Meteorological Phenomena Effects In the Ionosphere

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INTERNATIONAL COLLOQUIUM ON EQUATORIAL AND LOW LATITUDE IONOSPHERE, Abuja, Nigeria
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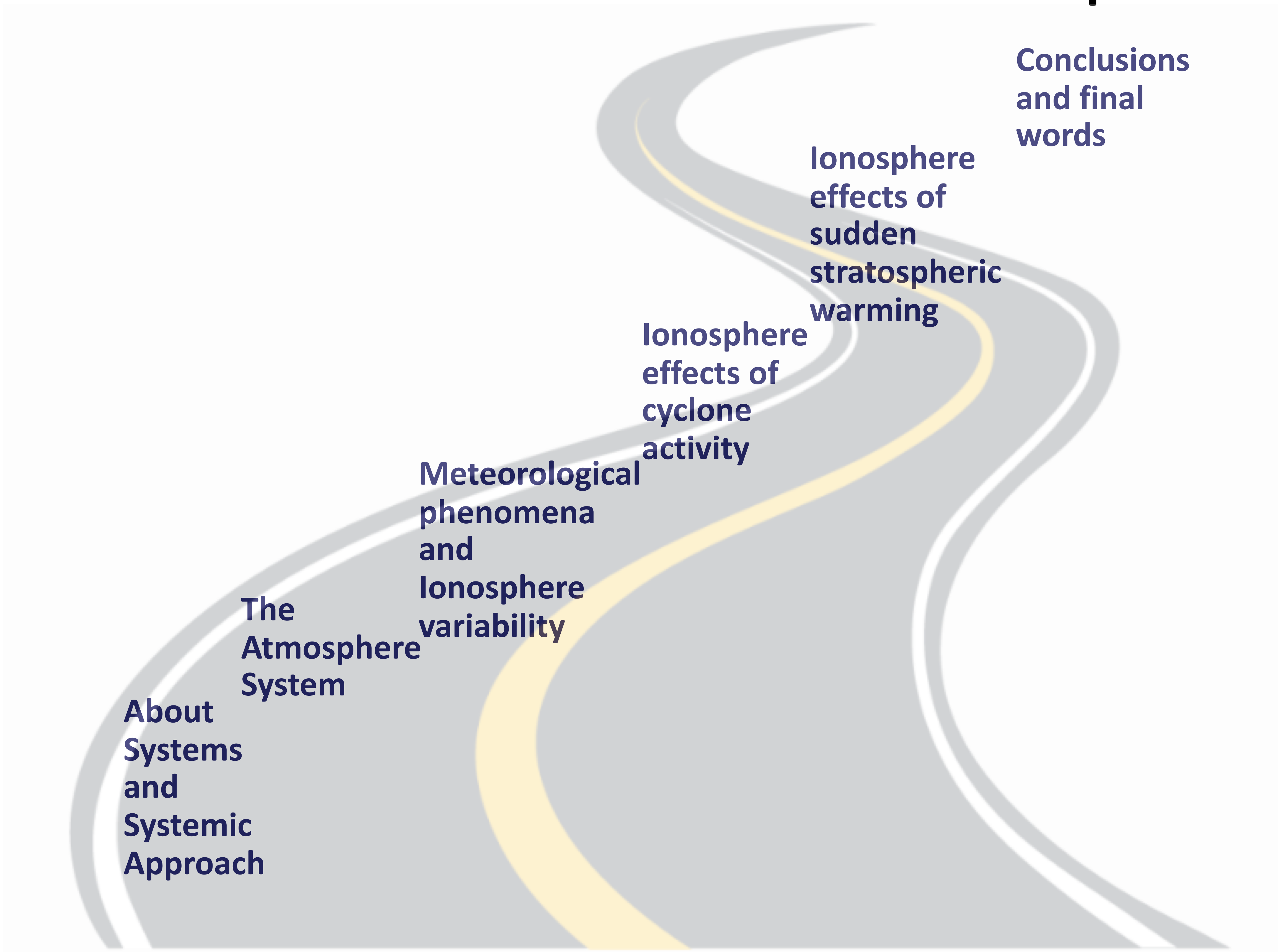
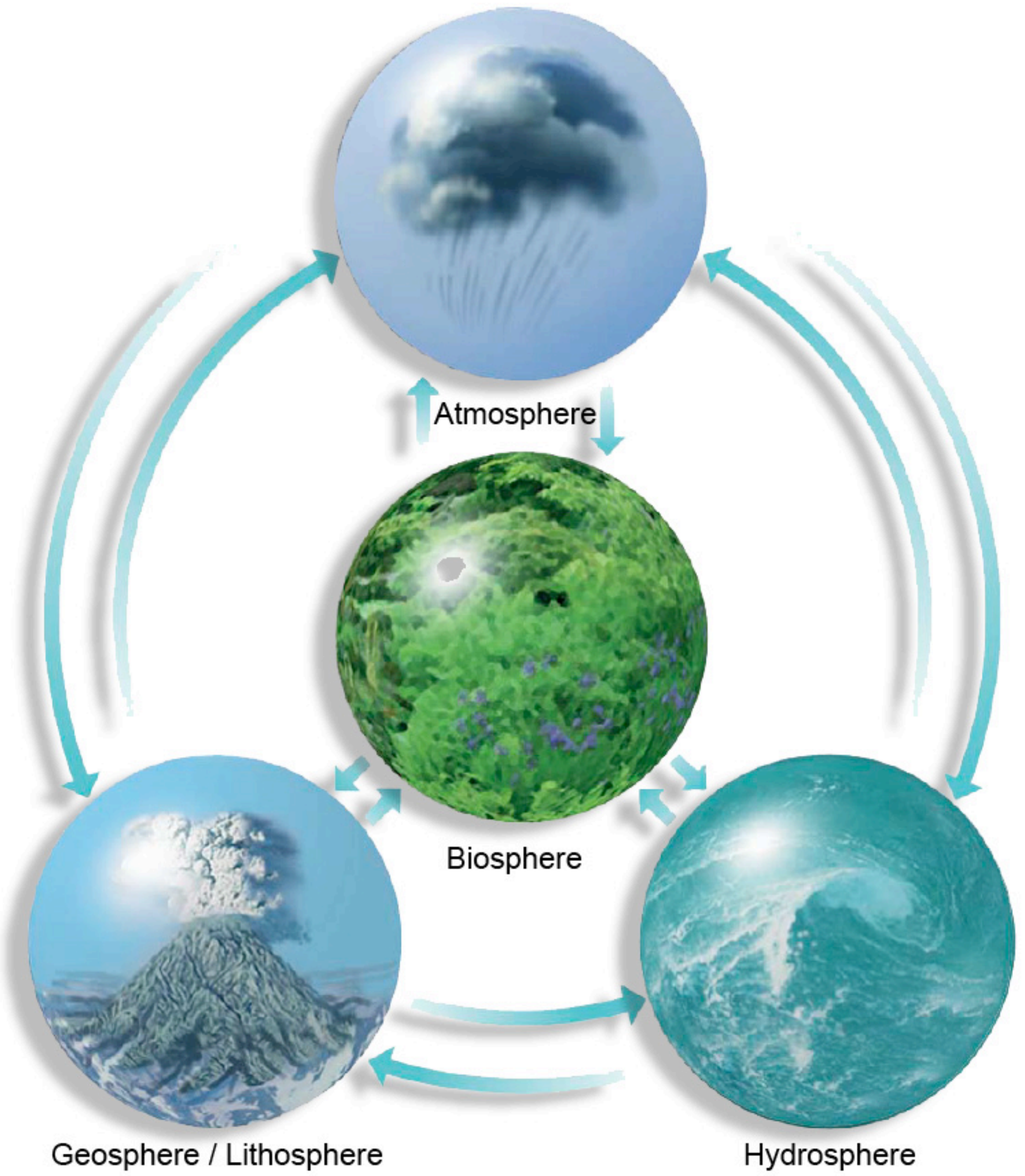
This lecture roadmap



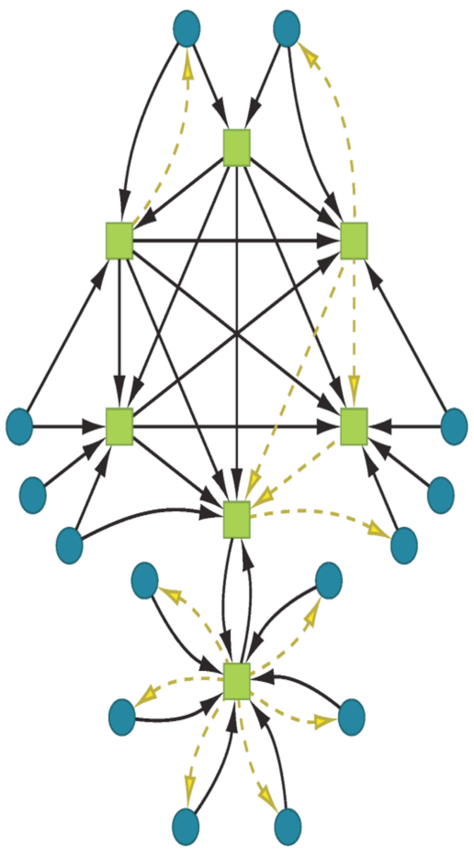
About Systems and System Approach

The Earth System



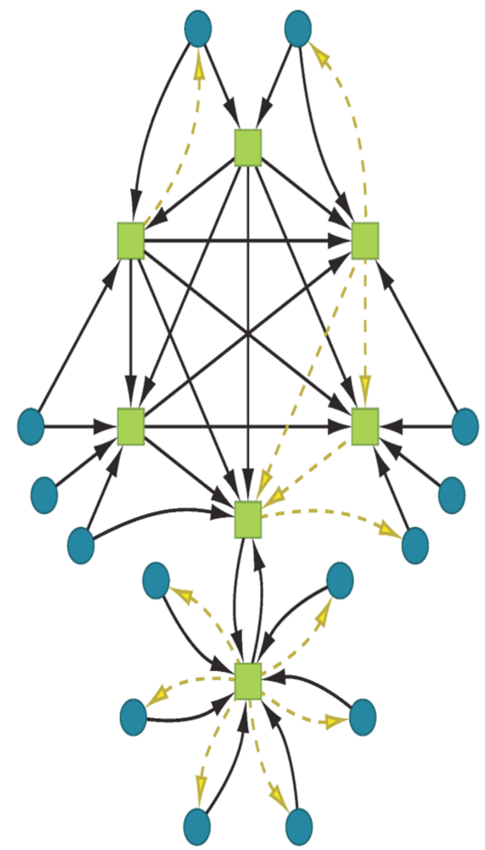
A System of *Interacting Systems*

What is the Earth System?

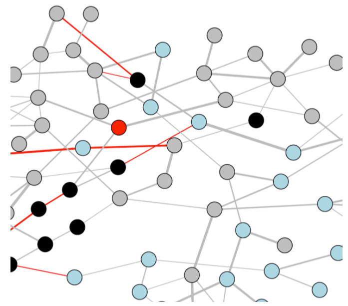


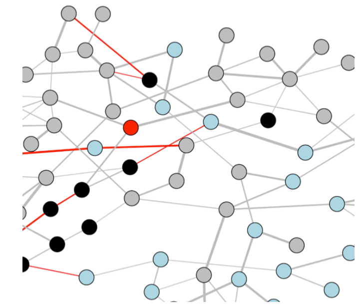
The Earth system as a whole is what we would call a really complex system.

General features of complex systems are the large numbers of characteristics, which are not easily accessible, which develop individually in a very dynamical way and which mutually interact.



More about Complex Systems

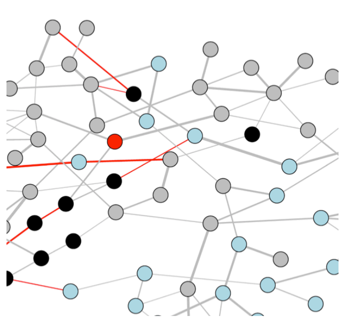


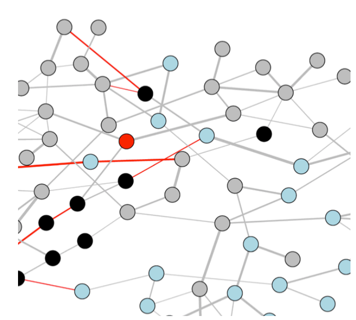


Another property of complex systems is a time delay between cause and effect.

From their evolution human beings are not suited to handle complex systems.

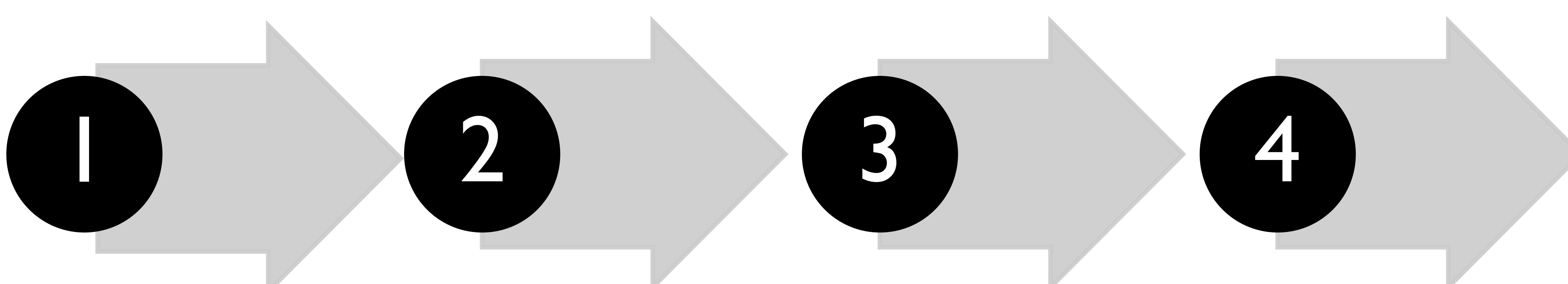
Humans usually think and act in a linear way and, thus, to solve problems systematically, one step after the other, assuming that one problem has only one solution.





Consequences of linear thinking

Different specific effects as a result of a particular cause are usually not considered at all.
Apparently most important problems are solved first, very often because they are obvious or by the available expertise.
If problems cover different disciplines, often the same methods of the subject area of the scientist involved are used to solve problems that are outside that subject area.



Studying complex systems need a "systemic approach"

Systemic Approach

A "systemic approach" is a way to handle a complex system with a global point of view without focalizing on details.

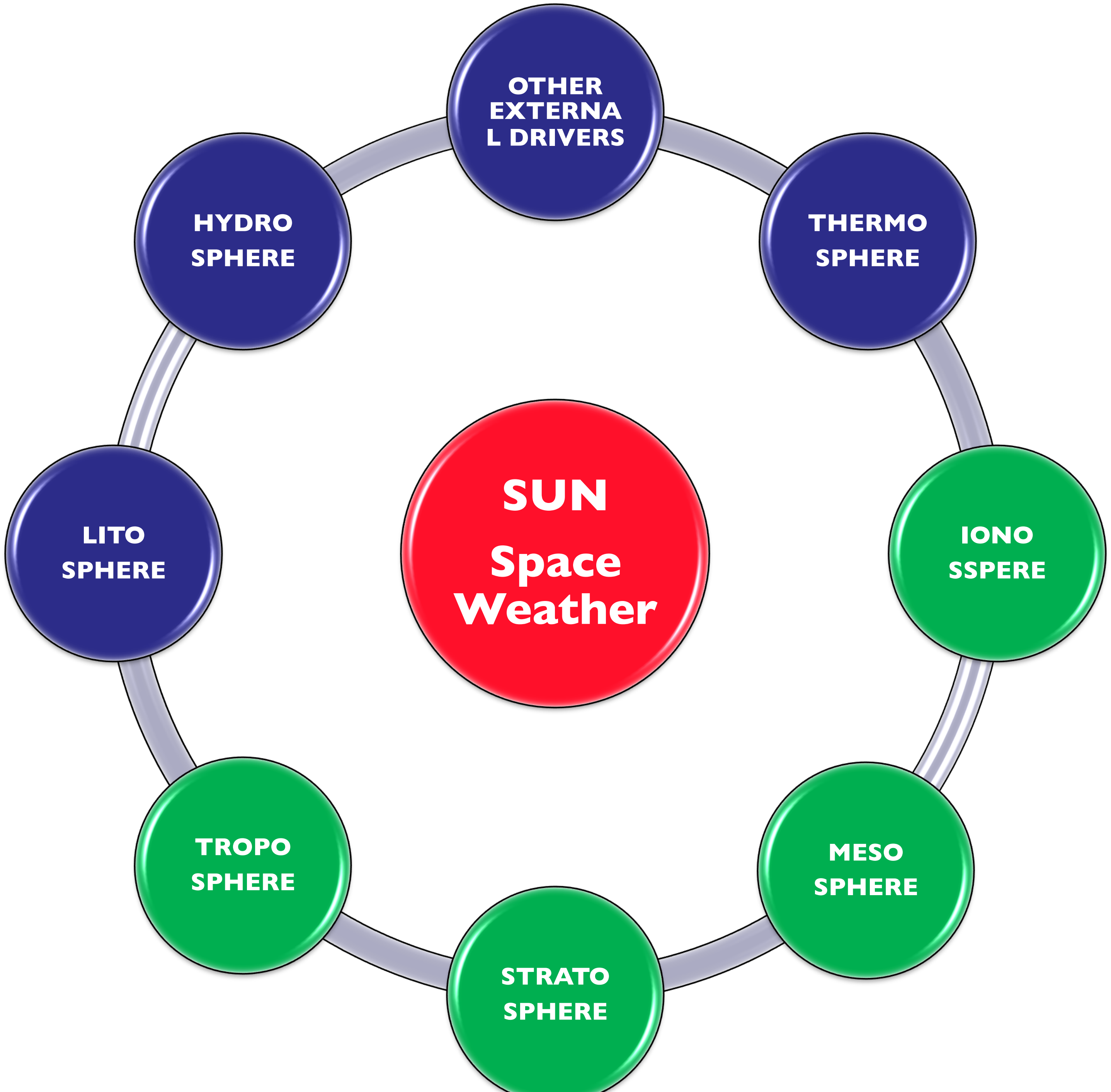
It aims for a better understanding of complexity through an interdisciplinary work.

It describes interactions between components of the system.

It avoids dividing systems into independent subsets

This talk

In this talk we will limit to the analysis of a portion of the Atmosphere System (a system in the even more complex Sun-Earth system) starting with a more “linear” analytical approach.



The Atmosphere System

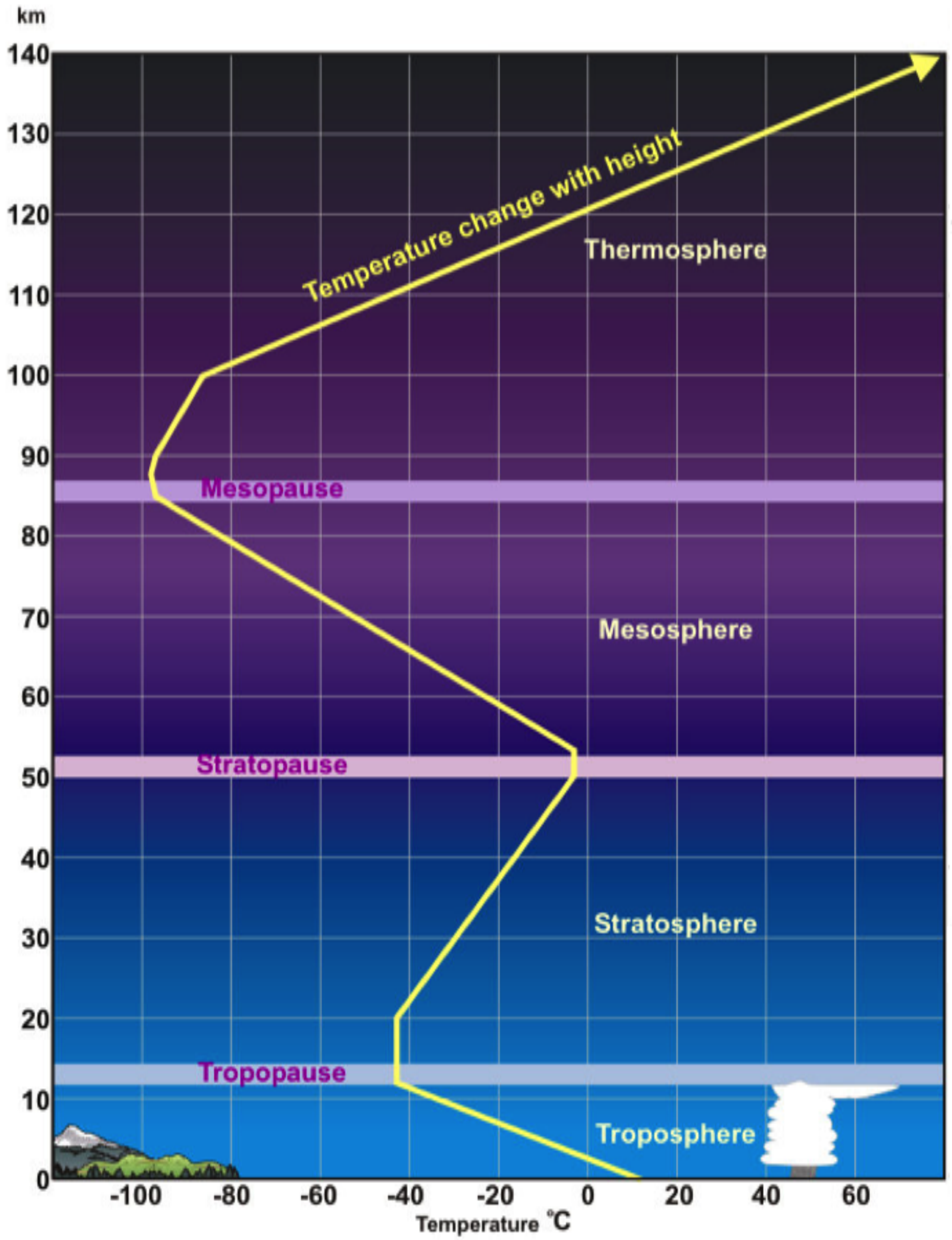
The atmosphere system

In a "linear" approach we use a number of variables to describe the atmosphere:

- Temperature
- Composition and Mixing ratio
- Ionization

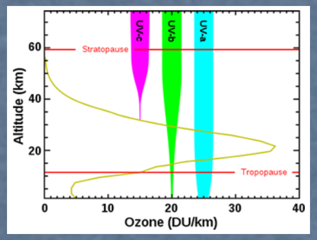
...

Temperature



THERMOSPHERE: Temperature increases steadly with altitude because is heated mainly by absorption of EUV and XUV radiation through dissociation of molecular oxygen. Temperature is highly variable with time of day and solar activity.

MESOSPHERE: Temperature decreases with altitude because ozone density decreases faster than the increase of incoming radiation.

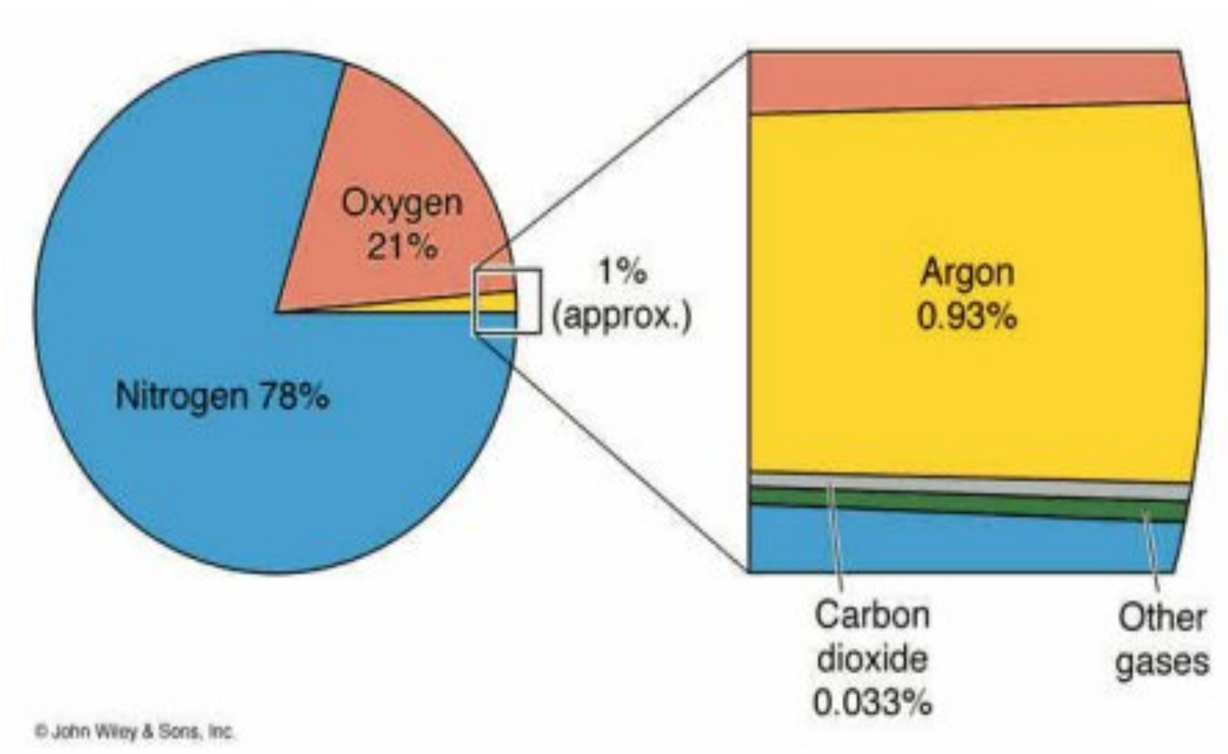


STRATOSPHERE: Temperature increases with altitude due to heating from the *ozone* which absorbs the solar ultra-violet radiation that penetrates down to these altitudes.

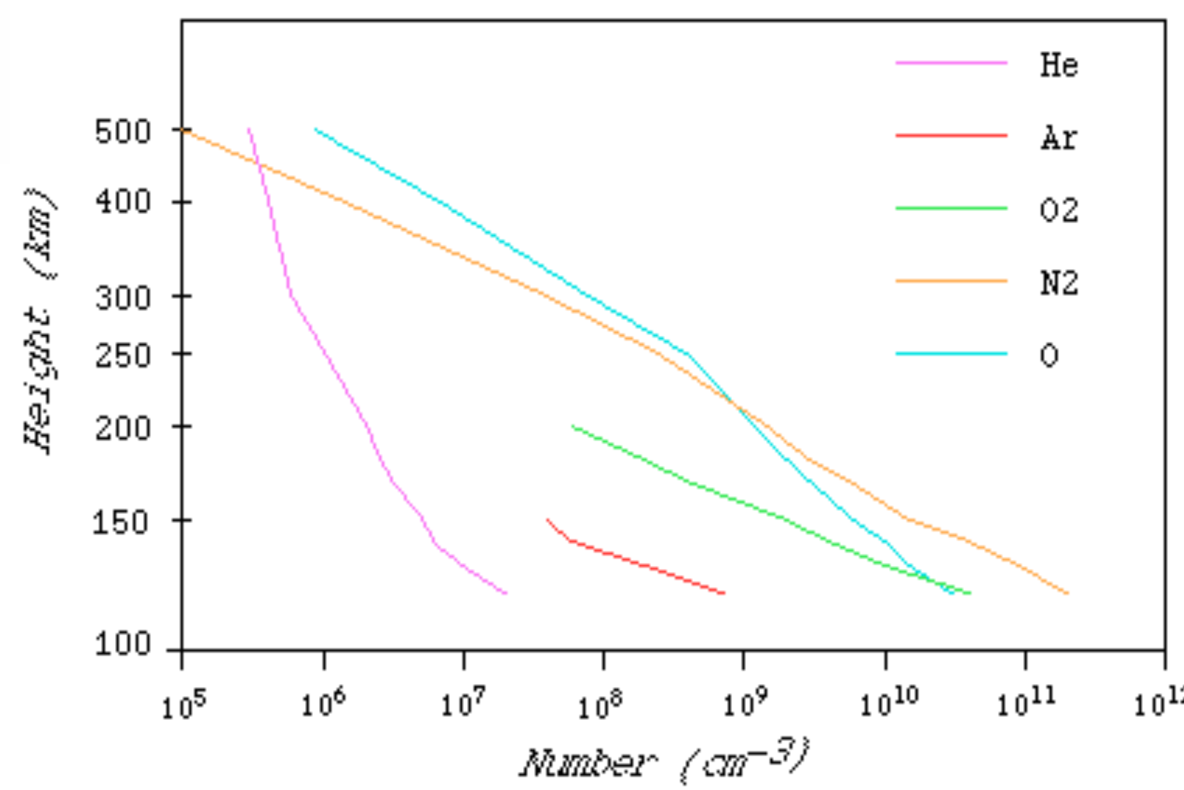
TROPOSHERE: Temperature decreases with altitude. Heated mainly by the ground, absorbs solar radiation and re-emits it in the infra-red.

Atmospheric composition:

Ground level



Above 100 Km



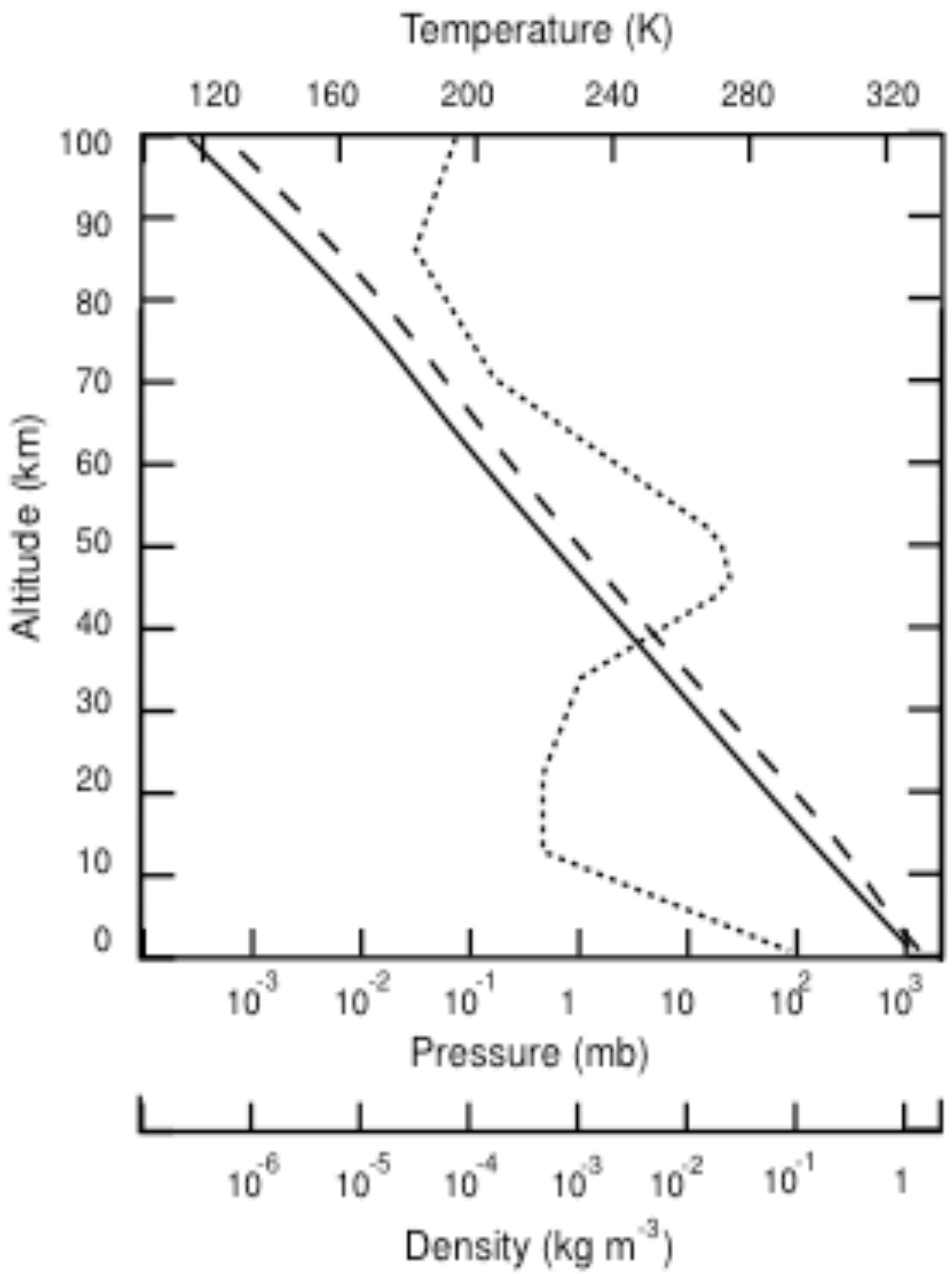
Mixing Ratio

Turbulent mixing: *lower and middle atmosphere*

- ✓ Does not depend on molecular weight
- ✓ Tends to be independent of height

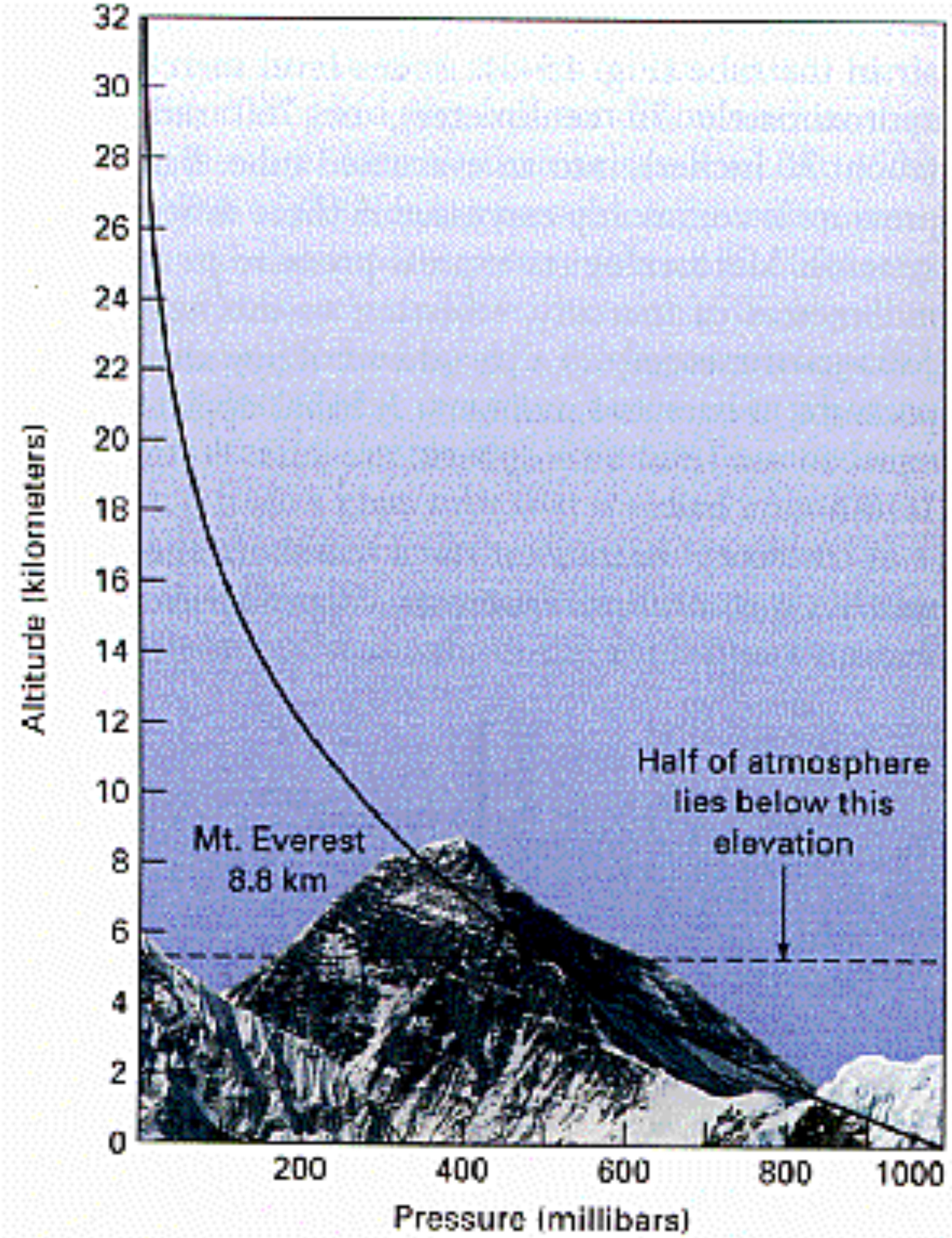
Diffusion: *upper atmosphere*

- ✓ Mean molecular weight of mixture gradually decreases with height.
- ✓ Only lightest gases are present at higher levels.
- ✓ Each gas behaves as if it were alone.



Near 100km: diffusion = turbulent mixing.
Density drops-off exponentially with height

A closer look to the atmospheric pressure



Ionization:

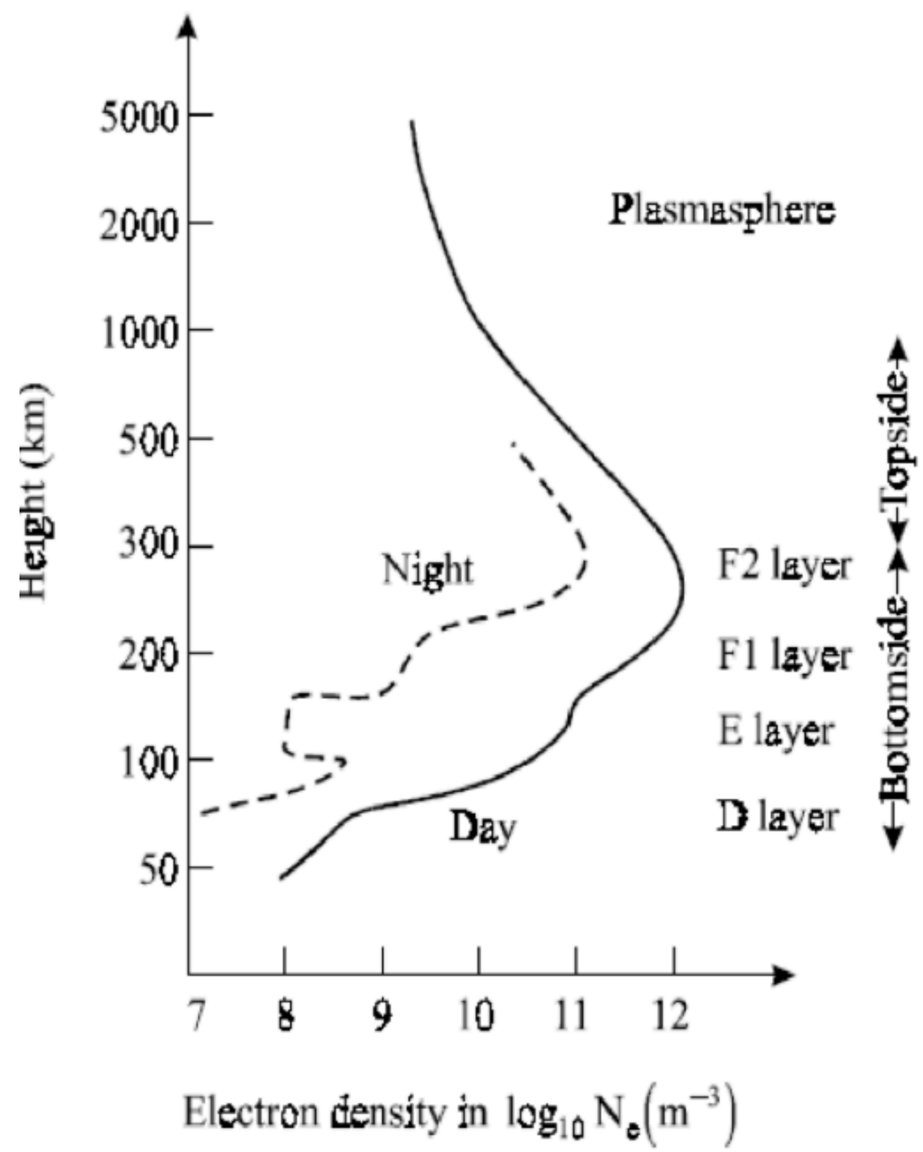
The ionosphere: a layered structure

$$\frac{\partial n_e}{\partial t} = P - L - div(n_e V)$$

Transport processes become important in the F2 region and upper, including ambipolar diffusion and wind-induced drifts along B and electromagnetic drifts across B.

E and F1 regions behave as a Chapman layer dominated by photochemical processes.
At the E region heights sporadic thin layers can be formed with electron densities above the background values.

D region is characterized by the presence of negative ions due to the attachment of electrons to neutrals



Meteorological phenomena and ionosphere variability

Meteorological (Tropospheric) Phenomena (1)

Meteorological phenomena are of diverse nature and intensity. Currently climate change is marking continuous changes due to global warming, as the atmosphere has warmed mostly because the concentrations of greenhouse gases have risen to unprecedented levels, the volume of ice and snow has decreased, the sea level has risen and intense phenomena become more frequent.

Meteorological (Troposphere) Phenomena (2)

Our focus on phenomena that have an impact on the ionosphere

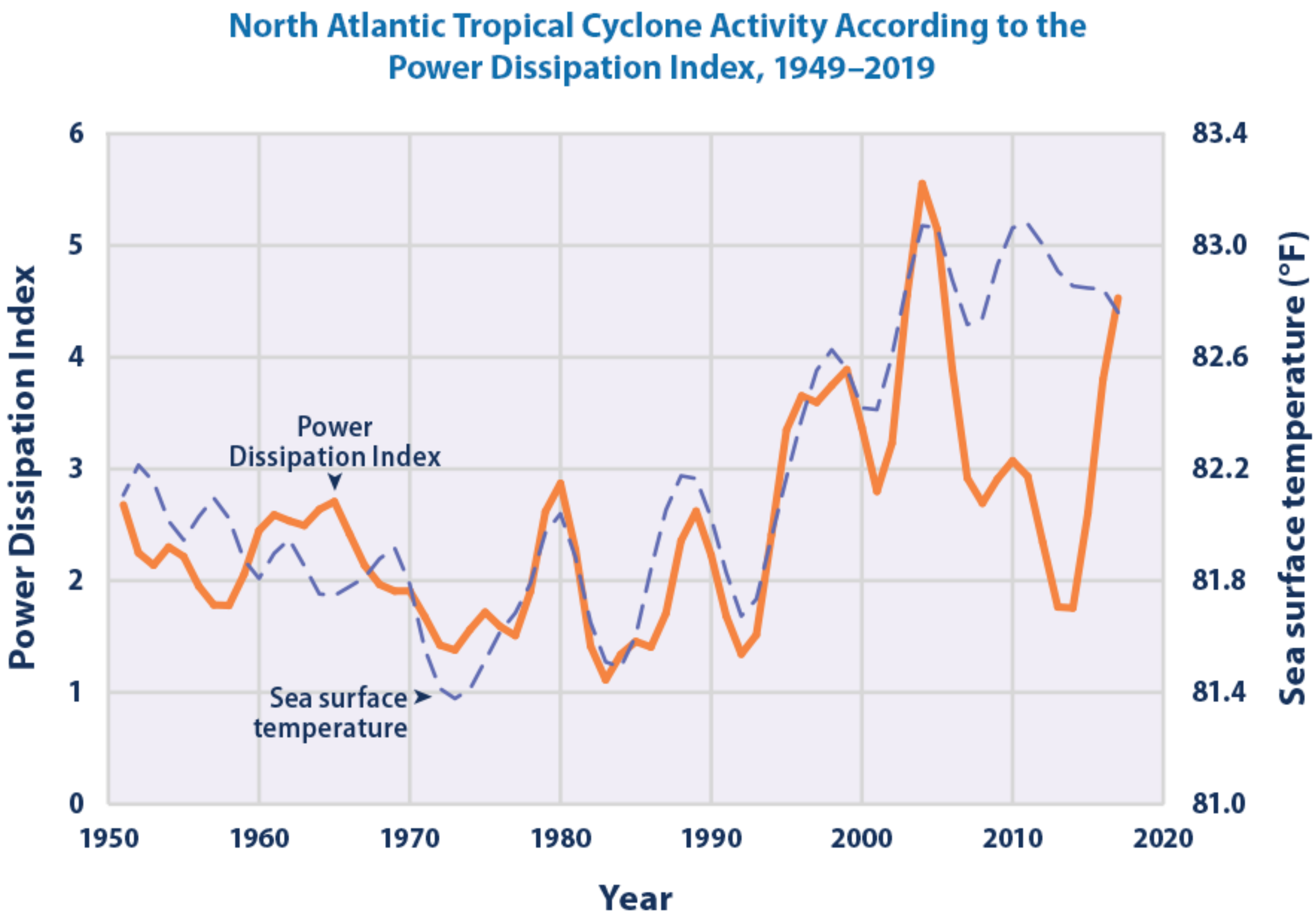
A tropospheric phenomenon:

- **Cyclone activity**

A Stratosphere phenomenon:

- **Sudden Stratosphere Warming**

Meteorological (Troposphere) Phenomena Trends: an example

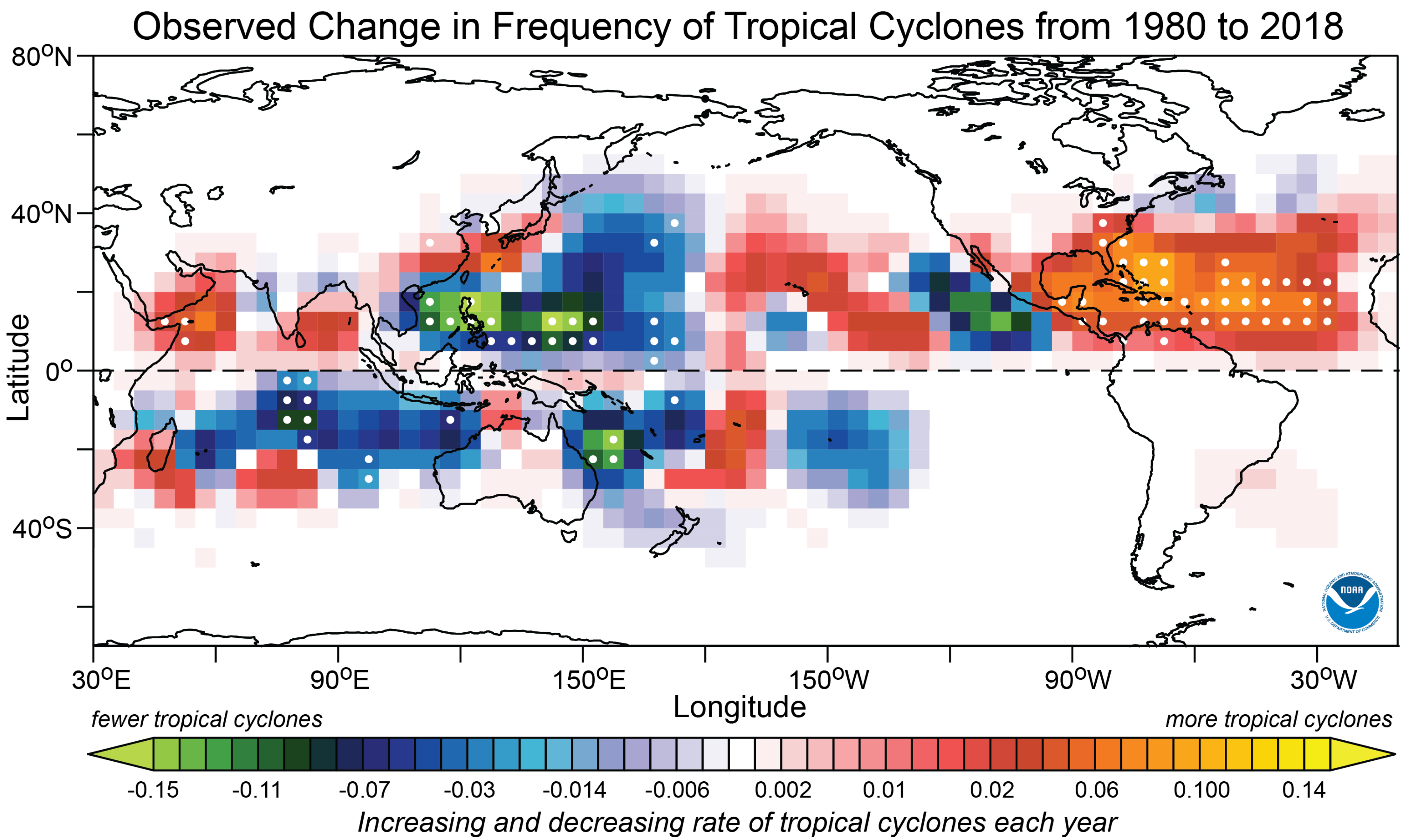


Data source: Emanuel, K.A. 2021 update to data originally published in: Emanuel, K.A. 2007. Environmental factors affecting tropical cyclone power dissipation. J. Climate 20(22):5497–5509.

For more information, visit U.S. EPA's "Climate Change Indicators in the United States" at www.epa.gov/climate-indicators.

The Power Dissipation Index (PDI) **measures the activity of cyclones by accounting for cyclone strength, duration, and frequency.**

Meteorological (Troposphere) Phenomena Trends: dependence on region (1)



This graphic depicts the global pattern of where the frequency of tropical cyclones has increased and where it has decreased around the world from 1980 to 2018. New NOAA research shows that while the global annual average number of tropical cyclones has remained at 86, climate change has influenced the location of where tropical cyclones have become more frequent, or less frequent.

(From: Murakami et al. (2019), https://www.pnas.org/doi/epdf/10.1073/pnas.1922500117)

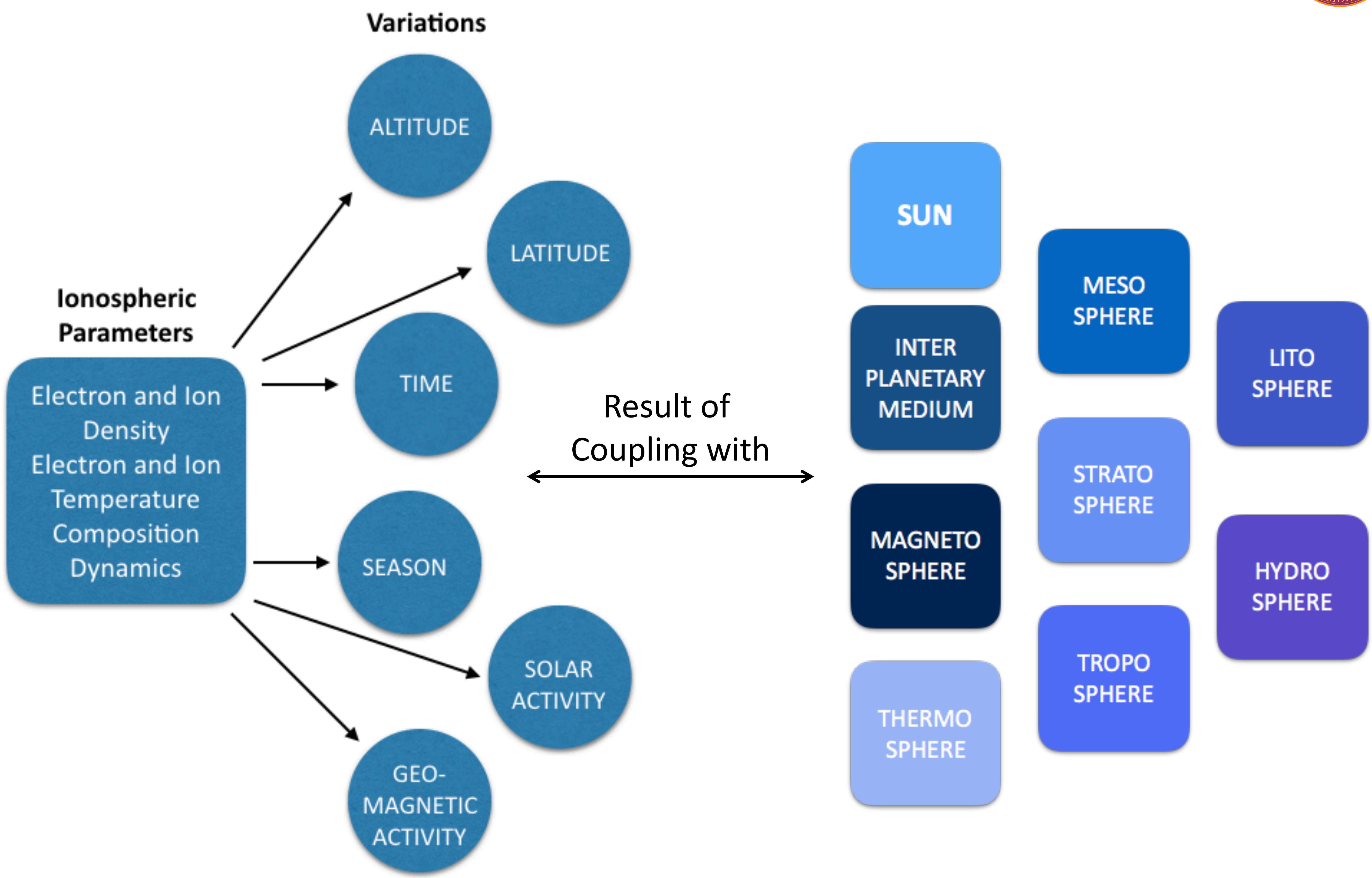
Meteorological (Troposphere) Phenomena Trends: dependence on region (2)

The study by Murakami et al (2019) revealed that the trend of occurrence of global Tropical Cyclone activity between 1980 and 2018 has been more evident in the spatial pattern, rather than the number of global TCs. Increases and decreases in TC occurrence depend on the region.

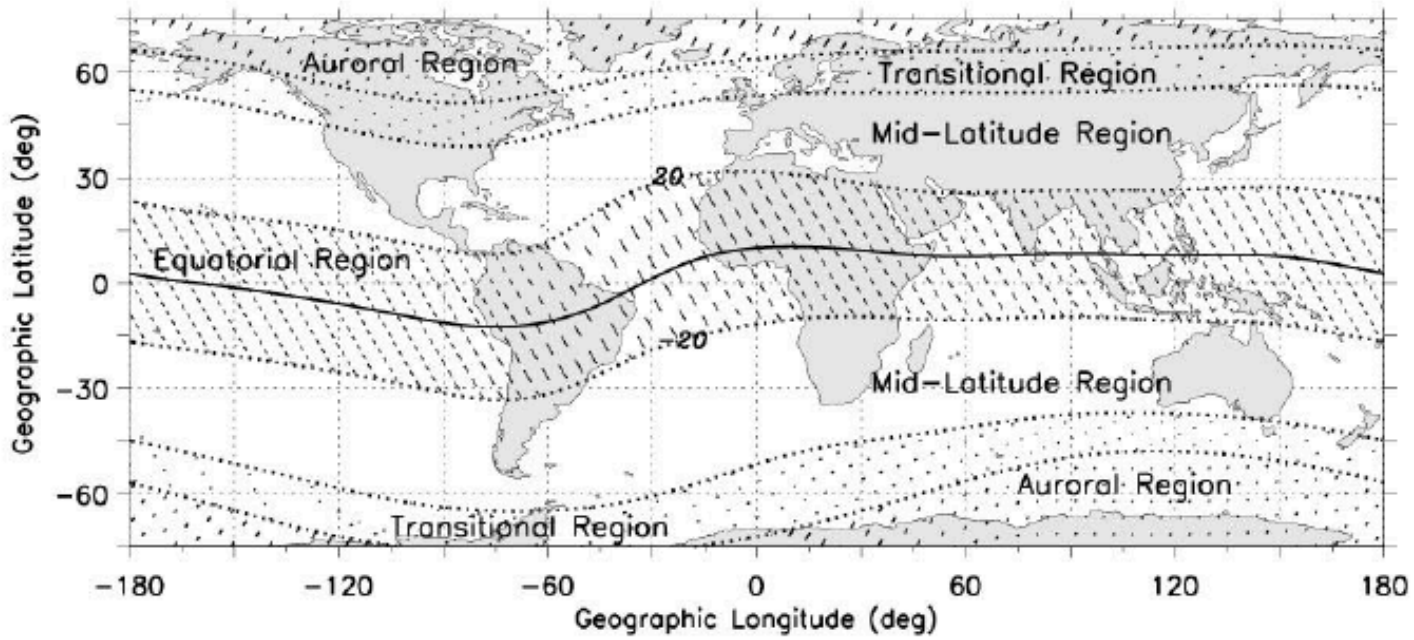
What does it means for our analysis?

It means that, if there are ionosphere effects of some meteorological phenomena and their occurrence increases, an increase of such effects will appear in some regions.

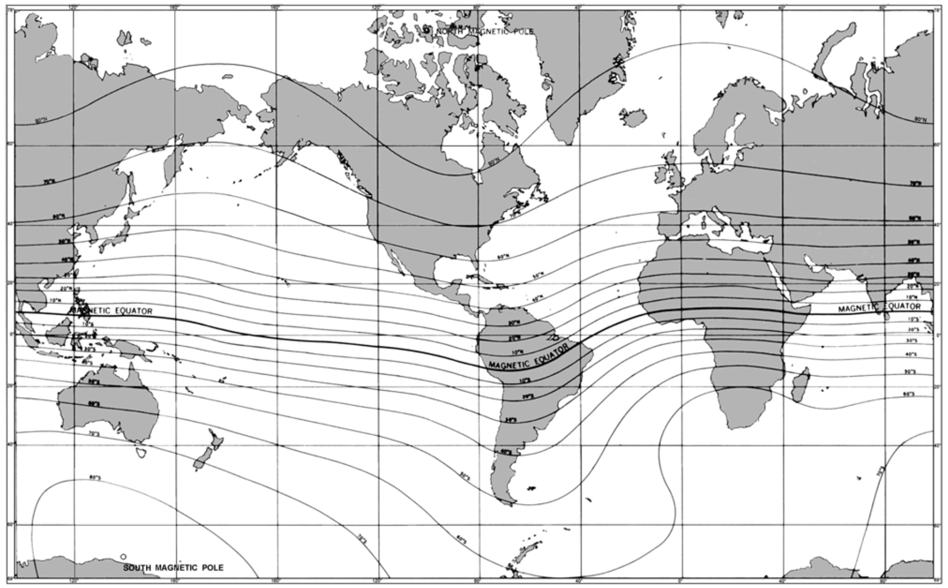
Ionospheric variability



Ionosphere by regions



This map illustrates the approximate geographic extent of each of these main regions. During typical geomagnetic conditions, the mid-latitude regions include the transitional regions. During disturbed geomagnetic conditions, the auroral regions can expand toward equator to include the transitional regions, reducing the width of the mid-latitude regions. During geomagnetic storms the extension of the IEA towards north and south could cause the a further reduction of the width of mid-latitude region.



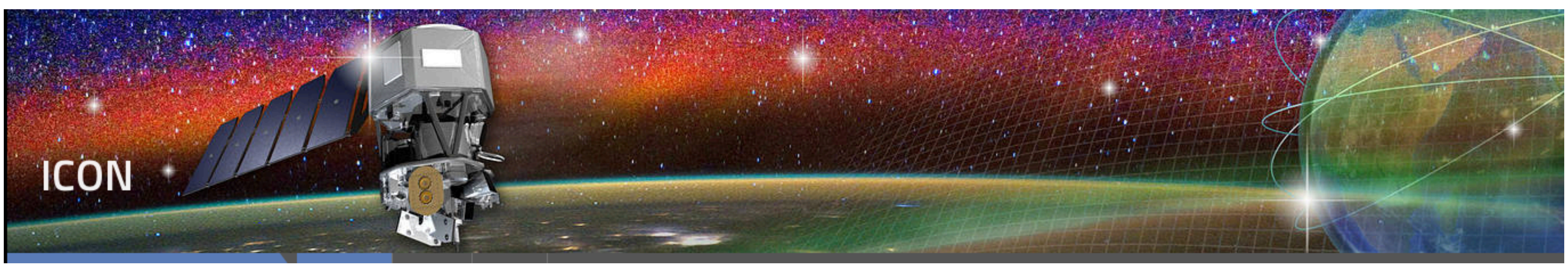
$$\tan \mu = \frac{I}{\sqrt{\cos \varphi}}$$

Where *I* is magnetic inclination or dip at 300 km and φ is the geographic latitude of the considered location. ***Modip is near magnetic dip at low latitudes and gets closer to geographic latitudes at higher latitudes.***

Ionospheric effects of Cyclone Activity

"To understand what drives variability in the ionosphere requires a careful look at a complicated system that is driven by both terrestrial and space weather."
(from the ICON Mission Overview)

Ionospheric Connection Explorer (ICON)



The Ionospheric Connection Explorer studies the frontier of space: the dynamic zone high in our atmosphere where Earth weather and space weather meet.

Ionospheric variations due to cyclone activity: the first mention?

Proceedings of the Institute of Radio Engineers
Volume 21, Number 5 — *May, 1933*

CYCLONES, ANTICYCLONES, AND THE KENNELLY-HEAVISIDE LAYER*

By
Robert Cameron Colwell
(Professor of Physics, West Virginia University, Morgantown, West Virginia)

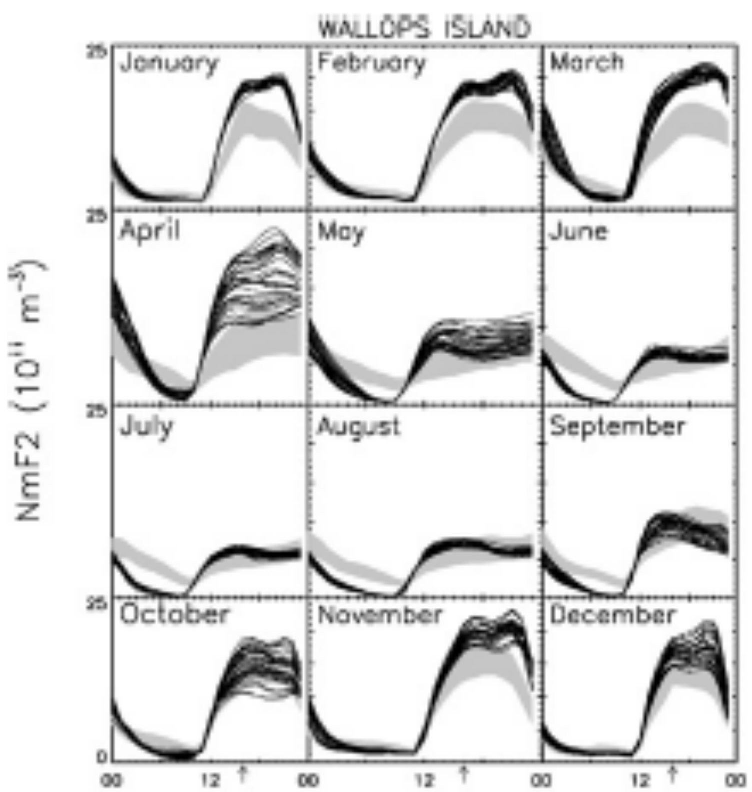
Summary—*Fading curves taken in Morgantown upon the signal of KDKA in Pittsburgh show an increase of intensity after nightfall provided a cyclonic area covers both cities or lies to the north of Morgantown. If a high pressure area covers both cities the night intensity does not increase above the day intensity and may even fall below it. These observations are explained by the theory that the Kennelly-Heaviside (E) layer is found at night in cyclonic regions but is not present in anti-cyclones. This theory is strongly supported by recent experiments of Ranzi on 100-meter waves.*

A starting point

- It is well known that solar and geomagnetic activity play an important role in electron density variation of the ionosphere.
- The influences from the lower atmosphere also contribute to ionosphere variability.
- Several studies show that there is a close correlation between ionospheric wave-like disturbances and severe meteorological phenomena, such as cyclone activity.
- Three papers at the start of the millennium are going to be mentioned first.

Mendillo et al. (2002)

Mendillo, M., Rishbeth, H., Roble, R., Wroten, J., 2002. Modelling F2-layer seasonal trends and day-to-day variability driven by coupling with the lower atmosphere. J. Atmos. Terr. Physics 64, 1911–1931.



From Fig. 1 of the paper. Ionosonde data are taken from the years 1960, 1967, 1970, 1978, 1983, and 1988. The shading shows the standard deviation from the monthly mean of ionosonde values recorded on all the individual days in all the years; the distinct daily curves are the model outputs for days 1–365.

From Mendillo et al. (2002) Abstract and Conclusions, ***This paper presents results from the TIME-GCM-CCM3 thermosphere–ionosphere–lower atmosphere-coupled model, and investigates how well the model simulates known F2-layer day-night and seasonal behaviour and patterns of day-to-day variability at seven ionosonde stations***… ***For the quiet geomagnetic conditions assumed here, we find that the disturbances propagating upward from the lower atmosphere cause variations in F2-layer electron density of order 10–30%...*** **we conclude that fluctuations in winds are the main cause…*****We consider that this work has shown the feasibility of including day-to-day variability in the lower atmosphere in ionospheric modelling.***

Kazimirowsky et al. (2003)

Kazimirovsky ES, Herraiz M, De la Morena BA (2003), Effects on the ionosphere due to phenomena below it, Surv Geophys 24:139–184

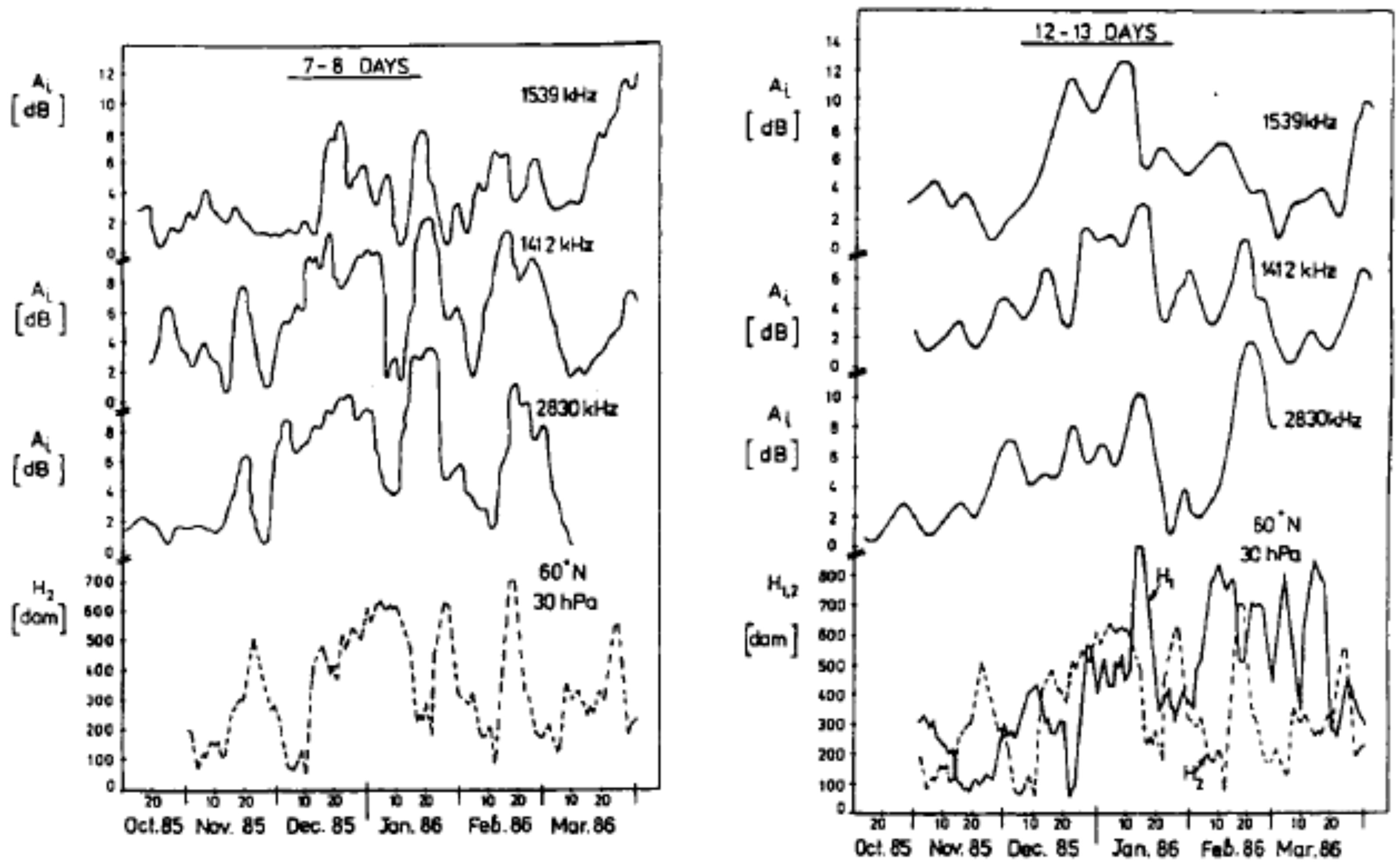


Figure 6. Time variations of amplitudes of radiowave absorption fluctuations (T = 7–8 and 12–13 days) for 1539 kHz, 1412 kHz and 2830 kHz and for the 30 hPa height wave 1 (full line) and height wave 2 (dashed line) at 60° N, winter period 1985/1986 (Pancheva et al., 1991).

Quasi-periodic fluctuations observed in absorption are caused not by fluctuations in the solar ionising flux but probably by planetary waves in the stratosphere/troposphere.

From Kazimirovsky et al. (2003). *"D-region aeronomy, the winter anomaly of radiowave absorption, wave-like travelling ionospheric disturbances, the non-zonality and regional peculiarities of lower thermospheric winds, sporadic-E occurrence and structure, spread-F events, the variability of ionospheric electron density profiles and Total Electron Content, the variability of foF2, etc., should all be considered in connection with tropospheric and stratospheric processes."*

Laštovicka (2006)

Laštovicka J (2006) Forcing of the ionosphere by waves from below, J. Atmos. Sol.-Terr. Phys 68:479–497

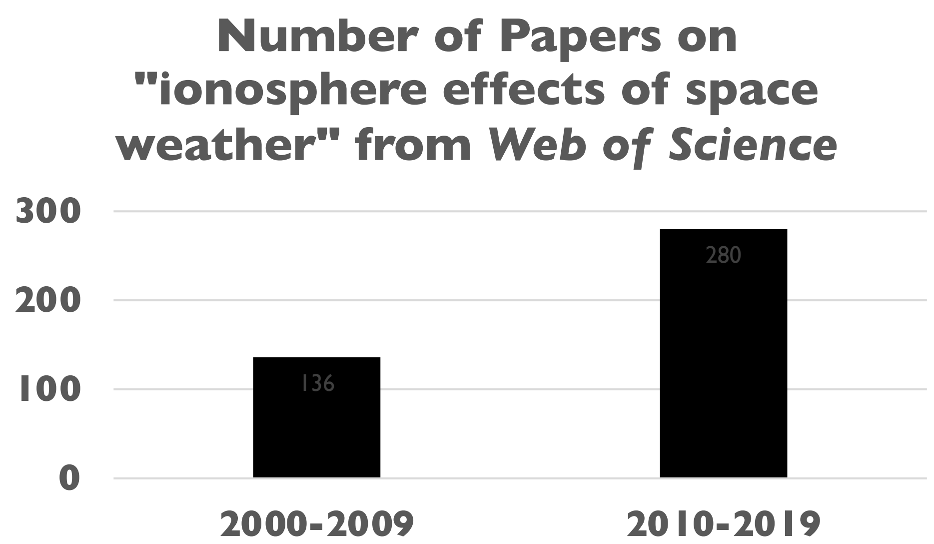
From Lastovicka (2006) conclusions.

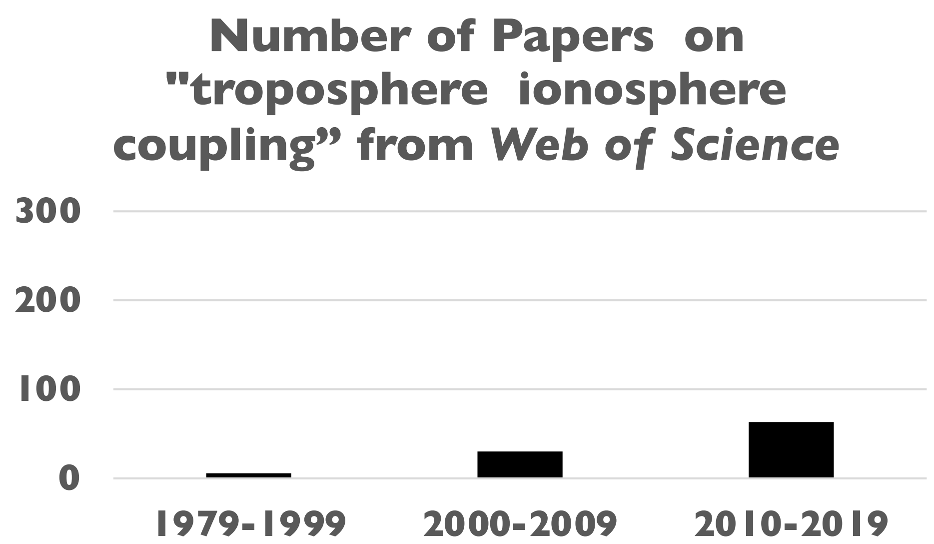
- ***Knowledge of the effects of waves coming from below into the ionosphere is very desirable for understanding the vertical couplings in the atmosphere–ionosphere system***, for the energy budget of the ionosphere, for ionospheric dynamics, ***and for predictions of the state of the ionosphere for communication and other purposes***.
- The effects of *tides coming from below* are important for the behavior of the ionosphere. They ***play an important role in the process of formation of the Es layers.***
- ***Tides contribution to the variability of f0F2 is significant***.
- The ***planetary waves significantly modulate the Es layers and their formation.***
- ***Gravity waves play an important role in the behavior of the ionosphere. They are responsible for a substantial (often dominant) part of the ionospheric effects of various tropospheric meteorological phenomena like cold fronts, mesoscale convective complexes, etc***.

Scientific interest about the possible coupling between troposphere and ionosphere

- “Space weather” effects in the ionosphere have interested scientists in a relevant way from the time when the topic was known as “Solar-Terrestrial Physics” several decades ago to our days.

- “Troposphere-ionosphere coupling” or “Tropospheric weather effects in the ionosphere” was studied only sporadically until the beginning of the new millennium when the systemic approach for atmosphere research was recognized as the way to go. Now the number of these studies is starting to increase.





Tropospheric induced ionospheric variations: the result of a more systemic approach

From the paper:

“Day-to-day ionospheric variability due to lower atmosphere perturbations” by H.-L. Liu, V. A. Yudin, and R. G. Roble; GEOPHYSICAL RESEARCH LETTERS, VOL. 40 (2013), 665–670.

This study demonstrates that the thermosphere-ionosphere-mesosphere electrodynamics general circulation model (TIEGCM) constrained by the atmosphere community climate model (WACCM) simulations is capable of reproducing observed features of day-to-day variations in the F2 region at low latitudes.

LIU ET AL: DAY-TO-DAY IONOSPHERIC VARIABILITY

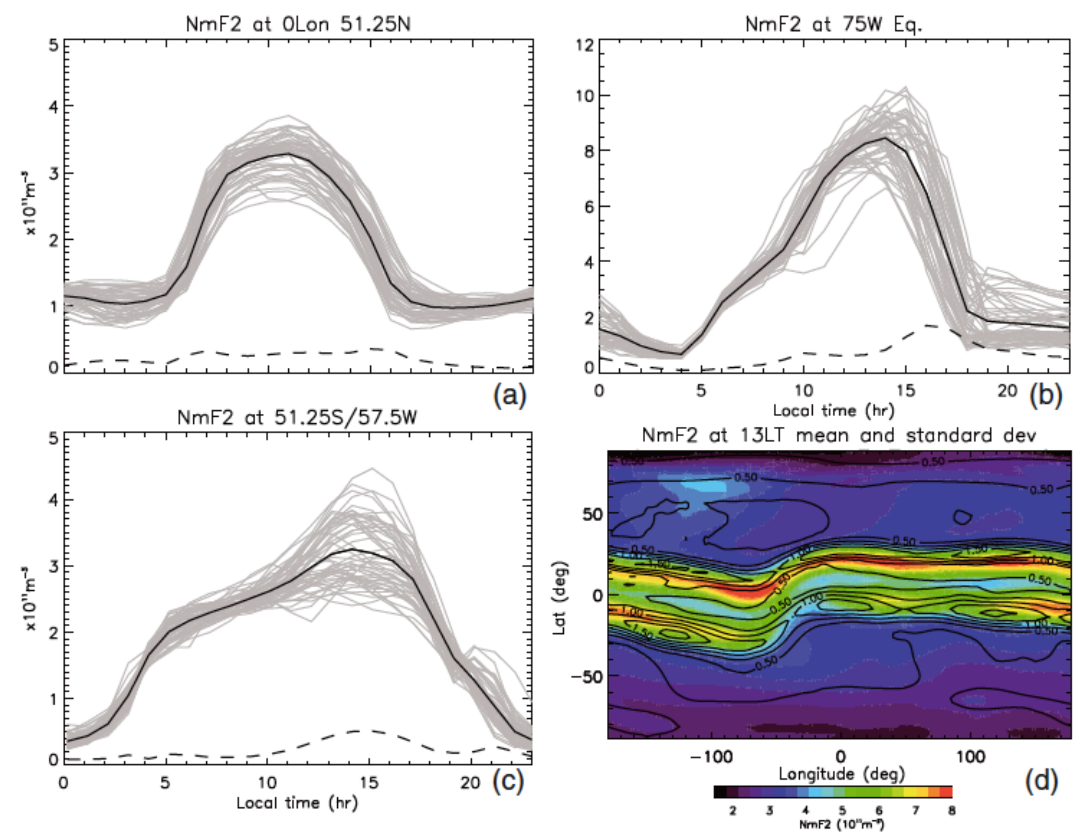


Figure 4. Daily values of NmF2 (gray), their mean values (black solid), and the standard deviation (dashed) for (a) 51.25°N/0 longitude, (b) equator/75°W, and (c) 51.25°S/57.5°W (all geographic). (d) Mean values (shades) and standard deviation (lines) of NmF2 for LT1300. Contour intervals: 2.5×10^{10} m^{-3}.

Under constant solar minimum and geomagnetically quiet conditions the meteorological driving may contribute comparably with geomagnetic forcing to the ionospheric day-to-day variability.

Low ionosphere effect of tropical depression prior hurricanes

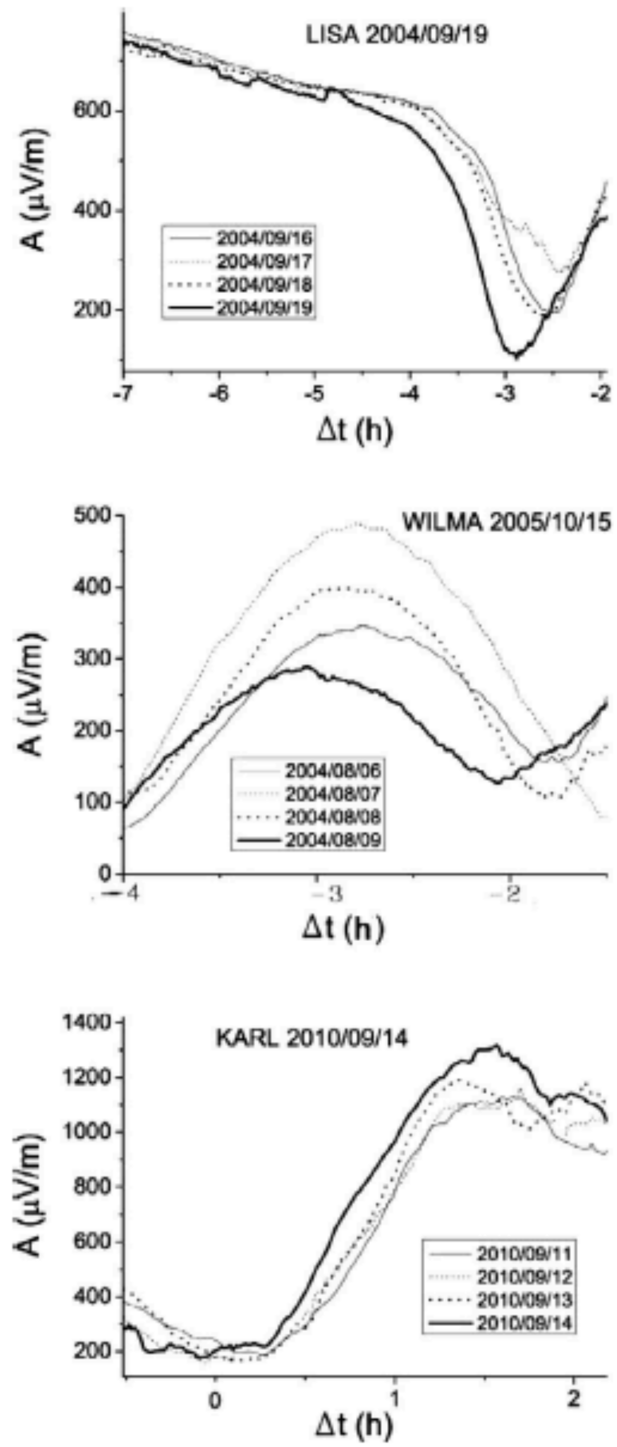


Fig. 4. Three types of amplitude changes several hours around depression beginnings. Upper panel: amplitude decrease during daytime conditions (usually immediately before ST period), middle panel: amplitude decrease during ST period before nighttime (in this case there were two TDB events), and bottom panel: amplitude increase at the end of ST period before nighttime conditions. The time 0 h refers to the time of TDBs.

From Nina et al (2017) abstract: We study the reactions of the low ionosphere during tropical depressions (TDs) which have been detected before the hurricane appearances in the Atlantic Ocean. We explore 41 TD events using very low frequency (VLF) radio signals emitted by NAA transmitter located in the USA and recorded by VLF receiver located in Belgrade (Serbia). We found VLF signal deviations (caused ionospheric turbulence) in the case of 36 out of 41 TD events (88%).

Nina A. , Milan Radovanovic, Bosko Milovanovic, Andjelka Kovacevic, Jovan Bajcetic, Luka C. Popovic, Low ionospheric reactions on tropical depressions prior hurricanes, Advances in Space Research 60 (2017, 1866–1877

Ionosphere TEC disturbance over Tropical Cyclones

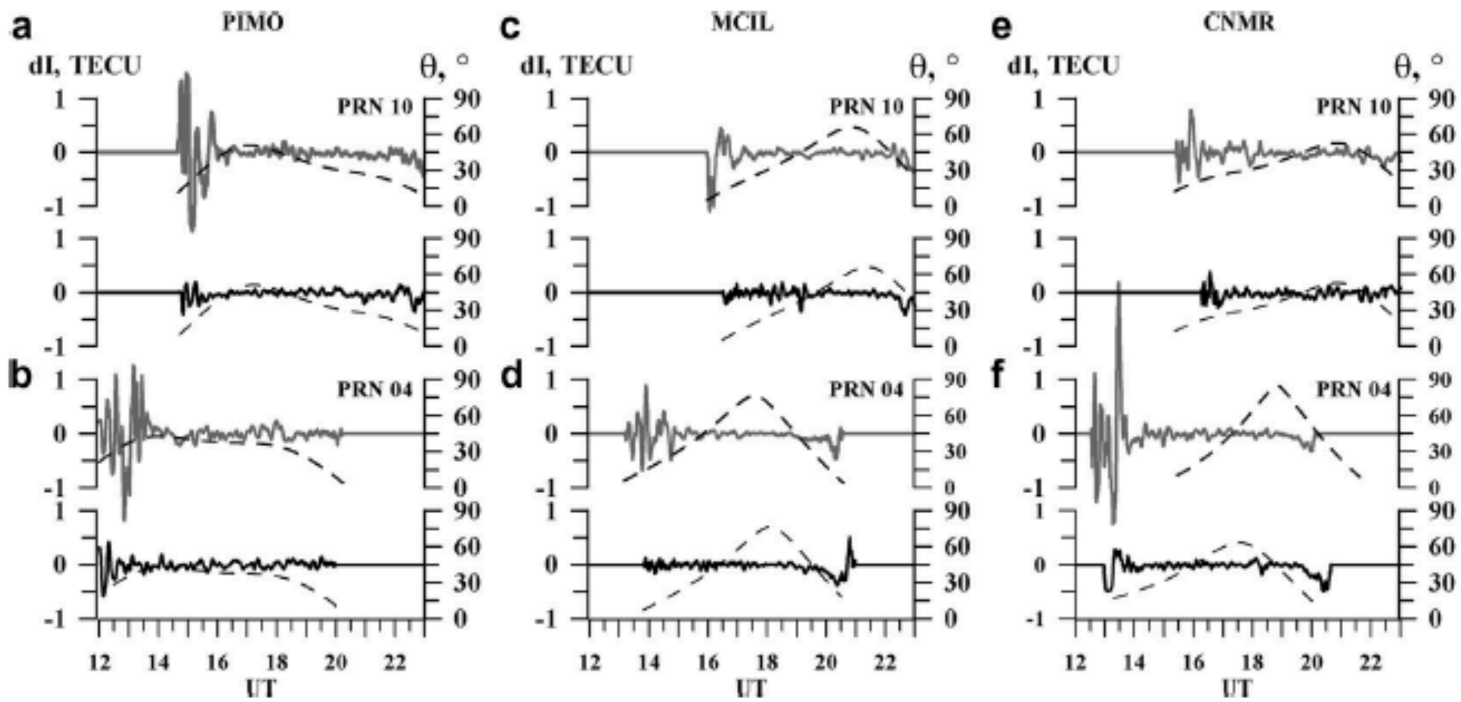


Fig. 6. The TEC variations filtered over the range of 02 –20 min on days of maximum development of the cyclones (gray lines) and on quite days (black lines).

TCs DAMREY (September 24, 2005, the PIMO station), SAOLA (September 25, theMCIL station), LONGWANG (September 30, the CNMR station) at their peak intensity.

From Polyakova&Perevalova (2013) abstract:TEC variations of different period ranges (02–20 and 20–60 min) are shown to be more intense during TC [tropical cyclone] peaks under quiet geomagnetic conditions. **The highest TEC variation amplitudes are registered when the wind speed in the cyclone and the TC area are maximum.** The intensification of TEC disturbances is more pronounced when several cyclones occur simultaneously. **We have revealed that the ionospheric response to TC can be observed only after the cyclone has reached typhoon intensity. The ionospheric response is more pronounced at low satellite elevation angles.**

Polyakova A.S. and, N.P. Perevalova, Comparative analysis of TEC disturbances over tropical cyclone zones in the North–West Pacific Ocean, Advances in Space Research 52 (2013) 1416–1426

Ionospheric TEC disturbance during a typical convective weather over China

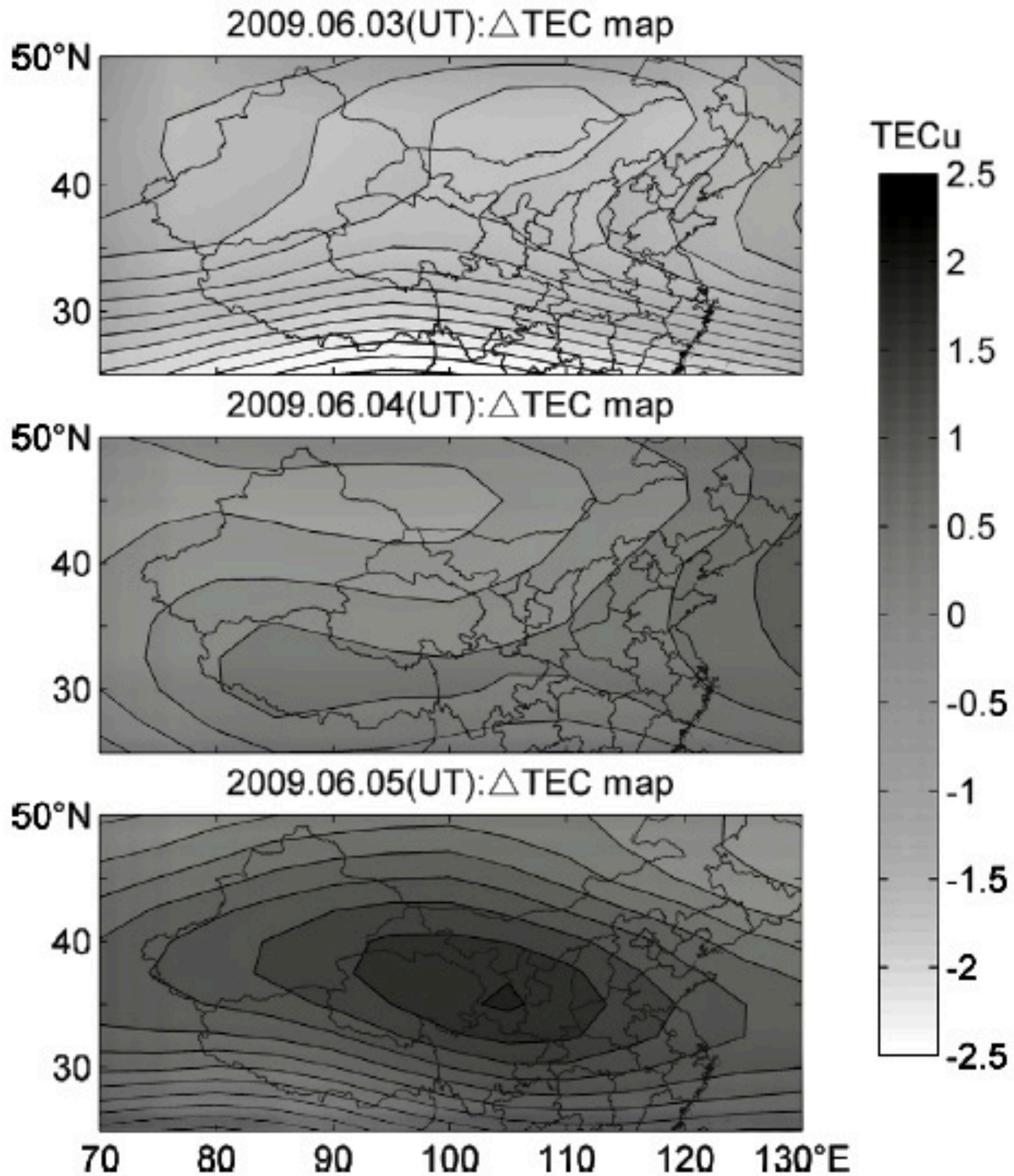


Fig. 3. The contour distributions of the anomaly of daily-average-TEC on June 3–5 (ΔTEC map).

From Cang et al. (2015):
Based on TBB data from Chinese FY-2 geostationary satellite, NCEP Reanalysis data and GPS-TEC data provided by IGS, by using sliding mean method, ionospheric anomalous disturbance during a typical convective weather was investigated.

Fig 3: On the day 5th (lower panel), TEC of surrounding areas of the strong convection increased to the peak, and the maximum deviation reached more than 2.5 TECU.

Cang Zhongya, Guangguang Cheng, Guosheng Cheng, Ionospheric anomalous disturbance during the tropospheric strong convective weather, J. Atmos. Solar-Terr. Phys. 129(2015)55–61

Ionosphere disturbances during Hurricane Michael

- An analysis of vertical total electron content (TEC) estimates from the MIT Madrigal database is performed for the regions surrounding the eye of Hurricane Michael.
- Absolute and detrended TEC values show a noticeable increase during the tropical cyclone (TC) relative to fluctuations at the same locations prior to the storm.
- Direct comparisons of TEC perturbation magnitudes to the number of lightning flashes showed no visible trends.
- The lack of a direct relationship between overhead TEC fluctuations and lightning/rainfall rates suggests that AGWs are most likely responsible for the large TEC perturbations supporting previous research.
- Analizing the MUF(3000) for three separate ionosonde stations near the Gulf of Mexico Region (Eglin FL, Wallops Island VA, and Austin TX) before and during Hurricane Michael, larger fluctuations after TC formation on 7 Oct. are shown.

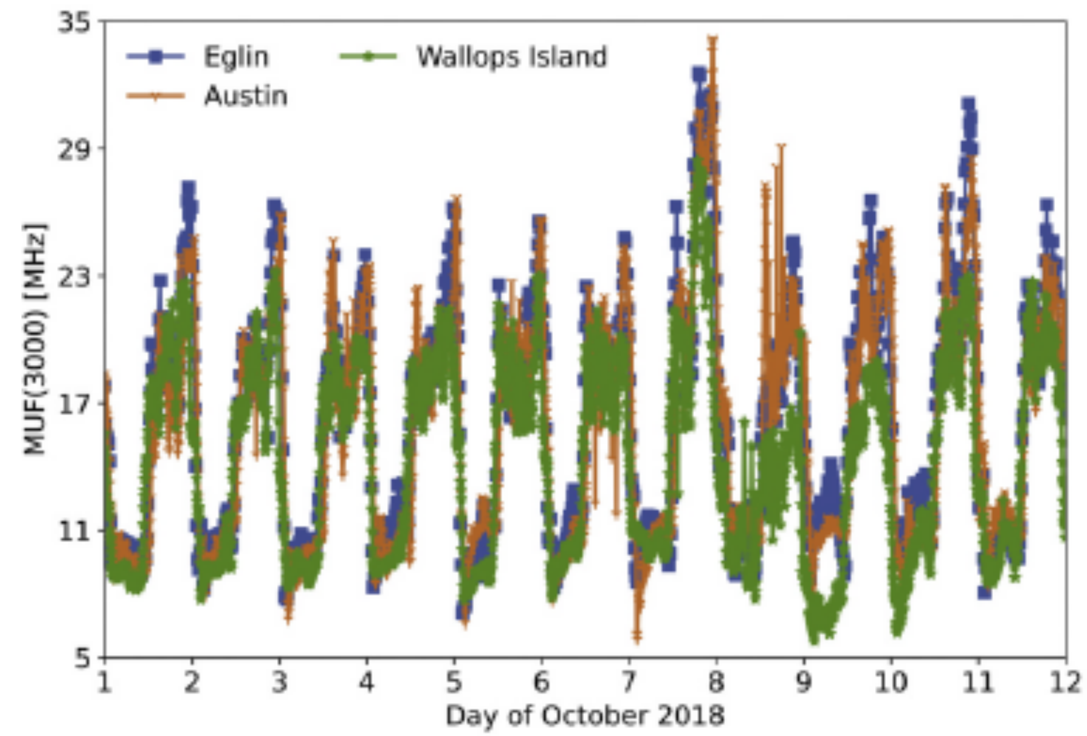
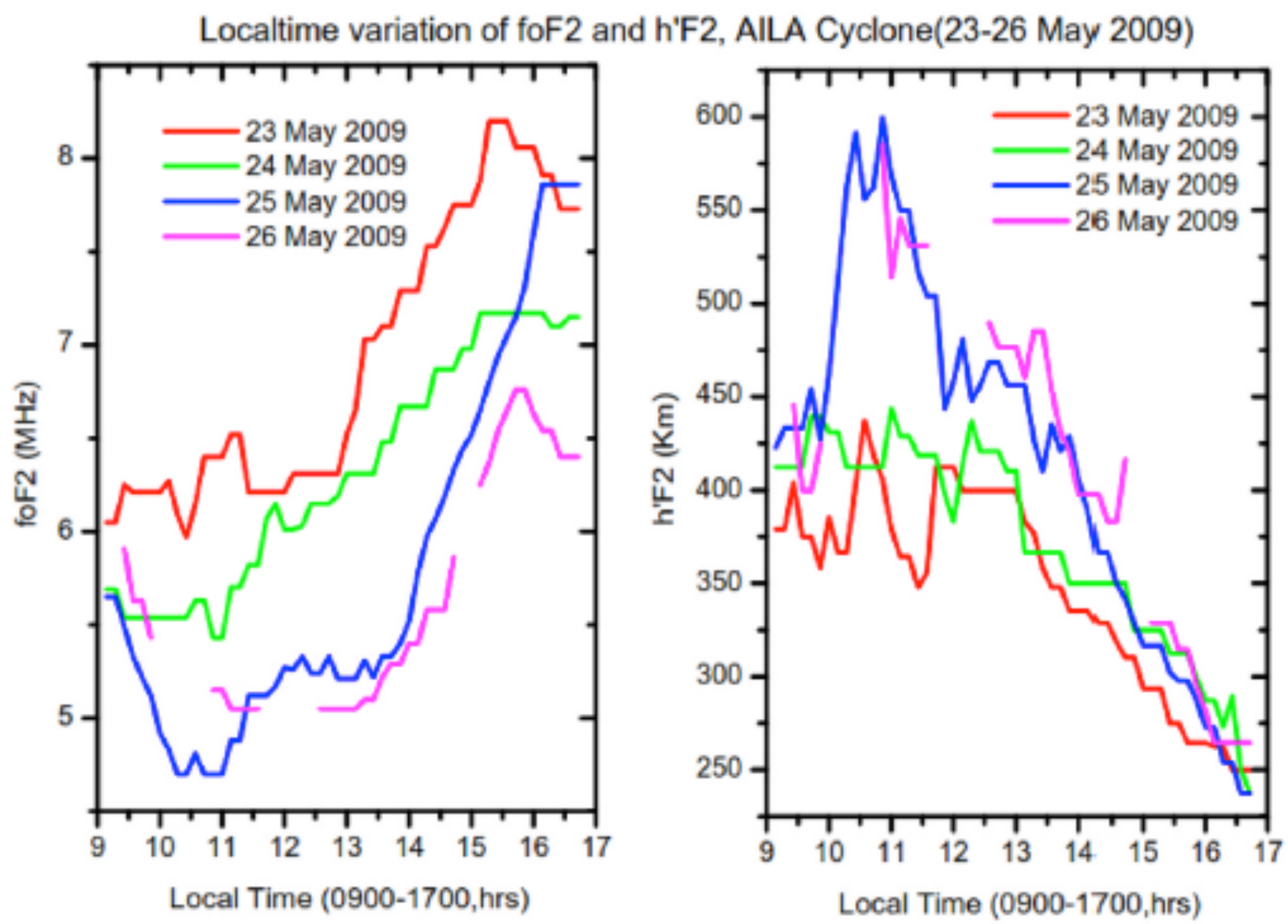


Figure displays the MUF(3000) estimates from the Global Ionosphere Radio Observatory

Williams, J. E. S., Tournay, R. C., Tseng, H. R., Emmons, D. J., & Nava, O. A. (2021). Impact of Hurricane Michael (2018) on local vertical total electron content. J. Atmos. Sol.-Terr. Phys, 219, 105647. https://doi.org/10.1016/j.jastp.2021.105647

Low latitude Ionosphere foF2 and h’F2 disturbance during a severe cyclone storm

From: Bhagavathiammal et al. (2020)
The value of h’F2 shows some significant change by rising from 435 km to 585 km at the time of AILA cyclone transformation from deep depression into a severe cyclonic storm on May 25, 2009. This sustained h’F2 increase continues on May 26, 2009, At the same time, the peak of foF2 shows a substantial decrease of about ~0.85 MHz on May 26, 2009 at the time of cyclone transformation from cyclonic storm into a deep depression.



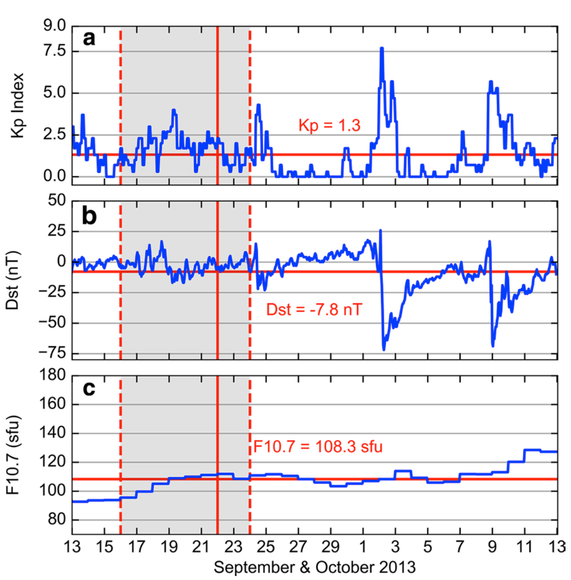
Bhagavathiammal G.J., Manohar Lal, K. Emperumal, Observational evidence of equatorial ionospheric response to severe cyclonic storms ‘AILA’ and ‘WARD’ observed over the North Indian Ocean, J. Atmos. Solar–Terr. Phys. 211 (2020) 105462

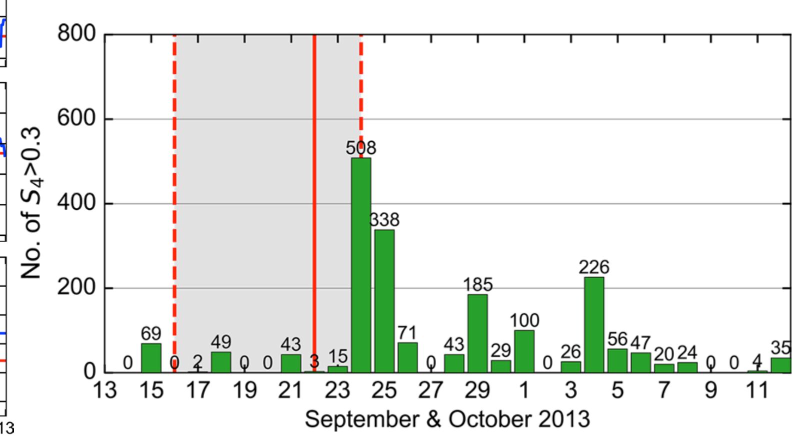
Ionospheric and positioning effects during a tropical cyclone (1)

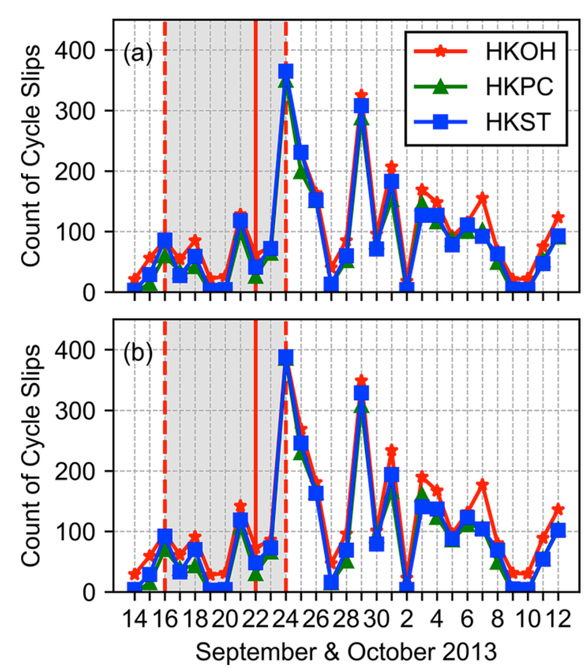
Yu and Liu Earth, The ionospheric condition and GPSpositioning performance during the 2013 tropical cyclone Usagi event in the Hong Kong region, Planets and Space (2021) 73:66
https://doi.org/10.1186/s40623-021-01388-2

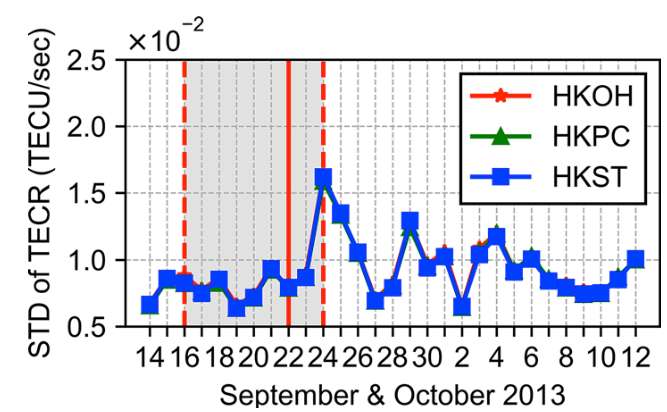
From Yu and Liu (2021) abstract:This study analysed the variation of three ionosphere-related parameters based on the GPS data including ***scintillation index S4, cycle slips, and total electron content (TEC) rate (TECR)**** during the tropical cyclone event (the 2013 TC Usagi) in the Hong Kong region. The results showed that the ionosphere-related parameters had a consistent significant increase on the second day after the Usagi made landfall near Hong Kong.

*** TECR from: Liu Z (2011) A new automated cycle slip detection and repair method for a single dual-frequency GPS receiver. J Geod 85(3):171–183. https ://doi.org/10.1007/s0019 0-010-0426-y**



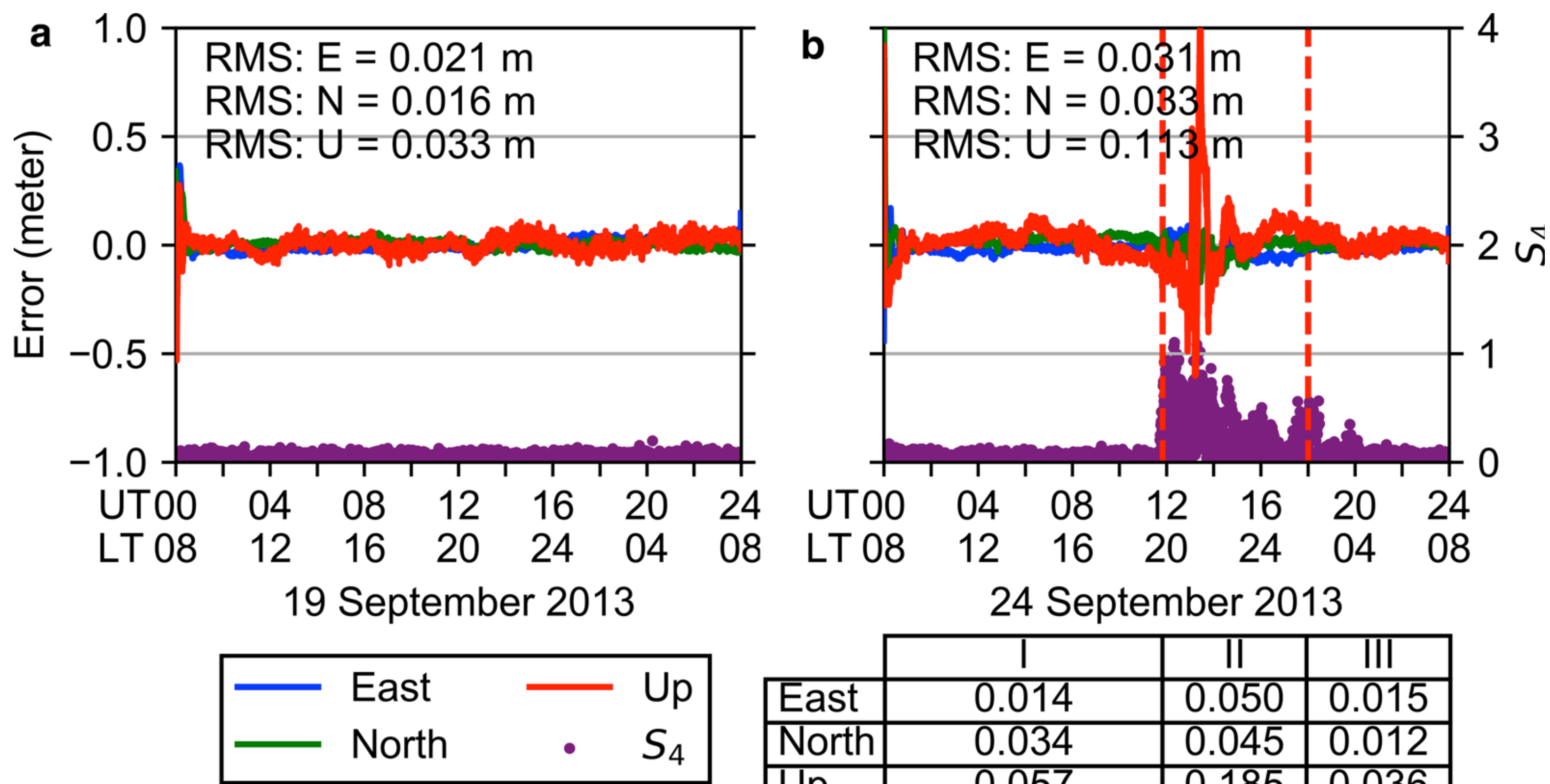






Ionospheric and positioning effects during a tropical cyclone (2)

Consequently, the positioning performance of GPS precise point positioning (PPP) and relative positioning modes was degraded. The degradation was ~ 138%, ~ 181%, and ~ 460% in the east (root mean square (RMS) 0.050 m), north (RMS 0.045 m), and up (RMS 0.185 m), respectively, compared with the RMS of 0.021 m in the east, 0.016 m in the north, and 0.033 m in the up on the normal day.

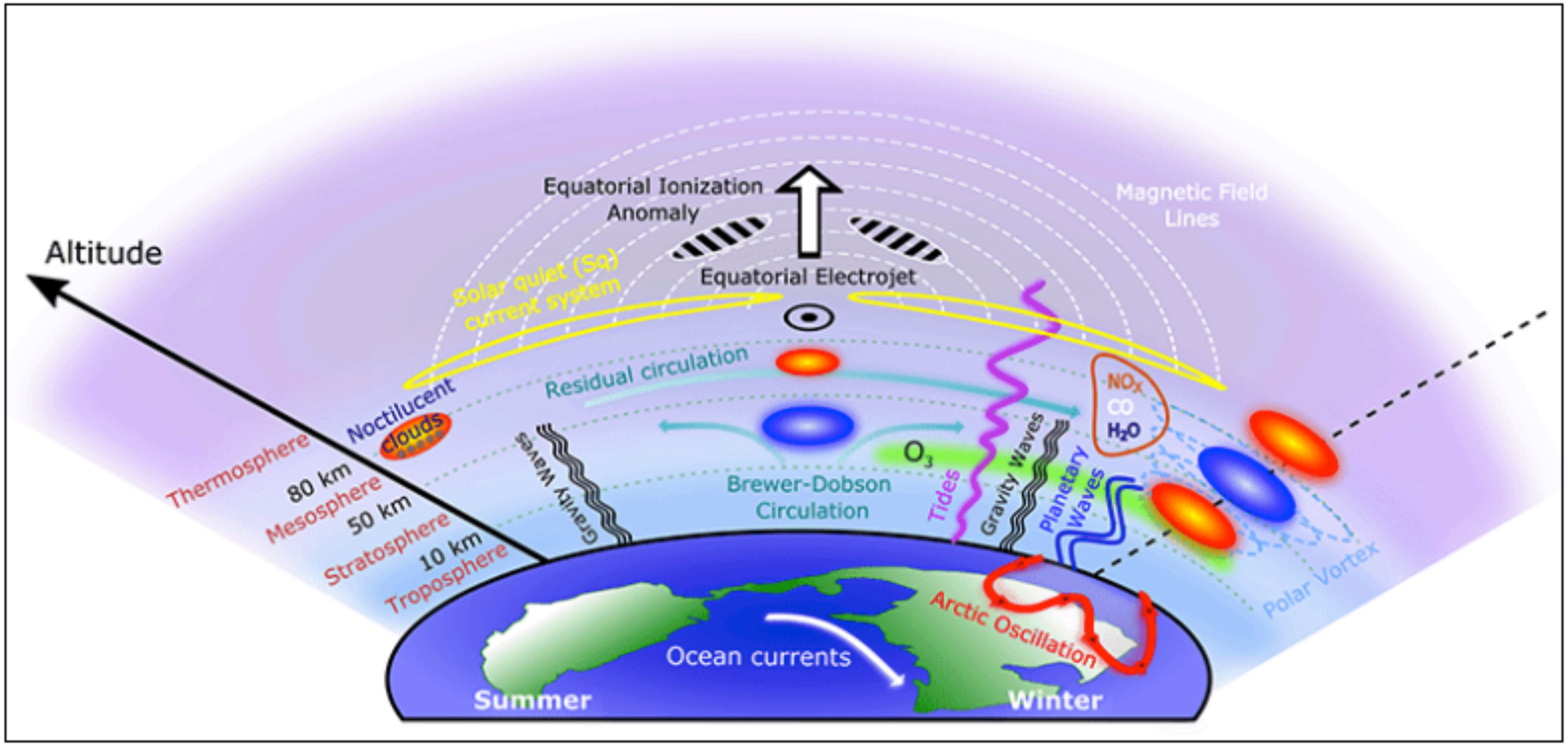


	I	II	III
East	0.014	0.050	0.015
North	0.034	0.045	0.012
Up	0.057	0.185	0.036

Ionosphere effects of sudden stratospheric warming

About Sudden stratospheric warming (SSW) (1)

Sudden stratospheric warmings (SSWs) are impressive fluid dynamical events in which large and rapid temperature increases in the winter polar stratosphere (~10–50 km) are associated with a complete reversal of the climatological wintertime westerly **winds**.



About Sudden stratospheric warming (SSW) (2)

Events 10–50 kilometers above Earth's surface like sudden stratospheric warmings (SSW), in the stratosphere, affect weather on the ground as well as weather-like conditions hundreds of kilometers above. Experiments demonstrate that understanding the way stratospheric disturbances propagate downward into the troposphere allows forecasters to predict surface weather farther into the future. *In upward coupling, a SSW is important factor in the development of global teleconnections, as a modifier of wave signatures and middle atmosphere circulation and as the driver of significant changes in ionosphere current systems*.

Sudden stratospheric warming (SSW) effects in the ionosphere

The Whole Atmosphere Community Climate Model with thermosphere and ionosphere extension (WACCM-X) is a **numerical model of entire atmosphere, from the surface to around 600 km in altitude**. Recent enhancements to WACCM-X include a fully coupled ionosphere, including electric field effects and ion transport.

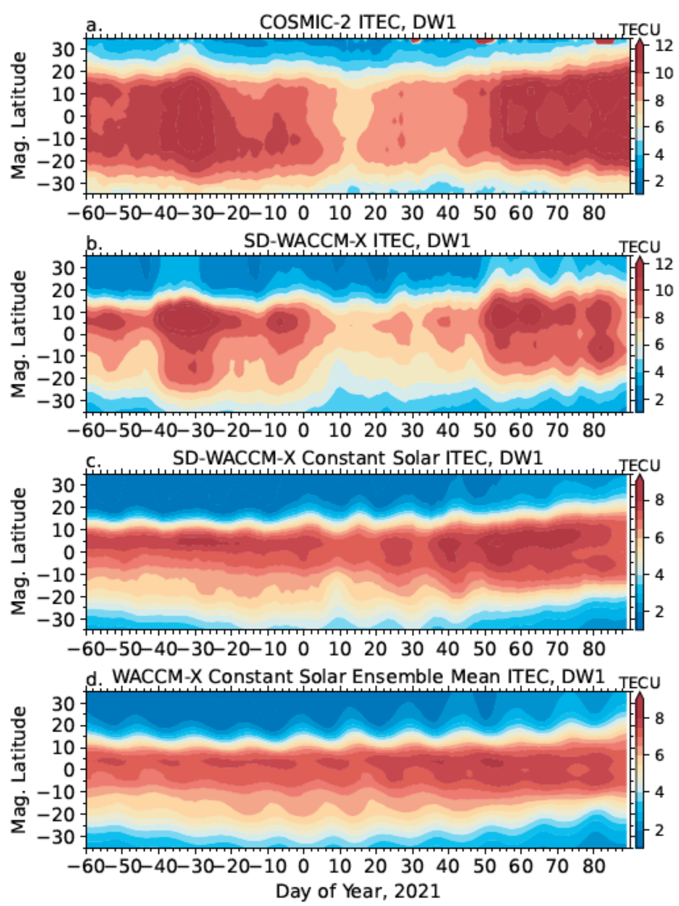


Figure 4. DW1 amplitude in ITEC from (a) COSMIC-2 observations, (b) SD-WACCM-X, (c) SD-WACCM-X Constant Solar, and (d) WACCM-X Constant Solar Ensemble Mean.

From Pedatella (2022): Motivated by the dense sampling of the ionosphere made possible by COSMIC-2, the objective of the present study is to investigate the ionospheric variability during the 2020–2021 SSW. The 2020–2021 SSW occurred when the COSMIC-2 constellation was nearly in its operational configuration, providing among the first opportunities to leverage the density of COSMIC-2 observations to investigate the short-term variability of the ionosphere that is driven by meteorological variability. The COSMIC-2 observations are complemented by numerical simulations performed using the Whole Atmosphere Community Climate Model with thermosphere–ionosphere eXtension (WACCM-X). The WACCM-X simulations enable understanding of the sources of the ionosphere variability observed by COSMIC-2**. The results** illustrate the capabilities of the COSMIC-2 observations to capture the rapid variations that occur in the ionosphere during SSW events and **demonstrate that the 2020–2021 SSW was associated with complex variability in the ionosphere that was driven by a combination of variability due to the SSW and from solar/geomagnetic activity.**

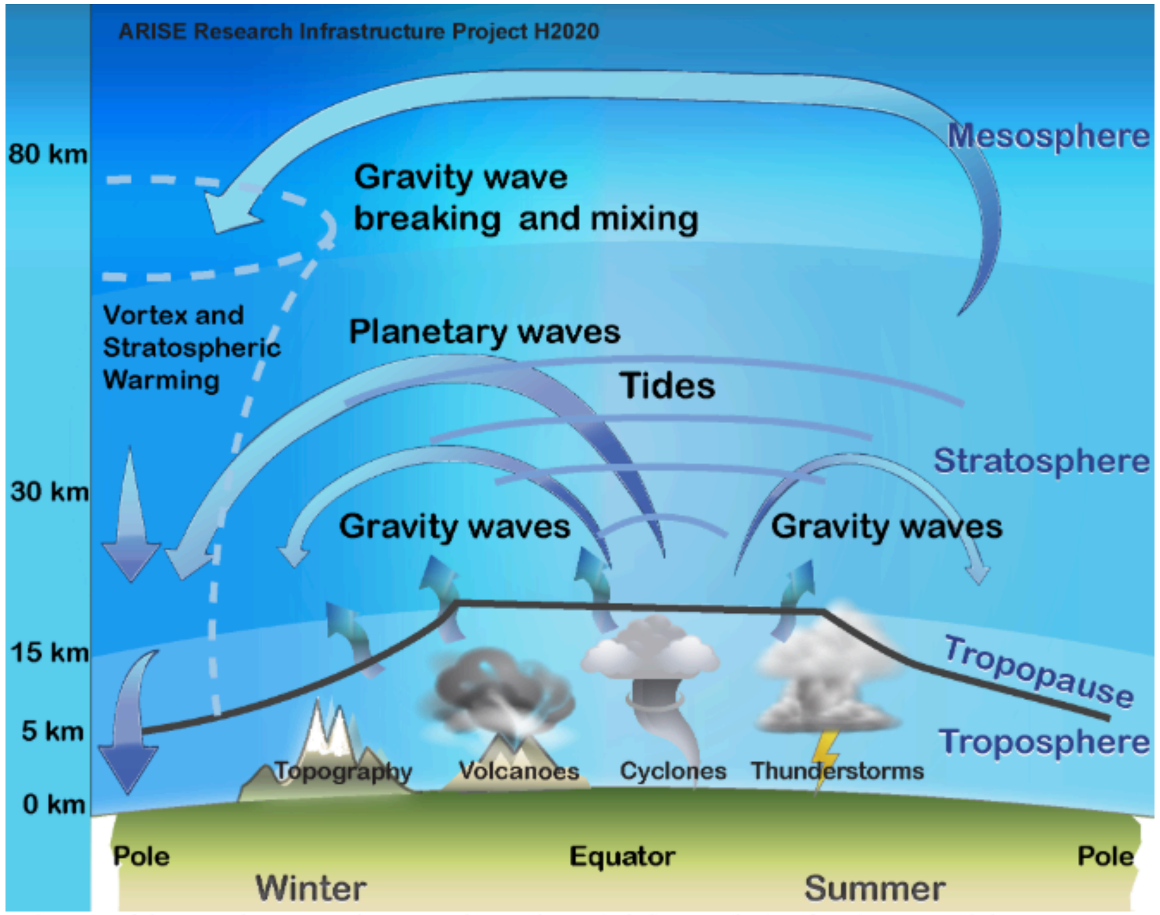
Pedatella, N. Ionospheric Variability during the 2020–2021 SSW: COSMIC-2 Observations and WACCM-X Simulations. Atmosphere 2022, 13, 368. https://doi.org/10.3390/atmos13030368

Conclusions and Final Words

Conclusions

Studies reported in this talk indicate that:

- Ionosphere variability is influenced by meteorological phenomena like cyclones in the troposphere and sudden stratospheric warmings in the stratosphere.
- The main cause appears to be related to waves coming from the area of the phenomenon propagating above.
- To identify the effects from below is necessary to have clear understanding of the complex interactions of the ionosphere also with the sun and the geomagnetic field.
- To identify the different physical processes involved in the complex interactions that controls the ionosphere is necessary to support measurements with simulations that use models able to simulate the atmosphere from the ground up to the ionosphere.
- To perform accurately the study of ionospheric effects of meteorological phenomena is necessary a multidisciplinary systemic approach involving scientists from different fields of science.



Dynamics of the troposphere-stratosphere-mesosphere exchanges including contribution of gravity waves and planetary waves.

From: http://arise-project.eu/atmospheric-dynamics.php

Final words

The topic touched in this talk is rather new!
For this reason, I hope it can be attractive to young scientists exploring the unknown,
not influenced by the older scientists "own expertise",
well gained through many years of hard "linear approach" work.

Thank you for your attention