2)\,\omega^2 / C^2 - \omega^2 (k_x{}^2 + k_z{}^2) + \omega_b{}^2 k_x{}^2 = 0$$

$\omega_a = \gamma g/2C$ is the acoustic cutoff frequency,
γ, C, g are the ratio of specific heats, speed of sound,
and acceleration due to gravity,
k_x and k_z are the components of the wave vector **k**.

Brunt-Väisälä (buoyancy) frequency ω_b is defined as

$$\omega_b{}^2 = (\gamma\text{-}1)g^2 / C^2 + (g / C^2)\,(dC^2 / dz)$$





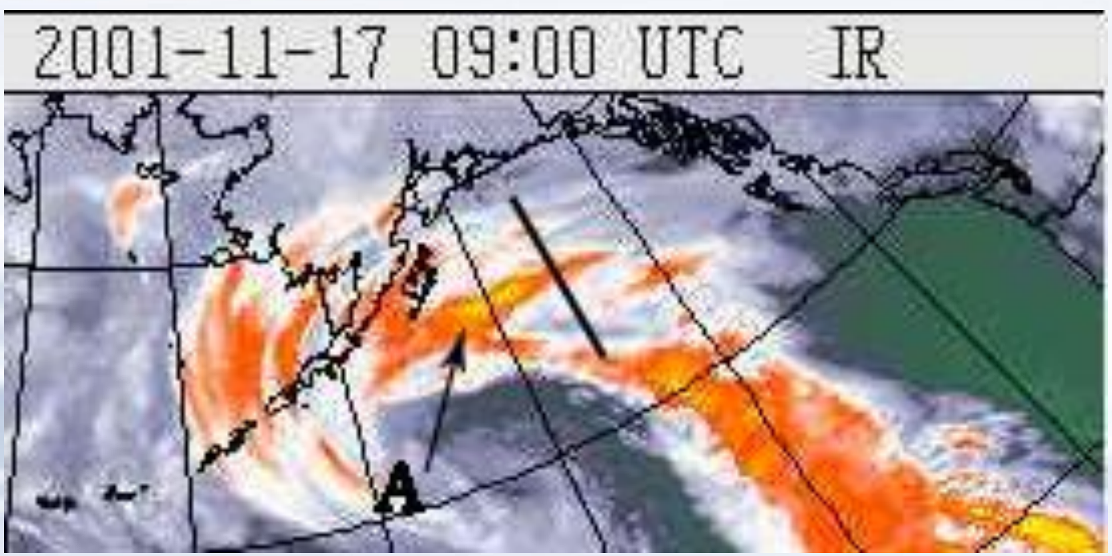
Gravity waves initiate convection

- Solar wind pressure pulses modulated ionospheric convection – a source of TIDs

  Ray tracing of gravity wave energy

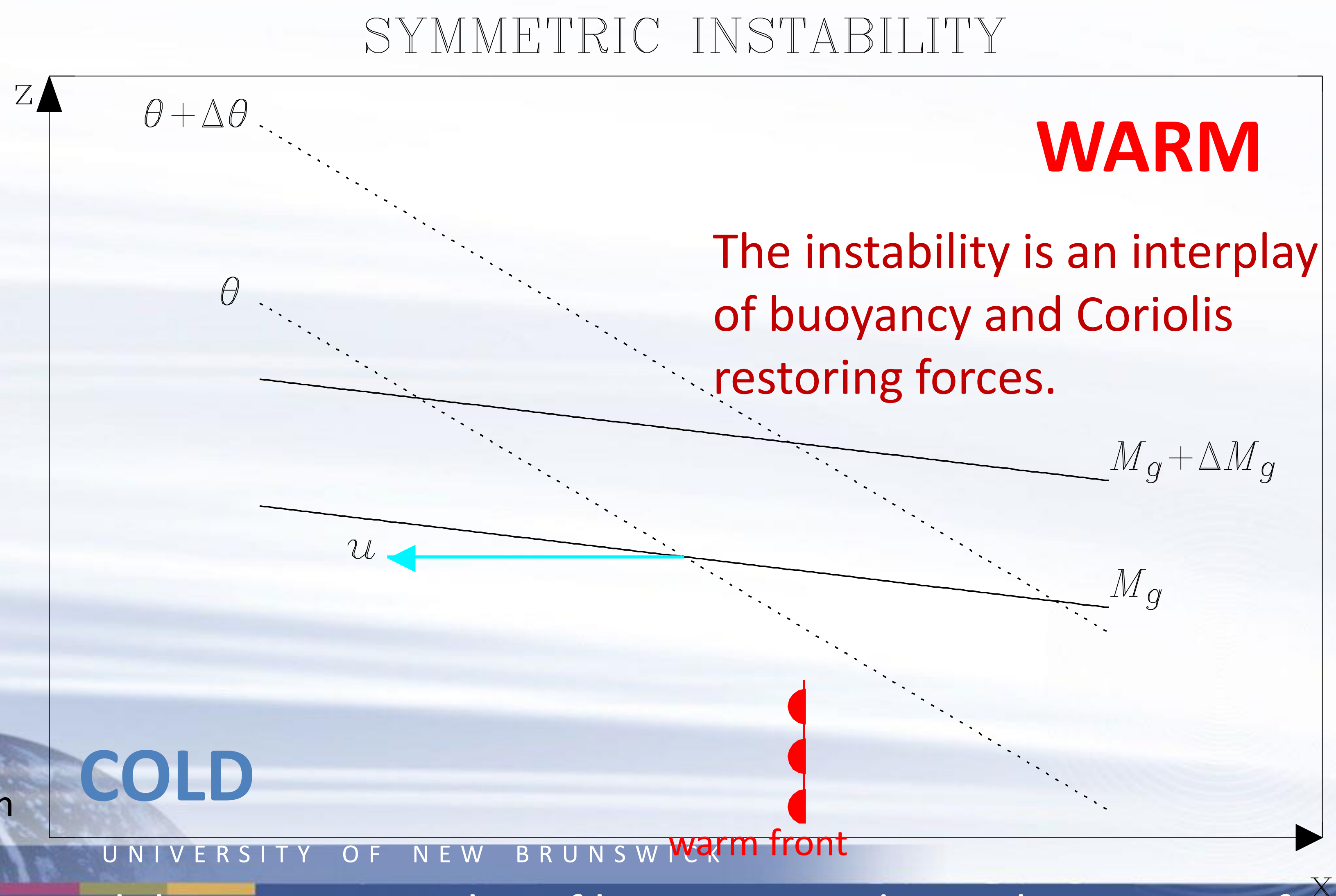
  using dispersion relation by Hines (1960)

  Down-going GWs reach troposphere may initiate convection forming cloud bands in extratropical cyclones.



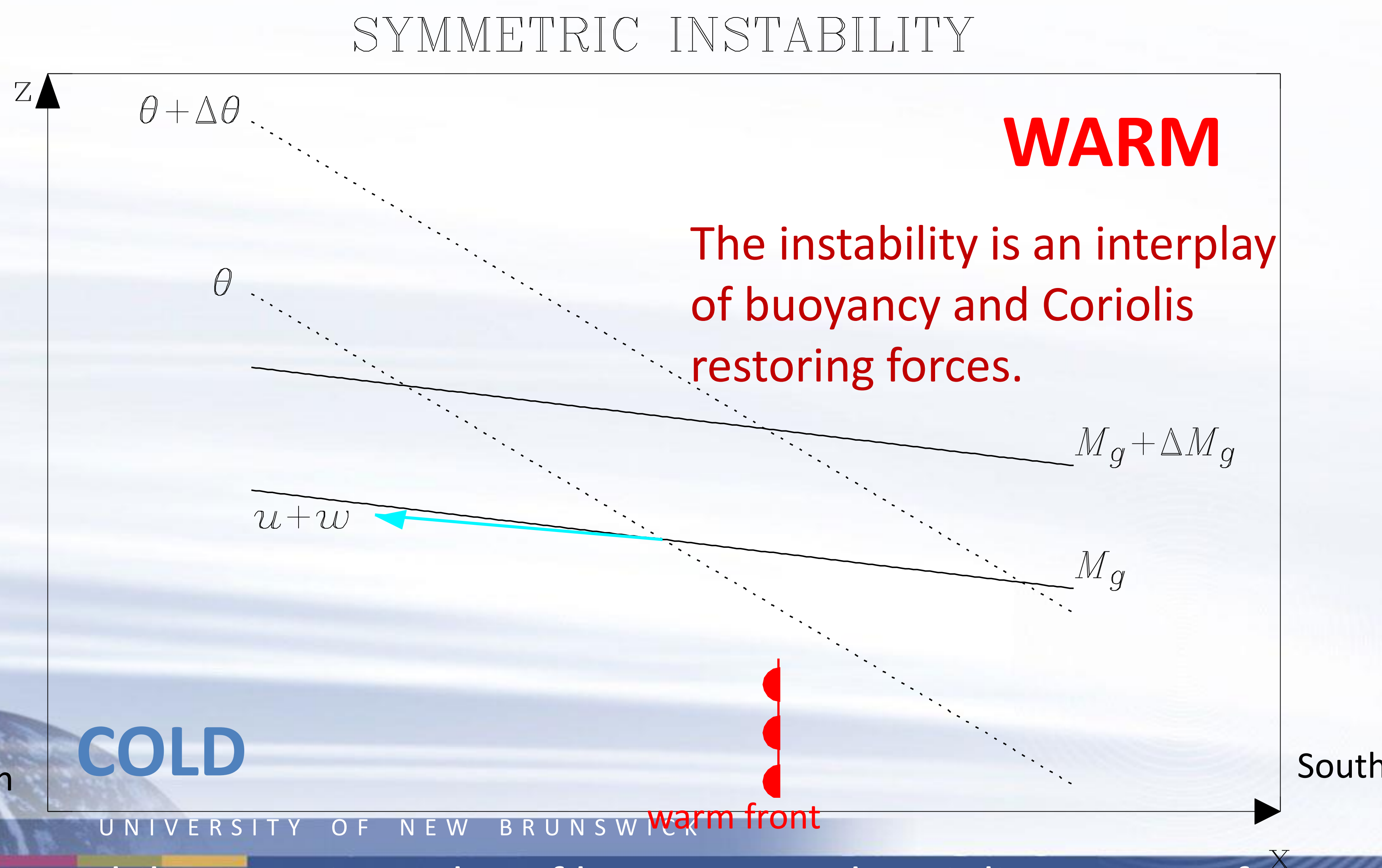
Prikryl et al., Ann. Geophys., 27, 1–30, 2009.

Cross-section of warm frontal zone



The instability is an interplay of buoyancy and Coriolis restoring forces.

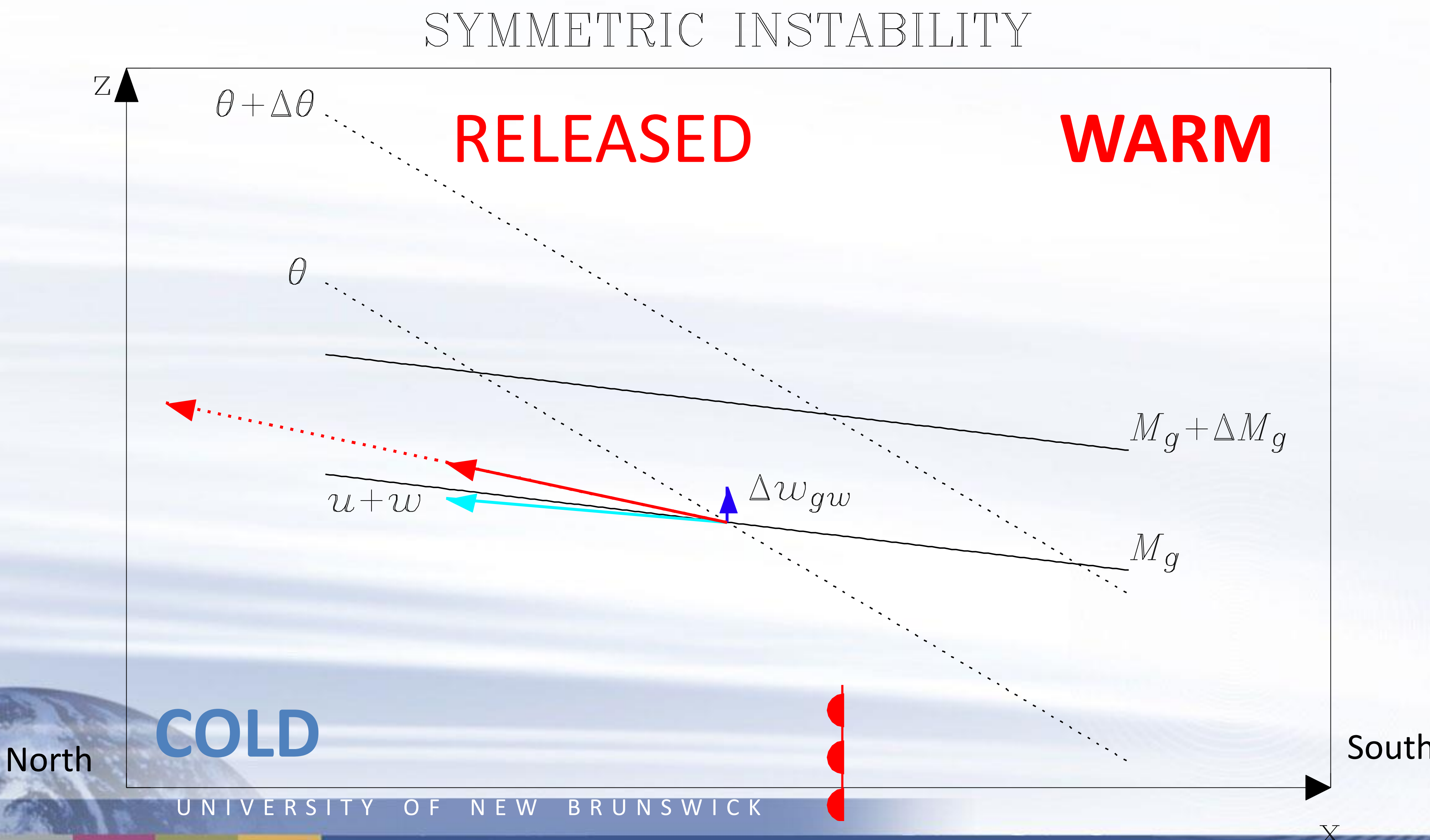
Warm air rising over cold air



The instability is an interplay of buoyancy and Coriolis restoring forces.

Slantwise convection initiated by AGWs

The slopes of isolines of potential temperature θ and geostrophic momentum Mg in the x-z plane are such that $\partial\theta/\partial z > 0$ and $\partial Mg/\partial x > 0$, meaning that **the atmosphere is stable to purely vertical and horizontal displacements**.



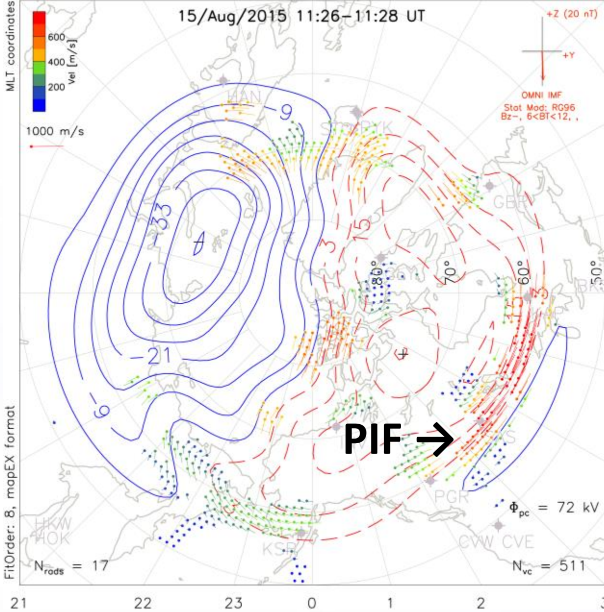
The instability is an interplay of buoyancy and Coriolis restoring forces.

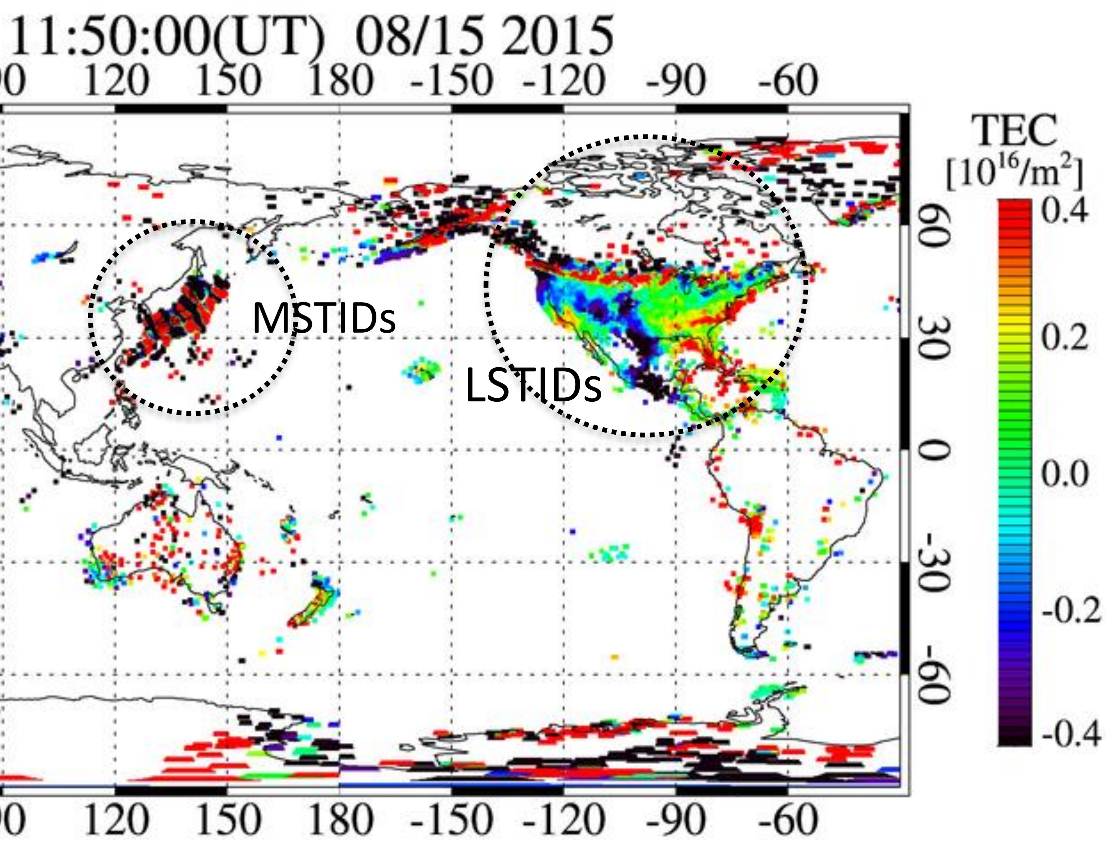
MSTIDs and LSTIDs in GNSS/TEC that preceded intensification of Goni & Atsani

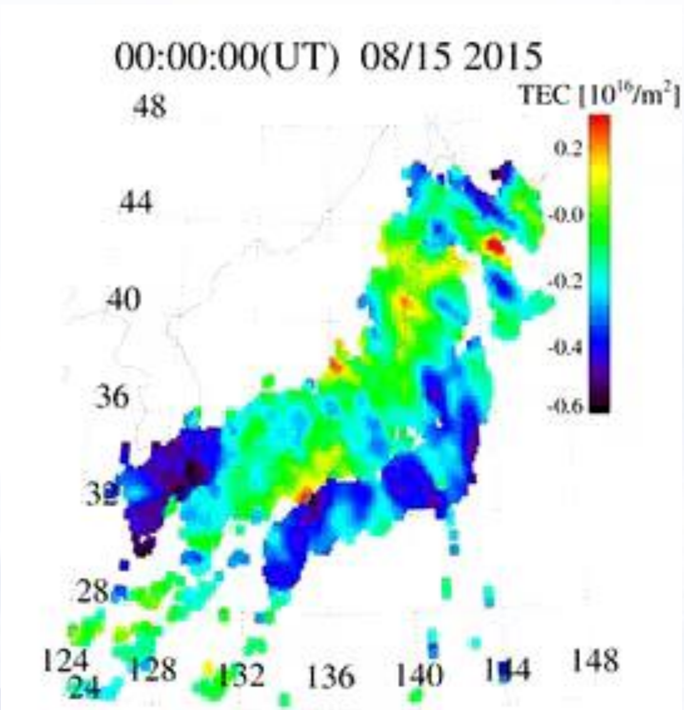
DRAWING-TEC

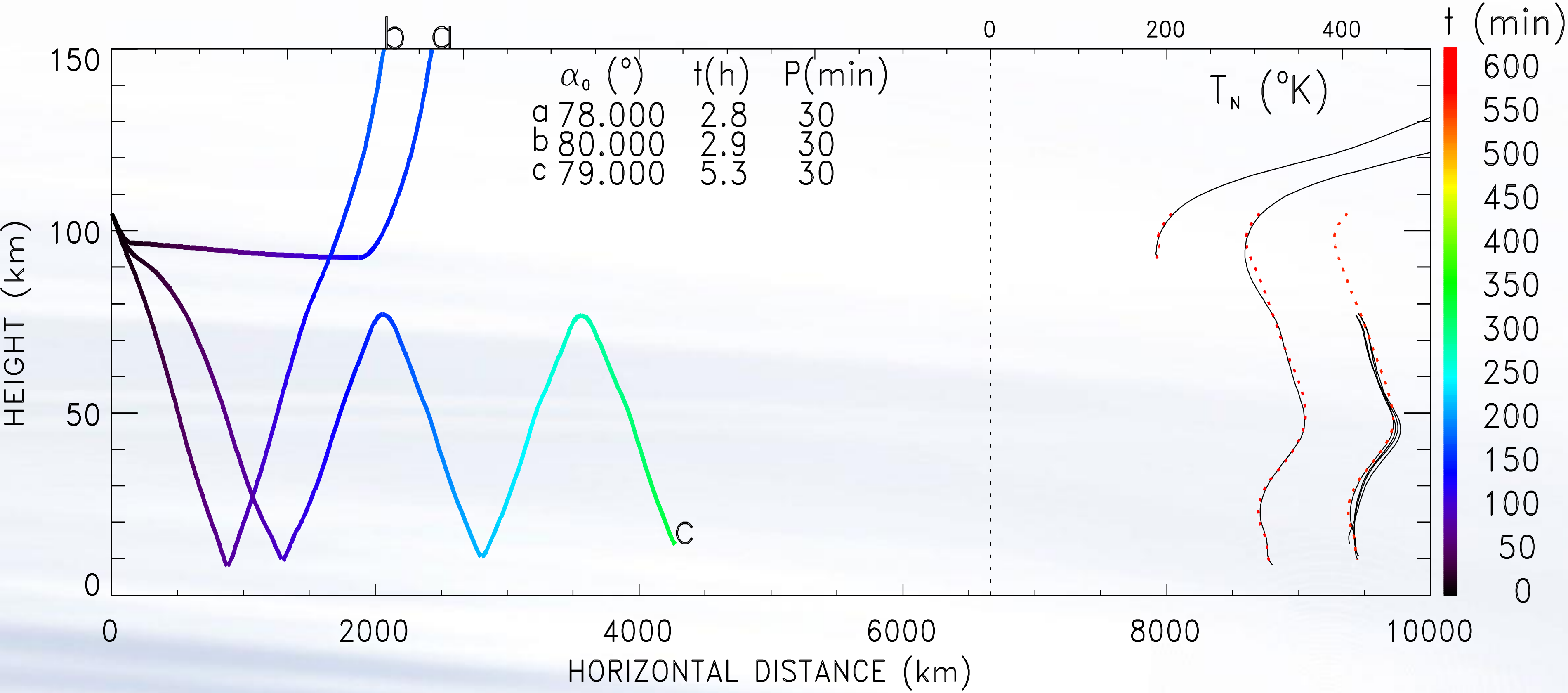
http://seg-web.nict.go.jp/GPS/N_AMRC/MAP/

Global Detrended TEC map (60-min window)

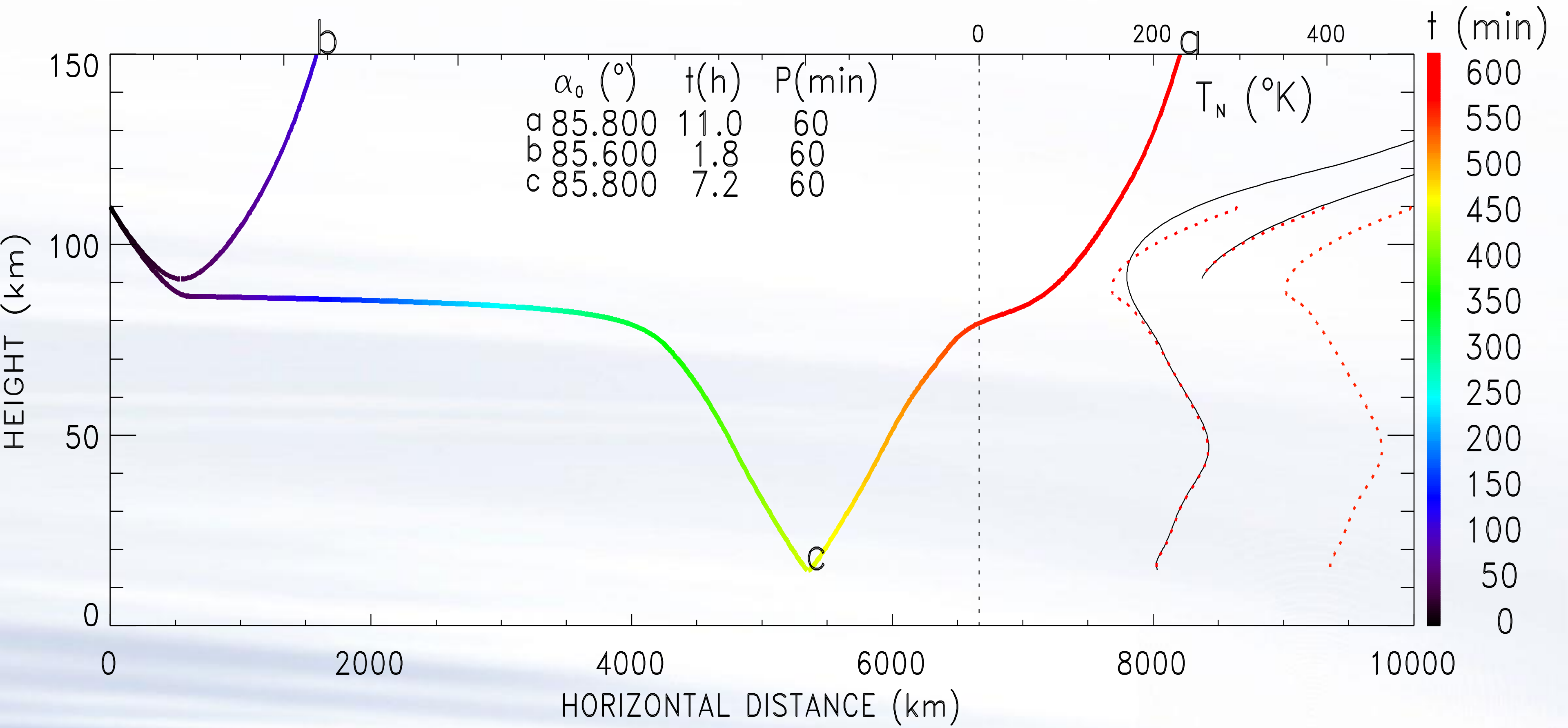






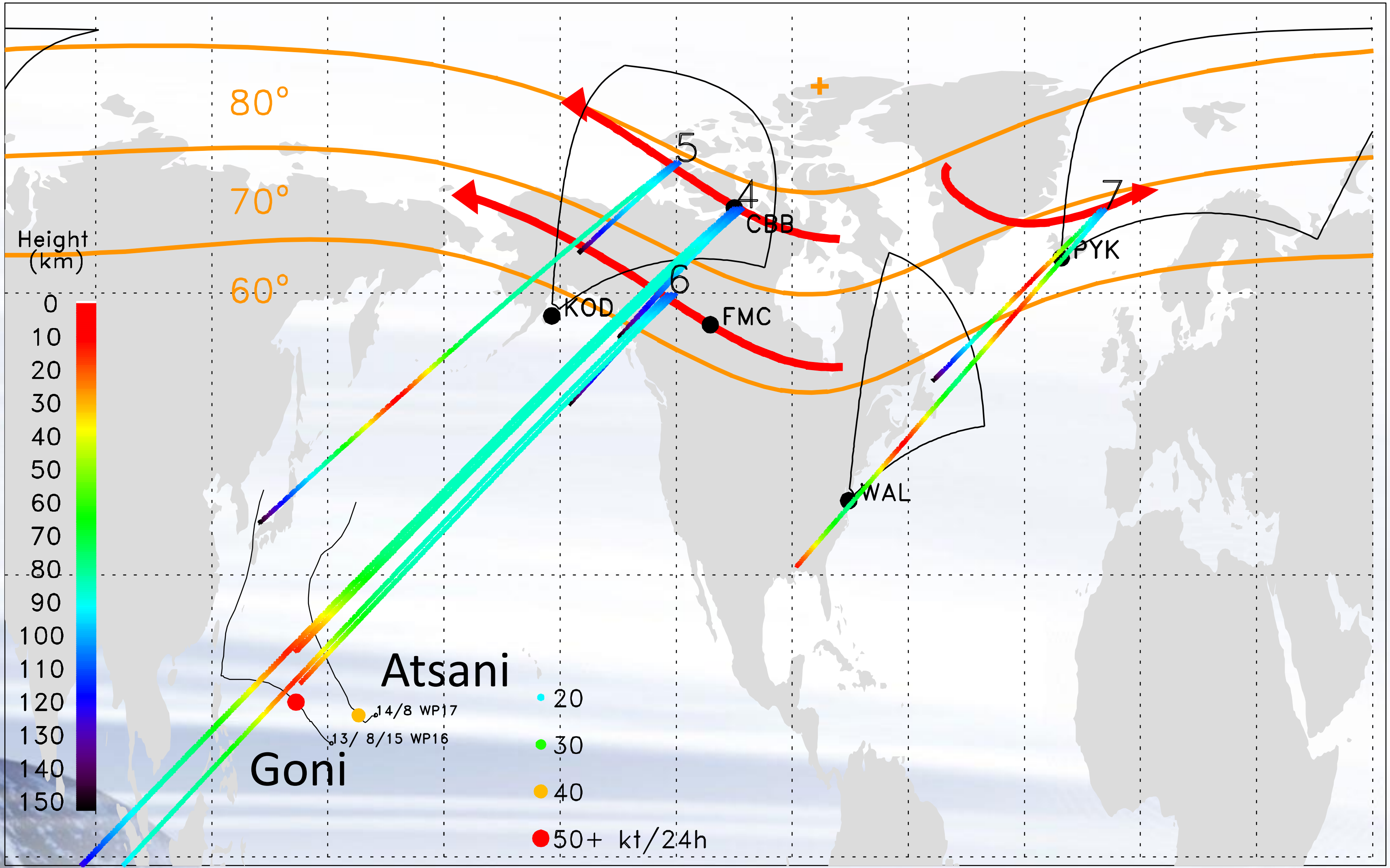


b a
150
100
50
0
HEIGHT (km)
α_0 (°) t(h) P(min)
a 78.000 2.8 30
b 80.000 2.9 30
c 79.000 5.3 30
c
0 2000 4000 6000 8000 10000
HORIZONTAL DISTANCE (km)
0 200 400
T_N (°K)
t (min)
600 550 500 450 400 350 300 250 200 150 100 50 0



b
a
c
0
200
400
t (min)
150
100
50
0
α_0 (°) t(h) P(min)
a 85.800 11.0 60
b 85.600 1.8 60
c 85.800 7.2 60
T_N (°K)
600
550
500
450
400
350
300
250
200
150
100
50
0
HEIGHT (km)
0
2000
4000
6000
8000
10000
HORIZONTAL DISTANCE (km)

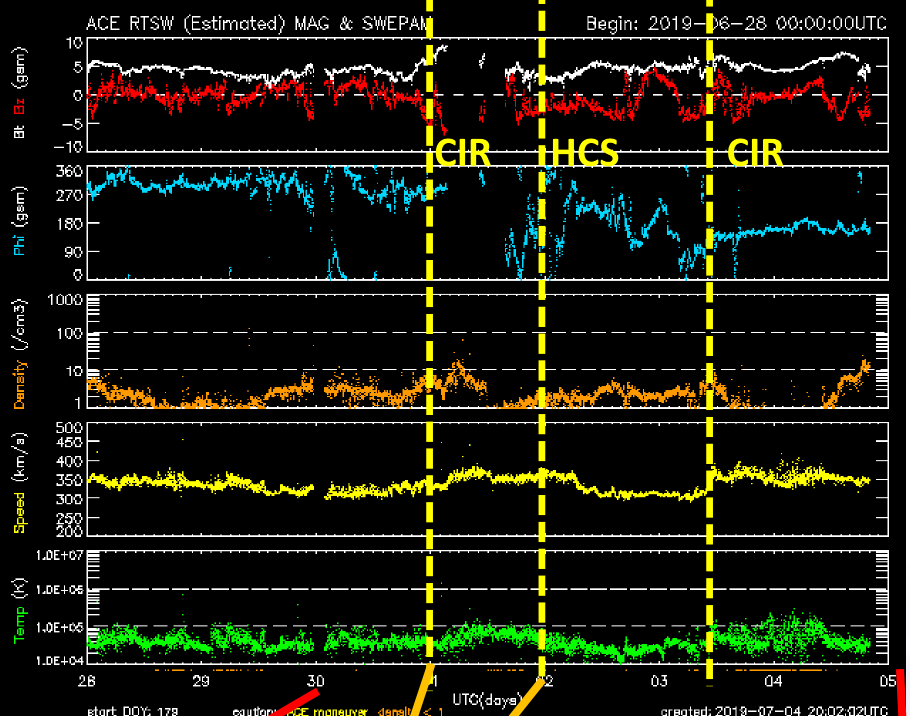
Ray tracing gravity waves: the group rays coded with altitude are projected on the map

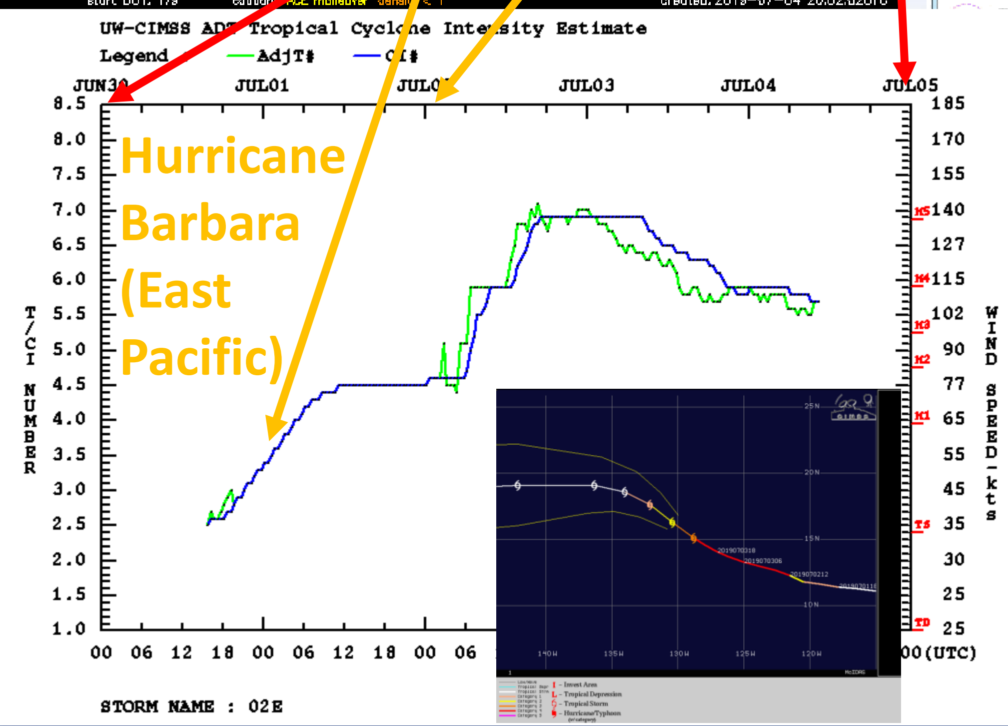


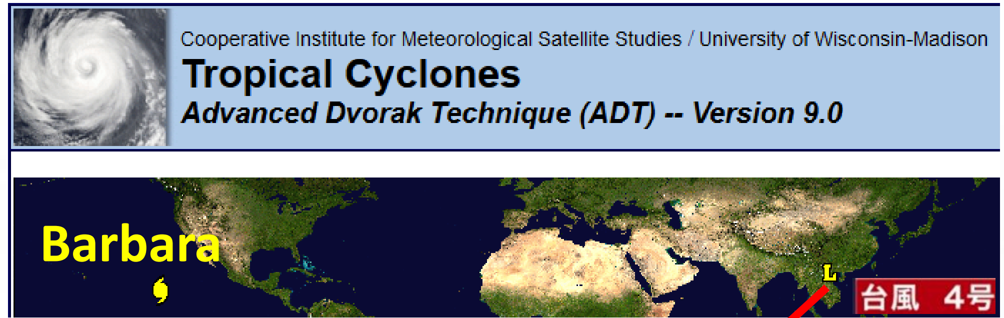
Summary and Conclusions

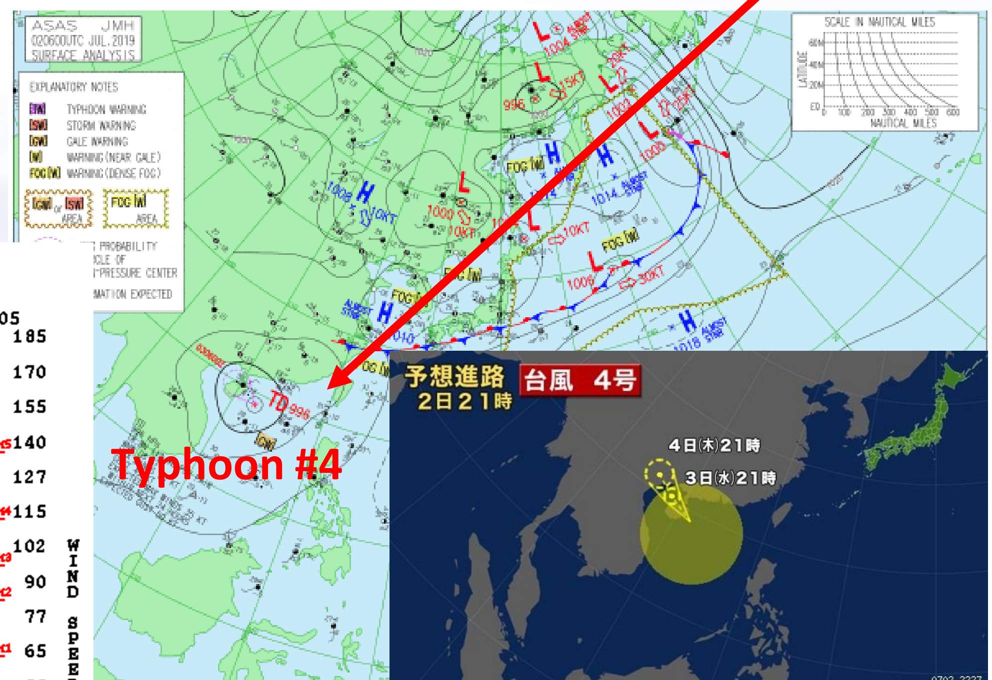
- Explosive extratropical cyclones, significant weather events and rapid intensification of TCs tend to follow arrivals of HSS/CIRs or ICMEs.
- The coupling of solar wind (Alfvén waves) to magnetosphere-ionosphere-atmosphere generates atmospheric gravity waves (AGWs).
- AGWs propagate globally from lower thermosphere at high latitudes upward & downward, can be ducted and reach middle and low latitudes.
- They can trigger/release moist instabilities, convective bursts leading to increased atmospheric circulation and rapid development of tropospheric weather.

30 June -5 July, 2019







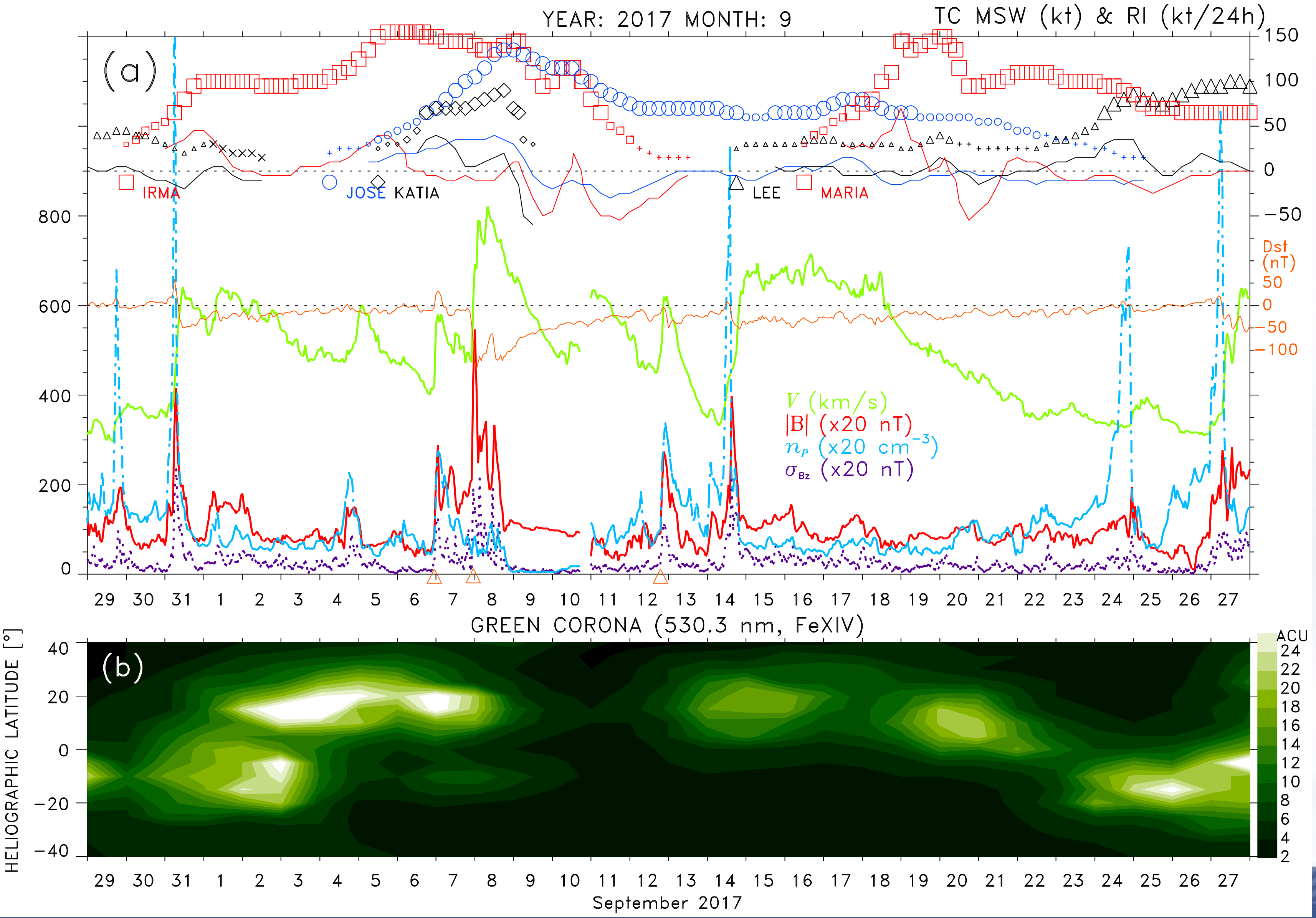


Thank you

Hurricanes in the North Atlantic in September 2017.

(a) (top) The “best track” TC data and (bottom) OMNI solar wind parameters

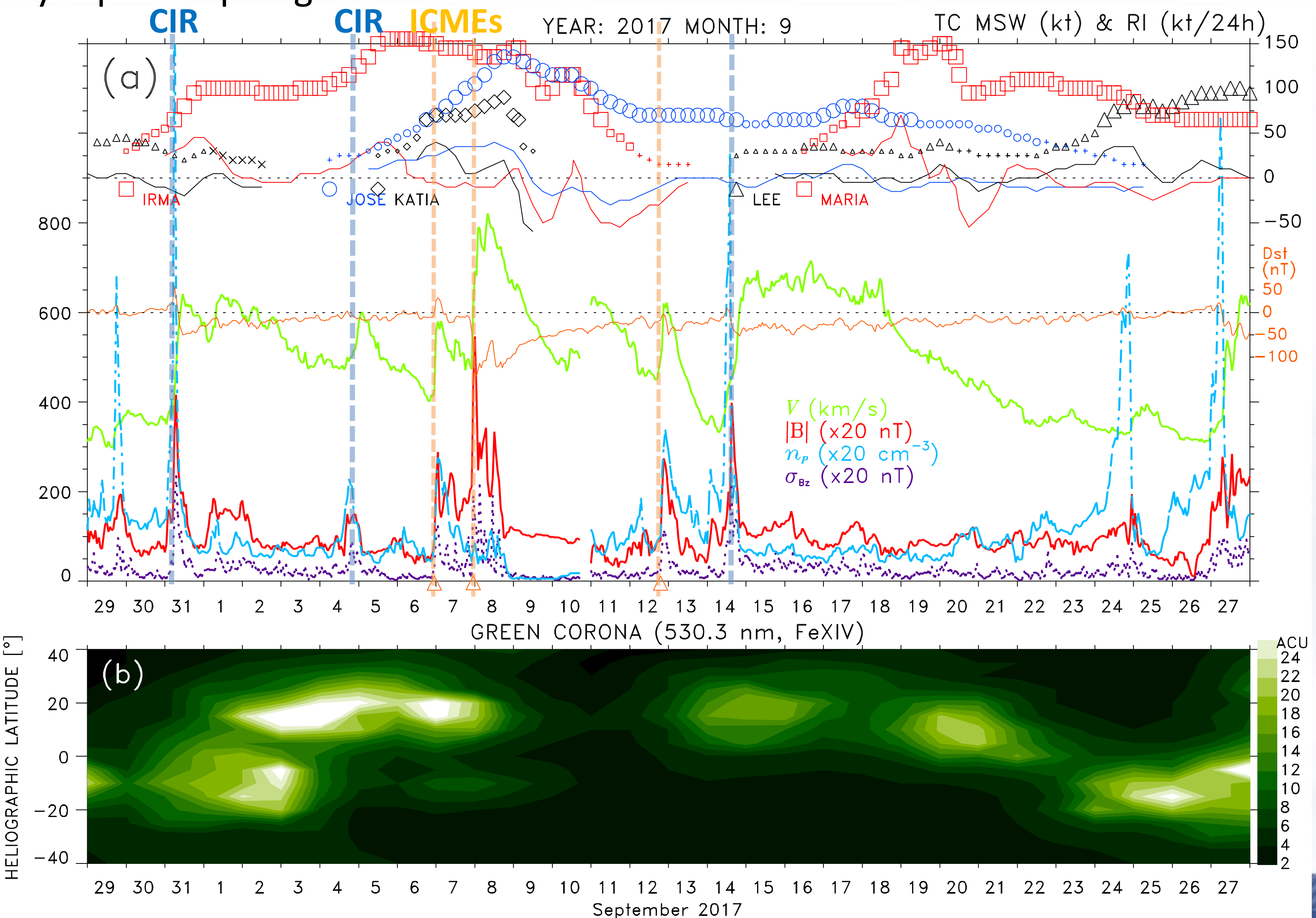
(b) Synoptic map of green corona.



Hurricanes in the North Atlantic in September 2017.

(a) (top) The "best track" TC data and (bottom) OMNI solar wind parameters

(b) Synoptic map of green corona.



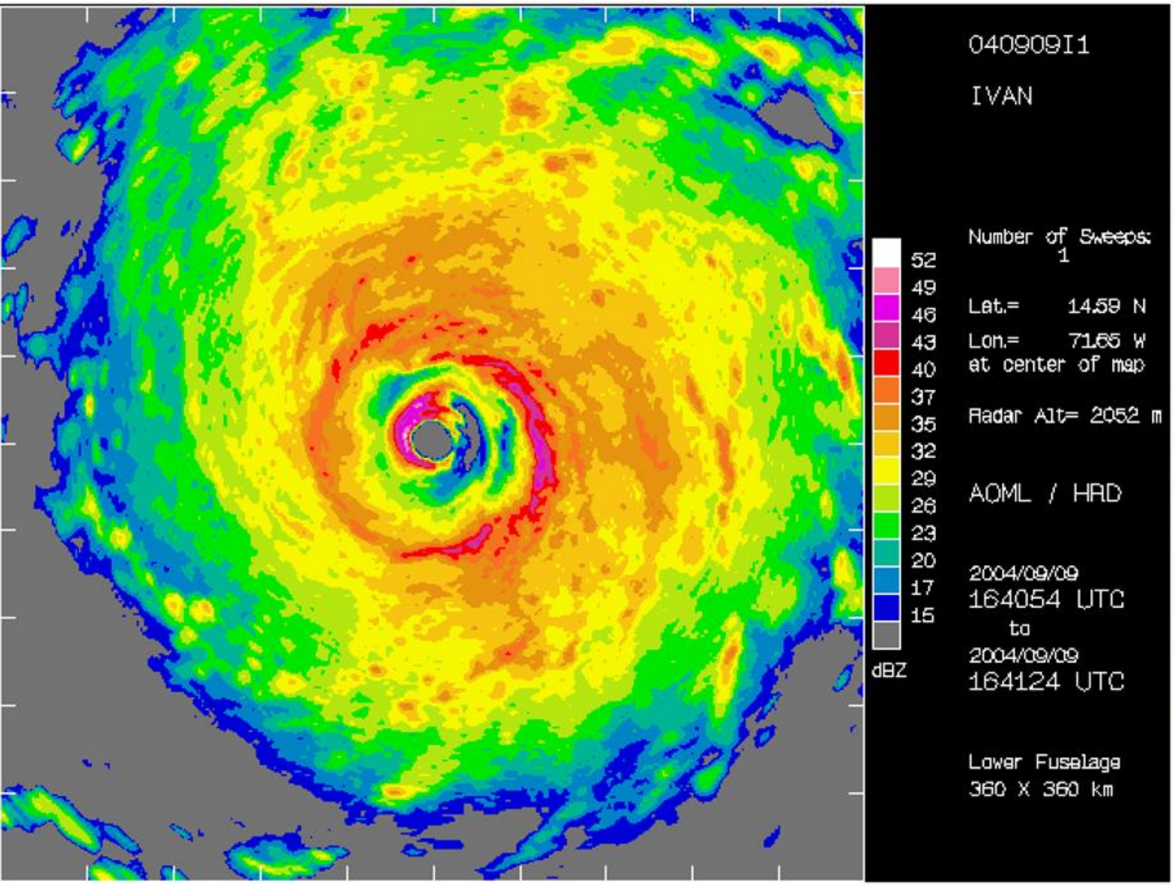
What is known about rapid intensification of TCs?

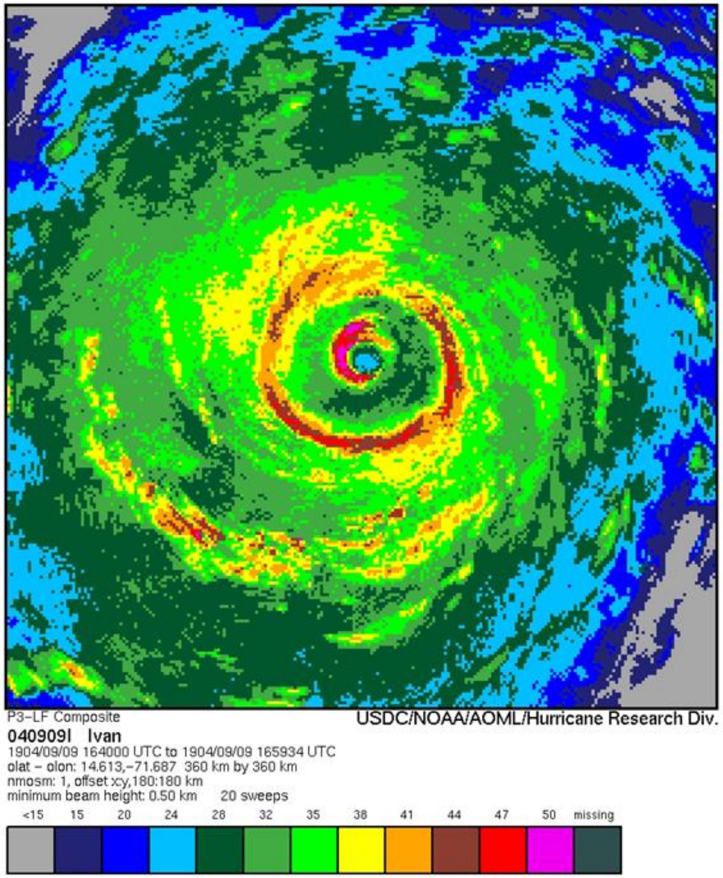
- Focus on a “**new paradigm”:** Strong axial asymmetry of rapidly developing storms (Montgomery and Smith, 2014).
- TC **eyewall replacement cycle (ERC)** (Willoughby et al.,1982) is now one of the well-established paradigm.

Convective bursts in hurricane Ivan in September 2004

- ## *TC eyewall replacement cycle (ERC)*

NOAA/HRD WP-3D lower-fuselage radar reflectivity (left) single sweep and (right) a composite of 20 sweeps obtained between 16:40 and 17:00 UT on Sept. 9, 2004. (http://www.aoml.noaa.gov/hrd/Storm_pages/ivan2004/radar.html).



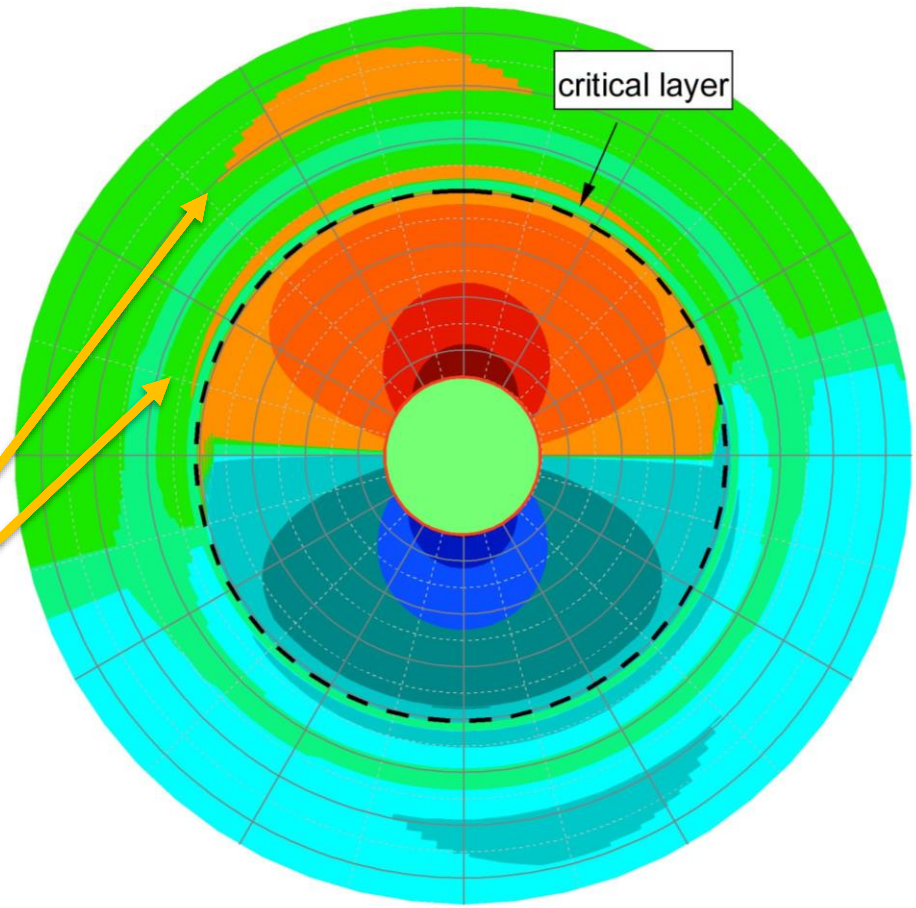


Vortex Rossby waves and formation of spiral bands

Nikitina and Campbell (2015 a,b) presented asymptotic solutions for a problem representing vortex waves propagation in a tropical cyclone and considered the interaction between the waves and the mean flow in the vortex.

Nikitina L.V., Campbell L.J., Stud. Appl. Math., 135, 377–446, 2015.

The perturbation **wave number equals to one** to represent the **asymmetric convective bursts**. **Waves are absorbed at the critical radius** (layer) with the phase shift and decreasing of the amplitude. The stream function positive values are coded in red-orange color. The orange arcs – ”spiral sleeves” beyond the critical radius represent the **outward propagating spiral bands of the hurricane**.



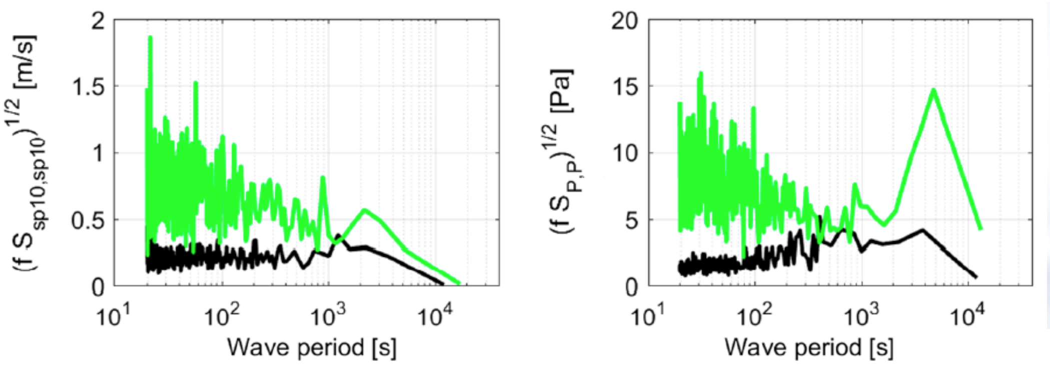
Prikryl et al., J. Atmos. Sol.-Terr. Phys., 183, 36–60, 2019.

Spiral gravity waves radiating from tropical cyclones

David S. Nolan[1] and **Jun A. Zhang**[2,3] Geophys. Res. Lett., 44, 3924–3931, 2017.

[1]Department of Atmospheric Sciences, University of Miami, Miami, Florida, USA, [2]Hurricane Research Division, NOAA/AOML, Miami, Florida, USA, [3]Cooperative Institute for Marine and Atmospheric Sciences, University of Miami, Miami, Florida, USA

Abstract Internal gravity waves are continuously generated by deep moist convection around the globe. Satellite images suggest that tropical cyclones produce short-wavelength, high-frequency waves that radiate outward, with the wave fronts wrapped into tight spirals by the large differential advection of the sheared tangential flow. This letter presents new in situ observations of such waves from two sources: flight level data from research aircraft that show radial wavelengths of 2–10 km and vertical velocity magnitudes from 0.1 to 1.0 ms^{-1} and surface observations from a research buoy in the Pacific that indicate the passage of gravity waves overhead as tropical cyclones pass by at distances of 100 to 300 km. Numerical simulations are used to interpret these observations and to understand the broader horizontal and vertical structures of the radiating waves. The simulations suggest a correlation between wave amplitude and cyclone intensity, which could be used to make remote estimates of peak wind speeds.



typhoon Fanapi
September 17, 2010

Figure 5. Power spectra (green curves) of surface pressure and surface wind speeds observed by the ITOP buoy in the Pacific in 2014 during the passage of Typhoons (top) Chaba, (middle) Fanapi, and (bottom) Megi, for (left column) wind speed and (right column) surface pressure. Included in each figure is a power spectrum from a similar time period where no TC was nearby (black curves).

Geophysical Research Letters

RESEARCH LETTER
10.1002/2017GL073572

Spiral gravity waves radiating from tropical cyclones

David S. Nolan[1] and **Jun A. Zhang**[2,3]

[1]Department of Atmospheric Sciences, University of Miami, Miami, Florida, USA, [2]Hurricane Research Division, NOAA/AOML, Miami, Florida, USA, [3]Cooperative Institute for Marine and Atmospheric Sciences, University of Miami, Miami, Florida, USA

Key Points:
- Tropical cyclones generate gravity waves that radiate outward as tight spirals

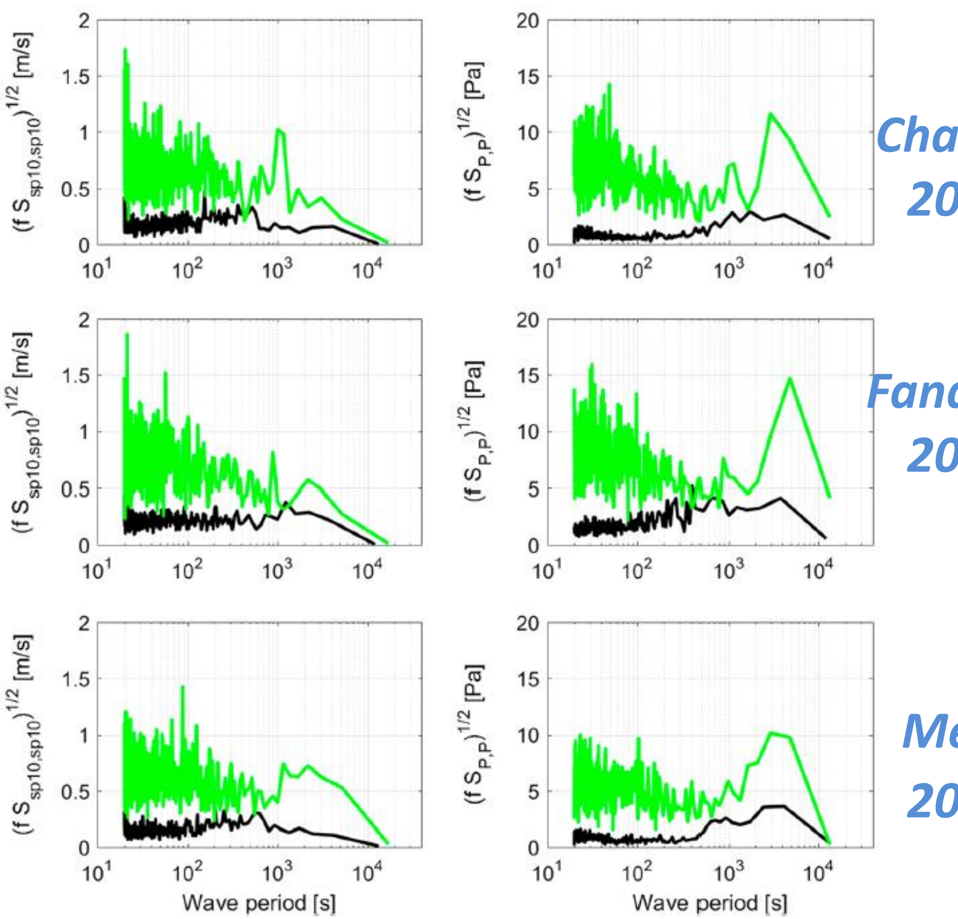
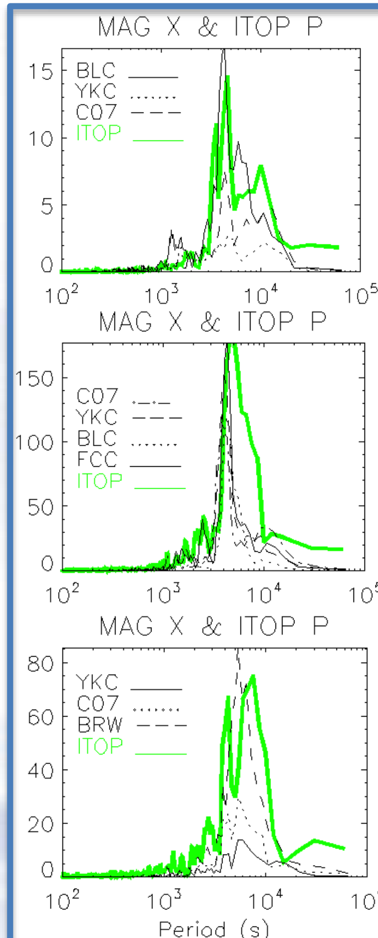


Figure 5. Power spectra (green curves) of surface pressure and surface wind speeds observed by the ITOP buoy in the Pacific in 2014 during the passage of Typhoons (top) Chaba, (middle) Fanapi, and (bottom) Megi, for (left column) wind speed and (right column) surface pressure. Included in each figure is a power spectrum from a similar time period where no TC was nearby (black curves).

Chaba 2010

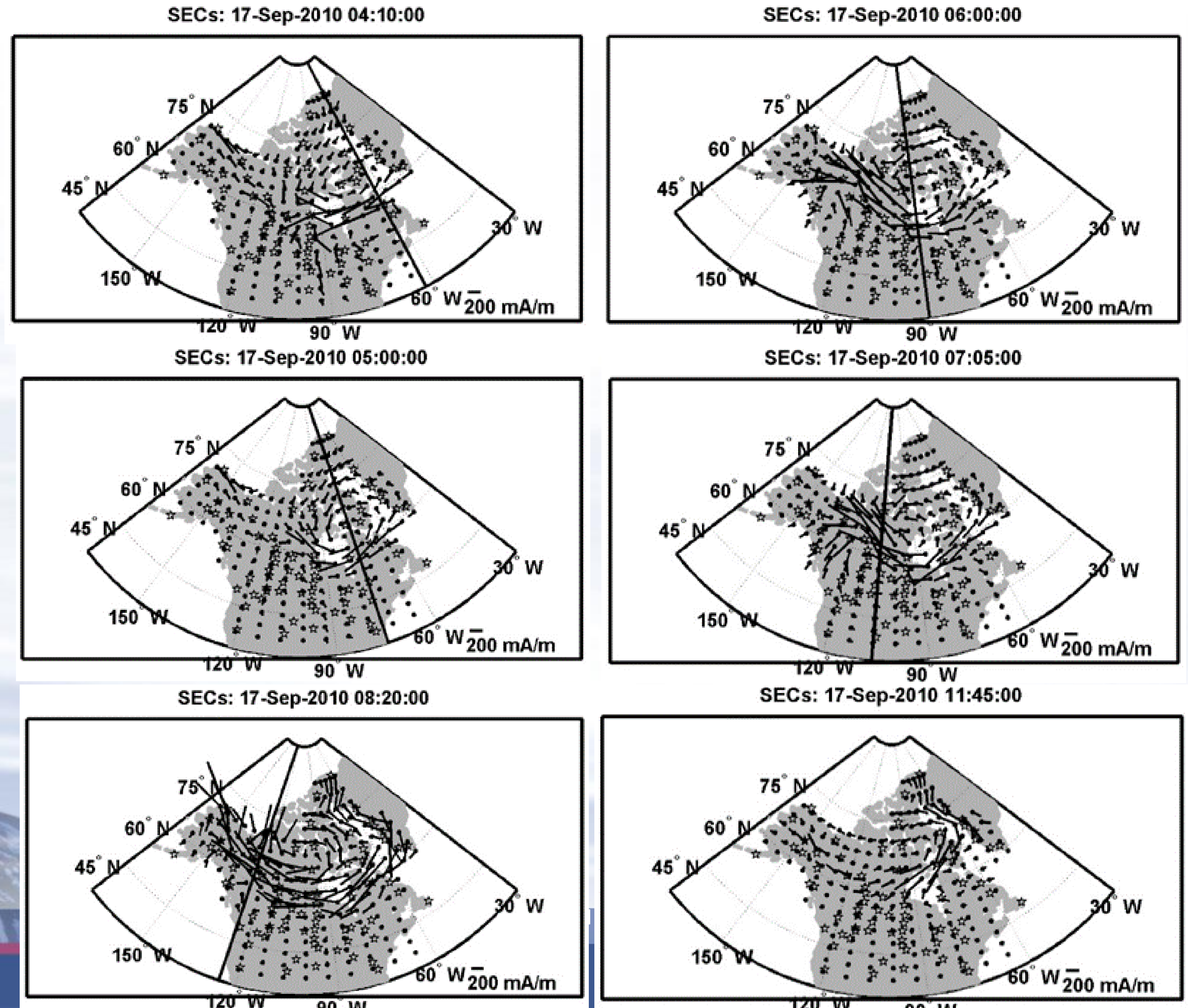
Fanapi 2010

Megi 2010

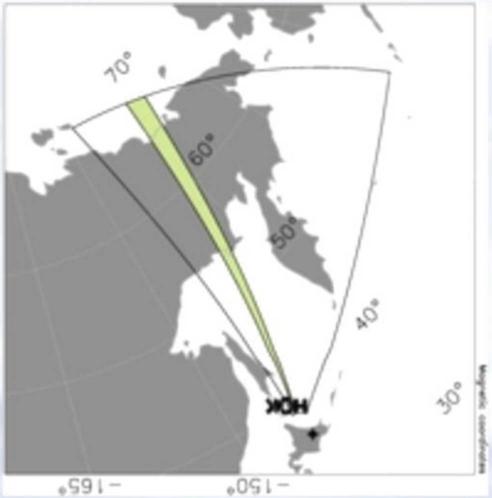


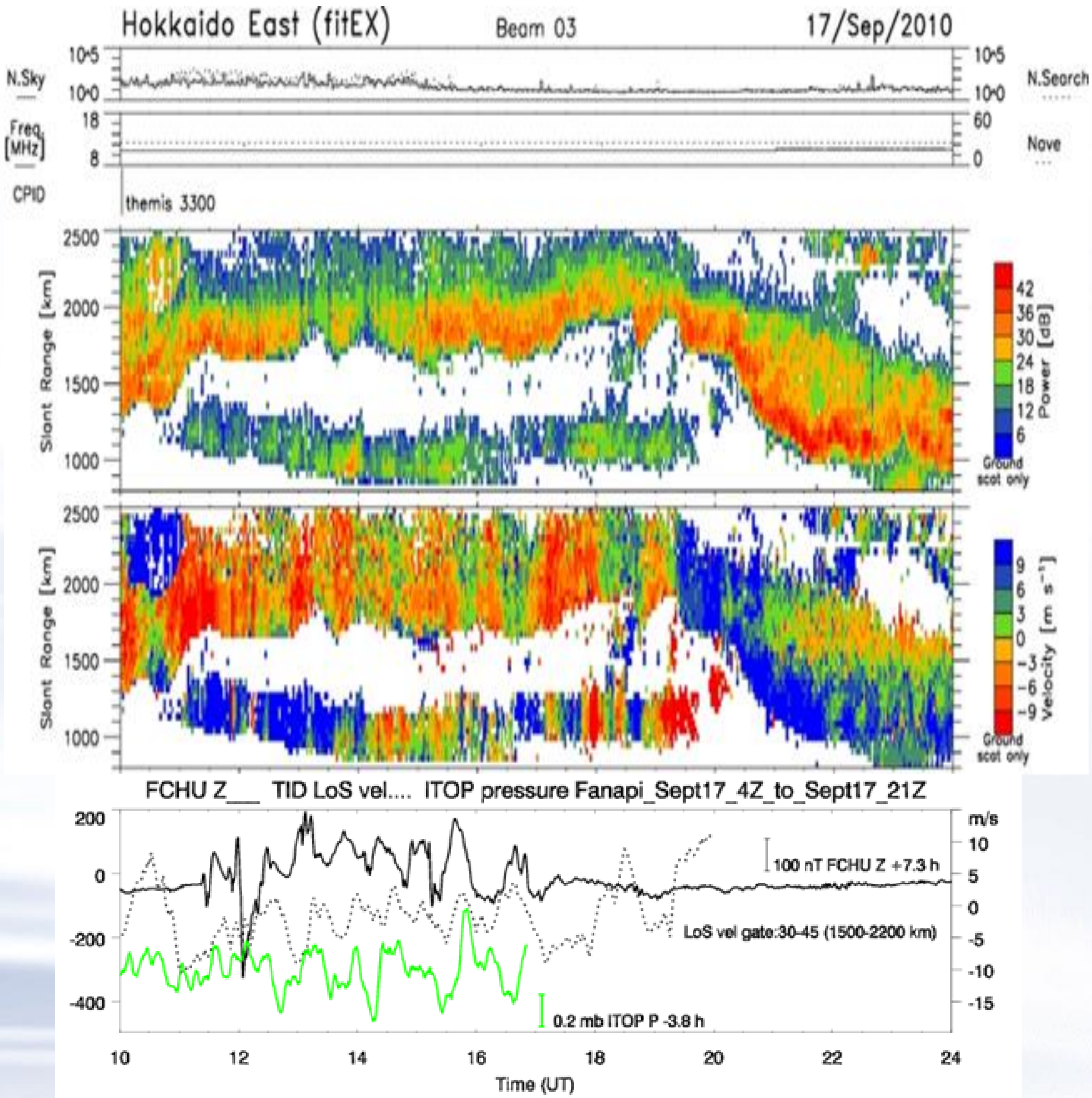
Power spectra of fluctuating ground mag. field X-comp. due to ionospheric currents: sources of AGWs observed ~8 hours earlier in the auroral zone.

Horizontal equivalent ionospheric currents (EICs) 17-SEP-2010

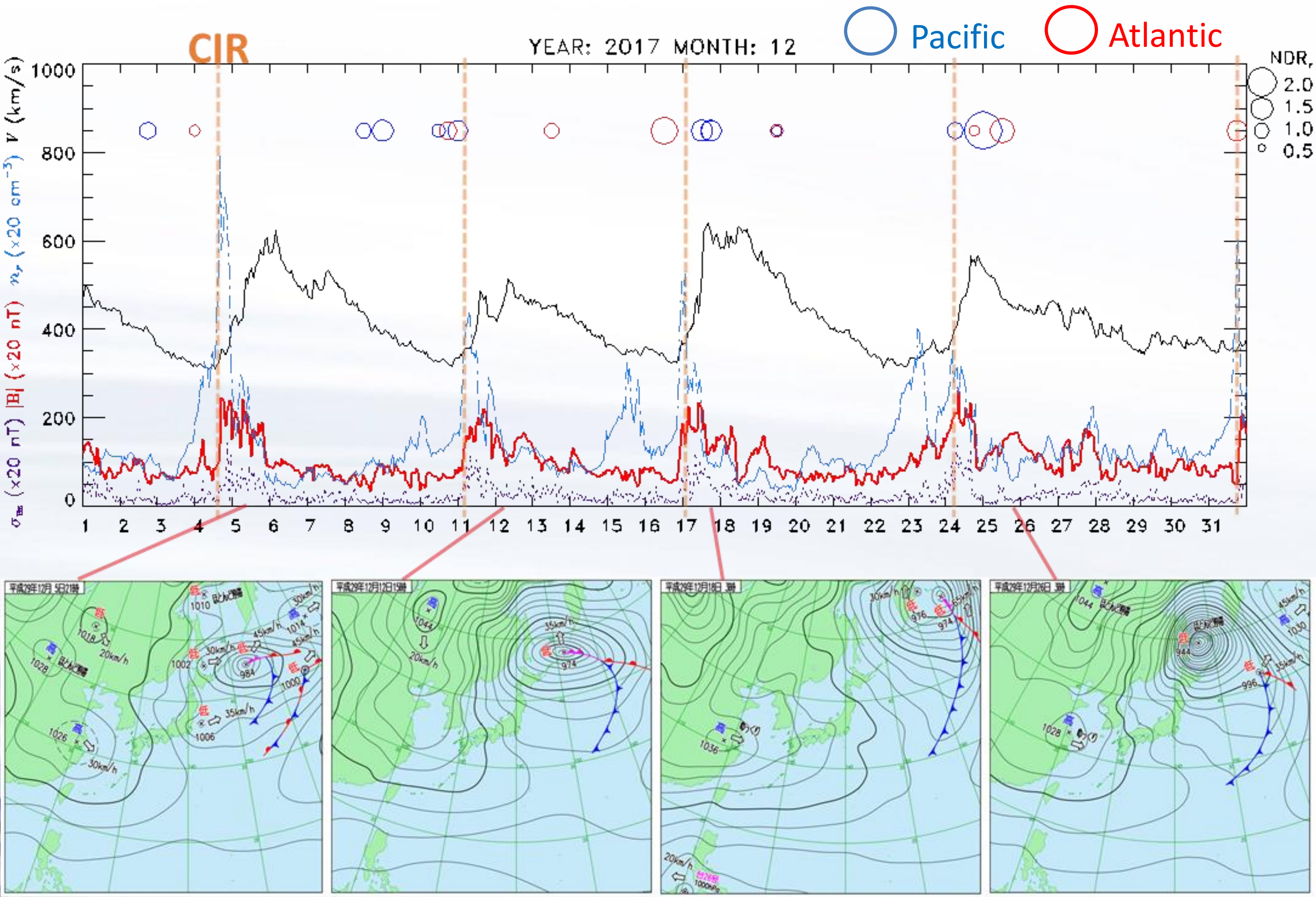


The ground scatter power, LoS velocity and elevation measured by the Hokkaido-East radar on September 17.

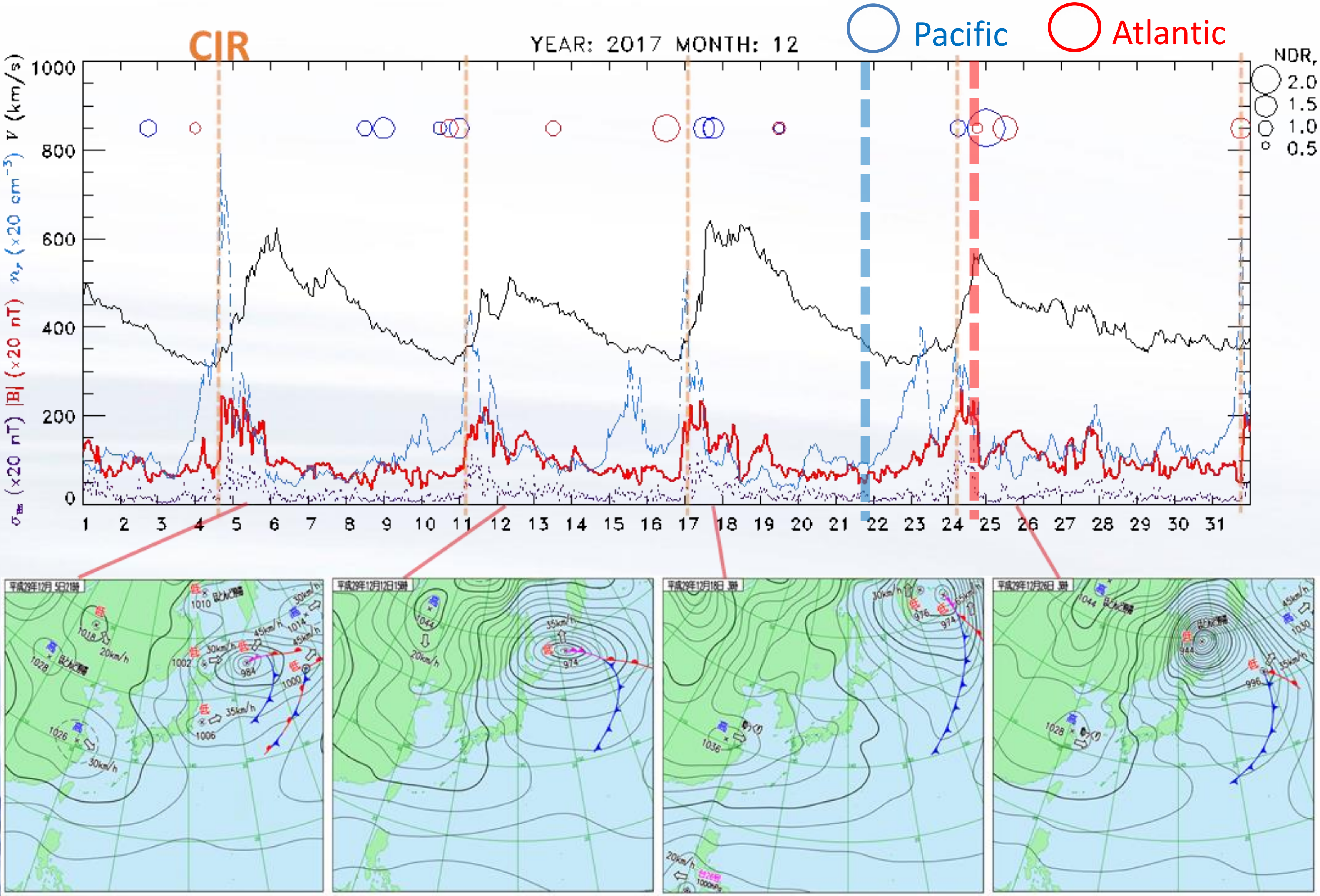




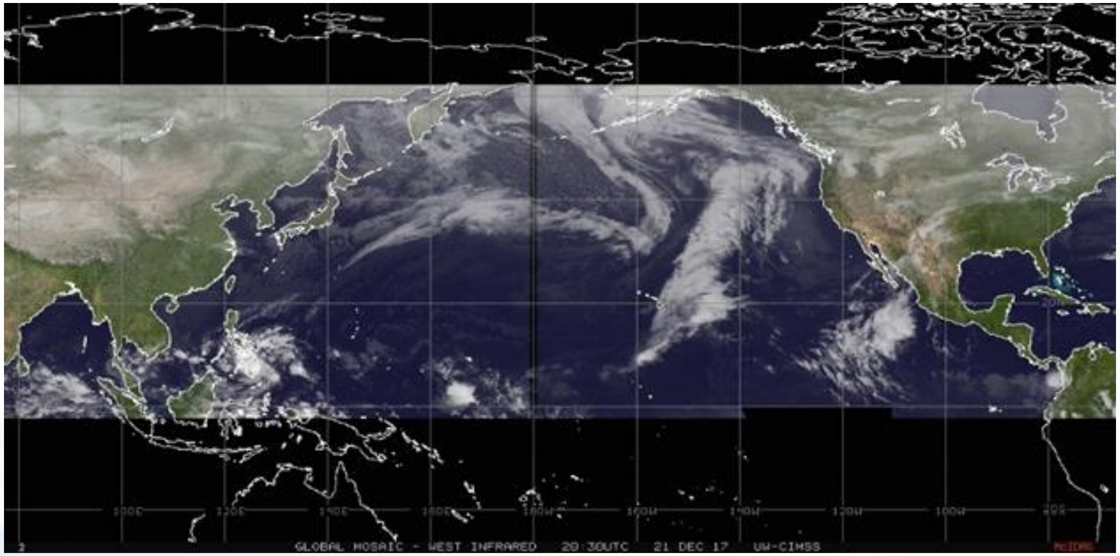
Explosive cyclones over Japan in December 2017



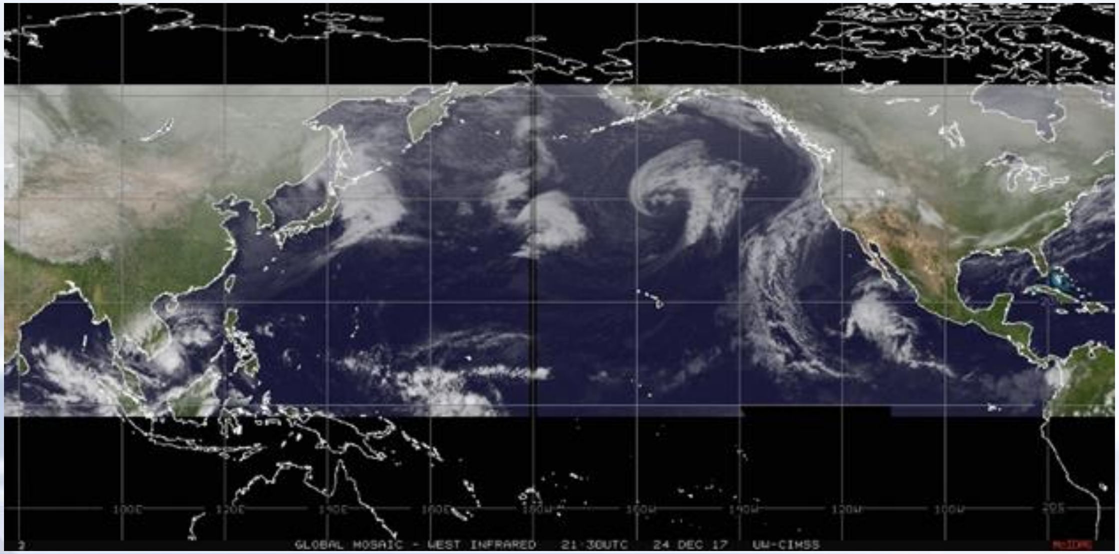
Explosive cyclones over Japan in December 2017

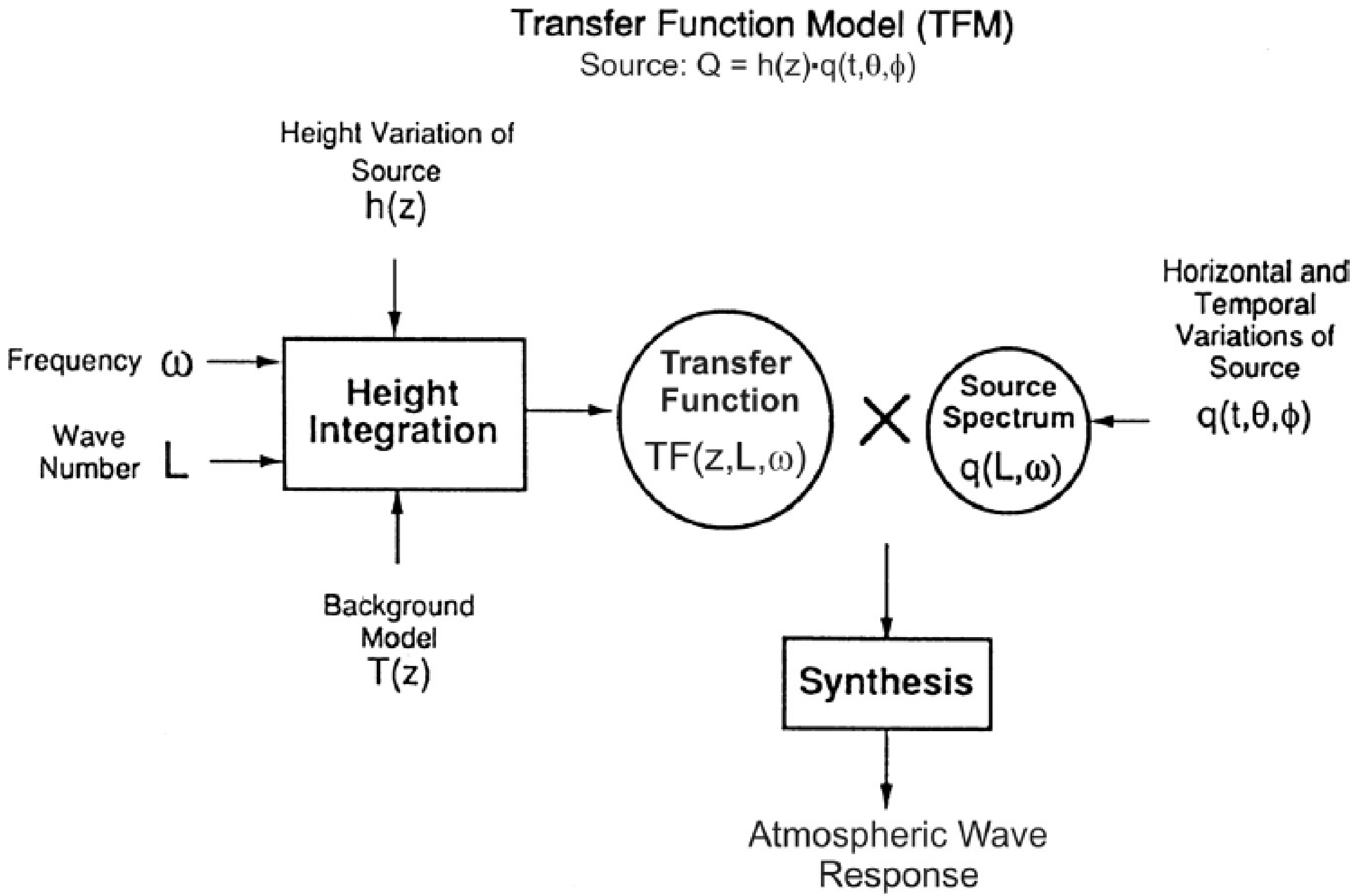


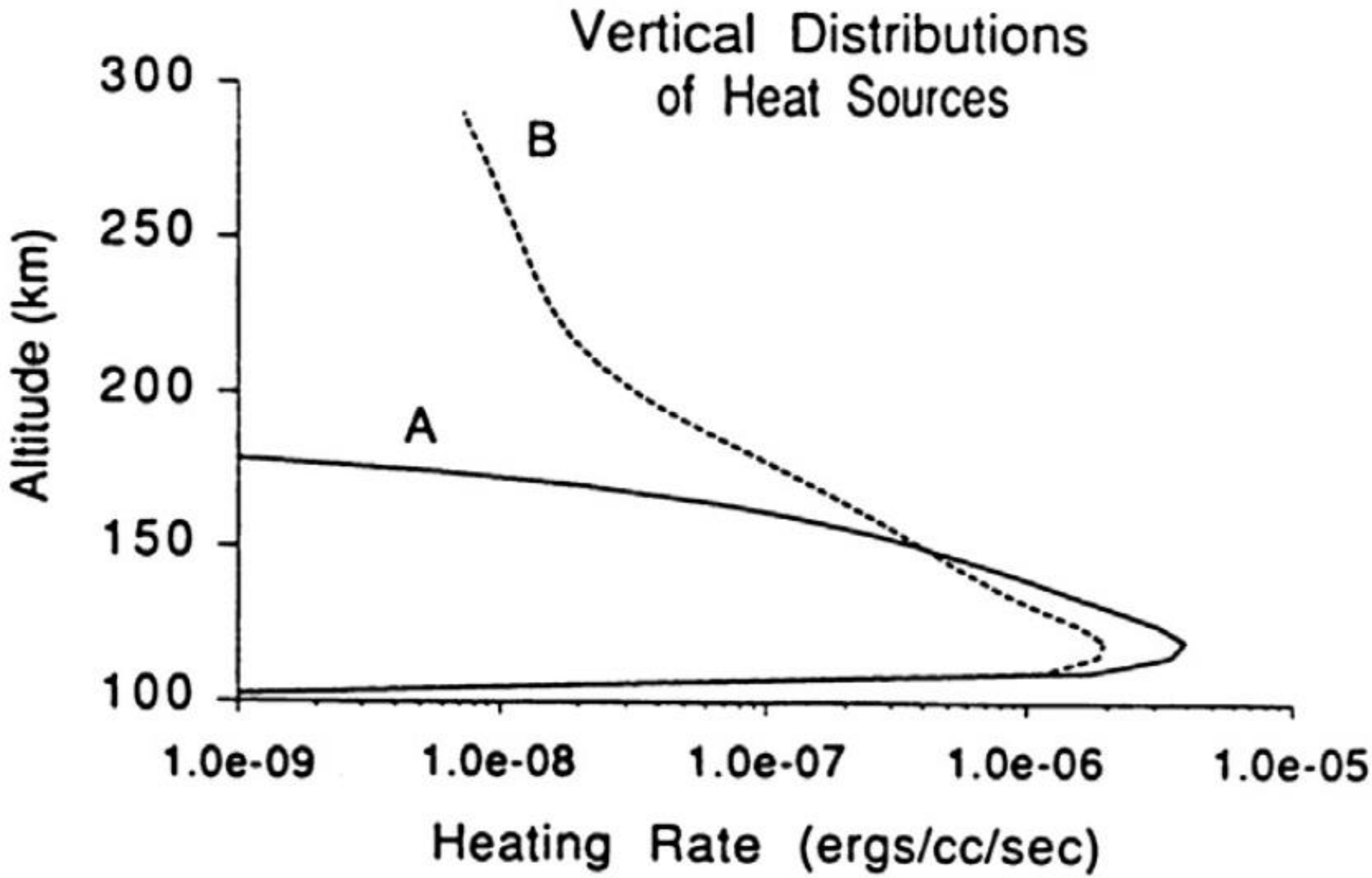
21 Dec 2017 20:30 UT



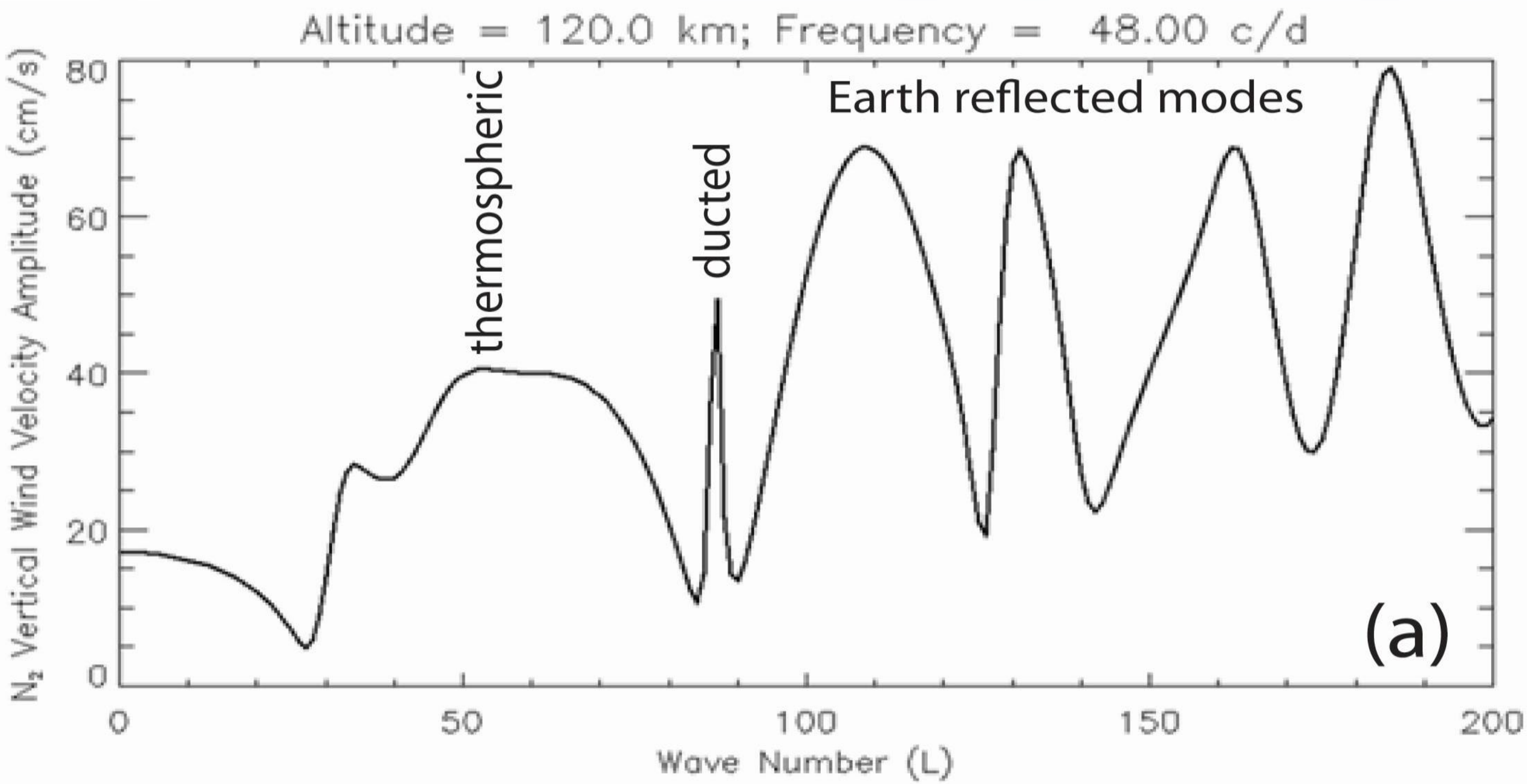
24 Dec 2017 21:30 UT




Transfer Function Model (TFM)
Source: Q = h(z)·q(t,θ,ϕ)
Height Variation of Source
h(z)
Frequency ω
Wave Number L
Height Integration
Background Model
T(z)
Transfer Function
TF(z,L,ω)
Source Spectrum
q(L,ω)
Horizontal and Temporal Variations of Source
q(t,θ,ϕ)
Synthesis
Atmospheric Wave Response

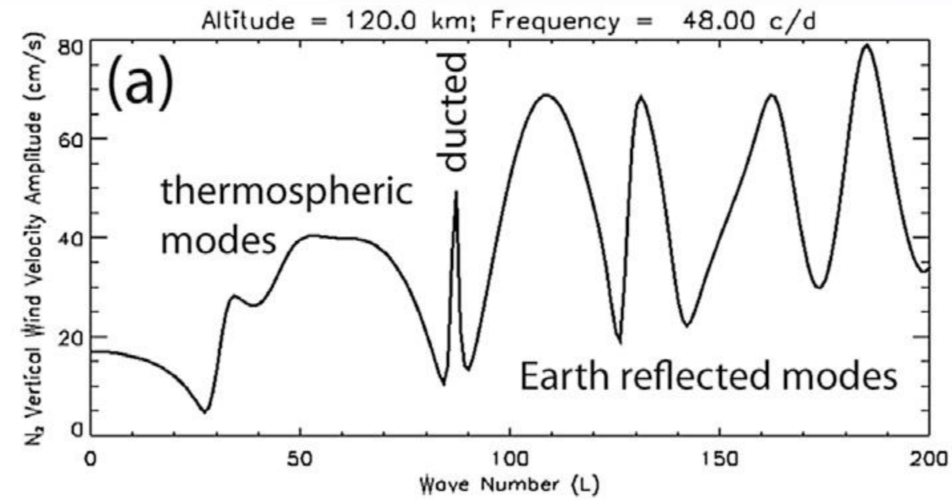

Vertical Distributions
of Heat Sources
300
250
200
150
100
B
A
Altitude (km)
1.0e-09
1.0e-08
1.0e-07
1.0e-06
1.0e-05
Heating Rate (ergs/cc/sec)

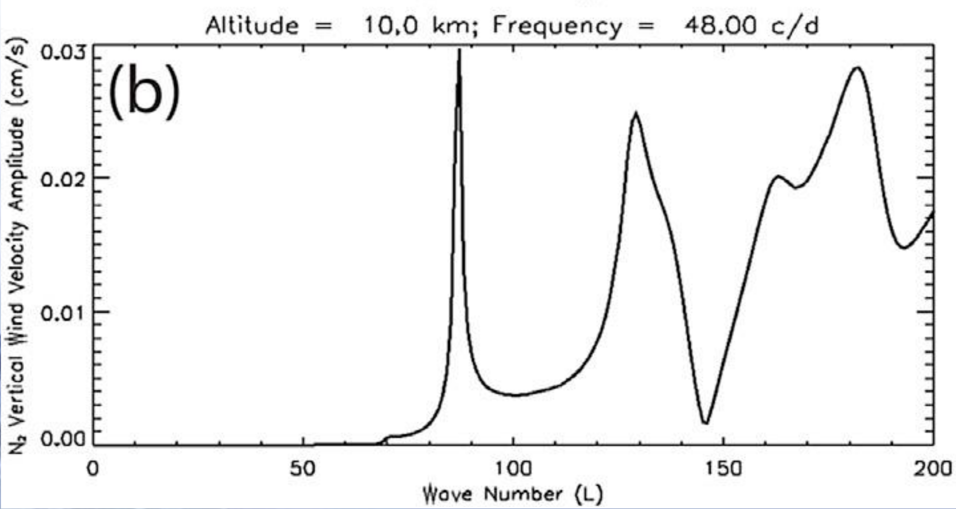
Transfer Function Model:
Vertical velocity amplitude (Period=30 min)



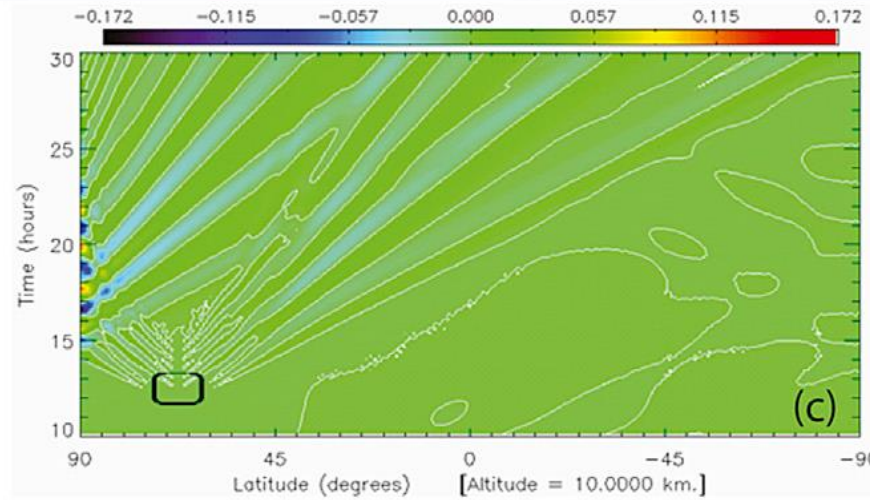
TFM results for a ring source at altitude of 120 km, centered at latitude 67.5°

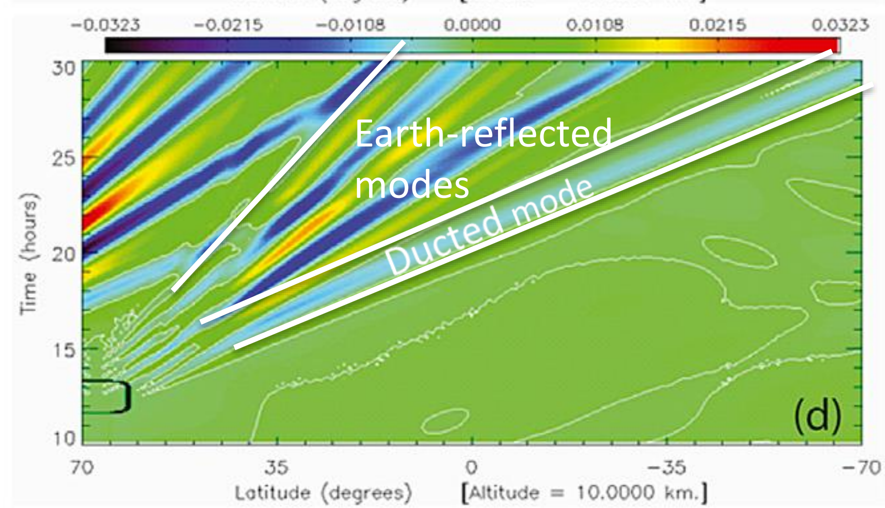
The vertical velocity transfer functions for the wave period of 30 min are shown versus wave number (a) in the thermosphere at 120 km and (b) lower atmosphere at 10 km.





A cut plane of vertical winds at altitude of 10 km shows vertical winds from a ring heat source.

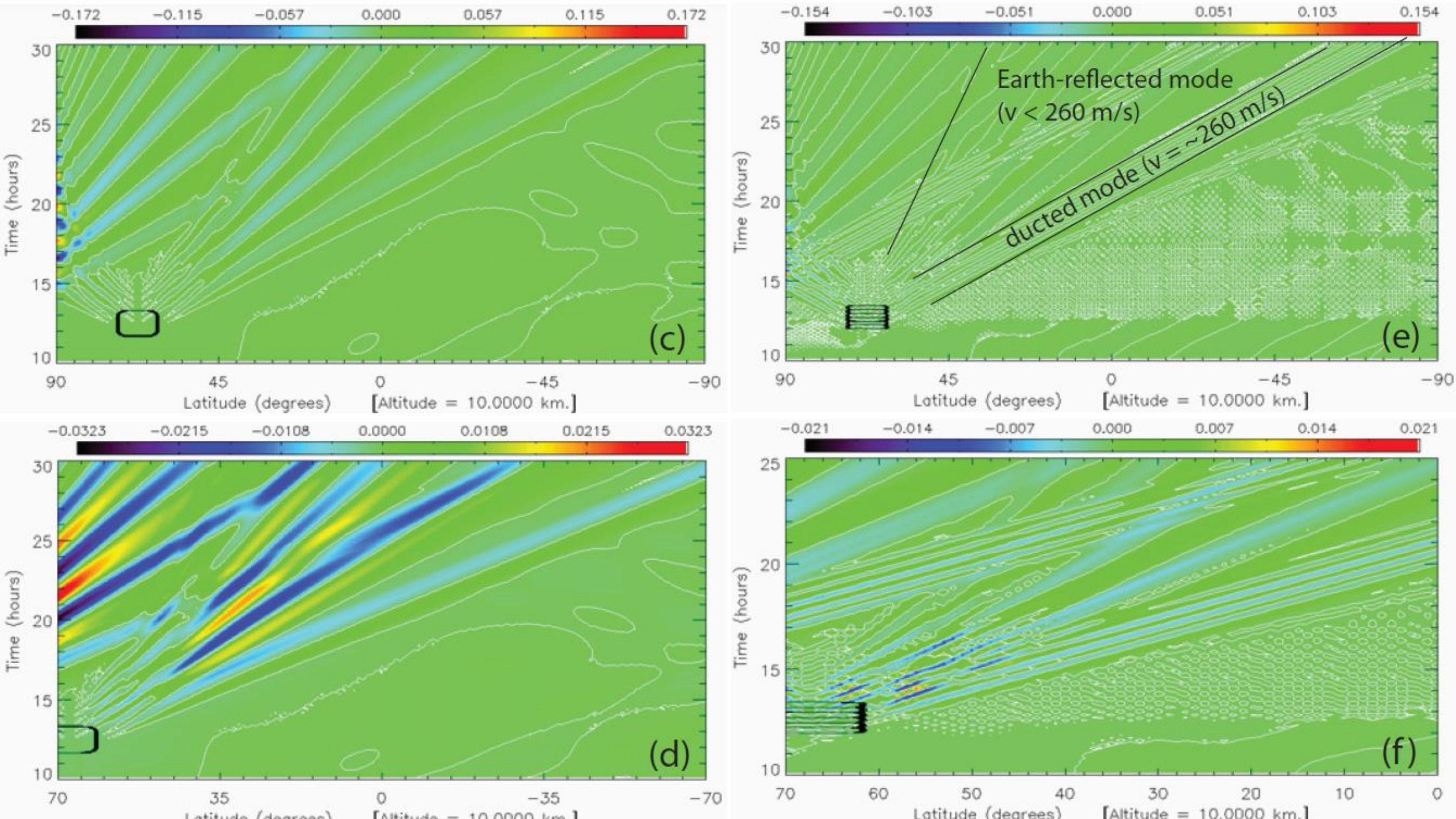




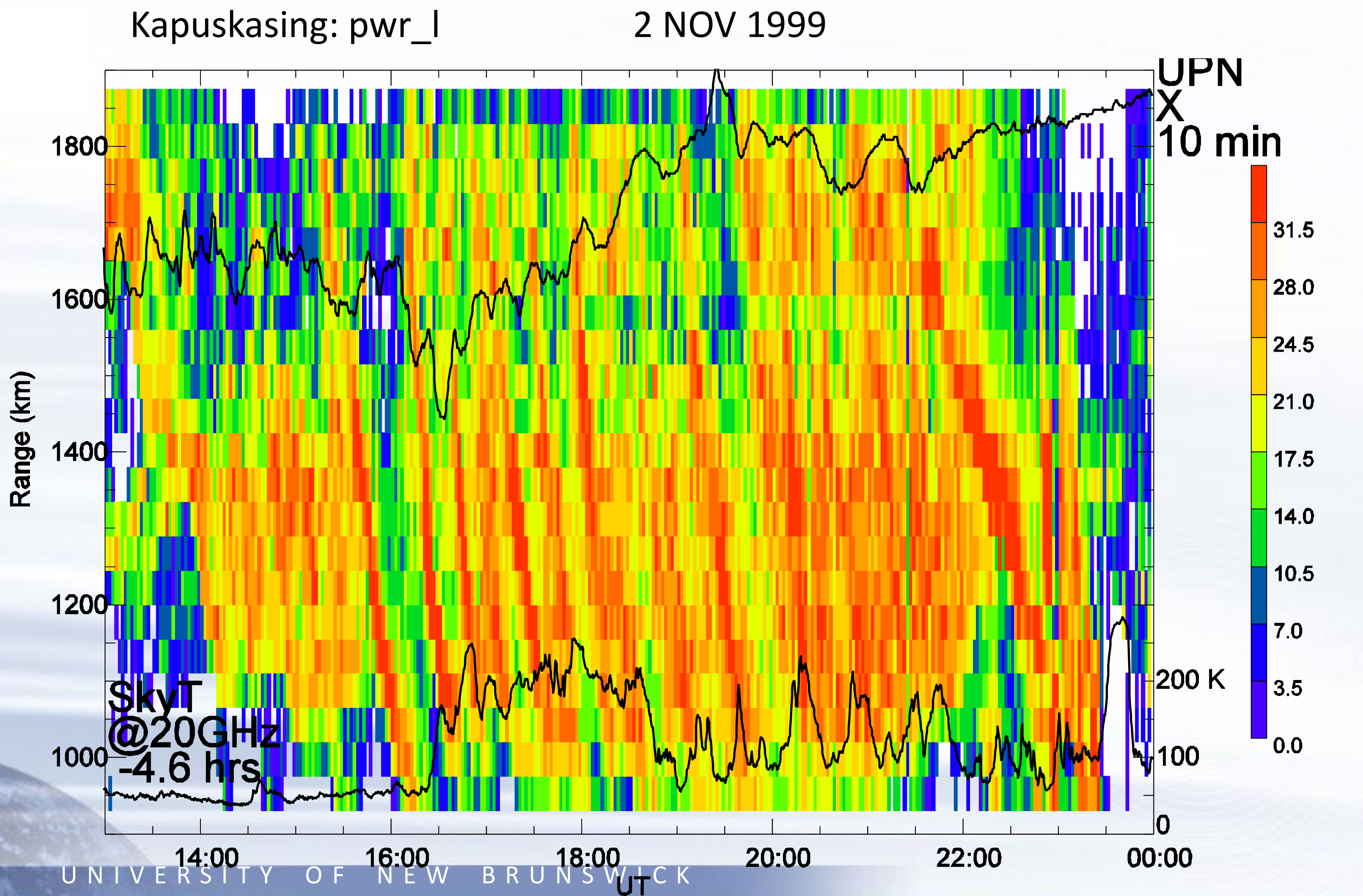
TFM results for a ring source at altitude of 120 km, centered at latitude 67.5°

A cut plane of vertical winds at altitude of 10 km shows vertical winds from a ring heat source at 120 km.

A cut plane of vertical winds at altitude of 10 km from an oscillating source with a period of 30 min at 120 km.



Correlation between PIFs/TIDs and rain bands observed by radiometer in Ottawa

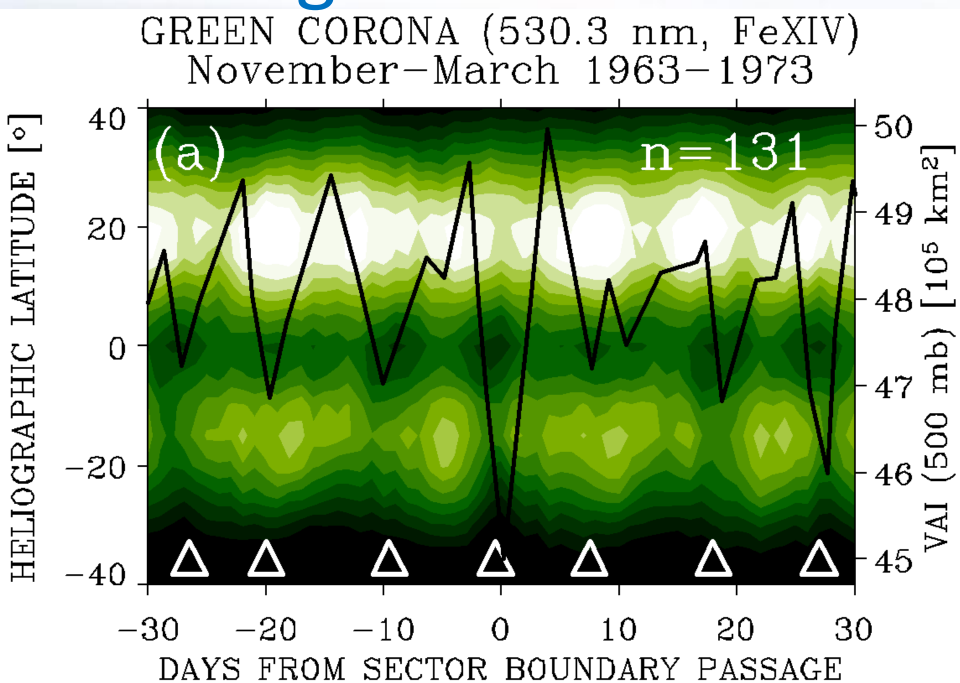


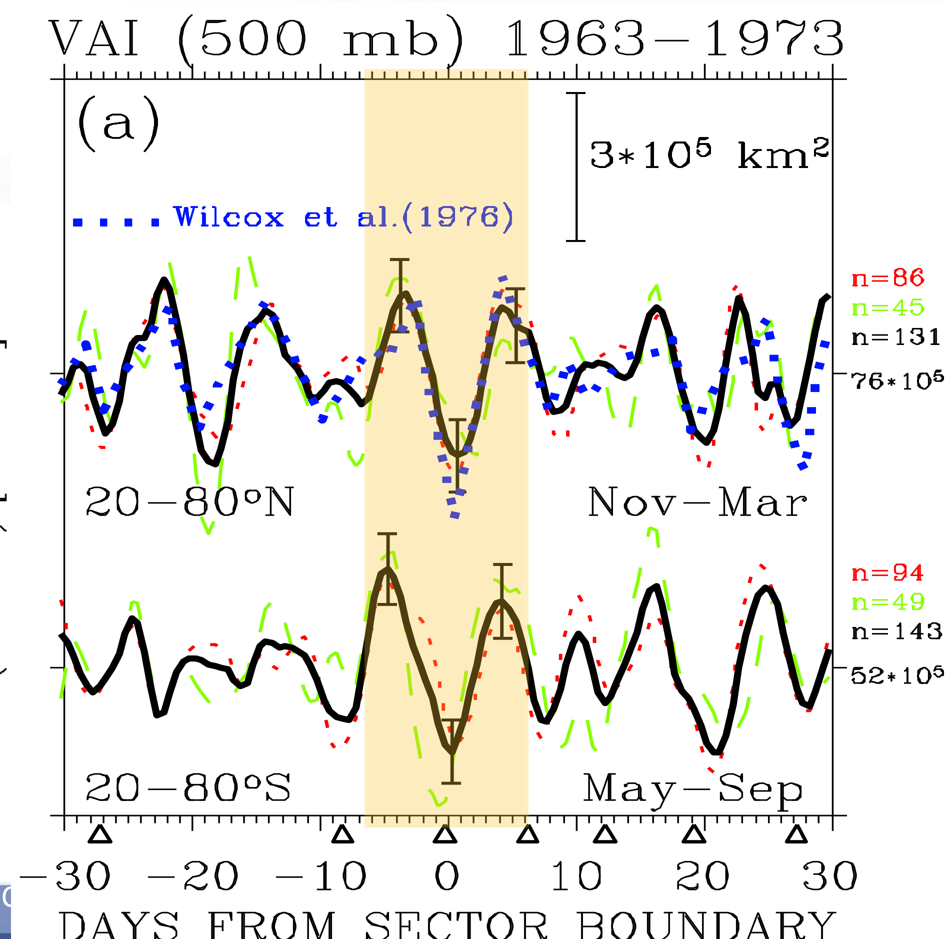
Prikryl et al., Ann. Geophys., 27, 31–57, 2009.

Motivation & Introduction

- Wilcox effect (Wilcox J. M., et al., Science, 180, 185-186, 1973.)
- Confirmed in the Northern and Southern Hemispheres

Superposed epoch analysis of green corona





Prikryl et al., Ann. Geophys., 27, 1–30, 2009.